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Predicting neoclassical toroidal viscous torque in present and future tokamaks: status and challenges

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This is an overview on the state of predictive modeling of neoclassical toroidal viscous (NTV) torque driven by non-axisymmetric magnetic perturbations in tokamaks [1]. Such perturbations arise from toroidal field ripple, error fields and auxiliary coils for intentional 3D perturbations. NTV torque results from perturbations of the magnetic field strength from both, direct Eulerian perturbation and Lagrangian contribution from distortion of flux surfaces. Since NTV torque scales with the square of the perturbation amplitude, accurate plasma response models are key for quantitative predictions. Currently, linear and nonlinear ideal and resistive magnetohydrodynamic models are available with options to include kinetic effects in perturbed equilibria. At reactor-relevant collisionality in present-day medium sized tokamaks, ion orbital resonances have been shown to add orders of magnitude to NTV torque predictions compared to models that don't account for this effect [4]. Significant influence is seen from electrons in collisional regimes, magnetic shear and finite ion orbit width effects. In addition, non-linear attenuation can modify the result. At fast rotation approaching the ion thermal velocity, usual model assumptions break down. We assess the importance of the listed NTV model details together with the underlying plasma response models for current devices and at reactor scale. The focus is on machines in the current EUROfusion task on tokamak exploitation and future EU-DEMO. Based on this analysis and currently available numerical models, we quantify the uncertainties in NTV torque predictions and identify their drivers. We conclude with a discussion of strategies in modeling and experiment to overcome these challenges.

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Non-linear gyro-kinetic Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEM) turbulence modelling in X-point geometry in negative and positive triangularity shapes.

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Sufficiently strong negative triangularity (NT) shaping of tokamak plasma prevent the bifurcation to H-mode while leading to high confinement regimes similar to H-mode plasmas but without Edge Localized Modes (ELMs) [1-2]. It could be a promising regime for fusion reactor. In the recent theoretical and numerical studies the conclusions vary depending on the physics included in either local, global, linear or non-linear models, plasma profiles and type of turbulence considered. The most general conclusion by now is that NT shaping is mainly stabilizing for the Trapped Electron Modes (TEMs) [3-5] and possibly also for Ion Temperature Gradient (ITG) modes [7].

The recent results of the comparative modelling of negative (NT) and positive (PT) triangularity plasmas will be presented. The non-linear global gyro-kinetic particle code JOREK-GK [8-9] in the realistic X-point tokamak geometry including Scrape Off Layer (SOL), divertor and walls was used. The equation of motion of gyro-centers of ions is solved in a time varying gyro-averaged electric field and time-constant magnetic field. The kinetic electrons follow the guiding center orbits. Electron-ion collisions are included in the model.

To begin, the comparison of JOREK-GK code with gyro-kinetic codes GS2 [4], GENE-X and GENE [5] was done on a few selected NT/PT triangularity TCV–like parameters. It showed good agreement between codes in linear growth rates of ITG/TEM modes in linear phase and clear beneficial effect of NT as compared to PT. Next, the global non-linear modelling of the ITG/TEM saturated turbulence for realistic DIII-D NT pulses was done and compared with constructed "mirror-flipped" PT equilibrium with the same plasma profiles. The larger time-space correlation of density fluctuations at PT compared to NT was demonstrated explaining larger turbulence and heat fluxes at PT. The direct comparison with experimental heat conductivities and Doppler Backscattering (DBS) measurements of density fluctuations correlation and edge poloidal ExB velocity in DIII-D showed a good agreement with JOREK-GK modelling. Weak dependence of plasma confinement on collisionality was found in NT. Counter-current plasma rotation is stabilizing factor for the edge turbulence since it increases the shear of the poloidal ExB flow. Finally, the confinement scaling with normalized ion radius ρ^* was estimated both for NT and PT. Bohm-like scaling was obtained in both configurations, however with better confinement for NT compared to PT which could be favorable factor for reactor size machines with high confinement operation without harmful ELMs.

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Predictive integrated modeling of core impurity transport in the Volumetric Neutron Source (VNS) Tokamak

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Significant efforts within the EUROfusion program have focused on developing the Volumetric Neutron Source (VNS), aimed at testing in-vessel components under high neutron fluxes representative of future fusion reactors. The concept involves injecting a deuterium neutral beam into a tritium plasma to maximize the fusion yield, as in JET's record fusion pulse [1]. To achieve a high Neutron Wall Load (NWL) of ~0.5 MW/m² while minimizing tritium consumption, the VNS is designed as a compact, high-aspect-ratio tokamak ($R \approx 2.5$ m), with beam-driven current and strong plasma rotation due to the absence of a central solenoid. Tungsten plasma-facing components are required to sustain high damage rates (dpa) in steady-state operation.

A first design point has been identified [2] and is currently being refined. To this aim, this work presents integrated core plasma transport modelling, focusing on micro-instability-driven turbulence and tungsten transport. Predictive simulations are carried out using ASTRA, coupled with FACIT [3] and TGLF-SAT2 for neoclassical and turbulent transport, respectively. RABBIT and TORBEAM are used for NBI and ECRH power deposition, while the NEUT subroutine accounts for recycling effects, mainly affecting tritium. Pedestal transport is treated using the scaling law by J. Puchmayr [4].

Due to the high tritium throughput - nearly an order of magnitude higher than deuterium pellets - the two species are simulated separately to avoid unphysical positive tritium density gradients. Additionally, the strong rotation driven by NBI generates large parallel velocity gradients, potentially triggering Kelvin-Helmholtz-like instabilities. Assuming $Pr = 1$ and an edge momentum diffusivity of ~1 m²/s ensures simulation stability, without entering loops, by which the parallel velocity gradient instability eventually leads to the collapse of the temperatures. Tungsten transport is analyzed by performing a scan of the source coming from the wall and the ECRH power to study core impurity accumulation.
The results identify preliminary operational limits for VNS, primarily related to the strong NBI-driven rotation, which could be mitigated, for instance, using static coils.

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Experimental Study on Pedestal Fluctuations in H-modes without Large ELMs during the Transition to A Detached Tungsten Divertor at EAST

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Studying on the pedestal fluctuations in small/no ELM H-modes may provide important insights into sustainment of large ELM elimination when compatible with a radiative divertor. H-mode operation without large edge-localized modes has been achieved in EAST with an ITER-like tungsten divertor, while being compatible with the partial and pronounced detachment in divertor, via either ramping-up of bulk density or injection of low/high-Z impurities. The pedestal characteristics during the transition from the attached to the detached divertor and the reversed transition (detached to attached) under different detachment methods are studied in detail, where the evolutions of multi fluctuating structures commonly residing in the H-mode pedestal of EAST (edge coherent mode (ECM) [1], magnetic coherent mode (MCM) [2] and high frequency mode (HFM) [3]) are highlighted. It is found that in the pronounced detachment which EAST has successfully achieved at the auxiliary heating power P_{source} = 2–6 MW, the ECM tends to disappear either by ramping plasma density up or by impurity injection in the divertor, while evolutions of the MCM and the HFM behaviours are not uniform. Further analysis shows that, in addition to the pressure gradient which is considered as a primary free energy source for the pedestal instabilities including the ECM, the MCM and the HFM, the pedestal collisionality also appears to play a crucial role in affecting the ECM amplitude, and subsequently influencing the MCM and the HFM intensities possibly via re-allocating free energy among the three modes. In addition, the radial structures of ECM, MCM and HFM are compared, for the first time, in one discharge.

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Blob structures and density shoulder formation in Alcator C-Mod

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Fluctuations in the boundary region of the Alcator C-Mod device are investigated with mirror Langmuir probe and gas puff imaging measurements in a series of experiments with a scan in core plasma density [1]. This reveals the familiar broadening and flattening of the radial electron density profile in the scrape-off layer. Time delay estimation and conditional averaging methods are applied to deduce blob sizes and velocities at various radial positions within the boundary region. In discharges characterized by low density, the dynamics of blobs manifest in the far scrape-off layer, exhibiting radial velocities reaching up to 500 m/s. As the core plasma density approaches the empirical discharge density limit, blob dynamics come to dominate the entire scrape-off layer, extending even inside the last closed magnetic flux surface with radial velocities exceeding 1 km/s. The fluctuations measured at any given location within the gas puff imaging field-of-view display pronounced intermittency in the region primarily governed by blob structures. Both the radial profiles and the fluctuations are in excellent agreement with a stochastic model describing the blobs as a super-position of uncorrelated pulses moving radially outwards, predicting a particle density profile e-folding length given by the product of the radial blob velocity and the parallel loss time [2]. With increasing core plasma density, the blobs move faster, the average particle density in the far scrape-off layer increases and the fluctuations become more intermittent, resulting in enhanced plasma interactions with plasma-facing components. Similar fluctuation statistics are shown to apply to H-mode plasmas in Alcator C-Mod.

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Flow shear turbulence suppression in GBS simulations of a RFX-mod diverted plasma in the presence of voltage biasing

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The **E**×**B** flow shear is believed to play a key role in suppressing plasma turbulence in the edge of magnetic confinement fusion devices, also enabling the transition to a high-confinement (H-mode) regime [1]. A direct method to generate **E**×**B** flow shear consists in biasing the tokamak plasma boundary region. Past RFX-mod tokamak experiments have shown that the H-mode can be routinely and robustly achieved at low power by inducing edge flow shear by means of a biasing electrode inserted into the plasma edge of a diverted magnetic configuration, providing further and direct evidence of the impact of flow shear on edge turbulent transport [2].

In this work, three-dimensional GBS [3] turbulence simulations of a RFX-mod diverted plasma are performed at various reference density values and in the presence of a biasing electrode, which has been recently implemented in GBS. The simulations show a strong suppression of turbulent transport caused by the flow shear generated by the biasing electrode, leading to the formation of an edge transport barrier with a pedestal-like structure, which agrees qualitatively and quantitatively with RFX-mod experiments. Significant flow shear turbulence suppression is also observed at high density near the crossing of the density limit. By building on the results of GBS simulations at high density, the theoretical scaling law of the maximum achievable edge density derived in Ref. [4] is extended to account for the effects of flow shear turbulence suppression. The improved scaling law predicts that the maximum achievable edge density in RFX-mod could be increased by a factor of two by generating a moderate flow shear with the biasing electrode, thus calling for future RFX-mod2 experiments with the aim of validated the prediction of the theoretical model.

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Small-ELM H-modes in strongly shaped MAST Upgrade tokamak plasma

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Future pilot tokamak power plants will likely maintain fusion-relevant conditions in high-confinement modes (H-modes), characterised by the formation of a "pedestal". However, the resulting steep radial pressure gradient often triggers edge localised modes (ELMs), the largest types of which (Type-I) can degrade core confinement and cause serious damages to vessel walls. Future tokamaks must therefore operate in Type-I ELM-free regimes, whilst maintaining the high core confinement of standard H-modes.

One such example is the quasi-continuous exhaust (QCE) regime, in which the pedestal height is still comparable to Type-I ELMy regimes, but with increased radial transport across the pedestal suppressing the ELMs. Observations on ASDEX Upgrade[1] indicate that QCE regimes can be triggered in strongly shaped plasmas with high elongation and triangularity, compared to the Type-I ELMy counterpart.

In recent experiments at MAST-U spherical tokamak, a number of discharges exhibited long Type-I ELM-free periods [2] with high triangularity and squareness, and elevated Dα emission level. MHD stability analysis using the ELITE code shows the pedestals are very close to the ideal ballooning limit, even though Type-I ELMs are not triggered. Doppler Back-Scattering system and Beam Emission Spectroscopy data show increased density fluctuation amplitudes in the pedestal region, with the modulation consistent with high-frequency Type-II ELMs. All the evidence points to these "Type-I ELM-free" periods corresponding to the QCE regime, which is the first such identification on MAST-U. If QCE regimes in spherical tokamaks are found to be scalable to reactor-relevant conditions, then our results will have significant impact on the scenario design of pilot power plants, such as STEP.

