Electromagnetic characterization of ITER jacketed IVCs via Ansys Maxwell finite element analysis

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Two sets of In-Vessel Coils (IVCs) are going to be installed in ITER: the Edge Localized Mode (ELM) coils aim at mitigating periodic bursts of ejected plasma typical of H-mode operation in tokamaks while the Vertical Stability coils (VS3) are designed to prevent, within certain limits, the loss of vertical position [1], [2], [3].

3D Finite Element Analysis (FEA) supports the design and the future exploitation of IVCs. In particular, FEAs allow the evaluation of electromagnetic (EM) loads generated within the tokamak passive structures due to both disruptive and operation scenarios, along with induced currents due to eddy effects. Previous literature explores the EM behavior of ITER IVCs [4], however there has been limited research into the impact of IVCs stainless steel jackets, which may play a non-negligible role in the regulation of plasma and may cause deterioration of the IVC-plasma coupling, especially for frequencies higher than 1 Hz.

The aim of the present work is to assess the influence of the IVCs steel jackets on the performance of the system. To this end, finite element EM analyses of relevant plasma operating scenarios and disruptions have been performed by means of Ansys Maxwell 3D models of an ITER 40-degrees generic sector.

In these analyses we assess, under different conditions, waveforms of current or voltages in central solenoid (CS) coils, poloidal field (PF) coils, IVCs and vacuum vessel (VV), aiming at quantifying inaccuracies depending on simplifications and hypothesis considered. A case with VS3 voltage ramp-up is also discussed to quantify the time delay due to the modelling of jackets. The frequency response of VS3 coils is finally investigated taking into account the effect of jackets on the computation of the transfer function.

Results, which are supported by analytical calculations using a lumped-parameter model, show that at higher frequencies (>1 Hz) jackets do affect the EM behaviour of the system via a screening mechanism which increases the system's time response.

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[2] A. Loarte et al., 2010 Proceedings of 23rd IAEA Fusion Energy Conference
[3] D. A. Humphreys et al., 2009 Nucl. Fusion 49
[4] C. Neumeyer et al., 2011 Fusion Science and Technology 60

RENATE – Open Diagnostics: a comprehensive fluctuation beam emission spectroscopy synthetic diagnostic

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RENATE-OD is a good example of a comprehensive beam emission spectroscopy (BES) synthetic diagnostic [1]. The model aims to accurately incorporate all relevant BES artefacts which affect the observation and interpretation of density fluctuations, such as atomic phenomena and correct means to compute them, 3D beam and observation effects as well as noise modelling.
BES is an active plasma diagnostic system used for plasma density and related fluctuation measurements. The diagnostic system relies on the emission caused by the interaction of high energy neutral beam atoms injected into the plasma [2].
At the core of the synthetic diagnostic lies a collisional radiative model (CRM) which computes the various collisions between plasma particles and beam atoms. The CRM receives collisional cross-sections through an API connected to the ALADDIN atomic database and has the capability to differentiate between plasma components based on charge, atomic number and atomic mass. A novel set of beam atom with neutral gas particle collisional cross-sections were added to the CRM on order to model the beam penetration in neutral gasses. The CRM is used to compute the valence electron distribution over higher excited atomic states to arrive at the beam emission profile along the beam, by solving a linear differential equation system. To speed up the calculation process, the synthetic diagnostic system can train a neural network to predict beam emission profiles based on fluctuating plasma profiles along the beam path. The beam modelling is fully 3D with sufficient numerical resolution to correctly resolve centimeter sized density fluctuations. The emission collection is approximated by a simple 3D pinhole optical system with the option of coupling to more detailed ray-tracing optical models. A detailed noise model is featured in RENATE-OD as well in order to correctly approximate the expected noise for various detector types typically used in BES measurements.
We coupled the RENATE-OD synthetic diagnostic to existing complex, first principle plasma physics models [3], to demonstrate the diagnostic systems perception of plasma density fluctuations. A validation was undertaken of first principle scrape-off layer turbulence scrape-off layer turbulence code comparing filament waiting time, amplitude and velocity distributions by correctly accounting for the diagnostics perception of filament dynamics.

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On the radial pellet cloud drift in stellarator plasmas

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The cryogenic pellet fuelling efficiency is - among others - largely determined by the drift properties of the high pressure pellet cloud elongated along the magnetic field line crossing the pellet ablating in the hot plasma. In tokamaks, the pellet cloud drift created by the gradient of the axially symmetric magnetic field - which pushes the pellet cloud to the low field side of the plasma - clearly enhances the fuelling efficiency of pellets injected from the inboard side of the torus [1].

In the much more complex (non-axially symmetric) magnetic field of stellarators the advantage of the inboard side pellet injection does not necessarily apply [2]. Most probably because the direction of grad-B in a poloidal plane looks more complicated than in a tokamak, and it does vary with the toroidal angle, it can even reverse along the high-pressure, field line elongated pellet cloud.

To better understand the radial drift of the pellet cloud in the stellarator geometry, experiments were performed in the W7-X and TJ-II stellarators. Both cryogenic and tracer-encapsulated solid (TESPEL) pellets were injected into the plasma and the evolution of the radiation distribution of the pellet cloud particles was measured by spectroscopic methods using fast framing cameras viewing from different directions. Wavelength selection by interference filters was used to separate certain ionic species of the cryogenic H pellet and polystyrene polymer $(C_8H_8)_n$ shell of the TESPEL (C I, C III and H I). An attempt was also made to detect the Bremsstrahlung of the ionised H pellet cloud. The temporal resolution of the fast camera observation is up to 500 kHz, which allows us to resolve the detachment and the radial drift of the ionised pellet cloud. This contribution presents a detailed study of these processes in various magnetic field geometries and both in ECRH and NBI heated plasmas.

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Characterizing the fragment plume of shattered pellets using laser curtain diagnostic

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Shattered pellet injection is regarded as the main disruption mitigation system (DMS) for ITER. The ITER DMS requires the use of large, 19x38 and 28.5x57 mm (diameter x length) cryogenic pellets, made of Hydrogen (Protium or Deuterium), Neon or a mixture of those, accelerated to several hundred m/s velocity. An ITER DMS Support Laboratory was set-up at the Centre of Energy Research [1], to investigate the shattering process and characterize the resulting fragment plume of such large pellets for various shattering geometries and pellet velocities.

Pellets, after passing a propellant gas retainment chamber and a 3-m-long flight tube, arrive at the shattering head, located at the entrance of the fragment analysis chamber. This large vacuum chamber allows the fragments to travel freely in space, enabling us to diagnose the plume undisturbed by using optical diagnostics. The spatio-temporal distribution of the fragments' size and velocity is determined at two different locations from the shattering head using the laser curtain diagnostic system [2]: a thin plane is illuminated by a narrow line laser perpendicular to the flight direction of the fragments; fragments passing through this plane scatter light, which can be detected by fast cameras.

This contribution presents the results of systematic tests carried out at the Support Laboratory, in order to characterise the dependence of the fragment plume on various pellet parameters and shattering geometries.

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Studies on EU-DEMO In-Vessel Coils requirements and conceptual design for axisymmetric plasma control

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This work presents the initial studies on the design requirements for In-Vessel Coils (IVCs) on EU-DEMO. The application of IVCs studied in this paper covers three main functional requirements the first of which is the Vertical Stabilization (VS) of elongated plasmas. An elongated plasma is unstable, with a growth rate that depends on its configuration and the surrounding conducting structures. A vertically unstable plasma requires an active stabilization control system, and the maximum vertical elongation represents a design driver for the machine. Since 2015 ITER employs a new criterion for the VS [Y. Gribov et al, NF 2015], which requires that the VS should be able to reject vertical movements up to 5% (for reliable operation) to 10% (for robust operation) of the minor radius. The second functional requirement is to react to high heat flux on the divertor in an emergency, through oscillatory movements of the plasma strike points to spread the power over a larger area. Two control schemes to achieve these oscillatory movements are described: i) strike point sweeping, and ii) plasma wobbling. The third functional requirement is to provide Fast Radial Control of the plasma, to counteract a range of possible plasma loss of energy confinement, and the related inward movement that derives from it. The goal is to avoid, if possible, or delay the potential contact of the plasma with the inner first wall. This paper reports the performance of IVCs in the present EU-DEMO design against each of the three functional requirements, and compares these with the capabilities of Ex-Vessel Coils. Preliminary considerations on the coil technology, design, power supplies, vacuum compatibility, nuclear integration, and maintainability are also presented.

First measurement of the scrape-off layer current profile using directional electron probe on W7-X with an island divertor configuration

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In order to optimize the performance of divertor operation scenarios, it is important to understand the effect of edge magnetic island topology. This in turn requires an accurate knowledge of the electron currents in the edge and especially crossing the islands since current is mostly driven by electrons in the plasma and the distribution of electron current indicates the structure of magnetic topology due to its small Larmor radius.

Recently, the scrape-off layer (SOL) current profile on W7-X has been measured for the first time in both high-iota and standard configurations by using directional electron probe (DEP)[1]. The DEP consists of two radial arrays of channels which have opposite directions and align along the local magnetic field line. This probe head has been mounted on the mid-plane multi-purpose manipulator (MPM) system during the OP2.1 experimental campaign on W7-X [2]. In the standard configuration, the net current in the far SOL region flows in the same direction of positive plasma toroidal current, while the net current in the near SOL region flows in the opposite direction. The maximum amplitude of the net current density is more than 20A/ cm^2. In the high iota configuration, the net current with a current density > 10A/cm^2 was observed in the ergodic layer, and it flows in the same direction of positive plasma toroidal current.

This contribution will present the edge current profile of both high-iota and standard configurations on the W7-X and discuss its dependency of different plasma parameters including plasma current, plasma beta and heating power.

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[2] Liang Y., et al. Nuclear Fusion 2017 57 066049

The role of high frequency modes in the plasma edge of W7-X on confinement

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In the last, as well in the recent experimental campaign at the optimized stellarator W7-X several experiments are performed with the aim to study the role of the magnetic configuration on confinement [1]. During the transition from high iota ($\iota = 1.2$) to the standard configuration ($\iota = 1.$) the 5/5-island moves from the plasma edge as close as possible to the last closed flux surface (LCFS) showing some remarkable increase of the diamagnetic energy when the island chain touches the LCFS. This increase is always perturbed by events which are clearly seen as burst in the plasma current. It is supposed that modifications in the plasma edge profiles are responsible which are related to the turbulence and radial transport and yield an increase in the diamagnetic energy. The position and size of the each island, the plasma density and the heating power was varied to investigate its influence on the diamagnetic energy.

To study the turbulence in the plasma edge and the 5/5-island chain the poloidal correlation reflectometer at W7-X [2] is used. It allows to study the poloidal rotation and the low wave number turbulence inventory in the plasma edge. Broad turbulent structures at a frequency of 500 kHz to 1000 kHz are observed in the spectra. In addition modes in the low kHz-range are observed. These modes disappear as soon as a burst in the plasma current happens. Some time after the burst the modes and turbulence appear again. Most likely a change in the density profile is the reason for these observations. Depending on the gradients in electron- and ion temperature as well as the density gradient different instabilities as resistive ballooning modes (RBM), ITG-modes and trapped electron modes (TEM) could be responsible for the observation

The contribution will describe the measurements and discuss the results within the different possible mode conditions.

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Modelling of local ^{13}C tracer injection via MPM in Wendelstein 7-X

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Erosion, migration and deposition of wall materials in fusion devices are crucial processes as they determine the lifetime of wall components, long-term tritium retention via co-deposition and impurity concentration in the core plasma. Tracer experiments are vital methods for detailed studies of the involved processes and rarely used in stellarators like Wendelstein 7-X (W7-X). For that purpose during two hydrogen discharges in standard magnetic configuration with a total duration of ~12s ^{13}C-marked methane CH_4 was injected for ~10s with a rate of ~1E20/s through the multi-purpose manipulator (MPM) at the outboard midplane. The top surface of the probe head in this experiment was located at a major radius R = 6.11 m in the far scrape-off layer of W7-X. Post-mortem analysis of the graphite probe head applying colorimetry, NRA and RBS revealed a ^{13}C deposition efficiency on the probe head of ~2% and thus ~98% of the injected ^{13}C atoms is not locally deposited, but somewhere else within W7-X or pumped out.
The 3D erosion and migration code ERO has been applied to model the local transport and resulting ^{13}C deposition of the injected $^{13}CH_4$ considering the full dissociation chain. Langmuir probe measurements with the MPM cannot be performed during the $^{13}CH_4$ injection, but have been done for reference standard plasmas without gas injection. They are resulting in radial profiles of the electron temperature and density, which are used as input for ERO. The ion temperature is assumed to be equal to the electron temperature. ERO simulations show that ~32% of the injected ^{13}C atoms return to the MPM probe surface, 9% as atoms and 91% as $^{13}CH_x$. Also ~30% of the injected H returns to the MPM head surface, 32% as H and H_2 and the remaining 68% within the returning $^{13}CH_x$. Assuming standard yields for physical sputtering based on SDTrimSP, a chemical erosion yield of 0.5%, TRIM-based reflection coefficients for carbon atoms and ions and reflection coefficients of $R_{neutral}$=0.9 for neutral CH_x and R_{ion}=0.5 for ionised CH_x^+ leads to a ^{13}C deposition efficiency of ~14%, thus much larger than measured. Also the modelled deposition pattern is much more localised than the experimental one. The simulations reveal that ^{13}C erosion is dominated by chemical erosion due to low energy H returning from the injection. Physical sputtering by returning ^{13}C is comparably small and also chemical and physical erosion by the background plasma is negligible due to small background plasma flux and low plasma temperature (~8 eV at surface). To match the measured deposition efficiency and pattern either enhanced re-erosion of deposited ^{13}C has to be assumed or high reflection of $R_{neutral}$=R_{ion} near to 1 for CH_x. Possible local plasma cooling has been studied but does not strongly influence the overall results. The simulations confirm tracer injection studies and according modelling e.g. at TEXTOR, JET or AUG where especially at high depositing fluxes enhanced re-erosion of redeposits compared to bulk material had to be assumed.

Application of neural-network-assisted flux surface mapping to diagnostic observations of the Wendelstein 7-X island divertor

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Modern Stellarators such as Wendelstein 7-X (W7-X) and the Large Helical Device (LHD) feature advanced divertor concepts tailored to their particular type of plasma shape and edge field structure. While these advanced divertors, such as the island divertor in Wendelstein 7-X, are key contributors to these devices' favorable performance characteristics, their 3D non-axisymmetric field line structure makes the combination or even the comparison of various diagnostic observations at different cross-sections a challenging effort.

To tackle this challenge, a new approach to coordinate-based flux surface mapping was developed over the recent years, which can identify magnetic surfaces and regions of closely co-located field lines in non-axisymmetric topologies, correctly treats magnetic islands, and behaves predictably in face of magnetic field stochastization. The computational load induced by this technique (which is based on pairwise distance calculations between long field line traces and shortest path calculations in this distance matrix) was then bypassed by training a neural network, which would simultaneously act as a high-quality interpolator.

In this contribution, a first application of this technique on actual diagnostic data will be presented. In particular, this entails a cross-comparison of measurements by the Multi-Purpose-Manipulator [1], the Helium beam [2], and the Thomson Scattering system [3] to relate up- and downstream observations of these systems in different magnetic configurations.

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3D edge impurity transport analysis using the EMC3-EIRENE code by taking into account multiple edge plasma measurements on W7-X

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Investigating three-dimensional edge impurity transport is crucial in W7-X, as its magnetic configurations feature intrinsic island structures at the edge. In order to better understand edge impurity transport behaviour in the standard configuration, the impurity emission lines measured by FZJ endoscopes[1, 2] and edge & divertor spectroscopy are used to optimize the free input parameters of EMC3-EIRENE. Several other diagnostic measurements, including Thomson scattering, MPM LPs and divertor LPs, are also employed to further validate the simulations. Preliminary simulation results show that the vertical intensity distributions of impurity emission lines (such as CII) and hydrogen Balmer series with respect to the target plate are sensitive to the separatrix electron density and radiation power. By adjusting cross-field transport coefficient distributions, the vertical intensity distributions of impurity emission lines can be improved and better matched with the experimental data. Based on this method, which can obtain more reasonable impurity cross-field transport coefficients, we focus on the effects of magnetic topology on impurity transport by utilizing different configurations. In addition, by integrating the 3D equilibrium code HINT and EMC3-EIRENE, beta effects on impurity transport are also studied, as the previous work[3] shows that the plasma boundary becomes more stochastic with an increase of plasma beta.

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EMC3-EIRENE modeling of divertor plasma transport with beta effects in the high-mirror configuration on W7-X

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Past studies have demonstrated that the magnetic topology changes caused by beta effects are highly sensitive to the plasma configuration on W7-X [1, 2]. Therefore, it is necessary to extend the previous island divertor transport work [3] from the standard configuration to other OP2 candidate configurations, such as the high-mirror configuration, using HINT and EMC3-EIRENE. The HINT code is utilized to establish the 3D plasma equilibrium with beta effects, and the resulting magnetic field distributions are incorporated into the EMC3-EIRENE modeling. The modeling results indicate that the magnetic topology changes induced by plasma beta effects are significantly reflected in plasma transport behaviors. The radiation distributions in the scrape-off layer and the divertor heat flux pattern are modified due to the island structure changes and enhanced edge stochastization. The proportion of the heat load on the vertical target relative to total heat loads is reduced in higher beta plasmas. As the separatrix density increases, the beta effect accelerates the transition of the island divertor plasma into the high recycling regime. Higher beta plasmas in the high-mirror configuration have a lower threshold separatrix density for accessing power detachment.

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Measurement of the scrape-off layer turbulence in ion and electron channels using the multiple-purpose manipulator on W7-X with an island divertor configuration

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On W7-X, two probe heads, the directional electron probe [1] and the retarding field analyzer probe [2], have been mounted on the mid-plane multi-purpose manipulator (MPM) system [3] to measure the scrape-off layer (SOL) profiles of electron current, ion and electron temperature and density. Furthermore, their combination demonstrates excellent capabilities to identify the SOL turbulent fluctuations and transport in ion and electron channels, respectively.

During the W7-X OP2.1 experimental campaign, the broad turbulent patterns at the low kHz-range (f < 100 kHz) were observed in the spectra of floating potential and ion saturation current fluctuations, but not in electron current fluctuation spectra. This indicates that these broad patterns are highly related to the ion behaviors. In this contribution, a cross-comparison of turbulent properties and transport in ion and electron channels, and an exploration of the role of magnetic topology on them will be presented. In addition, the relationship between the ion-to-electron temperature ratio, radial electric field and turbulent transport will be discussed.

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First predictive modelling of global tungsten erosion and re-deposition in the EU-DEMO with the ERO2.0 code

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Magnetic confinement fusion aims in constructing an environmentally friendly and abundant electric power source for the future. In that regard, control of plasma-wall interaction (PWI) processes, such as erosion and deposition of first wall materials as well as fuel retention, are key aspects in the design of economically efficient future fusion devices. The erosion of plasma-facing components (PFC) presumably made by tungsten has not only direct consequences on the first wall and divertor lifetime, but also via tungsten impurity transport on the stability of the core DT plasma, and so requires precise numerical simulations to ensure the envisaged operation.

ERO2.0 is a massively parallel Monte-Carlo code dedicated to study PWI and subsequent impurity transport in the scrape-off-layer (SOL) plasma. The plasma boundary is an input provided by e.g. SOLPS-ITER or EMC3-EIRENE. In particular, the massive parallelization of ERO2.0 enables global simulations of realistic reactor design shapes in fully three-dimensional geometry. In addition, impurity transport of eroded particles into the SOL plasma is done within a kinetic approach including atomic processes like ionization and recombination. Ultimately, a successful ERO2.0 simulation gives information about erosion and deposition patterns on PFCs, as well as on the impurity influx and concentration in the confined plasma. The ERO2.0 code was validated against experimental data from the currently largest fusion device JET equipped with beryllium and tungsten PFCs [1, 2] and predictions were made regarding the wall lifetime for the next step device ITER [3]. Recently, simulations of a hypothetical full tungsten ITER device were performed [4] as a proxy for the EU-DEMO, which is in the design phase.

In the present contribution, the focus is on applying ERO2.0 to model steady-state tungsten net erosion and deposition in EU-DEMO using the actual design geometry, magnetic equilibrium and the initial SOLPS-ITER plasma solution (D plasma, He ash and Ar seed gas as impurities) [5]. The current SOLPS-ITER solution provides the plasma parameters only up to a distance of approximately 15 cm close to the first wall; the importance of extrapolation models on the plasma-wall modelling is thus emphasized. In addition, the contributions of plasma ions, D charge exchange neutrals (CXN), and W self-sputtering to the total W erosion rate are compared for different wall locations, indicating Ar ions as the main source of erosion in the divertor and D CXN dominating erosion in the main chamber. For example, peak gross erosion fluxes of 1.03×10^{18} W-atoms/(m^2s) and 3.12×10^{20} W-atoms/(m^2s) are expected due to sputtering by D CXN at the outer midplane and by Ar ions at the outer divertor, respectively. Critical wall locations in terms of W net erosion and deposition are discussed, so that the ERO2.0 modelling delivers vital input for the DEMO design team in view of assessment of safety-relevant information regarding first wall and divertor lifetime.

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Measurement and analysis of density profiles in the island divertor region and in the plasma edge of W7-X

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One of the principal objective of optimized stellarator Wendelstein 7-X (W7-X) is to demonstrate the confinement of fast ions at finite plasma beta [1]. For the generation of fast particles an ion cyclotron resonace heating (ICRH) system is designed and implemented at W7-X [2]. For the coupling of the heating power into the plasma it is essential to know the density profile in front of the ICRH antenna. Therefore a density profile reflectometer is designed and installed in the ICRH antenna setup. The ICRH as well as the density profile reflectometer are under commissioning in the last campaign (OP2.1, until end of Mar.2023).

The dual-band frequency modulated continuous wave (FMCW) reflectometer [3] is capable of measuring the electron density profile in front of the ICRH antenna at two different poloidal positions. The two antenna pairs can be used as well for the measurement of the density in the island divertor region, covering in the standard configuration the island O-point as well as the island X-point respectively. Due to an intrinsic 3D structured magnetic topology for W7-X, mapping of the density profile measured at different positions is a non-trivial issue in particular around island structures in the plasma edge and outside the separatrix. Aside the high value of high-resolution edge profiles in support of core profile diagnostics such as Thomson scattering, a further task of the density profile reflectometer is to provide the localization of other edge diagnostics such as correlation- and Doppler reflectometers. Furthermore, with its high time resolution (tens of microsecond) the system is as well able to trace sudden changes in the electron density profile and will shed some light on fast transport processes in the plasma edge and the scrape off layer (SOL). This contribution will report on the achieved results on the density profile reconstruction during the last campaign.

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Synthetic Fullwave Doppler Reflectometry Diagnostic for Fusion Experiments

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Doppler reflectometry is a microwave plasma diagnostic for density fluctuations and flow velocities used in fusion experiments. It uses enhanced scattering at reflecting cutoff layers in the plasma.

Fullwave simulations of Doppler reflectometry are a necessity for connecting experimental results with turbulence simulations. The experimental scenario is matched in a turbulence code, whose output density fluctuations are used in the fullwave simulations to determine the non-linear signals of the Doppler reflectometer. In this report, the turbulence was simulated with the gyrokinetic code GENE for experiments at the ASDEX Upgrade tokamak, together with the fullwave code IPF-FD3D [1].

Comprehensive experimental measurements [2] of the wavenumber spectrum perpendicular to the magnetic field and the radial correlation length have been done for four combinations of plasma scenarios and radial locations in the plasma. The measured spectrum also depends strongly on the polarization of the probing beam, such that only the fullwave simulations are able to reconcile measurements taken with the O and X polarizations.

The fullwave simulation derived spectra show the same qualitative results as the experimental spectra. The simulated radial correlation lengths agree well for nearly all points with the experimental data.

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Gyrokinetic simulations of effects of magnetic shear on turbulent transport in EAST high β_p discharge

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Weak or negative magnetic shear is predicted to enhance core confinement with electron heating by gyrokinetic simulations[1]. The high β_p discharges on the JT-60U and JET tokamaks have also suggested that the weak normal shear or optimized magnetic shear q = 2, 3 surfaces facilitate the formation of internal transport barriers (ITBs) [2][3]. It is also well known that weak or negative magnetic shear suppresses micro-instability-driven turbulence and reduces the turbulent transport avoiding the energy confinement degradation. Therefore, it is of great importance to investigate the effects of magnetic shear on turbulence and thermal transport in existing EAST high β_p scenario and find the possible pathway of improving energy confinement by turbulence suppression for future experiments.

The turbulence suppression with lower internal inductance(l_i) is firstly observed experimentally by CO_2 laser collective scattering diagnostics in the core plasmas of EAST tokamak. As shown in Figure 1, the intensity of turbulence at $k_\theta = 10cm^{-1}$ shows a linear dependence on l_i and is effectively stabilized with decreasing l_i accompanied by broaden current profile causing an optimized magnetic shear.

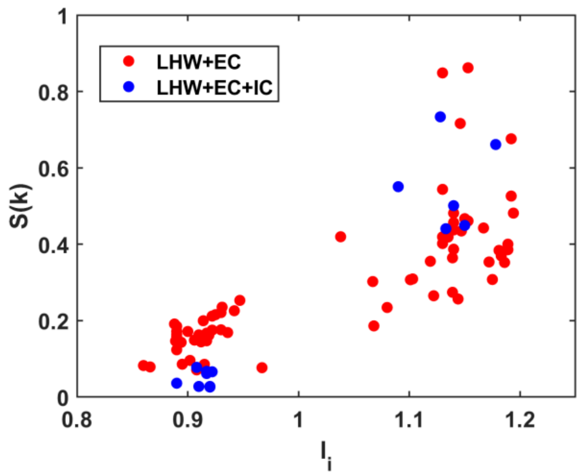

Figure 1 The dependence of intensity of turbulence at $k_\theta = 10cm^{-1}$ on l_i.

Furthermore, systematic simulation about the effects of three profiles of safety factor(q) and corresponding magnetic shear: positive magnetic shear, weak magnetic shear and negative magnetic shear on TEM turbulence is taken by gyrokinetic simulation with the NLT code. The dependence of growth rate on q when TEM modes dominate the spectrum have also been calculated with collisionless and electrostatic simulations. Gyrokinetic simulations is utilized and confirmed that TEM is stabilized in weak shear and negative shear which is consistent with the experimental results.

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Study of beta-induced Alfvén eigenmodes driven by runaway electrons in EAST tokamak

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The beta-induced Alfvén eigenmodes (BAEs) [1] excited by runaway electrons (REs) are observed in EAST low-density ohmic discharges. One or multiple-branches of BAEs can be obtained in this scenario.

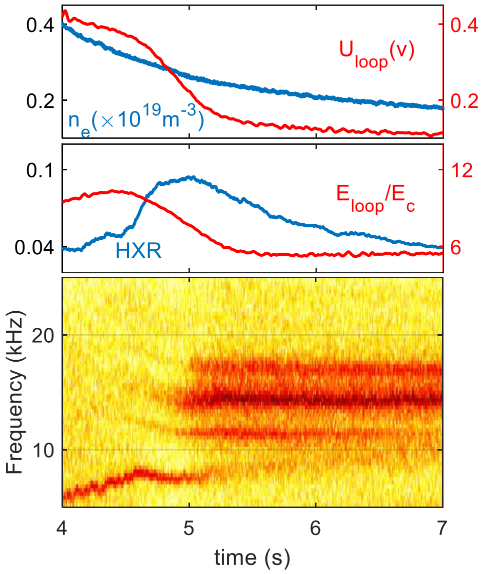

Figure 1 BAEs are observed during density ramp-down phase in the ohmic discharge.

Characteristics of BAEs in EAST are shown in figure 1. The electron density during the existence of modes is lower than 0.6×10^{19} m^{-3}. The mode frequencies range from 10 to 20 kHz and are comparable to that of the continuum accumulation point of the lowest frequency gap, which is induced by the shear Alfvén continuous spectrum due to finite beta effect [2]. Furthermore, the mode frequency is proportional to the Alfvén velocity [3]. The toroidal mode number n=1 is obtained by magnetic pickup probes.

Experimental dates are statisticsly analyzed among one-branch to four-branch BAEs and results show that higher mode frequencies are prone to be excited when multiple branches are observed. Amount of REs is attribute to the different frequency branches of unstable BAEs: More REs are yielded by controlling the decrease of electron density in the current flattop, and the resistive plasma current is replaced by that carried by the REs as indicated by a large drop of the surface loop voltage. This result suggests that BAEs depend sensitively on the plasma beta contributed from REs.

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Monte-Carlo simulations of runaway electron impact on tokamak plasma-facing components

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Runaway electrons (RE) with kinetic energy from tens of keV up to tens of MeV generated during a tokamak discharge [1] can deposit significant heat loads to the plasma-facing components. Electrons passing through the material lose energy mainly through two different processes. Firstly they lose energy due to collisions with electrons and nuclei in the material, and secondly due to bremsstrahlung radiation. Depending on the material of the first wall, the impacting electrons can deposit a significant part of their energy from several millimeters up to several centimeters below the surface. Therefore, it is useful to study the RE heat deposition by Monte-Carlo simulation codes for high-energy particle interactions with matter, such as FLUKA [2] or GEANT4 [3]. The deposited energy density in the 3D geometry of the components by the RE beam in an arbitrary magnetic field can be obtained from this code. The resulting profile of the deposited energy density can be further used as an input for thermal analysis in finite element analysis software ANSYS [4] to investigate the temperature change in the component after the impact of the RE beam.

In this contribution, we present an overview of RE impact simulations for plasma-facing components of COMPASS, COMPASS-U, JT-60SA and Golem tokamaks. Firstly, this analysis was performed for the RE calorimetry probe at tokamak COMPASS [5], which measured the total deposited energy by the RE beam on a protection limiter. Predictive simulations of RE heat loads for plasma-facing components of tokamaks COMPASS-U and JT-60SA to estimate potential damage to the component surface and heat sinks have been also carried out. On top of that, the FLUKA simulations were used for the design of the prepared calorimetry probe for tokamak GOLEM.

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The applicability of three and four parameter fits for analysis of swept embedded Langmuir probes in tokamak divertor plasmas

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The problem of power exhaust is one of the grand challenges of nuclear fusion research today. In order to understand the physics phenomena occurring in the scrape-off layer and the divertor regions of tokamaks, it is essential to correctly determine the divertor plasma parameters, which are often measured by swept Langmuir probes (LPs). While the construction and operation of this diagnostic can be straightforward, the data analysis using three- or four-parameter fits presents a challenge and can potentially lead to erroneous values of electron temperature and ion saturation current.

In this contribution, we present modelling and experiments aimed at determination of conditions for proper analysis of swept LPs using these two fitting models. Particle-in-cell modelling was employed to evaluate the sheath-expansion effects for particular probe geometry and plasma conditions, yielding a semi-empirical rule capable of predicting its magnitude. Experiments with unusually wide range of swept voltage in the divertor of the COMPASS tokamak explored the magnitude of voltage range required for successful analysis with either three or four-parameter fitting. With the use of our new semi-empirical rule, it is possible to improve the four-parameter fit reliability in situations where the available voltage range is limited [1]. In addition, we introduce the tangent method — an independent and fast method of electron temperature estimation, which allows to reliably determine the available voltage range and as such assist more complex methods of probe analysis.

The measurements using swept divertor Langmuir probes of the combined array in COMPASS have confirmed the presence of high electron temperatures (~ 50 eV) in the vicinity of the outer strike point, in agreement with previous measurements of the ball-pen probe technique [2] but contrasting to significantly lower temperatures observed by the swept Langmuir probe array at different toroidal location [3]. These high temperatures suggest that the COMPASS outer SOL plasma was commonly in the flux-limited regime. A comparison of the two diagnostic methods has yielded a practical empirical rule for the validity of the combined probe array measurements in L-mode and ELM-free H-mode plasmas.

