Status and physics basics of the SMall Aspect Ratio Tokamak (SMART)

D. J. Cruz-Zabala[1], M. Garcia-Munoz[1], A. Mancini[1], J. Segado-Fernandez[1], E. Viezzer[1], J. Dominguez-Palacios[1], J. Ayllon-Guerola[1], J. Berkery[2], F. Poli[2], M. Podesta[2], J. Galdon-Quiroga[1], L. Velarde-Gallardo[1], L. Delgado-Aparicio[2], A. Diallo[2], S. Munaretto[2]

[1] *University of Seville, Seville, Spain*

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

In this contribution, a review of the SMall Aspect Ratio Tokamak (SMART), its physics predictions and details of its commissioning will be presented. SMART is a new spherical tokamak (ST) currently being assembled at the University of Seville. SMART is designed to allow flexible shaping with triangularities $-0.6 \leq \delta \leq 0.6$, aspect ratios $1.4 \leq A \leq 3.0$, elongations $\kappa < 3$ and major radius $R_{maj} = 0.45$ m operating at $B_t \leq 1$ T and $I_p \leq 1$ MA. This new machine aims at exploring the combination of negative triangularity (NT) with low aspect ratio and its possible exploitation as scenario for a compact fusion power plant [1-4]. The magnetic system is composed by 12 toroidal field coils, 4 pairs of poloidal field coils and a central solenoid with 290 turns and 25 cm diameter. After an initial phase of ohmic heated plasmas, SMART plasmas will be heated by a Neutral Beam Injection (NBI) system with $P_{NBI} = 1$ MW and injection energy of 30 keV for hydrogen ions.

The target plasma scenarios have been designed following an iterative process between the FIESTA code for the magnetic equilibrium and coil settings (currents, positioning and geometry) and the ASTRA code for evaluating the plasma performance. Examples of plasma equilibria in the SMART tokamak are shown in figure 1. The NBI parameters have been optimized using the ASCOT and the TRANSP codes. Stability studies have been performed using the MARS-F code for linear MHD simulations and the MEGA code for non-linear MHD simulations. It has been observed that NT provides a smaller stable operational window against edge current and pressure gradient driven modes compared to positive triangularity.

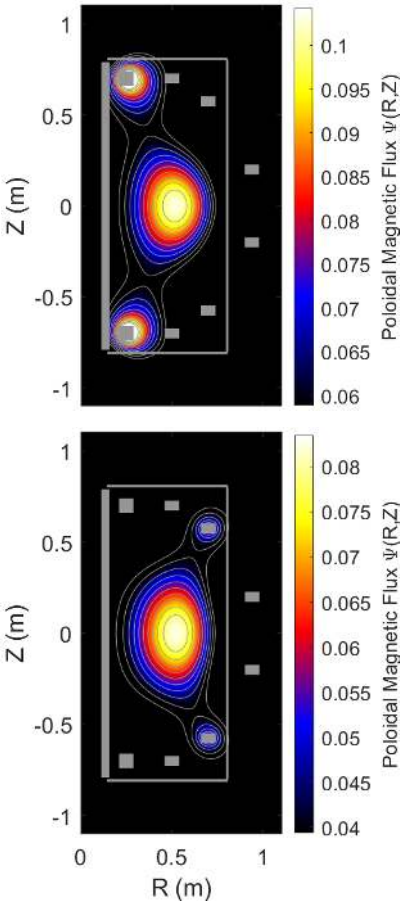

Figure 1. Examples of positive triangularity (upper figure) and negative triangularity (lower figure) plasmas designed for SMART

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Fast-ion losses induced by edge instabilities across different confinement regimes

J. Galdon-Quiroga[1], J.Poley-Sanjuan[2], J.F.Rivero-Rodriguez[3], A.Jansen Van Vuuren[1], M.Faitsch[4], G.F.Harrer[5], A.N.Karpushov[2], C.Michael[3], E.Parr[3], W.Suttrop[4], M.Vallar[2], L.Velarde[1] and the ASDEX Upgrade[a], TCV[b] and MAST Upgrade[c] Teams

[1] *University of Seville, Seville, Spain*

[2] *Ecole Polytechnique Fédérale de Lausanne, Swiss Plasma Center, Laussane, Switzerland*

[3] *Culham Science Centre, Culham, United Kingdom*

[4] *Max Planck Institute for Plasma Physics, Garching bei Muenchen, Germany*

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

Previous experiments in H-mode plasmas at ASDEX Upgrade showed that edge localized modes (ELMs) lead to increased levels of fast-ion losses, featuring an accelerated beam-ion population in low collisionality plasmas ($\upsilon<0.4$) [1]. In this contribution we extend this investigation by performing experiments in different confinement regimes in ASDEX Upgrade, TCV and MAST-U. The main diagnostics used in this study are scintillator based fast-ion loss detectors (FILD), which are available in all three devices. In ASDEX Upgrade, the effect of filaments in the Quasi-Continuous Exhaust regime (QCE) [2,3] is investigated. As the plasma transitions from an ELMy regime into QCE, the large ELM-induced spikes disappear from the FILD signal, while an increase in its mean and standard deviation is observed. The intermittency of the signal is investigated by analysing the probability density function of the signal level, which is compared against other regimes such as L-mode, I-mode and ELM mitigated/suppressed plasmas using externally applied magnetic perturbations. In TCV and MAST-U experiments performed in type-I and type-III ELMy regimes (respectively) confirm the correlation between the occurrence of ELMs and increased fast-ion losses. In both cases, the velocity-space of the fast-ion losses shows multiple structures in pitch angle, at energies equal or below the neutral beam injection energy. In TCV different levels of collisionality are explored ranging from $\upsilon\sim0.2$ to $\upsilon\sim1.6$. At low collisionality, magnetic activity correlated with ELMs is observed in three frequency branches of approximately 50, 120 and 180 kHz. These modes, which are also captured by the FILD detector, disappear as collisionality is increased. Orbit following simulations are carried out with ASCOT [4], including realistic NBI deposition in the scrape-off layer, in order to determine if the differences in signal level and velocity-space can be explained by changes in the edge kinetic profiles.

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

Impact of molecular emissions on impurity Charge Exchange Recombination Spectroscopy in the separatrix and Scrape-Off Layer

K. McKay[1], D.J. Cruz-Zabala[1], E. Viezzer[1], R. López-Cansino[1], A. Rodríguez-González[1], U. Plank[2], R.M. McDermott[2], R. Dux[2] and the ASDEX Upgrade Team

[1] *Dept. of Atomic, Molecular and Nuclear Physics, University of Seville, Seville, Spain*

[2] *Max-Planck Institut für Plasmaphysik, Garching, Germany*

When seeking to accurately determine edge plasma profiles, the behavior of atoms and molecules alike often must be taken into account during measurement analysis. One typical diagnostic method is Charge Exchange Recombination Spectroscopy (CXRS), which ascertains ion tem- perature, rotation, and density from the emission spectrum produced by charge exchange re- actions between injected neutrals and the plasma ions. However, if the injected neutrals are molecules, the light spectrum can be contaminated by molecular line emissions and produce inaccurate characteristic measurements.

To address molecular contamination of CXRS spectra, this work develops a multi-Gaussian fitting method capable of identifying and subtracting molecular lines from the complex spectra detected by the CXRS diagnostics at the ASDEX Upgrade tokamak. Impurity profiles are ob- tained from discharges in three different confinement regimes (H-mode, L-mode, and I-mode), with focus on the plasma edge and Scrape-Off Layer (SOL), where molecular contamination is most likely to occur [1]. For all three regimes, the multi-Gaussian fit is able to correctly identify molecular contributions, with results corroborated by simulated neutral density profiles modeled by the 1D kinetic code KN1D. Both the multi-Gaussian fitting method and the KN1D simulations show the greatest molecular contributions occurring in the SOL, with molecules penetrating farther in L-mode and I-mode as compared to H-mode.

FIDASIM, a code used to model charge exchange signals in magnetically confined plasmas, has been updated in acknowledgement of these results, expanding capabilities to include molec- ular contributions to gas-puff CXRS modelling. Overall, this work finds that molecular emis- sions have the potential to impact CXRS measurements in the SOL for all three confinement regimes analyzed, with the effects most likely to reach the separatrix in L-mode. FIDASIM modeling capabilities are updated to produce more reliable edge results.

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Effect of Edge Localised Modes and Magnetic Perturbations on fast-ion confinement in MAST-U

L. Velarde[1], J.F. Rivero-Rodríguez[2], J. Galdón-Quiroga[3], D. Ryan[2], L. Sanchís[4], R. Chacartegui[1], M. Garcia-Muñoz[3], K. McClements[2], J. Rueda-Rueda[3], E. Viezzer[3], T. Williams[2,5] and the MAST Upgrade team*

[1] Department of Energy Engineering, University of Seville, Seville, Spain

[2] United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxon, UK

[3] Department of Atomic, Molecular and Nuclear Physics, University of Seville, Seville, Spain

[4] Department of Applied Physics, Aalto University, FI-00076, Espoo, Finland

[5] Department of Physics and Astronomy, University of Exeter, Stocker Road, Exeter, UK

Instabilities such as Edge Localised Modes (ELMs) can enhance fast-ion losses, leading to damaging heat fluxes on the first wall [1, 2]. Externally applied Magnetic Perturbations (MPs) are used to mitigate, and even supress these instabilities [3]. This suppression technique is still under investigation in many tokamaks, and its understanding is crucial for future fusion devices like ITER, as applying these perturbations can also have an effect on fast-ion confinement [4]. Fast-ion losses are being directly measured and analysed in MAST-U, using a scintillator-based Fast-Ion Loss Detector (FILD) [5]. FILD consists of a probe near the plasma edge on the low field side that acts as a magnetic spectrometer. This diagnostic is equipped with two cameras, to infer both the velocity space and the frequency of the fast-ion losses, respectively. The installation of a fast high spatial resolution camera (3 kHz) for the 2022-2023 MAST-U campaign enables the measurement of fast-ion losses induced from instabilities in a wide variety of time scales, from MPs to ELMs. The velocity-space of the losses is analysed in this work using the FILDSIM code [6].

The modelling of first-orbit losses with the orbit-following Monte-Carlo code ASCOT [7] has enabled the benchmark of the experimental data measured by FILD. Fast-ion losses have been simulated for different configurations of I_p/B_t. The most favourable configuration to employ the light-ion beam probe method [8], in order to study the effect of MPs in the distortion of fast-ion orbits, has been identified. ASCOT is also used here to perform predictive simulations of the effect of externally applied MPs on fast-ion losses. An H-mode plasma with $B_t = 0.6$ T, $I_p = 750$ kA has been used as reference scenario for the modelling. Both the vacuum and the plasma response, computed with the MARS-F code [9], are considered and compared.

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Dependence of strike line characteristics on plasma parameters as seen through proper orthogonal decomposition

B. Zamorski[1],M. Sleczka[1],M. Jakubowski[2],

A. Puig Sitjes[2], Y. Gao[2], K. Hammond[3], H. Tanaka[4] and W7-X Team

[1] *Institute of Physics, University of Szczecin, Szczecin, Poland*

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

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

[4] *Graduate School of Engineering, Nagoya University, Nagoya, Japan*

Safe power exhaust within thermonuclear fusion reactors requires an understanding of the influence of plasma parameters on the strike line behaviour and its characteristics. This is especially important in helical systems such as the Wendelstein 7-X (W7-X) which uses the island divertor concept to efficiently disperse the heat fluxes [1]. Modelling of three-dimensional plasma boundary is a rather complex and challenging task, therefore tools which allow for comprehensive analysis of correlations among the plasma and the heat flux parameters may provide useful information for better understanding and optimisation of the plasma exhaust. For instance, the strike line up-down asymmetry between divertors has been previously found to be partially dependant on $\vec{\mathbf{E}} \times \vec{\mathbf{B}}$ drifts. The $\vec{\mathbf{E}} \times \vec{\mathbf{B}}$ drift, is made of two separate components, the poloidal drift and the radial drift, both of these components are dependent on plasma density in a non-uniform fashion [1, 2]. The implementation of edge drifts into 3D codes is still ongoing, thus the dependence on the plasma parameters has to be studied experimentally. In this work, we will use Proper Orthogonal Decomposition (POD) to investigate the parameter dependence of up-down asymmetry of the power loads within the Wendelstein 7-X.

The correlation, between the plasma parameters and the heat flux distribution on the divertor surface, will be calculated by obtaining time $a_k(t)$ and spatial $\Phi_k(x)$ coefficients describing the strike lines through proper orthogonal decomposition. POD allows one to identify a finite number of modes for which the significant level of contribution to the system can be expressed in a greatly simplified manner [3, 4]. This work will therefore present the correlation of plasma parameters with the strike line parameters such as the heat flux through the divertor surface expressed as POD coefficients.

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Isotope effect in the core for JET H-mode plasmas: external and internal considerations

E. Fransson[1], L-G. Eriksson[1], D.B. King[2], H. Nordman[1], P. Strand[1], E. Viezzer[3], D. Yadikin[1] and JET contributors*

[1] *Chalmers University of Technology, Gothenburg, Sweden*

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

[3] *University of Seville, Seville, Spain*

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

The influence of plasma isotope on the core confinement is important and still under investigation [1]. Here we assess local core physics of turbulent transport as well as the impact of the variation of the pedestal height in JET H-modes. Basic considerations of the turbulent transport yield a Gyro-Bohm scaling with fluxes ~ $M_{eff}^{1/2}$ [2]. In order to distinguish the impact of M_{eff} on the performance of JET plasma, three discharges were performed in a recent JET campaign with different M_{eff} and otherwise similar engineering parameters: a plasma current of 2.3 MA, a magnetic of field 2.3 T and NBI heating of 22 MW. The discharges were one in pure hydrogen, a second with mixed hydrogen and deuterium ($M_{eff} \approx 1.67$), and a third in pure deuterium. Extensive work has been performed to investigate the linear instabilities of these with the gyro-kinetic code GENE [3]. The results show that all discharges have an Ion Temperature Gradient (ITG)-mode as the most unstable mode at ion scales. The pure hydrogen discharge also displayed a significant Electron Temperature Gradient (ETG)-mode, indicating that for similar engineering parameters different modes can be important when M_{eff} is varied. Studies have shown the pedestal scales as anti-gyro Bohm [4], which may indirectly affect the core turbulence via a change of density and temperature gradients. Moreover, Results show a significant reduction in the instabilities in the cases with a higher M_{eff} at the pedestal. The external ExB-shearing has been suggested [5] as responsible for the anti-Gyro Bohm scaling from experiments and our result concur as the reduction was strongest for the discharges with the heaviest isotopes. Further investigations will be performed with the integrated tool ETS and non-linear gyro-kinetic simulations with GENE.

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Studying the pedestal dynamics with high time-resolution density profiles predicted via machine learning

A. Gillgren[1], D. R. Ferreira[2], A. Ludvig-Osipov[1], P. Strand[1], and JET contributors[*]

[1] *Chalmers University of Technology, Gothenburg, Sweden*

[2] *Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal*

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

In this work, we use machine learning to predict the electron density profile from reflectometry data [1], with the aim of achieving an accuracy close to HRTS (High Resolution Thomson Scattering) [2]. This allows an increase in the sampling rate, from Hz (the HRTS sampling rate) to kHz (the rate of reflectometry reconstructions), while keeping the spatial resolution of HRTS. For this purpose, the model was trained to transform the reflectometry data into a prediction of what the HRTS profile would look like at the same point in time. We employ this method to generate such density profiles in order to study the temporal dynamics of the JET pedestal during ELM (edge-localized mode) cycles. Specifically, we focus on the following pedestal parameters: pedestal top, position, width, and gradient. The parameters are obtained using a modified hyperbolic tangent fit, which is the same fitting function that was used to create the JET pedestal database [3]. The analysis is applied on the pulse that achieved the current energy record in the recent D-T (deuterium-tritium) campaign at JET. The results show a gradual increase in the pedestal top and gradient, as well as a narrowing of the pedestal width and an inward shift of the pedestal position between ELM crashes. At the ELM crash, it is possible to observe that the pedestal top and gradient abruptly drop, with the pedestal width rapidly increasing and the position shifting outwards.

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Bayesian optimization of disruption scenarios with fluid-kinetic models

I. Ekmark[1], I. Pusztai[1], M. Hoppe[2], P. Jansson[3], T. Fülöp[1]

[1] *Department of Physics, Chalmers University of Technology, Göteborg, SE-41296, Sweden.*

[2] *Swiss Plasma Center, Ecole Polytechnique Fédérale de Lausanne, Lausanne, CH-1015, Switzerland.*

[3] *Department of Computer Science and Engineering, Chalmers University of Technology, Göteborg, SE-41296, Sweden.*

The generation of highly energetic runaway electron beams during tokamak disruptions is a major challenge facing tokamak fusion reactors. One of the most studied disruption mitigation schemes is massive material injection (MMI). Finding MMI-parameters, such that the consequences of the resulting disruption – runaway electron impact, localized heat losses and mechanical stresses – are tolerable, is still an open question, and it represents a multi-objective optimization problem.

We have used a Bayesian optimization framework to optimize parameters describing MMI of deuterium and neon in a non-activated ITER-like tokamak set up. The cost function used depends on the maximum runaway current, final ohmic current, current quench time and conducted thermal losses, which were all calculated using the disruption modelling tool DREAM [1]. Besides a more systematic construction of the cost function, we go beyond the recent proof-of-concept study of [2] by performing the optimization in two layers of physics fidelity, using both fluid and kinetic plasma models. The fluid model is computationally cheap which is advantageous for exploring a large parameter space. Once promising parameter regions are located using a wide search with fluid models, these are further studied using kinetic simulations. These simulations resolve the energy distribution of the fast electrons allowing us to also account for kinetic ionization effects and kinetic heating. Using two layers, the advantages of each model can be utilized resulting in an efficient optimization with a reliable examination of relevant areas. Additionally, a qualitative comparison of the two models was made to illuminate the differences between the two layers.

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Tomographic Reconstruction of Radiation Distribution During Impurity Injection in GOLEM Tokamak Plasma Using Fast Visible Cameras

S. Abbasi[1], J. Chlum[1], J. Mlynar[1], V. Svoboda[1], J. Svoboda[1,2], J. Brotankova[1]

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

[2] *Institute of Plasma Physics of the Czech Academy of Sciences, Prague, Czech Republic*

Impurity content plays a considerable role in both performance and operation in the fusion reactor plasma. The impurity injection, due to the scattering and radiation, can lead to mitigate the damage to the plasma-facing components, and is expected to control radiative losses and material migration [1].

Plasma radiation provides diagnostic possibilities and valuable information on the impurity transport in fusion plasmas. The spatial distribution of tokamak plasma radiation can be determined by tomographic inversion using line integrated plasma radiation projections data [2]. For this purpose, fast visible radiation matrix cameras have been recently applied as a diagnostic system to capture the projection data in high temperature plasma studies.

The present work focuses on the reconstruction of the plasma radiation distribution during impurity injection in the GOLEM tokamak of the Czech Technical University in Prague. The tomographic inversions of plasma radiation profile are performed using the Tomotok package [3]. The diagnostic system consists of two crossed monochrome visible cameras (radial and vertical) with a frame rate of 40,000 fps (1280 × 56 pixels) with the additional optical measurements of the plasma core (e.g., plasma spectroscopy) to trace the injected impurities radiation. The main purpose is achieving novel insight into the fast plasma perturbation possibilities in the GOLEM.

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The Stellarator Base Case - a new MHD equilibrium designed for benchmarking codes in 3D geometry

J. H. E. Proll[1], M. Nakata[2], G. G. Plunk[3], K. Camacho Mata[3], A. Goodman[3]

[1] *Eindhoven University of Technology, Eindhoven, The Netherlands*

[2] *National Institute for Fusion Science, Toki, Japan*

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

Thanks to the successes of neoclassically optimised stellarators like Wendelstein 7-X and HSX, understanding turbulence is now at the forefront of stellarator research. In recent years, new codes have emerged, former tokamak-only codes have been rewritten to allow for the simulation of turbulence in full 3D stellarator geometry, and more codes are sure to follow. However, while for tokamaks the Cyclone Base Case [1] has been established as a standard case to be used to benchmark new codes, no simple base case exists for stellarators. So far, the only effort along those lines is the reference set of cases proposed in [2], which considers a W7-X VMEC equilibrium. In order to diminish the computational demand due to the different types of trapping wells and low shear, we propose here an entirely new equilibrium, designed to allow for benchmarking of 3D codes at reasonable computational costs. Boundary conditions for the design were a smooth magnetic field and to have few types of trapping wells, to reduce the required grid resolution along the field line and in velocity space, respectively, as well as a substantial rotational transform, so that in few toroidal turns different regions of the plasma surface were sampled. The found equilibrium is based on a quasi-isodynamic equilibrium obtained via a near-axis expansion [3, 4, 5] and subsequently optimised for higher shear while keeping the high degree of quasi-isodynamicity [6]. The configuration is designed to be well approximated by near-axis theory, which admits simple and smooth semi-analytical expressions for all the relevant metrics to completely describe the magnetic geometry. A base set of gyrokinetic simulations of typical electrostatic instabilities performed with the flux-tube codes GENE [7] and GKV [8] are also presented, to establish the foundation of a stellarator benchmark activity that can then be used by the entire community to compare potential new codes with.

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A system architecture model to coordinate complex systems engineering activities: The case of an optical diagnostic

T. Beernaert[1], M. De Bock[2], P. Etman[3], I. Classen[1], M. De Baar[1]

[1] *Dutch Institute For Fundamental Energy Research (DIFFER), Eindhoven, The Netherlands*

[2] *ITER Organization, Saint-Paul Les Durance, France*

[3] *Eindhoven University of Technology, Eindhoven, The Netherlands*

The design of nuclear fusion diagnostic systems is complex. Specialized physicists and engineers concurrently represent, analyze and design such systems, but use tools and language from their own domain. The diversity and scale of such development projects brings about significant risks: incomplete design information, misinterpretations between domains, and untracked design changes. Such coordination risks must be mitigated by system integrators. A helpful tool is a system architecture model, a centralized system representation that is domain-independent, scalable and adaptable. This model can then be analyzed, shared and visualized for domain-specific purposes.

In this oral contribution, we report on a 3-year period of systems architecting for the Visible Spectroscopy Reference System (VSRS). The VSRS is an optical diagnostic subsystem that will measure primarily Bremsstrahlung in ITER. In the early project stages, we have set up an architecture model of the VSRS in the Elephant Specification Language (ESL), a recently published open source language for function and requirements architecture modelling and visualization. This language formalizes a network of the system's components, functions and dependencies over multiple levels of granularity. Initially, our VSRS architecture model in ESL contained only a few dozen components and functions. But as the design progressed, more and more detailed design elements were added. ESL comes with a dedicated compiler that can automatically derive design dependencies and check for model inconsistencies, which enabled quick and adaptive change management during the course of the project.

The system architecture model has found many uses, of which only present a selection in detail: managing interfaces, distributing project responsibilities, identifying failure modes and effects, designing mechanical and electrical subsystems, and assessing technology readiness risks. We observe that each of these domain-specific activities requires at least the domain-independent definition of system components, affirming that this central piece of information should be managed actively.

Now that the VSRS is in the final design stage, we can conclude that the developed model-based system architecture in ESL has provided considerable support throughout multiple lifecycle phases. We highly encourage further development and applications of such methods in nuclear fusion engineering.

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organizaiton.

Benchmark of a 1D scrape-off layer model DIV1D from stagnation point to target using 2D SOLPS-ITER simulations.

G.L. Derks[1,2], M. van Berkel[1], E. Westerhof[1]

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

[2]*Eindhoven University of Technology, Control Systems Technology, Eindhoven, The Netherlands*

One of the major challenges in the design of commercial fusion reactors is the exhaust. In the exhaust, the wall must be protected from the heat and particles coming from the reactor core by means of a feedback control system [1]. The design of exhaust feedback control systems requires dynamic models for the exhaust plasma [2], which can be obtained with system identification experiments (e.g. [3]) or dynamic modeling. Recent modeling with a 1D divertor plasma model - DIV1D [4] - agreed with 2D stationary SOLPS-ITER simulations of the Tokamak á Configuration Variable (TCV)[5, 6]. Preliminary investigations indicate that the dynamics of DIV1D itself do not explain system identification measurements in TCV. A parallel investigation in [7] suggests that the coupling between core, scrape-off layer and neutrals could be essential to capture experimental exhaust dynamics in TCV.

As a first step towards coupled dynamic core-edge investigations, we extend DIV1D with a core scrape-off layer (core-sol). To facilitate core-edge coupling, the goal for DIV1D is to qualitatively describe the connection between the target and core as function of heat and particle fluxes from the core and as function of the external neutral density. In our assessment, we extract the geometry, source terms and boundary conditions for DIV1D from established SOLPS-ITER simulations. The DIV1D solutions are compared to 1D interpretations of the scrape-off layer in SOLPS-ITER, extending methodologies in [6]. The comparison shows that DIV1D can be used to simultaneously estimate outer midplane and target quantities qualitatively. Future work includes coupling DIV1D to core and neutral models to investigate the dynamics of the connected plasma-sol-neutral system.

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Influence of collisions on trapped-electron modes in tokamaks and low-shear stellarators

M. C. L. Morren[1], J. H. E. Proll[1], M. J. Pueschel[1,2], and J. van Dijk[1]

[1] *Science and Technology of Nuclear Fusion, Department of Applied Physics and Science Education, Eindhoven University of Technology, Eindhoven, The Netherlands*

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

Turbulence in stellarators and tokamaks is often studied in the collisionless limit, which can break down for smaller experimental devices and plasma edge conditions for future reactors. Here we present work investigating the influence of collisionality on the growth rate of plasma microinstabilities through analytical and numerical linear gyrokinetics. In particular, we focus on the trapped-electron mode (TEM), as collisions are expected to directly affect this instability through particle de-trapping. Both methods are applied to the magnetic geometry of the DIII-D tokamak, as well as the Helically Symmetric eXperiment (HSX) and Wendelstein 7-X (W7-X) stellarators.

A dispersion relation for TEMs is formulated based on a perturbative approach, modelling collisions by an energy-dependent Krook-operator [1]. While existing literature only provides solutions in the limit of either weak or strong collisionality in axisymmetric geometry [2, 3], the results presented here are valid at arbitrary collisionality, and in arbitrary geometry. In all three geometries it is observed that TEMs are stabilised above a certain collisionality, as the drift resonance is weakened. Differences between the geometries are, however, observed at low collisionality: In DIII-D the growth rate is unaffected by collisions at all wavenumbers. For stellarators this lack of sensitivity is only found for high wavenumbers. In contrast, at low wavenumbers, the modes are destabilised by small but finite collisionality.

Linear gyrokinetic simulations performed with the GENE code [4] confirm these qualitative trends in the growth rate with collisionality among the different geometries. Additionally, the simulation results show that the destabilisation of the low-wavenumber modes in HSX and W7-X is attributable to a collision-induced transition of the dominant mode towards the Universal Instability [5, 6].

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Enhanced transport at high plasma β due to sub-threshold kinetic ballooning modes in Wendelstein 7-X geometry

P. Mulholland[1], K. Aleynikova[2], B.J. Faber[3], M.J. Pueschel[1,4],
J.H.E. Proll[1], C.C. Hegna[3], P.W. Terry[3] and C. Nührenberg[2]
[1]*Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*
[2]*Max-Planck-Institut für Plasmaphysik, D-17491 Greifswald, Germany*
[3]*University of Wisconsin-Madison, Madison, WI 53706, USA*
[4]*Dutch Institute for Fundamental Energy Research, 5612 AJ Eindhoven, The Netherlands*

The impact of fluctuations of the confining magnetic field – brought about by finite normalised plasma pressure β – has been studied in detail in axisymmetric toroidal fusion devices. One consequence of finite pressure is the possible destabilisation of electromagnetic plasma waves such as the kinetic ballooning mode (KBM). Much remains to be better-understood in terms of linear and nonlinear KBM physics in the more complex three-dimensional magnetic geometries of stellarators.

Using the gyrokinetic Vlasov code GENE [1], we study the effect of plasma β on ion-temperature-gradient-driven (ITG) turbulence in Wendelstein 7-X (W7-X) geometry, revealing that subdominant KBMs are unstable well below the ideal MHD threshold and get strongly excited in the turbulent state. This finding of the sub-threshold KBM is novel and has not been seen hitherto in any geometry. We further report on the characteristics of KBMs in W7-X which, aside from being destabilised far below the MHD threshold, have finite parallel electric field. Such deviations from MHD could be due to the low-magnetic-shear of W7-X, or explained by kinetic effects such as trapped-particle dynamics or wave resonances.

By zonal-flow erosion, these highly non-ideal KBMs affect ITG saturation and thereby enable higher heat transport. Nonlinear energy transfer between the zonal flow, the sub-threshold KBM and another mode (possibly, stable-microtearing) is determined to be the likely mechanism behind this zonal-flow decay and subsequent enhanced transport. Therefore, controlling these KBMs will be essential in order to allow W7-X and future stellarators to achieve maximum performance.

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Runaway electron pitch angle scattering through resonant interaction with the toroidal magnetic field ripple in TCV

T.A. Wijkamp[1,2], M. Hoppe[3], J. Decker,[3], B.P. Duval[3], A.Perek[3], U. Sheikh[3], I.G.J. Classen[2], R.J.E. Jaspers[1] and the TCV team

[1] *Eindhoven University of Technology, Eindhoven, Netherlands*

[2] *DIFFER, Eindhoven, Netherlands* [3] *EPFL, SPC, Lausanne, Switzerland*

Runaway electron formation in tokamaks following disruption events threatens plasma facing component integrity. Design of mitigation strategies for reactor scale machines relies on present-day experiments. Therein, assessment of mitigation effectiveness is aided by the availability of diagnostics that are sensitive to the spatial and energy distribution of relativistic electrons. In previous work, filtered visible light camera imaging of synchrotron emission in Tokamak à configuration variable (TCV) [1] was used to infer the distribution of the most strongly radiating runaways [2]. The inferred large pitch angles θ_p ($\sim$0.5 rad) could not be explained just considering electric field acceleration, particle collisions and radial transport [1].

In this work, we demonstrate that these TCV observations are consistent with pitch angle scattering of runaways through resonant interaction of their gyromotion with the toroidal magnetic field ripple. A pitch angle diffusion operator [3] is incorporated in fluid-kinetic DREAM simulations [4], predicting strong scattering at a resonant momentum $p_{res}/(m_e c)\sim 45$ reached by the most energetic electrons. Synchrotron radiation power losses increase with pitch angle, yielding net deceleration of the scattered runaways after which these are re-accelerated to the ripple resonance. Ripple resonant interaction can thus act as an energy limiting mechanism. The ripple hypothesis is tested experimentally in TCV by exploiting the theoretically expected decrease in p_{res} during a toroidal magnetic field ramp down. Analysis of multi-wavelength multi-view MANTIS imaging data indicates momentum-space behaviour in agreement with modelling. These results highlight the importance of accounting for runaway-ripple interaction in interpreting present-day tokamak runaway experiments, and demonstrate the predictive and explanatory power of state-of-the-art kinetic runaway models.

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Available energy and its relation to turbulent transport

R.J.J. Mackenbach, J.H.E. Proll, P. Helander

Eindhoven University of Technology, 5612 AZ, Eindhoven, The Netherlands

E-mail: `r.j.j.mackenbach@tue.nl`

Abstract. Any collisionless plasma possesses available energy" (AE), which is that part of the thermal energy that can be converted into instabilities and turbulence. Here, I present an investigation into the AE carried by trapped electrons in tokamaks and stellarators. For tokamaks, the investigation focuses on how AE varies with the various parameters found in equilibria discussed by Miller *et al* [1]. This nonlinear measure remarkably captures many known phenomena; negative shear, high Shafranov shift, and negative triangularity all tend to be stabilizing as indicated by a reduction in AE. Next, a comparison is made between AE and saturated turbulent energy fluxes resulting from collisionless trapped electron modes in both stellarator and tokamak devices. A correlation is found, resulting in a power law, which can furthermore be explained by a simple argument. This highlights that AE can capture the effects of geometry on turbulence. Finally, I present an investigation into the AE of a two-species quasineutral plasma. Remarkably this generalized AE indicates that the heat flux scales as the ion temperature gradient to the third power, which is the same result found by invoking critical balance [2].

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Gyrokinetic study of transport in the Scrape-Off Layer with SPARC-relevant parameters

M. Calvo-Carrera[1], N. Mandell[2], N. Loureiro[1]

[1] *Massachusetts Institute of Technology, Cambridge, United States*

[2] *Princeton Plasma Physics Laboratory, Princeton, United States*

As fusion devices approach reactor-scale conditions, it is crucial to manage the heat poured into its walls and divertor. Due to the high temperatures of burning plasmas, fluid theory becomes unreliable not only in the core, but also in boundary plasmas. For this reason, first-principles gyrokinetic theory and modeling is important for understanding turbulent transport from the core to the edge and scrape-off layer (SOL) of burning-plasma reactors. This poster will present results obtained using the gyrokinetic code *Gkeyll* to perform simulations in a simple-model helical geometry with SPARC's characteristic magnetic field, temperature and density. In this project, we study the dependence of the temperature, density and divertor heat flux profiles on the magnetic configuration and simulation parameters. As the pitch angle of the magnetic field lines in the SOL is decreased, it is expected that the interchange stability driving transport across the field lines is enhanced and the characteristic time of transport along the field lines increases as well. Analytical work and numerical simulations support the conclusion that this results in broader profiles and a larger pressure gradient scale length, which could help to spread the heat load along the divertor plates. In addition, we study the dependance on the simulation box radial length to observe how our boundary conditions affect the decay lengths of the profiles. Ongoing work includes evaluating the driving terms from gyrokinetic equations with the objective of deriving a scaling law for the pressure decay length of the SOL, and comparing it with previous predictions from fluid theory and modeling.

Localized Phase Contrast Imaging Measurements at Wendelstein 7-X

S.K. Hansen[1], M. Porkolab[1], J.-P. Bähner[1], A. von Stechow[2], O. Grulke[2,3], E.M. Edlund[4], and the Wendelstein 7-X Team

[1] *Plasma Science and Fusion Center, MIT, Cambridge, MA 02139, USA*

[2] *Max-Planck-Institut für Plasmaphysik, 17491 Greifswald, Germany*

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

[4] *State University of New York College at Cortland, Cortland, NY 13045, USA*

Phase contrast imaging (PCI) is the primary core density fluctuation diagnostic at Wendelstein 7-X (W7-X) [1] and thus plays a key role in advancing the understanding of plasma turbulence in optimized stellarators. In its basic form, PCI provides line-integrated measurements of the fluctuating electron density along the line-of-sight of a laser beam, which passes radially through the plasma center at W7-X [1, 2, 3]. While standard PCI provides insight into the global turbulence characteristics at W7-X, its ability to provide information about local turbulence features is limited. Previous PCI studies at W7-X indicated that the signal in standard plasma scenarios mainly originates from extrema of the neoclassical radial electric field, based on matching the PCI phase velocities to neoclassical modeling [2] and using synthetic PCI techniques [2, 3]. In order to study the regions from which PCI features originate in non-standard plasma scenarios at W7-X, e.g., the high-performance plasmas observed in connection with neutral beam and pellet injection, it is useful to augment the above model-based, post-processing PCI localization techniques by experimental localization techniques as well. This may be achieved by installation of a mask in a focal plane of the laser beam reaching one of the two linear PCI detector arrays at W7-X [1]. The above scheme relies on the fact that turbulent fluctuations are almost perpendicular to the background magnetic field, such that fluctuations scattered from different magnetic pitch angles can be filtered out of the signal by a mask [1]. This contribution covers the first localized PCI measurements of W7-X plasmas utilizing a novel mask design supported by synthetic PCI results [3]. Localization of the PCI signal down to approximately half the plasma minor radius on the outboard side of W7-X is demonstrated.

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Initial report on TCV/DIII-D similarity experiments on Negative Triangularity plasmas*

A. Marinoni[1], S. Coda[2], S. Gorno[2], N. Offeddu[2], H. Reimederes[2], O.Sauter[2], M. Vallar[2], C. Tsui[3], M.E. Austin[4], M. Porkolab[1], K.E. Thome[5] and the TCV Team

[1]Plasma Science & Fusion Center, MIT, Cambridge MA, USA
[2]Swiss Plasma Center, Ecole Polytechnique Federale de Lausanne, Lausanne, VD, CH
[3]University of California at San Diego, San Diego, CA, USA
[4]Universtiy of Texas-Austin, Austin, TX, USA
[5]General Atomics, San Diego, CA, USA

A similarity experiment on diverted discharges with a negative triangularity cross-sectional shape has been executed on the TCV tokamak by creating plasmas whose separatrix closely resemble that of recent discharges on DIII-D[1].
The experiment explored the plasma current dependence of the heat flux power fall-off length in the scrape-off-layer (λ_q) at fixed q_{95} and compared the transition from the linear to the saturated ohmic-confinement (LOC-SOC) regimes between the target shape and matched discharges at positive triangularity.
The shape used in this experiment is a LSN with near-zero lower triangularity and strong shaping in the plasma section above the mid-plane. Matched discharges at positive triangularity hold the position of the X-point and strike points fixed, thereby excluding major shape induced modifications to wall recycling when modifying triangularity.
Preliminary results indicate that the current dependence of λ_q is broadly consistent with that given by the Eich's multi-machine scaling law[2], with numerical values being lower than those expected from the scaling law by an amount comparable to the statistical uncertainty of the scaling law itself. Detailed comparisons with prior measurements on TCV are being carried out, particularly regarding the impact of aspect ratio on the coefficients of the scaling law[3].
Negative triangularity is not observed to strongly affect the critical density at which the LOC-SOC transition occurs.

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Radiation pressure of electron cyclotron waves on plasma turbulence

Abhay K. Ram[1], Kyriakos Hizanidis[2]

[1] *Massachusetts Institute of Technology, Cambridge, MA, USA*

[2] *National Technical University of Athens, 157 73 Zographou, Greece*

While plasma turbulence in fusion devices can affect the propagation of radio frequency (RF) waves [1, 2], the electromagnetic waves can influence the turbulence through radiation pressure. This pressure can be significant if there is a narrow transition layer – in effect, an interface – separating two different density regions. In the scrape-off layer of magnetically confined plasmas, large scale density turbulence occurs either as incoherent fluctuations or coherent structures like filaments and blobs. In the core plasma, turbulence driven by instabilities is either wave-like or a mix of incoherent fluctuations. We use two different approaches to determine the radiation pressure due to electron cyclotron (EC) RF waves. The first approach is applicable to incoherent density fluctuations and is based on the Kirchhoff theory of scattering from rough surfaces [3]. In this theory, the electromagnetic field at any point on a turbulent surface is assumed to be that on the tangent plane at that point. The Kirchhoff theory is a useful for determining the radiation force due to EC waves in the edge plasma and in the core where long scale length fluctuations are present. We find that the radiation force will lead to a peaking of the density profile in the core. Recent experiments on ASDEX-U have observed peaking of the impurity density profile during ECRF heating of the plasma [4]. The second approach is relevant to determining the radiation force on a filamentary structure in the scrape-off layer. We assume that the filament is cylindrical and extends along the magnetic field line. The wave fields inside and outside the filament are determined from Maxwell equations, and the radiation pressure is evaluated using the Maxwell stress tensor [5, 6]. We find that the impact of the radiation force on the motion of a filament is large enough to be observed in experiments. This also suggests the possibility of utilizing EC waves to modify some aspects of edge turbulence.

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Drift-resonances modifications due to radial electric field in the pedestal

G. Anastassiou[1], P. Zestanakis[1], Y. Antonenas[1], E. Viezzer[2], Y. Kominis[1]

[1]*School of Appl. Math. and Phys. Sciences, National Technical University of Athens, Greece*

[2]*University of Seville, Seville, Spain*

The transition from Low confinement (L-mode) to High confinement (H-mode) operation in fusion devices is associated with a drastic increase of the radial electric field (E_r), and the consequent formation of an Edge Transport Barrier (ETB) which supresses the anomalous turbulent-driven transport due to $\mathbf{E}\times\mathbf{B}$ shear flow, and therefore improve the plasma confinement [1-3]. Due to its good confinement characteristics, H-mode is considered as the baseline scenario for ITER high-performance operation [4].

The impact of E_r on the resonant mode-particle interaction is of paramount importance in magnetically confined plasmas, as it drastically modifies the spectral content of the particle orbits and the resonance conditions that determine the momentum and energy transport phenomena. The orbital spectrum of particles circulating near the edge of an axisymmetric Large Aspect Ratio (LAR) magnetic equilibrium is investigated using the Hamiltonian formulation of Guiding Center motion [5], where bounce-averaged poloidal frequencies and toroidal precession frequencies are calculated using an Action-Angle semi-analytical transformation [6,7], underlining the role of E_r on the drift-resonant mode induced transport.

A detailed phase space analysis shows that under the presence of perturbative resonant modes, the location of the resonant islands obtained from Poincaré maps is in excellent agreement with the analytically obtained values, while the extrema of the resonant curves pinpoint the location of Shearless Transport Barriers [8] with a remarkable accuracy as well, highlighting the advantages of the underlying analytical model.

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Kinetic versus magnetic chaos in tokamak plasmas

H.T. Moges[1], Y. Antonenas[2], G. Anastassiou[2], Ch. Skokos[1], Y. Kominis[2]

[1] *University of Cape Town, Cape Town, South Africa*

[2] *National Technical University of Athens, Athens, Greece*

The presence of non-axisymmetric perturbations in an axisymmetric tokamak equilibrium is well-known to result in the breaking of smooth magnetic flux surfaces and the presence of magnetic field chaos. Particle motion in such magnetic field becomes also chaotic. In terms of the Guiding Center approach, particle orbits become chaotic due to the non-conservation of the canonical longitudinal momentum under non-axisymmetric perturbations rendering the system non-integrable.

In this work we systematically compare the kinetic versus the magnetic chaos. Both the magnetic field line topology and the Guiding Center particle motion are formulated under a Hamiltonian description. The Guiding Center motion is described in White-Boozer coordinates, allowing for the unique labelling of each orbit of the unperturbed system in terms of the three Constants Of the Motion (COM) and for the analytical calculation of the orbital frequencies (bounce/transit and toroidal precession frequencies) that determine the resonance conditions with non-axisymmetric perturbations and therefore the structure of the particle phase space [1]. In order to detect, quantify and compare the kinetic versus the magnetic chaos, we implement the numerical technique of the Smaller Alignment Index (SALI) [2] and discuss its several advantages in comparison to standard chaoticity measures, such as the maximum Lyapunov exponent (mLE) (see [3] and references therein). Detailed investigations in the COM space of the orbits along with Poincare surfaces of section for the magnetic field lines and the particle orbits, show that the orbit chaoticity of higher energy particles, having larger drifts from the magnetic field lines, is significantly different from the chaoticity of the underlying magnetic field, in sharp contrast to lower energy particles, approximately following the magnetic field lines, showing similar chaoticity with the magnetic field. Effects on particle transport and confinement are also discussed.

