Tokamak GOLEM for fusion education - chapter 14

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The GOLEM tokamak is the oldest still operational experimental device in the high temperature tokamak plasma physics. Currently, its main mission is to be an educational device to train future thermonuclear fusion specialists. GOLEM is unique thanks to its remote-control system [1], which allows to perform the discharge and instantly process experimental data remotely. This contribution is devoted to the current projects:

A system for visible light tomography of the tokamak plasma was calibrated and its accuracy was assessed using numerical modeling. Tomography was used to reconstruct the visible **plasma emissivity profiles during impurity injection**. **Plasma position** is estimated based on experimental measurements and numerical simulations. Numerical code NICE is used for the simulations of magnetic field topology, with the primary goal of magnetic field reconstruction. **A video about the GOLEM tokamak vacuum system** was created as the first in a newly emerging series of methodological materials for tokamak technology-relevant educational purposes. **AdvaPIX Timepix3 pixel detectors were installed** for HXR detection and a Compton camera was constructed from them. **Studies of runaway electrons (RE) interaction with the limiter** were performed using semiconductor detectors and HXR probes. **The strong dependence of ECE power on non-thermal electrons** due to the GOLEM plasma parameters allows for the use of ECE measurements for observation of REs. **Progress was made in the RE diagnostics** measuring their bremsstrahlung radiation, specifically in the automatization and robustness of processing methods. **Improvements were made to the interferometric hardware and evaluation software** for detecting and repairing parts of the signal damaged by the scattering of the interferometric probing wave. **A study of impact of the edge plasma potential biasing on turbulence** was performed with emphasis on excitation or amplification of ZF-like or GAM-like coherent modes in the edge plasma. **A system for plasma current stabilisation** based on current amplifiers is being developed in order to achieve a flat-top plasma current.

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A new theoretical method for modes localisation

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The modes localisation is of a particular interest in tokamak plasmas especially for the correction or the validation of the plasma safety factor profiles. A new method for the localisation of the modes of perturbation is proposed. Starting from the match between the calculated mode amplitude derived using our perturbed validated model [1] and the one provided by the JET MHD-python mode analysis code [2] our model is able to subsequently derive the dynamic radial position of the modes during plasma discharges. Therefore we rely on the assumption that a good match between the calculated and the experimental modes amplitude drives our model to trustfully deliver the expected good localisation of the modes. If CXRS data is also available our calculated modes frequency based on the plasma toroidal velocity data can be additionally compared against the modes frequency spectrogram in order to strengthen the model validity. Moreover our radial localisation method is supplementary checked against the JET data analysis for discharges that do provide the localisation of the modes just to test the model accuracy to be further confidently used for shots involving non localised perturbations. The proposed method is of a particular interest when no CXRS data is provided (no NBI present) and when the ECE diagnostic fails to deliver a reliable mode location. The method is specifically useful for instance for the locked modes case whose CXRS data is missing and the modes radial position seems to change during the locking disruptions, according to the proposed model. Hence this method has been extensively tested and checked in order to become a valid alternative to the usual localisation techniques.

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Gain enhancement of the p -^{11}B fusion process by energetic alpha injection

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Abstract

Up to date, the main difficulty for fusion ignition of the p^{11}B fuel is that its nuclear reaction cross section is efficient for energies higher than 250 keV. However theoretical interpretations [1, 2] of experimental results [3, 4, 5] show that the chain reaction alpha heating effect and the avalanche effect are the main processes improving the alpha production. Our previous numerical investigations [6,7, 8] regarding p-^{11}B fusion, prove the effective contribution of these effects to the energy transfer from the produced alpha to fusion species (p, ^{11}B), which results in their temperatures rise to values corresponding to the nuclear reaction cross section optimum (~675 keV) and consequently , to overcome the difficulty of fusion ignition. According to [6] important rise of the temperature of the fusion species, appears when the density of the produced alphas is one to two orders of magnitude lower than the initial fusion species medium density. The aforementioned effects establish a significant relation between the initiation of fusion ignition and the characteristic time interval, for the rapid enhancement of the RR. The later depends strongly on the initial conditions (density and temperature) of the fusion species and/or different initial Boron to proton density ratio, n_B/n_p. For relatively low initial fusion species (p, ^{11}B) temperatures (40 keV-80 keV) compared to the ~675 keV (value of the maximum fusion cross section), the simulations show fusion ignition for a relatively long-time interval until the maximization of the RR. The consequence is the reduction in the final produced alpha density, which leads to low output fusion gain, due to difficulties for efficient trapping of the expanded plasma. In order to face these difficulties and improve the fusion gain, numerical investigations of a new p-^{11}B fusion ignition scheme are described. In this context of this scheme, the initial fusion medium (p, ^{11}B) will also contain an initial alpha density, which is one order of magnitude lower, than the initial fusion species (refers to the proton density). In the present work, the numerical results refer to a neutral fusion plasma with initial Boron to proton density ratios, different from unity ($n_B/n_p < 1$), in order to optimize Bremsstrahlung losses and relatively low (40 keV - 80 keV) medium temperatures. The results of the simulations on the temporal evolution of the fusion species parameters enable the evaluation of the influence of the initially added supplementary alpha density, on the manifestation of the avalanche effect and the RR maximization in a shorter time. The proposed scheme allows the improvement of the fusion output gain.

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Fractional Laplacian Spectral Model of Anomalous Electron Diffusion in Magnetized Plasmas with Magnetic Islands and Stochastic Fields

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Energetic electrons (EEs) in magnetized plasmas are sub-populations of particles whose energy is orders of magnitude higher than the bulk electrons. These particles are known to exhibit anomalous diffusion in the cross-field direction, which results in non-Maxwellian energy distribution functions. While EEs are ubiquitous in laboratory conditions (tokamaks and stellarators) and in space plasma (the solar wind and the Earth's magnetotail), their origin and dynamics are poorly understood. Here we investigate how the anomalous diffusion of such particles is affected by the magnetic field topology in magnetized plasmas using data from the DIII-D tokamak and a Fraction Laplacian Spectral (FLS) model. In the FLS model, the probability for anomalous electron transport as a function of magnetic field topology is determined from the spectrum of the corresponding Hamiltonian. Here we examine the Hamiltonian structure of magnetic fields characterized by magnetic islands and stochastic regions. Nonlocal interactions due to magnetic islands are modeled by a fractional Laplacian operator, while random fluctuations of the field due to coil perturbations are represented by a stochastic potential term in the Hamiltonian.

The initial conditions for the FLS model are obtained from DIII-D experiments where Electron Cyclotron Heating and Current Drive (ECH/ECCD) pulses are used to excite electron populations around magnetic islands and stochastic regions. For each examined DIII-D experiment, TRIP3D reconstructions of the magnetic topology are used to quantify characteristic scales of magnetic islands and regions of stochasticity. Data from DIII-D energetic electron diagnostics (Thomson scattering and electron cyclotron emission) is analyzed to determine the observed electron diffusion regime (classical diffusion, sub-diffusion, or super-diffusion). The probabilities for transport calculated with the FLS model are then compared against detections of EEs from these experiments. We discuss universal relationships between magnetic island topology, the Hamiltonian operator that describes it, and the electron energy profiles expected to occur in that magnetic field.

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Detection of radiating magnetic islands in density limit disruptions of a current carrying stellarator

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Density limit disruptions in toroidal plasma experiments have been an active area of research for many decades. Density limit disruptions are plasma terminations that occur as the plasma density is increased and limit the maximum achievable density in tokamaks. A first principles understanding of the underlying physics causing these plasma terminations has been elusive and remains an open question to this day. We have shown previously that the density-limiting behavior of Compact Toroidal Hybrid (CTH) plasmas is qualitatively similar to that seen in tokamaks at low vacuum rotational transform, and is consistent with the classic final scenario of the density limit: current profile shrinkage leads to growing MHD instabilities (usually a $m/n = 2/1$ tearing mode) followed by loss of MHD equilibrium, and final disruption. As the vacuum rotational transform (and fractional rotational transform) is increased, the tokamak-like characteristics fade away and the discharges have a lack of MHD mode activity as well as the signatures of strong plasma current and negative loop voltage disruptive spikes. Recent observations of density limit-induced disruptions in the CTH experiment have made detailed measurements of the MHD dynamics just prior to the disruption. These measurements were aided by new bolometer arrays installed on CTH. A synthetically trained De-Convolution Neural Network (DeCNN) based inversion method was developed for the new bolometer arrays to capitalize on the available spatial information and enable tomographic inversion of the bolometer signals shown in the figure below. The inverted bolometer fluctuations show $m = 2$ spatial and temporal correlations with the poloidal magnetic field fluctuations indicating that the source of the radiation is the rotating $m/n = 2/1$ tearing mode observed prior to the density limit disruption. The peak radiation emission from the magnetic island is observed to correlate with the position of the island O-points. This result qualitatively supports and the theory of thermo-resistive magnetic islands being the underlying driving mechanism of density limit disruptions on CTH and possibly in tokamaks.

Characteristic profiles of radial electric field and parallel velocity obtained in W7-X using charge exchange recombination spectroscopy

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The initial operation of neutral beams in Wendelstein 7-X (W7-X) enabled the first measurements of the temperature and rotation of fully ionised carbon (C^{6+}) with a multi-chord charge exchange recombination spectroscopy system (CXRS). These results were presented in [1] together with the technical description of the CXRS installed in W7-X.

In the present work, a complete analysis of the radial electric field (E_r) and net parallel velocity ($V_{||}$) profiles of C^{6+} has been carried out for different NBI blips at several programs of the 2018 experimental campaign using the technique developed in [2]. The objective is to study trends in E_r and $V_{||}$ profiles in different plasma conditions and magnetic configurations, comparing it with neoclassical expectations. The profiles corresponding to individual measurement during short blips of neutral beam injection have been classified in an ECRH injected power (P_{ECRH}) and line integrated density (n_{eL}) parameter space for different magnetic configurations. Several measurements of E_r and $V_{||}$ profiles corresponding at comparable P_{ECRH}, n_{eL}, ion temperature profiles and electron temperature and density profiles are averaged in order to obtain representative profiles for both quantities.

The number of measurements available, covering a wide range of P_{ECRH} and n_{eL} values, for the standard and high-mirror magnetic configurations has allowed us to perform a study of the dependence of E_r and $V_{||}$ on P_{ECRH} and n_{eL} independently. In addition, we have compared the profiles of E_r and $V_{||}$ for different magnetic configuration in the range of $P_{ECRH} = 2000$ kW and $n_{eL} = 6 \cdot 10^9$ m^{-2}.

A study of high performance discharges was also carried out, in which the temporal evolution of the E_r and $V_{||}$ profiles is characterized. A parallel velocity increase during the diamagnetic energy peak is systematically observed.

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Impurity accumulation, radial electric field and turbulence in NBI heated plasmas in TJ-II

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Investigation of impurity transport in fusion plasmas is particularly relevant due to the deleterious effect that high concentrations of impurities have on plasma performance. Impurity transport can be driven by turbulent and neoclassical processes. In Stellarators, it is the neoclassical transport that determines the radial electric field, E_r: in plasmas with high density and comparable electron and ion temperatures, E_r is negative in the whole plasma column, i.e. the plasma is in the neoclassical ion root confinement regime. Under these conditions, neoclassical theory predicts a general impurity inward flux, which may lead to impurity accumulation in the plasma centre and, in the worst case, to a plasma collapse due to impurity radiation. Experimentally, however, the absence of impurity accumulation in some ion-root regime scenarios has been identified and attributed to turbulent diffusion [1,2].

In TJ-II plasmas, ion-root conditions throughout the plasma core are achieved in pure NBI heated plasmas at densities above n_e 1-1.2 x 10^{19} m^{-3} [3]. In these conditions, the impurity confinement time is higher than in electron-root regimes [4]. A rather good density control is achieved in NBI plasmas when operating under fresh lithium coated walls, however, as the lithium coating evolves, the good stationary conditions evolve towards a situation in which the plasma density rises relatively fast during the NBI phase, often ending up in a radiation collapse. A systematic comparison of plasmas heated with co- or counter-NBI shows differences in the maximum achievable density and stored energy; lower values are generally achieved in co-NBI heated plasmas associated to higher impurity accumulation. These differences can be hardly explained based on intrinsic differences between the two beam line geometries: both beams present similar re-ionization losses and transmission [5], as well as similar beam plasma coupling efficiency which increases with density for both co- and counter-injection geometries [6]. A slight difference is found regarding the amount of power deposited by each NBI; the counter-NBI is slightly higher, about 10%, due to the higher amount of prompt losses of co-NBI at the beginning of the slowing-down process. Prior to the plasma collapse, a more intense negative E_r and a reduction in the density turbulence are measured in co-NBI heated plasmas as compared to counter- NBI cases. Both, a more intense negative E_r and a reduction in the turbulence may explain the increase in the impurity accumulation by an increase in the neoclassical (inward) impurity pinch and a reduction in the turbulent (outward) impurity transport. In this presentation we report and discuss these findings aiming at the identification of the relevant physical mechanisms responsible for the experimental observations.

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TESPEL studies on the Z-dependence of impurity transport in different plasma scenarios in LHD

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The Tracer-Encapsulated Solid Pellet (TESPEL) method allows introducing a precise amount of a selected impurity inside the core region of a magnetic confinement plasma, via the injection of a polystyrene shell filled with a tracer material. The thickness of the outer plastic shell can be selected to achieve different deposition locations and a wide selection of elements can be used as tracers. These features make TESPEL a very powerful technique to undertake the studies of impurity transport in the core plasma, such as the mass effect of impurity transport [1].

Here, TESPEL injections are performed in the Large Helical Device (LHD) equipped with a wide variety of diagnostics [2], e.g., Reflectometers, Heavy-Ion Beam Probe (HIBP), Charge Exchange Recombination Spectroscopy (CXS), Vacuum ultraviolet (VUV) spectroscopy, etc. These diagnostics can be exploited to estimate the turbulence level and radial electric field in different plasma regions and to determine if impurity accumulation appears for various confinement scenarios. The main goal of our experiments was to change the turbulence by changing the electron temperature gradient and to study such an impact on impurity transport. For this purpose, the ECH power absorption profile was modified by changing the ECH power absorption position. And shell-type TESPELs, with an outer diameter of 700 μm, filled with Ti, Cu, and Mo, were injected into such plasmas. In addition, we performed TESPEL (with the same tracers above) injection experiments to investigate the impurity transport in plasmas with impurity hole phenomena [3]. To change the tracer-impurities' deposition location, we used the shell-type TESPELs, which diameter is 700um, and the ball-type TESPELs, which diameter is 900 um. Here, experiments are presented, and the experimental observations are presented and discussed.

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Studying fast-ion losses induced by Alfvén Eigenmodes and by pellet injection in NBI heated plasmas of the stellarator TJ-II

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A key scientific issue in the quest for fusion power is improving and maintaining plasma performance in a steady-state. This is hampered, in part, by fundamental wave-particle interactions in the plasma that can lead to significant particle transport, deteriorating the confinement of the plasma while can endanger also the integrity of the device. In magnetic confinement fusion, fast-ions constitute a source of particles and free energy that, under certain conditions, drive various unstable MHD instabilities that significantly degrade fusion performance. In particular, the study of the impact of Alfvén Eigenmodes [1, 2] and Alfvénic-acoustic waves in fusion plasmas [3-6] is of special importance for controlling fast-ion (i.e., suprathermal particle) transport across the magnetic field lines [7]. Efficient plasma core fuelling is also mandatory to maintain the appropriate plasma density profile for achieving the expected fusion power. Cryogenic pellet injection is currently the best candidate for efficient fuelling [8] and reaching an improved confinement regime, as it has been observed in TJ-II [9]. In this work, a recently upgraded Fast-Ion Loss Detector (FILD) [10-11], equipped with a dual detector system (PMT and CCD), has been used to study NBI-driven AEs in TJ-II plasmas. A ~120 kHz mode was observed in NBI plasmas with the upgraded FILD system, similar to AEs observed with Mirnov coils. In addition, a sharp reduction in fast-ion losses is observed when a hydrogen pellet is injected. This is followed by a gradual recovery of FILD signals to pre-injection values in the improved confinement phase induced by pellet injection. These observations require a detailed study in order to understand the particle transport induced by such interactions.

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Measurements of spatial periodicity and radial structure of NBI-driven Alfvén eigenmodes in the TJ-II stellarator

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Fast particle driven Alfvén eigenmodes (AEs) can be detrimental for plasma heating and plasma facing components, as they can enhance the transport of energetic particles [1]. On the other hand, the artificial excitation of selected eigenmodes has been proposed as a method for ash removal [2]. For these reasons, their study and control in present experimental devices is fundamental for burning plasma operation. To that effect, a new helical array of tri-axial Mirnov coils was recently installed and calibrated in the TJ-II stellarator [3] (heliac, R_0 = 1.5 m, a ≤ 0.22 m, four periods, B_0 = 0.95 T, V ≤ 1 m^3). This new set of magnetic coils enables the experimental determination of toroidal mode numbers, while enhancing the poloidal mode number determination capabilities of the existing poloidal array [4].

During the 2022 campaign the first experiments to test the capabilities of this diagnostic were carried out. Using on-axis Electron-Cyclotron Current Drive (ECCD) to modify the current profile (and therefore the rotational transform), a scan was made on magnetic configuration, EC beam incidence angle, and NBI injection direction (using co- and counter beams) to excite an assortment of different eigenmodes [5].

This work shows the results from this experiment, focusing on the determination of the spatial periodicity of the observed eigenmodes and using Heavy Ion Beam Probe (HIBP) [6] data to study the potential profiles of the perturbations. Tools such as the Lomb periodogram [7] and the SSI-method [8, 9] have been used for the mode identification, and a preliminary comparison between the experimental results and theoretical predictions obtained from the codes STELLGAP and FAR3D [10, 11] has been done.

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Nonlinear saturation characteristics of ITG and TEM turbulence in a tokamak using nonlinear gyrokinetic simulations and a POD method

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Magnetically confined plasma shows anomalous transport by micro-scale turbulence modes such as ion temperature gradient mode (ITG) and trapped electron gradient mode (TEM). The gyrokinetic code CGYRO [1] simulates the particle/energy transport induced by the microinstabilites in a local flux tube. Unlike ITG, which is saturated by zonal flows, TEM has different dominant saturation mechanisms depending on the electron profile [2]. In this study, we examine how the characteristics of turbulence differ depending on the saturation mechanism in ITG and TEM simulations by examining their proper orthogonal decomposition (POD) modes [3] and triad energy transfers [4]. The POD is a useful method to find a localized dominant basis contributing the saturation. Triad energy transfer between the modes shows whether the generated microinstabilities energy is transferred to larger or smaller scales.

The dependency of the electron density gradient and ion temperature gradient are investigated by both linear and nonlinear simulations in the cyclone base geometry. The results of the analysis revealed that different energy cascade patterns were observed among the low and high electron density gradient TEM and ITG. In the TEM with a low electron density gradient, no zonal mode POD pattern was observed. These results could potentially contribute to the development of reduced models for predicting plasma turbulence.

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Suppression of the m/n=2/1 tearing mode by electron cyclotron resonance heating on J-TEXT

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The experiments on the suppression of m/n =2/1 tearing mode (TM) by electron cyclotron resonance heating (ECRH) have been carried out on the J-TEXT tokamak. The effect of electron cyclotron wave (ECW) power amplitude and the deposition location on the suppression of the m/n =2/1 TM are investigated. It is found that the suppression is more effective when the wave is deposited closed to the rational surface. Partial suppression of the m/n=2/1 TM by ECRH have been observed when the ECW power is lower than 226 kW. With the ECW power increased to approximately 226 kW, the m/n=2/1 mode with approximately 3.16 cm can be suppressed completely. The rotation frequency of the m/n=2/1 TM is found to increase when the mode is suppressed. The amplitude of the m/n=2/1 mode has been modulated periodically by modulated ECW, which confirms that the local heating inside the magnetic island dominate in the mode suppression.

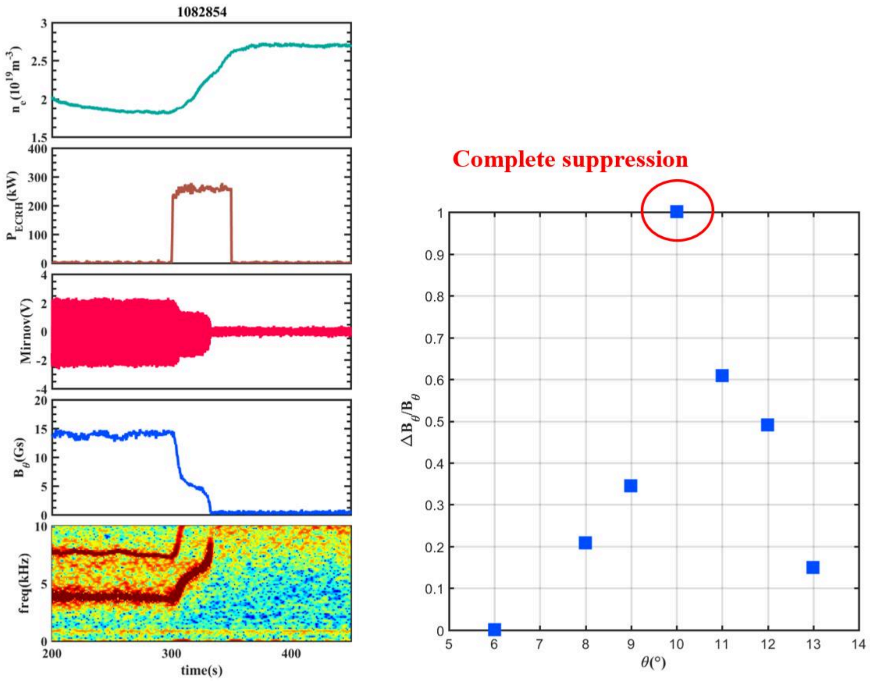

Figure 1. (left) Complete suppression of the m/n=2/1 tearing mode by ECRH. (right) The 2/1 mode suppression ratio as a function of the poloidal injection angle of ECRH launcher.

Predicting disruption in future tokamak with fewer data tokamaks by physics-guided approach

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Future tokamak disruption predictors will need to have the ability to learn from fewer data because of the high cost of acquire such large amount of experimental data. The data requirements for new tokamaks can be reduced by utilizing existing knowledge of disruption physics and tokamak discharge. Therefore, we propose a physics-guided disruption prediction approach to address the issue of few data for the next generation of tokamaks. The approach includes three disruption prediction methods to address three data scale scenarios. The IDP-PGFE (Interpretable Disruption Predictor based on Physics-Guided Feature Extraction) can achieve the performance of TPR (True Positive Rate) ~90% and FPR (False Positive Rate) ~10% when the number of disruptive discharges is as low as around 20 shots (and about 100 non-disruptive discharges) in J-TEXT. However, as the number of disruptive discharges drops to around 10 shots, only the data from one tokamak is unable to train an acceptable model (TPR~75%, FPR~15%). Therefore, we adapted the domain adaption algorithm CORAL (CORrelation ALignment) for the disruption prediction task. Benefitting from PGFE and CORAL, a cross-machine disruption prediction performance of TPR ~90% and FPR ~30% from J-TEXT to EAST could be achieved by using only 10 disruptive discharges (and 100 non-disruptive discharges) from EAST and thousands of discharges from J-TEXT. The beginning of tokamak operation is in a scenario without data, so the next generation of tokamak, such as ITER, needs to have the ability of zero-shot learning. We hope to build a transformer pre-training model applicable to tokamak discharges by utilizing the existing discharge data and plasma physics knowledge from various tokamaks to realize zero-shot learning for disruption prediction.

Effects of fast ions on collisionless trapped electron mode turbulence and zonal flow generation

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The self-regulatory drift wave-zonal flow (DW-ZF) system plays an important role in determining the transport and confinement in tokamak plasmas. Any effects on the DW-ZF system are worth to be paid attention. The stabilization effects of fast ions on the ion temperature gradient (ITG) mode turbulence have been widely reported in the literature. In future burning plasmas, the alpha (α) particles produced by the deuterium-tritium (D-T) reaction mainly heat electrons, and the collisionless trapped electron mode (CTEM) turbulence is thus one of the most promising candidates for the anomalous transport.

We firstly investigate the effects of fast ions on CTEM instability based on the linear gyrokinetic and bounce kinetic theories [1]. It is found that fast ions can stabilize the temperature gradient driven CTEM instability, which is qualitatively consistent with the gyrokinetic simulation results [2]. It is also found that the density gradient driven CTEM instability in long wavelength regime can be destabilized by fast ions mainly due to the downshift of real frequency by dilution effects, as compared to the case without fast ions. This is essentially attributed to more precession resonant electrons and the consequent stronger excitation of CTEM instability.

Furthermore, we also investigate the effects of fast ions on CTEM driven ZF [3]. The analytical expression for arbitrary wavelength polarization shielding of α particles has been also derived, and the reduction of total polarization shielding by α particles is qualitatively consistent with previous work [4]. Through the combination of fast ions' effects on both CTEM instability and polarization shielding, it is finally found that fast ions can enhance the CTEM turbulence driven ZF growth rate, and also broaden the range of radial wavenumber of ZF for positive ZF growth rate. This is mainly due to the destabilization of CTEM instability as well as the reduction of polarization shielding by the presence of fast ions. Moreover, the increment of ZF growth rate is further enhanced with higher fraction and steeper density profile of α particles.

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Investigation of edge plasma parameters approaching the density limit in J-TEXT Tokamak limiter and divertor configurations

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High density operation is considered as the baseline scenario for ITER[1]. However, the operational region of stable tokamak discharges is limited towards high plasma density. Cooling of the plasma edge is a key element in the density limit, which can lead to current shrinking and strong MHD activity, and ultimately disruptions[2]. Most of the research in this area has focused on the mechanisms that lead to strong edge cooling, such as impurity radiation and turbulent transport [3]. More basically, it needs more work to find out how much of the intensity and range of the edge cooling process will trigger MHD as approaching the density limit in experiments. And it is also significant to measure simultaneously the impurity radiation and the turbulent transport to judge whether there is a synergistic effect between them in the mechanism of the edge cooling.

For these purpose, edge plasma parameters investigations at approaching the density limit of the ohmic heating discharge in the J-TEXT tokamak have been performed under a variety of magnetic configurations: circular-section limiter configuration, high-field-side limiter configuration and high-field-side midplane-single-null (HFS-MSN) divertor configuration[4] with hydrogen fueling and methane seeding. In the experiments, the plasma parameters are plasma current I_p = 120 kA, central toroidal field B_T= 2 T, the safety factor q_a=6.3,5.5 and 4.2 respectively. In these three configurations, the CIII radiation observed from the visible light camera and photodiode array (PDA) system extend inward to the q = 3 rational flux surface. And the signal from electron cyclotron emission (ECE) indicates that the electron temperature near the q=3 surface in three configurations converge to a similar level. However, the edge electron temperature and density in the vicinity of last closed flux surface (LCFS) exhibit differences. The HFS-MSN divertor configuration has the highest electron temperature, density and turbulent thermal transport, measured by reciprocating Langmuir probe. These phenomena indicate that the fact that the cooling of the q=3 surface plays an important role in the density limit. Moreover, the edge cooling mechanism causing the q=3 surface is experimentally investigated and analyzed by comparing the injection of hydrogen and impurity methane, using Langmuir probes and absolute extreme ultraviolet (AXUV) bolometer array. It shows that impurity radiation and turbulent transport both have a effect on the cooling of q=3 surface, which deepens the understanding of the density limit.

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Study of runaway current dissipation on J-TEXT tokamak

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The mitigation of runaway current during disruption mitigation phase has been systematic studied on the J-TEXT tokamak. If the runaway electron suppression failed during the plasma disruption, a large runaway current will be formed, even if only a few RE seeds survived. The runaway current should be dissipated or soft landed within tolerance. It has been observed that the runaway current can be significantly dissipated by massive material injection, like massive gas injection (MGI) and Shattered pellet injection (SPI). The dissipation rate increased with the injected impurity particle number and eventually stabilizes at 28 MA s^{-1} by MGI. SPI has been chosen as the main disruption mitigation method, which has the capability of injecting material deeper into the plasma for higher density assimilation when compared to MGI. Another way to dissipate runaway current is soft landed by ohmic field, which the dissipation rate can be up to 3 MA s^{-1}. The robust runaway current dissipation provide an important insight on the disruption mitigation for future large tokamaks.

Roles of multiple modes during mode excitation by rotating RMP on J-TEXT

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The successive excitation of multiple modes,i.e.3/1 and 2/1 modes, by rotating RMP has been observed for the J-TEXT plasma with safety factor q_a is slightly smaller than 3, The evolutions of the modes' helical and radial structures can be obtained by magnetic probe arrays and local ECE measurement. The first destabilized mode is identified as an 3/1 external kink mode (EK), and the subsequent mode is 2/1 mode. The phase difference between the destabilized modes undergoes a conversion from -π to 0 during the excitation of 2/1 mode, and then the modes are kept in-phase during coexistence. Since the stability of the EK mode is sensitive to q_a, the in- fluence of 3/1 mode stability on 2/1 excitation is explored by setting various q_a platforms. The result suggests the presence of 3/1 EK mode significantly reduces the RMP current required for 2/1 mode excitation.It's found that the more unstable 3/1 mode provides a greater reduction in the RMP current required for 2/1 excitation as q_a approaching to 3. And this indicates the magnetic field component generated by the 3/1 mode through the toroidal coupling is involved in the excitation of the 2/1 mode. Flexible f_{RMP} can be used to adjust the initial frequency dif- ference between RMP field and the MHD frequency at q=2 surface. Different from the previous consideration on the single locked mode excitation, this work illustrates that with a pre-existed mode, the mode at the neighboring rational surface can be more easily excited with reduced external RMP or error field. This will be new challenge for the active MHD control actuator design.

Dynamic evolution of edge magnetic islands during the formation of island divertor configuration on J-TEXT

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Heat and impurity exhaust is a key issue for future fusion reactors to achieve long-pulse steady-state burning plasma. Although the standard poloidal divertor has been developed and studied on many tokamak devices, the concept has been recognized as problematic for future reactors due to a narrow power decay length (λ_q) which is inversely proportional to the plasma toroidal current [1]. On the W7-AS and W7-X stellarators that do not require plasma toroidal current, the island divertor configuration (IDC) has been successfully applied, and the experimental results have demonstrated the excellent properties of heat/particle exhausts. This provides a new perspective on the development of advanced divertor concepts in tokamak.

Recently, the IDC plasmas were established for the first time on the J-TEXT tokamak. In this experiment, a slow ramp-up of plasma current has been programmed to move the q=3 magnetic flux surface towards the plasma edge during an application of the m/n=3/1 resonant magnetic perturbation (RMP) [2], where m is the poloidal mode number and n is the toroidal mode number. However, surprisingly, when the edge safety factor, qa, is in the range of 3.6–3.3, edge-localized collapse events (ELCEs), characterized by a periodic process of excitation, rapid growth, sudden relaxation and disappearance of 3/1 edge magnetic islands, were observed. Furthermore, when qa is below 3.3, the ELCE disappears, while the 3/1 islands can be stably sustained by the RMP, but is opened by intersecting the divertor target plate. In this contribution, the dynamic evolution of the edge plasma profiles during the ELCE cycle will be presented. The stability of edge magnetic island is analyzed to explore the physical mechanism of ELCEs.

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Neural network assisted electrostatic global gyrokinetic toroidal code using cylindrical coordinates

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In the last three decades, several gyrokinetic simulation codes were developed, such as GTC, GYRO, ORB5, GENE, etc., to understand the microturbulence in the linear and nonlinear regime of the tokamak and stellarator core. These codes use flux coordinates, which encounter the mathematical singularity of the metric on the magnetic separatrix surface. To overcome such constraints, a neural network-assisted global toroidal PIC code in cylindrical coordinates has been developed to study electrostatic microturbulence in realistic geometry. A particular feature of GTC-X is a cylindrical coordinate system to advance particle dynamics, which allows particle motion in arbitrarily shaped flux surfaces, including the magnetic separatrix and the magnetic X-point in the tokamak. An efficient particle locating hybrid scheme for the charge deposition and field scattering using a neural network and iterative scheme-based algorithm as the search index for triangles has been implemented. GTC-X has used the field lines, particles, grid and mesh data for a given discharge to train the neural network built with the GTC-X as a universal approximator. This training data is used to speed up the major subroutines related to gathering and scattering operations of self-consistent gyrokinetic simulation. Presently GTC-X is the only code which integrates the multilayer neural network with field line geometry for self-consistent simulation in the world fusion program. Finally, as further verification of the capability of the new code, self-consistent simulations of ion temperature gradient and zonal flows in the core region of tokamak were carried out.

This work is supported by National Supercomputing Mission (NSM) (Ref No: DST/NSM/R&D_HPC_Applications/2021/4), Board of Research in Nuclear Sciences (BRNS Sanctioned nos. 39/14/05/2018-BRNS and 57/14/04/2022-BRNS), Science and Engineering Research Board EMEQ program (SERB sanctioned nos. EEQ/2017/000164 and EEQ/2022/000144).

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`gyronimo`: an object-oriented library for gyromotion applications

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The accurate computation of charged-particle motion in complex electromagnetic fields is a fundamental step for understanding many phenomena in plasma physics. In the magnetic-confinement fusion community, this fact translated into the development of a wide variety of numerical particle-tracing codes intended to address a diversity of issues such as ICRH/NBI heating and power deposition, resonant wave-particle interactions, or particle losses due to non-axisymmetric fields. Quite naturally, each particular application has very specific needs regarding the modelling tools it employs to achieve its goals: different coordinate systems and electromagnetic-field configurations or representations; distinct dynamical systems (guiding centre motion, full gyromotion, or something else in between) to be integrated in time with varying conservation properties to be followed and numerical requirements to be met; generic algorithm families (e.g., interpolation, root finding, and differential-equation integration) whose particular elements have assorted accuracy and convergence attributes. Most often, these modelling tools are developed and implemented in the particular context of each application, becoming thus hardwired to its specific requirements and traits. The end result is a low level of code reuse and a significant difficulty in sharing code improvements between different applications.

`gyronimo` is a library (or framework) designed around object-oriented programming concepts like inheritance, polymorphism, and specialisation in order to address the problems listed above. It provides a collection of abstract algorithms and other modelling tools that take care of many generic tasks such as evaluating differential operators over user-defined vector fields and coordinates or solving dynamical systems (the equations of motion or others) independently of specific geometries. Users may take advantage of the library functionality either by employing ready-to-use objects or by deriving new ones adapted to their own needs, in order to quickly test new ideas and workflows or to build specialised gyromotion applications. In this contribution, `gyronimo`'s main concepts and modelling tools are discussed. A set of examples, comparing full gyromotion and guiding-centre orbits for several magnetic configurations of the tokamak and stellarator type (both analytical and numerical), are presented in order to illustrate the potential of the library to leverage code reuse across different kinds of numerical plasma-physics simulations.

