Radiation transport modelling in EIRENE revisited

R. Chandra[1], D. Reiter[2], N. Horsten[3], M. Groth[1]

[1] *Aalto University, Espoo, Finland*

[2] *Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität, Düsseldorf, Deutschland*

[3] *KU Leuven, Department of Mechanical Engineering, Leuven, Belgium*

The radiation transport model in EIRENE is restored to assess line radiation opacity effects in high-density divertor plasma regimes. Ly-α and Ly-β re-absorption in particular can effectively modify the volume recombination and ionization balance, which in turn affects the required separatrix density to achieve plasma detachment [1, 2]. Radiation trapping in divertor plasmas was studied in the past by extending the EIRENE neutral particle transport code to include line photons as test-particles [3–6]. We restore this approach in the more modern plasma edge code SOLPS-ITER [7, 8] and investigate opacity effects in high-density divertor plasmas observed in JET [9, 10] as the first application. The sources of the Lyman lines used here, namely the population of excited hydrogen (at $n = 2$ and 3 for Ly-α and Ly-β emission, respectively), are calculated using a collisional-radiative model within EIRENE. The emission and absorption profiles of the Lyman lines include the Doppler, Zeeman, and natural broadening mechanisms, and a simple reflection model for photons at the boundaries. The distribution of the excited species is recalculated at subsequent iterations of EIRENE with additional sources from photon absorption by the ground state atom, thus providing a self-consistent neutral-photon gas description within a fixed plasma background. New effective plasma ionization, recombination, and electron energy rates are obtained with photon re-absorption effects included. The ionization and recombination rates can be used in the plasma fluid code to calculate plasma sources and sinks that incorporate opacity effects, hence producing a more accurate and consistent description of the high-density divertor plasma.

References

[1] J. L. Terry et al., Physics of Plasmas 5, no. 5: 1759–66 (1998)
[2] S. Lisgo et al., Journal of Nuclear Materials 337–339:139–45 (2005)
[3] D. Reiter et al., Plasma Physics and Controlled Fusion 44, 8:1723–37 (2002)
[4] S. Wiesen et al., 30th EPS Conference on Contr. Fusion and Plasma Phys., ECA Vol. 27A, P-3.194 (2003)
[5] S. Wiesen, PhD Thesis, Ruhr-Universität Bochum (2005)
[6] V. Kotov et al., Juel-Report 4257 (2007)
[7] S. Wiesen et al., Journal of Nuclear Materials 463:480–84 (2015)
[8] X. Bonnin et al., Plasma and Fusion Research 11:1403102–1403102 (2016)
[9] B Lomanowski et al., Plasma Physics and Controlled Fusion 62, 6:065006 (2020)
[10] N. Horsten et al., Nuclear Materials and Energy 33:101247 (2022)

Modelling of particle species effect on beam-ion losses in Wendelstein 7-X

L. Sanchis[1], T. Kurki-Suonio[1], S. Äkäslompolo[1], J. Kontula[1], S. Lazerson[2]

[1] *Aalto University, FI-00076 Aalto, Finland*

[2] *Max Planck Institute for Plasma Physics, Greifswald, Germany*

Predictive ASCOT simulations of the beam-ion behaviour proved themselves very useful when preparing W7-X for the first neutral beams in OP1 [1, 2]. This was particularly the case when considering the beam ion power loads to sensitive components on the vessel wall. Therefore simulation work has been continued for the new OP2 campaign that features additional beams. In OP2.1, experiments using H and He plasmas have been proposed to study the isotope effect. Some of these experiments will employ the NBI system, which requires beam modelling to assess the power loads in different scenarios. The NBI system consists of 2 boxes with 4 beams each. Although not all of them are currently in operation, all 8 beams were considered for this study. Furthermore, campaign OP2.2 is expected to introduce D plasmas.

Preliminary simulations indicate the number of beam-ion losses to grow from 13% in H beam and H plasma (H→H) to 29% in the D→D case for the standard scenario. There are two main factors affecting the increase of losses in the D case. First, the different masses and the higher energy of the D-beam, which is 60 keV compared to the 55 keV of H-beams, increase the width of the D-ion orbits. Additionally, the ionisation profile for the D beam features more ions at the plasma edge. It was also observed that the power-load wall patterns depend on the species and the magnetic configuration. This implies that even if the total beam-ion losses are not greatly increased between different configurations, some may lead to values exceeding the safety limit on critical components, such as the F-ports. In figure 1, a 3D view of W7-X shows where the leading edges of an upper F-port are concentrating loads of the order of $1\,\mathrm{MW\,m^{-2}}$. This study includes a wall mesh that is detailed enough to account for these small structures and provide realistic estimations of the wall loads.

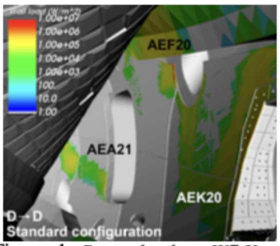


Figure 1: *Power loads at W7-X using D-beam on deuterium plasma.*

The analysis of these results will be completed with H and D-beams in He plasmas, and all cases will be presented for the standard, high-mirror and low-mirror configurations. Finally, a scan over a set of achievable parameters of density and temperature will be included to evaluate their effect on the power loads.

References

[1] S. Akaslompolo et al., Nucl. Fusion **58**, (2018) 082010

[2] J. Kontula et al., Submitted to Plasma Phys. Control. Fusion (2023)

Extension of high performance in high β_P scenario by optimising the fast ion confinement on EAST

J. Huang[1], X. Gong[1], A. M. Garofalo[2], J. Qian[1], X. Zhang[1], Y. Sun[1], M. Salewski[3], J. Wang[1], W. Zhang[1], J. Fu[1], J. Chang[1], Q. Zhong[1], T. Fan[4], B. Hao[1], Q. Zang[1], H. Liu[1], B. Lyu[1], Y. Xie[1], B. Wan[1], and EAST Team[1]

[1] *Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China*

[2] *General Atomics, San Diego, California, 92186-5608, USA*

[3] *Department of Physics, Technical University of Denmark, Kgs. Lyngby, Denmark*

[4] *Tsinghua University, Beijing, China*

EAST has demonstrated fully non-inductive scenarios with an extension of fusion performance at high density: β_P~3.1, β_N~2.1, $H_{98,y2}$~1.2, exploiting the device's long pulse capabilities with improved performance. Important synergistic effects are leveraged towards this result, which relies on reduced beam-ion loss and the acceleration of beam ions by ICRF wave fields at the harmonics. To enhance NBI and ICRF heating capabilities, beam sources are optimised to avoid significant orbit losses, and the parallel wave number of ICRF antennas is decreased to improve the antenna coupling. Further, to obtain high performance plasma and improve fast-ion confinement on EAST, related parameters (e.g. n_e, I_p, E_{NBI}, etc.) need to optimise to reduce the fast ion slowing down time and prompt loss. Experimental results show that prompt loss can be reduced by reducing beam voltage, increasing plasma current, and optimising gapout which is consistent with simulations. The synergetic effect of ICRF and NBI can be further enhanced by optimising the isotope ratio (H/H+D), which can accelerate beam ions with energy up to hundreds keV. In order to investigate fast-ion dynamics, the fast-ion velocity distributions are also investigated by combining FIDA and neutron measurements. The extension of high performance, fully non-inductive experiments on EAST at high density can potentially offer unique contributions towards ITER and CFETR.

Work supported by the National Natural Science Foundation of China under Grant 11975276 , the project National MCF Energy R&D Program 2019YFE03020004.

Core tungsten transport impacted by impurity seeding in EAST H-mode plasma

Xiuda YANG, Xianzu GONG, Jinping QIAN, Hongming ZHANG

Institute of Plasma Physics, Chinese Academy of Science, Hefei, 230031, China

Radiative divertor detachment with impurity seeding (nitrogen, neon and argon) offers a promising solution for the control of heat and particle fluxes on the divertor target. Tungsten content is expected to be decreased, as plasma at the edge is cooled down through impurity radiation, leading to less tungsten source. However, in EAST H-mode plasma, after impurities (neon and argon) are seeded, tungsten content is observed to be increased while tungsten source decreases. Extensive modelling by quasilinear gyrokinetic code QuaLiKiz and neoclassical code NEO are performed to explain above observations. On the one hand, it is found that turbulences (TEM and ITG) can be always to be stabilized, which decrease their ability to expelling tungsten. On the other hand, neoclassical transport can be enhanced when impurity is seeded, causing more peaked tungsten density profile. Except impurity's own effect on turbulent and neoclassical transport, additional increased toroidal rotation brought by impurity seeding can further weaken turbulence's ability to expelling tungsten and further enhance neoclassical convection velocity, contributing to the more peaked tungsten density profile. Additionally, at the edge of plasma, ELM's frequency is also observed to be decreased, which weakens its ability to expelling tungsten.

Keywords: impurity seeding, tungsten core transport, turbulent transport, neoclassical transport

Email: xdyang@ipp.ac.cn

Limits of energy confinement time and fusion energy gain in magnetic confinement fusion

C. Chen[1,2], J.R. Becker[2], J.J. Farrell[2]

[1]*Brookline Consultants, Needham, USA*

[2]*Beyond Carbon Energy, Belvedere Tiburon, USA*

Energy confinement is the single most important scientific issue in magnetic confinement fusion research. It is intimately related to fusion energy gain. In this paper a theory is presented for a quantitative calculation of the limit of confinement time for the plasma thermal energy in a magnetically confined thermonuclear fusion reactor [1]. The theory is based on radiation reaction associated with spontaneous electron cyclotron radiation as described by the Larmor formula. Good agreement has been found between theory and experimental data from the Tokamak Fusion Test Reactor (TFTR) [2] qualitatively and from the DIII-D tokamak [3], the Joint European Torus (JET) [4] and the Wendelstein 7-X stellarator [5] quantitatively. A new, advanced Lawson criterion for deuterium-tritium (D-T) ignition is derived. A theoretical limit of D-T fusion energy gain is predicted, offering plausible explanations for the sustained D-T fusion energy gain of $Q = 0.19$ from the earlier TFTR experiment [2], the equivalent D-T fusion energy gain of $Q = 0.32$ inferred from the earlier experimental measurement of deuterium-deuterium (D-D) fusion energy gain in DIII-D [3], and the new world D-T fusion energy record achieved experimentally in JET with $Q = 0.33$ sustained for 5 seconds [6].

1. C. Chen, J.R. Becker and J.J. Farrell, "Energy confinement time in a magnetically confined thermonuclear fusion reactor," Proc. 48th European Physical Society Conference on Plasma Physics, June 27 - July 1, 2022, P5b114.
2. D.M. Meade, "TFTR Twenty Year Perspective," 17th IEEE/NPSS Symposium Fusion Engineering, vol. 1,1997, p. 10. https://doi.org/10.1109/FUSION.1997.685658
3. E.A. Lazarup, G.A. Navratil, C.M. Greenfield, *et al.* "Higher fusion power gain with profile control in DIII-D tokamak plasmas," Nuclear Fusion **37**, 1997, p. 7.
4. J. Mailloux, N. Abid, K. Abraham, *et al.* "Overview of JET results for optimising ITER operation," Nuclear Fusion **62**, 2022, p. 042026.
5. T. Klinger, T. Andreeva, S. Bozhenkov, *et al.* "Overview of first Wendelstein 7-X high performance operation," Nuclear Fusion **59**, 2019, p. 112004.
6. E. Gibney, "Nuclear fusion reactor smashed new record," Nature **602**, 2022, p. 371.

Tokamak Disruption Event Characterization And Forecasting Research Including First Real-time Application

S.A. Sabbagh[1], Y.S. Park[1], J.D. Riquezes[1], J. Butt[1], M. Tobin[1], V. Zamkovska[1], J.G. Bak[2], J.W. Berkery[3], M.J. Choi[2], K. Erickson[3], C. Ham[4], H. Han[2], J. Kim[2], A. Kirk[4], W.C. Kim[2], J. Ko[2], W.H. Ko[2], L. Kogan[4], J.H. Lee[2], K.D. Lee[2], J.W. Lee[2], A. Piccione[5], M. Podesta[3], D. Ryan[4], A. Thornton[4], Y. Andreopoulos[5], S.W. Yoon[2]

[1]Dept. of Applied Physics and Applied Mathematics, Columbia U., New York, NY, USA
[2]Korea Institute for Fusion Energy, Daejeon, Republic of Korea
[3]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[4]Culham Centre for Fusion Energy, UKAEA, Abingdon, UK
[5]University College London, London, UK

Disruption prediction and avoidance is critical for ITER and reactor-scale tokamaks to maintain steady plasma operation and to avoid damage to device components. Physics-based disruption event characterization and forecasting (DECAF) research determines the relation of events leading to disruption, and aims to provide event onset forecasts with high accuracy and sufficiently early warning to allow disruption avoidance [1]. The first real-time application of DECAF was recently made on the KSTAR superconducting tokamak. Dedicated plasma experiments focusing on disruptions caused by locking MHD instabilities produced 53 plasma shots with nearly equal disrupted / non-disrupted cases that were forecast with 100% accuracy. An MHD mode locking forecaster, using a torque balance model of the rotating mode, was developed for off-line analysis and implemented and utilized in real-time to produce these results. This forecaster was also used to cue controlled plasma shutdown, trigger disruption mitigation using the KSTAR massive gas injection (MGI) system, and actuate electron cyclotron heating power and n = 1 rotating 3D fields for future disruption avoidance. DECAF warning triggers were issued well before the expected plasma disruption, exceeding warning guidance timing given for ITER disruption mitigation. Real-time and offline DECAF event algorithms are written to match closely given the constraints imposed by real-time operation. Offline analysis has access to data from several tokamaks to best understand, validate, and extrapolate models. Recent offline DECAF code analysis is showing very high true positive success rates, in some cases over 99% with early forecasting (on transport timescales) well before the disruption. While this result is very encouraging over broad ranges of shots, automated analysis development continues to ensure causality of the computed DECAF events with the detected disruption, rather than just correlation. Recent theoretical investigation of the density limit has progressed examining research using local criteria based on an increase in boundary turbulent transport from microinstabilities [2]. The resulting scaling relations depend on several plasma parameters and heating power. Initial analysis of MAST-U shows that plasmas disrupt after crossing these edge limits before reaching the global Greenwald limit. Physics research supporting DECAF is shown including resistive stability evaluation at high non-inductive current fraction, innovative counterfactual machine learning application to MHD stability limits, and experiments demonstrating mode locking avoidance by applied rotating 3D fields.
Supported by US DOE Grants DE-SC0020415, DE-SC0021311, and DE-SC0018623.

[1] S.A. Sabbagh, S.A., et al., "Disruption Event Characterization and Forecasting in Tokamaks", accepted for publication in Physics of Plasmas (2023).
[2] M. Bernet, et al., PPCF **57** (2015) 014038; M. Giacomin, et al., Phys. Rev. Lett. **128** (2022) 185003

DECAF multi-device investigation of abnormalities in plasma vertical position and current indicating disruptions and internal reconnection events

V. Zamkovska, S.A. Sabbagh, Y.S. Park, J.D. Riquezes, M. Tobin[1], J.W. Berkery, K. Erickson[2], J. Butt[3], J.G. Bak, J. Kim, J. Ko, J. Lee, S.W. Yoon[4], L. Kogan[5] and the MAST Upgrade team

[1]*Department of Applied Physics, Columbia University, New York, NY, USA*

[2]*Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA*

[3]*Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, USA*

[4]*Korea Institute of Fusion Energy, Daejeon, Republic of Korea*

[5]*Culham Centre for Fusion Energy, UKAEA, Abingdon, UK*

Deviations of the plasma current I_p and vertical position Z from their intended equilibrium values constitute common cross-device and cross-shot elements of a disruption, a phenomenon that is to be ultimately mitigated or preferably avoided in next-step reactor-relevant tokamaks. The physics-based DECAF code [1] captures those deviations and, among other actions, performs an abstracted cross-device and cross-shot automatic recognition and forecasting of disruptive chains of events (DCE). Abnormal I_p and Z variations can constitute important events within DCEs, such as current spikes, current quenches and vertical displacement events. Those events can appear in a different order and/or be missing in the DCE, depending on a particular machine operation space promoting various physics phenomena, preprogramed shot exit scenarios etc. Here, the DECAF code investigated the order and appearance of those events on a multi-device and multi-year database (MAST/-U 2013 & 2021, KSTAR 2019-2022, NSTX/-U 2009 & 2016) to investigate disruption occurrence indicated by a current quench-based disruption binary indicator, statistics of dominant DCEs, and location of DCEs in the machine operation space. This study provides an important insight in physics and/or engineering elements driving disruptions in the given device, a background for further study of disruption root causes, and hints for future development of real-time plasma control and termination schemes. Furthermore, current spikes are also associated with internal reconnection events (IREs), relaxation phenomena frequently appearing in spherical tokamaks (ST) [2]. Fast variations in the current density profile, plasma shape and temperature accompanying IREs makes them an unwanted element of a plasma discharge, despite the fact that they are usually not considered as disruption triggers. Understanding the conditions under which IREs develop, and eventually disrupt the plasma, is of a primary interest in STs. Here, the occurrence of IREs within device operation spaces and discharge phases was probed by DECAF, focusing on MAST-U 2021 and NSTX 2009 experimental campaigns.

[1] Sabbagh, S.A. et al., *Disruption Event Characterization and Forecasting*, accepted for publication in Phys. Plasmas (2023)
[2] Mizuguchi N. et al., *Dynamic of spherical tokamak plasma on the internal reconnection event*, Phys. Plasmas **7** (2000) 3

TRANSP-TGLF core predictive modelling of the JET D-T baseline scenario

F. Auriemma[1,2], D. Frigione[5], L. Garzotti[6], M. Gorelenkova[7], H.-T Kim.[6], J. Lombardo[1,3], R. Lorenzini[1,4], F. Rimini[6], G.M. Staebler[8], Ž. Štancar[6], D. Van Eester[9], V.K. Zotta[10], J. Garcia[11], J. Hillesheim[6], P. Lomas[6], C. Lowry[6], and JET contributors*

[1]*Consorzio RFX, CNR, ENEA, INFN, UNIPD, Acciaierie Venete SpA, C.so Stati Uniti 4,35127, Padova, Italy* [2]*ISTP, CNR, Padova, Italy* [3]*CRF - UNIPD, Italy* [4]*ENEA – FSN, Italy* [5]*UNIRoma Tor Vergata, Via del Politecnico 1, Roma, Italy* [6]*UKAEA, CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK* [7]Princeton Plasma Physics Laboratory, Princeton, USA [8]General Atomics, PO Box 85608, San Diego, CA 92121, USA [9]*Laboratory for Plasma Physics LPP-ERM/KMS, B-1000 Brussels, Belgium* [10]*Dip. di Ing. Astron., Elet. ed Energ., SAPIENZA UNIRoma, v. Eudossiana 18, 00184 Roma, Italy,* [11]*CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France* **See J. Mailloux et al 2022 Nucl. Fusion 62 042026*

In last years an intense modelling activity has been devoted to prepare and analyse the second JET Deuterium-Tritium (D-T) experimental campaign DTE2. Among the numerous scientific outcomes, such campaign gave the unique opportunity of testing and validating the state of the art of modelling tools with fusion relevant DT plasmas with the full metallic ITER-like wall, in different scenarios. This work reports about the core (ρ_t=[0,0.85]) predictive modelling of plasma density, electron and ion temperatures (n_e, T_e, T_i) performed using TRANSP coupled with TGLF-SAT2 for the JET D-T baseline scenario (I_p = 3.5 MA, q_{95}=3, β_N < 2, with pellet pacing). The tuning of the numerical tools has been done analysing the best performing pure D baseline discharge #96482: the result is that TRANSP+TGLF is able to predict the plasma temperatures and density. It is important to note that, to optimize the density prediction, the particle source needs to be properly tuned. The detailed study of the particle source, which involves pedestal and boundary physics not included in the present modelling, is beyond the scope of this work. Nevertheless, a simplified approach has been applied: the gas fuelling, wall recycling and pellet injection have been modelled as a single effective source S_n. S_n has been varied scanning both the neutral density and the temperature at the separatrix. It was found that, to match the density gradient at the modelling boundary of ρ_t=0.85, S_n must be approximately one order of magnitude larger than the nominal gas fuelling source. The same recipe is then used to predict the profiles of the D-T discharge with analogous engineering parameters #99948. Again the temperatures are in good agreement with the data and a similar increase in particle source is required to correctly predict the experimental data. The overall modelling agreement with the experimental neutron yield is within 10%. The analysis also provides insight into the modification of the turbulent flux spectra due to the change in the plasma isotopes. The sensitivity to the main experimental inputs (e.g. effective Z and impurity content, toroidal rotation, pedestal height, etc.) is also discussed in order to provide the quantification of the uncertainty to be ascribed to the TRANSP+TGLF(SAT2) prediction capability from D to D-T plasma, also in view of applying a similar procedure to ITER.

ORBIT simulations of ripple and TAE induced fast ion losses in DTT

M. Gobbin[1], G. Spizzo[1], M.V. Falessi[2], V. Fusco[2], G.Vlad[2], F. Zonca[2]

[1]*Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA) and CNR-ISTP, Corso Stati Uniti 4, 35127 Padova, Italy*

[2] *C.R. ENEA Frascati, C.P. 65, 00044 Frascati, Italy*

Neutral beam injection in tokamaks produces a population of fast ions that interacts with 3D magnetic fields in a variety of ways, often resulting in energetic particle losses in very short times to the wall. A careful design of neutral beams and active control of error fields are required to avoid very localized fast ion losses (or "hot spots"). Such an issue is discussed here for the Divertor Tokamak Test (DTT) facility [1] by numerical simulations using the Hamiltonian guiding centre code ORBIT [2] with one million test particles. Fast ions are deposited by the NNBI system (energy 510 keV and injection angle at the vacuum vessel α_{VV}=35º, corresponding to a tangent radius of 1.95m) in the standard, single null, full power scenario of DTT. Because of prompt losses and of toroidal magnetic ripple, two hot spots at the wall are produced which correspond respectively to the injection and exit angle of the beam. The first hot spot, in particular, is due to prompt losses and/or passing particles and is characterized by the maximum power load at the wall, of the order ~ 80 kW/m^2, well below the tolerance of plasma-facing components of the machine [3]. On the other hand, the second hot spot is associated to the dominant loss mechanism in the ORBIT run, namely the ripple-precession resonance of trapped ions, already described in a previous study [4]; such a localization might be linked to the intrinsic, localized nature of precession resonances [5].

The interaction between fast particle and Toroidal Alfven Eigenmodes (TAE) might represent another important source of losses in future DTT experiments. For this reason, preliminary numerical simulations - which include both ripple and TAE effects on the fast ion population - are reported in this work. The spectrum and radial profiles of TAE have been determined by DAEPS[6]/FALCON[7], MARS [8] and HYMAGYC [9] codes and are implemented in the ORBIT code. The fast ion losses and the power loads at the wall are thus re-calculated taking also into account the further losses induced by these instabilities.

[1] R. Albanese et al, Nuclear Fusion 57, 016010 (2017)
[2] R. B. White and M. S. Chance, The Physics of Fluids 27, 2455 (1984).
[3] M.Gobbin, G.Spizzo submitted to Plasma Physics and Controlled Fusion
[4] G. Spizzo et al, Nuclear Fusion 61, 116016 (2021).
[5] R. B. White, Phys. Rev. E 58, 1774 (1998).
[6] Y. Li et al, PoP 27 062505, (2020)
[7] M. V. Falessi, N. Carlevaro, V. Fusco, G. Vlad, F. (2019). Physics of Plasmas, 26(8), 082502.
[8] A. Bondeson, G. Vlad, H. Lütjens, Physics of Fluids, B4:1889–1900, 1992
[9] Fogaccia G., Vlad G. and Briguglio S. 2016 Nucl. Fusion 56 112004

Plasma response modelling in JT-60SA Initial Research Phase I scenarios

L. Pigatto[1], T. Bolzonella[1], E. Tomasina[2], Y.Q. Liu[3]

[1]Università degli Studi di Padova, Padova, Italy
[2] Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Corso Stati Uniti 4 – 35127 – Padova (Italy)
[3] General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA

JT-60SA is a superconducting tokamak in advanced construction stage in Naka, Japan [1]. Its main mission is to support the ITER project and address key physics issues for the DEMO generation. The device will be equipped with a wide set of diagnostics and actuators to address this task. Among these, 18 in-vessel Error Field Correction Coils (EFCC) will be implemented in experiments on disruption avoidance and mitigation of runaway electrons. Error Fields (EF) are non-axisymmetric components generated by misalignment or fabrication characteristic of the equilibrium coils, or by specific arrangement of the magnets' feedthroughs. EFCC can be used to correct these spurious components, or rather to compensate their effect on the plasma confinement and avoid locking of MHD modes [2] [3]. On JT-60SA the EFCC, carrying a peak current of 52.5 kA, will be mounted on the vacuum vessel inner outboard and organized in 6 (upper, middle, lower) sets [4]. During the device initial research phases the effect of (Resonant) Magnetic Perturbations on the different plasma scenarios will be assessed. In this work we model the RMP effect on predicted initial scenarios with the linear resistive MHD code MARS-Q [6]. With three toroidal rows of coils, the operational phase space is optimized for EF correction based on linear plasma response metrics. Plasma response models are calculated for the reference plasmas, that allow fast evaluation of perturbed fields in the Fourier domain and calculation of correction currents. Furthermore, stochastization of the edge magnetic field is studied in vacuum for toroidal mode numbers up to n=3.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

1. [1] SHIRAI, H., et al. Nuclear Fusion, 2017, 57.10: 102002.
2. [2] PARK, Jong-Kyu, et al. Nuclear Fusion, 2008, 48.4: 045006.
3. [3] SCOVILLE, J. T.; LA HAYE, R. J. Nuclear fusion, 2003, 43.4: 250.
4. [4] NAKAMURA, S., et al. Fusion Engineering and Design, 2021, 170: 112686.
5. [5] JT-60SA research plan -- version 4.0 (www.jt60sa.org/pdfs/JT-60SA_Res_Plan.pdf)
6. [6] LIU, Y. Q., et al. Physics of Plasmas, 2010, 17.12: 122502.

Investigating the role of plasma shaping in the evolution of high density H-mode SOL profiles and fluctuations in TCV

A. Stagni[1,2], N. Vianello[1,3], M. Agostini[1], C. Colandrea[4], S. Gorno[4], B. Labit[4], G. Sun[4], C.K. Tsui[5], M. Ugoletti[1], J.A. Boedo[5], H. Reimerdes[4], C. Theiler[4] and the TCV team[a]

[1]*Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Corso Stati Uniti 4, 35127 Padova, Italy*
[2]*CRF – University of Padova, Italy*
[3]*Istituto per la Scienza e la Tecnologia dei Plasmi, CNR, Italy*
[4]*École Polytecnique Fédérale de Lausanne, Swiss Plasma Center, Lausanne, Switzerland*
[5]*University of California San Diego, Center for Energy Research, La Jolla, CA 92093, USA*
[a]*See author list of H. Reimerdes et al 2022 Nucl. Fusion 62 042018*

Among the numerous efforts for a proper description of the SOL turbulent dynamics, in the recent years a theoretical framework has been proposed in [1] which, leveraging on the work done in [2, 3], attempts a description by means of the turbulence control parameter $\alpha_t \propto q_{cyl}\nu^*_{sep}$. Such a parameter represents the level of resistive ballooning turbulence over drift waves near the last closed flux surface. In the TCV tokamak, the role of α_t has been previously investigated by means of a separatrix density scan in high density H-mode [4] and correlated with a broadening of the heat load and density profiles in the near and far SOL, as well as an enhancement of the radial filamentary transport towards the first wall.

This contribution extends the observations made in [4] by reporting on an experimental work in TCV aimed at probing the behavior of the SOL profiles and fluctuations in high-density H-mode regimes with respect to a variation of q_{cyl} achieved by means of a plasma shaping scan. A change in upper triangularity δ_{up} between 0 and 0.6 at constant I_p, B_t led to a variation of α_t between 0.45 and 1.5 and, most notably, a regime transition from type-I ELMs at low shaping to the *Quasi-Continuous Exhaust* (QCE) [5, 6] at high shaping. The analysis shows once again a clear increase of the SOL power width λ_q and the near-SOL density e-folding length λ_n, both approximately by a factor ~ 3 within the achieved α_t range and at similar separatrix density. In the far SOL, a density shoulder is recovered whose amplitude, as defined in [7], increases until saturation at $\alpha_t \approx 0.85$. KN1D simulations [8] suggest that the observed changes in the SOL profiles are primarily due to the variation in shaping, rather than to an indirect effect on midplane wall recycling of plasma and neutral particles. The modification of SOL fluctuations and their contribution to the observed variation of the upstream profiles within the considered shaping scan will be assessed through in-depth analysis of Thermal Helium Beam and wall-mounted Langmuir probes data.

[1] T. Eich et al 2020 *Nucl. Fusion* **60** 056016
[2] B.N. Rogers et al 1998 *Phys. Rev. Lett.* **81** 4396-9
[3] B.D. Scott 2007 *Plasma Phys. Contr. Fusion* **49** S25–41
[4] A. Stagni et al 2022 *Nucl. Fusion* **62** 096031
[5] M. Faitsch et al 2021 *Nucl. Mater. Energy* **26** 100890
[6] B. Labit et al 2019 *Nucl. Fusion* **59** 086020
[7] O. Février et al 2020 *Plasma Phys. Contr. Fusion* **62** 035017
[8] B. LaBombard 2001, Technical Report PSFC/RR-01-3, Plasma Science and Fusion Center, Massachusetts Institute of Technology

Self-consistent modelling of STEP flat top scenario with realistic ECRH and ECCD

R. Sharma[1], K. Kirov[1], F. Casson[1], F. Eriksson[1], L. Figini[2], S. Freethy[1], M. Henderson[1], S. Marsden[1], H. Meyer[1], T. Wilson[1] and STEP team

[1]UKAEA, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom
[2]Istituto per la Scienza e Tecnologia dei Plasmi, Consiglio Nazionale delle Ricerche, 20125 Milano, Italia

STEP is the UK's Spherical Tokamak reactor design program that aims to demonstrate the net electrical gain through the STEP Prototype Powerplant (SPP). SPP is being designed to use an exclusively microwave-based heating and current drive (HCD) system using combination of Electron Cyclotron (EC) and electron bernstein waves [1].

Presently, a steady-state scenario is being developed for Electron Cyclotron Resonance Heating (ECRH) and Current Drive (ECCD) which uses a prescribed EC power deposition and current drive profiles. The prescribed ECCD profile is based on the analytic formula capturing the temperature and density dependence [2]. Hence, the current drive profile is sensitive to the plasma parameters, i.e., density, temperature, impurities but also subjected to limitations due to possible launcher positions (Fig. 1).

The work discusses fully self-consistent scenario modelling with realistic heating and CD. Therefore, requiring a series of iterative optimisation tasks including finding optimised launching parameters

which will provide requested heating and CD profiles [3] and benchmarking the evolution of plasma parameters versus the requirements of the reference steady-state scenario.

The GRAY [4] code has been used to perform single-ray parametric scans over possible launching angles (poloidal and toroidal) and frequencies for all the prescribed launchers for an O and X mode launch. These parametric scans are based on snapshot of the equilibrium and the plasma profiles from the above-mentioned steady-state scenario. A set of optimum launchers and launching conditions is then determined from the GRAY parametric scans to obtain the most efficient heating and current profile. The heating power of the launchers is also scaled to match the prescribed ECCD profile used in the steady state scenario (Fig 1b). The optimised launching conditions (power, launching angles and frequency) thus obtained from the stand-alone GRAY scans is input to the plasma transport code JETTO [5]. GRAY is called from JETTO to compute and update the heating and current profiles as the plasma evolves self-consistently.

For the ECCD scenario with z_{eff} = 2.8, $<n_e>$ = 1.55×10^{20} and $<T_e>$ = 9.85 keV, the average

(across radius) normalised current drive efficiency was estimated by the reference scenario is ζ_{CD} = 0.25. The self-consistent run with realistic EC beams run was successfully performed for 500 ms. A good matching of heating and current drive profiles has been obtained between GRAY standalone and prescribed ECCD from steady state scenario and normalized current drive efficiency of ζ_{CD} =

0.23 with 150 MW of injected EC power. The result of the evolution of the EC heating and current profiles along with the current contribution will be discussed in this report. Additionally, the work will also report on the similar GRAY optimizations done for plasma current ramp-up phase of the ECCD scenario and the preliminary results of the self-consistent plasma evolution.

References [1] M. Henderson, Concept Design of the STEP Heating and Current Drive System (2023). [2] E.Poli et al. Nucl. Fusion 53 (2013) 013011 [3] S.Marsden EPS 2022 [4] *D.Farina, fusion science and technology, 52, 154 (2007)* [5] http://www.eirene.de/JINTRAC_Report_2008.pdf

Modelling conductive paths between ITER blanket modules during disruptions

N. Isernia[1], F. Villone[1], M. Cavinato[2], A. Portone[2], P. Testoni[2]

[1] *DIETI, Università degli Studi di Napoli Federico II, CREATE, 80125 Napoli, Italy*

[2] *Fusion for Energy, Josep Pla 2, Torres Diagonal Litoral B3, 08019 Barcelona, Spain*

The computation of electromagnetic forces is a key element in the electromagnetic design of tokamak devices, which requires to accurately model currents flowing in all the conductors surrounding the plasma, especially during transient events like disruptions. Any plasma movement or current variation induces currents in the conductors. When the plasma hits the wall, the most common assumption in simulating such events is that so called halo currents are injected from the plasma into the structures and vice-versa. A different point of view is assumed by the Asymmetric Toroidal Eddy Current (ATEC) model, which has shown that the onset of a conductive path between the first wall tiles of the JET tokamak, with variable resistance along the toroidal angle to mimic an asymmetric plasma-wall interaction, is able to explain the sideways forces inferred from measurements [1]. A similar reasoning can be made also in the axisymmetric case, i.e. assuming that when an axisymmetric plasma hits the first wall, a conductive path arises between poloidally and toroidally adjacent first wall tiles. Motivated by these considerations, here we investigate the effect of possible conductive paths generated in the gaps of ITER blanket modules, which may significantly affect the pattern of the poloidal and toroidal currents induced in the passive structures, during a symmetrical Vertical Displacement Event. Given that such currents develop very close to the plasma, their effect on the plasma evolution may be significant in principle. To quantify this effect, we implement in the evolutionary equilibrium model CarMa0NL [2] a time-varying resistance between the gaps of the blanket modules, which is tuned according to the plasma evolution: a gap will be conductive only in case of significant plasma-wall contact in its proximity. The simulation results are compared with those obtained with the usual halo current injection assumption [3], in terms both of plasma evolution and of the forces generated on blanket modules.

References

[1] R. Roccella et al, Nuclear Fusion **56**, 106010 (2016)
[2] F. Villone et al., Plasma Physics and Controlled Fusion **55**, 095008 (2013)
[3] S.L. Chen et al., Nuclear Fusion **55**, 106039 (2019)

Large-scale integrated model validation with preliminary JET profile database

A. Ho[1], C. Bourdelle[2], Y. Camenen[3], F. J. Casson[4], J. Citrin[1], F. Koechl[4], JET Contributors*

[1] *DIFFER, De Zaale 20, 5612 AJ, Eindhoven, The Netherlands*
[2] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*
[3] *CNRS, Aix-Marseille Univ., PIIM UMR7345, Marseille, France*
[4] *UKAEA, CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*
* *See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. 2022 Nucl. Fusion 62 042026*

To prepare ITER operation and contribute to DEMO design, a cohesive plan to extend the state-of-the-art in predictive integrated tokamak simulation and associated validation methodologies has been endorsed by E-TASC (*EUROfusion-Theory and Advanced Simulation Coordination*) initiative under the acronym of TSVV11 (*Theory, Simulation, Validation and Verification task on 'Validated frameworks for the Reliable Prediction of Plasma Performance and Operational Limits in Tokamaks'*). In alignment with ITER technical choices, this project uses the High Fidelity Pulse Simulator (HFPS), a Python workflow based on an IMAS-compatible version of JINTRAC (JETTO+EDGE2D) coupled to other IMAS-compatible modules such as HCD. A sub-task of the project focuses on standardizing and automating the model validation and uncertainty quantification pipelines of the HFPS across multiple experimental regimes and multiple EUROfusion devices. This task also stress tests the existing ITER IMAS architecture, the IDS data structure, and any developed tools for facilitating cross-domain data communication and large-scale data analysis.

An automated simulation setup tool was developed to reduce the undesired impact of human errors and subjectivity on the validation results, which was combined with a rudimentary classification procedure to configure the HFPS settings while accounting for best practices within the tokamak modelling community. This work focuses exclusively on JET plasma discharges due to the plethora of raw and processed diagnostic data made available to the EUROfusion community. The amalgamation of multiple pre-existing 0D outputs (e.g. V_{loop}, l_i, W_p, P_{rad}, neutron flux, etc.) and 1D outputs (e.g. n_e, T_e, T_i at specified radial locations) allow the formulation of metrics to determine the 'goodness' of a given simulation. Further classification of these simulations via these metrics can potentially identify model discrepancies by their physical origins, providing a way to prioritize efforts to fill in missing physics within the simulation suite. Future work will incorporate a similar amount of data from the WEST, AUG, and TCV tokamaks to extend the validated regions and incorporate 2D line-of-sight information to increase the depth of validation possible.

Development and Initial Results of the MAST-U Coherence Imaging Spectroscopy Diagnostic

Rhys Doyle[1,2], Nicola Lonigro [2,3], Joseph S. Allcock [2], Huw Leggate[1],
Kevin Verhaegh[2], Miles M. Turner[1], MAST-U Team*
[1] *NCPST, Dublin City University, Dublin, Ireland*
[2] *Culham Centre for Fusion Energy, Abingdon, UK,*
[3] *University of York, Heslington, York, YO105DD, UK*

The flexibility of the MAST-U Super-X divertor provides us with the opportunity to study plasma detachment and power exhaust, thus making it the focus of various diagnostic developments. Coherence Imaging Spectroscopy (CIS) offers users the ability to measure plasma parameters such as impurity flow velocities, temperatures and densities by encoding these parameters within an interference pattern superimposed on images of a plasma. This technique has been used to quantify 2D impurity ion flow velocity profiles on devices such as MAST [1], DIII-D [2], Wendelstein 7-X [3] and ASDEX-U [4]. Following work by Allcock [5], the MAST-U CIS diagnostic takes the form of a triple-delay configuration. This configuration consists of two alpha Barium Borate (α-BBO) crystals and a sensor with polarisers bonded to it at the pixel level. This creates three distinct interference patterns and makes it the first multi-delay CIS diagnostic using a pixelated phase mask (PPM) to be installed on a tokamak device. These enable the measurement of complex spectral shapes, such as a Doppler broadened and shifted CIII multiplet or a Stark and Doppler broadened D_γ line. Here we present the first Super-X CIS data taken during high-power L-mode shots in the second MAST-U campaign (MU02), along with qualitative analysis of C III temperatures and velocities. This data further confirms the capabilities of CIS as a powerful diagnostic for fusion device development.

References

[1] S. A. Silburn et al. *Review of Scientific Instruments*, **85**, 11 (2014) 11D703
[2] C. M. Samuell et al. *Review of Scientific Instruments*, **89**, 9 (2018) 093502
[3] V. Perseo et al. *Review of Scientific Instruments*, **91**, 1 (2020) 013501
[4] D. Gradic et al. *Physics and Controlled Fusion*, **60**, 6 (2018) 084007
[5] J. S. Allcock et al. *Review of Scientific Instruments*, **92**, 7 (2021) 073506

*See author list of J. Harrison, et al. Nuclear Fusion **59** 11 (2019) 112011

Modeling of neutron activation foil measurements in MAST Upgrade

M. Cecconello[1,2], C. MacLean[2], S. Allan[3], C. L. Grove[3], K. Lennon[3], R. Worrall[3],
and the MAST Upgrade Team*

[1] *Department of Physics and Astronomy, Uppsala University, SE-751 05 Uppsala, Sweden*

[2] *Department of Physics, Durham University, Durham, DH1 3LE, UK*

[3] *CCFE, Culham Science Centre, Oxon OX14 3DB, UK*

Absolute calibration of neutron diagnostics is fundamental for the safe operation and the scenario development of both present day fusion devices and future power plant reactors. The most commonly used neutron emission monitors are fission chambers. The most common calibration method is to use a strong neutron source with a well characterized neutron emission spectrum placed at different locations inside the vacuum vessel while simultaneously recording the fission chambers' measurements [1]. Neutron transport Monte Carlo codes are then used to model the neutron source, the tokamak and its environment and the fission chamber (whose absolute efficiency is known either experimentally or via simulation) thus providing the absolute neutron flux. The fusion power can then be estimated using plasma transport codes such as TRASNP/NUBEAM by constraining the simulated neutron yield. This in situ method is, however, rather complicated and time consuming requiring in addition very strong neutron sources. An alternative approach, for the absolute calibration of the fission chambers, is to use reference plasma discharges as the neutron source in combination with neutron activation foils, located in the proximity of the plasma, coupled to neutron transport Monte Carlo codes. This requires the neutron emission from the plasma to be very well characterized.

Forward modeling of ^{115}In foil neutron activation measurements in MAST Upgrade using NBI heated plasma discharges coupled with TRANSP/NUBEAM codes has resulted in good agreement between the measured, $N_{\mathrm{m}} = (1.740 \pm 0.004) \times 10^5$, and the expected, $N_{\mathrm{e}} = (2.1 \pm 0.4) \times 10^5$, photo-peak counts for the γ-rays emission following the $^{115}\mathrm{In}(\mathrm{n},\mathrm{n}')^{115m}\mathrm{In}$ reaction. The experiment, modeling and results obtained in MAST Upgrade are discussed in detail in this work. These initial results are very promising suggesting that the absolute calibration of the MAST Upgrade fission chamber might be carried out using this approach without recurring to the more conventional method mentioned above. The successful modeling used in this study has the potential to be applied to ITER and future fusion power plants.

[1] P. Batistoni et al 2018 Nucl. Fusion 58 026012 and 2018 Nucl. Fusion 58 106016.

*See author list of J. Harrison, et al. 2019 Nucl. Fusion 59 11201

Status of the Project for the Bolometric diagnostic on DTT

G.M. Apruzzese[1], L. Senni,[1] V. Piergotti[1], G. Rocchi[1], L. Gabellieri1[1,2], A. Murari[3] and P. Franz[3]

[1]*C.R. ENEA, Frascati, Italy*

[2]*DTT S.c.a.r.l., Frascati, Italy*

[3]*Consorzio RFX, Padova, Italy*

The knowledge of the plasma radiated power is crucial for the studies of the power exhaust and divertor detachment specially in the devices, as DTT, aimed at testing divertor with an incident high density power. The measurement of the total radiated emission is essential from the first phase of DTT activity due to its primary function of protection and control. Furthermore, the bolometric measurement is particularly important in the divertor region where is crucial to map the radiation distribution with the best achievable spatial resolution accuracy. For these reasons, the DBO diagnostic is considered of fundamental relevance in the DTT DAY0 equipment.

The conceptual design of the bolometric diagnostics for DTT device is in progress, at the same time as, the choice of the detectors is under analysis, the integration and interface issues are addressed, the lines of sight and the housing of the detectors inside the port are being designed and optimized.
The paper reports the studies of the conceptual tomographic layout for a reduced Day0 setup, the installation on the machine, including such as the anchorage. The issues posed by the hostile environment, from thermal loads and neutron fluxes to stray radiation, are also discussed. Stray radiation represents a serious problem for bolometers operating in fusion devices with a considerable ECRH power, such as DTT. An estimation of unwanted ECRH stray radiation will be provided and a preliminary design of the mechanical shield (to minimize the absorbed radiation from ECRH) will be presented.

High beta long pulse scenario development on TCV and MAST-U

C. Piron[1], S. Coda[2], I. Voitsekhovitch[3], G. Cunningham[3], M. Agostini[4], F. Auriemma[4], A. Burckhart[5], A. Chomiczewska[6], J. Decker[3], S. Garavaglia[7], L. Garzotti[3], S. Gibson[3], A. Karpushov[2], A. Jardin[8], D. Mazon[9], A. Moro[7], S. Nowak[7], B. Patel[3], A. Pau[2], L. Piron[4], O. Sauter[2], L. Simons[2], M. Ugoletti[4], M.Vallar[2], N. Wendler[6], V. Yanovskiy[10], TCV[*] and MAST-U[**] Teams

[1]ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy; [2]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland; [3]CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK; [4]Consorzio RFX-ISTP CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA. I-35131 Padova, Italy; [5]Max-Planck-Institut fur Plasmaphysik, D-85748 Garching, Germany; [6]Institute of Plasma Physics and Laser Microfusion, 01-497 Warsaw, Poland; [7]ISTP-CNR, via R. Cozzi 53, 20125 Milano, Italy; [8]Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN), PL-31-342, Krakow, Poland; [9]CEA, IRFM, F-13108 Saint Paul Lez Durance, France; [10]Institute of Plasma Physics AS CR, Za Slovankou 1782/3, 182 00 Praha 8, Czech Republic; [*]See author list of “H. Reimerdes et al 2022 Nucl. Fusion 62 042018; [**]See author list of “J.R. Harrison et al 2019 Nucl. Fusion 59 112011”

One of the crucial challenges for steady state tokamak operation is the full replacement of the inductive current drive by a combination of the self-driven bootstrap current, that naturally occurs due to orbit effects at high pressure gradients, and the auxiliary current drive sources such as radiofrequency waves or Neutral Beam (NB) injection. High pressure, i.e. high normalized beta (β_N) long pulse scenarios have been developed in TCV and, more recently, in the MAST-U spherical tokamak to pave the way to future steady-state operations of JT-60SA, ITER and DEMO. Two operating recipes have been developed on TCV to meet the high beta target. A stationary fully non-inductive L-mode plasma scenario with an Internal Transport Barrier (ITB) has been heated for the first time with P_{NB} = 1 MW reaching a maximum $\beta_N \sim$ 1.8. The non-inductive sustainment of H-mode plasmas, i.e. featuring an external transport barrier (ETB), has been obtained only transiently, up to maximum $\beta_N \sim 2.0$. Initial attempts to combine the two strategies into a Double Transport Barrier (DTB) scenario are reported and will be further pursued in the future, exploiting the availability of additional auxiliary power. In recent MAST-U experiments, H-mode plasmas with maximum $\beta_N \sim 3.35$, among the highest achieved so far in MAST-U, have been obtained heating double null plasmas in conventional divertor configuration with P_{NB} = 1.3 MW at I_p / B_{t0} = 450 kA / 0.4 T.

Study on Differences of ECE and High Resolution Thomson Scattering temperature measurements in DT(Deuterium-Tritium) plasmas on JET

Francesco Paolo Orsitto[1] , M Fontana[2] , G Giruzzi[3], R Dumont[3] , L Figini[4] ,D Kos[2] , M Maslov [2], S Mazzi[3] S Schmuck[4], L Senni [1], C Sozzi[4] , C Challis[2] , D Frigione[1] , J Garcia[3], L Garzotti[2], J Hobirk[5], A Kappatou[5], D Keeling[2] , E Lerche[6], C Maggi[2], J Mailloux[2], F Rimini[2], D van Eester[6] and JET contributors(*)

[1] ENEA Department Fusion and Technology for Nuclear Safety, 00044 Frascati, Italy, [2] CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK, [3] CEA, IRFM F-13108 Saint Paul-lez-Durance, France, [4] Istituto per la Scienza e Tecnologia dei Plasmi, CNR, 20125 Milano, Italy, [5]Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany, [6]Laboratory for Plasma Physics, LPP-ERM/KMS, Brussels, Belgium

(*)See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. Nuclear Fusion 62 (2022) 042026

Corresponding Author Email:Francesco.Orsitto@enea.it

In Deuterium (DD) plasmas differences were detected in JET and TFTR between electron temperature (Te) measurements made by ECE (Electron Cyclotron Emission) and Thomson scattering diagnostics systems. The ECE Te (Te_ECE) was found higher than the LIDAR Thomson Scattering Te (Te_TS) for Te >5keV[1]. Recent high Te experiments on FTU done in DD plasma by ECRH heating showed Te_ECE<Te_TS for Te>8keV. Differences are found in Te measurement in recent DD and DT JET plasmas at medium to high (11 keV) temperatures: both Te_ECE >Te_TS and Te_ECE<Te_TS are measured. These differences can be due to the non-maxwellian nature of the Electron velocity Distribution Function(EDF). The radiation temperature (Trad) measured by ECE is equal to the Te only for maxwellian plasma: being Trad dependent on the derivative of the EDF in phase space. The paper describes differences of Te measured by ECE (Martin-Puplett interferometer) and High Resolution Thomson Scattering(HRTS) diagnostic. HRTS gives independent information on these differences, having shorter space resolution(2cm), and faster repetition time(20Hz) on a different line of sight (close to the magnetic centre) : HRTS measurements confirm the trends observed using LIDAR TS[2]. In addition, changes are detected on the ratio Te_ECE/ Te_TS(HRTS) during the evolution of fast-ion linked MHD in DT hybrid scenario: supporting the scheme of non-maxwellian EDF[3].

1. E. de la Luna et al Review of Scientific Instruments 74, 1414 (2003).
2. M Fontana et al , Investigation of Te measurements discrepancies between ECE and Thomson diagnostics in high-performance plasmas in JET, Workshop EC-21(ITER IO , 20-24 June 2022) paper 81 .
3. G Giruzzi , A model of non-Maxwellian electron distribution for the analysis of ECE in JET discharges, EC-21 paper 67

MHD studies in the hybrid scenario for D-T experiments at JET

G. Pucella[1], E. Alessi[2], F. Auriemma[3], D. Brunetti[4], P. Buratti[5], E. Giovannozzi[1], S. Nowak[2], M. Valisa[3], M. Baruzzo[1], C.D. Challis[4], A. Chomiczewska[6], D.R. Ferreira[7], J. Hobirk[8], I. Ivanova-Stanik[6], P. Jacquet[4], E. Joffrin[9], A. Kappatou[8], V.G. Kiptily[4], E. Lerche[10], M. Mantsinen[11], M Maslov[4], and JET Contributors*

[1]ENEA, Fusion and Nuclear Safety Department, Frascati, Italy. [2]ISTP, Consiglio Nazionale delle Ricerche, Milano, Italy. [3]Consorzio RFX, ISTP-CNR, Padova, Italy. [4]UKAEA, Culham Science Centre, Abingdon, United Kingdom. [5]Università degli Studi di Roma "Tor Vergata", Roma, Italy. [6]Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland. [7]IPFN/IST, University of Lisbon, Lisbon, Portugal. [8]Max Planck Institute for Plasma Physics, Garching, Germany. [9]CEA, IRFM, Saint-Paul-lez-Durance, France. [10]Laboratory for Plasma Physics-Ecole Royale Militaire, Brussels, Belgium. [11]ICREA, Barcelona, Spain.