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Interpreting the profile of MHD induced fast ion losses in ASDEX Upgrade using the resonance index technique.

P. A. Zestanakis[1], G. Anastassiou[1], J. Rueda-Rueda[2], Y. Kominis[1], J.Galdon-Quiroga[2] and the ASDEX Upgrade Team[3]

[1] *School of Applied Mathematics and Physical Sciences, National Technical University of Athens, Athens, Greece*

[2] *Department of Atomic, Molecular and Nuclear Physics, University of Seville, E-41012 Seville, Spain*

[3] *See author list of "U. Stroth et al. 2022 Nucl. Fusion 62 042006"*

We present the application of the Resonance Index (RI) technique on the interpretation of signals obtained by the Fast Ion Loss Detector (FILD) due to Fast Ion (FI) losses induced by Toroidicity induced Alfvén Eigenmodes (TAEs) or Neoclassical Tearing Modes (NTMs) in ASDEX Upgrade (AUG). The three cases presented involve H-mode shots in standard AUG operation, with the first exhibiting MHD activity due to a dominating $5/4$ NTM along with a core $1/1$ mode [1] and the other two due to Ion Cyclotron Range of Frequency (ICRF) driven TAEs [2]. In all cases FI losses correspond to ICRF ions with energies over 100 keV.

The RI technique is based on the calculation of the number of the resonant unperturbed FI orbits in the vicinity of a phase space point. It requires limited knowledge about the underlying modes (frequencies and wave numbers) and few computational resources, since it is based on unperturbed orbit tracing for a single poloidal period [3].

A series of recent improvements, such as better equilibrium representation by using the reconstructed q profile and accounting for the nonlinear relation between the magnitude of the magnetic field B and the major radius R, have facilitated the comparison between the calculated RI profile and the measured FILD signal. This has led to better understanding of the potential of the RI technique in explaining various characteristics of the lost FI population. In particular, we demonstrate that the extent of the measured signal coincides with discontinuities on the RI profile, due to the disappearance of particular resonances, and that the distribution of hotspots can often be attributed to resonance overlap due to a separatrix in the ion phase space.

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A system architecture model for the design of the plasma control system

M. de Baar,[1] T. Beernaert,[1] L.F.P. Etman,[2] M. De Bock,[3] W. Biel,[4] M. Ariola,[5] G. Vayakis,[3] D. Mazon,[6] W. Treutterer [7]

1 Dutch Institute For Fundamental Energy Research (DIFFER), Eindhoven, The Netherlands
2 Eindhoven University of Technology, Eindhoven, The Netherlands

3 ITER Organization, Route de Vinon-sur-Verdon - CS 90 046, 13067 St Paul Lez Durance Cedex, France

4 Institute of Energy and Climate Research - Plasma Physics (IEK-4), Forschungszentrum Juelich GmbH, D-52425 Juelich, Germany

5 Universita`degli Studi di Napoli Parthenope, Centro Direzionale di Napoli - Isola C4 - Office 501, 80143 Napoli Italy

6 CEA, IRFM, F-13108 Saint Paul-lez-Durance, France
7 *Max Planck Institute for Plasma Physics, Boltzmannstraße 2, Garching bei Muenchen, Germany*

The plasma control system consists of domain controllers for the magnetic configuration, the exhaust, the suppression of MHD modes and, possibly the control of profiles and plasma burn. These domain controllers rely on sensors, actuators, and models for controller synthesis, state observation and prediction. A supervisory controller will need to determine the priority of the control tasks and the allocations of the actuators to the control task. A network model of the plasma has been developed and projected onto the ITER sensor and actuator park. This provides an integrated overview of the main functions of the system, and shows how subsystems and plasma processes are interfaced.

When applying a clustering algorithm to the plasma network model without explicit spatial dependencies, we retrieve identifiable clusters for the magnetic configuration control, the vertical stability, the equilibrium, the transport and power deposition physics and the exhaust. Interfaces between these clusters are readily identified. For a model with spatial dependency the sequencing algorithm yields a mixing of spatial and physics processes and optimal clustering strategies must be devised.

For each diagnostic type in the ITER diagnostic park, it has been identified how the parameters in the model map to the signals of these instruments. A crude model of the effect of the equilibrium on the diagnostic signals is incorporated. Events, such as MHD instabilities, confinement mode transitions and impurity influxes and accumulation have been included in the network, and can be toggled on or off. The network modelling approach allows for the investigation of the undesirable states that can emerge within the system: sensor failure, actuator failure or constraints, or plasma instability. For actuator and sensor failure, a product-group approach can be applied to find (combinations) of suitable back-up solutions. The inclusion of the instabilities directly affects the parameters and these modifications propagate through the network. This allows for analysis of the temporal signatures of the disturbances, and hopefully the identification of these disturbances based on temporal signatures in the signals.

Reduced model of magneto-hydrodynamic dynamo enabled magnetic flux pumping for scenario development of hybrid tokamak discharges

I. Krebs[1,2], K. Lackner[3], S. Guenter[3], J. Graves[4], O. Sauter[4], E. Westerhof[2], E. Strumberger[3], M. Hoelzl[3], A. Burckhart[3], A. Bock[3], R. Fischer[3]

[1] *Science and Technology of Nuclear Fusion, Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands*

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

[3] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*

[4] *École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland*

The hybrid scenario has good confinement and stability properties and is a promising scenario for the operation of future tokamaks. In particular, hybrid plasma discharges do not exhibit sawtooth instabilities because of their characteristic safety factor profile which is flat and close to unity in the central region of the plasma [1]. In some mid-sized tokamaks, such as DIII-D and ASDEX Upgrade, it has been observed [2, 3] that a self-regulating current redistribution mechanism, called magnetic flux pumping, automatically maintains this characteristic safety factor profile in the central plasma region. A theoretical explanation for magnetic flux pumping based on 3D nonlinear magneto-hydrodynamic simulations has been brought forward [4, 5] and is supported by experimental evidence [6]. According to this explanation, a saturated, but continuously driven quasi-interchange instability redistributes the central current by generating a magneto-hydrodynamic dynamo. Our goal is to study whether this type of magnetic flux pumping enabled hybrid scenario is accessible in future tokamaks such as the European DEMO, and if yes, under which conditions it can be accessed. We report on the current status of work on a reduced model of magnetic flux pumping which should enable the incorporation of this effect into flight simulator codes used for scenario development and equilibrium reconstruction codes for reliable current profile estimation. One step on this path was the development and study of a simple toy model condensing the ingredients necessary for a system to end up in a saturated state that is continuously driven towards instability.

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Plasma-wall self-organization in magnetic fusion

D.F. Escande[1,2], F. Sattin[2], P. Zanca[2], J.-X.Liu[3], P. Zhu[3,4], J.-L. Zhang[3], D.-H. Xia[3], Y.-H. Wang[3], J.-M. Wang[3], Q.-H. Yang[3], J.-G. Fang[3], L. Gao[3], Z.-F. Cheng[3], Z.-P. Chen[3], Z.-J. Yang[3], Z.-Y. Chen[3], Y.-H. Ding[3], Y. Pan[3] and the J-TEXT team

[1] *Aix-Marseille Université, CNRS, PIIM, UMR 7345, Marseille, France*

[2] *Consorzio RFX (CNR, ENEA, INFN, Univ. di Padova, Acciaierie Venete Spa), Padova, Italy*

[3] *IFPP, Huazhong University of Science and Technology, Wuhan, 430074, China*

[4] *Engineering Physics, University of Wisconsin-Madison, Madison, WI 53706, USA*

The concept of plasma-wall self-organization (PWSO) in magnetic fusion was recently introduced [1]. It relies on the existence of a time delay in the feedback loop relating radiation and impurity production on divertor plates. Both a zero and a one-dimensional description of PWSO *at flat-top* were provided [1]. They lead to an iterative equation whose equilibrium fixed point is unstable above some threshold. This threshold corresponds to a radiative density limit. PWSO comes with two basins for this organization at flat-top : the usual one with a density limit, and a new one with density freedom, in particular for machines using high-Z materials. Furthermore, two basins of attraction of PWSO are shown to exist for the tokamak *during start-up,* with a high density one leading to this freedom at flat-top [1]. This basin might be reached by a proper tailoring of ECRH assisted ohmic start-up in present middle-size tokamaks, mimicking present stellarator start-up. In view of the impressive tokamak DEMO wall load challenge, it is worth considering and checking this possibility, which comes with that of more margins for ITER and of smaller reactors.

Both zero and one-dimensional descriptions lead to a delay equation whose simplest expression is $R+ = \alpha$ (P-R), where P is the total input power in the plasma, R is the total radiated power, and R+ is its delayed value. This makes the plasma-wall system unstable for $\alpha >1$. Since α is proportional to the density below detachment, this threshold defines a density limit, which can be reached for a ratio of total radiated power to total input power as low as 1/2. If detachment develops, the plasma temperature at the plates decreases, which makes α to vanish. This pushes the radiative density limit to very high values when physical sputtering dominates, in particular for tungsten. Hence density freedom. The 0D and 1D models of PWSO apply to the stellarator and to the reversed field pinch as well.

The higher density limit in stellarators might be due to their ECRH start-up, which produces few impurities. This suggests that a strongly ECRH assisted ohmic start-up in tokamaks might enable reaching the high-density scenario, especially for plates with high-Z materials [1].

The theoretical predictions were compared with recent experimental data of the J-TEXT tokamak with Ohmic or ECRH-assisted start-up. Increasing the ECRH power or pre-filled gas pressure in the start-up phase provides a higher density limit at flat-top, through the reduction of the impurity radiation, in agreement with theoretical predictions. The experimental density limit, plotted as a function of the target region plasma temperature, is compared with the model predictions computed with reasonable values of the impurity radiation rate and of the perpendicular diffusion coefficient of target impurities. The data agree qualitatively with the predictions of the 0 D model, and quantitatively with those of the 1D one, which couples an impurity transport equation and a heat transport equation. The experimental points are located in the density-limit regime, but are at the edge of the density-free one. This indicates the possibility of reaching the latter by further experimental improvements in J-TEXT, despite of its graphite targets. In contrast, experiments in a tokamak with tungsten targets might enter deeply the density-free regime.

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Cheap training sets for gyrokinetic surrogate models with high dimensionality for DEMO-class tokamaks ramp-up scenarios

L. Zanisi[1], J. Barr[2], T. Madula[2], A. Ho[3,4], J. Citrin[3,4], V. Gopakumar[1], S. Pamela[1], F. Casson[1], B. Patel[1], H. Dudding[1], F. Erikkson[1] C. Roach[1], D. Kennedy[1] and JET contributors *

[1] *Culham Centre for Fusion Energy, Abingdon, ;* [2] *UCL's Centre for Doctoral Training in Data Intensive Sciences, University College London;* [3] *Dutch Institute for Fundamental Energy Research, Eindhoven, Netherlands;* [4]*Science and Technology of Nuclear Fusion Group, Eindhoven University of Technology, Eindhoven, Netherlands*

Model-based plasma scenario development lies at the heart of the design and operation of future fusion powerplants. Notably, including gyrokinetic turbulence in integrated models is essential for delivering a successful roadmap towards operation of ITER and the design of DEMO-class devices. Given the highly iterative nature of integrated models, fast surrogates of gyrokinetic turbulence are fundamental to fulfil the pressing need for even faster simulations opening up pulse design, optimization, and flight simulator applications.

Previously, QLKNN [1], a feed-forward neural network (NN) surrogate model of QuaLiKiz [2], has shown a factor 10^4 prediction speedup. However, the training set generation still demanded considerable computational resources due to its size. Such brute-force approaches are thus inapplicable to nonlinear gyrokinetic models and unsuitable where the input dimensionality is high, as for example is the case of gyrokinetic models with shaping. Furthermore, by the nature of the critical threshold characteristic of tokamak turbulence, not all input plasma states result in unstable modes. We hypothesise that the critical gradient behaviour may be easier to learn for a separate surrogate, as opposed to previous work where the critical threshold behaviour was enforced by means of a physics-based loss function in a single surrogate [2,3].

In this work, we propose to use Active Learning [4], a sampling strategy that queries a given model by means of an acquisition function that identifies regions where additional data would improve the surrogate. We provide a benchmark study using available data from QuaLiKiz [3] and show a 40% reduction in training dataset size needed to achieve the same performance as random sampling. We validate the surrogate on integrated modelling of JET scenarios. As an application, we obtain more computationally affordable training data for surrogates of TGLF with the inclusion of shaping, which we use to provide self-consistent multi-channel integrated modelling to predict the evolution of the STEP non-inductive ramp up scenario.

Our methodology can be readily applied to obtaining general surrogates for expensive nonlinear gyrokinetic models (thus increasing the physics fidelity of integrated models) and to learning cheaper surrogates of any other physics model of interest.

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

First full-scale TCV L-mode edge turbulent simulation including neutral recycling with the SOLEDGE3X code

H. Bufferand[1], G. Ciraolo[1], R. Düll[1], G. Falchetto[1], N. Fedorczak[1], Y. Marandet[2], V. Quadri[1], M. Raghunathan[2], N. Rivals[1], F. Schwander[3], E. Serre[3], P. Tamain[1], H. Yang[1]

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

[2] Aix-Marseille Université, CNRS, PIIM, Marseille, France

[3] Aix-Marseille Université, CNRS, Centrale Marseille, M2P2, Marseille, France

Accurate modelling of cross-field turbulent transport in tokamak's edge plasma remains a challenge, many key experimental features such as edge transport barriers formation being still hard to simulate, especially for ITER size tokamaks. Being able to predict the SOL width or the power load imbalance between inner and outer divertor legs even for today's JET size tokamaks is still an open issue. First principle modelling of edge plasma turbulence is thus today a very active topic in the fusion community driving many dedicated research projects such as the TSVV "European boundary code" project in Europe.

In the last five years, the edge plasma code SOLEDGE3X [1] has been developed at CEA-IRFM in collaboration with experts in atomic and molecular physics and numerical methods at Aix-Marseille University. It aims at simulating plasma transport and plasma turbulence in the edge plasma based on a fluid description of the later. It includes several neutral models from a simple fluid description to a full kinetic description thanks to a coupling with the neutral Monte-Carlo code EIRENE. In the last two years, a significant effort has been paid to accelerate the code and enable full-scale simulations of tokamaks.

In this contribution, we present first simulation results of the so-called TCV-X21 case [2], a series of diverted ohmic L-mode discharges on TCV (Tokamak a Configuration Variable) designed as a dataset for edge turbulence codes validation. In [2], different turbulence codes (TOKAM3X - precursor of SOLEDGE3X, GBS, GRILLIX) have confronted their results with experimental measurements but without including neutral recycling. Here, we present new results obtained with SOLEDGE3X with a much higher resolution than in [2], enabling using realistic plasma resistivity, and including plasma recycling. In particular, we discuss the properties of the turbulence such as fluctuation spectra, ballooning and scrape-off layer decay length. Finally, a direct comparison with experimental data is carried out using synthetic diagnostics developed in that purpose.

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Tomographic inversions for radial electron temperature in WEST

A.Da Ros[1], D. Vezinet[1,2], G. Colledani[1], S. Mazzi[1], G. Miglionico[1] and the WEST Team[1]

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

[2]*Commonwealth Fusion Systems, Cambridge, MA, USA*

The imaging X-ray spectrometer installed on WEST [1] is designed to measure X-rays emitted by the whole plasma volume at wavelengths of ∼1 Å. Its Johann configuration permits to measure well resolved 2D spectra, thanks to a 2D Pilatus camera, from which a symmetrical image of the plasma height in the poloidal plane is obtained. 1D spectra are extracted by slices at a particular height. A number of photons per unit time is measured by each pixel of the camera, corresponding to the sum of all photons emitted by the plasma volume along a same line of sight. The extraction of the electron (Te) and ion (Ti) temperatures line-integrated profiles as well as the toroidal plasma rotation velocity (Vp) can then be done [2]. Those measurements are obtained with 3 sets of Bragg crystals, mounted on a rotating table, targeting the spectra of the following ion species of Ar XVII (λ∼3.97 Å), Ar XVIII (λ∼3.73 Å) and Fe XXV (λ∼1.86 Å). In this work, tomographic inversion methods are implemented in order to obtain inversed profiles of the electron temperature. This technique was introduced for X-ray imaging spectrometer by Reinke et al. [3] for Alcator C-Mod, by solving an inverse problem between the measured projections and the unknown distribution of sources among the plasma volume. It appears that the integrated profiles tend to under-estimate the temperature, especially in the core of the plasma, due to the integration of more Maxwellian emission profiles from cooler parts of the line of sight. At the same time, a systematic comparison of the Te measurements, proxy and inverted, between this diagnostic and those performed by the ECE diagnostic is presented.

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A new Electromagnetic Model in SOLEDGE3X

Raffael Düll[1], Hugo Bufferand[1], Eric Serre[2], Guido Ciraolo[1], and Patrick Tamain[1]

[1] CEA-IRFM, Cadarache, St-Paul-Lèz-Durance, France
[2] M2P2, Aix-Marseille University, CNRS, Centrale Marseille, France

Abstract. Electromagnetic effects and micro-instabilities are known to play a key role in driving plasma turbulence in the pedestal region. In particular, they affect turbulent filament propagation and plasma blob evolution in the Scrape-off layer [2]. For more realistic simulations it is thus desirable to integrate these effects into the physical model.

In its current form, the 3D turbulent transport code SOLEDGE3X uses an electrostatic assumption with a fixed magnetic field. Perpendicular fluctuations of the magnetic field B are derived from the local value of the magnetic vector potential in parallel direction $A_\parallel$, known from Ampère's law. To avoid unphysical speeds in the plasma, it is crucial to consider electron inertia [1] which requires solving for the time evolution of the parallel current density $j_\parallel$ in the generalized Ohm's law.

In this contribution, we will present the new physical model of SOLEDGE3X with the two global fields $A_\parallel$ and $j_\parallel$. They are solved implicitly along the electric potential Φ in a coupled system that combines the vorticity equation with Ampère's and Ohm's laws. Both fields are defined on a poloidally and toroidally staggered grid to take advantage of the parallel gradient and divergence in the new equations. The discretization converges with second order in space and we observe an improvement in the matrix condition.

The new electromagnetic model discloses basic MHD behaviour in the form of Alfvén modes. Simulations on a periodic slab case show that the plasma resonates to an excitation at the Alfvén wave frequency. These waves propagate faster than the species transport, which generally requires an appropriate small timestep. To avoid additional restrictions on the timestep size it is thus essential solving the stiff system on Φ, $A_\parallel$ and $j_\parallel$ implicitly.

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Comparing linear stability of electrostatic kinetic and gyro-kinetic ITG modes

G.T.A. Huijsmans[1,2], M. Becoulet[1], Z. Lu[3], JOREK team

[1]*CEA, IRFM, 13108 Saint-Paul-Lez-Durance, France*
[2]*Eindhoven University of Technology, 5600MB Eindhoven, The Netherlands*
[3]*Max Planck Institute for Plasma Physics, Garching, Germany*

The validation of nonlinear MHD fluid simulations of instabilities in tokamak plasmas requires a visco/resistive MHD model extended with kinetic effects, for example due to a finite Larmor radius. Such an extended MHD model will have to be compared (benchmarked) with a first principle electro-magnetic kinetic or gyro-kinetic model.

As a first step towards this, an electrostatic kinetic and gyro-kinetic model has been implemented in the framework of the nonlinear MHD code JOREK [1]. The full-f (gyro) kinetic models use the existing JOREK particle modules. The full orbit of the kinetic ions are advanced in time using the classical Boris method, whereas RK4 is used for the gyro-centre of gyro-kinetic particles. Electrons are treated as adiabatic (although kinetic electrons have also been implemented [2]). The electric potential is obtained from the solution of the Poisson equation for quasi-neutrality. In the gyro-kinetic model the Poisson equation includes the long wavelength form of the ion-polarization density, in the kinetic model this term does not appear. The electric potential is discretised with cubic C^1 Bezier finite elements in the poloidal plane and a Fourier series in the toroidal direction. The Poisson equation is similar in structure to the (existing) projection operations to calculate the particle moments. The projection operations include filtering terms to reduce the particle noise. Two types of filters are used, one in the poloidal direction and one in the parallel direction. The time evolution uses a straightforward explicit scheme with a time-advance of the particles, followed by a solution of the Poisson equation to update the electric field. With the parallelization of the kinetic particles on GPUs (on M100) and gyro-kinetic particles with MPI/OpenMP (Marconi), the two models have similar computing time.

Both the kinetic and gyro-kinetic models have been successfully benchmarked on the GENE/XGC case [3] for the linear growth rates of ITG modes. Good agreement is found between the kinetic and gyro-kinetic models and with the published GENE/XGC/ORB5 results. Thus, in this circular plasma case with $\rho^\star = 1/180$ and $L_\theta = 2\pi/k_\theta = 2\pi r/nq = 1/58$ (for n=50) there is no significant difference between the full-f 6D kinetic and 5D gyro-kinetic models.

To identify a regime where the kinetic and gyro-kinetic models may give different results, the temperature scale length was increased to destabilize higher-n modes with smaller poloidal structures, together with a scan in $\rho^\star$ ($1/\rho^\star$=180, 72 and 36). Indeed, significant differences in the linear ITG growth rates occur, starting from $\rho^\star > \pi/k_\theta$ (i.e. when $\rho^\star$ is larger than half a period of the poloidal mode structure. The marginal stability of gyro-kinetic model has a stronger (i.e. linear) dependence on $\rho^\star$ whereas the marginal stability limit in the kinetic model varies only weakly with $\rho^\star$. I.e., in the kinetic model high-n modes with poloidal mode structures smaller than $\rho^\star$ are significantly more unstable compared to the long wavelength gyro-kinetic model.

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Measuring X-ray and neutron spectra with gas detectors, from models to measurements

D. Mazon[1], A. Jardin[2], A. Wojenski[3], Y. Peysson[1], M. Scholz[2], M. Chernyshova[4], D. Colette[5], J. Colnel[1], P. Malard[1], W. Dąbrowski[6], K. Drozdowicz[2], D. Guibert[1], G. Kasprowicz[3], K. Król[2], A. Kurowski[2], B. Łach[6], K.T. Poźniak[3], M. Walsh[5], U. Wiacek[2] and the WEST team*.

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

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

[3] *Warsaw University of Technology, Institute of Electronic Systems, Nowowiejska 15/19, 00-665 Warsaw, Poland.*

[4] *Institute of Plasma Physics and Laser Microfusion, Hery 23, 01-497 Warsaw, Poland.*

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

[6] *AGH University of Science and Technology Faculty of Physics and Applied Computer Science, Krakow, Poland.*

*http://west.cea.fr/WESTteam

In future fusion reactors, the number of diagnostics might be extremely limited mainly due to the breeding blanket that will need to be maximized. Radiation spectra measurements will certainly remain among the most important ones. Indeed, essential plasma parameters can be inferred from the neutron spectrum measurement: ion temperature from thermal broadening, fuel ion ratio and rotation velocity, while several complementary parameters can be deduced from X-ray spectrum measurements like magnetic axis, electron temperature, impurity concentration and spatial distribution after tomographic inversion, fast electrons distribution, etc.

Despite being extremely rich in information, the access to continuous spectral measurements is nevertheless a technical challenge. This contribution reports on X-ray and neutron spectra measurements with gas detectors of different nature: at WEST tokamak X-ray spectra up to 20keV acquired by GEM detectors in an automatic and continuous manner are used to deduce W concentration. At CEA laboratories, multi-chamber LVIC measurements working in current mode efficiently reconstruct W spectrum thanks to optimized algorithms. Finally, at IFJ-PAN laboratories, first successful attempts to measure neutron spectra up to 15Mev by proton recoil with GEM detectors are described.

Synthetic diagnostics of these different gas detectors specially developed for the occasion to validate the obtained measurements allow extrapolation to some application on the ITER tokamak.

Turbulence Phase Velocity Reversal Caused by Electron/Ion Turbulence Transition Driven by Ion Temperature and Density Gradients

A.S. Liang[1], X.L. Zou[2], W.L. Zhong[1], G.L. Xiao[1], A. Ekedahl[2], J.Q. Xu[1], Z.C. Yang[1], J. Wen[1], X.X. He[1], L.Z. Liu[1], R.H. Tong[1], Z.Y. Yang[1], J. Yin[1], B.D. Yuan[1], Y. Zhou[1], Y.R. Zhu[1], M. Jiang[1], X.Y. Bai[1], B. Lu[1], D.L. Yu[1], Z.B. Shi[1], X.Q. Ji[1], W. Chen[1], M. Xu[1], X.R. Duan[1], and the HL-2A Team

[1] *Southwestern Institute of Physics, P. O. Box 432, Chengdu 610041, China*
[2] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

E-mail : xiao-lan.zou@cea.fr

Turbulent transport is a critical issue in tokamak fusion research. Identifying the nature of the turbulence responsible for heat and particle transport is of great interest. One of effective methods of identification is the turbulence phase velocity measurement, where the positive value of the phase velocity represents an ion turbulence in the present case, while the negative one represents an electron turbulence. Turbulence phase velocity v_{ph} is obtained by subtracting $v_{E\times B}$ from $u_\perp$ ($v_{ph} = u_\perp - v_{E\times B}$), where $u_\perp$ is the turbulence velocity perpendicular to the magnetic field measured by Doppler reflectometry, $v_{E\times B}$ is the $E \times B$ velocity calculated by using radial force balance equation with data obtained from CXRS.

The turbulence phase velocity reversal is clearly observed in the HL-2A tokamak during LHCD modulation in NBI-heated plasmas, indicating alternate switching of electron and ion turbulence triggered by LHCD. The measured wavenumber range of the turbulence by multi-channel Doppler reflectometry is from 3 cm^{-1} to 12 cm^{-1}, which corresponds to $k_\perp \rho_s < 1$. The density increase observed during the LHCD phase is qualitatively consistent with the inward particle pinch due to the dominant ion turbulence. Experimental results are consistent with theoretical results predicted by Gyro-kinetic turbulence simulation, which shows that the ITG-TEM turbulence transition is governed by the ion temperature and density gradients. These suggest that the ion temperature profile stiffness in tokamaks is resulting from the competition between ion and electron turbulence. This mechanism is very similar to that leading to the density profile stiffness as shown in [1].

The turbulence phase velocity reversal has also been observed during the L-H transition. It was shown in the HL-2A tokamak that the L-H transition is triggered when the $E \times B$ velocity shear reaches a critical value, and the main effect is due to the ion drift diamagnetic term (∇P_i) [2]. Turbulence measurement has shown that the formation of the edge particle transport barrier in H-mode plasmas is due to firstly the suppression of electron turbulence, which is dominant in L-mode, and secondly the presence of the residual ion turbulence in H-mode plasmas, which generates an inward particle flux in convection.

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Perturbation of the electron distribution function induced by Kinetic Ballooning Modes in high-temperature tokamak plasmas

S. Mazzi[1,2], G. Giruzzi[1], R. Dumont[1], M. Fontana[3], F. P. Orsitto[4], E. de la Luna[5], S. Brunner[2], S. Coda[2], Y. Camenen[6], J. Garcia[1] and JET contributors[a]

[1] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[2] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland
[3] United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy, Abingdon, UK
[4] ENEA Department Fusion and Technology for Nuclear Safety, C R Frascati, 00044 Frascati, Italy
[5] National Fusion Laboratory, CIEMAT, Madrid, Spain
[6] Aix-Marseille Université, CNRS PIIM, UMR 7345 Marseille, France
[a] see the author list of J. Mailloux *et al.*, *Nucl. Fusion* 62 (4), 042026 (2022)

As a still elusive and long-standing issue, discrepancies between Electron Cyclotron Emission (ECE) and Thomson Scattering (TS) diagnostic measurements have been observed throughout the last ~30 years in different devices, such as TFTR **[1]**, JET **[2]** and FTU **[3]**. This discrepancy is especially observed in the plasma core of high-temperature scenarios, even in the absence of EC or lower hybrid power. A recently developed model, tested on an extensive set of data made up of multiple pulses of recent JET campaigns **[4]**, showed that this kind of ECE-TS discrepancy is well explained by the introduction of a bipolar perturbation in the electron distribution function (EDF) at velocities close to the thermal velocity, modifying thereby the EC emission/absorption spectra **[5]**. Although such a model resolves the experimental ECE-TS discrepancy by reconciling the diagnostic measurements, the physical mechanisms underlying the formation of such a perturbation have not yet been provided. Advanced studies of the collisional relaxation of suprathermal ions on the EDF, producing bipolar perturbations similarly to the EC model **[6]**, offer a first physical cause of the perturbation. Moreover, in-depth studies about the possible correlation between the characteristics of the ECE-TS discrepancy and the MHD activity reveal compelling intuitions about the underlying physics **[7]**.

In this work, we unveil another possible path, that is the fundamental wave-particle interaction mechanism between electrons and Kinetic Ballooning Modes (KBMs). Hence, local gyrokinetic numerical studies, performed by means of the GENE code **[8]** in realistic plasma conditions, have been carried out for the inner core of a selected high-temperature pulse of the JET device. In this pulse, the electron-β was large enough to destabilize KBMs, which have been linearly characterized in the local simulations. It is thus shown that the bipolar structure in the velocity phase-space of the EDF is found when the KBMs are unstable, yielding a qualitative agreement with the perturbation implemented in the EC model for this class of JET pulses. It is also shown that already in the linear phase a wave-particle resonant interaction takes place in the range of the electron thermal velocity, leading to the bipolar structure in the energy phase space. Extensive nonlinear simulations are performed to evaluate the amplitude of the bipolar structure triggered by the KBM, as well as its dependence on physical and geometric parameters. The amplitude is found to be large enough to affect the experimental ECE measurements. Detailed studies on the resonant interaction provide additional explanations on the physics involved in the wave-particle interaction.

In conclusion, KBMs destabilized by the high-β plasma conditions achieved in the core of high-temperature scenarios may perturb the EDF forming bipolar structures in the velocity phase space and, thereby, modifying the EC spectrum and the ECE measurements.

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Multipactor Predictions for Complex Radiofrequency Components for Space and Nuclear Fusion Applications

Eva Al Hajj Sleiman[1,2], Julien Hillairet[1], Mohamed Belhaj[2]

[1]*CEA, IRFM, F-13108, Saint Paul Les Durance, France*
eva.alhajjsleiman@cea.fr
[2]*ONERA, DPHY, Université de Toulouse, F-31055, Toulouse, France*

Multipactor is an electron avalanche taking place in radiofrequency (RF) devices under vacuum, where the materials' secondary emissions are in resonance with the RF electric field and the electrons' motion [1]. This process affects space telecommunication payloads [2], particle accelerators [3], and nuclear fusion plasma heating RF antennas [4]. It can lead to undesirable effects such as signal perturbation [5], temperature increase [6], outgassing [7], and ultimately damaging components [7].

During experimental campaigns on the tokamak WEST, pressure rises have been observed inside the Ion Cyclotron Resonance Heating (ICRH) antennas used for plasma heating. In WEST, the ICRH system is composed of three resonant independent antennas [8], [9]. When only one antenna is powered while the remaining two are off, this pressure rise is observed in the two off-mode antennas. If the pressure in an antenna exceeds a certain threshold, safety interlocks prevent the application of the RF power to avoid generating an RF plasma inside the antenna. The main hypothesis to explain this pressure rise is the outgassing produced by multipactor occurring inside the antennas due to antenna cross talk. To understand and avoid operational limitations, it is essential to correctly model the conditions under which multipactor appears in the ICRH antenna, which is subject to waves resulting from an incident wave and a reflected wave induced by the plasma and the intrinsic RF design of the antenna.

After introducing multipactor, this contribution discusses the conditions for which it can appear inside the WEST RF antennas during plasma operations. First, the multipactor phenomenon is modeled for the different geometrically complex RF components of the ICRH antenna energized with different waveform conditions. In particular, the T-junction and the impedance transformer of silver-coated stainless steel metal, and the multi-material RF-feedthrough window made of silver-coated material and an alumina dielectric. Then, using an analytical formulation of the pressure rise, the multipactor-induced outgassing is computed and is directly compared to the measured pressure rise in the antennas, to conclude on the multipactor responsibility for the pressure increase. Such mutipactor modelling validated by experience shall contribute to designing a safe and efficient operational domain for the present ICRH system on WEST and future ICRH systems, such as ITER, where a similar problem could be of concern when similar operational scenarios are considered.

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Investigation of JET H-mode edge plasma and derivation of a scaling law for separatrix density as a function of engineering parameters

G. Ciraolo[1], J. Balbin-Arias[1,2], P. Muscente[3], J. Bucalossi[1], N.Fedorczak[1], H. Bufferand[1], P. Innocente[4] and and the JET contributors

[1] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.*
[2] *College of William and Mary, Williamsburg, VA 23185, United States of America*
[3]*Università degli Studi di Padova, Via VIII Febbraio, 35122 Padova, Italy*
[4]*Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy*.
Email of corresponding author: guido.ciraolo@cea.fr

A viable magnetic fusion power plant has to combine very high plasma density and temperature in the core region, in order to maximize fusion reactions, with cold plasma conditions in the peripheral region compatible with long life expectancy of plasma-facing components. In this contribution, taking inspiration from recent work on DIIID tokamak (see ref. 1), we examine this crucial issue for magnetic fusion research by adopting an approach based on the analysis of a large set of experimental data on H-mode plasmas from JET tokamak. In order to obtain a scaling law for the relationship between top pedestal density and separatrix density at the outer midplane (OMP) as a function of engineering parameters more than ninety discharges have been considered. The choice to examine this density ratio is motivated by the fact that, on the one hand, the density at the top pedestal is an indicator of core confinement and device performance, and on the other hand, the separatrix density has a strong impact on divertor conditions, indicating whether safe conditions for divertor targets are achievable or not.
After a short description of the dataset under consideration and the power balance method used for the determination of the separatrix position [2], two main engineering parameters have been identified and used for the scaling law on the density ratio, namely the plasma current I_P and the total injected power P_{TOTAL}. This first scaling law seems to predict the experimental data quite well for low and medium values of the separatrix density, while at high density a strong discrepancy appears. In order to get further insight on such behavior the discharges were analyzed in terms of divertor magnetic configuration. A clear difference is observed between experiments with a corner-corner divertor configuration compared to the horizontal-vertical or vertical-vertical ones. This result suggests the introduction of two parameters taking into account the quality of confinement as well as the divertor conditions [3, 4]. In this way, a better agreement between predictions from the scaling law and experimental results is obtained for both low and high-density values [5, 6]. Finally, numerical investigations for representative JET H-mode discharges in the three divertor configurations have been performed using the SOLEDGE code to analyze plasma conditions in the divertor region as well as in the main chamber and their impact on pedestal and separatrix density.

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Non-linear gyrokinetic study of the current ramp-up phase in TCV

Y. Camenen[1], M. Marin[2], P. Manas[3], C. Angioni[4], C. Bourdelle[3],
J. Citrin[5], E. Fable[4], A. Ho[5], P. Maget[3], O. Sauter[2] and TCV team

[1] *CNRS, Aix-Marseille Univ., PIIM UMR7345, Marseille, France*

[2] *EPFL, Swiss Plasma Center (SPC), Lausanne, Switzerland*

[3] *CEA, IRFM, F-13128 Saint-Paul-lez-Durance, France*

[4] *Max-Planck-Institut für Plasmaphysik, Boltzmannstrasse 2, D-85748 Garching, Germany*

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

In a tokamak plasma, the prediction of the plasma resistivity during the current ramp-up phase is essential to design scenarios that minimise the magnetic flux consumption and tailor the safety factor profile evolution to avoid deleterious MHD instabilities. The plasma resistivity directly depends on the electron temperature and the impurity content. Its prediction therefore largely relies on transport models for the electron heat flux and impurity flux (high Z impurities for the radiated power, which affects T_e, and low Z impurities for the resistivity, proportional to $Z_{\rm eff}$). The current ramp-up phase is characterised by plasmas with high T_e/T_i, high q, high collisionality (low T_e), low shaping and, often, a limiter configuration. For accurate predictions, anchoring and reduced transport models need to be validated in these very specific conditions. This is the goal of the present study performed in the frame of TSVV11 activities on "Validated Frameworks for the Reliable Prediction of Plasma Performance and Operational Limits in Tokamaks". The study is focused on the ramp-up phase of TCV plasma #64965 at line averaged density, $n_{el} = 5 \times 10^{19}\,\mathrm{m}^{-3}$, plasma current, $I_p = 320\,\mathrm{kA}$ and safety factor $q_{95} = 2.5$ (flat-top values). Carbon impurity temperature, density and toroidal rotation were measured by charge exchange spectroscopy using TCV non-perturbative diagnostic neutral beam. Electron temperature and density were measured by Thomson Scattering. Linear and non-linear gyrokinetic simulations have been performed with GKW for three selected time slices, $t = 0.07$, 0.12 and 0.17 s, and two radial positions $r/a = 0.5$ and 0.7. In the early phase of the ramp-up, the plasma is deep in the TEM regime and progressively moves towards the ITG regime, starting first from the innermost radial locations. This is reflected in the non-linear electron to ion heat flux ratio which reaches more than 10 at $r/a = 0.7$ for the first time slice and drops to about 1 at $r/a = 0.5$ for the last time slice. Carbon ions and trace tungsten ions were included in the non-linear simulations to assess impurity transport. Reduced models predictions with TGLF and QuaLiKiz will be compared to the non-linear simulations in standalone and to the experimental measurements within integrated simulations with the High Fidelity Pulse Simulator.

Experimental characterization of mutual interactions between filaments in COMPASS tokamak

S. Chouchène[1,3], F. Brochard[1], J. Cavalier[2], M. Desécures[3], N. Lemoine[1], V. Weinzettl[2]

[1] *Université de Lorraine, Institut Jean Lamour, Nancy, France*

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

[3] *APREX Solutions, Pulligny, France*

Cross-field turbulent transport in magnetically confined plasma is a topic of intense research since decades. Turbulent filaments, called blobs, are investigated experimentally with a variety of diagnostics like electrostatic probes, beam emission spectroscopy, reflectometry and fast visible imaging [1]. In order to localize structures and to improve temporal resolution, fast cameras are often used in combination with the local injection of gas, a technique called Gas Puff Imaging (GPI) [2]. To date, the possibility of mutual interaction between filaments has been theoretically investigated but has not been reported experimentally [3], probably due to the lack of measurements with sufficient spatial and temporal resolutions. In this contribution, we present experimental evidence of such interactions observed in the COMPASS tokamak, without GPI. Passive imaging video data realized at 1 million frames per second have been tomographically inversed to reconstruct the image of filaments in a poloidal plane with a spatial resolution of 2.5 mm across the separatrix [4]. Various kinds of interactions are evidenced: merging, splitting, as well as fast reversal of the blob poloidal propagation direction (Fig. 1). A method based on artificial intelligence has been developed to investigate these interactions statistically, demonstrating the significance of such interactions, enabling to better understand results obtained with classical tracking methods applied to data recorded at lower frame rates.

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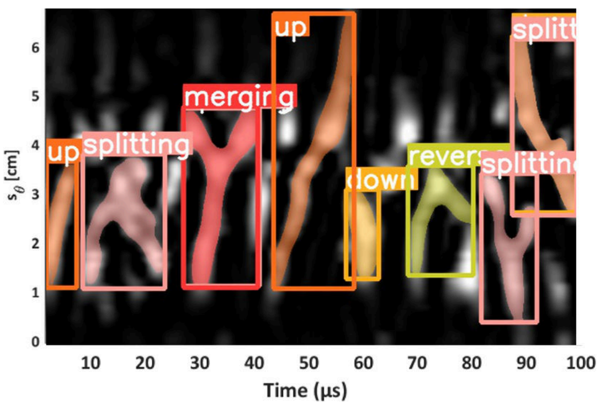

Figure 1: *Light kymograph along the separatrix after tomographic inversion, showing various kinds of filament interactions detected using machine learning technique.*

Calculations of WHAM2 Mirror Neutron Rates and FI Transport using the GENRAY/ CQL3D-M and MCGO-M codes

Yu.V. Petrov[1,] R.W. Harvey[1], C.B. Forest[2], J.K. Anderson[2]

[1] *CompX, Del Mar, CA, USA*

[2] *Univ. of Wisconsin, Madison, Wisc., USA*

The GENRAY ray tracing, and CQL3D-M axisymmetric mirror, neutral beam/RF/collisional bounce-average Fokker-Planck code are applied for calculation of D distribution functions in the WHAM2 mirror configuration, obtaining DD neutron rates in a manner similar to [1]. The multi-species CQL3D-M is updated to calculate the self-consistent parallel electric field keeping electron and ion densities approximately equal. The distributions are calculated simultaneously with the fully nonlinear particle- and approximately energy-conserving collision operator. WHAM2 is an upgraded version of the WHAM high field superconductor mirror being constructed at the Univ. of Wisconsin[2]. We compare calculated neutron rates from available 25 keV NB and RF fast wave (FW) power. For 0.5 MW second harmonic FW heating at 26 MHz with linearised collision operator, we obtain 5e14 neutrons per sec, , *i.e.,* 20X, compared to 2e13 n/s with 0.5 MW NB power. Electron density is 6e13/cm**-3; Te is 2 keV. In Epar-iterated runs the numbers are different, with density growing. The much higher D-energies obtained with FW are very effective for DD neutron production and maintaining the sloshing ion population. There has been concern that full gyro-orbit orbits may be subject to large pitch angle scattering in the strongly varying magnetic field as in WHAM[3], and thus causing fast ion loss into the mirror loss cone. Using the MCGO-M Monte Carlo orbit code, the full energetic deuterium orbits were following for collisional slowing down times. Orbits appear to be falling into Quantum-Like-Mode discrete states[4], and at least for the examined orbits the resulting diffusion is limited and does not appear large.

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Integrated data analysis of the multispectral imaging data on the TCV tokamak

A. Perek[1], B. L. Linehan[2], K.Verhaegh[3], T. A. Wijkamp[4,5], E. Huett[1], C. Theiler[1], J.T.W. Koenders[5,6], H. Reimerdes[1], M. van Berkel[5], B.P Duval[1] and the TCV team[a]

[1]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland

[2]Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A

[3]UKAEA-CCFE, Culham Science Center, Abingdon, United Kingdom

[4]Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands

[5]DIFFER − Dutch Institute for Fundamental Energy Research, Eindhoven, The Netherlands

[6]Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands

[a]See the author list of S. Coda et al. 2019 Nucl. Fusion 59 112023

Quantitative imaging is rapidly gaining interest within the tokamak community. At TCV, the state-of-the-art multispectral imaging systems (MANTIS) consisting of one 10-camera and two 6-camera systems installed in the lower, midplane and upper ports provide absolutely calibrated images of several hydrogenic and Helium emission lines [1]. Inverted under the assumption of toroidal symmetry, the diagnostic provides 2D poloidal emissivity maps.