Full Gyromotion versus Guiding-Centre in Fusion Devices

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For fusion reactors to be able to achieve a self-sustaining burning plasma, there are several challenges to overcome. One of those challenges is to ensure that fast ions – originated either from fusion reactions or heating systems such as NBI or RF heating – are confined long enough to transfer their energy into the plasma bulk. When fast ion losses are significant, the plasma bulk cools down and the reactor wall experiences intense loads of energy that degrade its components and reduce its lifetime. Fast ion confinement is usually assessed using simulations of charged particle trajectories inside the reactor. Conventional ways to address the dynamics of these particles involve full-orbit approaches, or guiding-centre theory for those cases when the fields vary little during a gyration period and over a gyroradius.

In this work, three algorithms to compute particle trajectories are implemented and compared: the conventional guiding-centre dynamical system [1], whereas in full-orbit the Lorentz force dynamical system was solved with 4th order Runge-Kutta ODEINT stepper and the leapfrog Boris algorithm [2]. For each algorithm, the integration of the trajectories of fast ions are compared against one another in tokamak and stellarator equilibria magnetic fields, and the conservation properties of those algorithms are explored by using the constants of motion when they do exist. It is found that full-orbit and guiding-centre approaches show good agreement in the limit when the gyroradius is very small compared to the length scale of the fields, and the cases where they disagree are discussed.

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Type-I ELM triggering mechanisms diagnosed on a synthetic framework

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Precursor signatures of ELMs have long been observed experimentally at the ASDEX Upgrade, in particular associated with electron density oscillations measured with reflectometry diagnostics [1].

A recently established numerical framework, including non-linear MHD simulations using the JOREK code and full-wave simulations using the REFMUL code, is considered here to study the dynamics of Type-I ELM cycles from the point of view of synthetic reflectometry diagnostics in a ASDEX Upgrade like scenario [2]. In particular, the response of a conventional reflectometer set-up employed at the mid-plane of the low magnetic field side is used to investigate the characteristics of density fluctuations along the periods between Type-I ELM crashes.

It is shown that signatures imprinted on synthetic reflectometry signals can be correlated with the ELM triggering mechanisms, at least until some point before the explosive onset of the ELM occurs. After the precursor amplitude $\delta n_e/n_e$ becomes large enough, the reflectometer response transitions to a non-linear regime. When possible, characteristics of the ELM triggering mechanisms, such as the precursor frequency, are derived from the reflectometry data.

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Inner scrape-off layer profiles in highly shaped plasma configurations

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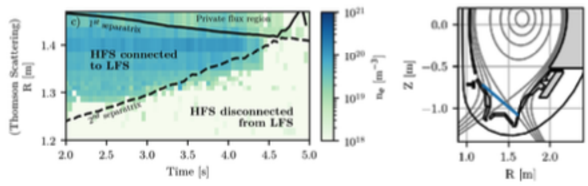
At ASDEX Upgrade, a highly dense and cold plasma often forms in the inner scrape-off layer (SOL). This high-density front is observable in the inner divertor and inner midplane using diagnostics such as reflectometry, Thomson scattering, divertor spectroscopy, and Langmuir probes. This contribution presents experimental evidence that two complementary phenomena regulate the high-density front formation: the ExB divertor drifts and the parallel outer-inner SOL transport. Our experiments cover L- and H-modes with highly shaped plasma configurations - relevant to future reactor concepts. We also compare experiments with forward and reversed toroidal field directions, resulting in opposite ExB drifts in the divertor region.

We observed that the magnetic connection between the inner and outer SOL strongly dictates the width of the high-density front, which is reduced to a minimum when the plasma approaches a double-null geometry. This effect might be explained by the decreased particle transport to the inner SOL as the magnetic connection decreases. Furthermore, near double-null, as the density front shrinks, the degree of detachment declines, plasma pressure and electron temperature increase near the inner strike point, and the neutral pressure decreases. Finally, we observed that the density front decreases drastically in a reversed toroidal field as the ExB drifts switch directions. This multi-diagnostic analysis furthers our understanding of the high-density front formation and its link to the inner divertor detachment.



Thomson scattering density measurements (left) along the blue line of sight (right). The electron density is higher in the inner SOL region magnetically connected to the outer SOL. This region is between the first separatrix (solid) and the second (dashed). As the configuration progresses from a lower single-null to a double-null, the second separatrix merges with the first, and the high-density region narrows.

AUG Shot #40085

Inner scrape-off layer profiles in highly shaped plasma configurations

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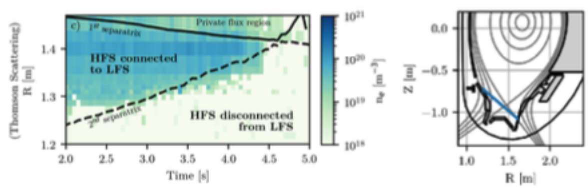

Thomson scattering density measurements (left) along the blue line of sight (right). The electron density is higher in the inner SOL region magnetically connected to the outer SOL. This region is between the first separatrix (solid) and the second (dashed). As the configuration progresses from a lower single-null to a double-null, the second separatrix merges with the first, and the high-density region narrows.

AUG Shot #40085

Magnetics only real-time equilibrium reconstruction on ASDEX Upgrade

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The real-time equilibrium reconstruction code for the ASDEX Upgrade tokamak [1], has been migrated to a Linux based C20++ code (JANET++). The motivation for this is the need for tighter integration with the control system and the goal of complementing the currently used function parameterisation based control when upper divertor coils are installed to investigate advanced magnetic configurations [2].

Time slices of three discharges with 5 poloidal betas of between 0.2 and 2.5 have been studied in detail. Cubic Hermite splines and cubic B-splines were used as basis functions for the equilibrium reconstruction. Cubic Hermite splines have the advantage over cubic B-splines that they are always positive along the normalised radius and that there is a simple expression for real-time evaluation. Magnetics only equilibrium reconstruction with 3 to 6 basis functions for the P' and FF' terms of the Grad-Shafranov equation was performed for 9 values of the regularisation weight. The equilibrium is compared to the equilibria calculated by CLISTE (magnetics only) [3] and IDE (pressure constrained and current diffusion coupled) [4].

The poloidal flux axis varies with the regularisation weight, but a particular regularisation weight at each poloidal beta can be found to give the best agreement with the other equilibrium codes. At the lowest poloidal beta, the energy content is extremely sensitive to the regularisation weight. This sensitivity decreases with increasing poloidal beta. At the highest poloidal beta the energy content for the optimum regularisation weight is 5% lower than the IDE value.

The performance of JANET++ in real-time simulated discharges will be reported. The inclusion of vessel wall currents in the real-time equilibrium reconstruction is planned.

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Tungsten Reflection Modelling for Raytracing Simulations

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Tungsten is considered for plasma facing components (PFCs) due to its high energy threshold and its chemical stability [1]. However, the reflectivity of tungsten was reported to be more than 90 % at 3 μm of wavelength [2]. Due to the high reflectivity, diagnostic systems will suffer from signal distortions as shown in the report of overestimation up to 85 % in an infrared imaging system [3]. For the concerns, the idea discriminating signals from reflections was proposed in PSI-25 [4]. It is the numerical method using full ray information, and the ray information was derived through the lab-built ray tracing program. For the realistic simulations, one of the most important issues is the reflection modelling of tungsten. Most measurements of tungsten optical properties are taken at room temperature, and the actual PFC has a quite different surface condition from those of the previous reports. So, the published data need modifications. Here, the measurements of emissivity of the actual PFC and its reflection modelling will be presented.

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Argon seeded-detachment during ELM control by RMPs in KSTAR

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In this study, we demonstrate argon-seeded discharges that exhibited a detached divertor during the full suppression and mitigation of edge localized modes (ELMs) by an ITER-like, three-row resonant magnetic perturbation (RMP) configuration in KSTAR. During the ELM suppression phase, the peak heat flux on the divertor target was successfully reduced from 1.6 MW/m^2 to 0.5 MW/m^2 via argon seeding. Further, the ion saturation current densities corresponding to the particle fluxes on both targets were reduced by more than 50%. During the RMP grassy-ELM regime, a further reduction to 0.1 MW/m^2 in the divertor heat load was successfully achieved. A highly localized radiation zone near the x-point was also observed during divertor detachment. The calculated degree of detachment (DoD) based on the two-point model increased to levels of approximately 3 and 2.3 for the outer target and inner target cases, respectively. These results provide valuable information regarding the effect of mid-*Z* impurities on RMP-detachment-compatible discharges.

Halo currents during downward vertical displacement events in the KSTAR tokamak

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The characteristics of halo currents (HCs), which flow through the supporting structures for the lower divertors between plasma and the wall of the vacuum vessel during downward vertical displacement events (VDEs) eventually causing plasma disruptions, have been experimentally investigated in the KSTAR tokamak [1,2]. The HCs are measured with small Rogowski coils enclosing the supporting structures between plasma facing component and the wall at four different toroidal locations, and they are also detected by a poloidal Langmuir probe array in the lower divertors at a certain toroidal position. In addition, the toroidal magnetic flux due to the HC can be estimated by using the diamagnetic flux measured with a poloidal loop mounted on the wall at a certain toroidal position. The investigation of the HC is carried out by using the experimental data obtained under the operational ranges of plasma current (= 0.4 –1.2 MA) and toroidal field (= 1.4 – 3.5 T) in the experimental campaigns from 2017 to 2022. Firstly, the correlations between the magnitude of the HC and two parameters, such as the vertical growth rate of the VDE and the current quench (CQ) rate, are investigated by using the HCs obtained from the three different methods, and the halo width is estimated from the Langmuir probe measurements. Secondly, the effect of the impurity seeding in the halo region on the magnitude of the HC is examined by adjusting the amount of the impurity puff (such as N_2) at the lower divertor region. Thirdly, the effect of the 3D magnetic field in the plasma edge region on the toroidal distributions of the HC is investigated by changing magnitude of the resonant magnetic perturbation field (n = 1), which is needed for understanding the toroidal asymmetric halo currents observed during the VDE in the KSTAR [1]. In this work, the results from the experimental investigations on the characteristics of the HC will be presented.

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New Langmuir Probe system in upgraded tungsten divertor of KSTAR

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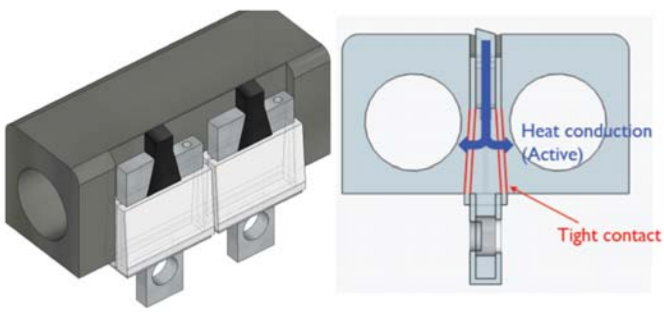
Langmuir probe (LP) system is designed to measure basic plasma parameters and their poloidal profiles and to handle a heat flux of up to 10MW/m2 will be installed in the upgraded tungsten divertor of KSTAR. The LP arrays will be installed in 2 cassettes in L and D ports among a total of 64 tungsten divertor cassettes. The LP array consists of 16, 18, and 18 LPs in the inboard, central and outboard divertors, respectively. The design of LP requires heat endurance, heat conduction, and replaceable probe tips. In addition, the measurement accuracy was improved by considering the tip shape as the plasma incident angle. The probe body is wedge-shaped for good contact. Figure 1 shows the shape of LP and the cross-sectional view of LP. The material of LP parts is selected through thermal analysis in ANSYS. The probe tip is CX-2002U from Toyo Carbon's CFC (Carbon fiber composites), the probe body is CuCrZr and the insulation jacket is AIN (Aluminum Nitride Ceramic). The cables inside the tokamak are insulated with fiberglass in stage 1 and copper and tin mesh tubes in stage 2 to protect against noise and heat from plasma. The LP array will be assembled as like figure 2 and can measure the plasma parameter of the poloidal profiles and is used by triple probes: this method allows the measurement of density, temperature, and floating potential as a function of time. The DAQ system consists of ACQ 424 32ch 1MHz, BNC connection panel, and battery system to communicate with PCS (plasma control system).



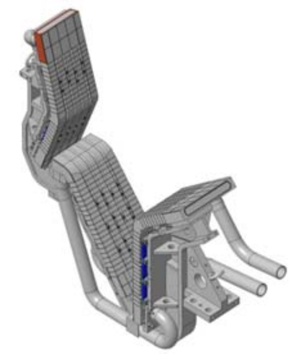


Fig. 1. Langmuir probe for tungsten monoblock divertor. Fig. 2. The array of LP in ID, CD, and OD.

Investigation of line-integrated effective charge (Z_{eff}) in KSTAR plasmas

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The effective charge (Z_{eff}) is a widely used measure of impurity level in fusion plasma research. Visible bremsstrahlung radiation measurement provides the best data for making Z_{eff} profiles since the analysis is relatively straightforward regardless of the impurity species in plasmas. In this study, line-integrated Z_{eff} has been calculated with a core channel of toroidal visible bremsstrahlung (TVB) array diagnostics. KSTAR TVB arrays were calibrated with a halogen light source and an integrating sphere. For the calculation of the line-integrated Z_{eff}, electron density and temperature at the plasma center were obtained from two-color interferometer (TCI) and electron cyclotron emission (ECE) diagnostics, respectively. The results were compared with the radial profiles of Z_{eff}, which were obtained from the reconstruction of TVB data and the fit of Thomson scattering measurement data. It has been found that the line-integrated Z_{eff} decreases with increasing electron density. The behavior of the line-integrated Z_{eff} has been investigated for L-, H-mode discharges, and impurity injection experiments. The line-integrated Z_{eff} can be used for monitoring overall impurity levels in KSTAR plasmas without the reconstruction or fitting of measured data

Toroidal rotation and impurity dynamics in KSTAR

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Korea Institute of Fusion Energy

Toroidal rotation and impurity dynamics play an important role for magnetic confinement fusion researches because the former is helpful for the stabilization of deleterious magneto-hydrodynamic modes and the latter contributes a critical role to improve plasma performance. A tiny amount of trace argon gas injection applies for these studies by measuring the helium-like argon x-ray line’s Doppler shift for toroidal rotation and total emissivity for impurity behaviors from an x-ray imaging crystal spectrometer (XICS) in KSTAR. The XICS utilizes for all experimental conditions including an ohmic heating and various auxiliary heating sources cooperating with controllable trace impurities such as argon gas injection that usually does not perturb discharge conditions. The core toroidal rotation and impurity dynamics with various plasma discharges are investigated. Especially, the core emissivity calculated from the measured helium-like argon x-ray lines stay a long time more than 30 s with a single argon gas injection at 0.5 s that implies the trace argon impurity confinement time is extremely long under certain experimental conditions. In this presentation, a possible mechanism of the extremely long impurity confinement time and toroidal rotation behaviors from various KSTAR plasmas are presented.

*Work supported by Ministry of Science and ICT under KFE R&D Program of "KSTAR Experimental Collaboration and Fusion Plasma Research (KFE-EN2101-12)".

Probabilistic modeling of signal intensity on the spectrograms of microwave reflectometry for the plasma diagnostics of electron density profile

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To reconstruct the electron density profile of tokamak plasmas, phase of the reflected microwave is measured depending on its radio frequency. As the phase information in the detected waveform can be captured on the vertical scale of its spectrogram, i.e. from the tone heights at each time slice of the wavelet transform. In practice, such a continuation of detected tone heights is traced as an imaginary path on the spectrogram. Thus, it is critically important to recover the line of path on the blurry and interrupted signal intensities over the unwanted clutters. As such an interruptions in patches is subject to the nodal waveform of raw signals with modulated amplitude to zero, special attention is paid to the recent idea of the Gaussian-derivative wavelet to revive the vanished traces around the nodes of irregular amplitude modulation. However, it is hard to recognize the pattern of vanishing intensities , i.e., where the Gaussian-derivative wavelet is advantageous over the common method, for instance, with the Morlet wavelet. On the difficulty to discriminate the nodal patterns against the noisy clutters, a probabilistic approach is proposed to describe the signal intensities at each slice as a mixture of ideal basis functions sampled from the beat pattern of a sinusoidal waveform. At first, we check the feasibility of our idea with the the fixed number of components in the probabilistic mixture by maximizing the log-likelihood of the signal intensities through the E-M (estimation-maximization) process. Then, on the success of the preliminary check up to recover the fixed number of signals, Bayeian inference of variational mixture is designed to develop the practical routines of phase recovery for the microwave reflectometry in KSTAR. Under the attempt of improved sensing, a generative NN (neural network) surrogate is also tested to implement a more realistic model of deformed ideal bases with latent parameters, by training the generative model of probabilistic basis with real waveforms.

The Visible Bremsstrahlung System for the calculation of the effective charge(Z_{eff}) in KSTAR

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The study of impurity behavior is an important part of fusion plasma research. The Impurity behavior must be understood to control impurities in fusion reactors. The effective charge (Z_{eff}) represents the total impurity contamination of the plasma, and the effective charge (Z_{eff}) can be experimentally derived from the intensity of the plasma bremsstrahlung emission.

The visible bremsstrahlung diagnostic systems have been developed and operated for calculate the effective charge (Z_{eff}) in KSTAR. An interference filter with a central wavelength of 523 nm was used for the analysis of the plasma bremsstrahlung emission. The visible bremsstrahlung diagnostic system consisted of a collection lens, an optical fiber, interference filter and the detector. The detector was used semiconductor photodetectors manufactured by Hamamatsu. The signal from PMT was measured by DAQ system through IV converter.

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Edge Turbulence Dynamics during Pedestal Evolution and Collapse in KSTAR H-mode Plasmas

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The pedestal turbulence appears as an electron temperature fluctuation while the electron transport barrier remains in its final form before the edge-localized mode (ELM) crashes. Because the pedestal turbulence is closely related to the pedestal evolution and collapse, in this study, the microscopic spatial structure and dynamics of electron temperature fluctuations have been investigated [1, 2]. We comprehensively compared the electron temperature fluctuations of pedestal turbulence observed during the pedestal evolution with different instabilities and revealed the role of pedestal turbulence in the pedestal evolution and collapse. Here, a new diagnostic method was used to analyze the micro-instability characteristics of the KSTAR pedestal more accurately [3]. Broadband ECE was measured using a recently built high-speed digitizer, and the high-frequency pedestal turbulence was accurately observed during the inter-ELM-crash and RMP-driven ELM suppression. A comprehensive comparison with the properties of various instabilities indicates that a micro-tearing mode was associated with the pedestal evolution and collapse. On the other hand, the turbulence characteristic in the ELM suppression is close to the interchange modes, which means that the transport characteristics of turbulence can induce two different pedestal structures and ELM dynamics. The quadratic transfer function (QTF) was calculated to investigate the effect of these turbulent fluctuations on the pedestal evolution and crash [4]. The QTF results show that in the inter-ELM-crash period, the pedestal energy is nonlinearly transferred from turbulent eddy to MHD mode, expanding the mode structure in the radial direction, while in the RMP-driven ELM suppression period, the dominant mode does not grow due to the energy exchange among the turbulent eddies in the pedestal.

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EMC3-EIRENE simulation of the magnetic field ripple effect on edge impurity flows in Heliotron J

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The transport of edge impurities is an important issue to achieve high-performance fusion plasma. The distribution of impurity depends on the bulk plasma parameters which are strongly influenced by the parallel gradient of the magnetic field. Fluid descriptions of the bulk plasma transport under a non-uniform magnetic field as in the scrape-off layer(SOL) of tokamaks have been studied [1]. However, those for non-axisymmetric devices have not been clarified in detail and the analysis for impurity is an ongoing work.

In this study, the transport of plasma and impurity in the SOL of non-axisymmetric device, Heliotron J, was analyzed using the EMC3-EIRENE code [2]. In the edge region of Heliotron J, the helical coil produces the helical magnetic field ripples along the field line. We found that the electron density and electric potential decrease with increasing magnetic field strength along the field line, which lead to a concentration of carbon impurity at the position of local minimum potential under a lower density condition while a dispersion under a higher density condition. Based on a fluid description, the plasma response is explained by the fact that the strong magnetic field shrinks the flux tube to create an electron density dip as in a subsonic nozzle in the neutral fluid. The potential dip, resulting from the density dip, creates an impurity concentration under lower density conditions since impurity pressure is balanced by the electric field force rather than the friction force. On the other hand, the potential dip creates an impurity dissipation under higher density conditions since friction force with ion dominates impurity transport with which the impurities are dragged by the electron and ion density.

This work was supported by JSPS Core-to-Core Program, A. Advanced Research Networks, "PLADyS".

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Two-dimension Kinetic full-wave analysis of cyclotron waves with the integral form of dielectric tensor

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Full-wave analysis including kinetic effects of plasmas has been extensively employed in describing wave heating and current drive in tokamak and mirror plasmas. Most of previous kinetic analyses of wave propagation and absorption in an inhomogeneous plasma are based on the wave number. The dielectric tensor in a hot plasma has been usually expressed as a function of wave number. In the full-wave numerical analysis, however, the wave number is not available a priori. Therefore the cold plasma wave number approach, the differential operator approach, and the Fourier expansion approach have been utilized in conventional kinetic analyses. Recently an integral operator approach based on the integration along unperturbed particle orbit has been introduced systematically. In this approach, Maxwell's equation with the integral form of dielectric tensor

$$\nabla \times \nabla \times E(r) - \frac{\omega^2}{c^2} \int \mathrm{d}r' \overleftrightarrow{\varepsilon}(r,r') \cdot E(r') = \mathrm{i}\,\omega\mu_0 j_{\mathrm{ext}}$$

is numerically solved as a boundary-value problem by extended finite element method (FEM). Usually the integration is localized in an element in FEM for differential equations, but in FEM for integro-differential equations coupling between different elements occurs. In a magnetized plasma, the guiding center motion along an inhomogeneous magnetic field and the cyclotron motion perpendicular to the magnetic field can be taken into account in deriving the dielectric tensor as an integral operator. 1D full-wave analysis using the integral form of dielectric tensor was applied to ion cyclotron (IC) heating in the presence of energetic ions and the O-X-B mode conversion of electron cyclotron (EC) waves. In this presentation, 2D full-wave analysis with the integral form of dielectric tensor is provided. The numerical code TASK/WF2D has been recently extended for the analyses of 2D mode structure of the O-X-B mode conversion, lower hybrid current drive, and IC heating in tokamak configuration as well as IC heating in mirror configuration. Comparison with conventional collisional cold plasma approach and differential operator approach is also presented.

Collaborative approaches between numerical plasma simulations and machine learning techniques

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Machine learning techniques, particularly deep learning techniques, have been widely applied to address issues in fusion plasma physics, providing support for experimental analyses and accelerating numerical simulations. We have developed and applied techniques that complement fusion plasma simulations using deep learning techniques. These techniques include the development of a surrogate transport model [1], a novel turbulent transport model [2], and a convolutional-neural-network (CNN)-based model that reads images to analyze and predict the evolution of flux-tube nonlinear gyrokinetic simulations [3]. The NN surrogate models behave as rapid transport models in conventional transport codes and the CNN-based models are expected to serve as a tool to support gyrokinetic simulations.

Very recently, the CNN-based model have been extended as a multimodal model that also incorporates numerical data of a fluctuation amplitude as input and can predict heat fluxes [4]. Moreover, it has been found that a newly developed combined model, consisting of a recurrent neural network and a CNN, has the potential to predict fluxes in the saturation phase based on data obtained during the fluctuation growing phase.

Stiff transport models are known to tend to produce transport coefficient profiles with spikes, and various approaches have been considered to overcome this issue [1]. Our recent work has shown that a Physics-Informed Neural Network (PINN) based transport code can stably deal with stiff transport models, even with large incremental time steps.

These machine learning-based methods will greatly assist traditional approaches to research in fusion plasma physics. Our study will be detailed in the conference.

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2D Imaging of Small Pellet Ablation Cloud Density in Heliotron J Based on High-speed Spectroscopy for Balmer-β Line Broadening

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Hydrogen pellet injection is regarded as an effective fuelling tool in fusion-relevant magnetic confinement devices. We have developed a small pellet injector, 0.6-1.2 mm in diameter, in Heliotron J, medium-sized helical devices having R = 1.2 m, a = 0.17 m, B ~ 1.5 T [1] and have observed a unique fluctuating behavior of the ablation cloud around the pellet [2]. The density of the cloud is one of the key parameters to evaluate the fueling processes and efficiency, as well as the driving mechanism of its dynamic motion. However, conventional spectroscopic methods for larger devices [3] are hard to be applied to this low-density cloud.

In this study, we measured the 2D image of intensity and density from the spectral line shape of H_β at 486 nm using a high-speed (10k fps) non-unity magnification (300/180 focal ratio) grating spectrometer. The emission collected from the viewing area, 144 x 144 mm^2 square at the midplane including the pellet trajectory, is rearranged using the 2D to linear optical fiber bundle onto the entrance slit of the spectrometer.

A typical result (shot#82554 ECH+NBI heating) shows that the bright "emission cloud", indicating the pellet location, traveled along the injection trajectory at the speed of around 230 m/s, which fairly agrees with the one obtained from the arrayed Hα signal. The "density cloud" deduced from the Stark broadening, on the other hand, exhibited different features — elongated along the local magnetic field line having a density around 10^{20} –10^{21} m^{-3}.

(This work was supported by JSPS Core-to-Core Program, A. Advanced Research Networks, "PLADyS".)

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Non-uniform Fluctuation Characteristics inside an Edge Magnetic Island Structure in Heliotron J

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A non-axisymmetric magnetic field is utilized in tokamaks and helical/stellarators to control heat and particle transport in the scrape-off-layer (SOL) and diverter region. In the SOL and divertor regions, the parallel transport is basically dominant. However, the perpendicular transport induced by turbulence and non-diffusive transport such as blobs potentially affects the footprint of heat and particle fluxes on the divertor plate, and the influence of the magnetic field structure on fluctuation and fluctuation-induced transport in the SOL region is not yet fully understood. This study aims to experimentally characterize the effect of magnetic islands in the SOL region on the fluctuation characteristics and transport in the medium-sized stellarator/heliotron device, Heliotron J with a flexible magnetic configuration controllability.

In Heliotron J, island divertor-like SOL configurations can be generated by controlling the rotational transform. In the configuration, the magnetic island is located outside the last closed flux surface and has a nested flux surface structure with a long connection length (> 1000 m) comparable with the core region in the vacuum condition. An ECH modulation experiment reveals the existence of the magnetic island even during plasma discharge, where a phase delay of the heat propagation is observed inside the island.

Fluctuation characteristics in the magnetic island are surveyed in the island configuration. The fluctuation of the ion saturation current $\widetilde{I_s}$ and the poloidal electric field $\widetilde{E_\theta}$ are measured with a multi-pin Langmuir probe, and the fluctuation-driven particle flux Γ_e is also evaluated. The $\widetilde{E_\theta}$ amplitude has a peaked profile inside the magnetic island, while $\widetilde{I_s}$ has a flat profile, resulting that Γ_e is peaked inside the magnetic island. This result demonstrates that the fluctuations and fluctuation-driven transport are not uniform but have a spatial structure inside the magnetic island in the SOL region.

This work was supported by "PLADyS", JSPS Core-to-Core Program, A. Advanced Research Networks.

Magnetic and electrostatic fluctuation effects on radial transport of ECH supra-thermal electrons and related toroidal torques in tokamak plasma

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Spontaneous flows related to the ECRH heating have been observed in tokamaks and stellarators: JT-60U[1], LHD[2], HSX[3], etc. We have studied the $\mathbf{j} \times \mathbf{B}$ toroidal torque due to the radial diffusion of supra-thermal electrons during ECH in LHD and HSX applying GNET code[5]. It is found that the $\mathbf{j} \times \mathbf{B}$ torque related to the supra-thermal electrons plays an essential role in the toroidal flow generation in the LHD and HSX plasmas[2, 4].

On the other hand, in axisymmetric tokamaks, it is well known that this $\mathbf{j} \times \mathbf{B}$ torque would be canceled by the collisional torque due to the toroidal precession motion of the supra-thermal electron. However, in the real tokamaks, finite non-axisymmetric fields exist, such as the toroidal field ripple, resonance magnetic perturbation (RMP) and electromagnetic fluctuations due to the plasma turbulence. These non-axisymmetric fields would generate the uncanceled toroidal torque. In this paper, we study the effect of magnetic and electrostatic fluctuations on ECH supra-thermal electrons' behavior and the associated toroidal torque, assuming a simple circular cross-section tokamak.

We apply the GNET code[5], which can solve a linearized drift kinetic equation for the deviation of the electron distribution function from the Maxwellian distribution, $\delta f = f - f_M$, by ECH in 5-D phase space using the Monte Carlo method, and evaluate the $\mathbf{j} \times \mathbf{B}$ and collisional forces. We introduce the magnetic and electrostatic fluctuations with 21 poloidal, m, and toroidal, n, modes $(m,n) = (10N\ to\ 30N, 10N)$ and N is an integer varying 1 to 5.

We show that fluctuations generate a uncalceled toroidal torque and that the magnetic and electrostatic fluctuations drive toroidal torques in opposite directions. The toroidal torque is proportional to the square of the fluctuation intensity in both cases, but the initial energy dependence is significantly different. It is also found that the fluctuation distribution and the heating location affect the direction of the toroidal torque.

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Particle Transport Study for Solid-hydrogen Pellet Injected Plasma Using Event-triggered Thomson Scattering Measurement System on Heliotron J

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Fuel supply to the plasma core by a solid-hydrogen pellet injection is a key issue to improve the performance of magnetically confined plasma. However, particle transports during and after pellet ablation are not well understood. In Heliotron J, we have developed an Event-triggered Thomson Scattering Measurement System that is synchronized with the pellet ablation event to investigate the particle transport during and after the injection. The system enables us to inject the Nd:YAG laser pulse into the plasma and measure electron temperature and density profiles 320 μsec after the event.

We measured the temperature and density profiles of electron cyclotron heated (ECH) plasma (70 GHz, 247 kW, $N_{//} = 0.38$) with pellet injection. A line-averaged electron density before the pellet injection is ~0.7×10^{19} m^{-3}. At ~0.1 msec after the end of the pellet ablation, the density profile was changed from hollow shape to peak shape. The density in the plasma core increased up to ~5×10^{19} m^{-3} at ~0.5 msec. At ~0.6 msec, the density gradually decreased. The shape of the profile returned to hollow shape after 30 msec.

Particle flux Γ is evaluated assuming that there are no particle sources in the plasma core after the end of the ablation. The direction of the evaluated flux is inward from ~0.1 to ~0.5 msec. At ~0.6 msec, the flux direction remains unchanged in the inner region (r/a > 0.55), while it changes outward in the outer region (r/a < 0.55). The particle flux can be described by diffusion and convection terms ($\Gamma = -D\nabla n_e + Vn_e$, where D is the diffusion coefficient and V is the convection term). Since the change of the evaluated flux is small as the density gradient changes, the diffusion coefficient is small compared to the convection term. The convection term is evaluated as ~-0.2 m/msec at r/a ~0.4 and the flux change is very small, then the inward convection dominates the particle flux. We can conclude that the peaking phenomenon of the electron density profile after the end of the ablation is caused by the inward convection.

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3D calculations of RF inductive coupling in the drivers of SPIDER: comparison with experimental data

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SPIDER is the 1:1 scale prototype negative ion source for the main NBI heating system in ITER. Before reaching the acceleration grids, negative ions are produced in the plasmas produced and sustained in cylindrical chambers commonly called drivers. In SPIDER, the power is transmitted from strong RF currents to the source plasma via electromagnetic induction. Previous experimental campaigns indicate that the requisites for the NBI ITER system may require some modifications in the design of the drivers. Indeed, a new parallel experiment, MINION, has been proposed as test bed for the proposed modifications, like the inclusion additional permanent magnets surrounding the cylindrical cavity of the drivers. The numerical modelling of SPIDER drivers must provide sound scientific grounds for the final development, which includes the design of new experiments in both devices, MINION and SPIDER. In previous works we have solved the induction equation for the magnetic vector potential using the Finite Element Method in 3D geometry, which provided information about the power transfer efficiency in agreement with other studies for SPIDER. In the present work we move forward with the comparison with experimental data: the equivalent impedance of the model driver and the power dissipation in the Faraday shield lateral wall (FSLW) are in acceptable agreement with the respective measurements of effective impedance and power exhaust from the cooling circuit. The ohmic power density is found highest in the extremes of the FSLW slits. We present a first estimate of temperature saturation due to the positive feedback loop: higher temperature of the copper parts $\Rightarrow$ higher copper resistivity $\Rightarrow$ higher dissipation $\Rightarrow$ higher temperature of the copper.

Multi-frequency ICRF simulations of NBI-heated plasma with TORIC-SSFPQL code

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One of the main differences between the present-fusion-device plasmas and a future burning one is the presence of a substantial fraction of energetic (MeV) fusion alphas in the core of the latter. Addressing the physics of burning plasmas and validating the present numerical codes have motivated in the years experiments to study the influence of energetic particles (EPs) on the nature and strength of MHD instabilities, Alfvén activity and microturbulence in the plasma core. Neutral beam injection (NBI) is one of the possible actuators of fast ions (FIs) in present devices, together with the ion acceleration by radio-frequency waves in the ion-cyclotron range of frequencies (ICRF). The EP energy of the former is limited to about the injection energy (presently up to a few hundreds of keV), whereas the latter suffers from the competition with direct electron absorption. However, because of the finite-Larmor-radius nature of the ICRF acceleration at the cyclotron harmonics, NBI-FIs can be selectively further energised by ICRF to increase their population (both in energy and density), and thus their effects on the plasma. It is possible to optimise further this synergetic ICRF-NBI process by exploiting a ladder-acceleration approach by simultaneously launching waves with frequencies corresponding to different IC harmonics inside the plasma. These experiments have been recently started on ASDEX Upgrade (AUG) tokamak, and they motivated the extension of the full-wave TORIC code coupled with the steady-state Fokker-Planck quasilinear (SSFPQL) solver to simulate multi-frequency ICRF scenarios. We discuss the implementation of the multi-frequency and multi-mode quasilinear operator with emphasis on the numerical challenges and necessary optimisations. We present results obtained for various AUG-like scenarios, and, in particular, we discuss the relevance of the choice of IC harmonics on the final EP distribution function. Accounting for energetic particles makes necessary to include finite-width orbit effects on the radially broadening of the RF absorbed power. We discuss a heuristic model for these effects implemented in TORIC-SSFPQL.