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COMPASS-U equilibrium control simulations using the NICE code

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Simulation programs called *flight simulators* are used to model and predict tokamak plasma behaviour to guide experimental campaigns. At present a simple working model of the flight simulator is under development at the IPP CAS, Prague, will contain a transport module using METIS code[1, 2], equilibrium module using NICE code[3] and a feedback module. The NICE code will be used for equilibrium reconstruction of the plasma.The NICE code has been implemented for COMPASS-U[4] parameters, for the direct and evolution mode. The direct mode is a static mode which finds the plasma shape given coil currents at a given time instant. In the evolution mode, using the voltages of the poloidal field circuits, this is done as function of time, . [5].

A simple linear equilbrium controller for the plasma, which uses clearances to determine optimal parameters for deployment during the discharge is under development which uses both the static and evolution mode. In this contribution, results using both modes have been implemented in a workflow for the controller and the effect of the induced currents on the robustness of the controller is studied.

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Runaway electrons measurements by ECE on the GOLEM tokamak

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Abstract

The GOLEM tokamak is a small machine (R = 40 cm, a = 8.5 cm). Due to the high loop voltage (U_{loop} > 5 V) during quasi-state phase the feature of this device is generating of significant amount of runaway electrons (RE) [1]. The experiments on COMPASS have demonstrated the possibility to study RE by vertical ECE system [2], however in this case the locality of measurements can not be defined properly. The plasma parameters on GOLEM allow observing the fast electrons by electron cyclotron emission (ECE) with radial placement of the antenna. Because of low density and temperature of electrons the plasma on GOLEM is optically thin and the measured power of ECE is mainly connected with radiation from non-thermal electrons. Such antenna position gives the possibility to get information about radial position of observation point. Recovering of electron energy distribution is more complicated. However the second advantage of thin plasma is possibility to model ECE as a combination of single electrons radiation. Matching this model to experimental data via variation of the electron energy distribution function allows estimating the energy distribution.

The presented work demonstrates results of the first ECE measurements with radial configuration of the antenna on the GOLEM tokamak. The diagnostic allowed observation of the presence of non-thermal electrons with a high time resolution in comparison with semiconductor HXR sensors and provided some information about the locality of measurements. Also, the electron energy distribution function was estimated by comparison of experimental data and simulation of ECE in thin plasma.

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Current density limitation during disruptions due to plasma-sheaths

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The recent experimental study realized in the COMPASS tokamak [1, 2] demonstrates, for the first time, that the current density that flows from the plasma into the vacuum vessel during disruptions is limited by the ion particle flux. This implies that the sheath that forms between the plasma and the first wall dominates the halo current flow. This observation is based on systematic measurements with grounded as well as negatively biased Langmuir probes on the COMPASS divertor. Further study with Mirnov coils also demonstrates that the total electric current entering the wall grows with the pre-disruptive plasma current while the (maximum) current density obtained by grounded Langmuir probes remains unaffected. This, together with the current density limitation, leads to a novel finding that the halo current width increases with the pre-disruptive plasma current, which limits the local forces.

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Effects of inboard-originating n=1 error fields on tokamak COMPASS plasma and consequences for central solenoid design of COMPASS-U

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Perturbations of the axisymmetric magnetic field of the tokamak can naturally occur as a consequence of the installation misalignments of the tokamak coil system, the coil inner winding geometry, the power feed lines, etc. Errors as low as $\delta B/B_0 < 10^{-4}$ can result in formation of large magnetic islands that deteriorate or even disrupt the plasma discharge [1]. The *resonant* component of δB couples directly to the rational $q(\psi_n) = m/n$ magnetic surfaces and has the dominant effect on plasma [2], and as such has been the focus of the research within the community. However, the typically neglected *non-resonant* component of the δB too can significantly affect the plasma rotation and assist the magnetic island formation [2]. Such fields may originate from misalignments of a tokamak central solenoid (CS).

In this contribution, the unique error field windings on tokamak COMPASS installed at the inboard side of the torus are utilized to simulate a controlled misalignment of the CS during plasma discharges without auxiliary torque input. Observed magnitude thresholds for opening of large magnetic islands by this weakly-resonant δB are related to those for highly-resonant δB - of scaling [3]. Experiment shows that for low q_{95} plasmas the inboard-originating error fields can be predicted - and corrected - in the same manner as the more typical highly-resonant error field sources. For higher q_{95} plasmas, however, this does not generally apply. The above findings are utilized in the optimization of the COMPASS-U CS coil, specifically of its inner winding geometries and of CS coil segment orientations with respect to each other - in order to minimize the resonant and possibly non-resonant coupling of its natural δB to plasma.

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The high density H-mode plasma operation in all-mental-wall EAST tokamak

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High density in the high confinement mode (H-mode) is required for a sufficient energy production and fusion performance in future fusion power plants. Experiments on high density operation have been carried out in small ELM H-mode plasmas with q_{95}~5.5-8.5 in EAST tokamak with all mental walls. In order to acquire densities on the order of the Greenwald density n_{GW}, multiple fueling methods, such as gas puffing, pellet injection and supersonic molecular beam injection (SMBI) are applied during the experiments. Eventually the density above n_{GW} is achieved in the plasma current platforms Ip~300&400kA. During the experiments, the fueling limit is observed, where the plasma density does not increase with the plasma fueling. And the density behaviour in the H-mode is mainly affected by confinement, with the hard limit on the H-mode density being imposed by the H-L transition. At densities close the Greenwald limit the inner divertor is completely detached during the stable H-mode. Although strong detachment is observed before H-L transition in EAST, by itself it was found to impose no limit on the density rise.

Research on high current and low inductance laminated transmission busbar in high-power long-pulse steady-state operations

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Abstract—The operation goal of future fusion reactors, such as China Fusion Engineering Experimental Reactor (CFETR), International Thermonuclear Experimental Reactor (ITER) is to realize high-power long-pulse steady-state plasma. The conventional DC busbar occupies too much space, and the large inductance leads to voltage drop, increase EMI (Electromagnetic Interference) and no on-line real-time diagnosis and detection of its state is not suitable to the long-pulse steady-state operation.

This paper presents an improved high current transmission busbar available for long-pulse steady-state operation. The fully insulated laminated transmission busbar with low inductance, low impedance, high power density and high current will be studied and analyzed. Three formulas are established to optimize the low inductance and insulation level. With same current and voltage, the new high current laminated transmission busbar can reduce 70% of the installation space, 50% of the stray inductance. Moreover, the contact resistance the transmission loss can be reduced by 20%. It can correspondingly reduce the current rise time and suppress the long-pulse current ripple.

To make the on-line real-time diagnosis during long-pulse operation, firstly, the influence of the oxide layer on the contact surface and the electrical contact resistance is analyzed. Secondly, the on-line real-time diagnosis and detection of the insulation performance of the first and second conductors of the laminated transmission busbar are studied, in which the electrical contact is analyzed for fatigue. The fatigue analysis could provide the basic information to determine for threshold of transmission busbar lifecycle, which is to ensure the high safety and reliability of long-pulse steady-state operations for TOKAMAK. Finally, the experimental test and analysis are carried out, and the calculation results are compared with the theoretical analysis to verify the effectiveness of the method and prove the main conclusions of this paper.

Hot spots of the first wall induced by fast ions in EAST

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The first-wall limiters in EAST were observed to endure high heat load and be damaged during the plasma operation [1]. To explore the heat load carried by fast ion loss, the neutral beam injection (NBI) and radio frequency (RF) power proportion experiment was conducted in EAST. The wall temperature of the first-wall limiters measured by the infra camera was found to be enhanced by increasing the NBI power. And this enhancement mainly occurred at the midplane of the limiters. The change rate of the wall temperature was also increased with the NBI power. The wall temperature distribution on the limiters shows that the injected NBI power in the perpendicular direction would enhance the wall temperature at the midplane of the limiters and expand their bright areas towards the bottom.

To understand the experiments, we performed NBI ion loss simulations in the presence of the toroidal field ripple and the Coulomb collision by using the orbit code GYCAVA and the NBI code TGCO [2]. The result shows that the NBI ion loss can contribute considerable heat load and form a bright area at the right side of the main limiter from the midplane towards bottom. The peak heat load of lost fast ions generated by co-perp NBI (~0.6MW/m^2) is roughly 5 times larger than that of co-tang NBI (~0.12 MW/m2) for 1MW NBI injected power. And the main loss mechanism is attributed to the ripple stochastic loss, which makes lost NBI ions finally hit the main limiter near the midplane. Increasing the gap between the limiters and LCFS would reduce the NBI ion loss and cause more fast ions in the gap back to the main plasma region inside the LCFS.

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Direct measurement of the SOL helical current filament induced by lower hybrid wave in EAST

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A new directional electron probe (DEP) has been developed to measure the edge non-thermal electron current in magnetically confined plasma, and the corresponding principle of DEP is demonstrated by a particle orbit simulation and experiments in EAST [1, 2]. Lower hybrid current drive (LHCD) is an efficient method to drive plasma current and control current profile. Strong mitigation of edge localized mode (ELM) has been observed in the lower hybrid wave (LHW) modulation experiment on EAST tokamak [3], and the edge magnetic topology change induced by the scrape-off layer (SOL) helical current filaments (HCFs) caused by LHW is proposed as a possible mechanism[4, 5]. In the previous publications, it is challenging to build a precise physical model for the ELM control by using LHW without direct measurement of the HCFs. Recently, a series of experiments have been performed in EAST to measure the HCFs induced by LHW with the DEP. One of the four HCFs driven by the 4.6 GHz LHW antenna covers a radial region over 20 mm with a maximum current density of about 20 A/cm^2. The dependence of HCFs on the plasma density and q_{95} are studied in these series of experiments. There is a density threshold for the excitation of the LHW SOL current. The current density of HCF is relatively small in low line-averaged density discharges, but it increases significantly when the density reaches a threshold around $\bar{n}_e = 2.8 \times 10^{19}$ m^{-3}, and then it continuously increases with the density. This experiment observation confirms that the SOL HCF is higher in larger density cases, which could be extremely important for large fusion devices, such as ITER, because the LHW could drive large SOL current and modify the edge magnetic topology. The HCFs of LHW are shifted continuously in the poloidal direction via decreasing the plasma current and increasing q_{95} simultaneously, which reveals a long poloidal elongation length of the HCF. The three-dimensional HCF is reconstructed by the field line tracing analysis based on the SOL current measured by DEP, which is essential for building a precise physical model of LHW HCFs. The cross-field transport is also measured by four Langmuir probe pins on the front surface of DEP, exhibiting strong enhancement of radial transport during the application of LHW. The dynamic evolution of the radial transport and the corresponding edge plasma parameters are analyzed to give a complete physical picture of radial transport caused by LHW. In this contribution, the three-dimensional structure of HCF caused by LHW is measured directly, and its dependence on some key parameters (plasma density and q_{95}) are also identified. Based on our investigation, it is possible to develop an ELM control scenario by using the LHW current.

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Experimental and gyrokinetic studies of turbulence and transport under the stepping-up of NBI power on EAST

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Anomalous thermal transport can limit the achievable density and temperature gradients and thus severely degrade energy confinement in the plasma core. ITG, TEM and ETG turbulence have been considered to be possible candidates for the explanation of ion/electron thermal transport. Characterizing, understanding and thus controlling turbulence are very important to future fusion reactors, e.g., ITER. In this talk, we report an observation of ion-scale turbulence enhancement in the core of EAST L mode plasmas in responding to the stepping-up of neutral beam injection (NBI) power. Measured by an ordinary mode reflectometer at r/a≈0.25, core ion-scale turbulence at $k_\perp \le 5$ cm^{-1} (i. e. $k_\perp\rho_s \le 1.5$, where ρ_s is the ion gyroradius with sound speed using locally measured T_e, and $k_\perp$ is the perpendicular wavenumber) is found to increase in the frequency-integrated spectral power S_{tot} following a stepping-up of NBI power. This positive correlation between turbulence spectral power and heating power and the time sequence of heating power stepping-up and turbulence enhancement strongly suggest the observed ion-scale turbulence is responsible for core plasma transports in these EAST L-mode plasmas, which is supported by the further power balance analysis from the TRANSP code and the GTS gyrokinetic nonlinear simulations. It is also found that the time scale of turbulence power increasing seems to positively correlate with the magnitude of NBI power stepping-up, e.g., turbulence saturation time being approximately equal to 20, 70 ms with $\Delta P_{NBI} \approx 0.5$, 0.8 MW, respectively. Linear gyrokinetic stability analysis using the GS2 code shows that the most unstable ion-scale instability is ITG mode, its linear critical ion temperature gradient is close to but a little lower than that at t = 3.7 s, and the linear growth rate of ITG mode calculated with experimental profiles is higher with increased NBI power, indicating the ITG nature of the observed ion-scale turbulence. Nonlinear simulation results from the GTS code sees much higher turbulence and transport with the increase of NBI power in the inner core region around r~0.25, which is consistent with the enhancement of experimentally observed turbulence at higher NBI power.

Real-time plasma kinetic prediction and feedback control using polynomial nonlinear state-space models on the EAST tokamak

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In this work, we propose a novel model identification method to systematically predict nonlinear plasma kinetic dynamics for real-time control on the EAST tokamak. The main contribution of this work is the finding of an elegant method [1-2] to transform linear control-oriented plasma kinetic models into nonlinear models in a higher dimensional space, so that we can easily characterize linear and nonlinear plasma kinetic dynamics simultaneously and distinguishably. The final nonlinear model has a unique structure composed of a linear baseline kinetic model, in the form of state-space equations, together with a vector of nonlinear polynomial expansion terms being added in the process state and output equations.

We first introduce two approaches operating in the time and frequency domains separately to extract an optimal linear state-space model [1], describing a perturbed linear response of plasma kinetic parameters with respect to additional heating and current drive system powers. After initializing the linear parts of a polynomial nonlinear model with the derived linear model coefficients, an iterative method is employed to identify nonlinear plasma kinetic dynamics from the actuation and diagnostic data, eventually driving the model prediction errors to a minimum in the extended nonlinear model space [1]. Interestingly, the identified polynomial nonlinear kinetic model can be subsequently reduced to a more concise form, sacrificing very little predictive capability, via the so-called canonical polyadic decomposition (CPD) technique [3].

Extensive open-loop METIS simulations have been conducted in H-mode plasma scenarios on EAST. Comparing the results with the control-oriented model prediction clearly demonstrates the enhanced real-time prediction accuracy of the new nonlinear kinetic model over the best linear kinetic model. This nonlinear model identification method has also been applied to the open-loop experimental data obtained from lower hybrid power modulations in an H-mode scenario on the EAST tokamak [4-5]. The identification results also show improved predictive performance of the polynomial nonlinear kinetic model over the best linear kinetic model, just in line with the conclusion obtained using the METIS simulated data. Further closed-loop METIS simulations suggest the potential of this new nonlinear kinetic model in predictive control of the nonlinear plasma kinetic dynamics on the EAST tokamak.

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First-order shift formula of stable and unstable manifolds under perturbation and its application in magnetic confinement

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In the established theory [1, 2] of the global structure of three-dimensional (3D) magnetic fields, we had derived *the first-order shift formula of X/O-cycles under perturbation* ($\delta\mathscr{B}$), based on which we further deduce *the first-order shift formula of stable and unstable manifolds under perturbation*. Note the perturbation field $\delta\mathscr{B}$ does not need to be axisymmetric and the field to be perturbed does not need to be divergence-free. These two formulae provide a clear framework for controlling the shape of magnetically confined plasma by applying them to the vacuum magnetic fields induced by various coils. Moreover, it is feasible to control the width of chaotic layers at the plasma edge and island chains. Of particular importance among all the "perturbing" fields, the time derivative of a realistic field, $\partial\mathscr{B}/\partial t$, can be considered a peculiar one in the formulae (*i.e.*, substituted for the perturbing field $\delta\mathscr{B}$), which yields the shift velocities of X/O cycles, stable and unstable manifolds.

For a divertor configuration, the connection lengths of magnetic field lines in the scrape-off layer (SOL) are greatly influenced by the Jacobian matrix eigenvalues of the Poincaré map of the outmost X-cycle(s). The Jacobian matrix is denoted by DP^m for a cycle of m toroidal turns, where P denotes the Poincaré map of one toroidal turn. Adjusting the eigenvalues of DP^m of the X-cycle(s) to be close to unity can significantly increase the connection lengths in the SOL. The first-order change of DP^m under perturbation is revealed by a formula deduced in the same manner as that of X/O-cycles and (un)stable manifolds. It is expected that pushing the two eigenvalues of DP^m towards unity will facilitate the achievement of edge plasma detachment due to the resulting increase in radiation loss from the longer connection lengths.

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Research on characteristics of electron heat transport and related mechanism in EAST high poloidal beta operation

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The confinement and transport of plasma in the tokamak plays an important role in the high poloidal beta (β_P) plasma is desirable for steady state operation which is considered by future fusion reactor ITER. Here, $\beta_P = P/(B_P^2/2\mu_0)$ with P the plasma thermal pressure and B_P the poloidal magnetic field strength. In this scenario, plasma could obtain better confinement and fusion gain with higher rate of bootstrap. The energy and particle transport of the thermal plasma is a critical concern for high β_P experiments since the bootstrapped current is proportional to the pressure gradient. It has long been recognized that a higher Shafranov shift, which is proportional to β_P, plays a crucial role in the suppression of turbulence and related transport. Most of the devices such as DIII-D and JT-60U has a lot of experiments towards the discharges with ITB, and get varies of good results and conclusions. So it is very important to discuss the intrinsic mechanisms of ITB for the higher performance in EAST and the researches of other reactor also provide the rich theoretical basis and experimental ideas for the research on EAST

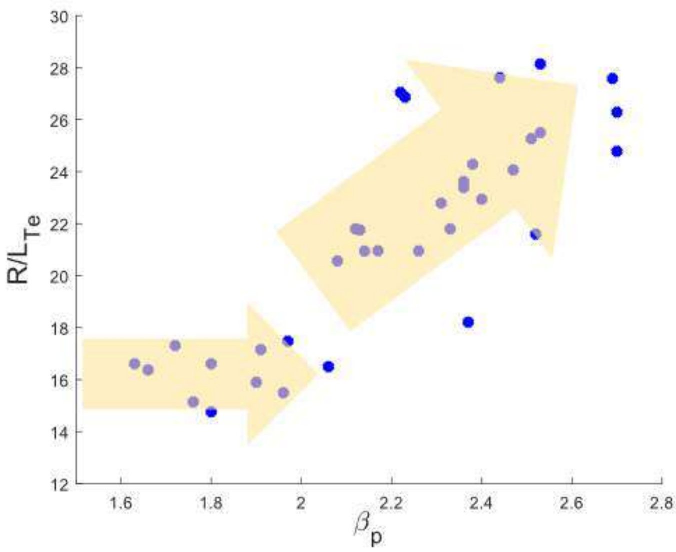

Figure 1 the results of relationship between the β_P *and the* normalized electron temperature gradient R/L_{T_e} *by statistical analysis and experimental data calculation of the smooth discharge with* β_P*>1.5*

This paper mainly introduces the analysis of some experimental phenomena of discharges with ITB in high operation β_P on EAST. Significant progress has been made toward realizing the relationship between the β_P and ITB by statistical analysis and experimental data calculation of the smooth discharge with β_P >1.5, and statistical results are shown in figure 1. The normalized electron temperature gradient R/L_{T_e} (Y-axis) is a important parameter to characterize the strength of the e-ITB (weak or strong). So that the fig.1 shows the electron temperature gradient has obvious differentiation in the range of β_P =2~2.2 we called 'turning point' here. Which may indicate that the plasma electron temperature rigidity is broken. And also indicate the formation of e-ITB through the 'turning point', Accurately, this may be the threshold for e-ITBs formation in EAST.

After that, the typical discharges within β_P=2~2.2 are selected for specific analysis. In 2021 EAST campaign, the discharge #101379(β_P=1.8) and #101449(β_P=2.5) has been chosen for they were on either side of the turning point. Which may contain the physical process and mechanism of the reason for the arising of the turning point.

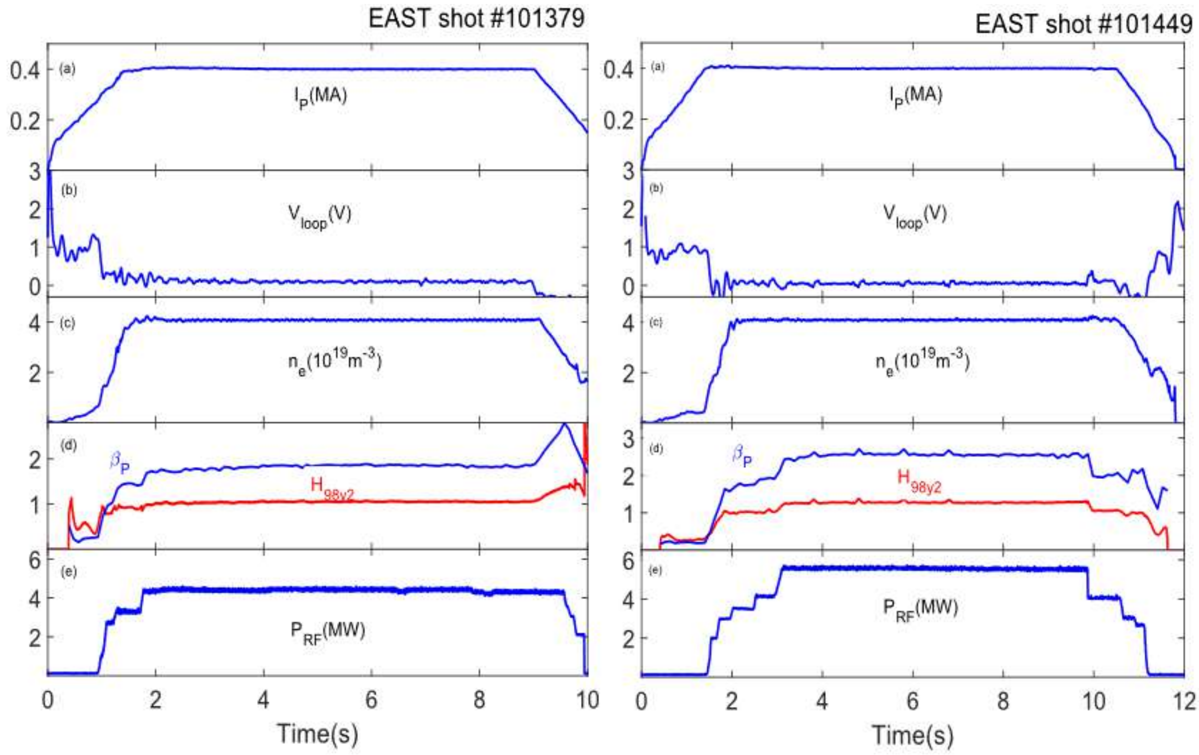

Figure 2 Time evolution of plasma parameters for shot #101379 and #101449 on EAST: (a) plasma current, (b) loop voltage, (c) line-averaged electron density, (d) poloidal beta β_P and energy confinement enhanced factor H98y2, (e) auxiliary heating powers of RF waves including LHW, ICRH and ECH

#101379 has 4.2MW auxiliary on-axis heating power, including 2.7MW lower hybrid wave (LHW), 1.4MW electron cyclotron heating (ECH) and 0.1MW ion cyclotron resonance heating (ICRH). the plasma current I_P=0.4MA; the line-averaged electron density ne ~ $4.05\times10^{19}m^{-3}$; β_P~1.8 and H_{98y2}~1.05. #101449 has 5.5MW auxiliary on-axis heating power, including 2.6MW lower hybrid wave (LHW), 1.4MW electron cyclotron heating (ECH) and 4.5MW ion cyclotron resonance heating (ICRH). the plasma current I_P = 0.4MA; the line-averaged electron density ne~$4.1 \times 10^{19} m^{-3}$; β_P~2.5 and H_{98y2}~1.25. The main plasma parameters for the discharge #101379 and #101449 are shown in Figure 2 the loop voltage is well controlled to be zero during the plasma flat-top, which indicates the fully non-inductive current drive condition.

In this work, the time slice t=6s for #101379 and t=6.75s for #101449 are selected for transport analysis. The experimental plasma profiles are provided by the following diagnostics: the electron temperature (Te) is measured by Thomson scattering (TS) diagnostics, the ion temperature (Ti) is measured by charge-exchange recombination spectroscopy (CXRS) and tangential X-ray crystal spectrometer (TXCS) and the electron density (ne) is reconstructed by Polarimeter-interferometer (POINT) and reflectometers. All the profiles are plotted in Fig. 3.

The Fig.3 shows that the electron temperature profile makes a very large difference in the core when the ne and Ti profile is similar. The normalized electron temperature gradient R/L_{T_e}~23 means the rigidity of the electron temperature gradient is broken, also indicate the formation of e-ITB

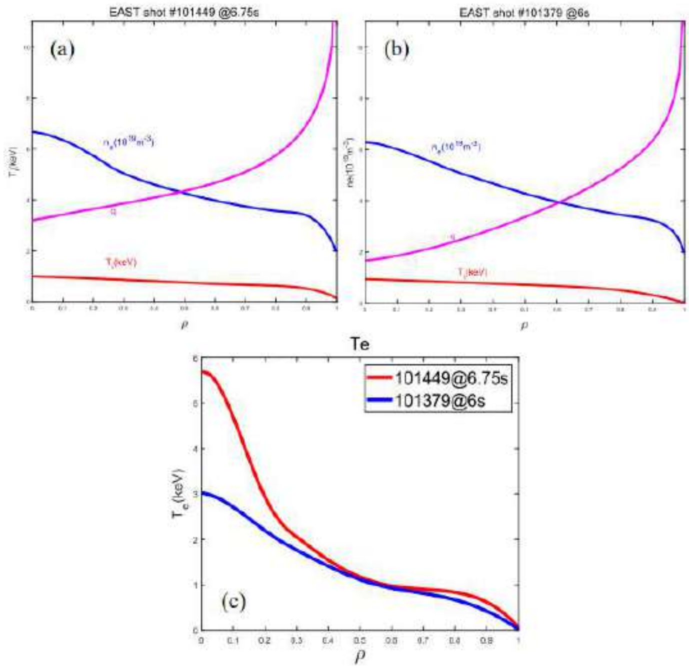

Figure 3 (a),(b) are profiles of Ti, ne and q at t=4.5s for EAST discharge #101379 and #101449 ,and (c) is the comparison Te profiles of #101379 and #101449

The polarization interferometer diagnosis system and the Moving Stark Effect diagnosis system provide the message support of internal magnetic field confinement in plasma kinetic equilibrium fitting, and analyse the different current rate and power deposition by varies current calculation models. At last carrying out the transport analysis. It is found that the electron heat transport coefficient decreases at $\rho <$ ITB radius though the auxiliary heating power of these charges is similar, and then the growth rate of turbulence is calculated by TGLF program to explore the internal physical relationship.

However, it can not to confirm whether the 'turning point' in fig.1 is the β_P threshold value of e-ITB formation or not. It still needs more experiments and data analysis to explore the mechanism further.

Experimental investigation of low-frequency Alfven Eigenmodes in EAST reversed shear plasmas with $q_{min} \simeq 2$

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Abstract:

The basic features and excitation conditions of low frequency Alfven eigenmodes (LFAEs) have been investigated in EAST for the condition $q_{min} \simeq 2$. Two kinds of LFAEs: BAEs and RSAEs are captured by ECE and SXR arrays synchronously, which can be generated as two formations: BAEs only and the pair of BAEs-RSAEs. The observed mode frequencies are usually higher than the estimated BAE accumulation point for the safety factor q_{min} is close to rational number of 2, namely the kinetic effects of finite Larmor radius (FLR) or finite orbit width (FOW) should be considered in EAST, KBAEs.

The KBAEs is excited for higher pressure gradient, while the pairs of KBAEs-RSAEs are observed for the further increases of pressure gradient. The radial position of the pairs of KBAEs and RSAEs is located at 1.98 $\leq R \leq$ 2.07 m, and the toroidal mode numbers for those branches are 1 $\leq n \leq$ 5, where the radial position of q_{min} is located at $R \approx$ 2.024 m (normalized minor radius $\rho \approx 0.3$). The structures of different branches of KBAEs are easily discriminated by the SXR array, and the different branches of RSAEs are differentiated by the different sloping rates of upward sweeping frequencies. Furthermore, the energetic ions and toroidal rotation are considered.

Kinetic effects in the COMPASS tokamak Scrape-off Layer and their treatment with SOLPS-ITER

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We present a benchmarking study of the 2D fluid code SOLPS-ITER and the 1D3V kinetic code BIT1 in modelling the Scrape-Off Layer (SOL) of the COMPASS tokamak in the inter- ELM H-mode discharge #16908. We gauge the strength of kinetic effects in the simulations, suggest optimal values for kinetic factors such as flux limiters or the sheath heath transmission coefficient, and perform a sensitivity study to these factors.

SOLPS-ITER [1] is a 2D edge plasma transport solver, consisting of the Braginskii code B2.5 and the Monte Carlo code EIRENE. A workhorse of predictive ITER modelling, SOLPS-ITER excels at assessing the overall edge plasma parameters by capturing both plasma and neutral physics but cannot treat kinetic effects (flux limiting, sheath effects etc.) in a self-consistent manner. It incorporates them, instead, in the form of boundary conditions and transport correc- tions.

BIT1 [2] is a 1D3V Particle in Cell Monte Carlo code which models plasma along a SOL flux tube. It has previously been used to identify the kinetic factors in COMPASS plasmas [3]. Our work follows up by testing these kinetic factors in fluid simulations.

COMPASS [4] was a compact-sized tokamak, whose scientific programme and extensive di- agnostics coverage were focused on edge plasma research. Interpretative simulations of COM- PASS are crucial steps toward predictive simulations of the COMPASS-Upgrade tokamak [5], which is currently being constructed.

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Investigation of steady-state long-pulse operation issues in EAST

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Recent EAST experiment has demonstrated 310s H-mode plasma (H_{98y2}>1.3, n_e/n_{GW}>0.6, f_{BS}>50%) with full metal wall using an actively cooled ITER-like tungsten divertor. The total injected energy into the plasma is ~1.50 GJ with Radio Frequency (RF) power. Key technical and scientific challenges have been addressed for the steady-state operation. A robust plasma control was demonstrated to keep the equilibrium with good accuracy overcoming the challenge of drift in magnetic measurements over long pulses. A large outer gap was chosen to avoid the formation of hot spots on the LH antenna and a continuous local gas puffing was set up to increase the electron density in the SOL for better LH coupling. An improved loop voltage control was developed to sustain fully non-inductive CD. Grassy ELMs were obtained in this long pulse H-mode discharge, facilitating the efficient RF power coupling and reducing divertor sputtering/erosion. The real-time lithium powder injection and low-density cleaning discharges before the exploration of long pulse H-mode were carried out to control the recycling. Meanwhile, new lower divertor can significantly mitigate the power exhaust challenge, enabling the handling of large divertor heat fluxes, up to 10 MWm^{-2}, preventing impurities (particularly tungsten from the divertor) from contaminating and cooling down the plasma core, and maintaining good particle exhaust to ensure that the plasma density does not rise in an uncontrolled way. Details relevant to this steady-state H-mode plasma operation will be presented.