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ATEP: A phase space resolved transport model for energetic particles

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In addition to increasingly realistic non-linear global simulations [1], a hierarchy of theory-based reduced models is needed to complement the predictions concerning the performance of future burning plasmas. Large parameter scans, sensitivity studies and multi-scale physics connecting energetic particle transport with neoclassical (transport) time scales require tools that go beyond what is presently feasible with first-principles numerical codes.
In the view of this challenge we report in this work on the implementation and verification of a phase-space resolved energetic particle (EP) transport model [2, 3]. It is based on the Phase Space Zonal Structure transport theory [4, 5, 6, 7] , which extends the conventional transport equations into Phase Space and consistently evolves a (nonlinear) equilibrium referred to as the Zonal State. Its focus is primarily directed toward understanding the meso-scopic character of EPs and its consequences [8] . Compared to the conventional description of thermal radial transport via a one-dimensional radial diffusion equation, the newly developed model is three-dimensional using canonical constants-of-motion (CoM) variables. The model does not assume diffusive processes to be dominant a priori, instead the EP fluxes are self-consistently calculated and directly evolved in CoM space. A Fokker-Planck collision operator with orbit-averaged numerical coefficients evaluated on the same CoM coordinate grid allows us to treat EP sources and wave-induced transport consistently on background transport and EP slowing-down time scales. The code named ATEP-3D is fully embedded in ITER IMAS framework and closely connected to the EP-Stability workflow [9]. The workflow contains a hierarchy of analytical, local and global models that as been automated and tested for an extended set of different Alfvénic instabilities in various Tokamak geometries.
As a first application, the phase space fluxes are determined either in the limit of constant mode amplitudes (kick-limit), or an energy-conserving quasi-linear model. Single and multi-mode cases addressing the transition from isolated to overlapping resonances are discussed and compared with ORB5 [10, 11]. Non-linearly evolving beat-driven zonal fields are included using an analytical model [12] for radial mode structure and saturation. Various strategies and first steps how to couple the workflow to 1-d transport codes are reported.

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Strong impact of separatrix conditions on full-radius L-mode predictive integrated modelling

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Turbulent transport in the tokamak edge region plays an important role in determining global confinement, pedestal structure, and the L–H mode transition [1]. Theoretical studies and numerical simulations of L-mode plasmas indicate that edge turbulence exhibits characteristics distinct from core turbulence, arising from steeper density and temperature gradients, higher resistivity, and increasingly non-adiabatic behaviour of passing electrons [1]. Moreover, L-mode database studies show clear correlations between separatrix parameters and core plasma performance [2], motivating a full-radius investigation to understand the causality behind the reported correlations.

The present study is based on a WEST L-mode plasma heated by Lower Hybrid Current Drive, for which electron density and temperature profiles have been successfully predicted up to the separatrix using the High Fidelity Plasma Simulator (HFPS)—an IMAS-coupled version of the JINTRAC workflow [3]. Turbulent transport is modelled using the TGLF-sat2, previously validated against experimental profiles in ASDEX Upgrade L-mode plasmas [4].

In this work, HFPS is employed to investigate the effects of separatrix parameters—electron density, electron and ion temperatures, and neutral energy—on particle and heat transport as well as plasma profiles. Radiative losses and heating sources are kept fixed. Changes in separatrix electron temperature and density have global impacts on the energy content, density peak through modified turbulent transport, while variations in ion temperature have expected impact on ion temperature profile only in case of stiff transport. The propagation of boundary condition changes is explored in various scenarios: frozen particle flux vs feedback on the line-averaged density (as applied experimentally). Moreover, standalone analyses with TGLF-sat2 and the higher-fidelity gyrokinetic code GKW [5] further explore the individual roles of collisionality, density peaking, and electron-ion temperature ratio (Te/Ti).

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Isotope mass dependence and physics of internal transport barrier trigger and sustainment in JET with Be/W wall

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In view of ITER and future fusion reactors, where internal transport barriers (ITBs) may form spontaneously, there is a need to fully understand the physics of ITB trigger and sustainment in order to avoid ITBs or control their strength. For the first time on JET with metallic wall, we reveal the importance of the main ion isotope mass (A_{eff}) on ITB triggering and strength by comparing a unique dataset of discharges performed in D, T and D-T. First-principle calculations of the reduction of anomalous transport with different isotopes are provided to shed light on the underlying physics. The JET-ILW D-T ITB scenario (3.4 T / 2.7 MA, q_{95} ~ 3.8, $n_e \leq 4$ x10^{19} m^{-3}, $T_{i,core} \geq 10$ keV, q_0 >1) had auxiliary heating from NBI only. The optimised q-profile in the phase prior to full NBI likely facilitates the transition to improved core thermal ion and electron confinement, as indicated by a semi-empirical ITB transport model, which combines magnetic and *ExB* rotation shear effects. The ITB appears to be triggered at the location of the plasma q = 2 surface, as observed in JET with C wall. After ITB onset, the density profile becomes very peaked, primarily due to a reduction in pedestal density ($n_{e,PED}$). A clear ITB is observed at mid-radius in both ion and electron channels. A significant impact of A_{eff} on ITB access and strength is observed: the ITB is more easily triggered (namely, at lower NBI power) and, once fully developed, has its foot at a larger radius in T than in D. With fully developed ITB, the core ion heat diffusivity χ_i is lower for T than D and over a wider plasma volume, reaching neo-classical values. GENE and CGYRO simulations of the core plasma are ongoing to understand the impact of A_{eff} on ITB trigger and strength, as well as the roles of magnetic and toroidal rotation shear, fast ion and thermal ion density and their interplay with respect to ITB formation. The discharge phase with ITB is correlated with a transition to a pedestal with 'small/high frequency ELMs' and strong decrease in $n_{e,PED}$. The pedestal density of plasmas with ITB decreases with A_{eff} from D to T, opposite to what observed in type I ELMy H-modes. GENE simulations of the ITB plasmas low-density pedestal are on-going to identify the dominant micro-instabilities at play and assess the isotope dependence of pedestal heat and particle transport. A key question is whether low $n_{e,PED}$ and absence of type I ELMs are necessary to trigger the ITB or if the formation of an ITB leads to degradation of the pedestal pressure gradient. Intrinsic impurities are Be, W and Ni. Core W and Ni impurity transport is explained with NEO predictions. The complex interplay of high Mach number (M_ϕ ~ 0.6) enhancing impurity screening at low plasma collisionality, but enhancing inward convection with increasing Z_{eff}, regulates the high and mid-Z impurity dynamics. Sensitivity scans on the gradients of the driving parameters,∇T_i and∇n_e, within experimental uncertainties, are carried out to enhance confidence in the model predictions.

Geometry effects on gyrokinetic instabilities and turbulence in W7-X

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The stellarator Wendelstein 7-X (W7-X) demonstrated the effectiveness of reducing neoclassical transport through magnetic field optimization [1]. Its confinement is primarily governed by turbulence arising from instabilities at scales comparable to the gyroradius [2,3]. For small plasma beta (the ratio of kinetic to magnetic pressure), these instabilities are predominantly electrostatic and often driven by ion temperature gradients (ITG). ITG-driven turbulence is sensitive to magnetic field properties—a dependence that needs to be considered in the design of the next-generation optimized stellarators. However, the experimental characterization and theoretical modeling of turbulence in W7-X remain incomplete, particularly regarding its geometrical properties.

In this contribution, we numerically investigate gyrokinetic plasma turbulence in W7-X, with a focus on potential performance improvements through the modification of geometrical properties. Specifically, we compare density fluctuation measurements from the Phase Contrast Imaging (PCI) diagnostic [4,5] with both linear and nonlinear simulations performed using the gyrokinetic code stella [6]. As part of this comparison, we examine the impact of the mirror ratio and the global value of the rotational transform on plasma performance [7]. Our simulations show good agreement with analytical expectations, although some experimental observations still remain puzzling. Finally, we propose a method for locally modifying ITG turbulence through tailored adjustments of the rotational transform profile [8]. This approach builds on the influence of electron cyclotron current drive in plasmas heated via electron cyclotron resonance [9].

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Addressing turbulence questions in the Wendelstein 7-X stellarator - a combined experimental and theoretical approach

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With the advent of stellarators optimised for low neoclassical transport like Wendelstein 7-X (W7-X), turbulent transport remains as one of the main obstacles to be overcome for both tokamaks and stellarators on the path to a working fusion reactor. With W7-X, a well-diagnosed advanced stellarator, we can directly probe turbulence in the flexible magnetic geometry and compare against state-of-the-art gyrokinetic codes. Recent findings on electrostatic and electromagnetic turbulence in W7-X will be shown, e.g. how, at much lower normalised plasma pressure than previously anticipated, kinetic ballooning modes that appear below the MHD threshold can lead to an increase in ITG turbulence [1,2] or that heat-pulse propagation experiments confirm rather benign transport caused by electron-temperature gradient modes [3]. We will also discuss whether the density-gradient-driven trapped-electron mode is indeed more benign in W7-X as predicted by theory [4], and discuss currently unanswered questions, such as whether the universal instability, recently [5] found in numerical simulations, can be identified in the experiment and whether it might be the cause of the sudden change in particle and heat diffusivity observed at high plasma density [6].

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Multi-device study of E_r and its sensitivity to magnetic topology in tokamaks

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The E_r "well" at the edge of tokamak plasmas displays a complex phenomenology. The main mechanisms controlling its detailed structure are not well identified yet. Moreover, the link between edge $E_r \times B$ shear and access to higher confinement regimes remains to be clarified. Among the most telling examples—and the focus of this study—is the empirical sensitivity of the E_r well to magnetic ($B\times\nabla B$) topology in L-mode [1–3] and its probable connection to the altered L-H transition threshold [4]: The sharper E_r well witnessed in "favorable" compared to "unfavorable" $B\times\nabla B$ drift (pointing towards or away from the X-point, respectively) appears consistent with facilitated H-mode access in the former. However, this causality is not established yet, and the fundamental cause for such pronounced asymmetry remains elusive. As part of a multi-device effort to elucidate this phenomenon, we present and compare results from the WEST, AUG, and TCV tokamaks. Particular focus is given to recent TCV experiments, enabled by a Doppler backscattering diagnostic on loan from LPP, which allowed the first extended edge E_r measurements on this device [5]. TCV results concerning the favorable/unfavorable asymmetry are broadly in line with AUG [1,3] and WEST [2], showing a shallower well in unfavorable $B\times\nabla B$ [6]. Yet, the observations in TORE SUPRA [7] and WEST [2,8] of a strong variation of E_r shear with I_p in unfavorable $B\times\nabla B$ is not recovered in TCV [6], nor in recent AUG experiments. Possible reasons for the discrepancy are discussed. Beyond the sensitivity to I_p, the role of other parameters including density and shaping is examined. Finally, the evolution of E_r approaching the L-H transition in favorable and unfavorable magnetic topologies points to a central role of the inner $E_r \times B$ shear layer in facilitating the L-H transition.

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Efficient steady-state predictions of core plasma profiles with delta-f nonlinear gyrokinetics using the PORTALS framework

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Recent advances in efficient transport solvers have enabled nonlinear gyrokinetic profile predictions, marking a paradigm shift in fusion modeling: high-fidelity projections of fusion performance can now be made directly from first-principles turbulence simulations. This paper presents the PORTALS framework [1, 2] and the key advancements that have enabled the efficient solution to the inverse transport problem of delta-f transport models using surrogate-based optimization and uncertainty quantification. PORTALS has been used to predict over 50 multi-channel (T_e, T_i, n_e) flux-matched plasma profiles to date, spanning present-day experiments (DIII-D [3], ASDEX Upgrade [4] and JET [5]) and future devices (SPARC [1, 6], ITER [7] and ARC), supporting both validation efforts and design activities. This paper will also discuss how PORTALS, coupled with nonlinear CGYRO [8] simulations, is used for the projection of SPARC plasmas with high-fidelity turbulence modeling, revealing the importance of edge pressure assumptions and impurity mixes in high-stiffness, ion-temperature-gradient dominated turbulence regimes in near-breakeven and burning plasma conditions.

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On the occurrence of regimes of suppressed anomalous impurity transport in W7-X and implications for stellarator reactors

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In view of feasible reactor operation regimes, the transport of impurities must be governed by a trade-off between low impurity confinement of helium ash and small inward transport of edge-sourced impurities. Therefore, identifying, understanding, and predicting reactor scenarios of compatible impurity transport is crucial on the path to self-sustained fusion burn.

The Wendelstein 7-X (W7-X) stellarator was optimized for low neoclassical transport in the $1/\nu$-regime, which led to transport of energy [1], particles [2], and impurities [3, 4] being governed by anomalous processes under standard operating conditions. In high-performance scenarios with tokamak-like confinement, anomalous transport is reduced [5], with impurity transport governed by neoclassical processes [6, 7]. The neoclassical convection is inward-directed and causes the impurity density profiles to strongly peak. Consistent with neoclassical predictions, the peaking strength scales linearly with impurity charge. The transition into the neoclassically dominated regime is found to be governed by a critical a/L_{n_e} of unity. The threshold value is present across several magnetic configurations and experimental scenarios, causing impurity accumulation to appear across a significant range of the W7-X parameter space.