To date, the hydrogenic and helium emission have been analyzed separately. The hydrogenic analysis provides information upon the electron density, temperature, atomic density of deuterium and the ionisation and recombination rates with their power loss rates [2]. The Helium line emission analysis also provides information upon the electron temperature, density and the helium's atomic density [3]. Each analysis has its regions of validity. The collisional-radiative model supplied by the ADAS code for hydrogen does not account for plasma-molecule interactions below $\sim 3\,\mathrm{eV}$ that contribute to the emission nor constrain the electron temperature above $\sim 10\,\mathrm{eV}$ [2,4]. The Goto collisional-radiative model for helium provides electron temperature constraints above $\sim 10\,\mathrm{eV}$ [3].

In this work, we present an integrated data analysis of multispectral imaging data for hydrogen and helium whilst applying the most appropriate model. The models are complementary and can better describe the complete system than when applied alone. Substantial reductions in uncertainty are obtained for the inferred neutral atomic density using hydrogenic emission at temperatures where the helium model is more appropriate. Together, this enabled estimates of the 2D neutral atom hydrogen to helium ratios in the recycling gas interacting with the SOL while reducing the uncertainties in other diagnostic state estimations.

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Validation of pulse reflectometer measurements for fast electron density fluctuations. Mack van Rossem, O. Krutkin, U. Kumar, S. Coda, B. Labit, and the TCV Team

Ecole Polytechnique Fe´de´rale de Lausanne (EPFL), Swiss Plasma Center (SPC) 1015 Lausanne, Switzerland

mackenzie.vanrossem@epfl.ch

The current work validates many of the underlying assumptions required to measure very fast electron density fluctuations with a short-pulse reflectometer (SPR). An analysis based on the WKB approximation is shown to correctly reproduce density profiles from SPR data, generated via a synthetic diagnostic using full-wave code. This analysis routine is then used to compare the synthetic data to real data taken on TCV tokamak under similar experimental conditions. A number of challenges specific to short-pulse reflectometry are addressed, and the planned ex- perimental strategies for measuring fast electron density fluctuations in H-mode pedestals are discussed.

The reflectometer launches ∼ns microwave pulses into the plasma, which reflect off the cut- off layer and are then received by the antenna. The measured group delay (time of flight, TOF) is then converted to density profile information through an inversion process based on the WKB approximation. In TCV, the SPR measures time-of-flights (TOFs) using a fast and precise 32 sam- ples/ns analog to digital converter (ADC) [1]. Measurements in the time-domain give confidence that measured signals are a direct result of plasma conditions, rather than spurious reflections from the waveguides or vacuum window. However, correct interpretation of the group-delays is often challenging due to the complex propagation of electromagnetic radiation in plasma.

To verify that our measurements and interpretations are correct, gyrokinetic GENE modelling was used to produce density profiles, including fluctuations. Equilibrium conditions meant to model a plasma in TCV are provided to GENE, which in turn models the fluctuations around this equilibrium. Full-wave modelling [2] is then performed for the microwave pulses in the plasma conditions provided by GENE, which are then used to simulate the signal measured by the ADC. The analysis code is then able to correctly invert (within tolerance) the TOFs generated from each timestep of GENE into the density profile during that fluctuation, in addition to recovering the equi- librium profile. Further, a simple requirement on the shape of the measured pulse signal is shown to suffice for correctly filtering non-linear scattering effects at the cut-off layer (a regime in which WKB is known to fail). This data trimming, combined with the time-domain resolution provided by the ADC, validates that each successful pulse TOF measurement can be reliably interpreted using the WKB approximation.

This work thus provides confidence that each measured group delay reflects a true snap- shot of the plasma (to within a few ns of transit time), and can thus be used to reconstruct plasma conditions throughout fast electron density fluctuations. Synthetic profiles with realistic and exper- imentally validated fluctuation amplitudes are reconstructed and used to put a confidence bound on measured density profiles. Future work will optimise the number of pulses per frequency sweep in order to maximise statistics (or time resolution), while not sacrificing spatial resolution. In particular, care will be taken to optimise measurements for the fast but narrow region inside of H-mode pedestals, with the goal of measuring the dynamics of H-mode pedestals.

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Magnetic island-like patterns in synchrotron radiation images of JET runaway electron beams: a comparison between the JOREK simulation and experiments via synthetic camera diagnostics.

C. Sommariva[1], M. Hoppe[1], A. Pau[1], E. Nardon[2], G.T.A Huijsmans[2,3], M. Hoelzl[4], S.J.P. Pamela[5], V. Bandaru[6], C. Reux[2], O. Ficker[7], S. Silburn[8], J. Decker[1], J.P. Graves[1], JET Contributors [8,§], TSVV8 and TSVV9 teams

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

[2] *CEA, IRFM, F-12108, Saint Paul-lez-Durance, France*

[3] *Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, Netherlands*

[4] *Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching bei München, Germany*

[5] *CCFE, Culham Science Centre, OX14 3DB, United Kingdom of Great Britain and Northern Ireland*

[6] *Indian Institute of Technology (IIT), Guwahati, Assam, India*

[7] *Institute of Plasma Physics of the CAS, CZ-18200, Praha 8, Czechia*

[8] *Eurofusion Consortium, JET Culham Science Center, Abingdon, OX14 3DB, 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 present contribution discusses the new synthetic fast camera diagnostic developed for the JOREK code. The JOREK code is a 3D time-varying non-linear magnetohydrodynamic (MHD) code used for simulating instabilities in both tokamak and stellarator plasmas [1]. The JOREK fast camera uses a virtual point light source approach [2] for rendering synthetic images of the plasma or of its minority species from 5D or 6D kinetic 'particle' simulations. Hereafter, the attention is focused on the rendering of synchrotron radiation images from relativistic electron simulations of the JOREK code [3-4]. The aim is to bridge the gap between the numerical and the experimental evidence for verifying the reliability of the JOREK simulations relating the triggering of benign termination of some of the JET runaway electron (RE) beams (highly relativistic electron beams possibly appearing after a plasma disruption) to the growth of double tearing modes. Indeed, recent analyses of the experimental images recorded during the 2018-2019 JET experimental campaign show the presence of magnetic island-like patterns in the RE beam synchrotron emission [5]. The dynamics of the synchrotron patterns have been characterised via feature identification and tracking methods [6]. The synchrotron pattern properties have been compared with possible configurations of the RE current profile inferred by CHEASE-SOFT [7-8] parameter scans and found compatible with the presence of islands in the beam magnetic configuration [9]. Similarly, JOREK fluid simulations of the JET experiment 95135 RE beam suggest that the cause of the global MHD instability safely terminating the hot electrons population is the growth of double tearing modes [10]. Indeed, the resulting magnetic island chains create stochastic magnetic fields when they overlap degrading the RE confinement [10]. In this respect, the newly developed synthetic fast camera diagnostics permit a direct comparison, not possible before, between the experiments and the JOREK simulated RE beams with 3D MHD instabilities via the rendering of synthetic synchrotron images. In the first part of the contribution the electron synchrotron models, and the virtual point light source method implemented in the JOREK fast camera are discussed. Afterwards, benchmarks based on 2D simulations of RE beams between the JOREK fast camera and the SOFT codes are provided together with code performance analyses. First results concerning the synchrotron images of 3D JOREK RE simulations are also presented and compared with the JET data.

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Analysis of the ramp-down phase using the Fenix flight simulator

R. Coosemans[1], E. Fable[2], C. Contré[1], P. David[2], F. Felici[1], S. Medvedev[3], A. Merle[1], T. Pütterich[2], O. Sauter[1], S. Van Mulders[1], C. Wu[4], the ASDEX Upgrade Team[i], and the TCV Team[ii]

[1]*Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), 1015 Lausanne, Switzerland*

[2]*Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany*

[3]*Tokamak Energy Ltd, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom*

[4] *Karlsruhe Institut für Technologie, 76344 Eggenstein-Leopoldshafen*

The capability to accurately design plasma scenarios is crucial for the successful operation of future fusion reactors. However, the rich physics involved, the multitude of actuators available, and the trade-off between conflicting objectives and operating constraints make this a daunting task. So called ‘’tokamak flight simulators’’ capable of simulating the complete discharge, including the interaction between the plasma and the control system, with reasonable accuracy in limited computational time provide a valuable tool to support this effort.

In this context, we illustrate the use of the Fenix flight simulator [1] developed for ASDEX Upgrade (AUG) to model the ramp down phase of scenarios developed for the ITER baseline [2,3]. This complex part of the discharge will be critical in future reactors because of the high-energy plasma needing to be terminated in a safe and controlled way. Next to the interest of the underlying physics, this provides a challenging case for testing the Fenix flight simulator.

Preliminary results are encouraging, indicating that the trends in the internal inductance when varying the plasma current ramp-down rate are in qualitative agreement between AUG discharges and Fenix simulations. The latter use the gyro-Bohm-like transport model with empirical modifications for AUG discharges available in Fenix [1]. Currently, the application of Fenix to TCV is being worked on to investigate which elements of the flight simulator are generic and which ones require tokamak-specific tuning. A comparison with TCV ITER baseline ramp-down phases should allow to validate the various models. This is expected to provide indispensable insights for application of flight simulators to future machines.

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Experimental and numerical evidence of electron turbulent transport enhancement by Electron-Cyclotron waves in tokamaks

J. Cazabonne[1], P. Donnel[2], S. Coda[1], J. Decker[1], G. Di Giannatale[1], A. Iantchenko[1], U. Kumar[1], Y. Peysson[2], L. Porte[1], S. Rienäcker[1], A. Tema-Biwole[1], L. Villard[1] and the TCV Team[1,a]

[1] *EPFL, Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland*

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

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

Electron-Cyclotron (EC) wave-plasma coupling is routinely used in tokamaks to heat and drive current through the electron channel. Technical applications such as MHD mode mitigation require power deposition with a high degree of localization. However, in tokamaks, a distribution of suprathermal electrons broader than predicted by standard drift-kinetic codes has been observed [1]. Two different phenomena have been proposed to explain this discrepancy: either the broadening of the EC beam before its absorption due to fluctuations in the plasma refractive index [2], or the enhanced radial transport of wave-accelerated electrons [3]. This contribution reports on the possible wave-induced increase of electron turbulent transport that may explain the experimental data, using power-modulated electron-cyclotron waves in the TCV tokamak [4]. In particular, an indirect measurement of the suprathermal electron population via hard X-rays exhibits enhanced radial transport with increased wave power. This correlates well with the measured increase of the electron density and temperature fluctuation level during the power pulses, associated with the destabilization of ion temperature gradient modes and trapped electron modes and with stiff electron profiles. Forward bounce-averaged drift-kinetic simulations show that a radial diffusion model directly proportional to the phase-space-dependent wave power deposition is required to match the experimental data. A power dependency is also shown in global flux-driven gyro-kinetic simulations, using a new realistic electron-cyclotron power source [5, 6], computing turbulent transport from first principles and showing a radial increase of electron transport with increased wave power.

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Rapid radial profiles simulation and scenario preparation on TCV discharges using the RAPTOR code

Cassandre E. Contré, Federico Felici, Simon Van Mulders, Olivier Sauter and the TCV team

[1] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland 654*

The fast prediction of plasma radial transport is of high interest for tokamak operations, for preparation, real-time control and rapid post-shot analysis of the discharges. This work presents results from the RAPTOR code, a fast and light simulator of the current density, heat and particle 1D radial transport equations, for full TCV discharges on various scenarios. RAPTOR [4] is a control-oriented model, which distinguishes itself by its high calculation speed, and is used both for real-time control and off-line scenario optimization [6][3]. Previous work has brought it to sufficient maturity to be used routinely and to move to another stage of its development: to prepare and validate discharges before they are executed, in addition to discharge optimization, in such a way to integrate it into the TCV preparation schedule used by the various session leaders. In this work, we aim to test the RAPTOR models on various TCV scenarios in order to validate and improve its modelling capabilities and to automate post-shot simulation. In a second phase, this work leads to the implementation of a pre-pulse preparation method, by coupling RAPTOR directly to the actuator settings and references programmed by the operator. This includes coupling RAPTOR with FBTE [5], a free-boundary equilibrium solver, to improve feedforward prediction of both internal profiles and equilibria. In parallel, steps towards the adaptation of RAPTOR to the FAIR principles [2] are undertaken. In particular, we will discuss the mapping of the set of input/output data to the IMAS structures [1] and the TCV databases.

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Realistic sheath boundary conditions for gyrokinetic codes

A. Geraldini[1], S. Brunner[1], F. Parra[2], R. Ewart[3]

[1] *Swiss Plasma Center, EPFL, CH-1015 Lausanne, Switzerland*

[2] *Princeton Plasma Physics Laboratory, Princeton, NJ 08540, USA*

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

When viewed on the length scale L of large-amplitude fluctuations in the Scrape-Off Layer (SOL) of a fusion device, the magnetised plasma sheath is an infinitely small boundary layer appearing next to the divertor/limiter targets [1]. Its thickness is $\rho_{\rm i}\cos\alpha$, where $\rho_{\rm i}$ is the ion gyroradius and α is the typically small angle between the magnetic field line and the target. The main role of the sheath electric field is to reflect enough electrons to achieve a (globally) ambipolar flow of ions and electrons to the solid target, consistent with a steady state. The region is itself multi-scale, including the Debye sheath as a sub-region, and is therefore rich in physics and complex. Yet, it would be unnecessary (and computationally prohibitive) to resolve its small length and time scales across the whole SOL. One can instead solve the SOL and magnetised sheath as separate regions by exploiting the asymptotic limit $\rho_{\rm i}/L \to 0$, and match the solutions. The sheath attracts ions to the target, but not all ion distribution functions reaching the sheath entrance are acceptable. We present the main steps of the derivation of the kinetic Bohm-Chodura condition which must be satisfied by the ion distribution function for a steady state asymptotic sheath solution. Our derivation includes the ExB drifts from spatial fluctuations competing with ion parallel streaming towards the target. We also present numerical solutions of the magnetised sheath for small angles $\alpha \ll 1$ [2] including the effect of finite electron gyroradius. The computed distribution function of reflected electrons accounts for a self-consistent magnetic moment dependence in the parallel velocity cutoff. In contrast, sheath boundary conditions used in edge gyrokinetic simulations have so far assumed a constant parallel velocity cutoff [3, 4]. We will discuss how the presented analytical and numerical results may be applied to refine gyrokinetic sheath boundary conditions.

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SOLPS-ITER simulation of an X-point radiator in TCV

G. Sun[1], O. Pan[2], M. Bernert[2], C. Colandrea[1], M. Carpita[1], B. P. Duval[1], O. Février[1], S. Gorno[1], H. Reimerdes[1], C. Theiler[1], S. Wiesen[3], the TCV team[3]

[1] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

[2] Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany

[3] Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung - Plasmaphysik, 52425 Jülich, Germany

The operation of future fusion devices requires stationary divertor conditions with acceptable power exhaust levels, which is usually achieved by seeding radiative impurities. With strong seeding, the radiation region can move past the X-point into the confined region. This X-point radiator (XPR) scenario features a high radiation fraction and a fully detached divertor, and can result in an ELM-suppressed regime as observed in AUG [1]. Here the SOLPS-ITER code is adopted to reproduce the XPR condition that was observed in recent TCV H-mode experiments with nitrogen seeding and provides further insights into the physical understanding of the XPR formation. The simulation setup is similar to that in recent SOLPS-ITER simulations of the XPR in AUG[2]. Radial distributions of cross-field transport coefficients are adjusted to fit upstream density and temperature profiles measured with Thomson scattering. The nitrogen seeding rate is increased while keeping the deuterium fueling rate constant. The radiation front is found to move away from the outer target and reside above the X-point when the target temperature drops to approximately 1 eV. In the SOLPS simulation, the overall radiation fraction is above 95% which is mainly due to nitrogen line radiation, while the carbon density drops significantly due to reduced target particle fluxes.

Both unbaffled and baffled TCV divertors are simulated to explore the influences of gas baffles on the XPR access condition. Once an XPR is formed, neutral density near the X-point increases by more than an order of magnitude for both configurations, due to strong volumetric recombination. The baffled divertor achieves an XPR with lower nitrogen seeding rate. The baffles are shown to increase the neutral pressure near the X-point and thereby facilitate the XPR formation, consistent with theory prediction[3].

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Development of a kinetic-MHD spectral code using the Van Kampen approach

F. Jeanquartier[1], J.P. Graves[1], S. Brunner[1]

[1] *École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), 1015 Lausanne, Switzerland*

Kinetic effects of bulk and fast particles in tokamaks can have a significant impact on MHD stability predictions. Current kinetic-MHD analytical work and codes estimating these effects rely on a number of assumptions and encounter several technical constraints. Indeed, many of the existing codes compute kinetic effects by solving a drift-kinetic equation semi-analytically, which implies strong limitations on the type of orbits that can be reproduced by the model. Other codes integrate guiding-center orbits numerically, which requires less assumptions but strongly increases the computational requirements. In this work, we implement a spectral hybrid kinetic-MHD code which solves the MHD equations and the drift-kinetic equation proposed by [1] as an eigenvalue problem in a self-consistent way. The linear eigenmodes including their frequency and growth rate are obtained. The Van Kampen approach [2] is used to solve the self-consistent eigenvalue problem. For unstable modes, it is more practical to implement than the standard Landau approach. The kinetic-MHD equations indeed reduce to a standard linear eigenvalue problem expressed in terms of the MHD displacement as well as the kinetic correction to the perturbed distribution function. On the other hand, the usual Landau approach would result in a nonlinear eigenvalue problem for the MHD displacement. We present the first results obtained with this new method in the case of an internal $m = n = 1$ kink mode in screw pinch geometry. This simplified cylindrical configuration allows us to solve the kinetic-MHD problem semi-analytically using the standard Landau approach. It can then be used as a first benchmark for the code.

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Study of fast ion-driven instabilities in TCV tokamak using short pulse reflectometry diagnostics

U. Kumar[1], S.Mazzi[2], S. Coda[1], O. Krutkin[1] , M. Vallar[1] and the TCV team[a]

[1] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland*

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

[a] *see the author list of H. Reimerdes et al., Nucl. Fusion 64, 042018 (2022)*

Instabilities such as Toroidal Alfvén Eigenmodes (TAEs) which are driven by fast ions can cause radial outward transport of fast ions and fusion alpha particles [1]. This can lead to the degradation of fusion plasma performance in a reactor due to the loss of the main internal heating source. Therefore it is crucial for the next generation tokamak devices to study in detail the characteristics of these modes and their effects on the bulk plasma properties.

In the present work, we use short pulse reflectometry (SPR) in the TCV tokamak to study the characteristics of TAEs excited by the fast ions generated through the counter-current injection of a neutral beam (NB). The TAEs in TCV taken into consideration for this work are localized around ρ_ψ= 0.5-0.65, with a frequency around 100 kHz [2]. The maximum NB power is 1.2 MW with nominal beam energy around 27.8 keV, and it is injected counter-current. The SPR technique [3] consists of sending broadband microwave pulses and measuring the round trip time-of-flight using a 32 GS/s Analog to digital converter (ADC). Therefore, the reflectometer is capable of measuring the density profile with sub-centimetre spatial resolution and microsecond temporal resolution, thus resolving most of the turbulent fluctuations and MHD modes as well. We will report the analysis of time-of-flight from SPR in a NB heated scenario demonstrating the presence of the TAE mode along with the characterization of other modes. The modes observed by SPR diagnostic correlate well with magnetic probe signals [4]. The detailed characteristics of these modes along with their impact on the bulk plasma properties will be discussed.

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Effect of triangularity on plasma turbulence and the SOL-width scaling in L-mode diverted tokamak configurations

K. Lim[1], M. Giacomin[2], P. Ricci[1], D. Mancini[1], A. Coelho[1], L. Stenger[1], O. Février[1] and D. Silvagni[3]

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

[2] *York Plasma Institute, University of York, York YO10 5DD, United Kingdom*

[3] *Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, D-85748 Garching, Germany*

Negative triangularity (NT) configurations have attracted increasing attention in recent years as an alternative to H-mode operation in positive triangularity (PT) [1]. A large number of experimental studies on NT were carried out in different tokamaks, showing H-mode like confinement and ITER-relevant beta ($\beta_N = 2.7$) in an intrinsically ELM-free L-mode regime [2]. Following the encouraging experimental results, the effect of triangularity on plasma turbulence was actively investigated also through first-principle numerical codes.

In this work, the effect of triangularity on tokamak boundary plasma turbulence is investigated by using global, flux-driven, three-dimensional, two-fluid simulations [3, 4]. The simulations show that negative triangularity stabilizes boundary plasma turbulence, and linear investigations reveal that this is due to a reduction of the magnetic curvature drive of interchange instabilities, such as the resistive ballooning mode. As a consequence, the pressure decay length L_p, related to the SOL power fall-off length λ_q, is found to be affected by triangularity. Leveraging considerations on the effect of triangularity on the linear growth rate and nonlinear evolution of the resistive ballooning mode, the analytical theory-based scaling law for L_p in L-mode plasmas derived in Ref. [5], is extended to include the effect of triangularity. The scaling is in agreement with nonlinear simulations and a multi-machine experimental database, which includes recent TCV discharges dedicated to the study of the effect of triangularity in L-mode diverted discharges. Overall, the present results highlight that considering effects of triangularity is important for a reliable extrapolation of λ_q from present experiments to larger devices.

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Global gyrokinetic simulations of turbulence using an adaptive control variate approach with an evolving background Maxwellian

M. Murugappan, L. Villard, S. Brunner, G. Di Giannatale

Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

In the framework of a delta-f Particle-In-Cell (PIC) scheme, long gyrokinetic simulations of turbulence have been challenging, especially for situations involving profiles evolving significantly from their initial values or having high fluctuation values. This results in a large contribution of the delta-f component and associated statistical sampling noise, which renders such simulations impractical. Therefore, an adaptive delta-f scheme involving a flux-surface-averaged local Maxwellian control variate with a time-dependent temperature profile is proposed [2]. As a first step, this is tested [1] with steep profile gradients in sheared-slab geometry with simplified collisionless physics. In this case, the implementation of the scheme allows for sustained heat flux, thanks to the avoidance of spurious zonal flows build-up due to noise accumulation. Furthermore, good signal-to-noise ratio values are maintained allowing for simulations to converge numerically with lower number of markers compared to the standard fixed background approach. As a follow-up, we implemented the same adaptive scheme in toroidal geometry using the gyrokinetic PIC code ORB5 [3] considering a canonical Maxwellian control variate with time-dependent temperature and density profiles. First results of the application of this scheme in TCV-relevant configurations [4] will be shown.

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Validation of SOLPS-ITER Simulations in the TCV-X21 Reference Case

Y. Wang[1], C. Colandrea[1], D. S. Oliveira[1], C. Theiler[1], H. Reimerdes[1], T. Body[2], D. Galassi[1], L. Martinelli[1], and TCV Team[a]

[1] École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

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

*[a] See Reimerdes et al 2022 Nucl. Fusion **62** 042018*

To address the plasma power and particle exhaust challenge in magnetic confinement fusion devices, it is necessary to have reliable modeling and a good understanding of the process governing the scrape-off layer (SOL). This work presents a quantitative validation of SOLPS-ITER simulations of the TCV-X21 reference case and provides insights into the neutral dynamics and ionisation source distribution. TCV-X21 is a well-diagnosed, diverted, L-mode, sheath-limited plasma scenario developed in the 'Tokamak à Configuration Variable' (TCV) and optimized specifically for the validation of turbulence simulations [1]. New data are added here to the extensive, publicly available set of observables of TCV-X21, namely, deuterium Balmer line intensities measured by the divertor spectroscopy system (DSS) and neutral pressure measured in the common and private flux region of the divertor. As expected, in the approach where the SOLPS-ITER input parameters are set to match upstream density and electron temperature profiles, agreement between simulation and experiment is found in the outer midplane and at the divertor entrance, with the exception of parallel Mach flows. Less good agreement is found in the divertor volume and at the divertor targets, for quantities such as density, temperature, and plasma potential profiles. To determine input parameters providing a better overall simulation-experiment agreement, quantified by an overall validation metric, a proof-of-principle test using the conjugate gradient method is presented. Despite considerable computational costs, this gives only a modest improvement in the overall validation metric by 5.5%, mainly due to density and temperature in the low-field-side target and divertor volume. Alternatively, a scan of the particle and heat diffusion coefficients is conducted and results in an improvement of the validation metric by 10.4%. Decrease of the peak divertor target density value and broadening of the radial profile are found to contribute to this improvement. The result shows that an increased transport coefficient compared to what is usually used on TCV [2] can lead to a better overall match with the experiments. The turbulence simulations of the TCV-X21 scenario in [1] did not include neutral dynamics and assumed simplified ionisation source profiles located in the outermost region of the confined plasma. The present study with SOLPS-ITER and its coupling with kinetic neutral dynamics via EIRENE [3] indicates that ~50% of the ionisation occurs in the SOL, motivating the inclusion of neutrals in future turbulence simulations on the path towards improved agreement with the experiment [4].

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Experiments and modelling to characterise the effect of connection length on power exhaust in TCV (Tokamak à Configuration Variable)

S. Gorno[1], O. Février[1], H. Reimerdes[1], C. Theiler[1], F. Bagnato[1], C. Colandrea[1], B. P. Duval[1], F. Felici[1], T. Lunt[2], L. Martinelli[1], A. Merle[1], A. Perek[1], L. Safar[1], L. Simons[1], M. Wischmeier[2] and the TCV team[a].

[1]École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland; [2]Max-Planck-Institut für Plasmaphysik, Garching bei München, Germany; [a] See the author list of H. Reimerdes et al. 2022 Nucl. Fusion 62 042018.

Plasma exhaust remains a major challenge in magnetic confinement fusion, as an unmitigated heat flux reaching the wall in future reactors is predicted to greatly exceed material limits. Divertor detachment will be required, where target heat loads are reduced by an enhancement of volumetric loss processes – often achieved through impurity seeding. Alternative divertor configurations are being developed on current devices that reduce target heat loads, should the standard single null not scale to reactors such as DEMO [1].

Additional divertor null-points, such as in the Snowflake-minus (SF-) configuration [2], can greatly increase the connection length ($L_{||}$) by enlarging the region of traversed low poloidal field. Simple analytical models suggest that divertor radiative cooling capability increases with $L_{||}$ [3]. However, SF- experiments on TCV do not show a significant increase in divertor radiated power with respect to the standard Single Null (SN) for low core plasma density [4], suggesting that another factor is competing with the effects of $L_{||}$. A weakening of SF- benefits with impurity seeding could indicate a reduction in divertor impurity content in this scenario. To probe divertor impurity retention, experiments at higher core plasma density were performed, in which we see stronger divertor power losses than expected from a simple density scaling, but where the SF- again shows only a small increase in divertor radiated power compared to the SN. These observations will be interpreted with EMC3-EIRENE simulations, where an increase in cross-field transport is inferred in the SF-LFS divertor.

To highlight the effect of $L_{||}$ on divertor power exhaust, a novel divertor geometry has been developed on TCV, named the Jellyfish, which features $L_{||}$ over 4x longer than in the SN (and a third divertor poloidal null). First results indicate a strong reduction of outer target heat flux in the regions of enhanced $L_{||}$ in the Jellyfish. However, this does not necessarily coincide with an increase in divertor radiated power.

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Role of aspect ratio in confinement enhancement in negative triangularity plasmas

A. Balestri[1], J. Ball[1] and S. Coda[1]

[1]*École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), 1015 Lausanne, Switzerland*

In the last few decades, experiments on several medium-size tokamaks (TCV [1], DIII-D [2] and AUG [3]) have shown that giving the plasma a Negative Triangularity (NT) poloidal cross-sectional shape can cause a reduction turbulent transport with respect to Positive Triangularity (PT) plasmas and inhibit the transition to H-mode. This allows a NT plasma to have an L-mode-like edge pressure profile and H-mode-like core pressure level. This is a promising configuration for a future reactor, where detrimental edge localized modes have to be avoided and high confinement times are needed. However, since a complete understanding of the physical mechanisms behind the stabilization of turbulent transport in NT plasmas is missing, it is vital to identify the main parameters that can limit or enhance this beneficial effect.

In this work, we studied the impact of aspect ratio $A = R/r$ (ratio of major to minor radius) on the beneficial effect of NT. We used high-fidelity flux-tube gyrokinetic GENE simulations, which allow us to explore the parameter space. We considered three scenarios: a NT TCV scenario idealized with pure-ITG drive (electron density and temperature gradients are artificially suppressed), a realistic TEM dominated NT TCV scenario and a scenario expected for the SMART device [4] a low-A Spherical Tokamak, currently under construction at the University of Seville which is expected to have high geometric flexibility, enabling the creation of NT and PT shapes in single-null and double-null configurations. In order to isolate the impact of the shape, in the first two scenarios we kept the kinetic experimental profiles fixed, while the triangularity and the aspect ratio were changed using the Miller local equilibrium model. In the pure-ITG drive scenario, linear and non-linear simulations show that NT is stabilizing in the considered range of A, i.e. from 2 to 50. The heat fluxes are reduced by 80% in NT regardless of the value of A. However, magnetic shear is very high ($\hat{s} = 2.1$), which could play an important role in enhancing the beneficial effect of NT [5], hiding the impact of A. Instead, in the regime dominated by TEM turbulence, linear and non-linear simulations show a progressive destabilization of NT as A is decreased. In the range $A = (50, 5)$ NT has heat fluxes halved with respect to PT, at a critical value of $A \simeq 2.5$ NT and PT has the same heat fluxes, while at $A = 1.7$, typical for a Spherical Tokamak, NT becomes more unstable and the heat fluxes double with respect to the PT counterpart. The previous simulations are idealized cases and show that a large aspect ratio enhances the impact of NT, while at tight aspect ratio, depending on the turbulent regime, NT can become detrimental. As a more realistic case for a tight aspect ratio scenario, we considered SMART, which is expected to have $A = 2.5$ and also large β, making electromagnetic effects non negligible. TRANSP predictive simulations for SMART have been used as a starting point for GENE simulations. Preliminary linear and non-linear simulations confirm that, at tight aspect ratio, NT is detrimental with respect to turbulent transport, with heat fluxes that are more than doubled with respect to the PT counterpart. Moreover, NT seems to be more sensitive to electromagnetic effects, with a dominant, linearly unstable MTM branch and an electromagnetic heat flux that is responsible for most of the total flux.

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The MEQ free-boundary tokamak equilibrium code suite and its application to simulation and reconstruction of doublet plasmas in TCV

F. Felici[1], A. Merle[1], F. Carpanese[1], A. Langmeier[1], S. Marchioni[1], S. Medvedev[2], P. Molina[1], J-M. Moret[1], O. Sauter[1], C. Sommariva[1] and the TCV team[a]

[1]*EPFL – Swiss Plasma Center, Lausanne, Switzerland*

[2]*Tokamak Energy Ltd, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom*

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

The MEQ (Matlab EQuilibrium) suite is a comprehensive collection of fast and user-friendly codes and tools for tokamak free-boundary equilibrium calculations. It is written in Matlab and C and covers inverse equilibrium problems [1], equilibrium reconstruction (including real-time) [2] as well as static and time-evolving forward solvers coupled to circuit equations for the surrounding conductors [3]. For the time-dependent forward evolution solvers, various plasma models can be used including rigid-body models, deformable linearized models, and the full Grad-Shafranov equation. The time-dependent solver can also be coupled to controllers for closed-loop simulations and has been used in the past to develop controllers based on reinforcement learning [4].

The MEQ suite has been used to study doublet plasmas in the TCV tokamak, which feature two local extrema in the toroidal current density distribution, yielding up to three separate domains with closed flux surfaces. We present an analysis of the axisymmetric stability of simulated doublets, comparing the results with those obtained using the CAXE/KINX package [5], and highlight operational constraints and their dependence on the assumptions on the internal current distribution. We also present the first results of closed-loop free-boundary simulations of TCV doublets and discuss the design of stabilizing controllers for the configuration. Finally, we show the first results of equilibrium reconstruction of experimental doublet-shaped plasmas in TCV, studies of their salient features and comparing the instability growth rates of the reconstructed equilibria to experimental observations.

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Divertor detachment in X-point target configuration in TCV L-mode plasmas

K. Lee[1], C. Theiler[1], O. Février[1], S. Gorno[1], D.S. Oliveira[1], M. Carpita[1], E. Huett[1], A. Perek[1], H. Reimerdes[1], U. Sheikh[1], L. Simons[1], M. Zurita[1], and the TCV team[*]

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

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

Email: kenneth.lee@epfl.ch

The X-point target (XPT) configuration [1] is an alternative, long-legged divertor configuration featuring an additional X-point close to the divertor targets. It is one of the options foreseen for the SPARC device and the ARC pilot plant for reactor-relevant power exhaust [2] and is also under consideration for risk mitigation in DEMO [3]. Early XPT power exhaust studies on TCV have shown hints of enhanced CIII emission front stability in L-mode [4] and significant inter-ELM target heat flux reductions in type-I ELMy H-mode [5].

As part of the proof-of-principle tests of the XPT concept, this work does a systematic assessment of the properties of divertor detachment in the XPT configuration on TCV during Ohmic L-mode density ramps. It is found from wall-embedded Langmuir probe measurements that particle flux and power sharing between the two activated outer strike points (dubbed SP2 and SP4) are highly sensitive to the value of X-point separation. By varying the X-point separation, it is observed that SP2 is easier to detach, while SP4 shows considerably weaker signs of ion flux rollover. The peak heat fluxes on both outer strike points can be simultaneously reduced with respect to a conventional single-null (SN), by a factor of ~3, via optimisation of the X-point separation. Two-dimensional CIII line emissivity profile in the divertor region from multispectral imaging data displays enhanced emission front stability in XPT compared to SN, with relatively little dependence on X-point separation. Based on bolometry measurements, the difference in the proportion of power entering the SOL that is radiated in the divertor and primary X-point region between the XPT and SN falls within the range of uncertainties and is insignificant. These results suggest that, despite a two-fold increase in parallel connection length, the benefits of XPT in divertor detachment in this L-mode scenario are mainly due to transport phenomena instead of enhanced radiative losses.

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First experimental results of the real-time plasma shape controller for the advanced divertor plasma configuration on MAST-Upgrade

H. Anand[1], W. Wehner[1], C. Vincent[2], G. McArdle[2], M. Kochan[2], A. Welander[1], Z. Xing[1], A. Lvovskiy[1], J. Barr[1], D. Humphreys[1], N. Eidietis[1], A. Leonard[1], A. Thorton[2], J. Harrison[2], B. Sammuli[1] and E. Cho[1]

[1]*General Atomics, PO Box 85608, San Diego, California 92186-5608, USA*
[2]*United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK*

A real-time (RT) plasma shape controller has been developed and experimentally tested on the Mega Ampere Spherical Tokamak Upgrade (MAST-Upgrade) for the advanced plasma configurations, such as the Double null and Super-X divertors. The successful experimental commissioning with minimal on-machine effort was enabled by the Integrated Plasma Control (IPC) approach provided by the General Atomics TokSys (GA Tokamak System Toolbox) modelling and simulation environment. TokSys closed-loop simulations with the axisymmetric linear and non-linear, free-boundary evolution code GSevolve have been successfully performed for the off-line assessment, identification, and verification of the algorithm implementation and controller performance for the various axisymmetric magnetic control systems. With the deployment of the sub-ms cycle time RT equilibrium reconstruction code LEMUR on MAST-Upgrade and extensive off-line validation of the controller performance with the help of TokSys-GSevolve closed-loop simulations, the RT plasma shape controller was applied successfully to various extended- and expanded-leg MAST-Upgrade divertor geometries during the 2021-2023 experimental campaign. Figure 1 shows an example of an excellent feedback regulation of the radial coordinate of the inner (R_{IN}), outer gap (R_{OUT}), and vertical position of X-point, (Z_X) for a MAST-Upgrade Super-X divertor plasma configuration. In addition to the RT feedback regualtion, feedforward control of the radial position of the outer strike point, (R_{OSP}) and poloidal flux expansion at the divertor target, ($f_{exp,div}$) was also successfully achieved on the Super-X divertor plasma configuration. The RT plasma shape controller has already played a key role in complex MAST-Upgrade detachment physics experiments involving advanced divertor geometries and for now is the only RT feedback controller for plasma shape, along with density controller on the MAST-Upgrade Plasma Control System (PCS).

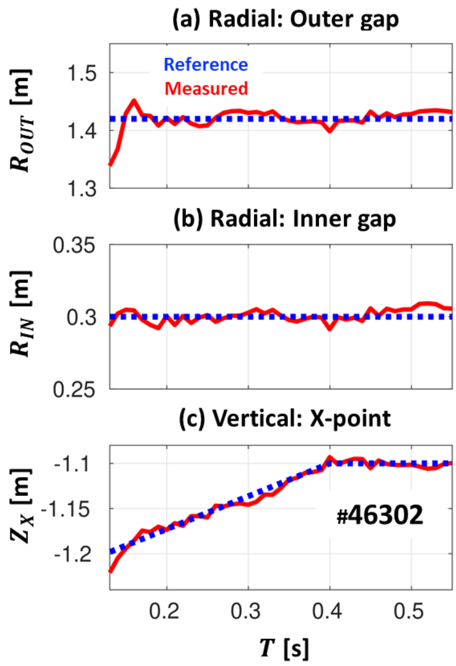

Figure 1. Experimental performance of the shape controller for a MAST-Upgrade Super-X plasma configuration. (a-c) Comparison between the measurement and the reference for R_{IN}, R_{OUT} and Z_X.

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A Performance Upgrade to Resolve the Integrated Tokamak Exhaust and Performance Gap for a Fusion Pilot Plant with DIII-D

R. J. Buttery[1], C. T. Holcomb[2], A. McLean[2], T. Osborne[1], J.M. Park[3], C.C. Petty[1], M. Shafer[3], and the DIII-D Team.

[1]*General Atomics, San Diego, U.S.A.*

[2]*Lawrence Livermore National Laboratory, CA, U.S.A.*

[3]*Oak Ridge National Laboratory, Knoxville, TN, U.S.A.*

The critical challenge to develop a viable concept for a compact fusion pilot plant is to resolve a highly dissipative divertor and its compatibility with a high-performance core. An upgrade to DIII-D is proposed to close gaps on reactor physics regimes in divertor, SOL, pedestal and core to test critical physics, pioneer solutions and resolve their mutual compatibility. The key is to raise pressure. This enables high density to be sustained at low collisionality to marry a high dissipation divertor with a high-performance core. This is achieved through a rise in shaping, current, volume and RF power, exploiting the natural properties of improved pedestals at high shape to close gaps and push limits (Fig. 1). Upgraded flexible heating and current systems enable development of a range of pulsed and steady state core solutions, with integrated modelling projecting β_N's up to 5, with unique access to low collisionality, thermalized, peeling limited reactor-like regimes, and short neutral penetration depths into the core to study relevant particle and impurity transport.

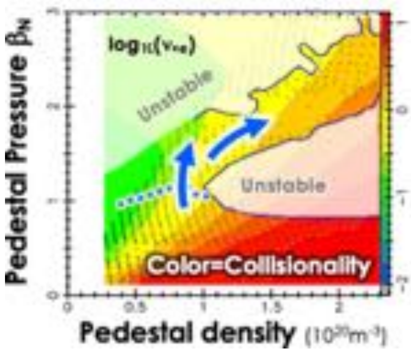

*Fig. 1: High shaping accesses high pressure & density at low ν**

The resulting increased parallel heat flux and density raise opacity and shorten mean free paths to access reactor relevant physics in the divertor (Fig. 2), where a new modular concept enables a staged divertor program to explore advanced closure schemes and isolate physics mechanisms. New limiter configurations, a tile test facility, and high Z wall coatings combine with this flexibility to thus enable DIII-D to pioneer integrated core and edge solutions, their materials compatibility and required control to resolve and project the approach for the pilot.

Fig. 2: Upgrades access relevant divertor physics metrics (left) and test scalings (right).

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Effects of divertor closure, shaping and drifts on energy dissipation and tungsten sourcing/leakage using the DIII-D SAS -VW Divertor*

D.M. Thomas, *General Atomics, San Diego, CA, USA*

The DIII-D SAS-VW divertor, a SOLPS-ITER-inspired V-shaped slot divertor with one graphite and one tungsten face has completed its initial series of experiments, providing detailed information about the function of shaping, plasma drifts, impurity puff species and location on detachment, as well as W sourcing and W transport from a slot divertor. Contrary to original modeling predictions, SAS-VW to date has shown no particular improvement in access to detachment for a given upstream density compared to the original, wider deep-slotted SAS, for ion $\mathbf{B}\vec{\times}\,\nabla\boldsymbol{B}$ drift direction into the divertor (i.e., the direction favorable for H-mode access). The evolution from attached to detached conditions remains a strong function of B_T direction, reaffirming the key role of drifts on dissipation in a slot divertor. The component of surface heat flux near the strike point attributable to non-charged particles increases with plasma density, with 30% of the total incident heat flux attributable to non-charged particles at detachment for $\mathbf{B}\vec{\times}\,\nabla\boldsymbol{B}$ drift into the divertor.

In-slot spectroscopy and gas injection systems allowed us to study tungsten sourcing and retention, along with low Z impurity retention for a range of target conditions and injected impurities. Gross W erosion was insensitive to exact strike point location in the slot and was dominated by ELMs, as expected from previous results; RMP ELM mitigation was successful in reducing the overall gross erosion and core buildup while pellet ELM mitigation was less successful. In-slot N_2 puffing yielded significant reduction in the detachment threshold, lower core Z_{eff} and less confinement degradation after detachment compared to other puffing locations. Ne puffing in the slot was also effective at retaining Ne in the divertor, yet led to higher gross W erosion and core buildup than injection in the main chamber. Finally, various ratios of N_2 and Ar were injected to determine the optimal mix for SAS-VW detachment, low confinement degradation, and core fuel dilution. These experiments and their discrepancy with modeling represent an important experiment/code validation challenge, which must be solved to ensure adequate design margin for future devices with their higher power densities.