**See the author list of J Mailloux et al 2022 Nucl. Fusion 62 042026*

MHD studies were performed to support the development of the JET hybrid scenario [1] at moderate I_p (2.3 MA) and high B_T (3.45 T) for the 2021 D-T experiments at JET with the ITER-like wall. Different MHD instabilities were observed through the main phases of pulses, with an impact on both disruption likelihood and plasma performance.

(i) The q-profile formation phase, aimed to produce a broad q-profile with $q_0 > 1$, showed the occurrence of double tearing modes in pulses with hollow electron temperature profiles, mainly due to a fast current ramp-up and core impurity accumulation at low density values. An effect of the isotope mass on the q-profile shape was also highlighted. **(ii)** The H-mode access phase, characterized by a target q_0 between 1.1 and 1.3, showed sometimes 3/2 and 4/3 tearing modes in pulses with higher beta and relatively flat q-profile, suggesting a possible role of already existing ideal kink modes or "infernal modes" in their destabilization. **(iii)** The main ELMy H-mode phase was usually sawtooth-free, but fishbone activity was commonly observed after a few seconds, suggesting that the q-profile was slowly evolving with q_0 decreasing to a value close to unity. A correlation between the core $n = 1$ MHD activity (fishbones or continuous mode), the core impurity content, and the fast particle losses was highlighted. **(iv)** The termination phase was often characterized by core impurity accumulation, with the destabilization of chains of classical tearing modes, due to the broadening/hollowing of the current density profile. An increasing percentage of disruptions, due to the occurrence of 2/1 locked modes, was observed with increasing isotope mass.

In this contribution, an analysis of the experimental observation of MHD instabilities in hybrid pulses is reported, together with the modelling activities carried out towards their interpretation and the strategies implemented for their avoidance and control.

[1] J Hobirk et al 2012 Plasma Phys. Control. Fusion **54** 095001

ENN's Roadmap for Proton-Boron Fusion Based on Spherical Torus

Hua-sheng Xie (xiehuasheng@enn.cn), Jia-qi Dong, Kai-ming Feng, Xiang Gu, Xian-li Huang, Xin-chen Jiang, Ying-ying Li, Zhi Li, Bing Liu, He Liu, Wen-jun Liu, Di Luo, Martin Y. K. Peng, Yue-jiang Shi, Shao-dong Song, Xian-ming Song, Tian-tian Sun, Mu-zhi Tan, Ming-yuan Wang, Xue-yun Wang, Yu-min Wang, Yuan-ming Yang, Gang Yin, Han-yue Zhao, Qing Zhou, Min-sheng Liu (liuminsheng@enn.cn), and ENN fusion team

[1] *Hebei Key Laboratory of Compact Fusion, Langfang 065001, China*

[2] *ENN Science and Technology Development Co., Ltd, Langfang 065001, China*

Abstract: ENN is committed to developing an environmentally-friendly and cost-effective method of generating fusion energy, requiring abundant aneutronic fuel. Proton-boron (p-11B) fusion is an ideal choice. Recent studies indicate that p-11B fusion, although challenging, is possible with the use of new cross-sectional data [1], provided electron radiation is minimized through achieving a hot ion mode and high wall reflection. The high beta and compactness of a spherical torus make it well-suited for p-11B fusion. Utilizing the new spherical torus energy confinement scaling law [2], a reactor with major radius R0=4m, central magnetic field B0=6T, central temperature Ti0=150keV, plasma current Ip=30MA, and hot ion mode Ti/Te=4 can yield p-11B fusion Q>10. A roadmap for p-11B fusion has been created, with the next-generation device named EHL-2 (ENN He-Long, meaning "peaceful Chinese dragon") as the primary target. The main target parameters include R0≈1.05m, A≈1.85, B0≈3T, Ti0=30keV, Ip=3MA, and Ti/Te=3. The existing fusion device EXL-50 [3] will be simultaneously upgraded to provide experimental support for the new roadmap, involving the installation and upgrading of central solenoid, vacuum chamber, and magnetic systems. The commissioning of the upgraded fusion device EXL-50U is scheduled for 2023, with the construction of EHL-2 estimated to conclude by 2026.

Reference

[1] M. H. Sikora and H. R. Weller, J Fusion Energ (2016) 35:538–543.
[2] G.S. Kurskiev et al 2022, Nucl. Fusion 62 016011.
[3] Y. J. Shi et al 2022, Nucl. Fusion 62 086047.

Towards iterative 2D and 3D kinetic modelling of RMP interaction with tokamak plasmas

P. Lainer[1], J. Schatzlmayr[1], C.G. Albert[1], M.F. Heyn[1], S.V. Kasilov[1,2], W. Kernbichler[1], M. Markl[1]

[1] *Fusion@ÖAW, Institut für Theoretische Physik - Computational Physics, Technische Universität Graz, Petersgasse 16, A-8010 Graz, Austria*

[2] *Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", 61108 Kharkiv, Ukraine*

Suppressing edge-localized modes (ELMs) with help of external resonant magnetic field perturbations (RMPs) is an experimentally proven technique for the reduction of tokamak first wall damage by large, type-I ELMs. Linear and nonlinear modelling of the interaction of RMPs with tokamak plasma is presently developing on the basis of MHD and kinetic theory. The latter [1] extends the validity range of MHD theory which is on the margin or even outside the applicability range for modern devices due to essentially kinetic effects like Landau damping and because the finite radial extent of ion orbits is comparable to the size of resonant layers. The kinetic description of this interaction in (quasi-)linear and nonlinear regimes in realistic tokamak geometry is, therefore, necessary to thoroughly understand plasma–RMP interaction.

In Ref. [2], an iterative approach has been proposed where the plasma response current density, computed in MHD or in the kinetic approximation, is coupled with a finite element Maxwell solver in realistic tokamak geometry. In the latter case, this current density is an integral functional of electromagnetic fields and has been computed with help of a delta-f Monte Carlo method. The approach has been refined and realized in the code MEPHIT for the ideal MHD plasma response in Ref. [3]. In parallel, a more advanced 3D geometrical guiding center orbit integrator has been developed in Ref. [4], which is specially suited for the problem at hand. In this report, we present implementations of the iterative Maxwell solver MEPHIT with the kinetic plasma response currents from the code GORILLA and of their analytical form obtained for the simplified geometry. The results are compared to the kinetic cylindrical model of the code KILCA [1].

References

[1] M.F. Heyn *et al*, Nuclear Fusion 54, 064005 (2014)

[2] C. G. Albert *et al*, Journal of Physics: Conference Series 775, 012001 (2016)

[3] P. Lainer *et al*, Journal of Physics: Conference Series 2397, 012014 (2022)

[4] M. Eder *et al*, Physics of Plasmas 27, 122508 (2020)

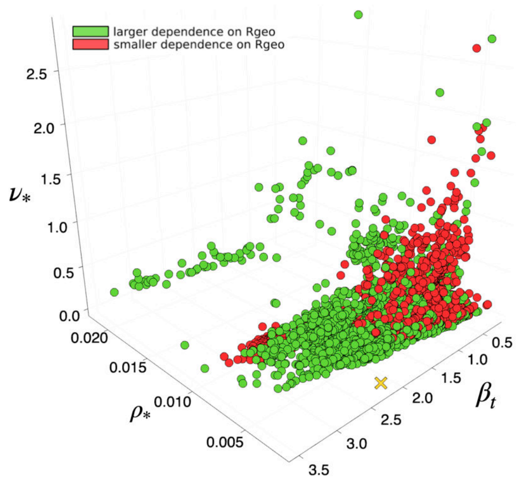
Confinement scaling with machine size in the updated ITPA global H-mode energy confinement database

J. Hall, P. Zhang and G. Verdoolaege

Department of Applied Physics, Ghent University, Ghent, Belgium

A revision of the International Tokamak Physics Activity (ITPA) global H-mode energy confinement scaling in tokamaks was carried out in 2020, using the latest version of the multi-machine ITPA database (DB5.2.3), including data from machines with fully metallic walls (mainly ASDEX Upgrade with the full tungsten wall (AUG-W) and JET with the ITER-like wall (JET-ILW)). This resulted in the ITPA20 scaling law [1] for ELMy H-modes, a power law estimated both in engineering and dimensionless form, exhibiting several dependencies that are different to those seen in the IPB98(y,2) scaling. One of the notable differences is a considerably weaker dependence on major radius. The present work aims to contribute to an explanation for this reduced size scaling. We clarify the role of multicollinearity i.e the linear relationships between the predictor variables in the data and identify a subset of the data that contributes the most to the reduced scaling.

In searching for an explanation for the weaker size scaling, we initially determine the extent to which multicollinearity in the data affects the regression, which appears to be significant. We then explore several ways to mitigate the effect of multicollinearity [2]: re-examining the scaling dependencies with feature selection algorithms, using dimensionality reduction procedures and finally applying regularisation regression methods. Next, we search for the smallest subset of points which most contributes to the reduction of the major radius dependence. The optimisation provides labels for a supervised classification, which shows a clear delineation of the subset in dimensionless space (Fig. 1). Moreover, the delineated region lies outside of ITER's expected operational regime, suggesting the confinement extrapolation to ITER to follow a size scaling resembling that of IPB98.



References

[1] G. Verdoolaege et al., Nucl. Fusion **61** 7 (2021) 076006 (29 pp.).

[2] Chan, J. Y.-L. et al., Mathematics **10** 8 (2022) 1283 (17 pp.).

Bayesian soft X-ray tomography and tungsten impurity concentration estimation at WEST

H. Wu[1], G. Verdoolaege[1], D. Mazon[2] and A. Jardin[3]

[1] *Department of Applied Physics, Ghent University, B-9000 Ghent, Belgium*

[2] *CEA, IRFM, F-13108 Saint Paul-lez-Durance, France*

[3] *Institute of Nuclear Physics Polish Academy of Sciences, PL-31-342 Krakow, Poland*

Estimation of the impurity concentrations in fusion devices is a key point to understand impurity transport. In addition, if the estimation can be done in a sufficiently fast and accurate way, it could be used for the purpose of impurity control. However, there are considerable challenges due to the involvement of multiple diagnostics for reconstructing the desired concentrations and the various sources of uncertainty that affect the corresponding measurements. We employ integrated data analysis (IDA) using Bayesian methods with the goal of jointly estimating impurity concentrations and kinetic profiles at WEST using line-integrated measurements from soft X-ray (SXR) spectroscopy, interferometry (for electron density) and electron cyclotron emission (ECE; for electron temperature). The IDA approach helps to avoid the accumulation of errors commonly seen in sequential analysis of diagnostic measurements and allows exploiting diagnostics interdependencies [1]. At WEST, two 1D cameras are planned for observing the SXR emissivity with a horizontal and vertical view, of which one (horizontal) is already operational [2]. We apply Gaussian process tomography for reconstructing the 2D SXR emissivity profile in real time and we validate the technique with synthetic data generated for both cameras [3]. We also show results using real data, where the single horizontal view poses an extra challenge that is addressed by adopting a nonstationary covariance function and forcing the length scale of the reconstructed emissivity profile to vary with magnetic flux [4]. Furthermore, as a first step toward an integrated estimation of impurity concentrations – mainly tungsten at WEST – we incorporate data from interferometry. We also investigate techniques for accelerating the inference process with a view to real-time applicability. Results are shown of fast reconstruction of density profiles by means of a neural network surrogate model trained on synthetic interferometry data corresponding to realistic profiles. This approach will eventually be extended to the joint estimation of impurity concentrations, as well as density and temperature profiles.

References

[1] R. Fischer et al., *Fusion science and technology* **58**, 675-684 (2010)

[2] D. Mazon et al., *Journal of Instrumentation* **11**, C08006 (2016)

[3] T. Wang et al., *Review of Scientific Instruments* **89**, 10F103 (2018)

[4] D. Li et al., *Review of Scientific Instruments* **84**, 083506 (2013)

Studies on the magnetic turnstiles in nonresonant stellarator divertors

Alkesh Punjabi[1], Allen H. Boozer[2]

[1] Hampton University, Hampton, VA 23668, USA [2] Columbia University, New York, NY 10027, USA

Nonresonant divertors are understudied in stellarator physics and characterization, both theoretically and the numerically, is extremely useful to advance the stellarator concept. For this reason, the study of the nonresonant stellarator divertor is important [A. H. Boozer and A. Punjabi, Phys. Plasmas 25, 092505 (2018), A. Punjabi and A. H. Boozer, Phys. Plasmas 27, 012503 (2020), A. Punjabi and A. H. Boozer, Phys. Plasmas 29, 012502 (2022)]. Magnetic field lines exiting and entering the outermost confining magnetic surface do so by traveling through magnetic flux tubes. The outgoing tube and the incoming tube form a pair called a magnetic turnstile. The magnetic fluxes travelling in the two tubes of a turnstile are exactly equal. The magnetic flux tubes are formed as the field line trajectories negotiate and cross the magnetic cantori that exist in the close vicinity of the outermost surface. The magnetic footprints have fixed locations on the wall. The turnstiles come in three varieties: the adjoining, the separated, and the pseudo. The tubes of adjoining turnstiles start at adjacent locations outside the outermost surface; the tubes of separated turnstiles start at separated locations outside the outermost surface; and the pseudo-turnstile have limited radial excursions. Here, we will present the results on the magnetic turnstiles for three different types of the nonresonant stellarator divertors: the nonresonant stellarator divertor, the hybrid stellarator divertor, and the two-mode stellarator divertor. The 3D structure, the type and the number of the magnetic turnstiles in these three different types of nonresonant stellarator divertors are calculated. The results of these calculations will be presented. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under Award Nos. DE-SC0020107 to Hampton University and DEFG02-03ER54696 to Columbia University. This research used resources of the NERSC, supported by the Office of Science, U.S. DOE, under Contract No. DE-AC02-05CH11231.

SPEKTRE, a linear radiofrequency device for investigating edge plasma physics

F. Brochard[1], D. Geneve[1], S. Heuraux[1], V. Bobkov[2], D. Del Sarto[1], E. Faudot[1], A. Ghizzo[1], E. Gravier[1], N. Lemoine[1], M. Lesur[1], N. Louis[3], J. Moritz[1], T. Reveille[1], V. Rohde[2], U. Stroth[2], F. Volpe[3], H. Zohm[2]

[1] *Université de Lorraine, Institut Jean Lamour, campus ARTEM, F-54000 Nancy, France*

[2] *Max-Planck Institute für Plasmaphysik, Boltzmanstr. 2, D-85748 Garching, Germany*

[3] *Renaissance Fusion, 22 rue Jean Pierre Timbaud, F-38600 Fontaine, France*

SPEKTRE (Sheaths, Plasma Edge & Kinetic Turbulence Radiofrequency Experiment) is a research platform in plasma physics and nuclear fusion, currently under construction in Nancy. SPEKTRE is the result of a cooperation within a research agreement between the University of Lorraine and the IPP Garching. It will produce a plasma 40 cm in diameter and 6 m long, under a maximum magnetic field of 0.5 Tesla generated by 13 large flat coils of the former W7-AS stellarator. SPEKTRE can be seen as a step beyond the IShTAR device [1], of which it integrates several components such as the helicon source chamber. SPEKTRE aims at studying the physics of RF sheaths and ICRF heating thanks to an antenna currently being designed that will be coupled to a 100 kW RF generator. Such long plasma column will also allow to study the physics of instabilities and turbulent transport, in particular of impurities, and to conduct targeted studies on plasma-wall interactions. SPEKTRE aims at being widely open to the whole plasma physics community. Finally, the device will host a liquid metal test bench in the framework of a collaboration with the company Renaissance Fusion, in order to study the interactions between plasma and a flowing lithium wall, in conditions similar to those of fusion edge plasmas.

In this contribution we will present the status of the project, which is due to produce its first plasma in November 2023, its characteristics in the first phase of operation and plans for future upgrades.

Design drawing of the SPEKTRE platform under construction at the University of Lorraine

References

[1] I. Shesterikov, K. Crombe, A. Kostic et al., *IShTAR: a test facility to study the interaction between RF wave and edge plasmas*, Rev. Sci. Instrum. 90, 083506 (2019)

Quasilinear Gyrokinetic Modeling of Reduced Transport in the Presence of High Impurity Content, Large Gradients, and Large Geometric α_{MHD}

C. D. Stephens[1], D. R. Hatch[1], M. Kotschenreuther[1], S. M. Mahajan[1], J. Citrin[2], and C. Bourdelle[3]

[1] *University of Texas at Austin, TX 78712-1192, United States of America*

[2] *DIFFER - Dutch Institute for Fundamental Energy Research, Eindhoven, The Netherlands*

[3] *Science and Technology of Nuclear Fusion Group, Eindhoven University of Technology, Eindhoven, The Netherlands*

[4] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

Transport barriers in tokamak discharges are often characterized by large gradients that can destabilize electrostatic microinstabilities, thereby driving anomalous turbulent transport [1]. However, large gradients can also lead to large geometric α_{MHD}, a stabilizing parameter in certain regimes [2]. The resulting transport is inherently constrained to be ambipolar; in effect, these large gradients can make this flux constraint impossible to satisfy, resulting in stabilization and the reduction of turbulent transport [3]. Due to the high computational cost of nonlinear gyrokinetic simulations, using a reduced turbulent transport model is ideal for predictive modeling. However, reduced models tailored for the tokamak core can become unreliable in transport barrier regimes, thus necessitating model development and improvement. We test the extent to which the gyrokinetic quasilinear code QuaLiKiz [4] can reliably predict anomalous transport in transport barrier discharge regimes to determine parameters that lead to turbulent transport reduction. We use the gyrokinetic code GENE [5], based on first principles, as a point of comparison for QuaLiKiz. Unlike GENE, QuaLiKiz uses many approximations to ensure computational tractability. In particular, QuaLiKiz assumes a Gaussian eigenfunction, uses $s-\alpha_{\mathrm{MHD}}$ geometry, and only captures electrostatic fluctuations. To ensure accurate predictions in transport barrier discharge scenarios, we improve the approximations made for trapped particles, and thus the trapped electron mode (TEM), by incorporating the bounce-averaged electrostatic eigenfunction [6, 7]. The Gaussian ansatz allows us to analytically estimate this bounce-averaging effect with sufficient accuracy. We also improve the approximate methods used to solve for the mode structure in order to accurately calculate bounce-averaging effects.

References

[1] C. Angioni et al., Nucl. Fusion, **57**, 116053 (2017)
[2] C. Bourdelle et al., Phys. Plasmas, **10**, 2881 (2003)
[3] M. Kotschenreuther et al., US-EU Joint Transport Taskforce Workshop (2022)
[4] C. Bourdelle et al., Plasma Phys. Control. Fusion **58**, 014036 (2016)
[5] F. Jenko et al., Phys. Plasmas, **7**, 1904 (2000)
[6] X. Garbet et al., J. Comput. Phys., **87**, 249-269 (1990)
[7] M. A. Beer et al., Phys. Plasmas, **3**, 4018 (1996)

Application of neural networks in beam emission spectroscopy modelling

M. Karacsonyi[1], O. Asztalos[1,2], A. Jalalvand[3], G.I. Pokol[1,2]

[1] *Budapest University of Technology and Economics, Budapest, Hungary*

[2] *Centre for Energy Research, Budapest, Hungary*

[3] *Princeton University, Princeton, NJ, USA*

Beam emission spectroscopy [[1] (BES) is an active plasma diagnostic employed for plasma density measurements. BES synthetic diagnostics are computationally expensive and comprehensive modelling suites designed to provide a better understanding of the diagnostic's perception of underlying plasma phenomena. RENATE-OD [[2] is an advanced BES synthetic diagnostic relying on a rate-equation solver to derive the beam emission for given input plasma profiles.

Due to the resource intensiveness of the calculation the capabilities of RENATE-OD are severely limited in three-dimensional modelling, where hundreds of thousands of calculations can be needed.

In this work, we examined conventional machine learning models and neural networks such as linear regression, feedforward networks as well as extreme learning machines [[3] as possible solutions for the problem described above. We generated a large artificial dataset consisting of realistic plasma density and temperature profile pairs and the corresponding linear emission density profiles calculated with RENATE-OD. This dataset was used to train and evaluate different machine learning models. We aimed to harness the advantages of both worlds, the precision of the classical numerical calculations done by RENATE-OD and the efficiency and scalability of machine learning models. We created a model that can significantly speed up 3D modelling by predicting the solutions of the underlying linear differential equation system. Obtaining the predictions this way was found to be faster by roughly three orders of magnitude. We coupled our artificial dataset with existing fluctuation models and added plasma fluctuations to the inputs of our models to increase their robustness and applicability to realistic scenarios, while using the results to further validate our work with the existing plasma physics models.

References:

[1] D.M. Thomas *et al*. Fusion Sci. Technol., 53 487-527 (2008)
[2] O. Asztalos *et al*. https://github.com/gergopokol/renate-od
[3] G.-B. Huang *et al*. Neuro-computing, 70 489-501 (2006)

Vertical charge separation characteristic of ECR plasma in low aspect ratio toroidal plasma

T. Ram[1, 2], Jagabandhu Kumar [1], P.K. Sharma [1, 2], D. Raju[1, 2], P.R. Parmar[1], K.K. Ambulkar[1]

[1] *Institute for Plasma Research, Bhat, Gandhinagar-382428, India*
[2] *Homi Bhaba National Institute, Anushaktinagar, Mumbai-400094, India*

E-mail: tulchhi.ram@ipr.res.in

Abstract

Electron cyclotron resonance heated plasma is formed in a simple aspect ratio machine assembly [1] (STARMA) having aspect ratio(A) ~1.5. The device holds high toroidicity which leads to high curvature and gradients in the toroidal magnetic fields which leads to separation of the charge. When plasma production starts electrons will move downwards and ions will move upwards according due to this charge separation [2], [3] to $V_z = m(v_\parallel^2 + v_\perp^2)/qRB_\phi$. Plasma maintains its equilibrium by flowing this charge through the vessel wall (known as short circuit effect [4]) and lower the developed potential in the +z and -z direction. Developed potential and short circuit current due to charge separation is characterized. We have observed that the potential developed due to this charge separation can be very high if it does not short circuit through the vessel wall. Measurements of the potential done by using two strips in the radial direction at +15cm and -15 cm apart in z direction. We observed that in the floating conditions of the electrode's electric fields up to 600V/m can be developed. The potential has been measured for different blocking resistors to see how potential I-V characteristics change. It has been observed that rather than decrease in the sort circuit current it has been initially increased and after reaching the certain level it started to decrease. Vertical magnetic field is introduced along with the toroidal magnetic field, to minimize the charge separation. A detailed experimental investigation is carried out to nullify the charge separation and reported herein.

References:

[1] T. Ram *et al.*, "Simple tight aspect ratio machine assembly to study ECR produce magnetized toroidal plasma." (Under publication process)

[2] S. Nishi, T. Sakabe, M. Uchida, H. Tanaka, and T. Maekawa, "Observation of vertical charge-separation current in an electron-cyclotron-heated toroidal plasma," *Plasma Phys Control Fusion*, vol. 52, no. 6, 2010, doi: 10.1088/0741-3335/52/6/065011.

[3] K. Kuroda, M. Uchida, H. Tanaka, and T. Maekawa, "Detection of vertical charge separation current in a toroidal ECR plasma by radially aligned multi-electrodes," *Plasma and Fusion Research*, vol. 7, no. 2012, pp. 1–4, 2012, doi: 10.1585/pfr.7.1302098.

[4] S. Yoshikawa, W. L. Harries, and R. M. Sinclair, "Equilibrium of a toroidal plasma with a conducting aperture limiter," *Physics of Fluids*, vol. 6, no. 10, pp. 1506–1515, 1963, doi: 10.1063/1.1710974.

Study of confined runaway electrons in ADITYA-U Tokamak

Suman Dolui[1,2] , Kaushlender Singh[1,2], Harshita Raj[1,2],Tanmay Macwan[1,2], Ankit Kumar[1,2],Bharat Hegde[1,2],Ashok Kumawat[1,2], Rohit Kumar[1], Suman Aich[1,2], K. A. Jadeja[1],K. M. Patel[1], Laxmikant Pradhan[1], Ankit Patel[1], Kalpesh Gadoliya[1], R.L. Tanna[1], Joydeep Ghosh[1,2] and ADITYA-U Team[1]

[1]*Institute for Plasma Research, Bhat, Gandhinagar, Gujarat 382428*
[2]*Homi Bhabha National Institute (HBNI), Mumbai 400 085*

E-mail: suman.dolui@ipr.res.in

Abstract

The study of confined runaway electrons is important to suppress or mitigate their population. Hard x-ray spectrometry is an established diagnostic to detect thin bremsstrahlung emission generated by confined runaway electrons. A diagnostic has been developed to measure and characterize the thin target bremsstrahlung [1] from the core plasma. A special setup, which is an arrangement of lead collimators and a shielded detector has been deployed in Aditya-U Tokamak to look at the selective region of the bulk plasma. It aims to measure solid angle integrated spectra of bremsstrahlung photons. Collimators with different pinhole diameters look at the different solid angles. By this experimental setup, the spatial energy distribution of runaway electrons is obtained. Also, there is evidence that sawtooth crash due to internal kink mode instability which occurs in the core accompany the HXR bursts [2]. So this special diagnostic is used to interpret the role of sawtooth-like core instability in the generation or the transport of runaway electrons. The thick target bremsstrahlung from the limiter is also recorded at the same time. Correlation analyses of the two types of signals demonstrate the stochasticity of the magnetic fluctuations in the core region and the consequent radial transport coefficient [3] of the non-thermal electrons.

References:

[1] Modeling of bremsstrahlung emission from the confined runaway electrons and applications to the hard x-ray monitor of ITER. Santosh P Pandya et al 2018 Phys. Scr. 93 115601

[2] Generation and transport of runaway electrons during sawtooth crash in the ADITYA tokamak. Harshita Raj *et al* 2018 *Nucl. Fusion* **58** 076004

[3] Radial transport of the nonthermal electrons in runaway discharges in the SINP tokamak from analysis of hard x-ray fluctuations. A.K. Hui *et al* 2009 *Nucl. Fusion* **49** 115025

Poloidal gradient driven off-target circulation and upstream density shoulder in EMC3-Eirene simulations of inboard limited circular scrape off-layer plasma

Arzoo Malwal[1,2], Bibhu P. Sahoo[3], Devendra Sharma[1,2]

[1]*Institute for Plasma Research, Bhat, Gandhinagar, India*
[2]*Homi Bhabha National Institute, Anushakti Nagar, Mumbai, India*
[3]*Bhubaneswar College of Engineering, Khurda, Odisha, 752055, India*

The coupled plasma-neutral transport simulations are done using EMC3-Eirene plasma-neutral code combination [1,2]. The plasma transport simulated in the Scrape-off layer (SOL) formed by a toroidally continuous high-field-side belt-limiter placed in a moderate size circular tokamak equilibrium recovers development of mutually counter-propagating toroidal plasma flows in top and bottom regions of the SOL for relatively high input power and diffusivity (300 kW and 3 $m^2\ s^{-1}$) respectively. The origin of the flows is traced to the poloidal asymmetry introduced by the inboard localized belt limiter by analysing the 3-dimensional simulation data. Two steady-state (flat-top) transport scenarios are simulated. In the first scenario, an effective injection of the neutrals from the limiter region exists with an off-limiter particle pumping because of recycling exclusively restricted to the limiter surface. In second, 100 percent recycling from limiter as well as the off-limiter locations is implemented. While in the first case the off-target flows are stronger, they are weaker in the second case owing to relatively smaller poloidal density gradients, given the greater poloidally uniformity of the ionization of the recycling neutrals. The radial profile of the flows are compared with the similar observations, for example, in Doppler shifted passive charge exchange line emission on the Aditya-U tokamak [3], highlighting the role played by larger diffusion in enhanced off-target recycling. The simulations additionally recover development relatively shouldered radial density profiles in the upstream location (high-field side midplane)for larger input power (300 kW) and smaller diffusivity (1 $m^2\ s^{-1}$) in comparison to low input power (60 kW) cases. The shoulder is also noted to be stronger in the first steady-state scenario and is explained by the stronger ionization of the recycling neutrals effectively localized in the target region, similar to detached plasmas that are often accompanied by an upstream density shoulder [4].

References

[1] Y. Feng, F. Sardei, and J. Kisslinger, J. Nucl. Mater 266-269, 812 (1999)
[2] D. Reiter et al., “The eirene code user manual,” Julich KFA Report (2005)
[3] G. Shukla et al., Nuclear Fusion 59, 106049 (2019)
[4] A. Wynn et al., Nuclear Fusion 58, 056001 (2018)

Effect of ion temperature on the dynamics of seeded impurities in the edge and SOL regions

Shrish Raj, N. Bisai, Vijay Shankar, and A. Sen
Institute for Plasma Research, Bhat Gandhinagar, 382428, India
Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai,400094, India
e-mail : shrish.raj@ipr.res.in

Seeding of medium-Z impurities, like neon, nitrogen, or argon, has been proposed as an effective strategy to reduce the heat and particle loads in many current tokamaks and stellarators. The plasma in the edge/SOL region of a tokamak is highly turbulent due to the presence of drift/interchange instabilities. The impurity–plasma interaction taking place in this region modifies the anomalous plasma transport, particle drifts, and radiation losses [1-4]. Earlier studies have looked at the dynamics of the impurity ions and plasma using the cold ion approximation. In the presence of a finite ion temperature, the ion diamagnetic drift modifies the ion polarization drift and hence it modifies the plasma vorticity. Since, the impurity ions move inwards via vortex structures [5], therefore, the presence of ion temperature can modify the impurity ion dynamics.

In this work, we present numerical simulation results of the edge and SOL regions in the presence of medium-Z impurities in and identify the role of ion temperature. The simulations have been performed using BOUT++ in a two-dimensional slab geometry to numerically solve the fluid model equations of electron continuity, vorticity, electron and ion energy, impurity gas and their ion continuity equations.

The simulation results show that the ion temperature increases the radial electric field and its shear in the edge and edge-to-SOL transition region while in the far SOL region the shear is reduced. Furthermore, the finite ion temperature increases the parallel sheath current (ion saturation) to the limiter/divertor plates, and hence it modifies the radial plasma density profile. It also decreases the overall cross-field heat and particle transport due to the ion temperature that yields the higher zonal flows in the edge region. We have reported that the zonal flows restricts the impurity ions to move in the inward direction, consequently, the abundance of certain impurity ion species increases which is markedly different from the earlier results of zero ion temperature. The temporal evolution of plasma density, electron temperature, impurity ion density and its radial flux are presented as a function of the ion temperature and its gradient. Our work also examines aspects of radiation power fluctuations and impurity ion trapping.

References

[1] Kallenbach A. et al 2013 Plasma Phys. Control. Fusion 55 124041.

[2] Bisai N., Chowdhuri M. B., Banerjee S. et al (2019). Dynamics of neon ions after neon gas seeding into tokamak plasma. *Nuclear Fusion*, *59*(12), 126013.

[3] Raj S., Bisai N., Shankar V., Sen A. (2020). Effects of nitrogen seeding in a tokamak plasma. *Physics of Plasmas*, *27*(12), 122302.

[4]Raj S., Bisai N., Shankar V. et al (2022). Studies on impurity seeding and transport in edge and SOL of tokamak plasma. *Nuclear Fusion*, *62*(3), 036001.

[5] Raj S., Bisai N., Shankar V. et al. "Argon, neon, and nitrogen impurity transport in the edge and SOL regions of tokamak "(http://arxiv.org/abs/2302.10608).

Plasma dynamics from application of edge biasing

Vijay Shankar, N. Bisai, Shrish Raj, and A. Sen

Institute for Plasma Research, Bhat Gandhinagar, 382428, India
Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai,400094, India
e-mail : vijay.shankar@ipr.res.in

The edge and scrape-off layer (SOL) regions of a tokamak are highly turbulent due to mainly drift and interchange instabilities that are primarily responsible for the occurrence of anomalous radial transport. Various control mechanisms have been investigated for the suppression or reduction of the instabilities; biasing in the edge or SOL region [1] is one of these mechanisms. Here, in this work, we have investigated the edge biasing technique numerically, where it is demonstrated that a strong radial electric field shear and Reynold stress are found to modify the plasma turbulence.

Biasing in the edge region by an electric probe creates a plasma sheath around the probe and collects a parallel sheath current that modifies the plasma turbulence. We have modeled the electrode biasing effect using two-dimensional fluid-based equations [2]. The model equations are solved using BOUT++ framework code using biasing from -64 volt to +64 volt. Results obtained from the numerical simulations before and after the application of the biasing are presented, where specific attention is given to the transition to fully saturated phases.

The plasma density increases after the application of the biasing, whereas at the saturated phase, it is increased by about 1.7 times for +32 volt biasing. In this case, the density growth rate measured from the numerical data is about 10^4 /s; we have compared it with the linear growth rate of the turbulence. Similar results are found for the electron temperature, also. We have also calculated Reynolds stress after the application of the biasing that in the edge nearby the biasing region changes the sign but its absolute magnitude increases compared to the case before biasing. But in the SOL region, the stress becomes very low, whereas in the absence of biasing it was finite but negative. It is found that Reynolds stress quickly saturates after the application of the biasing compared to the plasma density in the edge region. The numerical data also indicate that the acceleration of plasma by the stress is increased in the edge region by the biasing, but in the SOL region, it decreases from the case before the application of the biasing. The fluctuations of the stress, radial electric field shear, and velocity acceleration are presented with -64 to +64 biasing voltages.

References

[1] Ph Ghendrih, Y Sarazin, G Attuel, S Benkadda, P Beyer, G Falchetto, C Figarella, X Garbet, V Grandgirard, and M Ottaviani. Theoretical analysis of the influence of external biasing on long range turbulent transport in the scrape-off layer. Nuclear Fusion, 43(10):1013-1022, October 2003.

[2] Vijay Shankar, N. Bisai, Shrish Raj, and A. Sen. Edge biasing and its impact on the edge and SOL turbulence. Nuclear Fusion, 62(8):086030, June 2022.

Study of turbulence dynamics using fast reciprocating Langmuir probe in ADITYA-U tokamak

Kaushlender Singh[1,2], Bharat Hegde[1,2], Ashok K. Kumawat[1,2], M.S. Khan[1,2], Suman Dolui[1,2], Ankit Kumar[1,2], Harshita Raj[1], ,Tanmay Macwan[1], Sharvil Patel[1], Pramila Gautam[1], Rohit Kumar[1], Suman Aich[1], Laxmikanta Pradhan[1], Ankit Patel[1], Kalpesh Galodiya[1], Shwetang Pandya[1], Abhijeet Kumar[1], K. M. Patel[1], K. A. Jadeja[1], R.L. Tanna[1], Joydeep Ghosh[1,2] and ADITYA-U[1] Team

[1]Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India (382428)
[2]HBNI, Training School Complex, Anushakti Nagar, Mumbai, Maharashtra, India (40094)

Email: Kaushlender.singh@ipr.res.in

In tokamak plasma free energies associated with the gradients in density $(\boldsymbol{\nabla n_e})$ and temperature $(\boldsymbol{\nabla T_e})$ can drive turbulence which enhances the transport and degrade the confinement. Hence, characterizing the edge plasma i.e. the radial profiles of density, temperature and related turbulence becomes important [1]. Minimizing the turbulent transport is a primary challenge for the researchers in the nuclear fusion community and several experimental studies are being carried out in this regard [2].The formation of transport barriers and self-generated axis-symmetric structures such as zonal flows play a key role in controlling turbulence and associated transport. Techniques such as impurity seeding and fuel injection (gas puffing) have also proven effective in turbulence suppression [3-4].

In ADITYA-U tokamak we have designed a fast reciprocating Langmuir probe (FRLP) system to characterize the edge plasma i.e. to study $\boldsymbol{\nabla n_e}$, $\boldsymbol{\nabla T_e}$ and the associated nature of fluctuations in plasma parameters such as edge density $(\boldsymbol{\tilde{n}_e})$ and floating potential $(\boldsymbol{\tilde{V}_f})$. To study the effectiveness of gas puff on turbulence in detail we have calculated time and space correlations of turbulence and their radial nature before and after gas puff. It has been observed that turbulence de-correlation time increases going inside the plasma and after gas puff. The results indicate that the edge region of plasma is more turbulent and after the gas puff turbulence gets suppressed. We have also done a comparative study on the effect of gas puff locations (Installed at different poloidal and toroidal locations) on turbulence suppression. Effect on gradients is also investigated using the FRLP system and it is discovered that gas puff tends to flatten the profiles of density and temperature. The reduction in the gradients $(\boldsymbol{\nabla n_e}, \boldsymbol{\nabla T_e})$ basically reduces the turbulence and the related transport, measurement of flux ($\boldsymbol{\Gamma = <\tilde{n}_e \tilde{E}_\theta>}$) also confirms the same. In this paper, we will present the effect of gas puff on gradients and turbulence. The effect of gas puff locations on these phenomena will also be presented in detail.

References

[1] S. J. Zweben and R. W. Gould, "Structure of edge-plasma turbulence in the caltech tokamak," *Nucl. Fusion*, vol. 25, no. 2, pp. 171–183, 1985.

[2] A. Fujisawa, "Review of plasma turbulence experiments," *Proc. Japan Acad. Ser. B Phys. Biol. Sci.*, vol. 97, no. 3, pp. 103–119, 2021.

[3] G. R. McKee *et al.*, "Impurity-induced turbulence suppression and reduced transport in the DIII-D tokamak," *Phys. Plasmas*, vol. 7, no. 5 II, pp. 1870–1877, 2000.

[4] R. Jha *et al.*, "Investigation of gas puff induced fluctuation suppression in ADITYA tokamak," *Plasma Phys. Control. Fusion*, vol. 51, no. 9, 2009.

Detecting $\alpha-$particle heating in JET-ILW DT Hybrid discharges by the delayed electron temperature response to ICRH modulation

I. Casiraghi[1], P. Mantica[1], F. Auriemma[2], D. Gallart[3], K. Kirov[4], E. Lerche[5], M. Maslov[4], A. Salmi[6], Z. Stancar[4], E. Delabie[4], J. Eriksson[7], J. Garcia[8], P. Jacquet[4], T. Jonsson[9], V. Kiptily[4], E. Litherland–Smith[4], C.F. Maggi[4], M. Mantsinen[3], S. Menmuir[4], E. Peluso[10], G. Pucella[11], D. Rigamonti[1], G. Szepesi[4], M. Tardocchi[1], D. Van Eester[5] and JET contributors*

[1] *Institute of Plasma Science and Technology, CNR, Milano, Italy*
[2] *Consorzio RFX ISTP-CNR, Padova, Italy*
[3] *Barcelona Supercomputing Center, Barcelona, Spain*
[4] *CCFE, Culham Science Centre, Abingdon, United Kingdom*
[5] *Laboratory for Plasma Physics, ERM/KMS, Brussels, Belgium*
[6] *VTT, PO Box 1000, FI-02044 VTT, Espoo, Finland*
[7] *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden*
[8] *CEA, IRFM, Saint-Paul-lez-Durance, France*
[9] *Fusion Plasma Physics, EES, KTH, Stockholm, Sweden*
[10] *University of Rome Tor Vergata, Roma, Italy*
[11] *ENEA C.R.Frascati, Frascati, Italy*
**See the author list of "Overview of JET results for optimising ITER operation" by J. Mailloux et al 2022 Nucl. Fusion 62 042026*

In the recent DTE2 campaign of the tokamak JET–ILW, a new method to detect the $\alpha-$particle heating by the delayed electron temperature T_e response to the modulation of the Ion Cyclotron Resonance Heating (ICRH) has been tested. To better bring out the temperature modulation, JET–ILW hybrid scenarios have been used to avoid sawtooth activity and to minimise the core ion temperature stiffness level. Particularly, this work is focused on the JET T–rich hybrid plasma pulse #99965 [1] with 15 % − 85 % D–T mix, operating at 3.86 T and 2.5 MA, heated up by $\sim$ 29 MW of D Neutral Beam Injection (NBI) power and by 3–4 MW of ICRH square–wave modulated power (1 Hz with 50 % duty–cycle) used in $n = 1$ D scheme. Since this ICRH cycle leads to a direct ion temperature T_i modulation and to a modulation of the NBI fast ions, the $\alpha-$particle production from thermal–thermal and beam–thermal fusion reactions is also modulated. Hence the electron heating due to the $\alpha-$particles modulates T_e, but with a certain delay due to the long $\alpha-$particle slowing down time. Analysing the time evolutions of T_e and T_i, respectively measured by ECE radiometer and active charge exchange spectroscopy, modulation amplitudes of $\sim$ 10 % with centrally peaked profiles were found and the central phase delay with respect to ICRH power resulted much larger for the T_e ($\sim$ 105 deg) than for the T_i ($\sim$ 50 deg). Such large delay could only be due to αs since the NBI fast ion, even when accelerated by ICRH, are predicted to have energies $\sim$ 250 keV, with much shorter slowing down time than αs. An extensive modelling work of the discharge #99965 using different transport codes and ICRH and NBI codes has been carried out to support this conclusion.

References

[1] M. Maslov et al., to be submitted to Nuclear Fusion Special Issue of JET T & DT
[2] M. Romanelli, Plasma and Fus. Research **9** 3403023 (2014)
[3] L.-G. Eriksson et al., Nucl. Fusion **33** 1037 (1993)
[4] R.V. Budny et al., Nuclear Fusion **35** 1497 (1995)
[5] P. Strand et al., IAEA-FEC CN-258, India, TH/P6-25 (2018)

Full radius time-dependent simulations of the DTT tokamak plasmas

N. Bonanomi[1], P. Mantica[1], C. Angioni[2], T. Luda[2], I. Casiraghi[2], R. Ambrosino[3,4,5], A. Castaldo[6]

[1]ISTP-CNR, Milano, Italy; [2]IPP-Garching, Germany; [3]CREATE, Napoli, Italy; [4]Consorzio DTT S.C.a.r.l., Italy; [5]Università degli studi di Napoli Federico II, Napoli, Italy; [6]ENEA, Italy

The Divertor Tokamak Test facility, DTT [1], is a new tokamak being built in Frascati, Italy. It features a major radius R = 2.19 m, a minor radius a = 0.7 m, a magnetic field up to $B_T = 5.85$ T and a plasma current up to $I_p = 5.5$ MA. This study focuses on full-radius time-dependent simulations of DTT baseline scenario plasmas. These are performed using the transport code ASTRA [2] coupled with the neoclassical module NCLASS [3], the quasi-linear model for turbulent transport TGLF-sat2 [4, 5], and the IMEP [6] model for the calculation of the H-mode pedestals. The simulations cover the ramp-up L-mode phase, as well as part of the H-mode phase of the plasma, from t=0.65 s to t=20-30s. The boundary of the simulations is at the plasma separatrix and only engineering parameters, plus prescribed plasma boundaries calculated by the CREATE non-linear solver, are used as inputs. At the L-H power threshold, IMEP calculates the H-mode pedestals (in n_e, T_e and T_i) relaying on the L-mode conditions reached within the simulation. These pedestals are then imposed outside $r_{tor} = 0.9$ (change in boundary) and the plasma profiles are evolved inside this radial position. IMEP can eventually be called again once the desired condition is reached (every certain step in power, step in time etc.). With this approach, the L-mode phase, the L-H transition and the H-mode phase are all calculated with no need to stop the simulation between the different phases. The full radius evolution of the plasma temperatures, of the electron and impurities densities, of the plasma current and of the plasma equilibrium are calculated. The plasma line-averaged density is kept at the desired value using a feed-back control of the neutral source at the separatrix (imitating a feed-back control of the gas-puff level, as in [7]). The external heating power is composed by ECRH, ICRH and NBI heating (the TORBEAM and the RABBIT routines have been implemented for DTT for the self-consistent calculation of ECRH and NBI power deposition).

These reliability of the methods presented in this study is based on successful past studies on the edge turbulent transport [8], on full-radius simulations of ASDEX Upgrade plasmas [7] and of ASDEX Upgrade, JET-ILW and Alcator C-Mod pedestal studies with IMEP [6, 9]. The combination of all these new methods represents an important steps towards the use of theory-based, reduced model for the prediction of the plasma full-radial time-evolution of future machines. This study explores and shows the strong flexibility (and feasibility) of the DTT tokamak, especially regarding its ability to reach and maintain 5.5 MA of plasma current and its close comparison, in terms of important parameters such as beta and collisionality, with devices like ITER.

[1]https://www.dtt-project.it/#; [2]G.V. Pereverzev, P. N. Yushmanov, IPP-report 5/98, 2002; [3] W.A. Houlberg et al. *Phys. Plasmas* **4** (1997) 3230; [4]G. M. Staebler et al. Phys. Plasmas 14 2007; [5]G.M. Staebler et al. Nucl. Fusion 61 202 ; [6]T Luda et al 2023 Plasma Phys. Control. Fusion **65** 034001; [7]C. Angioni et al 2022 Nucl. Fusion **62** 066015; [8]N. Bonanomi et al. EPS 2022; [9]Luda *et al* 2020 *Nucl. Fusion* **60** 036023.

Progressing the understanding and applications of the QCE scenario

G. F. Harrer[1], M. Faitsch[2], E. Wolfrum[2], A. Cathey[2], M. Dunne[2], D. Brida[2], L. Gil[3], M. Griener[2], B. Labit [4], L. Radovanovic[1], F. Aumayr[1], the ASDEX Upgrade Team[5], the JOREK Team[6], and the Eurofusion MST1 Team[7]

[1] *Institute of Applied Physics, TU Wien, Fusion@ÖAW, Vienna, Austria*

[2] *Max Planck Institute for Plasma Physics, Garching, Germany,*

[3] *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal*

[4] *École Polytechnique Fédérale de Lausanne, Swiss Plasma Center, CH-1015 Lausanne, Switzerland*

[5] *see the author list of U. Stroth et al. 2022 Nucl. Fusion **62** 042006*

[6] *see the author list of M. Hoelzl et al. 2021 Nucl. Fusion **61** 065001*

[7] *see the author list of B. Labit et al. 2019 Nucl. Fusion **59** 0860020*

A potential solution for avoiding the non-tolerable large type-I ELMs in a future fusion reactor is to operate in the quasi-continuous exhaust (QCE) regime [1]. In the QCE regime the plasma is reported to be ballooning unstable just inside the last closed flux surface. The QCE regime is most easily achieved in highly shaped plasmas with significant gas fuelling where the local ballooning instability can keep the plasma below the global peeling-ballooning critical threshold and avoid type-I ELMs [2]. The instability providing transport at the foot of the pedestal was characterised as a kinetic or resistive ballooning mode using the thermal helium beam [3]. We use the ideal linear $n \to \infty$ code HELENA [4] to calculate the ideal ballooning stability as a proxy for the local stability of such modes. Analysis of 36 simulated ITER profiles shows that, similarly to the experimental cases from AUG, a high pedestal top pressure can be maintained simultaneously with an ideal ballooning instability at the pedestal foot, making QCE a promising scenario for ITER [5]. HELENA alone provides no information on transport. To estimate the transport caused by the pedestal foot instability, a large number of QCE discharges performed on ASDEX Upgrade was analysed with a database approach with one main result: The position of the instability shows a strong positive correlation with plasma confinement. This indicates that the instability leads to increased transport the further it is located radially inside. Using the predictive global IPED code we investigated the influence of shaping factors by scanning the elongation and triangularity of a 1 MA, 2.5 T AUG-sized plasma at constant pedestal density and global β_N. We determined the dependence of α_{crit} for local and global ideal MHD instabilities on plasma shape, showing a stronger dependence on elongation than on triangularity [6]. After ideal local linear and global linear simulations the QCE regime will be analysed using the resistive non-linear code JOREK [7]. Building on existing simulations for small ELM scenarios at low triangularity [8] and no-ELM scenarios at high triangularity [9], the shape dependence of the mode spectrum and the resulting transport will be analyzed. In terms of scenario development we were able to expand the safety factor range of the regime in the direction of the ITER parameters with the new record being q_{95}=3.3. We were also able to demonstrate that QCE access is possible in a discharge without any large type-I ELMs, with a transition to a partially detached divertor and with high normalised confinement. This is achieved by a double feed-back on β_{pol} and T_{div} used for the first time in AUG [10].

corresponding author: harrer@iap.tuwien.ac.at

References

[1] M. Faitsch et al. 2021 NME **26** 100890
[2] G.F. Harrer et al. 2022 PRL **129** 165001
[3] J. Kalis et al. 2023 this conference
[4] G. Huysmans et al. 1991 PICCP **p 371**
[5] L. Radovanovic et al. 2022 NF **62** 086004
[6] M. Dunne et al. 2023 in preparation
[7] G. Huysmans, O Czarny. 2007 NF **47** 659
[8] A. Cathey et al. 2022 PPCF **64** 054011
[9] A. Cathey et al. 2023 submitted to NF
[10] M. Faitsch et al. 2023 submitted to NF

Control of three-dimensional magnetic islands by currents in toroidal field coils in the CFQS quasi-axisymmetric stellarator

X. Su[1], X. Q. Wang[1], Y. Xu[1], S. Okamura[2], A. Shimizu[2,3], M. Isobe[2,3], H. F. Liu[1], J. Huang[1], J. Cheng[1], X. Zhang[1], H. Liu[1], C. J. Tang[4]

[1] *Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, China*

[2] *National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Gifu 509-5292, Japan*

[3] *The Graduate University for Advanced Studies, SOKENDAI, Toki, Gifu 509-5292, Japan*

[4] *School of Physical Science and Technology, Sichuan University, Chengdu 610041, China*

Magnetic island physics is one of important subjects for the Chinese First Quasi-axisymmetric Stellarator (CFQS) in case of high-β operation [1, 2]. In this study, we focus on the effect of currents in toroidal field coils (TFCs) on 3D magnetic islands using the HINT code [3]. Under the high-β operation of CFQS (volume-averaged plasma beta $<\beta>$~0.74% and the resultant bootstrap current I_{bs}~ 24.5 kA), double m/n=4/2 rational surfaces and large magnetic islands are generated. It is found that the islands can be significantly affected by the currents in the TFCs, which produce an additional toroidal magnetic field to modify the rotational transform ι profiles. With increase of TFC currents from 0-30 kA, the size of islands and also the effective confinement region change considerably, as shown in Figs.1 (a-c), where the red, blue and black colour denote normalized plasma pressure p/p_0 >10 %, 1~10 %, <1 %, respectively. Particularly, when I_{tfc}=−30 kA the m/n=4/2 islands can be completely suppressed and good flux surfaces are formed in the core region, because the m/n=4/2 rational surface vanishes, as illustrated in the iota profile in Fig.1 (d). Thus, it is concluded that the auxiliary TFCs can be considered as an effective tool to control magnetic islands by modifying the rotational transform in the CFQS.