In W7-X high-performance plasmas, high triple products and centrally peaked impurity profiles have always coincided. We show that the inward impurity transport present is incompatible with sufficient helium ash removal in a reactor scenario. This stresses the importance of tailoring impurity transport in a stellarator-type reactor, where possible routes to success have already been identified in core electron root confinement regimes [8] or active density control schemes that allow for steering the level of anomalous impurity transport utilizing external actuators.

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The poloidal distribution of electrostatic zonal flow drive in strongly shaped tokamaks

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Developing a physics-based understanding of confinement, including both transitions between confinement states and zonal flow (ZF) dynamics, requires detailed validation. Due to the limited poloidal coverage of experimental turbulence measurements, a missing but important piece is a theoretical estimate for the poloidal distribution of the nonlinear turbulence-flow interaction, and its dependency on macroscopic equilibrium parameters. Through spectral energy transfer functions, which appropriately weigh contributions from three-wave coupling, we obtain such an estimate directly from gyrokinetic flux-tube simulations. In previous work [1] a strong correlation between the envelopes of turbulent activity and the nonlinear coupling was observed for circular plasma shaping. With integrated diagnostic capabilities introduced in the GS2 release 8.2.0 [2], we uncover a non-trivial dependence on plasma shaping of both the ZF drive and the turbulent activity, thus breaking their degeneracy. Our study encompasses a wide range of shaped axisymmetric equilibria, including ones with up-down asymmetry. A common trend emerges, namely the ZF drive distribution develops multiple poloidal maxima which are aligned with those of poloidal curvature. This leads to the surprising implication that the ZF drive can be relatively weak at the outboard mid-plane, where the turbulent fluctuations are strongest and where the relevant turbulence diagnostics are located on most tokamaks.

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Gyrokinetic pedestal studies varying shaping in AUG

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The pedestal region in tokamak plasmas plays a critical role in determining overall confinement and performance, yet the interplay between turbulence and plasma shaping within this region remains to be fully understood. In this work, we present a comprehensive characterization of pedestal instabilities and their sensitivity to plasma shaping effects using the gyrokinetic code GENE [1,2]. We consider a well documented ELM-y H-mode discharge at two different times while varying pedestal shaping parameters at constant β_{pol} [3]. In order to maintain the value of β_{pol} the heating power (2 MW ICRH and 4-10 MW NBI) was reduced during the higher shaping phase. Key turbulence modes, including kinetic ballooning modes and electron temperature gradient (ETG) modes, are identified with local linear simulations and compared between the differently shaped scenarios to assess their impact on transport and stability. Global nonlinear fully electromagnetic simulations reveal a significant contrast between the high and low shaping cases, with ExB shear stabilization exhibiting a much stronger effect in the former. At electron scales, the nature and impact on transport of ETG modes is assessed, confirming a significant amount of transport driven by these modes, highlighting ion frequency ETG and comparing with reduced models. Finally, parallel magnetic fluctuations are found to only produce mild changes in transport for the parameters considered.

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Impact of the main ion species on the ASDEX Upgrade Pedestal

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Future fusion devices, such as ITER, will operate with a deuterium tritium mixture, whereas current experiments mainly use deuterium or hydrogen. Studying the isotope dependence is, therefore, crucial to accurately predict the performance of these future fusion devices. Previous studies have demonstrated positive isotope mass scaling of the thermal energy confinement time in H-mode plasmas. This phenomenon has been observed in several major tokamaks, including JET [1], JT-60U [2], ASDEX [3] and ASDEX Upgrade [4]. To further investigate the isotope dependence, this analysis compares plasmas with different main ion species from the ASDEX Upgrade tokamak, focusing on the pedestal region to understand the phenomena where the main ion type plays an important role. Discharges with different main ion species, but otherwise matched engineering parameters were selected for comparison. The analysis includes a comparison of kinetic profiles (temperature, density, and pressure profiles), stability analysis against peeling-ballooning modes, and investigation of inter-ELM transport. In addition to the main ion comparison, the study varies plasma shaping, the main ion fuelling, and the heating power (NBI and ECRH up to 10 MW total heating power). Varying these parameters alongside the main ion species provides a better understanding of their influence on pedestal behaviour and overall plasma confinement. The comparison between deuterium and helium discharges reveals differences in the pedestal behaviour. In deuterium, higher triangularity increases the pedestal top pressure, while helium shows no variation. Although ELMs are present in all studied cases, stability analysis suggests that deuterium operates close to the ideal MHD stability limit, whereas helium remains far from it. The inter-ELM transport analysis shows higher electron heat diffusivity in helium. The observed differences emphasize the importance of understanding the pedestal behaviour for different main ion species.

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Rotation Acceleration and Braking due to RMP in MAST-U Experiment

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Plasma toroidal rotation is less well-known transport channel than heat or particle transport [1], including both momentum transport and in particular rotation sources. In this work, we have studied rotation changes or torque sources induced by Resonant Magnetic Perturbations on MAST-U tokamak. Relatively repeatable pulses in L-mode plasmas in both n=2 and n=4 RMP coil configurations were performed on MAST-U by introducing RMP coil modulation waveforms at various amplitudes and frequencies. In the n=4 RMP coil configuration, quite surprisingly an edge rotation acceleration was measured due to the RMP coil current, resulting in an increase of relative edge rotation by 20% (~5km/s [2]) at ρ_{tor}≈0.97 at maximum RMP coil current of 1.9kA. This increase in rotation is limited to the region of $\rho_{tor} > 0.9$.

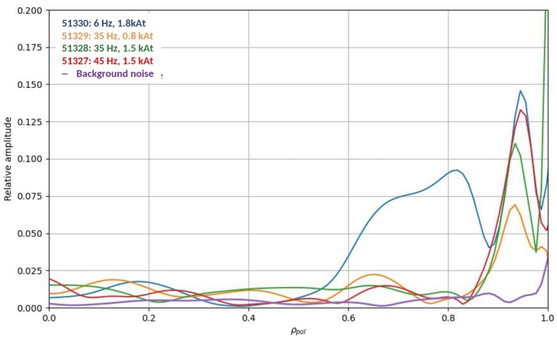

Figure 1. Relative rotation amplitude for different RMP coil current magnitudes.

In the n=2 RMP coil configuration, we performed an RMP coil current scan shown in figure 1. Similar edge rotation acceleration was observed as with n=4 configuration, the acceleration being higher with increasing RMP coil current. At the highest RMP coil current, significant rotation braking was also seen at ρ_{pol}≈0.55-0.85 as shown in figure 1.

To interpret and quantify the mechanisms responsible for this edge rotation acceleration and core braking, modelling with the MARS-F/K [3] code is being carried out. Modelling the n=4 case with MARS-K is suggesting the observed co-torque in the edge region while the modelling results in n=2 configuration are in disagreement with experiments. Investigation of other possible sources of RMP-driven torque, such as the stochastic torque, is on-going [4].

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Predictive full radius integrated modelling of plasma current impact on WEST L-mode confinement

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The energy confinement time scales with plasma current (I_P) as $I_P^{0.95}$ both in L and H-mode [1]. The validated full radius simulation on WEST L mode [2], is extended to 10 L-mode pulses with I_P ranging from 300 to 500 kA, at similar total power and density. The 10 full radius integrated modelling simulations predict an energy content within a RMSE of 11% compared to the experimental one. Since heat, particle and radiation are predicted, the only inputs to the modelling are engineering parameters and separatrix boundary conditions.

The integrated modelling is performed with the High Fidelity Plasma Simulator (HFPS), the IMAS-coupled version of JINTRAC workflow. Turbulent transport (heat and particle incl. impurities) is modelled up to the separatrix using the physics-based quasilinear model TGLFsat2. Stand-alone verification of TGLFsat2 against a higher fidelity gyrokinetic code GKW are carried out for WEST L mode parameters at radii from ρ=0.3 to 0.9. The turbulent fluxes reduction by lowering the safety factor $q \propto 1/I_P$ [3] is captured.

In the HFPS, TGLFsat2 heat and particle fluxes are self-consistently iterated with Low Hybrid Current Drive heating source, impurity transport (N and W) and radiation, the current diffusion and the equilibrium reconstruction. Particle sources adjustments are done by feedback loops on a target line averaged density. Impurities are initially set to match the experimental Z_{eff} (for N) and feedback is adjusted on their separatrix density to align with the radiated power (for W).

For the 10 pulses, the predicted temperature, density and radiation profiles are validated respectively against ECE, interferometry and bolometry. The fit agreement with the measurements ranges from 15-25% relative error, 40-60% with only heat self-consistent modelling and improves to 20-40% when also considering particles self-consistently. The HFPS captures the I_P dependency with a relative error of 32% compared to 48% using the L96 scaling law for the energy confinement time in this set of shots.

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Coupled 1D transport equation of METIS with full electromagnetic model for breakdown and burn through of DYON

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We present a novel coupling of the full electromagnetic breakdown and burn-through model of DYON [1] with the 1D transport solver METIS [2], enabling an integrated and predictive simulation of the plasma initiation phase in tokamaks. DYON self-consistently evaluates the Townsend avalanche on individual open magnetic field lines and tracks the evolving plasma volume during breakdown. It includes detailed atomic processes to estimate plasma density and predict the initial growth of plasma current. For the first time, these physics-based outputs are used as source terms for a 1D-transport equation solver: METIS then computes the evolution of kinetic profiles and plasma current profile throughout the early plasma formation phase with enhanced fidelity. This coupled framework provides a self-consistent description of the breakdown-to-burn-through transition and supports scenario development for next-generation devices.

The model is applied to experimental discharges from MAST Upgrade and TCV, showing convincing agreement between measured data and fully predictive simulations.

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Characterization of turbulent transport in COMPASS Upgrade scenarios with Electron Cyclotron Heating

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COMPASS Upgrade (CU) is a compact tokamak that will explore a variety of scenarios characterized by different magnetic field and plasma current [1]. Here we investigate turbulent transport in CU scenarios under different fractions of ECRH and NBI power. The equilibrium density and temperature profiles are obtained by employing the integrated transport code ASTRA [2], coupled with the gyro-Landau code TGLF, the equilibrium code SPIDER, the beam-tracing code TORBEAM and the guiding-center particle code RABBIT. An integrated model for core plasma transport which uses a similar set of tools was developed for ASDEX Upgrade [3] and it was recently adopted to assess plasma response to ECRH in CU [4]. Stability analysis with respect to ITG and TEM, which are expected to be the dominant turbulent modes in the core plasma, is addressed by using the quasi-linear gyrokinetic code QuaLiKiz [5]. A cross-validation of the codes TGLF and QuaLiKiz is attempted in some of the envisaged scenarios [6]. The dependence of the transition between ITG- to TEM-dominated turbulence on the amount of injected ECRH power and the consequent modification of the equilibrium profiles is studied; the consequences on density peaking [7] and L-H transition are evaluated.

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Advantages of multi-scale turbulence measurements using Collective Thomson Scattering on EAST tokamak

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Over the past decade, multi-scale turbulence covering ion-to-electron scales has been extensively studied through gyro-kinetic simulations[1]. For instance, devices such as JET, AUG, and TCV have identified the electron temperature gradient mode (ETG) as playing a significant role in turbulent transport within core regions[2]. However, the identification of these multi-scale modes in experiments requires fluctuation measurements with high wavenumber resolution, a topic that remains underexplored and warrants further attention. Additionally, obtaining multi-scale turbulence measurements through a single diagnostic system could be crucial, as results from diagnostics based on different principles may yield varying interpretations of the signals.

In this study, we highlight the advantages of **Collective Thomson Scattering (CTS)** for monitoring multi-scale turbulence on EAST tokamak. Recent upgrade of CTS system allows multi-scale turbulence measurements covering ion-to-electron scales [3], and the following investigations will be briefly summarized in this report:

(1) Electron temperature stiffness induced by broad-band turbulence and its dispersion relations[4];

(2) Identification of Electron Temperature Gradient (ETG) mode in experiments through multi-scale turbulence measurements covering ion to electron scales;

(3) Quasi-Coherent Mode (QCM) and its dispersion relations;

(4) Nonlinear interactions between multi-scale turbulence.