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A load model of high power magnet power supply for EAST based on GMPSO-BP neural network

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To provide an accurate dynamic load model for the stability analysis of Tokamak, a method of back propagation (BP) neural network employing particle swarm optimization(PSO) algorithm based on mutation of Gaussian white noise disturbance (GMPSO-BP) is recommended. This method performs high-precision fitting using the GMPSO-BP neural network on the measured data of the experimental advanced superconducting Tokamak (EAST) poloidal field magnet power supply, extracts network parameters to build a dynamic load model, and then compares the simulation results with the measured data to calculate the error coefficient. The revised algorithm has quick convergence times, good initial value adaptability, and error function accuracy of 0.003% to 0.03%. The simulation outcomes show that the approach has a greater training prediction effect, which can accurately define the impact effect of EAST pulsed loads connected to the power grid and improve stability analysis accuracy.

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Analysis of the influence of voltage harmonics on the maximum load capacity of the power supply transformer for the LHCD system

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Abstract. To study the influence of the voltage total harmonic distortion (THDV) and its spectrum on the harmonic loss factor (FHL) and the maximum allowable load capacity ratio (Imax(pu)) for the transformer of the LHCD system, we use MATLAB software to model the LHCD system and study the winding loss and maximum allowed load capacity of the LHCD system transformer when the supply voltage source is sinusoidal and non-sinusoidal, respectively. The calculation is carried out by the method of IEEE standard C57.110 and the method of considering the skin effect. The calculation results of both methods clearly show that the THDV value of the supply voltage has a significant effect on the harmonic dissipation factor (FHL) and the maximum allowable load capacity ratio (Imax(pu)) of the transformer. And the calculation method considering the skin effect increases the maximum allowable load capacity ratio of the LHCD system transformer by about 2%. The research results have important reference value for the future retrofit design of LHCD system transformers.

Keywords. THDV, transformers, LHCD, winding losses, maximum loading capability .

Comparison of Hermes-2 and EMC3 for the SOL transport of W7-X

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The edge and scrape-off layer (SOL) of modern stellarators provides a unique challenge for fluid simulations. The implementation of the Flux Coordinate Independent (FCI) method [1] for parallel derivatives and metric tensor components which vary in three dimensions in BOUT++ have allowed for such simulations within BOUT++ [2, 3].

The EMC3-Eirene code is a well established tool for modeling of the SOL of stellerator devices like Wendelstein 7-X (W7-X). EMC3 uses a Monte Carlo approach for solving the fluid equations for the plasma, while the kinetic Eirene code is used for the neutrals. While EMC3-Eirene has been used to reproduce and explain global trends in W7-X [4] significant differences remain as well [5]. EMC3 does not include drifts, which are a strong candidate for explaining at least some of the discrepancies observed between EMC3-Eirene simulations and experiments [6]. The inclusion of drifts into EMC3 is challenging, due to the inherent noise of Monte Carlos methods.

Hermes-2 is a hot-ion drift reduced SOL-model using the BOUT++ framework. The Hermes-2 model is currently modified to be able to handle the geometry of a stellerator using the FCI method. The model is capable of simulating turbulence in stellerator geometries. The here presented work compares the EMC3-Eirene code to the Hermes-2 model. The results of the two codes are compared when solving the geometry of Wendelstein 7-X. For a direct comparison, only the terms in Hermes-2 which are similar to those found in EMC3 are used, resulting in a transport simulation. Upon succesfull comparison to EMC3, additional terms, namely the drifts will be enabled, to study the impact of drifts on the SOL transport. To dampen the turbulence, a relaxation method for the vorticity has been implemented.

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A novel optimized stellarator-tokamak hybrid

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A novel hybrid design is presented which would allow the plasma configuration to be varied continuously from an axisymmetric tokamak to a quasi-axisymmetric stellarator. Perfectly quasi-axisymmetric stellarators have the same neoclassical properties as tokamaks Ref. [1]. Therefore, an experiment of this type would be suitable for studying three-dimensional effects on stability and disruptions without adversely affecting the neoclassical properties. In addition, such an experiment could evaluate how much of the three-dimensional shaping is needed to attain steady-state operation in attractive parameter regimes. The plasma design is based on the near-axisymmetric solution by Plunk et al. [2], generated by perturbing an initially axisymmetric equilibrium in a manner that preserves quasi-symmetry. Using the coil optimization feature of the Simsopt code, [3], we show that only a single type of non-axisymmetric coils is needed to realize the quasi-axisymmetric stellarator. This is an exceptionally simple coil configuration for a stellarator, which usually requires a large number of distinct three-dimensional coils to produce its field. In addition, we find that none of the plasma volume of the original tokamak equilibrium is lost due to the stellarator coils.

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Nonlinear tearing modes evolution and sawtooth crashes in a stellarator

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Tearing modes are an important topic in plasma physics. It is relevant for future fusion reactors since these modes are often associated with disruptions. In addition, their large spatial structure leads to enhanced plasma transport and degradation of confinement.

This work reports on the comprehensive study of resistive double tearing modes in a classical, Wendelstein 7-A type, stellarator equilibrium. Using the nonlinear resistive MHD code JOREK which was recently modified to handle 3D geometries (JOREK3D, [1]), low n (toroidal Fourier mode number) resistive double tearing modes are investigated. We study the dependence of their growth rates on the shape of the rotational transform profile and plasma resistivity.

This work aims to lay a foundation for the future study of experimentally observed sawtooth-like oscillations in W7-X, where external current drive modifies rotational transform in such a way that it passes through low-order rational values twice. Nonlinear evolution of the double-tearing mode usually exhibits more complicated dynamical behaviour than its single-tearing counterpart. It may lead to a disruption when the two islands interact with each other. These scenarios are of particular interest because of potential high heat and electromagnetic loads which are outside of a stellarator-safe operation window. JOREK3D is well suited for the analysis and modelling of such scenarios.

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Optimization of Error Field Correction in ITER

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Error fields are non-axisymmetric fields arising from misalignment during assembly of the magnet coils. Despite their relatively small amplitude ($\delta B/B_0 \sim 10^{-4}$) they are able to significantly degrade the plasma performance and limit the operational space. The most severe issue is that low-*n* error fields can induce mode locking which often leads to plasma disruptions, limiting future ITER operation. It is therefore of critical importance to correct these error fields and 18 ex-vessel error field correction coils (EFCC) have been designed in ITER for this purpose. Optimization of the error fields correction using these coils then becomes crucial to avoid mode-locking and disruptions, and is thus important for supporting the future steady-state operation of ITER.

In present tokamak devices, the optimal EFCC currents can be experimentally determined by the so-called polar map approach [1]. However, this approach requires deliberate disruptions via mode-locking whereas numerical modeling based on certain optimization criteria in full toroidal geometry offers a promising way to predict the optimal correction currents without deliberate disruptions and provides useful guidance for future ITER experiments.

In early modeling works to optimize error field correction, the vacuum field approximation was adopted. However, as has been demonstrated extensively in recent years, the effect of the plasma response cannot be ignored as it plays an important role in the optimization of error field correction [1] as well as ELM control using RMPs [2]. After taking into account the plasma response, numerical modeling by the MARS-F [3] and IPEC [4] codes is able to satisfactorily predict the necessary error field correction in MAST [5] and DIII-D [6] experiments.

In this work, we consider error fields in ITER, including those from magnetic ripple, ferromagnetic inserts (FI), Test Blanket Modules and irregular neutral beam ports. The possible error fields arising from inaccurate assembly of the central solenoid, poloidal and toroidal field coils are also considered. By utilizing MARS-F and GPEC, we numerically study the plasma response to the above error fields and externally applied 3D fields from error field correction coils in ITER scenarios, and investigate the optimization of error field correction based on different criteria.

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Error fields expected in ITER from sources other than misalignments of superconducting coils

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The purpose of this study is the estimation of "overlap" error fields [1] in ITER with toroidal modes $n = 1$ and $n = 2$ produced by sources other than misalignments of superconducting coils. These sources of error field are: 1) Ferromagnetic Inserts (FIs) built into the low field side walls of the vacuum vessel and for which the sectors with ports used for neutral beam injection violate the $n = 18$ toroidal symmetry of the FIs, 2) ferromagnetic structures of the four test blanket modules (TBMs), 3) ferromagnetic structures of the building (e.g. steel rebar) and 4) the magnetic field reduction system (MFRS) of the two heating neutral beam injectors (HNBIs).

The calculations of the overlap error fields were performed for the baseline 15 MA DT plasma during burn. They use simplified "engineering" algorithms, based on matrices calculated using the IPEC code [1]. For the plasma considered, the critical value of overlap error fields with $n = 1$ leading to locked modes (LM), assessed using the scaling proposed by the ITPA Topical Group on MHD, Disruptions and Control in 2017, is 2.5 G (if we use all exponents in the scaling expression minimizing the LM threshold). For the mode with $n = 2$, the LM threshold is found to be about a factor of two higher.

The following amplitudes and phases of the overlap error fields with $n = 1$ were obtained in the study: 1.80 G/152° for FIs together with TBMs, 0.52 G/-179° for MFRSs of two HNBIs, 0.47 G/-3.8° for ferromagnetic structures of the building, 1.83 G/154° for all sources of error field together. For the $n = 2$ mode the amplitudes and phases are the following: 2.13 G/160° for FIs together with TBMs, 0.1 G/89° for the MFRSs, 0.09 G/-108° for ferromagnetic structures of the building and 2.15 G/160° for all sources of error field together. The maximum current required in the six Side Correction Coils for reduction to zero of the $n = 1$ error field mode from all sources is 45 kAt (cf. the 200 kAt engineering limit). Such error field correction by nine Equatorial in-vessel ELM coils requires maximum current 6.2 kAt (engineering limit 90 kAt). The maximum current required in these same ELM coils for reduction to zero of the $n = 2$ error field mode from all sources is 8 kAt.

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Progress in the ITER Integrated Modelling Programme

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The ITER Integrated Modelling Programme is focused upon the delivery and exploitation of physics software to support the refinement and execution of the ITER Research Plan. This includes predictive tools capable of describing all aspects of the integrated plasma-plant system, as well as software able to infer plasma and plant parameters from the suite of measurements.
The Integrated Modelling & Analysis Suite (IMAS) is being developed and validated using expertise from across the ITER Members and builds around a community-developed representation of data described by a Data Dictionary that can be applied to any device through the inclusion of Machine Description data that makes it self-describing.
This paper will describe recent extensions to the IMAS infrastructure to support the development of increasingly advanced applications and workflows, including: improvements to the Access Layer for the handling of Interface Data Structures (IDSs), the basic elements of the Data Dictionary; improvements to tools that create workflow actors from native codes (iWrap); support for more sophisticated workflow actors facilitating co-simulations and the efficient exploitation of parallel computing resources (MUSCLE3); the introduction of a new URI enabling more flexible locating of data; as well as improvements to data management (SimDB) and remote access (UDA). Progress on the development of a High Fidelity Plasma Simulator (HFPS) based upon the coupling of the JINTRAC and DINA codes will be presented, as will initial work on a Pulse Design Simulator (PDS) and the rigorous inference of plasma properties using diagnostic models, so-called synthetic diagnostics.

IMAS Modelling of Neutron Spectra Measurements by VNC in ITER

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Computational modules designed for simulations of diagnostics are important elements of the Integrated Modelling & Analysis Suite (IMAS) [1] designed for ITER. Here we describe such a synthetic diagnostic (SD) developed for the ITER Vertical Neutron Camera (VNC). The VNC is an ITER diagnostic, which enables reconstruction of the neutron and α-source profile as well as the ion temperature profile based on measurements of the neutron emissivity and energy spectra in the poloidal cross-section. The VNC SD that has been developed includes a module calculating the energy and angle distribution of the neutrons born from fusion reactions of the thermal and fast D and T ions and a module simulating the VNC detector response signals. The fast fuel ions affecting the neutron energy distribution in ITER will be produced by auxiliary heating systems such as the Neutral Beam Injector (NBI) and Ion Cyclotron Resonance Heating (ICRH) system. The developed VNC SD is based on the Monte-Carlo method, allowing calculations of the angle and energy distribution of neutrons born in each spatial point of an ITER plasma. Modelling of the neutron spectra at the VNC detectors for a given neutron plasma source is based on the contribution matrices [2] calculated for the ITER VNC with the MCNP code.

The VNC SD developed is applied to ITER plasma scenarios stored in the IMAS scenario database. Results of the simulations show the difference in the detector signals with and without the presence of fast ions, which will help to estimate the efficiency of plasma heating. It is shown that the presence of the fast ions will not affect the measurements of ion temperature and particle source substantially in 50:50 DT plasmas, but may affect the measurements in DD plasmas and in the initial phase of DT scenarios with low density.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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Investigation of L-mode, L-H transition and H-mode phases in ITER via core-edge integrated simulations using advanced transport models

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Integrated modelling simulations are essential to predict future performance of ITER plasmas and guide revisions of the ITER research plan. Traditionally, and in order to speed up computations, such simulations are performed assuming simple boundary conditions at the separatrix and/or using reduced transport models for the core region. A recent MPI implementation of the JINTRAC suite (JETTO+Edge2D/Eirene) allows us now to extend these results using a realistic description of scrape-off layer physics and advanced transport models for the core region simultaneously, such as TGLF and QuaLiKiz. Heating sources are concomitantly simulated using an improved H&CD workflow that includes codes for ICRF, ECRH and NBI and can treat non-linear synergies such as the acceleration of NBI ions via ICRF. All the required modelling capabilities are now available in the ITER Integrated Modelling and Analysis Suite (IMAS), being continuously extended for integration into the ITER high-fidelity plasma simulator (HFPS). We apply this suite to the study of fusion plasma operation (FPO) L-mode, L-H transition and H-mode ITER plasmas' performance under different heating mixes, focusing on the feasibility of a main electron heated plasma to achieve Q=10 H-mode flat-top. Results will be analyzed to optimize plasma performance, assisting to the advancement of ITER scenario development using high-fidelity models. In order to expand the studied parameter space as much as possible, these simulations are complemented with a reduced-model approach using the ASTRA+TGLF codes. Impurity concentrations and heating mixes will be kept constant during given simulations and extensively scanned for comparison to the results of JINTRAC. This will aid to the validation of reduced-order models than can later be implemented in a Plasma Control System, as well as provide uncertainty quantification.

Validating neutral-beam current drive simulations in the TJ-II stellarator

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Progress in understanding fast-ion slowing down and confinement in fusion devices necessarily involves the validation of the available numerical tools against the experimental observations. Fast ions produced by neutral-beam injection (NBI) systems are key to this goal. Besides the results related to neutral beam power deposition and heating performance, the current induced by the injection of fast ions is an experimentally measurable quantity that can also be derived from slowing down simulations combined with a suitable electron-response analytical model [1, 2, 3], making it a perfect candidate for model validation.

In this work, we analyze the results of neutral-beam current drive (NBCD) experiments performed in the TJ-II stellarator with the aim of validating the theoretical predictions. Both parallel and anti-parallel injection with respect to the magnetic field were explored using co (NBI1) and counter (NBI2) beams at different injected beam power and plasma densities. All shots exhibit approximately stationary electron line density and temperature during the NBI phase. This guarantees that the source of driven current is roughly constant and that the time evolution of plasma current measured experimentally is only originated by the plasma self-inductive response to the internal current sources (NBCD and bootstrap).

The fast-ion current driven by both beams is simulated with the Monte Carlo code ASCOT [4] and the electron response to the fast-ion current is calculated analytically using a model valid for an arbitrary magnetic configuration and a low collisionality plasma [3]. The bootstrap current is calculated with DKES [5] and its contribution taken into account when comparing with the experimental results. The model reproduces with rather good agreement the toroidal current measured in NBI2 plasmas while the current driven by NBI1 is less than half the predicted one. Possible reasons for this discrepancy are discussed.

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Exploring the space of quasi-isodynamic near-axis stellarators

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Quasi isodynamic (QI) stellarators, a particular case of omnigenous magnetic configurations, are relevant candidates for fusion reactor design due to their good orbit confinement properties and reduced net toroidal current. But the design of existing QI experiments, like W7-X, usually require the use of arduous and computationally expensive optimisation procedures.

The near-axis expansion method, in which the MHD equilibrium equations are expanded in Boozer coordinates [1,2,3], has been used recently together with optimisation procedures to achieve excellent approximation to QI with relatively simple boundary shapes [4,5]. However, these computations are still highly dependent on the initial equilibria used for the optimisation, indicating the space of solutions is being incompletely explored.

The near-axis method allows for a direct, efficient and systematic construction of approximate QI equilibria by prescribing a magnetic-axis shape, the magnetic field strength along the axis, and a set of geometrical parameters characterizing the field in its vicinity. This method can be used to find better initial points for the optimisation and identify previously unexplored regions of the solution space. An analysis of this space is presented as well as the impact that the construction parameters have on the neoclassical transport, measured through the effective ripple, are presented. We find this metric to be a smooth target for the optimization. The geometric properties of optimal solutions are identified and discussed.

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Electron Cyclotron mode conversion in plasma with relativistic electrons

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Generation and absorption of electron cyclotron (EC) radiation is a fundamental physics phenomena underlying many observations in space [1], ionospheric [2], and fusion plasmas. A particular case is the resonant interaction of relativistic electrons (RE) with the EC waves [3], which has been considered in connection with auroral kilometric radiation. And while the lower frequency whistler-type waves generated by relativistic electrons have been observed in tokamaks [4], the higher-frequency EC waves (which are typically also "internal" modes) are not detectable outside the plasma without an intricate mode-conversion process.

The "free space" O- and X- waves are used routinely for plasma heating and current drive in tokamaks and stellarators. However, these waves do not interact directly with relativistic electrons due to their low phase velocity. A unique opportunity exists to convert the "free space" O-mode into an internal plasma slow-X mode in a so-called OX mode conversion process [5, 6]. The phase velocity of the slow-X mode can exceed the speed of light, providing the possibility for direct RE-wave interaction.

In this work we study OX conversion process in post-disruption plasma with runaways in DIII-D tokamak equipped with 110 GHz gyrotrons. OX conversion happens at the O-mode cutoff surface, i.e. electron density of $1.5 \cdot 10^{20}\mathrm{m}^{-3}$ - conditions accessible with extra gas injection in the post-disruption runaway plasma at DIII-D. Full wave calculation with the code CUWA [7] predicts 75% conversion of the injected O-mode power into X-mode. Because the ambient plasma temperature is very low in RE-dominated plasma, the collisional damping of the waves is strong. 1D profile modelling shows two distinct shapes of the plasma density profile in cases with and without OX conversion. The effect of the converted X mode on the runaway beam is also investigated.

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Direct Comparison of H^- and D^- Single Beamlet Divergence in View of ITER's NBI System

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The ITER Neutral Beam Injection system must deliver powerful beams of neutral atoms to effectively heat the core of the tokamak plasma to fusion relevant temperatures and provide current drive. To achieve this goal, RF ion sources used in each NBI beam line must deliver 66A of hydrogen and 57A of deuterium negative ions which are then accelerated to energies of 1MeV for pulse lengths of up to one hour. The intense ion beam will be composed of 1280 individual beamlets and has strict requirements on the beam optics and uniformity in order to minimise the power loads deposited on beamline components. The central core component (~85%) of each beamlet must have a maximum divergence of 7 mrad, and a requirement of 15-30 mrad for the broader halo component of each beamlet (~15%) [1]. The ITER NBI negative ion sources must meet these requirements when operated in both hydrogen and deuterium.

The BATMAN Upgrade test facility is a 1/8 size ITER source with 70 extraction apertures and a maximum ion energy of 45keV. It is well equipped for studies of negative ion beam optics and can be utilised for both hydrogen and deuterium negative ion beams. For this study a single beamlet aperture was isolated in the extraction system upper half for an investigation of single beamlet optics using beam emission spectroscopy, CFC tile calorimetry, and beam dump calorimeter diagnostics. This has allowed for a direct comparison of single beamlet divergence between hydrogen and deuterium originating from the same ion source. Results show similar trends but also interesting differences between ion species, such as the minimum beamlet divergence is lower for deuterium ions, and an overperveant regime for deuterium ions at the highest extracted current densities. However, an accurate measurement of the extracted single beamlet current is required to fully understand the observations.

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Optimization criteria for turbulent heat transport in stellarators beyond Wendelstein 7-X, using an empirical transport model

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The Wendelstein 7-X (W7-X) stellarator has been neoclassically optimized such that its effective magnetic ripple is low: $\langle\varepsilon^{eff}\rangle < 1\%$. However, in most of the parameter space of gas fueled electron cyclotron heated (ECRH) plasmas, turbulent-heat-transport dominates over the low neoclassical heat transport. As a result, these plasmas feature T_i-clamping with $T_{i,0} \sim 1.5$ *keV* irrespective of heating power and plasma density [1]. Only by means of turbulence suppression through e.g. active-density-profile-control to raise a/L_n can the anomalous heat transport be (transiently) suppressed [2, 3], and the benefits of the neoclassical optimization be revealed [4]. Sustaining an elevated a/L_n is not trivial in experiments, and usually requires an internal particle source. Hence, it would be desirable to reduce turbulent heat transport without the requirement of steep density gradients.

Quasi-isodynamic stellarators, like the W7-X concept, are found intrinsically robust against *trapped electron mode* (TEM) [5] and *electron temperature gradient* (ETG) [6] turbulence. Therefore, various theoretical studies are now ongoing to include minimization of *ion temperature gradient* (ITG) turbulence as an optimization criterion for future stellarators [7, 8]. The main parameters to be included in the optimization are (a) the maximization of the *critical ion temperature gradient* $a/L_{T\text{-}crit}$, as well as (b) minimizing the stiffness of the ITG response above $a/L_{T\text{-}crit}$, and (c) an optimum ITG reduction at low density gradients a/L_n.

To quantify the benefits of various optimizations in actual transport reduction, we developed an empirical transport model, focusing on the benefits of suppressing ion turbulent transport. For the electron-heat-transport we assume diffusive transport with an anomalous heat diffusivity $\chi_e^{ano} \approx 0.6$ m^2/s, and low degree of profile stiffness $\chi_e^{pert}/\chi_e^{PB} < 2$, based on experimental evidence [9]. The ITG driven ion heat transport shows a larger variability in experiments with $\chi_i^{ano} \approx 0.2$-1 m^2/s. The most general ad-hoc ITG model we use is:

$$\chi_i^{turb} = C \cdot \chi_{gB} \cdot \chi_{ITG} \cdot F(T_e/T_i) \cdot \chi_{\nabla n} = C \cdot \underbrace{\rho_i^2 c_i / a}_{\chi_{gB}} \cdot \underbrace{x \cdot H(x)}_{\chi_{ITG}} \cdot \underbrace{(T_e/T_i)^{\alpha}}_{F(T_e/T_i)} \cdot \underbrace{y \cdot H(y)}_{\chi_{\nabla n}} \qquad (1)$$

with Heaviside-step-function H, $x = a/L_{T_i} - a/L_{T_{crit}}$, and $y = a/L_{n_{crit}} - a/L_n$. We use the neoclassical transport solver suite (NTSS) [10], that can simultaneously solve the neoclassical and turbulent transport given by (1) to obtain T_e and T_i profiles. The n_e profiles are fixed.

We take the various levels of optimization found in the theoretical studies, e.g. [5, 6, 7, 8] and calculate the final impact of the turbulent heat transport on the kinetic profiles using our empirical transport model, which includes variations of (1). This greatly speeds up the analysis, as further gyrokinetic calculations are not required. Moreover, it provides insights to improve the stellarator optimization studies.

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Tungsten Measurements in Wendelstein 7-X: VUV Spectroscopy and Concentration Assessment

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The stellarator Wendelstein 7-X (W7-X) has performed its first operation phase with a fully water-cooled divertor between November 2022 and March 2023. One research objective of this phase was the exploration of scenarios, which are compatible with a future carbon-free operation and specifically with plasma facing components made from tungsten (W). Some 200 wall and divertor tiles made from tungsten have been installed in the machine to assess the impact on intrinsic W content. Defined amounts of tungsten were injected by means of laser blow-off (LBO) and tracer encapsulated solid pellets (TESPEL) for detailed studies on critical tungsten concentrations.

In this contribution, we report on measurements of intrinsic tungsten concentration and dedicated experiments for W spectra analysis and concentration determination with LBO and TESPEL. The main diagnostics for these measurements are the High Efficiency XUV/VUV Overview Spectrometer (HEXOS), which observes the W quasi-continuum around 5 nm with a high time resolution of 1 kHz, and 2D bolometry to register the total radiation and its change after impurity injection.

For the analysis, the 5 nm region of W emission is analysed using a fitting scheme adapted from ASDEX Upgrade. Based on these fits and bolometry, we attempt to construct a correlation between the intensity and structure of the W quasi-continuum (including the individual emission lines therein) and the W concentration in the plasma. This correlation would enable us to estimate the intrinsic W content in W7-X plasmas based solely on the regularly available VUV spectroscopy. Although the consequence of an elevated W concentration in a stellarator plasma is rather a radiation collapse than a disruption and thus less critical for machine safety, our measurements and observations help to identify and develop scenarios with an optimized W content safely below any critical values. They also provide experimental data that can be used to benchmark impurity transport models.

Analysis of shattered pellet injection experiments at ASDEX Upgrade

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Disruption mitigation is a critical outstanding issue for large tokamaks. ITER is planning to employ the Shattered Pellet Injection (SPI) technique [1], where pellets of frozen material (hydrogen potentially mixed with neon) are shattered near the plasma edge for optimal material assimilation. The aim is to radiate away a large fraction of the plasma stored energy isotropically as well as raising the plasma density to suppress the formation of runaway electrons.

To assist the development of the ITER disruption mitigation system, a highly flexible SPI was installed at ASDEX Upgrade (AUG). The AUG SPI allows a large variation of pellet parameters – such as diameter, length, velocity and composition – and is equipped with three different independent shatter heads. The primary goal of the project is to investigate the efficacy of different pellet shard size and velocity distributions on assimilation. An overview of the main experimental results will be presented by Jachmich et al. [2].

Prior to its installation at AUG, 10 different shatter head geometries were tested during laborabory commissioning and the resulting fragment sprays were recorded with an ultra high speed video camera. The fragment size and velocity distributions were analysed using modern computer vision algorithms. Comparisons to a pellet break-up model revealed that the number of small fragments is underestimated for large velocities and overestimated for low velocities [3]. We found that rectangular shatter heads with shallow angle mitre bends lead to more reproducible and collimated fragment sprays, which seems to benefit material assimilation.

A major upgrade to the bolometry system enables the measurement of radiation (with both foil bolometers and AXUV diodes) at 5 toroidal positions, including the injection position. Minimal neon doping in the pellets seem to significantly increase the radiated energy fraction (f_{rad}). We found that f_{rad} is a complex function of other pellet and injection parameters. For example, at 10% neon content higher f_{rad} values are achieved with larger parallel pellet velocity and smaller fragment sizes. In contrast to this, at neon doping of 0.17% – a composition beneficial for assimilation – larger fragments seem to increase f_{rad}. This contribution will present the analysis of approx 200 AUG SPI discharges from the bolometry perspective.

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Design criteria for a particle exhaust optimized divertor for Wendelstein 7-X

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The stellarator is an inherently steady-state machine, which has several advantages from a nuclear as well as power engineering standpoint. As the confining magnetic field does not rely on a plasma current and therefore the plasma itself, the confinement is fundamentally stable. Further, the absence of a Greenwald density limit, theoretically allows access to higher density operation, in comparison with a tokamak. One of the main goals of Wendelstein 7-X (W7-X), the largest advanced stellarator in the world, is to demonstrate these stable steady-state capabilities experimentally at high performance. Control of heat and particle exhaust is crucial for stable operation and is realized through the island divertor at W7-X, forming the key plasma-facing component (PFC). While the observed divertor detachment properties are extraordinarily favorable from a stability, controllability and heat exhaust perspective, it is less desirable from a particle exhaust perspective.

The necessary condition for a reactor relevant divertor is to enable sufficient Helium exhaust in accordance with the burn condition [1]. As particles leave the plasma, 99 % of the outflowing ion flux is neutralized at the divertor target plates, according to EMC3-EIRENE modeling [2]. These neutralized particles can recycle, be retained by the plasma-facing components, or be exhausted through the pumping ports behind the 10 divertor units. In modeling of attached divertor operation approx. 4 % of the incoming ion flux in the divertor is collected through the pump gap into the sub-divertor [3], of which 6% are actually exhausted, while the other 94% escape, predominantly through the pump gap, into the private flux region. H_α measurements reveal that 85% of the recycling particles ionize in the divertor region, while 15% recycle far away from the recycling surfaces in the main chamber [4], highlighting the feasibility of a toroidal segmented divertor.

The island divertor facilitates full magnetic flexibility with an effective, but in-efficient particle exhaust below 1%. The new cryo pump further enabled wall independent density control in most configurations and therefore fulfills the operational requirements. However, the low exhaust efficiency will likely not fulfill reactor requirements and the current DEMO Tokamak/Stellarator decision time schedule allows for 1 or 2 prototype cycles at W7-X. To achieve the innovation necessary, these cycles have to be reduced in time, allowing more iterations which will be achieved by a reduction in complexity through de-coupling of problems. Design criteria for particle collection, particle removal, and particle plugging will be presented. The development process, set up of iterations of CATIA modeling combined with EMC3-EIRENE modeling, is displayed based on first ideas for a new target geometry that prioritize particle exhaust over magnetic flexibility.

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Effects of NBI operation on the scrape-off layer and detachment at Wendelstein 7-X

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One of the key aspects of the development of the stellarator line for fusion reactors is the design of an effective exhaust concept. At the same time, the current investigations on the best plasma performance demand an exhaust concept suitable to cope with different plasma heating schemes necessary for the experiments. Wendelstein 7-X (W7-X), routinely operating with electron cyclotron resonance heating (ECRH) [1], started the exploration of neutral beam injection (NBI) for heating in the last experimental campaign (in 2018). The first NBI operation showed promising scenarios for core performance due to density peaking [2] [3] [4], increasing the interest in using the NBI as a density profile actuator. Given its broad deposition of heat compared to ECRH and its unavoidable particle source, NBI is expected to influence the W7-X scrape-off layer (SOL), formed by multiple magnetic islands intersecting discrete divertor targets. Crossing the SOL on its way to the plasma core, the NBI can deposit up to 12% of its power in the magnetic island passing in front of the beam duct [5]. Moreover, there is evidence of fast ions generated in the SOL domain [6], which could interact with the background SOL plasma and possibly change the gradients and the potential that govern the transport to the divertor targets. These effects could cause asymmetries in the island chain, influencing the line-radiation location and the transition to detachment, together with its stability. In the most recent experimental campaign (in 2022-2023), the SOL has been monitored during NBI operation in attached and detached conditions, in order to determine the compatibility of high performance scenarios and an effective exhaust concept. Measurements from coherence imaging spectroscopy, He beam, Alkali beam and divertor spectroscopy are used to characterize the effect of the use of NBI on the W7-X SOL, and explore to what extent this heating and fuelling system can be used to induce only the desired beneficial plasma core effects.

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Demonstration of X-point radiation condensation in the detachment regime of the W7-X plasma and its magnetic configuration dependence

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The Wendelstein 7-X (W7-X) stellarator exploits the so-called island divertor concept utilizing the iota = n/m = 5/6, 5/5, and 5/4 magnetic island chains intrinsically formed at the edge. The multi-X points periodically distributed on the separatrix play an important role in distributing the impurity radiation in highly radiative plasmas under detachment conditions. For the plasma in the iota=5/5 (so-called standard) magnetic configuration, bolometer tomography has shown that pronounced emission occurs near certain X-points when the radiation loss fraction approaches a high value ($f_{rad}>0.8$), clearly indicating X-point radiation condensation. The condensation degree (i.e. the amplitude of the radiation intensity peaking) usually exhibits a poloidal asymmetry among different X-points, in particular an up-down asymmetry, which has already been seen in the 'dirty' plasmas before wall boronization (OP1.2a) in a magnetically up-down symmetric triangular cross section [1].
Recent analyses of high-power, high-density discharges obtained from OP1.2b after wall boronization show that this up-down asymmetry in the standard magnetic configuration can change its sign when the plasma density rises beyond a critical value. As the plasma density is further increased, the most intense radiation can appear close to the X-points on the inboard side, with a concomitant inward radial shift of the radiative zone, indicating a high sensitivity of the radiation distribution in the deeply detached plasmas. The low- (5/6) and high- (5/4) iota configurations exhibit different features of radiation distribution. This work investigates the behavior of impurity radiation (mainly from the intrinsic carbon) in ECRH-generated hydrogen plasmas for the three different magnetic topologies. Correlations of the radiation asymmetry with downstream plasma parameters, such as the neutral pressure, Hα measurements in the divertor region, are analyzed. Experimental results are discussed with the help of 3D code modeling.