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New ASDEX Upgrade ICRF antenna vacuum feedthrough: design review

O. Girka[1], W. Helou[2], O. Boiko[3], H. Faugel[1], W. Tierens[1,4], V. Bobkov[1]

[1]*Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, D-85748 Garching, Germany*

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

[3]*Lublin University of Technology, 38A Nadbystrzycka Str., 20-618 Lublin, Poland*

[4]*Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831, USA*

ICRF heating is considered as a candidate for the future EU-DEMO reactor, primarily as a tool to enter the high confinement regimes. ICRF vacuum feedthrough is a critical component which can severely limit the ICRF power availability and requires careful design. Feedthrough design elements can be tested on the present experiments, such as ASDEX Upgrade (AUG). The current AUG ICRF antenna vacuum feedthrough has been in operation since 1992, and thoroughly demonstrated its robustness and reliability during 30 years of operation. Nonetheless, its 6-inch ceramic front window imposes limits on the voltage stand-off and thus on ICRF power. Simulations show relatively high 2.8 kV/mm in the torus vacuum and 2.4 kV/mm in the private vacuum of the front window for this current design at the relatively low maximum peak voltage of 25 kV. Moreover, standing wave patterns, built on the base of antenna scattering matrices from RAPLICASOL, demonstrate that the current front 6-inch window is located close to the voltage anti-node at the most used frequency of 36.5 MHz. Modelling of the new feedthrough design with two 9-inch windows shows less than 1.9 kV/mm in the torus and the private vacuum, what can serve as a pre-design for DEMO. The standing wave patterns indicate that the new RF windows' position is closer to the voltage node. Reflection coefficient is in the range from -30 to -55 dB for the whole operating frequency range (while it was ~ -25dB for the previous design of 9-inch windows). In order to choose the most lossless ceramic for RF windows, dielectric spectroscopy measurements are carried out for the following Kyocera ceramic types: A479S, A479U, A601L and CO720. The phase shift angle, loss factor and dielectric constant are measured for ceramic samples in the frequency range of 20 MHz – 100 MHz. Volume power losses for RF windows are calculated for four ceramic types and compared for the whole operating frequency range. Full geometry RF simulations including the near-antenna arc trap, bellows, front and rear RF window structures are shown. In order to get experimental E-fields distribution and return loss coefficients, the optimized design is planned to be tested at available ICRF testbed facilities using a real 2-strap antenna and one of AUG RF generators.

Characterisation of particle orbits in third harmonic ECR interaction

C.A.V. Johansson, P. Aleynikov

Max Planck Institute for Plasma Physics, Wendelsteinstraße 1, 17491 Greifswald, Germany

The standard startup scenario in the Wendelstein 7-X (W7-X) stellarator involves second harmonic electron cyclotron resonance heating (ECRH) at the frequency 140 GHz. This heating is involved in the breakdown process. Interest in operating W7-X with reduced magnetic field has raised the question of startup using third harmonic ECRH. Due to a much weaker interaction, a small background magnetic field inhomogeneity substantially affects the electron energy gain for the third harmonic interaction.

We write the equations of motion for a resonant particle and solve these analytically for parameters relevant for W7-X. We find that in an inhomogeneous magnetic field some electrons can reach much higher energies than in a homogeneous magnetic field, considered in [1]. These electrons have a pitch angle corresponding to magnetically trapped electron trajectories with their turning point inside the beam.

A comparison with numerical results using parameters close to the second harmonic case of TJ-II start up [2] shows that one gyrotron is not sufficient for third harmonic start–up in W7-X. We discuss the possibility of using multiple gyrotrons in an inhomogeneous magnetic field to facilitate start–up in W7-X.

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Diagnostic challenges in ECW heated plasmas

J.W. Oosterbeek[1], M. Stern[1], N. Chaudhary[1], M. Hirsch[1], J. Brunner[1], H. Cu Castillo, U. Höfel[1], A. Krämer-Fecken[2], H.P. Laqua[1], S. Marsen[1], D. Moseev[1], S. Pak[3], S. Schmuck[4], T. Stange[1], R.C. Wolf[1], D. Wagner[5], and the W7-X team

[1] *Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, Wendelsteinstraße 1, 17491 Greifswald, Germany*

[2] *Institut für Energie- und Klimaforschung, Forschungszentrum Jülich, D-52428 Jülich, Germany*

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

[4] *Institute for Plasma Science and Technology, CNR, via Cozzi 53, 20125 Milan, Italy*

[5] *Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, D-85748 Garching, Germany*

Electron Cyclotron Waves (ECW) are exploited in numerous ways in magnetically confined plasma experiments. For example, Electron Cyclotron Emission (ECE) is routinely used to obtain electron temperature profiles, while Electron Cyclotron Resonance Heating (ECRH) provides powerful localised electron heating. A practical problem is that the ECW in the case of plasma heating schemes carry megawatt power, but in ECE receivers the ECW power is at sub-microwatt levels. In-vessel diagnostic components must be robust to ECRH power not absorbed by the plasma, and notch filters are used to protect the ECE receivers. In this paper we report on measurements of non-absorbed ECRH power in the vicinity of diagnostic windows at Wendelstein 7-X (W7-X). Dielectric heating of vacuum windows is briefly discussed. Operation of the Martin-Puplett Michelson ECE Interferometer for measurement of second and third harmonic ECE in ECW heated plasmas is reported. The intererometer response function is modelled and the impact of excessive ECW power at the gyrotron frequency is examined and experimentally verified. Measurements of second and third harmonic ECE spectra from the ECE interferometer with a fundamental type notch filter 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.

Measurements with and improvements to Correlation microwave diagnostics on the Wendelstein 7-X stellarator during Operational Phase 2

G.M. Weir[1], A. Krämer-Flecken[2], T. Schröder[1], T. Windisch[1], O. Grulke[1], M. Hirsch[1], T. Klinger[1] and the Wendelstein 7-X team[1]

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

[2]*Forschungszentrum Jülich, Institut für Energie- und Klimaforschung/Plasmaphysik, Jülich, Germany*

During initial operation of the Wendelstein 7-X device (W7-X) [1] with a water-cooled divertor, correlation microwave radiometry and reflectometry diagnostics were used to measure electron temperature and plasma density fluctuations. These diagnostics benefited from improvements to both their hardware and technical operation that increased their sensitivity and data accessibility. The ZOOM device [2] is a 16-channel, frequency scannable radiometer extension that is used as a high-resolution radial correlation electron cyclotron emission (CECE) diagnostic when connected to the ECE radiometer on W7-X [3]. A new toroidally displaced radial correlation system with a focusing antenna has been installed that is optimized for core electron temperature fluctuation measurements between 30% and 70% of the plasma minor radius. A secondary CECE system has also been installed for plasma density-electron temperature cross phase measurements in the outer 80% of the plasma minor radius. The poloidal correlation reflectometer (PCR) diagnostic [4] measures plasma density fluctuations in the same toroidal plane as the new CECE antenna and has overlapping measurement volumes. A second frequency synthesizer and detection system has been added to the PCR system allowing access to plasma densities up to 4.5×10^{19} m^{-3} and radial correlation length measurements in the outer 80% of plasma minor radius. All of these systems can now stream their unprocessed data continuously to the W7-X Archive with sampling rates up to 4 MHz. This allows for on-the-fly data analysis and ensures data availability, particularly during long-pulse operation (>30 seconds).

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Use of Differential Rotation for Prevention of 2/1 Tearing Modes Driven by 3-Wave Coupling

N.J. Richner[1], L. Bardoczi[2], J.D. Callen[3], R.J. La Haye[2], N.C. Logan[4], E.J. Strait[2]

[1] *Oak Ridge Associated Universities, Oak Ridge, USA*

[2] *General Atomics, San Diego, USA*

[3] *University of Wisconsin-Madison, Madison, USA*

[4] *Lawrence Livermore National Laboratory, Livermore, USA*

A recent experiment demonstrated that differential rotation can be used to prevent the formation of tearing modes (TMs) seeded by 3-wave coupling. As TMs degrade confinement and can lead to disruptions, stabilization strategies are a crucial component to the successful operation of future devices. In ITER-relevant scenarios on DIII-D, deleterious m/n=2/1 'daughter' TMs can be seeded by nonlinear 3-wave coupling (e.g., from 1/1 and 3/2 modes) [1]. The frequency of a nonlinearly-driven mode is rigorously determined by the frequencies of the parent modes. This robust theoretical constraint was leveraged in an experiment on DIII-D to intentionally inhibit matching between the frequency of the nonlinearly driven 2/1 mode and the natural plasma rotation frequency. This mismatch is expected to have a stabilizing effect on the driven mode, e.g., through polarization current effects. The experiment found that sufficient differential rotation results in a mismatch between the natural mode frequency and the nonlinearly driven frequency that effectively prevents deleterious 2/1 TMs from forming by this mechanism. Neutral beam injection torque was used to scan the differential rotation to find a threshold for stabilization. Above the threshold, 2/1 modes from 3-wave coupling are stabilized. Below it, electromagnetic torque between the parent modes flattens the rotation profile until the frequency mismatch approaches zero, at which time the 2/1 mode is formed. The results of this work suggest that differential rotation provides a useful actuator for the prevention of TMs from 3-wave coupling and can be used to inform the development of stabilization strategies and scenarios.

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Measurement of radiation asymmetries in MAST Upgrade double null divertor plasmas

J. Lovell[1], F. Federici[2], J. R. Harrison[3], B. Lomanowski[1] and the MAST Upgrade team[a)]

[1]Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[2]York Plasma Institute, Department of Physics, University of York, Heslington, York, YO10 5DD, UK
[3]United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[a)]See author list of J. Harrison et al 2019 Nucl. Fusion 59 112011

A new bolometer camera was installed in the upper divertor chamber of MAST Upgrade between the MU01 and MU02 physics campaigns. Sharing viewing geometry with the existing lower divertor horizontal bolometer camera, this enables direct comparison of the radiated power in the two divertor chambers.

We compare the up/down radiation asymmetry in a range of plasmas from the MU02 physics campaign. L mode and H mode plasmas are studied, and the variation in divertor radiation asymmetry with the power crossing the separatrix (Psol) and the vertical position of the magnetic axis (Zref) are shown. The dependence of divertor configuration, comparing conventional and Super-X plasmas, is also presented.

Preliminary analysis indicates higher radiation levels in the lower divertor than the upper divertor for nominally connected double null plasmas where the magnetic axis is within a few mm of the midplane. However, this is accompanied by higher core radiation at the top of the confined plasma than at the bottom. This observation is consistent across the different divertor configurations and confinement modes and does not appear to depend strongly on Psol.

Where divertor radiation asymmetries are observed, we evaluate the extent to which the radiation is redistributed between the upper outer divertor leg and the inner lower divertor leg. We use the infra-red video bolometer (IRVB) to obtain spatially-resolved radiation profiles at the lower X point and evaluate changes in the radiation levels at the inner divertor.

Assessment of passive and active disruption forecasters for spherical tokamaks

J.W. Berkery[1], S.A. Sabbagh[2], C. Ham[3], S. Munaretto[1], Y.Q. Liu[4], V. Zamkovska[2], L.D. Corona Rivera[1], S. Gibson[3], S. Henderson[3], B.S. Patel[3], D. Ryan[3], R. Scannell[3], E. Trier[3], G. Xia[3]

[1] Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, 08543, USA [2] Department of Applied Physics, Columbia University, New York, NY, 10027, USA

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

[4] General Atomics, San Diego, CA, 92121, USA

Spherical tokamaks (STs) are currently being designed for fusion pilot plants (FPPs), both in the public sector (the UK STEP program), and the private (ST-E1 from Tokamak Energy). In STs higher beta can be obtained more stably, which represents an opportunity, but also a challenge. Instabilities disrupt the plasma current, releasing the stored energy of the plasma, potentially damaging surrounding structures. Reliable indicators of impending disruption are needed from either active probing or passive signal monitoring. The long- known density limit is just one event that can indicate susceptibility of a fusion plasma to disruption, but it is a critically important one. This limit has been expressed in a global sense through the Greenwald limit: line average density $n_e\,[10^{20}\mathrm{m}^{-3}] < n_G \equiv I_p\,[\mathrm{MA}] / \pi a^2\,[\mathrm{m}^2]$, where a is the plasma minor radius. Understanding the physics of the density limit in STs by testing multiple theories and determining their utility for disruption forecasting in STs is vital work to be carried out on present machines to have confidence in designs of stably operating future ST FPPs. The framework of the Disruption Event Characterization and Forecasting (DECAF) code, and its large database of discharge data from many machines, including these, represents an opportunity to test the density limit theories. Recently theoretical investigation of the density limit has progressed and mostly focuses on local criteria, including a scaling law based on an increase in boundary turbulent transport with collisionality. Additionally, in the ASDEX Upgrade and TCV conventional tokamaks a system monitoring the normalized edge density and comparing to empirical disruption limits has already been implemented in an off-normal event handler. These tests have now been implemented in DECAF and tested on ST discharges. The empirical and theoretical limits were found to give similar results and dependencies, and appear promising for determination of impending disruption due to rising density. In some cases in MAST-U plasmas were seen to disrupt after crossing the edge limits before they reached the global Greenwald limit, potentially giving early warning. Though not yet implemented in real-time, the warning algorithms are feasible, and additionally point to possible actuators beyond density control for maintaining stability, including heating power, plasma shaping, and edge safety factor. Additionally, active monitoring of the approach to the no-wall ideal stability limit has been assessed in MAST-U by experimentally determining the plasma response (resonant field amplification) to applied magnetic perturbations. Further data from MAST-U may be used to explore the possibility of measuring multimodal plasma response for the first time in a spherical tokamak, predicted with the resistive MHD code MARS, and, if measurable, to study its dependence on equilibrium quantities like β_N. Finally, designs for a controlled ramp-down of the plasma current with consideration for density limits and vertical stability will be presented with plans to test the scheme experimentally.

Design of x-ray imaging crystal spectrometer (XICS) for long-pulse (100 s) profile measurements at JT60SA

L. F. Delgado-Aparicio[1], M. Ono[1], J. Wallace[2], L. Perkins[1], F. Krauss[1], L. Gao[1], R. Ellis[1], K. Hill[1], T. Nakano[3], L. Glatt[4], P. Hofer[4], N. Pilet[4], S. Teal[5] and R. Drake[5]

[1]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[2]Department of Engineering Physics, University of Wisconsin-Madison, Madison, WI, USA
[3]National Institute for Quantum and Radiological Science and Technology (QST), Naka-shi, Ibaraki, JAPAN
[4]DECTRIS Ltd. Baden-Daettwil, SWITZERLAND
[5]PROTO MANUFACTURING, Michigan, USA

JT-60SA is a fusion experiment designed to support the ITER operations and to investigate how best to optimize the operation of fusion power plants that are built after ITER. It is a joint international research-and-development (R&D) project involving Japan and Europe and is being built at the QST in NAKA Fusion Institute in Japan using infrastructure of the existing JT-60 Upgrade experiment. The X-ray Imaging Crystal Spectrometer (XICS) on JT-60SA is viewed as one of the essential plasma diagnostics which would provide critical information on the local ion impurity density (e.g. n_{Ar}, n_W, n_{Xe}), the ion and electron temperatures ($T_{i,e}$) as well as the plasma flow velocity components ($V_{\varphi,\theta}$). The newly proposed JT-60SA XICS system is a significantly scaled-up, fully calibrated version of the modern XICS systems deployed on fusion experiments including WEST and W7-X, and it is similar in scale to one of the ITER XICS systems presently being designed at PPPL. In this contribution we discuss the design and architecture of the XICS, its integration to the JT60SA tokamak and the engineering challenges that the long pulse scenario (up to 100s with ~40 MW of beam power) with superconducting magnets pose to vacuum interface and electronics. Vacuum and thermal stress analysis and calculations will be presented and discussed including seismic analysis for 0.4g forces. We also present for the first time a new design for a tall chilled 1.6M PILATUS3 detector as well as well as a one-of-a-kind vacuum-compatible in-situ calibration capability using novel Cd, Ti and Ho x-ray tubes to calibrate the He-like Ar, H-like Ar, He-like Fe and Ne-like Xe spectra.

Quasi-linear relaxation of energetic ions in ITER mediated by Alfvén instabilities[1]

N. N. Gorelenkov[a], V. N. Duarte[a], M. V. Gorelenkova[a], S. D. Pinches[b]

[a]Princeton Plasma Physics Laboratory, Princeton, USA

[b]ITER organization, Cadarache, France

Due to their high energies at birth, $3.52MeV$ fusion alpha particles will be superalfvénic with the ratio of their birth velocity to the characteristic Alfvén speed evaluated as $v_{\alpha 0}/v_A = 1.86$ in planned ITER experiments whereas for $1MeV$ neutral beam injection (NBI) D fast ions that ratio will reach $v_{b0}/v_A = 1.43$ [1]. It is expected that the confinement of those energetic particles (EPs) could be endangered by the excitation of low-frequency Alfvénic eigenmodes (AE) such as toroidicity-induced Alfvén eigenmodes (TAE) and reversed shear Alfvén eigenmodes (RSAE). Background plasma parametric dependencies of various damping and driving rates has been investigated for adequate EP confinement in future fusion devices (see [1]). Both are well represented and verified in NOVA-C framework [2].

An application of the linear stability theory together with a new formulation of quasilinear (QL) theory [3] for discrete modes allows to evaluate the EP distribution relaxation in burning plasma (BP) conditions with additional contributions from the background microturbulence-driven effective pitch angle scattering [4]. Two important damping mechanisms that shape the EP profiles and control EP losses to the wall were identified [1]. They are the thermal ion Landau damping which is dominant near the plasma center, and the thermal trapped electron collisional damping that dominates near the plasma edge [5]. QL simulations performed with the help of a new, resonance broadened QL code (RBQ) takes those mechanisms into account in a perturbative manner [4]. What follows from previous studies, however, is that the EP relaxation is quite sensitive to the microturbulence level. This particular topic is out of the scope of our work. Nevertheless it is important to state that without that knowledge, RBQ can provide a rather optimistic level of EP relaxation.

1. TAE/RSAE LINEAR STABILITY IN ITER STEADY-STATE SCENARIO

A comprehensive stability analysis was performed with the help of the ideal MHD code NOVA [6] and its hybrid drift kinetic extension NOVA-C [2]. This was done for the Alfvénic eigenmodes in the frequency range spanning from the geodesic acoustic mode frequency up to the Ellipticity-induced Alfvénic Eigenmode (EAE) gap. In Fig.1 we present the ITER steady-state plasma profiles as computed by the ASTRA code [7]. One feature relevant to AE stability is that the steady-state ITER scenario presented here, unlike earlier baseline case scenario [1], is characterized by fusion α-particle pressure profile twice and beam ion beta profile ten times larger. It is not surprising that the NBI contribution to AE instability was ignored in follow-up studies [8, 9].

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Fusion α's and beam ions with distinctly different distribution functions (DF) are included in simulations. Their DF's contour maps are illustrated in Fig. 2. Both distribution functions are shown near their injection (birth) energies in the canonical angular momentum, P_φ, and the adiabatic moment, $\lambda = \mu B_0/\mathscr{E}$ plane. Given the ratio of their super-Alfvénic velocities to the Alfvén speed it is expected that the AE instability drive will be maximized against $v_{\alpha,b0}/v_A$ ratio. Furthermore, one can see jumps at the separatrix between the passing and trapped ions of alphas on the right figure. Those jumps are physical and they are due to the jumps in the drift orbit precession times associated with the transitions from trapped to passing ion orbits and vise versa.

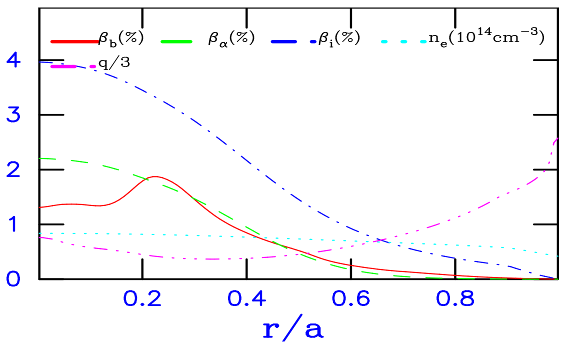

FIG. 1. *Plasma profiles of ITER steady-state scenario used in simulations. Shown are the radial profiles of beam beta, β_b, fusion product alpha particle beta, β_α, thermal ion beta β_i, electron density, n_e, and safety scaled by factor as $q/3$.*

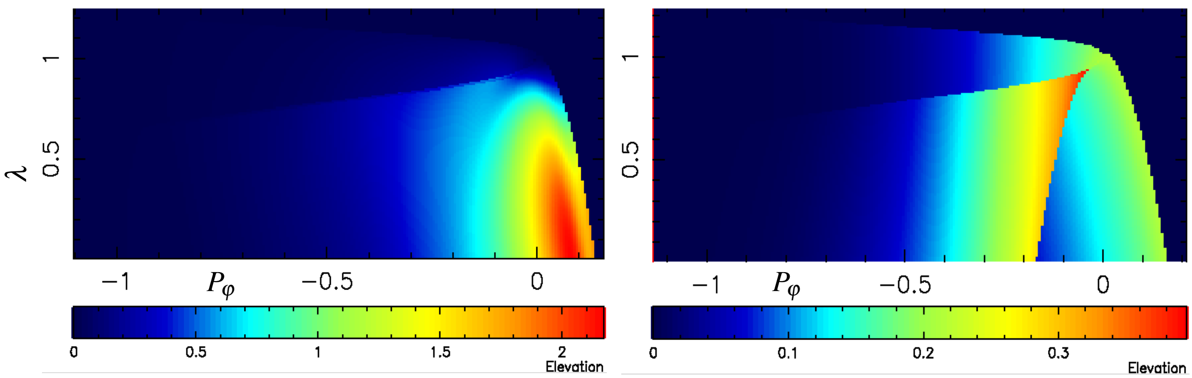

FIG. 2. *Beam ion (left) and alpha particle (right) distribution functions shown as contours in the plain P_φ, λ. Both DF are the sums over the distribution of different signs of EP parallel component of particle velocities, $\pm|v_\parallel|$.*

NOVA has found around 600 AE modes of interest out of which NOVA-C identified around 40 unstable of marginally stable eigenmodes for subsequent RBQ runs. The AE stability is addressed by the kinetic NOVA-C code which incorporates rich physics including the background dampings and advanced fast particle representation that allowed favourable benchmarks against main available codes [10]. We show AE growth rates in Fig. 3. More detailed report will be presented at the IAEA FEC this year.

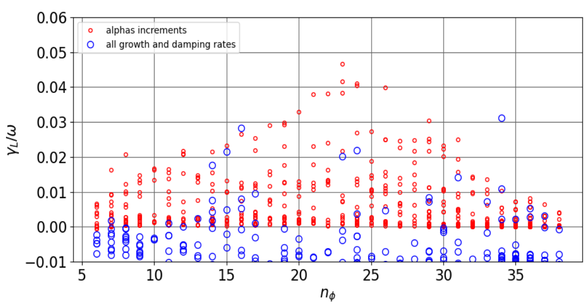

FIG. 3. *Sum of AE growth and damping rates for each mode are computed for the unstable and marginally stable eigenmodes. They are shown as blue open circles. Net growth rates due to fusion α-particles only are shown as smaller red circles. AE net growth rates include beam ion drive.*

From the linear AE stability results several important observations follow. First, our linear AE stability analysis is consistent with earlier results

[8, 9] especially the toroidal mode number range of the unstable AEs and their characteristic growth rates. The growth rates have the maximum or rolloever point at around $n = 20 \div 30$ in those calculations. Second, two regions in radius have strongest contributions to the growth rates: near the center and near the q_{min} location. Third, the multiplicity of AEs will likely result in the overlapping of the resonances in the constant-of-motion (COM) space due to the nonlinear broadening. Fourth, the dominant damping rate that controls the EP profiles near the edge is the trapped electron collisional damping. For reliable predictions such damping is required in simulations. Ignoring it would change the radial domain of EP confinement and, as a result, will overestimate the loss fraction such as reported in Ref.[11].

2. QUASI-LINEAR MODELING OF FAST PARTICLE RELAXATION

The recently built numerically efficient, self-consistent QL code RBQ is applied to ITER steady-state scenario [7]. It is capable of addressing the EP confinement in the presence of several to multiple Alfvénic modes by following the time evolution of their amplitudes and by advancing the EP distribution function in the COM space. This can be done either within the RBQ code itself or by providing the diffusion and convective coefficients for a subsequent calculation by a Whole Device Modeling (WDM) package such as NUBEAM [4]. Furthermore, the RBQ code is already interfaced with the WDM TRANSP code and has preliminary shown a good agreement in its application to DIII-D critical gradient experiments [4].

We applied RBQ to ITER steady state plasma characterized by 40 marginally unstable/marginally stable AEs and prepared the COM diffusion coefficients for WDM processing. Both beam ion and alpha particle plasma components contribute to the AE drive although linear stability indicates that beam ions have on average the growth rate twice as high. This is because beam ions are injected into the most unstable location in the COM space.

RBQ pre-computed diffusion coefficients are quite high locally where most of the unstable modes are driven unstable near the point of q_{min}, reaching values up to $\lesssim 10^2 m^2/sec$ at the q_{min} location and going down to $\sim 1 m^2/sec$ toward the periphery. This implies that local flattening of EP profiles near q_{min} is expected but overall the EP redistribution can be quite modest.

As we show in Fig.4, the AE amplitudes can reach values $10^{-4} \div 10^{-3}$ for AEs whereas no significant fast ions losses to the wall were seen. In the final stage, the standalone NUBEAM package was applied to evolve the fast ion distribution functions more accurately in the COM space. Both RBQ internal calculations and NUBEAM standalone calculations have found that the EP confinement with the Coulomb scattering does not result in significant fast ion losses, which is consistent with earlier studies [8, 9].

Microturbulence, however, can significantly boost the AE amplitude saturation by broadening the phase-space locations near the WPI resonances [4, 12]. For example, it was found that AE amplitude goes up significantly with the anomalous scattering, $\delta B_\theta / B \sim \nu_{eff}^2$ and EP losses can be enhances as a result.

Such strong dependence of fast ion relaxation on the microturbulence intensity, however, does not allow us to reliably predict the fast ion confinement in ITER advanced steady state scenarios without quantitative predictions of the microturbulence levels.

In summary, we have found that the beam ions injected at $1MeV$ lead to stronger growth rates to excite AEs in comparison with fusion alpha particles, which are born with the source isotropic in pitch angles, $\chi = v_{\|}/v$. This was not the case in earlier studies [1]. On the other hand, the background microturbulence can enhance EP losses in ITER plasmas which deserves future careful consideration. Present applications of RBQ and NUBEAM to ITER steady state case has shown a weak loss of fast ions to the wall at the level of a few percents.

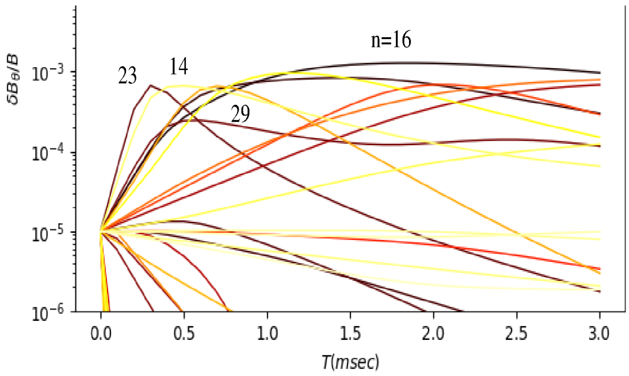

FIG. 4. *Time evolution of unstable and marginally unstable AEs computed by the RBQ code over* 3 *msec time window. Toroidal mode numbers of the most unstable modes are shown on the figure.*

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Tokamak self-driven current loss in the presence of magnetic Islands

W. X. Wang[1], M. G. Yoo[2], E. A. Startsev[1], S. Ethier[1], J. Chen[1], S. Kaye[1], W. Guttenfelder[1]
[1]Princeton Plasma Physics Laboratory
[2]General Atomics

Magnetic island (MI) perturbations, likely unavoidable in long pulse discharges, may strongly impact both neoclassical and turbulent dynamics (including bootstrap current generation) by altering the topological structure of the confining magnetic field in tokamak devices. MIs usually cause a bootstrap current reduction which could post a significant concern for the economic operation of a tokamak-based fusion reactor. A novel effect revealed by global gyrokinetic simulations results from island-induced three-dimensional ambipolar electric field. A magnetic island is shown to drive electric potential islands with dominant mode numbers the same as that of the magnetic island, whereas centered at both the inner and outer edge of the island. Such non-resonant potential islands may introduce a major change in plasma self-driven current through an efficient nonlinear parallel acceleration of electrons. In large-aspect ratio tokamak devices, this new effect can result in a significant global reduction of electron bootstrap current when the MI size is sufficient large, in addition to the local current loss across the island region due to the pressure profile flattening. It is shown that there exists a critical magnetic island width for large-A tokamaks beyond which the electron bootstrap current loss is global and increases rapidly with the island size. As such, this process may introduce a size limit for tolerable magnetic islands in large-A devices in the context of steady state operation. Remarkably, in low-A tokamaks (e.g., spherical tokamak), the new effect of MI on bootstrap current is much weaker. The reduction of the axisymmetric current by the magnetic island scales with the square of island width. However, the loss of the current is mainly local in the island region, and the pace of the current loss as the increase of MI size is substantially slower compared to large-A tokamaks. In particular, the bootstrap current reduction by MI in STs is even smaller in the reactor-relevant high-βp regime where NTM islands are more likely to develop. It is further noticed that, for the same level of magnetic perturbations $\delta B/B_0$, MHD island width is much smaller in ST geometry than in large-A tokamak. This fact further suggests that MHD islands are more tolerable in STs. The results of this study suggest a significantly favorable feature of ST for non-inductive steady state operation and for developing compact fusion reactors. The connection of this newly revealed effect of MI on the current to some experimental observations will be also discussed.

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First results and modeling of a multi-energy hard x-ray camera on the WEST tokamak

T. Barbui[1], L. F. Delgado-Aparicio[1], Y. Peysson[2], B. Stratton[1], O. Chellaï[1], R. Dumont[2], K.W. Hill[1], N.A. Pablant[1] and the WEST team[2]

[1] *Princeton Plasma Physics Laboratory, Princeton, NJ 08540, USA*

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

The WEST tokamak recently completed its first experimental campaign with the new water-cooled full tungsten divertor, which enables long pulse operation. Heating is provided by radiofrequency systems, including lower hybrid current drive (LHCD). In this context PPPL has operated for the first time a compact multi-energy hard x-ray camera (ME-HXR) for energy and space-resolved measurements of the electron temperature, the fast electron tail density produced by LHCD and runaway electrons, and the beam-target emission of tungsten at the edge due to fast electron losses interacting with the target.

This contribution presents first measurements of the new diagnostic on the WEST tokamak. Line-integrated measurements of hard x-rays were acquired during LHCD discharges along ~80 lines-of-sight covering most of the plasma cross section including the lower divertor. Beam-target emission was observed along the lines-of-sight intersecting the lower divertor. It was compared to tungsten spectra produced by an electron beam computed with the code Win X-ray[1] in order to estimate the energy of the fast electron losses.

The HXR profiles were modeled by the suite of codes ALOHA[2]/C3PO[3]/LUKE[4]/R5-X2[5] which simulates LH wave transmission, power absorption and current drive, and computes the non-thermal bremsstrahlung emission from fast electrons during LHCD considering the geometry of the ME-HXR. This modeling allows to understand the LHCD deposition profile.

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Low Frequency MHD Induced Alpha Particle Losses in JET's DTE2 Campaign

P. J. Bonofiglo[1,a], V. G. Kiptily[2], M. Nocente[3], M. Podestà[1], Ž. Štancar[2,4], M. Poradzinski[2], V. Goloborodko[5], S.E. Sharapov[2], M. Fitzgerald[2], R. Dumont[6], J. Garcia[6], D. Keeling[2], D. Frigione[7], L. Garzotti[2], F. G. Rimini[2], D. Van Eester[8], and JET Contributors*

[1]*Princeton Plasma Physics Laboratory, Princeton, NJ, United States*
[2]*Culham Centre for Fusion Energy, Abingdon, Oxfordshire, United Kingdom*
[3]*University of Milano-Bicocca, Milano, Italy*
[4]*Slovenian Fusion Association, Jozef Stefan Institute, Ljubljana, Slovenia*
[5]*Institute for Nuclear Research, Kyiv, Ukraine*
[6]*CEA, IRFM, Saint-Paul-lez-Durance, France*
[7]*Tor Vergata University of Rome, Rome, Italy*
[8]*Laboratory for Plasma Physics LPP-ERM/KMS, Brussels, Belgium*

*See the author list in J. Mailloux et al *Nucl. Fusion* **62** (2022) 042026
[a]email: pbonofig@pppl.gov

This report presents alpha loss measurements and analysis from JET's 2021-2022 DTE2 campaign. Measurements of fast ion losses were provided from two fast ion loss detectors: a scintillator probe which is capable of resolving lost ion pitch and gyroradius at a single geometric location, and a Faraday cup array composed of multiple cups that span a wide poloidal angle at a single toroidal position with a small radial extent. A database of pulses was created from JET baseline scenarios and the "afterglow" and bump-on tail energetic particle experiments. Alpha particle losses were recorded from both coherent (NTMs, kinks, fishbones, etc.) and non-coherent sources (ELMs and sawteeth). In particular, coherent losses with low frequency (<100 kHz) MHD were strongly observed. The bulk neutron rate was used as a proxy for the 3.5 MeV alpha production and an estimate of the alpha loss fraction was determined to be a maximum of 2-3% due to coherent, low frequency, MHD activity. A strong poloidal dependence was also observed and appears to peak around 25 degrees below the midplane. The radial trend is relatively flat and is consistent with the Faraday cup spacing being less than the typical alpha particle gyroradius (10-12 cm). Additionally, scintillator probe loss footprints show preferential losses in pitch-space. First orbit, prompt, losses have also been detected and are consistent with reverse orbit trajectory integration. Analysis for higher frequency Alfven eigenmode induced losses is ongoing along with numerical validation studies.

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Assembly of MUSE Permanent Magnet Stellarator and Error Field Measurement Using Electron Beam Mapping

X. Chu[1], T. Qian[1], M. Zarnstroff[2] and the MUSE Team
[1] Princeton University, Princeton, U.S.A.
[2] Princeton Plasma Physics Laboratory, Princeton, U.S.A.

February 28, 2023

MUSE is the world's first quasi-axisymmetric stellarator constructed with permanent magnets and planar circular coils[1]. The components manufacturing, sub-systems tests, quarter assembly, vacuum vessel assembly and final assembly have been completed over the past year. Detailed procedures have been developed in order to construct MUSE successfully[2]. First plasma is under way.

Electron beam mapping of the flux surfaces[3] will be conducted after first plasma to study error fields and adjust the position of the permanent magnets to minimize errors. By comparing the shape of the flux surfaces with the numerical models, the permeability of the permanent magnets will be calibrated and the position of the PM(permanent magnet) holders will be adjusted to maximize the agreement. A subsequent study of the island width of different island chains(including 1/5, 2/10, 2/11 etc.) by varying the toroidal field current will be conducted to quantify the field errors.

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Modeling of tungsten impurities with gyrokinetic bundles, atomic interactions, and sonic flows in the XGC code

J Dominski 1, M OMullane 2, A Sharma 1, C Bourdelle 3, P Maget 3, P. Manas 3, C.S. Chang 1, R. Hager, S. Ku 1, V Parail 2, A Scheinberg 4

1 Princeton Plasma Physics Laboratory, NJ 08543, Princeton, United States of America
2 CCFE, Culham Science Centre, OX143XU, Abingdon, UK
3 CEA, IRFM, F-13108 Saint Paul-lez-Durance, France
4 Jubilee Development, Cambridge, MA, USA

Tokamak physics in a tungsten environment is a critical topic of research, as tungsten impurities are found to degrade the confinement time of tokamaks. This physics is studied with the XGC code by simulating the whole device plasma with multiple gyrokinetic ions [1,2]. To take into account the many ionization states of tungsten, we have developed a new model that permits to model many (~50) ionization states of tungsten with only ~7 gyrokinetic bundles [3,4]. The new implementation in XGC of both the atomic interactions between bundles and the sonic-flow correction terms will be presented. Note that gyrokinetic bundles differ from fluid bundles, because of the gyrokinetic equation constraints. They are nonetheless necessary because of the formation of large (df/f~1) amplitude asymmetries, whose poloidal orientation depends on the charge number Z, form in the pedestal and edge regions [4]. In addition, we will introduce our preliminary results on the validation of tungsten modeling in a WEST plasma and, finally, we will discuss the modeling of tungsten radiation physics in XGC.

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Extended-MHD modeling of transients in spherical tokamaks and SPARC

A. Kleiner[1], N.M. Ferraro[1], G.P. Canal[2], B. Lyons[3], R. Maingi[1], J.T. McClenaghan[3], J. Menard[1], S. Munaretto[1], J. Parisi[1], M. Reinke[4], R. Sweeney[5]

[1] *Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA*

[2] *Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*

[3] *General Atomics, San Diego, California, USA*

[4] *Commonwealth Fusion Systems, Cambridge, Massachusetts, USA*

[5] *Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*

Edge-localized modes (ELMs) and disruptions are two transient phenomena that can cause serious damage to the vessel in reactor-scale tokamaks and thus need to be controlled or mitigated. We present extended-magnetohydrodynamic (MHD) simulations with the goal of accurately predicting ELM stability thresholds in spherical tokamaks (STs) and to inform the massive gas injection (MGI) layout for disruption mitigation in SPARC.

ELMs are typically associated with macroscopic peeling-ballooning (PB) modes in the edge pedestal, which arise due to strong pressure and current density gradients. In large aspect ratio devices these ideal-MHD modes are well understood. However, a long-standing problem has been the reliable modeling of such stability boundaries and prediction of pedestal parameters in some ST scenarios, particularly in NSTX [1]. In simulations with the extended-MHD code M3D-C1, it was found that plasma resistivity can significantly alter macroscopic edge-stability in ELMing H-mode discharges in NSTX [2, 3]. Nonlinearly saturated edge modes that exhibit similarities to edge-harmonic oscillations are found in NSTX enhanced-pedestal H-mode. The analysis of PB stability is extended to STAR, a preliminary ST-based power plant design. We show how these extended-MHD stability thresholds are incorporated into a higher-fidelity model to predict the pedestal structure in a wider range of tokamak scenarios.

We also present extended-MHD simulations of disruption mitigation in SPARC via massive gas injection. Fully three-dimensional simulations with M3D-C1 are carried out for various injector configurations with the primary goal of determining the effect of different MGI parameters on heat loads and vessel forces. The simulations include a model for impurity ionization, recombination, advection and radiation, as well as spatially resolved conducting structures in the wall.

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Experimental investigation of micro-tearing modes on MAST-U

M. Lampert[1], J. Berkery[1], M. Curie[2], D. Dunai[3], A. R. Field[4],
A. Kleiner[1], C. Michael[5], S. Saarelma[4], S. Sabbagh[6]

[1]*Princeton Plasma Physics Laboratory, Princeton, NJ, USA*

[2]*General Atomics, San Diego, CA, USA*

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

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

[5]*University of California, Los Angeles, CA, USA*

[6]*Columbia University, New York, NY, USA*

Edge turbulence accounts for a large fraction of the anomalous heat and particle transport in fusion plasmas. Micro-tearing modes (MTMs) driven by electron-temperature gradients could account for a part of this anomalous heat transport in the plasma edge . They degrade confinement and limit overall plasma performance. They are primarily electromagnetic phenomena due to their high-amplitude magnetic flutter, and are often visible in the magnetic probe measurements. MTMs have been identified in the pedestal of conventional aspect ratio tokamaks (JET [1] and DIII-D [2]) but not in spherical tokamaks. Theoretical and experimental work showed that MTMs get destabilized in plasmas where a rational surface aligns with the peak of the drift frequency profile (ω^*). Furthermore, high plasma beta and low collisionality also play a key role in their growth rate. If these circumstances are met MTMs can be studied by analyzing their magnetic signatures through Mirnov-coils, and by calculating their fingerprints such as their electron temperature gradient dependence or the $\delta n/n/\delta B/B$ ratio [3].

We conducted experiments aimed at destabilizing, identifying, and characterizing MTMs on the MAST-U spherical tokamak. To align a rational surface with the peak of the ω^* profile the plasmas were rapidly varied vertically and radially shifted. To characterize MTMs the frequency spectrum of fast Mirnov coils was calculated and the origins of the coherent fluctuations were identified. We have run numerical simulations to calculate the growth rate and the expected frequency of the MTMs and compare them to the experimental findings. The goal of our study is to gather sufficient evidence for identifying or falsifying MTMs in a spherical tokamak environment.

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Development of synthetic diagnostics for Fast Ion Loss Detection systems in Wendelstein 7-X

A. LeViness[1], S. A. Lazerson[2], A. Jansen van Vuuren[3], J. Rueda-Rueda[3], S. Bozhenkov[2], M. García-Muñoz[3], C. Killer[2], K. Ogawa[4], N. Pablant[1], and the W7-X team

[1]*Princeton Plasma Physics Laboratory, Princeton, United States*
[2]*Max Planck Institute for Plasma Physics, Greifswald, Germany*
[3]*University of Seville, Seville, Spain*
[4]*National Institute for Fusion Science, Toki, Japan*

In this work, a method is outlined for simulating signals to fast ion loss detectors (FILDs) in Wendelstein 7-X (W7-X), including those currently operating—the Faraday cup FILD (FC-FILD) and the FILD provided by the National Institute for Fusion Science (NIFS-FILD)—as well as the scintillating FILD (S-FILD), which is currently under development.

The confinement of fast ions is one of the primary targets of the optimization of W7-X. The heating systems of W7-X include 55 keV hydrogen neutral beam injection (NBI), which produces ions with normalized Larmor radii equivalent to those of 3.5 MeV alpha particles in a HELIAS-type reactor. As such, information about the success of this optimization can be gleaned by measuring the confinement of these NBI-produced fast ions with diagnostics such as FILDs, which can often measure not only fast ion loads but also their energy and pitch angle. Accurate simulation of their expected signals is necessary both to design FILDs that are sensitive to the expected fast ion distributions in W7-X as well as to compare measured losses to predicted confinement.

Using the Monte Carlo codes BEAMS3D and ASCOT5, markers representing NBI ions are followed from injection to a plane of constant toroidal angle near the chosen FILD. Simultaneously, simulations in ASCOT5 and FILDSIM are used to determine a probability matrix, binned by normalized energy, pitch angle, and gyrophase, for transmission from the plane, through the aperture of the FILD, and onto the sensor. This probability matrix is then convoluted with the simulated markers reaching the plane, allowing the FILD signal, including the position of ion strikes from which energy and pitch angle can be inferred, to be predicted from a relatively small number of markers. Simulated signals will be presented covering a range of W7-X experimental conditions.

Next-step low-aspect-ratio tokamak physics design studies at PPPL*

J.E. Menard[1], J. Berkery[1], T. Brown[1], N. Bertelli[1], E. Emdee[1], B. Grierson[2], W. Guttenfelder[1], A. Khodak[1], A. Kleiner[1], B. Linn[1], R. Maingi[1], M. Ono[1], J. Parisi[1], C. Rana[1], P. Titus[1], Y. Zhai[1]

[1] *Princeton Plasma Physics Laboratory, Princeton, NJ USA*

[2] *General Atomics, San Diego, CA USA*

Compact high-field superconducting tokamaks are being proposed in the U.S. as a means of potentially reducing the capital cost of a fusion pilot plant (FPP). Systems code analysis of steady-state tokamak FPPs with varied aspect ratio and fixed net electric power of 100 MWe (and other constraints) [1] indicates that $A \approx 2$ could significantly reduce the toroidal field and central solenoid coil volume and mass, which are major drivers for the fusion core cost [2]. Further, if the favorable confinement regimes observed in NSTX, MAST, and other spherical tokamaks scale to larger reactors, the auxiliary power, neutron wall loading, and blanket replacement volume will also be reduced. Compact tokamak FPPs with higher toroidal field and reduced major radius and surface area face the challenge of integrating high confinement, plasma pressure, and high divertor parallel heat flux and wall loading. This presentation will describe physics design activities for both a medium-scale (R=1-2m) Sustained High Power Density (SHPD) / EXhaust and Confinement Integration Tokamak Experiment (EXCITE) facility proposed by the U.S. community to close this integration gap and a larger and fully nuclear A=2, R=4-4.5m Spherical Tokamak Advanced Reactor (STAR) targeting 200-500MWe net electric power, tritium breeding ratio > 1 and including integrated vertical maintenance, power exhaust, and neutronics analysis. EXCITE/SHPD and STAR results that will be described include equilibrium and global stability analysis, H-mode power threshold and pedestal structure projections, non-inductive current-drive analysis, and power exhaust projections and mitigation approaches including detachment and SOL heat-flux broadening.