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NBI-Generated Fast Ion Transport in DTT: Ripple and TAE Effects

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The Divertor Tokamak Test (DTT) [1] is a key facility in fusion research, designed to investigate alternative power exhaust solutions for DEMO. With a major radius of R_0=2.19 m, a magnetic field of B_0≈6 T, and a plasma current up to I_p=5.5 MA, DTT will be heated with 45 MW of auxiliary power, including 15 MW from negative-ion-based neutral beam injection (NNBI) [2,3]. One of the critical challenges in tokamak operation is the loss of fast ions via mechanisms such as prompt losses, interactions with the toroidal field ripple [4], MHD instabilities, and other 3D field effects such as perturbations from RMP coils or error fields. In this work, we focus on specific loss channels, namely those associated with ripple and MHD activity. While the resonance between fast ions and ripple was a significant loss channel in previous experiments, recent studies show that, in DTT, the impact of ripple-induced losses is minimal, with only about 0.078% of 510 keV NBI fast ions being lost [5]. The interaction between energetic particles and toroidal Alfvén eigenmodes (TAEs) may contribute to increase the ion losses. These modes, driven by energetic ions, can enhance radial transport, leading to more complex transport dynamics and increasing the risk of localized heating of the plasma-facing components (PFCs), as observed in various fusion devices (the so-called "hot spots", see e.g. Ref. [6]). In DTT, resonances between TAEs and energetic particles may play a similar role, and managing these effects is crucial for safe operation. Here, using numerical simulations with the Hamiltonian guiding-center code ORBIT, we investigate in detail the effect of a TAE mode with a toroidal number n=10 on the transport dynamics and losses of 510 keV fast ions in DTT and we estimate the associated heat flux reaching the device wall.

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Study of core region turbulence transport and parametric ranges of ELM-free H-mode plasmas on EAST

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ITER will adopt H-mode as their baseline operational regime. However, the huge transient heat fluxes induced by ELMs, which frequently accompany H-mode operation, pose a significant threat to plasma-facing first-wall materials. ELM-free H-mode plasmas offer the advantage of avoiding huge transient heat loads, but they often face core accumulation of high-Z impurities, leading to degraded confinement and even plasma disruptions. Recently, we discovered a novel ELM-free H-mode discharge on the EAST tokamak under unfavourable magnetic configurations, which effectively suppresses high-Z impurity accumulation while exhibiting multiple favourable characteristics: sustained duration >10 times the energy confinement time (τ_E), good energy confinement (H_{98}, $y_2 > 1$), high density (n_e/n_GW ~ 0.7), low input torque. So, it has high compatibility with future fusion reactor operation scenarios. To further improve confinement, we conducted integrated experimental and modelling studies. Our observations reveal that both ion-scale turbulence ($k < 5$ cm^{-1}) and electron-scale turbulence ($k = 10–20$ cm^{-1}) increase over time during the ELM-free phase. TRANSP power balance analysis indicates anomalous thermal transport for both ions and electrons, with electron heat flux exceeding ion heat flux. To identify the turbulence type, quantify transport capability, and elucidate the suppression of high-Z impurity accumulation, we performed gyrokinetic simulations using GS2 and GTC, alongside neoclassical calculations with NEO. Linear simulations (GS2&GTC) confirm that trapped-electron-mode (TEM) turbulence dominates. Nonlinear simulations quantitatively reproduce the electron and ion heat fluxes observed in TRANSP analysis. NEO neoclassical simulations show that tungsten impurities (W^{44+}) exhibit inward transport in the core, while TEM turbulence drives stronger outward radial transport—explaining the experimental observation of decreasing high-Z impurities in the plasma core despite rising electron density during ELM-free phases. Additionally, in unfavourable configurations, we observed for the first time that the quasi-coherent mode (QCM) is localized not in the steep pedestal region but in the scrape-off layer, which may also contribute to W impurity suppression. To define the operational window for ELM-free regimes, we also systematically analysed key parameters, including elongation (κ), triangularity (δ), and plasma current (I_p).

Control of NTMs with ion cyclotron resonance frequency waves in EAST

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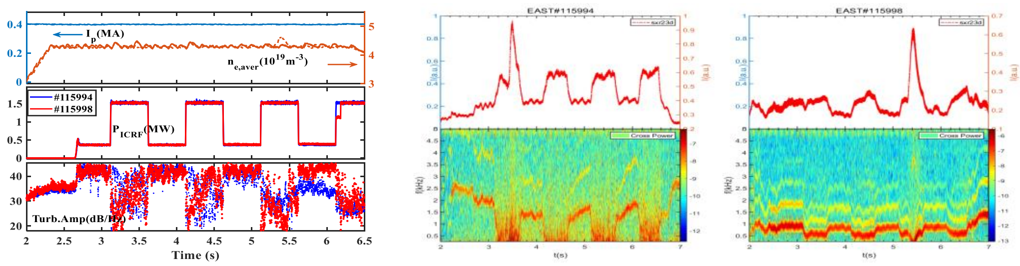
NTMs increase local plasma transport and degrade plasma confinement. Experimentally, various heating methods have been observed to suppress NTMs by modifying the plasma current or pressure profiles, altering the magnetic island size, adjusting the amplitude or the period of sawteeth. In the ion cyclotron resonance heating (ICRH), one approach to NTM suppression is through localized heating to tailor the pressure profile[1, 2]. This report focuses on actively controlling the ICRH power deposition location and modulation to separate the absorption regions of H minority, D majority ions, and electrons. By doing so, we aim to identify whether ions or electrons play a dominant role in NTM suppression via ICRH. This research contributes to expanding methods for controlling NTMs and plasma profiles.

The experimental parameters are as follows: plasma current Ip=400 kA, toroidal magnetic field B_0=2.5 T (#115994) and 2.6 T (#115998), plasma line averaged density = 4.3×10^{19} m^{-3}. The modulation frequency of the ICRH is 1 Hz, with power levels of 0.4 MW and 1.6 MW respectively, and the frequency is 37 MHz. Simulations show that in #115994, the ICRH power is deposited within a normalized radius of 0.25, while in #115998, the deposition occurs within a normalized radius of 0.3. Soft X-ray measurements indicate that NTM is moderately suppressed in discharge #115994, and the NTM frequency in #115998 is reduced, but the amplitude remains largely unchanged. Combining magnetic probe and multi-channel signal analysis, the NTM mode in #115994 is the (3, 2) mode, while that in #115998 is the (2, 1) mode. Further, 94.2 GHz of DBS measurements reveal that in both discharges, the core plasma turbulence decreases significantly with the application of ICRH.



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Optimizing fuelling pellet injection geometry for COMPASS Upgrade with HPI2

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COMPASS Upgrade [1] is a high-magnetic field (5 T) tokamak, currently being built at the Institute of Plasma Physics in Prague. The HUN-REN Centre for Energy Research plans to develop a pellet injector for COMPASS-U. This work aims to optimize the pellet injector parameters - pellet velocity, size, injection direction, and investigates the pellet-plasma interaction, using various plasma scenarios of the Compass Upgrade tokamak with the HPI2 code [2]. HPI2 is a widely used 2D+ pellet injection simulation code that can handle 3D geometries and related secondary phenomena, like inhomogeneous pellet ablation.

The dependence of material deposition and penetration depth on pellet size and velocity were examined, and for the desired material deposition, pellets with a radius of 0.6 mm should be injected into the plasma. Higher injection velocity is advantageous, but based on technical considerations, simulations were run using an injection velocity of 500 m/s.

The properties of different injection directions were explored, in several scenarios, from early L-mode to the high-performance H-mode scenario, based on which the optimal injection geometry of the pellet injector was defined. While LFS injection is the easiest to realize technically, it results in the least efficient fuelling, as expected, as drift phenomena quickly accelerates the pellet cloud out from the plasma. The internal, HFS injection is the most efficient, where the drift direction points inward the plasma; due to accessibility constraints, pellets cannot be delivered here. A good compromise is the vertical (VHFS) injection, from an existing port. Relaxation of the plasma profiles after the injection were also investigated to characterise the pacing requirements of the injection.

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Modelling type-I ELM detachment burn-through for SPARC

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Abstract

SPARC [1], a compact tokamak under construction by Commonwealth Fusion Systems, is expected to commence operations in 2026. With an on-axis magnetic field strength reaching 12T, SPARC aims to achieve H-mode plasma regimes with fusion power outputs approaching 140 MW and gains of ≈ 10 . While H-mode operation boosts core confinement by suppressing edge turbulence, it also results in steep pedestal gradients that periodically collapse, leading to large ejections of particles and heat into the scrape-off-layer in the form of type-I ELMs. SPARC's Advanced Divertor Mission will investigate the use of alternative divertor configurations such as the X-point target geometry, to improve detachment stability. In this study, we investigate whether SPARC's advanced divertor is able to passively maintain detachment during large type-I ELMs.

Simulations are performed for type-I ELM burn-through on a SPARC H-mode scenario in 1D using the Hermes-3 multi-fluid code. A simplified model of type-I ELM energy and particle fluence is constructed using multi-machine empirical scalings[2], infrared thermography diagnostics[3], and data from ASDEX Upgrade. This model is used to form type-I ELM-like upstream energy and particle sources that are applied to a steady-state SOL plasma. To accurately model plasma transport with low upstream collisionalities, we include non-local kinetic effects for the parallel heat flux via the reduced-kinetic Shurtz, Nicolai, and Busquet (SNB) model.

A scan of ELM energy fluence (7.5–45.5 $\mathrm{MJm^{-2}}$ injected upstream) is applied to a SPARC super-X detached divertor ($I_p = 5.0$ MA, $f_G = 0.43$) and detachment front response is observed. Results show rapid compression of the detachment front over ≈ 0.5 ms which scales inversely with ELM fluence. For all cases this is followed by a brief period (≈ 1 ms) of stagnation near the target before a slow recovery of the detachment front to its pre-pulse position over approximately 10 ms. The front movement is primarily due to compression, with ionisation occurring over long timescales compared to compression, ELM and other radiative time scales.The parallel detachment front approaches within 0.5 m of the target for all ADM-relevant ELM fluences but never fully reattaches, with neutral density remaining high at the target. This highlights neutral compression dynamics as a critical area for further development in 1D SOL codes in order to capture reattachment at realistic ELM fluences.

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Investigation of Edge Quasi-Coherent Fluctuations in the Wendelstein 7-X Stellarator Plasma Using Alkali Beam Diagnostics

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The largest current stellarator is the Wendelstein 7-X at the Max Planck Institute for Plasma Physics in Greifswald, Germany, whose Alkali Beam Emission Spectroscopy diagnostics (ABES) is built and operated by the Fusion Plasma Physics Department of the Centre for Energy Research. Quasi-coherent (QC) oscillations of the plasma density in the edge plasma of the stellarator and in the surrounding magnetic island divertor in the 10-25 kHz range were observed [1]. In addition to ABES, the fluctuations were also observed using other diagnostic techniques such as reflectometry, Mirnov coils [2] and soft X-rax detectors. This phenomenon was found in the spatial range where filaments are formed, and a link between the two phenomena was suggested. Using reflectometry, the parametric dependence of the frequency of the oscillations and the poloidal wavelength of the waves were studied in detail. However, this diagnostic cannot measure the plasma density profile and plasma filaments. In this paper we investigate the relationship between quasi-coherent modes in the edge plasma and in the edge island. Data from various magnetic configurations and plasma parameter regimes are investigated. Correlation and comparison with other diagnostic techniques are studied in order to reveal the spatial distribution of these phenomena.

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Investigation of mode structure from BES signals in MAST Upgrade

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In this work, we present results of using the continuous time-frequency transform-based tools of the NTI Wavelet Tools [1,2] data analysis package to characterize plasma waves observed in the beam emission spectroscopy (BES) signals of MAST-U [3]. These signal analysis tools are especially well-suited for the study of transient phenomena, like chirping Alfven eigenmodes or fast particle modes. NTI Wavelet Tools can be used to identify coherent plasma fluctuations across multiple signals, determine the phase relation between signals, and determine the mode number or wave number, and the radial structure of the modes, depending on the spatial localization of the available measurement channels. A high temporal resolution and time-shift invariance are ensured using continuous linear time-frequency transforms to acquire time-frequency spectra without major distortions.

The BES system of MAST-U provides a set of channels arranged in a 2D matrix, making the study of radial localization and poloidal structure of plasma modes possible. The effects of resonant magnetic perturbations, neoclassical tearing modes and fast-particle-driven MHD instabilities are widely studied at MAST-U, posing as prime candidates for such an analysis.