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Wall conditioning in preparation for long pulse operation at the Wendelstein 7-X stellarator

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An overview and quantitative assessment of the wall conditioning activities is presented from the latest operational campaign of Wendelstein 7-X (W7-X). The conditioning of the wall is crucial in reducing the level of impurities and outgassing to enable density control and better plasma performance. One of the main goals of the latest experimental campaign was to achieve long pulse plasma discharges with good performance. The campaign was carried out after the completion of W7-X, with structural modifications in relation to the previous experimental campaigns, including the installation of fully water cooled plasma facing components.

The current wall conditioning approach at W7-X includes various techniques. Baking prior to the plasma experiments removes high amounts of impurities from the wall, enabling sustainable H and He plasma discharges. Glow discharge cleaning in the initial phase of plasma operation improves the reliability and the length of the plasmas. Throughout the scientific phase, regular boronisation is carried out, which allows for higher density operation ($> 10^{20} m^{-3}$) by creating a boron layer on the wall for binding oxygen. Additionally, hydrogen ECRH pulse trains are used in the daily operation to reduce remaining fueling from the wall.

The effects of the listed conditioning activities on the plasma performance and wall fueling are presented in this work. A comparison to wall conditioning effects from previous campaigns [1] [2] will be given. The optimisation of both He and H glow discharges, as well as of the boronisation process is discussed going forward to future experimental campaigns.

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Modelling of the effect of magnetic islands on the bootstrap current in stellarators

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Magnetic Islands (MIs) are closed magnetic flux tubes isolated from the rest of the confinement region by a separatrix. A possible effect of the MIs on the bootstrap current, first described in the context of tokamaks, is as follows [1]: in the island region, the radial transport of heat and particles is increased. This in turn leads to the 'flattening' of density and temperature profiles. Consequently, in the island region, the pressure gradient decreases along with the bootstrap current.

Since MIs have an intrinsically 3D geometry, a global code is necessary for their analysis. Moreover, many gyrokinetic codes rely on the nested magnetic flux surfaces which are absent when MIs are included. We present a technique that allows the inclusion of island effects while preserving the ideal-MHD flux surfaces [2].

This work presents the first simulations of the bootstrap current in stellarators in the presence of MIs. We also present results for other thermodynamic quantities of interest. We compare the results with simulations without island effects.

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Impurity concentration measurements in the Divertor plasma of W7-X

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During detachment in the optimized, superconducting stellarator Wendelstein (W7-X), line radiation by impurities is the major contributor to power exhaust. While carbon as intrinsic impurity provides the radiation in detachment experiments accessed via a plasma density ramp, also seeding of extrinsic impurities is a tool to reach a detached plasma state. In a future fusion reactor, carbon is not considered a viable wall material and the seeding with extrinsic impurities is consequently a reactor-relevant subject. How the needed impurity concentration scales with different plasma and machine parameters as well as the enrichment of the impurities are timely research questions [1].

In this contribution, the measurement of impurity concentrations using divertor spectroscopy is presented. The intensities of multiple spectral lines emitted by the same ion species are measured to estimate the electron density and temperature in the emitting plasma volume, which is determined by tomographic reconstruction. The impurity concentration is calculated using absolute intensity of the radiation, which strongly depends on the plasma parameters.

During the most recent campaign of W7-X spectroscopic data of nitrogen, neon and argon in detached discharges is acquired utilizing the divertor spectroscopy system.

A new spectral region is tested which allows the simultaneous measurement of neon and argon lines showing improved characteristics like density and temperature sensitivity as well as signal intensity of the measured lines.

We compare the measured temperatures to the equilibrium temperatures as predicted by collisional radiative models. Depending of the by tomography reconstructed radiation location, comparison to parameters obtained by other diagnostics is made as well.

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Divertor optimisation in stellarators using the EMC3-Lite code

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The commercial viability of magnetically confined fusion depends upon simultaneously optimising fusion devices with respect to multiple physical and engineering factors. In the stellarator community, sophisticated tools have been developed to optimise properties in the plasma core, whilst (optionally) minimising the cost and complexity of the surrounding magnetic coils [1, 2]. Such approaches have led to a wide range of experimental and theoretical high-performance stellarator designs [3, 4]. However, these optimisation algorithms rarely consider the heat loads on plasma-facing components (PFCs). Given the stringent material limits for these components and the sensitivity of heat distribution to the magnetic geometry, it is highly desirable that the plasma edge and PFCs are modeled and optimised for effectively.

The work presented here describes the modeling and design of plasma-facing components in an iterable, optimiser-friendly framework. We use EMC3-Lite [5], a 3D Monte-Carlo code, to simulate heat loads on PFCs using a reduced physical model; this allows heat loads to be estimated for a given configuration in the order of seconds. We first describe the generalisation of EMC3-Lite to simulate an arbitrary stellarator geometry, and present simulation results for the HSX stellarator [6] and a comparison with alternative methods of divertor modelling. The role of EMC3-Lite in divertor design for HSX is described, and extensions towards the simultaneous optimisation of magnetic geometry and PFCs are discussed.

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The influence of electron temperature fluctuations and shear on turbulent transport in the Scrape-Off Layer of Wendelstein 7-X

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The W7-X SOL is comprised of intrinsic magnetic islands which results in complex three-dimensional magnetic structure and plasma profiles. To assess perpendicular particle transport in the island divertor SOL, we utilize reciprocating probes on the MPM, which allow us to examine the dynamical evolution of the fluctuating temperature, potential and electric fields in the plasma pressure gradient of the island SOL. We report on the exploitation of the enhanced capabilities of a multi-pin probe head (*IPP-FLUC2*) used in latest experimental campaign (2022-2023).

In the interchange instability picture, the radial particle flux Γ_r emerges in the SOL as a consequence of fluctuating poloidal electric field E_{pol} with resulting radial velocity $\tilde{v}_r \sim \boldsymbol{E}_{\mathbf{pol}} \times \boldsymbol{B}$ in phase with density $\tilde{n}$ fluctuations. The average product $\Gamma_r = \tilde{n}\tilde{v}_r$ typically results in a final non-zero cross-field particle transport, if both, $\tilde{v}_r$ and $\tilde{n}$, have a non-zero phase relation.

Such particle transport was previously studied on W7-X [1] with the fluctuating poloidal electric field determined as a difference of floating potential of two poloidaly separated Langmuir probes $E_{pol} = V_{fl,upper} - V_{fl,lower} / d_{pin}$. However, this approach neglects the influence of the electron temperature fluctuations $\tilde{T}_e$. While $\tilde{T}_e$ appear to be mostly in phase with V_{fl} in exemplary measurement [2], indicating the $\tilde{V}_{fl} \approx \tilde{V}_{pl}$, the overall picture is not entirely clear. Hence, the new probe head additionally features Ball-pen probes, which can be used for direct plasma potential measurement. Thus the $\tilde{T}_e$ fluctuations can be included into the estimate of poloidal electric field and density. Moreover, the presence of ExB shear, induced by the magnetic islands outer separatrix, is verified with a Ball-pen probe plasma potential measurement against poloidal ExB shear flow velocity inferred from a time-delay analysis of fluctuations passing a poloidal probe array. The radial position of the magnetic shear layer is compared with the one calculated using a vacuum magnetic equilibrium reconstruction. The relative fluctuation level of measured probe current and potential is studied with respect to the radial distance from ExB shear layer. Scenarios with reversed magnetic field are used to identify the effects of plasma drifts on propagation velocities.

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Experimental validation of BEAMS3D and application to ASDEX Upgrade

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** See author list of U. Stroth et al., 2022 Nucl. Fusion 62, 042006*

In this work, we validate the Monte Carlo code BEAMS3D [1] against experimental data and apply it to simulate the effect of magnetic islands on fast ion confinement at ASDEX Upgrade (AUG).

We compare simulation results against NUBEAM and validate them against experimental Fast-Ion D-α (FIDA) spectroscopy measurements [2] using the FIDASIM code [3, 4] as synthetic diagnostic. The simulations are validated against FIDA data obtained during on- and off-axis neutral beam heating. Kinetic profiles are reconstructed from integrated data analysis [5] and detailed wall geometries are used as inputs for the simulation. The results show that the NUBEAM and BEAMS3D agree well with each other both in simulating the neutral beam deposition and fast ion distribution function. The two codes perform equally well, as their forward modelled spectra produced with FIDASIM using the distribution functions from both codes compare well with the measured FIDA spectra within the uncertainties.

We then present results analysing a neoclassical tearing mode in AUG with rotating and locked phases. The mode is included into the equilibrium field of the BEAMS3D simulation. Cases with and without the mode are compared to isolate the magnetic effect from the change of the kinetic profiles.

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Nonlinear MHD simulations of external kinks in classical $l = 2$ stellarators using JOREK

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Studying the nonlinear magnetohydrodynamics of stellarators using state of the art MHD codes can help to understand if linear MHD stability thresholds should be treated as operational limits for such devices. The nonlinear MHD code, JOREK, has been extended to study stellarators using a recently derived reduced MHD model. This presentation will outline recent results, using the code to model the nonlinear dynamics of external kink instabilities in classical stellarator geometries. Simulations are carried out for $l = 2$ classical stellarators, with different field periodicities and fractions of external rotational transform, ι_{ext}. At constant edge safety factor, it is shown that the normalised magnetic energy of the initial dynamics decreases with increasing ι_{ext}. In all cases, the external kink mode is shown to trigger internal MHD instabilities, leading to disruptive dynamics. The degree of plasma ergodisation is studied to understand whether the cage-like magnetic field imposed externally in stellarators can mitigate the subsequent loss in confinement compared to the tokamak case.

Dynamics of particles being injected by means of Laser blow-Off in Wendelstein 7-X

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Since Wendelstein 7-X (W7-X) was designed for long pulse operation, the control of the overall performance is important. The presence of impurities is one aspect that can significantly degrade the performance of a fusion device. Hence, the understanding and control of impurity transport is a major research task.

In order to investigate the impurity behavior, dedicated injections of non-intrinsic impurity ions by means of a Laser Blow-Off (LBO) system [1] were done in the most recent campaign OP2.1. The characterization of the injection itself is important for comprehensive transport analysis. The dynamics of the injected particles, which can be set by different laser operation schemes and depend on the coating properties, influence the usability of the injection for transport studies. Especially, the particle fraction as well as the angle and velocity distribution define the source function of injected impurities.

With a fast camera system, the emission of neutral and weak ionized impurity ions was measured parallel and perpendicular to the injection axis during the most recent campaign OP2.1. Therewith, individual fragments and particles can be tracked separately in two observation cones being perpendicular to each other. The high time resolution (between 12500 and 300000 frames/s) allows to distinguish between the fast atoms, slower clusters as well as fragments. Beside the dynamics of the injected particles, also the deposition position in the plasma region can be estimated. The impact of different materials, laser energy density as well as magnetic field configurations effects are investigated in detail and presented with this contribution.

[1] Th. Wegner et al., Rev. of Sci. Instr. **89**, 073505 (2018)

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Simulating the effect of core magnetic island on fast ion confinement in Wendelstein 7-X

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Simulations exploring the effect of core islands on fast ion confinement in Wendelstein 7-X (W7-X) are performed using the BEAMS3D code [1]. The presence of core magnetic islands is predicted to degrade confinement in fusion devices, and as such is often the focus of stellarator optimization. However, experience from the Large Helical Device suggests that the presence of a magnetic island can be suppressed through neoclassical effects. While W7-X leverages large edge islands and good flux surfaces for nominal operation, limiter configurations with the $n/m = 5/5$ island chain placed at mid radius are possible (figure 1). The size and phase of these islands can then be changed via the trim and control coils on W7-X allowing $n/m = 5/5, 2/2, 1/1$ chains to be explored. Recently the BEAMS3D code has been upgraded to allow both gyro-center and gyro-orbit simulations to be performed [2]. Additionally, an interface to the HINT2 code [3] has been developed allowing core islands and stochastic regions in simulations.

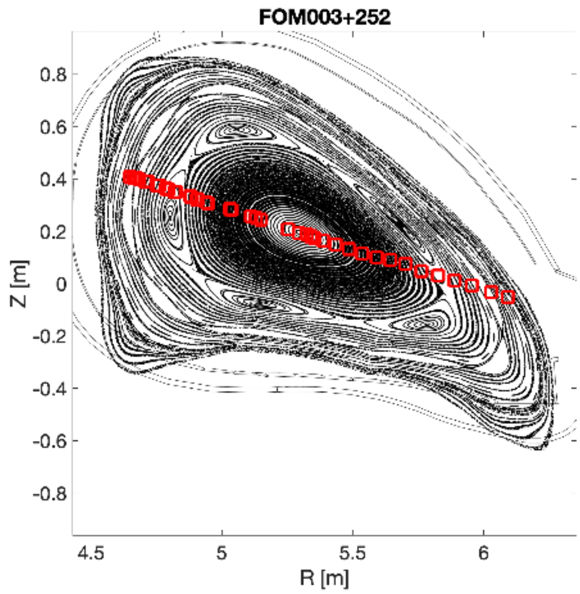

Figure 1: *Vacuum Poincaré plot of the W7-X core island configuration with islands at half radius. Squares depict the location of Thomson scattering volumes.*

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Configuration scan experiments in the latest experimental campaign of Wendelstein 7-X stellarator

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Wendelstein 7-X (W7-X) is an advanced stellarator, which uses the modular coil concept to realize magnetic configurations optimized for fusion-relevant plasma properties including MHD-equilibrium and -stability, small neoclassical transport at low collisionality, small bootstrap current and favorable fast particle confinement [1]. The machine went into operation in December 2015 at the Max-Planck-Institut für Plasmaphysik in Greifswald, Germany. The latest experimental campaign (OP2.1) was conducted from November 2022 to March 2023.

Configuration scans performed in the previous W7-X experimental phase (OP1.2b) between Standard and High iota magnetic configurations, revealed an unexpected increase of the plasma confinement time in the intermediate limiter configurations [2]. The confinement improvement was accompanied by MHD-activity, termed ILMs, observed by several diagnostics. Experiments performed in OP2.1 aimed to confirm observations from OP1.2b with a full set of diagnostics, complementing the scanned configuration space with new magnetic configurations. Power and density scans were conducted in one of the most promising of the intermediate configurations with improved confinement. In addition, a complementary scan in Standard-Low iota configuration space was performed. This contribution presents results observed in both – Standard-High iota and Standard-Low iota configuration scans.

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Particle transport in reduced turbulence NBI stellarator discharges

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In the search for high performance stellarator plasmas, the theoretical understanding and experimental verification of main ion heat and particle transport is essential. Wendelstein 7-X, the worlds largest stellarator experiment, was optimized to reduce the neoclassical particle losses and typical plasmas in W7-X are now dominated in the core by turbulent transport processes such as ITG and TEMs. Discharges with strongly peaked density profiles e.g. those with dominant NBI heating, exhibit significantly reduced turbulence levels. Exploitation of these improved performance scenarios will require the prediction and possibly control of the density profiles, for which a good understanding of the particle transport is critical.

The presented results investigate different transport regimes seen in NBI dominated plasmas. It is shown that the density profile evolution cannot be explained solely by the peaked NBI deposition profile but requires an abrupt change in particle transport between different regions of the plasma radius. By modeling the neutral beam particle deposition and computing the change of the electron density profile from time resolved Thomson data it is possible to compute the total experimental particle flux at each flux surface. When subtracting the neoclassical and classical flux one arrives at a measure of the experimental anomalous flux which is used in the presented analysis. The changes in particle transport are examined in detail over a number of different initial plasma conditions.

Heat flux calculation for water-cooled plasma-facing components in Wendelstein 7-X

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In Wendelstein 7-X (W7-X), power and particle exhaust is governed by the boundary helical magnetic island chains. These island chains are predominantly intersected by the 10 divertor plates [1], where 3-dimensional heat loads are deposited. To ensure safe operation, the surface temperatures of the divertor plates are constantly monitored by the 10 calibrated wide-angle infrared cameras [2].

In the first divertor campaign of W7-X, the inertially cooled test divertor units (TDUs) with divertor plates made of fine-grain graphite were installed. The perpendicular heat fluxes to the components were calculated using the 2D explicit heat diffusion solver THEODOR (THermal Energy Onto DivertOR) [3, 4, 5], given the measured time evolution of the surface temperature. In this campaign, all the TDUs are replaced with the water-cooled high-heat-flux (HHF) divertor [6], aiming for a steady-state operation under a maximum heat flux up to $10\,\mathrm{MW\,m^{-2}}$.

To calculate the deposited heat flux onto the water-cooled HHF divertor, further developments of the THEODOR code are required. Firstly, the calculation of the heat flux has been made per frame to enable the calculation from huge amounts of infrared images captured during the long-pulse operation of up to 30 minutes. Secondly, the code has to cope with the anisotropic heat conduction in the carbon-fiber composite (CFC), which is used as the top surface material for the HHF divertor. Thirdly, a significant cooling coefficient should be considered at the bottom bound of the calculation domain, in order to simulate heat removal from the cooling water. Finally, more materials may be allowed in the code to include not only the top surface but also the interlayer and the heat sink, which constraints the divertor upper thermal limit.

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Effect of magnetic islands on SOL plasma profiles and transport in W7-X

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The W7-X stellarator uses an island divertor, where the scrape-off layer (SOL) is formed by a chain of intrinsic magnetic islands. The islands separate the SOL plasma that interacts with the divertor targets from the main (*core*) plasma. Inside the islands, geometrically complex 3D transport processes take place:

- parallel transport along field lines to the target
- "true" poloidal transport via drifts
- "apparent" poloidal transport via parallel transport along long connection lengths (several 100m) on the magnetic islands' own flux surfaces
- radial transport via turbulence in the presence of pressure gradients

The interplay of these transport processes results in a 3D distribution of plasma conditions that already became apparent in the first operation phase of W7-X [1,2].

In this contribution, we present a selection of key results on the island SOL plasma from the recently started second W7-X operation phase. The role of island size and position for profile shapes, turbulent fluctuations, drifts, and modes is discussed.

The diagnostic focus is on reciprocating electric probes, where new features provide improved experimental insights: A set of two poloidally separated triple Langmuir probes provides T_e, n_e profiles at two different sections of the island simultaneously. A 2D poloidal-radial array of floating potential and ion saturation current probes sheds new light onto the propagation of turbulent events and the structure of (quasi-)periodic modes.

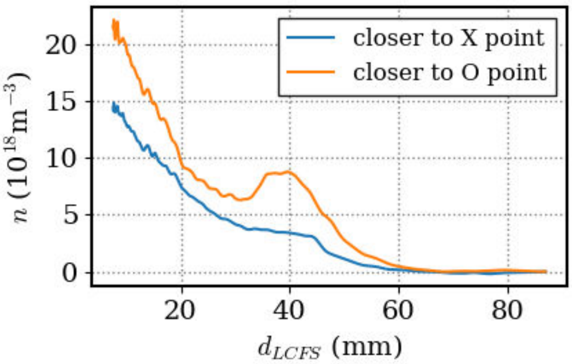

***Figure*: Two simultaneously taken density profiles across a magnetic island as a function of distance from the LCFS.**
Closer to the O point of the island, a distinct local density maximum is observed.

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Observation of Alfvénic modes correlated to the turbulence levels in the Wendelstein 7-X stellarator plasmas

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Investigations of Alfvén modes driven either by the thermal plasma or by turbulence are presented for the Wendelstein 7-X (W7-X) plasmas. We carried out studies of correlations be- tween Alfvén mode properties and plasma parameters, such as the plasma stored energy, and turbulent density fluctuations. Furthermore, we present correlations of mode activity with re- spect to different magnetic configurations, external heating systems (ECRH and/or NBI), pellet fuelling dedicated discharges and LBO impurity injection phases. A robust data collection of the dynamics of Alfvén modes was established with a newly developed tracking method. The method tracks the temporal dynamics of a frequency band in the magnetic fluctuations spec- trum. A strong correlation between the amplitude of the Alfvén modes and the turbulence levels at W7-X was found. The Alfvénic modes are often observed in plasmas without fast ions, hence a direct resonant fast-ion drive can be ruled out. However, in the 3D magnetic field of W7-X Alfvénic resonances are also present at low energies, allowing the potential of resonant drive by the bulk plasma. Simulations have been performed with the gyrokinetic EUTERPE [1] code for different thermal plasma profiles, but no instability could be found. This also points to the fact that the interaction of Alfvén modes and turbulence needs to be taken into account in the numerical studies in hopes of explaing the driving mechanisms of these observations.

Experimentally measured Shafranov shifts in Wendelstein 7-X

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The magnetic field design of the Wendelstein 7-X (W7-X) stellarator bases on the Helical Advanced Stellarator (Helias) concept. While keeping MHD stability (by forming a magnetic well) the Pfirsch-Schlüter current and in turn the Shafranov shift have been minimized. The modular coil system of W7-X allows to operate in a wide configuration space of magnetic field topologies. By adjusting the current ratios and polarities of the nonplanar and planar coils many magnetic field parameters can be varied, e.g. the iota profile, the mirror term and the shear. Since first operation in 2015 many of these operable magnetic field configurations have been used for experiments. With the currently available heating systems ECRH and NBI averaged plasma betas of $\langle\beta\rangle \leq 1\,\%$ have been achieved, resulting in measurable Shafranov shifts. The contribution concentrates on evaluations of the Shafranov shift experimentally determined from analysis of tomographic inversions of 2D soft X-ray measurements. The experimental results are compared to measurements of radial pressure profiles oftained from radial profile diagnostics. Consistency checks are performed via comparison between the experimentally determined Shafranov shifts and the results from the equilibrium reconstructions of the three-dimensional equilibrium code VMEC.

Performance evaluation of the W7-X island divertor for different island chains using EMC3-Eirene

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The W7-X island divertor can operate with the iota=5/6, 5/5, and 5/4 island chains with different island sizes and connection lengths. Here, an important question arises as to which one is best suited for exhausting the plasma and why, especially under detached conditions – the most likely operating regime in a low-shear stellarator reactor. While a full clarification of this question could be a long-term topic of the W7-X experimental program, here in this paper we present a preliminary numerical analysis of this issue using the EMC3-Eirene code in parallel with the ongoing experiments and data evaluation processes.

Focusing on geometric effects, we scanned the three island chains with otherwise identical code inputs, while leaving a more refined modeling to the next iteration step with experiments. Carbon is assumed as the only radiator. Particular attention is given to the cost of power removal via impurity line radiation, namely the impurity concentration at the SOL-core interface (core plasma contamination), the radiation fraction inside the confinement region (core plasma cooling), the degradation of recycling and the related downstream neutral pressure (particle exhaust). The simulation results show some general trends as the iota value is increased: a) the radiation becomes more concentrated around the X-points, b) for the same total amount of radiation, the carbon concentration at the last closed flux surface becomes lower - a positive effect, c) but with the drawback that more radiation takes place inside the confinement region.

In this paper, we interpret the numerical results and identify the most important ones for experimental comparison.

Alfvén Eigenmode dynamics during the recent operational phase at the Wendelstein 7-X stellarator

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The second operational phase (OP2) at Wendelstein 7-X (W7-X) in Greifswald, Germany, was conducted from November 2022 – March 2023. A major upgrade before the start of OP2 was the implementation of a fully water cooled high heat flux divertor, which in principle allows to operate high energy regimes for several minutes up to the envisaged half hour pulse. During the recent operational phase, OP2.1, a number of experiments were focused on investigations about the role of Alfvén Eigenmode (AE) activity in high power heating scenarios, which involve neutral beam injection and electron cyclotron resonance heating. The measurements of various fluctuation diagnostics (Mirnov coils, soft X-ray tomography, phase contrast imaging, electron cyclotron emission) are analyzed and closely compared to findings of past operational campaigns. Observations typically showed well pronounced broad band fluctuations in the frequency regimes 100-150kHz, 200-250kHz and 300-400kHz, which would roughly correspond to toroidally induced AE, elliptically induced AE and helically induced AE, respectively. Experimentally identified poloidal mode numbers were in the range of -5 to 5. One important aspect of this study is the driving mechanism of AE (specifically in the absence of fast ions) and their prospective impact on high performance experiments.

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

Impurity transport characterization using CXRS measurements and gas puff modulation in W7-X

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Understanding of the impurity transport in fusion plasmas is crucial to predict the impurity content in a future reactor as this will limit the accessible parameter space for a burning plasma due to dilution (low Z) and radiative losses (high Z). In the stellarator Wendelstein 7-X (W7-X), impurity transport in plasmas heated by electron cyclotron resonance heating (ECRH) are found to be dominated by anomalous diffusion [1, 2] due to neoclassical optimization of the W7-X magnetic field geometry [3].

To assess the impurity transport in the confined region of W7-X, charge exchange recombination spectroscopy (CXRS) [4] is used to derive radial impurity density profiles of individual ionization states. As steady state profiles of single charge states restrict the underlying impurity transport properties only loosely, gas puff modulation of impurities [5] is applied. This approach, novel to the impurity transport analysis in W7-X, introduces a periodic impurity source outside the last closed flux surface. From monitoring the local impurity density response in the confined region characterized by its amplitude and phase, local transport properties can be derived with higher precision.

In the current experimental campaign, the gas puff modulation scheme for impurity transport in W7-X for the fusion ash helium is being developed. By comparison of transport in different magnetic configurations as well as ECRH dominated plasmas of different power, a first parameter scan in its transport properties is performed, aiming to establish a CXRS based impurity transport analysis with high sensitivity even in steady state scenarios.

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Parametric Decay Into Ion Cyclotron Quasi-modes and Ion Bernstein Wave Sidebands During Helicon Experiments on DIII-D*

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High power helicon (whistler) waves at a frequency of 0.476 GHz have been launched on DIII-D with the goal of demonstrating efficient off-axis current generation. We have shown in past work [1, 2] that under typical experimental conditions strong parametric decay instability (PDI) is expected in the pedestal region that may scatter the incident helicon wave and compromise the expected current drive efficiency. The dominant driver of the PDI is the $E \times B$ and/or polarization drift velocity which can destabilize ion cyclotron quasi-modes and lower hybrid (or more importantly, high $k_{\perp}\rho_{ci}$ ion plasma or ion Bernstein) sideband waves. Using one-turn magnetic pickup loops located at both the low-field and high-field sides of the torus near the midplane, initial experimental results showed evidence of PDI corresponding to the cyclotron frequency and its harmonics at the outboard edge of the plasma [2]. Here we present numerical calculations of growth rates and frequencies and subsequently estimate convective thresholds and PDI saturation levels and compare them with experimental observations. While in past work we concentrated on studies of PDI with the electrostatic lower hybrid wave as the dominant sideband, in the present work we examine the more important case of $k_{\perp}^2\rho_{ci}^2 \gg 1$ at which the sideband waves are high-harmonic ion cyclotron waves (ion Bernstein waves with non-zero values of $k_{\parallel}$). This makes estimating the convective thresholds considerably more difficult than with lower hybrid wave sidebands in the warm (or unmagnetized) plasma approximation. However, this is the relevant regime for dominant PDI that might lead to pump depletion in the vicinity of the lower hybrid resonance. In addition, we will present calculations to show that in case of parasitic excitation of the slow lower hybrid wave in the plasma edge, the threshold for PDI can be considerably lower due to the dominant $E_{\parallel}$ driving term as opposed to the case considered above for pure helicon (whistler) wave excitation.

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Magnetic configuration dependence of turbulent core density fluctuations in Wendelstein 7-X

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The Wendelstein 7-X (W7-X) stellarator is optimized for reduced neoclassical transport and its confinement consequently dominated by turbulent transport [1, 2]. The phase contrast imaging (PCI) diagnostic [3, 4] measures line-integrated turbulent density fluctuations throughout the core of the plasma and is therefore an important tool to experimentally investigate turbulence. In previous experiments, the density fluctuation amplitude was observed to be lower in certain magnetic configurations, as seen in figure 1. The reason for this is not clear yet, especially since the trends do not match expectations based on mirror ratio (stabilizing) and flux compression (destabilizing). A better understanding of the influence of magnetic geometry on turbulence is necessary for the development of turbulence-optimized configurations.

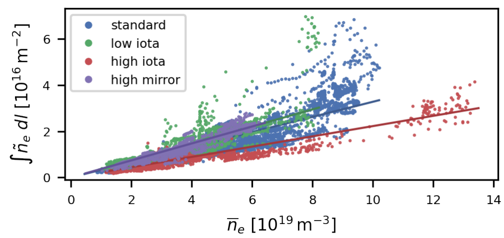

Figure 1: Line-integrated density fluctuation amplitudes versus line-averaged density in various magnetic configurations of W7-X.

This work presents new experimental data from the latest operation phase of W7-X, which provides an improved experimental characterisation enabled by surveys and dedicated experiments comparing turbulence in various magnetic configurations. Upgraded diagnostic capabilities enable a discrimination of fully line-integrated and core-focused measurements. With the help of gyrokinetic simulations, the influence of the magnetic geometry on turbulent fluctuations, and ultimately transport, is evaluated and related to the experimental findings.

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Access to Edge Transport Barriers in the SPARC Tokamak

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Power requirements for a high edge pedestal are examined for the SPARC tokamak, a medium scale (R=1.85m, a=0.57m) high field (B_T up to 12.2T) device being built to produce net energy from DT fusion [1]. L-H power thresholds P_{L-H} have been assessed using established scaling laws [3—5], indicating a pathway to accessing H-mode in DT plasmas in the Primary Reference Discharge (PRD) with full field [2]. Additionally, available auxiliary heating (25MW of ICRF) should allow access to DD H-modes at 8T. Reduced field H-modes can provide a first examination of H-mode behavior on SPARC, in a regime with reduced pedestal pressure and having smaller edge localized mode (ELM) energy than the PRD. This presents a scenario for gaining operational experience in H-mode and exploration of ELM mitigation techniques, prior to high fusion gain campaigns. Projections of I-mode access have also been made, and this regime should be accessible in single null plasmas with B×∇B directed away from the active X-point, offering an opportunity to operate with elevated energy confinement but avoiding large ELMs altogether. I-mode thresholds are less well characterized than those for H-mode, but experience on existing devices [6—9] holds promise for I-mode access at SPARC parameters, primarily due to the observation that L-I power thresholds scale less strongly with B_T than P_{L-H}. Power threshold projections for the I-mode regime with B×∇B opposite the X-point are comparable to P_{L-H} with B×∇B toward the X-point, with I-H power thresholds expected to be higher still. Initial projections of I-mode pedestals from existing devices to SPARC show promise for utilizing the regime to achieve high energy confinement without large ELMs.