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Integrated RMP for long-pulse ELM control in KSTAR

J.-K. Park[1], S. K. Kim[1], S. M. Yang[1], G. W. Shin[2], R. Shousha[3], M. W. Kim[2], H. Hahn[2], Y. M. Jeon[2], H.-S. Kim[2], Q. Hu[1], G. Park[2], W. H. Ko[2], E. Kolemen[3], N. C. Logan[4], J. Snipes[1]

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

[2] *Korean Institute of Fusion Energy, Daejeon, Korea*

[3] *Princeton University, Princeton, USA*

[4] *Lawrence Livermore National Laboratory, Livermore, USA*

Non-axisymmetric Resonant Magnetic Perturbation (RMP) is an outstanding method to control the edge-localized-modes (ELMs) in the tokamak H-mode scenarios under the level of tolerance of plasma facing components (PFCs). A notable recent progress is to use the integrated RMP schemes to extend the ELM control period reliably over long pulses, as demonstrated in the Korean Superconducting Tokamak Advanced Research (KSTAR) facility up to the record long 45 seconds, using the $n = 1$ RMPs. The successful use of $n = 1$ RMPs is also promising as it can be easily generated by non in-vessel coils, which are required in the future reactor environments.

The integrated RMP schemes include 4 major components. First, the RMP spectrum optimization over 3 rows of the KSTAR RMP coils has been done predictively through the edge-localizing RMP (ERMP) method [1], which minimizes not only the probability of mode locking but also fast ion losses which are the primary sources of poloidal limiter heating. Then the machine-learning (ML) L-H detection algorithm has been adopted to launch the RMP preemptively [2] and thus to control all ELMs during the entire H-mode phase including the initial ones. Next the adaptive ELM controller [3] has been deployed in sequence after the initial ML-base controller, to minimize excessive RMP. This reduced the unnecessary confinement degradation, inductive flux consumption, as well as heat flux to the divertor. Lastly, operational long-pulse control has been integrated with RMP physics consideration. As for an important example, gradual drifting in real-time EFITs has been adjusted to keep the critical RMP accessibility conditions, such as q_{95} or dR_{sep}. These integrated RMP schemes will be extended into the regimes compatible with non-inductive current drive or other power exhaust solutions such as impurity gas puffing, which will be the next step for long-pulse RMP experiments in KSTAR with its new tungsten divertors.

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Resonant layer responses to 3D magnetic perturbations across linear, two-fluid, drift-MHD regimes

J. Waybright, J.-K. Park

Princeton Plasma Physics Laboratory, USA

3D magnetic perturbations arising in a tokamak can induce complex plasma responses near the resonant surface. In this region, the plasma will no longer adhere to ideal MHD and will instead demand the reconnection of magnetic field lines which can grow and significantly alter the plasma profile. This resonant layer response can be characterized in a linear regime by a single parameter called the inner-layer Δ. Here we apply a two-fluid drift-MHD model to identify the scaling of Δ in various asymptotic regimes while investigating the effects of electron viscosity and parallel flow and confirm the predictions using a numerical method based on the Riccati transformation [1]. In particular, the Δ variations across the strong viscous or recently proposed diffusive [2] regimes have been further investigated and compared with additional analytic solutions. These Δ calculations have also been used to predict the field penetration threshold by matching to outer-layer response solutions in general perturbed equilibrium code (GPEC), and validate the predictions over the tokamak error field database.

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MUSE: A Simple Optimized Stellarator Using Permanent Magnets

M.C. Zarnstorff, X. Chu, C. Pagano, D. Patch, T. Qian, and the MUSE Team

Princeton Plasma Physics Laboratory, Princeton, NJ USA

Stellarators can be constructed simply and inexpensively using permanent magnets combined with toroidal field coils. This strategy is demonstrated in the quasi-axisymmetric optimized stellarator MUSE which has been constructed using commercial rare-earth permanent magnets to generate the 3D magnetic field structure combined with simple planar toroidal field coils. The magnet support structures are precisely fabricated by additive manufacturing, simplifying metrology and the assembly process. The resulting free-boundary stellarator equilibrium is highly optimized for good particle-orbit confinement and low neoclassical transport, with the effective helical ripple $\epsilon_{eff}^{3/2} < 10^{-6}$ for $0.3 < \rho < 0.7$, where ρ is the normalized minor radius. This is significantly lower than in any previous stellarator experiment and should result in tokamak-like confinement physics, but without the need for driven plasma current. This degree of quasi-axisymmetry is calculated to be insensitive to expected construction tolerances. MUSE has been constructed as a table-top scale experiment with $R = 0.30$ m, $B = 0.15$ T, and two field periods, suitable for basic physics experiments. It can operate in steady state, limited only by the coil cooling. First plasma has been produced. Initial experimental results assessing the flux surfaces and plasma properties will be presented. Related methods suitable for larger stellarators with higher magnetic fields will be discussed.

Some Aspects of Alpha Channeling in Open Magnetic Field Devices

N. J. Fisch

Department of Astrophysical Sciences, Princeton University, Princeton, USA

What has become known as *alpha channeling* is the diffusion by waves of byproducts of a DT fusion reaction, namely the alpha particles, in such a way that energetic alpha particles leave a magnetic confinement device with much less energy, with their energy captured by the resonant waves [1]. The power flow to the waves is enabled by the population inversion along a wave diffusion path, which connects high-density, high-energy phase space in the device center to low-density, low-energy phase space at the device periphery. In closed magnetic field devices, such as tokamaks or stellarators, the periphery is the physical edge of the device; however, in open magnetic field devices, the periphery could be either the physical device periphery, or some boundary in phase space separating trapped and untrapped particles. Thus, alpha channeling in simple mirror machines [2], or in centrifugal mirror machines [3, 4] allow for a greater variety of diffusion paths to accomplish the alpha channeling. Waves that might be suitable waves for alpha channeling in open field machines [5] will also differ from waves that have been proposed for closed field devices such as tokamaks [6, 7, 8]. Thus, the wide variety of open-field devices offers a correspondingly wide variety of possibilities for realizing the alpha channeling effect.

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Compact plasma equilibria for next-step HTS stellarators

A. Evangelias[1]

[1] Renaissance Fusion, Fontaine 38600, France

Renaissance Fusion strives to make smaller, easier to build, stellarators via High-Temperature Superconducting (HTS) coils and simplified coil winding surfaces. As a starting point towards the design of a compact, profitable stellarator reactor, we calculate equilibria of low aspect ratio, high magnetic field, in connection with HELIAS configurations with three and four field periods. In addition, we optimize those equilibria with respect to several physical targets such as the rotational transform profile, reduced bootstrap current and neoclassical transport. Also, we investigate the impact of finite plasma pressure and decreasing aspect ratio on the equilibrium characteristics.

Direct temperature measurements across the outer divertor leg during detachment experiments in TCV

L. Martinelli[1], D. Mykytchuk[1], B.P. Duval[1], P. Blanchard[1], M. Carpita[1], C. Colandrea[1], O. Février[1], S. Gorno[1], J. T. W. Koenders[3,4] B. Linehan[2], A. Perek[1], H. Reimerdes[1], C. Theiler[1], B. Vincent[1] and the TCV team[a]

[1]*Swiss Plasma Center (SPC), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland;* [2]*PSFC, MIT, Cambridge, MA, USA;* [3]*DIFFER - Dutch Institute for Fundamental Energy Research, Eindhoven, the Netherlands;* [4] *Dep. of Mechanical Engineering, Control Systems Technology Group, Eindhoven University of Technology, Eindhoven, the Netherlands;* [a]*See author list of H. Reimerdes et al 2022 Nucl. Fusion 62 042018*

For divertor detachment studies, a detailed characterisation of the entire outer divertor leg, and of the surrounding plasma, was carried out in TCV, by exploiting a fruitful combination of TCV edge diagnostics and its signature configuration flexibility in obtaining *ad hoc* magnetic equilibria. In dedicated experiments, the Divertor Spectroscopy System provides impurity ion temperature, from high resolution Doppler broadening analysis of their spectral line-shapes [1] along the divertor leg. These measurements were further differentiated from 2D emissivity distributions of the analysed spectral lines obtained from tomographic inversions of the spectrally filtered camera images provided by the Multispectral Advanced Narrowband Tokamak Imaging System. Direct radial profiles of n_e and T_e were simultaneously measured using TCV's divertor Thomson Scattering system, from near repeat discharges where the distance between the outer divertor leg and the Thomson Scattering probed volumes was finely scanned across a $\sim$1.5 cm interval. This combined information was used to compare emission-weighted T_e and T_i in the high collisionality divertor plasma as it transited from an attached towards a detached regime. One immediate result was an analysis of characteristic temperatures associated with the C III radiation front, an observable often used in detachment control experiments [2] as a proxy for *a threshold* electron temperature. Here, we reconstructed the electron temperature profiles at the salient C III front position - where the C III spectral line intensity drops by 50% - independently resolving an average and peak T_e, rather than a *parametric*, *generalised* value. Herein, measurements are available across the full divertor leg. This provides a one to one comparison with modelled divertor descriptions, such as the 2-Point Model [3], that predict target parameters from upstream plasma quantities, assuming pressure conservation along the flux tubes.

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Impact of parallel flows on total flux expansion effect in the divertor

M. Carpita[1], O. Février[1], H. Reimerdes[1], C. Theiler[1], B. P. Duval[1],
C. Colandrea[1], G. Durr-Legoupil-Nicoud[1], D. Galassi[1], S. Gorno[1], E. Huett[1], J. Loizu[1],
L. Martinelli[1], A. Perek[1], L. Simons[1], G. Sun[1], C. Wüthrich[1] and the TCV team[a]
[1] *EPFL-SPC, CH-1015 Lausanne, Switzerland*
[a] *See author list of H. Reimerdes et al 2022 Nucl. Fusion 62 042018*

Due to material limits, future fusion reactors must operate with a detached divertor. Uncertainties on the standard lower Single-Null (SN) performance in reactor-relevant conditions make the investigation of Alternative Divertor Configurations (ADCs) crucial [1]. The Super-X divertor (SXD) [2] is an ADC leveraging total flux expansion at the outer strike point (OSP) to increase the outer target wetted area. Key features of the SXD are the benefits on detachment access and control [3], as detailed by the extended 2-point model (2PM) [4] under simplified assumptions (single active divertor, no modifications of neutrals or cross-field transport effects). In particular, the 2PM predicts target temperature decrease and particle flux increase with increasing total flux expansion. However, parallel flows are not consistently included in the 2PM and total flux expansion effects appear explicitly only in the power balance equation. In this work, the 2PM is refined to overcome this limit: the role of total flux expansion on total pressure balance is now made explicit, by including the effect of parallel flows. Consequently, the effect of total flux expansion on detachment access and control is weakened, compared to predictions of the 2PM. This new model partially explains discrepancies between the 2PM and experiments performed with the TCV tokamak, in Ohmic (I_p = 250 kA) L-mode scenarios, presented in this work: I) in core density ramps (f_g = [0.20 - 0.55]) in lower SN configuration, with different fuelling locations, the CIII emission front movement in the divertor outer leg - used as a proxy for the plasma temperature – is studied. This movement happens at 10-20% lower core density with increased total flux expansion (R_t = 0.62 vs 1.03 m), while the 2PM predicts 40%; II) in OSP sweeps (R_t = [0.62 - 1.03] m) in lower and upper SN configurations, with constant core density (f_g = 0.31), the integrated particle flux at the OSP remains independent of R_t, while the 2PM predicts a quadratic dependence. Simulations with the SOLPS-ITER code, reproducing experimental scenarios, are also used to study flow patterns. Finally, parallel flows and mechanisms for Mach number evolution in the divertor are discussed self-consistently. It is shown that an increase in total flux expansion can induce supersonic flows at the OSP, and the impact on target conditions, detachment access and control is addressed, using both numerical modelling and experimental measurements.

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Fast-ion dynamics and instabilities on the TCV tokamak

A.N.Karpushov[1], M.Baquero-Ruiz[1], M.Dreval[2], B.P.Duval[1], B.Labit[1], D.Mykytchuk[1], J.Poley-Sanjuán[1], L.Porte[1], B.Schmidt[3,1], M.Vallar[1], S.Vincent[1], and the TCV Team*

[1] *Swiss Plasma Center, EPFL, 1015 Lausanne, Switzerland*

[2] *National Science Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*

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

Fast-ion (FI) dynamics and confinement is one of the most challenging problems in magnetic confinement fusion [1]. Scientific objectives for FI studies are focused upon the assessment of FI transport and losses induced by MHD perturbations (ELMs, NTMs, Sawteeth, Alfvén eigenmodes (AEs), etc.); a quantification of the impact of FI driven instabilities on plasma transport; an identification of control actuators to minimize MHD-induced fast-ion losses. The newly installed neutral beam injectors (NBIs) allow TCV [2] to contribute to worldwide FI research using its unique shaping capabilities and a powerful ECH-ECCD. The TCV FI experimental program is focused upon the study of (1) the impact of plasma tiangularity, in particular negative (NT), on fast ions; (2) control of FI confinement and related MHD (e.g. AEs) with ECH/ECCD and (3) fast-ion losses and dynamics across ELMy H-mode regimes. TCV is equipped with a several FI-sensitive diagnostics, including Fast Ion D-alpha (FIDA) spectroscopy, a Compact Neutral Particle Analyzer (CNPA), neutron counters and the Fast Ion Loss Detector (FILD) [3]. Necessary modelling, data analysis and synthetic diagnostic tools (ASTRA, TRANSP/NUBEAM, ASCOT, LIGKA, FIDASIM, FILDSIM, etc.) have been implemented at TCV for FI characterization. The FI velocity distribution function reconstructions from FIDA spectra, using velocity-space tomography [4], have been implemented on TCV.

A set of AEs in negative triangularity has been observed and explored in the whole operational space of the TCV shaping capability. The amplitude and frequencies of the magnetic fluctuations and FI losses are correlated with triangularity. suppression of TAEs has been demonstrated with an optimized ECCD profile that modified the plasma current, safety factor and shear profiles. H-mode scenarios with regular ELMs and MHD modes measured by magnetic diagnostics and FILD were developed. The amplitude (spikes) on FILD signals were found to be correlated with ELMs (D-alpha emission) and indicate an increase of FI losses by ELMs. High correlation between MHD spectrograms (10-150 kHz) measured by magnetics and FILD during the ELM cycle were observed at low plasma density and collisionality.

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* See the author list of H. Reimerdes et al 2022 Nucl. Fusion, 62 042018

Integration of a multi-rate electron density profile observer in the plasma control system of TCV

F. Pastore[1], F. Felici[1], T.O.S.J. Bosman[2,3], C. Galperti[1], T. Ravensbergen[4], O. Sauter[1], B. Vincent[1], T. Vu[1] and the TCV team[5]

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

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

[3] *Eindhoven University of Technology, Dept. of Mechanical Engineering, 5600 MB Eindhoven, The Netherlands*

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

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

Real-time integrated modeling represents an active research field for fusion devices. The coupling of different codes, algorithms and available measurements contributes to provide an estimate of plasma magnetic and kinetic profiles for monitoring and control purposes. In this framework, the integration of plasma state observers for the reconstruction of kinetic profiles in the Plasma Control System (PCS) of fusion machines enables an effective decoupling between available diagnostics and controllers, yielding a more robust and accurate control of the desired plasma quantities while ensuring at the same time the rejection of diagnostic faults and errors.

In this work we present the integration into the PCS of the TCV tokamak of RAPDENS [1][2][3], a multi-rate electron density profile observer, which uses an Extended Kalman Filter (EKF) to combine low-frequency Thomson Scattering (TS) and high-frequency FIR signals with the numerical results of a predictive model. This integration allows for leveraging the magnetic equilibrium reconstruction code, particle actuator signals like gas puff, the LDH plasma state detector (Low, Dither and H-mode) and electron density measurements for accurate real-time estimation of the electron density profile. The RAPDENS code is implemented in Matlab/Simulink, and an object-oriented initialization of fixed and tunable parameters has been performed for multi-machine portability. Automated code generation of the algorithms/codes integrated in the PCS is carried out for robust real-time performances and offline testing of the integrated system. A specific module to pre-process in real time the raw density data provided by the available diagnostics, detect and discard corrupted channels and integrate the measurements uncertainties in the EKF procedure is also introduced. The code is validated for different offline high-density TCV discharges in H-mode, where the numerical results are compared with the available experimental measurements in the various phases of the discharge and different covariance matrices are designed and tuned for an optimal weighting between the predicted density profile, the TS measurements and the FIR signals.

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Numerical techniques for computational magneto-hydrodynamics: application to gas-plasma interactions in tokamaks

A. Bhole[1], B. Nkonga[1], S. Pamela[2], M. Hoelzl[3], G. Huijmans[4,5], JOREK Team and JET Contributors

[1] *Université Côte d'Azur & INRIA/CASTOR, CNRS/LJAD, 06108 Nice, France*

[2] *CCFE, Culham, United Kingdom of Great Britain and Northern Ireland*

[3] *Max Planck Institute for Plasma Physics, Garching b. M. and Greifswald, Germany*

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

[5] *Eindhoven University of Technology, Eindhoven, Netherlands*

Gas-plasma interaction (GPI) is of fundamental interest, for instance regarding disruption mitigation via Massive Material Injection (MMI). We present here methods to improve numerical simulations of such GPI. The physics involved is highly nonlinear, convection-dominated, anisotropic, and may contain shocks, and strong sources. We consider extended full MHD equations to model GPI and use the numerical stabilized techniques [1] along with special treatments of grid singularities [2] to perform simulations of MMI in JET plasma. The developments are carried out in the nonlinear MHD code JOREK, can be used for fusion plasma applications other than MMI as well, and are highly relevant for ITER goals.

Computational tools using the high-order Galerkin finite element method (FEM) often encounter two challenges: First, the Galerkin FEMs give central approximations to the differential operators and may lead to dispersion errors when simulating convection-dominated flows. Secondly, high-order numerical methods are known to produce high wave-number oscillations in the vicinity of shocks/discontinuities in the numerical solution adversely affecting the stability of the method. We present stabilized FEMs for plasma fluid models to address the two challenges. The numerical stabilization is based on two strategies: Variational Multiscale (VMS) and the shock-capturing approach. The former takes into account the effect of the unresolved scales onto resolved scales to introduce upwinding in the Galerkin FEM. The latter adaptively adds artificial viscosity only in the vicinity of shocks. These two strategies can improve the stability and robustness of the Galerkin FEMs used for a wide range of problems including fusion and astrophysical plasma.

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Full-orbit Toroidal Accelerated PArticle Simulator (TAPAS) to study the transport and losses of energetic particles in fusion plasmas

H. Betar[1], D. Zarzoso[1], J. Varela[2], D. del-Castillo-Negrete[3], D. A. Spong[3], J. Ortiz[2]

[1] *Aix-Marseille Université, CNRS, Centrale Marseille, M2P2 UMR 7340, Marseille, France*
[2] *Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain*
[3] *Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830*

There are different possible sources of energetic particles (EPs) in magnetic confinement fusion devices, including, for example, the fusion reactions that produce alpha particles, and the auxiliary heating systems like neutral beam injection (NBI) and ion cyclotron resonant heating (ICRH). The confinement of EPs is crucial to ensure transferring their energy to the thermal plasma and achieving self-sustained fusion reactions. However, due to the complexity and the multi-scale nature of a fusion plasma, different types of micro- and macro-instabilities may develop. The interaction of these instabilities with EPs can drastically reduce their confinement and therefore limit the performance of the device. Therefore, understanding the EP transport in the presence of electromagnetic perturbations is essential to achieve self-sustaining fusion reactions.

One strategy to study the EP transport is by integrating the trajectories of particles in the presence of externally imposed instabilities. In this context, a new code called TAPAS (for Toroidal Accelerated PArticle Simulator) was developed [1] to study the transport in the presence of turbulence and electromagnetic perturbations. TAPAS is parallelized and accelerated on GPUs using a hybrid MPI-OpenACC parallelization (including a GPU-accelerated B-spline interpolation module). The new version is full-orbit, allows the integration of particle trajectories in realistic geometry (tokamak and stellarator) and includes Coulomb collisions through deterministic and stochastic operators representing friction and diffusion in velocity space.

In this presentation we show the coupling between TAPAS and the gyro-fluid nonlinear Far3d code [2] to study the transport and the losses of EPs in the presence of Alfven Eigenmodes and tearing modes for DIII-D and JET tokamaks, highlighting the differences between the two approaches, namely full-orbit *versus* guiding-centre with gyro-average, in the presence and in the absence of collisions.

Because these simulations can be computationally expensive, alternative approaches to predict losses of EPs and link them to the core activity should be envisioned. In this context, we propose an artificial intelligence model based on the combination of generative deep learning algorithms [3] and dense deep neural networks to predict the EP losses and/or find the eigenmodes corresponding to a given pattern of EP losses.

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A Comparison of VMEC, SIESTA and SPEC Equilibria

A. S. Ware[1], S. R. Hudson[2], J. C. Schmitt[3], M. Cianciosa[4], and J. Hansen[3]

[1] *University of Montana, Missoula, Montana, USA*

[2] *Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA*

[3] *Auburn University, Auburn, Alabama, USA*

[4] *Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA*

The numerical calculation of three-dimensional MHD equilibria is an essential step in designing and analyzing toroidal magnetic confinement devices. The type of equilibrium is determined by the assumptions used in designing the code that calculates the equilibrium. The VMEC code is an Ideal MHD code that assumes nested toroidal flux surfaces [S. P. Hirshman and H. K. Meier, Phys. Fluids 28, 1387 (1985)] and it has been widely used in stellarator and tokamak physics. The SIESTA code relaxes the assumption of nested toroidal flux surfaces and switches between Ideal and Resistive MHD in the process of searching for an equilibrium [S. P. Hirshman, R. Sanchez and C.R. Cook, Phys. Plasmas 18, 062504 (2011)]. The SPEC code is designed with the concept of multi-region, relaxed MHD [S. R. Hudson, et al., Phys. Plasmas 19, 112502 (2012)]. In this work, these three codes are used to calculate tokamak and stellarator equilibria, with a comparison of the differences and similarities of the results. The focus here will be on obtaining equilibria from each of the different codes for the same equilibrium. The challenges and limitations of the codes will be discussed.

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Calculation of α knock-on neutron spectra from JET DT plasmas

J. Eriksson[1], M. Nocente[2,3], E. Andersson Sundén[1], C. Challis[4], S. Conroy[1], A. Dal Molin[2], G. Ericsson[1], J. Garcia[5], J. Hobirk[6], L. Hägg[1], A. Kappatou[6], D. Keeling[4], D. King[4], E. Lerche[7], C. Maggi[4], J. Mailloux[4], M. Maslov[4], D. Rigamonti[2], Z. Stancar[4], M. Tardocchi[2] and JET Contributors*

[1]Uppsala University, Dept. of Physics and Astronomy, SE-75120 Uppsala, Sweden; [2]Institute for Plasma Science and Technology, National Research Council, 20125 Milan, Italy; [3]Dipartimento di Fisica, Università di Milano-Bicocca, 20126 Milan, Italy; [4]UKAEA, Culham Centre for Fusion Energy, Abingdon, Oxon, OX14 3DB, UK; [5]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France; [6]Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching; [7]Laboratory for Plasma Physics LPP-ERM/KMS, B-1000 Brussels, Belgium

A deuterium-tritium (DT) experimental campaign was carried out at the JET tokamak during 2021, providing the first demonstration of steady, high-power fusion performance (~10 MW of fusion power sustained for ~5 s) in a tokamak with an ITER-like all-metal wall. These experiments provide the opportunity for studying the behaviour of fusion-born α-particles in reactor-relevant plasmas.

When α-particles slow down in the plasma they occasionally undergo large-angle elastic scattering on the D or T ions, transferring a significant portion of their energy to the scattered ion in one single collision. These “knock-on” reactions give rise to a small population of supra-thermal D and T ions in the plasma, which manifest themselves as a high-energy tail in the energy spectrum of the neutrons emitted from the plasma via the D(T,n)α fusion reaction. One way of obtaining information about the α-particles is hence to study the α knock-on (AKN) tail in the neutron spectrum.

In previous analyses of the AKN tail, the expected tail shape and amplitude were calculated under the assumption of uniform plasma parameters and by using 1-dimensional Fokker-Planck modelling for the slowing-down of the α, D and T ions. In this work, we extend this method by coupling the AKN calculations to state-of -the-art plasma modelling tools such as TRANSP and ASCOT. These tools can model the steady-state slowing down distribution of the α-particles in realistic tokamak geometry and by using such distributions in the AKN calculations it is hence possible to calculate the expected AKN neutron spectrum emitted from arbitrary points in the plasma. It is then possible to determine the expected AKN spectrum for a given neutron spectrometer, by integrating over the spectrometer viewing cone.

The framework is used to determine the expected AKN spectrum for several of the best performing JET DT discharges, and the potential for observing these tails with the different neutron spectrometers at JET is discussed.

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

Estimating the neutron yield from JET DT plasmas using neutron camera measurements

L. Hagg[1], S. Conroy[1], G. Ericsson[1], Z. Ghani[2], L. Giacomelli[3], D. Marocco[4], A. Milocco[5], M. Riva[4], E. Andersson Sundén[1], JET contributors[*]

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

[2] *UKAEA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*

[3] *European Commission—Joint Research Centre, Via E. Fermi 2749, 21027 Ispra (VA), Italy*

4 Fusion and Technology for Nuclear Safety and Security Department, ENEA, C.R. Frascati, Via E. Fermi 45, I-00044 Frascati, (Roma), Italy

[5] *University of Milano–Bicocca University, Physics Department 'G. Occhialini', Milano, Italy*

[3] *Institute, City, Country*

JET recently had a successful deuterium-tritium (DT) campaign with record breaking results. Neutron measurements are important for the analysis of these experiments, e.g. for estimating the fusion power, the ratio of D and T concentrations, and for studying energetic ions in different plasma heating scenarios. One of the prominent neutron detection systems at JET is the JET neutron camera. It has 19 sightlines that measure the neutron emission along both the horizontal and the vertical axis of the plasma.

In this work we estimate the DT neutron yield based on JET neutron camera measurements, by fitting a modelled neutron emissivity profile to the neutron camera data. The method uses detailed Monte Carlo calculations of the neutron camera system and the JET tokamak in order to model the neutron camera response to arbitrary neutron emissivity profiles. This work investigates the effects of using different parametrized models of the neutron emission profile, as well as neutron emission profiles calculated by TRANSP, for the neutron yield determination. This is to better describe features like how the neutron emission profile is affected by trapped particle orbits. The method improves upon previous attempts to utilize the JET neutron camera in this way. It uses the digital KN3N data acquisition for improved event identification and control over the data. The proposed method also models the effect of neutron scattering and attenuation near the detectors. This work builds on a method that was

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

developed for DD plasmas. On average, the DD neutron yield estimates with that method were within 10% agreement with corresponding estimates using the JET fission chambers. The method is now expanded to DT plasmas to assist in the analysis of important shots from the DT campaign.

Predictive studies of Deuterium fuelling strategies in the Divertor Tokamak Test facility

B. Baiocchi[1], L. Aucone*[1,2], I. Casiraghi[1,2], L. Figini[1], F. Koechl[3], P. Mantica[1]

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

[2]*Dipartimento di Fisica 'G. Occhialini', Universita` di Milano-Bicocca, Milan, Italy*

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

In order to fulfil the main aims of the new Divertor Tokamak Test facility (DTT) [1] the sustainment and the evolution of the plasma density are key topics which need to be deeply investigated, taking into account the peculiarities of the foreseen operational scenarios. An integrated modelling study of the full power DTT (R=2.19 m, a=0.7 m, Bt=5.85 T, Ip=5.5 MA) H-mode Single Null scenario is performed with the transport code JETTO [2], starting from the fixed pedestal reference simulation [3]. Main ion and impurity densities, ion and electron temperatures, current and toroidal momentum are predicted, evolving the transport equations until the separatrix, and using the core anomalous transport model QuaLiKiz [4]. The EPED1 [5] reference pedestal values are recovered by tuning the transport parameters of the edge transport barrier and of the continuous model of the Edge Localized Modes (ELMs), taking into account full power scenario peculiarities as high separatrix density and significant impurities concentration. Two fuelling methods (gas puffing and pellet injection) are considered and self-consistently modelled. The Electron Cyclotron (EC) deposition is taken fixed using the reference peaked profile or self-consistently calculated with the code GRAY [6], changing locations and radial widths. The levels of gas puffing required to sustain the full power scenario plasma are higher than the feasibility limits of the pumping system presently foreseen. Conversely the plasma pedestal is sustained using workable frequencies and pellets with realistic dimensions, velocities and launching position. Only with spread EC deposition the whole density can be sustained, recovering the performances of the reference scenario, with no detrimental interaction between the EC and pellet depositions. Varying the EC power deposition width can change the turbulence type and the associated transport, and then giving an essential contribution for the whole plasma density sustainment.

*second main author

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Particle-In-Cell modeling of laser-driven wakefield acceleration for the generation of high quality electron beam

Srimanta Maity, Eugene Vishnyakov, Alamgir Mondal, and Alexander Molodozhentsev

Extreme Light Infrastructure ERIC, ELI Beamlines Facility, Za Radnicí 835, 25241 Dolní Břežany, Czech Republic

Laser-driven wakefield acceleration (LWFA) [1] has been the subject of active research over decades to generate high-quality electron beams with up to GeV energies [2]. A significant effort is being made to improve the quality, e.g., high charge, low energy spread, small beam emittance, and low divergence of the accelerated electron beam. The electron beam quality in a laser-plasma accelerator (LPA) strongly depends on the injection mechanism. Recent works [3, 4] have indicated that a controlled ionization-induced injection scheme can be one of the promising techniques to produce intense electron bunches with high mean energy and low divergence.

In the present study, we have investigated the two-stage configuration for LWFA using Particle-In-Cell simulations. In the first stage, the ionization-induced injection occurs where a short region of nitrogen-doped hydrogen is considered. In the second stage, these injected electrons are accelerated in a long plasma plateau formed from pure hydrogen. The injection process, as well as accelerated electron beam properties, have been characterized in detail. The dependence of laser parameters and density profile on the quality of accelerated electron beams has been explored. In our study, we have observed the electron beam with a relatively high mean energy of 0.6 GeV, low energy spread of less than 10% (FWHM), low divergence of approximately five milliradians (FWHM), and a beam charge of roughly 3.5 pC/μm.

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Optimisation of the PIXE analysis method with laser-accelerated ions using a helical target and a tube

C. Lacoste[1,2,3], E. Catrix [1], C. Boynukara[1] , S. Fourmaux[1], A. Hirsch[2,3],
M. Bardon[2,3] E. D'Humières[3] et P. Antici[1]
[1] *INRS EMT, Varennes, J3X 1P7, Canada*
[2]*CEA-CESTA, Le Barp 33114, France*
[3]*CELIA, University of Bordeaux-CNRS-CEA, Talence 33405, France*

Proton acceleration by TNSA (Target Normal Sheath Acceleration) [1] has many applications. One of these is PIXE (Particle Induced X-ray Emission) [2], a technique that allows the precise analysis of the chemical composition of a material without causing damage. When protons interact with the target to be analysed, they will ionise the target by ejecting electrons from the inner layers. An electron from the outer layer will then de-excite, emitting an X-ray. As the wavelength of X-rays is characteristic of the atom, we can know the composition of a material by obtaining the X-ray spectrum emitted. The disadvantage of the TNSA acceleration mechanism is that it generates a proton beam with a relatively large angular divergence (±20°). For this reason, we have been interested in helical targets [3] that focus and post-accelerate a proton beam produced by TNSA [4].

During laser-matter interaction, a discharge current is generated when hot electrons are ejected [5]. With a helical target, this current will propagate along a conductive helix connected to the backside of the target. This propagation will then generate an electromagnetic pulse inside the helix that will focus and accelerate the TNSA proton beam. However, with only the helical coil, because of the dispersion of current, most application, including PIXE, do not benefit fully from this setup. So, finally, we have developed a theoretical model of a helical coil and a tube to considerably limit the dispersion of the current.

In this poster, I will present the TNSA and PIXE results obtained with the high repetition rate ALLS laser (2.5Hz, 22fs, 3.2J) from INRS EMT (Canada) and the proton spectra obtained with the helical target and coil theoretical model. The coupling of these two methods has many advantages. First of all, the increase in proton fluence allows an increase in induced X-ray fluorescence. It also allows for deeper probing, especially for high Z materials [2,6,7]. Finally, I will conclude with a presentation of the next experiment that will be performed in spring 2023 on the ALLS facility at INRS.

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Two stage electron acceleration by laser-plasma interaction

M. C. de Sousa[1], S. Marini[2], M. Grech[3], C. Riconda[4], M. Raynaud[1]

[1] *LSI, CEA/DRF/IRAMIS, CNRS, École Polytechnique, Institut Polytechnique de Paris, F-91128 Palaiseau, France*

[2] *CEA, IRFU, DACM, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*

[3] *LULI, CNRS, CEA, Sorbonne Université, École Polytechnique, Institut Polytechnique de Paris, F-91120 Palaiseau, France*

[4] *LULI, Sorbonne Université, CNRS, CEA, École Polytechnique, Institut Polytechnique de Paris, F-75252 Paris, France*

The development of ultraintense ($\geq 10^{18}$ W/cm^2), short pulsed (≤ 25 fs) lasers with high contrast ($\sim 10^{12}$) allows the exploration of new mechanisms for particle acceleration. In particular, when such lasers irradiate overdense plasmas, electromagnetic waves appear at the vacuum-plasma interface which enable local field confinement and enhancement for electron acceleration up to relativistic energies. Since these mechanisms involve an overdense plasma, high values of total electron beam charge ($\sim$ nC) can be achieved. This may be important for applications in the fields of plasma-based accelerators, electron sources, among others. In Ref. [1], it was shown by means of Particle-in-Cell (PIC) simulations [2] how a laser pulse interacting with the wedge of an overdense plasma can produce a diffracted electromagnetic wave with an intense longitudinal electric field that efficiently accelerates plasma electrons. For a laser with intensity $I\lambda_0^2 = 3.5 \times 10^{19}\mathrm{W}\mu\mathrm{m}^2/\mathrm{cm}^2$, collimated electron bunches with high charge ($\sim$ nC) were accelerated to relativistic energies on the order of 10^2 MeV. In this work, we investigate with PIC simulations [2] the possibility of coupling the scheme proposed in Ref. [1] to generate highly charged electron bunches with the wakefield produced by the laser propagating through an underdense plasma. Electrons trapped by the wakefield can indeed be accelerated even further, enabling us to obtain highly charged and highly energetic electron bunches at the end of this second acceleration stage.

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Highly efficient ion beam generation in foil plasma expansion driven by large spot petawatt lasers

N. Iwata[1,2], A. J. Kemp[3], S. C. Wilks[3], and Y. Sentoku[1]
[1] *Institute of Laser Engineering, Osaka University, Suita, Osaka, Japan*
[2] *Institute for Advanced Co-Creation Studies, Osaka University, Suita, Osaka, Japan*
[3] *Lawrence Livermore National Laboratory, Livermore, CA, USA*

Kilojoule-class petawatt lasers with relativistic intensities such as LFEX and NIF-ARC have demonstrated efficient electron and ion accelerations from thin foil plasmas. In the multi-picosecond (ps) laser-plasma interaction, the foil plasma expands significantly to make a large-scale coronal plasma, and the heated foil surface starts to push the laser light back, resulting more efficient laser energy absorption. In addition, owing to the large laser spot, fast electrons are confined in the laser spot area [1], and the slope temperature of fast electrons keeps increasing in the interaction. In this new stage, the plasma expansion structure changes from the self-similar, isothermal mode to a non-isothermal, fast expansion mode [2].

We here study the temporal evolution of fast electron and ion energies in the expanding plasma under a continuous laser energy input in 1-10 picosecond scale, to model the efficient proton beam generation seen in kJ laser experiments. Using two-dimensional particle-in-cell simulations, we found that fast electron energy density in the expanding foil plasma increases temporally, by which a strong sheath electric field is maintained in the expansion. This effect is stronger when the ratio of the laser spot size to the foil thickness is larger. On a multi-picosecond time scale, about one half of the absorbed laser energy is eventually converted to the ion kinetic energy through the sheath field maintained by the fast electrons, resulting a high energy coupling nearly five percent from laser to MeV protons.

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Coherent subcycle optical shock from superluminal plasma wake

H. Peng[1], T.W. Huang[1], K. Jiang[1], R. Li[1], C.N. Wu[1], M.Y. Yu[1], C. Riconda[2], S. Weber[3], C.T. Zhou[1], and S.C. Ruan[1]

[1] *Shenzhen Key Laboratory of Ultraintense Laser and Advanced Material Technology, Center for Advanced Material Diagnostic Technology, and College of Engineering Physics, Shenzhen Technology University, Shenzhen 518118, China*

[2] *ULI, Sorbonne Universit´e, CNRS, Ecole Polytechnique, CEA, F-75252 Paris, France*

[3] *Extreme Light Infrastructure ERIC, ELI Beamlines Facility, 25241 Doln´ı Bˇreˇzany, Czech Republic*

High-energy subcycle radiation pulses are useful for many applications. For many applications, it is desired to have high intensity, tunable frequency, stable carrier envelope phase (CEP), and foremost a simple setup. However, to our best knowledge, currently there is not such a radiation source that possesses all of these desired properties simultaneously. As recently demonstrated by Vieira et al.,[1], when a rarefied high-energy electron bunch is suitably modulated, its radiation can form a coherent optical shock at the Cherenkov angle. Prerequisites for this superradiance radiation, or generalized Cherenkov radiation (GCR), are that all the electrons in the bunch have similar trajectories and are modulated with a superluminal phase, such that they form a superluminal radiation point (SRP), whose speed stays constant above the light speed c.

In this work[2], we found that the cusp-like rear of the superluminal wake bubble in plasma with up-ramped density can be exploited as an SRP that leads to coherent GCR. As observed in three-dimensional (3D) particlein-cell (PIC) and far-field time-domain radiation simulations, an isolated subcycle optical pulse in the form of a shock can be generated from a superluminal wake bubble of a relativistic electron beam(REB). Such radiation has many interesting and unique features: radiations from the involved electrons are phase-locked at the Cherenkov angle, it is CEP stable, as well as of subcycle attosecondscale duration. It has also excellent directionality, namely at the Cherenkov angle with very small angular divergence, and high intensity that scales with the square of the propagation distance. In addition, the frequency can be readily tuned by adjusting the densities of the plasma and REB.

γ-photon emission and radiation reaction effects in surface plasma waves in the ultra high intensity regime

P.S. Kleij[1], M. Grech[2], S.Marini[3], C. Riconda[2], M. Raynaud[1]

[1] *LSI, CEA/DRF/IRAMIS, CNRS, Ecole Polytechnique, F-91128 Palaiseau, France*

[2] *LULI, Sorbonne Université, CNRS, Ecole Polytechnique, CEA, 75005 Paris, France*

[3] *IRFU, CEA-Saclay, F-91191 Gif-sur-Yvette, France*

Manipulating and harnessing plasmonic phenomena in the ultra relativistic regime reveal promising prospects in using surface plasma waves (SPW) for the creation of high-energy particle and radiation sources on the next generation of multi-PW lasers. Indeed, relativistic high-charge electron bunches can be produced by SPW excited by ultra-high intensity fs lasers impinging on a periodically-modulated solid-density target. In this regime, there is good evidence that SPW excitation survives [1] and that the produced electron bunches experience strong acceleration, therefore emitting large amounts of electromagnetic radiation [2] with interesting characteristics. We present a series of Particle-In-Cell (PIC) simulations with the open-source PIC code SMILEI [3] which prove that extending the study to ultra-high laser intensities ($I > 10^{21}$ W/cm^2), the use of a resonant grating for SPW generation enhances the acceleration and emission of the electrons along the surface. This scheme represents an interesting alternative of light source as the energy lost by electrons due to radiation emission is transferred to high-energy γ photons. In addition, we show that using a laser with wavefront rotation coupled with a tailored blazed grating, which has proved to generate ultra-short (few fs) multi-MeV electron bunches in the relativistic regime [4], leads to more energetic and collimated electron bunches as well as improved photon emission in the ultra relativistic regime of interaction.

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Enhancement of Proton-Boron Nuclear Reactions by Utilizing a Meshed Catcher Target

A. D. Liu[1], Z. Y. Liu[1], K. Li[1], B. Qiao[1*]

[1] *Centre for Applied Physics and Technology, HEDPS and State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*

The proton-boron nuclear reaction has been investigated since the 1930s and has received growing interest in recent years. As this reaction has the advantage of releasing its energy mainly to alpha particles with a very low neutron emission, it becomes attractive as a safe fusion reactor for solving energy crisis. With intense laser, driving proton-boron nuclear reaction under non-equilibrium conditions becomes one of the most effective ways to produce alpha particles. The most common scheme is the pitcher-catcher geometry where protons are accelerated through Target-Normal-Sheath-Acceleration (TNSA) mechanism. However, the number of protons accelerated is small and the energy is far from the optimal value for proton-boron reaction which is 675 keV in the traditional scheme. This becomes one of the most critical issues of laser-driven proton-boron nuclear reaction. Depending on this, a scheme for laser-driven proton-boron reaction enhancement based on pitcher-catcher geometry by utilizing meshed catcher target is explored by theory and self-consistent simulations.

Hot electrons generated by the interaction between laser and pitcher target spread into meshed target and induce plenty of micro sheath fields in the meshes, then a large number of protons in the catcher target are accelerated to drive the proton-boron nuclear reaction. The meshed target greatly increases the action area of sheath field to enlarge the number of protons, and controls the protons energy to make the nuclear reaction cross section at the optimal value by adjusting the size of meshes based on the laser intensity. Two-dimensional particle-in-cell simulations show that compared with the solid target, meshed target can bring an order of magnitude enhancement in the yield of proton-boron nuclear reaction, which is also proportional to the laser intensity.