Phase Space Zonal Structures and equilibrium distribution functions in ORB5

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Abstract. Phase space zonal structures (PSZS), obtained by averaging out dependencies on angle-like variables in the energetic particle (EP) distribution function, play a fundamental role in regulating EP transport induced by Alfvén instabilities in burning plasmas [1, 2], acting as a slowly varying nonlinear equilibrium state. Therefore, they are of great interest for the development of reduced models for the description of EP heat and particle transport on long time scales, comparable with the energy confinement time, for future burning plasma experiments. The information provided by the finite element projection of the distribution function could also be used for significantly improving the quality of δf PIC simulations, by adjusting and updating the plasma reference state (background distribution function), during the nonlinear evolution of the system, consistently with PSZS dynamics. In this work, we discuss the implementation of a PSZS based background distribution function in the global gyrokinetic code ORB5 [3, 4], in experimentally relevant conditions.

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Main and impurity ion heat transport studies at ASDEX Upgrade

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Understanding and optimizing energy confinement is fundamental for the success of future fusion power plants. Main ion energy transport is particularly important, as the main ion temperature directly impacts the fusion power production. The development of a new edge main-ion spectroscopic diagnostic and a forward model for the interpretation of the deuterium spectra have enabled the direct measurement of the edge main ion temperature (T_D) at the full-metal-walled ASDEX Upgrade tokamak [1]. The diagnostic covers 6 cm in the steep gradient region with a spatial and temporal resolution of 3 mm and 1.5 ms, enabling detailed characterization of energy transport in the main ion channel.

In this work, experiments have been carried out in H-mode plasmas, with different collisionalities and heating schemes to investigate the main ion energy transport in the plasma edge [2]. It is found that the main and impurity ions are in thermal equilibrium when the direct ion heating via NBI is high, while the pedestal top T_D is observed to be higher than the impurity temperature (T_Z) in inter-ELM phases with low Q_i/Q_e. The experimental observations are further interpreted by multi-species power-balance analysis with the transport code ASTRA [3-4], which consistently includes the two ion species and collisional heat exchange terms. The main ion and impurity NBI power depositions are calculated with the ASCOT code [5]. The heat diffusivity ratio χ_D/χ_Z is compared to a database of gyrokinetic simulations carried out with the GKW code [6].

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Edge turbulence characterization of the EDA H-mode in ASDEX Upgrade

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The mitigation of ELMs is crucial for ITER in order to avoid damaging plasma-facing components along its operation. Among the ELM-free regimes, the enhanced D-alpha (EDA) H-mode combines several requirements for ITER and beyond, such as high energy confinement, low impurity accumulation, high Greenwald fraction, and compatibility with a highly radiative cooling edge [1]. The main signature of the EDA is the presence of a quasicoherent mode (QCM) that is believed to prevent the pressure gradient from overcoming the peeling-ballooning boundary, making EDA an ELM-free regime. Nevertheless, the driven instability responsible for the appearance of the QCM is not well understood, making any extrapolations to future devices challenging. With the aid of a high-heat flux ball-pen probe head installed on the midplane manipulator of ASDEX-Upgrade [2], the QCM in EDA was extensively investigated. Profiles of density, electron temperature, and plasma potential from the scrape-off layer (SOL) to the edge, as well as fluctuations, are measured simultaneously, allowing the mode to be localized and measured at its driven location. Analysis reveals that the mode is located in the pedestal gradient region but spreads into the near SOL, largely impacting the turbulence level there. The QCM induces significant particle transport as deduced from the fluctuations of density and potential measured with the probe. However, the mode structure has a radial dependency. At the driven location, an anti-correlated cross-phase between density and potential fluctuation was observed, which is a fingerprint of kinetic shear Alfvén wave [3], as also observed in simulations where the kinetic ballooning mode (KBM) is the dominant instability [4, 5]. Further outside, the cross-phase approaches zero, suggesting that the QCM changes its character to drift-interchange [3].

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Characterisation of the divertor conditions with impurity seeding in reversed field H-mode discharges at ASDEX Upgrade

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A set of impurity seeding experiments characterizing the role of neutrals in modifying divertor and scrape off layer (SOL) properties has been performed in the ASDEX Upgrade tokamak. The impurities (nitrogen, argon and neon) have been injected into high density ($n_{e,av}/n_{GW} \sim 0.8$) H-mode plasmas with the ion $B\times\nabla B$ drift away from the X-point. The modifications of the divertor profiles have been identified by the divertor Thomson scattering measurement. In the near SOL at the high field side close to the X-point the electron temperature $T_{e,div}$ decreased from ~ 30 to ~ 2 eV and electron density $n_{e,div}$ increased from ~ 2 to ~ 5×10^{20} m^{-3}. In the SOL at the low field side, we see a slight decrease of $n_{e,div}$ and an increase of $T_{e,div}$. The neutral particle flux increases in the private flux region, and neutral compression between the divertor and main chamber increased strongly. The target neutral recycling decreases with a globally decreased density profile inside the pedestal. The divertor radiation power decreases by ~ 2 MW with an increased core radiation power, and the radiation front moves further upwards at the high field side close to the X-point, as measured by the multi-channel bolometry. Particle balance analysis by SOLPS-ITER modelling including drifts shows that volumetric recombination driven by impurity seeding not only can lead to strong changes in local plasma parameters, but also plays a role in modifying the global particle sources. The simulation offers a qualitative explanation of the experimental results.

Edge stability analysis and mode locking in 3D tokamak plasmas

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In H-mode tokamak plasmas, edge localized modes (ELMs) limit the achievable pressure-gradient in the edge region. Since ELMs are projected to cause severe damage to future fusion devices, it is important to understand the onset conditions of ELMs as well as the methods to mitigate or suppress them. One such method is the application of magnetic perturbation (MP) fields. The plasma responds to the applied MP field by developing corrugated flux surfaces, breaking the axisymmetry of the plasma. The ELM onset is well-described by the growth of magnetohydrodynamic (MHD) instabilities at the edge. This provides a framework to analyze the operational space of ELMs and their mitigation/suppression. While there are linear MHD stability studies in the limit of small MP fields or for special types of instabilities, the impact of MPs on MHD stability in general is not well understood.

In this work, we use the linear MHD stability code CASTOR3D [1, 2] for the numerical stability analysis of selected non-axisymmetric (3D) tokamak plasmas. We show that the instabilities are helically localized such that they mainly occupy energetically favourable regions of the 3D equilibrium and distinguish two types of localization: strict locking and quasi-locking. Strictly locked instabilities are localized with respect to a certain corresponding 3D equilibrium harmonic. These instabilities are locked below a critical value of the plasma rotation; above this critical threshold the modes start to rotate non-uniformly. Quasi-locked instabilities are localized by an envelope related to the dominating 3D equilibrium harmonic; they rotate nearly uniformly even at small values of plasma rotation, but their amplitude is determined by their envelope which remains locked. The localization calculated by linear MHD is successfully compared to experimental ECE measurements. Finally, results on the effect of the MP fields on the linear MHD stability limit, i.e. the marginally stable edge pressure, are presented. In general, MP fields lead to a reduction of the stability limit, as empirically observed in experiments.

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Excitation of high frequency waves in non-linear fully kinetic Vlasov simulation

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The Vlasov-Fokker-Planck-Maxwell system can describe physical phenomena in a tokamak plasma on all scales starting at large dynamics of the size of the device down to micro-scales of the order of the Larmor radius. However, up until recent years full 6D simulations were beyond the available computational capabilities. As an approximation, gyrokinetic transport simulations are in good agreement with experiments in the tokamak core regime, where only small perturbation amplitudes and gradients are present. However, in regimes of high gradients and large turbulence fluctuation amplitudes, such as the plasma edge of a tokamak, the gyrokinetic approximation is debatable and at least those models based on a δf approximation break down completely.

On the other hand, experimental results from the PLT (Princeton Large Torus) tokamak at the Princeton Plasma Physics Laboratory (PPPL) have shown the suppression of fluctuations through the injection of high intensity ion Bernstein waves (IBWs) [1]. These studies focused on the empirical effect of externally excited IBWs, but do not explain the mechanisms. IBWs break the gyrokinetic approximation and therefore neither their intrinsic stability nor their influence on energy and particle transport can be studied by current gyrokinetic turbulence and stability codes. The capability to simulate the excitation of IBWs, would be an important stepping stone toward a more comprehensive understanding of the high-frequency regime in the plasma edge.

We developed an optimized and scalable semi-Lagrangian solver for the fully kinetic Vlasov system based on a highly efficient scheme to treat the $\boldsymbol{v} \times \boldsymbol{B}$ acceleration from the strong background magnetic field. This allows us to simulate the excitation of plasma waves and turbulence with frequencies beyond the cyclotron frequency without a limitation by the gradient strength or fluctuation level. It is well tested in the low-frequency regime and produces correct results for the dispersion relation as well as energy fluxes in the linear and non-linear regime [2].

In this contribution, the first results going beyond the low-frequency regime will be presented. We developed a comprehensive understanding of the stability properties of the ion Bernstein waves and have been able to show their destabilization for steep temperature and density gradients. The growth rates can thereby exceed those of the ITG instability, especially when a density gradient is present. The predicted instability is accurately reproduced by our simulation in a local gradient set-up as well as using a fully non-linear treatment of the gradients. The results will be presented along with the (rather non-trivial) description of the various turbulent fluxes in the kinetic system.

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Gyrokinetic investigation of linear and non-linear excitation of energetic particle driven instabilities in ASDEX Upgrade with experimentally relevant distribution functions

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1 Abstract

Excitation of Alfvén Waves (AW) and Geodesic Acoustic Modes (GAM) by energetic particles (EPs) and their impact on confinement and transport is an important topic of study for the physics of fusion reactors. We examine the effects of experimental-like anisotropic-in-velocity distribution functions of EPs on the excitation of such instabilities with the gyrokinetic particle-in-cell code ORB5. The growth rate of (E)GAMs is found to be sensitively dependent on the phase-space shape of the distribution function as well as on the non-linear wave-wave coupling with AWs. The simulation results are compared to experimental findings, which show TAE-triggered EGAM activity for the NLED-AUG case (ASDEX Upgrade #31213). This emphasizes the importance of retaining non-linear effects for qualitative and quantitative agreement, without which the excitement of ZS is not possible using experimental-like distribution functions.

The impact of divertor neutral pressure on confinement degradation of Advanced Tokamak Scenarios at ASDEX Upgrade

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On the pathway towards realization of a fusion power plant (FPP) based on the tokamak concept, steady-state operation is a critical challenge, as tokamak scenarios are typically operated in a pulsed way due to the current induced by the central solenoid. Advanced Tokamak (AT) scenarios promise to mitigate this issue via maximization of non-inductive toroidal plasma current, increasing in this way the attractiveness of tokamaks as an energy producing system. It is for this reason that all pilot FPPs based on the tokamak concept rely on AT scenarios to be economically viable [1].

During previous experimental campaigns at the ASDEX Upgrade tokamak, the confinement quality of AT scenarios executed with similar, if not identical, engineering parameters was difficult to reproduce. The confinement quality factor H_{98} could vary from 0.8 to 1.2 for similar engineering parameters; such different values would make a tremendous impact on the final design of a pilot FPP. Therefore, in this work the causes of such confinement variation are investigated.

Amongst all plasma quantities analyzed, the confinement quality of AT scenarios best correlates with the divertor neutral pressure [2], highlighting the key role of edge and scrape-off layer physics in determining the global plasma confinement. In particular, it is found that the main cause of confinement degradation is the reduction of pedestal stability, which is in turn caused by the outward shift of the maximum density gradient position typically observed when the divertor neutral pressure increases. Owing to the low density of AT discharges in present-day tokamaks, the movement of the maximum density gradient position can be caused either by minute variations of gas puff rate or by changes in deuterium out-gassing from the wall. Furthermore, a secondary role in the confinement degradation is attributed to the pedestal top ion to electron temperature ratio, T_i/T_e, which tends to stabilize core ion temperature gradient modes, and hence improve confinement, when T_i/T_e increases. The impact of ion cooling due to charge exchange reactions with recycled neutrals and of impurities in the observed change of edge T_i/T_e is further investigated. Last but not least, the predictive capability of confinement quality with the integrated model IMEP [3] is tested on these discharges. IMEP is able to reproduce the outward shift of the maximum density gradient position and, hence, the confinement degradation, increasing confidence in the applicability of such integrated modeling for confinement estimation.

The main implication of this study is that good confinement levels of current AT scenarios obtained at low density and with $T_i/T_e > 1$ may not extrapolate to a DEMO-like reactor where density will be higher and $T_i = T_e$. These results highlight the importance of predicting H-mode confinement with a core-edge-SOL integrated modeling approach, rather than with scaling laws which are not based on physics models.

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Studies of tokamak edge density variation with the use of novel intensity refractometry diagnostic in ASDEX Upgrade

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The tokamak plasma edge density influences and is influenced by many physics phenomena. The edge density is linked to the plasma parameters in the core, and in the Scrape-Off-Layer (SOL) it is connected to particle transport regimes, divertor conditions, plasma-wall interaction (PWI) and consequent impurity sputtering, power coupling of the Ion Cyclotron Range of Frequency (ICRF) heating, ICRF-induced PWI, etc. Detailed knowledge of the edge density and its temporal variation on short and long time scales could help in understanding the involved physics processes.

The recently developed microwave intensity refractometry diagnostic technique [1] provides measurements of SOL electron density profile and its variation on the time scale down to 1 µs [2-3]. Density profile reconstruction within several cm can be obtained by employing a synthetic diagnostic and metaheuristic methods of solution optimization [1,3].

In this work, we present versatile applications of the intensity refractometry for edge physics studies. First, a large database obtained from three experimental AUG campaigns enables statistical characterization of the density in the SOL, especially in the poorly diagnosed far-SOL region, and its correlation to other plasma parameters. Second, density perturbations are studied, both for the very fast turbulent oscillations seen as continuous signal variation and for filaments and ELMs, which are distinguished as single events on top of a background signal. JOREK ELM cycle simulations provide input for the synthetic intensity refractometry diagnostic, from which a characteristic signature of the diagnostic output during an ELM is obtained and compared to experimental measurements. Third, local density modifications caused by ICRF waves are studied and used as a link to characterize the rectified DC potential induced near ICRF antennas, which can cause increased PWI during ICRF operation. The presented results expand the previous knowledge of the plasma edge behaviour.

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Experimental Characterization of the Quasi-Coherent Mode in EDA H-Mode and QCE Scenarios at ASDEX Upgrade

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For future reactors based on the tokamak concept, it is necessary to establish high-confinement modes without type-I edge localized modes (ELMs). Several natural ELM-free operation scenarios like the enhanced D_α high confinement mode (EDA H-mode) [1] or the quasi continuous exhaust regime (QCE) [2] have been achieved in ASDEX Upgrade. In both regimes a characteristic edge fluctuation is prominent, called the quasi-coherent mode (QCM). The mode is believed to be the key feature for the stabilization of ELMs and thus, the better confinement. In order to understand the physical nature of the QCM and extrapolate a possible EDA H-mode or QCE scenario to large-scale machines like ITER, we determined different spectral properties of the QCM. Due to its high temporal and spatial resolution the thermal helium beam (THB) diagnostic is well suited to investigate the characteristics of the QCM. In both plasma scenarios, the QCM has been localized inside but close to the separatrix. The mode propagates in ion diamagnetic direction in the plasma frame and the poloidal wavenumber of the QCM k_θ normalized to the hybrid gyroradius ρ_s is about $k_\theta\rho_\mathrm{s} \approx 0.05$, being deep in the electromagnetic regime, i.e. $k_\theta\rho_\mathrm{s} < k_\mathrm{EM}\rho_\mathrm{s} \propto \sqrt{\beta}$. The radial wavenumber vanishes, suggesting a streamer-like appearance. The mode is visible in the magnetic pick up coils in QCE and EDA H-modes, emphasizing the electromagnetic character of the QCM. All the properties are consistent with ideal, resistive or kinetic ballooning modes. In EDA H-modes, high harmonic modes appear exclusively in magnetic coils, which are found to be a disjoint phenomenon from the QCM.

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Modelling of ion and electron heat fluxes and temperatures close to the separatrix and comparison to experiments

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Understanding ion and electron heat fluxes and temperatures near the separatrix is crucial for predicting the confinement in the pedestal [1], studying Scrape-Off Layer (SOL) heat fluxes and describing turbulence in the edge region [2]. While SOL electron and ion temperatures T_i and T_e have been measured in several tokamaks, [3, 4], extrapolation to future tokamaks remains difficult due to a lack of simple physical models. In this contribution the physics of electron and ion heat fluxes in ASDEX Upgrade (AUG) from the pedestal to the divertor is investigated numerically using the plasma and neutral transport code EMC3-EIRENE [5], to develop parameter based physics model for T_e and T_i at the separatrix.

By analyzing a set of simulations with a broad range of densities, heating powers and ion and electron perpendicular transporting coefficients, the effects of the individual parameters on the heat fluxes across the separatrix and into the divertor region as well as on T_i and T_e are studied. The simulations show that the heat fluxes crossing the separatrix depend only weakly on the electron to ion heating ratio set at the inner simulation boundary (located at $\rho_p \approx 0.9$), except for the lowest collisionality cases. For higher collisionalities the electron to ion heat flux ratio crossing the separatrix depends only on the perpendicular transport coefficients and is independent of the density. Moreover, the electron heat flux into the SOL is typically larger than the ion heat flux. The simulated T_i/T_e ratios at the separatrix are compared to the scaling from [6], which assumes that the ratio is mainly determined by the SOL collisionality. While the simulations confirm that the heat exchange in the SOL can be important, also the ion and electron heat fluxes into the SOL and the SOL decay lengths play a role. The simulation results are compared to recent measurements from an ongoing effort within EUROfusion to characterize T_i and T_e around the separatrix in several tokamaks.

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Influence of ICRH on runaway electron generation in ASDEX Upgrade: first experimental attempts.

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Tokamak plasmas are subject to disruptive events. During such incidents, part of the electrons can be accelerated to relativistic energies and can cause serious damage to the device [1]. Typical variants of action against these runaway electrons (e.g. massive material injection via gas or shattered pellets) are not yet demonstrated to completely solve the problem in a reactor. In our experiments in ASDEX Upgrade, we have tried to avoid runaway beam generation with Ion Cyclotron Resonance Heating (ICRH, 30 MHz) [2]. The main idea is to provoke higher radial transport by introducing electromagnetic waves in the system during the generation phase of the runaway beam. The ICRH system has two pairs of antennas which can be independently configured and give the flexibility to change the injected wave spectra. We have tried several different spectra in our experiments. One of the main issue was the reproducibility of runaway scenarios. From 9 reference discharges *without* ICRH in the generation phase, which should always have runaways, 2 were without runaways. From 11 discharges with ICRH 6 were without runaways and another 5 had runaways. At the same time, we did not succeed in finding a particular recipe for ICRH that would always avoid runaway generation. Statistical analysis with two proportion Z-Test was also not conclusive. It requires a larger number of experiments to clarify the influence of ICRH on runaways. In the paper, we report the details of the experiments and show how other potential factors, for example, possible differences in tungsten concentration, were excluded by the design of the experiments.

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Tin concentrations in ASDEX Upgrade H-mode plasmas with a liquid tin divertor target

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A capillary porous tungsten structure with a plasma facing area of 16x40 mm^2 has been filled with tin (Sn), flush mounted in a dedicated target tile, and inserted into ASDEX Upgrade with the divertor manipulator. Before each discharge, the sample was electrically heated above the melting point of tin.

The VUV spectrum as measured by the SPRED spectrometer on an almost horizontal line-of-sight through the plasma centre and a number of channels of the bolometers which see the main plasma but not the region of the lower divertor were used to determine the tin concentration in the main plasma. The discharges started out with ramping up the heating powers during the current flattop. Then the outer strike point was moved down from an initial position above the liquid tin probe to a position on the probe where it was held fixed for up to 3.5 s and then moved up again. The signals on the bolometer and the VUV emission lines of Sn were rising during the time when the strike point was on the probe and the differences of the signals with the strike point being situated on and above the probe can be used to identify what emission lines are emitted by Sn and what extra total radiation is due to Sn.

In these plasmas, the electron temperature at the plasma centre is 3.7 keV and VUV lines from charge stages Z=20 (Zn-like), Z=21 (Cu-like), Z=35 (P-like), Z=38 (Mg-like), and Z=39 (Na-like) could be identified. The ionisation balance of tin has been modelled with the impurity transport code STRAHL which solves the transport equations of all ion stages of Sn where neighbouring stages are coupled via ionisation and recombination reactions. The rate coefficients for these reactions were taken from ADAS. For the recombination data, only the ADAS data set, that is based on improved calculations of the di-electronic recombination gave a good consistency of model and experiment. Charge exchange from neutral deuterium atoms onto impurity ions has been shown to be another important recombination channel at the edge and has been included. The average charge of the tin ions is about 15 at the separatrix and 39 on the plasma axis.

Assuming a constant Sn concentration of 1.4×10^{-4}, the bolometric measurements as well as the VUV line radiances from all ion stages are in very good agreement with the modelled radiances with relative deviations between 5-20%. This is a very large concentration for a sample that covers only about 0.16% of the total circumference and can be compared with the measured tungsten concentration, which is 5.5×10^{-5} from the quasi continuum and 2×10^{-5} from the central line emission.

Validation of theory-based core transport models against full discharges in ASDEX Upgrade

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Abstract

The capability to predict the evolution of full plasma discharges in tokamaks has significantly improved in the last decade. Integrated modeling that couples physics of the core and the edge allows to simulate the plasma evolution from early ramp-up to plasma termination. Moreover, recent effort has shown that full-radius L-mode plasma profiles can be obtained from first principles [1].

Motivated by this observation, in this work the validation of the latest state-of-the-art core transport models TGLF [2] and QualiKiZ [3] is presented, as these tools are employed in the flight simulator Fenix [4] to evolve the plasma core profiles. As both TGLF and QuaLiKiZ require a non-negligible computational time compared to real-time, we cross-validate surrogate models against the complete ones. That is, we also run the neural-network version of QualiKiZ, "QuaLiKiZ-NN", and a physics- driven analytical fast model based on a TGLF database [5].

During the current ramp-up L-mode phase, the kinetic profiles are simulated full-radius, whereas in the H-mode phase of the flat-top the pedestal top is adopted as boundary condition for the core. The pedestal itself is assumed to be clamped to a maximum pressure, which is given by a simple regression, mimicking the peeling-ballooning limit and the pedestal gradient transport (as in the EPED model [6]).

The focus of this study is in particular on the evolution of the profiles during the ramp-up, the achieved confinement in H-mode, and the behavior of the profiles under perturbations imposed during the flat-op phase (power modulation, shape variations). The comparison between simulation and experiment will allow to assess the quality of the employed theory-based tools to simulate this variety of scenarios.

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Characteristics of I-phase bursts and their identity to type-III ELMs

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In tokamak plasmas a regime of regular kHz oscillations is often observed in the parameter range between the low and the high confinement mode. This regime is called I-phase [1] at ASDEX Upgrade (AUG) and is similar to the M-mode at JET [2]. The most prominent and visible feature of an I-phase is the periodic and simultaneous flattening of temperature and density profiles around the separatrix, which is perceived as burst. At AUG these regular burst at the plasma edge appear as a periodic oscillation with a frequency of 0.5–3.5 kHz. Utilizing the high spatiotemporal resolution of the AUG He-beam diagnostics [3] we see the burst, i.e. the profile relaxation, as the result of periodically increased transport at the plasma edge. These events seem to be driven by high frequency modes of 30–60 kHz, which vanish at the maximum impact of each burst and are localized in the confined region close to the separatrix. The driving mode lives very shortly in the case of periodic high frequency and low amplitude bursts in the parameter range close to L-mode. In a continuous transition towards the fully developed H-mode the bursts show an increase in amplitude, whereas the frequency decreases, leading ultimately to a loss of periodicity in the regime which was classified as type-III ELMs. This could be explained by the driving mode living longer in a saturated state before the burst is initialized. As the driving mode is present in all cases we support the similarity of I-phase bursts and type-III ELMs as suggested in [4]. Within this contribution we demonstrate the dynamic evolution of I-phase bursts. We further show the generation of SOL filaments which are triggered by the increased transport and the impact in the divertor.

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Location and Quantification of non-absorbed EC-power in ITER

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Electron cyclotron resonance heating will be an essential heating system for ITER. Although the single pass absorption reaches nominally 100%, stray radiation may be due to a non-negligible fraction of cross polarisation as well as due to operation very early in the start-up phase or due to heating at the 3rd harmonic of the electron cyclotron frequency (1/3 of full magnetic field). These cases require to model where the non-absorbed power hits in-vessel components and in particular with which power density. Such information may even be required in real time to protect sensitive components. In contrary to smaller machines in operation nowadays, ITER will be safe with respect to cut-offs of the heating beams, since the ratio B_t^2 / n_e is much higher. Still a cut-off situation will occur for the cross polarisation, when heating ITER at full field with the ordinary (O-)mode. The so called extra ordinary (X-)mode is reflected at the right-hand (RH) cut-off, which can lie as far out as the scrape-off layer, giving rise to well-focussed reflections in the vicinity of the launchers. In this contribution we describe how we optimised the beam-tracing code TORBEAM [1] within the IMAS suite [2] as a post processor to a modelling-scenario from the ITER IMAS scenario database [3], in order to analyse the evolution of these X-mode reflections. Those move closer to the launchers as the density builds up / the RH-resonance moves outward. The results indicate that these reflections may exceed 1 MW/m^2 even if only 1% cross polarisation is assumed. Of course, highly reflective surfaces do ameliorate the problem. Here we only use a rotational polygon to mimic the vessel wall and to map the reflections, but the outgoing beams are available as IMAS data (Interface Data Structures or IDS) and could be combined with CAD programs in case of concerns. The validity of beam tracing in the vicinity of the RH cut-off will be discussed comparing to existing full-wave code results for reflectometer geometries on ASDEX Upgrade. *The views and opinions expressed herein do not necessarily reflect those of the ITER Organization*.

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Loss of ELM suppression with non-axisymmetric magnetic perturbations in ASDEX Upgrade helium plasmas

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We study the possibility to suppress Edge Localised Modes (ELMs) with Resonant Magnetic Perturbations (RMP) during the gradual transition from pure deuterium to pure helium plasmas in ASDEX Upgrade (AUG). This is motivated by the possibility that ITER will use helium plasmas during its initial, pre-nuclear operations phase.

The starting point is a reproducible, ELM suppression plasma scenario in deuterium [W. Suttrop et al, Nucl. Fusion **58** (2018) 096031], which is modified by successively increasing the helium gas puff on a shot-to-shot basis. The RMP is configured for maximum plasma response, as predicted by MHD calculations and verified experimentally in the past for deuterium plasmas. Full ELM suppression is maintained up to a helium concentration of $n_{He}/n_{e,ped} \sim 20\%$. Between this concentration and $n_{He}/n_{e,ped} \sim 40\%$, small ELMs return despite the pedestal density being significantly below the empirical density maximum for ELM suppression in deuterium plasmas in AUG. At highest helium concentrations, the pedestal density could not be kept below the empirical limit, and plasmas remained in ELMing H-mode. Plasmas with helium concentrations below and slightly above $n_{He}/n_{e,ped} \sim 20\%$ have very similar edge ion and electron temperatures and rotation profiles, which fall well within the ranges covered by the deuterium ELM suppression database in AUG. In all cases with ELM suppression, i.e. at low helium concentration, we observe edge turbulence activity that replaces the transport due to ELMs [N. Leuthold et al, accepted for Nucl. Fusion, DOI 10.1088/1741-4326/acb1c5]. As the He concentration limit is approached, the turbulence becomes intermittent and gives way to ELM bursts above this limit. Although the role of the edge turbulence for ELM suppression is not yet clear, we may speculate that the intermittency which appears with increasing helium density arises from a weaker linear drive of the underlying instability.

Our result complements that of DIII-D where in pure helium plasmas, RMP ELM suppression has been demonstrated only for low net torque input (pure electron cyclotron heating or balanced neutral beam injection) and slow plasma rotation [T Evans *et al* Nucl. Fusion Nucl. Fusion **57** (2017) 086016], but not for strong plasma rotation. In contrast, ELM suppression in deuterium plasmas is observed for a wider range of plasma rotation, both in DIII-D and AUG. The marked effect of the ion species on ELM suppression access at otherwise similar plasma parameters is not yet understood; implications for ELM suppression models will be discussed.

Numerical simulation of driven plasma rotation shear and fast magnetic reconnection caused by double tearing modes

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Advanced scenarios, generally found in tokamak experiments with non-monotonic profiles of the safety factor q and reversed magnetic shear in the central region, allow for the possible steady operation of a fusion reactor due to their high bootstrap current fraction. Experimental results indicate that the internal transport barriers (ITBs) in these scenarios start preferentially when the minimum q reaches an integer value. On the other hand, strong MHD instabilities or even disruptions are also observed when the low order rational q surfaces are inside the plasma, especially when the minimum q is well below 2.

In order to understand the experimental results, numerical calculations have been carried out for medium-size tokamak plasma parameters, based on two-fluid equations, for the first time. It is found that for a small distance between two resonant surfaces, the local plasma pressure between them is flattened due to the fast magnetic reconnection in tens of microseconds, in agreement with experimental observations. Meanwhile, a large plasma rotation shear in the order of $10^5 \sim 10^6/s$ is generated by the electromagnetic torque around the edge of the pressure flattening region right after the magnetic reconnection, which could lead to the suppression or the decorrelation of plasma turbulence and trigger the ITB formation. Furthermore, it has also been found in numerical simulations that for a medium distance and a low rotation frequency difference between two low order rational q surfaces, the plasma pressure is flattened over a large region up to the magnetic axis during the fast magnetic reconnection in tens of microseconds, in agreement with experimental observation too.

Low-shear configurations to test MHD-stability in Wendelstein 7-X

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The magnetic configuration of Wendelstein 7-X was designed for good MHD-stability as one aspect of several different optimization criteria. Although the optimization targeted a specific configuration, this property is to some extent inherent in most configurations. However, specific tuning of the magnetic field by changing the coil currents makes it possible to lower the MHD-stability limit by lowering the rotational transform, by increasing the toroidal mirror field, and by shifting the plasma column horizontally outward. All three changes decrease the shear in the rotational transform profile and push the values of the vacuum magnetic well towards a vacuum magnetic hill. The so-called low-shear configuration – an outward-shifted high-mirror configuration – has an MHD-limit-β of about $\langle\beta\rangle \approx 1.7\%$ depending on the pressure profile and thus seems a good candidate to test MHD stability experimentally in an earlier stage of plasma operations. However, field-line-tracing calculations in finite-beta equilibria of this configuration show that dangerously large heat loads may arise due to the growth of the magnetic islands with beta and due to the β-induced Shafranov-shift calling the feasibility of these experiments into question.

We describe the construction and the properties of vacuum magnetic configurations with similar rotational transform and vacuum magnetic well properties by tuning the coil currents to achieve similar MHD-stability properties at finite β and whose heat patterns that are compatible with the acceptable divertor and baffle loads. Experiments in one of these configurations are planned to be performed during OP2.1 in early 2023.

Multi-fluid and gyrokinetic Landau collisions

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A fast scheme for the machine accuracy calculation of gyro-kinetic (GK) and multi-fluid (MF) collision coefficients of the full (linearized) Landau collision operator has been developed. The code allows multiple species with finite mass ratios and differing temperatures and can be used to put the well-known Braginskii equations, which were obtained by analytic approximations with infinite ion/electron mass ratio, on a completely new basis. It will also be used to provide reliable tokamak edge turbulence simulations.

GK collision operators customarily are either based on a reduced number of moments for the (gold standard) Landau-Fokker-Planck operator, which have been transformed to GK gyro-center coordinates [1], or to the full Landau operator but in a purely drift-kinetic setting [2], owing to analytic limitations or overpowering computational cost. MF transport coefficients have been obtained in several complex analytical calculations and approximations [3] for infinite ion-electron mass ratio, but with rather intransparent ordering schemes and some missing coefficients. It should be noted that differing levels of collision representation in GK [4] and MF [5] turbulence simulations have precluded stringent comparisons between both frameworks for high collisionality, where both should be valid.

A code for the efficient calculation of the matrix elements of the complete linearized Landau operator using uniform orthogonal polynomials has been developed. On one hand, the computational cost is low – the coefficients for hundreds of polynomials can be obtained in seconds on a laptop. On the other, the matrix elements are computed up to machine precision, as confirmed by tests for various mass ratios ($1 - 10^{10}$), which makes them automatically fulfill all the required conservation laws and invariances. For GK simulations, the above matrix elements are then transformed to gyro-center coordinates. The collisional MF transport coefficients are calculated rapidly and completely by determining perturbed eigenspaces of the combined system of streaming and collision operator for arbitrary orders in perpendicular and parallel wavenumbers, which yields the complete transport matrix far more accurately than in literature [3, 6]. Due to the precision of the calculation, the (necessary) Onsager symmetries are automatically fulfilled. In addition, unlike the traditional analytic expansions, the code does not require infinite mass ratio and works for more than two species.

Due to the modular nature, the method can also guide the implementation of more accurate collision treatments, such as a combination of the small-angle Balescu-Lenard operator with the Boltzmann operator for large collision angles. This would only render the initial calculation of the matrix elements more costly but not the gyro-transformation or the transport coefficients. Moreover even the nonlinear Landau operator seems now to be in range, since it just requires a bilinear extension of the scheme.

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MHD numerical analysis of global flow in 3D magnetic configurations

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The global flow can affect the global stability of fusion plasmas. In tokamaks, for example, the effects of the plasma rotation on the edge localized mode and resistive wall mode are studied extensively. However, in stellarators, the effects of the flow have not been studied systematically. One reason is that the evaluation of the global flow is not very easy in three dimensional (3D) magnetic configurations. For this point, we proposed a numerical scheme to calculate the 3D profile of the global flow and showed an application result for the flow in the Large Helical Device (LHD) plasma [1]. Also, the effects of the obtained flow on the stability against the interchange instability was examined by utilizing the HINT code[2] and the MIPS code[3]. The preliminary result that the global flow has a stabilizing contribution on the instability was obtained in the early nonlinear phase.

In the present study, we have improved several points in the flow calculation and in the stability analysis. In the flow calculation, the accuracy on the incompressibility which is assumed in the formulation is improved through the modification of the coordinate transform manner between Hamada, VMEC, and cylindrical coordinates. As a result, the continuous stream lines of the global flow are obtained. In the stability analysis, we make the viscosity work only on the perturbed component of the flow. Also, the linear growth rate of each toroidal component of the instability can be evaluated from the kinetic energy component now, which was masked by the big contribution by the global flow. By applying this stability method to the LHD plasmas, we have found reduction range of the growth rates due to the global flow.