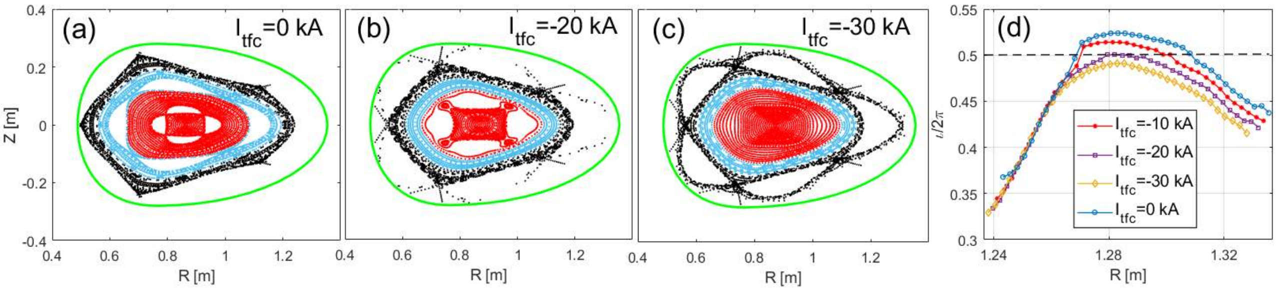


Figure 1 Poincaré plots of magnetic surfaces (a) without TFC current (I_{tfc}=0 kA), (b) with TFC current I_{tfc}=-20 kA, (c) with TFC current I_{tfc}=-30 kA, (d) the radial profiles of the rotational transform with different TFC currents.

References:

[1] Wang X Q *et al.*, Nuclear Fusion 2021 61 036021

[2] Okamura S. *et al.*, Journal of Plasma Physics 2020 86 815860402

[3] Suzuki Y *et al.*, Nuclear Fusion 2006 46 L19

MHD instability dynamics and turbulence enhancement towards the plasma disruption in the HL-2A tokamak

Y.C. Li[1], Y. Xu[1], M. Jiang[2]

[1] *Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610041, Sichuan, Peoples Republic of China*

[2]*Southwestern Institute of Physics, PO Box 432, Chengdu 610041, Sichuan, Peoples Republic of China*

The evolutions of MHD instability behaviors and enhancement of both electrostatic and electromagnetic turbulence towards the plasma disruption have been clearly observed in the HL-2A plasmas. Two types of plasma disruptive discharges have been investigated for similar equilibrium parameters: one with a distinct stage of a small central temperature collapse (~5%-10%) around 1 millisecond before the thermal quench (TQ), while the other without. For both types, the TQ phase is preceded by a rotating 2/1 tearing mode, and it is the development of the cold bubble from the inner region of the 2/1 island O-point along with its inward convection that causes the massive energy loss. In addition, the micro-scale turbulence, including magnetic fluctuations and density fluctuations, increases before the small collapse, and more significantly towards the TQ. Also, temperature fluctuations measured by electron cyclotron emission imaging enhances dramatically at the reconnection site and expand into the island when approaching the small collapse and TQ, and the expansion is more significant close to the TQ. The observed turbulence enhancement near the X-point cannot be fully interpreted by the linear stability analysis by GENE. Evidences suggest that nonlinear effects, such as the reduction of local $E_r \times B$ shear and turbulence spreading, may play an important role in governing turbulence enhancement and expansion. These results imply that the turbulence and its interaction with the island facilitate the stochasticity of the magnetic flux and formation of the cold bubble, and hence, the plasma disruption.

The characteristics of ITG and TEM instabilities in CFQS

M. S. Li[1], J. Huang[1], Y. Xu[1], M. Nakata[2,3,4], A. Shimizu[2,3] M. Isobe[2,3] S. Okamura[2], H. F. Liu[1], X. Q. Wang[1], X. Zhang[1], H. Liu[1], J. Cheng[1], J. F. Shen[1] and C. J. Tang[1]

[1] *Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, China*

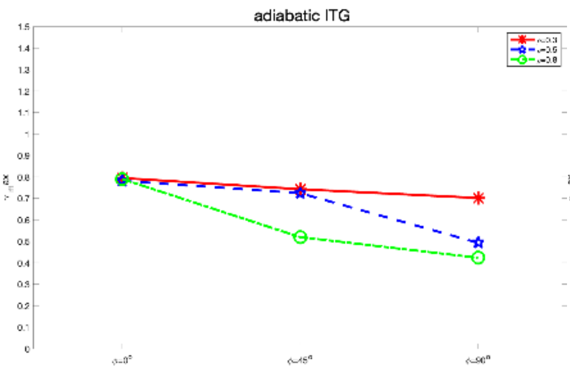
[2] *National Institute for Fusion Science, National Institutes of Natural Sciences, Toki 509-5292, Japan*

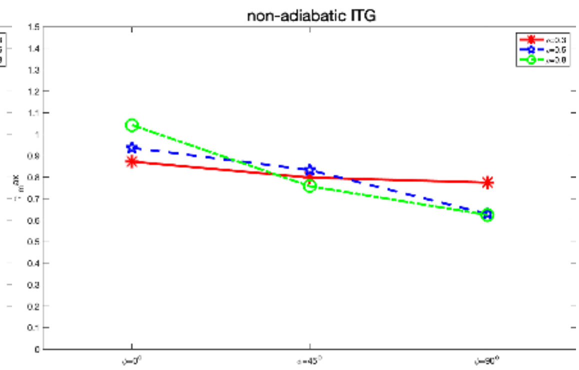
[3] *The Graduate University for Advanced Studies, SOKENDAI, Toki 509-5292, Japan*

[4] *PRESTO, Japan Science and Technology Agency, 418, Honcho, Kawaguchishi, Saitama 332-0012, Japan*

Chinese First Quasi-axisymmetric Stellarator (CFQS) is currently the only quasi-axisymmetric stellarator under construction in the world [1,2]. To theoretically explore the nature of turbulent transport in the CFQS magnetic configuration, it is necessary to carry out simulation of turbulent transport driven by microinstabilities [3], such as ion temperature gradient (ITG) mode and trapped electron mode (TEM). This work investigates the characteristics of the ITG mode and TEM at three different toroidal angles (φ=0°, 45°, 90°) and three radial positions (ρ=0.3, 0.5, 0.8) in CFQS using gyrokinetic Vlasov code GKV [4,5] to obtain a global picture of microinstabilities in CFQS.

The simulation results show that (1) for adiabatic ITG, at the three given radial locations, the growth rate decreases with the increasing minor radius ρ for all three toroidal angles. At the core of CFQS (ρ=0.3), the growth rate changes very little at various toroidal angles. When φ=0°, all the growth rates at different radial locations are nearly the same. When φ=45°, the maximum growth rate at ρ=0.8 decreases while the maximum growth rate at the other two radial positions changes very little. When φ=90°, both the maximum growth rates at ρ=0.5 and ρ=0.8 decrease. (2) For non-adiabatic ITG, it is different from that of adiabatic ITG. When φ=0°, the growth rate is maximum at ρ=0.8, whereas φ=90°, the growth rate becomes minimum at the same location. (3) For TEM, the growth rate is maximum at ρ=0.8 for all toroidal angles and the growth rates at three radial positions change very little at various toroidal angles.





Reference:

[1] A. Shimizu, et al. *Plasma Fusion Res.* 13, 3403123 (2018)
[2] H. F. Liu, et al. *Nucl. Fusion* 61, 016014 (2021)
[3] J. Huang, et al. *Phys. Plasmas* 29, 052505 (2022)
[4] T.-H. Watanabe, et al. *Nucl. Fusion* 46, 24 (2006)
[5] M. Nakata, et al. *Phys. Rev. Lett.* 118, 165002 (2017)

Experimental observation of low-frequency zonal flow in HL-2A plasmas

X. Chen[1*], J. Cheng[1], Y. Xu[1], L.W. Yan[2], Q.Zou[1], Z.H. Huang[2], W.C. Wang[2], Y.He[2], Z.B. Shi[2], N. Wu[2], X.Q.Ji[2], C.J. Tang[1], W.L. Zhong[2] and M. Xu[2]

[1]Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, People's Republic of China,

[2]Southwestern Institute of Physics, Chengdu 610041, People's Republic of China

E-mail address of submitting author*marguerite@my.swjtu.edu.cn

Abstract:

It is well known and widely accepted that zonal flow plays a crucial role in regulating turbulence in magnetically confined plasmas [1-2]. Zonal flows are theoretically predicated to exist in two types, i.e., geodesic acoustic modes (GAM) and low-frequency zonal flow (LFZF). For the GAM spatial characteristics and its generation mechanism, it has been intensively studied in theoretical simulations and experiments [3]. For the LFZF, several experimental results suggest the critical role of LFZF in the confinement improvement by reducing the local turbulent transport. For example, the H-1 experimental results indicates that the LFZF could act as a trigger for the spontaneous transition to H-mode [4]. JET work has shown that stationary ZF is the main source for amplifying E_r in L-mode [5]. In JFT-2M the LFZF is thought to be correlated with the formation of internal transport barrier (ITB) [6]. However, there is few experimental report for confirming the LFZF by toroidal long-range correlation and the nonlinear-coupling simultaneously evidenced in experiments.

In this work, we present the experimental evidences on the LFZF at edge region in HL-2A Ohmically-heated plasma by using two Langmuir probe arrays toroidally separated by 2100 mm. The experimental results illustrated that the floating potential measured inside LCFS about 20 mm was dominated by a coherent oscillation with a central frequency at f=1.98 kHz and the toroidal correlation could reach 0.8. Meanwhile, the bicoherence analysis illustrated that the nonlinear coupling of small-scale turbulence (300-500 kHz) had the main contribution for the formation of the coherent oscillation. These characteristics were well consistent with the theoretically predicated LFZF [2]. It was found that the inward turbulence spreading significantly increased as the amplitude level of LFZF dramatically rose, which was also consistent with the reduced particle flux monitored by H_a emission. The opposite behaviors between LFZF and particle flux indicated the crucial role played by the LFZF in modulating local turbulent transport. The detailed experimental results will be presented in this conference.

This work was supported by the National Science Found of China (Grant number 12175186) and the National Key R&D program China (Grant number 2022YFE03070001)

References

[1] Z. Lin et al. 1998 Science 281 1835

[2] P. H. Diamond 2005 Plasma Phys. Control. Fusion 47 R35

[3] G. D. Conway et al. 2022 Nucl. Fusion 62 013001

[4] H. Xia et al. 2006 Phys. Rev. Lett. 97 255003

[5] J. C. Hillesheim et al. 2016 Phys. Rev. Lett. 116 065002

[6] A. Fujisawa et al. 2004 Phys. Rev. Lett. 93 165002

Influence of electric potential on electrostatic micro-instability in advanced stellarator

Xiaofeng Zheng[1], Haifeng Liu[1], Yuhong Xu[1], Jie Huang[1], Shoichi Okamura[2], Akihiro Shimizu[2,3], Mitsutaka Isobe[2,3], Xianqu Wang[1], Jun Cheng[1], Xin Zhang[1], Hai Liu[1] and Changjian Tang[4]

[1] *Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, China*

[2] *National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Gifu 509-5292, Japan*

[3] *The Graduate University for Advanced Studies, SOKENDAI, Toki, Gifu 509-5292, Japan*

[4] *School of Physical Science and Technology, Sichuan University, Chengdu 610041, China*

Gyrokinetic theory is of great importance in the study of micro behaviors in stellarator and tokamak, which provides an efficient way of obtaining the appropriate reduced kinetic equations while still retaining the finite Larmor radius effect[1].It has been comprehensively applied to investigate the low-frequency turbulence driven by micro-instabilities, such as ion temperature gradient (ITG), trapped electron mode (TEM) etc[2-4]. However, many previous works were focused on analyzing the micro-instabilities in various devices without considering radial electric field $\boldsymbol{E_r}$. This work aims to discuss the influence of the equilibrium potential on electrostatic micro-instabilities in advanced stellarator and a new dispersion equation is achieved, which shows that the equilibrium potential can affect micro-instabilities in three ways. First, as described in many other articles, the $\boldsymbol{E_r} \times \boldsymbol{B}$ flow shear always stabilizes the micro-instabilities. Secondly, the $\boldsymbol{E_r} \times \boldsymbol{B}$ drift can affect the micro-instabilities by changing the adiabatic invariant J. Thirdly, the introduction of $\boldsymbol{E_r}$ makes another new term appears in the gyrokinetic Vlasov equation, which can greatly modify velocity distributions of particles.

References

[1] Gregory G. Howes et al 2006 ApJ 651 590

[2] Haifeng Liu et al 2023 Nucl. Fusion 63 026018

[3] Jie H. et al 2022 Phys. Plasmas 29 052505

[4] P. Helander 2014 Phys. Rev. Lett. 113 135003

Dynamics of pedestal in the recovery phase in EAST type-I ELM plasmas

H. Zhou[1], T. Zhang[2], Y. Xu[1], J. Cheng[1], J. Huang[1], Q.X. Wang[1], H. Liu[1], H.F. Liu[1], Q. Zang[2], X. Zhang[1], C.J. Tang[1,3]

[1] *Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu, China*

[2] *Institute of Plasma Physics, Chinese Academy of Sciences, PO Box 1126, Hefei, Anhui, China*

[3] *Physics Department, Sichuan university, Chengdu, China.*

In the EAST high-confinement mode plasmas, a low-frequency n=1 magnetic coherent mode with frequency f=20-50 kHz and a high frequency mode with electromagnetic characteristics (HFEM, f~280 kHz) have been found between type-I ELMs. Both the HFEM and n=1 mode located at pedestal region but their radial locations seem to be some different. It seems from present data that the HFEM is closer to the maximum density gradient region while the n=1 mode maybe closer to the separatrix. The experimental results demonstrate that the electron temperature recovers more rapidly than pedestal density and the n=1 mode is excited in pedestal after an ELM collapse. With the increase of the pedestal density, the HFEM appears and becomes dominant, while the amplitude of n=1 mode decreases significantly. The observation indicates that the HFEM may suppress the amplitude of the n=1 mode. In the pre-ELM phase, the pedestal electron density and temperature are saturated as well as the characteristics of HFEM show a significant change (a much broader frequency spectrum and reduced mode amplitude) and the n=1 mode recovers again. Analysis by using wavelet bispectrum reveals that a nonlinear coupling between the n=1 mode and the high frequency magnetic fluctuations exists in the pre-ELM phase. The relations among the nonlinear mode coupling, the reappearance of n=1 mode and the ELM crash are discussed.

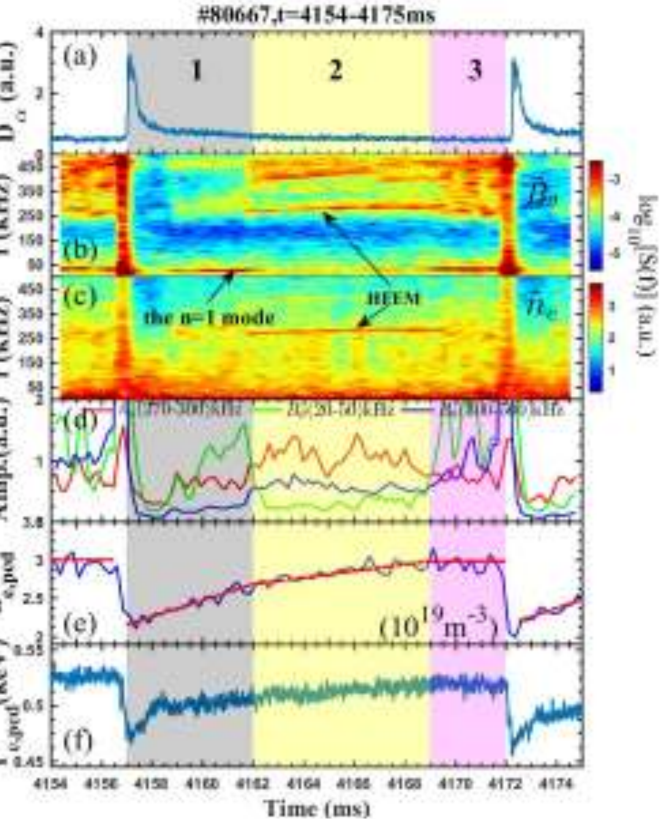


Fig. 1: Time evolutions of (a) D_α in type-I ELM discharge during an ELM cycle from 4154 to 4175 ms (b) spectrum of $\tilde{B}_\theta$ and (c) spectrum of $\tilde{n}_e$ (d) the integrated spectral power over the different frequency bands of $\tilde{n}_e$ and $\tilde{B}_\theta$. (e) the pedestal top density (n_e^{ped}) evolution fitted by DPR (f) the pedestal top temperature (T_e^{ped}) evolution measured by ECE.

Keywords: pedestal, mode coupling, pedestal modes, type-I ELM

Modelling of ICRH slow wave propagation and absorption in Wendelstein 7-X stellarator

D. Grekov[1], Yu. Turkin[2]

[1] *Institute of Plasma Physics NSC KIPT, Kharkiv, Ukraine*

[2] *Max Plank Institute for Plasma Physics, Greifswald, Germany*

The new ICRF system is installed in Wendelstein 7-X (W 7-X) stellarator and will be used in experimental campaigns OP 2.1 and OP 2.2. The main features of the W 7-X ICRF system are given in [1]. It should be noted that, when studying the interaction of the ICRF antenna with the W 7-X plasma, the main attention was paid to the coupling and absorption of the fast wave. The electric field of this wave is polarized in the poloidal direction at the plasma edge. It is fast wave that is launched by the current-carrying conductors of the ICRF antenna. The other part of the radiofrequency (RF) power is delivered to the plasma by the toroidal RF electric field. This electric field is due to the oscillating differences of the potentials in the gap between the unshielded current-caring conductors and in the gaps between the conductors and the grounded antenna box. Being expanded in Fourier series in poloidal and toroidal angles, this field can be divided into two parts. One part of the RF toroidal field forms the so-called near field of the antenna. The other part of the Fourier spectrum is radiated as the small scale slow waves (SW). What is the effect of the SW on the W7-X plasma? To answer this question, propagation and absorption of the SW were investigated accounting for the real geometry of W7-X plasma. Due to small scale of this wave, the geometrical optic approach was justified. The conversion of the SW into ion Bernstein mode in the vicinities of the plasma resonances was taken into account. The possibility of transformation of the SW to fast wave was also taken into consideration. Electron Landau damping, ion cyclotron damping and collisional absorption were included into calculations. Numerical simulations of the SW propagation and absorption were performed for W7-X H-D plasma with 0.1-5% 3He minority. The wave frequency was set to 25 MHz. A strong influence of the 3He minority concentration on the propagation and absorption of slow waves was found.

1. T.S. Pedersen et al // *Phys. of Plasmas*. 2017, v. 24, p. 055503.

Prompt effects of partially ionised W dust in the JET shallow SOL

F. Causa[1], G. Gervasini[1], F. Ghezzi[1], E. Lazzaro[1], H. Kumpulainen[2], D. Borodin[3], I. Borodkina[4], D. Douai[5], A. Huber[3], E. Pawelec[6], R. Solano[7], M. Sertoli[8], A. Widdowson[9] and JET Contributors*

[1]*Istituto per la Scienza e Tecnologia dei Plasmi-CNR, Milano, Italy*

[2]*Aalto University, Espoo, Finland*

[3]*Forschungszentrum Julich GmbH, Jülich, Germany*

[4]*Institute of Plasma Physics of the CAS, Prague, Czech Republic*

[5]*CEA, Saint-Paul-Lez-Durance, France*

[6]*University of Opole, Opole, Poland*

[7]*Laboratorio Nacional de Fusion, Madrid, Spain*

[8]*Tokamak Energy Ltd, Abingdon, UK*

[9]*Culham Science Centre, Abingdon, UK*

**See author list of J. Mailloux et al. 2022 Nucl. Fusion 62 042026*

Experimental evidence of a systematic time-correlation between W dust influx across the separatrix and transient radiative bursts (TIEs) in the visible band was established, for example, in ITER Like Wall JET campaigns [1]. On time scales much shorter than those typical of transport in the tokamak edge, the ingress of macroscopic W dust from the divertor region across the separatrix is responsible of sudden, short-lived, radiative events and localized perturbations of edge density and temperature profiles. Eventually the deposition of ionized micrometric W dust released occasionally and randomly by the tokamak divertor tiles and nearby PFCs, affects plasma performance and stability. We address here the challenge of assessing the influx extent of dust particles ensembles, across flux surfaces, subject to the interaction with the plasma, and possible side effects due to the partial ionisation of the dust projectile. The important conclusions of this study are that W dust transport is dominated by ballistic mechanisms, [2], necessarily complemented by the adiabatic ablation-deposition model, and that in the shallow, very low-T_e SOL edge, electrostatic wave bursts can be excited, which could be detected by Langmuir probes, [3], as additional monitor for pedestal evolution.

References

[1] E. R. Solano et al., P1006, 41st EPS Conference, Berlin, Germany, 2014

[2] E. Lazzaro et al., Nucl. Fusion 62 (2022) 126037

[3] W Gekelma, J. Wise P. Pribyl et al Am. J. Phys. **75** _2_(2007)

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 EUROfusion). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. This work was supported in part by the Italian Consiglio Nazionale delle Ricerche.

Impurity transport with a transport barrier in 5D gyrokinetic simulations

G. Lo-Cascio[1], E. Gravier[1], T. Réveillé[1], M. Lesur[1], X. Garbet[2,3], Y. Sarazin[2], K. Lim[4], G. Dif-Pradalier[2], P. Donnel[2], A. Guillevic[1], T. Rouyer[1], V. Grandgirard[2]

[1] *IJL, UMR 7198 CNRS, Université de Lorraine, 54000 Nancy, France*

[2] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

[3] *School of Physical and Mathematical Sciences, Nanyang Technological University, 637371 Singapore*

[4] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center, EPFL SB SPC, Station 13, CH-1015 Lausanne, Switzerland*

Impurity transport in tokamaks is a complex process that is governed by turbulent and collisional (i.e. neoclassical) transport. Heavy impurities, such as tungsten, are known to be accumulated in the core region of tokamaks mainly due to the inward neoclassical convection[1]. The impact of a transport barrier on this transport is studied using 5D gyrokinetic GYSELA[2] simulations. Such a transport barrier is triggered and maintained by a strongly sheared $E \times B$ poloidal flow driven by an external poloidal momentum source (i.e. vorticity)[3] that locally polarizes the plasma. It results in a locally reduced turbulent heat diffusivity coefficient and a slight increase in core pressure as compared to the case without transport barrier[4].

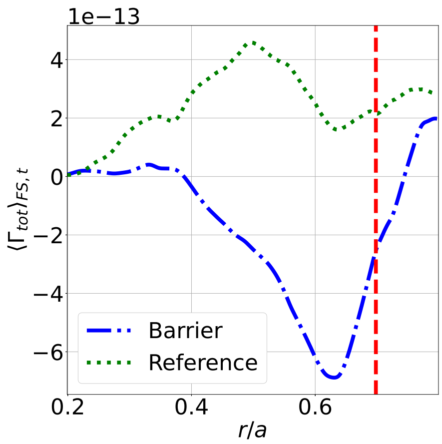


Figure 1: *Time-averaged total radial particle flux of helium impurities with (blue dash-dotted line) and without transport barrier (green dotted line). The red dashed vertical line indicates the transport barrier position.*

Several impurity species are scanned in the trace limit. First, we explore helium ahes ($Z = 2$, low collisionality "Banana-Plateau"), the product of the fusion reaction. Argon ($Z = 18$) and neon ($Z = 10$) are studied as intermediate Z-species (medium-high collisionality), which are seeded to mitigate heat flux in the boundary region. We also investigate tungsten ($Z = 40$, high collisionality "Pfirsch-Schlüter"), which is sputtered from PFC (Plasma-Facing Components) like divertors and heavily impacts the reactor efficiency through major radiation loss. As shown in Fig.1, the radial flux of helium changes sign from positive (outward) to negative (inward) when the transport barrier is turned on. This is due to the strong reduction of turbulent transport, which is the main transport channel for low-Z impurities like helium. A strong impact of poloidal asymmetries and anisotropies on neoclassical transport is observed in the transport barrier case. Also, the change affects a large part of the plasma although the barrier is fairly localized.

References

[1] K. Lim et al., Nucl. Fusion, vol. 61, no 4, p. 046037, 2021.

[2] V. Grandgirard et al., Comput. Phys. Commun., vol. 207, pp. 35–68, 2016.

[3] A. Strugarek et al., Plasma Phys. Control. Fusion, vol. 55, no. 7, p. 074013, 2013.

[4] G. Lo-Cascio et al., Nucl. Fusion, vol. 62, no. 12, p. 126026, 2022.

Runaway electron dynamics in the Tokamak à Configuration Variable

M. Hoppe[1], J. Decker[1], U. Sheikh[1], T. Wijkamp[2,3], J. Cazabonne[1], B. Duval[1], G. Papp[4], A. Perek[1], Y. Peysson[5], L. Simons[1], A. Tema-Biwole[1], B. Vincent[1], L. Votta[1] and the TCV team[1]

[1]*Swiss Plasma Center, EPFL, Lausanne, Switzerland,* [2]*Eindhoven University of Technology, Netherlands,* [3]*DIFFER, Eindhoven, Netherlands,* [4]*Max Planck Institute for Plasma Physics, Garching, Germany,* [5]*CEA, IRFM, St-Paul-Lez-Durance, France*

An ambitious research program into the generation, suppression and overall dynamics of runaway electrons (RE) has been conducted on the Tokamak à Configuration Variable (TCV) [1]. Scenarios for studying RE during the startup, flat-top and disruption phases have been developed, and hundreds of dedicated experiments have produced a wealth of data from a diverse set of diagnostics.

In this contribution, we present results from kinetic and fluid-kinetic simulations of RE during the flat-top and disruption phases of TCV discharges, using the codes DREAM [2] and LUKE [3]. The simulations give insight into several aspects of importance to the RE dynamics:

(i) Kinetic simulations, combined with measurements of basic plasma parameters, allow the radial transport rate of fast electrons to be quantified. The radial transport of RE can normally not be measured directly in experiment, but can be constrained via simulation, requiring that simulations reproduce the measured plasma current. Radial transport remains one of the key features of RE dynamics yet to be accurately characterized.

(ii) In RE dominated post-disruption plasmas, it is found that RE-plasma collisions significantly enhance the background plasma temperature. Since recently developed benign termination techniques [4]—envisioned as a second line of defense against RE in ITER—rely on reaching a sufficiently low post-disruption temperature [5], a thorough understanding of the plasma energy balance in the RE plateau is important.

(iii) The toroidal field ripple limits the maximum energy attainable by RE on TCV. The resulting characteristic energy distribution is used to design and dimension hard x-ray diagnostics which give insight into the energy distribution of RE. Experiments suggest that the RE energy distribution may play a key role in the benign termination of RE beams [5].

References

[1] J. Decker *et al*, Nucl. Fusion **62** 076038 (2022)
[2] M. Hoppe *et al*, Comp. Phys. Comm. **268** 108098 (2021)
[3] J. Decker *et al*, Plasma. Phys. Control. Fusion **58** 025016 (2016)
[4] C. Reux *et al*, Phys. Rev. Lett. **127** 175001 (2021)
[5] U. Sheikh *et al*, Invited talk at the 49th EPS Conference on Plasma Physics, July 2023

Fully kinetic Particle-in-Cell simulations of tearing mode instabilities in fusion tokamaks

Jincai. Ren[1], Wei. Zhang[2], Yuchen. Xu[3], Nikolai. N. Gorelenkov[4], Minyou. Ye[3],
Wei. Jiang[5], Giovanni. Lapenta[1]

[1] *Centre for mathematical Plasma-Astrophysics, KU Leuven, Leuven, Belgium*

[2] *Institute for Fusion Theory and Simulation, Zhejiang University, Hangzhou, China*

[3] *School of Nuclear Science and Technology, University of Science and Technology of China, Hefei, China*

[4] *Princeton Plasma Physics Laboratory, Princeton, USA*

[5] *School of Physics, Huazhong University of Science and Technology, Wuhan, China*

The tearing mode is one of the most dangerous instabilities in fusion tokamaks since it can destroy the plasma confinement and even cause disruptions in experiments. There have been lots of simulation studies which use magnetohydrodynamics (MHD) methods to investigate its mechanism. However, it is advisable to use kinetic methods to study this problem especially considering the fact that the plasma in tokamak core region is collisionless and the real resistivity is actually very low.

Here we present the Particle-in-Cell simulations (as shown in Fig. 1) of the tearing mode in tokamaks using a semi-implicit, fully kinetic and energy-conserving code ECsim, which is developed by Lapenta [1] and has been successfully used in the study of magnetic reconnection in solar physics. We conducted simulations starting from the same equilibrium as [2] and studied the effect of electron diamagnetic drift on the structure and growth rate of the 2/1 tearing mode. We also investigated the energy evolution of tearing modes under various conditions. Then we compared our results with [2] and discussed the causes of results differences. Besides, we analyzed the role of pressure tensor in the occurrence of tearing modes by combining PIC simulations with previous theoretical studies.

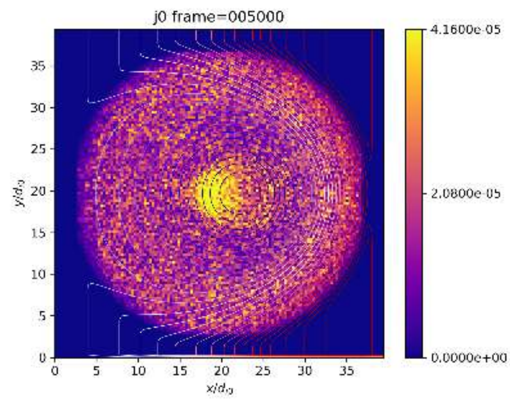


Figure 1: *electron current profile*

References

[1] G. Lapenta, Journal of Computational Physics **334**, (2017)

[2] W. Zhang, Z. W. Ma, and S. Wang, Physics of Plasmas **24.10**, (2017)

Local movement analysis using tomography in PANTA

D. Nishimura[1], A. Fujisawa[2,3], Y. Nagashima[2,3], C. Moon[2,3], K. Yamasaki[4], T. Nishizawa[2,3], T. Yamada[3,5], Y. Kosuga[2,3], T-K. Kobayashi[1]

[1] *IGSES, Kyushu University, Kasuga, Japan*

[2] *Research Institute for Applied Mechanics, Kyushu University, Kasuga, Japan*

[3] *Research Center for Plasma Turbulence, Kyushu University, Kasuga, Japan*

[4] *GSASE, Hiroshima University, Higashihiroshima, Japan*

[5] *Faculty of Arts and Science, Kyushu University, Fukuoka, Japan*

Tomography systems have been developed to measure multi-scale turbulence in a linear plasma device, PANTA, and have succeeded in reproducing local plasma emission and its fluctuations [1, 2]. Several unique analysis methods have been proposed for tomography images to extract plasma structure and dynamics, such as Fourier-rectangular function (FRF) expansion [3] and the modal polarization analysis [4]. These methods can characterize fluctuations in the Fourier space of wave number and frequency. Recently, another novel method, called Local Movement Analysis (LoMA), has been developed for characterizing plasma dynamics in real space. The method estimates the plasma movement or local plasma velocity to choose the velocity that minimizes the difference between predicted and observed patterns of temporally evolving patterns. Using FRF expansion above, poloidal movement or velocity v_θ has been successfully evaluated. Furthermore, LoMA has been extended to include radial velocity v_r by fully utilizing two-dimensional emission patterns. Two methods are tested: the local and global ones. The former evaluates the 2D velocity from the local evolution of emission patterns, while the latter does from global emission patterns to which the Fourier-Bessel functions are fitted using the least square fitting. These methods are applied to the plasma where the fluctuating pattern of m=4 azimuthal mode is dominant, and the results agree well with each other on average. The estimated velocity field by the global method is shown in Figure 1. In the presentation, we will give the details of the developed methods and the obtained results, with a discussion on if the fluctuations obtained in the methods should be the real ones originating from the plasma.

This work was supported by JSPS KAKENHI Grant Numbers JP20K14443, JP22H00120, JP22J11823.

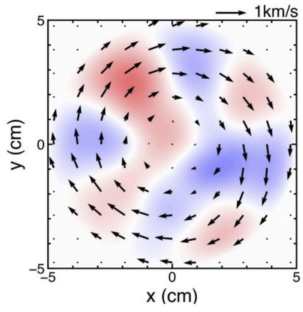


Figure 1. Estimated velocity field by LoMA.

References

[1] A. Fujisawa, *et al.*, Plasma Phys. Control. Fusion **58**, 025005 (2016)
[2] C. Moon, *et al.*, Scientific Reports **11**, 1 (2021)
[3] K. Yamasaki, *et al.*,Journal of Applied Physics **126**, 043304 (2019)
[4] D. Nishimura, *et al.*, Journal of Applied Physics **129**, 093301 (2021)

Core plasma transport including impurity in improved confinement mode using integrated code TASK

S. Mochinaga[1], N. Kasuya[1,2], A. Fukuyama[3], M. Yagi[4].

[1] *Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka, Japan*

[2] *Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka, Japan*

[3] *Kyoto University, Nishikyo-ku, Kyoto, Japan*

[4] *National Institutes for Quantum Science and Technology, Rokkasho, Aomori, Japan*

High density and temperature plasma is achieved in improved confinement modes with formation of an internal transport barrier (ITB), but the steep gradient can induce high Z impurity accumulation in the core plasma to cause plasma collapse [1]. The impurity accumulation is known to be suppressed with RF heating by controlling the bulk plasma profiles [2]. To maintain high-performance plasmas, it is important to clarify the driving mechanism of inward particle pinch in impurity accumulation with ITB formation. Currently, an integrated transport simulation code TASK[3] is being developed to predict the behavior of core plasmas. This code performs transport calculations by linking one-dimensional transport modules for bulk plasmas and impurities. Using neoclassical and turbulent transport models, the dynamics of the plasma including impurity evolution can be simulated. Typical negative magnetic shear mode and weak magnetic shear mode (high β_p mode) simulations for medium size tokamaks are carried out to show tungsten peaking at the plasma center in case of strong plasma density gradients. The impurity peaking is relaxed in accordance with increase of the bulk temperature. Since the direction of the particle convection is determined by the balance between density and temperature gradients, we will show the results for the bulk plasma and impurity profile formation process in different discharge conditions.

This work was supported by JST SPRING program, Grant Number JPMJSP2136, and by the collaboration program of QST on development research of the fusion DEMO reactor.

References

[1] C. Angioni, *et al.*, Nucl. Fusion **54**, 083028 (2014).

[2] R. Neu, *et al.*, J. Nucl. Mater. **313** 116 (2003).

[3] M. Honda, *et al.*, Nucl. Fusion **46**, 580 (2006).

Model-based Scenario Optimization in Tokamaks by Integrating Free-boundary Equilibrium and Fast Transport Solvers*

X. Song, Z. Wang, B. Leard, T. Rafiq, E. Schuster

Lehigh University, Bethlehem, Pennsylvania, USA

The scenario planning problem in tokamaks can be formulated as a model-based, constrained, optimization problem by combining plasma-response predictive models and nonlinear optimization techniques as originally proposed in [1]. The solution of this optimization problem yields feedforward control laws for the different actuators by minimizing a cost function quantifying the distance between actual and desired plasma scenarios. Machine-learning surrogate models recently developed for transport and sources can be leveraged to solve the trade-off between high prediction accuracy (needed to make the optimization useful) and low computational cost (needed to make the optimization tractable). An integrated optimization scheme combining free-boundary equilibrium (FBE) and fast transport (FT) solvers is employed in this work for the development of advanced scenarios in tokamaks like EAST and NSTX-U, which are characterized by high-confinement, magnetohydrodynamic (MHD) stability, and possible steady-state operation. The FT solver provides solutions for the magnetic diffusion equation (MDE) and electron heat transport equation (EHTE) by exploiting neural-network models for both transport and sources such as MMMNet [2] (Multi-Mode-Model (MMM) for anomalous transport) and NUBEAMNet [3] (NUBEAM for neutral beam effects). By integrating FBE and FT solvers, both the plasma shape and core conditions can be optimized simultaneously starting from the ramp-up phase of the discharge. Within the limits imposed for actuators and the plasma state (e.g., constraints on the plasma state to avoid MHD instabilities), optimized trajectories are determined for the current of central solenoid (CS) and poloidal field (PF) coils (to achieve a desired shape) and for the powers of different sources such as neutral beam injection (NBI) and lower hybrid wave (LHW) (to achieve desired *q*-profile and β_N).

[1] Y. Ou, C. Xu, E. Schuster et al., Plasma Phys. Control., 50 (2008) 115001.

[2] S. Morosohk. A. Pajares, T. Rafiq, E. Schuster, Nucl. Fusion 61 (2021) 106040 (10pp).

[3] S. Morosohk, M.D. Boyer, E. Schuster, Fusion Eng. Des. 163 (2021) 112125.

*This work has been supported by the U.S. Department of Energy under DE-SC0010537 and DE-SC0021385.

Transport and zonal flows dynamics in flux-driven interchange and drift waves turbulence

O. Panico[1,2], P. Hennequin[1], Y. Sarazin[2], Ö. Gürcan[1]

[1] LPP, CNRS, Sorbonne Université, Ecole polytechnique, Institut Polytechnique de Paris, 91128 Palaiseau, France

[2] CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France.

Minimizing cross-field transport in the core of fusion plasmas is a constant issue in view of maximizing the energy confinement time, hence the performance in terms of power amplification factor. Heat and particle transport mostly originates from turbulence, with collisions governing the damping of large scale flows. Via Reynolds forces, ion-scale turbulence contributes to these flows that, in back reaction, participate efficiently to its saturation [1]. It has been found recently – in numerical simulations [2] and later in experiments [3-4] – that the self-generated zonal flows (ZF) can structure into so-called staircases. The mechanisms of their generation, their impact on turbulent transport and their robustness with respect to the various types of turbulence remain active research topics.

In the present work, these issues are addressed by means of a reduced nonlinear model that features two types of turbulence drives that are suspected to be active at the edge of tokamak plasmas, namely interchange-like and drift-waves [5]. The model derives from the continuity and charge balance equations, where single poloidal and parallel wave numbers are retained and constant ion and electron temperatures are assumed. A generalized Ohm's law closes the system, linking the parallel current to the electric field and the electron pressure gradient. One of the strengths of this 1-dimensional model is to be flux driven: it evolves self-consistently the equilibrium and fluctuations of density and electric potential. In particular, it allows one to study the generation and structuration of large scale flows as well as their impact on turbulent transport.

The linear properties of the two underlying instabilities are controlled by two plasma parameters, the mean curvature of the magnetic field g and the adiabaticity parameter C that scales like the square of the parallel wave vector divided by the electron-ion collision frequency. They already exhibit rich characteristics in the parameter space. Consistently with previous findings, all the three control plasma parameters – g, C and the ion to electron temperature ratio $\tau=T_i/T_e$ – are found to have a dual role, either stabilizing or destabilizing depending on the parameter regime. Also, they govern the phase shift between the density and electric potential fluctuations, hence the efficiency of the quasi-linear transport at prescribed fluctuation magnitude.

The generation and structuration of ZFs and their interplay with turbulence and transport are then analysed in nonlinear simulations on confinement timescales. Whatever the values of the scanned parameters g, C and τ, ZFs are always active. They are driven by both components of the Reynolds stress, electric and diamagnetic [6], the contribution of the former being dominant when interchange dominates (large g). Two regimes are observed, where ZFs are either structured in staircases or not. Staircases are found to emerge as a result of an anti-diffusive process. Not so much the shear of the ZFs but more critically their curvature proves to be an essential characteristics to control the turbulent transport, mainly by mitigating the cross phase between density and electric potential fluctuations.

These results help to characterize the large scale flow dynamics and their efficiency in regulating turbulent transport, and to discriminate plasma regimes where staircases are likely to be observed experimentally.

[1] P.H. Diamond et al., Plasma Phys. Control. Fusion, 2005; [2] G. Dif-Pradalier et al., Phys. Rev. E 2010; [3] Hillesheim et al., Phys. Rev. Lett., 2016; [4] G. Hornung et al., Nucl. Fusion, 2017; [5] B.D. Scott, Plasma Phys. Control. Fusion, 1997; [6] Y. Sarazin et al., Plasma Phys. Control. Fusion, 2021

Rotating Waveplate Stokes Polarimeter Using Anisotropic Optical Absorption in Waveplate for ITER Poloidal Polarimeter

R. Imazawa[1] and Y. Nunoya[1]

[1] *National Institutes for Quantum Science and Technology, Naka, Ibaraki, Japan*

A poloidal polarimeter (PoPola) will be installed and employed in ITER for measurement of current profile with parameters of (1) radial profile of safety factor, q, (2) a location of a rational surface of q = 1.5 and 2 in real time, and (3) a location of the minimum of q in real time. ITER project Japan domestic agency has been developing PoPola and adopts rotating waveplate Stokes polarimeter as a technique to measure polarization state. The rotating waveplate Stokes polarimeter rotates a quarter waveplate made of crystalline quartz at rotating speed of 16,000 rpm in order to modulate polarization state of probing far infrared (FIR) laser light with the wavelength of 119 μm.

It is usually explained that second and forth harmonic signals of the rotating waveplates Stokes polarimeter provide ellipticity and orientation angle of polarization state, respectively. However, the signal analysis is not simple because of nonuniformity of retardation, axial runout of a motor, nonuniform thermal distribution, and centrifugal force of the rotating waveplate. The authors find that anisotropic optical absorption of crystalline quartz at the wavelength of 119 μm has large impact to the signal analysis. The study presents a new analytic model of the measurement signal including the anisotropic optical absorption. The analytic model shows that the orientation angle of the polarization state is still calculated only from forth harmonic signal and that the second harmonic signal depends on all Stokes parameters. Thus, degree of polarization (DOP) can be identified by using the rotating waveplate Stokes polarimeter with the anisotropic optical absorption, while DOP cannot be identified by using the isotropic one.

In addition, the analytic model show that, when measuring fully polarized light, the ratio of ordinary and extraordinary absorption needs to be calibrated to calculate the ellipticity of the polarization state but the absolute value of them dose not. This study presents a new calibration procedure taking into account the anisotropic optical absorption.

Plasma behavior to hydrogen supersonic molecular beam injection in the Uragan-2M stellarator

Yu. V. Kovtun[1], A. V. Lozin[1], A. N. Ozerov[1], V. E. Moiseenko[1,2,3], M. M. Kozulya[1], A. N. Shapoval[1], R. O. Pavlichenko[1], N. V. Zamanov[1], S. M. Maznichenko[1], D. I. Baron[1], A. Yu. Krasiuk[1], S. A. Tsybenko[1], I. E. Garkusha[1,2], A. Dinklage[4], T. Wauters[5]
and the Uragan-2M Team

[1]*National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine*

[2]*V.N. Karazin Kharkiv National University, Kharkiv, Ukraine*

[3]*Ångström Laboratory, Uppsala University, Uppsala, Sweden*

[4]*Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

[5]*ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St Paul Lez Durance Cedex, France*

Magnetically confined controlled fusion experiments use supersonic molecular beam injection for fuelling, plasma diagnostics, and other applications [1, 2]. Studies on ion-cyclotron resonance radio-frequency (ICRF) discharge plasma production at hydrogen minority regime are being conducted on the Uragan-2M (U-2M) stellarator [3-5]. To extend the experimental capabilities of the supersonic molecular beam injection (SMBI) system was designed, manufactured, and installed on the U-2M. This work presents the first results of using the SMBI system in U-2M.

The SMBI system has been used in experiments on ICRF plasma production at the hydrogen minority regime. Hydrogen was used for the additional pulse gas injection into the helium or hydrogen-helium plasmas. The maximum average plasma density was determined after pressure scanning and the steady-state gas injection. After the SMBI pulse the maximum average plasma density in helium had been increased two times up to 0.4×10^{13} cm^{-3}. The increase in density is likely due to the formation of hydrogen-helium plasma and a change in ICRF heating conditions, see [4, 5]. In hydrogen-helium plasma SMBI increased plasma density by 30% up to 1.3×10^{13} cm^{-3}.

[1] G.L. Xiao et al. Rev. Mod. Plasma Phys. 7, 2 (2023).

[2] A. Murakami et al. Plasma Phys. Control. Fusion 54, 055006 (2012).

[3] V. Moiseenko et al. J. Plasma Phys. 86, 905860517 (2020).

[4] Yu.V. Kovtun et al. Plasma Fusion Res. 17, 2402034 (2022).

[5] V.E. Moiseenko et al. J Fusion Energ 41, 15 (2022).

Investigation of TCV boundary plasmas in negative triangularity by SOLPS-ITER modelling

E. Tonello[1], F. Mombelli[1], O. Février[2], S. Gorno[2], P. Ricci[2], T. Bolzonella[3], N. Vianello[3], M. Passoni[1] and the TCV Team[a]

[1] *Politecnico di Milano, Milano, Italy*

[2] *Ecole Polytechnique Fédérale de Lausanne (EPFL), SPC, Lausanne, Switzerland*

[3] *Consorzio RFX, Padova, Italy*

[a] *See author list of H. Reimerdes et al 2022 Nucl. Fusion 62 042018*

Experiments in TCV [**1**] and DIII-D [**2**] showed that negative triangularity (NT) L-mode discharges exhibit improved confinement compared to similar positive triangularity (PT) experiments. These observations opened the possibility to pursue high confinement scenarios with L-mode plasmas and motivated interest in NT as an alternative configuration for DEMO. From the point of view of power exhaust, however, NT still needs to be characterised. Recent experimental observation in TCV indicated that plasma detachment could be harder to achieve in NT than PT [**3**]. To further the investigation, this contribution aims to support the interpretation of NT detachment experiments by modelling through the SOLPS-ITER code [**4**, **5**].

The work presents a comparison of two TCV simulations with PT and NT, performed with constant anomalous transport and with different field-aligned plasma meshes. The two computational domains were built on the reconstructed PT and NT experimental equilibria and simulation results were benchmarked against experimental data from Thomson Scattering and wall-embedded Langmuir probes. Simulations were performed with spatially uniform anomalous diffusivities and the same values of D_n, κ_e and κ_i were used for both triangularities. This allowed differences between PT and NT plasma profiles to be attributed only to the different shapes of the magnetic equilibria. PT and NT simulations at increasing density and fixed anomalous diffusivities were also performed to study trends of density and temperature at the strike points throughout a density ramp. SOLPS-ITER results confirm the reduced outer target cooling in NT observed in TCV experiments. The peak T_e is found to be $\sim 5-7$ eV lower for PT simulations than in NT, in agreement with experimental observations. The analysis also suggests that the experimental trends are compatible with a reduction of anomalous transport for NT configuration.

References

[1] Y. Camenen et al, Nucl. Fusion 47 510 (2007); [2] M. E. Austin et al, Phys. Rev. Lett. 122 115001 (2019); [3] O. Février, Invited contribution at this conference; [4] S. Wiesen et al, J. Nucl. Mater. 463 480 (2015); [5] X. Bonnin et al, Plasma and Fusion Research 11 1403102 (2016);

Stability analysis of the axi-symmetric vertical mode in MHD simulation

D. Banerjee[1], C. C. Kim[2], T. Barberis[1], F. Porcelli[1]

[1] *DISAT, Polytechnic University of Turin, Torino, Italy*

[2] *SLS2 Consulting, San Diego, USA*

In support of a recent analytical study [1, 2] on the axi-symmetric vertical mode (toroidal mode n=0) in ideal MHD limit, we have carried out linear simulations for the same mode with a well known MHD code NIMROD [3]. For an elongated plasma in straight tokamak, the analytical calculation unfolds three instability regimes of the n=0 mode - unstable, marginaly stable and oscillatory - with varying location of a perfectly conducting wall [2]. The green line curve in Fig. 1 demonstrates all those three instability regimes for a plasma of elongation $\kappa = 1.4$; the segments below and above zero indicate respectively the growing and oscillatory behaviours while the zero cross-point denotes marginal stability for ideal wall passing through the locations of X-points.

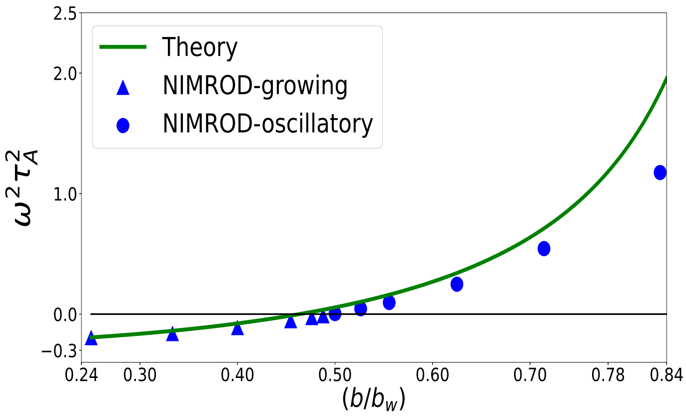


Figure 1: *The squared normalized frequency vs. wall location parameter (b/b_w, $2b$ = length of major axis of elliptical plasma and $2b_w$ = vertical scale of the simulation domain.) for $\kappa = 1.4$. A very good agreement is seen between the analytic curve and NIMROD data.*

Similarly, in NIMROD simulation, the n=0 mode is found to be unstable when the simulation domain includes the two X-points inside i.e. the stability of the n=0 mode is influenced by the X-points, and it becomes oscillatory if the X-points are kept outside the simulation area. The blue circles (oscillatory) and triangles (unstable) in Fig. 1 that come from NIMROD runs are mostly in proximity of the theoretical curve, thereby justifying a good agreement between theory and simulation. The logistics of this numerical study - geometry, profiles and method - along with our explanation of the physical mechanism will be presented in the conference.

References

[1] A. Yolbarsop and F. Porcelli and R. Fitzpatrick, Nucl. Fusion **61**, 114003 (2021)

[2] A. Yolbarsop and F. Porcelli and W. Liu and R. Fitzpatrick, Plasma Phys. Contr. Fusion **64**, 105002 (2022)

[3] C. R. Sovinec and A. H. Glasser et. al. J. Comp. Phys. **195** 355 (2004)

Sawtooth-induced fast-ion distribution function

T. Barberis[1], F. Porcelli[1]

[1] *Department of Applied Science and Technology, Polytechnic University of Turin, Torino 10129, Italy*

The impact of sawtooth oscillations on the distribution function of alpha particles in tokamak plasma discharges is discussed. As suggested by recent experimental results, sawtooth activity may affect the fast ion distribution function, leading to the destabilization of energetic particle modes [1]. Similarly to the case of beam-induced distributions [2], a fast-ion distribution modified by sawtooth oscillations with a period shorter than the slowing down time, i.e. $\tau_{saw}/\tau_s > 1$, may represent a source of free energy for the destabilization of otherwise-stable modes that require an $\partial F/\partial E > 0$, like those characterized by toroidal mode number n=0 [3]. It has been shown that fast ions characterized by high energies, like fusion alphas, may not undergo a strong spatial redistribution after sawtooth crashes [4,5]. Thus, focusing only on the velocity space distribution of the alpha particles, here we show how two effects, directly induced by the temperature drop associated with a sawtooth crash, may affect the distribution function. The first effect is a modulation of the particle source on the sawtooth period timescale, as the fusion yield drops together with the temperature. The second effect is associated with the growth of the slowing down time during the sawtooth ramp. As a direct consequence, particles born in the later stages of the sawtooth cycle will experience less slowing down with respect to those born at the beginning of the cycle, leading to an accumulation-like mechanism at higher energies. The Kadomtsev relaxation model [6], is used in order to describe analytically the plasma pressure evolution during sawtooth oscillations. The resulting temperature evolution is considered for the source term and the slowing down time of the Fokker-Plank equation describing the alpha particles. Within this framework, a periodic time-dependent distribution function is obtained analytically. Due to the combination of the two effects discussed above, the shape of the alpha energy distribution may strongly vary from the standard slowing down distribution function, and a positive derivative in energy can be produced.