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A High Resolution Neutron Spectrometer for Burning Plasma Studies on SPARC

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This poster presents the design for the high-resolution neutron spectrometer to be installed on the SPARC tokamak, a compact high field tokamak under construction in Devens, MA. Neutron spectroscopy provides unique insight into the kinetic physics of fusion plasmas and is particularly well suited to studying alpha heating and the transition to the burning plasma regime. The neutron spectrum can be directly related to the alpha particle birth spectrum since there is a one to one kinematic relationship between two body collision products. In addition, the precise form of the spectrum gives information about the fuel ion distribution functions, and can therefore be used to learn about the mechanism of alpha heating. The spectrometer is of the Magnetic Proton Recoil design, inspired by the system used at JET[1]. Collimated neutrons elastically scatter protons out of a polyethylene wafer and into an ion optical system where they are focused by a pair of multipoles and a large dipole magnet disperses the protons according to their momentum. The spectrum of incident neutrons can then be determined from the distribution of proton counts along an array of detectors. The spectrometer has been optimized using COSY[2], an ion optics code, and is designed to have a variable energy acceptance ranging from 1-20MeV in order to measure fusion neutron spectra in both deuterium and deuterium-tritium plasmas. This enables investigations of fuel ratio and tritium burn-up during low-tritium concentration commissioning campaigns, and detailed kinetic studies of burning plasmas during high performance discharges. The spectrometer is designed to target an energy resolution better than 200keV when centered on the 14MeV peak and a time resolution less than 200ms (energy confinement time on SPARC is 700ms) during high power shots, enabling observation of the evolution of the fusion power and production spectra over the course of a discharge.

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First Results of Gas-Puff Imaging of Edge Turbulence in the W7-X Stellarator

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Neoclassical and turbulent transport in stellarators contribute to the challenge of developing an economically attractive reactor concept. In order to study turbulent transport in the scrape-off layer (SOL) in and around the magnetic islands that are key to the divertor concept employed on the W7-X stellarator [1], a gas-puff imaging (GPI) diagnostic [2] has been operated for the first time. In this work, we present initial observations from the OP2.1 campaign. The GPI system consists of two converging-diverging nozzles that emit a supersonic highly-collimated cloud of hydrogen or helium gas, which minimally perturbs the main plasma, and when excited by the local plasma electrons reveals turbulent plasma fluctuations in a 4.5$\times$7.8 cm area in the magnetic island region, imaged using an 8$\times$16 array of avalanche photodiodes. GPI recordings with a frame rate of 2 MHz show coherent structures 1-2 cm in diameter in the direction perpendicular to the magnetic field. These structures are most probably filaments when viewed in three dimensions [3], and are observed to move poloidally up to $\sim$5 km/s, with a shear layer near the last closed flux surface. The radial profiles of the fluctuations' poloidal phase velocities are determined by frequency-wavenumber spectra. The profiles are compared in various configurations of the magnetic field and at various levels of density and heating power. The poloidal motion of fluctuations reverses direction when the toroidal magnetic field is reversed, indicating that this motion is likely due to $E_r \times B$, and the magnitudes of low- and high-frequency fluctuations are impacted by plasma detachment. Overall, GPI successfully delivers detailed 2D recordings of turbulence in the SOL and magnetic island region of W7-X, and is expected to offer further insights into the dynamics of SOL transport in W7-X.

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High Field Side Scrape-off Layer Density Profile Characterization and Implications for DIII-D High Field Side LHCD Experiment

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A high-field side (HFS) scrape-off layer (SOL) reflectometer has been designed and installed on DIII-D to characterize the local density profile, providing necessary measurements for the upcoming high-field side lower hybrid current drive (HFS LHCD) system. The reflectometer currently operates in the O-Mode polarization in the 6-19 GHz range, corresponding to a density profile range of $4.5 \times 10^{17} - 4.5 \times 10^{18}$ m^{-3}. HFS LHCD is a potential tool for efficient off axis current drive in present and future fusion devices. The DIII-D HFS LHCD experiment provides an excellent opportunity to investigate the expected benefits of HFS launch and to validate HFS RF wave physics and LHCD physics models. Furthermore, HFS launch is expected to mitigate coupling and plasma material interaction issues due to a quiescent HFS SOL [1]. From simulations, off-axis current at r/a~0.6-0.8 with peak driven current density of up to 0.4 MA/m^2 and 0.4 MA/MW coupled is achievable with $n_{\parallel}$~2.7 at 4.6 GHz. A novel compact launcher utilizing a traveling wave, 4-way splitter in combination with a multi-junction minimizes electric fields in the coupler allows for coupling power over a wide range of plasma parameters [2]. One of the critical challenges is sensitivity of coupling to variations of the SOL density profile. Prior to the coupler installation, HFS SOL reflectometer measurements during scans of the inner gap at constant line-averaged plasma density showed the HFS SOL profile expanding and contracting in phase with the inner gap for lower single-null plasma topologies. For double-null and near double-null topologies, the measured plasma density was significantly lower than the lower single-null configuration. Commissioning of the klystron-based transmitter has begun and installation of the in-vessel waveguide and coupler is expected in 2023. The latest HFS reflectometer results and HFS LHCD system status will be presented.

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Tomographic reconstructions of perturbative events in Wendelstein 7-X stellarator

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Impurity transport is an important field of research in stellarators since the neoclassical transport can lead to accumulation in the plasma core, thereby limiting the operational space of the device. Wendelstein 7-X stellarator is fitted with a high resolution soft-X-ray tomography system, which is routinely operated since the last operational phase. The tomographic inversion of the radiation distribution in a poloidal plane is calculated from more than 330 channels through the plasma (one camera and a small set of single diodes are defunctional). The data is typically recorded with a time resolution of 1 MHz, but the bandwidth of the electronics (comprising of in-vessel preamplifiers, twisted pair cables with lengths of 30 - 60 m, Nyquist filter boards and input impedances of the ADC boards in a distant rack) limits the bandwidth to f_{3dB}<100 kHz. This is a very good time resolution to study the dynamics of the plasma reacting on external perturbations like injection of impurities by laser blow off diagnostics or impurity pellets.

Time series of tomographic images form the basis of the data set. The observed dynamics is often complex. By means of singular value decomposition methods it is possible to separate relevant dynamics within the poloidal plane of the tomographic reconstruction and resolve poloidal modes. It is found that the plasma response to localized perturbations often displays a rotating m=1 mode structure as final state. In experiments in reversed main magnetic field, the rotation direction is found to be reversed for certain radial deposition locations. The aim of this contribution is to characterize the plasma response for different perturbation sources.

Initial results of the upgraded Doppler reflectometry systems at Wendelstein 7-X

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For the recent experimental campaign OP2.1 of Wendelstein 7-X the Doppler reflectometry (DR) systems have been upgraded substantially. Additional reflectometer systems allow to investigate the evolution of the radial correlation length of the ambient turbulence. The correlation technique further improves the detection of coherent low-frequency fluctuations with small amplitudes. Two reflectometer systems at different toroidal positions have been equipped with steerable plasma-facing mirrors to measure flow asymmetries caused by potential variations on the flux surface [1] . By changing the angle of the incident microwave beam the wavenumber spectrum of density fluctuations is measured. In addition, poloidal asymmetries of the turbulence amplitude can be estimated, which are predicted from gyrokinetic simulations [2]. As the poloidal localization of the microturbulence is directly related to the radial electric field, the versatile ECRH and NBI heating systems at W7-X offer excellent prospects to investigate the behavior in mixed electron/ion-root conditions with strong central electron heating and pure ion-root conditions. Supplementary, with simultaneous measurement at two different toroidal positions low-frequency zonal flows can be detected. As the latter are driven nonlinearly by microturbulence, the saturation level of drift-wave turbulence is thought to be directly linked to the zonal-flow damping. The interaction can be analyzed in detail because both amplitudes, i.e. microturbulence and zonal-flow, are measured simultaneously.
This contribution gives an overview of the measurement capabilities of the upgraded DR systems and presents first results from the recent experimental campaign.

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X-ray spectrometers based on superconducting transition edge sensors for magnetically confined plasmas

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High-resolution X-ray spectroscopy is a key diagnostic tool for measuring the concentrations of multiple impurity high-Z ion species in the hot plasma core of future fusion reactors.

Cryogenic X-ray instruments based on superconducting transition edge sensors (TESs) microcalorimeters are non-dispersive spectrometers, which provide an exquisite resolving power ($E/\Delta E > 2000$) over a wideband energy range, from few eV up to 20 keV or more, along with almost 100% quantum efficiency [1]. The detectors are fabricated in large arrays with high filling factor and relatively large collecting area, providing imaging capability or high countrate potential when no imaging is required. TES based calorimeters have been originally developed for astrophysics research in future X-ray space observatories. Nowadays, they have reached a technological maturity level such that they are as well employed at accelerator beamlines, synchrotron facilities and laboratory plasmas for a wide range of applications.

At SRON we have recently demonstrated the simultaneous readout of about 71 pixels from a 32×32 pixels array of TES microcalorimeters optimized for astrophysics applications. We achieved a combined energy resolution of $\sim 2.2\,\mathrm{eV}$ at 6 keV using two channels of our frequency domain multiplexing (FDM) read-out. This is a milestone demonstration for FDM that paves the road to develop a full instrument with thousands of pixels active.

In this paper, we will discuss the potential application of our X-ray spectrometer in nuclear fusion experiments. Thanks to its high sensitivity and collecting efficiency, a TES spectrometer could provide fast high resolution spectra even with a reduced line-of-sight and when placed far away from the plasma. We have adapted the end-to-end simulator originally developed for the X-ray Integral Field Unit (XIFU) of the ESA Athena mission to model the TES detectors response to ITER-like plasma photons flux. We have study few diagnostic scenarios described in the literature and compared the TES performance with the existing baselined diagnostic instruments such as the SDD based Pulse Height Analysis system and the X-ray crystal spectrometers. The preliminary results will be reported in this paper.

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Orbit sensitivity and tomography based on projected velocities in constants-of-motion space

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Tomographic reconstruction of fast-ion distribution functions in fusion plasma devices has proven to be useful for both the theoretical understanding of the behaviour of fast-ions, as well as in the practical utilisation of diagnostics. In general, a diagnostic signal is related to the fast ion distribution by a so-called weight function, which quantifies the phase-space sensitivity of the given diagnostic.

In this work, we have numerically calculated fast-ion orbit weight functions in constants-of-motion coordinates, using the projected velocities of fast ions along the lines of sight as proxy for several spectral diagnostics. This allows us to quickly and easily test new inversion methods for tomographic reconstruction. In addition to this, calculating the orbit weight functions in the constants-of-motion coordinates, the energy E, the toroidal canonical angular momentum P_ϕ and the magnetic moment μ, provides a direct link to the stability analysis often done in constants-of-motion space.

Here we provide a detailed explanation of the sensitivity patterns seen in the weight functions given different viewing angles and measurement volumes. We will illustrate our methods with examples of fast-ion systems from MAST and COMPASS Upgrade.

Physics basis of a Collective Thomson Scattering diagnostic for DEMO

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The harsh environment around the DEMO plasma, and the space restrictions and need to maximize the first-wall area used for T breeding, set limitations on the number and type of diagnostics to be installed. This will also focus the efforts on diagnostics needed for control of the DEMO plasma. The robustness and versatility [1] of a microwave-based Collective Thomson Scattering (CTS) diagnostic make it worthwhile to investigate the potential of a DEMO CTS diagnostic.

The CTS diagnostic for ITER, based on a dedicated 1 MW 60 GHz (sub-EC fundamental resonance) gyrotron has recently passed the Final Design Review [2]. The ITER CTS diagnostic will focus on measurements of fast ion dynamics in the burning ITER plasma [3]. The development was founded on experience from both TEXTOR and ASDEX Upgrade.

The feasibility study for a CTS diagnostic for DEMO is in the initial phase and builds on the experience of the past experiments and the development of the ITER CTS system. The original target was to use an ECRH gyrotron beam as the probing source beam, with the receiving quasi-optical system being a dedicated CTS setup. Based on raytracing calculations including signal-to-noise estimates, we here show that such a setup is not viable and present preliminary studies of alternative solutions, including a first assessment of which plasma parameters that can be determined.

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On implementing calculations of parametric decay instabilities into a ray tracer for microwave beam planing in magnetically confined plasmas

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A popular method for heating and current drive in magnetically confined fusion plasmas are the microwave based electron cyclotron (EC) resonance heating (ECRH) and EC current drive (ECCD) schemes. Although in general considered to interact only linearly with the plasma except in the immediate vicinity of the harmonics of the EC resonances, there are conditions and regions of the plasma which cause nonlinear effects to become important. Under those conditions, unstable three-wave interactions known as parametric decay instabilities (PDIs) can cause anomalous absorption to occur in unintended regions of the plasma, in some cases leading to a deterioration of ECRH and ECCD efficiencies. However, making estimates for the impact of PDIs is currently not an available feature of beam planning tools like ray tracers and the literature is often either overwhelming or tailored to specific scenarios.

The PDIs are of particular importance for example in high beta spherical tokamaks like MAST upgrade, where there is an interest in exploring a more advanced mode coupling scheme known as O-X-B[1]. This scheme couples an injected O-mode to an electrostatic electron Bernstein wave (EBW). The EBWs in principle have no high density cutoff and there are indications that the EBWs can drive current efficiently[2]. But the O-X-B scheme is also associated with PDIs[3] and it is not well explored what the impact of PDIs would be on current drive. A very different motivation to factor in PDI calculations into beam planning comes from the fact that EC waves may interact with ion waves through PDIs, and there has been some interest to explore if nonlinear wave interactions may allow for ion heating schemes using EC waves[4].

In this contribution, we discuss strategies to implement PDI calculations into ray tracers to allow for beam planning to take PDIs into account. We go over ways of efficiently solving PDI selection rules without resorting to limiting dispersion relations. We also look into how to avoid diverging behavior when describing wave amplification near beam turning points.

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Radially resolved thermal and fast-ion dynamics with collective Thomson scattering at ASDEX Upgrade

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For magnetically confined plasmas, fast ions and their behavior will play a key role in the performance of reactor-grade machines. To monitor their dynamics, Collective Thomson Scattering (CTS) has been chosen as a primary fast-ion diagnostic in ITER for diagnosing fusion-born alpha particles across their full energy range [1]. In current machines such as ASDEX Upgrade (AUG), various plasma properties can be inferred with CTS [2], providing a reliable tool to study thermal- and fast-ion transport in preparation for ITER operation. However, despite this diagnostic's versatility, CTS at AUG is usually confined to a single measurement volume, thus limiting its use in obtaining spatially resolved measurements.

Here we present the first highly radially-resolved CTS measurements at AUG, obtained by repeatedly sweeping a single measurement volume from the plasma core to mid-radius ($\rho \in [0.1; 0.7]$) for a sweep duration of 0.65 s. This results in 70 measurement locations, in which the fast-ion velocity distribution, ion temperature and rotation velocity were measured with CTS, in a moderate-density ($n_e \approx 6 \times 10^{19}$ m^{-3}), MHD-quiescent, H-mode discharge, with both on- and off-axis neutral beam (NBI) deposition. The plasma conditions (notably magnetic equilibrium, plasma pressure and stored energy) being remarkably stable across many confinement times allow the inference of thermal- and fast-ion radial profiles, and detailed comparison to other diagnostics. Thus, neoclassical predictions can be confronted with the inferred ion transport in real- and velocity-space.

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Reconstruction of Spatial Distribution of Visible Light in Spherical Tokamak Device QUEST Considering Reflected Light

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One of the conditions to achieve H mode is closely related to particle recycling on boundary plasmas[1]. Since the boundary plasmas contain more neutral particles and emit more visible light than the core plasmas, spatial distribution of the light should be a key to analyze the particle recycling[1]. Therefore, it is important to establish a method to reconstruct an accurate distribution of light considering reflected light in a device. The objective of this study is to reconstruct distribution of light on poloidal cross section from a camera image of plasma discharge in spherical tokamak device QUEST owned by Kyusyu university.

By spatially discretizing light source, radiant flux entering each pixel of a camera can be expressed as matrix product of a ray transfer matrix (RTM) and the discretized light source. The spatial distribution of light can be obtained by solving the linear equation about the light source[2]. Since plasmas in a tokamak device can be regarded as axisymmetric, the space is split on $R-Z$ plane in cylindrical coordinates, and in each small toroidal space, emissivity of the light is constant. The equation is solved with Tikhonov regularization and Phillips regularization where the former method is like L2 regularization and the latter method smooths the distribution.

The reconstruction method was applied to a simulated image and a camera image. The reconstructed distribution from the simulation image are close to assumed distribution. On the other hand, the reconstruction from the camera image failed. The distribution with Phillips regularization was over smoothed while the regularization norm with Tikhonov regularization couldn't be reduced. For more accurate reconstruction with regularization, it is necessary to develop and explore methods which doesn't over-smooth the distribution nor generate noise.

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Analysis and prediction of the plasma instabilities using NLP techniques

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Achieving and maintaining the conditions necessary for nuclear fusion is a complex and challenging task. One of the key challenges is the suppression of plasma collapse and disruption. Regarding the respective issues of plasma vertical displacement and radiation collapse related to plasma disruptions, we adopt Bidirectional Encoder Representations from Transformers (BERT) based on Natural Language Processing (NLP) models in order to investigate correlations of observed values and controlled variables, and predict the plasma instabilities. BERT is a powerful deep learning model for text classification and answering. A key aspect of BERT can process input sequence data in both forward and backward directions. It is distinct from traditional unidirectional language models, which only consider the context to the left of a token when making predictions. It makes complex sequence structures tractable by improving contextual understanding and performance on downstream NLP tasks. Transfer learning is a machine learning technique where a pre-trained model, such as BERT, is used as a starting point for a new task, enabling the model to build upon its existing knowledge and reduce the amount of data and resources needed for training. The objective of this study is to identify the precursors and correlations of the observed and controlled parameters, and to forecast plasma instabilities within the near future, with a focus on predicting 0.1 seconds ahead. To achieve this goal, we used measured data of Kyushu University Experiment with Steady-state Spherical Tokamak (QUEST) at three different points in time whose interval is 0.01 seconds. The relationships between the parameters related to radiation collapse and plasma vertical displacement were analysed, and we can accurately predict the radiation collapse and plasma vertical displacement. This result serves as the basis for developing a predictive model that is capable of forecasting the plasma instabilities with high accuracy, up to 0.1 seconds into the future. We can also interpret the precursors and correlations of the parameters using BERT.

Outermost magnetic surface identification by Gaussian process regression

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The shape and outermost magnetic surface of a fusion plasma is one of the important indicators to determine the equilibrium configuration of the plasma. In our small tokamak device PHiX, which has an iron core, the filament current approximation method is used to calculate the outermost magnetic surface during operation by assuming that the plasma is composed of several line currents and calculating the magnetic surface from the magnetic flux produced by the filament currents. However, this method is difficult to apply in the presence of magnetic materials. In this study, we propose a new method of magnetic surface reconstruction using Gaussian process regression as an alternative to the filament current approximation method, which is an existing method of magnetic surface reconstruction.

In this study, the equilibrium solution without an iron core was first obtained numerically, and then Gaussian process regression was applied to the numerical solution to obtain the outermost magnetic surfaces. The outermost magnetic surface was identified with sufficient accuracy even when only the values at the magnetic flux loop position installed in PHiX were used as the data for the regression.

Next, a simplified model of the tokamak geometry was created by COMSOL Multiphysics, a finite element method software. The magnetic structure in this model is the iron core, but in PHiX, the iron core is placed inside the poloidal field coil. Since the equilibrium configuration cannot be obtained with this model, the coil current and plasma current were given based on the experimental data, and the resulting calculated data were used as the measured data for regression. The outermost magnetic surface obtained only from the flux loop position data installed in the actual device did not agree with the magnetic surface obtained by the finite element method, but good results were obtained by increasing the number of measurement points.

Non-axisymmetric Equilibrium Analysis of Tokamak Plasmas with Saddle Coils by Multi-layers Method

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By applying a non-axisymmetric magnetic field to a conventional tokamak, we have proposed a configuration with a longitudinal cross sectional with no vertical positional instability. Even though this applied field has a value of zero when averaged over the toroidal direction, its effectiveness in improving positional stability has been demonstrated experimentally[1]. The goal of this study is to obtain non-axisymmetric equilibria with separatrix subject to the condition of magnetic energy minima including the vacuum region and conductors with finite resistivity.

Under the condition of minimal magnetic energy, including the vacuum region, we obtain an equilibrium with this non-axisymmetric component and also assess the stability of the position and shape. A stable equilibrium plasma configuration can be achieved by minimizing the magnetic energy. This method is the basis of VMEC, the standard program for determining helical eqiuilibria. VMEC, on the other hand, uses magnetic coordinates, so it cannot be used in the presence of a seperatrix. Alternatively, the equilibrium coordination of a system comprising a current source may be achieved under the minimum free energy condition by defining the free energy to include the energy provided by the current source of energy[2]. The free energy of a line current system is given by

$$U = \frac{1}{2} \sum_{\psi_i = \text{const.}} \psi_i I_i - \frac{1}{2} \sum_{I_j = \text{const.}} \psi_j I_j \tag{1}$$

where ψ_i, I_i are the linkage flux and current of the ith line current. The first term represents the energy in the plasma, the vacuum vessel, and other parts that are not connected to the energy source. While the second term represents the contribution of the coil to which the feeder is connected. The magnetic flux ψ_i and current I_i are related by

$$\psi_i = \sum_j M_{ij} I_j \tag{2}$$

where M_{ij} is inductance matrix. Because M_{ij} is the orbital position functional of the line current, the condition of minimum free energy yields the stable equilibrium. We show computational results for the case in which the plasma is simulated by a line current.

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FBEE: an efficient and flexible free boundary dynamic control-oriented equilibrium solver

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A new free boundary equilibrium evolving code (FBEE) dedicated to AI-assisted plasma control in a tokamak is developed in the MATLAB environment. FBEE self-consistently solves the dynamic system of plasma coupled with surrounding passive and positive conductors. The plasma is described with the Grad-Shafranov equation for the radial force balance and the 0D current diffusion equation for the current evolution. The conductors are constrained with circuit equations. The code takes as input the controller's actions on the coils' voltages and then gives as output the equilibrium at the next time point based on the previous one. In the numerical implementation, the system is converted into a root-finding problem solved by a Newton-like method. And much effort has been made to improve the efficiency. Firstly, instead of intensive computation of explicit Jacobian, we define a MATLAB direction gradient function with a finite difference approximation as the input of the generalized minimum residual (GMRES) algorithm to update the solution. And when evaluating the gradient function in one iteration, the residual of the current solution is needed to be updated only once. This approach is much more efficient while preserving the Newton algorithm's stability property. Secondly, A suitable preconditioner, the inverse of the Jacobian of the problem at the initial time point, is used in GMRES to speed up the convergence. Thirdly, the vectorization strategy is used extensively since this is much faster than loops in MATLAB. After that, a typical calculation of one frame needs 5~8 iterations under the convergence criterion of 1e-6 error. And this costs about 5~10 s on a personal computer with a CPU of i7-12700KF. Moreover, since this is a root-finding problem, other constraints, such as poloidal beta and internal inductance, can easily be included. Finally, FBEE, which serves as a fast and flexible physics simulator, along with external magnetic[1] signals, can support subsequent neural network training to learn the strategy of control.

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Study of core-localized bursting Alfvén instabilities driven by energetic electrons during EAST Ohmic discharges

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A series of core-localized bursting high-frequency (400 kHz ~ 1MHz) perturbations has been observed during EAST ohmic discharges (Figure 1), especially with low toroidal field and low electron density. The perturbations are regarded as Alfvén eigenmodes because the frequencies of modes are proportion to $B_t/\sqrt{n_e}$, which satisfy the Alfvén scaling. The toroidal numbers of the modes are identified as 2 ~ 4 by the magnetic coil array and they propagate in the ion diamagnetic drift direction. The multichannel Doppler backscatter system measurement indicates that the modes locate in the core region of the plasma ($\rho_{tor} = 0.2{\sim}0.4$). There are three distinctive characteristics of the Alfvén instabilities, which can be summarised as bursting, chirping and multi-branch coexisting. The modes are bursting rather than continuous pattern, and the burst process is influenced by the sawtooth events. When the sawtooth collapse occurs, the modes disappear, and then reappear as the plasma core temperature gradually recovers. This process also confirms that the modes are core-localized. The frequencies of the instabilities are always chirping at each burst period. Some branches chirp downwards, while other branch chirps upwards at the same time, implying nonlinear interactions between wave and particles. The modes might be ellipticity-induced Alfvén eigenmodes (EAE) because the frequencies are around the EAE gap of the Alfvén continuum. We speculate that these Alfvén instabilities are driven by barely trapped or passing energetic electrons under such discharge conditions, and the specific simulation works are ongoing. This will contribute to a better understanding of the physical mechanisms of the core-localized Alfvén instability driven by energetic particles.

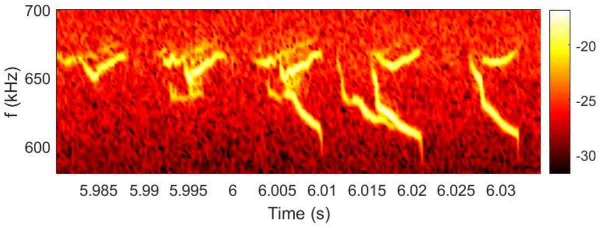

Figure 1. The frequency spectrum of the Alfvén instabilities.

Recent advances in energetic-electron driven Alfvén instabilities in the EAST tokamak

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Three different types of Alfvén instability driven unstable by energetic electrons have been found in the EAST low-density ohmic discharges. The *n*=1 toroidal Alfvén eigenmodes (TAE) in the 100-300 kHz range are observed. The mode frequencies are consistent with a precession drift resonance condition with barely trapped/circulating energetic-electron energies in the range 180-230 keV, in agreement with hard X-ray photon measurements. Nonlinear simulation using HMGC-code suggests that the phase-space resonance structure plays an important role on the eventual saturation amplitude, supporting that low-n TAEs are prevalent in the experiment. Besides, nonlinear mode couplings between multiple TAEs and geodesic acoustic mode (GAM) are conclusively identified. GAM is strongly driven due to the synergy effects of multiple TAE pairs with their frequency difference being comparable to GAM frequency.

A series of core-localized bursting high-frequency (400-1000 kHz) instabilities has been detected, especially with low toroidal field (B_t <1.8 T). The mode is identified as ellipticity-induced Alfvén eigenmodes (EAE) and the toroidal mode number is 2-4. Rapid frequency chirping indicates strong nonlinear interaction between wave and energetic electrons. Besides, the bursting modes totally disappears when the sawtooth collapses, suggesting that there is a resonant interaction at low order rational q values.

The *n*=1 beta-induced Alfvén eigenmodes (BAE) in the low frequency range from 10 to 25 kHz, are found to be unstable when the electron density decreases to less than 0.6×10^{19} m^{-3}. By decreasing electron density or increasing plasma current, the resistive plasma current is replaced by that carried by the REs. Then more branches of unstable BAEs are simultaneously observed, indicating that BAEs depend sensitively on the plasma beta contributed from REs.

Characterization of the filamentary energy transport to the first wall components in high density small ELM regimes in ASDEX Upgrade

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For the realization of a future fusion reactor, large Type-I ELMs have to be avoided to prevent excessive erosion or permanent damage of the divertor or the first wall components. A suitable operating scenario must fulfill several properties, in particular high plasma density, both in the core and at the separatrix, high radiative fraction and simultaneous absence (or at least surpression) of large Type-I ELMs. The so-called *'Quasi-Continuous-Exhaust'* (QCE) regime [1] may satisfy these requirements for future machines. As a drawback, such a regime is generally accompanied by a significant radial filamentary transport potentially increasing the heat flux deposited on the first wall. Thus the heat loads on the non-divertor components is studied on the ASDEX-Upgrade tokamak by means of the cooling water calorimetry [2] and of probes (BPP, RFA) operating close to the limiter surface in a dedicated set of discharges in order to investigate the properties and consequences of the filamentary energy transport $q_{\mathrm{r,fil}}^{\mathrm{total}}$.

A set of discharges with constant heating power, long flattop phases and heating schemes combining NBI+ECRH or NBI only have been executed using a highly shaped, QCE-typical, magnetic geometry. This database considers scans in safety factor q exploiting different B_{tor}-values and in separatrix density covering $n_{\mathrm{sep}}/n_{\mathrm{Greenwald}}$ between 0.2-0.6. At lowest density, being Type-I ELMing, a fraction of 6% of calorimetrically captured energy at the first wall is found. For the highest fuelling case, being in QCE, up to 16% of the energy at the first wall can be found. This increase of the first wall heat loads follows linearly the turbulence control parameter α_{t} [3]. Probe measurements indicate that the key mechanism increasing the energy transport to the first wall is an increase of the filamentary particle flux Γ_{fil}, caused primarily by the increase of the packing fraction f_{fil} and the blob density $n_{\mathrm{e,fil}}$ [4]. The electron and ion temperature $T_{\mathrm{e}}/T_{\mathrm{i}}$ measured close to the limiter surface remain at high values in QCE. Both, the energy found at the first wall and $q_{\mathrm{r,fil}}^{\mathrm{total}}$ deduced from the probe measurements reaches a magnitude relevant to be considered for future fusion reactors.

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Comparison of the approaches to the solution of the outer Magneto-Static-Problem in free-boundary MHD solvers

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The solution of free-boundary MHD problems, both static and dynamic, via Finite Element Methods requires the correct set up of the electro-magnetic boundary conditions at the boundary of the computational domain [1]. A convenient formulation of the problem reduces this general task to the problem of determining the magnetic field tangent to the boundary as a function of the magnetic vector potential tangent to the boundary itself, plus all the external currents. In the framework of extending the free-boundary capabilities of the JOREK code [2, 3], via its coupling with CARIDDI [4], we compare here three different implementations of the ideal Dirichlet-to-Neumann map in absence of external currents, *i.e.* three possible ways of computing the relation $A_{tan,pl} \rightarrow B_{tan,pl}$. The first implementation (a) is based on the virtual casing principle: the JOREK boundary is discretized via 3D hexahedral elements and the equivalent current to the plasma is represented via standard CARIDDI edge basis functions [5]. In solution (b) the equivalent current to the plasma is decomposed in toroidal harmonics, as for JOREK primary variables, allowing not to discretize toroidally the JOREK computational boundary. Finally, last solution (c) is based on a direct Boundary Element approach, where the singularity is solved as suggested in [6]. The latest formulation allows to stay completely within the JOREK finite element space. The accuracy of the three approaches is compared first against assigned current distributions for which we have analytical solutions. Later, we compare the free-boundary equilibria obtained via the different maps and we sketch the pros and cons of the different strategies on the general coupling scheme.

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Evaluation of DTT NBI energetic particle confinement and prompt-losses through the constant of motion phase space

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The Divertor Tokamak Test (DTT) [1] is a fusion experimental device under construction in Frascati (IT). DTT was proposed to investigate alternative divertor configurations to tackle the power exhaust problem in view of ITER operation and DEMO design. DTT will be equipped with a Neutral Beam Injection (NBI) system characterized by one of the highest injection energies foreseen before ITER (E_{NBI} = 510 keV, P_{NBI} = 10 MW). NBI Energetic Particle (EP) confinement is crucial both for plasma performances and to avoid potentially harmful particle losses to the machine first wall. In this contribution, we study EP confinement and losses through a topological map in the Constant of Motion (CoM) phase space defined by EP constants of motion and adiabatic invariant of the system [2]. Topological maps in the CoM phase space are a fast analytical tool to predict EP orbits and relative prompt losses before collisions with background species occur, requiring only EP ionization information without a full slowing down simulation. The CoM phase space has been characterized and used to classify EP orbits in order to estimate the fraction of prompt losses, i.e. particles born in non-confined orbits which are lost almost immediately after the ionization. EP orbit topologies are analyzed for different DTT plasmas and different injection energies. The orbit-following Monte Carlo ASCOT code [3] is used to obtain the necessary information on newly-born fast ions to populate topological maps. We show that, among the possible EP orbits, passing, trapped and lost particle orbits are identified for DTT case. No potato or stagnation orbits are predicted. Significant changes of the EP orbit topology are observed by changing plasma density or NBI energy, e.g. the fraction of prompt losses decreases with the plasma density. Even if DTT NBI is directed co-current, a fraction of prompt losses remains.