In the conference, we will discuss the Pfirsch-Schluter component in the global flow and the beta dependence and the flow amplitude dependence on the linear stability and the nonlinear saturation level of the instabilities.

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Non-ambipolar radial transport of tangentially injected NB-produced fast ions in quasi-axisymmetric stellarators

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In future NBI-heating experiments of quasi-axisymmetric stellarators such as the CFQS(Chinese First Quasi-Axisymmetric Stellarator)[1], in which the usual ripple diffusion is strongly reduced, the beam-driven radial transport of thermalized target plasma species that is predicted in Ref.2 will be important. Not only the thermalized particles, the NB-produced fast ions also have the non-ambipolar radial transport accompanied by the parallel viscosity force discussed in Ref.3. When using this external momentum input for the control method of the ambipolar radial electric field, this radial transport flux of fast ions also must be included in the ambipolar condition. This flux can be obtained by applying the adjoint equation method.[4] However, it also was found in the Heliotron-J experiment[5] that the charge exchange (CX) loss of the fast ions is not negligible in the small- or medium-size devices such as the CFQS. This loss can be experimentally investigated by applying the FIDA(fast ion D-alpha) measurement.[5] In this study, the adjoint equation method is extended to include the CX loss for investigating the radial transport of the fast ions in the quasi-axisymmetric stellarators. The calculation example using the CHS-qa configuration[6] will be presented.

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GAM eigenmode observation by ECE Imaging diagnostics on LHD

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8 (vertical) x 24 (radial) =192-channel ECE imaging (ECEI) diagnostics in V-band & Q-band has been constructed on LHD. When the high power tangential NBI beams injects to a low density plasma (which optical thick is not thin), some energetic particle driven instabilities has been excited. In some cases, the energetic particle driven geodesic acoustic mode (eGAM) are also exited [1, 2]. It is known that a GAM has an eigenmode structure in tokamak [3]. Now we can measure the GAM eigenmode structure observed by the electron temperature oscillation. For example, after t =7.4 s, the magnetic probe is able to capture two coherent fluctuation components as shown in Fig.1. As shown in Figure 2, the 16 kHz and 19 kHz components measured by ECEI have different radial structures at each.

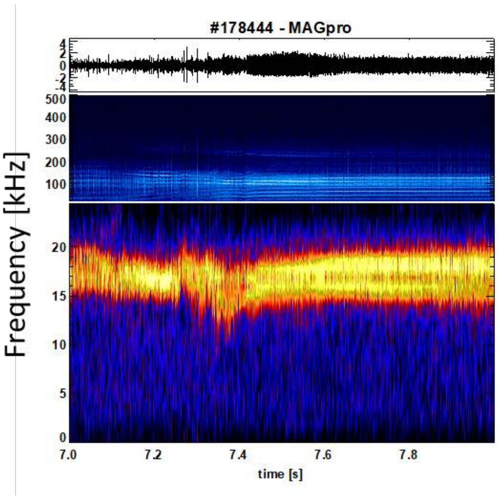

FIG. 1. Spectrogram of magnetic fluctuation.

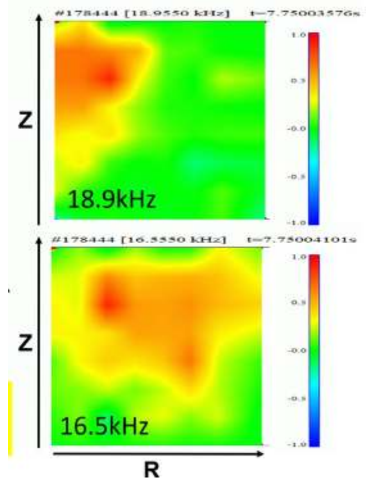

FIG. 2. Radial structure of GAM oscillation

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Pedestal properties of negative triangularity plasma with favorable/unfavorable ∇B drift direction in ASDEX Upgrade

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Negative triangularity (NT) experiments in TCV [1], and DIII-D [2] have shown H-mode level confinement without Edge Localised Modes (ELMs), setting a path for NT as an operating scenario for burning plasmas. At ASDEX Upgrade (AUG), the first overview studies have shown that for the avoidance of H-modes at $|\overline{\delta}| < 0.2$, AUG should operate with unfavorable ∇B drift direction [3]. For better physics understanding and the extrapolation of the such regime, in this work, we compare MHD and turbulence measurements between four NT discharges from the 2022 AUG campaign. One pair of favorable and unfavorable ∇B drift direction discharges is heated with ECRH, while the second is heated with a combination of ECRH and NBI heating. In both drift directions, the plasma enters into an H-mode and is accompanied by ELMs with a high repetition frequency of about 1 kHz. A regular ELM repetition rate is observed in unfavorable while incoherent and non-constant in size ELMs are characteristic of the favorable ∇B drift. Despite an increase in ELM frequency with power, indicating their type-I ELM nature, the global ideal peeling-ballooning (PB) stability analysis reaches the limit only in one of the four cases. This suggests a potential role of resistive MHD or bursty turbulence during such ELM dynamics. Local, long wavelength ($k_\theta \rho_s < 0.3$) temperature fluctuations are measured with the correlation ECE instrument across the outer core and the pedestal. These measurements do not differ between favorable and unfavorable ∇B drift direction at the highest matching heating power levels. We measure an increase in coherency levels for all four discharges when moving radially outwards towards the separatrix. Such strong coherency levels are characteristics of MHD modes or the weakly coherent mode as measured in I-mode.

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Experimental and Simulation Study on Nonlinear Coupling of Turbulence, GAM and Tearing Modes in HL-2A Edge Plasma

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Abstract: We performed statistical analysis on the spectral features of geodesic acoustic modes (GAM) and their nonlinear coupling with background turbulence to investigate their dependence on magnetic island (MI) width (W) in the edge region of HL-2A tokamak plasma. Experimental observations show that, as the MI width increases, the strength of nonlinear interaction between GAM and turbulence as well as the modulation effect usually decreases while the coupling between MI and turbulence is enhanced. The MI primarily reduces the coupling between GAMs and electrostatic potential fluctuations, whereas the changes in the nonlinear interaction between density fluctuations and MIs are more pronounced. In addition, we found a non-monotonic relationship between turbulence-correlated length scales and island width, with a minimum near W of approximately 3.7 cm, indicating significant suppression of turbulence transport by MIs in this scale range. We also discuss a comparison between experiments with static magnetic islands and nonlinear global gyrokinetic simulations.

Multi-field singular value decomposition for nonlinear quantities in turbulent plasmas

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In recent decades, verious mode decomposition techniques are utilized to extract essential contributions and to lower the dimensionality of huge and multi-dimensional data obtained from turbulence simulations and measurements. In this work, the SVD is extended to decompose multiple fields simultaneously for analyzing nonlinear quantities in turbulent systems effectively, which is referred to as the multi-field SVD.

In the conventional SVD, a time-dependent multi-dimensional field quantity $f(\mathbf{x},t)$ is discretized and rearranged to a matrix F, and then F is decomposed to the SVD modes. As an extension of this method, multiple fields are aligned in the matrix F on an equal footing and decomposed as usual. We consider the particle flux $\Gamma_n = -\int \mathrm{d}\mathbf{x}\, \partial_y \phi\, \tilde{n}$ as an example of the 2-field case, where ϕ is the electrostatic potential and $\tilde{n}$ the turbulent component of the electron density. The temporal evolution of the turbulence fields is obtained by numerically calculating the Hasegawa-Wakatani equation [1, 2] in the 2-D slab geometry. Then, the multi-fields SVD is applied to the two fields $\partial_y \phi$ and $\tilde{n}$, and they are decomposed as $\partial_y \phi(\mathbf{x},t) = \sum_i \partial_y \phi_i = \sum_i s_i h_i^{(\phi)}(t)\psi_i(\mathbf{x})$ and $\tilde{n}(\mathbf{x},t) = \sum_i \tilde{n}_i = \sum_i s_i h_i^{(n)}(t)\psi_i(\mathbf{x})$. When the contribution of each mode to the flux $\Gamma_n^{(i)} = -\int \mathrm{d}\mathbf{x}\, \partial_y \phi_i \tilde{n}_i$ is aligned in the descending order of the singular value s_i, the spectrum is separated into the positive and the negative contribution (Fig. 1). This is the consequence of the decomposition including the information of the phase difference between the turbulence fields due to the multi-field SVD, and thus it is considered to be effective to the analysis of verious nonlinear quantites.

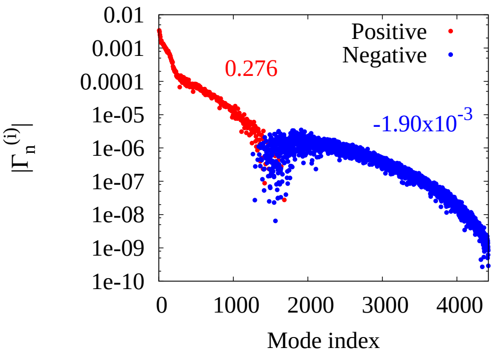

Figure 1: *The singular value spectrum of the time-averaged particle flux*

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Development of dynamically coupled simulation for global turbulent transport and profile formation

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The quantitative prediction of turbulent transport and pressure profile is one of the most critical issues in magnetically confined fusion plasmas. Many efforts have been devoted to the development of global gyrokinetic turbulence simulations. However, coupling effects between the turbulent transport and dynamic variations of the confining magnetic field and/or external heating remain open.

To this end, we have been developing a dynamically coupled simulation(DCS) based on the direct multiscale coupling between a 1D global transport solver and radially distributed local gyrokinetic calculations, following the earlier work[1]. The framework of DCS has a wide extensibility to incorporate further couplings with the other physical calculations. In order to reduce the computational costs of turbulent transport calculations, a novel simplified turbulent transport model to fast and accurately reproduce the nonlinear gyrokinetic calculation results has been constructed[2, 3]. The model includes both the turbulence nonlinearity and the zonal-flow effects based on the phenomenological arguments. Applying a mathematical optimization technique such as the gradient descent algorithm, a mean regression error of $\sim 16\%$ has been achieved for a wide parameter range including both the near- and far-marginal ITG stabilities(Fig.1). In the conference, we will report the more details about the simplified turbulent transport model and its application to DCS for the tokamak ITG-driven turbulence.

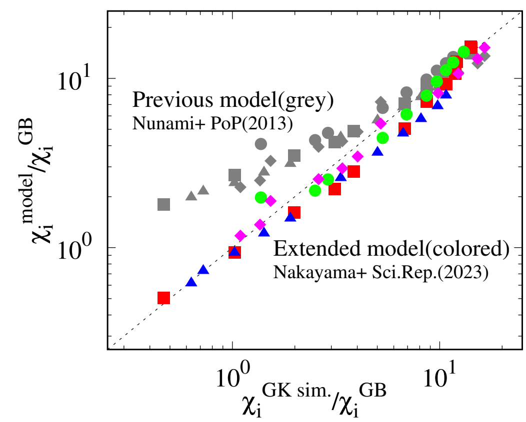

Figure 1: Comparison of prediction accuracy between the extended model(color plots) and previous models(grey plots).

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Observation of electron-scale turbulence threshold in LHD plasma

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It has been reported that electron heat transport is rapidly degraded when the electron temperature gradient exceeds a certain threshold [1]. This "temperature profile stiffness" is thought to be due to the excitation of electron temperature gradient (ETG) mode, but in our knowledge the experimental growth of ETG mode itself has not been confirmed. In this study, the response of electron-scale turbulence was investigated using millimeter-wave backscattering [2] when only the electron temperature gradient was varied by controlling the on-/off-axis of the ECH power injection under a constant electron temperature. We obtained widely ranging $R_{\mathrm{ax}}/L_{\mathrm{Te}}$ from 0 to 10 at the observed position of $r_{\mathrm{eff}}/a_{99} = 0.5$. The electron-scale turbulence ($\rho_{\mathrm{e}}k_{\perp} \sim 0.13$, where ρ_{e} is the electron gyro-radius) intensity becomes rapidly stronger from the range of $R_{\mathrm{ax}}/L_{\mathrm{Te}} > 7$. The estimated electron heat flux was also rapidly increased. This manifestation of electron temperature profile stiffness is similar with the phenomena reported in some tokamaks. The previous simulation research in a tokamak geometry showed the model that $R_{\mathrm{ax}}/L_{\mathrm{Te}}$ threshold of ETG instability can be estimated by the following equation [3], $\left(R_{\mathrm{ax}}/L_{\mathrm{T_e}}\right)_{\mathrm{threshold}} = \max\left\{(1 + z_{\mathrm{eff}}\, T_{\mathrm{e}}/T_{\mathrm{i}})(1.33 + 1.91|s|/q), 0.8\, R_{\mathrm{ax}}/L_{\mathrm{n_e}}\right\}$. The estimated threshold of $R_{\mathrm{ax}}/L_{\mathrm{Te}}$ from this model is 6.6, and the observed threshold ~ 7 looks quantitatively consistent with the theoretical value.

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Study of neoclassical transport characteristics by Monte Carlo method in the CFQS quasi-axisymmetric stellarator

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Stellarator provides steady-state magnetohydrodynamic (MHD) equilibrium configuration of the plasma by only external coils without plasma current. However, in the case of three-dimensional torus magnetic field configuration without any symmetry like conventional stellarators, the larger neoclassical diffusion is expected in low-collisional-regime. In order to overcome this disadvantage, advanced stellarators have been proposed and studied. A quasi-axisymmetric (QA) stellarator is one of those advanced stellarators, and it has a magnetic configuration embedded with axisymmetry like tokamaks. As a first experiment device of QA in the world, CFQS was designed and is being constructed now[1]. We study effects of radial electric field and β on neoclassic transport in CFQS. Here, the neoclassical diffusion coefficient is investigated with Monte Carlo method[2]. Radial electric field plays an important role in neoclassicaltransport, because particle orbit is influenced by it. β is important on neoclassical transport, because Shafranov shift changes QA configuration. CFQS experiment will be performed in various QA magnetic configurations using toroidal field coils (TFCs) and poloidal field coils (PFCs). Therefore, we also investigated the neoclassic transport in various magnetic configurations. We will report the neoclassic transport characteristics in CFQS in this presentation.

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Characterization of transition to detachment of magnetic confinement plasmas via data-driven approach

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This study aims to clarify the transiton conditions of detached plasma in the Large Helical Device (LHD), and performs state classification and feature-parameters extraction by using machine learning. Transition between detachment and attachment is defined as a problem of binary classification.

Reduction of excessive heat load to the divertor is a critical issue in the development of magnetic confinement fusion reactors. For this reason, so-called detached plasma operation is inevitable where the edge plasma does not contact directly the divertor plate. LHD has succeeded in realizing a stable detached plasma by applying resonant magnetic perturbation (RMP) field [1]. The *m*/*n* =1/1 magnetic island generated at the plasma edge regulates radiation which secures detached plasma with preventing radiation collapse.

In this study, Support Vector Machine (SVM) and Exhaustive Search (ES) were used as a machine learning method. SVM was used as a binary classifier. Since the phases of attachment / detachment can be identified by the drastic changes in ion saturation current onto the divertor plate I_{sat} as well as the electron temperature at the plasma edge $T_{e,edge}$, the phase is labelled by using I_{sat}. ES was used to extract feature parameters to describe the condition of detached plasma from 13 parameters such as the line averaged electron density $\bar{n}_e$, the magnetic field strength B, the radiation power fraction $P_{\mathrm{rad}}/P_{\mathrm{input}}$, the plasma beta β, the impurity line emissions, the *m*/*n* = 1/1 resonant perturbed magnetic flux $\Delta\Phi_{eff}$ including plasma response, and the RMP coil current, etc. The ES is a sparse modeling technique in which all possible combinations of parameters are evaluated and compared each other [2].

As the result of the ES-SVM analysis, the following 5 parameters were extracted: $\bar{n}_e$, B, $P_{\mathrm{rad}}/P_{\mathrm{input}}$, OVI line emission, and $\Delta\Phi_{eff}$. Attachment and detachment can be classified according to the combination of $\Delta\Phi_{eff}$,which is an indicator of the magnetic island width actually generated in plasmas, and other parameters.

Since the present ES-SVM analysis does not take care of temporal changes, the result indicates correlation but not causality. Therefore, the pre- and post-relationships of each parameter in time are also discussed towards causality the detachment transition from the anomaly detection by the singular value decomposition of waveforms. The changes in $P_{\mathrm{rad}}/P_{\mathrm{input}}$ and emissions of CIII and CIV are earlier than the change in I_{sat}. The change in OVI coincides the change in I_{sat}, while the changes in $\bar{n}_e$ and $\Delta\Phi_{eff}$ appear later. This order could give a hint for causality of the transition to detarchment.

Effect of Ne puff, which facilitates detachment, is also discussed in order to examine the extrapolation and inductivenenss of the model.

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Optimization of the plasma heating efficiency in nuclear fusion devices using a Landau closure model: the gyro-fluid FAR3d code

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This study is dedicated to the analysis of the Alfven Eigenmode (AE) stability in nuclear fusion devices, particularly the optimization of the plasma heating efficiency. On that aim, linear and nonlinear simulations are performed with the gyro-fluid FAR3d code that solves a reduced MHD model for the thermal plasma coupled with a gyrofluid model for the energetic particles (EP) species [Varela, J. et al *Nucl. Fusion*, **57**, 046018, (2017)]. The AE stability is analyzed in several nuclear fusion devices including Tokamaks and Stellarators, identifying the dominant and sub-dominant modes destabilized along the discharges, modeling results validated by comparing simulations and experimental data (fig 1). Parametric studies are performed to identify the optimal operational regime of the neutral beam injectors (NBI), thermal plasma parameters and magnetic configurations to maximize the AE stability. In addition, the effect of external actuators on the AE stability as the current drive induced by the NBI, the electron cyclotron current drive (ECCD) and the electron cyclotron heating (ECH) are studied. Next, the role of the resonance overlapping, generation of shear flows and zonal currents is discussed during the AE saturation phase.

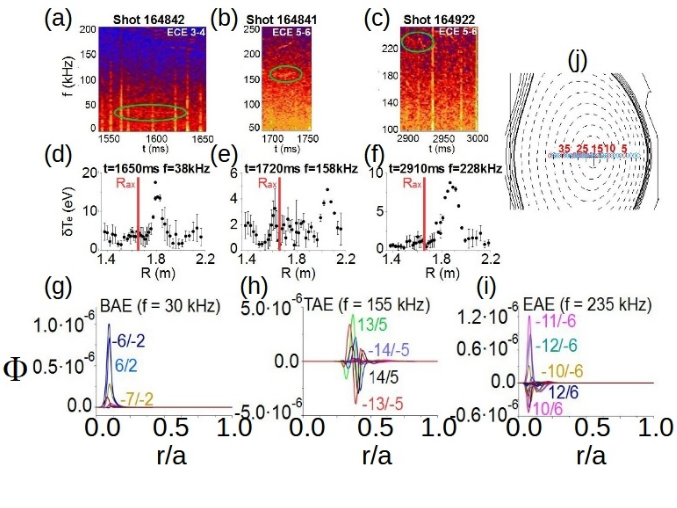

Figure 1: *ECE data and electron temperature fluctuation of (a and b) shot* 164841 *at* $t = 1650$ *ms for* $f = 38$ *kHz, (c and d) shot* 164842 *at* $t = 1720$ *ms for* $f = 158$ *kHz and (e and f) shot* 164922 *at* $t = 2910$ *ms for* $f = 228$ *kHz. Location of the ECE chords in the panel (j). Simulation eigenfunction to each instability (g to i).*

FLIPEC: a free-plasma boundary solver for axisymmetric ideal MHD equilibria with flow

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The ability of calculating ideal MHD equilibria is needed not only during the design of a magnetic fusion device, but also in its normal operation. In the case of tokamak axisymmetric configurations with significant plasma flow, the majority of codes consist of a fixed-boundary solver for the Grad-Shafranov-Bernoulli system of equations in which the plasma edge is maintained fixed as the code iteratively searches for the equilibrium. However, plasma flows may induce changes in the configuration such as displacements of the position of the X-point, the magnetic axis or the shape of the plasma boundary, to name a few, that cannot be quantified properly in a fixed-boundary setup. In this contribution we present a new code [1] that can iteratively obtain free-boundary axisymmetric ideal MHD equilibria for arbitrary plasma flows. The code employs a mesh discretization that combines pseudo-spectral and finite differences together with a free-plasma-boundary scheme previously proved [2, 3] for 3D, non-axisymmetric configurations in the absence of flow within the SIESTA equilibrium code [4]. Examples of application of the code to ITER standard configuration will be used to showcase the capabilities of the code. Additional developments currently in progress, such as the move to a general coordinate formulation to expand the type of devices/configurations to which it can be applied or the implementation of techniques to improve the iterative convergence to equilibrium solutions avoiding the onset of vertical instabilities will be discussed as well.

Acknowledgement: *This work has been performed under the auspices of the ITER Scientist Fellow Network.*

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Filament structures, intermittent fluctuations and broad average profiles at the boundary of magnetically confined plasma

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A stochastic model has been developed in order to describe the dynamics of intermittent fluctuations due to radial motion of blob-like structures in the scrape-off layer (SOL) of magnetically confined plasma. Uncorrelated pulses move radially outwards with a random distribution of amplitudes, sizes and velocities. The pulses have a fixed shape and an exponentially decaying amplitude due to parallel drainage towards the divertor plates. In its simplest form, the model leads to exponentially decaying average radial profiles.

More generally, we investigate the implications of correlations between filament parameters on the mean profiles and higher-order statistical moments. A broad distribution of pulse velocities leads to non-exponential profiles and strongly increased intermittency in the far-SOL. It is demonstrated that this explains many features from experimental measurements. An initial correlation between pulse velocities and amplitudes leads to even stronger intermittency levels in the far-SOL while keeping the same average signal levels as in the uncorrelated case.

Model predictions will be presented for theoretically predicted relations between pulse amplitudes, sizes and velocities in inertial and sheath dissipative regimes. This demonstrates the formation of a shoulder structure in the average density profile with broad far-SOL profiles, high relative fluctuation levels throughout the SOL, and strong intermittency with positively skewed and flattened probability density functions in the far-SOL. The results will be discussed in the context of first-principles-based turbulence simulations of the SOL as well as experimental measurements of the Alcator C-Mod device. The relevance for plasma-wall interactions like sputtering will be pointed out.

Consequences of pellet injection on the turbulent transport in TJ-II

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Pellet injection is used in many magnetic confinement fusion devices to achieve deep and efficient core plasma fueling. An increase in confinement time has been observed in many pellet injection experiments some time after the injection of the pellet. In recent experiments, this improvement was observed in TJ-II after the injection of multiple pellets [1]. It was also found that the electrostatic potential became more negative in this time period. This result was consistent with some neoclassical calculations also described in Ref. [1].

Here, we use the resistive MHD model that we already tested for the dynamics of TJ-II stellarator [2] as a basis for the turbulence transport dynamics and we apply it to study the effects of pellet injection on the turbulent transport. We do not model the penetration of the pellet in the plasma, because we only look for the consequences of the change in the density profile. The interaction of the pellet with the plasma is modeled by having an additional density source for a very short time in order to obtain an increase of the density profile similar to that of the experiment. We have seen that the increase of the density gradient by the pellets excites resistive interchange modes at the low order rational surfaces. These instabilities show a strong coupling with each other and generate multiple barriers. They also generate a strong negative electrostatic potential through Reynolds stress. This strong nonlinear dynamic process is responsible for an improvement in the confinement. Transfer of entropy [3] calculations confirm the contribution of nonlinear coupling to the increase in the shear flow.

Another result from the experiment was that one or several additional pellets makes the confinement improvement more significant. We have also seen with the model that in the case that the second pellet is injected shortly after the first, the effect is to prolong the period of higher confinement and to improve it. However, if the second pellet is injected when the plasma goes back to steady state, the enhancement is only a short second peak.

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Analysis of the AE activity in the TJII periphery using Landau closure model

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The aim of this study is to analyze the Alfven Eigenmodes (AE) activity at the plasma periphery in the frequency range of 200 kHz observed in TJII discharges heated by neutral beam injectors (NBI)[1]. The analysis is performed using the linear version of the gyro-fluid code FAR3d [2], that solves the reduced MHD equations for the thermal plasma coupled with moments of the kinetic equation for the energetic particles (EP), and the STELLGAP code [3] including the effect of the sound wave and the helical couplings. The simulations indicate the presence of $8-12$ and $3-7$ helical gaps at $r/a = 0.65$ and 200 kHz as well as unstable $n/m = 8/5-12/7$ and $3/2-7/4$ Helical AEs (HAE) triggered around $r/a = 0.65$ showing a frequency of 230 and 210 kHz, respectively. A parametric study is performed with respect to the thermal ion density and iota profile at the plasma periphery to verify the simulation results by mimicking the uncertainty of the experimental profile. The analysis confirms the destabilization of the same dominant HAEs for all the configurations tested, although the helical gaps radial location and frequency range change from $r/a = 0.6$ to 0.65 and from 170 to 230 kHz, respectively, as well as the dominant HAEs growth rate, frequency and eigenfunction radial location. To reproduce different NBI operational regimes [4], an AE stability analysis is performed for the $n = 5,9,13,17$, $n = 6,10,14$ and $n = 7,11,15$ helical families as well as a wider range of energetic particle (EP) energies and EP β values, identifying the EP populations leading to the strongest drive. The simulations indicate the EP populations with energies above 25 keV leads to the destabilization of a dominant $n = 5,9,13,17$ HAE at the plasma periphery with a frequency around 200 kHz.

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Three Dimensional effects on neoclassical particle transport of heavy impurities in ITER pedestal

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In this work, we propose to examine the consequences of the toroidal symmetry breaking in the equilibrium and the impurity transport in the pedestal region for the reference ITER Q = 10 baseline plasma scenario[1]. Luckily, the sole existence of the pedestal, i.e. a steep pressure gradient region at the edge of the plasma, implies that anomalous radial transport of particles and energy is strongly reduced in this region and impurity transport is found to be well described by the neoclassical theory.

Here, SFINCS[2,3] code is used to calculate the neoclassical transport and the ambipolar radial electric field, E_r, in the pedestal due to ITER toroidal field ripple and the Resonant Magnetic field Perturbations (RMP), used for ELM control[4]. Our results indicate a negligible effect on high Z impurity transport of the ITER toroidal field ripple. On the other hand, RMP produces a strong modification, to more negative values, of the pedestal ambipolar radial electric field along with the appearance of multi-valued solutions for E_r, similar to those appearing in stellarators. These modifications result in an increased outward neoclassical transport in the pedestal for both the main plasma ions (D and T in ITER) and high Z impurities, possibly modifying the background plasma profiles.

Despite experiments show a strong correlation between RMP fields and the E_r in the pedestal region[5], the high poloidal Mach number of high Z impurities, due to the large ion mass and the pedestal high electric fields, put into question the neoclassical theory ordering and their radial flow direction, which, needless to say, is of paramount importance for ITER success.

Acknowledgement

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Scrape-off-layer sheath model for effect of coherent mode on divertor particle and heat flux on EAST tokamak

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Recently, the effect of pedestal turbulence, namely coherent mode (CM) with a frequency of approximately 15 kHz, on the total particle flux, particle flux distribution, and heat flux distribution, as well as their respective decay lengths in the scrape-off layer (SOL) region, has been investigated in the EAST tokamak (F. F. Long et al., Nucl. Fusion 62 (2022) 096018). Direct evidence indicates that the CM in the pedestal can spread to the SOL region, resulting in an increase in the particle flux decay length (λ_{js}). This length is correlated with the density radial decay length ($\lambda_{n,SOL}$) in the SOL region, which is largely modulated by the change of pedestal CM amplitude. Moreover, the Langmuir probes clearly detect an electrostatic mode with a frequency of approximately 15 kHz in the divertor inner target, while no similar structure is observed in the divertor outer target. These results suggest that a new driven regime exists in the SOL region. We have proposed a model to provide a possible interpretation of the CM, which is peeled off and spreads to the SOL region.

Reconstruction of Magnetic Fields via Field Neural Network

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The measurement of magnetic fields is an indispensable method in different subfields of physics and engineering, especially in the research of plasma physics and magnetized confinement fusion. Magnetic probes placed in magnetized plasma devices are usually used for the direct measurement of magnetic fields. Due to extremely high temperature and various other limitations, direct measurement is invalid in a number of situations, such as in the core region of Tokamaks. Indirect methods are thus required to obtain the information of magnetic fields. Electromagnetic waves or charged particles are commonly used for the detection of electric and magnetic fields. By injecting electromagnetic waves or charged particles into a plasma and recording their initial and final state, the field distribution in this region can be solved as inversion problems. However, the difference between the initial and final states only provides the integral information of physical quantities along particle trajectories or wave paths. It is hard to solve the magnetic fields $\mathbf{B}(\mathbf{r})$ without assuming its form in advance.

We propose a machine learning method to reconstruct magnetic fields from the initial and final states for indirect measurements. Without the loss of generality, we consider a batch of charged particles moving through a region with a certain magnetic field. Their initial and final states, say their phase space states ($\mathbf{x}$,$\mathbf{v}$), can be measured. We design a neural network to represent the magnetic field, coined magnetic field neural network (MFNN). By training this MFNN using particle data, the magnetic field can be properly obtained even for complex field distributions. This method can be widely applied to different indirect measurement techniques. The accuracy of reconstruction and properties of MFNN are introduced.

Drift dynamics of a pellet-produced plasmoid in the presence of fast electrons

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Fast electrons exist extensively in tokamak plasmas in the presence of the toroidal electric field, or when applying LHCD to drive the plasma current, or during plasma disruptions. Fast electrons with high energy usually enhance greatly the pellet ablation [1], decreasing the pellet penetration depth and the fueling efficiency, which will decrease the output fusion power in future fusion reactors [2]. However, in recent experiments it is observed in TJ-II that the pellet fueling efficiency is increased by about 50% in the presence of fast electrons [3], the mechanism of which is not well understood. In this work, simulation study on dynamics of the pellet ablation and the cross-field drift of the pellet-produced plasmoid is carried out using the HPI2 code [4], which predicts well pellet ablation and deposition dynamics in most current devices [5]. The distribution of fast electrons generated by LHCD is obtained with the ray tracing code GENRAY coupled with the 3D quasi-linear Fokker-Planck equation solving code CQL3D. The predicted pellet deposition agrees well with EAST experimental data. The simulation results indicate that fast electrons influence the drift dynamics of a pellet-produced plasmoid through influencing the plasmoid parameters during its evolution. Finally the pellet fueling scheme on EAST is systematically optimized to achieve the deepest fueling depth in the presence of fast electrons.

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Linear modelling of electron Bernstein current drive in STEP

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Electron Bernstein current drive (EBCD) is being considered for the Spherical Tokamak for Energy Production (STEP) design. Current drive performance is sensitive to plasma and launch parameters, and therefore requires large parametric scans of ray-tracing and quasilinear simulations. A significant speed-up to this workflow is possible through the use of linear, adjoint current drive models (ex. the Lin-Liu model [1]). In this work, various linear current drive models are adopted for EBCD, applied to STEP, and benchmarked against the quasilinear code CQL3D [2]. Thus, for the first time, the validity of linear EBCD models is tested in reactor-grade tokamak plasmas. These models are found to accurately predict the current deposition location and efficiency, at least far from the pedestal and at low powers.

Three key findings regarding model accuracy are reported. First, given the high temperatures expected in STEP ($T_{e0} > 14$ keV), the scale separation between thermal and resonant electrons is small. Hence, the use of the high-speed-limit approximation is invalid when accounting for collisions. A higher fidelity momentum conserving collision operator is necessary [3]. Second, the EBW has a large enough wavenumber such that finite Larmor radius (FLR) effects are important for the wave-particle resonance responsible for driving current [4]. Lastly, the threshold at which quasilinear effects become important, and therefore the linear model is no longer valid, corresponds to a launch power of $P_{EBW} \sim 1$MW (though this strongly depends on wave parameters at the location of damping, as discussed below).

The quasilinear threshold in terms of dissipated RF power density is found to be notably low, given that the electron cyclotron current drive (ECCD) threshold is orders of magnitude higher [5]. However, further analysis reveals the dissipated power threshold is a proxy, and what really matters is the RF electric field amplitude, which is inversely proportional to the group velocity. Thus, the lower EBCD quasilinear threshold is attributed to the relatively low group velocity of the EBW. Further experimental validation of this limit is prudent. MAST-U will be equipped with a 1.8MW, steerable EBW system capable of on- and off-axis EBCD. A scan of P_{EBW} will allow for model validation and characterization of the quasilinear threshold.

Given the above considerations, the linear model is strictly not valid for realistic EBCD scenarios in STEP (of order $P_{EBW} \sim 100$MW). Nevertheless, the linear model may be useful as a rough, approximate model for scoping studies in STEP, and as validation for quasilinear codes in the low power regime.

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The hunt for zonal flows and the ExB staircase through velocity field measurements in MAST-U

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Drift-wave turbulence and the associated zonal flows are ubiquitous phenomena in tokamak plasmas [1]. Zonal flows are known to be driven exclusively by the drift-wave turbulence and they simultaneously act to strongly suppress the turbulent fluctuations from which they were created. Considering that turbulence is known to be the primary driver of anomalous radial transport in the confined region, the study of the drift-wave—zonal-flow system is essential for the suppression of radial transport and ultimately, improvement of the plasma energy efficiency [2]. Despite numerous indirect experimental measurements which hint at the presence of zonal flows, direct measurements remain scant [3]. As a result, many zonal flow theories and related simulations currently remain unvalidated, driving the need for reliable zonal flow measurement techniques.

Zonal flows are expected have radial scales of 1-10cm with characteristic frequencies roughly on the order of kHz. For reference, the beam emission spectroscopy (BES) system on MAST-U measures density-fluctuation images at 4MHz with a spatial resolution of ~1.6cm. Image-velocimetry methods (which infer velocities from density-fluctuation data) are conventionally operated with an effective inference frequency at least 2 orders of magnitude slower than the diagnostic frequency, which means that zonal flows exist at the limits of current diagnostic capabilities. Theoretically, inference frequencies could be significantly improved, but a lack of uncertainty studies have necessitated long averaging times. A recent uncertainty study of the two main image-velocimetry techniques has broadly quantified operational limits and enabled confident velocimetry with improved inference frequencies [4]. These uncertainty tests, in combination with the advanced BES system on MAST-U, will provide reliable velocity field inferences with inference frequencies up to ~100kHz. Velocity fields will be presented in the MAST-U tokamak in conjunction with a discussion on zonal flow measurement.