References

[1] V. G. Kiptily et al 2022 Plasma Phys. Control. Fusion 64 064001
[2] Ya.I. Kolesnichenko and V.V. Lutsenko 2019 Nucl. Fusion 59 126005
[3] T. Barberis et al 2022 Nucl. Fusion 62 06400
[4] Ya.I. Kolesnichenko and Yu.V. Yakovenko 1996 Nucl. Fusion 36 159
[5] A. Bierwage, et al. 2022 Nat Commun 13, 3941
[6] B.B. Kadomtsev, 1975 Fiz. Plazmy 1, 710; B.B. Kadomtsev, 1976 Sov. J. Plasma Phys. 2, 389.

Ion cyclotron parametric instabilities and the anomalous absorption of the helicon travelling wave in the scrape-off layer of the tokamak plasma

V.V. Mykhaylenko(Mikhailenko)[1], V.S. Mikhailenko[2], Hae June Lee[3]

[1] *BK21FOUR, Pusan National University, Busan, S. Korea*

[2] *Plasma Research Center, Pusan National University, Busan, S. Korea*

[3] *Department of Electrical Engineering, Pusan National University, Busan, S. Korea*

The steady-state plasma operation in tokamaks requires efficient radio frequency (RF) heating of the plasma core, and of the non-inductive current drive (CD) for supporting the steady plasma current. Among different CD systems, the high harmonic fast wave (HHFW) with wave frequency $\omega_0 \sim (15-50)\omega_{ci}$, often called helicons, is considered as the most efficient for CD in high beta tokamaks. This conclusion was derived on the base of the predictions of the linear theory propagation and absorption, which, however, are not valid for the scrape-off layer (SOL) plasma adjacent to the FW antenna, where a significant fraction of the HHFW power (up to 50% or more) is absorbed. This parasitic loss of the helicon wave power is attributed to the development of the nonlinear processes. The development of the parametric instabilities, observed in the SOL near helicon wave antenna, is considered as a possible channel of the loss of the HHFW power in SOL.

In our report, we present results of the numerical analysis of the dispersion properties of the ion cyclotron (IC) parametric instabilities, driven by the HHFW with frequency $\omega_0 \sim 20\omega_{ci}$, generated by the travelling wave antenna. It was derived that the accounting for the finite wavelength along the magnetic field of the pumping helicon wave strongly enriches the spectrum of the detected parametric instabilities in the HHFW frequency range. We find that in this frequency range the dominant parametric instability is the IC quasimode decay instability, driven under conditions of the IC resonance. This instability is absent in the model of the spatially uniform helicon wave, in which the inverse electron Landau damping is a decisive process in the development of the IC parametric instabilities, which, however have the growth rates in order of value less than the detected IC quasimode decay instability.

References

[1] S. J. Wang, H. H. Wi, H. J. Kim, J. Kim, J. H. Jeong and J. G. Kwak, "Helicon wave coupling in KSTAR plasmas for off-axis current drive in high electron pressure plasmas", Nucl. Fusion **57**, 046010 (2017)

[2] R.I. Pinsker, R. Prater, C.P. Moeller, J.S. deGrassie, C.C. Petty, M. Porkolab, J.P. Anderson, A.M. Garofalo, C. Lau, A. Nagy, D.C. Pace, H. Torreblanca, J.G. Watkins and L. Zeng. "Experiments on helicons in DIII–D–investigation of the physics of a reactor-relevant non-inductive current drive technology", Nucl. Fusion **58** 106007 (2018)

Integrated modelling of the ramp-up phase of the hybrid scenario for the JT-60SA tokamak

S. Gabriellini[1], L. Garzotti[2], V. K. Zotta[1], R. Gatto[1], G. Giruzzi[3], L. Figini[4] , C. Sozzi[4]

[1] *Dipartimento di Ingegneria Astronautica, Elettrica ed Energetica, Sapienza Università di Roma, via Eudossiana 18, 00184, Roma, Italy*

[2] *CCFE, Culham Science Centre, Abingdon, UK*

[3] *CEA, IRFM, F-13108 Saint Paul Lez Durance, France*

[4] *ISTP Istituto di Scienza e Tecnologia del Plasma – CNR, Milano, Italy*

JT-60SA is a large superconducting tokamak built and operated by Europe and Japan under the Broader Approach Satellite Tokamak Program. The machine is designed to support the exploitation of ITER and the investigation of key physics and engineering issues for future demonstration power plants. The main operational parameters of the plasma scenarios, envisaged for the Integrated Research Phase and described in the JT-60SA Research Plan [1], were simulated using the 0.5-dimensional code METIS and the 2-dimensional equilibrium code ACCOME, as reported in [2]. Moreover, the feasibility of the flat-top phase of these scenarios was confirmed by means of 1.5-dimensional transport codes [3, 4]. However, it is of primary importance to simulate the ramp-up in order to assess whether the main plasma parameters foreseen for the scenario are achievable and under which range of assumptions.

The goal of this study is to model the ramp-up phase of the scenario 4-2 (hybrid) (3.5 MA/2.28 T, q_{95}=4.4, β_N =3.0) with the JINTRAC [5] suite of codes and the Bohm/gyro-Bohm [6] semi-empirical transport model, taking as starting point the modelling performed with the METIS code. We are predicting the current density, ion density, ion temperature and electron temperature, self-consistently with the plasma equilibrium. The speed of the current ramp-up is imposed, while a feedback loop acting on the gas puff rate is controlling the density in order to follow the target volume averaged density. The heating power deposition profiles and current densities of ECRH and NBI are modelled with the GRAY [7] and PENCIL [8] codes respectively, injecting the power of 37 MW (7 MW of ECRH and 30 MW of NBI).

The results of the modelling in terms of plasma kinetic profiles evolution, L-H transition, flux consumption and neutral beam shine-through are presented for different levels of ECRH power and different NBI switching on times. JINTRAC results are fairly close to the ones predicted by METIS, however the L-H transition, predicted by Martin scaling, is found at an earlier time in JINTRAC. The electron temperature profiles are also very sensitive to the different shape of the ECRH power deposition computed by GRAY, with respect to the Gaussian-like profiles imposed by METIS.

References

[1] JT-60SA Research Plan, version 4.0 www.jt60sa.org/pdfs/JT-60SA_Res_Plan.pdf (September 2018)

[2] G. Giruzzi *et al* 2020 *Plasma Phys. Control. Fusion* **62** 014009

[3] L. Garzotti *et al* 2018 *Nucl. Fusion* **58** 026029

[4] J. Garcia *et al* 2014 *Nucl. Fusion* **54** 093010

[5] Romanelli M. *et al* 2014 *Plasma and Fusion Research* **9** 3403023

[6] M Erba *et al* 1997 *Plasma Phys. Control. Fusion* **39** 261

[7] D. Farina, Fusion Science and Technology 154, **52** (2007)

[8] C.D. Challis *et al* 1989 *Nucl. Fusion* **29** 56

Analysis of the n=1 MHD beta limits in VEST spherical tokamak

Qingyun Hu[1], Boseong Kim[1], Yong-Su Na[1*] and Ohjin Kwon[2*]

[1] *Department of Nuclear Engineering, Seoul National University, Seoul, South Korea*

[2] *Department of Physics, Daegu University, Gyeongbuk, South Korea*

Spherical tokamaks (STs) have the advantages of operating in high beta and high bootstrap current fractions. High bootstrap current fraction requires high normalized beta, β_N. However, it is well understood that ideal magnetohydrodynamic (MHD) modes in the plasma limit the β_N. In a high-beta JET discharge, it has been shown that the mode onset has a strong correlation with the crossing of predicted stability boundaries [1]. A plasma exceeding the beta limit may terminate a tokamak operation with disruption. To achieve high β_N in STs without disruptions, the beta limits of the plasma should be understood. Analysis of ideal MHD stabilities of plasmas in MAST-U [2] and NSTX [3,4] has provided insights into the instabilities, wall effects, and advanced operations in STs. However, stability studies on the operation regime of Versatile Experiment Spherical Torus (VEST) have been of little interest. In VEST, operations are approaching an advanced tokamak regime where the no-wall limits and the with-wall limits of plasma beta are crucial. In this work, we conduct a stability analysis of a set of VEST equilibria in the present operation regime. Experimental plasma boundary and current data were captured at a time slice of a VEST discharge using the VFIT code. Pressure and current profiles are set to be polynomial functions of the normalized poloidal flux ψ_N. We scan the $\beta - l_i$ parameter space by varying those profiles with fixed plasma boundary and current, by solving the Grad-Shafranov equation with the CHEASE code [5]. To assess the beta limits, we calculate the stability of those equilibria with both the DCON code [6] and the MISHKA-1 code [7]. Since ideal conducting walls have been shown to have significant effects on beta limits [2], the wall effect will be considered. Furthermore, the effect of boundary shaping has been shown to be significant to the beta limits [8]. Plasma shaping and plasma current will be varied, and stability boundaries will be compared.

This research is supported by National R&D Program through the National Research Foundation of Korea (NRF) funded by Ministry of Science and ICT (2021M3F7A1084419).

[1] O. J. Kwon *et al.*, Plasma Phys. Control. Fusion **54**, 045010 (2012).
[2] J. W. Berkery *et al.*, Plasma Phys. Control. Fusion **62**, 085007 (2020).
[3] J. E. Menard *et al.*, Nucl. Fusion **37**, 595 (1997).
[4] S. A. Sabbagh *et al.*, Nucl. Fusion **53**, 104007 (2013).
[5] H. Lütjens *et al.*, Computer Physics Communications **97**, 219 (1996).
[6] A. H. Glasser, Physics of Plasmas **23**, 072505 (2016).
[7] A. B. Mikhailovskii *et al.*, Plasma Physics Reports **23**, (1997).
[8] J. E. Menard *et al.*, Phys. Plasmas **11**, (2004).

First-principles study of mechanical properties of $La_{1-x}M_xB6$ (M=Ba, Sr, Ca) for the plasma electrode applications in NBI system

Jun Hu[1], Xin Zhang[1], Yuhong Xu[1], Guangjiu Lei[2], Shaofei Geng[2], Sanqiu Liu [3], Xiaochang Chen[3], Heng Li[1], Zilin Cui[1], Yiqin Zhu[1], Xiaolong Li[1], Haifeng Liu[1], Xianqu Wang[1], Jie Huang[1], Hai Liu[1], Jun Cheng[1]and Changjian Tang[1,4]

[1]Institute of fusion science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu,610041, People's Republic of China.
[2] Southwestern Institute of Physics, Chengdu,610041, People's Republic of China.
[3]Department of Physics, Nanchang University, Nanchang 330031, People's Republic of China.
[4]School of Physical Science and Technology, Sichuan University, Chengdu, 610041, People's Republic of China.

In this paper, the structure, elastic constants and mechanical properties of $La_{1-x}M_xB_6$ (M=Ba, Sr, Ca) (x=0, 0.125, 0.25, 0.375, 0.5, 0.625, 0.75, 0.875, 1) were studied by using first principles calculation method based on density functional theory (DFT). In particular, we estimated the bulk modulus, shear modulus, Young's modulus, B/G ratio, and Poisson's ratio dependence of the elastic data C_{ij}. Results show that the bulk modulus of $La_{1-x}M_xB_6$ (M=Ba, Sr, Ca) decrease linearly with the increase of heteroatom concentration x, $La_{1-x}Ba_xB_6$ decreases the fastest, $La_{1-x}Sr_xB_6$ decreases the second, and $La_{1-x}Ca_xB_6$ decreases the slowest. Therefore, the hardness of LaB_6 is the highest and decreases with the increase of the concentration of doping atom M (M=Ba, Sr, Ca). The change curves of $La_{1-x}Ca_xB_6$ and $La_{1-y}Sr_yB_6$ shear modulus and Young's modulus decrease with the increase of doping concentration. $La_{1-x}Ba_xB_6$ shows an increasing trend with the doping concentration, the B/G of $La_{1-x}Ca_xB_6$ increases with the doping concentration of Ca atoms. $La_{1-x}Ba_xB_6$ decreases rapidly with the increase of Ba atom doping concentration while $La_{1-x}Sr_xB_6$ slightly decreases with the increase of Sr atom doping concentration. And it is found that the Poisson's ratio has the same trend with B/G results. All of the results provide a theoretical basis for the plasma electrode applications and further developments of $La_{1-x}M_xB_6$.

Reference

[1]Hanai, K., et al. *Plasma and Fusion Research* 15 (2020): 2401029-2401029.
[2]Hanai, K., et al. *Fusion Engineering and Design* 146 (2019): 2721-2724.
[3]Ueno, A., *Review of scientific instruments* 75.5 (2004): 1714-1719.
[4]Zhou S.L., et al. *Journal of Alloys and Compounds* 611(2014):130-134.
[5]Ma T.Y., et al. *Journal of Physical Chemistry C* 125(2021): 17400−17410
[6]Bao L., et al. *Journal of Alloys and Compounds* 731(2018): 332-338.
[7]Luo K., et al. *Ceramics International* 42 (2016): 6632–6639

Effects of edge biasing on blob dynamics and associated transport in the edge of the J-TEXT tokamak

W. Li[1], Y. Xu[1], J. Cheng[1], H. Liu[1], Z.P. Chen[2], J.Q. Xu[3], X.Q. Wang[1], Z.Y. Chen[2], N.C. Wang[2], Z.J. Yang[2], Y.H. Ding[2] and Y. Pan[2]

[1]*Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu, People's Republic of China*

[2]*International Joint Research Laboratory of Magnetic Confinement Fusion and Plasma Physics, State Key Laboratory of Advanced Electromagnetic Engineering and technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, People's Republic of China*

[3]*Southwestern Institute of Physics, PO Box 432, Chengdu, People's Republic of China*

Effects of edge radial electric field E_r and $E_r \times B$ flow shear on edge turbulence and turbulent transport, in particular, on large-scale blobs and blobby transport have been investigated in the positive and negative biasing discharges in the J-TEXT tokamak. The results show that under certain conditions, the positive electrode biasing induces better plasma confinement than the negative biasing. Further studies reveal that in addition to flow shear effects on blob dynamics, the local radial electric field at the edge region plays a significant role in repulsion of the blobs and associated transport, leading to improvement of particle confinement when the outward motion of the blobs is blocked [1]. The results are consistent with the existing theory on blob dynamics.

[1] W. Li, *et al.*, Plasma Physics and Controlled Fusion **64,** 035013 (2022)

On the Role of Zonal Flows in Trapped-Electron-Driven Turbulence

Haotian Chen[1,2], Liu Chen[3,4,2] and Jiquan Li[1]

[1] *Southwestern Institute of Physics, Chengdu, China*

[2] *Center for Nonlinear Plasma Science and ENEA C.R. Frascati, Frascati, Italy*

[3] *Institute for Fusion Theory and Simulation, Zhejiang University, Hangzhou, China*

[4] *Department of Physics and Astronomy, University of California, Irvine, USA*

The role of self-generated zonal flows (ZFs) in the collisionless trapped-electron-mode (CTEM) turbulence is a long-standing open issue in tokamak plasmas. We show, for the first time, that the zonal flow excitation in the CTEM turbulence is formally isomorphic to that in the ion temperature gradient turbulence [1]. Interestingly, although the turbulence is driven by trapped electrons, the nonlinear CTEM-ZF interplay is governed by ions and circulating electrons. Trapped electrons, in contrast, only enter implicitly through linear physics. Therefore, linear CTEM properties play a unique role in determining the importance of ZF. Theoretical analyses further suggest that, for short wavelength CTEMs, the zonal flow excitation is weak and, more importantly, not an effective saturation mechanism. Linear short wavelength CTEMs are thus revisited analytically. It is found that the short wavelength CTEM instability without ZF scattering channel is essentially of two types. One is kinetically excited via toroidal precessional resonance. In this case, the instability threshold depends on the aspect ratio between major and minor radii, the temperature ratio, magnetic shear, and electron temperature gradient. The other case is a fluidlike interchange-driven instability set by η_e (the ratio between gradients of the density and electron temperature) in the steep density gradient regime. These findings not only offer a plausible explanation for previous seemingly contradictory simulation results, but can also facilitate controlling the CTEM instability and transport with experimentally accessible parameters.

References

[1] Haotian Chen and Liu Chen, Phys. Rev. Lett. 128, 025003 (2022).

Mechanism of accessing a higher fueling efficiency by the low-pressure SMBI fueling technique

G.L. Xiao[1,*], Y.R. Zhu[1], W.L. Zhong[1], B.B. Feng[1], C.Y. Chen[1], J. Yin[1], Z.H. Wang[1], Z.C. Yang[1], X.K. Wu[1]

1. Southwestern Institute of Physics, P.O. Box 432, Chengdu, China

* Email address of submitting author: xiaogl@swip.ac.cn[1]

Fueling and particle control is a key area of current fusion research and is challenging for the high-density operation with opaque scrape-off-layer (SOL). The opaque SOL region impedes the deposition of injected neutral particles in the main plasma owing to the radially outwards shift of the ionization front into the open field SOL region, especially for the gas puffing case. This study shows a possible fueling scheme to access a deeper deposition and higher fueling efficiency than current gas fueling approaches by the low-pressure supersonic molecular beam injection (SMBI) technique.

The low-pressure SMBI technique is originally developed for tritium fueling, where low gas pressure is mandatory for safety regulations. The operation of the low-pressure SMBI fueling scheme in HL-2A reveals that its fueling efficiency is larger than the cases by SMBI with higher gas pressure. The statistic of experimental data clearly shows the enhancement of the fueling effect with the decrease of the gas pressure. Comparison of beam profiles by the fluent simulation and measurements of the schlieren system shows a shape distinction between the density profiles, but a subtle difference in velocity. Based on these, the edge fueling processes are simulated by BOUT++ with different density profiles but similar velocity profiles of neutral particles. The simulation result has good agreement with the experimental statistic, which also suggests that higher fueling efficiency can be accessed with lower gas pressure. The plausible mechanism is also revealed by simulations. High particle velocity is beneficial for deep penetration, and soft edge density gradient for low-pressure cases can weaken the outwards convection. The low-pressure SMBI with similar high velocity, but low particle density can maintain a soft edge density gradient, where the gas injection and dissociation rates are smaller than the parallel particle spreading rate. Thus, it increases the penetration depth and fueling efficiency.

Effect of resonant magnetic perturbations including toroidal sidebands on magnetic footprint and fast ion losses in HL-2M

G.Z. Hao[1], G.Q. Dong[1], Y.Q. Liu[2], Y.H. Xu[2], Y.F. Zhao[2], S. Wang[2]

[1] *Southwestern Institute of Physics, Chengdu, China*
[2] *General Atomics, San Diego, USA*
[3] *Southwest Jiaotong University, Chengdu, China*
[4] *Dalian University of Technology, Dalian, China*

Externally applied resonant magnetic perturbations (RMPs), generated by magnetic coils located outside the plasma (referred to as RMP coils), provide an effective way to control the edge localized mode (ELM) in tokamak devices. Due to the discrete nature of toroidal distribution of these window-frame coils, toroidal sidebands always exit together with the fundamental harmonic designed for ELM control. In this work, the MARS-F code (*Liu et al., Phys. Plasmas 7, 3681 (2000)*) is applied to investigate detailed features of the RMP spectra considering both the dominant harmonic (n=2) and the associated sideband (n=6), and the impact of the combined fields on magnetic footprints as well as on the fast ion losses for a reference double-null scenario in the HL-2M device (figure 1).

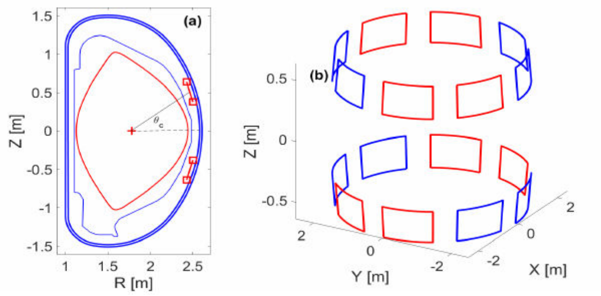


Figure 1. Plotted are (a) the geometry of RMP coils on the poloidal plane (red squares), the plasma boundary (red line) for the reference equilibrium, together with the limiter and the double vacuum vessels (blue lines) for the HL-2M device. The RMP coil configuration shown in (b), with the constant coil current of 10 kAt, yields ~10.5 kAt and ~5.7 kAt effective coil currents for the n=2 (dominant harmonic) and n=6 (sideband) components, receptively.

The key results include: **(i)** The mixed n=2 and n=6 RMP fields split the footprint and widen the footprint area, compared with the single-n (n=2) harmonic case. Resistive plasma response breaks the up-down symmetry of the footprint pattern on the outer divertor plates, which is otherwise symmetric assuming vacuum RMP fields. **(ii)** Considering fast ion losses, a threshold value exists for the initially launched radial position of test particles as well as for the RMP coil current, before the loss occurs. As the threshold criterion is satisfied, the combined n=2 and n=6 RMP fields enhance the fast ion loss rate by ~20% (figure 2), compared with that of the n=2 component alone. These results illustrate the important role of the sideband of RMP fields on the magnetic footprints and fast ion losses in tokamak plasmas.

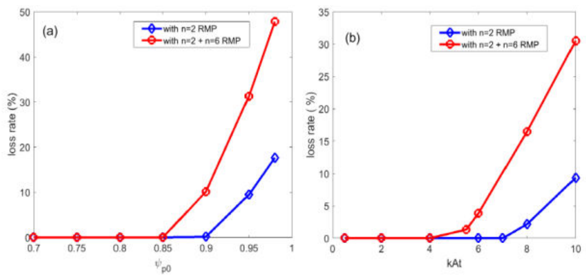


Figure 2. Loss rate of fast ions as a function of the initially launched radial position (a) and of the assumed RMP coil current, for the case with only n=2 component (in blue) and with both the n=2 and n=6 components (in red). Here, the resistive plasma response is included in the RMP fields. A 10 kAt RMP coil current is assumed in (a), and the initial position of test particles \psi_{p0}=0.95 is adopted in (b). The RMP coil configuration shown in figure 1 is adopted.

Turbulence spreading and flow shearing dynamics in high density operation

T. Long[1], P. H. Diamond[2], R. Ke[1], M. Xu[1], Z. P. Chen[3], L. Wang[3]

[1] *Southwestern Institute of Physics, Chengdu, China*

[2] *University of California, San Diego, CA, United States of America*

[3] *Huazhong University of Science and Technology, Wuhan, China*

Turbulence spreading generally refers to the spatial propagation of turbulence energy due to nonlinear interactions [1]. It plays a significant role in the comprehensive performance of magnetic fusion devices. It is related to the breaking of gyro-Bohm scaling. It is also important in the core-boundary coupling to affect the pedestal structure as well as the divertor heat load width. Recent studies show that, the collapse of edge shear layer and the increased turbulence spreading is strongly associated with the edge cooling as the line-averaged density $\bar{n}$ increases [2]. Thus, the density limit can be regarded as a state linked to the breakdown of turbulence self-regulation [3]. However, studies about the plasma current dependence (i.e. the key content of Greenwald scaling $n_G = I_p/\pi a^2$) of turbulence and shear flow are still incomplete. In this paper, we present the recent experimental results of enhanced edge turbulence spreading and its connection to shear flow dynamics on the J-TEXT tokamak. The experiments are conducted in Ohmic discharges with the ratio $\bar{n}/n_G$ from 0.45 to 0.63, which lies in the saturated Ohmic confinement regime and below the disruption density at ~$0.7n_G$.

It is found that the edge turbulence intensity flux $\langle \tilde{v}_r \tilde{n}^2 \rangle/2$ increases as $\bar{n}$ increases for the same I_p, while decreases as I_p increases for the close $\bar{n}$. This is shown by Figure 1(a-b). The normalized turbulence spreading power $\mathcal{P}_S/\mathcal{P}_I = (-\partial_r \langle \tilde{v}_r \tilde{n}^2 \rangle/2)/(-\langle \tilde{v}_r \tilde{n} \rangle \partial_r \langle n \rangle)$, a measure of turbulence internal energy increment due to the spreading relative to the local production, shows the same trend when $\bar{n}$ or I_p changes. This is presented in the Figure 1(c-d). Taken together, $\mathcal{P}_S/\mathcal{P}_I$ near the last close flux surface (LCFS) increases significantly as $\bar{n}/n_G$ increases, which is consistent with the observed cooling of edge plasma as $\bar{n}/n_G$ increases.

Figure 2(a-c) show that, the poloidal flow shearing rate $\omega_s = k_\theta l_{cr} |\partial_r v_\theta|$ decreases as $\bar{n}$ increases, the turbulence random scattering rate $\omega_t = 4D_t/l_{cr}^2$ decreases as I_p increases, and the normalized flow shearing rate $\omega_N \equiv \omega_s/\omega_t$ decreases as $\bar{n}/n_G$ increases. From BDT model [4], turbulence is suppressed when poloidal flow shear is larger than turbulence random scattering. This in turn states that turbulence is enhanced as the normalized flow shearing rate decreases. Figure 2(d) shows that the turbulence spreading power near the LCFS increases as ω_N^{-1} increases. This is in agreement with the theoretical result. These indicate the turbulence spreading dynamics is strongly associated with the interaction between poloidal flow and turbulence scattering.

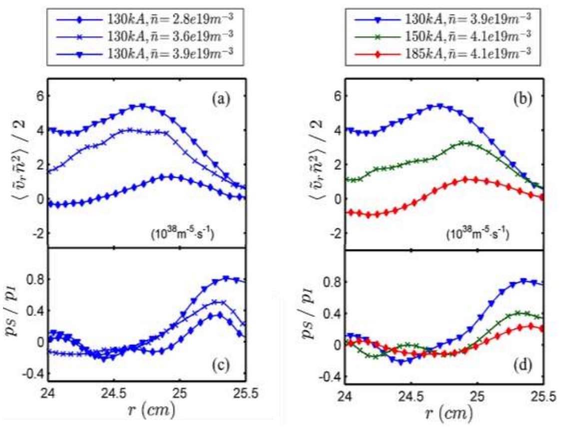


Figure 1. *(a) Turbulence intensity flux for different $\bar{n}$; (b) turbulence intensity flux for different I_p; (c) normalized turbulence spreading power for different $\bar{n}$; (d) normalized turbulence spreading power for different I_p*

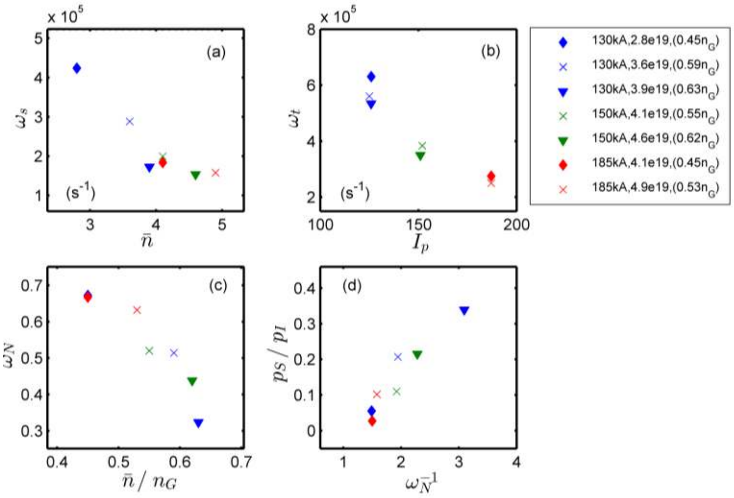


Figure 2. *(a) Flow shearing rate VS $\bar{n}$; (b) turbulence scattering rate VS I_p; (c) normalized shearing rate ω_N VS $\bar{n}/n_G$; (d) normalized turbulence spreading power VS ω_N^{-1}*

References

[1] GÜRCAN Ö. D. Physical review letters, **97** 2 (2006)

[2] LONG T. Nuclear Fusion, **61** 12 (2021)

[3] DIAMOND P. H. Philosophical Transactions of the Royal Society A, **381** 2242 (2023)

[4] BIGLARI H. Physics of Fluids B, **2** 1 (1990)

Effects of fishbone-like mode on energetic particle transport and loss in tokamak plasmas

Y.Q. Wang[1], G.Z. Hao[1], Y.P. Zou[1], Y.Q. Liu[2], W. Chen[1], G. Meng[3], G.Q. Dong[1], Y.F. Zhao[4], Y.G. Ming[1]

[1] *Southwestern Institute of Physics, Chengdu, People's Republic of China*

[2] *General Atomics, San Diego, United States of America*

[3] *Max Planck Institute for Plasma Physics, Garching, Germany*

[4] *School of Physics, Dalian University of Technology, Dalian, People's Republic of China*

Transport and loss of beam injected energetic-particles (EPs) due to three-dimensional (3D) perturbations, fishbone-like mode (FLM), are numerically investigated utilizing the guiding center following code ORBIT for static toroidal plasmas in HL-2A. The perturbation structure for the FLM is computed by the MARS code and then mapped to the Boozer coordinates as defined in ORBIT. The simulation shows that the EP profile experiences a significant change in the middle of the plasma column, when the FLM-induced radial magnetic field perturbation amplitude, normalized by the equilibrium field, exceeds a threshold value of about 10^{-2}. The EP transport is found to be dominated by a diffusion process instead of convection. Furthermore, by scanning the perturbation frequency as a free parameter while maintaining the mode structure, redistribution and loss of EPs are found to be substantially enhanced due to strong resonances between the FLM and EPs, when the mode frequency exceeds a threshold value of ~2 kHz for the case considered. For FLM, the response of passing EPs to the perturbation is dominant due to the assumed tangential neutral beam injection. Most lost EPs due to these instabilities are initially passing particles but are eventually lost through trapped orbits.

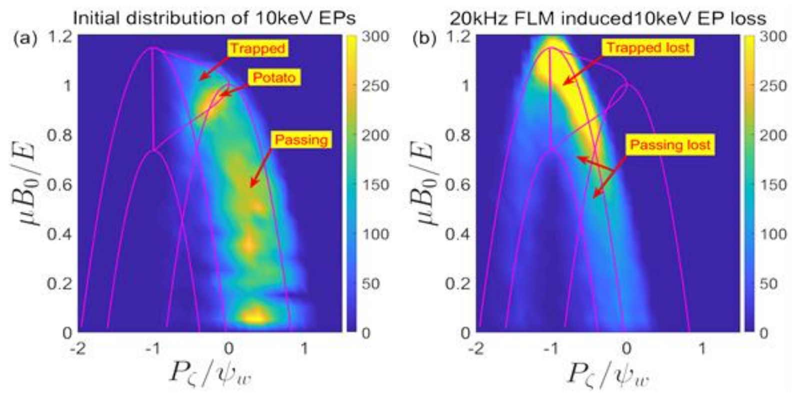


Fig 1. (a) The initial distribution of lost EPs and (b) the distribution of lost EPs in $P_\zeta-\mu$ phase space. The EPs with 10 keV kinetic energy are chosen in these plots. The amplitude and frequency of FLM are $\delta B_r/B = 5\times10^{-3}$ and 20 kHz, respectively. The pink curves are the boundaries of various orbit types. The color bar represents the number of EPs.

Observation of Resonant Tearing Mode Induced by Energetic-ion Redistribution Due to Sawtooth Collapse in HL-2A NBI Plasmas

L.M. Yu[1], X.L. Zhu[2], W. Chen[1], P.W. Shi[1], X.Q. Ji[1], Z.B. Shi[1], R.R. Ma[1], X.F. He[1], X.Y. Yan[3,1], X.X. He[1], Y.M. Hou[1], Y.G. Li[1], Y. Huang[1], W. Deng[1], W.P. Gou[1], H.L. Wei[1], Y.P. Zhang[1], Yi Liu[1], D.L. Yu[1], Z.X. Wang[2], W.L. Zhong[1] and M. Xu[1]

[1]Southwestern Institute of Physics, Chengdu, China

[2]School of Physics, Dalian University of Technology, Dalian, China

[3]Institute of Nuclear Science and Technology, Sichuan University, Chengdu, China

Email: chenw@swip.ac.cn

The tearing modes or neoclassical tearing modes (TMs or NTMs) is one of most dangerous low-frequency magnetohydrodynamic instabilities in magnetically confined plasmas. Experimental and theoretical research show that energetic particles (EPs), not only can drive the Alfvén eigenmodes and energetic particle modes, but also affect the behaviours of TM/NTMs, and even resonant with them. The resonance between EPs and TM/NTMs have been found and studied on TFTR, ASDEX-U, EAST, DIII-D, KASTAR, and so on. Further, the obvious evidence of resonance between co-passing EPs and TMs is found in HL-2A NBI plasmas.

Recent observations in HL-2A tokamak give new experimental evidences of resonant-TMs caused by the redistribution of energetic ions (EIs) due to sawtooth collapses in high-density NBI plasmas. The m/m=2/1 (m and n are the poloidal and toroidal mode numbers) resonant-TMs with frequencies chirping down rapidly from 6 to 2 kHz are found after the strong busts of fishbones and closely followed sawtooth collapses, as shown in Fig.1. The fishbones excited by EIs propagates in ion diamagnetic directions. In contrast, the resonant-TMs propagate in electron diamagnetic directions. This suggests the counter-direction EIs, which generated by the redistribution of EIs due to sawtooth collapses, excite the resonant-TMs. The radial velocity of EIs from the positions of core to the q(=m/n)=2 surface are estimated as convective transport. The simulation results from M3D-K code show that the counter-passing EIs play an important role on the excitation of resonant-TMs.

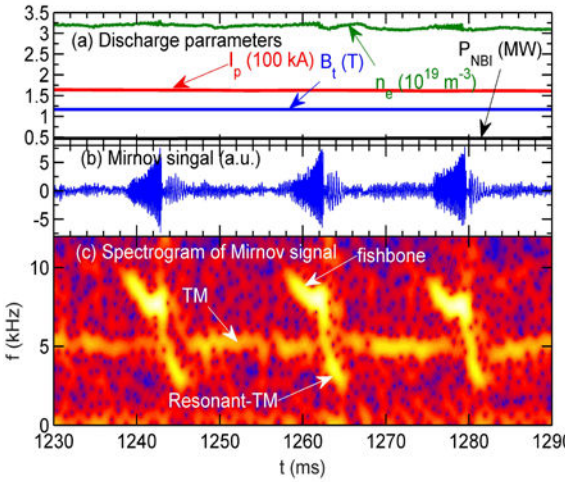


Fig.1 Resonant-TMs excited by the counter-passing energetic ions on HL-2A Tokamak

Toroidal modeling of plasma flow damping and density pump-out by RMP during ELM mitigation in HL-2A

N. Zhang[1], Y.Q. Liu[2,1], D.L. Yu[1], Yi Liu[1], L. Liu[1], G.Z. Hao[1], X.X. He[1], T.F. Sun[1], S. Wang[1], G.Q. Dong[1], X.Bai[1], Z.B. Shi[1], W.L. Zhong[1] and M. Xu[1]

[1]*Southwestern Institute of Physics, P. O. Box 432, Chengdu 610041, China*
[2]*General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA*

Email: zhangn@swip.ac.cn

Reduction of both the plasma density and toroidal flow speed, due to application of the predominantly n=1 (n is the toroidal mode number) resonant magnetic perturbation (RMP) for controlling the edge localized mode in the HL-2A tokamak, is numerically investigated utilizing the quasi-linear initial-value code MARS-Q (Liu *et al* 2013 *Phys. Plasmas* **20** 042503). Simulation results reveal that the neoclassical toroidal viscosity (NTV) due to 3D fields plays the key role in modifying the plasma momentum and particle transport in the HL-2A discharge. By comparing the modeling results with the measured density pump-out in the experiment, the electron NTV particle flux model, in combination with the free-boundary condition for the axi-symmetric change of the density at the plasma edge, is found to yield the best agreement in terms of both the pump-out level and the overall time scale. Further sensitivity studies show that the simulated density pump-out level is reasonably robust against variations in the model assumptions, including the particle diffusion coefficient and the non-ambipoar versus ambipolar NTV particle flux. The latter however affects the time scale for reaching the steady state solution. Finally, it is found that the plasma edge-peeling response, the NTV torque, as well as the plasma momentum and particle transport, all being sensitive to the toroidal phase difference between the upper and lower rows of the RMP coil currents in HL-2A, with the 30 degrees coil phasing producing the minimal side effects on the plasma.

Simulations on edge localized modes mitigation with impurity seeding in the HL-2A tokamak

Yiren Zhu[1], Guoliang Xiao[1], Xiaolan Zou[2], Wulyu Zhong[1] and HL-2A team

[1] *Southwestern Institute of Physics, Chengdu, China*

[2] *CEA, IRFM, Saint-Paul-lez-Durance, France*

Abstract

Impurity seeding has been confirmed to be a potential way for edge localized modes (ELMs) to be mitigated in tokamaks. By combining the integrated equilibria reconstruction framework and edge simulation codes such as BOUT++, this study's aim is to dive deeper into the mechanism of the ELM mitigation by impurity injection. On the one hand, impurity injection changes the pedestal pressure and current profiles that are closely related to ELM activities. The nonlinear simulation result shows that ELM size decreases by a factor of 2 to 4 when the current exceeds a threshold after impurity injection. On the other hand, the decrease of E_r shear is supposed to cause a larger ELM size for a less stabilized effect. However, ELMs are mitigated with smaller E_r shear as observed in the HL-2A experiment. This indicates that changes in the profiles of pressure gradient and hence the current density may play a more important role than E_r shear in this ELM mitigation process. In contrast to the high *n* modes destabilized by the pellet pacing, metallic impurity seeding leads to more unstable low *n* modes. The simulation results indicate that the combination of changes in pressure/current and E_r shear is a plausible explanation for the ELM mitigation by metallic impurity seeding.

Keywords: impurity seeding, edge localized mode, integrated simulation, E_r shear

Toroidal modelling of interactions between internal kink instability and energetic ions in HL-2M

G.Q Dong[1], Y.Q. Liu[2], G.Z. Hao[1] and S. Wang[1]

[1] *Southwestern Institute of Physics, Post Office Box 432, Chengdu 610041, China*

[2] *General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA*

A systematic investigation is carried out, studying the two-way interactions between the n=1 (n is the toroidal number) internal kink (IK) instability and the neutral beam injection induced energetic particles (EPs) in the HL-2M tokamak, utilizing the MARS-F/K code (Liu et al. 2000 Phys. Plasmas **7** 3681, Liu et al. 2008 Phys. Plasmas **15** 112503) and a recently developed test particle tracing module. A high-beta sawteething HL-2M scenario, simulated by the TRANSP code (Breslau et al. 2018 Computer Software), is chosen for this study. Compared to the fluid model, non-perturbative magnetohydrodynamic (MHD)-kinetic hybrid computations with MARS-K show a generally stabilization effect on the IK, due to drift kinetic resonances associated with EPs. The bounce resonance of trapped EPs has minor influence on the mode stability. In the absence of the plasma equilibrium flow and with the assumed particle pitch distribution, the transit resonance of co-current (counter-current) passing EPs destabilizes (stabilizes) the IK. With plasma flow, both co- and counter-current passing EPs tend to stabilize the mode but the effect is stronger with the counter-current particles. 3-D perturbations due to an unstable IK affect the EP drift orbit, confinement and loss in HL-2M, but the effect is generally moderate. The IK instability induced EP loss fraction is found to be typically less than 10%, without counting the prompt orbit loss associated with the 2-D equilibrium field for counter-current particles. The latter reaches about 16% in HL-2M. For co-current EPs, a 100 G IK perturbation (inside the plasma) does not induce any EP loss. A sawteething-like time-varying perturbation field, with the maximum amplitude reaching 1000 G, produces about 30% loss for the co-current EPs in HL-2M. The majority of lost EPs tend to strike the lower divertor region, with only a small fraction of particles striking the low-field side mid-plane region of the limiting surface. These modelling results provide useful guidance for the future high-performance experiments in HL-2M.

Supershot-like behaviour of ST40 plasmas

Francesco Paolo Orsitto[1], Michele Romanelli[1], *and the ST40 Team*

[1] *Tokamak Energy Ltd, 173 Brook Drive, Milton Park,*

Didcot, OX14 4SD Oxfordshire United Kingdom

Corresponding author : fporsitto@gmail.com

The experimental program of ST40 demonstrated the achievement of 9keV ion temperature[1] in a hot-ion plasma scenario similar to TFTR supershots[2] characterized by a ratio Ti/Te (ion temperature/electron temperature) >>1. It is important to assess the similarities between the ST40 hot ion scenario and supershot plasmas and whether a scaling law of energy confinement (supershot like) already tested positively on a limited ST40 dataset [3] can be used to describe a more comprehensive ST40 dataset. Typical characteristics reported on the TFTR supershots are[2] : slow dependence on the beam power and plasma current , strong dependence on the plasma density, density peaking and beam energy. The TFTR supershots characteristics related to beam power , plasma current and density are retained in the high power (Ptotal>1.5MW) entire dataset of ST40 hot-ion discharges.

Starting from TFTR supershot scaling law of energy confinement [2], a more general scaling law was proposed[3] which merges together the geometry dependence of L-mode scaling and the dependence on plasma current and magnetic field given by the supershot confinement scaling. In [3] a preliminary comparison of the scaling using a limited dataset was carried out positively : the comparison of the scaling law on the entire available dataset of ST40 high power discharges , reveal a substantial agreement with the scaling law already reported .

The paper is dedicated to a report on the characteristics of ST40 hot-ion similar to the TFTR supershots and to a more general test on ST40 database of the supershot-like energy confinement scaling law proposed in [3].

[1] S McNamara et al (2023), accepted for publication in NF Letters.
[2] J Strachan et al ., ‘Neutron Emission from TFTR Supershots’ , Nuclear Fusion 33 (1993) 991
[3] Francesco Paolo Orsitto and Michele Romanelli 48° EPS Conference on Plasma Physics 2022 , ‘Plasma Parameters of Compact Fusion Reactors using Similarity Scaling Laws of Spherical Tokamak Fusion Plasmas , P5a.103

Overview of recent results from the ST40 high-field spherical tokamak

S. A. M. McNamara[1], the Tokamak Energy* Team and External Collaborators*

[1]*Tokamak Energy Ltd, Milton Park, Oxfordshire, UK*

**For a full list of contributing authors see [1]*

ST40 is a compact high field spherical tokamak (ST), built and operated by Tokamak Energy Ltd, which to date has operated with parameters: $R_{geo} \approx 0.4-0.5$m, $A \approx 1.6-1.9$, $\kappa < 1.7$, $I_p \approx 0.4-0.8$MA, and $B_T \approx 0.8-2.2$T. Plasma heating is provided by two co-current deuterium neutral beams deliver 1.0MW at 55kV and 0.8MW at 24kV. The goal of ST40 is to expand the physics basis for the high field ST, by exploring confinement, start-up, exhaust, and high-performance operating scenarios at high toroidal field.

In 2022, ST40 obtained a central deuterium ion temperature of 9.6 ± 0.4keV [1]. Such high ion temperatures have previously only been reached in significantly larger devices and never in a ST. These high temperatures were achieved in hot ion mode, where $T_i \gg T_e$, in both hydrogen and deuterium plasmas with deuterium neutral beam injection.

This contribution will summarise results from recent ST40 operations and discuss projections for future experiments. This will include: the transport properties of these high temperature plasmas [2]; the impact of impurity injection on confinement; an assessment of the applicability of reduced and analytic transport models to ST40 plasmas; the observed interplay between beam-driven chirping modes with L-H and H-L back transitions [3]; linear and nonlinear perturbative analyses of low-frequency instabilities [4]; and characterisation of dithering H-mode phases [5].

References

[1] McNamara S. A. M. *et al* 2023 Achievement of ion temperatures in excess of 100 million degrees Kelvin in the compact high-field spherical tokamak ST40 *Accepted for publication in Nucl. Fusion*

[2] Kaye S. M. *et al* 2022 Transport Characteristics of High Performance ST40 Plasmas *Submitted to Nucl. Fusion*

[3] Bland J. *et al* 2022 Interplay between beam-driven chirping modes and plasma confinement transitions in spherical tokamak ST40 *Nucl. Fusion* **63** 016024

[4] Duarte V. N. *et al* 2023 Perturbative analysis of low-frequency instabilities in high-field ST40 experiments *Nucl. Fusion* **63** 036018

[5] Andrew Y. *et al* 2022 H-mode dithering phase studies on ST40 *Phil. Trans. R. Soc. A* **381** 20210225

Recent progress in diagnosing and interpretating plasma discharges in the ST40 high-field spherical tokamak

Marco Sertoli[1], J. Bland, P. Buxton, C. Colgan, M. Gemmell, T. O'Gorman, H. Lowe, R. Mirfayzi, D. Osin, T. Pyragius, A. Sladkomedova, H.V. Willett, J. Wood, L. Zhang, the Tokamak Energy team, and External collaborators *

[1] Tokamak Energy Ltd., 173 Brook Drive, Milton Park, Oxfordshire, OX14 4SD, United Kingdom

** See the author list of "Achievement of ion temperatures in excess of 100 million degrees Kelvin in the compact high-field spherical tokamak ST40" by S.A.M. McNamara et al. accepted for publication in Nuclear Fusion*

The ST40 spherical tokamak has recently demonstrated central ion temperatures of 9 keV operating at 0.5 MA plasma current, 1.9 T magnetic field on axis and 1.8MW neutral beam heating power [1]. Since then, the characterization of the diagnostic systems has been improved, new diagnostics have been installed, and analysis and modelling tools have been further developed.

This contribution presents results from the early-2023 experimental campaign. Preliminary data from the new Thomson scattering diagnostic, an upgraded setup of the CXRS spectrometers viewing the two NBI injectors, new midplane tangential AXUV diode array and upgraded neutron diagnostics will be shown. Improvements in the diagnostic analysis suites and recent advancements in forward models will be discussed, examining data consistency, and investigating parametric correlations. The results from 2022 [1, 2, 3] are reviewed considering the additional information from the new diagnostics and revised analysis methodologies, supported by interpretative and predictive transport analyses.

[1] S.A.M. McNamara et al. "Achievement of ion temperatures in excess of 100 million degrees Kelvin in the compact high-field spherical tokamak ST40", accepted for publication in Nuclear Fusion
[2] P. Thomas et al. "High Temperature Plasmas in ST40" invited talk at the 2022 APS Conference
[3] S.M. Kaye et al. "Transport characteristics of high performance ST40 plasmas" submitted to Nuclear Fusion

Plasma Tomography by means of CVD Diamond Photodetectors

S. Palomba[1], S. Cesaroni[2], M. Marinelli[1], E. Milani[1], C. Verona[1], G. Verona-Rinati[1], M. Angelone[2], F. Bombarda[2], M. Iafrati[2], F. Causa[3]

[1] *"Tor Vergata" University of Rome, Industrial Engineering Department, Rome, Italy*

[2] *ENEA, Fusion and Nuclear Safety Department, Frascati (Rome), Italy*

[3] *CNR- ISTP, Milan, Italy*

Tomography is an imaging technique [1] developed for medical diagnostics, that is widely applied also to the diagnostics of magnetically confined plasmas in fusion reactors, allowing the 2D reconstruction of the plasma emission in a poloidal section at a toroidal point. The plasma emissivity function (*g)* is reconstructed from the power measured by *n* detectors. In the narrow solid angle approximation, the sensed power can be viewed as a line integral per unit volume (W m^{-3}) and each detector can be defined by its *line-of-sight*. Nevertheless, the mathematical concept of tomography is ill-posed because there are more unknowns than known conditions. In this research, a pixel-based tomographic reconstruction method is used, in which the area to be reconstructed is divided into N rectangular pixels, with N >> *n* given the limited space available for diagnostics [2]. In order to minimize χ^2 between the measured and reconstructed brightness (*f*) other conditions are necessary. Tikhonov regularization is then applied to obtain a unique solution from the inverse matrix [3]. This work was carried out with the purpose of developing a handy tool to guide the design of new tomographic diagnostic systems based on thin single crystal CVD diamond detectors [4]. Diamond detector are sensitive to the VUV and SX radiation but are visible blind. Relative to Si diodes, diamonds can provide a more extensive coverage of the plasma poloidal section both in terms of geometry, thanks to their very small dimensions, and of a larger spectral sensitivity range, extending the detection all the way to the plasma edge. Various reconstruction simulations of emission profiles were performed by varying first the mathematical parameters in the reconstruction algorithm. Subsequently, tests regarding the best set up of the devices were carried out, varying their number and arrangement. Under the best mathematical and layout conditions, which will be discussed in this paper, various emission profiles were reconstructed. Furthermore, spectrally resolved plasma emission profiles were simulated and convolved by the detectors responsivity curves, so to produce realistic phantoms on which the reconstruction algorithm can be tested.

[1] S. R. Deans ," *John Wiley & Sons Ltd*., New York, (1983).
[2] Anton, M., et al. *Plasma Physics and Controlled Fusion* **38.11** (1996), 1849.
[3] Jardin, A., et al. *The European Physical Journal Plus* **136.7** (2021), 1.
[4] Bombarda, F., et al., *Nuclear Fusion* **61** (2021) 116004

Neoclassical toroidal viscous torque due to 3D magnetic perturbations in EU-DEMO

R. Buchholz[1], C.G. Albert[1], S.V. Kasilov[1,2,3], W. Kernbichler[1], P. Lainer[1], L. Pigatto[4]

[1] *Fusion@ÖAW, Institut für Theoretische Physik - Computational Physics, Technische Universität Graz, Petersgasse 16, 8010 Graz, Austria*

[2] *Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", 61108 Kharkiv, Ukraine*

[3] *Department of Applied Physics and Plasma Physics, V. N. Karazin Kharkiv National University, 61022 Kharkiv, Ukraine*

[4] *Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), C.so Stati Uniti 4, 35127, Padova, Italy*

3D external magnetic perturbations are planned in the future tokamak EU-DEMO for several purposes [1]: (1) Avoidance and manipulation of locked modes leading to disruptions, (2) possible suppression of edge-localized modes (ELMs), (3) toroidal rotation control to reach ELM-free regimes. The non-resonant part of these perturbations induces a neoclassical toroidal viscous (NTV) torque [2] as a side-effect or by intention. Here we quantify this torque for resonant magnetic perturbations and toroidal field ripple, using the current baseline of EU-DEMO. Based on linear and non-linear 3D magnetohydrodynamic equilibrium computations, we apply and compare various numerical models for NTV. The analytical and kinetic formulations of the code MARS-Q [4] are used to estimate the importance of resonant transport regimes in a linearly perturbed equilibrium. The code NEO-2 is used to model both, ion and electron NTV across all quasilinear collisionality regimes [5] with non-local extensions to the standard neoclassical ansatz [6]. The Hamiltonian approach in the code NEO-RT [3] is applied to ion NTV in the resonant plateau in the low-collisional quasilinear limit. Nonlinear resonant trapping at even lower collisionality and finite orbit width effects are taken into account. These features are especially relevant for alpha particles with wide drift orbits [7] and very few collisions [8].