In Summary, we have proposed a scheme for laser-driven proton-boron reaction enhancement based on pitcher-catcher geometry by utilizing meshed catcher target, which have made essential steps towards solving the critical issue concerning low yield of laser-driven proton-boron nuclear reactions based on pitcher-catcher geometry.

*Corresponding author: bqiao@pku.edu.cn

Development of a coupled frequency-shifted Photonic Doppler Velocimetry (PDV) and triature Velocity Interferometer System for Any Reflector (VISAR) diagnostic and application to an experimental platform dedicated to evaluate x-ray-generated stress in materials at the Laser MegaJoule (LMJ) facility

G. Boutoux[1,2], C. Baccou[1], R. Beuton[2], J.-M. Chevalier[2], D. Hébert[2], P. Maury[2], M. Primout[1], L. Videau[1], B. Villette[1,2] et al.

[1] *CEA, DAM, DIF, F-91297 Arpajon, France*
[2] *CEA, DAM, CESTA, F-33114 Le Barp, France*

In a first section, we present a series of stress-wave measurements on Aluminium generated by electron-induced (CESAR facility, CEA Cesta, France) and laser-induced direct heating (HERA facility, LULI, Ecole Polytechnique, France and BELENOS facility, ENSTA Bretagne, France). We developed a diagnostic based on the use of a simultaneous frequency-shifted Photon Doppler Velocimetry (PDV) and triature Velocity Interferometer System for Any Reflector (VISAR). This dual setup can accurately measure shock velocities, especially in the low-speed range (<100 m.s^{-1}) and fast dynamics (<10 ns) where measurements are critical in terms of resolution and unfolding techniques. Especially, the direct comparison of both techniques at the same measurement point helps us in determining coherent settings for the Short Time Fourier Transform (STFT) analysis of the PDV, providing increased reliability the velocity measurement with a global resolution of few m.s^{-1} in velocity and few ns FWHM in time. The advantages of such coupled velocimetry measurements are discussed, as well as new opportunities in dynamic materials science and applications [1].

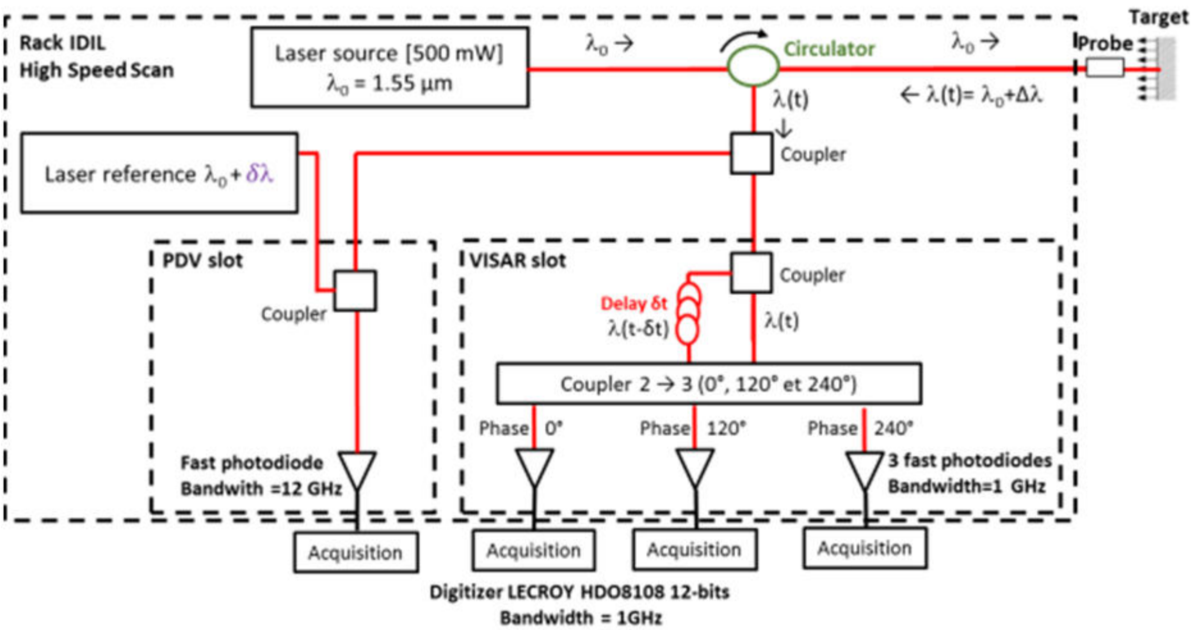

Figure 1: Schematics of our coupled PDV and triature VISAR acquisition system.

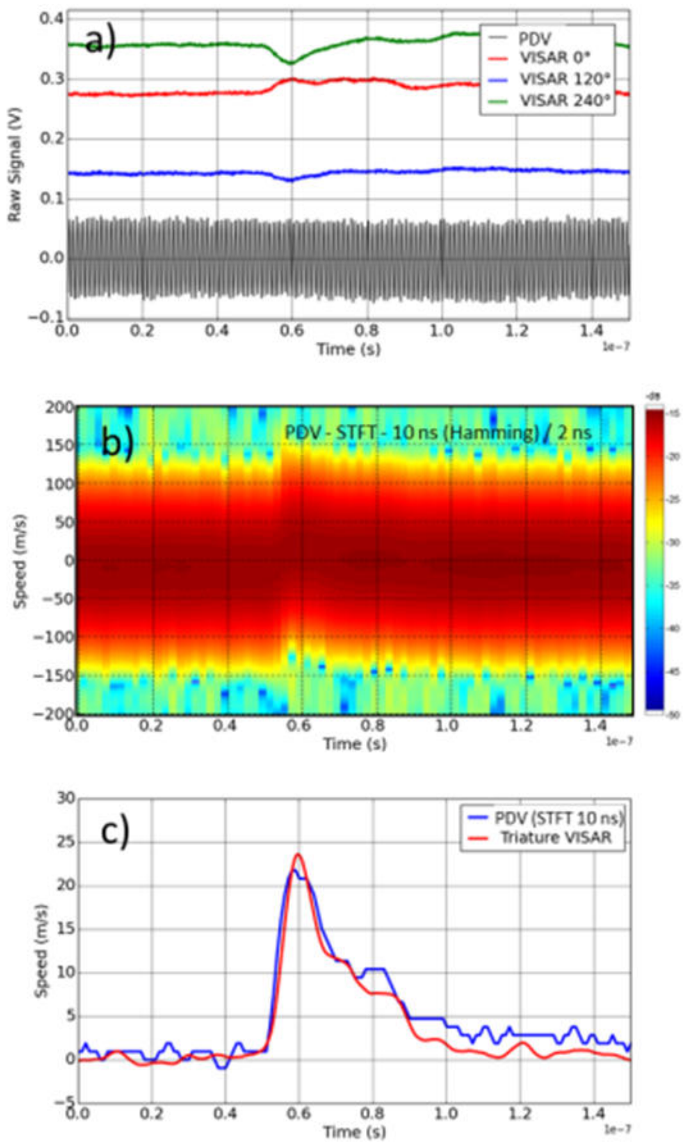

Figure 2: Example of velocity measurements of the rear surface of an Aluminium target irradiated by the BELENOS laser (a) PDV/VISAR raw signals, (b) PDV spectrogram, resulting from an STFT analysis and (c) the derived PDV and VISAR velocities.

In a second section, we present an experimental platform developed on LMJ facility (Laser MegaJoule, CEA Cesta, France) to measure the x-ray-generated stress and impulse in materials using this coupled PDV/VISAR approach [2]. Our platform is very analog to the XTRRA test platform developed at the NIF (National Ignition Facility, Lawrence Livermore National Laboratory, USA) [3].

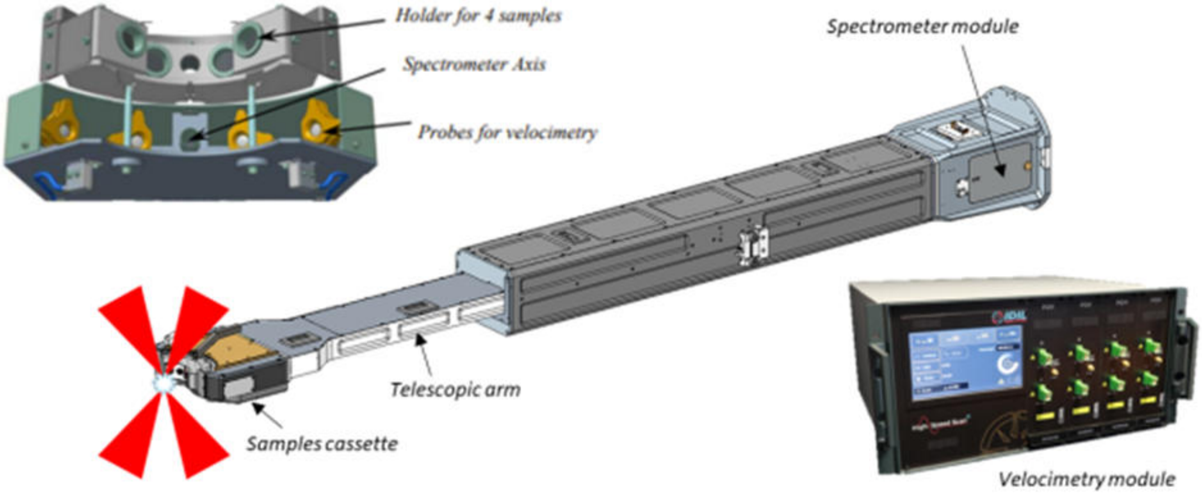

Figure 3: CAD drawings of the LMJ diagnostic dedicated to the study of materials behavior under X-ray irradiation. This device holds four samples in the vicinity of TCC at a distance of 70 or 100 mm. PDV/VISAR channels are connected to the samples; a spectrometer module, made of 4 X-ray diodes with different filters, is used to characterize the X-ray flux which irradiates the samples.

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Active spectro-spatial characterisation of high-energy laser-driven protons

J.K. Patel[1,2], C.D Armstrong[1], R. Pattathil[1], R. Deas[3], R.Gray[2], P. McKenna[2]

[1] *Central Laser Facility, STFC, Oxfordshire, United Kingdom*

[2] *University of Strathclyde, Glasgow, United Kingdom*

[3] *Defense Science and Technology Laboratory, United Kingdom*

High intensity laser-plasma interactions have been demonstrated as a bright source of energetic protons[1]. Next generation laser facilities such as SCAPA and EPAC have the potential to generate these sources at $>$ Hz repetition rates, while 10s PW laser facilities such as ELI-NP and Vulcan2020 will extend energies to 100s MeV[2]. Active spectro-spatial characterisation of these beams is key for validating novel acceleration schemes and suitability for applications in medicine, industry and research.

Recent advances in active proton beam diagnostics enable spectro-spatial measurements of < 10 MeV beams at high-repetition, allowing fine sampling of high-dimensional parameter spaces, and opening the field up to the power of statistical analyses, and machine learning methods. However, technical limitations of differential filtering[3,4,5] and plane scintillator stack[6,7] designs necessarily limit these methods to sparse energy sampling or low bandwidth.

Here, we present an alternative design based on a stacked array of scintillating fibers to encode and compress the spatial and spectral information. Relative rotation between layers enables tomography-like reconstruction of the spatial profile, while each layer yields spectral information as the beam is attenuated. We present initial experimental results, demonstrating operation in high-flux and high-sensitivity regimes, and an outline for scaling to high energies and bandwidth.

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Developing X-Ray Phase-Contrast Imaging for High-Energy Density Hydrodynamics Applications

W. Theobald,[1,2] D. Cao,[2] L. Ceurvorst,[2] J.J. Ruby,[2] L. Antonelli,[3,4] M. Khan,[3] N. Woolsey,[3] V. Bouffetier,[5] A. Casner,[6] D. Batani,[6] F. Barbato,[6,7] O. Turianska,[1,6] and R.H.H. Scott[8]

[1]*Focused Energy, Darmstadt, Germany*

[2]*Laboratory for Laser Energetics, U. of Rochester, USA*

[3]*York Plasma Institute, Department of Physics, U. of York, UK*

[4]*First Light Fusion Ltd., Kidlington, UK*

[5]*European XFEL GmbH, Germany*

[6]*CELIA, U. of Bordeaux, France*

[7]*Department SBAI, La Sapienza Università di Roma, Italy*

[8]*Rutherford Appleton Laboratory, UK*

The application of x-ray phase-contrast imaging in the field of laser-driven high-energy density hydrodynamics is a powerful technique to image and locate shock-front positions in both high- and low-density regions of the target with higher accuracy than in standard absorption-based radiography.[i] It is expected that this technique will provide new physics insights in inertial confinement fusion and high-energy density physics experiments on MJ-class laser facilities such as the National Ignition Facility and LMJ-PETAL. We applied the technique on OMEGA EP to measure the density profile of strong shocks in solid CH targets and to image turbulent flows from hydrodynamic instabilities in CH foam targets. The IR short-pulse beam from OMEGA EP (50 ps, 250 J, ~2×10^{17} W/cm^2) was focused normal on either a 10-μm diameter Cu wire or a 5×30×300 μm^3 strip of Cu foil glued onto a 10 μm thin CH substrate producing ~8.6 keV x rays. The experiment demonstrated a spatial resolution of ~15 μm at sufficiently high photon energies to mitigate the strong x-ray self-emission from the plasma generated by the drive beams. One or two 2-ns, 1250-J, and 351-nm laser beams with an overlapped intensity of up to ~2×10^{14} W/cm^2 generated shock waves in the main target. High-quality radiographs of the shock front with phase-contrast enhancement were obtained for single-shock and double-shock experiments. Initial experiments to apply the technique to spherical implosions are discussed. This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856.

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Predicting the number of pairs emerging from the collision of relativistic electron or photon beams with high-intensity laser pulses

M. Pouyez[1], C. Riconda[1], A. Mironov[1], T. Grismayer[2], A. Mercuri-Baron[1], M. Vranic[2] and M. Grech[3]

[1] *LULI, Sorbonne Université, CNRS, CEA, Ecole Polytechnique, 75255 Paris, France*

[2] *GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal*

[3] *LULI, CNRS, Sorbonne Université, CEA, Ecole Polytechnique, 91128 Palaiseau, France*

The upcoming generation of multi-petawatt lasers provides us with new opportunities for the production of electron-positron pairs. Subjected to an intense electromagnetic field, a high-energy photon can decay into an electron-positron pair, a process known as non-linear Breit-Wheeler. The resulting electrons and positrons can in turn emit new photons via non-linear Compton Scattering which may decay into new pairs, driving a so-called QED cascade.
Modeling the coupling of these two processes is essential to support future experiments. In this work, we predict one of the most important experimental observables: the number of pairs created when a photon or electron beam collides with an ultra-intense laser. Our work builds up on two previous studies. The first one [1] considers electron-seeded cascades, while the second [2] focuses on photon-seeded cascades. Our work first allows to clearly identify the regime of validity of both studies, which we discuss in the light of upcoming laser facilities. It also provides a semi-analytical model, with a broader range of validity that covers all facilities currently under construction, and which allows us to evaluate the number of pairs generated in both type (electron- or photon-seeded) of collisions.

A systematic study using the particle-in-cell code SMILEI [3] shows an excellent agreement with our model predictions. They demonstrate in particular that, considering conditions available at laser facilities that will start operating within this decade, QED cascades develop only over a few generations (2 at most), or cycles of photon emission and pair production. Our results give important insight for the design of forthcoming experiments.

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Simulations of beam-beam collisions with WarpX

A. Formenti[1], R. Lehe[1], E. Zoni[1], A. Huebl[1], J.L. Vay[1], C. Schroeder[1], S. Gessner[2], T.L. Barklow[2], M.J. Hogan[2], M. Peskin[2], G. White[2], C.K. Ng[2], G.J. Cao[2], T. Raubenheimer[2], L. Fedeli[3], H. Vincenti[3]

[1] *Lawrence Berkeley National Laboratory, Berkeley, CA, USA*

[2] *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*

[3] *LIDYL, CEA-Université Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette, France*

The high energy physics community has recently proposed future linear colliders (e.g. electron-positron, gamma-gamma) with center-of-mass energies up to 15 TeV and luminosities up to 50×10^{34} cm^{-2} s^{-1} to be achieved with minimal power consumption [1]. One of the main challenges is to mitigate radiation losses (beamstrahlung) due to beam disruption, namely bending of particle trajectories under the influence of the electromagnetic field provided by the oncoming beam [2]. This requires a satisfactory understanding of the physics at the interaction point for which we need high-performance, high-fidelity modeling of complex multi-physics processes, from collective effects typical of relativistic plasmas to strong-field QED processes [3]. Particle-In-Cell (PIC) codes coupled to Monte Carlo modules offer a robust and flexible computing tool to address a wide variety of physical scenarios relevant in the plasma physics community and beyond [4]. Among them, WarpX is an exascale open-source computing platform that serves as a cross-disciplinary simulation tool for investigations in the fields of particle acceleration, nuclear fusion, astrophysics, and low-temperature plasmas [5].

Here, we present WarpX as a tool for advancements towards the ultimate goal of modeling ultra-high energy linear colliders and, specifically, to provide insights into beamstrahlung mitigation techniques. We detail recent code developments and new 3D PIC simulation campaigns of electron-positron collisions apt to investigate the role and competition between different QED effects (e.g. coherent vs. incoherent pair creation) and the consequent beam disruption and emission at the interaction point depending on the beam parameters. Our results constitute a valuable bridge between the plasma acceleration community and the high-energy physics community, extending the capabilities of PIC simulations as a tool for beamstrahlung calculations.

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Commissioning experiments at the ELIMAIA user beamline

L. Giuffrida[1], F. Schillaci[1], F. Grepl[1,2], M. Tryus[1], S. Stancek[1,3], A. Velyhan[1], V. Istokskaia[1,2], G.A.P. Cirrone[4,1], J. Cupal[1,2], L. Koubikova[1], D. Peceli[1], J. A. Jarboe[1], T. Chagovets[1], V. Kantarelou[1], N. Gamaiunova[1], A. Hadjikyriacou[1,2], T. Levato[1,+], M. Cuhra[1], J. Ridky[1], G. Korn[1], J. Psikal[1,3], M. Tosca[1,5], B. Rus[1], and D. Margarone[1]

[1] ELI–Beamlines Center, Institute of Physics, Czech Academy of Sciences, Dolni Brezany, Czechia
[2] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czechia
[3] Joint Laboratory of Optics of Palacky University, Institute of Physics of Academy of Sciences of the Czech Republic, Faculty of Science, Palacky University, Olomouc, Czechia
[4] Laboratori Nazionali del Sud, INFN, Catania, Italy
[5] Charles University, Faculty of Mathematics and Physics, Department of Macromolecular Physics, Prague, Czechia
[+] Current address: Advanced Material Research Center, Technology Innovation Institute, Abu Dhabi P.O. Box 9639, United Arab Emirates.

The ELI Multidisciplinary Applications of laser-Ion Acceleration (ELIMAIA) beamline is the laser-driven ion target area available at the ELI Beamlines facility (Czech Rep.), which aims to provide a fully characterized and tuneable ion source generated by the HAPLS PW-class laser (>10J in <30 fs), operating at relativistic intensities (>10^{21} W/cm^2) and high repetition-rate (up to 10 Hz) for multidisciplinary applications.

We report on the commissioning of the ELIMAIA beamline with the goal of evaluating the main performances of the system. Using targets of different composition and thickness, the laser-plasma Ion Accelerator section of ELIMAA was optimized and proton cutoff energies beyond 35 MeV and fluxes above 10^{11}/sr/shot were demonstrated.

Moreover, we have demonstrated an excellent performance reliability and shot-to-shot stability (1-2% in cutoff energy) of the Ion Accelerator using a repetition rate of 0.5 Hz for several hundreds of consecutive shots, along with the reliability of the target positioning, data acquisition, and data analysis systems.

Additionally, preliminary results of the commissioning of the ELIMED particle beam-transport system will be shown, demonstrating its effective and efficient control on the proton beam handling and energy selection.

These results demonstrate the robustness of the developed technology available for users at the ELIMAIA beamline, thus paving the way towards its future use for fundamental and applied research, including biomedical ones.

Hole boring and energy transport with kJ petawatt laser light for fast ignition scheme of laser fusion

Y. Sentoku[1], N. Iwata[2], FIREX-NEO team[1]

[1] *Institute of Laser Engineering, Osaka University, Osaka, Japan*

[2] *Institute for Advanced Co-Creation Studies, Osaka University, Suita, Osaka, Japan*

Recently the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) had realized a burning plasma initiating fusion reactions and had achieved an energy gain exceeding 1.0 against the laser energy irradiated on the target. The goal of laser fusion research now moves to the next stage, namely, understanding the burning plasma dynamics and how to make a high gain laser fusion. Fast ignition (FI) scheme is a prospective option for high gain laser fusion. The FI scheme separates steps of the conventional laser fusion, that is implosion and heating. For the implosion by applying a tailored laser pulse as the Kidder's solution, we had demonstrated a high compression of a solid ball instead of a thin shell target, which is unstable hydrodynamically against the non-uniformity of implosion, and heating of the core over 2 peta-pascal energy density by a kJ petawatt laser [Matsuo *et al.* PRL (2020)].

For the ignition scale of FI, we must deliver an energy of 50 kJ to the core in a time scale of a few tens of picoseconds before the imploded core being dissolved. The intensity of ignition laser would then exceed 10^{20} W/cm^2 if the heating laser has 50 um spot diameter and 20 ps pulse duration. Such a huge energy is difficult to construct as just one single laser beam, so that it will be a combination of more than 100 beamlets equivalent to the current state-of-arts kJ petawatt laser, e.g., LFEX, NIF-ARC, LMJ-PETAL. It is an urgent issue to understand the relativistic picosecond laser plasma interaction (LPI) in terms of energy conversion from the laser to nonthermal particles and energy transport in the dense core plasma. In this presentation, we will show the advantageous feature of kJ petawatt LPI for FI.

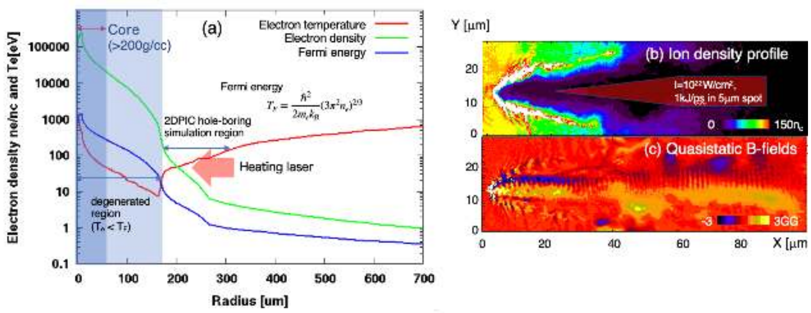

Fig. 1: (a) Density and temperature profiles of the imploded solid ball obtained by a hydrodynamics code, PINOCO. (b) A kJ petawatt laser light is capable of hole-boring in a coronal plasma beyond 100s of the critical density, simulated by a particle-in-cell code, PICLS.

Spatially resolved x-ray emission lines as a signature of electron dynamics in short-pulse solid-density laser-plasma interaction

R. Štefaníková[1,2], S. Assenbaum[1, 2], F. Brack[1], M. Kozlová[1, 3], S. Kraft[1], F. Kroll[1], T. Meric[1, 2], X. Pan[1, 2], I. Prencipe[1], M. E. P. Umlandt[1, 2], H.-P. Schlenvoigt[1], M. Šmíd[1], M. Vescovi[1, 2], U. Schramm[1, 2], K. Zeil[1], J. Metzkes-Ng[1], K. Falk[1, 2, 3]

[1] *Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany*

[2] *Technische Universität Dresden, Dresden, Germany*

[3] *Institute of Physics of the ASCR, Prague, Czech Republic*

Short-pulse high-intensity laser-plasma interaction with solid-density targets is a rapidly developing topic with a number of promising applications such as laser-ion acceleration or backlighters for ultra-fast radiography or x-ray scattering. Challenging questions concerning processes like laser absorption into the target, laser-to-electron energy conversion or hot electron dynamics have not been fully unraveled and are pivotal themes for the work presented here.

In this talk, we present experimental results from DRACO PW laser facility (Ti:sapphire 30 fs laser system), which specializes in laser-driven proton acceleration. We investigated various target systems including Ti foil targets, layered targets, micro-structured targets under different laser incidence angles and laser parameters, i.e. laser energy and contrast. Generated laser-plasmas were inspected not only via x-ray spectroscopy, but also via additional diagnostics, namely electron, proton and bremsstrahlung spectra measurements.

Two x-ray crystal spectrometers with quartz and Ge crystals were employed to study Ti emission lines from front and rear side of the target. Furthermore, 1D imaging of the target rear side was performed via the Ge spectrometer providing lateral information of characteristic x-ray emission. Our data sets show that some target configurations can lead to an increase in K-α production or a change in emission source size. Additionally, we witnessed emission line shifts pointing towards different absorption and heating mechanisms within selected targets. By correlating x-ray spectroscopic measurements with complementary diagnostics key parameters and processes within such laser-generated plasmas and their hot electron populations are investigated.

A fast and efficient model to describe the physics of helical-coil targets

M. Bardon[1,2], A Hirsch[1,2], J G Moreau[1], C Lacoste[1,2,4], E D'Humières[2] et V T Tikhonchuk[2,3]
[1]CEA-CESTA, Le Barp F-33114, France
[2] CELIA, University of Bordeaux-CNRS-CEA, Talence F-33405, France
[3]ELI-Beamlines, Institute of Physics CAS, Dolní Brežany 25241, Czech Republic
[4]INSRS-EMT, Varennes (Québec), Canada
matthieu.bardon@u-bordeaux.fr

Helical-coil targets [1] focus, post-accelerate and bunch proton beams resulting from the TNSA process [2]. This acceleration scheme uses the discharge current [3], generated by the ejection of charges resulting from the laser-plasma interaction, to propagate it in a conductive helix. The propagation of this current produces an electromagnetic pulse (EMP) inside the helix which focuses, post-accelerates and bunches a part of the proton beam. This type of device has been validated in several experiments [1, 4]. This technique is of great interest for many applications ranging from isochoric heating of dense materials to the production of isotopes or neutrons [5].

However, the latest publications on this topic do not show any new increase in performances. In particular, the use of longer helical-coil (>15 mm) does not increase post-acceleration or bunching, as one might have hoped. This is due to the fact that the helix is a dispersive medium. Its capacitance and inductance vary with frequency. The intensity of the current is modulated during its propagation along the helix, and the protons are subjected alternately to accelerating and decelerating, and focusing and defocusing fields. To optimize the geometry of this helix, we have therefore developed an efficient model which makes it possible to model the dynamics of protons and fields inside the helix: this is the DoPPLIGHT code [6]. This code makes it possible to calculate the energy spectrum of the protons at the exit of the helical-coil, and this in 2 minutes on a laptop. I will present this code, and the comparison of the DoPPLIGHT results with PIC simulations and results of experiments that we have conducted on LULI2000 and Apollon laser facilities.

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Simulation and characterization of the interaction of fast quasi-monoenergetic ion beams and deuterium-tritium plasma

J.M. Gil[1], P.R. Beltrán[2], R. Rodríguez[1], G. Espinosa-Vivas[1]

[1] *IUNAT, Physics Department, Universidad de Las Palmas de Gran Canaria, Spain*

2 Instituto de Astrofísica de Canarias (IAC), E-38200 La Laguna, Tenerife, Spain

Fast ignition (FI) scheme was proposed as an alternative to the standard central ignition of inertial fusion targets [1]. FI scheme intends to reduce the drive requirements by separating target plasma compression and ignition. Due to the large divergences and the high energies found in electron-driven fast ignition experiments and simulations [2], ion-driven fast ignition (IFI) has been taking an increasing interest. IFI scheme offers several advantages, such as generation of collimated beams, well known interaction with the plasma and localized hot spot or energy deposition on compressed deuterium-tritium (DT) plasma. On the other hand, the potential of Maxwellian and Gaussian ion beams to heat fusion target plasma at stagnation state has been extensively investigated [3-6]. There are previous studies of the optimal energies or radius beams for efficient ignition, but they do not perform analysis of the relevant properties of the hot spot. Therefore, detailed analysis about the characteristics of the heated region and hot spot are welcome. In this work we present a model for the calculation of the spatial and temporal temperature field of a compressed DT plasma heated by time dependent and independent fast quasi-monoenergetic Gaussian ion beams. Furthermore, from simulations performed on a wide range of ion beam parameters, we carry out an analysis of the generated hot spot. We focus the study on the influence of the characteristic parameters of the quasi-monoenergetic ion beams (particle density, initial mean energy and energy spread) on the spatial temperature field reached by the heated region at the end of the heating process. The main objective of this work is to characterize, as a function of the energy spread of the beams, some relevant properties of the hot spot generated inside the heated region such as length, average temperature, maximum temperature and its position. The results presented in this work were obtained for fully ionized vanadium ion beam in a wide range of ion beam characteristic parameters and for compressed DT plasma conditions of interest in the context of the ion fast ignition scheme.

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Effects of impurities on beam-plasma interaction and hot spots properties in fast ignition nuclear fusion

P.R. Beltrán[1], J.M. Gil[2], R. Rodríguez[2], G. Espinosa-Vivas[2]

[1] *Instituto de Astrofísica de Canarias (IAC), E-38200 La Laguna, Tenerife, Spain*

[2] *IUNAT, Physics Department, Universidad de Las Palmas de Gran Canaria, Spain*

Fundamental research in ion beam-plasma interaction is essential to advance in the understanding of high energy density plasmas. This interaction is expected to occur at a future confinement fusion power plant in the ion fast ignition (IFI) scheme. In IFI, the fusion process is decoupled: the fuel is compressed with a laser system and then a short beam with high energy is focused on one side of the fuel, heating it and starting ignition. Therefore, a precise knowledge of the energy deposition of the beam in the target plasma is required to design this scheme [1]. The small spherical target contains the fuel which is typically made up of deuterium-tritium (DT) although it is possible to find traces of impurities due to the detached components from the ablator material. Therefore, it is a priority to analyze the influence of these impurities in this system.

The aim of this work is to study the interaction between an ion beam and a plasma fuel of DT with impurities and also the resulting heated plasma and its properties. For this purpose, we use a spatial-temporal numerical model to simulate the stopping of an ion beam in a plasma target, as well as the plasma heating process. Three kinds of beams have been considered (p+, C6+ and V23+) in a wide range of kinetic energies and number of particles. The ion beam is assumed as perfectly collimated, cylindrical and monoenergetic with constant flux impacting on a radial direction on the plasma, so the interaction beam-target can be described as 1D [2]. With respect to the plasma, we have considered a compressed sphere of DT fuel with a 50 μm radius, with temperature and density homogeneous distributions, and three kinds of common impurities (C, Cu and Au) at different concentrations. It is assumed that the time of the interaction is considerably shorter than the characteristic hydrodynamic times and thus, the plasma heating can be considered as isochoric. Therefore, the change in the plasma temperature depends exclusively on the energy deposited by the beam projectiles, since the mechanical work and conduction can be neglected [3]. The energy by the beam deposited is obtained in a classical dynamic context by means of the calculation of the stopping power of the plasma [4]. With this numerical model, we calculate the temperature field after the interaction, and we define a region of special interest named hot spot. From the distribution of temperatures, we extract key parameters such as the maximum temperature and its position and the length and the mean temperature (of both the heated region and the hot spot), analyzing the influence of the different impurities and their concentrations in these properties.

Acknowledgments:
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Ionization and recombination cross sections for charge state of argon ions traversing carbon plasmas

José Vázquez-Moyano, Manuel D. Barriga-Carrasco, Alejandra Mendez, Javier Chacón-Gijón

E.T.S.I. Industrial, Universidad de Castilla-La Mancha, E-13071 Ciudad Real, Spain

In this work, we reanalyze the experimental energy loss data of [1], in which energy loss measurements of argon ion projectiles at 4 MeV/u were made as they passed through a carbon plasma. The plasma was created by using 2 laser beams with a wavelength of 532 nm incident on both sides of a thin carbon foil. The estimation of the energy loss of an ionic projectile in a plasma has a quadratic dependence on the charge state of the projectile, therefore a correct estimation of the instantaneous charge state of the projectile is of great importance. For this purpose, we will use our successful model that uses rate equations based cross sections that describe all the processes of losses and electronic captures that the projectile undergoes in its interaction with the plasma, which we have already defined in [2]. In addition to this charge state model, we will use for comparison the semiempirical models of Kreussler [3] and Gus'kov [4]. For the calculation of the stopping power due to plasma free electrons we will use the T-Matrix model as described in [2], while for the calculation of the stopping power due to plasma bound electrons we will use PLASTOP [5]. Finally, the interaction of the projectile with the plasma will be treated in detail, since the plasma parameters are not constant along the projectile trajectory, causing instantaneous variations in the charge state of the projectile, which directly affects the stopping power and the resulting energy loss. By taking into account the changing stopping power experienced by the projectile, the energy of the projectile is updated, which in turn affects all of the above parameters.

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Dependence of neutron fluence rate on discharge current and voltage of compact fusion neutron source applying a ring cathode beam discharge

M. Watanabe[1+], Y. Takahara[2], H. Watanabe[2], A. Fujita[2], Y. Yamagata[2]

[1] *Institute of Quantum Science, Nihon University, Tokyo 101-8308, Japan*

[2] *Graduate School of Quantum Science and Technology, Nihon University, Tokyo, Japan*

[+] Email < watanabe.masayuki66@nihon-u.ac.jp>

1. Introduction

High-energy neutron beams belong to the radiation category. Neutrons have no electric charge, so the penetrability of neutron beams into matter is very high. And the neutron has both particle and wave properties as a quantum. From these reasons, neutron beams are expected to be an effective tool in a wide range of medical engineering, industrial development, and nuclear engineering. However, a compact, high-power, and controllable neutron beam source has not yet been realized. The development of such a neutron source is very important to promote the widespread use of neutrons.

Neutrons can be generated by a nuclear reaction. Inertia electrostatic confinement fusion (IECF) is one of a compact neutron source by a nuclear fusion reaction. The concept of the IECF was first conceived by Elmore[1] and by Hirsch[2]. After that, discharge properties and instabilities of IECF have been reported in the whole world[3-5]. Our experimental device is also one of improved concepts of IECFs. Characteristics of general IECF device are as follows; (1) a simple and a compact, (2) a high controllability of the neutron output, (3) a monochromatic neutron energy and (4) a low cost. In addition, the IECF under development in our research are characterized by (5) a straight type, (6) a high durability of the electrode. In this presentation, the dependences of neutron fluence rate on discharge current and voltage in a compact fusion neutron source applying ring cathode discharge are reported.

2. Experimental device and setup

Figure 1 shows the schematic drawing and the photograph of the IECF device in our resaerch. The experimental device mainly consists of the one ring cathode and two anodes. The ring cathode is located at the centre of the vacuum vessel. Although various size of ring cathodes is prepared, the ring cathode with the inside diameter of ϕ=25 mm and the width is L=20 mm is used in this experiment. Two anodes are located at both side of the ring cathode and are connected to the electrical earth. The ceramics breaks are inserted between the ring cathode and

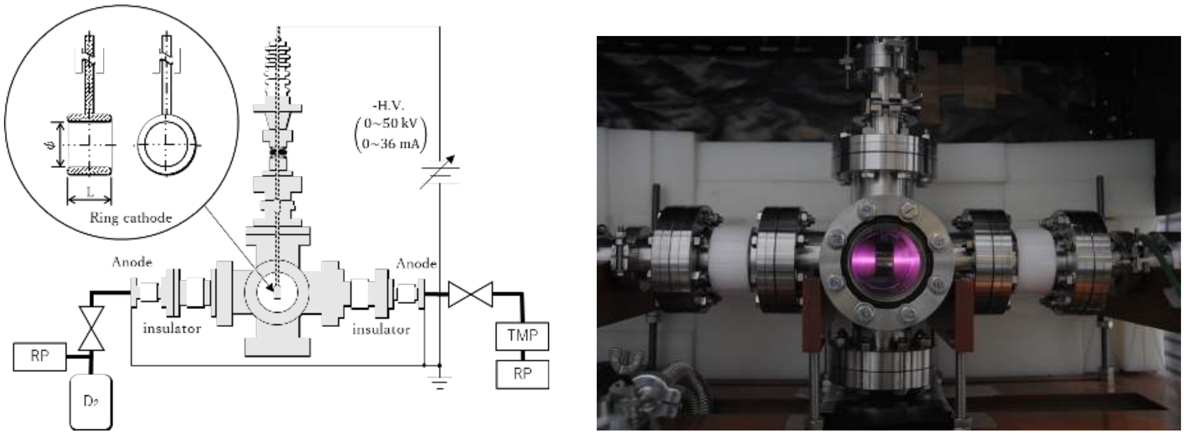

Figure 1: Schematic drawing and photograph of a compact neutron source by a high voltage ring-shaped cathode discharge.

two anodes. The turbo molecule pump creates the high vacuum inside the vacuum vessel and the pressure of deuterium gas is controlled by piezo electric valve. After the evacuation and insert the deuterium gas inside the vacuum vessel, a negative voltage applies to the ring cathode. The formation of a glow discharge can be confirmed between the electrodes. Deuterons in the glow discharge accelerates and converges on the centre of the ring cathode. Consequently, the linear beam plasma discharge is formed as shown in Fig.1 (photograph). Under the condition of the high applied voltage up to the -10 kV, a nuclear reaction begin to enhance around the centre of the ring cathode. The neutron fluence rate was measured by the neutron survey meter. In our currently research, the maximum voltage and current of the power supply are -50kV and 36 mA respectively.

3. Experimental results

Figure 2 shows the dependence of the neutron fluence rate at 15 cm from the neutron source on the applied voltage. We can see that neutron fluence rates rapidly increases with increasing the applied voltage for all discharge current values. The neutron fluence rate is approximately 250 cm^{-2} s^{-1} at the distance of 15 cm from the centre of the ring cathode under the condition that the cathode voltage is -40 kV and discharge current is 20 mA.

Figure 3 shows the dependence of the neutron fluence rate at 15 cm from the source on the discharge current. Here, the discharge current is not the current value of the beam discharge, but that of the glow discharge formed around the ring cathode. We can see that the neutron fluence rate increases almost linearly with increasing the discharge current for all applied voltage values.

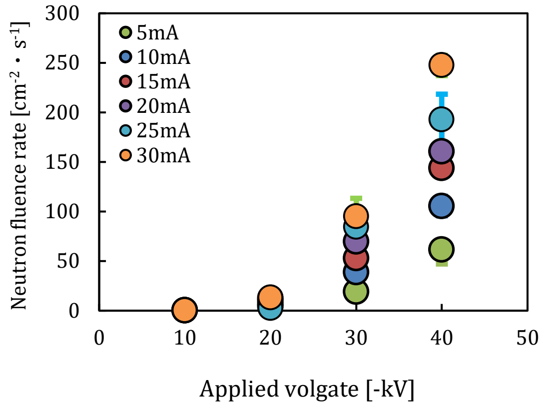

Figure 2: Dependence of neutron fluence rate on applied voltage

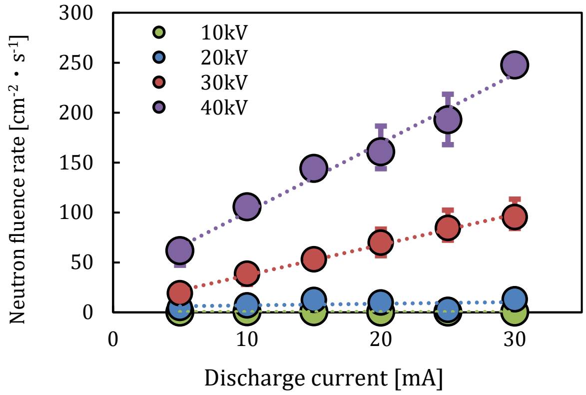

Figure 3: Dependence of neutron fluence rate on discharge current

4. Discussions and Conclusions

As shown in Fig. 2, the neutron fluence rate increases rapidly with increasing the applied voltage was confirmed in this experiment. Here, the kinetic energy of deuterium nuclei in the beam discharge increases with increasing the applied voltage. In the region below 100 MeV of the D-D nuclear reaction, the fusion reaction cross section is known to increase in proportion to the kinetic energy. Therefore, the number of neutrons produced is expected to have increased due to the enhancement of the fusion reaction cross section by the increase in the applied voltage to the ring cathode. The relationship between the kinetic energy and the fusion reaction cross section is explained in detail below. The fusion reaction cross section σ can be expressed as $\sigma = \pi\lambda_d^2\gamma$ with the de Broglie wavelength $\lambda_d = h/\sqrt{2mE_k}$ and the probability of tunnelling effect γ, where h is Planck's constant, m is the mass of the nucleus, and E_k is the kinetic energy. The probability of tunnel effect $\gamma = |\psi(r)/\psi_0|^2$ can be obtained by solving the one-dimensional time-independent Schrodinger equation. By solving the Schrodinger equation for the Coulomb potential, the fusion reaction cross section σ can be derived as follows.

$$\sigma = \frac{\pi\hbar^2}{2mE_K}\exp\left[-\frac{\sqrt{2m}e^2}{4\varepsilon_0\hbar}\frac{1}{\sqrt{E_K}}\right]$$

The fitting equation for the neutron fluence rate in this neutron source was obtained based on the Gamow plot[6]. The results are shown in the following equation.

$$f = \frac{8.87\times10^5}{\sqrt{E_K}}exp\left[-\frac{45.8}{\sqrt{E_K}}\right]$$

Figure 4 shows the predicted neutron fluence rate (solid line) of the discharge current of 10mA when applied voltage is increased to 100kV. Here the relationship between the applied voltage

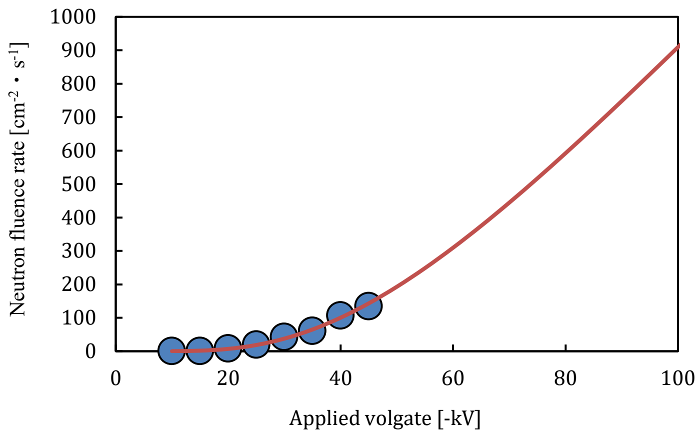

Figure 4: The solid line shows the predicted neutron fluence rate of the discharge current of 10mA when applied voltage is increased to 100kV. The distance from the neutron source is 15 cm.

V and the kinetic energy of the deuterium nucleus is expressed by $E_k = eV$. The prediction of the neutron fluence rate is in good agreement with previous experimental results. However, the dependence in the region of applied voltage above 50 kV needs to be experimentally verified.