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Turbulence Dynamics in Confinement Transitions of Tokamak Plasmas

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Abstract
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Turbulent transport is the major performance limiting factor of tokamak plasmas. The high confinement mode (H-mode) provides a promising way to achieve a plasma state of reduced transport and therefore higher core pressures, which are required for any future fusion device. While regularly achieved experimentally, the physics of the transition into H-mode is poorly understood. The nonlinear transfer of energy between drift-wave turbulence and zonal flows (DW-ZF interaction) has previously been shown to be associated with the transition into H-mode [1] and explains the transition as a quenching of turbulence through self-organisation. The measurement of this interaction can serve as a path towards a better understanding of confinement transitions.

In this project we investigate the DW-ZF interaction in the upgraded Mega-Amp spherical tokamak (MAST-U) as well as in gyrokinetic simulations. The aim is to investigate the turbulence dynamics associated with H-mode transitions in MAST-U and to analyse whether the DW-ZF interaction remains a valid predictor of the H-mode transition for MAST-U's new super-X divertor. Preliminary results of turbulence dynamics based on density fluctuation measurements with the beam emission spectroscopy system [2] will be presented. Gyrokinetic simulations complement the localised experimental measurements by simulating the nonlinear plasma dynamics on a full flux tube. Here we use the local δf gyrokinetic code `GS2` [3] to investigate the poloidal distribution of the DW-ZF interaction. Whereas prior work has investigated this distribution for a simple circular flux tube (Cyclone base case) [4], this project will take this investigation towards realistic plasma geometry. Preliminary results from gyrokinetic simulations will also be presented.

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First measurements of turbulence in L-mode super-X diverted plasmas on MAST-Upgrade with the upgraded beam emission spectroscopy diagnostic

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Turbulence is thought to be responsible for the majority of transport in tokamaks [1], limiting plasma confinement and performance. As such, the study and characterisation of this turbulence is of great interest, as is the design and construction of a diagnostic capable of detecting it.

Recently, the beam emission spectroscopy (BES) diagnostic from MAST [2] has been upgraded for use on MAST-Upgrade. BES is an active spectroscopic technique for measuring ion-scale ($k_{r,\theta}\rho_i < 1$) density fluctuations. It requires a neutral beam, injected for the purpose of heating the plasma, to provide the active signal. Collisional excitation of neutrals with the plasma, and the associated spontaneous emission, give light intensity fluctuations proportional to the density fluctuations, $\delta I/I \approx \delta n/n$. An in-vessel mirror allows steering of the diagnostic to view the entire minor radius on a shot-by-shot basis. The emission is collected with an optical imaging system onto an upgraded 8×8 array of avalanche photo-diodes (APDs) [3] covering an approximate 13×15 cm area in the radial-poloidal plane, capable of sampling at up to 4 MHz.

This work presents first measurements of turbulence with the upgraded BES diagnostic on MAST-U. Three similar beam heated L-mode discharges in the super-X divertor configuration [4] were performed, with the BES viewing $R \in [1.16, 1.25, 1.34]$m, covering $0.15 < \Psi_N < 1.1$. Signal-to-background ratios of $> 10\times$ were achieved with an NBI energy and power of 57.5 keV and 1.25 MW. The turbulence is characterised through measurements of relative fluctuation amplitude, frequency spectra, wavenumber-frequency spectra, correlation lengths, decorrelation times, turbulence flow velocities, and measurements of non-linearity.

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Synthetic Aperture Microwave Imager mark 2 (SAMI-2) at MAST-U: design, hardware implementation and first results

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The first generation Synthetic Aperture Microwave Imager (SAMI) successfully operated at both MAST and NSTX-U in two modes of operation:

(a) imaging spontaneous emission of mode converted electron Bernstein waves (EBWs) [1]

(b) measuring the magnetic pich angle at a given density [2]. In this second mode of operation, SAMI injects a microwave signal at the plasma and images the 2-D Doppler back-scattered signal returned to the diagnostic from the critical density surface. Since turbulence in magnetised plasmas is elongated along magnetic field lines, the largest back-scattered amplitude is oriented perpendicular to the field.

The entirely redesigned Synthetic Aperture Microwave Imager mark 2 (SAMI-2) has now been built and is installed at MAST-U. SAMI-2 has three missions: (1) to make routine measurements of the edge current density; (2) to diagnose edge turbulence e.g. through cross-polar scattering; (3) to image mode-converted EBW emission. SAMI-2 has up to 30 dual polarisation sinuous antennas and can simultaneously acquire at two RF frequences in the range 24-40 GHz (thereby enabling correlations between signals at two radial locations). The system has been designed and built at component level (employing surface mount rather than connectorised technology). The data acquisition system is demanding: each antenna corresponds to a data stream of 2 GB/s.

We will present details of the SAMI-2 hardware and first results from MAST-U.

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2D electron density measurements using Coherence Imaging Spectroscopy in the MAST-U divertor

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A Multi-delay Coherence Imaging Spectroscopy (CIS) diagnostic has been installed on MAST-U, with the goal of measuring 2D poloidal profiles of the electron density in the divertor. Regions of higher density will correspond to a lower contrast in the imaged CIS fringe pattern, due to the greater Stark broadening of the measured D_γ Balmer line [1]. Measuring the contrast at multiple interferometric delays allows to separate the contributions of Stark and Doppler broadening, enabling density estimations even when the Doppler contribution is significant. Assuming toroidal symmetry, the contrast images can then be inverted into a 2D density profile through a non-linear optimization. The 2D density profile resulting from the inversion of a downsampled noiseless synthetic image based on a SOLPS simulation of the Super-X configuration is shown in figure 1, along with the relative error in the reconstruction for the regions with significant D gamma emission. The upper part of the outer leg is not in view of the camera and so it has been masked-off in the reconstruction.

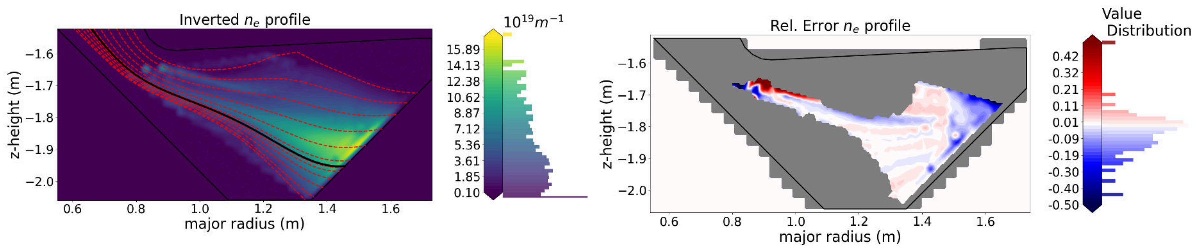

Figure 1: *Electron density profile resulting from the inversion of a downsampled noiseless synthetic CIS image, based on a SOLPS simulation of the Super-X divertor (left), and the corresponding relative error compared to the SOLPS density profile in the regions with emissivity above 1% of the maximum(right). The black and red lines in the left image represent the separatrix and magnetic flux surfaces respectively.*

The relative error peaks in the region closest to the X point are due to poor camera coverage and higher Doppler broadening in that region, while in the rest of the divertor leg the relative error is in the range [-20%,+10%]. The performance of the inversion will be characterized further in simulations with lower density and temperature and will be tested on experimental measurements.

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Integrated Data Analysis Technique for Investigating Divertor Physics

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The control of heat and particle flux from the core plasma to chamber walls remains a key challenge for nuclear fusion tokamak reactors. Divertors are designed to manage this flux and MAST-U is exploring the effects of novel magnetic configurations in the divertor region. To aid the understanding of processes occurring in the divertor, an integrated data analysis (IDA) system based on Bayesian inference is being developed toward experimental data at MAST-U.

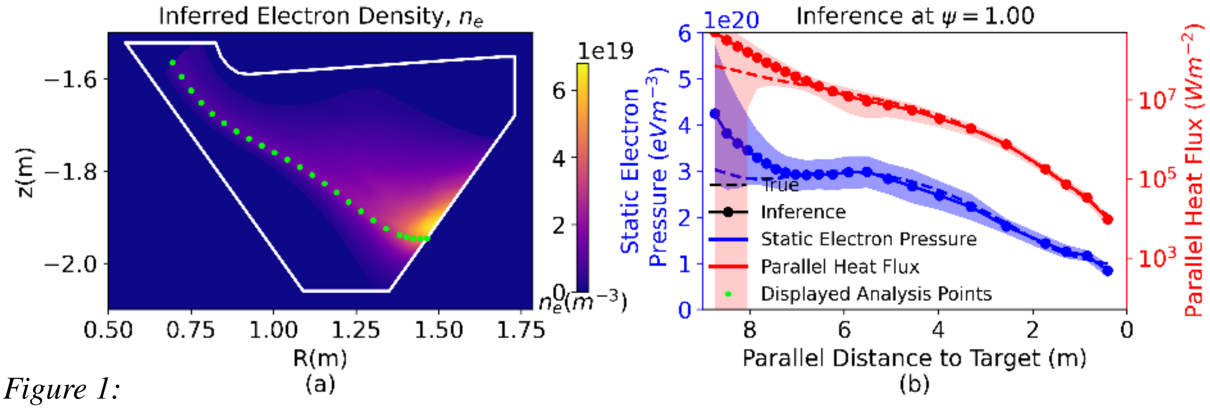

Figure 1:

(a) Electron density inference based on a synthetic MAST-U Super-X Scenario from SOLPS-ITER. Included synthetic diagnostics: divertor Thomson scattering; tile 5 Langmuir probes; multi-wavelength imaging of Balmer lines α to ε (hydrogenic transitions [3..7]$\rightarrow$ 2).

(b) Derived quantities (with their 95% confidence intervals shaded) from the inference of T_e, n_e and n_0 along a surface of constant, normalised poloidal flux, ψ, of 1 (the separatrix, green markers of (a)).

The IDA offers inference of electron temperature (T_e), electron density (n_e) and neutral density (n_0) plasma characteristics (fields) over a two-dimensional, poloidal cross section. The collective treatment of these plasma characteristics (analysed at grid points throughout the divertor) combined with the aligning of grid points to surfaces of constant poloidal magnetic flux permits the natural inclusion of expected physics into Bayes' theorem (which powers the inference). Tests on synthetic data have shown that this approach can circumvent limited diagnostic coverage in the divertor and achieve 4.7%, 2.7% and 8.7% mean absolute percentage error for T_e, n_e (shown in Figure 1a) and n_0 respectively across the relevant divertor region. As shown in Figure 1b, these parameters can be used to derive further quantities which give insight into plasma processes in the divertor.

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Pedestal stability survey of MAST-U H-mode plasmas

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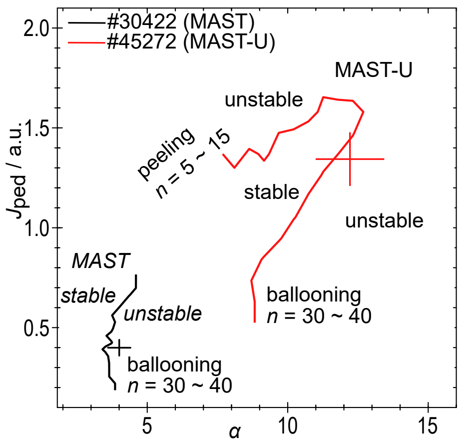
Modern tokamaks can operate in high-confinement (H-)modes, in which a steep edge plasma pressure gradient is established, creating a “pedestal”. H-modes are, however, subject to a class of explosive edge localised modes (ELMs), which could cause serious damage to the vessel walls. Large ELMs, especially of Type-I kind, must therefore be mitigated or suppressed. According to the “peeling-ballooning theory” [1], stability of the pedestal region depends primarily on two parameters: normalised pedestal pressure gradient, α, and pedestal plasma current density, J_{ped}. Too steep a pressure gradient tends to trigger high-n ideal ballooning modes (n is the toroidal mode number), which typically result in Type-I ELMs. On the other hand, too high a pedestal current density at lower α tends to make plasma unstable to low-n peeling modes. The challenge of improving confinement involves optimising the pedestal stability, in order to guide the plasma towards higher values of J_{ped} and α.



The recent comparison between MAST Upgrade and its predecessor, MAST [2], has shown that their pedestal stability characteristics were radically different: MAST-U H-modes were closer to the peeling boundary, with a narrow region of stability extending to significantly higher values of J_{ped} and α, indicative of weaker coupling between the peeling and ballooning modes.

This presentation reports on further detailed study of MAST-U pedestal stability, surveying a range of H-mode discharges from the first and second campaigns. Our analysis shows a clearer pathway to improving pedestal performance, by steering plasma towards the peeling limit with a careful control of parameters, including the edge density and current profile. These results will make a valuable contribution towards the design of compact prototype reactors, such as STEP.

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Improved magnetic diagnostics on General Fusion Plasma Injectors: developments towards the Fusion Demonstration Program

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General Fusion (GF) ran an experimental campaign over the course of 2022 with the aim of improving the accuracy of the Mirnov coils (B-probes) mounted on their largest plasma injector machine, PI3. This is part of a broader project aimed at reaching the 2% relative uncertainty required for the magnetic diagnostics on GF's Magnetized Target Fusion (MTF) experiment currently under construction as part of the Fusion Demonstration Program (FDP) at the UKAEA's Culham Centre for Fusion Energy in the United Kingdom.

Several improvements to sensor design, data acquisition (DAQ) stability and isolation, frequency calibration methodology, and processing algorithms confirm a net improvement on Mirnov coil data by about a factor 3 (from ~15-20% to 6-8%, depending on coil position around the flux conserver). The results of the experimental campaign show a marked improvement in measurement quality and redundancy, as well as a positive impact on GF's Bayesian reconstruction model of plasma equilibrium, with typical fit quality metrics (akin to reduced chi-square statistics) near the ideal value of 1 over a wide range of plasma shots.

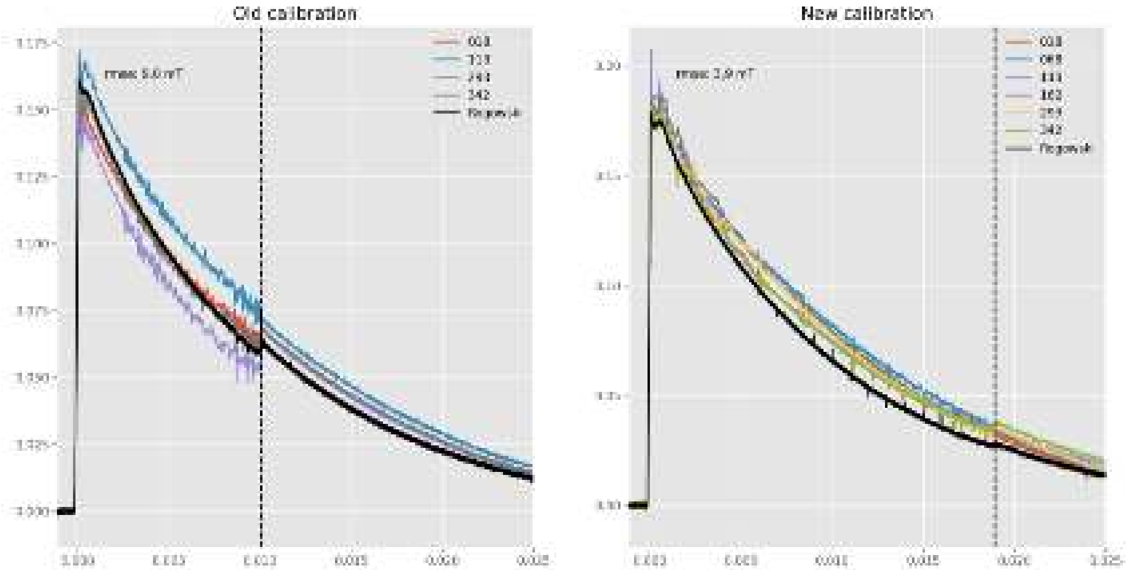

Figure 1: comparison of data from the improved Mirnov array (right) with the older setup (left) for two shots with the same experimental setup. Signal traces from redundant sensors show much better agreement, with a RMSE improvement of a factor 3.

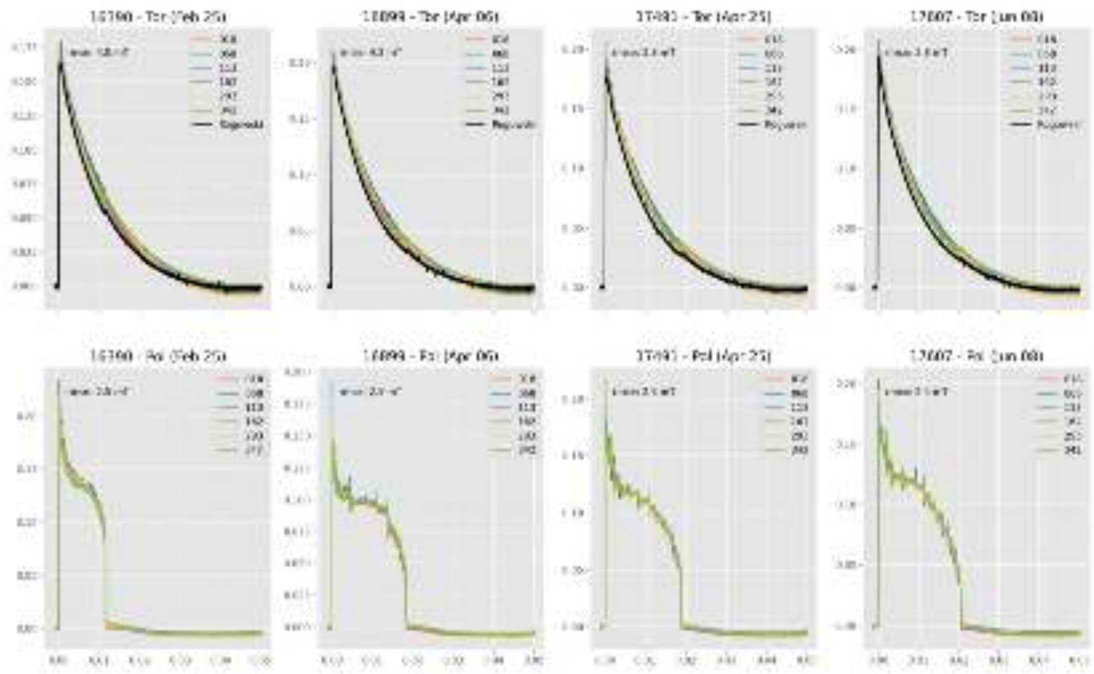

Figure 2: comparison of data taken over a ~6 months' time window confirms no detectable drift in the Mirnov sensor arrays at different positions and along both toroidal and poloidal directions over the whole campaign.

Current efforts are prioritizing further improvements to data quality and fidelity through upgrades to DAQ, digitization solutions, and calibration strategies, in order to bring the uncertainty down to a consistent 5% across all sensors on PI3, and eventually to the 2% target.
New materials and manufacturing techniques are also under testing to meet the harsh requirements of the FDP operating conditions, including high temperatures (up to ~600 C), repeated shocks (pressures up to ~350 MPa), high vacuum, and exposure to liquid Lithium.

In addition, an in-depth study is under way to identify the optimal layout of Mirnov sensors around the compression cavity of all FDP configurations, in order to support magnetic field measurements, reconstruction models, and mode analysis.
This study relies on a range of statistical analysis and machine learning methods applied to simulated plasmas, including:

- Principal Component Analysis of large libraries of Grad-Shafranov (GS) equilibria
- Sensitivity analysis of GF's reconstruction algorithm over a range of plasma configurations and diagnostics layouts
- Monte Carlo simulations of specific solutions to the GS equation (e.g. Solov'ev solution) to assess impact of different noise levels
- Comparison with measured data and 3D VAC simulations from our current generation of plasma injectors

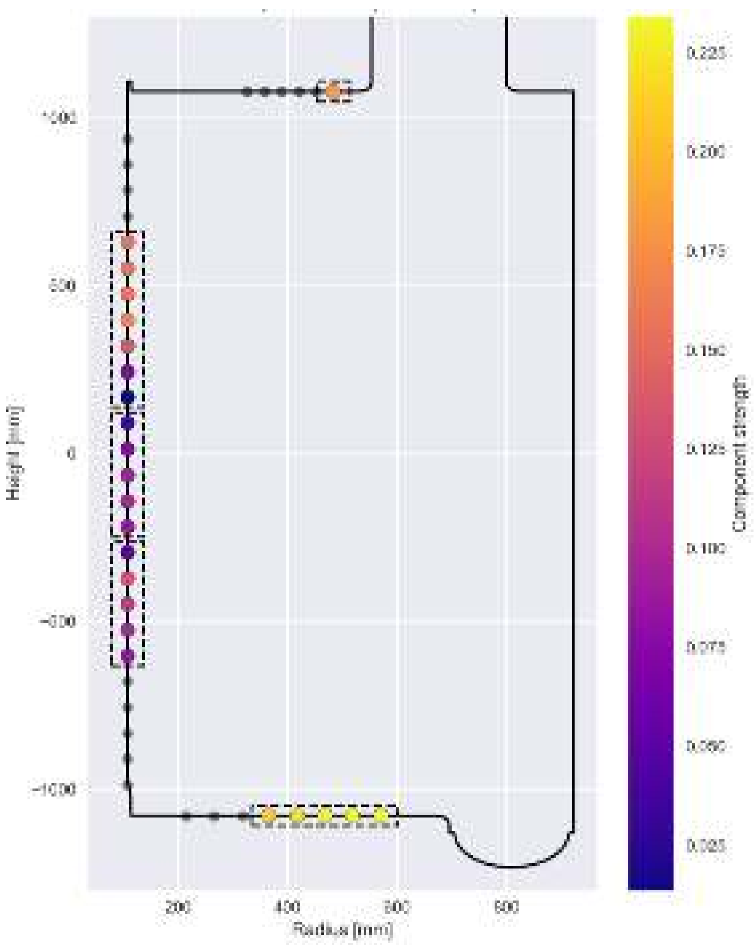

Figure 3: results of PCA applied to simulations for a test injector design, identifying the highest-yield positions for Mirnov sensors according to principal component eigenvalues, for ~100000 GS equilibria.

The results of these studies are expected to provide an optimal layout for the placement of Mirnov sensors for all FDP configurations, and for the expected noise levels of the diagnostic suite.

Design of a High-Temporal-Resolution Thomson Scattering System for a Magnetised Target Fusion Device

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We present a preliminary design for the Thomson scattering (TS) system on General Fusion's Compression Build (CB) reactor. The CB is a magnetised target fusion device, where a hot magnetised deuterium plasma is compressed to fusion conditions by a rapidly imploding liquid lithium liner. Precise knowledge of the evolution of the plasma temperature and density profiles during the compression is critical to the success of this machine. The TS system must therefore be capable of measuring the plasma temperature and density with sufficient spatial and temporal resolution in a harsh environment with limited optical access.

The goal of the CB TS system is to measure the plasma density and temperature profile equatorially with $< 20\%$ fractional error. The plasma electron temperature T_e and density n_e are expected to range from $T_e \approx 250\,\mathrm{eV}$, $n_e \approx 1 \times 10^{19}\,\mathrm{m}^{-3}$ at the beginning of compression to $T_e \approx 10\,\mathrm{keV}$, $n_e \approx 2.5 \times 10^{22}\,\mathrm{m}^{-3}$ at maximum compression. Unique challenges presented by the reactor design include limited optical access, long beam paths into the plasma, potential lithium coating of optical windows, high temperature (up to 500 °C in the location of collection optics), vibration from the high-speed lithium wall rotation, a variable plasma volume (pre:post-compression ratio of 500:1), and a small time window in which to measure (5 ms).

An Overview of the Fusion Demonstration Program and Related Plasma Diagnostic Systems in General Fusion

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General Fusion (GF) is pursuing a Magnetized Target Fusion (MTF) approach that involves compressing a magnetically confined plasma inside a cavity formed in liquid metal. General Fusion's approach builds from concepts originally developed under the LINUS program at the US Naval Research Laboratory and combines it with advances from experiments such as CTX and SSPX in compact toroid plasmas and coaxial Marshall gun systems. General Fusion's evolution of this approach involves forming a spherical torus deuterium-tritium plasma in a large (~4 m diameter) cavity formed in lead-lithium eutectic, and then collapsing that cavity with an array of pneumatic piston drivers. If compression on a timescale faster than the thermal confinement time of the plasma is achieved, volumetric compression of 350X would achieve the Lawson criterion and ignition. The advantages of this approach include a 1.5 m thick liquid metal blanket with 4π coverage surrounding the plasma, which provides straightforward heat extraction, a good tritium breeding ratio, and excellent neutron shielding for all structural components. The pneumatic drivers, synchronized with modern digital servo control systems, provide a low-cost driver, and the plasma target enables a pulsed system without manufactured consumables (e.g. tritium).

Since 2009, General Fusion has made significant investments in developing the underlying technologies required and the company is now undertaking a program to design and construct a large scale, integrated prototype of its technology (a "Fusion Demonstration Program", or "FDP") using a deuterium plasma target. Marshall gun plasma injector technology has been advanced through many generations of smaller (38 cm diameter) plasma injectors. Recent results from a larger 2 m diameter plasma injector (PI3) suggest we can achieve the temperatures, densities, and thermal confinement performance required for the initial plasma target. The company's capabilities in Marshall gun plasma injectors, in terms of scale, energy, and plasma performance are world leading.

FDP consists of two main phases, Plasma Build (PB) and Compression Build (CB). The main goal of the PB phase is the design and construction of a machine to inject a a full-scale deuterium plasma target into a static target chamber. For the CB phase, liquid lithium and the compression system will be added to the machine to compress the plasma target to fusion conditions with the spherical collapse of the liquid lithium liner. A diagnostic suite is being developed to measure plasma parameters before and during compression. These diagnostics include Thomson scattering, Mirnov coil, polari-interferometer, visible and x-ray ion Doppler, visible and VUV spectrometers, bolometry, neutron spectrometer, and multi-filter AXUV systems.

This poster will give a general overview of the FDP and of related diagnostics which will be developed in collaboration with other partners in academia and industry.

Study on the effects of pulsed x-ray emitted from a plasma focus device on different types of cells of medical and radiological interest

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In recent times, the knowledge of the biological effects of pulsed radiation (charged particles, X-rays and neutrons) coming from a pulsed plasma source, such as a plasma focus device, has aroused great interest due to its potential applications in areas such as radio medicine and radiobiology. In this study, a monolayer of isolated lymphocytes was irradiated using 5, 10, 20, 40 and 60 X -ray pulses (FWHM ~ 90 ns, dose rate ~ 10^7 Gy/sec) emitted from a kilojoule plasma focus device, PF-2kJ, and unstable chromosome aberrations (UCA) frequencies were estimated for each sample and, in order to have the highest cellular yield, mitotic index (MI) was evaluated to establish optimal culture conditions. The results obtained could evidence a different behavior of pulsed radiation compared to radiation from a continuous source. Therefore, the incorporation of cytogenetic markers may contribute to the characterization of the pulsed X-ray radiation generated by plasma focus devices, since they allow direct evidence and quantification of the effects of radiation in biological systems. On the other hand, low dose hyper-radiosensitivity (LDHRS) effects have been explored in various cancer cell lines using conventional x-ray irradiation. Cell death was evaluated in human colorectal (DLD-1 and HCT-116) and breast (MCF-7) cancer cell lines (monolayer cell cultures) irradiated with 10, 20, and 40 pulses. The cell death in the DLD-1 cell line irradiated with pulsed x-ray is three times higher than the reported for a conventional continuous x-ray source at two times higher doses [1]. LDHRS was also observed in HCT-116 and MCF-7 cells exposed to 10 and 20 x-ray pulses, respectively, which are reported not to exhibit LDHRS when conventional continuous x-ray sources are used [2].

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Measurement of Radial and Poloidal Temperature and Density Profiles in the Island Divertor of Wendelstein 7-X via the Helium Beam Diagnostic

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Understanding the basic plasma parameters of temperature and density, as well as their gradients in the scrape-off layer (SOL), is a topic critical for providing information about the performance of a divertor concept. The stellarator Wendelstein 7-X features a novel resonant island divertor with an adjustable rotational transform of $\iota = 2\pi$ (5/6, …, 5/4). In order to study the performance of this divertor concept, an active spectroscopy system on an atomic helium beam [1] was developed and installed on the stellarator [2]. The diagnostic was successfully operated in the first two divertor campaigns of the device in two magnetically connected modules. In this work, measured poloidal and radial electron temperature and density profiles are shown for two different magnetic configurations, "standard" $\iota = 2\pi$ (5/5) and "low iota" $\iota = 2\pi$ (5/6), across a scan of radiated power fraction, f_{rad}. Comparisons to EMC3-EIRENE modeling are presented, and profile differences arising from the differing connection length and transport effects are discussed, as well as observed profile characteristics at the high f_{rad} cases seen in detached divertor conditions.

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Exploration of on and off-axis beam fast-ion confinement physics with active and passive FIDA on MAST-U

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The toroidal-viewing fast ion deuterium-alpha (FIDA) system on the MAST-U spherical tokamak is same as that on its predecessor, MAST [1], and is sensitive to high energy passing fast ions. In this presentation, new results from MAST-U campaigns will be presented, particularly focusing on dedicated commissioning shots which elucidate the dependence of the emission on plasma current Ip, the role of on and off axis beams, as well as the validity of background subtraction, comparing beam notch data with (non beam-viewing) toroidally-displaced reference views. Owing to the presence of reflections, a matrix method is used to map reference onto active views [2]. The active FIDA signal, which is only visible when the on-axis beam is used, provides information on the fast ion confinement and, by comparing with simulations using TRANSP/NUBEAM and FIDASIM, can validate or refute fast ion models. Whilst the system is absolutely calibrated, several challenges have had to be overcome relating to the beam power and current fractions, leading to a scaling factor required to match experiment and simulation. Earlier [1] there was a residual scaling factor of 0.6, and the present factors will be described and discussed. The discrepancy can also be elucidated by comparing with neutron measurements obtained using a fission chamber. Commissioning shots include MHD-free periods for validation. Drops in signal intensity due to steady or bursting fast ion MHD will be discussed. The modes considered include fishbones, which can produce notable effects of FIDA intensities, and TAEs, whose effect is generally less obvious. The off-axis beam produces only a small active FIDA signal, but a strong passive signal. This component is ideal for examining ELM and RMP-induced transport, as well as the effects of additional charge-exchange losses due to low-field side gas puffing. Accurate modelling of this with FIDASIM requires independent neutral density measurements [3]. Finally, persistent toroidal asymmetries are present in the background passive FIDA signals, with spikes at certain wavelengths, which cannot be explained by asymmetries in neutrals or instrumental effects. Orbit following of fast ions near the edge will be carried out to assess whether prompt losses could explain the asymmetries.

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On dimensionless parameters and the self-verification of edge plasma codes

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Both 2D transport and 3D turbulence codes (e.g. Refs. 1, 2) used for the modeling of the edge plasmas in magnetic fusion devices are becoming more and more sophisticated and complex. As a result, the issue of the code verification, in the sense of the correctness of the implementation of the physical model and the accuracy of the numerical solution *per se*, become a very important task. In most cases the code verification is performed with so-called "manufactured" and existing (if any) analytic solutions (e.g. Ref. 3 and the references therein). However, such approaches do not necessarily answer the main question: does the code demonstrate the consistency with the approximations and equations describing the physical model.

On the other hand, by adopting the results of the seminar works by Kadomtsev and Connor & Taylor, to the atomic physics effects, ubiquitous in the edge plasma, in Ref. [5] it was shown that within an electrostatic approximation and binary collisions the plasma parameters at the edge of different magnetic fusion devices become similar, providing the similarities of the magnetic configurations and geometries of plasma facing components as well as the equity of the products nR and BR, and the ratio Q_{edge}/R, where n, R, B, and Q_{edge} are the plasma density, major radius of the device, magnetic field strength, and the energy flux from the core into the edge region. Even though in [6] it was shown that Ref. [5] misses an impact of step processes on atomic rates, the whole approach of the code self-verification based on the dimensionless parameters looks very appealing for the verification of both transport and turbulence codes.

The results of the first application of such approach [6] to the 1D version of SOLPS transport code will be presented and discussed.

Acknowledgements

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Experimental Comparisons and Analysis of MAST-U Solid State Neutral Particle Analyzer Data with Synthetic Diagnostic Signals

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A solid state neutral particle analyzer (SSNPA) [1] diagnostic oriented to measure trapped ions and a tangentially viewing fast-ion deuterium alpha (FIDA) [2] diagnostic that measures mainly passing fast ions operates in Mega Amp Spherical Tokamak Upgrade (MAST-U). A dedicated experiment designed to validate the SSNPA system in MHD-quiescent discharges was performed in the second MAST-U science campaign. This experiment yielded excellent baseline results with repeated shots using multiple NBI duty cycles. Similar experiments were also used to validate SSNPA performance across a wider range of plasma conditions, including different plasma currents, densities and NBI energies. A careful analysis of the instrumental results has been performed. Additionally, synthetic diagnostic signals have been computed using the FIDASIM[3] and SRIM[4] codes and deviations between synthetic and instrumental results are explored in this work. Active diagnostics show evidence of fast ion transport during Alfven wave and MHD activity. The phase space sensitivity of the SSNPA and thus the capacity it provides to diagnose the fast-ion population is discussed.

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A research program to measure spin polarized fusion reactions*

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The use of spin polarized fuel could increase D-T fusion reactivity by a factor of 1.5 and, owing to alpha heating, increase fusion Q in ITER even more [1]. The use of polarized D and ^{3}He in an experiment avoids the complexities of handling tritium, while encompassing the same nuclear reaction spin-physics, making it a useful proxy to study issues associated with full D-T implementation. ^{3}He fuel with 65% polarization can be prepared by permeating optically-pumped ^{3}He into a shell pellet [1]. Dynamically polarized ^{7}Li-D pellets can achieve 70% vector polarization for the deuterium [1]. The polarization lifetimes in cooled ^{3}He fuel capsules are days but only minutes for ^{7}Li-D [1]. Cryogenically-frozen pellets can be injected vertically into tokamaks and similar geometries by special injectors that minimize depolarizing field gradients. The use of a Sona transition [2] to polarize neutral beams is also under investigation. Theoretically [3], nuclei remain polarized in a hot fusion plasma but the predictions have never been tested experimentally. Measurements that exploit spin-induced changes in differential cross section are more sensitive than measurements of the reaction rate alone [4]. One possible scenario uses an unpolarized ^{3}He fast-ion population and tensor-polarized deuterium pellets; in another, both species are polarized in a thermonuclear plasma with ion temperatures above 10 keV. Modeling shows that a T_i>10 keV DIII-D plasma generates 14.7 MeV proton and 3.6 MeV alpha signals that are sensitive to depolarization with high accuracy [4]; additionally, nearly all reactor-relevant depolarization mechanisms are accessible for study in DIII-D. With a sufficiently intense polarized beam, accurate measurements of the depolarization rate could also be performed in the Wisconsin HTS Axisymmetric Mirror. Experiments in a compact spherical tokamak are also under investigation.