References

[1] F. Maviglia *et al*, 32nd Symposium on Fusion Technology, P-2.39 (2022)

[2] K.C. Shaing *et al*, Nuclear Fusion 55, 125001 (2015)

[3] C.G. Albert *et al*, Physics of Plasmas 23, 082515 (2016)

[4] Y. Liu *et al*, Physics of Plasmas 20, 042503 (2013)

[5] S.V. Kasilov *et al*, Physics of Plasmas 21, 092506 (2014)

[6] A.F. Martitsch *et al*, Plasma Phys. Control. Fusion 58, 074007 (2016)

[7] R. Buchholz *et al*, Journal of Physics: Conference Series 2397, 012012 (2022)

[8] C.G. Albert *et al*, 43rd EPS Conference on Plasma Physics, P1.051 (2016)

Exploring the influence of plasma triangularity on pedestal stability and structure in ASDEX Upgrade

L. Radovanovic[1], E. Wolfrum[2], M.G.Dunne[2], T. Görler[2], C. F. B. Zimmermann[2], G. Harrer [1], M. Cavedon [3], F. Aumayr [1] and the ASDEX Upgrade Team[4]

[1] *Institute of Applied Physics, TU Wien, 1040 Vienna Austria*

[2]*Max Planck Institute for Plasma Physics, 85748 Garching, Germany*

[3]*Dipartimento di Fisica "G. Occhialini", Università di Milano-Bicocca, Milano, Italy*

[4]*see the author list of U. Stroth et al. 2022 Nucl. Fusion 62 042006*

The confinement and the performance of a tokamak plasma in the high confinement regime are closely related to the structure of the pedestal, which is characterised by its gradient and its width. Although the highest achievable pedestal, before the onset of an edge localised mode (ELM), is well predicted by the peeling-ballooning theory, the structure of the pedestal before an ELM crash is not well understood.

One possible factor limiting the pedestal width is the onset of kinetic ballooning modes (KBMs) at the top of the pedestal [1, 2], which we approximate by local ideal ballooning modes (IBMs). The stability can be altered by varying the plasma shape, from the lower to the higher upper triangularity ($\delta_{up} \approx 0.1$ to $\delta_{up} \approx 0.25$). It is shown that with increased shaping, the most unstable region for the local IBMs moves inward, and correlates with the position of pedestal top in the electron density and the electron pressure profiles. Due to its widening, at a similar gradient, the pedestal also grows higher. This is in agreement with the empirical observation made at ASDEX Upgrade, where increased shaping also causes increased pedestal top density [3, 4, 5]. Despite the clear changes in electron pressure, no changes in the ion temperature profile in the pedestal are found. This shows that different physical mechanisms are influencing the pedestal width of the electrons and ions with respect to their density and temperature. These individual effects are nevertheless conditioned by the overall limit on the total pressure, set by the ideal magnetohydrodynamic (MHD) stability.

To determine the role of local IBMs at the pedestal top, other possible instabilities present at the pedestal top are analysed with the gyrokinetic code GENE.

The radial electric field (E_r) profiles have been reconstructed from the charge exchange recombination spectroscopy. The E_r well shows an outward shift at the higher shaping. The impurity measurements indicate an overall radially inward-directed flux of momentum in high triangularity at the constant β_{pol}. Consequently, the toroidal velocity significantly increases at the plasma edge. A slight outward shift of the poloidal velocity of the main impurity is also observed.

In this study, the influence of plasma shape on the pedestal, with a focus on the outer core and the pedestal top region, is explored using versatile tools. The objective is to link physical processes in frameworks of MHD, transport and gyrokinetics with the experimentally observed pedestal structure.

References

[1] D. Dickinson, et al. *Plasma Physics and Controlled Fusion*, 53(11), oct 2011.

[2] P.B. Snyder, et al. *Nuclear Fusion*, 51(10), 2011.

[3] T. Luda et al. *Nuclear Fusion*, 60(036023), 2020.

[4] F.M. Laggner, et al. *Nuclear Fusion*, 58(4), 2018.

[5] A. Kallenbach, et al. *Nuclear Fusion*, 42(10), 2002.

Plasma Simulations of Vertical Displacement Events for STEP

S. Bakes[1], O. Bardsley[1], S. Biggs-Fox[1], A. Fil[1], T. Hender[1], M. Subramani[1], E. Trier[1], Z. Vizvary[1]

[1]*United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*

STEP (Spherical Tokamak for Energy Production) is a UK program to build a net electric prototype fusion power plant. To optimise performance ST operation at high elongation is required, increasing the growth rate of the vertical instability. This means that vertical displacement events (VDEs) are a significant risk for the device.

The large plasma current (∼20 MA) and thermal energy (∼500 MJ) needed to achieve fusion conditions means that the risk of serious damage to the device in the event of an unmitigated disruption is high. It is critical that such events are understood, from their mitigation and avoidance to assessment of impacts in the worst-case scenarios. Here, we present initial modelling for an unmitigated VDE. Using values extrapolated from multi-machine databases for the current quench (CQ) and thermal quench (TQ) durations, free boundary equilibrium modelling has been used to assess the induced currents and forces on toroidally conductive structures, as well generating data for codes such as SMARDDA and HEAT to assess the heat loads on the first wall. This method, while not as high fidelity as full MHD models, has the advantage that simulations can be done quickly in order to assess different design choices. We also assess how late into a downward VDE a poloidal field coil pulse can change the direction of the displacement. This is motivated by the fact that with current maintenance strategies, performing repairs on the top half of the vessel is significantly easier.

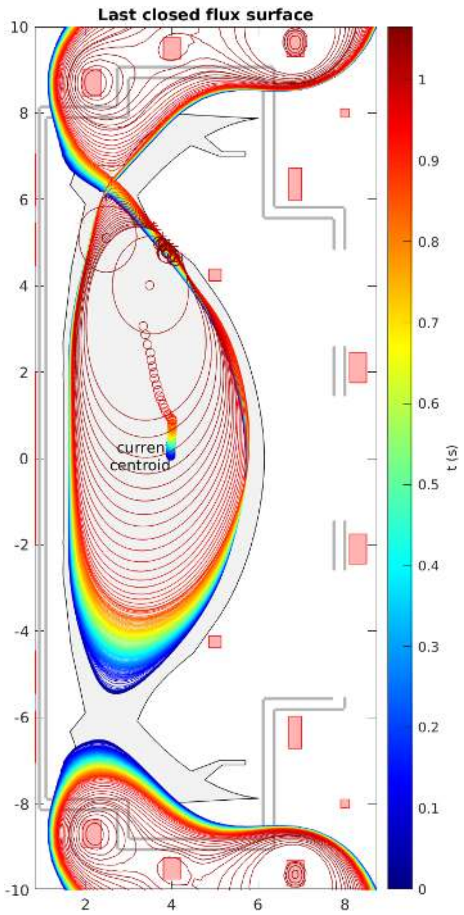


Figure 1: *Equilibrium boundary evolution as a function of time for a STEP VDE*

PLASMA CONFINEMENT MODE CLASSIFICATION FROM FAST CAMERA IMAGES

[1]V. Gopakumar, [1]S. Pamela, [1]D. Brennand, [2]V. Tibrewal, [2]A. Anandkumar, and [1]MAST Team

[1]UK Atomic Energy Authority, Oxford, United Kingdom.
[2]Caltech, California, United States of America.
Email: daniel.brennand@ukaea.uk

1. ABSTRACT

The confinement mode of the plasma inside a Tokamak can be simplistically characterised as one of two states: Low confinement (L-mode) or high confinement (H-mode). In each of these modes the properties of the plasma are very different, in L-mode there is generally more turbulence and the confinement degrades with temperature while after the transition to H-mode there is an marked improvement in confinement, characterised by a smoother plasma. Due to the better confinement, a transition from L-mode to H-mode is preferred for a more favourable regime in fusion scenarios.
The MAST tokamak was fitted with several fast cameras along the visible spectrum, imaging the appearance of the plasma at different wavelengths throughout an experiment. In this work an image classification neural network based on AlexNet is used on the images produced by the visible photron bullet cameras to classify the confinement mode of the plasma over time. The overall accuracy of the system is ~93% with many of the false predictions being in one of three places: the start of an experiment when the plasma is still forming, at the end of experiment when it is dissipating, and the transition point between confinement modes. The L-H neural network classifier has allowed for the identification of the transition point between L-mode and H-mode with considerable accuracy.
It is also hoped that when used in conjunction with a plasma prediction model (such as the FNO) that the transition of confinement modes can be predicted in advance, allowing for integrating within the control loop.

Poster Abstract: Initial work on the application of an ‘observational’ random walk model to simulations of the Scrape-Off Layer

F. Militello[1], J. J. Rasmussen[3], T. Gheorghiu[1,2]

[1] *United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, OX14 3DB, UK*

[2] *York Plasma Institute, Department of Physics, University of York, Heslington, York YO105DD, UK*

[3] *Physics Department, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark*

Anomalous diffusion has been observed in the scrape-off Layer (SOL) of MCF devices, and has made analytical modelling of this region challenging.

We have developed an ‘observational’ random walk concept based on the classical and continuous random walk formalism with the aim of examining and describing the transport properties of particles in turbulent systems. The concept is first validated on a synthetic field, in which it provides a description consistent with classical diffusion theory. It is then applied to the classical and modified Hasegawa-Wakatani system, as this has been previously considered as a system with analogous features to the tokamak scrape-off-layer. The concept applied to this system appears to demonstrate that particle transport can be modelled with a linear combination of normal and fractional transport terms in certain cases.

We also present initial work on applying this approach to 2-dimensional simulations of the Scrape Off Layer using the STORM module of BOUT++ in different cases, as well as further work on improving and updating the random walk approach such that it can be used to examine transport in systems with suspected spatial variation in transport, in concert with the use of tracer particles. If we can demonstrate that the simulated SOL can be modelled with this random walk approach, we may be able to model dispersive transport in the SOL.

Isotope mass dependence of low-density pedestals of D, T and D-T ITB H-modes in JET with Be/W wall

CF Maggi[1], S Saarelma[1], R Dumont[2], F Fitzgerald[1], D Keeling[1], J Garcia[2], E Delabie[3], L Garzotti[1], D Kos[1], E Litherland-Smith[1], S Menmuir[1] and JET contributors*

[1]*UKAEA, Culham Science Centre, Abingdon, OX14 3DB, UK*
[2]*CEA, IRFM, F-13108 Saint Paul Lez Durance, France*
[3]*Oak Ridge National Laboratory, Oak Ridge, TN 37831-6169, USA*
See J Mailloux et al., Nucl. Fusion **62 (2022) 042026*

Experiments in JET with Be/W wall have highlighted a strong sensitivity of H-mode pedestal confinement and transport to variations in the effective hydrogen isotope mass (A_{eff}). In 2021, new JET experiments in T and D-T yielded additional, unique information in view of ITER predictions. The particle channel is primarily affected, with the pedestal density increasing with A_{eff}, while the pedestal temperature is only weakly affected by A_{eff} [1], [2], [3], [4]. Recent gyro-kinetic modelling of JET H and D pedestals suggests a reduction in inter-ELM particle transport with decreasing isotope mass [5], and recent pedestal stability studies with resistive linear MHD indicate an increase of the normalized pedestal pressure from D to T, qualitatively consistent with experiment [3].

In this contribution we present an experimental characterization of the unexpected and yet unexplained isotope mass dependence of the low-density pedestals of JET H-modes with internal transport barrier (ITB): in these plasmas, the pedestal density ***decreases*** with increasing A_{eff}, instead of *increasing* with A_{eff}, as observed in the H-mode pedestals with type I ELMs described above. The dataset analysed comprises ITB plasmas at 2.6MA/3.4T, developed in D and T and exploited in D-T for the observation of destabilization of toroidal Alfven eigenmodes by α-particles [6]. Although highly transient, these H-modes provide the lowest pedestal densities in JET-ILW at the given plasma current. The low edge density conditions are conducive to ITB trigger and sustainment and are enabled by pellet-pacing, resulting in small/high frequency/compound ELM activity. Although the exact nature of these 'small ELMs' is not yet clear, linear MHD pedestal stability analysis confirms the operating point to be deeply stable to peeling-ballooning modes, ruling out the type I ELMy regime. D-pellet pacing was used in the D and D-T plasmas and H-pellet pacing in the T plasmas (due to D-T neutron budget restrictions), with additional D plasmas with H-pellet pacing for comparison. The combined dataset thus yields a variation in A_{eff} from 1.84 (D/H) to 2.78 (T/H). The response of the low-density pedestals of ITB plasmas to A_{eff} variations and H-pellet pacing is contrasted to that of 3.5MA/3.3T baseline scenario H-modes, which operate at the highest $n_{e,PED}$ in JET-ILW. In these high density pedestals, with pellet paced, mixed type I/compound ELMs, $n_{e,PED}$ increases with A_{eff} from D to T/H in qualitative agreement with the type I ELMy pedestal results.

These studies motivate gyrokinetic simulations and pedestal fluctuation analysis for the identification of the micro-instabilities controlling pedestal transport of ITB H-modes, which we hypothesize being of different nature from those of type I ELMy pedestals [5], [7].

References:[1] CF Maggi et al., Plasma Phys. Control Fusion **60** (2018) 014045; [2] L Horvath et al., Nucl. Fusion **61** (2021) 046015; [3] L Frassinetti et al., *this Conference;* [4] P Schneider et al., *this Conference;* [5] I Predebon et al., Nucl. Fusion **63** (2023) 036010; [6] M Fitzgerald et al., subm. Phys. Rev. Lett. 2023 and *this Conference;* [7] B Chapman-Oplopoiou et al., Nucl. Fusion **62** (2022) 086028.

Pellet fuelling and impurity seeding for the STEP powerplant

C. Olde[1], F. J. Casson[1], E. Tholerus[1], F. Koechl[2], M. Lord[1], L. Garzotti[1], S. Marsden[1] and H. Meyer[1]

[1] *CCFE, UKAEA, Culham Science Centre, Abingdon OX14 3DB, UK*

[2] *ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France*

The STEP programme plans to demonstrate the ability to produce net electricity with a prototype power plant based on a spherical tokamak (ST). The ST will operate in a fully non-inductive regime, where a combination of electron cyclotron (EC) and electron Bernstein wave (EBW) systems will be used for auxiliary heating and current drive. The current design point proposes a 3.6m major radius and an aspect ratio of 1.8, that will aim to generate a fusion power P_{fus}~1.8GW. This modelling work covers the effect that injecting fuelling pellets has on the core plasma and determines viable injection trajectories that will optimise pellet performance. Additionally, we explore the impact that seeded impurities and impurity transport have on plasma performance and what implications this may have on the overall STEP design. These studies use the integrated core plasma modelling tool JETTO and HPI2 pellet code to investigate these concepts during the ramp-up and flat-top operational phases.

The pellet fuelling system for STEP will use HFS (High Field Side) injection, as this is the optimal method for achieving deep fuel to plasma penetration due to the $\mathrm{E} \times \mathrm{B}$ drift of a charged pellet dipole. In the scenario where a single 1.7mm, spherical pellet is injected at 600ms^{-1} into the core plasma during the flat-top phase, the electron density changes by up to ~9% locally and up to ~1.2% when considering the volume average. These changes in density due to discrete pellet injection fall below the approximate limits that the plasma is expected to be able to tolerate whilst remaining in a stable state. This gives confidence that during flat-top operation, the core plasma will be reasonably robust to fuel pellet injection for the current working assumption of the pellet size. Pellet modelling during ramp-up is also being investigated, to determine how the pellets effect a phase with lower density compared to the flat-top. Our impurities studies consider scenarios where the core plasma contains three impurities: He, Xe and Ar. Seeding pellets provide the source for Xe, which are required to control a high core radiation fraction for divertor protection. Ar is assumed to come from the divertor, and He is a by-product of the fusion reactions. Since Ar seeding in the divertor is necessary for detachment, limiting the amount that makes its way into the core plasma will be crucial in preventing plasma performance from deteriorating. This is dependent on the performance of the pedestal and future sensitivity scans will give insight into how the amount of Ar in the core plasma can be reduced. Our initial analysis suggests that having ~0.3% Ar introduced into the core plasma has a significant impact on fusion power, particularly in the lower density scenarios, due to fuel dilution in the core caused by impurity accumulation. Further studies will focus on using upgraded neoclassical transport models to better understand the impurity transport during flat-top operation.

Impact of the q profile on observed MHD instabilities on MAST Upgrade

S. Gibson[1], L. Kogan[1], A. Kirk[1], C. Ham[1], C. Beckley[1], C. Michael[2], A. J. Thornton[1], J. Harrison[1] and the MAST Upgrade Team[3]

[1] *UKAEA/CCFE, Culham Science Centre, Abingdon, UK*

[2] *University of California Los Angeles, Los Angeles, USA*

[3] *See author list of J. Harrison, et al. Nucl. Fusion **59** (2019) 11201*

In the first experimental campaigns on MAST Upgrade, a neutral beam heated 750kA plasma current H mode plasma scenario was developed. Understanding the q profile evolution in these plasmas facilitates the development of high performance scenarios and the avoidance of deleterious low n MHD instabilities.

To infer the q profile evolution, the equilibrium reconstruction code EFIT++[1] is internally constrained with measurements from the motional Stark effect (MSE) diagnostic. The central poloidal flux surfaces are well constrained by the high spatio-temporal resolution MSE system on MAST-U[2], producing reconstructed pressure profiles consistent with measurements from the core Thomson scattering system. The central q evolution is also consistent with the onset of core MHD such as the sawtooth instability. These reconstructions are subsequently used to further investigate MHD such as the tearing modes and long lived mode (LLM).

To minimise the internal inductance ℓ_i, the scenario uses a fast plasma current ramp up of dI/dt = 7MA/s. An observed consequence is an internal re-connection event (IRE) at the start of the flat top phase. We investigate the effects of the IRE on the q shear and q_{min}, and the MHD that follows. Signatures of a low frequency 3-10kHz tearing mode are observed in MHD spectrograms of these plasmas. MSE constrained EFIT reconstructions reveal that the location of the $q = 2$ surface co-incides with a flattening in the electron temperature profiles, indicating the presence of an $m = 2$, $n = 1$ tearing mode. Contrary to the behaviour on MAST, where low (m,n) modes were triggered by the sawtooth instability[3], the mode grows in the absence of sawteeth. This tearing mode limits the achievable core temperature and flattens the core rotation as measured by the Charge Exchange Recombination Spectroscopy (CXRS) diagnostic. Finally, we demonstrate that modifications to the plasma current ramp up influences the onset of this IRE and the subsequent MHD, leading to the $n = 1$ long lived mode.

References

[1] L. Kogan et. al, 48$^{\text{th}}$ EPS Conference on Plasma Physics, (2022)

[2] N. J. Conway, et al., Rev. Sci. Instrum. **81**(10), (2010)

[3] R. J. Buttery, et al., Phys. rev. lett. **88**(12), (2002)

Validation of the pre-burn phase of advanced non-inductive operational scenario for tokamak-reactor in the high beta long pulse TCV experiments

I. Voitsekhovitch[1], S. Coda[2], C. Piron[3], F. Auriemma[4], M. Vallar[2], M. Agostini[4], F. Bagnato[2], A. Burckhart[5], R. A. J. Coosemans[2], J. Decker[2], S. Garavaglia[6], A. Jardin[7], D. Mazon[8], A. Moro[6], S. Nowak[6], A. Pau[2], L. Piron[4], O. Sauter[2], L. Simons[2], M. Ugoletti[4], V. Yanovskiy[9], WPTE and TCV Teams

[1]CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK; [2]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland; [3]ENEA, Fusion and Nuclear Safety Department, C.R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma) Italy; [4]Consorzio RFX-ISTP CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA. I-35131 Padova, Italy; [5]Max-Planck-Institut fur Plasmaphysik, D-85748 Garching, Germany; [6]ISTP-CNR, via R. Cozzi 53, 20125 Milano, Italy; [7]Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN), PL-31-342, Krakow, Poland, [8]CEA, IRFM, F-13108 Saint Paul Lez Durance, France; [9]Institute of Plasma Physics AS CR, Za Slovankou 1782/3, 182 00 Praha 8, Czech Republic

The performance of fully non-inductive (NI) burning plasma in a tokamak-reactor is largely determined by plasma confinement, which is crucial also to the requirements for fuelling, heating and external current drive (CD) sources used in different scenario phases. The key element of one possible optimisation strategy for the NI scenario is the formation of a reversed shear (RS) configuration and an Internal Transport Barrier (ITB) at the early stage and their sustainment during the density rise and burn phase. Strong non-linear coupling between plasma transport, kinetic and current density profiles, and external CD efficiencies complicates the scenario development. Predictive modelling with transport models validated in NI plasmas with similarly strong multi-parameter coupling would help to optimise such scenarios. Computationally fast models would be also useful for real-time plasma control.

Recent success is being reported in the development of advanced NI scenario in TCV [1, 2]. Strong RS configurations with improved core thermal confinement have been obtained in L-mode plasmas at zero loop voltage by applying ECCD initially at low density, followed by ion heating by NBI accompanied by a density rise. A valuable database has thus been built for model validation.

Interpretative analysis performed with ASTRA and TRANSP codes shows that in the low density (n_e) L-mode cases a nearly zero (or even slightly negative) voltage is achieved transiently in the entire plasma region with off-axis ECCD, radially distributed bootstrap (BS) current density peaked at the ITB location and a small NBCD contribution. The magnetic configurations obtained are characterised by a deeply reversed q-profile with q_{min} = 1.5 ± 0.3 around mid-radius. In the next step, the density has been increased following the standard burning plasma scenario route. In the considered n_e range limited by the X2 wave cutoff density the beam driven current increases with n_e due to improving beam absorption, however, it does not compensate the reducing EC-driven current due to a low NBCD fraction (5-6 %). Consequently, the OH current re-appears in the plasma centre and the reversed q-profile slowly evolves to a monotonic one.

The stabilising effect of reversed magnetic shear on thermal and particle transport is estimated by using the semi-empirical magnetic and *ExB* shear correction to transport coefficients validated in the dynamic modelling of ITB triggering, sustainment and decay in TFTR, DIII-D and JET discharges where the q-profile varies between flat (JET) and strongly reversed (TFTR) shape [3]. This correction is used here in combination with the Bohm-gyroBohm model well validated in L- and H-mode plasmas in different machines [4]. It is found that the Bohm-gyroBohm model allows to predict reasonably well the L-mode electron temperature (T_e) in the region with monotonic q (i.e. outside the mid-radius) in the representative L-mode TCV discharge [2], while the core T_e is strongly underpredicted (by factor ~2) in the RS region. This large discrepancy is reduced to ~20% when the magnetic shear stabilisation is taken into account. Following these first results, the modelling of advanced NI TCV discharges will be presented aiming in particular at the understanding and accurate prediction of n_e evolution in RS configurations under conditions of competing effects of the ECRH density pump-out and NBI fuelling.

[1] C. Piron et al, 49th EPS Conf., July 3-8 2023, Bordeaux, France; [2] S. Coda et al, 29th IAEA FEC, October 16-21 2023, London, UK; [3] I. Voitsekhovitch et al, Phys. Plasmas **6**, 4229 (1999) and Czech. Journal of Physics **49** (1999) Suppl. S3, p. 41; [4] M. Erba et al, Plasma Phys. Contr. Fusion **39**, 261 (1997)

Convective Transport in the SOL and its Effects on Divertor Asymmetry in Tokamaks

L. Xiang[1], D. Moulton[1], F. Subba[2], F. Militello[1]

[1]Culham Centre for Fusion Energy, UKAEA, Abingdon, OX14 3DB, UK

[2]Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy

In the field of SOL and divertor physics research in tokamaks, it is common practice to focus on the more critical divertor, i.e., to investigate the plasma between the “upstream”, which is usually the low field side midplane or the X-point, and the “downstream” which is the divertor target. However, through a numeric study with SOLPS-ITER [1] code package in which we varied the connection length in the outer divertor of single-null plasma configuration by changing the outer divertor leg from being conventional, to long-legged, and to X-divertor, in order to modulate the conductive power into the inner and the outer divertor according to two-point model [2], we found that the partition of total power between the two divertors is altered by the convective flux going around the SOL. The convective flux is present at all levels of asymmetry regarding parameters of concern e.g., T_e and $q_{\perp,target}$, between the two targets and can be as significant in conditions where both targets are detached as it is when one target remains attached. However, the mechanisms that drive the convective flux changes with the conditions at the two targets. When the one target is attached and the other detached, large temperature difference establishes significant thermoelectric and electrostatic current between the two targets, resulting in significant electron convective heat flux directing towards the hotter target, hence enhancing the model predicted asymmetry in power partition. Besides these two dominant driving factors, the integral of the parallel pressure gradient normalized to the local density from the inner target to the outer target also causes relatively less significant convective heat flux to be transported between the targets through the SOL. When both targets are detached, the first two mechanisms subside, and last mechanism prevails. The convective ion flux from one target to the other, driven by particle source imbalance in the inner and outer divertor usually directs towards the colder divertor, opposite that of the electron convective flux due to thermoelectric and electrostatic currents. Its magnitude is lower than the electron convective flux when the currents are significant but can become comparable when both target progress towards detachment. Indeed, when the electrostatic current is switched off, the ion and electron convective heat flux are comparable even when T_e and $q_{\perp,target}$ are very asymmetric. The ion convective flux seems to act as a mechanism that helps the two targets at either end of the SOL to be less asymmetric and to achieve detachment, through fuelling or impurity seeding, temporally nearer.

[1] X. BONNIN, W. DEKEYSER, R. PITTS, D. COSTER, S. VOSKOBOYNIKOV, and S. WIESEN, “Presentation of the new solps-iter code package fortokamak plasma edge modelling", Plasma and Fusion Research, vol. 11, no. 1403102, 2016.
[2] P. STANGEBY, The Plasma Boundary of Magnetic Fusion Devices. IOP Publishing, 2000.

Eulerian Video Magnification for the Analysis of Fast-Ion Losses in MAST-U

T.G.E. Williams[1,2], J.F. Rivero-Rodriguez[1], K.G. McClements[1], L. Velarde[3], and the MAST-U Team*

[1] *United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*

[2] *Department of Physics and Astronomy, University of Exeter, Stocker Road, Exeter, EX4 4PY, UK*

[3] *Departamento de Ingeniería Energética, Universidad de Sevilla, Sevilla, Spain*

Abstract

Understanding fast-ion loss mechanisms in spherical tokamaks like MAST-U is important as the velocities of the NBI ions relative to the Alfvén speed are comparable to those of fusion-born α-particles in future devices like STEP and ITER. The MAST-U Fast-Ion Loss Detector (FILD) is a scintillator-based plasma diagnostic that directly measures fast ions escaping from the plasma [1], making it possible to study the velocity space of the fast-ion losses and their fluctuations on the timescale of the wave-particle fluctuations. The light emitted by the ions impinging on the scintillator is photographed simultaneously with a 1kHz high spatial resolution camera and a 4MHz avalanche photo-diode (APD) camera. The FILD head is mounted on a rotary and reciprocating mechanism that allows for independent orientation to the magnetic field line and radial position of the probe. Due to FILD's fixed radial position in the first MAST-U campaign ($R = 1.56$m, relatively far from the plasma edge at R $\approx$ 1.4m) most of the data obtained displayed a poor signal-to-noise ratio, restricting the analysis of these losses. With FILD's improved capabilities (remote control of the radial position and a faster high resolution camera) we can provide a complete analysis of fast-ion losses and determine how these losses correspond to different modes within the plasma.

The FILD revealed fast-ion losses correlated with a wide variety of plasma instabilities, such as Fishbones, Long Lived Modes (LLM), Sawteeth and high frequency Alfvén Eigenmodes. Here, the fast-ion losses correlated with LLM are studied. The velocity space of these losses are inferred from the 1kHz camera data using the FILDSIM code [2], which accounts for the FILD geometry and the tokamak magnetic field. The results reveal fast-ion losses in a wide range of pitch angles. However, the sampling rate of the 1kHz camera is below the frequency of the LLM causing the fast-ion losses. Thus, to infer the fluctuations in velocity-space of the fast-ion losses induced by the modes, another numerical tool has been adapted to analyse FILD data; Eulerian Video Magnification (EVM) is used to reveal subtle temporal variations in the high time resolution video [3]. EVM has previously been used in MAST and MAST-U to highlight changes in the fast visible camera data associated with specific frequencies in order to view the structure of plasma instabilities [4, 5]. By applying EVM to the APD data we can reveal hidden changes in the fast-ion loss velocity space associated with specific mode frequencies. In the case of LLM-induced losses, the wider range of pitch-angle fast-ion losses are observed to fluctuate with the mode frequency, suggesting that these losses are induced by the mode. In contrast, a localised spot does not fluctuate with the mode frequency, these losses correspond to the NBI prompt-losses. The velocity space of the losses is used as input to the orbit-following code ASCOT [6] to compute the orbits traced by the lost fast-ions in order to investigate their cause. By using the MARS-F stability code [7] we are able to show that the loss of co-current beam ions caused by LLM could be detected by FILD. By generating synthetic FILD signals using MARS-F, ASCOT and FILDSIM we can compare the results with FILD measurements during long-lived modes.

References

[1] J.F. Rivero-Rodgriguez et al. In: *Rev. Sci. Instrum.* **89**, 10I112 (2018).

[2] J Galdon-Quiroga et al. In: *Plasma Phys. Control. Fusion* **60**, 105005 (2018).

[3] Hao-Yu Wu et al. In: *ACM Transactions on Graphics (Proc. SIGGRAPH 2012)* **31**, 4 (2012).

[4] C. Ham and J. Harrison. "Insights on disruption physics in MAST using high speed visible camera data". In: Second Technical Meeting on Plasma Disruptions and their Mitigation. ITER headquarters, 2022.

[5] D. Ryan. "Amplification of Plasma Edge Phenomena with Eulerian Video Magnification". University of York, 2014.

[6] E. Hirvijoki et al. In: *Computer Physics Communications* **185**, 4 (2014), pp. 1310–1321.

[7] Yueqiang Liu et al. In: *Plasma Physics and Controlled Fusion* **58**, 114005 (2016).

* See author list of J. Harrison et al 2019 Nucl. Fusion 59 112011

VDE mitigation with SPI on JET-ILW

S.N. Gerasimov[1], P. Carvalho[1], D. Craven[1], I.H. Coffey[1,2], O. Ficker[2], Z. Huang[1], S. Jachmich[4], D. Kos[1], M. Lehnen[4], M. Lennholm[1], M. Maslov[1], A. Peacock[1], P. Puglia[1], S. Silburn[1], G. Szepesi[1], J. Wilson[1], L.E. Zakharov[11,12] and JET Contributors*
[1] *UKAEA/CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*
[2] *Astrophysics Research Centre, Queen's University, Belfast, BT7 1NN, UK*
[3] *Institute of Plasma Physics of the Czech Academy of Sciences, Prague, Czechia*
[4] *ITER Organization, Route de Vinon, CS 90 046, 13067 Saint Paul Lez Durance, France*

The Vertical Displacement Event (VDE) cause large Electro-Magnetic (EM) loads on the tokamak and thermal loads on the Plasma Facing Components (PFCs). On JET, an unmitigated VDE becomes an Asymmetric VDE with additional dangerous sideways forces and asymmetric thermal loads. The consequences of VDEs are especially dangerous for large machines like JET and even more so for ITER. On JET, the use of Massive Gas Injection (MGI) to mitigate VDE is mandatory for $I_p \geq 1.25$ MA. However, ITER plans to use Shattered Pellet Injectors (SPI) to mitigate the effects of VDEs.

Thus, VDE mitigation with SPI has been investigated on JET-ILW. The original SPI experiment on JET-ILW was performed in 2019 and the most recent SPI experiment was conducted in December 2022.

According to the magnetic diagnostics, the exponential vertical motion of the plasma current centroid is interrupted. The Z-motion goes into a stationary state or reverses with a slow motion. At the same time, the rate of I_p drop increases, which leads to cessation of the fall in safety factor q_{95}. This prevents the excitation of the m/n = 1/1 kink mode mainly responsible for AVDE, and consequently, sideways displacement of the vessel and asymmetric thermal loads. In the course of the unmitigated upward VDE plasma hits and can damage the beryllium Upper Dump Plate (UDP). During mitigated VDE, presumably cold plasma can also come into contact with the UDP, but energy deposited to the beryllium UDP is much less (about 5 times) than for unmitigated VDE. As a result, the beryllium UDP does not overheat and is not damaged. Thus, SPI can be considered as a reliable method for protecting the first wall of the ITER from VDE.

---

* *See 'Overview of JET results for optimizing ITER operation' by J. Mailloux et al, to be published in Nucl. Fus. Special Issue for 28th Fusion Energy Conference (2021), J. Mailloux et al 2022 (https://doi.org/10.1088/1741-4326/ac47b4) for the JET Contributors*

Observation of alpha-particles in the recent D-T experiment on JET

V.G. Kiptily and JET contributors*

UKAEA, Abingdon, United Kingdom

* *See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al 2022 Nucl. Fusion **62** 042026*

The fusion-born alpha-particle heating in magnetically confined fusion machines is a high priority subject for study. A comprehensive set of diagnostics for both confined and lost α-particles was employed for studying their behaviour in *D-T* and *T*-plasmas. To make such measurements at the high neutron and γ-ray fluxes in *D-T* experiments we used the enhanced neutron/γ-ray spectrometers, 2D neutron/γ-ray camera, two fast ion loss detectors – a scintillator probe with energy and pitch-angle resolution and an array of the lost α-particle collectors with poloidal, radial and an energy resolution. JET with the ITER-like wall (*Be*-wall and *W*-divertor), improved energetic-particle diagnostic capabilities and enhanced auxiliary heating systems producing significant population of α-particles provided a great opportunity to study the α-particle behaviour giving a stepladder approach for modelling and extrapolating to ITER. In the talk the JET capabilities for measurements of α-particles are shown and selected results of the fast-ion and fusion α-particle measurements in both *D-T* and *T*-plasmas are highlighted.

One of the important results – the first direct evidence of α-particle heating obtained in the high-performance NBI afterglow discharges will be presented. It was found that *D-T* α-particles continue transferring their kinetic energy to plasma electrons during slowing-down after the NBI power cut. The transport modelling of the relevant *D-T* and reference deuterium discharges is consistent with the alpha-particle heating observation.

The *T-T* and *D-T* α-particle losses have been observed in hybrid and baseline scenarios as well as in a novel heating scheme – 3-ion ICRF heating of *Be*-impurity (could be used in ITER). It was found that α-particles losses related to MHD instabilities are correlated with fishbones and long-lasting modes in both the baseline and the hybrid scenario discharges. In the baseline scenario, significant changes in α-particle losses were observed to be associated with L–H confinement transitions in the plasma. Anomalous *D-T* α-particle losses have been observed in the 3-ion ICRF heating of *Be*-impurity. The pitch-angle distribution of α-particle losses in most of the cases has a single maximum, however two maxima at different pitch-angles are detected in the dedicated toroidal current scans. The physics reason behind this feature is being investigated. The high-energy α-particle loss spikes correlated with ELMs were observed. The orbit calculations shows that the related α-particles are lost from the passing-trapped boundary. Also, we observe a loss spikes, which are characterized by very high rate relative to classical first orbit rate detected, which could be linked to core α-particle redistribution triggering ELMs. Modelling is ongoing.

In conclusion, importance of the JET α-particle observations for future fusion reactors will be highlighted.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion) and from the RCUK Energy Programme (grant number EP/P012450/1). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk .

Measurements of fishbone instabilities and their effects on fast ions and plasma rotation in the MAST-U spherical tokamak

A R Jackson[1,2], K G McClements[2], C A Michael[3]

[1]*Department of Physics, University of Durham, South Road, Durham, DH1 3LE, UK*
[2] *UKAEA, Culham Science Centre, Abingdon OX14 3DB, UK*
[3]*Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, CA 90095-7099, USA*

The MAST-U spherical tokamak is equipped with an extensive array of instruments for studying the behaviour of fast ions (originating from neutral beam injection [NBI]) and instabilities driven by these particles. Such studies are important because anomalous fast ion behaviour generally degrades the overall plasma performance. In addition to a whole-plasma fission chamber-based neutron detector and a scintillator-based neutron camera with several lines of sight, fast ion diagnostics on MAST-U include a solid-state neutral particle analyser (ssNPA), a fast ion loss detector (FILD) and a fast ion deuterium-alpha (FIDA) spectrometer. In several pulses in the first MAST-U campaign, chirping "fishbone" instabilities, detected using Mirnov coils at initial frequencies of a few tens of kHz in plasmas with central safety factor q approaching unity, were found to be correlated with drops in FIDA, neutron and ssNPA fluxes, indicating fast ion redistribution and loss. In the latter stages of each fishbone, when the frequency had stopped chirping, the plasma was also observed to lose toroidal rotation. In all the pulses with fishbones, only on-axis NBI was used; an off-axis beam injector is also available but was not used in these pulses. Fishbones may have occurred in these pulses because on-axis NBI drove substantial current in the plasma core, reducing q, while the absence of off-axis NBI meant that there was a particularly steep fast ion pressure gradient in the core, increasing the fishbone drive. We present experimental analysis of these pulses and discuss three possible explanations of the rotation slowdown: (i) expulsion of fast ions providing the rotation torque; (ii) a counter-current torque driven by a return current balancing the radial current due to lost fast ions; (iii) a counter-current torque arising from the fishbone perturbation to the magnetic field itself. We conclude that the current generated by lost fast ions was not sufficient for (ii) to account for the full slowdown, and that (i) or (iii) must also be playing a role. The detrimental effects of fishbones in MAST-U contrast with their impact in other devices, for example in the JET hybrid regime where fishbones are often excited but do not significantly degrade plasma performance and can even have benign effects [1].

[1] T Pütterich et al 2013 Plasma Phys. Control. Fusion **55** 124036

High-performance Ohmic H-mode in Super-X MAST-U divertor plasmas, access, and relation to other confinement regimes

P. Shi, Terry Rhodes, Clive Michael, Rory Scannell

A high-performance H-mode Super-X divertor regime has been found on MAST-U that exhibits very good density and temperature pedestal performance (along with β_N~1, τ_e~60 ms). This operational mode exhibits both temperature and density pedestals (at the pedestal top 100 eV and 2.2e19 m^{-3} respectively), reduced density turbulence levels, and bursty ELM-like activity that controls the density levels all without external NBI or RF heating. These plasmas have similar pedestal performance as compared to some 3MW NBI H-mode plasmas and improved performance over similar recent Ohmic H-modes with conventional divertors. A new Doppler backscattering system (in collaboration with UCLA) provides significant insight into the density turbulence and flow behaviour both before and during these H-mode plasmas. Density turbulence (wavenumber range $k\rho_s$~.5-1 and radial range Ψ_N=0.8-1.04) increases in amplitude (over the baseline) just after the ELM bursts, and decreases in amplitude prior to the next ELM burst. The decrease in amplitude coincides with an increase in flow shear consistent with both shear flow turbulence reduction. The increased pedestal heights and gradients then lead to the next ELM. This behaviour provides insight into the sequence leading up the next ELM burst. These results potentially lead to an improved understanding of H-mode access that in turn could lead to lower power H-mode access in future machines and plasmas.

Review of plasmoid reconnection and two-fluid dynamo studies in the CHI experiments on Helicity Injected Spherical Torus (HIST)

M. Nagata[1], H. Miyamoto[1], N. Fukumoto[1] and T. Kanki[2]

[1] *University of Hyogo, Himeji, Hyogo 671-2280, Japan*

[2] *Japan Coast Guard Academy, Kure, Hiroshima 737-8512, Japan*

Coaxial Helicity injection (CHI) has been utilized as an efficient current-drive and start-up method in many gun-spheromak and ST experiments. The Helicity Injected Spherical Torus (HIST) device has been developed towards high-β ST plasmas by the CHI method. The plasmoid-mediated magnetic reconnection and two-fluid effects have been investigated in the CHI experiments on HIST. We have investigated the fast magnetic reconnection required for the flux closure and the ion heating driven by the plasmoid reconnection occurring during CHI discharges. Here, we will review them as follows; (a) In the ejection of plasma flow from the magnetized coaxial plasma gun during the helicity injection phase, a narrow current sheet is elongated and broken apart at some points inside it due to a tearing instability, so that three or four small-size plasmoids are born in sequence. The separation and coalescence of the multiple plasmoids are repeated through the reconnection, leading to a bigger plasmoid, namely closed flux surfaces. We have observed the phenomena as magnetic field oscillations, which was newly named as the plasmoid oscillation. (b) Doppler ion temperature increased from ~10 eV up to 80 eV during the plasmoid oscillation. The ion heating driven by the regular reconnection during the repeated plasmoid merging has been for the first time identified on HIST. In this conference, we will report the other topics (two-fluid dynamo, high performance of the open flux column) of the HIST experiments that was completed.

Energy dissipation in microtearing turbulence

M. Yagyu[1], R. Numata[2]

[1] *Graduate School of Simulation Studies, University of Hyogo, Kobe, Hyogo 650-0047, Japan*

[2] *Graduate School of Information Science, University of Hyogo, Kobe, Hyogo 650-0047, Japan*

Electromagnetic microtearing (MT) turbulence driven by electron temperature gradients leads to the electron thermal transport associated with the degradation of confinement performance in fusion devices. The thermal transport coefficients in MT turbulence have been evaluated by some gyrokinetic simulations dedicated to specific experimental devices [1, 2]. However, the fundamental physics on MT turbulence, such as the energy dissipation and saturation mechanism, are not fully understood. In this work, we discuss the saturation mechanism of the MT turbulent transport in terms of the energy dissipation mechanism in weakly collisional plasmas.

In weakly collisional plasmas, the phase mixing due to kinetic effects creates a fine-scale structure in the velocity space, which leads to the energy dissipation. During magnetic reconnection excited by the normal tearing mode not having the electron pressure gradient, the energy dissipation and resulting plasma heating are caused by the phase mixing, as demonstrated by [3] using fully gyrokinetic model.

We present the result of gyrokinetic simulations of the nonlinear MT mode in the weakly collisional plasmas. Figure 1 shows that the energy evolution of the nonlinear MT. On the MT mode, the energy due to the electron temperature fluctuations $\tilde{T}_{\perp,e}$ and $\tilde{T}_{\parallel,e}$, which are higher moments of the velocity distribution function, are dominant, while the perpendicular magnetic energy $M_\perp$ remains at a very low level, unlike the normal tearing mode [3]. The phase mixing may lead to the energy dissipation mechanism in MT turbulence dominated by the anisotropic temperature fluctuation. In this presentation, we show the saturation mechanism of the MT turbulent transport by detailed analyses of the energy dissipation due to the phase mixing process.

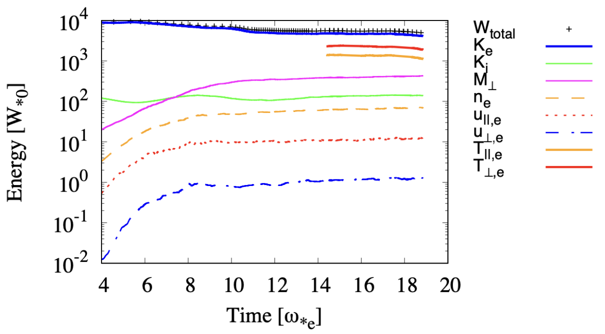


Figure 1: *Energy evolution in the nonlinear microtearing mode.*

References

[1] H. Doerk, F. Jenko *et al.*, Physics of Plasmas **19**, 055907 (2012)
[2] E. Hassan, D.R. Hatch *et al.*, Nucl. Fusion **62**, 026008 (2022)
[3] R. Numata and N.F. Loureiro, J. Plasma Phys. **81**, 305810201 (2015)

Investigating the role of vibrationally resolved H_2 on detachment in coupled Yacora-SOLPS-ITER MAST-U simulations

J.E. Bryant[1], K. McKay[1], J.R. Harrison[2], K. Verhaegh[2], D. Moulton[2], D. Wünderlich[3], U. Fantz[3]

[1]Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool L69 3GJ.
[2]Culham Centre for Fusion Energy, Culham Science Centre, Abingdon OX14 3EB.
[3]Max-Planck-Institut für Plasmaphysik, Garching, Germany, 85748

Contemporary work suggests that the vibrational distribution of H_2 may have a strong impact on detachment evolution. SOLPS-ITER simulations mainly utilise the AMJUEL database for its rate data. AMJUEL contains effective rates for H_2 that average over an assumed distribution of vibrational states. H2VIBR contains individual rates for each of the vibrational states of H_2. These databases are believed to be outdated [1]. Therefore, a new vibrationally-resolved database based on rates calculated by the Yacora ODE solver will be created. Simulations utilising the Yacora database (H2YAC) and tracking individual vibrational states will be compared with similar simulations utilising H2VIBR and standard simulations utilising AMJUEL and tracking the ground state only, as well as with MAST-U experimental data.

Verhaegh defines detachment in four phases [2]. The first is the detachment of the ionisation front from the target, increasing the molecular density in this region. This increases plasma-molecular interactions (PMI) in the region such as molecular-activated recombination (MAR) and molecular-activated dissociation (MAD), resulting in excited atoms and greater Balmer emissions. In the second phase the MAR region detaches from the target leaving a cold region behind. Thirdly, strong emission via eletron-ion recombination (EIR) occurs. Finally resulting in a decay of the n_e near the target. The creation of molecular ions below $T_e = 5eV$ requires the presence of H_2 excited to high vibrational levels [3]. Therefore, the vibrational distribution of H_2 has a strong impact on PMI, and subsequently on MAR. This increased neutral density may lead to further plasma-neutral interactions, enhancing detachment further [4].

Work by Holm utilises a 0D EIRENE setup to explore the differences between AMJUEL and H2VIBR [5]. Holm observes a 25-65% decrease in the dissociation rate from the AMJUEL case to the H2VIBR case. This indicates a reduction of momentum losses from plasma-neutral friction and radiative losses. From the nature of the simulation setup, transport effects and plasma-neutral interactions were excluded from Holm's investigation. Modifying this approach for this investigation in SOLPS-ITER will include these effects, in addition to providing a route to compare detachment evolution between H2YAC, H2VIBR and AMJUEL simulations.

The collisional-radiative model (CRM) used to calculate the AMJUEL and H2VIBR rate data is no longer in use. Yacora will be used as a replacement CRM to form the H2YAC database. Yacora is a flexible solver for sets of coupled ordinary differential equations, and as such can be used to form a CRM and evaluate rate and cross-section data. This provides up-to-date rates including the missing off-diagonal transitions, depletion of H_2 via electronic excitation, and de-excitation of H_2 via heavy particle collisions (quenching) [6] not seen in H2VIBR. The Yacora team has used this tool to approximate low-temperature plasmas that contain H, He, and H_2. This results in a highly accurate model that produces data close to experimental equivalent [7]. Implementing a Yacora based database into SOLPS-ITER MAST-U simulations, should provide the missing transport, plasma-surface interactions, and plasma-neutral interactions not found in Holm's work. The inclusion of the Yacora rates should alter the population of higher vibrational states of H_2. Each population density is believed to increase by an order of magnitude [5]. This may result in an increased amount of MAR in simulations.

MAST-U's diagnostics can be utilised to compare with these simulations. Verhaegh utilises a synthetic diagnostic of MAST-U's DMS to compare SOLPS-ITER simulations with experiment [2], this can be used in this investigation. Synthetic diagnostics for MAST-U's MWI, bolometry systems, and langmuir probes will be made for verification.

References

[1] R. Chandra, A. Holm, and M. Groth. Impact of vibrationally and electronically excited H2 on the molecular assisted recombination rate in detached plasma regimes. *Nuclear Materials and Energy*, 34:101360, 3 2023.

[2] K.Verhaegh. Spectroscopic investigations of detachment on the MAST Upgrade Super-X divertor. *Arxiv*, pages 1–35, 4 2022.

[3] R K Janev and Detlev Reiter. Isotope Effects in Molecule Assisted Recombination and Dissociation in Divertor Plasmas. *Berichte des Forschungszentrums Jülich*, 'Juel-4411, 2018.

[4] Akira Ichihara, Osamu Iwamoto, and R K Janev. Cross sections for the reaction H+ + H2 (v = 0-14) H + H2+at low collision energies. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 33(21):4747–4758, 11 2000.

[5] Andreas Holm, Dirk Wünderlich, Mathias Groth, and Petra Börner. Impact of vibrationally resolved H2 on particle balance in Eirene simulations. *Contributions to Plasma Physics*, 2022.

[6] Dirk Wünderlich, Ursel Fantz, Bastiaan J Braams, Xavier Urbain, Detlev Reiter, and Viatcheslav Kokoouline. Evaluation of State-Resolved Reaction Probabilities and Their Application in Population Models for He, H, and H2. *Atoms 2016, Vol. 4, Page 26*, 4(4):26, 9 2016.

[7] D. Wünderlich, M. Giacomin, R. Ritz, and U. Fantz. Yacora on the Web: Online collisional radiative models for plasmas containing H, H2 or He. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 240, 1 2020.

High resolution Fulcher band analysis of rotational and vibrational distributions of D_2 molecules in the MAST-U and TCV divertors

N. Osborne[1], K. Verhaegh[2], M.D. Bowden[1], L. Martinelli[3], H. Reimerdes[3], C. Theiler[3], the MAST-U and TCV teams

[1] *University of Liverpool, UK*

[2] *Culham Centre for Fusion Energy, Culham, United Kingdom*

[3] *Swiss Plasma Center, Lausanne, Switzerland*

In reactor scale fusion devices such as DEMO, the divertor plates must be protected from intolerable heat loads. “Detaching" the plasma from the divertor plates and thus reducing the momentum, energy and particle flux reaching the target surfaces is key to this task, and it is increasingly clear that plasma-molecule interactions play an important part in this process [1].

The Fulcher band is a band of visible lines between 590 nm and 640 nm generated by de-excitations of excited states of the hydrogen molecule from $d^3\Pi_u^- \rightarrow a^3\Sigma_g^+$ and can be prominent in D_2 divertor plasmas. While overall Fulcher band emission can give important information regarding the position of the ionisation front and divertor temperature [1], high resolution data can provide information about the rotational and vibrational distributions of the molecules; and plasma-molecular chemistry reactions are sensitive to the vibrational distribution [2].