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3D plasma-wall interaction during magnetic reconnection events in the RFX-mod device

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This paper is devoted to the characterization of MHD tearing modes causing plasma-wall interaction (PWI) during a magnetic reconnection event in a high current plasma discharge in the RFX-mod reversed field pinch device ($R = 2$ m, $a = 0.5$ m). PWI is measured via a fast camera [1] observing the inner graphite wall of the device, showing two separated stripes of neutral carbon radiation. The main goal of the analysis is to simulate and understand the origin of the pattern, following the methods used in pioneering experiments in the TEXTOR device [2].

A preliminary study with a simplified model of 3D topology shows that the maximum toroidal mode number of MHD modes involved in the reconnection event is $n \approx 40$, larger than the measured $n \leq 23$. This information is important in view of the upgraded RFX-mod2 machine, which will be commissioned in 2024.

A more refined analysis with the guiding center code ORBIT [3] involves the calculation of the 3D map of connection lengths to the wall $L_{c,w}(r,\theta,\varphi)$. This map reproduces quite well the experimental PWI pattern measured by the fast camera, showing that the two stripes are due to modes with different poloidal numbers, $m = 0$ and $m = 1$. This result confirms the importance of the $m = 0$ tearing modes [4] in the edge of the RFP, especially during reconnections [5].

The relationship between the observed PWI and the physics of magnetic reconnection phenomena in the RFP, in particular regarding the behavior of fast ions accelerated during these events [6], will also be discussed.

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MHD spectroscopy through Resonant Field Amplification on RFX-mod: modelling and experiments

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Non-axisymmetric magnetic perturbations are often used to control the stability of a fusion plasma, for example applying resonant fields to change the plasma edge structure [1] or using feedback techniques for global mode control [2]. Coupling a fusion plasma with external fields may stimulate a response field that can be quite different, in shapes and amplitudes, with respect to the applied vacuum field. In particular an amplification effect can occur when marginally stable MHD modes are present. This phenomenon is known as Resonant Field Amplification (RFA) and it can be exploited to perform MHD spectroscopy studies of the plasma, in order to probe stability without necessarily ending the discharge [3][4]. The RFX-mod experiment [5], presently being upgraded to RFX-mod2, can operate both in RFP and Tokamak configuration and is equipped with one of the largest sets of magnetic actuators (192 active coils) among fusion experiments. Hence it is well suited for plasma response and active control studies. In this work plasma response experiments in RFX-mod tokamak plasmas are investigated. Perturbations with varying poloidal and toroidal spectra are applied to marginally stable plasmas, approaching the current-driven kink threshold q_a=2. Plasma response is measured with 192 saddle coils (4 toroidal arrays of 48 sensors), for the radial component, and 4 sectors of 8 poloidally distributed bi-axial pick-up sensors. The geometry of the RFX-mod active coils has been implemented into a MARS-F [6] for comparison of the RFA elaborated from magnetics with numerical predictions. The model used for the calculation is thus validated by interpreting experimental data, yielding information on the plasma response physics in RFX-mod tokamak plasmas. This is expected to support the upcoming program of RFX-mod2.

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Investigation of intrinsic error fields in MAST-U device

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In magnetic fusion devices, undesired non-axisymmetric magnetic field perturbations, typically called error fields (EF), have been observed to have a detrimental effect on plasma stability and confinement [1]. EFs components with toroidal mode number n = 1 can destabilize magnetic islands in otherwise tearing-stable plasmas, potentially leading to disruptions [1]. The main strategies adopted to minimize EFs consist in a careful alignment of the field coils, when assembling the fusion device [2], and in the installation of EF correction coils, which could be used to counteract the non-axisymmetric fields. In this work, a database of compass scan tests [3], performed in MAST-U, in the framework of EUROfusion WPTE RT01 programme, has been analyzed: i) to identify the n=1 EF magnitude and ii) to investigate possible dependencies of the locked mode (LM) threshold with the main plasma parameters. To perform this study, a correct identification of the LM onset is needed. To this purpose a reliable method based on the identification of transfer functions between the n=1 radial magnetic field amplitude and various coil systems, has been developed, which allows the calculation of the n=1 plasma response [4]. The LM onset has been identified as an abrupt growth of the plasma response signal and has been corroborated with data from multiple diagnostics, as plasma density, tangential emission activity and temperature profiles. The development of the signal compensation method is presented in this contribution, accompanied by the main experimental results obtained which can be summarized as follows: i) the empirical correction currents for n=1 EF minimization are relatively smaller (about 0.1 kA) than the ones used in MAST (1 kA range) [5]. This suggests that the fine installation of poloidal and divertor coils for n=1 EF compensation in MAST-U during assembling the new device has been a valuable procedure [2] ii) the linear scaling of the LM threshold with plasma density has been retrieved in MAST-U, confirming results obtained in other fusion devices, such as JET, C-mod, DIII-D [6], MAST [3] and NSTX [7].

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Simulation of a collisional plasma interacting with electron emissive divertor monoblocks

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At CNR-ISTP, we have developed "DESPICCO" (Divertor Edge Simulator of the Plasma-wall Interaction with Consistent COllisions), a code that simulates the interaction between a hydrogen plasma and the Tungsten divertor monoblocks of a Tokamak fusion reactor. The code is available in two different Fortran versions, using respectively OpenMP and CUDA parallelization. Its main goal is to characterize the particle/energy fluxes along the walls, and the global sheath heat transmission used as input boundary condition by fluid models of the scrape-off-layer. The simulated domain covers a portion of the divertor surface extending a few mm along the normal (to wall) direction and a few cm in the toroidal direction (to cover a relevant monoblock portion).

The model is based on the Particle-In-Cell approach [1], complemented by a Monte Carlo Collisions model [2] with the null collisions [3] method. The main physical processes that characterize the last mm of plasma region in front of the divertor are reproduced self-consistently: (i) the non-neutral Debye sheath and quasineutral magnetic pre-sheath formation [4],(ii) the secondary electron emission (SEE) due to electron impacts [6], (iii) the thermionic electron emission [7], and (iv) the collisions between ions/electrons and recycled neutrals [5]. Neutrals recycling from the wall due to the recombination of impacting ions is accounted for by considering them as a fixed background. Moreover, the 2D shaping of the monoblocks is reproduced accurately including the toroidal surface beveling, used in real divertors to protect the exposed edges against parallel energy fluxes.

The paper will describe the overall structure of the code and of its CUDA GPU implementation, and numerical results of different simulation scenarios. First, a Divertor Tokamak Test (DTT) scenario is considered at two critical locations, one on the Inner Vertical Target (IVT) and another one at the Outer Vertical Target (OVT). These simulations feature a Deuterium plasma with a Tungsten divertor and consider, selectively, the effects of ion/electron collisions, and electron wall emission (SEE and thermionic). Secondly, a parametric analysis of the plasma-wall interaction figures of merit (energy flux distribution along the walls, peak energy flux of ions and neutrals, sheath heat transmission coefficient) is carried out considering a parametric space featuring varying (i) plasma density and (ii) temperature, (iii) recycled neutrals density, and (iv) monoblock temperature and bevel angle, again for different collisional/wall emission effects. This parametric analysis is being carried out within the scope of the EUROFUSION HPC project "PARADIGM: PARametric Analysis of DIvertor Geometry considering Multiple kinetic effects".

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Multi-devices edge transport analysis of positive and negative D-shape plasmas in high power tokamak scenario

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One of the major problems for future fusion tokamak devices are the Edge Localized Modes (ELMs) as they can lead to large, uncontrolled heat fluxes to the walls. In recent years experimental evidences have shown that plasmas with negative triangularity shape (NT) can achieve in L-mode the same performance as positive triangularity (PT) H-mode, hence avoiding ELMs. Within the roadmap to DEMO, the Divertor Tokamak Test (DTT) facility aims to test alternative magnetic divertor configurations considering also the NT option. To study features of this configuration and prepare for future exploitation, TCV (Tokamak à configuration variable) and AUG (ASDEX Upgrade) devices have been used to perform experiments aimed to produce plasmas as similar as possible to the DTT high power scenario in both D-shapes, i.e. PT and NT.

An in-depth investigation is necessary to understand how NT can be a good alternative from the power exhaust point of view. This work studies the edge transport behaviours of NT L-mode with respect to the PT in L and H-mode. In particular, the fluid code SOLEDGE2D, coupled with the EIRENE Monte-Carlo kinetic code for neutrals, is used to investigate the edge features in the two different configurations.

Our analysis is focused on couples of NT L-mode and PT L-mode pulses and couples of NT L-mode and H-mode PT pulses. The discharges in each couple are chosen with similar characteristics in order to reduce the degrees of freedom in the comparison. They are all in single null magnetic divertor configuration and the triangularity is similar to the DTT full power scenario both for TCV and AUG cases, i.e. $\delta_{top}\simeq+0.35$ and $\delta_{bottom}\simeq+0.45$ for PT configuration and $\delta_{top}\simeq-0.35$ and $\delta_{bottom}\simeq+0.07$ for NT shape. Moreover, the couples have also similar input parameters, i.e. the plasma current of about 200kA for TCV and 600kA for AUG cases and equal toroidal field, B_T=1.4T for TCV and B_T=2.5T for AUG. Input power, provided by NBI and ECRH, covers a range from 0.5MW and 3MW.

Present analysis improves our previous study using ohmically heated TCV pulses, which have shown that the two configurations have different edge transport and that the triangularity affects more the particle transport than the energy one in the Scape-off-layer (SOL), and extends the analysis to high power and PT H-mode pulses with specific reference to DTT. To study the edge transport, the SOLEDGE2D-EIRENE particles and energy diffusion profiles have been optimised to match experimental measurements, such as those given by Thomson scattering, Langmuir probes and spectroscopic diagnostics. Furthermore, core-edge modelling integration has been done matching profiles and fluxes, obtained by the TRANSP code, at the boundary between the two modelling domains.

Parametric dependencies in the formation and structure of co-deposited beryllium layers on the wall structures of fusion reactors

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Interaction between the edge plasma and wall materials of fusion reactors can result in erosion of various plasma-facing components, migration of the eroded material into new locations, and finally formation of co-deposited layers. We have carried out a systematic study to understand the origin of the characteristic features of such deposits. To that end, we have produced reference samples and extensively characterized their physical and chemical properties. Here we will report on the results of such studies for beryllium (Be)-based compounds; Be will be the baseline material of the main plasma chamber of ITER and is already used in the JET tokamak. The focus of the study has been assessing how the composition, structure, and retained plasma-fuel content of the co-deposited layers depend on various growth parameters such as the impurity content of the plasma as well as the temperature and morphology of the underlying surface.

The results of our analyses show that increasing surface temperature will lead to strongly modified surface textures and larger stresses in the layers but simultaneously to fewer defects in their structure. As a result, the co-deposits tend to become more loosely bound and contain less plasma fuel. However, repetitive heating-cooling cycles of the layers, occurring during successive plasma discharges in a fusion reactor, as well as the presence of typical seeding and other impurity elements adds more complexity to the interpretation of the observations. We will discuss the impact of such factors in detail to complement earlier investigations in [1] and compare the new database with the published information collected from the main-chamber and divertor wall tiles of JET.

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On Nonlinear Scatterings between Drift Waves and Toroidal Alfvén Eigenmodes in Tokamak Plasmas

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Using electron drift waves (eDWs) as a paradigm model, two nonlinear scattering processes between microscopic drift waves and Toroidal Alfvén Eigenmodes (TAEs) in tokamak plasmas are investigated analytically. First, we investigate the scatterings of a TAE by ambient eDWs [1]. Here, it is found that, given eDW density fluctuations $\delta n_s/n_0 \sim O(10^{-2})$ and typical tokamak parameters, TAE instabilities can be effectively reduced or even suppressed due to stimulated absorption via scatterings into short-wavelength electron Landau damped kinetic Alfvén waves (KAWs). We then investigate the reverse scattering process; i.e., the scattering of eDW by a TAE. Here, in contrast to the previous case, it is found that, given TAE fluctuations $|\delta B_\theta/B_0|^2 \sim O(10^{-7})$, nonlinear scatterings to short-wavelength KAWs have a negligible damping effect on eDW due to the near cancellation of stimulated absorption via the upper-sideband KAW and spontaneous emission via the lower-sideband KAW. Implications to anomalous electron heating as well as ion-temperature-gradient (ITG) modes will also be discussed.

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Existence of optimized stellarators with simple coils

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In this work, we have developed a new method of directly optimizing stellarators from coils, and explored the possibility of stellarator design and optimization using simplified coils. We have developed a suite of optimization codes, and used global optimization algorithms to scan coils shape in order to improve the neoclassical confinement and MHD stability of stellarators. Meanwhile the complexity of the coils shape can be controlled effectively within an acceptable range during the optimization process. We chose the Columbia Nonneutral Torus (CNT)[1], a four-coil stellarator configuration, as the starting point of our optimization. CNT consists of two circular interlocking (IL) coils and two circular poloidal field (PF) coils. In our work, only the shape and current of the interlocking coils are varied, so that the number of parameters to be optimized is limited. By using grid search and random search algorithms, a few configurations with good magnetic surface properties are found. The Zhejiang University Compact Stellarator (ZCS)[2] is obtained by targeting only neoclassical transport in optimization. The results show that, by just changing the shape of the interlocking coils from circular to elliptical, the effective helical ripple amplitude of CNT is reduced by an order of magnitude. Furthermore, by targeting neoclassical transport and MHD stability simultaneously, a compact stellarator with simple coils (CSSC) is obtained with vacuum magnetic field[3]. CSSC has favorable properties of magnetic well and a low helical ripple amplitude comparable to that of W7-X. Meanwhile, CSSCs interlocking coils are much simpler than those of W7-X. Finally, the low ripple level of CSSC can be maintained at finite plasma beta by reducing the current of interlocking coils. The results of this work indicate that it is possible to optimize stellarators with simplified coils. This has important implications for reducing the complexity and cost of future advanced stellarators.

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Core localized alpha-channeling via low frequency Alfvén mode generation in reversed shear scenarios

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A novel channel for fuel ions heating in tokamak core plasma is proposed and analyzed using nonlinear gyrokinetic theory. The channel is achieved via spontaneous decay of reversed shear Alfvén eigenmode (RSAE) into low frequency Alfven modes (LFAM), which then heat fuel ions via collisionless ion Landau damping. The conditions for RSAE spontaneous decay are investigated. An explicit expression for the fuel ion heating rate is derived and found to be comparable to the collisonal heating.

The channel is expected to be crucial for future reactors operating under reversed shear configurations, where fusion alpha particles are generated in the tokamak core with the magnetic shear being, typically, reversed, and there is a dense RSAE spectrum due to the small dimensionless alpha particle characteristic orbits.

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Transient laser-induced breakdown of dielectrics in ultra-relativistic laser-solid interactions

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Research on the interaction of petawatt-class lasers with matter drives the development of novel plasma-accelerator infrastructure and enables new applications like the investigation of warm-dense matter. Especially for high-intensity laser-solid interactions, the leading edge of the laser determines the amount of target pre-expansion and by that the interaction mode of the target with the ultra-relativistic laser peak. Accurate modeling of target pre-expansion is required to strengthen the predictive power of associated computer simulations. For this, a reasonable starting point of the simulation is given by the phase transition of the target from the solid to the plasma state, i.e., the breakdown of the solid.
In this contribution, we report on the time-resolved observation of transient laser-induced breakdown (LIB) during the leading edge of high-intensity petawatt-class laser pulses with peak intensities up to 6 x 10^{21} W/cm^2 in interaction with dielectric cryogenic hydrogen-jet targets. The results show that LIB occurs much earlier than what is typically expected following the concept of barrier-suppression ionization and that the laser-pulse-duration dependence of LIB and laser-induced damage threshold (LIDT) is very relevant to high-intensity laser-solid interactions. We demonstrate an effective approach to determine the onset of LIB, i.e., the starting point of target pre-expansion, by comparing a laser-contrast measurement with a characterization study of the target-specific LIB thresholds.
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OSIRIS open-source

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The OSIRIS [1] Electromagnetic particle-in-cell (EM-PIC) code is widely used in the numerical modeling of many kinetic plasma laboratory and astrophysical scenarios. In this work, we report on a new parallel project, the OSIRIS open-source code [2]. This project aims to provide the community with an open-source PIC code capable of tapping into Exascale resources with all the tools required for plasma physics science and applications from laser-plasma accelerators to novel radiation sources. OSIRIS open-source shares most of the features of the OSIRIS [1] code, including high-order interpolation schemes, hybrid MPI / OpenMP parallelization with demonstrated parallel scalability to over 2 million processes, and explicit CPU vectorization. It features an extended PIC algorithm, including ionization and binary collisions, and alternative field solvers and particle pushers. The code supports multiple geometries, advanced initialization routines, and diagnostics. More features from the OSIRIS code will be added to OSIRIS open source as they mature. OSIRIS open source includes detailed documentation on compiling and launching the code, and on setting up your simulation. For more details on the OSIRIS open-source project please check our website at https://osiris-code.github.io/

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Advanced targetry for high repetition-rate laser-driven ion accelerators

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Laser-driven ion acceleration has emerged as a promising technology for generating high-energy ion beams with unprecedented properties, opening new opportunities for a wide range of scientific and technological applications. Unlike conventional ion sources, laser-based ion accelerators offer several advantages, including compactness, lower shielding requirements, and reduced operational costs. A range of fields could benefit from these assets, including applications in medical therapy, material science, and nuclear physics [1]. However, most of the proof-of-principle experiments exploring these techniques have been limited to single-shot irradiations due to the low repetition rates of the high-power laser systems available.

As high-power lasers with multi-Hertz repetition rates become readily available following improvements such as diode-pumped lasers [2], the development of an industry-class plasma-based ion accelerator becomes a feasible goal. A key requirement for such an accelerator is the production of advanced targetry capable of replenishing the target at such rates after being destroyed by the laser following the interaction, while being maintained on the focal plane with micron precision. In this work, we present recent progress on target systems and results on laser-driven ion acceleration using the STELA laser, a 45 TW system delivering pulses with energies up to 1.2 J and duration of 25 fs at a rate of 10 Hz, hosted by the Laser Laboratory for Acceleration and Applications (L2A2, Universidade de Santiago de Compostela) [3]. In particular, two target systems have been developed at L2A2. Firstly, a multi-target rotating wheel has been tested, capable of operating for hundreds of shots, with an automatised alignment procedure ensuring accuracies greater than 4 µm thanks to the use of a high-precision positioning sensor. This system has been experimentally demonstrated to enable the continuous and stable acceleration of ions. Secondly, in order to further extend the operation life to tens of minutes at 10 Hz rates, a tape-drive system is being commissioned, with a tension-based positioning control, already exhibiting stabilities of up to 8 µm standard deviation.

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Optical emission from intense laser interactions with preheated targets

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Ultra-intense (> 10^{18} W/cm^2) laser-solid interactions can produce hot and dense matter relevant to studies of lab astrophysics [1], and can also provide a source of intense and ultra-short X-ray and high energy particles [2]. Fast electrons and accelerated ion beams are generated during this interaction, with the potential for use in the fast ignition variant of inertial confinement fusion [3,4].

A recent experiment irradiating planar foil targets with a laser pulse of intensity > 10^{20} W/cm^2 was subject to a particularly intense prepulse (~10^{17} W/cm^2), causing significant preheating and expansion at both the front and rear surfaces of the targets by the time of main pulse irradiation. Measurements of optical emission at the rear surface were taken to diagnose fast electron transport [5], but analysis has been complicated in light of the disrupted rear target surface. In this paper we present the experimental measurements of optical emission, and results from hydrodynamic and particle-in-cell simulations to determine the source of our observed emission.

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The use of AM foams in laser-plasma interaction experiments

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Additive manufactured (AM) foams present significant interest in the context of high-power laser-matter interaction. Printed foam targets provide a highly controlled environment and permit a high degree of versatility in terms of density, spatial structure and materials. This presentation describes an approach to the design and fabrication of low-density AM foams and their use in a laser-plasma interaction experiment.

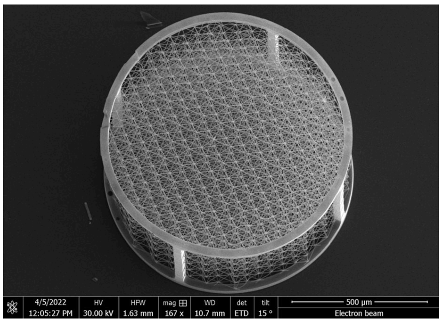

Figure 1: Photo of a 8.5 mg/cc AM target of diameter 0.95 mm, depth 0.6 mm, 2.2 μm beam diameter.

Foams with an octet truss cellular structure have been designed using a finite element approach and printed on a 7 μm thick copper substrate using two-photon laser lithography, see Fig. 1. A foam in a form of a cylinder of a diameter 0.95 mm and depth 0.6 mm has a stiffness of $2-4$ MPa sufficient for it use in experiment in a free standing geometry [1].

AM foams are irradiated at the PALS laser facility using the third harmonic of iodine laser at wavelength of 438 nm with pulse duration of 300 ps and energy of 200 J focused in a spot of diameter of 120 μm. The electron density of a fully ionized foam is about one third of the critical density. We measured the velocity of ionization front propagating inside the foam and characteristics of hot electrons generated in a plasma and compared them with chemically produced foams of the same average density.

Experimental results are simulated with a hydrodynamic code FLASH equipped with a subgrid model describing laser interaction with foam and its homogenization [2]. Excitation of parametric instabilities and generation of hot electrons is simulated with a particle-in-cell code SMILEI. The results of simulations and a comparison with experiments will be presented.

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Implementation of Non-Equilibrium Equation-of-State Model in Radiation-Hydrodynamics code HELIOS-CR

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HELIOS-CR is a 1-D radiation-magnetohydrodynamics code that is used to simulate the dynamic evolution of plasmas created in high energy density physics (HEDP) experiments [1]. Radiative and atomic processes in plasmas play a critical role in a wide variety of such experiments. We will discuss a new model that accounts for the effect that collisional-radiative atomic kinetics may play on the equation-of-state (EOS) and on overall plasma evolution. In the implementation of EOS models affected by collisional-radiative kinetics, we closely follow the formalism developed at LLNL [2]. We will present the details of the newly developed model and discuss the simulation results for typical applications where the non-equilibrium atomic kinetics is expected to be important, e.g., for photoionized plasmas.

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A hybrid (ablation-expansion) model for over-critical foams

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The interaction of a laser with a foam target is of great interest for the high energy density physics. In application to the direct drive inertial fusion, foams are a promising material to smooth out the laser intensity modulations [1]. Compared to homogeneous targets, the laser propagation in foam is a more complicated problem. One has to account for the interaction between the laser and the foam microstructure to model the processes at a macroscopic scale. However, the resolution of the microscale structure in a hydrodynamic simulation is time consuming and one needs to find a way to simplify the model on this scale [2, 3]. By investigating the detailed interaction between the laser and a solid sub-wavelength cylinder in one pore using both particle-in-cell and hydrodynamic simulations, we found that the laser is mostly absorbed at the surface of the cylinder [4]. As a result, the foam homogenization process is dominated by ablation, which increases the homogenization time. Using our new microscale model of the foam homogenization that has already been investigated for under-critical average density foams [5], we demonstrate its capability to also model the over-critical foam with the FLASH code. It is found that the laser is better absorbed in the foam compared to a homogeneous target. The velocity of the laser-induced shock in the foam is similar to the homogeneous case but can propagates slower or faster depending on the size of the pores. Also, there is a significant increase of the ion temperature behind the shock as a result of the foam microstructure homogenization.

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Evaluation of laser-driven proton-Boron nuclear reactions from particle-in-cell simulations

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Proton-Boron reaction is often presented as an aneutronic path to achieve a fusion reactor and is also considered in designing source of particles for medical and fundamental perspectives. In the context of an alpha source design, from Particle-In-Cell (PIC) simulations, we evaluate the number of events and the source characteristics from a post-processing treatment as well as from directly modelling nuclear fusion in the "Smilei" PIC code [1]. We review the case of a ps relativistic laser interacting with a solid target when a pre-plasma is present at the front of the target. We analyze the role of the pre-plasma extension and the influence of the target geometry in several configurations. In particular, we discuss the respective evolution of nuclear rates obtained from the pitcher-catcher scheme and from the direct laser-target interaction setup due to the hole-boring mechanism. The contribution of the various channels are considered, including the neutron yields, which appear to put constraints on the laser characteristics and the source design.

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Laser energy determination on the LMJ facility considering laser-plasma-interaction losses

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The Laser MegaJoule facility is a key scientific instrument designed to achieve high pressure and high temperature with the on-target-focusing of high-energy laser beams. In order to constrain as much as possible the simulations, incertitude on laser parameters, among other experimental parameters, has to be as low as possible. The laser energy, the pulse shape, the synchronization of the beams and the alignment precision are calibrated and monitored as often as possible depending of the need of the experiments. In this work, the problematic of the accurate determination of the laser energy is tackled. Each instrument involved in the measuring of the laser energy on the LMJ facility is depicted. From the sampling of the incident main beam after frequency conversion and focusing, to the measurements of the loss in transmission of the final optics assembly due to debris and laser induced damage, and the laser plasma interaction processes that lead to backscattered light in the Brillouin and Raman spectral domains.

With the combined use of laser diagnostics and laser-plasma-interaction diagnostics , the determination of the on-target energy is made possible. However, this method is only fully applicable on 28U and partially on 29U because it is not yet equipped with its own backscattered-light-diangostics. The future commissioning of this kind of diagnostics for this quadruplet will allow us to fully control the energy loss for both internal and external cones. The control of the symmetry of the illumination of the target is also one key parameter that is dependent on the experimental configuration itself (i.e. not always symmetrical) and on the laser performances. Moreover, with the mastering of the measurement of the observables described in this poster, the problematics of LPI and debris-induced transmission loss can be addressed.

Towards new direct-drive facilities: comparison of novel chamber beam geometry robustness to mispointing, imbalance and target offset.

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A decade of experiments at the National Ignition Facility [1] (NIF) has proven that inertial confinement fusion (ICF) is a credible approach to energy production, with experiments having exceeded the ignition regime [2]. However, the indirect-drive approach is not suited for high-gain implosions and reliable energy production.

The direct-drive ignition approach is favoured for energy production as it features simpler target designs and couples more energy to them. It has been explored by physicists across the world and supported by experiments on small-scale facilities in Europe (PALS, ORION), Japan (GEKKO) and the US (OMEGA). There are currently no ignition-scale laser facilities configured for the standard direct-drive approach. Integrated direct-drive experiments have mostly been focused on understanding the physics at reduced scales, with the ultimate goal of demonstration of necessity and feasibility of construction of an international direct-drive laser facility.

In this talk, we will present studies about the irradiation and low-mode perturbations in 3D at NIF scale (also called “ignition scale”). While the stability of direct-drive targets to low mode was analysed in the past on the basis of 2D simulations, only 3D simulations can capture correctly the effects of beam imbalance, beam mispointing and target offset errors. We first perform optimisation studies of innovative chamber designs [3, 4, 5] (where the beam ports are arranged differently) using a solid sphere illumination thanks to the inverse-ray-tracing code IFRIIT [6]. We sample and select free parameters – the super-gaussian order and the spot size of the laser that reduce the most the initial laser perturbations on target. Robustness to systematic low-mode asymmetries is then evaluated between the chamber geometries using gaussian sampling and statistical methods. We will also assess how the in-flight stability of the target is affected for different ignition schemes.

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High-flux Neutron Generator Based on Laser-driven Collisionless Shock Acceleration

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Neutrons have played an important role in characterization, development and testing of materials over the past sixty years, which can gather important and sometimes unique information about the materials that cannot be obtained by other types of radiations. The 1994 Nobel Prize in Physics, awarded to Clifford G. Shull and Bertram N. Brookhouse, for example, is the reflection of recognition of the impact of neutron scattering. Historically, nuclear reactors and accelerator-based spallation devices have been primarily used for various applications. Unfortunately, they not only take up large space but also are extremely expensive to build and maintain. Laser-driven neutron source provides an attractive alternative with low cost and compact size. However, all present laser-driven schemes are based on target normal sheath acceleration, which, in nature, suffer from low efficiency for acceleration of deuterons and exponentially decaying energy spectra feature, and as a result, their output neutron fluxes are rather low. In this talk, I shall report on our recent progress [1] on proposing and experimental verification of a novel compact high-flux neutron generator with a pitcher-catcher configuration based on laser-driven collisionless shock acceleration (CSA). Different from those previously relied on target normal sheath acceleration (TNSA), CSA in nature favors not only acceleration of deuterons (instead of hydrogen contaminants) but also increasing of the number of deuterons in high-energy range, therefore, having great advantages for production of high-flux neutron source required for applications. The proof-of-principle experiment has observed a typical CSA plateau feature from 2 to 6 MeV in deuteron energy spectrum and measured a forward neutron flux with yield 6.6×10^7 n/sr from the LiF catcher target, an order of magnitude higher than the compared TNSA case, where the laser intensity is 10^{19} W/cm^2. Self-consistent simulations have reproduced the experimental results and predicted that high-flux forward neutron source with yield up to 5×10^{10} n/sr can be obtained when laser intensity increases to 10^{21} W/cm^2 under the same laser energy.

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Influence of spatial-intensity contrast in ultraintense laser-plasma interactions

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An experimental and numerical investigation on the role laser focal spot spatial-intensity contrast plays in ultraintense laser-solid interactions is presented [1]. Increasing the focused intensity of high-power laser pulses opens new research possibilities, including new approaches to particle acceleration and phenomena such as high field quantum electrodynamics. Whilst the peak intensity obtained can be increased via tighter focusing, the focal spot spatial distribution can also a significant role in the interaction physics. We show that the spatial-intensity distribution, specifically the ratio of the intensity in the peak of the laser focal spot to the halo surrounding it (the 'spot wings'), is important to the overall interaction dynamics of ultraintense laser pulses with solid targets.

Through comparison of proton acceleration measurements from foil targets irradiated by a near-diffraction-limited wavelength scale (1.054 µm) focal spot, employing F/1 focusing plasma mirrors [2,3] and larger F-number focusing (F/3), we measure significant differences in the beam properties, including a x2.7 enhancement in the laser-to-proton energy conversion efficiency for F/1 focusing, at equivalent peak intensity to the larger F-number case. This is explained in terms of the differences in the focal spot spatial-intensity contrast between the two focusing cases, which is found to strongly influence laser energy coupling to fast electrons at the target front surface. Employing an analytical model to describe the acceleration mechanism and 2D particle-in-cell (PIC) simulations, we establish that the relativistically intense light in the spot wings generates an additional population of fast electrons at the target front surface, which contribute to the generation of the sheath field at the target rear and subsequent proton acceleration. Finally, to aid the community in identifying when the focal spot spatial-intensity contrast should be considered a simple model to define the parameter space for which the light surrounding the central focal spot contributes significantly to the interaction physics is introduced.

As the coupling of laser energy to electrons, and the subsequent injection of these into the target foil, is primary to a wide range of laser-solid interaction physics including the generation of high harmonics, X-rays and THz radiation, the findings of this study are of fundamental importance to the field. With ever increasing peak pulse intensities, as multi-petawatt laser system come online, focal spot spatial-intensity contrast influence will become more significant and should be a key parameter to consider, measure and communicate when reporting results, as with pulse energy, duration, peak intensity and temporal-intensity contrast.

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Visualizing Ultrafast Kinetic Instabilities in Laser-Driven Solids using X-ray Scattering

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Ultra-intense lasers that ionize and accelerate electrons in solids to near the speed of light can lead to kinetic instabilities that alter the laser absorption and subsequent electron transport, isochoric heating, and ion acceleration. These instabilities can be difficult to characterize, but a novel approach using X-ray scattering at keV energies allows for their visualization with femtosecond temporal resolution on the few nanometer mesoscale. Our experiments on laser-driven flat silicon membranes show the development of structure with a dominant scale of 60nm in-plane the laser axis, and 95nm in the vertical direction with a growth rate faster than 0.1/fs. Combining the XFEL experiments with simulations provides a complete picture of the structural evolution of ultra-fast laser-induced instability development, indicating the excitation of surface plasmons and the growth of a new type of filamentation instability. These findings provide new insight into the ultra-fast instability processes in solids under extreme conditions at the nanometer level with important implications for inertial confinement fusion and laboratory astrophysics.