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Pedestal instabilities during the L-H transition

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The improved confinement regime or H-mode is the result of transport barrier at the plasma edge where the pressure rises steeply as to form a pedestal. This work reports on instabilities and turbulence measurements occurring in this decisive and narrow edge region in ASDEX Upgrade tokamak plasmas. Using the high sampling rate allowed by an ultra-fast frequency sweeping reflectometer [1], a high spatio-temporal resolution analysis of density, gradients and turbulence provides new and thorough insights on plasma instabilities from the competing turbulence and flow system during the I-phase [2]. The reflectometer's performances make it possible to record the instabilities of the plasma with a great temporal precision and a subcentimetric radial resolution, particularly adapted to the studies of edge pedestal and its turbulence. The model for the transition from L-mode to H-mode is based on driving zonal flow and the suppression of the turbulence in the pedestal region. In the realization of a turbulence/zonal flow cyclical process, the I-phase sequence has been precisely measured radially and temporally. It is observed the alternation in the turbulence frequency spectra between the broadband frequency driven transport and the low frequency zonal flow with an energy transfer between them along with the effect on the pedestal gradient. This occurs mainly towards the top pedestal region at rho ~ 0.95. In its turn, this pressure gradient, a potential free energy source for turbulence, would create particle transport producing rapid release of the gradient in an alternating process leading to a Limit Cycle Oscillation (LCO) sequence. Following this sequence and reaching the H-mode, a signature of blob-filaments is observed on the density, which grow locally in the pedestal until the ELM crash.

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Investigation of the coupling between zonal flow activity and multi-scale turbulent phenomena at the stellarator TJ-K

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Zonal flows have been found to regulate turbulent transport in magnetically confined plasmas at TJ-K [1]. Characterized by a finite radial wavenumber and infinite poloidal and toroidal extend, zonal flows are themselves driven by ambient turbulence. Intrinsically associated with poloidal shear flow, their interplay with background turbulence as well as coherent structures like blobs and geodesic acoustic modes is addressed in this work. Through the use of convergent cross mapping (CCM) [2], the causal coupling between small-scale fluctuations and zonal flows can be studied. This analysis method relying on time delay embedding and predictability estimation allows for the quantification of the causal coupling existing between two variables measured in the same dynamical system.

Flux surface-resolved Langmuir probe measurements of fluctuations in $E \times B$ velocity components coupled with conditional averaging enables the study of the Reynolds stress drive of the sheared flow from a new perspective: causality. In this frame, the causal coupling between the Reynolds stress drive ($\partial r < \tilde{v}_r \tilde{v}_\theta >$) and the acceleration of the poloidal flow ($\partial t < \tilde{v}_\theta >$) and its dependency on collisionality is presented. A reduction of the causality is observed with increasing collisionality which, in the frame of the underlying potential-density decoupling, suggests increased particle transport at decreased zonal flow activity. Consequences for the zonal flow energy loss channel like geodesic acoustic modes and other turbulent transport phenomena like blob detachment into the scrape-off layer can be expected and will be analysed.

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High temporal resolution measurements of filamentary transport with the ASDEX Upgrade Thermal Helium Beam diagnostic

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For future magnetic fusion devices, it is essential to control the power deposition on the plasma facing components (PFCs), in order to prevent melting and too high erosion [1]. One intrinsic process appearing in all plasma scenarios is the convective transport by filaments, which influences the power and particle distribution between the divertor and other PFCs [2]. The transport is caused by a positive pressure perturbation associated with filaments, which leads via an electric polarization to a radial outwards motion of the filament [2].

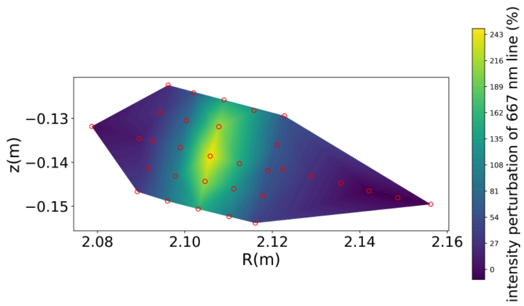

Figure 1: Intensity perturbation of a filament displayed in the 2D line of sight grid of the ASDEX Upgrade Thermal Helium Beam.

As in previous attempts [3], one has to measure the temperature and density of the filament as well as its size and velocity to obtain the power flux. The determination of these quantities is done the first time with a new diagnostic, the thermal helium beam at ASDEX Upgrade [4]. It allows to use a single diagnostic measurement to get the electron temperature and density, the size and velocity of filaments. Due to the used two-dimensional grid of lines of sight, the diagnostic measures filaments passing through the radial-poloidal plane. A view of a single time point can be seen in figure 1. The measured dynamics show a temporal decay of the filament electron temperature and density. As a result, the perpendicular power flux of the filaments decreases over time as well.

In this study, the filamentary behaviour for different regimes will be shown, and the measurements are compared to an analytical model for the filament energy, with the goal to calculate the individual power flux.

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Numerical studies of coupling to electron Bernstein waves in MAST Upgrade

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Microwaves in the GHz range of frequencies play an indispensable role for localized heating and current drive in plasmas. In conventional tokamaks or stellarators, injected microwaves resonate either directly at the corresponding electron cyclotron frequency or at their first harmonic. Higher harmonics are rarely considered as the absorption strongly decreases with the harmonic number. This is in particular a challenge in spherical tokamaks, where the plasma density usually exceeds the cut-off density of the injected microwave by several times. A solution is provided by the electrostatic electron Bernstein wave (EBW), which needs to be coupled to injected electromagnetic waves.

In this work we present numerical investigations of coupling to the EBW in the spherical tokamak MAST Upgrade. The simulations are understood as a feasibility study and preparation for EBW-heating experiments which are planned to be conducted at MAST Upgrade in 2024. Four different numerical codes are used to identify optimal coupling scenarios for an L-mode and an H-mode plasma. The importance of having a sufficiently wide beam is demonstrated together with a relatively large tolerance against angular mismatch due to the steep normalized density gradient length. The effect of plasma density fluctuations is studied in detail, and is found to result in an overall deterioration of the conversion efficiency, which is, however, small for the parameters considered at MAST Upgrade. Overall, scenarios with coupling efficiencies well above 90 % are identified making the EBWs an attractive and promising candidate for heating and current drive experiments in MAST Upgrade.

Observations of the $T(T,n)^5He$ resonance reaction in NBI heated fusion plasmas

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The Joint European Torus (JET) has recently performed experiments with fusion plasmas consisting of a majority of tritium (T) with trace amounts of deuterium (D), heated using neu- tral beam injection (NBI) with T ions. The dominating reactions for such fusion plasmas with high tritium fuel density ratios, $n_T/(n_T+n_D) > 0.9$, are the DT reaction, $D(T,n)^4He$, which produces 14 MeV neutrons, and the TT reaction, $T(T,2n)^4He$, which due to the 3-body end state produces neutrons with a continuum of energies with an upper limit given by the reaction kine- matics. The TT reaction has been observed to sometimes go via an intermediate resonant state, $T(T,n)^5He$,whichpromptlydecaysvianeutronemission$^5He \rightarrow {}^4He+n$.Thereiscurrentlylim- ited information on the branching ratio for the three-body reaction and the intermediate resonant reaction, with a possible energy dependence observed in previous publications. We have made neutron time-of-flight (TOF) spectrometry measurements of the DT and TT reactions for several T-dominated plasmas at JET. Since the neutrons produced in $T(T,n)^5He$ have a distinct energy given by the two-body kinematics of the reaction, it is possible to discern them in the neutron TOF spectrum as a peak. By modeling the neutron emission energy spectra for the various re- actions using the R-matrix formalism outlined in [1] and fitting the models to our TOF data we determine the shapes and relative intensities of the neutron energy distributions which best describe our observations. Finally, we estimate the branching ratio for the three-body reaction and the intermediate resonant reaction and compare it to previous results.

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RF plasma production at relatively low magnetic fields in the LHD

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The production of plasma in low magnetic fields is of interest to provide conditions for investigating high beta plasma confinement and to create discharges suitable for wall conditioning. In low magnetic fields, plasma production by resonant electron cyclotron waves, which is routinely used at stellarators, is not possible. In this situation, the radio frequency (RF) system can be used to produce plasma. Such discharges have been applied previously for wall conditioning in smaller stellarator devices [1,2]. In a low magnetic field, fast and slow waves can propagate even in a small plasma column. Such a plasma production have a chance to be successful in large machines too.

RF plasma production in low magnetic fields was studied for the first time at LHD. The frequency of the RF generator was 38.47 MHz with input power of up to ≈ 1.2 MW, at a range of magnetic fields of 0.4-0.5 T. The experiments were carried out in a deuterium gas atmosphere. The highest average plasma density of up to ~ 1.5×10^{19} m^{-3} was achieved using a pulsed gas puff, as compared to continuous gas flow. The obtained density is higher than recommended for wall conditioning. Both electrons and ions had low values of temperature, indicating a low state of ionisation of the plasma impurities. Optical emission spectroscopy indeed observed mostly low ionized light impurities. Nevertheless, the dense plasma can serve as a target plasma for further NBI heating, allowing high beta plasma studies in LHD.

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Density peaking and particle transport in negative triangularity discharges on DIII-D

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In this paper, we investigate the impact of various plasma parameters related to particle transport on core density peaking in negative triangularity plasmas on DIII-D. In DIII-D, line averaged densities twice the magnitude of the Greenwald density limit were observed in negative triangularity without causing a disruption. These high electron densities are not achieved through increased peaking in the core, but by increasing the separatrix density to much higher levels ($\sim 5 \times 10^{19}$) than are typically observed on DIII-D using gas puffing.

We do find that similar to positive triangularity plasmas, core density peaking increases with decreasing collisionality over a wide variety of parameters [1]. To investigate the impact of collisionality on density peaking, two experiments were performed scaling collisionality by changing the toroidal magnetic field $B_T = -2.0\,T$ to $-1.2\,T$ and plasma current $I_P = 1.0\,MA$ to $0.6\,MA$ and neutral beam heating power $P_{NBI} = 5.7\,MW$ to $2.7\,MW$ to match $\beta_N \sim 2.3$. Both discharges operated with $q_{95} \sim 2.7$ and the electron density peaking expressed as $ne_{0.4}/ne_{0.8}$ increased from 1.1 to 1.3 when the collisionality decreased by a factor 2-3.

Gas puff modulations were applied to disentangle the contributions from NBI core fueling versus an inward pinch in setting the core density profile [2]. Counter to previous gas puff modulations in positive triangularity discharges, the frequency of the gas puff modulation and its amplitude had to be reduced to mitigate the slow increase in the line averaged density profile. Even with these changes, the density profile kept rising during the modulation, with in some cases no noticeable decay in the electron density for $200-300\,ms$, after the gas puff was turned off, indicating an improvement in particle confinement time when compared to similar observations in both L- and H-mode positive triangularity plasmas. Additional particle balance and further analysis of these experiments will be performed and compared to a variety of L- and H-mode DIII-D plasmas in positive triangularity.

Acknowledgments

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Title: The Sheared-Flow-Stabilized Z-Pinch Approach to Fusion Energy

The sheared-flow stabilized (SFS) Z-pinch concept, developed at University of Washington with LLNL collaborators, is now on a path to commercialization at Zap Energy Inc. Recent experiments corroborate expected thermonuclear fusion reaction rates, as the discharge current is scaled towards compact reactor conditions. The Fusion Z-pinch Experiment (FuZE) employs high power-handling electrodes, flexible gas injection, and independently-switched capacitor bank modules to tailor the discharge current and gas distribution to establish stabilizing sheared flow and pinch current. Experimental campaigns are underway to increase the pinch current, stability duration, and DD fusion neutron production. We've recently achieved record pinch currents, > 600 kA, electron temperature > 2 keV, ion temperature > 2.5 keV and neutron yield > 2e8/pulse. These efforts aim to scale the pinch current, plasma density, and plasma temperature to reach scientific breakeven in the next generation device FuZE-Q, which is now operational. Zap Energy also has parallel programs developing power handling systems suitable for future power plants. Technologies under development include high-average-power repetitive pulsed power, high-duty-cycle cathodes, and liquid metal wall systems. Scientific and engineering status of these efforts will be discussed.

Efficient 5 GeV e-beam generation with the upcoming 10PW line commissioning at ELI-NP

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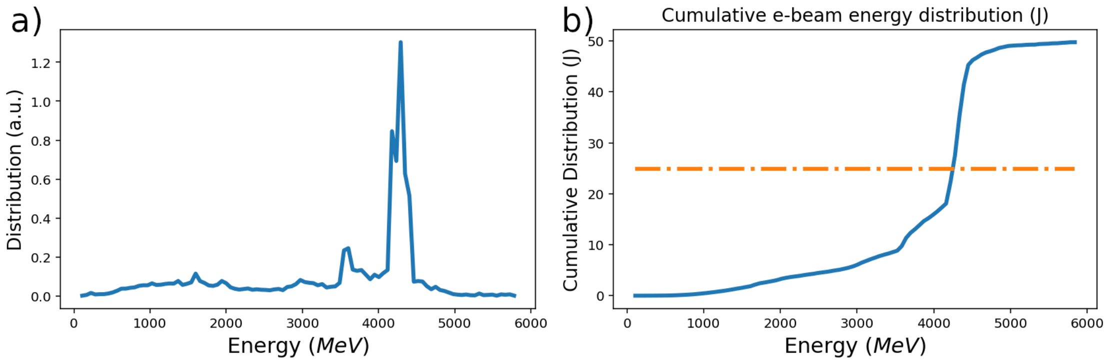
The ELI-NP facility [1] is currently in the commissioning phase of Arm B for the 10PW line , the Laser Wake Field Acceleration regime experiments being planned in Autumn. The Ti:Sa laser arm delivers 23fs long pulses having 240J energy and cental wavelength of 810nm. After pulse focusing with the 32m long on-axis spherical mirror, an estimated spot of 50 μm waist containing about 110J of encircled energy will be obtained, therefore realizing a peak intensity $I=1.2x10^{20}W/cm^2$ with corresponding pulse amplitude of $a_0=7.5$. In the commissioning experiment gas-cell and gas-jet targets with variable lengths, without preformed channel pulse guiding, will be used.



Here we show q-3D PIC simulations results conducted with the FB-PIC code [2], aimed at the optimization of the e-beam in terms of charge and median energy, for applications on secondary sources generation (*e.g.* γ rays through Inverse Compton/Thomson scattering, γ/neutron/muon generation with converters) . We found that by using a 4cm long gas target of He-N_2 mixture, an electron beam of modal energy of 4.3GeV, energy spread of 12% FWHM [see Fig. a)] and charge exceeding 12nC can be generated. Noticeably, the whole beam would deliver about 50J of energy, whose 50% is of with median of 4.1GeV [see Fig. b)], thus achieving a laser to electron beam conversion efficiency of about 20%.

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Modeling a novel laser-driven electron acceleration scheme with Particle-In-Cell simulations on exascale-class supercomputers.

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Laser WakeField Acceleration (LWFA) can accelerate ultra-short electron bunches up to very high energies (from hundreds of MeV to several GeV). However, LWFA usually does not provide enough charge for most of the foreseen applications, especially if high beam quality and high energies are also required.

Recently, we have devised a novel injection scheme consisting of a solid target coupled to a gas jet to accelerate substantially more charge than conventional injection schemes, while preserving at the same time the quality of the beam. In 2022 we validated this concept with proof-of-principle experiments at the LOA (France), and with a large-scale Particle-In-Cell simulation campaign, carried out with the open-source WarpX code[1,2]. In this contribution, we will summarize the insights gained from these simulations, carried out on the most powerful supercomputers in the world, including Summit (OLCF, #5 in the Top500), Fugaku (Riken, #2 in the Top500), and Frontier (OLCF, #1 in the Top500). A work describing the technical challenges that we addressed to make these simulations possible was awarded the Gordon Bell prize in 2022 [3].

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Acceleration of positrons in plasmas with high energy efficiency

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Density dowmramp injection has been demonstrated to be an elegant and efficient approach for generating high quality electron beams in laser wakefield accelerators. Recent researches has demonstrated possibilities of generating electron beams from tens to hundreds of pC when keeping a good beam quality. However, the plasma and laser parameters in these studies are limited in specific ranges or attentions are focused on separate physical processes such as: beam loading which affects the uniformity of the accelerating field and thus the energy spread of the trapped electrons; repulsive force from the rear spike of the bubble which reduces the transverse momentum of the trapped electrons and results in small beam emittance; and the laser evolution when travelling in plasma. In this work[1], we present a comprehensive numerical study of the downramp injection in laser wakefield, where we demonstrate that the current profile of the injected electron beam is directly correlated with the density transition parameters which further affects the beam charge and energy evolution. By fine-tuning the plasma density parameters, high-charge (up to several hundreds of pC) and low-energy-spread (around 1% FWHM) electron beams can be obtained. All these results are supported by large-scale quasi three-dimensional particle-in-cell simulations. We anticipate that the electron beams with tunable beam properties generated from this approach are attractive for a wide range of applications.

[1] Matter and Radiation at Extremes 8, 024401 (2023)

Betatron resonance as a source of high charge electron bunches

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A relativistic laser pulse propagating through an underdense plasma creates a positively charged ion channel. Electrons inside the ion channel perform betatron oscillations around its axis while they are oscillating in the field of the laser pulse. If conditions are favorable, electrons can get resonantly accelerated to energies exceeding the vacuum interaction limit. The acceleration mechanism is called direct laser acceleration (DLA) and is capable of accelerating 100s of nC of charge to multi-GeV energies using 10 PW lasers.

The maximum energy that can be achieved during the acceleration is given by the background plasma density and the initial transverse oscillation amplitude of a resonant electron. We show that the reason why electrons are able to achieve higher energies due to a higher laser field amplitude a_0 is, that it allows for the acceleration of electrons initially further from the axis. This has been demonstrated using a test particle model and quasi-3D particle-in-cell simulations.

In our work, we have investigated the optimal strategy of electron acceleration using DLA. The knowledge of a maximum transverse distance of an electron that leads to the resonant acceleration allows for estimating the optimal laser beam width. It turns out, that the focusing geometry aiming for the highest possible a_0 close to the diffraction limit is not the most favorable for the acceleration and the wider focusing ($\sim 10\lambda$) is beneficial for a wide range of background plasma densities. We present the equation for the optimal focusing as a function of laser power and background plasma density as well as the estimates for energies (exceeding 5 GeV for multi-PW lasers that are expected to be commissioned in the near future) that can be achieved if the pulse is guided for a sufficient distance.

This work was supported by FCT grants CEECIND/01906/2018, PTDC/FIS-PLA/3800/2021 and FCT UI/BD/151560/2021. We acknowledge PRACE for awarding access to MareNostrum based in the Barcelona Supercomputing Centre.

Superradiant scattering of electrons in evanescent waves

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Radiation emission plasmas is often a result of collective effects associated with the dynamics of relativistic charged particles. A common numerical approach to model their motion involves the Particle-In-Cell scheme which solves the full set of Maxwell's equations and the relativistic Lorentz force for the charged particles.The Radiation Diagnostic for OSIRIS (RaDiO) can retrieve the emitted spatiotemporal electromagnetic field structure of the emitted radiation in OSIRIS simulations, even at wavelengths smaller than the PIC resolution, by relying on the Liénard-Wiechert Potentials. These codes can run with a high level of efficiency in most of the largest CPU-based supercomputers [1]. Nevertheless, GPU accelerator boards are nowadays employed in supercomputers to the point where some of the most powerful machines nowadays are GPU-based systems. Recently, the radiation algorithm has been adapted to the GPU architecture, and this adaptation was integrated into OSIRIS. This allowed for a deeper study of new radiation generation schemes in plasma accelerators.

In this work, we use RaDiO to explore radiation emitted by charged particles in evanescent fields, like the ones present at the interface between a laser and an overdense plasma. These waves provide extremely localized fields that are able to induce rapid accelerations in charged particles, which can then radiate. Here we demonstrate, with theory and numerical simulations, that scattering electrons across evanescent waves can generate more high energy photon beams (e.g., x-rays) than similar processes such as transition radiation, even for moderately relativistic electrons with relativistic factors ($\gamma < 10$), leaving a trace tha should be easily experimentally verifiable in laser-plasma acceleration experiments. We also show that this process can lead to superradiant [2] emission provided that the electron bunches is suitably modulated.

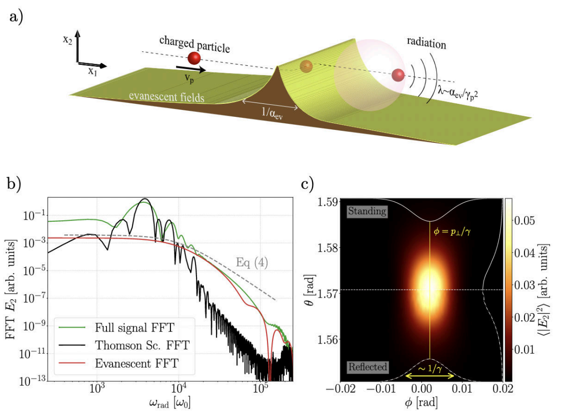

Figure 1: *Setup (a) and spectra (b-c) of radiation emitted by particles in evanescent fields.*

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Multi-10-MeV proton beam with ultra-low divergence driven by twisted light

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Plasma-driven proton beams show striking characteristics such as ultrashort (ps) duration, a high number of protons ($10^9 - 10^{13}$), and high energies (multi 1-100 MeV), which are suitable for impactful applications in areas ranging from medicine to high energy density physics and accelerator physics [1]. However, highly energetic proton beams often suffer from an angular spread (up to a few tens of degrees), leading to losses using magnetic quadrupoles and complicating the beam transport [2]. Recent studies have demonstrated that double-layer targets can support enhanced proton energies in comparison to single foil targets due to an improved laser energy coupling [3] and twisted light [4] can support a lower divergence of the proton beam at ultra-high intensities [5]. Here, we present a setup dedicated to a reduced angular spread ($<$ 1 mrad divergence) of a highly energetic (multi-10 MeV) proton beam by exploiting the benefits of a double-layer target and twisted light at moderate laser energies, which has yet to be unexplored. The self-consistent laser–plasma dynamics is investigated analytically and with three-dimensional particle-in-cell simulations in OSIRIS [6]. The work was devoted to examining the effects of relativistic self-focusing of a Gaussian and twisted laser in the near-critical plasma part of the target. The results demonstrate that by utilizing the cylindrical symmetry and the slower self-focusing properties of a twisted laser [7], the laser can drive high-energetic proton bunches with a significantly reduced divergence, compared to a Gaussian driver containing the same energy. Furthermore, we identified a simplified relation between the laser pulse energy and the target composition, which leads to the consistent generation of high-quality proton bunches for a broad range of moderate laser pulse energies.

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Recent achievements in high-intensity, high-power laser-matter interaction at the ELI Beamlines user facility

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The ELI Beamlines Facility is a pillar of the ELI (Extreme Light Infrastructure) ERIC pan-European Research Infrastructure hosting the world's most intense laser sources. ELI Beamlines developed and operates four cutting edge high-peak, high-average power femtosecond laser systems and offers a unique combination of primary (lasers) and secondary (high-energy particles and X-rays) sources to the international user community. Currently, several beamlines are operational and being upgraded to reach their full performances, while other beamlines are in their commissioning phase.

Laser-driven particle accelerators have gained interest in the recent years thanks to their versatility and innovative features. This interest has pushed forward the development of beamlines where users can exploit the unique parameters (e.g. ultrashort bunch duration and ultrahigh dose rate) of laser-driven particle accelerators (ion and electron beams) and radiation (XUV to gamnma-ray sources) for a wide range of applications.

The current performance of particle and radiation sources available at the ELI Beamlines user facility will be presented and discussed along with their potential use for multidisciplinary applications. The high repetition rate capability of the available primary and secondary sources will be highlighted in combination with a range of advanced target delivery solutions and diagnostics in operation in extreme laser-plasma conditions ($>10^{21}$ W/cm^2 at >1 Hz and $>5\text{x}10^{18}$ W/cm^2 at 1 kHz).

Laser-Initiated $^{11}B(p,\alpha)2\alpha$ fusion reactions in petawatt-scale, high-repetition-rate laser facilities

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The interaction of lasers with matter can trigger fusion reactions in laboratory conditions. In particular, the p+^{11}B→ 3α + 8.7 MeV represents a potential alternative for alpha generation to the most studied deuterium-tritium (DT) reaction, the best-known candidate for future reactors. The aneutronic p+^{11}B reaction is, indeed, attracting for many applications such as fusion energy production [1,2], astrophysics [3] and medical treatments [4]. One possible scheme for laser-driven p+^{11}B reactions is to irradiate a boron sample with laser-accelerated protons. This technique was successfully implemented, so far, with energetic lasers yielding hundreds to thousands of joules per shot [5-7]. This is possible on a few large installations but limited to very few shots. Instead, we present here a complementary approach, exploiting the high-repetition rate of the VEGA III petawatt laser at CLPU (Spain), aiming at accumulating results from many interactions at lower energy (20 J in about 50 fs at maximum compression), and at moderate intensity (about 10^{19} W/cm^2), for a better control of the parameters and statistics of the measurements. TNSA accelerated protons irradiated a thick natural boron sample and alpha-particles from p+^{11}B fusion reactions were measured by ad-hoc diagnostics, optimally arranged in space to increase solid angle of detection and thus enhance the number of revealed fusion products. Advanced techniques for detecting and discriminating alphas from backscattered particles, which represents a major challenge in this type of experiments, were developed and optimized during the last years [8] and were used in this campaign. Moreover, the proton beam impinging on the natural boron secondary target allowed to study the production of ^{11}C radionuclide, which can be relevant for PET medical diagnostic applications [9,10]. We present here in detail the experimental setup and the diagnostics that were used during the campaign, as well as the first preliminary results of the experiment.

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Stable high repetition rate laser-driven proton beam production for applications in material science

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The advent of high-power ultra-short lasers has opened up the field of laser-driven particle acceleration, in particular proton and electron acceleration. The investigation of these laser-accelerated beams and its use is currently challenging many research laboratories worldwide, in particular for the improved characteristics of these sources such as compactness, versatility and tunability. As such, this new acceleration technique has a strong potential of being employed in diverse applications.

In this talk I will present the newly installed 0.5 Hz high-repetition rate setup of the ALLS ion beamline located in Varennes (Canada), in which a laser with 2.5 % RMS energy stability is irradiating a solid target with an intensity of up to 10^{20} W/cm², to explore proton energy and yield variations, both on a large number of shots (up to about 400) and using different interaction targets.

Then, I will present the use of laser-accelerated protons and X-rays obtained on this facility as powerful diagnostics in the analysis of materials, namely the Particle-Induced X-Ray Emission (PIXE) and X-ray fluorescence (XRF) technique, where the intense, short and large proton and photon beam allows for a quicker analysis of the materials. This is of benefit for material science, aerosol detection and cultural heritage.

Keywords: *Laser-driven ion acceleration, Target Normal Sheath Acceleration, high-repetition rate targetry, Beamline stability.*

SPECT3D, Imaging and Spectral Analysis Package

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SPECT3D is a collisional-radiative spectral analysis package designed to compute detailed emission, absorption, or x-ray scattering spectra, filtered images, XRD signals, and other synthetic diagnostics [1]. The spectra and images are computed for virtual detectors by post-processing the results of hydrodynamics simulations in 1D, 2D, and 3D geometries. SPECT3D can account for a variety of instrumental response effects so that direct comparisons between simulations and experimental measurements can be made. We will present new features of SPECT3D and highlight their application to the analysis of HEDP experiments. We will discuss a newly implemented capability to simulate scattering signatures from realistic experimental configurations, which include the influence of plasma non-uniformities and collecting scattered x-rays from a range of angles. Other improvements include support for a wider range of hydrodynamics codes, utilization of FAC atomic data, and improved lineshape models

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Absolute calibration of X-ray cameras over the 0.1-9 keV enery range for MégaJoule Laser requirements by means of monochromatic X-ray generators.

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In this paper, we present some calibrations of different x-ray cameras used in conjunction with plasma diagnostics distributed all around the experiment chamber of the MégaJoule Laser (LMJ). Different x-ray cameras are thus calibrated before each experiment campaign, mainly x-ray streak cameras and x-ray gated cameras. Calibrations presented here are done in the static mode for these cameras and are carried out using two multi-anodes x-ray generators covering together the whole 0.1-9 keV energy range. To achieve radiometric calibrations required by physicists each x-ray generator operates with a monochromator specially designed to operate one in soft x-ray range and the other in hard x-ray range. Each x-ray calibration bench uses a silicon drift detector calibrated at the PTB on Bessy synchrotron to serve as secondary standard detectors. Last year, we demonstrated our ability to calibrate a gated x-ray camera in the 0.1-1.2 keV range. More recently, after great efforts, we succeeded in calibrating a LMJ x-ray bilamellar streak tube camera over the 0.1-9 keV spectral range with high accuracy (~ 4%). Equipped with a CsI photocathode, the obtained sensitivity measurements show discrepancies with Henke model especially below 1 keV. Physicists eagerly awaited these new results because they make it possible to constrain more strongly the predictions of hydrodynamic and atomic physics codes.

Statistical analysis of electron flux characteristics generated by kinetic laser absorption processes for lasers with intensities of $10^{14\text{-}16}\mathrm{W/cm^2}$

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In laser-plasma interactions with laser intensities $10^{14\text{-}16}\mathrm{W/cm^2}$ and sub-nanosecond interaction time, kinetic processes such as stimulated Raman (SRS) or Brillouin scattering (SBS) play an important role in the energy conversion from laser to plasma. The fast electrons generated by these processes transport energy into the dense plasma and change the hydrodynamics of the plasma, such as shock waves.

In this study, we performed plasma-in-cell (PIC) simulations over 100 ps with laser intensities $I_L = 10^{14\text{-}16}\mathrm{W/cm^2}$ and plasma density scale lengths $L =$ 50-800 μm to investigate the dependence of the generated fast-electron flux on these parameters. Figure 1 shows an example of the energy spectrum of the flux measured in the simulation. The spectrum consists of two components: thermal electrons and non-thermal fast electrons. We found that the average energy T_h and energy flux F_h of the fast electrons become constant after 20 ps. Their magnitudes, which are roughly proportional to the powers of the laser intensity I_L as $T_h \propto I_L^{0.5}$ and $F_h \propto I_L^2$, vary with plasma density scale length L. The change in trend regarding L seen in Fig. 2 is expected to be related to the location of the SRS. A detailed analysis will be presented in the presentation.

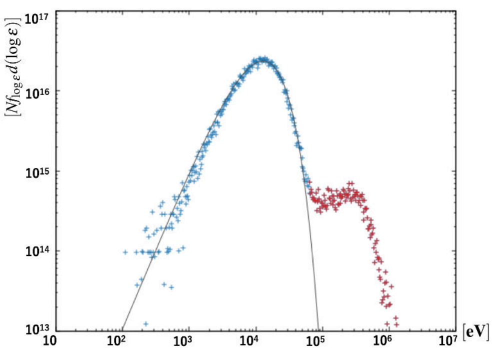

Figure 1: The energy spectrum of the electron flux (cross dots). It consists of two components: a thermal component (blue) that has the Maxwell distribution (solid gray line) and a non-thermal one (red) that departs from the Maxwellian.

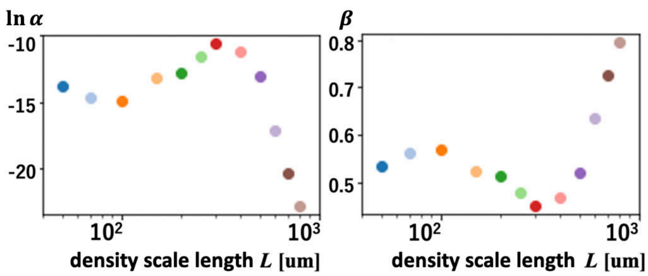

Figure 2: The dependence of the mean energy T_h of fast electrons on the laser intensity I_L and on the plasma density scale length L. We define $T_h \equiv \alpha I_L^{\beta}$, and plot the dependences of the coefficients $\ln\alpha$ and β on L. The trends change at $L = 100\,\mu$m and $300\,\mu$m.

Weibel filamentation of heat flow in laser-plasmas

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We show that non-linear heat flow from a laser-heated hotspot is subject to a collisional variant of the Weibel instability. The growth of the instability depends on the presence of plasma anisotropies of a higher order than those present in the Spitzer theory. These anisotropies are weak in planar heat flow but become strong when the heat flow is spatially divergent and non-local. Using the new fastVFP code to solve the time-dependent Vlasov-Fokker-Planck (VFP) equation in two spatial dimensions with full anisotropy and magnetic field generation, we demonstrate the growth of the instability on distance and time scales relevant to Inertial Fusion Energy (IFE). The heat flow breaks into filaments under the influence of self-generated magnetic field.

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k-space theory of stimulated Raman and Brillouin side scattering

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Side scattering, in contrast to backscattering, is a stimulated scattering process where the scattered light is perpendicular to the density or flow velocity gradient. It includes stimulated Raman side scattering (SRSS) and stimulated Brillouin side scattering (SBSS), where a pump laser is scattered by Langmuir wave and ion acoustic wave, respectively.

Recent ignition-scaled experiments have observed SRSS and attracted a renewed interest on the excitation of side scatters in inertial confinement fusion (ICF). These experiments involve a variety of parameter spaces, such as those on the national ignition facility (NIF), OMEGA laser facility, LULI, and SGII laser facility [1-4], implying a robust existence of side scattering in ICF.

However, the inherent complexity of side scattering is much greater than the backscattering, which is not fully understood. Previous theories were mostly based on the analyses of real space (x-space) equations and path integral method [5-7]. There are also some incorrect formulas and ambiguous physics in those old references, for example the absolute threshold of SBSS was not correct, the convective gains of side scatterings and effects of finite beam width are still very unclear.

To settle these problems and to better understand the behavior of side scattering in the linear stage, we have developed a k-space (or Fourier space) theory for both stimulated Raman and Brillouin side scattering [8,9]. The linear physics of side scattering can be described by a general Schrodinger equation with a quartic potential in k space. It shows intrinsic differences with backscattering. This Schrodinger equation is analytically solved through WKBJ method, and its eigenvalue reveals an absolute nature of side scattering. Therefore, we obtained absolute thresholds for both Raman and Brillouin side scatterings, and analytic formulas of convective gains when the threshold is not surpassed. Effect of finite beam width on side scattering has also been discussed.