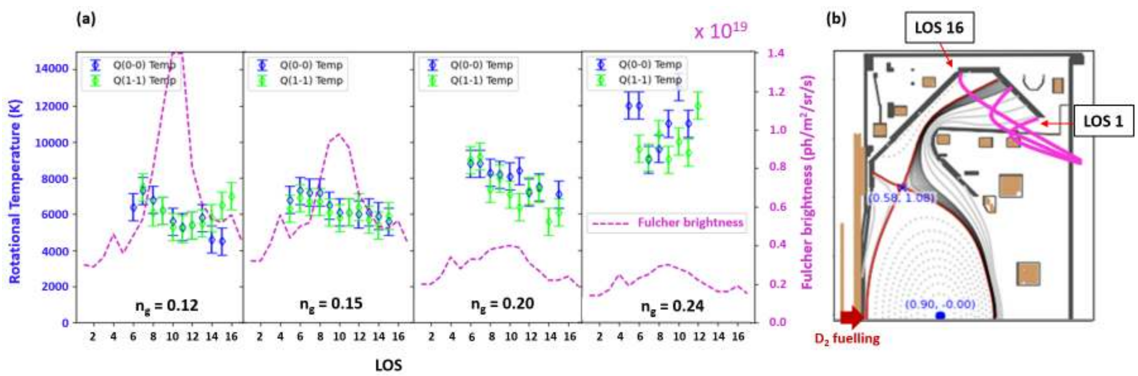


Figure 1: (a) *The evolution of the rotational temperature and Fulcher brightness in a MAST-U Super-X density ramp. n_g is the Greenwald fraction. Q(0-0) and Q(1-1) refer to the Q-branch transitions preserving vibrational quantum number.* (b) *The equilibrium and the lines of sight (LOS).*

The rotational & vibrational distribution in the MAST-U and TCV divertor has been analysed at a range of different divertor densities. Figure 1 shows an example where increasing rotational temperature is observed as the divertor detaches more deeply in the MAST-U Super-X divertor. Characterising rotational and vibrational distributions may also provide further insight into processes occurring in the divertor, which has important implications for plasma-edge modelling.

[1] Verhaegh, K et al, Nuc. Fus. **63**, 016014 (2022) [2] Laporta, V et al, Pl. Phys. Control. Fus. **63**, 085006 (2021)

Measuring Ion Temperatures in the MAST-U divertor

Y. Damizia[1,2], S. Elmore[2], J. W. Bradley[1], P. Ryan[2], S. Allan[2], K. Verhaegh[2] and the MAST-U Team[2]

[1]University of Liverpool, Liverpool, L69 3GJ, UK.

[2]UKAEA, Culham Science Centre, Abingdon, OX14 3DB.

This research project is focused on investigating the characteristics of ions in the MAST-U divertor plasma using a Retarding Field Energy Analyzer (RFEA). The diagnostic, which was originally employed on MAST, will aid in gaining a deeper understanding of the edge plasma physics of ions reaching divertor surfaces in MAST-U. The study will compare the measurement of ion temperature and energies in a conventional divertor leg configuration to the super-X divertor configuration on MAST-U[1].

To improve the measurement capabilities of the RFEA, the probe design has been upgraded and inserted into the Divertor Science Facility (DSF) of MAST-U. A new data analysis tool, written in Python, has also been developed to analyse the data. Measurements during the third experimental campaign on MAST-U will be taken using a scenario developed in the previous campaign, which shifts the strike point to the location of the DSF, see figure (1,2). This will enable the study of a variety of plasma scenarios, including L-mode attached to detached conditions and H-mode with ELMs. This will also build on the measurements made with the Langmuir Probe (LP) DSF probe head of T_e in the last campaign. allowing for comparison and analysis of the T_i/T_e ratio, which is commonly assumed to be equal, but is strictly dependent on the regime and collisionality in the SOL [2]. The measurement results obtained through the utilization of LP DSF during the recent MAST-U experimental campaign have revealed an electron temperature (T_e) in the range of 10-20 eV.

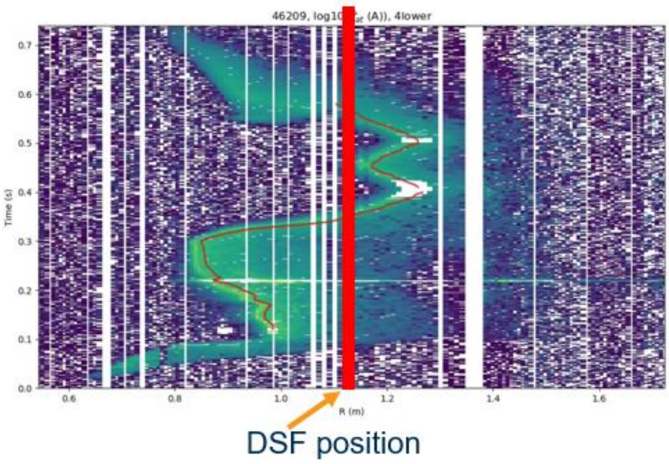


Figure 1: Sweep of the strike point from the LP system.

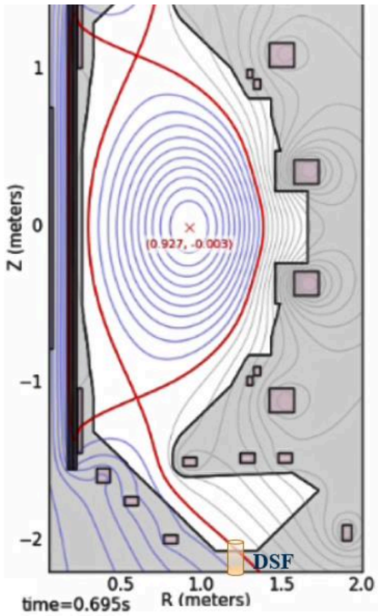


Figure 2: Cross section of magnetic equilibrium with location of DSF in T4.

[1] Fil, Alexandre, et al. "Comparison between MAST-U conventional and Super-X configurations through SOLPS-ITER modelling." Nuclear Fusion 62.9 (2022): 096026.

[2] Elmore, S., et al. "Upstream and divertor ion temperature measurements on MAST by retarding field energy analyser." Plasma physics and controlled fusion 54.6 (2012): 065001.

Scale invariance and critical balance in electrostatic drift-kinetic turbulence

T. Adkins [1], P. G. Ivanov[1], A. A. Schekochihin[1,2]

[1] *Rudolf Peierls Centre for Theoretical Physics, Oxford University, Oxford, OX1 3PU, United Kingdom*

[2] *Merton College, Oxford, OX1 4JD, United Kingdom*

The equations of electrostatic drift kinetics are observed to possess a symmetry associated with their intrinsic scale invariance. Under the assumptions of spatial periodicity, stationarity, and locality, the symmetry implies a particular scaling of the turbulent heat flux with parallel system size. This macroscopic transport prediction is then confirmed numerically in the context of a reduced model of electron-temperature gradient driven turbulence. The system realises this scaling through a constant-flux, critically-balanced cascade from large to small perpendicular spatial scales, mediated by the presence of significant parallel dissipation through thermal conduction. The outer scale of the turbulence, on which the heat flux depends, is determined by the breaking of drift kinetic scale invariance due to the existence of some large-scale parallel inhomogeneity (e.g., the parallel system size), demonstrating that the largest scales play a significant role in determining the turbulent transport properties of the plasma.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under Grant Agreement No. 633053, and from the UKRI Energy Programme (EP/T012250/1). The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) [EP/R034737/1]. TA was supported by a UK EPSRC studentship. The work of AAS was supported in part by grants from STFC (ST/W000903/1) and EPSRC (EP/R034737/1), as well as by the Simons Foundation via a Simons investigator award.

Structure formation in plasma turbulence with an imposed flow shear

P. G. Ivanov[1], M. Barnes[1], A. A. Schekochihin[1]

[1] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, OX1 3PU, UK*

Gyrokinetic simulations of subcritical ion-scale turbulence have shown that, in the presence of background flow shear, the near-marginal saturated state is dominated by spatially localised, long-lived structures [1, 2]. Similar ‘ferdinons’ (see fig. 1) were later found in much simpler cold-ion fluid models of the Dimits transition in ion-temperature-gradient-driven turbulence [3, 4]. Additionally, beam-emission-spectroscopy measurements of MAST plasma have provided experimental evidence for the existence of radially travelling, long-lived, large-amplitude perturbations near the plasma edge that are consistent with the numerically observed ferdinons [5]. Here, we present a comprehensive study of the properties of these structures in the reduced fluid model [3, 4]. In the presence of steady mean flow shear, they have an infinite lifetime (in a periodic domain) and quasi-steady shape and amplitude. They are vortex dipoles in the perturbed $E \times B$ flow, and their instantaneous radial velocity is consistent with a balance of nonlinear advection and linear energy injection.

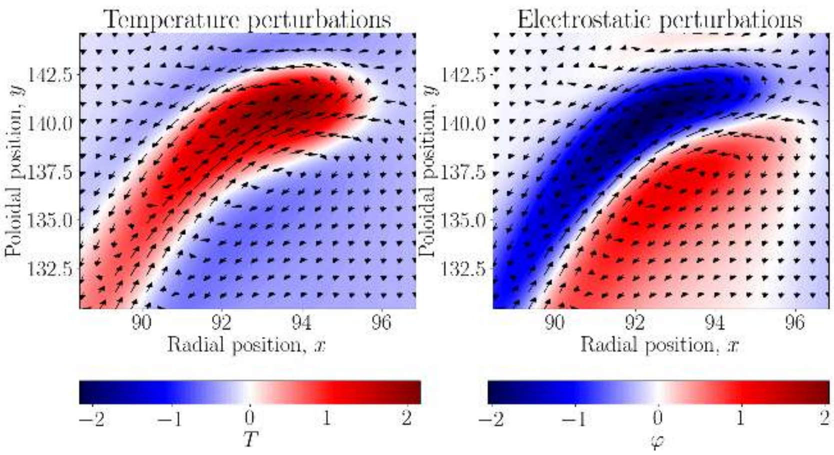


Figure 1: A ‘hot’ ferdinon moving radially outwards (to the right in these coordinates) in a background poloidal flow of positive flow shear. The arrows show the local perturbed $E \times B$ flow. Taken from [3].

References

[1] F. van Wyk *et al.*, J. Plasma Phys. **82**, 905820609 (2016)
[2] F. van Wyk *et al.*, Plasma Phys. Control. Fusion **59**, 114003 (2017)
[3] P. G. Ivanov *et al.*, J. Plasma Phys. **86**, 855860502 (2020)
[4] P. G. Ivanov *et al.*, J. Plasma Phys. **88**, 905880506 (2022)
[5] A. Sladkomedova *et al.*, *in preparation* (2023)

On the role of deeply sub-Alfvénic energetic ions in generating ion cyclotron emission from fusion and laboratory plasmas

O Samant[1], R O Dendy[1], S C Chapman[1,2] and A Zalzali[3]

[1]*Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry CV4 7AL, U.K.*

[2]*Department of Mathematics and Statistics, University of Tromsø, Norway*

[3]*General Atomics, P.O. Box 85608, San Diego, CA 92186-5608, U.S.A.*

Ion cyclotron emission (ICE) is widely observed from toroidal magnetically confined fusion (MCF) plasmas in both tokamaks and stellarators, and from cylindrical plasmas in the LAPD facility. ICE is generated by the collective relaxation of non-Maxwellian energetic ion populations, notably by fusion-born protons in deuterium plasmas and alpha-particles in deuterium-tritium plasmas, and by neutral beam injected (NBI) ions. ICE is excited under conditions where the deviation of the energetic ions from a Maxwellian velocity-space distribution is both substantial and spatially localised. This results in the characteristically well-defined spectral structure of ICE, with narrow-band peaks at local cyclotron harmonics. The ICE spectrum depends both on local plasma conditions and on the velocity-space distribution, where a key parameter is the ratio of the perpendicular and parallel components of energetic ion velocity to the Alfvén speed. The magnetoacoustic cyclotron instability (MCI) drives ICE, and diagnostic exploitation of ICE is assisted by simulations of the fully nonlinear MCI from first principles. Here we report such simulations for conditions relevant to deeply sub-Alfvénic NBI ions in the W-7X stellarator and in LAPD. These simulations, which use the particle-in-cell (PIC) kinetic code EPOCH to self-consistently solve the Lorentz force equation and Maxwell's equations for tens of millions of gyro-motion-resolved ions, together with electrons, are computationally expensive. Recent simulations of other plasmas in this regime have enabled the identification of ICE from fusion-born proton populations in pure deuterium plasmas in the LHD heliotron-stellarator (B Reman *et al.* 2022 *Plasma Phys. Control. Fusion* **64** 085008). The sub-Alfvénic MCI also gave rise to ICE from NBI ions in DT plasmas in the TFTR tokamak, investigated analytically (R O Dendy *et al*. 1994, Phys. Plasmas **1** 3407). Our new simulations address the electrostatic versus electromagnetic character of ICE in this regime; the relation between the MCI and, at higher frequencies, the lower hybrid drift instability; the role of parallel versus perpendicular components of energetic ion velocity; and the likely observational signatures of these effects in ICE driven by NBI ions in W-7X and LAPD.

This work was carried out within the framework of the HPC Midlands Plus partnership.

The consequences of varying tritium mix for simulated ion cyclotron emission spectra from deuterium-tritium plasmas

T W Slade-Harajda[1], R O Dendy[1] and S C Chapman[1,2]

[1]*Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry CV4 7AL, UK*

[2]*Department of Mathematics and Statistics, University of Tromsø, Norway*

Measurements of ion cyclotron emission (ICE) from magnetically confined fusion (MCF) plasmas are helpful for understanding the physics of energetic ion populations therein. ICE is studied in most large MCF experiments, and may be used in future to measure properties of the fusion-born alpha-particle population in deuterium-tritium (DT) plasmas in ITER. Diagnostic exploitation of ICE is assisted by high fidelity simulations from first principles, using the particle-in-cell (PIC) kinetic code EPOCH which self-consistently solves the Lorentz force equation and Maxwell's equations for tens of millions of computational ions and electrons. EPOCH fully resolves gyromotion and hence captures the cyclotron resonant phenomenology which underlies ICE. This has approach has enabled the recent identification of ICE from fusion-born proton populations in pure deuterium plasmas in the KSTAR tokamak (B Chapman *et al.* 2017 *Nucl. Fusion* **57** 124004) and LHD heliotron-stellarator (B Reman *et al.* 2022 *Plasma Phys. Control. Fusion* **64** 085008), and previous analysis of ICE from fusion-born alpha-particles in JET DT plasmas (J Cook *et al.* 2013 *Plasma Phys. Control. Fusion* **55** 065003; L Carbajal *et al.* 2014 *Phys. Plasmas* **21** 012106). In all these cases, ICE is driven by an energetic, spatially localised, strongly non-Maxwellian ion population relaxing under the magnetoacoustic cyclotron instability (MCI). Here, for the first time, we incorporate a population of thermal tritons in addition to deuterons in EPOCH simulations of ICE relevant to MCF DT plasmas. Physically, the tritium population may support additional cyclotron harmonic waves; and tritons may also participate in wave-particle cyclotron resonant interactions involving thermal deuterons and the alpha-particles driving ICE, particularly at frequencies where deuteron and triton cyclotron harmonics are degenerate. The presence of tritons also reduces the local Alfvén velocity (a key parameter for ICE) with respect to otherwise similar pure deuterium plasmas. We examine how the simulated ICE spectra vary with tritium concentration, focusing on trace (1%), JET 26148 (11%), and future ITER (50%) cases, which have only recently become computationally affordable. We quantify the resulting variation in the distribution of ICE spectral peak intensities with tritium concentration. This is noticeable, and therefore important for the development of ICE diagnostics for future DT plasmas; nevertheless, simulations involving only thermal deuterons remain a good overall guide. Our conclusions are reinforced by analysis of the time-evolution of kinetic and field energy densities in the simulations, together with bicoherence analysis of the nonlinear interactions which couple energy flow between different cyclotron harmonics.

This work received support from the RCUK Energy Programme grant no. EP/T012250/1 and was carried out within the framework of the HPC Midlands+ partnership.

The skeleton of periodic orbits illuminates the transition to tokamak turbulence

Ben F. McMillan[1], Oliver J. Smith[2], Chris C.T. Pringle[3]

[1,2] *CFSA, Dept. of Physics, University of Warwick, UK*

[3] *AMRC, Coventry University, UK*

As the Reynolds number increases in Taylor-Couette flow, increasingly complex structures form as the system develops an initial instability, which nonlinearly saturates as a periodic array of rolls, which, at stronger forcing, become subject to further instabilities and eventually transitions to unsteady motion and fully developed turbulence. This provides a way to understand the transition to turbulence in this system, but developing this kind of framework in general requires a method for finding nonlinear solutions and determining their stability; otherwise, one is restricted to investigating highly symmetrical states like zonal flows, and instabilities that emerge from the laminar (equilibrium) state. Relatively recently, tools for direct numerical solution for stationary states, periodic orbits, and relative periodic orbits (which are periodic modulo some symmetry) have been applied in fluid mechanics to illustrate the role of these states in the transition to turbulence. This has been particularly useful for understanding subcritical turbulence in, e.g., pipe flows. We apply a tool for direct discovery of relative periodic orbits to a simple toy model for tokamak turbulence, illustrating how the propagating *avalanche-like* state found in the edge of chaos is directly connected to the stable travelling-wave observed in initial-value simulations, and how Hopf bifurcations arise leading to increasingly complex time-dependence as the system transitions to turbulence. Similarly, the edge-of-chaos state in a gyrokinetic simulation of ITG turbulence with a background shear flow is also found to connect to a propagating travelling-wave state, which also undergoes Hopf bifurcations as the system transitions to turbulence. In each case, the exact nonlinear solutions provide a framework, or skeleton, around which the turbulent state is organised. Rather than a set of weakly interacting plane waves, the key active agents in the transition-to-turbulence are the relative periodic orbits, which are manifest in direct simulation as propagating bursts, and from which fully developed turbulence unfurls.

Proton-recoil spectrometer for fast neutron spectrum based on GEM gas detector

M. Scholz[1]*, U. Wiącek[1], K. Drozdowicz[1], A. Jardin[1], U. Woźnicka[1], A Kurowski[1], A. Kulińska[1], W. Dąbrowski[2], B. Łach[2], D. Mazon[3]

1Institute of Nuclear Physics Polish Academy of Science, Kraków, Poland
[2]AGH University of Science and Technology Faculty of Physics and Applied Computer Science, Kraków, Poland
3CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
*Corresponding author: marek.scholz@ifj.edu.pl

A proton-recoil spectrometer has been designed to measure fast neutron energy spectra in the wide energy range up to 15 MeV. The principal feature of this spectrometer is its ability to operate reliably with the source-end of its collimator in high gamma fields. Such operation is made possible by the use of Gas Electron Multiplier detector and by the techniques used to reduce background. This type of spectrometer can be successfully used to measure the spectrum of neutrons emitted from the fusion plasma core, taking into account various plasma heating scenarios. The spectrum measured in this way allows to determine important plasma parameters, such as: ion temperature, fuel ratio and/or plasma rotation.

The concept and principle of operation of the innovative TPR neutron spectrometer based on GEM technology, intended for future applications of fusion plasma spectrometry, is presented here. Computer simulations of the possible configuration of the detector are presented. In particular, the results of the optimization of the detector geometry, estimation of its overall efficiency and the expected quality of the energy resolution are discussed.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. This work has been published in the framework of the international project cofinanced by the Polish Ministry of Education and Science, as program "PMW", contract no 5235/HEU - EURATOM/2022/2. The foregoing research was supported in part by computing re-sources of PL-Grid Infrastructure (ACC Cyfronet AGH) in Krakow (Poland).

Using X-ray measurements to assess uncertainties in plasma temperature and impurity profiles in tokamaks

A. Jardin[1], K. Król[1], D. Mazon[2], J. Bielecki[1], D. Dworak[1], D. Guibert[2], Y. Peysson[2], M. Scholz[1] and J. Walkowiak[1]

[1] *Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN), PL-31-342, Krakow, Poland.*

[2] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.*

In tokamaks, the local X-ray plasma emissivity is a complex quantity resulting from the contribution of several plasma parameters, i.e. electron temperature, density and concentration of impurities in multiple ionization states. In particular, the impurity core concentration can be estimated from the emissivity in the soft X-ray (SXR) range 0.1 – 20 keV, while information about the superthermal electron population can be obtained in the hard X-ray (HXR) range 20 keV – 200 keV [1]. The estimation of the tungsten concentration profile is subject to many uncertainties, in particular it requires accurate knowledge of plasma temperature, magnetic equilibrium, atomic processes leading to its cooling factor and the spectral response of the diagnostic [2]. A global W concentration can, for example, be inferred with integrated simulation codes in order to match the total radiated power. When all other plasma parameters are well-known, the impurity density profile can be reconstructed in the core with the help of SXR tomographic tools [3]. Nevertheless, in the case of a significant fraction of superthermal electrons e.g. due to RF heating, accurate estimation of electron temperature from ECE measurements can become a challenging task [4].

Therefore, the goal of this contribution is to establish a methodology to assess the uncertainty in the core electron temperature and impurity concentration profiles based on X-ray measurements. The proposed strategy is to define a grid of candidates (T_e, c_W) scenarios and identify the ones having the highest consistency with respect to multiple line-integrated measurements. In order to determine the capabilities and limitations of such an approach, the method is first tested on well-known synthetic profiles in an arbitrary tokamak geometry. In a second step, first experimental tests are presented for some selected WEST discharges.

References. [1] D. Mazon, et al (2022) JINST 17 C01073. [2] T. Pütterich et al (2010) Nucl. Fusion 50 025012. [3] A. Jardin et al (2021) Eur. Phys. J. Plus 136:706. [4] P. V. Subhash et al (2017) Fusion Sci. Technol. 72 49–59.

Acknowledgements. *This work has been partially funded by the National Science Centre, Poland (NCN) grant HARMONIA 10 no. 2018/30/M/ST2/00799. We gratefully acknowledge Poland's high-performance computing infrastructure PLGrid (HPC Centers: ACK Cyfronet AGH) for providing computer facilities and support within computational grant no. PLG/2022/015994. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.*

Influence of impurity radiation loss on the L-H transition power threshold

E. Pawelec[1], W. Gromelski[2], A. Chomiczewska[2], E. R. Solano[3], G. Birkenmeier[4,5], P. Carvalho[6], M. Chernyshova[2], I. S. Carvalho[7], I. Coffey[8], J. Hillesheim[6], P. Jacquet[6], I. Jepu[9], E. Lerche[10], B. Thomas[6], and JET contributors *

[1] Institute of Physics, Opole University, Oleska 48, 45-052 Opole, Poland; [2] Institute of Plasma Physics and Laser Microfusion, Hery 23, 01-497 Warsaw, Poland; [3] Laboratorio Nacional de Fusión, CIEMAT, Avda Complutense 40, 280040 Madrid, Spain; [4] Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany; [5] Physik-Department, Technische Universität München, 85748 Garching, Germany; [6] United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK; [7] Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal; [8] Queens University Belfast, BT71NN, UK; [9] The National Institute for Laser, Plasma and Radiation Physics, Magurele-Bucharest, Romania; [10] Laboratory for Plasma Physics, Koninklijke Militaire School, Ecole Royale Militaire Renaissancelaan

Since the discovery of the high-confinement mode (H-mode) significant work has been devoted to study the conditions for entry to this mode, especially the threshold power (P_{LH}). The threshold power depends on many different parameters, including magnetic field, plasma current and density. One of the important elements of the power balance is the power radiated out from the plasma, in many L-H transition studies directly subtracted from the input power to determine scaling laws ([1], [2], [3]). The possibility of mathematical subtraction does not mean though that this loss can be neglected in reality and in predictions for ITER.

Radiation loss in a tokamak plasma has a very large contribution from mid- and large-Z impurities, which in the case of the JET ITER-Like-Wall (ILW) the are predominantly: tungsten, with sources in the divertor and at different locations on the main-chamber walls, nickel from the RF antennas and copper from the walls of the ports of neutral beam injectors (NBI). In this contribution we present and discuss estimates of the power radiated from different impurities just before successful L-H transitions, how the level of radiated power is influenced by heating system (NBI/RF) and how it depends on isotopic or species plasma composition (H/D/T and He) with some comments on the impurity sources. We show that the total radiation is much stronger in RF heated pulses, where it increases with fuel atomic mass and the main impurity radiators are W and Ni. In the NBI cases, where the predominant impurity is Cu (though some pulses can have also strong W influxes), the isotopic dependence is less clear, with relatively high radiation loss in the light hydrogen case.

To concentrate on the isotope and heating dependencies we use a specific dataset of the L-H transition database (the same as in [3]): B_t = 1.8 T, I_p = 1.7 MA, horizontal target (with outer strike line on an outward tilting tile, almost horizontal, inner strike on a vertical divertor tile).

[1] C. Maggi et al, Nucl. Fusion **54** (2014) 023007 [2] E. R. Solano et al, Nucl. Fusion **62** (2022) 076026 [3] G. Birkenmeier et al, Nucl. Fusion **62** (2022) 086005

* See the author list of Mailloux et al, Nucl. Fusion **62** (2022) 042026

Progress of the PlasmaLab@CTU

J. Brotankova[1], J. Mlynar[1], O. Bares[3], D. Svorc[1], J. Hecko[1], V. Svoboda[1], D. Mazur[1]

[1] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic*

PlasmaLab@CTU [1] is a laboratory focused on the fusion diagnostics methods. It reflects the importance of practical classes in the thermonuclear fusion technology, necessary for education of skilled experimentalists, both physicists and engineers. The laboratory was established in between 2017 and 2022 at the Czech Technical University in Prague in the scope of the Joint Degree programme with the Gent University [2]. It consists of two parts: one new with three workspaces, and the upgraded GOLEM tokamak [3]. An important feature is the aim of integration of remote education into the curriculum: the GOLEM tokamak is a fully remotely controlled device with long history of remote campaigns, the new part has a high level of remote access, too. The laboratory has been developed in cooperation with the PlasmaLab@TU/e at the Technical University in Eindhoven [4], and the e-lab at the IST Lisbon [5].

The contribution will present the new part of the laboratory and the main achievements so far. Practical classes started already in the start-up phase. Beginning of the full operation is dated to the academic year 2021/2022. Currently, regular classes on Bc and MSc level are running. Two Bc theses were defended, several projects are undergoing or has been finalized.

[1] Website of the plasmalab. URL: https://www.plasmalab.cz (accessed 10 June 2023).

[2] CTU–UGent bilateral joint doctoral programme in high-temperature plasma physics and thermonuclear fusion. URL: https://www.ugent.be/ea/appliedphysics/en/education/ctu-ugent/fusion-bjdp.htm (accessed 10 June 2023).

[3] O. Grover et al., Fusion Eng. Design 112 (2016) 1038-1044.

[4] Website of the PlasmaLab@TU/e. URL: https://www.tue.nl/en/department-of-applied-physics/research/research-groups/science-and-technology-of-nuclear-fusion/fusion-facilities/plasmalabtue.

[5] Website of the e-lab. URL: http://www.elab.tecnico.ulisboa.pt/.

Verification of CGYRO-SAT2 model in the L-mode edge

Arash Ashourvan, G M Staebler

General Atomics, San Diego CA, USA

The gyrokinetic CGYRO-SAT2 model[1] is a 3D model of the saturated potential fluctuation intensity fit to a set of 56 CGYRO turbulence simulations. Using the most unstable linear CGYRO eigenmode spectrum a quasilinear calculation of the fluxes with the SAT2 model yields 10% accuracy for energy fluxes and 19% for particle fluxes compared to the non-linear simulations[2]. In this work we tested the CGYRO-SAT2 model with a new database of 47 nonlinear CGYRO simulations with parameters characteristic of the L-mode edge region. This database includes scans of density, electron and ion temperatures, safety factor, and collisionality, in the edge (r/a=0.9). Quasilinear (QL) fluxes of particle $\boldsymbol{\Gamma}$, electron energy (Q_e) and ion energy (Q_i), and also QL error[2] $\boldsymbol{\sigma}_{WQi}$ are calculated for the database. The latter measures the validity of application of QL theory. We find that while the QL calculated Q_e is generally in good agreement with nonlinear CGYRO, for cases in the plasma edge with high safety factor, collisionality or electron temperature inverse gradient scale-length, Q_i and $\boldsymbol{\Gamma}$ are underpredicted. In these cases, $\boldsymbol{\sigma}_{WQi}$ is significantly higher. A theory is presented to shed light on this shortcoming of QL theory. Species dependent, unitless ratios, similar to Kubo number (K_e, K_i) are defined to quantify the different turbulence strength as felt by each species. These Kubo numbers take into account collisionality, and 3D geometry of turbulence in tokamak. For the electrons it is found that generally $K_e \ll 1$ due to short electron transit time and higher collisionality in the edge. For ions, in the edge, for the cases with high $\boldsymbol{\sigma}_{WQi}$ it is generally found that $K_i \sim 1$. This may imply departure form QL theory due to stronger turbulence.

Work supported by US DOE under DE-FG02-95ER54309

[1] G Staebler *et al* Plasma Phys. Control. Fusion **63** (2021) 015013
[2] G Staebler *et al* Nucl. Fusion **61** (2021) 116007

IDENTICAL DECELERATING WAKEFIELDS FOR DRIVER-BUNCHES AND IDENTICAL ACCELERATING WAKEFIELDS FOR WITNESS-BUNCHES FOR THEIR PERIODIC SEQUENCE

I.V. Demydenko[1], V.I. Maslov[1]

[1] *V.N.Karazin Kharkiv National University, Kharkiv, Ukraine*

Acceleration by the wakefield in the plasma can provide compact sources of relativistic electron beams of high brightness. Free electron lasers and particle colliders, using plasma wakefield accelerators, require high efficiency and beams with low energy dispersion. Achieving both conditions can be ensured by the formation of identical fields for all accelerating bunches and identical fields for all decelerating bunches by controlled selection of bunch currents and their spatial distribution for a given plasma wave [1-4]. We demonstrate such optimal bunch currents and their spatial distribution in the linear regime in a plasma accelerator with wakefield excited by electron bunches injected from the RF accelerator with high quality.

1. Katsouleas T. et al. Particle Accelerators. 22 (1987) 81.
2. Tzoufras M. et al. Phys. Rev. Lett. 101 (2008) 145002.
3. Romeo S., Ferrario M., Rossi A.R. Phys. Rev. Accel. Beams. 23 (2020) 071301.
4. Maslov V.I. et al. Problems of Atomic Science and Technology. 6 (2020) 47.

Undepleted Direct Laser Acceleration

I. Cohen[1,2], T. Meir[1,2], K. Tangtartharakul[3], L. Perelmutter[1,4], M. Elkind[1,2], Y. Gershuni[1,2], A. Levanon[1,2], A.V. Arefiev[3], I. Pomerantz[1,2]

1. *The School of Physics and Astronomy, Tel Aviv University, Tel-Aviv, 6997801, Israel*
2. *The Center for Light-Matter Interaction, Tel Aviv University, Tel-Aviv, 6997801, Israel*
3. *Department of Mechanical and Aerospace Engineering, University of California San Diego, La Jolla, 92093, CA, USA*
4. *Department of Applied Physics, Soreq NRC, Yavne, 81800, Israel*

For the past two decades, intense lasers have supported new schemes for generating high-energy particle beams in university-scale laboratories. With the direct laser acceleration (DLA) method, the leading part of the laser pulse ionizes the target material and forms a positively charged ion plasma channel into which electrons are injected and accelerated. DLA has been realized over a wide range of laser parameters, using low-atomic-number target materials. A striking result is the extremely high conversion efficiency from laser energy to MeV electrons, with reported values as high as 23% [6], which makes this mechanism ideal for generating large numbers of photo-nuclear reactions [4]. DLA is well understood and reproduced in numeric simulations. Specifically, the electron beam energy has been confirmed to scale with the normalized laser intensity up to values of $a_0 \sim 1.5$ [2]. However, the electron energies obtained with the highest laser intensities available nowadays [4, 6], fail to meet the prediction of these scaling laws [5]. Here we reveal that at these higher laser intensities, the leading edge of the laser pulse depletes the target material of its ionization electrons prematurely. We demonstrate that for efficient DLA to prevail, a target material of sufficiently high atomic number is required to maintain the injection of ionization electrons at the peak intensity of the pulse when the DLA channel is already formed. Applying this new understanding to experiments on multi-petawatt laser facilities now coming online is expected to increase the electron energy overlap with the neutron production cross-sections of any material. These increased neutron yields are required to enable a wide range of research and applications, such as investigation of nucleosynthesis in the laboratory [1], performing non-destructive material analysis [7], and industrial applications [3].

References

[1] S. N. Chen, F. Negoita, K. Spohr, E. D'Humières, I. Pomerantz, and J. Fuchs. Extreme brightness laser-based neutron pulses as a pathway for investigating nucleosynthesis in the laboratory. *Matter and Radiation at Extremes*, 4(5):054402, sep 2019.

[2] C. Gahn, G. D. Tsakiris, G. Pretzler, K. J. Witte, P. Thirolf, D. Habs, C. Delfin, and C. G. Wahlström. Generation of MeV electrons and positrons with femtosecond pulses from a table-top laser system. *Physics of Plasmas*, 9(3):987, 2002.

[3] Christian Grünzweig, David Mannes, Anders Kaestner, Florian Schmid, Peter Vontobel, Jan Hovind, Stefan Hartmann, Steven Peetermans, and Eberhard Lehmann. Progress in Industrial Applications using Modern Neutron Imaging Techniques. *Physics Procedia*, 43:231–242, jan 2013.

[4] I. Pomerantz, E. McCary, A. R. Meadows, A. Arefiev, A. C. Bernstein, C. Chester, J. Cortez, M. E. Donovan, G. Dyer, E. W. Gaul, D. Hamilton, D. Kuk, A. C. Lestrade, C. Wang, T. Ditmire, and B. M. Hegelich. Ultrashort pulsed neutron source. *Physical Review Letters*, 113(18):1–6, 2014.

[5] A. Pukhov, Z. M. Sheng, and J. Meyer-ter Vehn. Particle acceleration in relativistic laser channels. *Physics of Plasmas*, 6(7):2847–2854, 1999.

[6] Olga Rosmej, Mikhail Gyrdymov, Marc M Günther, Nikolay E Andreev, Parysatis M Tavana, Paul Neumayer, Sero Jakob Zähter, Nadiya Zahn, Viacheslav S Popov, Nataliya Borisenko, Alexey Kantsyrev, Aleksey Skobliakov, Vsevolod Panyushkin, Anton Bogdanov, Fabrizio Consoli, Xiaofei F Shen, and Alexander Pukhov. High-current laser-driven beams of relativistic electrons for high energy density research. *Plasma Physics and Controlled Fusion*, aug 2020.

[7] Marc Zimmer, Stefan Scheuren, Annika Kleinschmidt, Nikodem Mitura, Alexandra Tebartz, Gabriel Schaumann, Torsten Abel, Tina Ebert, Markus Hesse, Sêro Zäahter, Sven C. Vogel, Oliver Merle, Rolf Jürgen Ahlers, Serge Duarte Pinto, Maximilian Peschke, Thorsten Kröll, Vincent Bagnoud, Christian Rödel, and Markus Roth. Demonstration of non-destructive and isotope-sensitive material analysis using a short-pulsed laser-driven epi-thermal neutron source. *Nature Communications 2022 13:1*, 13(1):1–11, mar 2022.

PIC simulations of on-axis injection dynamics of charged particle bunches propagating through a low-density plasma ramp in a PWFA

P. I. Morales Guzman, J. Farmer, P. Muggli

Max Planck Institute for Physics, Munich, Germany

A long relativistic proton bunch that has undergone self-modulation [1] can drive high-amplitude wakefields to accelerate charged particle bunches [2, 3]. Before the entrance to the long plasma in which the bunches propagate, there is a ramp [4, 5]. One meter before the plasma entrance, the plasma density in the ramp is five orders of magnitude lower than in the long plasma and three orders of magnitude lower than that of the bunch. The non-linear response of the plasma is to create a high-density electron filament on the proton bunch propagation axis [6, 7].

We present here numerical simulation results obtained with LCODE [8] and QV3D [9] with parameters based on experiments at AWAKE. Simulations results in 3D confirm those using 2D axisymmetric geometry. We show that the fields sustained by the filament are detrimental for acceleration of an electron or positron bunch injected on axis through the ramp. We further show that self-modulation seeding from within the proton bunch is possible with positron bunches, but not with electron bunches.

References

[1] N. Kumar et al., PRL 104, 255003 (2010)
[2] A. Caldwell et al. (AWAKE Collaboration), NIM A, 829 3-16 (2016)
[3] AWAKE Collaboration, Nature 561, 363–367 (2018)
[4] G. Plyushchev et al., J. Phys. D: Appl. Phys., 51 025203 (2018)
[5] G. D. Danilatos, AIP Conference Proceedings., 585 (2001)
[6] M. J. Hogan et al., Phys. Rev. Lett. 90, 205002 (2003)
[7] A. Gorn et al., Physics of Plasmas 25, 063108 (2018)
[8] K. V. Lotov, PRAB 6, 061301 (2003)
[9] A. Pukhov, CERN Yellow Reports 181 (2016)

Laser polarization control of ionization-injected electron beams in LWFA

Arghya Mukherjee[1,2], Daniel Seipt[1,2]

[1] *Helmholtz Institute Jena, Fröbelstieg 3, 07743, Jena, Germany*

[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany*

We present a detailed investigation of the dynamics of LWFA electron beams generated by the optical ionization-injection of a high-Z gas doped in a plasma background [1], with an emphasis on the influence of the laser polarization on the beam properties. This study has been performed using full 3D particle-in-cell (PIC) simulations with the code SMILEI [2] using a variety of dopant gas species. Depending on the polarization state of the laser, the injected electrons transverse phase space distributions are modified due to a nonzero transverse momentum gain via above threshold ionization (ATI), which does also affect the trapped beam charge, beam emittance and its energy spectra [3]. We have further shown that effective injection of good quality beams essentially depends not only on a matching between the laser intensity and the ionization potential of the inner shell electrons in the dopant, but is also polarization dependent. Thus the precise choice of laser polarization state can also be used to control the properties of betatron x-ray radiation emitted from the accelerating electron beams.

[1] A. Pak, K. A. Marsh, S. F. Martins, W. Lu, W. B. Mori, and C. Joshi, Phys. Rev. Lett. **104**, 025003 (2010).

[2] J. Derouillat, A. Beck, F. Pérez, T. Vinci, M. Chiaramello, A. Grassi, M. Flé, G. Bouchard, I. Plotnikov, N. Aunai, J. Dargent, C. Riconda, M. Grech, Comput. Phys. Commun. **222**, 351 (2018).

[3] Y. Ma, D. Seipt, A. E. Hussein, S. Hakimi, N. F. Beier, S. B. Hansen, J. Hinojosa, A. Maksimchuk, J. Nees, K. Krushelnick, A. G. R. Thomas, and F. Dollar, Phys. Plasmas **28**, 063101 (2021).

Simulation and optimization of an X-ray source for non-destructive testing

B. BEL MOUSSA, A. FLACCO, C. THAURY

LOA, CNRS, Ecole Polytechnique, ENSTA Paris, Institut Polytechnique de Paris, 181 Chemin de la Hunière et des Joncherettes, 91120 Palaiseau, France.

An electron beam generated by a laser-plasma accelerator is converted into an X-ray source by means of bremsstrahlung radiation in a dense material. This radiation source can be used to perform non-destructive testing (NDT) of dense objects. Over other NDT techniques, X-ray imaging benefit from a high resolution in terms of defect detection and also in a high penetration in terms of material thickness. The advantages of laser-plasma acceleration for this application are the small source size of the electron beam, the wide range of energies that is generated, and the compacity of the source as well as of the experimental setup compared to conventional acceleration systems.

Nowadays, NDT applications in industry are extremely varied, covering safety, performance and quality control. Our study is to provide X-ray sources capable of performing NDT for defense purposes. Therefore, the main challenge is to maintain a small source size when the electrons beam is converted to X-rays.

As the variation of one parameter influences the others, a numerical optimization of the whole experiment is essential to ensure the optimal balance between the source parameters, and, the resolution and penetration depth, for a given application. There are two major parts to deal with, the laser-matter interaction for which we use a Particle-In-Cell code, and the X-ray emission part for which we use a Monte Carlo code. In this talk we will discuss our recent approaches for tackling the limitations of NDT for dense objects : increasing the energy of the source and reducing its size.

Bibliographie

[1] J. Faure, Accélération de particules par interaction laser-plasma dans le régime relativiste, Mémoire HDR (2009).

[2] A. Ben-Ismaïl, et al., Compact and high-quality gamma-ray source applied to 10 μm-range resolution radiography, Appl. Phys. Lett. 98, 264101 (2011).

Laser Interactions with Gaseous Targets: Nozzle Damage and Generation of Electromagnetic Pulses

P. Bradford[1], M. Ehret[2], J.-L. Henares[2], P. Puyuelo-Valdes[2], V. Ospina-Bohórquez[1], C. Vlachos[1], G. Hicks[3], C. Verona[4], M. Sciscio[5], J. J. Santos[1], F. Consoli[5] and V. Tikhonchuk[1,6]

[1] *Université de Bordeaux-CNRS-CEA, Centre Lasers Intenses et Applications (CELIA), Talence, France*

[2] *Centro de Láseres Pulsados, Villamayor, Salamanca, Spain*

[3] *The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK*

[4] *Industrial Engineering Department, University of Rome "Tor Vergata", Rome, Italy*

[5] *ENEA - Fusion and Technologies for Nuclear Safety and Security Department, Frascati, Rome, Italy*

[6] *Extreme Light Infrastructure ERIC, ELI-Beamlines Facility, Dolní Brezany, Czech Republic*

Laser interactions with near-critical density gases are currently being studied as secondary sources of particles and radiation that can accommodate high shot rates without producing debris. Progress in the field is hampered, however, by persistent damage to gas jet nozzles and the emission of broadband electromagnetic pulses (EMPs). Nozzle damage leads to progressively smoother gas density profiles, while gigahertz-frequency EMPs couple to electronic and electromechanical equipment - this reduces the performance of the gas target as a secondary source and moreover makes it difficult to diagnose conditions in the plasma. Despite these obstacles, the physical mechanism of nozzle damage and EMP emission in gas jet targets has not yet been systematically studied.

In this paper, we present a theoretical model of electromagnetic pulse emission from high power laser interactions with gas jets. The laser accelerates a population of suprathermal electrons that are ejected from the laser channel, leaving behind a positively-charged plasma that expands and ionises the ambient gas until it reaches the gas jet nozzle. When an ionised channel is formed between the plasma and the conducting nozzle surface, a discharge current propagates to ground and an electromagnetic pulse is radiated via an antenna emission mechanism. Damage to gas jet nozzles is found to be caused by heating from plasma ions rather than Ohmic heating via a discharge current. Our model appears to be broadly consistent with data from two experiments on the VEGA-3 laser. Other possible emission mechanisms, such as a spark gap discharge, are discussed. We also propose methods for an experimental validation of the model.

Electron beam self-focusing and X-ray radiation in a self-ionized plasma wakefield accelerator

V. Zakharova[1] and the E300 collaboration*

[1] *LOA, Palaiseau, France,* [2] *University of Oslo, Norway,* [3] *SLAC, Menlo Park, USA,* [4] *University of Colorado Boulder, USA,* [5] *University of California Los Angeles, USA,* [6] *GoLP, IST, Lisbon, Portugal,* [7] *Stone Brook University, New York, USA*

The upgraded Facility for Advanced Accelerator Experimental Tests (FACET-II) at SLAC has started delivering the first electron beams in 2022 for the initial phase of several experimental campaigns hosted at the facility. The E300 experiment on plasma wakefield acceleration (PWFA) [Joshi *et al.*, PPCF 60, 034001 (2018)] relies on electron and X-ray/γ-ray detectors to measure the beam dynamics and assess its matching in the plasma [San Miguel Claveria *et al.*, PTRSA 377, 20180173 (2019)], with the aim of preserving the beam quality during its acceleration in the plasma, one of the most important milestone for the field of PWFA. For the first physics investigations of plasma wakefield acceleration at FACET-II, the plasma accelerator was operated in a self-ionized hydrogen plasma. The electron beam had a large enough peak current (helped by microbunching instabilities developing in the LINAC) and density to trigger some level of ionization of the H_2 gas. The first observations revealed a very strong beam-plasma interaction over several meters, with the 10 GeV 1.6 nC beam transferring more than half of its energy to the plasma, and with bright betatron X rays being emitted. Dedicated detectors enabled the characterisation of the spatial and spectral distribution of the emitted betatron radiation at different plasma densities, with typical photon energies in the 10-100 keV range. They allowed to infer a beam size in the plasma and a betatron oscillation amplitude of a few μm, thus providing an experimental evidence of the electron beam self-focusing dynamics in the self-ionized plasma, from an initial size of 30 μm down to a few μm. This is confirmed by the comparison with the data taken with the 20 GeV FACET-I beam at higher plasma densities, with betatron radiation reaching the gamma-ray range and photon energies exceeding 10 MeV. We will report on these experimental results highlighting how the characterization of betatron radiation can provide crucial insight into the plasma beam dynamics for PWFA.

*Full list of E300 Collaborators: E. Adli[2], J. Allen[3], R. Ariniello[3], G. Cao[2], J. Cary[4], C. Clarke[3], S. Corde[1], C. Doss[4], H. Ekerfelt[3], C. Emma[3], S. Gessner[3], M. Gilljohann[1], M. Hogan[3], K. Hunt-Stone[4], C. Joshi[5], A. Knetsch[1], V. Lee[4], C. Lindstrom[2], M. Litos[4], K. Marsh[5], A. Matheron[1], W. Mori[5], N. Nambu[5], Z. Nie[5], B. O'Shea[3], P. San Miguel Claveria[1,6], D. Storey[3], N. Vafaei-Najafabadi[7], Y. Wu[5], X. Xu[5], V. Yakimenko[3], J. Yan[7], C. Zhang[5]

Abstract

Signatures of ignition DT fusion gamma reaction history

Hermann Geppert-Kleinrath
Los alamos National Laboratory

Gas Cherenkov Detectors (GCD) measure the DT fusion burn rate on Inertial Confinement Fusion (ICF) experiments (shots) at the National Ignition Facility (NIF). GCD performs energy-thresholded, high bandwidth measurements providing crucial benchmarks for simulations and experiments such as fusion bang time and fusion burn width. The novel Pulse Dilation – PMT (PD-PMT) makes measurements at a temporal resolution of 10 ps possible. This improvement allows for comparing shapes of the DT gamma reaction history to simulation results possible for the first time. Measured fusion gamma reaction histories show clear signatures of the transition into the ignition regime. First results - including a record yield shot at NIF – and performance trends are presented. Improvements in dynamic range will provide additional information relevant to understanding the transition into the ignition regime like hot spot formation and the onset of alpha heating.

Justification

Dr. Hermann Geppert-Kleinrath is a leading expert for Gas Cherenkov Detector (GCD) measurements and pulse dilation technology. His work includes providing gamma reaction histories for Inertial Confinement Fusion (ICF) experiments at the National Ignition Facility (NIF), OMEGA and the Z-machine, including DT fusion burn history measurements and ablator performance, as well as understanding and quantifying signatures from nuclear reactions such as X(n,n')γ reactions. His reaction history data is a crucial metric for performance at high yield experiments in ICF at NIF and a key in proving the transition into the ignition regime. He has authored more than 30 publications with over 600 citations in peer reviewed academic journals. He holds a PhD in physics from Vienna University of Technology.

Opacity measurement of aluminium heated and backlighted by a dynamic hohlraum X-ray source

Qiang Yi, Fan Ye, Shijian Meng, Jian Lu, Xiaosong Yan, Ruihua Yang, Faxin Chen, Dongming Wang, Haibo You, Zeping Xu, Faqiang Zhang, Zhenghong Li, Jianhua Zhang

Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang, 621900, China

After demonstrating the forming of a high-temperature backlight source with a temperature near 180~eV, a further experiment of opacity measurement for aluminum is conducted on China's 8-MA generator. The sample consists of two half moon-like parts, one is CH material used for measuring the unattenuated (tamper only) spectra, and the other part is CH-Al-CH sandwiched material used for measuring attenuated (tamper plus Al) spectra in a same shot. To obtain aluminium's absorption line spectra and consequent opacity, two elliptical bent crystal spectrometers at two symmetric directions are in commission, each using multiple slits to project spatially resolved images onto the concave crystal that disperses the spectrum before recording on imaging plates (IP). Their energy observation range is from ca. 900~eV to 2300~eV. After heating, the sample becomes an intense source of self-emission, measurement of absorption spectra after backlighting is difficult. Much collimation, shielding and scattering X-ray suppression is required in the bent crystal spectrometer design and mounting, which will be emphasized in this paper.

Status of implementing diagnostics at the Laser MegaJoule (LMJ) – PETawatt Aquitaine Laser (PETAL) facility.

E. Alozy[1], G. Boutoux[1,2], T. Caillaud[2], A. Chaleil[1], S. Chardavoine[1,2], C. Chollet[1], L. Chopineau[1], S. Darbon[1], C. De-Boyer-d'Eguilles[2], R. De-Mollerat-Du-Jeu[2], R. Diaz[2], A. Dizière[1], V. Drouet[1], W. Duchastenier[1,2], A. Duval[1], T. Ferraro[1], J.-P. Jadaud[1], T. Jalinaud[1], O. Landoas[1], I. Lantuejoul[1], L. Lehmann[1], C. Meyer[2], G. Soullié[1], M. Sozet[1,2], M. Prat[1], V. Prevot[2], P. Prunet[1,2], C. Reverdin[1], R. Rosch[1], A. Rousseau[1], V. Trauchessec[1], J.-L. Ulmer[1], B. Vauzour[1], B. Villette[1,2], R. Wrobel[1], et al.

[1] CEA, DAM, DIF, F-91297 Arpajon, France
[2] CEA, DAM, CESTA, F-33114 Le Barp, France

We present the status of implementing diagnostics at the Laser MegaJoule (LMJ) – PETawatt Aquitaine Laser (PETAL) facility, with special emphasis on each class of diagnostics:

- X-ray imagers,
- X-ray spectrometers,
- Back-scattered light (Brillouin and Raman) diagnostics,
- EOS diagnostics, such as streaked optical pyrometry (SOP), Velocity Interferometer System for Any Reflector (VISAR) or frequency-shifted Photon Doppler Velocimetry (PDV),
- Neutron diagnostics,
- High-energy particle (ions, electrons, X-ray) diagnostics.