Numerical study of high-energy photon emission in double-layer targets

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High-energy photons (x-rays and γ-rays) are a possible output radiation of ultra-intense (>10^{18} W/cm^2) laser-plasma interaction with different types of targets. Relativistic electrons accelerated during the interaction emit these photons mainly through two processes: non-linear inverse Compton scattering (NICS), when electrons scatter off an ultra-intense ($\gg 10^{18}$W/cm^2) laser pulse [1] and bremsstrahlung [2]. In the numerical investigation of laser-plasma interaction, including these emission processes contributes to more complete and accurate simulations that help design experiments and laser-based high-energy photon sources for applications. This contribution presents the results of numerical simulations that investigate NICS and bremsstrahlung in the case of laser interaction with a double-layer target (DLT) made of a low-density nanostructured foam deposited on a solid substrate. DLTs can enhance the production of fast electrons in terms of efficiency and energy [3] and are interesting for boosting the consequent photon emission. The available tools to study laser-driven high-energy photon emission are particle-in-cell (PIC) methods coupled with Monte Carlo modules [4, 5]. After considering the rationale of simulation approaches based on open-source codes, we use these tools with the support of analytical models to study the leading processes and properties of emission and assess the role of the DLT and laser parameters [6, 7]. Our 2D and 3D simulations show the relevance of the DLT in enhancing and tuning the emission (Fig. 1), making DLTs worthy of investigation in experimental campaigns, as demonstrated in [8]. To this scope, this work explores the possible competition and relevance of the two emission processes in the realistic scenario of future experimental campaigns and a potential application, i.e. laser-driven tomography, combining PIC, Monte Carlo and other numerical techniques.

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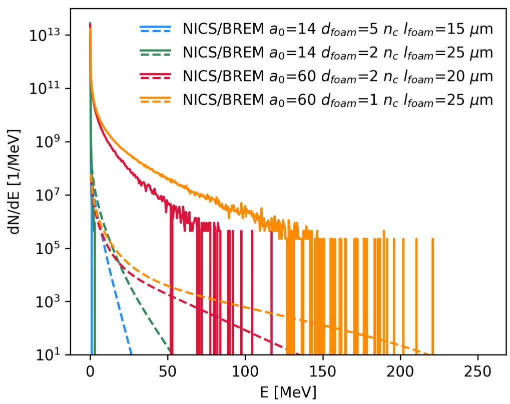

Figure 1: *Emitted photon spectra in different laser and DLT conditions. NICS spectra from 3D PIC are in solid lines, and analytical estimates of bremsstrahlung spectra are in dashed lines.*

Analytical models and numerical framework of particle distributions in electron-laser scattering

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The state-of-the art and near-future laser facilities will allow accessing extreme regime of interactions, in parameter space where radiation reaction and strong field QED models have never been tested. The most common experimental setup that maximizes the strenght of the laser field in the electron rest frame is a head-on collision. The highest intensity section of the laser can provide the desired extreme conditions for the laser-electron interaction, but will be surrounded by lower intensity parts of the wavepacket that will contribute to the experimental outcome. In addition, the probe beam will have non-negligible dimensions when compared to the laser characteristic scales (spotsize, Rayleigh range and duration) and to possible fluctuations in alignment (either temporal synchronization or transverse offset). The final signal measured in experiments (e.g. photon or electron spectrum) will depend on all these factors. It is therefore challenging to describe this analytically and full-scale QED particle-in-cell simulations are frequently used for this purpose. However, these require substantial computational resources, and cannot be used for extensive or quick parameter scans.

In this work, we develop theoretical models and a numerical framework to obtain approximate particle distributions, including several non-ideal features such as offset from the laser focus, non-monoenergetic beams, and beam divergence. These models may be used to support large-data high-repetition rate experiments in the future, leveraging on its speed for optimization or reconstruction of experimental parameters, namely when searching for specific signatures of Quantum Radiation Reaction and nonlinear Breit-Wheeler pair production in electron distribution or emitted radiation.

This work was supported by the European Research Council (ERC-2015-AdG Grant No. 695088) and Portuguese Science Foundation (FCT) Grants No. CEECIND/01906/2018 and UI/BD/153735/2022. Simulations were performed at the IST cluster (Lisbon, Portugal).

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QED cascades in counter-propagating Laguerre-Gauss beams and growth rate predictions

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In quantum electrodynamic (QED) cascades, electrons and positrons interacting with a strong electromagnetic are accelerated and emit gamma photons, which are then converted into pairs which in turn may further contribute to the cascade. Under the right conditions, which are mainly defined by the electromagnetic field structure [1], electrons and positrons are continuously accelerated and one enters the avalanche (or self-sustained cascade) regime, where the number of pairs grows exponentially with time. A promising configuration to achieve such a regime relies on the use of two counter-propagating ultra-high intensity gaussian laser pulses as shown in [2, 3, 4].

We have developed a simple model that relies on the description of the short-time dynamics of charged particles in arbitrary electromagnetic fields discussed in [1]. This model allows us to assess the pair creation yield in arbitrary field configurations. The model is first applied to the case of a homogeneous rotating electric field. The predictions are in very good agreement with the simulations and allow to extend previous works [2, 3] for parameters where no satisfying model was available.

We apply the model to various configurations with two counter-propagating Laguerre-Gauss (LG) beams, which produce richer field configurations driven mainly by their polarisations and LG beam orders. It is shown that LG beams, depending on the chosen field configuration, can perform better (at same maximum field amplitude) than the usual gaussian beams for what concerns the development of the cascade and its growth rate. This is confirmed by a series of 3D Particle-In-Cell simulations with the code SMILEI [5].

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Radiation reaction of stationary or uniformly accelerating charged particle

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The high energy electrons generated by interactions of high intensity laser pulses with matters could generate energetic photons with short duration, which could be further utilized to generate various quantum beams such as positrons and neutrons [1]. The motions of charged particles need to be precisely evaluated to correctly understand the above phenomena. The equation of motion for radiating charged particles, including a radiation reaction effect, is known as the Lorentz-Abraham-Dirac (LAD) equation, which is written in the Lorentz covariant form and properly includes the energy loss rate of the Larmor formula [2]. However, since the solutions suffer from problems known as a ran-away solution and violation of causality, alternative equations are proposed known as the Landau-Lifshitz, the Mo-Papas, the Ford-O'Connell equations, and others [3-5].

To clarify the differences of these proposed equations, we compared the solution of LAD equation and those of the Landau-Lifshitz, the Mo-Papas, and the Ford-O'Connell equations [6]. We obtained charged particle solutions under a static magnetic field and a rotating electric field using each equations, and evaluated the parameters such as the Lorentz factor, radiation loss rate, the Lorentz invariant quantum parameter. It is shown that these parameters have quite similar values and the relative differences are less than 10^{-6} in the regime where classical radiation reactions are applicable..

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The role of polarization, polarization smoothing and modal power in laser plasma interaction

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In high power and high-energy laser facilities, several beam smoothing techniques such as spatial smoothing or polarization smoothing aim to mitigate the development of Laser Plasma Instabilities (LPI), due to their deleterious effects on the control of energy deposition in plasmas on one hand [1], and due to the generation of damages on the optical components on the other hand [2]. Because of their strong impact on the laser architecture, the implementation of these techniques in large laser facilities must be carefully designed to maximise their benefits. New components such as fused silica metamaterial quarter-wave plate [3] are currently being developed, offering new possibilities for polarization smoothing implementation. However, if these components are used, it must be ensured that laser-plasma interaction in circular polarization is equivalent to that obtained in linear polarization. On the other hand, high-energy lasers are based on multi-beams, arranged for example by quadruplet, and the impact of the modification of the speckle shape on the smoothing efficiency has to be studied.

Here we report on an experimental campaign we carried out on LULI2000 laser facility where a nanosecond 100 J laser beam, divided into two beamlets with a rectangular near-field shape, was focused on a preformed N_2 gas jet plasma and lead to the excitation of Stimulated Brillouin Scattering (SBS). The SBS reflectivity and the transmission of the laser pulse through the plasma were temporally diagnosed when varying the laser energy. We compared the values obtained for linear and circular polarized laser beams. We compared two implementations of polarization smoothing: one where the two orthogonal polarization were presents within each beam, and one where the two were split on each beam. We also studied the role of the speckle anamorphosis, which appears when the shape of the near field is not square.

All of these laser configurations lead to reflectivity and transmission curves with clear and instructive differences. We also introduced a modal power and we will show that this laser parameter seem to govern the reflectivity for each configuration

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Backward Raman Amplification with Finite-Length Effect in Hot Plasma

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Stimulated Raman scattering (SRS) in plasma is a promising technique for amplifying laser pulses to high intensities. However, SRS in finite length plasma can be affected by parasitic stimulated Raman scattering, which can reduce the efficiency of energy transfer from the pump to the seed. In previous work, several strategies are proposed to suppress the parasitic Raman scattering, such as lowering the electron density[1], increasing the electron temperature[2] ,induce phase mismatch via chirping the pump and seed laser[3] or density inhomogeneity[4]. In this work the effects of finite-length effect and Landau damping effect on SRS in the context of Raman amplification is examined using the three wave interaction (TWI) code and Particle-in-cell (PIC) code. We discuss the mechanisms of parasitic stimulated Raman scattering and how they can be mitigated through careful control of the plasma properties. Additionally, we explore the advantages and limitations of strategy for reducing parasitic stimulated Raman scattering, including the use of multiple small plasma pieces and high electron temperature. With the TWI code, PIC code and the theory proposed from our previous work[5,6], the gain factor reach maximum while the length of each piece of plasma reach the half of the start oscillation length. With proper choice of electron temperature, the parasitic Raman scattering can also be reduced. Finally, combining the Landau damping effect and finite-length effect, the new and effective Raman amplification scheme is proposed.

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A Gaussian Process Augmented Ray-Tracing Framework for Multi-Scale Modelling of Stimulated Raman Scattering in ICF

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Stimulated Raman Scattering (SRS) is a process of significant importance in laser-driven inertial confinement fusion (ICF) implosions. It is a process which reduces the efficiency of the implosion, both by direct scattering of light away from the fuel target, and by creation of hot electrons which preheat the target core. SRS occurs in the coronal plasma on timescales and lengthscales several orders of magnitude less than the hydrodynamic progression of the plasma, rendering modelling a challenge.

Contemporary predictive modelling of SRS in fluid codes relies on 1D linear kinetic theory in the steady-state and strong damping limits, bolted on to traditional laser ray-tracing [1]. The newly proposed modelling scheme is an extension of the method outlined by Debayle et al. [2], which is an iterative method, progressively updating cell-averaged intensities, wavenumbers, and frequencies for laser and Raman light until convergence is reached. Cell averaged quantities are used to model convective SRS along laser ray paths, with Raman rays created and propagated in addition to the laser rays.

It is proposed to add a Gaussian process (GP) surrogate model into this scheme which predicts effective linear convective SRS gains in each cell based on data produced by a hierarchy of underlying solvers. The most basic augmentation with a GP surrogate uses a boundary value problem solver based on linear kinetic theory, and provides robustness to hydrodynamic grid resolution by resolving intra-cell intensity changes. Next, the fluid plasma wave-solver LPSE [3] provides time dependency, electron plasma wave propagation, and dephasing. Then, going to higher fidelity, inclusion of kinetic effects is possible by using the particle-in-cell code EPOCH [4]. Finally, on-the-fly training allows for efficient fitting of the GP in regions of input space relevant to ICF, with a training point added when the predicted SRS gain variance in a cell is above a threshold value.

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Simulations of ICF implosion asymmetry seeded by laser inhomogeneities

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Direct-drive Inertial Confinement Fusion (ICF) is particularly sensitive to non-uniformities in laser drive. Idealised beam geometries, which illuminate the targets uniformly, are rarely realised in experiments. Previously [1], central hot-spot, direct-drive simulations have investigated laser power imbalance, mistiming, offset, and fine-scale imprinting. In this poster we present results from a code framework which models asymmetric drive in the shock-ignition regime. The hydrodynamics is simulated using the *Odin* 2D cylindrical geometry radiation-hydrodynamics ALE code driven by a 3D laser ray-tracing package. A simplified LPI model is adopted in which rays reaching the quarter critical surface have a fraction of their energy removed as a proxy for accumulated SRS and TPD losses. A fixed fraction of this energy loss is converted into fast electrons injected into *Odin* as Monte-Carlo sampled particles. These electrons deposit energy [2], and are scattered, along their 3D trajectories. Thus while the LPI model is simple the framework captures drive asymmetry and the effect of hot-electrons generated during the laser igniter spike. Results are presented on the sensitivity to drive asymmetry and the effect of the late time injection of hot-electrons from the shock-ignition igniter spike.

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Modelling of rear-driven collisional plasma jets from solid thin foils

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Collisional plasma jets present a scientifically interesting environment, where multitude of physical phenomena can be observed. These jets naturally appear in the astrophysical systems, such as accretion disks, protostars or elsewhere [1]. However, they can be downscaled to the laboratory setting, providing not only a model of astrophysical objects, but also a testbed for exploration of the fundamental transport processes in the plasma. The importance of an accurate description of these effects goes beyond the context of laboratory astrophysics and is crucial for handling the technique of inertial confinement fusion among other major applications. Though, characterization of the experimentally produced plasma jets and cross-correlation of the measured values with the numerical models has not been done systematically.

This contribution presents such a comparison for different materials of the targets. The laboratory setup consisted of a streak camera and a 4-frame interferometer, which measured the velocity of the plasma outflow from the rear side of a solid thin foil irradiated by a laser pulse. The configuration is then numerically simulated by the recently developed multi-dimensional MHD code PETE2 [2]. The Lagrangian nature of the method provides a high fidelity in modelling of the shock propagation, breakout at the rear surface and expansion of the plasma jet.

The data from the different diagnostic methods are matched with their numerical counterparts and the results are discussed. The extension of the setup by an external magnetic field is outlined for measurements of the dynamics and transport properties of magnetized plasmas.

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Interaction of high-power laser pulses with inhomogeneous laser-driven plasma density gratings

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Plasma density gratings have received growing interest over the past years as they may allow to manipulate high-power radiation in the microwave and optical regime. In particular in the context of high-power laser pulse manipulation these gratings are discussed as possible nearly damage-less optical replacements for solid-state devices. Applications such as mirrors [1], waveplates [2], holograms [3,4], beam-combiners [5], pulse splitter [6], and many more have been proposed over the recent years [7,8].

In the optical regime, volume density gratings can be created by interference of multiple laser pulses in initially homogeneous underdense plasma. The ponderomotive beat of the pulses causes bunching of electrons, which in turn will initiate ion motion, ultimately leading to a quasi-neutral periodic plasma density modulation. The modulation period is half of the wavelength of the driving laser pulses, leading to the formation of frequency band gaps in the dispersion relation for em waves inside the modulated plasma region.

For most of the proposed applications of plasma density gratings it is assumed, explicitly or implicitly, that the modulation amplitude of the grating is constant. However, the mechanism of driving such gratings by overlapping short laser pulses naturally leads to the formation of plasma gratings with inhomogeneous amplitude distributions. This has impact on inter-pulse phase-relations when pulses are reflected off or transmitted through such inhomogeneous gratings. We discuss the formation of inhomogeneous plasma density gratings and the consequences of spatial inhomogeneity on reflection and transmission properties. For the interpretation of the numerical results, we refer to coupled mode equations and an effective medium approach.

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Inertial confinement fusion involves the creation of plasmas far from local thermodynamic equilibrium. The temperature scale-length in the plasma can become shorter than the collisional mean free path of the heat-carrying electrons and thus the thermal transport can therefore become nonlocal. How to capture this in our modelling tools is a long standing problem in the field. Nonlocal transport was identified as one cause of discrepancies between LASNEX modelling and the National Ignition Campaign. The most common way to capture nonlocal transport is to continue using a diffusive, LTE model, but to limit the heat flux to prevent it becoming unphysical. This flux limiter can only be tuned post-hoc to match experiments and therefore its use limits the predictive capability of codes. Non-LTE thermal transport models should do a better job of capturing nonlocal transport but also necessarily make several assumptions. Here we present recent work to assess the accuracy of various models for nonlocal transport, using both ab-initio calculations and simplified experiments. We find that nonlocal modes can be accurate to within ~10% over a relatively wide range of parameters in the absence of magnetic fields. Self-generated magnetic fields substantially complicate this picture though and we will present a simplified experimental platform for investigating the effects of magnetic field, for example directly measuring the advection of magnetic field by the heat flow (the Nernst effect) in a plasma for the first time.

Thermal balance of a quantum dot on a plasma-facing surface of a microparticle

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Development of optical measurement of charges on microparticles immersed in plasmas is necessary to overcome the necessity of (often) not easily verifiable assumptions and limited spatiotemporal resolution of dynamical methods. One of the approaches to the optical measurement of charges is the usage of quantum dots (QDs) deposited on microparticle surfaces and observation of the red spectral shift of the spectrum of their photoluminescence associated with quantum-confined Stark effect.

Along with the quantum-confined Stark effect, heating of the QDs would also lead to the red shift of their photoluminescence spectra. The microparticles are known to heat up from units to tens K with respect to the surrounding neutral gas when immersed in low-temperature low-pressure plasmas. Therefore, the thermal shift of the fluorescence of the QDs deposited on the microparticle surface may exceed the expected Stark shift due to charge. It was proposed to distinguish the two effects by pulsing the plasma. Such a distinction will, however, only be possible in case of sufficiently good thermal contact between the QD and the microparticle [1]. To work out the quantitative requirements to this thermal contact, a simplified, but realistic thermal model of the QD on the plasma facing surface of a microaprticle was developed.

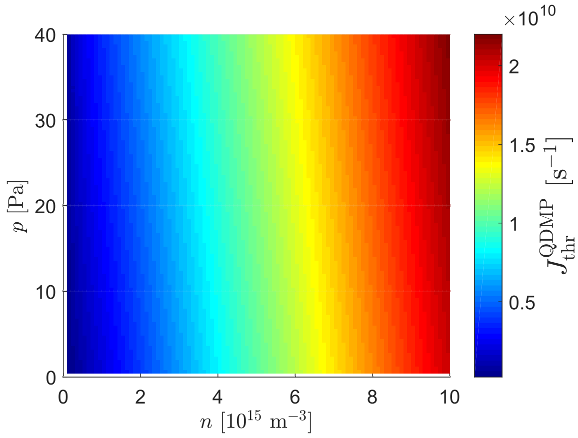

Figure 1: *Values of the threshold thermal contact flux $J_{\mathrm{thr}}^{\mathrm{QDMP}}$ calculated at different plasma densities n and pressures p.*

In Fig. 1, the values of the thershold thermal contact flux $J_{\mathrm{thr}}^{\mathrm{QDMP}}$ calculated at different neutral gas pressures and plasma densities are shown. For the thermal contact flux exceeding $J_{\mathrm{thr}}^{\mathrm{QDMP}}$, the QD temperature oscillations associated with the plasma pulsing become spectrally undetectable. The estimations of real thermal contact flux between the QD and microparticle result in at least two orders of magnitude higher values than those shown in Fig. 1.

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Effect of the ion drag force on dust grains in a strongly coupled plasma On a head-on collision between two nonlinear waves

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The effect of dust grain on the head-on collision of two dust-acoustic solitary waves in a non-magnetized, collisionless and strongly coupled dust plasma, has been investigated [J. Plasma Phys. (2020), **86**, 905860111]. In this note, the model is extended by including ion drag force on dust grains. Through the extended perturbation method (PLK), Korteweg-de-Vries (KDV) equations are derived. The wave's characteristics along with the phase shift, after the head-on collision, are calculated and analyzed. It is revealed a non-negligible decrease of the wave amplitude and the phase-shift.

Keywords: Ion drag force; Head-on collision; solitary waves; Korteweg-de Vries Equation; Nonlinear waves in plasma; Perturbation method

Theoretical study of the interaction of an oxygen plasma containing dust grains with a solid surface

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The interaction of plasma with solid material surfaces plays a crucial role in a wide range of laboratory and industrial environments, such as in fusion devices. Indeed, this interaction affects the edge-plasma properties and gives rise to the formation of a non-neutral region called the electrostatic sheath. In reality, the plasma is contaminated with impurities, referred to in the literature as dust grains, and consequently the interaction of plasma with solid material surfaces becomes more complicated.

In the present work, we have established a theoretical model which describes an interaction of a 1D, non-stationary and non-magnetized oxygen plasma containing multi-sized impurities with a solid wall. For this, we have assumed that the electrons are in a local thermodynamic equilibrium, however all other species are described by the fluid model. The impurities charges are described using the Orbit Motion Limited model (OML) and their size distribution are modelled by a Gaussian law. Then, in order to solve the set of differential equations, we have developed a numerical code based on the initial value method with a variable step.

The numerical results show that the presence of impurities reduced considerably the charge separation and consequently the sheath thickness. Moreover, the presence of negative ions promotes the elementary processes which make the profile of particles densities more oscillatory. The other physical parameters are also analysed and discussed.

I investigate the effect of quantum difractional effect and exchange correlation potential effect on the profile of dust acoustic solitary waves(DASWs) propagating in a dense degenerate dusty unmagnetized plasmas, which consist upon degenerate ions, electrons and classical dust grains. Theoretical investigation of linear and nonlinear long wavelength electrostatic waves propagation have been made in the non-relativistic regimes. We have analyzed the linear acoustic waves by using the multi-fluid model. A modified Korteweg de Vries (KdV) equation is derive by using the reductive perturbation theory, to study the small amplitude DASWs.

Investigation on propane deplection by cylindrical SDBD

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Our work is focused on the investigation on the performance of cylindrical SDBDs to abate VOCs at high concentrations up to 5,000 ppm. This study permits to better understand the plasma ability and to evaluate the depletion efficiencies in dynamic regime, fluxing an air mixture containing propane. A comparison of the latter with the literature experiments demonstrate that these discharges are very promising in view of applications in the industry. The results will also allow to deep the knowledge on the abatement processes in view of a possible scale-up of the system.

We use a cylindrical SDBD with inner radius 2.4 cm, outer radius 5.5 cm and height 18 cm connected to a low frequency power generator. The plasma source is located in a cylindrical box which volume is 1,7 l. The box is connected to a gas chromatograph in order to measure the VOC concentrations and to a nozzle to flux the air gas mixture containing propane. We performed a parametric study varying the relevant parameters such as power, propane concentration and air fluxes.

The non thermal plasma is able to produce reactive species in air, such as, atomic oxygen, ozone, nitrogen oxides and energetic electrons, promoting the oxidation of propane and its dissociation.

The VOC abatement is dependent mostly on power and air fluxes. It decreases with fluxes while increases with power. When power is increased plasma expands around the surface, intercepting a larger gas volume, increasing the abatement rate of propane. Fluxes are related to the residence time of the air mixture inside the cylindrical box. Working at fixed propane concentrations the depletion decreases with increasing the air fluxes because the residence time also decrease diminishing the probability of the pentane molecules to collide with the energetic and reactive species.

The abatment efficiency is also evaluated in order to validate the possibility of a scale up for industrial application.

Plasma etching polymeric surfaces: from nanostructure to fractals

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Polymers have been the subject of many studies oriented to surface chemical functionalization and morphological modification in order to tailor their macroscopic properties. Between the huge set of explored technologies and methods, plasma treatments of polymer fibers have been largely experimented for many purposes. Cold plasmas have the advantage to treat the polymeric surfaces by grafting chemical groups, depositing monomers, promoting chemical and physical etching at ambient temperature, without damaging or degradation of the bulk polymeric chains so retaining the bulk macroscopic properties.

Very recently cold plasmas have been experimented to promote hierarchical nano-structures by means deposition of thin films or by oxygen chemical etching on a variety polymers such PET [1], TEFLON, PP and on degradable polymers. These nano features have strong effect on the macroscopical properties of polymers for biomedical applications, like antifouling and antibacterial properties and also for obtaining superior properties such super hydrophilicity and hydrophobicity.

The different nano-textures on polymers depend strongly on the polymer chemistry and the processing gas.

In this study the cold plasma effects on the morphology of PP polymer using different processing gas, such as O2, CO2 and Ar, are investigated. The polymeric substrates are treated in a radio-frequency device at vacuum pressure. The different morphological features are analyzed by means Scanning Electron and Atomic Force Microscopes and the macroscopic properties are investigated by means of the surface tension and contact angle measurements.

A simple statistical model based on the AFM analysis is able to derive the fractal indexes of the plasma treated surfaces and their relationship with the macroscopic properties. The model is compared with the relevant literature models, such Cassie-Baxter and Wenzel ones.

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Tunning the surface wettability of graphene-coated polymeric substrate by plasma treatment

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Plasma technology to textiles proposes a dry, clean, and safe method for modifying the surface of different materials without changing their bulk properties. This is particularly advantageous for heat-sensitive polymers commonly used in textiles, as atmospheric non-thermal plasmas can be applied in a continuous process.

This work reports on the tunning of the surface wettability of graphene-coated polymeric substrates by plasma treatment at different conditions. Surface wettability plays a critical role in the behaviour of substrates. The adhesion and behaviour of coating can be influenced by the surface's level of hydrophobicity or hydrophilicity. Two methods will consider, for optimizing the hydrophobicity coating of graphene nanoparticles on the polymeric substrate and for optimizing the hydrophilicity by applying plasma treatment on the graphene-coated polymeric substrate.

By the treatment of plasma, the chemical composition, and physical structure of a material's surface will change, which in turn can affect its thermal properties such as thermal conductivity and heat transfer. Scanning electron microscope (AFM), Energy dispersive X-ray (EDX) and X-ray photoelectron spectroscopy (XPS) will be performed for structural information of substrates. Raman spectroscopy, Thermogravimetric analysis (TGA), and Differential scanning calorimetry (DSC) measurements will perform for graphene-coated polymeric substrates for the thermal analysis of substrates.

The expected results of this idea in the textile industry can lead to the development of high-performance protective clothing and smart fabrics with enhanced heat resistance and temperature regulation capabilities. The results of this study highlight the potential for future advancements in the application of plasma technology in the textile industry and provide a basis for further research and innovation.

Characterization of a Gliding Arc Tornado device for lignin particles functionalization

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The Gliding Arc Tornado (GAT) was proposed in the past to improve properties of gliding arcs reactors, in particular to have a better insulation of the device walls from the discharge, with a higher level of non-equilibrium and, besides this, much larger residence times to boost efficiency [1]. These devices were mostly used for industrial applications including fuel conversion, carbon dioxide conversion and waste treatment [2]. Their name refers to the formation of a reverse vortex flow configuration, a tornado, usually achieved by tangential gas injection near the walls in a cylindrical chamber. We have developed and used a kind of these devices for the treatment of lignin by plasmas [3]. Particles in powder, such as lignin, can be easily injected in the gas flow, separated and exposed to the plasma gas-phase while they are transported by the hydrodynamical flow. So optimal interaction with the discharge gas-phase could be achieved. Lignin is a major waste product of cellulose industry and in general agriculture, whose recycling problem has not solved yet.

Here we present the results of an experimental characterization of the discharge and of the plasma gas-phase, based on spectroscopy and time resolved imaging. We discuss briefly also plasma processing and the prospect of using lignin in polymer blends, which we have studied during a dedicated, now completed research grant, the POLISTE project [5].

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Plasma-assisted processing of gold-manganese oxide nanomaterials as electrocatalysts for oxygen evolution in water splitting

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The overall efficiency of electrochemical water splitting to yield hydrogen, a strategically appealing energy vector, is to date limited by the sluggish kinetics of the oxygen evolution reaction (OER), that requires the use of highly efficient, durable and eco-friendly catalysts. In this regard, the present study proposes an original plasma-assisted route for the fabrication of nanomaterials based on manganese oxides (Mn_2O_3, MnO_2). The target materials were grown at moderate temperatures on conductive glass substrates by plasma enhanced-chemical vapor deposition (PE-CVD) and subsequently functionalized with highly dispersed Au nanoparticles (NPs) by radio frequency (RF)-sputtering, followed by *ex-situ* annealing in air or inert atmospheres. Characterization results highlighted the selective obtainment of the desired oxide (Mn_2O_3, MnO_2), with an open dendritic morphology and an intimate contact with the deposited metal NPs. Material functional activity in OER processes could be modulated as a function of the pertaining chemico-physical features. In particular, Mn_2O_3-based systems yielded current density values higher than the corresponding MnO_2-based ones, which could be further boosted thanks to gold introduction. Taken together, the obtained results pave the way to the improvement of transition metal oxide OER performances by a controllable surface and interface engineering. In perspective, these results are of key importance not only for water splitting, but even for electrochemical processes involving the valorization of biomass derivatives based on naturally abundant transition elements.

Particle Tracking and Beam Line Diagnostic Reconstruction for Applications in Large Negative NBI sources.

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Large scale RF driven negative hydrogen or deuterium ion sources are essential parts of the neutral beam injection (NBI) systems of the upcoming ITER fusion device. The ion beam requirements to be fulfilled by these sources combine high accelerated current density (230 A/m^2 in H, and 200 A/m^2 in D) with low core divergence (<7 mrad) and high uniformity over the whole extraction surface (better than 90%). With a total extraction area of 0.2 m^2 the acceleration grid will feature 1280 individual apertures, arranged in 16 groups consisting of 16x5 apertures each. A thorough understanding of the beam properties is necessary to predict and control the behavior of these large ion beams. The experimental information of the properties of the beam is limited to the number of diagnostics, their location and resolution. Particle tracking and simulations of beam diagnostics are essential to complement the experimental information with otherwise unobtainable beam properties.

Beam divergences and uniformity, are investigated at the test facilities BATMAN Upgrade (BUG) and ELISE, which represent ITER's prototype source with one beamlet group and half-size source with 8 beamlet groups, respectively [1]. These test stands are equipped with a variety of diagnostic systems for the ion source parameters and for the beam properties. For diagnosing the beam, several non-invasive diagnostics of Beam Emission Spectroscopy (BES) and diagnostic calorimeters are available, all placed at different distances from the acceleration system. BBCNI (Bavarian Beam Code for Negative Ions, [2]) is a full 3D particle tracking and ray tracing code which is used to close the knowledge gap between the information provided by the beam diagnostics and the characteristics of the beam. The BBCNI simulations accurately reproduce the results of the calorimetric and BES diagnostics at BUG and ELISE test facility from which then the beam divergence and uniformity are obtained spatially resolved and with higher accuracy than from the measured signals alone. BBCNI is used to simulate diagnostics at several locations for in-depth examinations of the evolution of beam parameters with distance and the effects of long-range magnetic fields on the beam transport.

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Monitoring total soil carbon using laser-induced breakdown spectroscopy

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Soils form the second largest storage of carbon on Earth after the oceans, and hence are an important factor in mitigating climate change. Agriculture and related land use have caused around 24% of all anthropogenic greenhouse gas emissions since pre-industrial times [1]. However, by adopting novel cultivation methods, some of the carbon can be stored into the soil instead of releasing it to the atmosphere. This requires efficient monitoring of the carbon concentration on agricultural sites. Owing to the robustness, speed and information richness of Laser-Induced Breakdown Spectroscopy (LIBS), it has the potential to overcome the issues of current carbon measurement standards [2]. In this work we have designed a mobile LIBS based measurement device and provided a calibration model that was validated using 167 samples from a single field. All of the samples were reference measured using dry combustion (LECO). The model was then used to demonstrate the 3D spatial variation of total soil carbon in the field (Figure 1). All the measurements were performed in laboratory conditions and due to the promising results, we plan to demonstrate the method on-site next.