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Theory and observation of hydrodynamic shocks in a plasma flowing across randomized ICF scale laser beams

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High-energy randomized laser beams interacting with flowing plasmas can produce a plasma response that leads to beam bending and, by momentum conservation, slows down the plasma flow velocity [1]. For the incoming plasma flow, with a velocity slightly greater than sound speed, the plasma response to a ponderomotive force exerted by speckled laser beams is the strongest, such that slowing down the flow to subsonic velocities leads to the formation of a shock. Nonlinear fluid simulations have shown large density and velocity jumps satisfying Rankin-Hugoniot relations. We will discuss theoretical predictions and interpretations of OMEGA and NIF experiments. In the experiments, plasma flows across the crossing beam configuration with reduced size of the speckles and enhanced laser intensity. Thomson scattering measurements on OMEGA were compared with rad-hydro simulations and the results are consistent with the shock generation. The NIF experiment is designed to demonstrate shock formation in conditions relevant to ICF hohlraum plasmas.

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Modeling the interaction of a 10^{23} W/cm^2 laser pulse with a micro-cone target

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Re-entrant cones were so far mainly used for high energy density physics research especially for laser fusion and has been proven to have an effective control on the fast electrons mainly for fast ignition research [1]. We showed in a previous paper [2] that a plastic micro-cone target can be used to enhance the intensity of a focused laser pulse higher than one order of magnitude from the initial value of 8x10^{20} W/cm^2 by performing two-dimensional particle-in-cell (PIC) simulations.

In this study, we perform three-dimensional PIC simulations for the interaction of a 10 PW focused laser pulse with a plastic micro-cone target with the height of 10 μm. The initial laser pulse intensity is 10^{23} W/cm^2. We obtain for different micro-cone tip diameters an intensification higher than 20 times as can be seen in Figure 1. We plotted also in Figure 1 the intensification for the foil targets with different thicknesses. We can see that the laser pulse is intensified more than twice by the micro-cone in comparison with the foil. Figure 2 shows us that the laser pulse is shortened by the micro-cone from 16 optical cycles to 9 optical cycles. We observe also that the electrons are directly accelerated by the laser field [3] which can be used in fast ignition and high energy physics. The maximum on-axis electron density has a sharp drop after 60 fs for a micro-cone tip diameter d = 1.25, 2.5, 3 and 3.2 μm and a slower drop for d = 4.8 μm as can be seen in Figure 3.

Therefore, micro-cone targets can be used as optical devices for guiding, intensifying and shortening a 10 PW laser pulse without refurbishing the laser system.

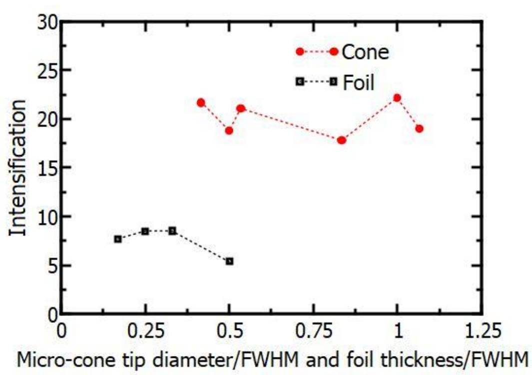

Figure 1. Intensification of the laser pulse versus cone tip diameter/FWHM and foil thickness/FWHM, where FWHM is the full width at half maximum of the focal spot.

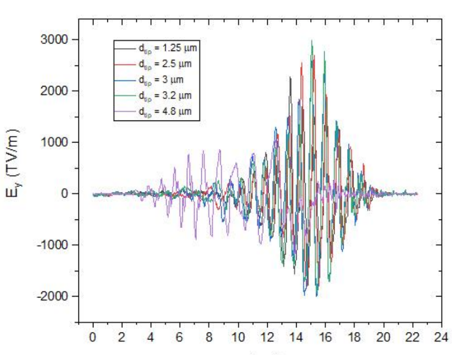

Figure 2. Maximum value of the electric field E_y variation on *x*-axis for different micro-cone tip diameters.

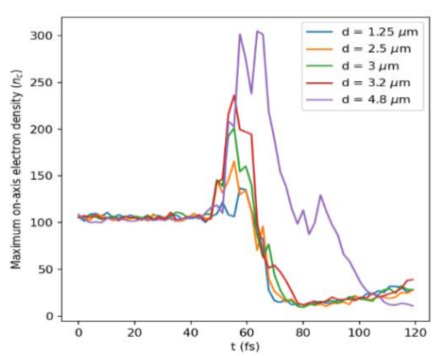

Figure 3. Maximum on-axis electron density versus time for different micro-cone tip diameters.

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Generation of intense magnetic fields with Ultra-High Intensity lasers

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The inverse Faraday effect (IFE) driven in plasmas by ultra-intense laser beams has recently gained increased interest as a possible path toward the creation of quasi-static magnetic fields of unprecedented strength (100s of kT) and as a macroscopic signature of radiation reaction (RR) [1].

In this talk, we present a different theoretical approach with respect to previous works [1], starting from the basis of the kinetic plasma treatment, that provides the scaling of the B-field amplitude in a broader range of laser parameters (e.g. intensity, duration, and focal spot) and might be extended to more general transverse beam structures (e.g. Laguerre-Gaussian beams).

We tested this approach against a series of 3D Particle-in-Cell simulations performed with the open-source code SMILEI [2] in a broad range of densities and laser characteristic parameters. In our simulations, the laser-target interaction can be studied with or without RR effects modeled via either the (quantum-corrected) Landau–Lifshitz equation or a Monte-Carlo module, the last one being necessary to account for QED effects arising at extreme laser intensities.

Our approach allows us to identify the key quantities to optimize the B-field strength, duration, and extension. In addition, this physics is strongly related to fundamental aspects of angular momentum exchange between laser and particles, which will be discussed with the support of the numerical results.

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EPS Abstract Temour Foster QUB

Positron beams, at both high energy and low energy, are a useful tool in detecting defects at the sub-nanometre range via Positron Annihilation Lifetime Spectroscopy (PALS). Current conventional accelerators typically give positron beams of low KeV energies and long durations, resulting in poor penetration depth and durations that match the annihilation timescale of a defect-free material. Laser-driven positron sources, e.g., at EuPRAXIA, can fix these issues by creating a positron beam that is ultrashort and higher energy, resulting in higher penetration depth and improved spatial resolution. We performed a proof-of-principle experiment at TARANIS laser system in Queen's University Belfast, with preliminary experimental data to be shown and simulations indicating an expected positron yield of 10^6 positrons per shot. The project has so far used the TARANIS laser at Queen's University Belfast, with preliminary experimental data to be shown. We plan to move this experimental platform to SYLOS at ELI-ALPS at the end of this year to commission the PALS capabilities at high-repetition rate, which will be suitable for industrial applications.

Inference of laser intensity in laser-electron collisions using the emission profile

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When an intense laser pulse interacts with a beam of relativistic electrons, the electrons emit radiation in a characteristic angular profile around their direction of propagation. By measuring the variances of the emission profile in the planes parallel and perpendicular to the laser polarisation axis, as well as the mean initial and final energies, one can infer the intensity of the laser pulse at the interaction [1]. In laser-electron collisions the beam alignment can fluctuate from shot to shot. Therefore, it is crucial to measure the laser intensity at the interaction point to to compare theoretical calculations and experimental data.

We have expanded our previous approach [1], which applied to the energy-weighted distribution, to include the number distribution, which is more commonly accessible in experiments, and explore its limitations as quantum effects become significant.

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Laser-driven quasi-static magnetic fields for magnetized high energy-density experiments

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Abstract

The use of seed magnetic-fields (B-fields) in laser-driven target-compression experiments is expected to lead to > 10 kT B-fields across the compressed core due to advection of the in-flow plasma. B-fields exceeding 10 kT are promising for magneto-inertial fusion since they reduce electron thermal conduction perpendicular to the field lines and may even increase alpha-particle energy deposition in the hot spot. Studying the formation of these compressed B-fields may also improve our understanding of extreme plasma magnetization phenomena relevant to astrophysics or extended magnetohydrodynamics.

In order to reach compressed B-fields exceeding 10 kT, one important challenge is to generate strong seed B-fields on major laser facilities. Where external pulsed power hardware is not available, it is possible to use laser-driven coil (LDC) targets to generate a multi-tesla quasi-static field. These targets allow easy access for diagnostics and do not produce a significant quantity of debris.

We have tested LDCs on several different nanosecond laser facilities under laser drive conditions similar to those at the Laser MegaJoule (LMJ). The goal was to predict the B-fields that might be achieved on LMJ by benchmarking a laser-driven diode model of B-field generation. At the LULI2000 and OMEGA facilities we used comparable laser intensities, $\sim 10^{15}$ -10^{16} W/cm^2, at

1.06μm and 0.35μm wavelengths respectively. We generated discharge currents of ~20 kA and ~8 kA yielding B-fields of ~50 T and ~6 T respectively, with targets of different size (and inductance).

Where possible, magnetic fields were measured using proton deflectometry directed along two axes of the target. Comparing our experimental deflectograms with proton tracking simulations enables us to identify various deflection features that can be linked to the looping current or static charging of the coil's wire surface. Measured discharge currents are broadly consistent with predictions from our model for all the experimentally tested conditions, which give grounds for the successful use of LDCs on large-scale facilities like LMJ.

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The Application of Nuclear Reactions in Non-thermal Equilibrium Plasma

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The non-thermal equilibrium plasmas widely exist and are frequently discovered in experiments, interstellar mediums, and extremely astrophysical events. The nuclear reaction yields and product energy spectrum can be diverged significantly by the non-Maxwellian velocity distribution of non-thermal plasma. Depending on this, we can properly utilize the nuclear reaction in plasmas to approach more fusion energy gain or obtain much information about the plasma state. In our work, we have investigated how the non-thermal plasma velocity distribution modifies nuclear reactions. We find that the non-Maxwellian velocity distribution modifies the nuclear reactions by restricting the reactant collision angle probability distribution to increase/decrease the average collision energy.

On the one hand, the non-thermal effect is beneficial to increase the fusion energy gain in fusion devices like tokamak, Z-pinch, and magneto-inertial confinement fusion devices, where the plasma involving non-ignorable non-thermal distribution is confined by a strong magnetic field. Taking the temperature anisotropy distribution as an example of non-thermal distribution, the theoretical analysis and simulations demonstrate that the fusion energy gain factor can be doubled to Q=10 from the originally designed Q=5 on the condition of ITER. On the other hand, the unique characteristics of nuclear reactions in non-thermal plasma systems are proven to be reserved in their reaction product energy spectrum. Based on this, we have proposed a nuclear diagnostic approach for probing the non-thermal ion energy spectrum in high-energy-density (HED) plasmas. In our series of simulations, we demonstrate clearly how this method is applied for probing the non-thermal high-energy protons produced in the HED magnetic reconnection experiment. The simulations also show that the reaction rate is increased by 4 orders of magnitude and the peak of the product energy spectrum shifts significantly towards the high-energy range due to the non-thermal protons accelerated from the reconnections.

In Summary, we have proposed a new perspective to using nuclear reactions in plasma systems. It is beneficial for nuclear fusion engineering, diagnostics in plasma experiments, and explanation of the nuclear astrophysical phenomenon.

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Magnetized Radiative shocks: their role in global evolution of interstellar medium.

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In astrophysics, many phenomena involving strong radiative shocks (RS) disturb and inject energy into the interstellar medium, affecting the rate of star formation in galaxies. They are referred to as "feedback mechanisms," and studying them is critical to understand galaxy evolution. Therefore, the interaction of strong radiative shock waves with other structures is a central problem in astrophysics. As often happens, most fascinating things are difficult to understand. Many physical process steps occur in the birth and growth of such objects: hydrodynamic instability, photoionization, ablation, recombination, molecular heating and cooling, and probably magnetic fields. Indeed, magnetic fields play an important role in accretion discs and in the interstellar or intergalactic medium. They drive jets, suppress fragmentation in star-forming clouds or in hydrodynamic instabilities of supernovae remnants and can have a significant impact on the accretion rate of stars. The magnetic field can also play a role additionally to radiation for example in protogalaxies giving rise to globular clusters. It also can stabilize thermal instability with a transverse magnetic field. Recent results of radiative shock (and their interaction with an obstacle) experiments on laser facilities are shown where we have measured many of the variables involved such as shock velocity, radiative precursor length and temperature, ablation of an obstacle by the radiation, shock generated in the obstacle after shock impact. In the meanwhile, we performed 2d numerical investigations using FLASH code when an external B field is present. Here we do observe the generation of a magnetosonic wave ahead of the RS for a B field perpendicular to the shock propagation that could be easily measured on large laser facilities such as NIF.

Hybrid ablation-expansion model for laser interaction with low-density foams

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Plasmas created by laser ionization of foams have attractive properties for research in the field of inertial confinement fusion (ICF). The addition of an extra foam layer to the ICF target capsule can improve implosion symmetry and suppress the formation of hydrodynamic instabilities in direct drive ICF or increase the efficiency of laser to X-ray conversion in indirect drive. However, modelling of the foam target as a homogeneous material, i.e. without taking the influence of the internal foam micro-structure into account, results in heat-front velocities that are considerably faster than those observed experimentally. Dedicated sub-grid models for laser-foam interaction are therefore needed to correctly describe laser propagation in foam and partition of absorbed laser energy between electrons and ions in the resulting plasma.

The novel hybrid model [1] describes laser-driven homogenization of an individual foam elements as a competition between isothermal expansion (due to volumetric heating by electron heat flux) and surface ablation by the incident laser. The model is formulated in terms of ordinary differential equations for mass, momentum and energy conservation and its parameters are chosen according to the detailed PIC simulations of laser-cylinder interaction [2]. Cross-sections for laser absorption and scattering are calculated from the Mie theory for electromagnetic scattering on sub-wavelength cylindrical particles.

The proposed micro-scale model is implemented in the PALE and the FLASH hydrodynamic codes for laser-plasma interaction. The capabilities of the hybrid model are demonstrated by successfully reproducing experimental data for several experiments at PALS facility [3] or the SG3-P laser [4].

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Laser Driven Muon Production For Materials Inspection and Imaging

We numerically show that laser-wakefield accelerated electron beams obtained using a PetaWatt-scale laser system can produce high-flux sources of relativistic muons that are suitable for radiographic applications. Scalings of muon energy and flux with the properties of the wakefield electron beams are presented. Applying these results to the expected performance of the 10-PW class laser at the Extreme Light Infrastructure Nuclear Physics (ELI-NP) demonstrates that ultra-high power laser facilities currently in the commissioning phase can generate GeV-scale muon beams with more than 10^4 muons per shot. Simple magnetic beamlines are shown to be effective in separating the muons from noise, allowing for their detection using, for example, silicon-based detectors. It is shown that a laser facility like the one at ELI-NP can produce high-fidelity and spatially resolved radiographs of enclosed strategically sensitive materials in a matter of minutes.

Unfolding signatures of magnetic field compression from the Ar K-shell emission recorded in OMEGA direct-drive cylindrical implosions

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The use of external magnetic fields in ICF implosions has been identified as a way to improve the hot-spot performance, reducing thermal losses and enabling higher fusion yields. To facilitate the investigation of the magnetic-field compression mechanism, a cylindrical geometry is particularly appropriate. Here, we discuss the application of Ar K-shell spectroscopy to characterize the core conditions in magnetized cylindrical implosion experiments performed at the OMEGA laser facility. Targets filled with Ar-doped deuterium were symmetrically imploded by a 40-beam, 14.5 kJ, 1.5 ns laser drive. According to 2D numerical simulations using the extended-MHD code Gorgon, the seed B-field of $\sim$30 T delivered by the MIFEDS pulsed-power device is compressed with the target up to $\sim$10 kT, which should be strong enough to alter the hydrodynamic evolution and therefore the conditions of the compressed core. Recorded Ar K-shell spectra show highly reproducible differences in the line ratios, indicative of a higher temperature in the magnetized implosions compared to the non-magnetized case. Forward-directed simulations of the spectra, obtained by post-processing the MHD output using detailed atomic-kinetics and Stark-broadened line shapes, reproduce reasonably well the observations. Furthermore, the use of advanced minimization algorithms shows potential for a quantitative spectroscopic analysis. The methodology is able to extract a coarse-grained representation of the core conditions radial profile at stagnation and supports the formation of a hotter central spot in the magnetized scenario.

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Investigating thermal transport in gas jets using Thomson scattering

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Thermal transport in plasmas, in presence of self-generated or externally imposed magnetic fields, is a long standing problem in the laser-plasma community. Among the different issues, we are concerned by i) the relevance of transport coefficients from very low to high Hall parameters, and ii) the modeling of non local transport in plasmas conditions where the Knudsen number is typically greater than 10^{-3}.

Those questions have recently exhibited a renewed interest with the updated transport coefficients proposed by [1, 2], but still in the local regime where electron distribution functions are Maxwellian. Detailed experimental results regarding thermal transport in the local and non local regimes were given by [3], but very few detailed measurements have been done since. For those reasons, we believe that investigating thermal transport in plasma conditions spanning several order of magnitudes of Knudsen and Hall parameters is necessary. We performed recent experiments at LULI where plasma conditions are inferred from spatially resolved Thomson scattering spectra, Fig. 1, and compared to different thermal transport modeling.

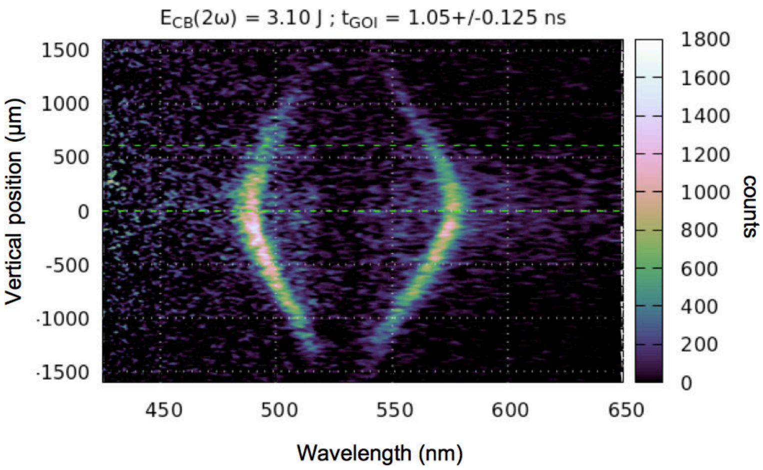

Figure 1: *Spatially resolved electron features of a Thomson scattering spectrum in hydrogen, 1 ns after the beginning of the pulse.*

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Simulation of Shear Flows in 2D Dipole Systems

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Two-dimensional dipole systems are realized in colloidal suspensions [1], in complex plasmas [2], in systems of polar molecules [3], and in quantum systems [4]. In more detail, the structural properties, oscillation modes, and thermodynamic characteristics of two-dimensional dipole systems was discussed in [5]. In this work the shear viscosity in classical two-dimensional (2D) dipole systems have been investigated [6]. The viscosity at various shear rates is calculated on the basis of the nonequilibrium molecular dynamics method. It is found that, the shear viscosity of 2D dipole systems has a minimum at intermediate coupling parameters. Increasing of the screening degree of the system led to shift the minimum of the shear viscosity to larger values of the coupling parameter. A single universal scaling law valid for both the bare dipole-dipole pair interaction potential and the screened dipole-dipole pair interaction potential are founded.

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Synthesis of carbon nanoparticles and their application

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This work is devoted to the investigation of the carbon nanoparticles synthesis in RF discharge with a mixture of gases (Ar/CH_4 and Ar/C_2H_2) and the influence of plasma parameters on the formation and growth of nanoparticles and nanomaterials. A method for determining the diameter of nanoparticles based on the measurement of self-bias voltage and electron density was considered. The study showed a significant influence of the diameters of synthesized nanoparticles on the optical properties of the plasma, in particular, on the emission intensity. This phenomenon can be applied to increase the efficiency of illumination devices. The results of a complex study of superhydrophobic surfaces obtained by plasma deposition of synthesized nanoparticles are also presented. The experimental results showed that the contact wetting angle ranged from 140° to 165°.

We investigated the influence of the carbon nanoparticles synthesized in the RF discharge on the emission intensity of the discharge plasma. During the investigation of the plasma intensity, it was revealed that the nanoparticles with diameter of 60 nm led to the strongest glow intensity enhancement. It should be noted that up to this value of diameter the intensity increases steadily, and after that with further increase in the diameter of nanoparticles a decline in the glow intensity takes place. Eventually, taking into account this fact, we developed an experimental illumination lamp with nanoparticles of diameter 60–70 nm inside. The presence of nanoparticles results in twice as much light emission as conventional fluorescent lamps [1]. Also, a complex study of superhydrophobic surfaces obtained by PECVD methods in RF discharge plasma with gas mixtures (Ar/CH_4 and Ar/C_2H_2) was carried out. The results of the experimental study showed that the contact angle varies in a range 140°-165° and highly depends on the plasma parameters. The contact angles of coatings obtained by the PECVD method in Ar/CH_4 plasma change from 160° to 135° over 18 months storage, whereas for Ar/C_2H_2 plasma the contact angle decreases sharply, from 150° to 80° in over 6 months [2].

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COMPACT – the future complex plasma facility for the ISS

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Complex, or dusty, plasmas consist of micrometer-sized grains injected into a low temperature noble gas discharge. The grains become charged and interact with each other via a screened Coulomb potential. On ground, gravity compresses the system and prevents the generation of larger, three-dimensional particle clouds.

The future complex plasma facility COMPACT [1, 2] will allow the investigation of large three-dimensional complex plasmas under microgravity conditions on the International Space Station (ISS). Its technology is mainly based on pre-studies (Ekoplasma, PlasmaLab), including a novel plasma chamber with adaptive internal geometry [3], a four-electrode radio-frequency system for plasma generation, and a stereoscopic particle diagnostic that allows to record 3D particle dynamics in real-time.

We will present the scientific goals of COMPACT, scientific and technology results from the pre-studies, technologies currently under discussion, and the project status.

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Development of combining plasma and catalyst hybrid type scrubber for large capacity PFCs gas

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A POU scrubber system is essential for the abatement of waste gases containing PFCs emitted during the semiconductor and display manufacturing processes. While the technology of semiconductor and display manufacturing process is developing, the scrubber technology is still stay almost same state. In recent years, the development of low-power and large-capacity scrubbers is required due to greenhouse gas emission regulations.

The conventional POU plasma scrubber uses average 12kW of electrical energy to process a capacity of 150LPM, but also requires a larger capacity and lower power. Also, abatement of PFC gases using only catalyst requires an average of 10 kg of catalyst, and the electrical energy used to make the activation temperature of the catalyst consumes approximately 10 kW.

Previous research has successfully dumped microwave into arc plasmas to produce plasmas with enlarged volume of approximately 45% more. The 5000ppm of NF_3 in 600LPM of N_2 was abated DRE 92% at electric energy 16 kW using by a hybrid type scrubber in which the developed combining arc and microwave plasma connected with a catalyst. The plasma-treated PFCs gas has a high temperature, which makes it possible to raise the catalyst to activation temperature without using electrical energy.

State changing collisions of H_3^+ with H_2

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H_3^+ ions play a great role in cosmic chemistry as universal proton donor [1]. H_3^+ ions exist in two nuclear spin configurations: ortho and para. H_2 collisions with H_3^+ are one of the reasons of the relaxation of the ortho:para ratio in H_2. The goal of our study is to measure ortho-para conversion rate coefficients of reactions between ortho/para states of H_2 and H_3^+ in order to explain the non-equilibrium of H_3^+ and H_2 populations that were observed in the ISM [2].

The cryogenic 22-pole radiofrequency (RF) ion trap was used for this study [3]. We used H_2 (25% fraction of para-H_2) and para-enriched H_2 (99.5% fraction of para-H_2) produced by catalytic conversion in para-hydrogen generator [4].

Laser Induced Reaction was used to determine the quantum state of H_3^+ ion. The number of excited ions was measured from reaction: $H_3^+ + Ar \rightarrow ArH^+ + H_2$, $\Delta H_0 = 0.57$ eV. An infrared laser was used to stimulate the second overtone transitions of ortho and para H_3^+.

The time evolution of the number of H_3^+ and ArH^+ ions in the 22 pole trap is presented in the figure (Fig. 1). The open points are without laser – background, the full points were measured with laser switched on (that time is denoted on the lower panel). As a result, we are able to probe the time evolutions of relative number densities of different rotational states of H_3^+ ion.

Acknowledgements: This work was partly supported by the Czech Science Foundation (GACR 21-28560S, GACR 22-059358, GACR 23-05439S) and by the Charles University (GAUK 337821, GAUK 332422, GAUK 376721).

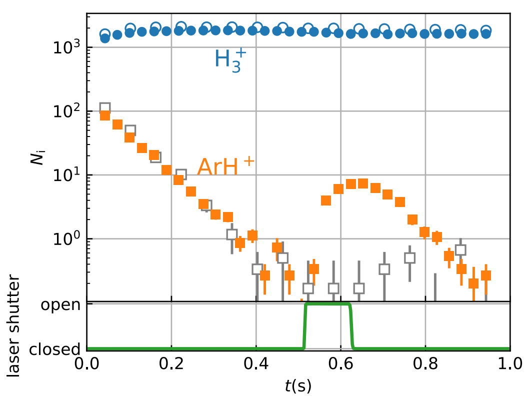

Figure 1: *Time evolution of the number of* H_3^+ *and* ArH^+ *ions.*

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Probe Diagnostics of Titanium Nitride Plasma in Hollow Cathode Jet at Low Pressure

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We present Langmuir probe and curling probe diagnostic of a DC discharge generated by titanium hollow cathode [1] in the mixture of argon and nitrogen at room temperature and at low pressure. We have chosen this arrangement since transition metal nitrides like TiN have undergone rapid developments recently and are used as high performance plasmonic and optoelectronics materials. The major reason for their rapid advancements is their tunability and stability.

We performed a diagnostic using the Langmuir as well as the curling probe [2]. We present the dependences of electron density (n_e) on the applied power and the argon-nitrogen flow ratios in the mentioned system together with a qualitative discussion of the obtained results.

It is interesting to note here that both probes show the same behavior with changing processing parameters i.e. power (Fig. 1). However, the density measurement determined by the curling probe is five times of magnitude lower than when determined from Langmuir probe data with increasing distance from the hollow cathode plasma jet.

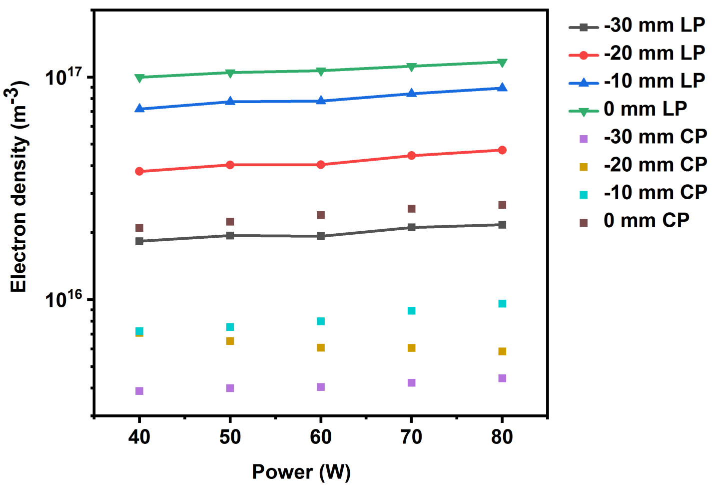

Figure 1: Comparison of electron density obtained from Langmuir and Curling probes

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Plasma potential control in a magnetized plasma: modeling and challenges

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Predictions on fine control of plasma potential profile in $\mathbf{E} \times \mathbf{B}$ plasma discharges would open up new opportunities in laboratory and industrial plasma (e.g. for plasma centrifuges [1]). Recently, there has been a growing interest in the use of emissive cathodes to achieve plasma potential control [2, 3, 4] and experiments at low emission showed remarkable agreement with modeling [5]. The extension to strong emission regimes is reported here.

Experiments were carried out in a magnetized Argon plasma column, generated by a 1 kW RF inductive source (magnetic fields between 170 G and 340 G) at 1 mTorr, under high thermionic emission from an emissive tungsten cathode [3]. The radial evolution of the plasma potential for increasing values of the emitted current I_b (Fig. 1) shows that electron injection is efficiently controls the profile of plasma potential.

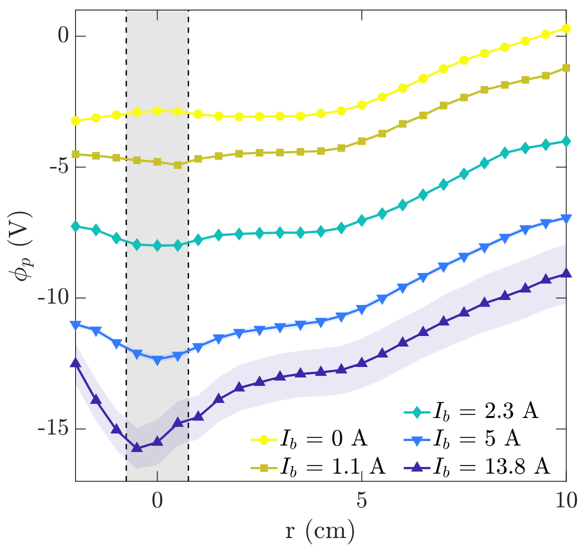

Figure 1: *Plasma potential profiles for various emission current from the cathode located around r = 0 cm.*

Measurements of plasma parameters (n, T_e, ϕ_p) are compared to model predictions obtained by assuming that the perpendicular conductivity is dominated by ion-neutral collisions [2]. The voltage drop due to thermionic emission is consistent with the predictions, resulting in a two-fold increase at high thermionic emission (see Fig. 1). However, an unexpected anode sheath at the edge of the plasma column ($r = 10$ cm) has a dramatic effect and needs to be incorporated in refined models.

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Breakdown measurements in low GWP gases

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In past decades several technological breakthroughs were based on the use of fluorocarbon gases. The most important impacts were achieved in plasma etching for microchip fabrication, plasma-based nanotechnologies, particle detection, refrigeration, and gas insulation. With all the benefits of new technologies, environmental issues related to global warming arose. Consequently, the research in the field of low-temperature plasmas was shifted in direction of finding eco-friendly solutions – gases with low global warming potential (GWP) and low ozone depletion potential (ODP), that would sustain or improve the efficiency of applications.

Our work is focused on studies of elementary processes in fluorocarbon gases that can be used in the modelling of real-life applications of gas discharges. We compare breakdown data for 1,1,1,2-Tetrafluoroethane (R134a, $C_2H_2F_4$) and its replacement gas 2,3,3,3-Tetrafluoropropene (HFO-1234yf, $C_3H_2F_4$). The analysis is based on measurements of breakdown voltages, critical fields, spatially and spectrally resolved emission distributions of the discharge, effective ionization coefficients and available cross-section data [1,2].

Acknowledgements

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Low-Cost High-Frequency Power Supply for Cold Atmospheric Plasma Sterilization

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1.Introduction

Surface treatment using plasmas is a process widely used in industry. Examples of technological applications include deposition of thin films, removal of material through the sputtering (etching), welding of metals, doping of semiconductors, electric thrusters, fabrication of nanomaterials and elimination of biological contaminants.

There are different ways to sterilize medical equipment, for example, using ovens, antiseptics, disinfectants, autoclave, ultraviolet, among others [1,4]. Surface treatment using plasmas is a promising technique for the sterilization of medical equipment.

Atmospheric Plasma processes, which are the focus of this paper, can be applied in open and closed environments, at atmospheric pressure, ionizing the atmospheric air, producing a cold plasma and thus reactive ions that are capable of eliminating viruses, bacteria, fungi, depending on the duration of exposure to the ionized gas [8]. This plasma generated from atmospheric air, and at pressures close to 1 atm, is known as cold atmospheric plasma (CAP).

The ongoing COVID-19 pandemic led to the development of different and affordable ways to sterilize surfaces, objects and environments in a safe and reliable way. In recent years, several applications for atmospheric plasmas have been studied and developed, with a focus on eliminating the SARS-CoV-2 virus. This concept has been applied to the treatment of surfaces [12] such as PFFF3 masks [5], in the sterilization of environments, wounds, dressings and medical equipment [3,8]. This scientific effort also brought other applications for CAPs, such as in food preservation processes [6] and in the manufacturing process of medical materials [12].

Plasmas can inactivate and eliminate biological contaminants through different mechanisms, such as the production of free radicals, reactive nitrogen species (RNS), reactive oxygen species (ROS), electric fields, charged particles and ultraviolet (UV) photons [3, 13]. These mechanisms can act directly or indirectly on sterilization, for example, the production of free radicals and reactive species can act directly on biological contaminants (through the diffusion of gas around the object to be sterilized), or by dissolving these chemical compounds in a liquid solution to be used as an antiseptic cleaning material [3,13].

2.Cold Atmospheric Plasma Sources

Cold atmospheric plasmas sources can be obtained with different electrical discharges such as corona discharge, dielectric barrier discharge and glow discharge. These types of plasma can contain electrons, UV photons, ions, neutral atoms and molecules [3].

The glow discharge can be used to obtain a cold plasma jet. This jet is an extension of the plasma density decay from the generation point [3]. Thus, by regulating the electrical parameters of the discharge and the flow of the gas, we can control the parameters of the jet, such as density, intensity, and plume size. These devices are usually pen-shaped, with a dielectric material serving as the structural body, an electrode on the inside of the tube, and an electrode on the outside of the tube.

Corona-type plasma discharges use electric fields capable of ionizing the gas around an electrode, but without allowing arcing or dielectric breakdown to occur [3]. These electric fields can be continuous (DC) or alternating (AC).

Atmospheric corona and glow discharges require high voltage and low current. The electric arc in these systems uses a low voltage and high current. The electric arc also has applications in the generation of CAPs and in different industrial processes, such as the generation of ultra-fine particles, cutting, welding, waste treatment, plasma spraying, among others.

DC Pulsed is a circuit that uses pulses from a DC signal on the primary of the transformer to create high voltage pulses on the secondary. These pulses are in the form of a PWM signal (square wave) and make it possible to control the frequency and pulse width of the generated signal. A possible example of this topology consists of a PWM signal generator circuit, which in turn controls a power stage, made up of transistors. These, in turn, are responsible for switching the primary of the transformer, creating voltage and current pulses in it. In addition to signal adjustment, these circuits make it possible to control the power delivered to the transformer (and in turn to the plasma), allowing operation with varying levels of power and avoiding the transition to electric arc.