About 20 diagnostics are currently in operation [1]. Developments on existing diagnostics and the design/implementation of future diagnostics will be discussed.

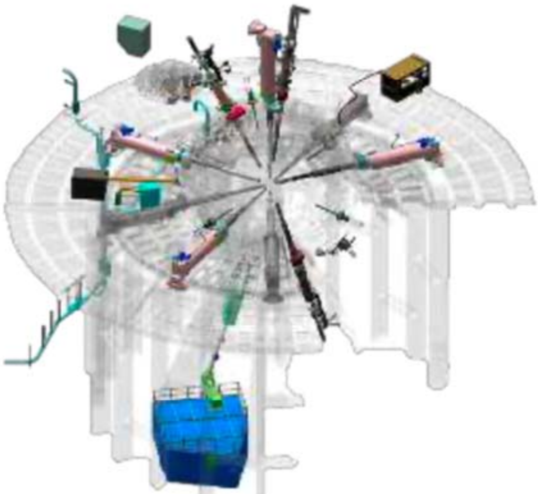


Figure 1: Overview of the LMJ-PETAL diagnostics around the target chamber.

References:

[1] see https://www-lmj.cea.fr/LMJ-PETAL-User-Group.html for more details.

Kinetic modelling of distribution functions and heat-flow

A. Dearling[1], C. Arran[1], M. Read[2], C. P. Ridgers[1], N. C. Woolsey[1]

[1] *York Plasma Institute, University of York, York, UK*

[2] *First Light Fusion, Oxford, UK*

Heat-flow is of fundamental interest in plasmas with extreme temperature gradients. These plasmas can range from those found in laser-plasma experiments, to relativistic jets or tokamak divertors. Transport effects such as heat-flow are fundamentally driven by anisotropy within the distribution function in plasma systems. Magnetic fields affect this anisotropy, thus modifying the heat-flow.

Here we describe how the kinetic modelling of plasmas, using both Vlasov-Fokker-Planck (VFP) and particle-in-cell codes (PIC), can aid in our understanding of plasmas as they are driven away from local thermodynamic equilibrium (LTE). This regime is commonly encountered in high-energy-density systems, such as inertial confinement fusion experiments, where the mean-free-path of heat-carrying electrons can exceed the temperature length scale causing the heat-flow to become non-local. Fluid models, which often assume the anisotropy leads to only a small perturbation away from a Maxwellian distribution, can then fail to accurately describe transport effects far from LTE. This has led to significant discrepancies between simulation and experiment. Magnetic fields in the plasma, which can be self-generated or applied, then add a layer of complexity to the problem by modifying the effective mean-free-path of electrons. This can fundamentally limit non-locality, leading to local transport in plasmas which otherwise appear far from LTE.

First cross beam energy transfer experiment on Shenguang-180 kJ laser facility

Tao Gong[1], Liang Hao[2], Zhichao Li[1], Bo Deng[1], Yaoyuang Liu[1], Hang Zhao[1], Qi Li[1], Yunsong Dong[1], Dong Yang[1], Jiamin Yang[1], Zongqing Zhao[1], Baohan Zhang[1], Shiyang Zou[2], Yongkun Ding[2]

[1]Laser Fusion Research Center, China Academy of Engineering Physics, Mianyang, China

[2]Institute of Applied Physics and Computational Mathematics, Beijing, China

The Shenguang-180 kJ laser facility, which is currently the primary platform for indirect-drive inertial confinement fusion research in China, was upgraded in 2022 to operate at different wavelengths among beams. With this capability, the first cross beam energy transfer (CBET) experiment was carried out recently, by injecting 24 laser beams through a laser entrance hole into a shortened gas-filled hohlraum. Two of the inner beams (28.5° and 35° relative to the hohlraum axis, respectively) hit a gold witness plate after transmitting through the hohlraum. The generated x-ray spots, together with several additional spots produced by calibration beams with known intensities on another neighboring plate, were recorded by an x-ray frame camera, which provided a way to infer the powers of the transmitted inner beams. The results displayed a prominent CBET process as the wavelength difference between the inner and outer beams was increased. A maximum enhancement of ~80% in the peak power of inner beams was recorded, corresponding to an enhancement of ~60% in the x-ray flux of the spot, which was measured by a space-resolving flux detector. These results were favorably reproduced by simulations and would play an important role in subsequent integrated experiments, which suffered a long-standing issue of drive deficit at the hohlraum waist.

Phase Control of Nonlinear Breit-Wheeler Pair Creation

B. Barbosa[1], J. P. Palastro[2], D. Ramsey[2], K. Weichman[2], M. Vranic[1]

[1] *GoLP/Instituto de Plasmas e Fusão Nuclear, Universidade de Lisboa, Lisbon, Portugal*

[2] *Laboratory for Laser Energetics, University of Rochester, Rochester, NY, USA*

Electron-positron pair creation occurs throughout the universe in the environments of extreme astrophysical objects, such as pulsar and magnetar magnetospheres and black hole accretion disks. Despite the difficulty of emulating these environments in the laboratory, the development of ultrahigh-intensity lasers is providing new opportunities for studying the strong-field quantum electrodynamical processes responsible for pair creation. For instance, in the multiphoton Breit-Wheeler process, a high-energy photon collides with a high-intensity laser pulse and decays into an electron-positron pair. The electron and positron move predominantly in the direction of the high-energy photon, but also acquire equal and opposite drift velocities in the polarization direction of the laser pulse. This drift velocity depends on the phase of the laser pulse and alternates every half period, preventing the formation of a net transverse current. Here we show that a phase offset between a laser pulse and its second harmonic can be used to control the relative transverse motion of the electrons and positrons created in multiphoton Breit-Wheeler. With the appropriate phase offset, the electrons always drift in one direction and the positrons in the other, producing a net transverse current. This current may provide a macroscopic signature of multiphoton Breit-Wheeler without the need for a high-density pair plasma, while the spatial separation resulting from the relative motion may facilitate isolation of positrons for subsequent applications.[1]

References

[1] B. Barbosa, J. P. Palastro, D. Ramsey, K. Weichman and M. Vranic, Phase Control of Nonlinear Breit-Wheeler Pair Creation (to be submitted)

Light-Matter Interaction Near the Schwinger Limit Using Tightly Focused Doppler-Boosted Lasers

Neïl Zaïm[1], Antonin Sainte-Marie[1], Pierre Bartoli[1], Luca Fedeli[1], Axel Huebl[2], Jean-Luc Vay[2] and Henri Vincenti[1]

[1] *Université Paris-Saclay, CEA, CNRS, LIDYL, 91191 Gif-sur-Yvette, France*

[2] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States of America*

Plasma mirrors can boost the intensity of high-power lasers by several orders of magnitude [1]. This intensity gain comes from the relativistic oscillation of the plasma surface, which periodically compresses the incident laser energy in a small volume by the relativistic Doppler effect. With this method, the simple reflection of a PW-class laser on a solid target can lead to light with a peak intensity in the 10^{25}-10^{26} W/cm^2 range. We have previously shown that these intensities could enhance the signatures of Strong-Field QED (SF-QED) processes [2], such as the creation of electron-positron pairs by the Breit-Wheeler mechanism, in coming experiments.

Yet, one of the most attractive aspects of this technique is that enormous intensities, in the 10^{27}-10^{29} W/cm^2 range, can in principle be reached with already achievable laser powers (1-10 PW) if the Doppler-boosted lasers are focused close to their diffraction limit [3, 4]. In this contribution, we will present results from 2D QED-PIC [5] simulations of light-matter interactions at these unexplored intensities, that approach the Schwinger limit ($I_S = 4.7 \times 10^{29}$ W/cm^2). We show that novel SF-QED dominated interaction regimes are attained.

For instance, the interaction of a tightly focused Doppler boosted laser with a solid target leads to an abundance of SF-QED events, with up to 70% of the laser energy eventually converted to high-energy γ photons, while the interaction with a counterpropagative relativistic electron beam provides access to the fully nonperturbative regime of SF-QED [6]. Furthermore, a bunching of the generated particles by the laser is observed and leads to relativistic electron-positron jets with extremely high density (up to 10^{34} m^{-3}).

References

[1] Vincenti, H. Physical Review Letters, 123(10), 105001 (2019).

[2] Fedeli, L., et al. Physical Review Letters, 127(11), 114801 (2021).

[3] Gordienko, et al. Physical Review Letters, 94(10), 103903 (2005).

[4] Quéré, F., and Vincenti, H. High Power Laser Science and Engineering, 9, e6 (2021).

[5] Gonoskov, A., et al. Physical Review E, 92(2), 023305 (2015).

[6] Fedotov, A. Journal of Physics: Conference Series (Vol. 826, No. 1, p. 012027) (2017).

Self consistent effects in the ponderomotive acceleration of electron beams

I. Almansa[1], S. Marini[2], F.B. Russmann[1,3], E. Peter[1], and F.B. Rizzato[1]

[1] *Instituto de Física-UFRGS, Porto Alegre-RS, Brasil*

[2] *LULI, Sorbonne Université, CNRS, CEA, École Polytechnique, Paris, France*

[3] *Instituto de Física-UFRJ, Rio de Janeiro-RJ, Brasil*

The purpose of the present paper is to extend results obtained in a previous analysis of single particle acceleration by uphill accelerating ponderomotive potentials obtained from an Inverse Free-electron laser (FEL) arrangement [1].

The FEL scheme involves a homogeneous laser wave and a non-homogeneous static wiggler. The resulting ponderomotive forces pre-accelerate electrons up to the subluminal phase-velocity of the beat wave formed by laser and wiggler, and much larger levels of resonant acceleration are henceforth achieved.

What we now consider is not only single-particle dynamics, but a full, dense electron beam, where self-consistent charge effects must be taken into account [2]. The single particle previous ponderomotive formalism is thoroughly revised in order to accommodate for the self-consistent effects, but the revised formalism still agrees very well with particle simulations.

Charge effects have a set of consequences, like beam transverse spread and a beam braking action that can overcome the essential process of uphill acceleration. Both effects are discussed in this work.

[1] Physics of Plasmas **26**, 033105 (2019); https://doi.org/10.1063/1.5058748

[2]Physics of Intense Charged Particle Beams in High Energy Accelerators; Davidson & Qin; World Scientific (2001).

Channel acceleration of laser-created Bethe-Heitler positrons

B. Martinez[1], V. Haugaard[1], N. Marques[1], M. Vranic[1]

[1] *GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal*

Although plasma-based electron acceleration is well-explored both theoretically and experimentally, hardly any solutions have been established to accelerate positrons [1]. Previous attempts rely on acceleration in plasma wakefields, whereas in our case, the accelerating field is the laser itself. It was recently proposed to create and accelerate positrons in vacuum during the interaction of an intense laser pulse and a relativistic electron beam in a 90° geometry [2]. In light of this, we proved that the positron beam can be further guided and accelerated if we place a plasma channel on the laser propagation axis [3]. The main limit of that scheme is that a high laser power of 80 PW is necessary to create positrons via the Breit-Wheeler process and inject them into the guiding structure.

In this work, we propose to overcome this limit and investigate the direct laser acceleration of positrons with laser power in the range of 5 to 10 PW. Positrons are created by the Bethe-Heitler process during the interaction of the laser pulse with a thin foil placed in front of the plasma channel. Our main result is that direct laser acceleration of positrons is possible with a laser power of 5 to 10 PW. We identified what conditions are necessary with quasi-3D particle-in-cell simulations conducted with the OSIRIS framework [4]. We also present analytical estimates for the acceleration process accounting for the static field created by the dense and self-loaded electron beam. Finally, we provide guidelines on choosing the laser pulse, the thin foil, and the plasma channel to witness and optimize this new acceleration process for positrons.

Acknowledgment

This work is supported by the European Research Council (ERC-2015-AdG Grant 695088), the FCT grant CEECIND/01906/2018 and PTDC/FIS-PLA/3800/2021. We also acknowledge EuroHPC for awarding access to LUMI based in CSC, Finland and the University of Évora for awarding access to Oblivion based in Évora, Portugal.

References

[1] S. Corde et al., Nature **524**, 442-445 (2015)

[2] M. Vranic et al., Scientific Report **8**, 4702 (2018)

[3] B. Martinez et al., arXiv:2207.08728 (2022)

[4] R. A. Fonseca et al., Computational Science - ICCS (Springer, Berlin), **2331**, 342 (2002)

Influence of novel liquid sheet target on the stability and flux distribution of laser-accelerated proton beams.

C. A. J. Palmer[1], M. J. V. Streeter[1], B. Loughran[1], H. Ahmed[2], S. Astbury[2], M. Balcazar[5], M. Borghesi[1], N. Bourgeois[2], C. B. Curry[3,4], S. J. D. Dann[2], S. DiIorio[5], N. P. Dover[6], T. Dzelzainis[2], O. Ettlinger[6], M. Gauthier[3], L. Giuffrida[7,10], G. D. Glenn[3,8], S. Glenzer[3], R. Gray[9], J. S. Green[2], G. Hicks[6], C. Hyland[1], V. Istokskaia[7,10], M. King[9], D. Margarone[1,7], O. McCusker[1], P. McKenna[9], Z. Najmudin[6], C. Parisuana[3,11], P. Parsons[1], B. Loughran[1], C. Spindloe[2], D. R. Symes[2], A. G. R. Thomas[5], F. S. Treffert[3,12], N. Xu[6]

[1]*School of Maths and Physics, Queen's University Belfast*
[2]*Central Laser Facility, STFC Rutherford Appleton Laboratory*
[3]*SLAC National Accelerator Laboratory*
[4]*Department of Electrical and Computer Engineering, University of Alberta, Edmonton*
[5]*Gérard Mourou Centre for Ultrafast Optical Science, University of Michigan*
[6]*The John Adams Institute for Accelerator Science, Imperial College London*
[7]*Extreme Light Infrastructure Beamlines Centre, Institute of Physics, Czech Academy of Sciences*
[8]*Department of Applied Physics, Stanford University*
[9]*Department of Physics, SUPA, University of Strathclyde*
[10]*Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague*
[11]*Department for Mechanical Engineering, Stanford University*
[12]*Institüt fur Kernphysik, Technische Universität Darmstadt*

Despite the huge potential of laser-driven proton acceleration to provide low emittance, compact sources of MeV protons suitable for a variety of applications, several characteristics of these beams hamper their wider adoption. In particular, the typical 10s degrees beam divergence associated with the acceleration of protons from solid density, micron scale foils via sheath acceleration leads to a rapid drop in proton flux with distance from the source and makes these beams challenging to combine with plasma or RF-based beam transport systems. We will report on experimental results from the Gemini TA2 laser facility that demonstrated consistently low-divergence proton beams with high-flux and MeV energies. These beams were generated by 300 mJ, 10 TW laser pulses focused onto a sub-micron thickness water-sheet target, developed at SLAC National Accelerator Laboratory[1]. The experiment was able to operate at 5 Hz repetition rate (limited by the laser), which in combination with the improved beam quality represents an important step towards exploitation of these compact accelerators for applications.

[1]Crissman et al., Lab. Chip. 2022, 22, 1365; Treffert et al., APL 2022, 121, 74104; Treffert et al., PoP 2022, 29, 123105

Laser harmonic generation with tuneable orbital angular momentum using a structured plasma target

R. Trines[1], H. Schmitz[1], R. Bingham[1]

[1] *Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot, OX11 0QX, United Kingdom*

In previous studies of spin-to-orbital angular momentum (AM) conversion in laser high harmonic generation (HHG) using a plasma target, one unit of spin AM is always converted into precisely one unit of OAM [1, 2]. Here we show, through analytic theory and numerical simulations, that we can exchange one unit of SAM for a tuneable amount of OAM per harmonic step, via the use of a structured plasma target. The target absorbs the difference in total AM between that of n fundamental photons and the outgoing n-th harmonic photon. We introduce a novel way to analyse the frequency, spin and OAM content of the harmonic radiation which provides enhanced insight into this process. The prospects of structured targets for HHG with high-order transverse modes [1, 2] will be discussed.

References

[1] J. W. Wang, M. Zepf and S. G. Rykovanov, Nature Communications **10**, 5554 (2019).

[2] Shasha Li *et al.*, New J. Phys.**22**, 013054 (2020).

Study of relativistic electrons dynamics in high intensity laser solid interaction with Bremsstrahlung diagnostics

I. Prencipe[1], A. Laso Garcia[1], J. Metzkes-Ng[1], N. Alexander[2], F. Donat[1], A. Ferrari[1], F. Kroll[1], L. Huang[1], M. Molodtsova[1,3], M. Rehwald[1], M. Sobiella[1], R. Stefanikova[1,3], M. E. Umland[1,3], M. Vescovi Pinochet[1,3], T. Toncian[1], K. Zeil[1], U. Schramm[1,3], T. E. Cowan[1,3]

[1] *Institute of Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany*

[2] *Energy Group, General Atomics, San Diego, USA*

[3] *Technische Universität Dresden, 01062 Dresden, Germany*

The optimization of high-power-laser-driven radiation sources such as ions or X-rays requires a detailed understanding of the coupling of laser energy into relativistic electrons and of the electron dynamics in the sample. In general, relativistic electrons accelerated in the intense laser fields build up a Debye sheath at the target rear surface. Only a small fraction of hot electrons having energy high enough to overcome the sheath potential can escape the target and be detected using magnetic electron spectrometers. However, the majority of hot electrons are confined to the target by the sheath fields, being reinjected in the target every time they reach the target edges. The spectral and angular distribution of these recirculating electrons is imprinted in the emitted Bremsstrahlung whose detection can shed light onto electron dynamics in the target and mechanisms coupling laser energy into secondary radiation sources [1]. Experimental studies on this topic were enabled by the development of IP-based Bremsstrahlung dignostics at the Draco 150 TW – 1 PW laser facility of Helmholtz-Zentrum Dresden–Rossendorf [2,3]. In the last year, we have successfully implemented a CsI-based Bremsstrahlung calorimeter with optical readout enabling single-shot online Bremsstrahlung detection.

In this contribution, we present the results of a systematic study of electron recirculation in solid foils performed at Draco 1 PW with target thickness ranging between 1 μm and 200 μm and different target materials. We also discuss results of first tests aimed at shaping the distribution of accelerated electrons and optimizing laser-driven proton acceleration through target structuring, i.e. using targets composed of arrays of microtubes and micropillars produced by two-photon-polymerization on μm-thick foils.

[1] L. Huang, *et al.*, Phys. Plasmas **29**, 023102 (2022)

[2] A. Hannasch, *et al.*, Sci. Rep. **11**, 14368 (2021)

[3] A. Laso Garcia, *et al.*, Rev. Sci. Instrum. **93**, 043102 (2022)

Experimental techniques for measurement of ultra-high-intensity laser generated gamma rays at ELI Beamlines

G. Fauvel, P. Rubovic, F. Condamine, M. Manuel, A. Arefiev, K. Tangtartharakul, Y. He, S. Weber

Production of intense and energetic gamma-ray sources in dense laser-irradiated plasmas is of fundamental interest in many fields of science (two-photon pair production, medical isotope production, nuclear waste analysis, etc.). One of the techniques to generate such photons is the interaction of an ultra-high-intensity laser pulse with low-mass foam targets. In these conditions, where the electron density is close to the plasma critical density, very strong magnetic fields (multi-GG) are generated. These magnetic fields enhance electron acceleration inside the plasma, which consequently, emit gamma rays from tens to hundreds of MeV. The currently available L3 high-repetition rate PW-class laser (30J, 30fs, 10Hz) at ELI Beamlines fulfills the requirements for such research.

However, an important work must be made regarding diagnostics for being able to operate such experiments at decent repetition rates. Indeed, standard gamma-ray diagnostics use passive detectors to record the signal, which are not suitable for high-repetition rate operation at ELI Beamlines. Here, we describe the design and the challenging implementation of an active gamma-ray calorimeter in extreme environments (i.e. electromagnetic pulses, particles and ultra high-vacuum).

Funding Acknowledgments

This research was supported by the National Science Foundation (PHY-2206777) and by the Czech Science Foundation (project No. 22-42890L). (NSF-GACR: Study of Gamma-Ray Generation in High-Intensity Laser-Plasma Interactions at ELI Beamlines).

This research was supported by the projects ADONIS (Advanced research using high intensity laser produced photons and particles, CZ.02.1.01/0.0/0.0/16 019/0000789) and by High Field Initiative (HiFI, CZ.02.1.01/0.0/0.0/15 003/0000449), both from European Regional Development Fund.

Implementation of high pressure gas targets on LMJ

M. Ferri[1], S. Debesset[1], C. Guerrier[1], L. Delaval[1], D. Antigny[1], L. Le Déroff[1], P. Dupré[1], T. Caillaud[1], R. Diaz[1], B. Fourton[1], R. De Mollerat du Jeu[1], R. Botrel[2], W. Cayzac[3], S. Depierreux[3],

[1] *CEA-CESTA, Le Barp, France*

[2] *CEA-VALDUC, Is-sur-Tille, France*

[3] *CEA-DIF,* Bruyères-le-Châtel*, France*

Implementation of gasbag targets on Laser MégaJoule (LMJ) facility was operational for 3 years with Gas Regulation Module (GRM) for gas pressure ranging from 0,3 to 1,5 bars. As experiments program on LMJ evolves, new types of high pressure targets need to be developed for higher gas pressures.

Implosion experiments with Holhraum containing capsules filled by capillary with high pressure (> 5 bars) room temperature D2 gas need a specific system for filling the capsule during shot operations just before the shot. We have designed a new GRM in order to manage combination of low and high pressures for this new type of targets.

Experiments such as Self-Modulated Laser Wakefield Acceleration, planed for 2023, requires specific Helium electronic density (typically 1018-1019 cm-3 upon 4-10 mm length) at Target Chamber Center (TCC) for interaction with PETAL laser. For that purpose a high pressure (> 5 bars) pulsed gas jet equipped with supersonic nozzle has been designed for use on this kind of experiment.

We will describe the implementation of this new type of GRM system on the target positioner for non cryogenic targets.

Characterisation of Laser Wakefield Acceleration Efficiency with Octave Spanning Near-IR Spectrum Measurements

M.J.V. Streeter[1], Y. Ma[2], B. Kettle[3], S.J.D. Dann[4], E. Gerstmayr[1], F. Albert[5], N. Bourgeois[4], S. Cipiccia[6], J.M. Cole[3], I. Gallardo González[7], A.E. Hussein[8], D.A. Jaroszynski[9], K. Falk[10], K. Krushelnick[2], N. Lemos[5], N.C. Lopes[11], C. Lumsdon[12], O. Lundh[7], S.P.D. Mangles[3], Z. Najmudin[3], P.P. Rajeev[4], R. Sandberg[2], M. Shahzad[9], M. Smid[10], R. Spesyvtsev[9], D.R. Symes[4], G. Vieux[9], and A.G.R. Thomas[2]

[1]*School of Mathematics and Physics, Queen's University Belfast, BT7 1NN, Belfast, UK*

[2]*Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, USA*

[3]*The John Adams Institute for Accelerator Science, Imperial College London, London, UK*

[4]*Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot,UK*

[5]*Lawrence Livermore National Laboratory (LLNL), Livermore, USA*

[6]*Diamond Light Source, Harwell Science and Innovation Campus, Didcot UK*

[7]*Department of Physics, Lund University, Lund, Sweden*

[8]*Department of Electrical and Computer Engineering, University of Alberta, Canada*

[9]*SUPA, Department of Physics, University of Strathclyde, Glasgow, UK*

[10]*Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany*

[11]*GoLP, Instituto Superior Técnico, U.L., Lisboa, Portugal*

[12]*York Plasma Institute, Department of Physics, University of York, York, UK*

We report on experimental measurements of energy transfer efficiencies in a laser wakefield accelerator [1]. Both the transfer of energy from the laser to the plasma wakefield, and from the plasma to the accelerated electron beam were diagnosed by simultaneous measurement of the deceleration of laser photons and the acceleration of electrons as a function of plasma length. The extraction efficiency, which we define as the ratio of the energy gained by the electron beam to the energy lost by the self-guided laser mode, was maximised at 19±3% while the electron beam reached a maximum energy of 1.2 GeV. The efficiency is shown to depend on plasma density, with dephasing and laser evolution playing key roles.

References

[1] "Characterization of laser wakefield acceleration efficiency with octave spanning near-IR spectrum measurements" M. J. V. Streeter *et al.* Phys. Rev. Accel. Beams **25**, 101302 (2023).

Radiation reaction in spatially modulated fields accelerators

I. Almansa[1], **F. Russman**[1], **S. Marini**[2], **E. Peter**[1] **and F.B. Rizzato**[1]
[1]Instituto de Física, Universidade Federal do Rio Grande do Sul, Caixa Postal 15051, 91501-970 Porto Alegre, RS, Brasil.
[2]LSI, CEA/DRF/IRAMIS, École Polytechnique, Institut Polytechnique de Paris, CNRS, F-91128 Palaiseau, France.

It is possible to accelerate efficiently a charged particle towards the speed of light through a spatially modulated electrostatic field and through the superposition of a spatially modulated magnetic field and a laser. In both cases, the acceleration process requires an adequate initial velocity of the particle and depends on the amplitude of the fields, the length scale of the modulation and the wavenumbers, and frequencies of the fields. The physics behind these accelerators involves a resonance between the particle's velocity and the field's phase velocity. The promising results, however, may be affected when the radiation reaction effect is included in the calculations. Understanding the role of the radiation reaction over these schemes is the aim of the present work. As we are going to show, in a counter-intuitive way, the effects of radiation reaction can help to accelerate charge particles under some specific conditions.

Alpha particles sources produced through proton-boron nuclear reactions by means of intense lasers

Thomas Carrière[1] , Didier Raffestin[1], Dimitri Batani[1] , Katarzyna Batani[2] , Fabrizio Consoli[3] , Marine Huault[4], Howell Lareur[1,4], Diluka Singappuli[1] , Philippe Nicolaï[1]

[1] CELIA, Université de Bordeaux, Talence, France [2] IPPLM , Warsaw, Poland [3] ENEA, Frascati, Italy [4] University of Salamanca, Salamanca, Spain

Proton-Boron nuclear reactions have been actively studied these last few years as a possible way of producing secondary alpha particles sources. Proton acceleration by interaction of ultra-high intense lasers with hydrogenated targets is the preferred way to initiate those type of reactions. [1] The alpha particles sources are studied for production of radio-isotopes as medical applications to be able to achieve an effective alternative to cyclotrons classically used.

The two main mechanisms of ion acceleration studied for this nuclear scheme are the Target Normal Sheath Acceleration (TNSA) and the Hole-Boring (HB) process. In the first case, protons are accelerated at the rear side of the target via the electrostatic field induced by laser driven electrons escaping from the target. The exponential shape of the proton energy spectrum induces a great number of nuclear reactions throughout a Boron secondary target despite a decrease of the cross-section above the main resonance at 675 keV.

For the Hole-Boring process, ions are accelerated at the front side thanks to the electric field induced by the electrons pushed by the radiation pressure of these high laser intensities. Accelerated protons interact directly with boron atoms contained within the same target [2].

Particle-in-Cell (PIC) and Monte-Carlo simulations have been conducted to better understand experimental campaigns done on the VEGA-III laser at CLPU, Salamanca, Spain in november 2022 and march 2023. This laser is characterized by a short pulse duration, 30fs and a high-repetition rate 1Hz. The two ion acceleration schemes are tested and will be compared.

[1] Margarone Daniele, Alessio Morace, Julien Bonvalet, Yuki Abe, Vasiliki Kantarelou, Didier Raffestin, Lorenzo Giuffrida, et al. « Generation of α-Particle Beams With a Multi-KJ, Peta-Watt Class Laser System ». *Frontiers in Physics* 8 (9 septembre 2020): 343. https://doi.org/10.3389/fphy.2020.00343.

[2] Margarone, Daniele, Julien Bonvalet, Lorenzo Giuffrida, Alessio Morace, Vasiliki Kantarelou, Marco Tosca, Didier Raffestin, et al. « In-Target Proton–Boron Nuclear Fusion Using a PW-Class Laser ». *Applied Sciences* 12, n° 3 (28 janvier 2022): 1444. https://doi.org/10.3390/app12031444.

Numerical investigation of the influence of the magnetic field on the hot electron flux generated at laser irradiation of a disc-coil target

J. Domanski[1], Z. Rusiniak[1], O. Renner[2,3,4], R. Dudzak[3,2], J. Badziak[1] T. Chodukowski[1], J. Dostal[2,3], M. Krupka[2,3], S. Singh[2,3], M. Ehret[5], P. Gajdos[2], A. Zaras-Szydłowska[1], M. Szymanski[1], J. Krasa[3], T. Burian[3,2], S. Jelinek[2,3], G. Kocourkova[3], D. Batani[6], K. Batani[1], J. Santos[6], C. Vlachos[6], V. Ospina-Bohórquez[6], L. Volpe[5], L. Juha[3], M. Krus[2], and T. Pisarczyk[1]

[1] Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland

[2] Institute of Plasma Physics, CAS, 182 00 Prague, Czech Republic

[3] Institute of Physics, CAS, 182 21 Prague, Czech Republic

[4] ELI Beamlines Center, Institute of Physics, CAS, 252 41 Dolni Brezany, Czech Republic

[5] C.L.P.U. (Centro de Láseres Pulsados), Salamanca, Spain

[6] Univ. Bordeaux, CNRS, CEA, CELIA, UMR 5107, F-33405, Talence, France

Laser-driven generators of quasi-static, strong magnetic fields are considered to be a useful tool for generating and studying magnetized plasma, in particular for astrophysics and inertial fusion research. One such generator uses a disc-coil (DC) target in which a disc of high-Z material coupled to a coil is irradiated by an intense laser beam. In a recent experiment at the PALS laser facility [1], it was shown that in the DC scheme it is possible to generate magnetic fields > 5T with a laser driver energy of ~ 0.5 kJ. Such magnetic fields appear to be sufficient to create a highly magnetized plasma and/or to modify the properties of the charged particle fluxes emitted from the plasma.

In this contributions we will present the numerical investigation of the influence of magnetic field on the hot electron flux produced in the DC target. Our study is related to the PALS experiment in which the laser pulse interacted with a DC target composed of a Cu disk connected to a single-turn coil [1]. To examine the effect of the magnetic field on the flux of hot electrons generated in the DC scheme, full 3D PIC simulations were performed using the appropriately adapted EPOCH code. The initial positions and velocities of the particles (at the beginning of simulation) were recreated, with the Monte Carlo method, based on the measurements of angular distributions of the electron energy spectra made with the multichannel electron spectrometer for the Cu disc without the coil [1] and the information about size of the beam source obtained from 2D imaging of Kα line emission from Cu. The distribution of the B-field around the coil was determined on the basis of the shape of the coil and measurement of the current in the coil performed by complex interferometry with respect to the Biot-Savart law.

It was found that the magnetic field generated in the DC scheme leads to a strong collimation of the hot electron flux and a very significant increase in the electron current density. It also causes an increase in the average energy and temperature of the electrons near the axis of the collimated flux. In the presentation, the above issues will be discussed in detail, and the possibilities and perspectives of controlling laser-generated electron fluxes using magnetic fields produced in DC systems will be considered.

1. T. Pisarczyk et.al. , Plasma Phys. Control. Fusion **64,** 115012, 2022.

Experimental observation of a triple point for a complex (dusty) plasma

Swarnima Singh, Krishan Kumar, P. Bandyopadhyay and A. Sen

Institute for Plasma Research, A CI of Homi Bhabha National Institute, Bhat, Gandhinagar-382428

The triple point is a thermodynamic concept referring to the confluence point of three distinct coexisting phases of a substance. Such coexisting stable phase states that are in mechanical, thermal and chemical equilibrium with respect to each other have been extensively studied at a macroscopic level for water, various metals, and colloidal systems [1, 2]. In this work, we present the first experimental observation of a triple point in a strongly coupled 2D complex plasma medium. The experiments are carried out for a dusty plasma system created in a glow-discharge Argon plasma environment using an L-shaped Dusty Plasma Experimental (DPEx-II) device. Initially a 2D crystalline structure of the dust component consisting of mono-dispersive micron-sized Melamine Formaldehyde (MF) particles is created. The evolution of this monolayer dust as a function of the discharge voltage is then investigated and in the course of this evolution we have discovered the co-existence of three distinct phases of the system consisting of a liquid region and two crystalline regions with square and hexagonal lattice configurations. The onset of such a state has a threshold in the dust density. Details of tour experimental findings and theoretical modeling in support of them will be presented.

References:

[1] J. C. Heyraud and J. J. Metois, Equilibrium shape and temperature—Lead on graphite, Surf. Sci. 128, 334 (1983).

[2] M. Chaudhuri, E. Allahyarov, H. Löwen,S. U. Egelhaaf, and D. A. Weitz, Triple Junction at the Triple Point Resolved on the Individual Particle Level, PRL 119, 128001 (2017)

Experimental observation of cylindrical and spherical precursor solitons in a flowing dusty plasma

Krishan Kumar, Pintu Bandyophadhyay, Swarnima Singh, Abhijit Sen

Institute for Plasma Research, A CI of Homi Bhabha National Institute, Gandhinagar, India

The simultaneous excitation of precursor solitons ahead of a fast-moving object with wakes behind it is a phenomenon that has been widely studied in hydrodynamics. The topic of this fore-wake excitations has, however, received very limited attention in the field of plasma physics until now. The first experimental demonstration of the generation of a precursor soliton in a flowing dusty plasma over a 1-D charged object was reported by Jaiswal et al. [1]. Afterwards, this fore-wake phenomena have been extensively studied via experimental investigations [2], theoretical modelling [3], and computer simulation [4] in a dusty plasma medium. However, to the best of our knowledge, there has so far been no experimental demonstration of precursor solitons excited by cylindrical and spherical charged objects in a dust fluid. In this work, we report an experimental observation of cylindrical and spherical precursor solitons in a flowing dusty plasma as shown in fig. 1. The experiments are performed in the Dusty Plasma Experimental (DPEx) device [5] in which a dusty plasma is created in the background of DC glow Ar plasma using micron-sized Kaolin particles. The flow of dust fluid over cylindrical and spherical charged objects are made using single gas injection technique over a range of flow velocities and strength of the charged object. In the frame of dust fluid, the cylindrical (or spherical) solitons propagate in the upstream direction whereas wakes structures propagate in the downstream direction. It is observed that the amplitude of spherical soliton decreases faster than the cylindrical soliton. It is also found that the curvature of the cylindrical and spherical soliton decreases with the strength of the charged object. The fluid and molecular dynamics simulations provide good theoretical support to the experimental findings.

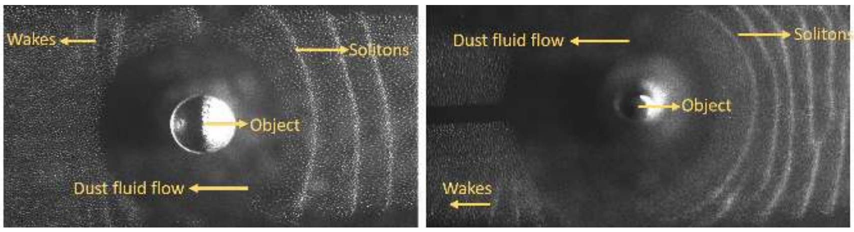


Fig. 1 Top view of (a) spherical soliton and (b) cylindrical soliton

References:

[1] S. Jaiswal, P. Bandyopadhyay, and A. Sen, Phys. Rev. E 93, 041201 (2016).

[2] G. Arora, P. Bandyopadhyay, M. G. Hariprasad, and A. Sen, Phys. Plasmas 26, 093701 (2019).

[3] S. Tiwari, and A. Sen, Phys. Plasmas 23, 022301 (2016).

[4] S. Tiwari, and A. Sen, Phys. Plasmas 23, 100705 (2016).

[5] S. Jaiswal, P. Bandyopadhyay, and A. Sen, Rev. Sci. Instrument. **86**, 113503 (2015).

Behaviour of multi-component plasma sheath in presence of charged dust particles in an oblique magnetic field: Fluid picture

A. K. Shaw[1], A. K. Sanyasi[1] and D. Sharma[1,2]

[1]Institute for Plasma Research, Bhat, Gandhinagar-382 428, Gujarat, India

[2]Homi Bhabha National Institute, Training School Complex Anushaktinagar Mumbai 400094, India

Abstract

Investigation of plasma sheath in presence of charged dust specie is one of the topics of high relevance in fundamental plasma research [1] and multiple industrial applications such as etching, sputtering, thin film deposition, and ion implantation [3]. The present work makes an approach to describe the behaviour of the magnetized two isothermal positive ions (and) plasma sheath in presence of charged dust particles. A fluid treatment has been adopted to study the He^{+}, and Ar^{+} ion density and velocity dynamics inside the sheath region in the presence and absence of charged dust species having nano-meter (nm) sizes. In presence of the charged dust inside the sheath, the ions are found to get accumulated near the sheath edge, hence the ion density drops in the downstream direction or in approach to the wall. Further, magnetic field strength has been shown to have a direct influence on the peaking and intensification of ion densities near the sheath edge. The ion density bunching and shifting are also observed at the sheath edge with a change in magnetic field projection to the wall along with a substantial change in sheath potential drop [4]. A qualitative explanation of the mechanism that accounts for the presence of dust species in the sheath is presented.

References

[1] Winske D and Jones M E, IEEE Trans. Plasma Sci. **22** 454, (1994)

[2] A. A. Howling, Ch. Hollenstein, and P.-J. Paris, Appl. Phys. Lett. **59**, 1409 (1991)

[3] A. K. Shaw, A. Sanyasi, and S. Kar, Phys. Scr. **98**, 015606, (2023)

Nonlinear excitations within strongly coupled quasi-localized regime of dusty plasma

Prince Kumar[1], Devendra Sharma[1]

[1] *Institute for Plasma Research, A CI of Homi Bhabha National Institute, Gandhinagar 382428 , India*

The strongly coupled quasi-localized regime of the dusty plasma is governed by a more sophisticated theoretical formulation, such as Quasi-localized charge approximation (QLCA), which accounts for the localization effects of the medium [1]. While the linear collective excitations in localized regime are widely explored over a broad range of spectral scales by invoking the conventional spectral version of the QLCA model, its saptio-tempraol version which allows unique access to the non-linear excitations, remains largely unexplored despite its capacity to more effectively cover the structures of a wide range of spectral scales [2]. In order to adopt QLCA in its saptio-tempraol domain, we let fluid conservation equations represent the ensemble averages of individual collective modes and calculated the isothermal compressiblity of the dust from the basic QLCA constructions (mainly dynamical matrix, or D-matrix). First, the nonlinear analytical KdV model is developed to test its reliability in an existing limit (weak screening ($\kappa < 1$) and long-wavelength) of the strongly coupled dusty plasma obtaining the nonlinear soliton solutions that are identical to those prescribed by existing models (e.g., Generalized Hydrodynamic model) [3,4]. Such analytical QLCA model despite being valid only in weak screening ($\kappa < 1$) and long-wavelength limit, continues to prescribe soliton solutions in highly screened limit. This issue is addressed by a more sophisticated form of the D-matrix to test the reliability of analytical solutions beyond their present validity limit. This limit of the correct solutions is overcome by the present treatment that adopts the recently developed excluded volume approximation [5] and its numerical implementation for evaluating the QLCA dynamical matrix in the spatiotemporal domain which is exclusively achievable under a nonlinear pseudospectral framework. It is shown that when existing KdV solutions are used as initial condition in present the spatiotemporal simulations, they undergo strong modification before propagating coherently after larger screening parameter value, $\kappa > 1$. These newer coherent numerical solitary structures are far steeper than those predicted by the analytical approximation underlying the KdV equation [2].

[1] Prince Kumar and Devendra Sharma, Phys. Plasmas 28, 083704 (2021)
[2] Prince Kumar and Devendra Sharma, Phys. Plasmas (2023) DOI: 10.1063/5.0121733)
[3] P. Kaw, Physics of Plasmas 8, 1870 (2001)
[4] S. Sharma, et al, Physical Review E 89, 013110 (2014)
[5] S. A. Khrapak, et al, Physics of Plasmas 23, 023702 (2016)

Linear behaviour of a plane-Couette flow in 3D Yukawa liquids

Suruj Kalita[1,2], Rajaraman Ganesh[1,2], Pawandeep Kaur[1,2]

[1] *Institute for Plasma Research, Bhat, Gandhinagar, Gujarat 382428, India*

[2]*Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai 400094, India*

It is very well known that a plane-Couette flow in a 3D Yukawa liquid undergoes sub-critical transition to turbulence, when a finite amplitude perturbation is applied [1]. A plane-Couette flow is linearly stable at all the values of Reynolds number. Therefore, a non-linear finite amplitude perturbation is applied to make the flow unstable and as a result of the instabilities, the system becomes turbulent[1]. However, the behaviour of a plane Couette flow, when perturbed with a linear infinitesimal amplitude perturbation, has not been studied in a 3D Yukawa liquid.

The linear behaviour of a plane Couette flow is very interesting to study, because it leads to "layer formation" phenomenon in hydrodynamics, in the presence of a density stratification created under the action of an external gravitational force [2] and the exact reason behind the formation of layers is not clearly known. In our present work, taking a 3D Yukawa liquid, we have performed numerical simulation of a linearly perturbed plane Couette flow in the presence of an external gravity. The instability mechanism depends upon the "structure" of the applied perturbations. When the vorticity of the applied perturbation is zero or have no structure, then the instability mechanism is "Phillips/Posmentier" type [3] and when the applied perturbation has non-zero vorticity or have structure, then "Zig-Zag" instability[2] is observed. The detailed study of the two instabilities will be presented in the conference.

[1] S Kalita, R Ganesh, Physics of Fluids 33, 095118 (2021).

[2] S. A. Thorpe, Journal of Fluid Mechanics , Volume 793 , 25 April 2016 , pp. 380 - 413.

[3] O.M. Phillips , Volume 19, Issue 1, January 1972, Pages 79-81

Experimental investigation of ion flux reduction at the sheath edge in low temperature plasmas due to ion–neutral collisions

Yegeon Lim[1], Young-chul Ghim[1]

[1] *Korea Advanced Institute and Science and Technology (KAIST), Daejeon, Republic of Korea*

The reduction of ion flux at the sheath edge caused by ion-neutral collisions in low temperature plasmas is experimentally estimated for the first time at intermediate neutral gas pressures ($p \lesssim 10^2$ mTorr). The normalized ion flux at the sheath edge is represented by an additional ion collecting area (α_{EE}) of the disc Langmuir probe, formed as the sheath expands. The power-law parametrization method which follows a systematic scan of normalized plasma parameters is utilized to estimate α_{EE} from the Langmuir probe data. A heuristic equation expressing α_{EE} is formulated from the experimentally scanned parameter space, and its constituting coefficients are found to be dependent to the neutral gas pressure, i.e., ion–neutral collision. The coefficients of the heuristic equation on α_{EE} are estimated with varying neutral gas pressures as 0.2–30.0 mTorr for Ar and 1.0–65.0 mTorr for He discharges generated in a multidipole chamber with hot filaments. The evaluated ion flux at the sheath edge is compared with theoretical predictions.

Correlation Analysis of Inductively Coupled Plasma Data of the Comprehensive Data Collection Equipment

Yong-Hyun Kim[1,2], Jong-Sik Kim[1,2], Jong-Bae Park[1,2], Dae-Chul Kim[1,2], Young-Woo Kim[1,2], Ji-Ho Cho[1,2]

[1] *Fundamental Technology Research Division, Institute of Plasma Technology, Korea Institute of Fusion Energy,37 Dongjangsan-ro Gunsan-si Jeollabuk-do 54004, Korea*

[2] *Plasma E.I. Convergence Research Center, Korea Institute of Fusion Energy,37 Dongjangsan-ro Gunsan-si Jeollabuk-do 54004, Korea*

In this study, various diagnostic tools were constructed and plasma factors were measured to evaluate the intelligence of plasma process equipment. We used an ICP reactor with an RF power of 13.56 MHz, a power of 400 to 800 W, and a pressure of 10 to 30 mTorr. Plasma parameters such as electron density (n_e), electronic temperature (T_e), plasma potential (V_p), and floating potential (V_f) were measured using measurement devices (VI probe and mass/energy analyzer, Langmuir probe, Cutoff probe, OES etc.) and simultaneously analyzed. Regression analysis was performed to correlate the measured data with the plasma parameters. As a result, the plasma density (n_e) and temperature (T_e) were observed to be in good agreement with the non-invasive measurement results. In particular, the VI probes were highly correlated with almost all the measured plasma parameters. Therefore, this results provide a basis for the estimation of plasma parameters using non-invasive measurement techniques. In addition, in order to verify whether the non-invasive measurement method using VI probe is generally applied, plasma data will be measured in ICP systems with different reactor sizes, antenna shapes, gases, RF power, etc. The correlation between VI probe and plasma parameters from the collected data will be analysed and this result will be discussed.

Research on plasma and process sensing data for the development of intelligent plasma process equipment

J.S. Kim[1], Y.H. Kim[1], J.B. Park[1], J.H. Shin[1], D.C. Kim[1], Y.W. Kim[1], J.H. Song[1], K.H. Cho[1], J.S. Yoon[1]

[1]Plasma Equipment Intelligence Convergence Research Center, Korea Institute of Fusion Energy, Gunsan 54004, Korea

Recently, as the capacity of a semiconductor device increases and the degree of integration increases and the structure becomes more complicated, technical difficulties and processes of a semiconductor device manufacturing process are increasing. In order to solve these technical difficulties, it is necessary to improve the quality of the process and minimize the defect rate.
Additionally, exponential growth in data volume, speed, quality, merging and analysis requirements in recent years has forced semiconductor manufacturers to take new approaches to data management and use across fabs[1]. Therefore, in order to solve these problems, the "Development and Demonstration of Intelligent Technology for Semiconductor Plasma Process Equipment" Convergence Research Center(Plasma.E.I. Convergence Research Center) is developing intelligent plasma process equipment technology that can control equipment using data. By displaying the plasma and process status inside the process equipment, abnormal processes are detected in the semiconductor manufacturing process and the causes of defects are analyzed.
In this study, we are developing and researching intelligent sensors and plasma engineering databases necessary for the development of intelligent plasma process equipment. We are analyzing plasma and process data measured by diagnostic devices and sensors mounted on equipment, and we are conducting research on the development of intelligent sensors that can measure and predict the results of plasma and processes by upgrading existing sensors and researching the development of new sensors. In addition, research on the development of plasma engineering data, which can be used as a reference for equipment development and process analysis in industrial sites, is introduced by using data that analyzes the relationship between plasma variables according to process conditions and process results.

References

1. J. Moyne, J. Samantaray, and M. Armacost, IEEE Trans. Semicond. Manuf. 29 (4), 283-291 (2016)

Development of large volume microwave plasma torch with expanded high-density plasma zone for efficient reforming of methane to syngas

S. M. Chun[1,2], G. W. Yang[1], and Y. C. Hong[1]

[1] *Institute of Plasma Technology, Korea Institute of Fusion Energy(KFE), Gunsan-City, Republic of Korea*

[2] *Department of Applied Plasma & Quantum Beam Engineering, Jeonbuk National University, Republic of Korea*

Atmospheric concentration of carbon dioxide (CO_2) and methane (CH_4) significantly contribute to global climate charge, necessitating the search for methods of reducing the emissions of this greenhouse gas to zero. Electrodeless microwave plasma torch can use an oxygenating gases such as CO_2 to discharge the plasma. A microwave plasma torch can convert CO_2 + CH_4 to syngas using a dry reforming reaction at atmospheric pressure. The CO_2/CH_4 reforming can be completely converted into synthesis gas (conversions: 68.4%, CO_2; 96.8%, CH_4, a total flow rate of 30 L/min: CO_2 15 L/min and CH_4 15 L/min, CO_2:CH_4 = 1:1) through their reforming reactions at a microwave power of 6 kW. Also, the energy yield is 240 g/h and 41.4 g/kWh. On the one hand, from an economic point of view, it is necessary for this CO_2 microwave plasma torch to be become more energy efficient and cost effective. Additionally, a large volume microwave plasma torch expended high-density plasma zone was developed to efficiently reforming of methane to syngas. A large volume microwave plasma torch generated by electromagnetic mode transition has 3 times than volume of microwave plasma torch.

Hydrogen-Nitrogen Mixed Arc Plasma on Direct toluene conversion into C_2 product

C. Jung[1], D.K. Dinh[2], Y.N. Kim[2], D.H. Lee[1,2]

[1] *Korea University of Science and technology, Daejeon, Republic of Korea*

[2] *Korea Institute of Machinery and Materials, Daejeon, Republic of Korea*

The chemical industry produces various by-products, such as residual oil, tar, and volatile organic compounds, during its processes. Toluene is one such material that has typically been reused as fuel. However, given the urgent need to prevent extreme climate crises, achieving carbon neutrality has become a critical goal. Consequently, strict regulations have been put in place to control CO_2 emissions, and toluene treatment must also be reevaluated in light of this goal. One promising technology for toluene treatment is the use of arc plasma to convert toluene into C_2 species. Plasma generated by electrical sources thereby avoiding CO_2 emissions.

This study investigated toluene conversion using a hydrogen-nitrogen mixed arc plasma. Unlike previous studies that focused on removing or converting to hydrogen [1,2], this study converted toluene into C_2 hydrocarbons. Specifically, a rotating arc plasma with a swirl flow was used to expand the 2D arc into a 3D volumetric arc [3]. The research examined the effects of various hydrogen-nitrogen gas ratios and power conditions on discharge and product selectivity under different conditions. As a result, the study confirmed the feasibility of toluene conversion into C_2 species and the effects of the hydrogen-nitrogen gas ratio on rotating arc plasma.

References

[1] F. Zhu et al., *Fuel 176*, 78 (2016)

[2] D. Mei et al., *J. Energy Inst. 98*, 131 (2021)

[3] D. H. Lee et al., *P. Combust. Inst. 31*, 3343 (2007)

A Study on the Density and Energy Distribution Characteristics of Nitrogen Ions (N_2^+, N^+) in the Plasma Nitridation Process

Dae-Chul Kim[1,2], Jong-Sik Kim[1,2], Yong-Hyun Kim[1,2], Jong-Bae Park[1,2], Jong-Hyun Shin[2], Young-Woo Kim[1,2], and Jung-Sik Yoon[2]

[1]*Fundamental Technology Research Division, Institute of Plasma Technology, Korea Institute of Fusion Energy, Jeollabuk-do 54004, Korea*

[2]*Plasma E.I. Convergence Research Center, Korea Institute of Fusion Energy, Jeollabuk-do 54004, Korea*

The important process parameters in the Plasma nitridation process are the density and energy distribution of nitrogen ions. The density of nitrogen ions affects the concentration of nitrogen ions formed in the SiON thin film, and the energy distribution of nitrogen ions affects the depth profile of nitrogen ions distributed in the SiON thin film. In order to measure these process parameters, a mass/energy analyzer (MEA) was installed on the wall of the ICP reactor and under the substrate to measure the flux and density of N_2^+ and N^+ ions and ion energy distribution (IED) and compare them with each other. The experimental conditions changed RF power and pressure. In order to obtain the density of each ionic species, relative area ratio of IEDs of N_2^+ and N^+ ions were obtained, and ion saturation current and electron temperature measured by Langmuir probe were used. As a result of the measurement, as the RF power increases under the same pressure conditions, the N_2^+ ratio tends to decrease, and the N^+ ratio tends to increase. In the case of ion density, as RF power increases under the same pressure conditions, both N_2^+ and N^+ density tend to increase. Under the same RF power conditions, N_2^+ density tends to decrease and N^+ density tends to increase as pressure increases.