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Turbulence Phase Transition in Hasegawa-Wakatani

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Hasegawa-Wakatani is an archetypical minimal model of plasma turbulence, being an instability driven β-plane-like model of drift-wave turbulence, conserving potential vorticity. In addition to waves and instability, it features a transition between two-dimensional hydrodynamic turbulence and quasi-one-dimensional zonostrophic turbulence. The proper control parameter for this transition is the ratio of the adiabaticity parameter to the background density gradient (i.e. C/κ). We show that this transition displays a characteristic hysteresis loop [1], in a fixed gradient formulation, when the control parameter is slowly increased, then decreased. One can also see this as a transition between weak (drift) wave-turbulence, which is eventually dominated by zonal flows, and strong turbulence dominated by eddies somewhat similar to transition from 2D to 3D turbulence in thin layers or rotating systems. Note that the parameter further plays the role of a zonostrophy parameter in the regime where the zonal flows dominate, effectively defining a characteristic length scale, such that larger scales are dominated by zonal flows while smaller scales are basically 2D turbulence with forward enstrophy cascade[2]. Some implications are discussed, and a simple rule for incorporating the effects of zonal flows on quasi-linear fluxes are proposed.

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The confinement dependence on the magnetic field in ST40 spherical tokamak

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High magnetic field Spherical Tokamak (ST) could be a viable path to commercial fusion power. The dependence of plasma energy confinement time on the magnetic field was demonstrated to be much stronger in STs, such as MAST, NSTX and GLOBUS-M2, than in conventional tokamaks with high aspect ratio A>2.5. The maximum toroidal field achieved in those STs was 0.9T [1] and, therefore, to be applicable for future ST-based fusion devices with foreseen toroidal field 4-5T the extrapolation of the ST confinement scaling law is required.

Experiments on ST40 device [2] with a toroidal magnetic field scan from 0.6T to 1.6T at the plasma geometric axis in the L-mode plasmas with NBI beam of power around 1MW were carried out. Interpretation of these experiments have taken into consideration all available measurements including bolometry emission, spectroscopic data, neutron data, magnetic sensors and Thomson scattering data. Results of the analysis of this experimental series are presented.

ASTRA transport code [3] together with built in NBI code and separately coupled NUBEAM code [4] were used for interpretative analysis. Predictive modelling has been performed using the integrated modelling framework, TRIASSIC [5] to investigate the effect of magnetic field on the plasma performance. TRIASSIC was coupled with NUBEAM for NBI heating and current drive, NCLASS [6] for neoclassical transport and TGLF [7] for anomalous transport, allowing for a comparison between predicted dependence of confinement on the magnetic field and experimental results.

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Neutral density and penetration measurements in a poloidal fuelling scan on MAST Upgrade

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The impacts of edge fuelling on the H-mode pedestal and core plasma performance in the spherical tokamak (ST) MAST Upgrade are addressed experimentally by changing the poloidal fuelling location, with an emphasis on inferring edge ionisation sources, S_{iz}, and neutral density, n_0, profiles. The fusion power of tokamak plasmas is strongly dependent on the core plasma density, $P_{\mathrm{fusion}} \propto n^2$. The density and temperature gradients achievable in these plasmas is limited and set by the levels of transport, where reduced transport at the edge in H-mode plasmas can allow gradients to become large in the pedestal region, allowing for increased core densities. Plasmas require fuelling for sustained long pulse operation, particularly for future fusion power plants. Fuelling efficiency is not currently well quantified, particularly for STs, as most studies have focused on the more abundant conventional aspect ratio devices.

This work focuses on analysis from the high-speed video (HSV) diagnostic on MAST-U[1]. HSV utilises a Photron Fastcam SA-X2 camera with a high refresh rate (up to 30kHz in this study) with a wide-angle view covering most of the MAST-U main chamber. It is fitted with a narrowband optical filter centred at the D_α emission line ($n = 3 \rightarrow 2$ with wavelength $\lambda = 656.1$nm) and has recently been improved for diagnosing the low-field side edge with a spatial resolution of $\approx$ 5mm in the pedestal region. The D_α brightness signal is inverted[2] to yield a radial profile of emissivity, ε, which, when coupled with electron density and temperature profiles from the Thomson scattering diagnostic, informs the S_{iz} and n_0 profiles[3,4]. We show how the neutral penetration and neutral opacity changes as a function of the poloidal fuelling location in the plasma, and report on changes to the pedestal profiles, diffusive and convective transport coefficients, and core performance. Comparisons with inversions from other D_α diagnostics (e.g., Celeste-4, E-Celeste, HOMER, and RGB) are made, where possible.

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Characterization of fluctuations in three dimensional numerical simulations in FELTOR

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Properties of plasma turbulence in the boundary of magnetically confined plasmas are investigated in three-dimensional full torus numerical simulations modelling the TCV tokamak experiments [1]. Simulations are performed using the full-F, isothermal, electromagnetic, gyro-fluid model, Feltor [1]. They are initiated with identical setups but for differing magnetic field configurations. The total magnetic field direction is inverted, changing the toroidal direction and the field line winding. A comparative analysis of particle transport and intermittent fluctuations is presented for favorable (ion diamagnetic current towards the outer divertor leg) and unfavorable magnetic field directions, utilizing synthetic field-aligned probes sampling at 10 MHz. Cross-field transport shows strong ballooning behaviour. The transport maximum is situated above, for favorable direction, and below the outboard midplane, for unfavorable direction. Fluctuation level and intermittency of fluctuations are likewise increased near the maximum. Examining the fluctuation structures reveals coherent plasma filaments with a poloidal scale length of π/2 in the scrape-off layer that are not strictly field aligned. As filaments cross the separatrix, the scale length halves, and a time delay is observed between the centre and the ends of the filaments along the magnetic field lines.

We have performed verification of the three-dimensional simulations through the replication of universal statistical properties observed in experimental measurements, as previously performed for two-dimensional simulations [2]. These properties are well described by a stochastic model based on a superposition of uncorrelated pulses [3]. The statistical properties of the fluctuation time series measured at a fixed radial position compare favorably with the model in the low-field side scrape-off layer.

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Flux-driven turbulent transport using penalisation in the Hasegawa-Wakatani system

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First numerical results from the newly-developed pseudo-spectral code P-FLARE (Penalised FLux-driven Algorithm for REduced models) [1, 2] are presented. This flux-driven turbulence/transport code uses a pseudo-spectral formulation with the penalisation method in order to impose radial boundary conditions. Its concise, flexible formulation allows implementing various two dimensional reduced fluid models in flux-driven formulation. Here, results from simulations of the modified Hasegawa-Wakatani system [3] are discussed. It is shown that coupled spreading/profile relaxation that one obtains for this system is consistent with a simple one dimensional model of coupled spreading/transport equations [4, 5]. Then, we investigate the effect of a source of density, which results in the observation of sandpile-like behaviour. The model displays profile stiffness for certain parameters, with very different input fluxes resulting in very similar mean density gradients. We find that this is due to different zonal flow levels around the critical value for the control parameter (*i.e.* the ratio of the adiabaticity parameter to the mean gradient) and the existence for this system of a hysteresis loop [6] for the transition from 2D turbulence to a zonal flow dominated state.

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Extension of the ion heat transport channel in IMEP

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Fusion reactors are expected to operate in the H-mode regime, characterized by the formation of an edge transport barrier. Accurately modeling this regime is crucial for predicting performance and optimizing reactor operation. The IMEP framework [1, 2, 3] has demonstrated strong predictive capability across a wide range of present-day experiments by combing the ASTRA-TGLF transport solver with the MHD stability code MISHKA. Notably, IMEP has reproduced key trends across devices of varying sizes and plasma currents.

However, a key assumption in the original IMEP implementation is the equality of the electron and ion heat diffusivities (χ_E and χ_i). This assumption is increasingly questionable in low-collisionalty regimes, such as those expected in ITER.

In this work, we present an extension of IMEP that places greater emphasis on ion heat transport. Specifically, we explore the impact of ExB shear suppression of ion-scale turbulence, thus reducing χ_i relative to χ_e. This modified approach enables IMEP to capture the high performance of AUG carbon-wall discharges at low density with high ion pedestal temperatures. Importantly, this is achieved without degrading the model’s accuracy in reproducing tungsten-wall discharges.

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Experimental observation of temperature oscillations driven by nonlinear coupling to the current profile on EAST

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Nonlinear temperature oscillations were observed in non-inductive EAST discharges, exhibiting dynamics analogous to the O-regime previously reported in Tore Supra [1] and TCV [2]. Periodic oscillations in the *q*-profile(safety factor) were identified as the key driver, modulating turbulence intensity and inducing electron temperature oscillations through nonlinear coupling. The current density profile was reconstructed using EFIT equilibrium modeling constrained by electron density and Faraday angle measured by the POlarimeter-INTerferometer (POINT) system [3]. Turbulence intensity evolution during the oscillation was simultaneously diagnosed by the CO_2 laser scattering system, revealing a clear correlation between the *q*-profile, turbulence suppression, and temperature oscillations. These results provide critical experimental validation of the nonlinear coupling between the current distribution and temperature in O-regime physics, and highlight the impact of self-organized processes on current profile control and sustainment of steady-state high-performance plasmas.

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Fast ITG-TEM stability evaluation in arbitrary geometry based on a variational approach

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Anomalous transport arising from microinstabilities is the main deleterious factor for confinement in both tokamaks and modern stellarators optimised for neoclassical transport [1]. The turbulence is predominantly attributable to ion temperature gradient (ITG) modes, trapped-electron modes (TEM), and kinetic ballooning modes, each displaying sensitivity to the magnetic geometry. These instabilities and their associated transport are conventionally studied using gyrokinetic simulations, but such approaches are too computationally expensive for extensive geometry surveys and optimisation, requiring faster alternatives.

We explore a semi-analytical method for solving the electrostatic dispersion relation—applicable to ITG and TEM—based on a variational approach. The model is valid in arbitrary geometry and is benchmarked against high-fidelity GENE [2] simulations, showing qualitative agreement in both adiabatic- and kinetic-electron scenarios when exact GENE eigenmodes are used as input trial functions. Importantly, salient geometric effects, such as ITG stabilisation by negative triangularity in TCV and differences in maximum-J quality between W7-X configurations, are reproduced by the model. Preliminary results of a self-consistent adiabatic-electron ITG model are also presented, where eigenmode proxies are directly and efficiently determined from flux-tube geometry. This enhances the faithfulness of eigenmode predictions—with respect to imposing a Gaussian shape as common in tokamak reduced modelling [3,4] —in devices with strong shaping and at low magnetic shear.

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Scrape-off layer profiles in SPARC based on blob motion

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We present analysis of outboard mid-plane profiles of the SPARC device [1] from recent SOLPS modeling efforts and predictions from blob scaling theories and stochastic modeling. This comprises the SPARC primary reference discharge, a candidate Q>1 L-mode scenario, and the so-called ARC-like low-collisionality SOL conditions considered for SPARC's advanced divertor mission. The radial variation of the particle density and temperatures in the far SOL of magnetically confined plasmas is generally determined by radial motion of blob-like plasma filaments, with increased filamentary transport leading to broadening and flattening of the time-average profiles [2,3]. A stochastic model describing the plasma fluctuations as a superposition of uncorrelated pulses moving radially outwards reveals a profile e-folding length determined by the radial blob velocity and the parallel transit time [4]. This is here shown to be consistent with estimated blob parameters and profiles in the Alcator C-Mod device. A blob velocity scaling theory for sheath-connected filaments describes how their size and velocity scale with plasma and device parameters. Using plasma parameters from SOLPS transport modeling of SPARC and assuming the same dimensionless blob velocity scaling regime [2] as for Alcator C-Mod suggests similar flat time-average profiles in the far-SOL of SPARC, though the breakpoint location can not be determined from this analysis. The results agrees with the elevated far-SOL effective diffusivities used for the transport simulations. The estimated blob parameters for SPARC also provide requirements for the spatio-temporal resolution for fluctuation diagnostics.

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Isotope mix effect on edge turbulent transport in pre-L-H transition conditions in JET-ILW

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The heat flux at the edge of L-mode JET-ILW [1] (ITER Like Wall, Be wall and W divertor) discharges is studied using the gyrokinetic code GENE [2,3] in its flux-tube configuration as well as the quasi-linear turbulent transport model TGLF [4] using the SAT2 and SAT3 [5] saturation rules. We use reference JET-ILW plasmas with different hydrogen isotopes and isotope mixes in which a power scan to identify the LH power threshold P_{LH} has been performed [6]. The study focuses on two discharges with an effective mass of $A_{eff}=2$, either with pure deuterium or a 50% hydrogen - 50% tritium mix. Additional power is required to trigger an H-mode in the mix (2.98 MW) compared to the pure deuterium case (1.68 MW) despite their similar effective mass. Following the observation that $P_{LH} \propto \chi_{eff}$ in these JET-ILW plasmas [6], χ_{eff} being the effective heat conductivity, quasi-linear (TGLF) and non-linear (GENE) simulations were performed at $\rho_{tor}=0.95$. Heat fluxes were within the magnitude of experimental values without $E\times B$ shear. The use of experimentally relevant $E\times B$ shear levels in GENE non-linear simulations resulted in an overall reduction of transport, for both energy and particles, with a stronger effect observed for the pure deuterium case than the isotope mix case. A deviation between the two cases appear, when using a modelled $E\times B$ shearing, with a 50-80% stronger heat flux for the isotope mix case than for the pure deuterium case, both being lower than experimental values. TGLF SAT2 and SAT3 cannot reproduce this behaviour.