In this work a test circuit was developed using the DC Pulsed philosophy. A PWM signal generator, using a 555 IC and an LM741 operational amplifier, was coupled to a MOSFET, IRF540N, in order to create pulses in the primary of a FLYBACK transformer, model OV20762F, taken from a CRT television. The plasma wand was built with a 5 mL hypodermic syringe, which was modified to allow air to enter through the upper part, and the positive electrode to pass through. The purpose of this initial circuit, in addition to making it possible to adjust the discharge in order to find the optimum operating point for the system, was to develop a low-cost system (approximately 20 dollars).

Figure 1 shows the prototype mounted on a universal perforated board. The power supply for this circuit was carried out with a bench source, model PS-1502DD, supplying 13 V and 1.2 A approximately. This circuit can also be operated with a 12V battery.

Figure 2 displays the corona discharge between the plasma wand and the ground plane connected to the ground of the high voltage transformer. The body of the plasma pencil consists of a hypodermic syringe. The biocide action against biological contaminants is currently ongoing work.

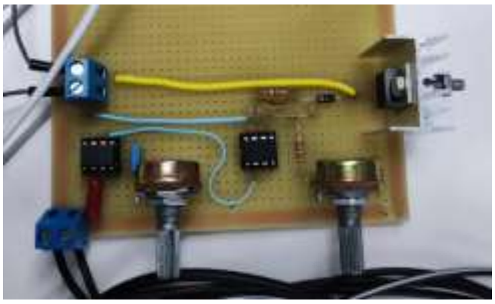

Figure 1. Electronic circuit of the prototype of the low-cost plasma pencil.

Figure 2. Corona discharge between the plasma pencil and the ground plane.

4.Acknowledgements

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Filamentation Morphology in Capacitively Coupled Highly Magnetized Plasmas

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Due to the small charge-to-mass ratio of dust particles, it is often necessary to use large magnetic fields of $B \geq 1$ T, in order to observe the influence of magnetic forces in laboratory dusty plasmas. However, when experiments are performed at high magnetic fields in capacitively coupled, radio frequency discharges, the background plasma is often observed to form filamentary structures between the electrodes that are aligned to the external magnetic field which disrupt the uniformity of the plasma and can adversely impact our dust experiments. Experiments performed in the Magnetized Dusty Plasma Experiment (MDPX) device have led to identification and characterization of these filamentary structures. More recent experiments have implemented new configurations which allow for the confinement of a single filament thus providing more detailed studies. This presentation discusses the morphology of several distinct filamentary modes that are formed in low temperature plasmas with different neutral gases. There is strong evidence that each spatial mode has a threshold condition that is dependent on the ion Hall parameter – which is a function of magnetic field, neutral pressure, and ion mass. The criteria for the formation of the filaments are shown to be consistent with predictions of numerical simulations.

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TIME-RESOLVED SPECTROSCOPY OF DISCHARGES IN CsCl SOLUTIONS

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Time resolved optical spectra have been recorded of discharges in aqueous CsCl solutions. The strongest atomic lines observed are from the hydrogen Balmer series, but there are also broader features in the spectrum. There are significant changes in the intensity and shape of these features in the spectra with time.

Plasma discharges have been generated in caesium chloride (CsCl) solution between two tungsten pin electrodes. Time resolved optical spectra have been recorded with an ICCD iStar Andor camera and a small broad band UV-visible spectrometer. Approximately 320 nm of the UV-visible spectrum can be recorded with the camera and a 300 line/mm diffraction grating in the specgtrometer with a optical resolution of approximately 1 nm and time resolution of better than 10 ns. In reality time windows for spectra are generally significantly wider than 10ns. The Balmer Hα, Hβ, andHγ are being analysed to try to determine electron densities as a function of time.

The importance of ion temperature profile in collisional sheath modelling

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Plasma discharges contains two distinct zones having different physical properties, namely the quasi-neutral bulk plasma and the sheath which is a buffer zone between the plasma and the confining walls where the quasi-neutrality does not hold. These two zones are separated by an intermediate transition zone called pre-sheath [1]. In particular, the sheath has a strong impact on the entire gas discharge since it is where the plasma interacts with the boundaries. However, the bulk plasma-sheath transition is still a subject of active research today mainly due to its complex structure [2,3]. The modelling of an entire plasma discharge including the dynamics of sheaths is crucial to understand the behaviour of different plasmas such as nano-particle creation in sputtering magnetron discharge [4], also observed in the coldest region of tokamaks [5].

In this context a new and reliable numerical model for low-temperature plasma discharges including the sheaths is currently under development. These discharges are often simulated using Particle-In-Cell (PIC) or kinetic models [6, 7]. PIC simulations are limited by numerical constraints on the simulation time and memory requirements due to the high number of macro-particles necessary to accurately simulate high density plasmas and the sheaths. Fluid approaches are limited by the model accuracy itself, but are less demanding in computational resources and can give insights of the main physical phenomenon. In this work, we focus on 1D plasma fluid model adapted for the simulation of medium to high pressure (10^{-1} - 10^{2}Pa) direct-current (DC) argon discharges. In particular, a non quasi-neutral drift-diffusion model of two fluids – ions and electrons was developed in order to correctly model the sheaths. The results are compared with PIC simulation outputs. Our results emphasize for the first time the importance of the ion temperature profile when the collisionality in the sheaths is not negligible.

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Laser Induced florescence study of a plasma immersion ion implantation system

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Plasma Immersion Ion Implantation (PIII) consists in immersing in a plasma a negatively biased target (or electrode) with high voltage (HV) pulse in order to drive ions into the target and change the target surface structure and/or composition. Improving PIII operational efficiency depends on a precise control of the ion fluence which itself relies on a rigorous empirical knowledge of the plasma behaviour during the HV pulses and in close proximity (~1 mm) to the electrode surface. The aim of this research is to study the behaviour of plasma parameters (electron density, electron and ion temperature, plasma potential and ion velocity) in a low-temperature inductively coupled plasma (ICP) chamber used for PIII. In order to obtain spatially resolved information with minimal plasma disturbance, Laser-Induced Fluorescence (LIF) was chosen to study the ion velocity distribution function.

Ion temperature measurements were made in the bulk plasma during steady state operation for a range of power and pressure values (350-500W and 0.8-2 mTorr). It was found that ion temperature increases with increasing pressure. LIF was also used to perform spatially resolved measurements of the ion velocity distribution function in the vicinity of the pulsed HV electrode in order to measure the average ion velocity near the electrode, deduce the sheath structure and measure the Bohm velocity, Cs. It was found that the ion velocity reaches Cs at 2 mm from the electrode surface. This falls within the theoretical estimate of the sheath length according to the electron density and temperature measured by means of Langmuir probes [1]. This result is significant since the ion velocity and sheath length are essential parameters in an ICP used for PIII. Future experiments will focus on time-resolved measurements of the plasma under PIII relevant conditions.

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Full-wave investigation of microwave propagation through plasma density inhomogeneities

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A suitable method to describe electromagnetic wave propagation is the full-wave solution, since Maxwell's equations are exactly solved. Here we propose a method, where an in-house finite-difference time-domain (FDTD) simulation code and the commercial software package COMSOL Multiphysics are used to assist the development of a novel interferometry technique. While single-chord interferometry allows to obtain the line-integrated density of the plasma, our technique yields in addition information on the spatial profile of a cylindrical plasma.

The FDTD code simulates a microwave that is propagating through a similar-sized (with reference to the beam) plasma, which is confined in a quartz glass tube [1]. The electric and magnetic field of the microwave, as well as the plasma current density, are evolved with the leapfrog method in both time and space. This method leads to an explicit calculation of the fields for each time step. The spatial profile of the beam power is monitored after the interaction with the quartz tube and the plasma, and it is shown that its shape depends on both the density profile and the peak density. An example of the probing beam's electric field is plotted in Fig. 1.

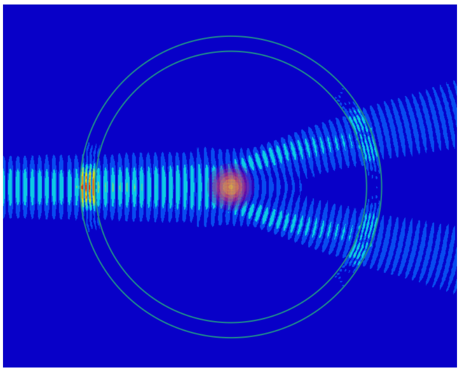

Figure 1: *Beam propagation through quartz tube and plasma*

The COMSOL Multiphysics software is used to benchmark the FDTD code and acts as a bridge between simulations and experiment. In the experiment, the receiving antenna of the interferometer is mounted on a stepping motor, which can be operated with sub-millimeter precision. This enables the spatial measurement of the intensity of the wave electric field after the beam's interaction with the quartz tube and an atmospheric pressure plasma. In these simulations, the plasma density profile can be set arbitrarily. Finally, comparison between the experimental results and the simulations allows to deduce information on the actual plasma profile.

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Radiation reaction effects in relativistic plasmas

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In the past decades, there has been a steady increase in interest in intense field plasma physics [1]. This has been motivated by the fast technological development of the laser facilities [2]. Both classical and quantum radiation reaction effects on the dynamics of plasma are of interest. In [3], one found that the quantum radiation reaction mechanism leads to a heating effect in the background plasma. For the case with the classical radiation reaction, it is found in [4] that the temperature of the background plasma drops. In [4], the evolution of electrostatic plasma waves, using the relativistic Vlasov equation extended by the Landau-Lifshitz radiation reaction [5] has been studied. Here, the model includes the back-reaction effect due to the emission of single particle Larmor radiation. In particular, the Langmuir wave damping is calculated as a function of wavenumber, initial temperature, and initial electric field amplitude. Moreover, the background distribution function loses energy in the process, and the cooling rate as a function of initial temperature and initial wave amplitude were calculated, see Fig.1 for more details. Finally, it is found that the relative contribution to the energy loss associated with background cooling decreases slowly with the initial wave amplitude. A further study to find the transition regime from classical to quantum radiation reactions is planned [6]

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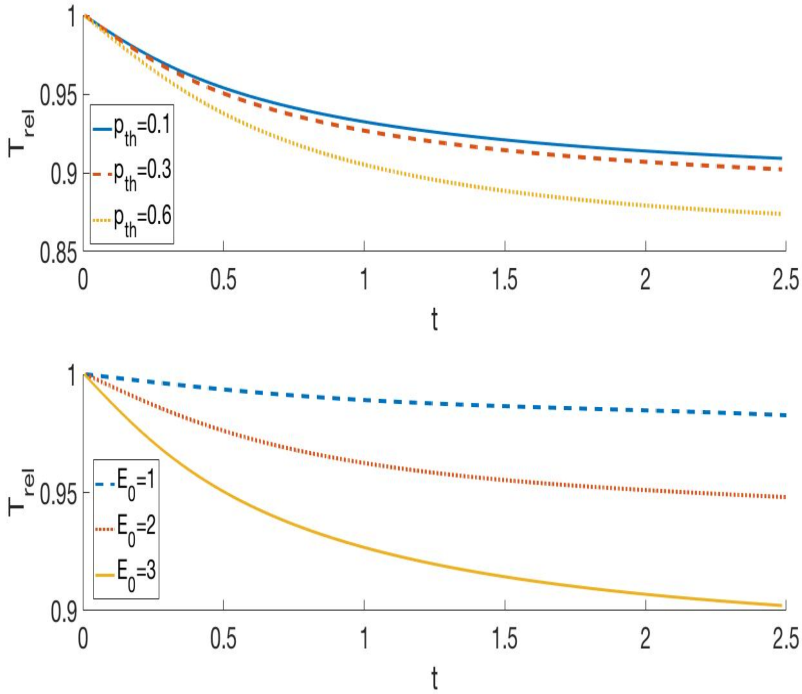

Figure 1: The cooling rate of the background distribution function T_{rel} is plotted over time. In the first panel, the cooling rate is plotted for three different temperatures. In the second panel, the cooling rate is plotted for three different values of the initial electric field.

Non local transport theory in relativistic plasmas

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Abstract

A linear theory of non local transport in relativistic unmagnetized plasmas is presented. The relativistic effects are due to high thermal energy of electrons which is not negligible with respect to their rest energy. The electron distribution function for arbitrary collisionality range is calculated by solving the Fokker-Planck equation with the use of the Legendre Polynomial expansion and the continued fractions. The electron collisions are considered in the limit of high ion charge Z. Using the Branginskii notations [1] the expressions of the electron heat flux and the transfer of momentum from ions to electron have been established for an arbitrary collisionality from the high collisional regime to the collisionless one and for arbitrary temperature value ranging from the non relativistic to the ultra-relativistic limit. In the limit of non relativistic temperature and high collisonal regime, the Spizer-Härm thermal conductivity [2], the frictional force [1] and the thermal force [1] were recovered. Furthermore, in the collisonless regime and arbitrary temperature values the result reported in Ref. 3 were also retrieved. New transport coefficients valid for arbitrary relativistic regime and collisionality were derived which can be used as reliable closure relations in fluid equations.

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Investigation of the collisionless plasmoid instability based on gyrofluid and gyrokinetic integrated approach

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Non-collisional current sheets that form during the nonlinear development of spontaneous magnetic reconnection are characterized by a small thickness, of the order of the electron skin depth. They can become unstable to the formation of plasmoids, which allows the magnetic reconnection process to reach high reconnection rates. In this work we carry out a detailed study of the impact of a finite ße, the latter being a parameter corresponding to the ratio between equilibrium electron kinetic pressure and magnetic pressure, on the collisionless plasmoid instability, in the case of a strong guide field. We consider inertial reconnection, and finite electron FLR effects arise from the combination of the presence of electron inertia with a finite ße parameter. This study is conducted through a comparison of gyrofluid and gyrokinetic simulations. We analyze the geometry that characterizes the reconnecting current sheet, and what promotes its elongation. Once the reconnecting current sheet is formed, we identify the regimes for which it is plasmoid unstable. Our study shows that plasmoids can be obtained, in this context, from current sheets with an aspect ratio much smaller than in the collisional regime, and that the plasma flow channel of the marginally stable current layers maintains an inverse aspect ratio of 0.1.

Image rotation in rotating magnetised plasmas*

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The properties of wave propagation in a medium differ whether the medium is at rest or moving with respect to the observer. The best known example of such manifestation is arguably the Fresnel drag effect postulated by Fresnel and demonstrated by Fizeau for a medium moving uniformly along the wave vector **k**, but analogous drag effects have been observed for transverse [1] and rotational motion [2] of an isotropic dielectric.

In the particular case of rotation, two effects are know to occur, namely polarisation drag and image rotation, the sum of which is sometimes referred to as rotational photon drag. Polarisation drag corresponds to a rotation induced rotation of the plane of polarisation of a linear polarised wave as it propagates along the rotation axis of a medium [3], which is interpreted as a phase shift introduced by rotation between eigenmodes with opposite spin angular momentum $\pm\hbar$. Image rotation corresponds to a rotation induced rotation of the transverse structure of a wave as it propagates along the rotation axis of a medium [4], which is interpreted as a phase shift introduced by rotation between eigenmodes with opposite orbital angular momentum $\pm l\hbar$. Although these two manifestations of rotation are relatively well documented in isotropic dielectrics, they remain largely unexplored in the case of rotating plasmas [5].

Here we review recent findings on the effect of rotation on orbital angular momentum carrying wave in plasmas [6], considering more specifically low frequency waves in magnetised plasmas, and discuss these results and their implications in the broader context of the properties of image rotation in rotating dielectrics.

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Study of E x B electron drift instability in Hall-thruster simulations using XOOPIC code

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Abstract

Hall thrusters are electrostatic ion accelerators which have application in satellite propulsion and in deep space missions. They employ a combination of an externally applied crossed electric and magnetic field in order to generate and accelerate ions. In this configuration, E x B drift instability is frequently observed in all the Hall thruster experiments[1] as well as simulations[3]. This instability has a dominant role in the generation of cross-field particle transport, also known as anomalous transport, which is also responsible in affecting the thruster's performance in space[2].

In this present study, we intend to characterize the E x B drift instability in the Hall-Thruster configuration and also analyse their effect on the cross-field particle transport. For this, a 2D Particle In Cell simulations (PIC) are performed by means of an open source code XOOPIC to get an insight into the physics of anomalous cross-field transport in Hall thruster devices. E x B drift instability is generated for a fully ionized Xenon plasma in the presence of an externally applied axial electric and radial magnetic field configuration akin to real Hall thrusters[2,3]. Depending on the strength of external radial magnetic field taken, different unstable modes of the E x B electron drift waves are generated, as shown in Fig. 1 for the magnetic field strength B = 100 G, and eventually saturated by the ion trapping. The mode frequencies obtained are in the range (0.19 – 1.75)x10^4 kHz. The modes with lower $k_\perp$ are generated as we increase the B value. In the linear phase, these modes seem to follow a linear dispersion relation of a modified ion acoustic instability. Finally, in the presence of different modes of the E x B drift waves, the cross-field electron transport, determined by effective Hall parameter or effective collision frequency, changes significantly.

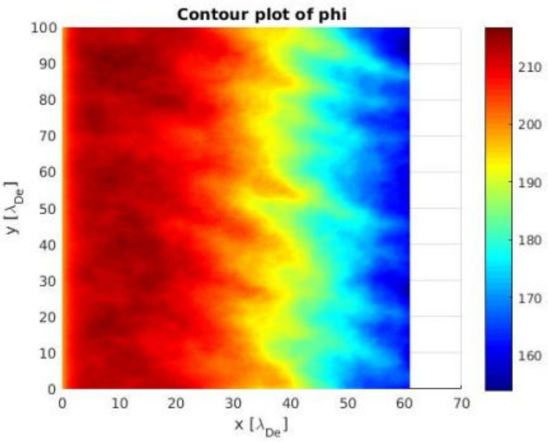

Fig.1a: Contour plot of potential vs debye length

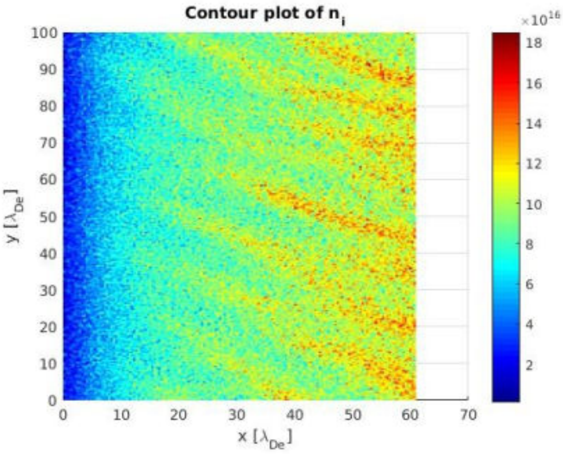

Fig. 1b: Contour plot of ion density vs debye length

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Three-fluid model of potential formation in front of a negative electrode

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A one-dimensional fluid model is used for the analysis of potential formation in front of a negatively biased planar electrode. The plasma is composed of singly charged positive ions, electrons and a third group of singly charged negative particles. These particles can be either electrons with different temperature than the basic electron population or singly charged negative ions. Positive ions are assumed to obey the continuity, momentum transfer and energy transport equation, while the electrons and the second negative species are treated by the continuity and momentum transfer equation. For the positive ions the closure is done by assuming that heat flux in the plasma is zero, while both negative species are treated as isothermal, with the pressure gradient term being proportional to the density gradient. Two types of solutions are observed. In the type one solution the pre-sheath potential drop is determined by the basic electron population and in the type two solutions it is determined by the second population of negative particles. Transitions between both types of solutions are discussed in some detail.

Ion-driven electron cloud dynamics in a non-axisymmetric torus: A 3D3V Particle-in-Cell study

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Abstract

Recently, a quiescent quasi-steady (QQS) [1] of pure electron plasma confined using a toroidal magnetic field, in a tight aspect ratio, axisymmetric toroidal device, has been numerically discovered using a 3D3V particle-in-cell code PEC3PIC [1, 2]. The effect of ions on this quasi-steady equilibrium state has been reported [3]. Ions are introduced in the device in two ways viz. (i) ion cloud is preloaded along with the electron cloud at QQS state at certain pre-determined time and (ii) ions are generated in the device via impact ionization using Monte-Carlo Collisional (MCC) method [4]. In both cases, as the ion fraction in the device increases beyond certain value, the electron cloud is found to be destabilized resulting in a finite amplitude m = 1 toroidal Diocotron mode.

A quiescent quasi-steady state of pure electron plasma in experimental-like non-axisymmetric toroidal device with negative potential grids, has been achieved recently [5] using the non-axisymmetric version of the PEC3PIC [2] code. In the present study, the effect of ions on the quasi-steady equilibrium state of the electron cloud has been investigated. In contrast to the axisymmetric device, it has been demonstrated that the QQS state of the electron cloud dynamics is not affected by presence of ion population, for both the preloaded case and the MCC case. To verify if the results are unique to the QQS case, the MCC technique has been applied for the already destabilized electron cloud exhibiting m = 1 toroidal Diocotron mode. For this case, the amplitude of m = 1 toroidal Diocotron mode increases at initial time and later saturates. Details and probable physics reasons of such behaviors will be explained in the presentation.

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Rearrangement and Free Energy for Understanding Plasma Stability

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For a wide variety of plasma systems, it is helpful to quantify the kinetic energy that can be extracted from a given phase-space configuration: the “free" or “available" energy. For example, in alpha channeling [1], the goal is to extract energy from fusion products using wave-particle interactions, and the extracted energy will not exceed the theoretically available value. The available energy can also measure how much energy could be accessible to feed instabilities.

There are a number of different ways of quantifying available energy. Each corresponds to a different rule for how the distribution of particles may be rearranged in phase space. The Gardner free energy is the energy that can be released through any process that conserves the volumes of phase space elements [2, 3, 4]. The diffusively accessible free energy is the energy that can be released by those processes that mix the volumes of phase space elements [5, 6, 7, 8, 9]. In this presentation we will discuss progress on characterizing these different free energies, and possible applications, with a particular focus on characterizing instabilities.

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Inertial corrections to polarization drag in rotating plasmas ⋆

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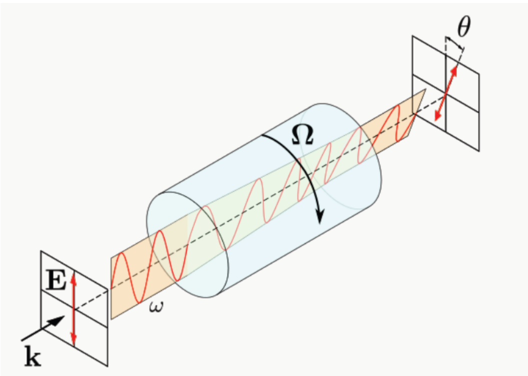
Polarization drag, as illustrated below, is the rotation of the polarization of an electromagnetic wave induced by its passage through a rotating dielectric medium. It can be interpreted as a mechanical analog of the Faraday effect in magnetized materials. The general theoretical description of this effect in isotropic dielectrics was proposed by Player [1] in 1976, in agreement with experimental results obtained simultaneously by Jones who examined the polarization of light exiting a rotating glass rod [2]. These results were more recently extended to rotating gyrotropic media, with an eye to rotating magnetized plasmas [3, 4].



Polarization drag θ induced by the passage of a wave $(\omega, \mathbf{k})$ in a dielectric rotating at frequency Ω.

An assumption that is common to these theoretical studies [1, 3, 4] is that the dielectric properties of the medium in its rest-frame are unaffected by the medium's motion. Although this hypothesis appeared to be supported with the experimental data obtained by Jones [2], Baranova and Zel'dovich [5] suggested that an additional term should be included, and proposed to do so through the addition of a equivalent magnetic effect. Here we revisit this problem, underlining when Players's assumption is valid, how Baranova and Zel'dovich's correction is recovered from the response of rotating dielectric media, and finally how these effects are expected to affect polarization drag in a rotating plasma.

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Dynamics and precise control of fluid V-states using an electron plasma

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An electron plasma can be confined for a theoretically infinite time in a Penning-Malmberg trap, a linear, azimuthally-symmetric magneto-electrostatic device where upon suitable conditions (high magnetization) the transverse dynamics of the plasma column is isomorphic to the one displayed by a two-dimensional ideal fluid. Fluid dynamics can thus be reproduced in these systems [1] with a very high degree of control on the system's parameters and active excitation of fluid perturbations is made possible by the use of static or time-dependent electric fields (i.e., fluid strains) imparted by electric potentials applied to the azimuthal patches of a sectored electrode of the trap. An example is represented by azimuthal velocity shear phenomena and the insurgence of Kelvin-Helmholtz (KH) instabilities in fluid vortices. We present a study where we exploit multipolar rotating electric fields to generate V-states [2] and observe their dynamics and stability properties. A V-state is the generalization of the 2D Kirchhoff (elliptical) fluid vortex to a generic KH mode, in the nonlinear regime. In particular, we discuss first how we can exploit a combination of techniques (plasma evaporation and tilt-induced transport) to tune the radial vorticity profile, which may have an effect on the dynamics of the growth and decay of the selected KH wave. We also investigate autoresonant (swept-frequency, self-locking) excitation - useful, e.g., for the precise control of the KH mode growth - and discuss the features of autoresonance applied to higher-order KH waves.

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Irreversible stochastic heating via phase-space entropy cascade in nearly collisionless plasma turbulence

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We consider a '1D-1V' nearly collisionless plasma of a species of 'test particles' stirred by an externally imposed stochastic electric field, a kinetic analogue of the Kraichnan model of passive advection. The mean effect on the particle distribution function is turbulent diffusion in velocity space—known as stochastic heating. Accompanying this heating is the generation of fine-scale structure in the distribution function, which we characterize with the collisionless (Casimir) invariant $C_2 = \int dxdv\, f^2/2$—a generalized (negative) entropy of the distribution function. We find that C_2 is transferred from large scales to small scales in both position and velocity space via a phase-space 'entropy' cascade driven by both particle streaming and nonlinear interactions between particles and the stochastic electric field. We compute the steady-state fluxes and spectrum of C_2 in Fourier space, with k and s denoting spatial and velocity wavenumbers, respectively. In our model, the nonlinearity in the evolution equation for the spectrum turns into a fractional Laplacian operator in k space, leading to anomalous diffusion. Whereas even the linear phase mixing alone leads to a constant flux of C_2 to high s (up to the collisional dissipation range) at every spatial scale, nonlinearity accelerates this cascade by mixing velocity and position space in such a way that the flux of C_2 is to both high s and high k simultaneously, primarily in the 'critical-balance' region in phase space where the linear and nonlinear time scales are comparable. The resulting spectrum in the inertial range is a self-similar function in

the (k,s) plane, with power-law asymptotics at large k and s. Integrating over velocity (spatial) wavenumbers, the k-space (s-space) flux of C_2 is constant down to a dissipation length (velocity) scale that tends to zero as the collision frequency does, even though the rate of collisional dissipation remains finite. These results suggest that stochastic heating is made irreversible by this entropy cascade and that phase mixing can be suppressed in the inertial range of a turbulent collisionless plasma while simultaneously being an effective means of dissipation.

Dissipative structures in dusty plasma with Cairns-Gurevich distributed ions

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Abstract: Many theoretical studies have been devoted to the study of the effect of trapped non-Maxwellian particles on both linear and nonlinear structures in magnetized and unmagnetized plasmas. Indeed, the presence of these trapped particles in the plasma media affects significantly the main properties of coherent and dissipative structures, vortex, and rogue waves. In this communication, we analyze the effect of the adiabatically-trapped nonthermal ions on dust-acoustic oscillations in a charge varying dusty plasma. For this purpose, a modified Schamel like-equation will be established, and a numerical investigation will be presented.

Keywords: Dissipative structures, Dusty Plasma, Cairns-Gurevich distributed ions

Dynamics of electron Langmuir waves in the presence of inhomogeneous kinetic ions

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Abstract

Landau damping in a collisionless plasma is a well-known example for wave particle interaction [1]. In the past, this phenomenon was addressed for homogeneous equilibria in the linear and non-linear limit of the perturbation amplitude [2]. However, in reality, equilibria are almost always inhomogeneous or non-uniform in space. In the recent past, evolution of electron plasma mode dynamics has been extensively studied as an initial value problem in both linear and nonlinear limits of perturbation amplitudes in the presence of periodic immobile background ion inhomogeneities [3, 4, 5, 6, 7]. A more realistic situation to address would be to consider a self-consistent non-stationary ion non-uniformity, with electron dynamics very close to a Maxwellian distribution, followed by launching of a linear and/or nonlinear electron plasma wave (EPW).

In the following, we present an extensive study of role of inhomogeneous kinetic ions on the dynamics of electron plasma wave (EPW) by first applying adiabatic electric field drive at ion acoustic frequency in a Vlasov-Poisson system consisting of kinetic electrons and kinetic ions. This adiabatic drive long after it is turned off, is shown to result in a quasi-steady ion phase space vortex structure moving at ion acoustic speed and the ion and electron density profiles are shown to be nonuniform in space, with Maxwellian electron distribution in velocity. Now, using this quasi-stationary ion inhomogeneity background thus created at certain scale k (where k is the wavevector) as starting point, fate of finite amplitude Langmuir perturbation at a wavenumber smaller than ion scale k is investigated using OpenMp Vlasov-Poisson solver i.e VPPM-OMP 1.0 [4]. Details of the dynamics of EPW in inhomogeneous kinetic ion background will be presented.

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Vlasov simulations of whistler destabilization by electron beams having anisotropic velocity distribution

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The whistler mode in warm space and laboratory plasmas is destabilized by anisotropy of electron temperatures with respect to direction of the ambient magnetic field. In finite plasma-current based magnetic confinement scheme such destabilization potentially results from fast electrons/beams having highly nonthermal velocity distribution functions (VDF) originated in transient processes[1,2]. In present set of electromagnetic Vlasov simulations the dependence of dispersion and growth rate on the magnetic field strength is examined for broadly three categories of anisotropic electron velocity distributions, namely, bi-Maxwellian, bi-kappa [3] and beam-plasma. The generalized beam VDF is defined for the simulations to achieve a systematic parametric reduction, from a standard bi-Maxwellian electron beam distribution to an increasingly run-away like beam, by quantifying the tendency of the beam source to be a large parallel accelerating loop electric field E [2] as available in toroidal confinement schemes. In confirmation with the tendency of poorly scattered fast particle beams being observed beyond a threshold magnetic field, the growth rate of whistlers in bulk destabilized by an anisotropic beam of electrons shows a reduction with increasing magnetic field strength. The nonlinear saturation of the instability in the Vlasov simulations further shows the slower approach to saturation for a strongly nonthermal beam in comparison to a rather ideal bi-Maxwellian beam of fast electrons.

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Charged-Particle Acceleration by Electrostatic Waves Propagating across Magnetic Field

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In magnetized plasmas, the longitudinal electrostatic waves, travelling perpendicular to external magnetic field, can accelerate resonant particles to very large energy via Surfatron Mechanism [1]. Even the non-resonant particles can be accelerated using these waves by introducing an inhomogeneity in the external magnetic field [2]. This mechanism of particle acceleration will work provided the electrostatic waves survive a "long enough" time in the presence of inhomogeneity and relativistic effects. As the inhomogeneity inevitably results in breaking of the wave via phase-mixing [3]. In the present work, we estimate the maximum energy gained by the particle before the wave breaks. These results are relevant to laboratory as well as astrophysical plasmas where magnetic field plays an important role.

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Determining wave fields from particle orbits

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We test a procedure for determining electric fields over a finite volume based on measurements of a space, time, and velocity resolved measurement of a velocity distribution function at a single location. The technique is based on an exploitation of the non-local dielectric response of weakly-collisional plasma. As an example, we consider electron plasma waves in a 1-D simulation with periodic boundary conditions. Previously, it was found that ion-acoustic fields over a finite volume can be determined from a local measurement of the ion distribution function directly by means of an integral transform introduced by Morrison [1]. That technique cannot straightforwardly be applied in circumstances where one needs to perform a Fourier transform in space in order to construct the Morrison transform. Since most wave modes require Fourier transformation, it is of interest to generalize the procedure so that it can be applied to the more general case. The new procedure is tested for the electron plasma wave is with numerically generated data from a Vlasov code.

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Unveiling the structure and thermodynamics of the dilute uniform electron gas

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The uniform electron fluid (UEF) constitutes the simplest, yet realistic, bulk electronic system capable of exhibiting strong correlation effects. It is often referred to as homogeneous electron gas, jellium or quantum one-component plasma being the quantum analogue of the classical one-component plasma (OCP). Early studies focused *on the ground state at metallic densities*, due to its relevance for valence electrons in simple metals, leading to remarkable insights such as the BCS theory of superconductivity, the Wigner crystallization paradigm, Landau's Fermi liquid theory & the Kohn-Sham formulation of density functional theory. More recent studies focused on the *warm dense matter (WDM) regime*, due to its relevance for highly compressed high temperature matter encountered in dense astrophysical objects and intense laser-matter interactions [1]. An accurate description is nowadays available for the thermodynamic, static, dynamic and even nonlinear behavior of the UEF under WDM conditions thanks to numerous breakthroughs in quantum Monte Carlo (QMC) simulations at finite temperatures[2,3]. On the other hand, despite well-founded speculations of exotic collective phenomena at low densities [4,5], the *strongly coupled regime* of the UEF has remained sparsely studied. This is primarily owing to the difficulty of rigorously treating the complex interplay between strong Coulomb correlations, thermal excitations, quantum diffraction effects and exchange interactions.

In this talk, I will discuss recent theoretical progress in the description of the thermodynamics and structure of the strongly coupled UEF that has been achieved with two novel schemes of the self-consistent dielectric formalism that combine quantum linear density response theory (LRT) with the non-perturbative integral equation theory (IET) of classical liquids. The **IET-based scheme** [6,7] includes quantum effects exclusively via the Lindhard density response and features a static local field correction that is derived by combining the classical fluctuation dissipation theorem, the Ornstein-Zernike equation and the non-linear equation including the classical OCP bridge function [8]. The **qIET-based scheme** [9] treats quantum effects beyond the random phase approximation and features a dynamic local field correction functional that also incorporates bridge function contributions. Systematic comparison of the predictions of these schemes with quasi-exact results from dedicated path integral Monte Carlo (PIMC) simulations [7,9] has revealed that: (a) The IET-based scheme yields excellent predictions for the interaction energy benefitting from favorable cancellation of errors [7]. (b) The qIET-based scheme yields unprecedentedly accurate predictions for the static structure factor for any state with the exception of the Wigner crystallization vicinity [9]. These advances pave the way for the accurate treatment of collective effects without computationally costly PIMC simulations, for which dynamic property extraction is handicapped by an ill-posed analytical continuation.

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