Coherent structures from MHD to kinetic scales in solar wind turbulence at 0.17 and 1 au

O. Alexandrova[1], A. Vinogradov[1], A. Artemyev[2], P. Demoulin[1], M. Maksimovic[1], A. Mangeney[1], S. Bale[3],

[1] *LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, Meudon, France*

[2] *Institute of Geophysics and Planetary Physics, University of California, Los Angeles, USA*

[3] *Space Science Laboratory, Physics department, University of California, Berkeley, USA*

We study magnetic turbulence in the solar wind from MHD to kinetic plasma scales at 0.17 au, using Parker Solar Probe measurements during its first perihelion and using Cluster and Wind data at 1 au. One of the inherent properties of the turbulent cascade is intermittency which is due to coherent structures. Coherent structures are localized in space and characterised by high amplitudes of magnetic fluctuations. Such events can be detected using Morlet wavelet transform, which localise the energy inhomogeneity of magnetic fluctuations at the given time and scale. The observed magnetic energy inhomogeneities peaks across a large range of scales, meaning embedded coherent structures from MHD down to kinetic scales. At 0.17 au we do a statistical study of amplitude anisotropy of magnetic fluctuations within coherent events at MHD, ion and at sub-ion scales, and we comparer the observed anisotropies with crossings of different model structures (Alfvén vortices, current sheets, magnetic holes). The dominant type of the structures seems to be Alfvén vortices (>90%) at all scales. Co-existance of magnetic vortices from MHD to sub-ion scales is shown here for the first time. Current sheets may reach only 5% at MHD scales, 8% at ion scales and 1% at sub-ion scales. The population of structures resembling magnetic holes is negligible so close to the Sun. Further away from the Sun, at 1 au, magnetic holes appear in the slow wind streams, as well as magnetic solitons and shocks [1]. In the fast wind, Alfvén vortices are the dominant events [2, 3] as is observed closer to the Sun.

References

[1] Perrone, D. et al., APJ, vol. 826, no. 2 (2016)
[2] Lion, S., Alexandrova, O., and Zaslavsky, A., APJ, vol. 824, no. 1 (2016)
[3] Perrone, D. et al., APJ, vol. 849, no. 1 (2017)

Steep electrostatic excitations in highly quasi-longitudinal whistlers propagating along resonant cone

Gayatri Barsagade[1,2], Devendra Sharma[1,2]
[1]Institute for plasma Research, Bhat Gandhinagar 383428, India
[2]Homi Bhabha National Institute, Training School Complex Anushaktinagar Mumbai 400094 India

Whistler waves propagating both parallel and oblique to the ambient magnetic field play central role in magnetospheric plasmas and have also been found relevant to the process of fast electrons generation in large scale fusion plasmas [1]. The nonlinear character of whistlers is uniquely visible in the limit of their oblique propagation where they are expected to develop steep electrostatic fluctuations in their hydrodynamic simulations [2,3], potentially accelerating magnetospheric electrons [4]. The question that whether fluctuations arise by a resonant mode coupling activity or by its nonlinear quasi-electrostatic nature while propagating along the resonant cone is explored recently by detailed numerical computations [5]. Motivated by highly quasi-longitudinal whistlers reported in laboratory experiments [6]. The present investigation covers also the high-density regime ($\omega_{pe} >> \omega_{ce}$) finding that for the propagation close to resonant cone angles high-frequency electrostatic oscillations are co-excited in the limit $k \rightarrow \infty$ by the relatively low k whistler perturbations. While for the moderate quasi-longitudinally of the whistlers, or for small obliqueness, the frequency of steep electrostatic oscillations confirms with the hybrid electrostatic mode, for the case of highly quasi-longitudinal whistlers possible in the high-density cases this frequency is noted to have a considerable down-shift from the upper-hybrid oscillations that are expected to be excited this regime. This down-shift of the resonant frequency is noted to be caused by the highly quasi-longitudinal whistlers by repeating the computations in absence of the whistlers in which the frequency of the oscillations is restored at its linear analytic value. The oscillations are consistently located in very narrow frequency interval of the generalized linear dispersion relation in which the refractive index of the resonant electrostatic branch tends to infinity. Since the parameters of the quasi-longitudinal whistlers for these cases are well described by the linear dispersion, the steep electrostatic fluctuations are identified as co-excited resonant oscillations influenced by the presence of quasi-longitudinal whistlers.

[1] W. W. Heidbrink, C. Paz-Soldan, D. A. Spong, X. D. Du, K. E. Thome, M. E. Austin, A. Lvovskiy, R. A. Moyer, R. I. Pinsker, and M. A. V. Zeeland, Plasma Phys. Controlled Fusion 61, 014007 (2018).
[2] C. Cattell, J. R. Wygant, K. Goetz, K. Kersten, P. J. Kellogg, T. von Rosenvinge, S. D. Bale, I. Roth, M. Temerin, M. K. Hudson, R. A. Mewaldt, M. Wiedenbeck, M. Maksimovic, R. Ergun, M. Acuna, and C. T. Russell, Geophysical Research Letters 35 (2008), https://doi.org/10.1029/2007GL032009.
[3] P. H. Yoon, V. S. Pandey, and D.-H. Lee, Journal of Geophysical Research: Space Physics 119, 1851 (2014).
[4]T. Umeda, S. Saito, and Y. Nariyuki, Astrophys. J. 794, 63 (2014).
[5] G. Barsagade and D. Sharma, Phys. Plasmas 29, 112104 (2022).
[6] A. K. Sanyasi, L. M. Awasthi, P. K. Srivastava, S. K. Mattoo, D. Sharma, R. Singh, R. Paikaray, and P. Kaw, Physics of Plasmas 24, 102118 (2017).

3D High-Resolution Simulation of a Solar Prominence

D. Donné [1] and R. Keppens[1]
[1] *Centre for mathematical Plasma-Astrophysics, KU Leuven, Leuven, Belgium*

In this work we exhibit our findings of a 3D solar prominence simulation with incorporated fine structures. We extend the 2.5D levitation-condensation model of [1] into a 3D context by adding a z-dependence to the footpoint motion of the initial magnetic arcades to form a magnetic flux rope above the polarity inversion line, similar to the work of [2]. By making use of *adaptive mesh refinement* of our open-source `MPI-AMRVAC` code (http://amrvac.org), we solve the governing magnetohydrodynamic equations with included source terms such as anisotropic thermal conduction, optically thin radiative cooling and a fiducial coronal heating term, allowing us to reach resolutions up to $\sim$ 60 km in grid domain on the order of $\sim$ 10 Mm. This allows us to examine the fine structures within the prominence and unveil how mass is transported along the individual magnetic fibrils of the flux rope. We compare our 3D results with its 2.5D counterpart and analyse the differences regarding the final prominence mass as well as its evolution, clarifying aspects that require a full 3D model versus an assumed translationally invariant 2.5D representation.

References

[1] Jenkins, J. M., Keppens, R. (2021). Prominence formation by levitation-condensation at extreme resolutions. Astronomy & Astrophysics, 646, A134.

[2] Kaneko, T., Yokoyama, T. (2017). Reconnection–condensation model for solar prominence formation. The Astrophysical Journal, 845(1), 12.

Metastability of magnetically supported atmospheres

D. N. Hosking[1], D. Wasserman[2], S. C. Cowley[3]

[1] *Princeton Center for Theoretical Science, Princeton, USA*

[2] *Northeastern University, Boston, USA*

[3] *Princeton Plasma Physics Laboratory, Princeton, USA*

The linear and nonlinear stability of a hydrodynamic atmosphere against adiabatic perturbations is determined by the well-known Schwarzschild criterion: an atmosphere is stable if its entropy increases with height[1]. However, the generalisation of this criterion to atmospheres that are partially supported by magnetic pressure only guarantees linear stability. In this contribution, we demonstrate that there exist "metastable" magnetised atmospheres, which are unstable to large perturbations despite being stable to small ones. We show how the density, pressure and magnetic-flux profiles of metastable atmospheres can be derived analytically, demonstrate their nonlinear relaxation using numerical simulations, and explain how the nonlinearly relaxed states can be determined theoretically. We discuss possible applications of the metastability phenomenon to explosive releases of energy in astrophysical and fusion plasmas.

[1] Schwarzschild, K., 1906, Gottinger Nachr., 41.

Nonlinear growthrate of a phase-space electron hole

M. Lesur[1], A. Guillevic[1], D. Mandal[1]

[1] *Institut Jean Lamour, CNRS - Université de Lorraine, Nancy, France*

Self-organisation of phase-space structures is ubiquitous in collisionless (or Vlasov) plasmas. Here we focus on 1D electron-ion plasmas with periodic boundary conditions. The phase-space (PS) of particle trajectories in that case is composed of position x and velocity v. In this context, BGK-like islands in PS with a local deficit of particles, called as a phase-space holes (PS holes) form spontaneously in a range of velocities where ion and electron distribution function have velocity gradients of opposite signs. Growth and acceleration are closely linked to the equilibrium velocity gradient via the Liouville conservation of phase-space density.

The aim of this research is to develop the theory of PS hole growth and acceleration. The Vlasov-Poisson system is solved numerically with the semi-Lagrangian code COBBLES [1]. For each simulation, the initial condition includes a single electron PS hole with prescribed dimensions and shape, which satisfy a non-linear dispersion relation [2]. Fig. 1 shows the measured instantaneous nonlinear growthrate of the PS hole against the bounce time of particles most deeply trapped inside the hole, for 4 different sets of hole parameters. The results are in qualitative agreement with analytical theory, which assumes constant equilibrium velocity gradients in the velocity region spanned by the hole [3, 4]. To improve the validity range of this theory, we account for the variations of velocity gradients, which are in fact significant.

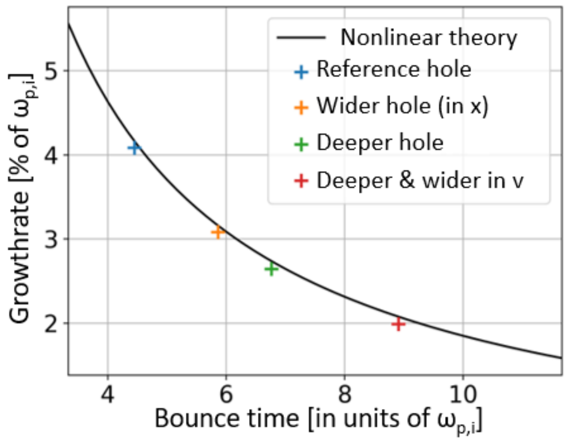


Figure 1: *Nonlinear growthrate of an isolated electron phase-space hole, against the bounce time of particles inside the hole, for 4 sets of hole parameters. The legend indicates how the parameters vary around one reference case. Times normalized to the ion plasma frequency $\omega_{p,i}$.*

Further, based on a similar procedure, but in the context of a gyro-bounce-averaged model [5], we calculate an analytic expression for the nonlinear growth-rate of a PS hole in trapped-particle driven drift-wave turbulence.

References

[1] M. Lesur, Y. Idomura, X. Garbet, Phys. Plasmas **16**, 092305 (2009)
[2] H. Schamel, Plasma Phys. **14**, 905 (1972)
[3] T. H. Dupree, Phys. Fluids **26**, 2460 (1983)
[4] D. J. Tetreault, Phys. Fluids **26**, 3247 (1983)
[5] M. Lesur, et al., Phys. Plasmas **24**, 012511 (2017)

Plasma parameter inference from combined multi-instrument measurements

R. Marchand[1]

[1] *University of Alberta, Edmonton Canada*

Space plasma parameters are usually inferred from measurements made with a single dedicated instrument. However, unless additional information is available concerning the state of the plasma, the inference made from these measurements must rely on assumptions and approximations. This is the case, for example, with plasma density and temperature inferred from Langmuir probes (LP) measurements on satellites, which depend on the plasma flow velocity in the spacecraft frame, the distribution of ion masses, and the satellite potential. Without independent measurements of these parameters, LP inferences must rely on assumptions, which in turn, lead to unknown uncertainties. A technique is presented, based on machine learning, to combine concurrent measurements from different complementary instruments, to make more general inferences of parameters characterizing the state of a plasma while reducing the need for assumptions. The method is applied to the Electric Field Instrument (EFI) instrument on the Swarm satellites. On each satellite, EFI consists of a pair of spherical Langmuir probes, a front plate which can be used as a large planar probe, and a thermal ion imager (TII). Kinetic simulations are carried out to construct a large synthetic data set consisting of instrument low level responses, with corresponding environment plasma parameters such as electron and ion densities, temperatures, plasma flow velocity, and ion effective masses. Following standard machine learning procedures, models are constructed to infer physical parameters and determine confidence intervals from a combination of measurements from these instruments. A case is made for enhancing traditional inference techniques based on theory and approximate analytic expressions, with the use of multivariate regression and well established machine Learning techniques.

Modelling Space Plasma in the Inner heliosphere and its impact on Earth's Magnetosphere

Prateek Mayank[1], Arghyadeep Paul[1], Bhargav Vaidya[1] [1] Indian Institute of Technology Indore, Indore, India

The heliospheric plasma is also a powerhouse for micro-scale processes including magnetic reconnection and particle acceleration. Magnetic reconnection has been detected in a variety of locales, including the Solar corona and planet magnetospheres, and is frequently accompanied by the presence of a velocity shear. Furthermore, macro-physical phenomena occurring inside the heliospheric plasma domain, such as the propagation of Coronal Mass Ejections (CMEs) and the interplay of slow and rapid solar wind, influence in-situ particle acceleration via shocks. Linking various scales that account for the interaction of numerous physical processes necessitates the use of unique numerical modeling methodologies.

In this presentation, I'll discuss new efforts to model space plasma using 3D global-MHD and MHD-PIC models from the open source astrophysical gasdynamics code PLUTO. The discussion will concentrate on how large-scale dynamical processes inside the inner heliosphere affect the Earth's magnetosphere, especially in terms of assessing its geo-effectiveness. Initially, I'll show how ambient solar wind influences CME evolution and how it interacts with stream/corotating interaction zones (SIR/CIR) using the indigenous SWASTi framework [1]. The unique role of CME shocks in creating solar energetic particles, as well as the mechanism of fast reconnection in double layer current sheets as plausible techniques for accelerating particles within the inner heliosphere, would be discussed. Using this toy model, we discovered that the scaling of the reconnection rate with shear is altered due to a structure-driven instability. We also discover that shocklets linked with small plasmoid injections are in charge of energizing particles within the domain's large scale plasmoids [2]. In addition, we will discuss our latest results from the 3D global-MHD, which use the adaptive mesh refinement (AMR) technique to examine the process of magnetic reconnection in a more realistic scenario of dayside magnetopause. The talk will further specifically demonstrate the production and evolution of Flux Transfer Events (FTEs) in our simulation as helical flux ropes at the dayside magnetopause, as well as discuss our unique toolkit for isolating the volumes of these structures using an agglomerative hierarchical structure detection algorithm and studying FTE evolution from a volumetric perspective [3]. Our findings confirm that the mechanism of continual reconnection is the primary cause of FTE development during the early to mid stages of evolution. We also discover that the FTE volumes rapidly drift towards a linear force free configuration over time; however, the continual reconnection prevents this from happening. We also compare the flux content of these FTEs to the estimates supplied by the observational models and discover that the observations regularly underestimate the FTE flux content by a significant margin. Lastly, for assessing the geoeffectiveness of these transient events, we would outline a two-way coupled ionospheric model into the global-MHD model.

References

[1] Prateek Mayank, Bhargav Vaidya, and D. Chakrabarty. SWASTi-SW: Space Weather Adaptive Simulation Framework for Solar Wind and Its Relevance to the Aditya-L1 Mission. *The Astrophysical Journal Supplement Series*, 262(1):23, September 2022.

2. [2] Arghyadeep Paul and Bhargav Vaidya. Effects of a velocity shear on double current sheet systems: Explosive reconnection and particle acceleration. *Physics of Plasmas*, 28(8):082903, August 2021.
3. [3] Arghyadeep Paul, Bhargav Vaidya, and Antoine Strugarek. A Volumetric Study of Flux Transfer Events at the Dayside Magnetopause. *The Astrophysical Journal*, 938(2):130, October 2022.

Coherent structures and complexity-entropy in intermittent plasma turbulence

R. A. Miranda[1], A. C.-L. Chian[2,3], J. A. Valdivia[4], A. L. Piragibe[1], S. G. S. P. Costa[1]

[1] *University of Brasilia, Brasilia-DF, Brazil.*

[2] *University of Adelaide, Adelaide-SA, Australia.*

[3] *National Institute for Space Research, São José dos Campos-SP, Brazil.*

[4] *Universidad de Chile, Santiago, Chile.*

The solar wind is a natural laboratory for the study of turbulence in plasmas. The power spectrum of magnetic field fluctuations in the interplanetary solar wind displays an inertial subrange with power-law scaling and spectral index of -5/3, which is indicative of a turbulent state. The magnetic field turbulence displays intermittency evidenced by non-Gaussian probability distribution functions, departure from self-similarity, multifractality, and amplitude-phase synchronization among scales.

Intermittency within the inertial subrange is due to the presence of coherent structures which dominate the statistics of complex fluctuations at small scales. Here we demonstrate that coherent structures are responsible for the decrease of disorder and the increase of complexity in turbulent plasmas. We apply the normalized Shannon entropy to the spatiotemporal patterns of the magnetic field obtained from numerical simulations of a three-dimensional incompressible MHD model of a Keplerian shear flow. We also compute the Jensen-Shannon entropy-complexity index of magnetic field data within reconnection exhausts detected in the solar wind at 1 AU. Our results show that coherent structures are responsible for decreasing entropy and increasing complexity in turbulent plasmas.

References

[1] A. C.-L. Chian, H. Q. Feng, Q. Hu, M. H. Loew, R. A. Miranda, P. R. Muñoz, D. G. Sibeck and D. J. Wu, The Astrophysical Journal 832:179 (2016).

[2] A. C.-L. Chian, et al. Reviews of Modern Plasma Physics, 6:34 (2022).

[3] R. A. Miranda, E. L. Rempel, A. C.-L. Chian. Monthly Notices of the Royal Astronomical Society 448 (2015).

[4] R. A. Miranda, J. A. Valdivia, A. C.-L. Chian and P. R. Muñoz, The Astrophysical Journal 923:132 (2021).

Electromagnetic Turbulence in Magnetospheric Plasmas

R. Numata[1]

[1] *Graduate School of Information Science, University of Hyogo, Kobe, Japan*

It is well known that plasmas in planetary magnetospheres are confined due to the inward pinch phenomenon whereby particles are transported against the density gradient. Turbulent transport due to the electrostatic entropy mode can be a possible mechanism for the inward pinch. Gyrokinetic simulations of the entropy mode in a dipole configuration have successfully demonstrated the existence of a particle pinch regime [1]. However, the observed plasmas in the RT-1 magnetospheric experiment and in planetary magnetospheres are generally high-beta, therefore electromagnetic effects may play roles in determining turbulent transport. In fact, magnetic fluctuations associated with the inward diffusion in RT-1 are reported [2]. In this work, we extend the studies of turbulent transport in a dipole configuration to high-beta plasmas.

We have performed linear and nonlinear gyrokinetics simulations using GS2 code including electromagnetic effects, namely the change in the equilibrium due to high pressure and the inclusion of magnetic fluctuations. We mainly consider the Z pinch configuration, as a limiting case of the dipole configuration, where the magnetic field along the field line is constant. In the Z pinch, there's no magnetic shear, and the curvature of the magnetic field and density gradient are the energy source for driving the entropy mode. Figure 1 shows the particle transport against the density gradient for $\beta = 1$. The particle flux shows similar dependence on the density gradient as in the electrostatic case [3]. The particle transport is reduced by self-generated zonal flows (and zonal magnetic fields in the electromagnetic case) when the gradient is weak. In some case, we observe the zonal flows/fields are destroyed and transport increases. In the presentation, we discuss how the electromagnetic effects change the transport properties in the Z pinch and dipole configurations.

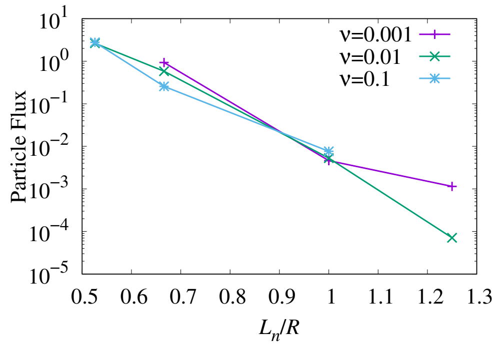


Figure 1: Particle flux against the density gradient for $\beta = 1$.

References

[1] S. Kobayashi, B. N. Rogers and W. Dorland, Phys. Rev. Lett. **105**, 235004 (2010).
[2] N. Kenmochi, *et al.* Nucl. Fusion, **62**, 026041 (2022).
[3] P. Ricci, B. N. Rogers and W. Dorland, Phys. Rev. Lett. **97**, 245001 (2006).

Gyrofluid simulations of energy and generalized cross-helicity cascades for imbalanced Alfvenic turbulence

T. Passot[1], P.L. Sulem[1], D. Laveder[1], and G. Miloshevich[2]

[1]*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, CS 34229, 06304 Nice, France*
[2]*Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212 CEA-CNRS-UVSQ, IPSL & U Paris-Saclay, CE Orme des Merisiers, Gif-sur-Yvette, 91191, France*

A two-field Hamiltonian gyrofluid model for kinetic Alfvén waves in a collisionless plasma, retaining ion finite Larmor radius corrections and parallel magnetic field fluctuations [1,2], is used to study direct turbulent cascades from the magnetohydrodynamic to the sub-ion scales [3]. In addition to the energy, this model has another invariant, referred to as generalized cross-helicity (GCH), which identifies with the cross-helicity at the magnetohydrodynamic scales and with the magnetic helicity at the sub-ion scales. It is known that cross-helicity cascades to small scales and magnetic helicity to large scales [4], resulting in the presence of a "helicity barrier" at the ion scale, discussed in Meyrand et al. (J. Plasma Phys. **87**, 535870301, 2021) in the case of strong magnetic fluctuations. Our simulations show that, in the weak amplitude regime, the perpendicular flux of GCH displays a significant decay past the ion scale, confirming the presence of a GCH barrier in this case also. In both regimes, the spectrum of the transverse magnetic field displays a steep transition zone near the ion scale, as commonly observed in the solar wind. Nevertheless, in the weak amplitude regime, the perpendicular energy flux remains almost constant and transfer and dissipation in the parallel direction remain weak. This contrasts with the case of strong magnetic fluctuations where both invariants dissipate strongly in the parallel direction, at the transverse ion scale, in order to circumvent the perpendicular barrier, through a process which, in a full kinetic description, involves ion-cyclotron resonance (Squire et al., Nat. Astron. **6,** 715–723). A phenomenological model suggests that the interactions between co-propagating waves present at the sub-ion scales can play a central role in the development of a transition zone in the presence of a helicity barrier at small amplitudes where ion-cyclotron waves are not expected to be efficiently excited.

[1] Passot, T., Sulem, P.L. & Tassi, E. 2018 Gyrofluid modeling and phenomenology of low-β_e Alfvén wave turbulence, Phys. Plasmas **25**, 042107.
[2] Passot, T. & Sulem, P.L. 2019 Imbalanced kinetic Alfvén wave turbulence: from weak turbulence theory to nonlinear diffusion models for the strong regime, J. Plasma Phys. **85**, 905850301.
[3] Passot, T., Sulem, P.L. & Laveder, L. 2022 Direct kinetic Alfvén wave energy cascade in the presence of imbalance, J. Plasma Phys. **88**, 905880312.
[4] Miloshevich, G., Laveder, D., Passot, T. & Sulem, P.L. 2021 Inverse cascade and magnetic vortices in kinetic Alfvén-wave turbulence, J. Plasma Phys. **87**, 905870201.

Exploring the Dynamic Interplay between Kinetic Alfvén Waves and Magnetic Structures in the magnetosphere

Garima Patel, R.Uma, R.P.Sharma

Department of Energy Science and Engineering, Indian Institute of Technology, New Delhi, India, 110016

The nonlinear interaction between kinetic Alfvén waves (KAWs) and null points in the magnetosphere can result in the transfer of energy and the release of stored magnetic energy in the form of particle acceleration and generation of heat. KAWs are a type of plasma wave that can propagate in the magnetosphere and are generated by the motion of charged particles in a magnetic field [2]. Null points, on the other hand, are locations where the magnetic field strength is zero and the magnetic field lines intersect. Magnetic reconnection which can cause a change in the magnetic field configuration plays a cradle role for this interaction to take place [1, 3].

In this work, We have studied the nonlinear interaction and the temporal evolution of the spawned structures. Being coherent and symmetric at the outset, we observed these structures to be chaotic and turbulent in nature. As these turbulent structures grow further, these waves can cause changes in the magnetic field strength, direction and play a pivotal role in the dynamics of the magnetosphere. This process can have significant effects on the dynamics of the magnetosphere and the radiation environment in the region.

To examine these structure developed in the magnetosphere by the nonlinear interaction of propagating KAW and null points, we proposed a 3D Kinetic Alfven wave model. We have used the finite difference method for temporal domain and pseudo spectral approach with the predictor-corrector method for spatial domain to solve and simulate this model equation. The numerical simulation demonstrates that without nonlinearity, the field structure changes slowly, but keeping the pondermotive nonlinearity on, it changes rapidly and approaches quasi-steady state with a fully chaotic structure, indicating turbulent filamentation with further temporal evolution. Further we have also done the semianalytical analysis and studied the current sheet structures.

References

[1] J. W. Dungey. Interplanetary magnetic field and the auroral zones. *Phys. Rev. Lett.*, 6:47–48, Jan 1961.

[2] Chaston et. al. Drift-kinetic alfvén waves observed near a reconnection x line in the earth's magnetopause. *Phys. Rev. Lett.*, 95:065002, Aug 2005.

[3] Vytenis M. Vasyliunas. Theoretical models of magnetic field line merging. *Reviews of Geophysics*, 13(1):303–336, 1975.

A new plasma instability driven by cosmic rays sets their transport speed and feedback strength in galaxies

C. Pfrommer, M. Shalaby, T. Thomas

Leibniz-Institut für Astrophysik Potsdam (AIP), Potsdam, Germany

Understanding the plasma physics underlying galaxy formation is an outstanding problem in modern astrophysics. Recent simulations of forming galaxies have demonstrated that cosmic rays accelerated at supernovae appear to be an important agent in driving galactic-scale winds from the interstellar to the circumgalactic medium, which is critical in obtaining realistic disk galaxies and to slow down star formation to the small observed rates. The power of galactic winds critically depends on the macroscopic cosmic ray transport coefficient, which in turn is governed by cosmic ray-driven instabilities. These instabilities amplify magnetic fields and modulate cosmic ray transport so that the intrinsically collisionless cosmic ray population is tightly coupled to the thermal plasma and provides dynamical feedback. Here, we show that cosmic rays with a finite pitch angle drive electromagnetic waves (along the background magnetic field) unstable on intermediate scales between the gyro-radii of ions and electrons as long as cosmic rays are drifting with a velocity less than a factor $\sqrt{m_\mathrm{i}/m_\mathrm{e}}/2$ times the Alfvén speed. By solving the linear dispersion relation, we show that this new intermediate-scale instability typically grows faster by more than an order of magnitude in comparison to the commonly discussed resonant instability at the ion gyroscale. We identify the growing modes as background ion-cyclotron modes in the frame that is comoving with the cosmic rays. Particle-in-cell simulations enable us to study the non-linear saturation of this instability. Most importantly, this new instability helps to solve another major problem in galactic cosmic ray transport: fast ion-neutral damping damps Alfvén waves grown via the gyroscale instability throughout the entire galaxy, thus presenting a major problem in understanding cosmic ray scattering and their transport in galaxies. Because the unstable background ion-cyclotron modes are comoving with the cosmic rays, their polarity changes in the galactic rest frame so that they are not subject to fast damping and can provide the required cosmic ray scattering. This demonstrates the need of this new instability to modulate the transport of cosmic rays and their feedback strength in galaxies and galaxy clusters.

References

[1] M. Shalaby, T. Thomas and C. Pfrommer, ApJ, **908**, 206 (2021).

Obliquely Propagating Nonlinear Electrostatic Waves With (r,q) Distributed Electrons in Space Plasmas

M. N. S. Qureshi

Department of Physics, GC University, Lahore 54000, Pakistan

Abstract

Electron velocity distributions (EVDs) in space plasmas, such as bow shock, magnetosheath and Earth's magnetosphere, are frequently observed with flat tops at the low energies and enhanced tails at high energies. Such observed distributions can only be fitted with the two spectral indices generalized (*r*,*q*) distribution function. In the limiting cases $r > 0, q \to \infty$, $r = 0, q \to (\kappa + 1)$ and $r = 0, q \to \infty$ the (*r*,*q*) distribution reduces to Druyvesteyn-Davydov, kappa and Maxwellian distributions, respectively. Fittings of these observed distributions show that neither Maxwellian nor kappa distributions fit the observed EVDs at low energies as well at high energy part. We, thus employ the (*r*,*q*) distribution function for electrons and derive the expression of density. By adopting the fully nonlinear Sagdeev potential technique, we derive the Sagdeev potential for electrostatic waves such as ion-acoustic and Langmuir waves, using the values of the spectral indices *r* and *q* which fit the observed distributions. We found that propagation characteristics of such nonlinear waves alter significantly from the Maxwellian or kappa values.

Magnetospheric Electromagnetic Ion Cyclotron Waves originated by Multi-Ion Oscillitons

Konrad Sauer[1] and Eduard Dubinin[2]

[1]Retired from Max-Planck-Institute of Solar System research, Göttingen, Germany. [2]Max-Planck Institute of Solar System Research, Göttingen, Germany.

The recent spacecraft observations by MMS and Van Allen Probes associated with electromagnetic ion cyclotron (EMIC) waves in the Earth magnetosphere emphasize the important role of multi-ion plasma composition for generation and characteristics of these emissions. We show that main properties of the coherent EMIC waves can be explained with the concept of “multi-ion oscillitons” (Sauer et al., 2001). In a plasma with two types of ions of different masses (e.g., protons and oxygen ions), oscillitons arise from the exchange of momentum and energy between the two ion components, with the electromagnetic field acting as a mediator. At frequencies near cross-over frequencies of different wave modes in the multi-ion plasma the nonlinear resonance which strongly amplifies the seed unstable mode can be excited. A small phase difference in oscillations of different ion species leads to a nonlinear wave beating and generation of wave packets. The “resonance” frequency is characterized by a local maximum of the phase velocity and the coincidence of phase and group velocity. It is suggested that the oscillitons are triggered by the instability due to the proton temperature anisotropy and may survive outside the source region for long distances. The generation of coherent waves by oscillitons is of a general nature and may contribute to understand the manifold of phenomena in other space plasma environments in which the dynamics of minor ion admixtures cannot be neglected. The concept of oscillitons can also be applied to the momentum exchange between particle groups of the same mass, but different temperature.

Nonlinear interaction of low-frequency Alfvén waves and ions

Xianshu Wu[1], Chao Shen[2], Kehua Li[1], Jiaqi Dong[3], Jingchun Li[1]

[1] *Department of Earth and Space Sciences, Southern University of Science and Technology, Shenzhen 518055, China.*

[2] *School of Science, Harbin Institute of Technology, Shenzhen 518055, China.*

[3] *Southwestern Institute of Physics, Chengdu 610041, China.*

Introduction

The plasma heating by the Alfvén waves is generally believed to be one of the significant possible dissipative mechanisms for explaining the dynamics of coronal heating and solar wind acceleration [1–3]. Low-frequency Alfvén waves are generally considered to have no strong interaction with ions to accelerate or heat plasma because their frequency, which is lower than the ion cyclotron frequency, does not meet the cyclotron resonant condition ($\omega - k_{\|}v_{\|} = n\Omega_p$, where n is an integer). The theoretical analysis and numerical experiments done by Wu et al. [4] show that ions can be picked up by the large amplitude low-frequency Alfvén waves through nonlinear interactions even if the cyclotron resonance condition is not satisfied. Similarly, Chen and White [5] studied heating by the obliquely propagating low-frequency Alfvén waves and found that significant perpendicular stochastic heating can be obtained with a sufficiently large wave amplitude. Kolesnychenko et al. [6] demonstrated that the nonlinear subharmonic resonance exists for any $k_\perp$ and not for $k_\perp = 0$ only, and it can decrease the stochasticity threshold when $k_\perp \neq 0$. Lu et al. [7] extended Kolesnychenko et al. [6] work and showed that the increase of frequency, propagation angle and the number of modes can decrease the threshold when spectrum waves are taken into consideration.

Karney [8] was the first to use Poincare plot to study the stochastic state of particles during interactions with waves. Chen et al. [5]discussed the oblique propagating waves with the help of the Poincare plot. However, no one has studied the parallel propagating waves by Poincare plot. The motion of ions in parallel propagating waves field are simple and regular without carrying any chaos. For multiple modes, Lu et al. discussed the influence of various parameters on the threshold of stochastic heating. However, the actual heating effect by multiple waves was not discussed.

Simulation

The left-hand circularly polarized waves that propagate parallel to the ambient magnetic field are used in this work. Moreover, the heating and acceleration of plasma caused by waves are studied. We assume that the background magnetic field $B_0 = B_0\mathbf{i}_z$, and the Alfvén wave is nondispersive with $\omega = k_z v_A$, where $v_A = B_0/(4\pi n_0 m_i)^{1/2}$ is the local Alfvén wave speed. Thus, the electromagnetic field of the wave can be expressed as follows.

$$\mathbf{B}_w = \sum_j B_j \left(\cos\psi_j \mathbf{i}_x - \sin\psi_j \mathbf{i}_y\right) \tag{1}$$

$$\mathbf{E}_w = -v_A \mathbf{i}_z \times \mathbf{B}_w \tag{2}$$

Where $\mathbf{i}_x, \mathbf{i}_y$ and $\mathbf{i}_z$ are the unit vectors of the three dimensions. $\psi_j = k_{jz}z - \omega_j t + \phi_j$ is the phase of the wave, and ϕ_j denotes the random phase of mode j. The particle equation of motion in the wave field can be summed up as follows.

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{q_i}{m_i}\left[\mathbf{v} \times (\mathbf{B}_0 + \mathbf{B}_w) + \mathbf{E}_w\right] \tag{3}$$

$$\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = \mathbf{v} \tag{4}$$

Where the subscript i indicates ions labeled as i. The coupling between those variables of the entire system shows a strong nonlinear effect, which cannot be solved by the general analytical methods.

The acceleration and heating mechanism of ions in parallel propagating Alfvén wave field is explained by the mapping on the Poincaré section of the system mentioned above. To obtain the Poincaré section of the ions, we used a test particle simulation to study the differential equation system by ignoring the influence of particle motion on waves. The Boris algorithm has been used to solve equations. The time step was $\Delta t = 0.025\Omega_p^{-1}$. Initially, all particles were placed in the same position, which was the center of the simulation space. The length of the space in each direction was $40000 v_A \Omega_p^{-1}$. For sake of simplicity though, the simulation is one-dimensional that only position change along the background magnetic field was considered, it is also the direction of wave propagating to.

Results and discussion

Through the Poincaré plot to analysis the interaction process of low-frequency Alfvén wave propagated parallel to the ambient magnetic field with plasma qualitatively, the parallel velocity of ions will change periodically as shown in Fig. 1. In the wave frame, ions are accelerated in the direction of wave propagation within the phase interval $-\pi/2 \sim \pi/2$, and the parallel (background magnetic field) direction velocity at the initial moment is maintained in other intervals. This effect can be enhanced by increasing the frequency or amplitude. The macroscopic physical quantities of plasma will show oscillation in the early stage of interaction due to the velocity changes on ion's microscopic scale, during this time, ions in velocity phase space will be scattered into arc-shaped band distribution due to the energy conservation in the frame of wave. While the ions scattering uniformly, macroscopic quantity get equilibrium eventually. Moreover, the whole process can be easily divided into two stages: "Non-resonant heating" and "Stochastic heating" according to the Poincaré plot.

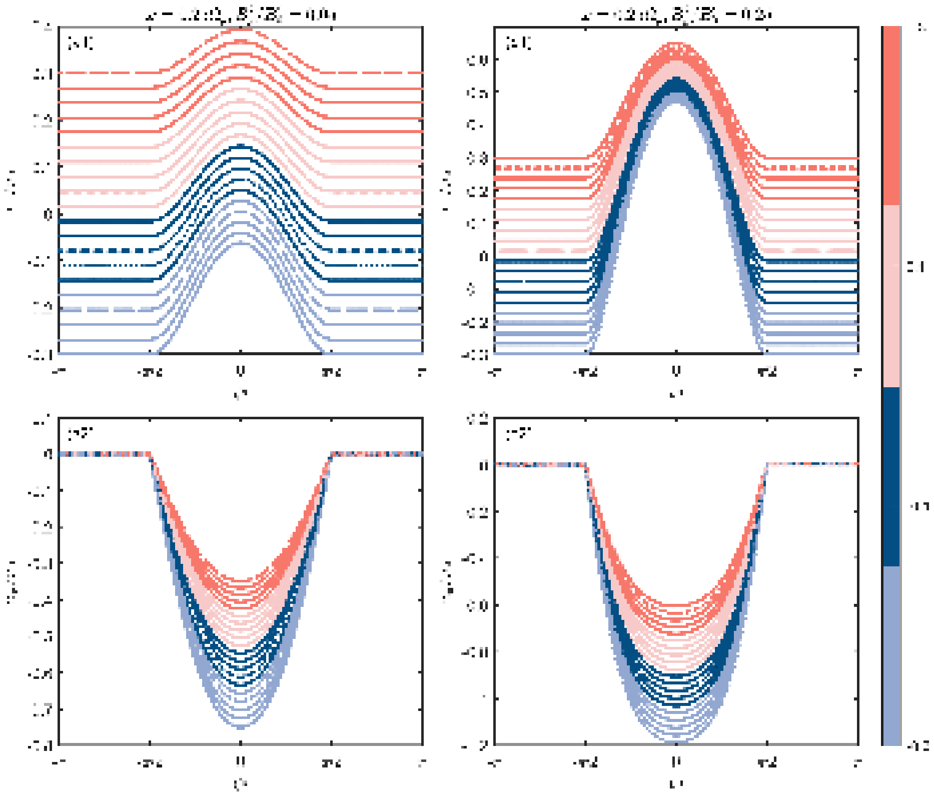


Figure 1: Poincaré plot of parallel propagating Alfvén wave when it interacts with ions.

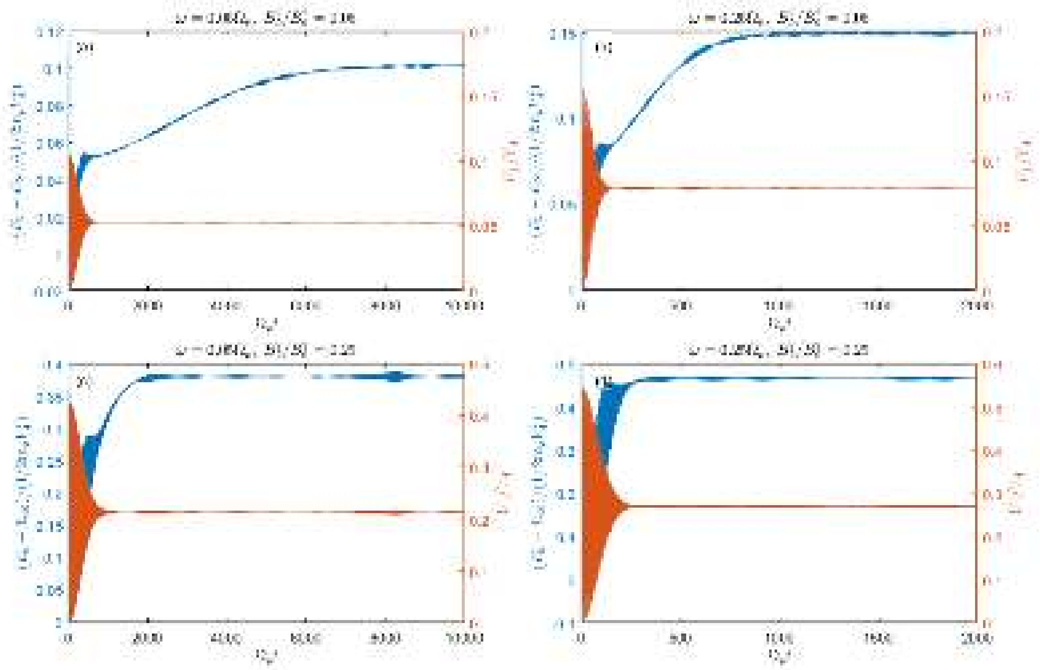


Figure 2: The evolution of plasma energy over time, you can clearly see the two different stages of "Non-resonant heating" and "Stochastic heating".

The waves with a spectrum have been considered in this study as well. The stochastic regions appear with the spectrum, which do not effectively enhance the heating in this work. Stochastic region or "chaos structure" in Poincaré plot of oblique propagating waves can obtain a significant perpendicular stochastic heating, which is different from our results. The stochasticity in our multi-waves study is caused by the turbulent fluctuation of magnetic field. However, the chaos in the oblique propagating waves case can undergo a complete transition from regular to chaos with the increasing of wave amplitude. Although the chaos existed in the motion of ions, a sufficiently weak magnetic field generate by multi-waves superposed still can make the heating noneffective. The effect of the random phases of each wave should be discussed as well. However, the heating of plasma by waves with a spectrum is so complicated that we discussed the identical frequency wave modes instead. An apparent regularity and nonlinearity were found in this case.

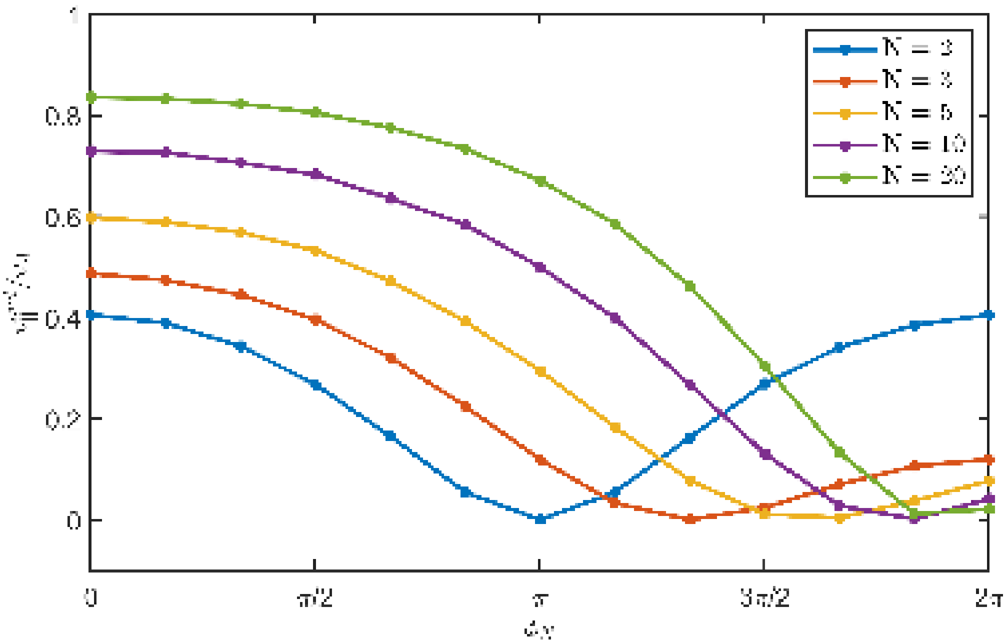


Figure 3: Influence of the range of random phase distribution of multiple waves on heating effect.

References

[1] H.F. Liu, C.J. Tang, X.Q. Wang, X. Zhang, Y. Zhao, ApJ **829**(1), 36 (2016)

[2] J. Zhao, L. Lee, H. Xie, Y. Yao, D. Wu, Y. Voitenko, P. Viviane, ApJ **930**(1), 95 (2022)

[3] B. Wang, C.B. Wang, P.H. Yoon, C.S. Wu, Geophysical Research Letters **38**(10) (2011)

[4] C.S. Wu, P.H. Yoon, J.K. Chao, Physics of Plasmas **4**(3), 856 (1997)

[5] L. Chen, Z. Lin, R. White, Physics of Plasmas **8**(11), 4713 (2001)

[6] O.Y. Kolesnychenko, V.V. Lutsenko, R.B. White, Physics of Plasmas **12**(10), 102101 (2005)

[7] Q. Lu, L. Chen, ApJ **704**(1), 743 (2009)

[8] C.F.F. Karney, The Physics of Fluids **21**(9), 1584 (1978)

Experimental study of the relationship between asymmetric plasma background structure and plasma turbulence

T-K. Kobayashi[1], A. Fujisawa[2], Y. Nagashima[2], C. Moon[2], T. Nishizawa[2], S. Inagaki[3], T. Yamada[4], Y. Kosuga[2], K. Yamasaki[5], D. Nishimura[1], Y. Guo[1]

[1] *IGSES, Kyushu University, Fukuoka, Japan,* [2] *RIAM, Kyushu University, Fukuoka, Japan,* [3] *IAE, Kyoto University, Kyoto, Japan,* [4] *FAS, Kyushu University, Fukuoka, Japan,* [5] *GSASE, Hiroshima University, Hiroshima, Japan*

Recently, it has become clear that plasma turbulence is "global" and "asymmetric," and there is a growing need for global measurements of the entire plasma to advance our understanding of plasma. Therefore, tomography measurement has been attracting attention, and our laboratory have demonstrated tomography measurement of the entire plasma in linear plasma and we have been conducting research based on 2D measurement of plasma turbulence.

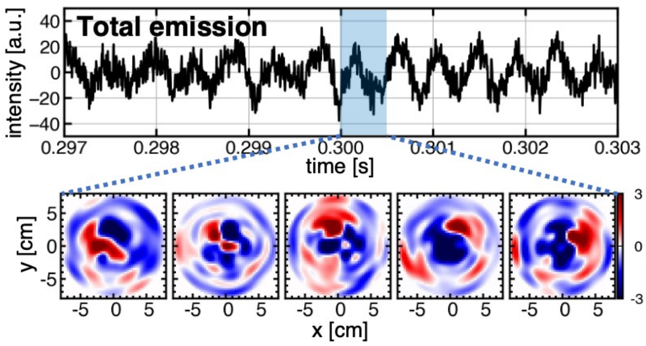


Figure 1: *Distortion in temporal evolution of spatial pattern of plasma turbulence.*

In previous studies, the entire plasma measurement using the tomography found, as is shown in Figure1, that the solitary oscillation dominated by m=2 structure should be not rotationally symmetric and spatiotemporally distorted [1]. In addition, it was also found that asymmetry existed in the plasma background structure, and we hypothesized that the existence of background asymmetry might cause distortion in the spatial patterns of the solitary oscillation. Therefore, we extracted the deterministic trend of solitary oscillation using conditional averaging and, we investigated the relationship between the deterministic trend and the background structure using pattern recognition [2,3]. The results suggest that these distortions are caused by the nonlinear interaction with the background structure. Moreover, we have found that the distorted spatial patterns could be described by the contamination of linear polarization to circular ones and that the emergence the linear polarization could be ascribed to a nonlinear coupling between the background structure and the dominant m=2 mode. In this paper, we present a series of obtained results of the tomography measurement in PANTA, and discuss a nonlinear coupling model that can describe the observed distortion quantitatively in the solitary oscillation.

This work was supported by JST SPRING, Grant Number JPMJSP2136, and by JSPS KAKENHI JP22H00120.

[1] C. Moon *et al.*, Sci. Rep. **11**, 3720 (2021).
[2] T.-K. Kobayashi *et al.*, Plasma Phys. Control. Fusion **63**, 032001 (2021).
[3] T.-K. Kobayashi *et al.*, Plasma Fusion Res. **16**, 1201082 (2021).

Simulation of the formation and structuration of a diamagnetic cavity in laser experiments

M. D. Menu[1], B. Bernecker[1,2], C. Couillaud[1], S. Bouquet[1,2]

[1] *CEA, DAM, DIF, F-91297 Arpajon, France*

[2] *Université Paris-Saclay, CEA, LMCE, Bruyères-le-Châtel, France*

The expansion of an energetic plasma in an ambient magnetic field has various applications among domains from laboratory experiments to astrophysics. One of the first stages observed is the generation and growth of a diamagnetic cavity, inside which the magnetic field almost vanishes, due to fast ions going through the magnetic field lines.

Once the diamagnetic cavity is formed, several boundary instabilities are allowed to rise, like the Rayleigh-Taylor instability or the large Larmor radius instability. These instabilities lead to a structuration of the plasma, appearing mainly as striations or flutes at the interface [1].

During the last decades, these phenomena have been studied with full-particle, hybrid or non-ideal magnetohydrodynamics (MHD) codes and compared to laser experiments results [2]. We propose to use an adapted version of the 3D multi-fluid MHD code CLOVIS, initially developed to investigate ionospheric natural disturbances. The model is based on Euler equations for the neutral fluid and Euler-Maxwell equations with ideal MHD assumptions for the charged fluid.

Our simulation results were already able to reproduce features of a diamagnetic cavity observed in baryum releases experiments [3]. Further advances in the development of CLOVIS allow us to explore conditions closer to laser experiments, and compare our measurements of the cavity radius to those found in experimental studies. Other key features will be exploited such as the emergence of striations at the plasma edge or the size of these structures, as they provide valuable insights on the growth of instabilities.

References

[1] Cauvet, Q., Bernecker, B., Bouquet, S., Canaud, B., Hermeline, F. and Pichon, S., Effect of collisions with a second fluid on the temporal development of nonlinear, single-mode, Rayleigh-Taylor instability, Physical Review E, 105(6), (2022)

[2] Winske, D., Huba, J. D., Niemann, C. and Le, A., Recalling and Updating Research on Diamagnetic Cavities: Experiments, Theory, Simulations, Frontiers in Astronomy and Space Sciences, 5, (2018)

[3] Bernecker, B., Simulation of the Formation and Structuration of a Diamagnetic Cavity in a Magnetosphere Barium Cloud, 48th EPS Conference on Plasma Physics (2021)