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A comparison of heat pulse propagation analysis using Electron Cyclotron Emission and Thomson scattering diagnostics on Wendelstein 7-X

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The optimized stellarator Wendelstein 7-X (W7-X) [1] is designed to have an approximately quasi-isodynamic magnetic field and reduced neoclassical particle and heat transport [2-3]. Modulated ECRH experiments are used to study electron heat transport on W7-X, and the heat pulse propagation analysis is typically performed using data from an absolutely calibrated, 32-channel Electron Cyclotron Emission (ECE) diagnostic [4,5]. ECE diagnostics are generally preferred for heat pulse propagation analysis because of their ability to achieve high temporal and spatial resolution; however, finite optical depth effects and the relativistic downshift of electron cyclotron emission to the low-field side of the plasma can significantly alter these measurements (s. for example Ref. [6]). Combined with the relatively long energy confinement times on W7-X, the development and calibration of a 4-laser Thomson Scattering diagnostic with a 90 Hz measurement rate [7] allows for the possibility to compare the heat pulse propagation analysis results between ECE and Thomson scattering diagnostics. Initial analysis from Thomson scattering data obtained in the second operational phase of W7-X indicates a heat pulse electron thermal diffusivity on the order of 1 m^2/s. A comparison of the experimental results obtained between the two diagnostics in operational phase 2 of W7-X will be presented. Additionally, the ability of the Thomson scattering diagnostic to resolve core heat pulse propagation motivates the analysis of edge gas puff modulation experiments on W7-X. An analytic model for the gas puff modulation analysis will be presented and prospects for further perturbative transport studies [8] will be discussed.

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Accelerating Hasegawa–Wakatani simulations with machine learning for out-of-distribution predictions

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Simulating plasma turbulence is computationally challenging due to its multi-scale dynamics. In this work, we investigate using convolutional neural networks (CNNs) to accelerate simulations of the Hasegawa-Wakatani model. The networks learn closure terms in large eddy simulations (LES), offering a cost-effective alternative to high-resolution solvers for capturing high-frequency effects. This is the first successful application of machine learning to predict plasma behavior for adiabatic coefficients beyond the training range [1]. The models generalize well, training using an adiabatic coefficient C in the range [0.2, 5] we are accurately predicting particle flux up to a factor of 5 outside the training range.

We will discuss wether the same results can be obtained with a scale-variant C directly in the Hasegawa-Wakatani model, which would provide a simple test for the applicability of learned LES models and in turn their applicability to more complex problems.

Finally, we will discuss the necessity of integrating the numerical solver into the machine-learning framework as opposed to using it as a black-box model.

Overall, the results demonstrate the model's strong generalization capabilities and its potential for accelerating plasma turbulence simulations with more complex equations and parameter sets.

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Gyrokinetic modelling of lithium turbulent transport in the core plasma

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Recent advances in nuclear fusion research have identified liquid lithium as a promising plasma-facing component (PFC) [1] for next-generation compact reactors. Unlike traditional solid tungsten monoblocks, liquid metals offer several key advantages: their high heat capacity enables efficient extraction of intense plasma heat fluxes (up to 10 $\mathrm{MW/m^2}$), they are less susceptible to neutron-induced damage, and they require less frequent maintenance. Furthermore, lithium coatings and liquid PFCs have demonstrated improved performance compared to solid tungsten PFCs, owing to their lighter impurity content and strong affinity for hydrogen and oxygen isotopes. However, these benefits come at the cost of significant erosion rates, which raise concerns about lithium transport between the plasma edge and the core. This transport can lead to unwanted dilution of the fusion fuel and must therefore be carefully assessed. Experiments such as lithium powder injection on HT-7U (EAST) [2] have already shown that lithium can impact turbulence levels, improving confinement regimes like the I-mode. These observations reinforce the need for a detailed understanding of lithium behavior in the plasma, from edge interaction to core penetration.

In the core plasma, contrary to heavier impurities such as tungsten, lithium is governed by a transport physics similar to that of helium or hydrogen isotopes, with a turbulent/anomalous contribution generally much higher than the neoclassical one [3]. This turbulent transport in the core plasma is mainly induced by Ion-Temperature Gradient (ITG) and Trapped-Electron Mode (TEM) micro-instabilities, and can be divided, under the trace assumption, into four main components [4]. In general, the most influential components are the turbulent diffusion and pure convection, associated to the impurity density gradient and the main ion velocity pinch respectively. However for lithium and other light ions, thermodiffusion, associated to the impurity temperature gradient can also play an important role, even if the related coefficient is lower than others, while the last component, rotodiffusion, is usually negligible in the absence of poloidal momentum source, for instance produced by NBI heating.

The objectives of the present study consists in using the 3D2V gyrokinetic code GYSELA [5, 6] to isolate each lithium turbulent transport coefficients in order to evaluate the effect of the different components on the global transport of lithium in the core plasma. Two methods will be used. The first one is based on the linear dependence of the lithium turbulent flux regarding impurity gradients, whereas the second one isolates each components by using flat initial gradients.

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Phase Contrast Imaging and Gas Puff Imaging at Wendelstein 7-X - overview of core and SOL density fluctuation measurements

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Two diagnostic system for studying turbulent density fluctuations in Wendelstein 7-X (W7-X) have successfully been implemented and operated in the last three operation phases in collaboration between MIT and the Max Planck Institute for Plasma Physics. The Phase Contrast Imaging (PCI) system [1] measures line-integrated electron density fluctuations throughout the core of W7-X. It utilizes a CO_2 infrared laser beam, which scatters on turbulent density structures in the plasma. An image of the fluctuations is created on two 32-channel detectors, enabling measurements of poloidal wavenumber spectra. Additional masking allows for radially selective measurements. PCI provides data on core turbulence studies in various magnetic configurations across a large range of operational parameters. The Gas-Puff Imaging (GPI) system [2] enables studying plasma turbulence boundary dynamics in the scrape-off layer (SOL) of W7-X. The system utilizes converging-diverging nozzles for gas puffing, a pop-up mirror for side-view emissions, and a high-throughput optical system that directs light onto an 8x16-pixel fast camera. GPI provides detailed 2D measurements of plasma fluctuations in the magnetic island of the island divertor configuration. We present highlights from the latest experiment campaigns, comparing core and SOL turbulence between various operation scenarios of W7-X. By providing imaging data of density fluctuations and flows in both the core and the SOL, the two diagnostic systems enable a validation of turbulence and transport models in support of a stellarator FPP design.

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Multimachine analysis of intermittent fluctuations in the scrape-off layer of magnetically confined fusion plasmas

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At the outboard mid-plane scrape-off layer (SOL), radial transport of particles and heat is dominated by plasma structures called filaments or blobs. These plasma structures are elongated along the magnetic field lines, spatially localized in the cross-field direction, and are hot and dense compared to the ambient plasma [2, 3]. The filamentary transport typically gives rise to order-unity fluctuation levels, contributes to profile broadening and flattening in the SOL and may be related to the discharge density limit. Interactions between fluctuation-induced particle flux and the surface of the main wall material may result in increased erosion rates and interactions with RF waves [2, 4].

To account for the fluctuation-enhanced transport, a stochastic model has been developed [5]. In this model, which well describes the fluctuations due to filaments [3, 6], measurements from Langmuir probes and gas puff imaging are modeled as a superposition of two-sided exponential temporal pulses with randomly distributed amplitudes arriving according to a Poisson process. The key parameters of this model are the mean waiting times between consecutive pulses, the pulse duration times and the mean of the pulse amplitudes.

We present a comprehensive analysis and comparison of fluctuation data from six tokamaks: Alcator C-Mod, DIII-D, TCV, KSTAR, MAST, and MAST-U, under the context of stochastic modeling in Ohmic and low confinement mode scenarios [1]. The study examines the influence of line-averaged density, plasma current, aspect ratio, and elongation. The mean amplitudes are shown to increase with the Greenwald fraction across devices. Notably, spherical tokamaks exhibit higher fluctuation amplitudes, longer durations and longer waiting times compared to conventional tokamaks, which display clear trends in duration and waiting times related to aspect ratio. In conventional tokamaks, shorter waiting times and consequently higher blob frequency results in more frequent plasma-wall interactions. Overall, the study highlights the influence of machine and engineering parameters on L-mode far-SOL fluctuation statistics, thereby providing insights for future devices.

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Advancing plasma turbulence understanding with synthetic reflectometry in tokamaks

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Tokamak plasmas are complex systems in which turbulence and transport interplay in a multi-scale manner and across a broad range of dynamics. Ultra-fast sweeping reflectometry is a diagnostic technique capable of measuring electron density fluctuations with very high spatial and temporal resolutions, capturing effects arising from MHD or micro-turbulence. This technique has been used to observe meso-scale structures, such as the **ExB staircase —** a successive radial pattern of poloidal flows and avalanches [1]. This tertiary structure emerges from the self-organization of turbulence and regulates turbulent transport by alternating spatially between phases of free energy accumulation (zonal mean flows) and intermittent outward transport events. Such organization is believed to enhance plasma confinement. Doppler reflectometry, which probes the plasma at an oblique angle, offers complementary access to the radial electric field, which is believed to be crucial for the self-organization of edge turbulence and transition to H-mode confinement regimes. However, experimental observations are often limited to indirect measurements, requiring complementary simulations (i.e. synthetic diagnostics) for interpretation.

In this work, we carefully confront experimental observations and calculations using the synthetic reflectometry diagnostic **FeDoT** [2]. We validate past interpretations of the experimental data and improve its reliability. The code is based on a two-dimensional (2D) Finite Difference Time Domain (FDTD) full-wave numerical scheme with absorbing boundary conditions. It supports arbitrary antenna configurations, including monostatic and bistatic setups, and can simulate both O-mode and X-mode polarizations at any incidence angle, enabling realistic modeling of conventional or Doppler reflectometry. Significant effort has been devoted to verifying the full-wave solver, an essential step in enabling meaningful comparisons between simulation and experimental data.

Recent coupling between **FeDoT** and turbulence maps generated by the gyrokinetic code **—GYSELA** enables probing of the ExB staircases. These structures are identified by detecting successive shear layers, indicated by corrugations in the radial profile of the radial correlation length, which align with the periodic deepening of the radial electric field. This synthetic diagnostic also confirms the reflectometry diagnostic's ability to track additional or enhanced signatures of staircases or shear layers. For example, it can detect the differential tilting of eddies stemming from asymmetry in turbulence frequency spectra. These new capabilities pave the way for measuring the dynamics of shear layers and turbulent fluctuations concomitantly, thereby advancing our understanding of turbulent mechanisms in tokamak plasmas.

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Radial electric field profile and geodesic acoustic modes in tokamak plasmas

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The radial electric field (Er) is known to have a significant impact on turbulent transport reduction [1] and a key role in the transition toward the higher confinement regime. Experimentally, the radial shape of the perpendicular velocity of density fluctuations, dominated by the ExB velocity, appears significantly influenced by the magnetic topology [2-5], the plasma current [2] and the plasma shape [6]. Among the various possible mechanisms involved in the formation of the Er profile, turbulence related effects could explain some of these sensitivities [7,8] through the generation of zonal flow (ZF) via Reynold's stress. Part of these turbulence-generated flows, Geodesic Acoustic modes (GAMs), appearing in the form of a coupling between a ZF and an axisymmetric (*m* = 1) pressure sideband mode due to geodesic curvature, may inform on the turbulence intensity in case of constant flow damping.

In this contribution, we investigate how GAMs evolve in relation to different Er profiles. In particular, based on Doppler Backscattering measurements from WEST [3] and TCV [6,9] experiments, the evolution of turbulence intensity and GAM characteristics between favourable and unfavourable gradB drift configuration is addressed as well as the influence of the plasma current. In addition, the GAM behaviour is compared between positive and negative triangularity plasmas in different heating schemes.