As shown in Fig. 3, the neutron fluence rate increases linearly with increasing the discharge current was confirmed in this experiment. When the applied voltage is constant, the kinetic energy of the deuterium nucleus is assumed to be constant. The density of deuterium nuclei in a glow discharge will increases with increasing the discharge current. It was considered that the number of fusion reactions increased as the number of deuterium nuclei increased, and as a result, the neutron fluence rate also increased in proportion to the discharge current.

The dependence of the neutron fluence rate on the applied voltage and discharge current in a compact neutron source with a ring cathode was investigated. The following are the conclusions. The neutron fluence rate increases rapidly with increasing the applied voltage. This increase in the neutron fluence rate is attributed to the increase in the fusion reaction cross section due to the increase in the applied voltage. The neutron fluence rate increases linearly with increasing the discharge current. This increase in the neutron fluence rate is due to the increase in the number of deuterium nuclei in the beam discharge due to the increase in the discharge current.

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The temperature relaxation of dense plasma in a weak magnetic field

M.K. Issanova[1,2], S.K. Kodanova[1,2], T.S. Ramazanov[2]

[1]*Institute of Applied Sciences and Information Technology, Almaty 050438, Kazakhstan*

[2]*Institute for Experimental and Theoretical Physics, Al-Farabi Kazakh National University, Almaty 050400, Kazakhstan*

The physics of short-pulse laser-matter interaction experiments in which high-density, multi-temperature plasmas are readily produced has attracted wide interest [1,2]. Knowledge of energy transfer between electrons and ions is necessary to model target behavior, especially during the relaxation phase following a laser pulse. Such information is also needed to simulate the evolution of the fusion capsule in inertial confinement fusion scenarios. The molecular dynamics (MD) method was used to study relaxation characteristics of ions in the warm dense matter regime in a weak magnetic field. The results of MD simulations within microcanonical ensemble were analyzed by computing the relaxation time and energy transfer of particles. To show the correctness of the model, its results are compared with the results of available results of simulations.

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Investigation of transport properties of dense plasma on the oscillations potential

S.K. Kodanova[1,2], M.K. Issanova[1,2], T.S. Ramazanov[2], G.K. Omiraliyeva[1,2]

[1] *Institute of Applied Sciences and Information Technology, Almaty 050438, Kazakhstan*

[2] *Institute for Experimental and Theoretical Physics, Al-Farabi Kazakh National University, Almaty 050400, Kazakhstan*

The physics of dense non-ideal plasma is important for various applications, such as inertial fusion, laboratory astrophysics, and heated dense matter. Therefore, dense plasma is of fundamental importance and relevance for applications in the development of new technologies, such as laser and ion beams induced by inertial fusion [1]. The transport properties of the ion component of a dense plasma can be calculated directly from molecular dynamics simulations [2]. Various models of the shielded ion potential in plasma have been analyzed [3]. The statically shielded ion potential in dense plasma, taking into account the so-called quantum diffraction effect [3-5]. Recently [6] investigated the effect of oscillations of electronic single particles in an external field on diffusion and viscosity of the ion component of dense plasma.

In this work, the transport properties of dense plasma will be investigated using the oscillatory potential and the molecular dynamics method. The transport properties of the ion component of a dense plasma are investigated on the basis of effective potentials, taking into account the presence of an external alternating electric field. The last creates single-particle oscillations of electrons and significantly changes the sample charge shielding in the plasma. The transport characteristics of a dense plasma at different values of temperature and system density will be determined.

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Kinetic modelling of autoresonant beat-wave excitation of plasma waves

M. Luo[1], A. Grassi[2], C. Riconda[2], J. S. Wurtele[3], T. Fülöp[1]

[1] *Department of Physics, Chalmers University of Technology, Göteborg, SE-41296, Sweden.*

[2] *LULI, Sorbonne Université, CNRS, École Polytechnique, CEA, 75252 Paris, France*

[3] *Department of Physics, University of California, Berkeley, California 94720,USA*

If two co-propagating lasers are detuned from each other by the electron plasma frequency, their beating can resonantly excite a large-amplitude, high-phase-velocity plasma wave. For fixed beat frequency, the peak longitudinal electric field is constrained by detuning effects, the Rosenbluth-Liu (RL) limit [1]. By including a negative frequency chirp in the laser with the higher frequency, an autoresonant phase-locking of the plasma wave to the beat-wave frequency of the driving lasers can be achieved [2]. This scheme can drive plasma waves beyond traditional detuning limits and has several advantages, e.g. insensitive to uncertainties and variations in plasma and laser parameters. Previous investigations of the autoresonant wakefield excitation were performed with fluid models [3], and did not include the kinetic response of the background plasma and the self-consistent propagation of the lasers, which could impact phase-locking during the strongly nonlinear regime.

Here we use particle-in-cell simulations performed with SMILEI [4] to show that autoresonant wakefield excitation with electric fields more than two times above the Rosenbluth limit can be achieved, with a frequency shift that is of the order of a few percent of the laser frequency. The critical value of chirp related to the drive strength for the plasma wave to be autoresonantly excited is found to be similar to that seen in fluid simulations and analytic calculations.

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Ion temperature deduced from double Langmuir characteristics – collisionless theory and comparison with experiments

Ph. Guittienne[1], A.A. Howling[1], R. Jacquier[1], I. Furno[1]

[1] *Swiss Plasma Center, Ecole Polytechnique de Lausanne, Lausanne, Switzerland*

Langmuir probes are very commonly used for electron temperature T_e and plasma density n_e measurements. But can they also be used for ion temperature T_i determination, and if yes to what extent? We show here how a two fluid solution for isothermal and collisionless plasma sheaths can be applied to the analysis of double Langmuir probe characteristics. In this approach, for both ion and electron fluids, the particle flux conservation and the momentum conservation equations are analytically reduced by using the Lambert function, so that both densities and fluid velocities are expressed as functions of the sole electric potential. The determination of radial density, velocity and potential profiles in the sheath can then be obtained by the sole numerical integration of Poisson equation. In a 1D Cartesian geometry, this solution provides an analytical expression for single or double Langmuir probes characteristics at any bias potential. Considering the cylindrical geometry, the model leads to semi-analytical solutions for Langmuir probes, in the sense that iterative numerical integrations of Poisson equation have to be performed to determine an important parameter, the sonic radius R_s, which corresponds to the point where the accelerated species reaches a fluid velocity equal to the thermal velocity. Considering double probes, the cylindrical solution predicts that the ion current will not become saturated for large biasing, in contrast to the 1D Cartesian solution, and as expected from experiments. This effect can be attributed to the increase of the sonic radius with biasing, leading to an enhanced collection area while the particle flux density at R_s remains almost constant. This is actually equivalent to the usual concept of sheath expansion, but without the need of defining a sheath entrance. On the basis of this model, we show how an approximated analytical expression for the double probe characteristic can be established, and used for practical extraction of plasma parameters n_e, T_e and T_i from measurements. From an experimental point of view, we currently use double Langmuir probes for characterization of the helicon plasma generated at the Swiss Plasma Centre on RAID (Resonant Antenna Ion Device). Plasma parameters are also to be measured by means of Thomson Scattering (TS), which is a reliable diagnostic for density and electron temperature, and Light Induced Fluorescence (LIF), for the ion temperature. A comparative study of measurements from double Langmuir probes, TS and LIF is presented.

Dust charging under strong electron depletion

Franko Greiner[1], Andreas Petersen[1]

[1] *Institute for Experimental and Applied Physics, Kiel-University, Germany*

Nanodusty plasmas can be generated by using a reactive mixture of argon and acetylene in a radio-frequency (rf) driven parallel plate reactor. These plasmas can have very high dust densities, up to $6 \times 10^{13}\,\mathrm{m}^{-3}$ at a certain ion density ($n_i = 1 \times 10^{15}\,\mathrm{m}^{-3}$). Due to the high dust density, almost all electrons get bound to the dust, causing a significant depletion of electrons, known as the Havnes effect. This effect may not only affects the plasma production mechanisms but also reduces the charge of the dust particles far from the value predicted by the OML approximation ($q_d = 4\pi\varepsilon_0 a\Phi_f$). To estimate the concrete floating potential (Φ_f) of a dust particle in an electron-depleted plasma, we can use the Constant-Iondensity-Model (CIM)[1], which is incorporated into the dust density wave diagnostics (DDW-D)[2]. This method not only allows us to determine the spatially resolved dust charge but also the ion density and electric field. In the parallel plate reactor, the dust and ion density profiles are typically radially inhomogeneous, resulting in a strong radial variation of the Havnes parameter. The dust charge is dramatically reduced compared to low Havnes parameter (< 2) plasmas. For example, for dust particles with a radius of $a = 200\,\mathrm{nm}$, the OML charge would be $q_{\mathrm{d,OML}} \approx 1500e$, but it is reduced to $q_d < 50e$ due to the Havnes effect.

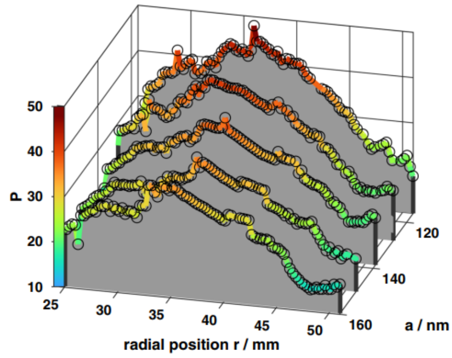

Figure 1: *Havnesparameter P for different dust radii (and dust density) along the radial direction. See Ref. [3].*

Interestingly, despite of a strong deviations in dust densities and size, and at a constant radio frequency heating power, the underlying ion density and plasma potential profiles remain almost unchanged. This suggests that the plasma production processes are decoupled from the dust cloud [3].

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Bispectral analysis of the response of the dust acoustic wave to an external modulation

J. Williams

Wittenberg University, Springfield, OH, United States

A dusty plasma is a traditional plasma system with a third charged species consisting of nanometer to micron sized particulate matter. The presence of this third charged species results in a system that is notably more complex than the traditional plasma system and supports a wide range of physical phenomena, including a wave mode known dust acoustic wave. The dust acoustic wave is low-frequency, longitudinal mode that propagates through the dust component of the dusty plasma system and is self-excited by the free energy from the ion streaming through the dust component. Previous work has shown that the naturally occurring dust acoustic wave will synchronizatize to an external drive can occur under the appropriate experimental conditions. This presentation will focus on the application of bispectral analysis to study the nonlinear interaction between wave modes in the dust acoustic wave in waves response to an externally applied drive at one or two sinusoidal frequencies.

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Measurement of the thermal state at the change in the frequency of polarity switching in the PK-4 Experiment

J. Williams[1], L. Scott-McCabe[2], E. Thomas[3], U. Konopka[3], M. Pustylnik [4], H. Thomas[4]

[1] *Wittenberg University, Springfield, OH, United States*

[2] *Mount Holyoke College, South Hadley, MA, United States*

[3] *Auburn University, Auburn, AL, United States*

[4] *Institut für Materialphysik im Weltraum, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Köln, Germany*

In the PK-4 microgravity laboratory on the International Space Station, particles are injected into a dc glow discharge plasma and flow along an axial electric field. Upon the application of a periodic oscillation of the electric field (polarity switching), a sudden change in the bulk motion of the dust and a change in the spatial ordering of the particles is observed. In some cases, this change in the spatial ordering is accompanied by a redistribution of energy from the bulk (macroscopic) motion to the particle (microscopic) motion and a change in the thermal state of the dust component. This presentation will focus on the analysis of data from the PK-4 microgravity laboratory on the International Space Station examining the thermal state at the onset of polarity switching and as the frequency of the polarity switching is changed. Data from the ISS is compared against numerical simulations.

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Generation of energetic electrons by surface waves in VHF CCPs

D. Eremin [1], E. Kemaneci [1], M. Matsukuma [2], I. Kaganovich[3] , T. Mussenbrock [1], R.P. Brinkmann [1]

[1] *Ruhr University Bochum, Bochum, Germany*

[2] *Tokyo Electron Technology Solutions Limited, Nirasaki City, Japan*

[3] *Princeton Plasma Physics Lab, Princeton, New Jersey, USA*

Capacitively coupled plasmas (CCP) comprise one of the main tools in active use in the plasma processing industry. However, increasing the driving frequency and electrode size is limited by the emergence of plasma radial nonuniformity detrimental for applications. The nonuniformity is caused by interactions of surface waves natural to the plasma-filled reactor [1,2] with electrons of the plasma, leading to the complex electron energization and ionization dynamics. To demonstrate this, we use the fully electromagnetic 2d3v particle-in-cell GPU-parallelized code ECCOPIC2M, described in detail in [3], to simulate the "Testbench B" experiment conducted previously [4].

The code utilizes the implicit charge- and energy-conserving algorithm initially suggested in [5] and adapted for bounded collisional plasmas in [6], then generalized further to 2d cylindrical geometry [7] and a fully electromagnetic model [3]. Such a numerical algorithm does not suffer from the usual limitations on the time step and the cell size (which have to be smaller than the light-wave transit time through a cell and the Debye length, respectively) plaguing the conventional explicit momentum-conserving PIC algorithm. This significantly reduces the net computation time, despite the increased algorithmic complexity.

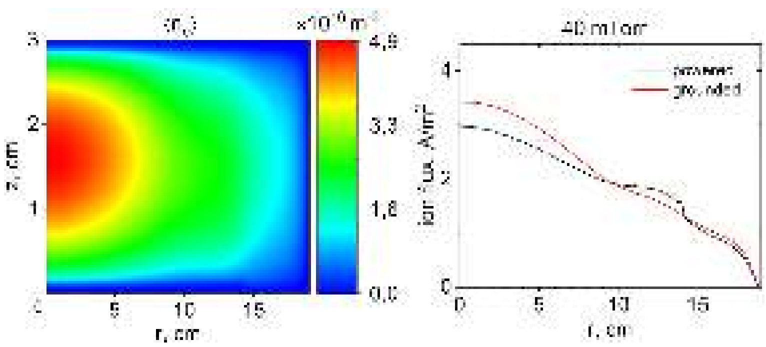

Fig.1: Time-averaged electron density and ion flux radial profiles at the powered and grounded electrodes obtained from a simulation of a CCP discharge in argon at 40 mTorr, driven at 106 MHz and 37 W.

The simulated geometry models an (r-z) cross-section of the cylindrical capacitively coupled reactor. Fig.1 shows the reactor chamber with plasma, which is bounded at the bottom by a powered electrode (r<14 cm) and by a dielectric spacer (14 cm < r < 19 cm), at the side by a grounded wall, and at the top by a grounded electrode. One can see that for a discharge driven at 106 MHz, as indicated in the caption to Fig.1, plasma density has indeed a strongly nonuniform radial profile. Ion flux at the electrodes, which is more relevant for the plasma processing technologies, also exhibits radial nonuniformity, whereas the ion energy distribution is virtually radially uniform at the electrodes (not shown here; for details, see [3]), which is to be expected for conducting electrodes. As demonstrated in [3], this radial nonuniformity is caused by the radial nonuniformity of the ionization source.

Since the ionization is caused by energetic electrons with kinetic energy above the ionization threshold, the ionization rate profile is intimately related to the electron energization, i.e., generation of such fast electrons. On the one hand, this can occur as a result of the collision-dominated Ohmic heating caused by the relatively small energy gains from the electric field on a distance approximately equal to the mean free path. Formation of the energetic electron tail results then from collisional diffusion in energy space. On the other hand, there is an essentially collision-less electron heating mechanism enabling electrons to gain large energy through interaction with the potential barrier of an expanding plasma sheath [8]. Such a mechanism is referred to as the “stochastic” or “pressure” heating and can be enhanced by excitation of the plasma series resonance (PSR) by the sheath motion [9] or by collisions reversing the electron motion, which causes additional collisions with the expanding sheath and lead to further increase in the kinetic energy [10]. At low pressures, the second mechanism can become comparable to or even dominate over the first one.

There are two important aspects related to the electron heating, first being the total energy absorbed by electrons and the second being the energy absorbed per electron. Fig.2, left, shows radial profiles of the total power density absorbed by electrons from the electric field in the bottom (dashed) and the top (dotted) half of the discharge, as well as their sum (solid line).

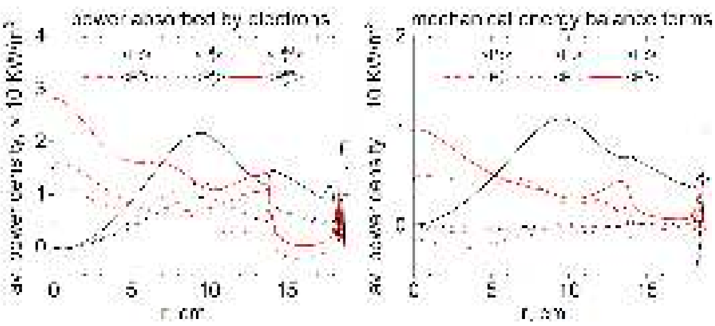

Fig.2: Time-averaged power density absorbed in the radial (black) and axial (red) directions in the top and bottom half of the discharge (left) and its “mechanical energy balance” decomposition [11] (right).

It can be observed that the biggest difference is demonstrated by the radial profiles of the total power density absorbed by electrons from the radial and the axial electric field. The former peaks close to r = 10 cm and is small close to the center, while the latter peaks at the center and falls down to the edge. Recalling the centrally peaked radial profiles of the electron density and the ion flux, one can conclude that it is the electron heating in the axial direction that is responsible for the observed radial nonuniformities. One can note that electrons are similarly heated in different discharge halves, except region above the dielectric spacer and the difference between the power density absorbed in the axial direction close to the powered electrode's edge (9 cm < r < 14 cm).

Fig.2, right, plots different contributions in the "mechanical energy balance" analysis [11]: the pressure, the inertial, and the Ohmic terms. Evidently, electron heating in the radial direction is by far dominated by the Ohmic term, whereas in the axial direction both pressure and Ohmic terms are significant. The difference can be attributed to the various heating mechanisms: whereas in the radial direction it is mostly of the Ohmic nature and reflects profile of the fundamental radial eigenfunction [1,2], in the axial direction the heating occurs to a significant degree due to the interaction with the electric field of the expanding sheath, which accelerates electrons towards the bulk. As argued in [3], such an interaction energizing electrons often occurs predominantly at the fundamental harmonic of the driving frequency if the latter is not very high and the driving field amplitude is not very large, so that no significant excitation of higher harmonics happens. Otherwise, higher harmonics can substantially contribute to the generation of the energetic electrons.

As far as the electron energization is concerned, it is more important to know how much energy is absorbed per electron, rather than the total energy absorbed by the whole electron population. Fig.3 shows that, despite comparable total absorbed power at the center and the edge, a lot more energetic electrons with energy above the ionization threshold are produced close to the center. Again, this can be attributed to the very high efficiency of the electron energization due to the axial sheath expansion, which can be enhanced due to the excitation of higher surface modes and due to the fact that a surface wave, which is excited at a periphery and propagates towards the center, grows in amplitude due to the energy conservation.

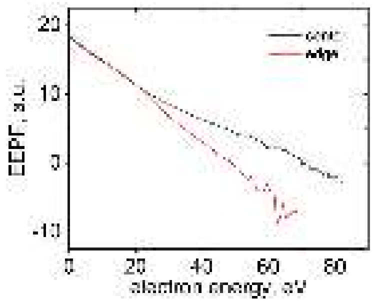

Fig.3: Electron energy probability function obtained from the described simulation, sampled at the discharge center (black) and the edge of the powered electrode (red).

An indirect indication of such a phenomenon seems to be observed in Fig.4, where a population of energetic electrons is produced as a result of the surface wave excitation at r = 8 cm. It can be seen that the density of energetic electrons is higher at the center. One can also see how the electrons are successively produced as the corresponding surface wave propagates towards the center. The resulting beam of energetic electrons propagates axially towards the bulk, taking place in the ionization events and only weakly decreasing in intensity. The reason is that the electron mean free path in Ar at 40 mTorr and 10 eV is approximately 3 cm, which is equal to the electrode distance.

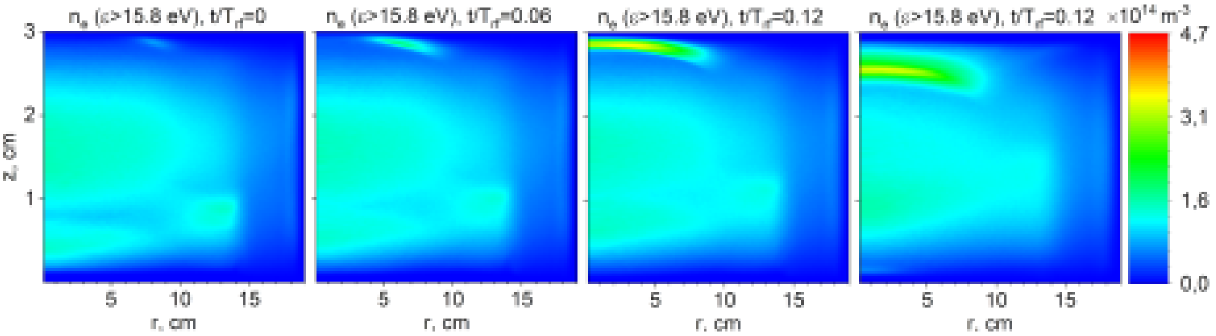

Fig.4: Evolution of an energetic electron population at the grounded electrode as a result of the excitation of surface wave at r = 8 cm, shortly before t=0.

One can see that the underlying physics involves an interplay of different phenomena and requires a self-consistent, kinetic, nonlocal, and electromagnetic description, which takes into account the finite electron inertia effects. We believe that the implicit energy-conserving electromagnetic PIC/MCC code utilized in this study fully meets all these requirements.

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Modeling of Plasmadynamic System with Fast Electrons

I. Litovko[1], A. Goncharov[2], V. Maslov[3]

[1] *Institute for Nuclear Research NAS of Ukraine, Kyiv, Ukraine*

[2] *Institute of Physics, Kyiv, Ukraine*

[3] *NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine*

The problem of filtering microdroplets from a plasma flow dates back more than a dozen years and has not yet been fully resolved. Existing filters and methods for removing the microdroplet phase from the working stream are based on the removal of the droplet phase substance from the stream. This approach leads to significant losses in the performance of the process. An alternative method consists in using the fundamental principles of plasma optics to build a filtration system that is not associated with the removal of the droplet substance from the flow, but on the contrary, with the addition of this substance to the flow, thereby increasing the synthesis performance coatings. The main idea is to effectively destroy microdroplets in a plasma flow passing through a plasma-optical system by a high-energy electron beam, which is self-consistently formed near the inner cylindrical surface of the system and injected along the radius towards the axis. This principle of ion-plasma flow filtration will make it possible to obtain high-quality coatings of any thickness without losing the productivity of the technological process.

This paper presents the results of modelling a plasma dynamic system with fast electrons. A plasma lens is considered as such a system, the central electrode of which is supplied with a negative potential of 2 kV. It is shown that self-consistent formation of fast electrons occurs in such a system due to secondary ion-electron emission from the inner cylindrical surface of the gas-discharge system by the plasma flow passing through this system. It is shown that the presence of fast electrons in the plasma volume introduces additional energy for efficient evaporation and removal of microdroplets from the plasma flow. Based on the energy balance equations, it is shown that the electron beam contributes to the rapid heating of the drop to the boiling temperature and promotes the evaporation of the droplets. It is shown that the plasma heats up under the influence of the beam, even taking into account the fact that the electrons and ions of the plasma lose energy for the evaporation of microdroplets. It is shown that small microdroplets evaporate more intensively.

Spectroscopic investigation of improved plasma density in capillaries with different cross-sections for LWFA

Alamgir Mondal[1], Konstantin O. Kruchinin[2], Petr Zimmermann[1], Eugene Vishnyakov[1], Sebastian Niekrasz[1], Srimanta Maity[1], and Alexander Molodozhentsev[1]

[1]*Extreme Light Infrastructure ERIC, Za Radnici 835, 25241 Dolni Brezany, Czech Republic*
[2]*High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan.*

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Plasma produced by an electrical discharge in a narrow gas channel has a special radial density profile which plays an important role in Laser Wake-field Accelerators (LWFA). A controlled density distribution along the capillary length, as well as at the cross-section, can help to increase the length of laser-plasma interaction much longer than the Rayleigh length.

In this study, plasma has been produced using a high voltage ($\sim$ 25 kV maximum) electrical discharge in two H_2-filled 10 mm long sapphire capillaries having square cross-sections of 500 μm and 300 μm. Experiments have been carried out for both capillaries as a function of different gas pressures inside capillary and discharge voltages to get tailored plasma density profiles suitable for a Free Electron Laser development project - LUIS at ELI-Beamlines in the Czech Republic. Temporal and spatial profiles of plasma density along the capillary, as well as at the cross-section, have been measured using spectroscopic method from Stark-broadened hydrogen H_α and H_β lines. A wide range of plasma densities have been produced and controlled by different experimental input parameters. The length of the peak density in the middle of the plasma channel and the density gradients near the entrance and exit of the capillaries have been compared for both capillary cross-sections. Estimation of plasma temperature inside the capillary has also been attempted from H_α and H_β lines using Boltzmann relation.

Here we present an overview of the experimental setup, instrumentation, plasma diagnostics, and experimental results from the studies carried out to improve the plasma density profile suitable for LWFAs. This work was supported by the project "Advanced Research using High Intensity Laser produced Photons and Particles" (ADONIS) (CZ.02.1.01/0.0/0.0/16_019/0000789) from European Regional Development Fund (ERDF).

Turbulent dynamics around a cylindrical plasma torch with a two-temperature model

J.A. Alcusón[1], N. Mendoza[1], M.E. Morsli[2], J. Muñoz[1], R. Rincón[1] and M.D. Calzada[1]

[1] *Laboratorio de Innovación de Plasmas, Universidad de Córdoba, Spain*

[2] *Plasma Processing Laboratory, McGill University, Montreal, Canada*

Analysis of the relevant parameters to characterize the turbulent transport regimes around a generic cylindrical plasma torch (microwave generated plasmas) with a multi-species (ions and electrons) two-temperature model [1] and an extended electromagnetic field. The TIAGO (*Torche à Injection Axiale sur Guide d´ Ondes*) plasma-torch has reported interesting results on the graphene production with atmospheric pressure Argon plasmas [2]. The accumulation/deposition of the carbonic material on the reactor walls is not modeled or understood yet, but has shown important connections with the turbulent transport and the associated circulation particle fluxes at microwave plasma experiments [3]. As a first approach for a TIAGO plasma torch modeling [4], the temperature evolution and the circulation of particles inside a general cylindrical reactor is investigated. Regimes of turbulence are studied considering different sources, plasma heat & particle fluxes, geometries and temperatures. We implement a two temperature model [1] in the commercial software FLUENT [5] and use a Renormalization-Group-based $k-\varepsilon$ turbulence model [6] to solve transport & Maxwell equations extending the computational domain of the electric fields beyond the plasma domain. This approach constitutes the first TIAGO-plasma torch modeling with a commercial software which ensures an user friendly environment and expands its possible application outside of the academia[1].

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Diagnosing Plasma Electronegativity using Electron and Ion Saturation Current Ratio

P. Singh[1], S. Dahiya[1], A. K. Pandey[1], S. Karkari[1]

[1] *Institute for Plasma Research, A CI of Homi Bhabha National Institute, Gandhinagar, Gujarat-382428, India*

Negative-ion-containing plasmas have wide range applications in plasma processing. Since negative ions have a higher recombination efficiency than positive ions, they are proficient at generating a MeV range of neutral beams for auxiliary heating of the tokamak plasma up to fusion requirements. Negative ions have a mass comparable to positive ions and have the same electric charge as electrons. Thus, their presence in the discharge significantly impacts global plasma parameters, charge particle transport, and particle loss towards the walls [1].

Conventionally, the laser photo-detachment technique (LPD) combined with a Langmuir probe or hairpin probe (HP) is used to diagnose the electronegative plasma [2,3]. However, this technique is limited to in-line laser beam measurements [4]. Negative ions can also be diagnosed from the electron-to-ion saturation current ratio (SCR) using a simple Langmuir probe. Due to the confining field for electrons, the stagnated negative ions in the bulk plasma significantly alter the positive ion flux at the sheath edge. Therefore, SCR reduces with the increase in negative ion density. This reduction, however, is also observed in pure electropositive argon plasmas. This anomaly is perhaps attributed to the expanding ionic sheath with negative bias, ground sheath resistance, and inaccurate determination of plasma potential.

Consequently, the present work aims at addressing various limitations associated with the SCR method and investigate the applicability of this method. This work suggests a hairpin probe-assisted SCR approach for an accurately determining negative ions.

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Performance of RF Compensated DC Biased Hairpin Probe in an Electronegative CCRF Discharge

Swati Dahiya[1], Pawandeep Singh[1], Avnish K Pandey[1], Nishant Sirse[2] and Shantanu K Karkari[1]

[1]*Institute for Plasma Research, A CI of Homi Bhabha National Institute, Bhat, Gandhinagar382428*

[2]*Institute of Science & Research and Centre for Scientific & Applied Research, IPS Academy, Indore-452012, India*

Email: dahiyaaswati@gmail.com

A *hairpin resonator probe (HP)* is an electromagnetic resonator popularly used to measure absolute electron density in low-temperature plasmas [1]. It is a parallel wire transmission line, with one end shorted, such that the characteristic length of the line is equivalent to the quarter wavelength. Typically the resonance frequency is on the order of a few GHz, and it is inversely related to the dielectric medium in which the probe is immersed. The resonance frequency shifts upwards when introduced in the plasma since the plasma dielectric is smaller than in the vacuum. In an ideal case, the separation between the probe pins is more significant than the sheaths formed around the probe pins. Therefore the electron density is calculated by noticing the shift in the resonance frequency. However, it is observed that a thicker sheath around the hairpin affects the accuracy due to electron depletion around the probe surface. This limitation can be circumvented by applying sheath correction, which is possible by applying an external DC potential to the hairpin probe [2]. This method has been demonstrated in the case of DC plasma [3]. However, in capacitive-driven RF discharge, the plasma potential oscillates with the applied RF voltage. It leads to forming a DC sheath around the hairpin due to sheath rectification. We propose a DC-biased hairpin probe with an RF-compensated circuit constructed very close to the probe tip to overcome this limitation. Application of the probe has been demonstrated in 13.56 MHz CCRF discharge in oxygen and argon. The results obtained are compared with an uncompensated DC-biased hairpin probe.

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Centrifugal instability in a weakly magnetized bounded plasma column

S.Aggarwal[1], Y. Camenen[1], A. Escarguel[1], A. Poyè[1]

[1]Aix-Marseille University, CNRS ,UMR 7345, PIIM, Marseille, France

Understanding the formation of large-scale structures in weakly magnetized plasmas is of particular interest for both fundamental research and technological applications like magnetron sources, Penning discharges, negative ion sources, and Hall thrusters. A canonical configuration for the study of weakly magnetized plasmas is a cylindrical plasma column immersed in an axial magnetic field. MISTRAL is such a linear magnetized plasma column device based at the PIIM laboratory used to study ExB plasmas with magnetized electrons and weakly or not magnetized ions. The MISTRAL plasma has been characterized experimentally [1]-[2] with several diagnostics (Langmuir probe, fast camera, emission spectroscopy). Coherent structures rotating in the azimuthal direction have been observed in MISTRAL rotating at a frequency comparable to the ExB rotation frequency with azimuthal wave number m = 1, 2. However, the cause of the formation of these rotating structures is still not fully understood.

Our goal is to complete the characterization of the observed instabilities along with the theoretical modeling to understand the origin of coherent structures in MISTRAL. Most of the models formulated so far to study ExB plasmas are based on low-frequency approximation (LFA) which is valid when the instability frequency (ω) and the plasma azimuthal frequency (ω_0) are small compared to the ion cyclotron frequency (ω_{ci}). This assumption is challenged in many laboratory plasma devices including MISTRAL.

The linear stability of MISTRAL plasma has been explored by extending the two-species fluid model developed in [3] to obtain a radially global dispersion relation valid at arbitrary frequency values [5]. The validity domain of the LFA has been discussed by comparing the solutions obtained using the dispersion relations with and without LFA. In addition, the impact of radial boundary on the growth rate and perturbation frequency of the instability has been studied. The comparison of the radially local solution of the dispersion relation [4] to the global solution indicates that rotating plasmas subject to centrifugal instability like MISTRAL, require a non-local treatment taking the boundary into account. The instability's growth rate is found to be strongly dependent on the equilibrium azimuthal flow ω_0, which in turn depends on the ExB flow and the diamagnetic flow. No instability is predicted for $\omega_0 = 0$. For fixed ω_0 and density gradient, the azimuthal mode number m and the radial boundary limit are found to be the dominant factors affecting the growth rate. As the stability mechanism of weakly magnetized plasma systems can be highly influenced by ion-neutral collisions, an extension of the fluid model to include ion-neutral friction is presently in progress.

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Picosecond two-photon absorption laser induced fluorescence measurements of atomic hydrogen in fusion relevant plasmas

M. Baquero-Ruiz[1], L. Kadi[1], Ph. Guittienne[1], R. Jacquier[1], C. Stollberg[1], R. Karimov[1] and I. Furno[1]

[1] *EPFL, Swiss Plasma Center (SPC), Lausanne, Switzerland*

Atomic hydrogen (H) dynamics plays a crucial role in several areas of fusion research. Despite its importance, measurements of H densities in plasma conditions relevant to fusion are nonetheless scarce due to the difficulty in accessing the regions of interest within the experimental devices, and the complexity of the atomic and molecular processes involved.

In this context, we have recently designed and installed a two-photon absorption laser induced fluorescence (TALIF) system using a picosecond (ps) laser beam [1] in the Resonant Antenna Ion Device (RAID) which allows absolute, spatially-resolved, probing of H densities (n_H) and temperatures (T_H) in helicon hydrogen plasmas with $n_e \approx 10^{17}$ - 10^{19} m^{-3} and T_e = 1-10 eV at neutral pressures $p_n \geq 0.4$ Pa. These conditions are favorable to volumetric generation of H^-, of potential interest for neutral beams [2]. They also constitute an interesting proxy to scrape-off layers (SOLs) in tokamaks, thereby allowing validations of codes like SOLPS-ITER which are used to model the SOL of present devices like TCV [3] and future ones like ITER.

One of the crucial features of TALIF on H is the simplicity of the modeling required to interpret the fluorescence signal and obtain n_H and T_H. Nevertheless, the fluorescence branching ratio, which has a value close to 1 in low density plasmas, may significantly change under high electron density conditions due to the increase of competing depopulation mechanism rates. In that situation, the determination of n_H must correctly account for the lower branching ratio [4].

We present a series of measurements of n_H at varying plasma conditions in RAID that include corrections due to changes in the fluorescence branching ratio. These results illustrate the potential as well as possible limitations of this technique to diagnose fusion relevant plasmas.

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Energy partition in collisionless shocks: a microphysical perspective

F. Fiuza[1,2]

[1] *SLAC National Accelerator Laboratory, Menlo Park, USA*

[2] *Instituto Superior Técnico, Lisbon, Portugal*

Astrophysical shock waves are among the most powerful particle accelerators in the Universe. Generated by violent interactions of supersonic plasma flows with the interstellar or intergalactic medium, shocks are inferred to heat the plasma, amplify magnetic fields, and accelerate electrons and protons to highly relativistic speeds. However, the exact mechanisms that control energy partition in shocks remain a mystery. This is particularly challenging for high Mach number shocks, such as those associated with supernova remnants, where spacecraft data in the relevant regime is scarce and the shock structure cannot be directly resolved from observations. I will discuss recent progress in using the combination of fully kinetic simulations and laser-driven laboratory experiments to study energy partition in high-Mach number collisionless shocks. In particular, I will present results on magnetic field amplification, plasma heating and particle acceleration, and discuss how experimental measurements are helping benchmark models of the shock microphysics.

[1] Institute for Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, e.V., 01328 Dresden, Germany
[2] Department of Mechanical and Aerospace Engineering, University of California San Diego, La Jolla, CA 92093, USA
[3] Institute for Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, e.V., 01328 Dresden, Germany

Electric-Magnetic suppression effect of bremsstrahlung in high power laser-plasma interactions

M. Habibi[1], A.V. Arefiev[2], T. Toncian[3]

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Numerous quantum electrodynamics phenomena rely heavily on ultrarelativistic charged particles and strong magnetic fields. In a novel regime of laser-matter interactions known as relativistically induced transparency (RIT), it is anticipated that recently commissioned high-power laser facilities will be able to achieve such extreme conditions. In this regime, a high-intensity laser pulse can penetrate deeply into a dense plasma due to the relativistic motion of the electrons, as the plasma's optical properties change. This profound laser pulse penetration enables unprecedented particle acceleration in the dense plasma, producing strong magnetic fields [1, 2, 3] as well as emitting Bremsstrahlung, one of the most critical processes for producing impulsive photons. However, depending on the interaction's environment factors, such as magnetic fields, bremsstrahlung cross-sections can vary dramatically, resulting in significant emission suppression [4].

This study aims to quantify the suppression of bremsstrahlung in high-intensity laser-plasma interactions involving strong magnetic fields. Such interactions necessitate the presence of both electric and magnetic fields; consequently, we have expanded the analysis employed for the magnetic suppression to incorporate a strong electric field. To evaluate the suppression effect consistently, we have upgraded the standard bremsstrahlung module of the EPOCH particle-in-cell code [5, 6] to include the effect of electric and magnetic fields. Using this module, two-dimensional PIC simulations have revealed that the bremsstrahlung emission within laser-irradiated plasma can be significantly suppressed, with the total emitted energy for some electrons decreasing by as much as 30 percent.

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Boosting electron emission from liquid droplet microplasma

Sonali Khanna[1], Ratul Sabui[1,3], Deepak Kumar Sahu[2], Angana Mondal[2],
Sourabh Singh[1], Haritha Venugopal[3], Gaurav Rajput[1], Ram Gopal[1], M. Krishnamurthy[1,2,*]
[1] Tata Institute of Fundamental Research Hyderabad, Telangana, India.
[2] Tata Institute of Fundamental Research, Maharashtra, India
[3] Indian Institute of Technology Hyderabad, India
∗ mkrism@tifr.res.in

Abstract: Laser plasma interaction is table-top source of high energy electrons, ions, electromagnetic radiation ranging from THz to X-rays. Bright particle beam and source size of µm order has potential applications in wide range of contexts, from medical physics to defence and many other industries. To make the source viable for many applications production of high energy electrons with high repetition rate of laser that can be handled by non-experts is necessary. The recent developments from our group have shown that structural modification of microdroplets with the help of pre-pulse provide efficient environment for two plasmon decay (TPD) instability growth and boosts electron acceleration to MeV energies even at intensity of 10^{16} W/cm^2 with 1kHz Titanium Sapphire laser. However, according to intensity scaling law for hot electron temperature, temperature of MeV is expected at an intensity of 10^{18} W/cm^2 having repetition rate of few Hz only. Therefore, two orders of magnitude intensity threshold reduction is obtained with the help of TPD instability. In this work, we studied the effect of bandwidth, pulse-width by changing the chirp of pulse and measuring electrons spectrum and wavelength dependence is studied by changing wavelength using Optical Parametric Amplification to check its feasibility with MHz lasers which have a shorter bandwidth, longer pulse width and longer wavelength.

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Light olefin production with controllable selectivity by plasma process

Y-N. Kim[1], CM.Jung[2], DH.Lee[3]

[1 2 3] *Korea Institute of Machinery and Materials, 156 Gajeongbuk-Ro Yuseong-Gu, Daejeon, Republic of Korea*

Text of the contribution.

1. Introduction

Light olefins are significant raw materials in downstream chemical industry. Main process for light olefin production is thermal cracking of hydrocarbons such as light naphtha in the presence of steam. The thermal cracking process is the most energy intensive process in petrochemical industry and cause high amount of CO_2 emission [1,2]. However, this half of century used industrial process is being asked to change due to the recent climate change and strong demand for CO_2 emission suppression. Here, we demonstrated an environmentally benign way for the light olefin production by using plasma. The plasma process can provide enough thermal conditions for conversion of feedstock to light olefin from renewable electricity. Also, several kinds of different compound having same carbon number were compared as feedstock for olefin production in order to reveal the effects of molecular structure. In results, this work shows that electrified plasma process can produce highly selective light olefins having flexible range depending on operation conditions and molecular structures.

2. Experimental

The mixed gases for plasma discharge and the reaction are injected to the reactor having swirl flow. The feed for the olefin production is injected by syringe pump as a liquid phase. The feed and product gases are analysed by online GC-MS(5975C model, Agilent 19091P-K33 column, Agilent Technologies) and microGC(990 Micro GC, MS5A SS and PoraPLOT U FS columns, Agilent Technologies) using sample bag. In the GC-MS analysis method, the oven temperature started at 343.15 K and was raised to 463.15 K at a ramping rate of 293.15 K, followed by holding for 15 minutes. In the case of microGC, the analysis method was injector temperature 373.15 K, back flush time 11 s, column temperature 353.15 K, initial pressure 100 kPa for the first channel, and injector temperature 373.15 K, back flush time 7 s, column temperature 373.15 K, initial pressure 150 kPa for the second channel.

3. Result and Discussion

Fig.1 shows the selecitivty of C_1-C_4 products depends on flow rate of liquid hydrocarbons. The selectivity was calculated as following equations.

$$Selectivity_{C_xH_y}(\%) = \frac{x \times moles\ of\ C_xH_y\ produced}{z\ \times moles\ of\ C_z\ converted} \times 100$$

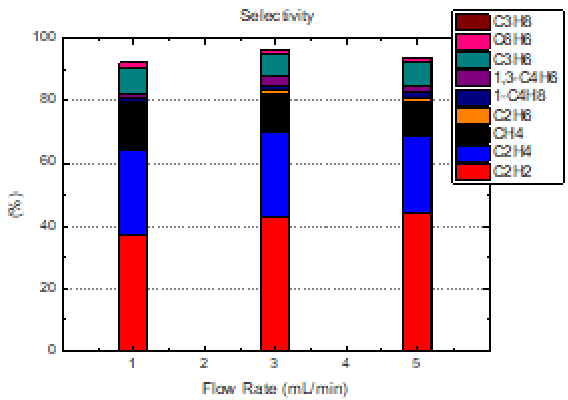

Fig. 1. Product selectivity of light olefins.

In this graph, the ethylene selectivity is range from 20 – 30% depending on the flow rate conditions. Especially, the selectivity of propylene is almost 10%. In results, more than 30% selectivity of C_2-C_4 olefin are produced. Moreover, ethylene selectivity can be increased about 40% by simple hydrogenation process of acetylene. As considered light olefin selectivity (C_1-C_4) of conventional thermal cracking process and previous researches, this potential selectivity for light olefins is extraordinary. This study shows the feasibility of light olefin production process with high selectivity by electrified way using plasma.