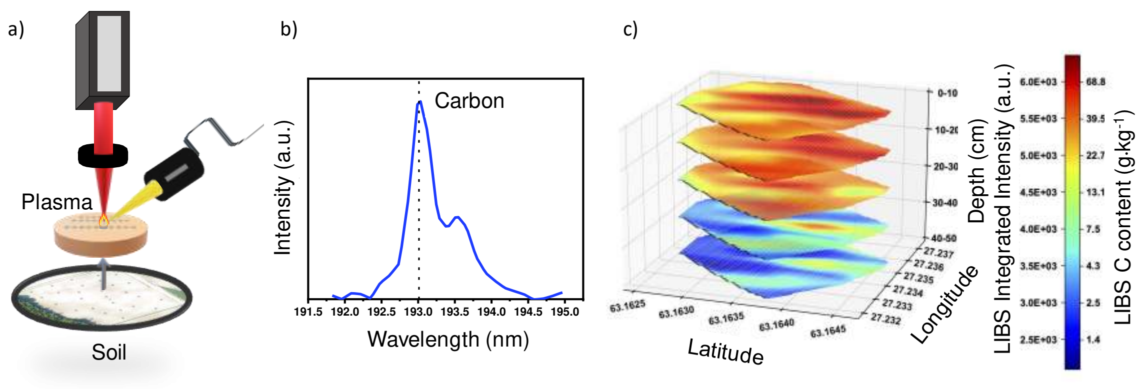

Figure 1: a) a simple schematic of LIBS, b) an emission line of carbon at 193.03 nm and c) a 3D variation of soil carbon over an agricultural site.

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The Delectric Properties of SF_6-N_2 Plasma in the Presence of a Copper Impurity

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Abstract. The objective of this work is to contribute to the study of discharges in SF_6-N_2 gas mixtures in the presence of copper impurities in order to improve the dielectric properties of SF_6-N_2, used in high voltage circuit breakers. The ionisation coefficient is an important indicator for the evaluation of breakdown in SF_6 and its mixtures. The discharge will be described by the Townsend model evolving in a weakly ionised mixture at low pressure. Two types of elastic collisions have been considered: electron-electron collision and electron-ion collision. The electronic transport coefficients of the SF_6-N_2 mixture are obtained by integration of the Boltzmann equation in the stationary case and for a uniform field.

Keywords: SF_6-N_2, Copper, High-voltage, Onization coefficient, Electron attachement cofficient

The very good dielectric properties of SF_6 have led to its use in circuit breakers and under increasing voltages up to 800 kV. The SF_6 is particularly suitable for switching off the arc and the rapid dielectric regenaration of the arc plasma in the SF_6 eliminates the need for cut-off resistors, which helps to simplify the design of these device .

Despite these many advantage, SF_6 is considered a greenhouse gaz with a global warming power 22900 times higher than CO_2 and many studies are looking at the possibility of substituting this filling gas .

According to, one of the possible solutions for the above mentioned greenhouse problem is to use SF_6 mixture with other gases instead of pure SF_6, and numerous studes have been carried out on the tempering and insulation properties of the mixtures.

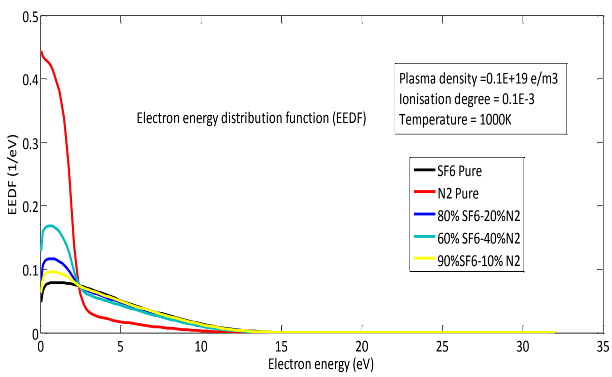
Electron distribution function (EEDF)

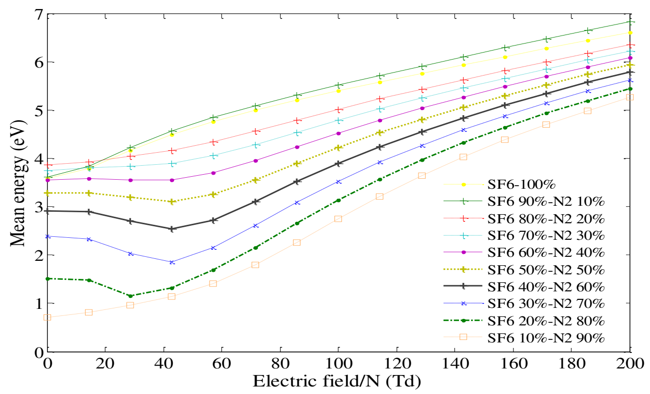
Mixture SF_6-N_2

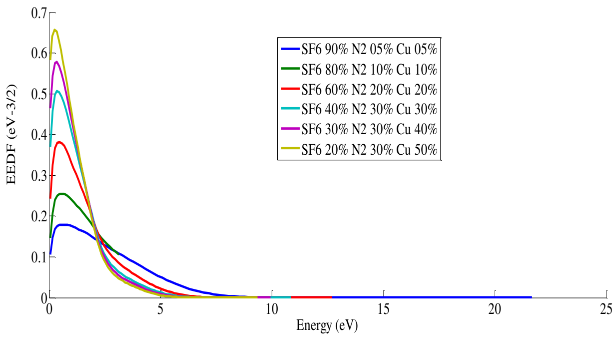
We shows the evolution of the EEDF in the SF_6-N_2 mixture. It is clear that an increase in the concentration of the SF_6-N_2 mixture in N_2 leads to an increase in the number of energy electron below 2 eV. The calculations were made with a temperature T=1000K, an ionization degree of $0{,}1.10^{-3}$ and a plasma density of $0{,}1.10^{+19}$ e.

Mixture SF_6-N_2- Cu

The calculations were made with a temperature T=3000K, a degree of ionization that is $0{,}1.10^{-3}$ and a plasma density $N=0{,}1.10^{+19}$ e/m^3







The infulence of copper concentration was studied numerically by analysis of the Boltzmann equation.
It is shown that the addition of N_2 in SF_6, sighnificantly reduces the number of high energy electrons, which effectively improves the resistance to clacking, it is also found that copper increases the concentration of high energy electrons.

Advancing MHD energy convertor performance -
"To 'B' or not to 'B', that is the question" [1]

S. Frank, J. Freidberg, M. Clingerman, D. Whyte

Abstract: Magnetohydrodynamic (MHD) energy conversion is a well-known, but rarely used, thermodynamic energy conversion technology. Its mission is to substantially improve the efficiency of moderate to large power plants using fossil or nuclear (fission and fusion) fuels. The mission is even more important today in terms of climate change than when the idea was first put forth, about 1/2 century ago. One major limitation on early convertor performance was the low magnetic field strengths, approximately 3-5 T, of the available low-temperature superconductor technology. Therefore, cycles with MHD energy conversion could not realize the thermodynamic efficiencies achieved by turbine combined cycles in fossil fuel plants. Furthermore, MHD convertors had stability difficulties operating in closed cycles, like those in lower temperature nuclear power plants, further limiting their applicability. However, the spectacular high-temperature superconductors (HTS) recently developed for fusion energy applications enable MHD convertors to be constructed with magnetic fields well in excess of 15 T [2]. The increase in magnetic field can potentially improve MHD convertor efficiency, energy density, and economics [3]. This suggests that the MHD energy convertor deserves re-evaluation, which is the main thrust of our work. We have developed new 1-D analytic models for Faraday, Hall, and diagonal MHD generators in linear and cylindrical disk geometries. These models are based upon a self-consistent expansion technique, and we've applied our models to study the impact of high magnetic fields on MHD convertor performance. We have also developed a new formulation for the ionization instability, a common limit on MHD convertor performance when operating at the lower gas temperatures used in closed-cycles, and investigated how this instability is affected by the use of higher magnetic fields.

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Investigations on Plasma Turbulence in Complex magnetic Field Configurations of LVPD-Upgrade

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Abstract

A weakly magnetized, moderate density ($\sim 2 - 3 \times 10^{17} m^{-3}$), low temperature (~ 2-5 eV), high beta($\beta \sim 0.8$) plasma is produced in LVPD-U by making use of a modified source function comprises of a large area multi filamentary plasma source(LAMPS)[1] and electron energy filter(EEF)[2]. The EEF is a combination of 19 nos. of solenoidal shaped variable aspect ratio coils embedded at the axial centre of the device which divides its plasma into three characteristically different regions of source, EEF and target plasmas. The EEF introduces a uniform, transverse magnetic field of ≤120G intercepting applied axial magnetic field of Bz~ 6G. The transverse magnetic field of EEF induces cross-field transport in target plasma region. The EEF is subjected to two externally imposed conditions namely; 1) the variation of active number of coils of EEF and 2) the variation of the ratio of transverse (B_X) to ambient field (B_Z). The evolution of influenced plasma and its correlation with excited fluctuations is investigated in excited plasma scenarios. Initial investigations exhibits excitation of broad band, low frequency fluctuations ($\delta n_e / n_e \sim 4\%$) having frequency ordering $f_{ci} < f << f_{ce}$ for different imposed conditions [3]. The observed low frequency electromagnetic fluctuations shows high degree of correlation between $\delta n_e - \delta B_z$ and $\delta n_e - \delta \phi$ fluctuations in the target plasma region. The excited plasma imbeds various free energy sources viz., $L_{T_e}, L_{n_e}, \nabla P$, and energetic electrons at different configurations. Hence it proposes exciting scenarios for investigations on plasma turbulence. The paper will discuss characteristic features of evolved cross-field diffused plasma, excited turbulence under two imposed conditions and end with identification of excited modes in presence of above mentioned free energy sources.

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Graph Neural Networks for Kinetic Simulations of a 1D Plasma Sheet Model

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In recent years, attempts have been made to combine existing plasma kinetic codes with machine-learning surrogate models, in order to obtain a computational speed-up. In this work, we explore the possibility of fully replacing the plasma physics simulator with a graph neural network-based simulator [1, 2]. We show that our model learns the kinetic plasma dynamics of the one-dimensional plasma model introduced by J. Dawson [3] (a predecessor of contemporary kinetic plasma simulation codes). We focus on this class of surrogate models given the similarity between their message-passing update mechanism and the traditional physics solver update, and the possibility of enforcing known physical priors into the graph construction and update. We assess the generalization capabilities of such a model regarding the emergence of well-known kinetic plasma processes, including plasma thermalization, electrostatic fluctuations about thermal equilibrium, and the drag on a fast sheet and on a Fourier mode (Landau damping). Additionally, we compare the performance against the original plasma model in terms of running time, conservation laws, and temporal evolution of key physical quantities. The limitations of the model are also discussed and possible directions for higher-dimensional surrogate models for kinetic plasmas are outlined.

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ELECTRON TRANSPORT MODELLING IN MATTER WITH AN FDTD-PIC CODE, SOPHIE.

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The Sophie code is a 3D electrodynamics code which solves the Maxwell-Vlasov evolution equations in vacuum by the PIC-FDTD method [1] while respecting the charge conservation law and the Gaussian constraint. It was developed to simulate 3D SGEMP effects in vacuum, i.e. electromagnetic (EM) effects generated by the emission of electrons from materials exposed to strong pulsed X-ray irradiation.
We have recently implemented in the Sophie code, an inelastic diffusion model for electrons [9][10][11] which allows their transport in matter, always in the presence of a coupling with self-induced EM fields, such as in the void. This new functionality is necessary to simulate the EM effects of electron deposits in materials (ECEMP problem [5]): it is not accessible to our knowledge with the codes of usual particle transport (Monte-Carlo codes MCNP, GEANT, etc.).
In the method presented, the inelastic scattering of charged particles is modeled during each step of the Maxwell-Vlasov calculation carried out by the Sophie code: during each step, the code performs an angular draw according to a distribution function derived from the multiple scattering theories, while taking into account the slowing down using tabulated data as a function of the kinetic energy of the particle (NIST tables [8]).
We first recall the specificities and functionalities of the Sophie code already validated and used in the SGEMP and CEM applications. Then we describe the numerical methodology and the physics formalism on which the diffusion model is based. Finally, we validate this model by comparing it with simulations of elementary cases of diffusion treated with the MCNP code [56], reference code of the Los Alamos National Laboratory (LANL) for the transport of particles in matter in the absence of field effects.

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Kinetic description of plasmons on quantum Dirac plasmas: from model to applications

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The advances in quantum plasmas and the field of plasmonics have brought new and exciting problems to the plasma physics community, with a wide range of foreseen applications, from telecommunications and sensing to quantum information.

In this talk, we will focus on the realm of the bidimensional Dirac plasmas where the carriers follow a linear dispersion relation, with an ill-defined mass. Such systems can now be readily attained in novel 2D materials and integrated into electronic devices. Moreover, owing to the 2D nature, the plasma excitations are gapless; thus, constantly present, being also long-lived.

In order to analyze such systems, we present a framework where the plasma oscillations are treated as quasi-particles – the plasmons. Thus, we discuss a system of coupled Boltzmann equations – for electrons, holes, and plasmons – which models the plasma of 2D quantum systems [1]. Allowing us to effectively describe the wave–particle interactions, as a collisional plasma of fermions and bosons.

From this model, we found significant corrections to the transport coefficients, due to the plasmons. Particularly in the Dirac liquid regime at finite temperature, where we obtain, for instance, the thermal conductivity increases up to twofold [2] and the shear viscosity fourfold [3]. Moreover, in the hydrodynamic limit, we will discuss the occurrence and nature of unstable modes of the plasmon sector, and their interplay with nonlinear phenomena.

We will end with some considerations about applications and devices, in the domain of THz technologies, that could exploit the plasma instabilities produced in these systems.

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Microscopic properties of xenon plasmas in a wide range of plasma conditions

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Xenon is an element of current interest in the field of high energy density plasmas since it is commonly used, for example, in experiments of laboratory astrophysics [1-4] and extreme ultraviolet lithography [5,6]. For the radiation-hydrodynamics simulations of these plasmas or their spectroscopic diagnostics, it is useful to have a predictive numerical model of the microscopic properties of xenon. However, this is not an easy task due to the complexity of the low charge ion stages of this element.

In this work, we present numerical simulations of microscopic properties of xenon plasmas such as the average ionization, the charge state distributions, the emissivities and the opacities in a wide range of plasma conditions, with electron temperatures from 1 to 1000 eV and mass densities between 10-6 and 10-1 gcm-3. Since these conditions cover both equilibrium and non-equilibrium thermodynamic regimes, the calculations were performed using a collisional-radiative model that includes the common atomic processes in thermal plasmas such as collisional excitation and de-excitation, collisional ionization and three-body recombination, autoionization and electron capture, spontaneous decay and radiative recombination. This collisional model is implemented in the computational package MIXKIP/RAPCAL [7]. As the number of configurations and transitions of low charge xenon ions is very high (with open 4d sub-shells) and the study carried out was made in a wide range of plasma conditions, the atomic data were obtained in the relativistic detailed configuration account. For this purpose, the FAC code was used [8]. In order to group detailed transition lines, the unresolved transition array formalism has been used [9].

Acknowledgments:

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Impacts of Coil Optimization Parameters on Quasisymmetry for the EPOS Stellarator

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The EPOS (Electron Positron Optimised Stellarator) project part of the APEX (A Positron Electron eXperiment) Collaborations aims to build a small-scale stellarator using High Temperature Superconductor (HTS) tape for the confinement of pair plasmas. The discovery of quasisymmetry (QS), a symmetry in the magnitude of the magnetic field but not the direction, allowed for stellarators to theoretically achieve good confinement. The magnetic field in EPOS is planned to be quasi-axisymmetric, meaning that the magnetic field amplitude is invariant along a toroidal coordinate, therefore implying that the guiding center of particles behaves as if it was in a real axisymmetric field. This target must be balanced against the mechanical constraints imposed on the torsion, length and curvature of the HTS coils. The goal is to reach a good experimental approximation of a quasi-axisymmetric field while minimizing the stress on the HTS coils.

Here, we will present the effects of macroscopic coil parameters on the QS properties using the SIMSOPT code. We first focused on finding the optimal number of coils with regards to the QS error calculated. The magnetic field is based on a given target equilibrium. The measure of the quasisymmetric error can be based on local geometric deviations that are then summed together or it can be deduced from single flux surface properties such as the Boozer spectrum. Both methods have been applied to quantify the departure from QS for an increasing number of coils. Initial studies found that the QS error is a non-monotonic function of coil number, contrary to expectations. In order to account for the influence and interplay of the optimization parameters, and to obtain better understanding of the fundamental behavior of the QS error as a function of the number of coils, a statistical study is being performed where the optimization parameter space is mapped and the QS error analysed. At the same time, more work targeting the local QS error along the surface is being done in order to identify patterns that can help with coil optimization. Further studies based on stochastic coil optimization will be conducted to reach better Quasisymmetry and as well as improved paths for HTS coil packs.

Optimizing HTS coils for the EPOS pair plasma stellarator

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The future EPOS (**E**lectrons and **P**ositrons in an **O**ptimized **S**tellarator) aims to confine an electron positron pair plasma with coils made from high-temperature superconductors (HTS) [1]. HTS tapes contain a functional ceramic layer that cracks under sufficient mechanical strain, making non-planar coils particularly challenging as they put the tape under torsion and hard-way bending. The number of available positrons is small and limited, so a small volume is necessary to achieve plasma conditions in EPOS. However, smaller coils results in higher strains on the conductor.

In this conference, we present numerical optimization schemes that focus on the buildability of stellarator coils with regards to the mechanical strains on HTS. To address this, we optimized the tape orientation along the coil filament to construct a winding path for the HTS tape within the limits of torsion and hard-way bending, similar to the approach used in [2]. It has been verified by constructing two demonstrator coils with 3D-printed downsized W-7X coils, which demonstrated superconducting operation in liquid nitrogen. We present critical current measurements of the tape after being wound around an optimized coil former as well as resistive measurements of the coils in liquid nitrogen.

The next step is to integrate constraints arising from HTS tape usage into the cost function of the coil optimization within the `SIMSOPT` framework [3]. In addition to quasisymmetry, additional terms that factor in torsion and hard-way bending of the winding path are included in the cost function. This approach can be applied to the optimization of single-filament coils and finite-build winding packs, providing a solution for the future EPOS coilset and enabling more compact devices. We are currently preparing experimental verifications of this approach.

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Quantum Operations Formalism in Collisional Magnetized Plasmas

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Quantum simulation of classical linearized dynamics requires unitary evolution. Classical systems admit unitary evolution when they are considered closed and the energy is conserved. This is the case for the linearized wave dynamics of collision-less magnetized plasmas where relevant quantum computing implementation concerning RF wave propagation has been proposed [1]. On the other hand, dissipating processes such as collisions in plasma introduce a non-Hermitian part in the generator of the dynamics [2] resulting to non-unitary evolution. In order to cope with this difficulty we treat the dissipative system as an open system. In that way, we construct a physical environment coupled with the plasma so the total plasma-environment system evolves unitarily.

Since we are interested on quantum computation implementation of dissipative magnetized plasmas we incorporate elements from the theory of open quantum systems [3]. The number of qubits and the initial correlations between the states of the principal plasma system and environment dictate the form of the unitary evolution for the total system. Application of the formulation is considered for the simple phenomenological model of Krook collisions in cold magnetized plasma but can be extended to other dissipating plasma cases such as wave propagation in magnetized, temperate and collisional plasmas through the Boltzmann-Maxwell system of equations.

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Filamentation in spin-polarized quantum plasma

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The study of electron beam-wave interaction in the presence of background plasma has attracted a lot of interest over the past few decades. In plasmas, when the de-Broglie wavelength of the charge carriers is comparable to the dimension of the plasma system, quantum mechanical effects are expected to play a major role in the behavior of charged plasma particles. Filamentation in quantum plasma have been studied by various authors but all the previous studies considered electrons as a single fluid of macroscopically averaged spin-1/2 plasma. The different electron spins (up and down) are not taken into account and their mutual interactions are ignored which is in violation of the Pauli's exclusion principle. In the present talk, filamentation of a short laser pulse in a magnetized quantum plasma will be presented in detail, taking the spin-up and spin-down electrons to be separate species of particles, thereby considering the spin-spin interaction. The effects of quantum Bohm potential, electron Fermi pressure and spin will also been taken into account. The direction of the external field will be taken to be along the direction of electron beam propagation in the first case and oblique in the second case. The growth of filamentation will be analysed for both the cases. The results will be helpful in the analysis of filamentation produced in the interaction of laser pulse with magnetized quantum plasma and will find application in diverse fields like spintronics, astrophysics, ICF, x-ray FEL's, future generation high density plasma experiments, etc.

Energy Conserving semi implicit (ECSim) method for astrophysical and fusion energy applications

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The full 6D discretization of global system with Particles in a Cell (PIC) methods is a great challenge. Practical application of PIC is determined by two constraints. Stability and accuracy. Accuracy is needed to describe correctly the processes of interest. However, numerical stability is required to prevent numerical errors and in partciular the onset of numerical instabilities that lead to gross violation of physical contractions such as energy conservation. A way to avoid the latter problem and focus on accuracy instead is the use of semi-implicit methods. Semi-implicit temporal discretization is a simpler temporal discretization compared to fully implicit to avoid non-linear iterations. The coupling of the particles and field is retained, but in a linear formalism that requires a matrix solver rather than a non-linear iteration. The Energy Conserving Semi-Implicit Method (ECSim) introduced a new formalism based on the mass matrix to enforce energy conservation in the particle-field interaction. This is a property that has been elusive in all previous explicit and semi-implicit methods. EC thus combines numerical stability and physical fidelity from exact energy conservation with simplicity of implementation (compared to fully implicit nonlinear methods) that allows efficient execution on massively parallel super-computers of the present and future generation. For practical application, the ECsim method allows a flexible choice of resolution scales [2-4] that allows modeling of large systems. EC has found wide application to space and astrophysics [4] and has recently been applied to magnetic fusion devices. We will present the latest developments of the ECsim approach [6] and our recent results in the study of magnetic reconnection [7].

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On the intensity of focused waves near turning points

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A wave near an isolated turning point is typically assumed to have an Airy function profile with respect to the separation distance. This description is incomplete, however, and is insufficient to describe the behavior of more realistic wavefields that are not simple plane waves [1]. Asymptotic matching to a prescribed incoming wavefield generically introduces a phasefront curvature term that changes the characteristic wave behavior from the Airy function to that of the hyperbolic umbilic function. This function, which is one of the seven classic 'elementary' functions from catastrophe theory along with the Airy function, can be understood intuitively as the solution for a linearly focused Gaussian beam propagating in a linearly varying density profile, as we show. The morphology of the caustic lines that govern the intensity maxima of the diffraction pattern as one alters the density lengthscale of the plasma, the focal length of the incident beam, and also the injection angle of the incident beam are presented in detail. This morphology includes a Goos-Hanchen shift and focal shift at oblique incidence that do not appear in a reduced ray-based description of the caustic. The enhancement of the intensity swelling factor for a focused wave compared to the typical Airy solution is highlighted, and the impact of finite lens aperture is discussed. Collisional damping and finite beam waist are included in the model and appear as complex components to the arguments of the hyperbolic umbilic function. The observations presented here on the behavior of waves near turning points should aid the development of improved reduced wave models to be used, for example, in designing modern nuclear fusion experiments.

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Partial-ionization deconfinement effect in magnetized plasma

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We show that multi-ion transport changes its nature in partially ionized plasma, where ions can be in different charge states and each charge state can be described as a different fluid for the purpose of multi-ion collisional transport. [1] In the case of two charge states, transport pushes plasma toward equilibrium which is found to be a combination of local charge state equilibrium and generalized pinch relations between ion fluids representing different charge states. Combined, these conditions lead to a dramatic deconfinement of ions, which happens on the timescale similar but not identical to the multi-ion cross-field transport timescale, as opposed to electron-ion transport timescale in fully ionized plasma. Deconfinement occurs because local charge state equilibration enforces the disparity in diamagnetic drift velocities of ion fluid components, which in turn leads to the cross-field transport due to ion-ion friction. This deconfinement effect is potentially important in a number of applications, including nuclear fusion and plasma mass filters.

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Static exchange–correlation kernels for high-energy density plasmas and warm dense matter

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The properties of materials at high pressures and temperatures in high-energy density plasmas and warm dense matter (WDM) differ significantly from those under ambient conditions. At these conditions, basic atomic properties like an atomization energy become ill defined and basic material properties such as bulk moduli cannot be accurately measured due to extreme conditions. Therefore, ab initio methods such as thermal density functional theory are particularly important for description of experimental data and for guiding experimental developments. One of the key quantities for describing dense plasmas and WDM is an exchange-correlation (XC) kernel, which is defined as the second order functional derivative of the XC functional with respect to density. We developed a new method that allows one to compute material specific static exchange-correlation kernel across temperature regimes using standard DFT codes and for any XC functional available in Libxc [1]. In this presentation we show the results of the static exchange-correlation kernel analysis from computations using various XC functionals for dense electron gas and warm dense hydrogen. By comparing the data to the exact QMC results, we are able to understand the effect of thermal excitations and density inhomogeneity on the exchange-correlation kernel. Moreover, we discuss the results of the analysis of the accuracy of the commonly used exchange-correlation (XC) functionals for warm dense matter simulations [1-4]. The analysis is performed by comparing highly accurate path-integral quantum Monte-Carlo (QMC) data with KS-DFT results. Finally, a new methodology for linear-response time-dependent density functional theory approach to warm dense matter with static exchange–correlation kernels is presented [5].

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Generalized Multi-Temperature Zhdanov Closure for the Calculation of Plasma Transport Coefficients

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Impure plasmas are ubiquitous with their presence in applications ranging from nuclear fusion to industrial plasmas. However, the presence of impurities can cause the transport properties of the plasma to change, and in turn, one must also know the behaviour of impurities in the plasma. One such method of calculating the plasma transport coefficients and the forces on impurities has been given by Zhdanov et al[1]. The thus-named Zhdanov closure prescribes the friction and thermal forces, and the viscous-stress tensor of each species, however it does so assuming that the temperatures of all colliding species are near each other. However, different plasma species being at different temperatures is a common phenomenon in both fusion and industrial plasmas. Therefore, we generalize the Zhdanov closure for the multi-temperature case, and provide a general derivation method for the multi-temperature collision coefficients[2, 3]. We find that the single-temperature transport coefficients are generally valid for small temperature differences ($\sim 10\%$) for multi-species plasmas with ions of comparable mass like deuterium-tritium plasmas and for heavy ions such as tungsten in trace density levels. However, for light impurities like argon and neon, significant differences are found to persist between the single-temperature and multi-temperature Zhdanov closure for values of transport coefficients (up to 80%) and friction/thermal forces very different (up to 40%) even for small temperature differences. These key results, alongwith a general overview of the Zhdanov closure and its assumptions, will be presented in this contribution.

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2D Electromagnetic Scattering from Anisotropic Dielectric Objects using the Qubit Lattice Algorithm

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Abstract

By determining an appropriate Dyson map, we have developed a basis from which one can discern a unitary representation for Maxwell equations in anisotropic dielectric media. In particular, one of the simplest representation for an inhomogeneous tensor dielectric for uni- or b-axial media. is the basis set $(\sqrt{\boldsymbol{\epsilon}} \cdot \mathbf{E}, \mathbf{B})$. where $\boldsymbol{\epsilon}$ is the permittivity tensor, and $\mathbf{E}, \mathbf{B}$ are the electromagnetic fields. Our Qubit Lattice Algorithm (QLA) directly encodes these fields into a qubit representation. A unitary set of interleaved collision-streaming operators are then applied to these qubits: the unitary collision operators entangle the on-lattice site qubits, while the streaming operators move this entanglement throughout the lattice. With our current set of unitary collision-streaming operators, we do not generate the effects of derivatives on the dielectric tensor $\boldsymbol{\epsilon}$. These terms are included by the introduction of external potential operators - operators that are sparse but non-unitary..

Here we present QLA simulations on 2D scattering of a 1D electromagnetic pulse from a localized Hermitian tensor dielectric object. The two different polarizations of the electromagnetic field lead to two different scattering profiles since the dielectric scatterer is anisotropic. The QLA we consider here are based on the two curl equations of Maxwell. Moreover the QLA is a perturbative representation, with small parameter δ representative of the spatial lattice width, with $QLA \rightarrow$ curl-curl-Maxwell as $\delta \rightarrow 0$. It is not at all obvious that the QLA has the right structure to recover Maxwell equations - but only through symbolic algebra (Mathematica) do we determine this Maxwell limit. Hence it is of some interest to see how well QLA satisfies the two divergence equations of Maxwell that are not directly encoded in our QLA . We find spontaneous field generation in the QLA so that $\nabla \cdot \mathbf{B} = 0$, $\nabla \cdot \mathbf{D} = 0$ to appropriate accuracy.

The energy $\mathcal{E}$ is nothing but the norm of the qubit representation, and so would be conserved in a fully unitary algorithm. Since here the external potential operators are not unitary, QLA yields an $\mathcal{E} = \mathcal{E}(t, \delta)$. However as $\delta \rightarrow 0$, $\mathcal{E}(t, \delta) \rightarrow$ const. to good accuracy. We are actively pursuing a fully unitary QLA.

Nonadiabatic frequency chirping Alfvén mode in Fusion plasmas

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Chirping is a phenomenon commonly observed in both space and laboratory plasmas, where the frequency increases (up-chirping) or decreases (down-chirping) with time. In space, Chorus excitation and the associated nonlinear dynamics are among the long-studied physics problems in Earth's magnetosphere. Chorus chirping has implications for particle acceleration and redistribution in the radiation belts. In Tokamak fusion plasmas, frequency chirpings of Alfvénic fluctuations driven by energetic particles (EPs) are frequently observed. Such chirping is a major issue in connection with increased fast ion losses in tokamaks and there is currently little understanding of how to systematically predict and avoid it. As the theory predicts [1], the frequency chirping of Alfvén modes driven by EPs in realistic Tokamak fusion plasmas is a nonadiabatic process when the modes are away from marginal stability. In this work, we use first principles gyrokinetic simulations [2, 3] to investigate various nonadiabatic features of the chirping modes in Tokamak geometry. By maximizing wave-particle power exchange, the mode continuously traps and detraps the resonant particles, and self-consistently adjusts its frequency and mode structure. Consequently, the mode frequency chirping rate is found to be linearly dependent on the saturation amplitude that can also be observed in the experiment. It is worth noting that the corresponding numerical results are also found in Chorus studies [4], which have been analytically explained in [5] within the same theoretical framework as demonstrated in [6].

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Moment tracking to improve macroparticles

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In particle-in-cell codes, particles are often grouped together into 'macroparticles' but this loses detail about small-scale distributions within a macroparticle. This work proposes adding additional structure to macroparticles, by tracking the moments of the group of particles represented by the macroparticle. Tracking moments provides additional information about the underlying distribution of particles, at a cost of increased computational time and memory usage. By taking moments to higher orders it may be possible to model a large section of a plasma with a single macroparticle and its moments.

The theory for moment tracking is developed through distributions (derivatives of Dirac delta-functions) [1]. The moment tracking equations are not closed – higher order moments can generate lower order moments. This means the moment tracking method is only valid in situations where higher order moments can be considered negligible.

By using the theory of distributions, the coordinate transformation rule for the moments can be found, which cannot be done by other methods for moment tracking. This is particularly useful for astrophysical plasmas, where there is a choice in the coordinate system used. Numerical validation of the moment tracking equations is performed by modelling the accretion disc around a black hole in Schwarzschild and Kruskal-Szekeres spacetimes.

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