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Interpreting scale-dependent velocity measurements from Doppler Backscattering diagnostic on WEST tokamak

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The Radial electric field (E_r) plays a central role in the reduction mechanism of turbulence and the formation of transport barriers, making it a key element in understanding and improving confinement in magnetised fusion plasmas[1,2]. Doppler Backscattering (DBS) systems have been widely employed as diagnostic tools for inferring the E_r via measurement of the $E \times B$ flow, bringing significant contribution into confinement and transport dynamics in different tokamak machines[3–5]. However, the interpretation of DBS measurements remains nontrivial, as the extracted velocity may contain additional contributions beyond the $E \times B$ flow, most notably the phase velocity of density fluctuations, which are often neglected in standard analysis. The latter may vary with spatial scale and it potentially carries valuable information about the nature of the underlying turbulence and the dominant instabilities driving it[6].

The study presented in this contribution has been motivated by experimental evidence observed in previous analyses[7,8], which showed a consistent increase in the measured velocity when probing lower wavenumbers. This behaviour, identified in a different plasma configurations and heating scenarios especially in the E_r well, underlies a possible influence of the phase velocity on the measurements. An experimental investigation has been conducted using the DBS system installed on WEST tokamak[9], with the aim not only of documenting the wavenumber sensitivity of perpendicular velocity across a range of plasma conditions, but also of investigating other potential contributions to the measurements, with a view to disentangling diagnostic-related effects from those inherent to turbulence.

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Carbon density fluctuation measurements at the plasma edge using the prototype low-noise, high-speed BES detector on W7-X

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Carbon density fluctuations are measured by observing the C-VI emission line (n = 8→7, λ~529 nm) resulting from charge exchange (CX) between neutral beam atoms and the intrinsic carbon population on Wendelstein 7-X (W7-X). A low-noise, high-speed multi-channel Beam Emission Spectroscopy (BES) diagnostic has been customized to observe high-frequency, low intensity light signals. BES consists of a telecentric optical assembly for collimating and bandpass selecting the emission, a detector enclosure for signal compensation and amplification, and a thermoelectric cooling (TEC) unit to actively cool down the enclosure to -20 ºC, providing a significantly improved signal-to-noise ratio. This detector has been designed as a part of the future BES diagnostic for studying 2D ion gyro-scale turbulence on W7-X[1,2], whereas the C-VI emission measurement is achieved by replacing the bandpass optical filter to the one with the desired wavelength passband. BES turbulence measurement capabilities will be summarized.

During the NBI heating phase in the OP2.3 campaign, carbon fluctuations are measured by using available fibers from a CXRS system[3]. Here we present the performance of the diagnostic and investigate the carbon fluctuations at the plasma edge. A carbon density fluctuation at 14 kHz is commonly observed at the plasma edge in the standard configuration (EIM), whose frequency is constant with a narrow bandwidth. Characteristics of the mode are shown, including the mode radial structure, poloidal phase velocity, and cross-correlation with the electron density fluctuation measurements from other diagnostics at different toroidal cross-section locations.

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Predicting the isotope scaling of confinement in JET-ILW Ohmic and low power L-modes with H, D and T

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Predicting the isotope scaling of confinement in tokamaks is essential as experiments move from D to DT. The best reduced models have been found to be accurate for D but not for H [1], and comparisons with T have been less explored due to their experimental scarcity. In this work, the capability of recreating this confinement scaling in simulations is validated with integrated modelling and the quasilinear transport model TGLF [2] for low power JET discharges across H, D and T. All the TGLF saturation rules SAT1-SAT3 are seen to predict a similar isotope scaling of confinement across both the ITG- and TEM-dominated discharges simulated, despite for the latter case the inclusion of the TEM branch of SAT3 [3] which aims to recreate the anti-gyroBohm scaling of TEM transport observed in gyrokinetics. The models demonstrate good agreement with experiment for the scaling between D and T plasmas, however a greater discrepancy is observed for H in the discharges of higher density, as well as a systematic overprediction of the confinement time in most cases on the order of ~20%. A retuned version of the SAT3 model which was fit to better recreate fluxes close to the transport threshold is seen to improve the magnitude of confinement predictions across all shots owing to an increased transport stiffness, motivating the inclusion of such cases in future saturation model databases. This retuning was not seen to influence the confinement isotope scaling however, and investigations into possible transport mechanisms responsible for the continued discrepancy of Ohmic and L-mode discharges in H at higher density are discussed.

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Radial impurity transport studies in the pedestal of ASDEX Upgrade

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A new framework for experimental determination of impurity diffusion and convection in the pedestal has recently been developed at ASDEX Upgrade (AUG) [1]. Based on charge-exchange spectroscopy data, it provides high-resolution profiles of the flux-surface averaged transport coefficients with Bayesian uncertainty quantification. We apply this framework to analyze neon transport across different confinement regimes and compare the results to simulations of neoclassical transport with NEOART [2] and NEO [3] to distinguish collisional and turbulent contributions.

Our study confirms earlier findings of predominantly neoclassical transport in the H-mode edge transport barrier region between type-I ELMs [4], with the ELMs acting qualitatively as an additional diffusive mechanism [5]. The resulting steep impurity density pedestal is in contrast to the L-mode edge, where dominant turbulent diffusion is shown to yield flat impurity density profiles. Moreover, reactor-relevant scenarios without large ELMs are investigated. Quasi-continuous exhaust (QCE) discharges – averaged over their small type-II ELMs driven by ballooning modes [6] – exhibit significant anomalous diffusion in the pedestal, which reduces the impurity density peaking relative to type-I ELMy H-modes. Dedicated experiments have also been conducted in the ELM-free enhanced Dα (EDA) H-mode and in H-mode with ELM suppression by resonant magnetic perturbations (RMPs), with detailed transport analyses ongoing. The 3D structure of the plasma edge with RMPs poses particular challenges for both data evaluation and transport modeling, which will be discussed.

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Physics uncertainties: impact and mitigation on a DEMO burning plasma

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The requirements for the EU-DEMO are at least 2h of pulse length, and at least 350 MW of net electric power, a lower aspect ratio (A=2.8) baseline has been recently proposed [1]. The operational space is optimized using the system code PROCESS. Given the epistemic uncertainties on the physics assumptions, the design aimed at q_{95}=3.6 allowing to increase the plasma current in case of underperforming plasma.

In order to explore further the robustness of the operational domain, METIS, a physics code, combining current diffusion in 1D and 0D scaling laws for the density and temperature profiles [2] is used. Assuming a built machine (R=8.6 m, A=2.8, B=4.4T, 50 MW of ECRH), the pulse length and the plasma current are adjusted to fulfil the requirement on a target fusion power (P_{fus} =1.5-1.7 GW). When varying the scaling law and the density limit, the pulse length and plasma current (I_p) vary from less than 30 minutes and more than 26 MA to more than 4 h and less than 16 MA. Moreover, for a given scaling law and H factor, the fusion power can vary from 1.6 to 3 GW depending on the assumption constraining the profile shapes [1,3]. Such large sensitivity is stronger as the ratio of alpha power to auxiliary power increases from ~0.08 in JET DT record to 2 in ITER Q=10 and up to ~6 in DEMO Q=30-40.

In order to mitigate the uncertainties, physics based turbulent transport models applicable at high beta and in presence of alphas need to be developed and verified. Recently, the reduced model TGLF has been verified against GKW on JET high beta experiments [4]. In parallel, ITER at 15 MA is modelled by nonlinear global gyrokinetic simulations [5]. While verification is on-going, DEMO burning plasma nonlinearities are nonetheless studied using TGLF in the High-Fidelity Pulse Simulator. Heat, particle fluxes and fusion power are self-consistently evolved with feedback loops on pellet fueling on the density and on Xe content on the power entering the SOL. Oscillations of P_{fus} in time for different boundary conditions and Q values are presented. The impact of increasing I_p to recover the possible loss of performances is explored for DEMO A=2.8 baseline.

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The impact of electromagnetic effects on turbulent transport in the core of JET, JT-60SA and ITER

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The turbulence in the core of future devices will be very different from current devices. [1]. Fast ions and electromagnetic (EM) effects have a complex impact on the turbulence both through linear effects, such as linear EM stabilization of electrostatic (ES) modes, and non-linear effects, such as enhanced coupling to zonal flows. As an initial step towards better understanding this regime we focus on the local electromagnetic effects in current and future devices. We study three baseline discharges: JET discharge 102433 [2], an ITER like discharge for JT-60SA [3] and ITER 15MA-scenario. Firstly, we perform predictive integrated modelling simulations with JINTRAC of our discharges with and without EM effects with the gyro-fluid model TGLF to see the impact on the predicted profiles. We evolve densities, temperatures and the current as well as reevaluate the equilibrium continuously with an internal boundary at ρ=0.9. For the EM simulations at the magnetic axis the normalized plasma pressures, β_e, are JET 3.7%, JT-60SA 3.4% and ITER 5.1% and the result of the predicted ion temperatures is displayed in Figure 1. The difference is largest for the ITER discharge in the bottom figure. Based on these simulations, we plan to perform stand alone linear analysis with TGLF and the gyro-kinetic code GKW to study the unstable modes at several radial positions. Preliminary results suggest the emergence of Kinetic Ballooning Modes in the core which could explain the difference in the ITER simulations. Additionally, this study is being used to verify TGLF and its settings against GKW. Understanding the new transport regime in upcoming devices will enable the development of improved reduced transport models critical to future device design and operation.

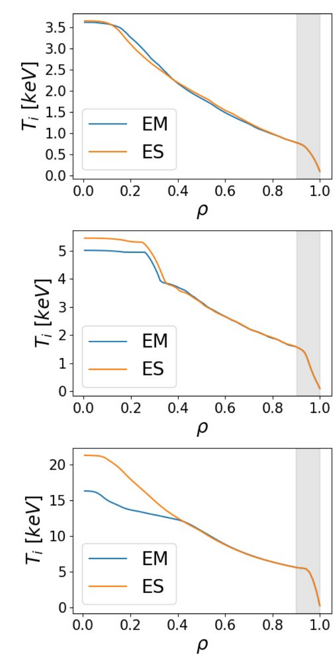

Figure 1 – Ion temperatures profiles for predictive simulations with/without EM effects of JET (Top), JT-60SA (Middle) and ITER (bottom)

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A multi-diagnostic approach to investigate filament activity on the Wendelstein 7-X stellarator

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This presentation highlights the findings of studies on plasma filament [1] behavior in the Wendelstein 7-X (W7-X) stellarator using two diagnostic tools: video diagnostics and Alkali-Beam Emission Spectroscopy (ABES). Video diagnostics are instrumental in revealing filament dynamics and their three-dimensional structure within complex magnetic topology of W7-X. They provide insights into the poloidal velocity, width, lifetime, and toroidal characteristics of filaments, which can vary depending on the magnetic configuration. [2] However, these observations are confined to a narrow region at the plasma edge that emits visible radiation. The width and position of this radiation belt can be estimated using the EDICAMs of the video diagnostic system. [3]

ABES, on the other hand, offers high radial resolution in the SOL, but it is one dimensional. By examining correlation patterns between the two diagnostics, one can identify areas of filament activity and track their movement across a broad poloidal and radial extent and several toroidal segments. ABES data reveals two distinct radial zones of intense activity that are not correlated with each other. Where ABES channels intersect with the radiation belt observed by the cameras, strong correlations are found. Surprisingly, some correlations appear in parts of the camera images that are not magnetically connected to the ABES channels. Another unexpected observation is the correlation between the camera images and ABES channels located beyond the peak of the ABES light profile—regions usually deemed less informative due to “shadows” of outward events.

This presentation explores possible explanations for these findings and discusses their implications for understanding filament formation in stellarators and their relevance for safe and effective operations.

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Impurity Transport Using Tracer Particles and the Hasegawa–Wakatani Model

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Anomalous cross-field transport in the edge and scrape-off layer of magnetically confined plasmas remains a critical challenge for achieving efficient confinement in fusion devices [1]. This region hosts hydrogenic ions, helium ash, injected impurities (e.g., neon, argon), and eroded wall materials, all of which interact with turbulent structures to drive complex, non-diffusive transport behaviour [1, 2]. Coherent vortices and shear flows—particularly ExB shear and zonal flows—are known to act as transport barriers in fluid systems [3, 4], yet their role in regulating impurity dynamics in the plasma edge is not fully understood [2].

In this work, we develop a versatile particle-tracer framework coupled to a two-field Hasegawa–Wakatani (HW) turbulence model [5], implemented within BOUT++ [6]. Tracer particles are advanced under the Lorentz force using a Boris push integration scheme, ensuring second-order accuracy and energy conservation. To detect and quantify coherent structures and transport barriers, we introduce the Lagrangian Averaged Vorticity Deviation (LAVD).