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Collisionless shock acceleration in tight focused laser driven exponential density profile target

Q. Moreno-Gelos[1], S. H. Zhai[1], O. Klimo[1,2], S. Weber[1,3]

[1] Extreme Light Infrastructure ERIC, ELI Beamlines Facility, Dolní Břežany, Czech republic

[2] FNSPE, Czech Technical University in Prague, 11519 Prague, Czech Republic

[3] School of Science, Xian Jiaotong University, Xian, China

Solid targets irradiated by high-intensity laser can lead to several well-known ion acceleration processes [1]. In an experiment, the laser pre-pulse interacts first with the thin target, leading to its expansion and a modification of its density profile [2]. The main laser pulse interacts thus with a target much larger and dilute which presents a density gradient.

Laser interaction with a non-homogenous target density profile, which can vary from under to over critical density, is primordial to understand the several ion acceleration mechanisms taking place during an experiment.

We perform 2D particle-in-cell (PIC) simulations of a Gaussian laser pulse irradiating a CH target, which presents a logarithmic density profile from both sides. The laser dugs an electron cavity through the target building an electrostatic piston [3] and accelerates the ions. The ion acceleration can become large enough to launch a collisionless shock into the target leading to specular reflection at the shock front toward the direction normal to the cavity. These ion acceleration mechanisms at the front side target are well captured by our analytical model where some preferential angles of acceleration are predicted. When the laser break through the peak of target density new mechanisms like break-out afterburner BOA acceleration [4] start to appear at the target rear side, coupling with the previous acceleration mechanisms and letting the ions reach even higher energy.

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Ultrahigh-Pressure Generation in the Relativistic Transparency Regime in Laser Irradiated Nanowire Arrays

J. F. Ong,[1] P. Ghenuche,[1] and K. A. Tanaka[1]

[1]*Extreme Light Infrastructure - Nuclear Physics (ELI-NP), "Horia Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului Street, RO-077125 Bucharest-Măgurele, Romania*

Abstract

The ultrahigh pressure using laser-irradiated nanowire arrays has been relying on nanoscale z-pinch. There have been experiments and simulations on these topics by using a laser with intensities $a_0 = 10 - 34$. However, the pressure generation at higher intensities may differ when different regimes are involved, which includes the associated magnetic instabilities. In addition, the plasma pressure generated by the z-pinch is not only limited by the magnetic instabilities as previously thought, but also by the return current. Here, we demonstrate via three-dimensional particle-in-cell simulation (3D PIC), that other mechanisms can generate pressure higher than z-pinch and suppresses the magnetic instabilities. We found that the plasma undergoes density modulation inside the laser field with a pressure of more than 10 Tbar when the plasma is transparent. These plasma layers have a separation of half laser wavelength and the modulation persist over the duration of the laser pulse. At these intensities, the influence of the magnetic instabilities and return current to the ultrahigh pressure generation is no longer the bottleneck. The demonstration of pressure generation higher than the laser-induced z-pinch mechanism could substantially advance the physics of high pressure, especially high-power laser facilities that could provide such intense laser pulses are currently available. These understandings open up a new perspective in the studies of micro-fusion, warm dense matter, and extending the equation of state research to the sub-exabar regime.

Modelling electron deflectometry measurements of magnetic fields in ultrahigh-intensity, femtosecond laser-foil interactions

S. Passalidis[1,2], S. Corde[3], X. Davoine[1,2], M. Gilljohann[3], O. Kononenko[3], Y. Mankovska[3], P. San Miguel Claveria[3], L. Gremillet[1,2]

[1] *CEA, DAM, DIF, 91297 Arpajon, France*

[2] *Université Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France*

[3] *LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91762 Palaiseau, France*

We examine via particle-in-cell (PIC) simulations the processes of magnetic field generation in relativistic femtosecond laser-solid interactions. Chief among those processes is the current filamentation instability (CFI) [1], which excites strong ($> 10^3$ T), kinetic-scale B fields around the laser spot [2]. Weaker CFI-type fields can also develop in the collisional target bulk [4] or in the plasma plumes at the target surfaces [5]. Another mechanism relies on the fountain-type motion of the fast electrons near the plasma-vacuum boundaries, leading to azimuthal B fields surrounding the laser spot up to $\sim 100\,\mu$m radii [6, 7].

Our study is motivated by a recent experiment at LOA, whereby the B fields induced in a thin ($\sim 20\,\mu$m) solid foil by a $\sim 10^{19}\,\mathrm{W\,cm^{-2}}$, ~ 30 fs laser pulse were diagnosed via electron deflectometry. In contrast to a previous experiment [8], the probe beam was here produced by an auxiliary laser-wakefield accelerator. Its mean angular deflection and rms spread after exiting the irradiated foil were measured as a function of time and transverse position, showing nontrivial dependencies owing to the dynamic interplay of the CFI and fountain-type B fields at the front and rear target sides. We will compare the measurements with the results of 2D collisional PIC simulations run under conditions as close as possible to the actual ones. Notably, we will take into account the 2D preplasma created by the laser's pedestal and describe self-consistently the interaction of the probe electrons with the induced plasma fields.

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Plasma characterisation for microwave-plasma interaction experiments

L. Selman[1], K. Wilson[1], P. MacInnes[1], C.G. Whyte[1], A.D.R. Phelps[1], A.W. Cross[1], B. Eliasson[1], D.C. Speirs[1], C.W. Robertson[1], K. Ronald[1], R.A. Cairns[1,2], R. Bingham[1,3], R. Bamford[3], M.E. Koepke[1,4]

[1] *SUPA and Department of Physics, University of Strathclyde, Glasgow, G4 0NG UK*

[2] *School of Mathematics and Statistics, University of St Andrews, St Andrews, KY16 9SS, UK*

[3] *STFC Rutherford Appleton Laboratory, Oxford, OX11 0QX, UK*

[4] *Department of Physics, West Virginia University, Morgantown, WV26506-6315, USA*

Resonant non-linear interactions (e.g. Raman and Brillouin) can resonantly exchange energy between multiple electromagnetic and electrostatic (Langmuir and ion-acoustic) plasma waves. These interactions are important in laser plasma interactions and other fields. In magnetised plasma, beat-waves can also excite the upper hybrid and electron cyclotron resonances. This is of interest for current drive in overdense magnetically confined fusion plasma.

Progress is reported on the status of the apparatus, plasma characterisation, and the supporting numerical simulations for fundamental microwave-plasma coupling experiments. The vacuum vessel is 1m in diameter and 3m long, with a flat spiral antenna driven at 14 MHz to produce a plasma in either helium or argon. Experiments can produce unmagnetised (inductive), or magnetised (helicon [1]) plasma using a set of magnet coils 1.6m in diameter. In inductive mode with 200W of drive power RF compensated Langmuir probes and microwave interferometry indicate a cool, $T_e \sim$ few eV, stable plasma with $n_e < 2\times10^{15}$ m^{-3}.

Using microwave frequencies and a cool tenuous plasma allow for precise control of injected waves and diagnostic accessibility. Pulsed high power microwaves, 9-10 GHz, are launched across the vessel between horn antennae [2] which convert the wave into a Gaussian beam at their aperture. Lenses are used to focus the beam into the centre of the plasma. The high power microwaves are generated by a 9.4 GHz magnetron and frequency flexible TWT amplifiers, which allows for the tuning of the microwaves to select a chosen resonance.

The project builds on previous laboratory plasma experiments [3-5]. The authors gratefully acknowledge support from the UK EPSRC through grants EP/R004773/1 and EP/R034737/1.

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Moving into higher fields and collective behavior: recent advancements toward confined matter-antimatter pair plasmas

E. V. Stenson[1], for the APEX Collaboration, including

A. Card[1*,2], J. R. Danielson[3], A. Deller[1,3], U. Hergenhahn[1*], J. Horn-Stanja[1*],
C. P. Hugenschmidt[2], P. Gil[1], P. Huslage[1], S. Nissl[1,2], T. Sunn Pedersen[1*], C. W. Rogge[1,2],
H. Saitoh[4], L. Schweikhard[5], M. Singer[1*], M. Singer[1,5], J. Smoniewski[1],
P. Steinbrunner[1,5], C. M. Surko[3], M. R. Stoneking[6], J. von der Linden[1]

[1] *Max Planck Institute for Plasma Physics, Garching & Greifswald, Germany*

[2] *Technische Universität München, Garching, Germany*

[3] *University of California, San Diego, La Jolla, CA, U.S.A.*

[4] *The University of Tokyo, Kashiwa, Japan*

[5] *University of Greifswald, Greifswald, Germany*

[6] *Lawrence University, Appleton, WI, U.S.A.*

[*] *prior affiliation (during contribution)*

The ultimate goals of the APEX (A Positron Electron eXperiment) Collaboration are the generation and investigation of confined, strongly magnetized, electron-positron plasmas in the laboratory. The mass symmetry of such plasmas simplifies many aspects of the plasmas physics, as has been described in more than four decades of theory and simulation predictions. Our "road map" to conducting experimental studies requires unifying and advancing state-of-the-art physics and engineering in several areas, including:

- extended accumulation and high-capacity storage of large numbers of positrons, originating from a world-class source;
- two superconducting, tabletop-sized toroidal confinement devices with complementary magnetic topologies (a dipole and a stellarator), in which the positrons will be combined with electrons and their plasma properties studied; and
- the development and verification of a number of essential enabling techniques — e.g., efficient transport of positrons across magnetic flux surfaces and subsequent trapping.

This contribution will summarize recent headway made along that road map, with has included progress in non-neutral plasma trapping; new techniques for injection into toroidal geometries, including with an electron space charge present; and the development of the toroidal traps.

Microscopic fingerprints of hard X-ray radiation material damage and structural modification on femtosecond time scale

V. Tkachenko[1,2], I. Inoue[3], K.J. Kapcia[4,2], V. Lipp[5,2], B. Ziaja[2,5]

[1] *European XFEL GmbH, 22869 Schenefeld, Germany*

[2] *Center for Free-Electron Laser Science CFEL, Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany*

[3] *RIKEN Spring-8 Center, 1-1-1 Koto, Sayo, Hyogo 679-5148, Japan*

[4] *Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland*

[5] *Institute of Nuclear Physics, Polish Academy of Sciences, 31-342 Kraków, Poland*

Hard X-rays produced at FEL facilities serve as an efficient instrument for studying radiation damage and material structure. Here we report on recent achievements in these two topics performed at SACLA FEL facility in the SPring-8 research center in Japan. In one experiment, the high intensity X-ray pulse created an isotropic charge distribution surrounding diamond atoms on a time scale longer than 5 fs which indicated covalent bonds breaking [1]. At the same time, the atomic disordering took place with a delay of 15 fs from the bond breaking, which is a sign of a non-thermal process. In another experiment, the transient structural changes of Al2O3 were investigated on subatomic length scales, following irradiation with a hard X-ray laser pulse [2]. The measurement revealed that aluminum and oxygen atoms remained in their original positions for 20 fs after the intensity maximum of the pump pulse. This was followed by directional atomic displacements at the fixed unit cell parameters.

In both cases, by comparing the experimental results and theoretical simulations, we interpreted that electron excitation and relaxation triggered by the pump pulse modified the potential energy surface and drove the atomic displacements. Our simulation model provided a comprehensive description of transient atomic and electronic properties on femtosecond time scales by coupling classical molecular dynamics and Monte Carlo with a tight-binding [3] or density functional tight-binding [4] calculation of the band structure. Our results indicate that high-resolution X-ray structural analysis with the accuracy of 0.01 Angstrom is feasible even with intense X-ray pulses by making the pulse duration shorter than the timescale needed to complete electron excitation and relaxation processes, which usually take up to a few tens of femtoseconds. This observation opens a promising prospect for high-precision diffraction imaging of nanocrystals with X-rays.

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Magnetized Blast Waves: Insights from Laboratory Astrophysics

A. Triantafyllidis[1], J. R. Marquès[1,2], Y. Benkadoum[1], A. Dearling[3], N. Ozaki[4,5], M. Koenig[1,2,5], B. Albertazzi[1,2]

[1] LULI, École Polytechnique, Institut Polytechnique de Paris-F-91120 Palaiseau Cedex, France

[2]CNRS, CEA, Sorbonne Universités

[3]York Plasma Institute, Department of Physics, University of York, YO10 5DD

[4]Institute of Laser Engineering, Osaka University, 2-6 Yamada-Oka, Suita, Osaka, 565-0871 Japan

[5]Graduate School of Engineering, Osaka University, Osaka, 565-0871, Japan

The interaction between supernova remnants (SNRs) and a strong magnetic field is a fundamental problem that has captured the attention of the astrophysical community in hopes of explaining astronomical observations like the barrel-shaped SNR G296.5+10.0 [1,2]. Magnetic fields are omnipresent in the universe, and a considerable number of blast waves (BW) observed, such as SNRs, coronal mass ejections, and shocks from stellar winds, are magnetized or interact with the magnetized interstellar medium (ISM). The consequences of this interaction can be crucial; the propagation and shape of the shock are highly modified, particle acceleration may be influenced, and it could lead to an efficient compression of the background ISM magnetic field. However, astronomical observations of such systems usually do not have the necessary spatial and temporal resolution to accurately determine all associated parameters (e.g. shock structure and morphology). For this reason, we have adopted a different approach: laboratory astrophysics. During the last decade, the development of high-power laser facilities coupled with a strong external magnetic field has allowed the experimental investigation of numerous magnetized astrophysical phenomena [3]. Here, we will present experimental results obtained at LULI2000 where we examined the influence of parallel and perpendicular magnetic fields (compared to the BW normal direction) on the morphology and structure of BWs mimicking an SNR in its Taylor-Sedov phase. Our findings demonstrate that the BW structure changes significantly, resulting in a more spheroidal shape, and its propagation deviates from the typical Taylor-Sedov phase. Additionally, the velocity of the BW is higher when the magnetic field is parallel to the propagation axis and lower when it is perpendicular.

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Features of helicon waves in a non-uniform magnetic field

F. Filleul[1], A. Caldarelli[1], K. Takahashi[2], R.W. Boswell[3],
C. Charles[3], J. Cater[4], N. Rattenbury[1]

[1] Department of Physics, The University of Auckland, Auckland, New Zealand

[2] Department of Electrical Engineering, Tohoku University, Sendai, Japan

[3] Space Plasma, Power and Propulsion Laboratory, Research School of Physics, The Australian National University, Canberra, Australia

[4] Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand

felicien.filleul@auckland.ac.nz

The high ionisation fraction associated with helicon modes is desirable for a variety of applications, from magnetic confinement fusion, to semiconductor manufacturing and fundamental plasma physics [1, 2, 3, 4]. The coupling mechanisms of helicon waves have been debated since their first association with efficient high density plasma generation ($\geq 10^{12}$ cm^{-3}) in the 1960's, and this question remains a dynamic field of research today [5, 6, 7]. While the textbook cases of helicon waves make the simplifications of considering an infinite and uniform plasma with an uniform applied magnetic field, natural and laboratory helicon plasmas rarely fulfil these conditions.

Waves propagating along a converging-diverging magnetically confined plasma column having the characteristics of a bounded $m = 0$ helicon mode are reported and experimentally characterised. The discharge features a 30 cm separation between the region of radiofrequency energy deposition by a single loop antenna and the region of maximum magnetic field applied by a pair of coils. With 200 W of rf input power, the resulting plasma exhibits a strong axial plasma density gradient peaking at the magnetic mirror throat where an Ar II blue-core is observed [8]. Two dimensional B-dot probe measurements show that the rf magnetic fields are closely guided by the converging-diverging geometry. The wave is characterised by a $m = 0$ mode satisfying the helicon dispersion relation on-axis with a radial boundary condition approximately matching the plasma column radius. Analysis of the wave's phase velocity and wave's axial damping failed to identify collisionless or collisional wave-plasma coupling mechanisms. This suggests that other considerations are needed to explain the axial damping of the wave in non-uniform magnetoplasmas.

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Dust acoustic wave properties in varying discharge volumes

C. A. Knapek[1,4], M. Schwabe[2,4], V. Yaroshenko[3,4], P. Huber[4], D. P. Mohr[1,2,4], U. Konopka[5]

[1] *Institute of Physics, University of Greifswald, Greifswald, Germany*

[2] *Institut für Physik der Atmosphäre, DLR, Oberpfaffenhofen, Germany*

[3] *Institut für Solar-Terrestrische Physik, DLR, Neustrelitz, Germany*

[4] *Institut für Materialphysik im Weltraum, DLR, Köln, Germany*

[5] *Physics Department, Auburn University, Auburn, Alabama, USA*

Complex or dusty plasmas consist of nano- or microparticles suspended in a low-temperature plasma. The microparticles get highly charged by collecting ions and electrons from the surrounding plasma, and interact with each other via a screened Coulomb potential.

In astrophysical environments, dusty plasma occurs for instance in the rings surrounding Saturn, above the lunar surface, in the vicinity of comets, and in interstellar clouds. Dusty plasma are intensively studied also in laboratory surroundings, where the individual components (dust, ions, and electrons) can be more easily controlled and their individual contribution to the dynamics and structure can be examined.

An ion flow through a cloud of microparticles suspended in a low-temperature plasma can induce an ion streaming instability and lead to the formation of dust acoustic waves.

The properties of such self-excited dust acoustic waves under the influence of active compression of the dust particle system were experimentally studied [1]. Ground based laboratory experiments show clearly that wave properties can be manipulated by changing the discharge volume and thus the dust particle density. Complementary experiments under microgravity conditions (parabolic flights) were less conclusive due to residual fluctuations in the planes acceleration indicating the need for a better microgravity environment. A theoretical model, using plasma parameters obtained from PIC (particle-in-cell) simulations as input, supports the experimental findings. It shows that the waves can be described as a new observation of the dust acoustic mode which demonstrates their generic character. This work is funded by DLR/BMWi (FKZ 50WP0700, FKZ 50WM1441).

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Development of microwave assisted arc plasma scrubber

S. H. Lee[1], S.S.Yun[1], K.S.Kim [1], and N. J. Choi[1], D. H. Shin[2], S. M. Chun[2], and Y. C. Hong[2]

[1] *Young Jin IND, Icheon-City, Rep. of Korea*

[2] *Korea Institute of Fusion Energy, Gunsan-City, Rep. of Korea*

Currently, the scrubber of semiconductor waste gas field mainly uses existing burn-wet, which is a hindrance to carbon reduction policies. Semiconductor technology has advanced development to 3-nanometer, and the use of EUV (Extreme Ultraviolet) equipment is increasing. According to this trend, as the use of process gases increases, so does the amount of waste gases, continuous research is being conducted to increase waste gas throughput and improve treatment efficiency. In this context, abatement of CF_4 gas which the highest GWP was researched using by the Arc + Microwave hybrid plasma. Conventional Arc plasma has the drawback that the higher the power, the shorter the plasma length and the smaller the decomposed reaction area.

When microwave is applied to the arc plasma, the plasma flame length can be enlarged by nearly 200% with respect to a single arc plasma source, and this was applied to the reactor to progress the test of abatement CF_4. The reactor was designed with insulation applied to maintain enlarged plasma flame length and decomposition temperature. The abatement test was performed with 5000 ppm of CF_4 in 300 lpm of N_2 and which is twice the capacity of 150 lpm of N_2, which is the CF_4 decomposition standard for commercially available scrubbers.

As a result of the test, a decomposition efficiency of over 90% was obtained at 15 kW of arc and 3 kW of MW, and a power saving effect of 40% was obtained for a single arc plasma source.

The CF_4 gas that were not decomposed by 23 kW (19780 kcal) of arc plasma can be decomposed by 18 kW, and the decomposition performance can be improved by increasing the reaction time by increasing the electron emission rather than increasing the core temperature of the plasma.

Ion acceleration from optically shaped high density gas jet targets

K. Bontemps[1], J.R. Marquès[2], A. Maitrallain[1], T.Carrière[3], F. Hannachi[1], V. Bagnoud[4], J.L. Henares[5], J. Hornung[4], A. Huber[1] , E. D'Hummières[3], L.Lancia[2] P.Loiseau[6,7], P.Nicolaï[3], J.Santos[3], V.Tikhonchuk[3], B.Zielbauer[4], M.Tarisien[1]

[1] *Univ. Bordeaux, CNRS, LP2I, UMR 5797, F-33170 Gradignan, France,*

[2] *LULI, CNRS, \'Ecole Polytechnique, CEA, Sorbonne Universit\'e, Institut Polytechnique de Paris, F-91128 Palaiseau Cedex, France,*

[3] *Univ. Bordeaux-CNRS-CEA, CELIA, UMR5107, Talence, France,*

[4] *Plasma Physik/PHELIX, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany,*

[5] *Centro de Laseres Pulsados, C/ Adaja 8, 37185, Villamayor, Spain,*

[6] *CEA, DAM, DIF, F-91297 Arpajon, France,*

[7] *Univ. Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France,*

The ENL group (LP2IB) aims to accelerate ions up to several tens of MeV by the interaction of a high-intensity laser with an overcritical gas jet. This gas target is self-regenerating and does not create debris; so it can be used with the new generation of high-power lasers operating at high repetition rates.

One way to accelerate ions in a gas jet is to create a shock wave at its centre where the density is overcritical ($n_c \approx 10^{21} cm^{-3}$) with a strong gradient. This acceleration process is called Collisionless Shock Acceleration (CSA). However, around the gas jet, there is an extended peripheral zone with low molecular density where the laser pulse interacts and is degraded, thus losing its coherence and its energy needed to trigger the CSA process. To address this problem our collaboration aims to minimise this low density region by shaping the gas jet with a low intensity prepulse.

An experimental campaign at GSI on the PHELIX laser facility has been set up with a low-energy prepulse ($1J$, $\tau = 500fs$) that precedes the intense main pulse (same pulse duration, $E \in [50;100]J$ i.e. an intensity $10^{20} W.cm^{-2}$) by less than 1ns. To characterise the modified target interacting with the main pulse, a small part of the pulse is frequency doubled to illuminate a Nomarski interferometer and an shadowgraphy setup, and the kinetics of the target shaping is recorded with a streak camera illuminated with a backlighting laser of few *ns*. The accelerated ions are measured at different angles (0°, 45° and 90°) by 3 Thomson parabolas equipped with Image Plates from which energy spectra can be extracted. First results will be presented in this poster.

Using machine learning methods for scaling and optimization of laser-driven ion acceleration

F.Wasser[1,2], C. Müller-Kett[1], K. Schaaff[1], T. Zöller[1]

[1] *IU Internationale Hochschule GmbH, Erfurt, Germany*

[2] *Focused Energy GmbH, Darmstadt, Germany*

Ion acceleration from the interaction of ultra-intense laser beams with plasma has been investigated for more than 20 years. Thanks to the exceptional qualities of the generated ion beams, many potential applications have been considered. Particularly, laser-accelerated proton beams have the potential to be used as ignitors in inertial confinement fusion (ICF) experiments to circumvent major obstacles in the classical hot spot ignition scheme [1].

To use these ion beams, their properties must be controlled precisely. For this purpose, several models have been developed to describe the influence of input parameters such as laser energy, pulse duration, and focal spot size and to predict important qualities like the maximum energy. While these models are mainly based on theoretical considerations, we propose an empirical, data-based approach. Thanks to recent developments in laser technology, experiments with high repetition rates have become possible, enabling the generation of large datasets. This allows for applying machine learning methods for scaling and predicting output parameters.

In this contribution, we report on the application of machine learning models that were trained with empirical data from different laser facilities to predict maximum proton energies for a broad range of laser energies, pulse durations, focal spot sizes and target thicknesses. We demonstrate, that very precise predictions are possible with a root mean squared error of only around 2.2 MeV. The model will continuously be updated with more data to further improve the precision and extend the parameter range. This will help to plan future laser systems and facilities, especially for ICF with laser-accelerated proton beams.

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Femtosecond Resolution of the Electron Energy Transport in Warm Dense Copper with a Betatron X-ray Source

A. Grolleau[1], F. Dorchies[2], S. Briand[1,2], K. Ta Phuoc[3], J. Gautier[3], P. Renaudin[1], V. Recoules[1], L. Lecherbourg[1,4]

[1] *CEA, DAM, DIF, F-91297 Arpajon, France*

[2] *Univ. Bordeaux, CNRS, CEA, CELIA, UMR 5107, F-33400 Talence, France*

[3] *LOA, ENSTA, CNRS, Ecole Polytechnique, UMR 7639, F-91761 Palaiseau, France*

[4] *Univ. Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France*

The study of the laser induced ultrafast solid-plasma phase transition (ICF, laser ablation) implies to cross the path of the Warm Dense Matter (WDM) domain. It can also be found in astrophysics in planets core or gas giants atmosphere. This particular regime is characterized by temperatures of about 0.1 to 100 eV, and densities close to the solid density. When this regime is produced by the interaction of a sub-picosecond laser pulse with a solid target at ambiant conditions, the valence electrons can be brought to several eVs while the crystal lattice remains at moderate temperature, below the fusion point. Then, the electron-lattice system thermalizes few picoseconds after the laser interaction. We studied the out-of-equilibrium WDM regime for copper, using the betatron X-ray source of the Laboratoire d'Optique Appliquée (LOA) [1]. We used the X-ray Absorption Near Edge Structure (XANES) of copper, which is modified depending on the thermodynamical conditions of the target and the probed atomic structure. A diagnostic was developped for warm dense copper thanks to *ab initio* DFT-MD simulations, validated by experiments, which allows us to infer the average electron temperature of copper [2]. We performed a pump-probed experiment during which we measured the XANES spectra of 30 nm and 100 nm copper samples at differents delays after the laser heating. It allowed us to follow the evolution of the electron temperature during the first picosecond with a resolution better than 70 fs thanks to the betatron source [3]. We observed that beyond an absorbed flux limit established by Chen and cowerkers [4], the electron energy transport is no longer due to ballistic transport of non-thermal electrons, but is representative of the slower thermal diffusion.

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A study of the demixing of the H-He mixture, in the Gibbs ensemble.

Etienne Jaupart[1] & François Soubiran[1]
[1]CEA DAM-DIF, 91297 Arpajon, France

The precise knowledge of the H-He demixing diagram is of particular importance for the study of gas giants [1]. Under the temperature (T) and pressure (P) conditions of planetary interiors, electrons must be treated in a quantum manner. Theoretical studies have therefore investigated miscibility properties with molecular dynamics simulations in the canonical ensemble using density functional theory (DFT) [2,3,4,5]. This method has allowed the calculation of demixing diagrams, but these simulations can suffer from finite size effects limiting the predictive character of the resulting diagrams. Recently, a series of experiments has suggested demixing in a T, P regime in disagreement with theoretical predictions [6]. This result calls for a resumption of the theoretical study of the H-He mixture and for minimizing the sources of uncertainty.

We have therefore studied the H-He mixture in another statistical ensemble than the canonical one: {\the so-called Gibbs ensemble}. This ensemble consists in considering two boxes that can exchange volume and particles, but isolated, so that the particles of one box do not interact with those of the other one. During a demixing, the two phases separate in two different boxes, thus avoiding surface effects.

We will present a new general study of this ensemble and its advantages as well as our first results on its application to H-He mixing under Jupiter and Saturn conditions. We will provide a first ab initio H-He demixing diagram using this framework and discuss its implication for planetary models.

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Probing the nonlinear stage of the ablative Rayleigh-Taylor instability at the National Ignition Facility

L. Ceurvorst[1], S. F. Khan[2], D. Martinez[2], N. Izumi[2], V. Smalyuk[2], L. Masse[3], T. Goudal[3], B. Canaud[3], V. Bouffetier[4], V. Goncharov[1,5], I. Igumenshchev[1], A. Casner[6]

[1] *Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA*

[2] *Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550, USA*

[3] *Commissariat à l'Energie Atomique, DAM, DIF, F-91297 Arpajon, France*

[4] *European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany*

[5] *Department of Mechanical Engineering, University of Rochester, Rochester, NY, 14623, USA*

[6] *CEA-CESTA, 15 Avenue des Sablières, CS 60001, 33116 Le Barp CEDEX, France*

The Rayleigh-Taylor instability is present at all scales of the universe – from cloud formation to supernovae. It has been the subject of intense study since its original discovery in the 19th century, yet despite its prevalence and history, much about its late-stage development is still unknown. This is especially true in the presence of ablation such as would be found in inertial confinement fusion implosions. It is theorized that in this regime, a self-similar behavior would develop where the bubble heights become proportional to their distance traveled. The constant of proportionality between these two, known as the mixing factor, varies significantly between simulations and experiments and its dependencies, such as on initial conditions, acceleration, and ablation velocity, are heavily debated. In this presentation, a series of experiments performed on the National Ignition Facility quantify these three factors by examining the Rayleigh-Taylor development of a laser-imprinted, directly driven planar target. Side-on streaked radiography captured the targets' trajectories, and face-on x-ray radiographs were collected late in the systems' development and converted to optical depth to infer the bubble and spike amplitudes. A strong dependence on initial conditions was demonstrated, where removing a continuous phase plate from the imprint beam increased nonlinear growth by ~80%. The effects of acceleration and ablation velocity on nonlinear growth rates were measured by changing the target's thickness and composition. However, in all configurations, self-similarity was not directly observed in any of these experiments. Fourier analysis revealed that this was due to modes stagnating shortly after entering the nonlinear regime rather than continuing to grow linearly as expected. This effect was

Coherent emission of electrons interacting with an intense laser pulse

E. Gelfer[1], A. Fedotov[2], O. Klimo[1,3], S. Weber[1]

[1] *The Extreme Light Infrastructure ERIC, Dolni Brezany, Czech Republic*

[2] *National Research Nuclear University MEPhI, Moscow, Russia*

[3] *FNSPE, Czech Technical University in Prague, Prague, Czech Republic*

Radiation emission via nonlinear Thomson/Compton scattering (NTS/NCS) is the basic phenomenon arising in the interaction of strong lasers with plasmas. The theory of NTS by a single electron is well known [1]. However, when the laser interacts with many particles, the coherence modifies the radiation spectrum [2], and this effect is usually overlooked.

We investigate the radiation of several particles interacting with a strong electromagnetic plane wave and establish the conditions for the coherent radiation. Depending on parameters, coherence might substantially enhance radiated power and modify the shape of the spectrum as compared to the single particle case, especially for modest laser intensities $10^{18}\mathrm{W/cm}^2 < I < 10^{20}\mathrm{W/cm}^2$. We determine the radiation spectrum of a cold electron beam colliding with an intense laser pulse and prove the analytical estimates with 3D numerical simulations using particle-in-cell (PIC) code SMILEI [3], see Figure 1.

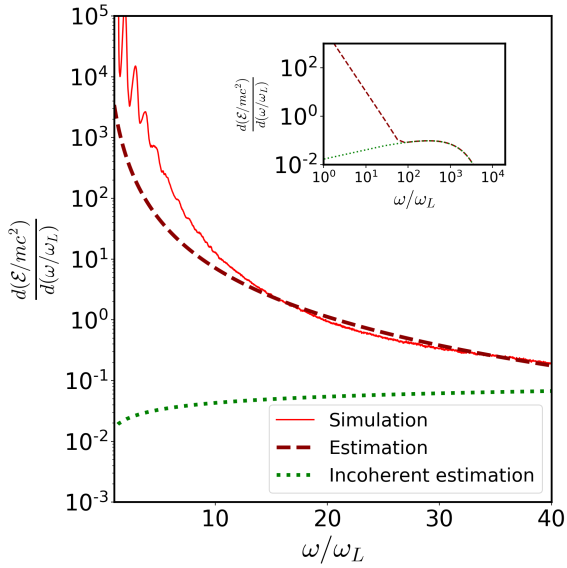

Figure 1: *Radiation spectrum of the cold bunch of electrons (density $n = 10^{20}cm^{-3}$, volume $V = 0.125\mu m^3$) colliding with an intense ($I = 2.7\cdot 10^{20}$ W/cm^2) laser pulse. Red solid line – 3D PIC simulations result, dark red dashed line – estimation based on the developed analytical theory, green dotted line – incoherent radiation of $N = nV$ electrons in the bunch. Inset: coherent and incoherent estimations of the spectrum in a wider frequency range.*

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Particle-resolved study of the onset of turbulence

E. Joshi[1], M. H. Thoma[2], and M. Schwabe[3]

[1] *Institut für Materialphysik im Weltraum, DLR, 51147 Köln, Germany*

[2] *I. Physikalisches Institut, Justus–Liebig Universität Gießen, 35392 Gießen, Germany*

[3] *Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, 82234 Oberpfaffenhofen, Germany*

The transition from laminar to turbulent flow is an immensely important topic that is still being studied. Complex plasmas, which consist of microparticles immersed in a low temperature plasma, can also become turbulent [1, 2]. This allows us to study turbulence at a particle-resolved level as each microparticle can be imaged directly. In this work, we show how turbulence develops in complex plasmas flowing past an obstacle in the presence of damping due to friction with the background gas. We also show a transition from turbulence in a damped to an undamped system. For this, we performed 3D MD simulations using the open source software LAMMPS [3]. We found that we could reliably trigger the onset of turbulence by changing key parameters such as the flow speed and particle charge, and used this to study the transition from laminar flow to turbulent flow. We also found that turbulence in our simulations with damping always followed the formation of shock fronts, such as bow shocks and Mach cones. This can be seen in Figure 1 where vortices are present around the shock fronts. We also observed intermittency during both the onset of turbulence and fully developed turbulence.

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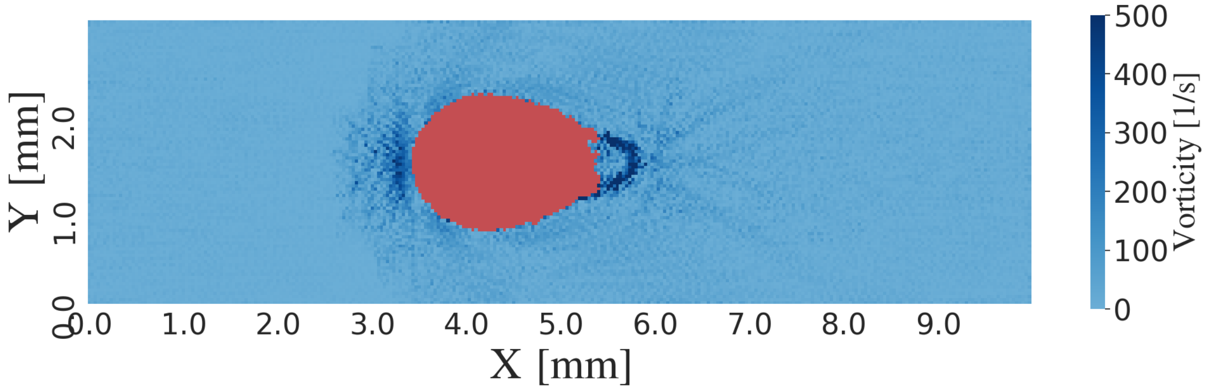

Figure 1: *Vorticies around an obstacle due to supersonic flow. The vorticity is averaged over one second in bins of size* $0.03 \times 0.03 \times 0.2$ *mm*^{3}. *The void around the obstacle is coloured red.*

Investigation on the effect of femtosecond laser wavelength (UV and IR) on the plasma characteristics on various materials, using femtosecond laser induced breakdown spectroscopy

Gytis Zaremba[1], Ona Balachninaitė[1], Domas Paipulas[1]

[1] *Laser Research Center, Vilnius University, Saulėtekio ave. 10, LT – 10223 Vilnius, Lithuania*

Laser induced breakdown spectroscopy (LIBS) is a widely used versatile tool for elemental analysis of various materials, both in-situ and in the laboratory [1]. Using fs pulses for LIBS has many advantages, like reduced sample damage [2], low continuum emission, lower ablation threshold and better repeatability [3]. An important parameter of LIBS is the wavelength used for plasma generation. The choice of wavelength for LIBS measurements is thought to be more important for longer pulses, closer to the regime of nanoseconds, but in the case of fs - LIBS, the laser-matter interaction is different, the pulse duration is much shorter than material heat transfer, there is no plasma shielding of the pulse. However, the dependence on wavelength for fs - LIBS has not been extensively studied.

In this work, the femtosecond Yb:KGW laser "Pharos" (Light Conversion Ltd) with pulse duration of 170 fs, 6 kHz repetition rate and up to 6 W of average power was used. The spectra were recorded using Andor Mechelle Spectrograph with ICCD camera. The fundamental (1030 nm) and third (343 nm) harmonics were used to determine the effect of source wavelength on LIBS parameters. The peak energy fluence on the sample was constant with both wavelengths. The samples used were O. F. H. C. copper (99.95+% purity), AISI 301 stainless steel, a glass and a ceramic.

Plasma temperature was evaluated at thermal equilibrium using the Boltzmann plot method. At 400-800 ns delay after laser ablation, the plasma temperature was around 9000 K on copper, 8000 K on steel and 6000 K on a glass filter, and there was no difference, within error, between UV and IR wavelengths, except for ceramic, where the use of UV laser wavelength resulted in ~2000 K higher plasma temperature. Electron density was estimated to be $(1.2 \pm 0.4) \cdot 10^{18}$ cm^{-3} on copper sample and $(1.4 \pm 0.4) \cdot 10^{16}$ cm^{-3} on steel, glass filter and ceramic samples, the use of UV and IR wavelengths resulted in equal densities. Signal-to-noise ratio (SNR) was evaluated for all samples and is shown in Fig. 1. Our experiments showed that fs UV-LIBS gives higher SNR than fs IR-LIBS on all the samples investigated, at the same energy fluence. By using UV laser wavelength on ceramic sample, we were able to observe spectral lines that were not present when using IR wavelength. Since UV light can be focused to a smaller spot, the sample damage is reduced, enabling higher resolution in applications like LIBS chemical imaging.

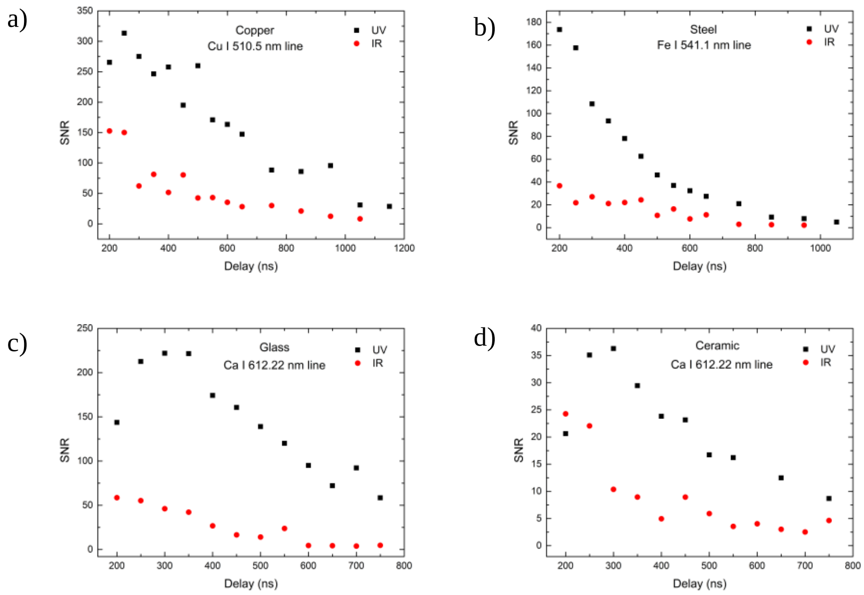

Fig. 1 Comparison of UV and IR LIBS signal to noise ratios of Cu I 510.5 nm spectral line on copper (a), Fe I 541.1 nm line on steel (b), Ca I 612.22 nm line on glass (c) and ceramic (d).

Acknowlegments

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amplified as the relative role of ablation increased across experiments, pointing to an ablative stabilization mechanism not currently accounted for in theoretical studies.

MHD Stability and Scenario Development of Negative Triangularity Plasmas in DIII-D

W. Boyes[1], F. Turco[1], A. Marinoni[2], A. Turnbull[3], J.M. Hanson[1], M. Austin[4], G. Navratil[1]

[1] *Columbia University in the City of New York, New York NY, United States*

[2] *Massachusetts Institute of Technology, Cambridge MA, United States*

[3] *General Atomics, San Diego CA, United States*

[4] *University of Texas, Austin TX, United States*

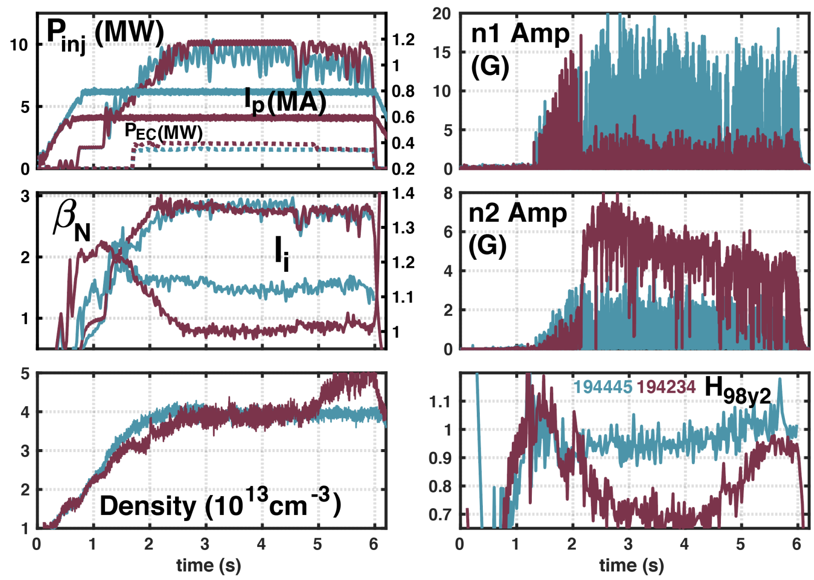

Figure 1: *Negative Triangularity armor campaign discharges showing performance and stability to* $2/1$ *tearing modes over two values of* q_{95}

A dedicated campaign has been conducted on DIII-D to assess strongly shaped ($\delta_{avg} \approx -0.5$) negative triangularity (NT) performance. Phenomena resembling the positive triangularity hybrid scenario such as anomalous flux pumping and minimum safety factor value near unity were observed in NT L-mode plasmas prior to the campaign. These observations lead to recent experiments that successfully accessed and maintained this scenario for multiple current relaxation times with hybrid scenario access phase trajectories. MHD stability limits and scenario access were studied over a scan of q_{95}. Experiment (Fig. 1) and modeling of ideal stability and classical tearing show that a NT hybrid-similar scenario can be developed at $\beta_N \approx 3$ at $q_{95} \geq 4.5$ and a higher gain scenario could be developed at similar β_N, $q_{95} \approx 3$. Lost confinement from the hybrid-like n=2 mode was mitigated at higher volume, density, and q_{95} in past experiments compared to the armor campaign shape. Either path would likely replicate β_N and confinement similar to that in H-mode, at Greenwald fraction between 50-65%, but without ELMs and possibly without sawteeth. These metrics were reached in experiments stable to $2/1$ tearing modes for multiple current relaxation times. Work supported by US DOE under DE-FG02-04ER54761, DE-FC02-04ER54698, DE-FG02-97ER54415, and DE-SC0016154.