By combining tracer trajectories with LAVD-based identification of vortical structures, we show how the charge-to-mass ratio of impurities influences their trapping, escape, and radial transport. We analyse probability distribution functions of particle displacements as functions of both adiabaticity and particle characteristics, providing insight into convective, non-Fickian transport driven by persistent vortices.

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Orbit-Averaged Collisional Modelling for Energetic Particle Transport in Constants-of-Motion Space

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Energetic particle (EP) transport in fusion plasmas spans wide spatial and temporal scales due to their large orbit widths and complex interactions with background plasma and collective modes. Traditional 1D transport models are inadequate to capture the physics of EP dynamics, particularly the finite orbit width effects and the structure of distribution in phase space.

In this work, we model EP transport using the Phase Space Zonal Structures (PSZS) framework [1], formulating the transport equation in constants-of-motion (CoM) space to capture finite-orbit-width effects at meso-scales [2, 3]. A key advancement is the implementation of a collision operator directly in CoM space [4], constructed via orbit-averaged collisional coefficients derived from the guiding-center code HAGIS [5]. This enables consistent modelling of neoclassical slowing down and pitch-angle scattering. The resulting orbit-averaged transport model treats long-time collisional effects and wave-driven transport on the same footing [6, 7, 8]. ATEP-3D, a finite-volume solver for long-time EP transport in 3D CoM space is developed and fully integrated into ITER's Integrated Modelling framework [4, 7]. To reflect realistic conditions, source and sink terms based on ITER scenarios are included. This work provides a basis for realistic EP transport simulations, with extensions to include cross-scale interactions and mode evolution.

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Study of the transition of ∇Te and ∇ne driven TEM and their transport in small-ELM H mode plasmas using ECRH modulation

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H mode plasma with edge transport barriers (ETB) has been recognized as one of the most promising operation regimes in future fusion devices. However, the formation of ETBs are often accompanied by edge localized modes(ELMs) bursts which may severely damage the plasma facing components(PFCs) and degrade plasma confinement. Therefore, H mode plasmas with small ELMs or ELM free are favorable in future fusion operations.

In our study, an EAST H mode shot with small ELMs is studied with ECRH modulation at a 2Hz duty cycle. With mainly electron heating provided by neutral beam injection (NBI), lower hybrid wave (LHW) and electron cyclotron resonance heating(ECRH), combined with power balance code ONETWO and trapped gyro landau fluid code TGLF, the turbulence instability and its induced transport are investigated.

Both the experimental measured critical gradients and fluxes calculated by power balance code (ONETWO) are compared with linear and quasilinear estimations. It is found that modulated ECRH power could lead to a transition from temperature driven trapped electron mode (TGTEM) to density gradient driven TEM (DGTEM) due to the flattened Te profile between $0.3<\rho<0.6$ and the heat flux induced by these two modes show different characteristics which may explain the confinement improvement caused by ECRH modulation.

The propagation of modulated heat pulse are also investigated both by linear critical gradient induced heat conductivities model and self consistent quasilinear evolution code TGYRO. It is also found that the transition between TGTEM and DGTEM may be the main reason for the miss prediction of linear and quasilinear models.

Keywords: TEM turbulence, Small-ELM H mode, TGLF/TGYRO, ECRH modulation

Reference:

【1】C Gillot et al 2023 Plasma Phys. Control. Fusion 65 055012

【2】Y.F. He et al 2024 Nucl. Fusion 64 076064

Leveraging synthetic diagnostics for driftfluid turbulence model validation

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Synthetic beam emission spectroscopy (BES) measurements of modelled scrape-off layer (SOL) turbulence were compared to experimental BES measurements taken on ASDEX Upgrade, in an effort to investigate features of filament dynamics and validate the underlying turbulence model. Previous experimental findings at ASDEX Upgrade by Birkenmeier et al. were taken as a reference as they provide a well-established baseline for current study [1], which provides a radial observation of filaments.

A turbulence workflow, developed within EUROfusion Integrated Modelling framework was used to generate SOL turbulence and subsequent synthetic fluctuation BES signals. A turbulence code generated fluctuating density and temperature field are passed to BES synthetic diagnostic via integrated data structures [2]. Time-dependent density and temperature fluctuations are provided by 2D fluid code, HESEL, where the filaments are generated by interchange dynamics in the SOL. Flux tube expansion of turbulent structures within the beam geometry allows for a 3D approximation of modelled SOL filaments [3]. RENATE is a fluctuation BES synthetic diagnostic [4], featuring 3D beam and 3D observation geometry modelling capabilities, as well as accounting for the underlying magnetic geometry, thereby incorporating all relevant spatial artefacts of the diagnostic. Furthermore the synthetic diagnostic is equipped with detailed detection noise modeling capabilities.

A comprehensive statistical analysis was conducted observing the features of synthetic and experimental measurements such as filament frequency, distributions of waiting time, amplitude, size and velocity. These features were individually compared to the respective counterparts for synthetically and experimentally observed discharges showing some systematic discrepancy mostly attributed to the synthetic nature of the measurement, by combining an imperfect turbulence model with an imperfect BES synthetic diagnostic. These studies were repeated over multiple L-mode plasma discharges, where plasma parameters were kept the same with the exception of the connection length. The study of velocity and filament size distributions in function of the connection length showed inconclusive results, while a good agreement was observed in the dependence of amplitude distribution and filament frequencies in function of the connection length. The study clearly shows HESEL to be able to successfully reproduce certain features of filament dynamics, whereas other features require a multi diagnostics validation effort.

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Saturation of fishbones due to zonal flow in weak temperature gradient equilibria : a gyrokinetic study

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Energetic particles (EPs) in burning plasmas play a crucial role in heating. However, EPs can trigger instabilities at various spatial scales such as meso-scale Alfven eigenmodes and global kinetic-MHD modes. One of these global kinetic-MHD modes that could result in large EPs transport is fishbone. Recently, studies using the gyrokinetic code GTC have revealed the critical influence of fishbone-induced zonal flows on the mode saturation for equilibria with spatial gradients in density and temperature profiles. This finding is based on a DIII-D discharge characterized by an ion internal transport barrier (ITB), which is possibly sustained by the zonal flows generated through fishbone activity. In the present work, we explore the interplay between zonal flows and fishbone dynamics in experimental settings, with weak to no temperature gradient profiles, as observed, for example, in LTX machine [3,4] wherein zonal flows are observed to play an insignificant role in kinetic drift modes saturation [4], for subcritical η (ITG) cases. Using the global gyro-kinetic code ORB5 [5], for a set of real MHD equilibria generated using CHEASE [6], we perform first-principles simulations in low to intermediate beta limit. It is observed that ZF do get generated, even in the absence of strong temperature gradients, triggered by EP-driven fishbones, thus providing valuable insight into the generality and role in transport regulation discovered earlier [1,2].

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Integrated transport modeling for SPARC H-modes: sensitivity to physics inputs.

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In this work, an overview of predicted SPARC H-modes performance is provided, testing the sensitivity of fusion gain and H-mode robustness with respect to few input assumptions. Extensive databases of performance have been obtained for three H-mode scenarios [1], employing the ASTRA framework, with the quasilinear transport model TGLF-SAT2 EM for the turbulent transport, and a neural network (NN) fitted on EPED results for the pedestal stability. In this framework, a few uncertain input parameters (W and DT concentration, temperatures ratio at pedestal and deviation of pedestal pressure from EPED-NN prediction) have been randomly assigned in reasonable ranges to assess their effect on performance. The databases indicated low density and high input power as optimal conditions to reach high performance targets, while maintaining a robust H-mode configuration. Additional simulations have been obtained using the analytical model FACIT [2] and TGLF to predict neoclassical and turbulent impurity transport, and STRAHL to compute the charge state equilibrium and radiation in the plasma. Additionally, scans of impurity sources, auxiliary input power (ion cyclotron heating), density at top of pedestal and rotation have been performed to identify preferable operational windows. The results have been compared to the previously obtained extensive databases, to show the impact of impurity peaking on transport, radiation and H-mode robustness, highlighting the importance of high fidelity simulations to reduce uncertainties on the fusion performance of future devices.

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Development of a synthetic Atomic Beam Probe diagnostic

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Abstract

The study of Edge Localized Modes (ELMs) plays a critical role in the operation of magnetic confinement fusion devices, such as tokamaks. Larger (Type I) ELMs have the potential to damage the first wall; therefore we cannot allow them in reactor-scale devices, such as ITER. The mechanism of ELM cycles is described by the Peeling-Ballooning model, which depends critically on the edge pressure gradient and the edge current density. To validate this theory, diagnostics are needed to measure these parameters within the timescale of ELM cycles, and so far, no diagnostic method exists to measure edge plasma current fluctuations in such timeframes. One such candidate for this diagnostic is the Atomic Beam Probe (ABP)[1]. This technique uses an accelerated beam of neutral alkali atoms (mostly Li and Na), which is injected into the plasma. These atoms ionize due to collisions with the plasma's particles, and their paths are deflected due to the local magnetic field. We can measure the ion current distribution of this beam with a Faraday-cup matrix detector[2], which is positioned close to the wall of the machine. Since the current density distribution of the plasma influences the trajectory of the beam, the measured ion current contains information about the magnitude and spread of edge plasma currents[3].

To further examine the connection between the edge plasma current density profile and the ion current distribution measured by the Faraday-cup matrix detector, we present ABPSimulator, a numerical model developed for the purpose of predicting the ABP detector's current distribution, given the beam's initial parameters and the plasma's magnetic equilibrium configuration. The simulation treats the plasma current as small perturbations flowing along flux surfaces, which is superimposed on the equilibrium current profile. These perturbation profiles can be generated by using an arbitrary linear combination of basis functions, which could be either triangular or Gaussian. The code embeds the resultant current profile into the poloidal plane using a magnetic equilibrium reconstruction code. The magnetic field generated by this plasma current is calculated using a discretized version of Biot-Savart's law. From here, the simulation solves for the equations of motion of the beam, and calculates the expected signal at the ABP detector.

Using ABPSimulator, it is now possible to examine the connection between the edge plasma current profile and ABP detector measurements. The code is modular, and machine-independent (*i.e.* other devices' magnetic equilibrium reconstruction codes can be utilized). In addition, computationally intensive routines are multi-threaded in order to decrease simulation runtimes. By using the numerical model, we show that the total toroidal current and the B_z component of the poloidal magnetic field can be reconstructed from the ion beam current distribution at the detector.

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Characterization of Type III ELM Precursors on MAST-U with Beam Emission Spectroscopy

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The Beam Emission Spectroscopy (BES) diagnostic installed on the MAST-U device [1] enables two-dimensional turbulence imaging using an 8 × 8 pixel array, providing poloidal–radial resolution. The diagnostic observes the on-axis heating beam and is equipped with a rotatable first mirror, which allows coverage from the magnetic axis to the scrape-off layer (SOL) at the midplane. During the MU04 campaign, the BES system was upgraded, resulting in improved signal-to-noise ratio measurements [2] at the plasma edge, which enabled detailed characterization of edge plasma instabilities.

Type III edge localized modes (ELMs) are known to exhibit precursors prior to their onset, and such signatures have been observed on MAST-U using BES. These ELMs occur at higher frequencies compared to Type I ELMs, providing an opportunity to investigate their distinct dynamics. With the high spatial and temporal resolution of BES, both the amplitude and propagation direction of Type III ELM perturbations can be quantified.

As an example, the #50938 recent MAST-U discharge is analysed, which is an 800 kA, on-axis beam-heated plasma discharge. Type III ELMs are observed following the L–H transition, which subsequently evolve into Type I ELMs. Oscillatory activity is clearly detected in the BES signal prior to Type III ELM onset. Short-time Fourier transform analysis reveals a characteristic precursor frequency of ~25 kHz [3]. The spatio-temporal resolution of BES further allows determination of the apparent poloidal velocity evolution [4] and wavelength of the observed mode, with an estimated wavelength of ~25 cm. A comparative analysis of Type I and Type III ELM precursors is also presented in the contribution.

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A new multigrid solver for stellarator neoclassical transport

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Solution of the drift kinetic equation [1] is a required step in analyzing and optimizing neoclassical transport in stellarators. A variety of codes [2-6] have been developed to handle the complex geometry and wide range of collisionality regimes present in stellarators. Existing codes are generally either high fidelity codes that are accurate in a wide range of regimes, but are too expensive to be efficiently used in optimization loops or predictive transport frameworks, or lower fidelity codes that are faster are limited in their regimes of validity or miss important physical phenomena such as the bootstrap current or ambipolar electric field. We have developed a new neoclassical code that attempts to bridge this gap, offering high fidelity solutions capturing as much of the physics as possible, while being significantly faster and more memory efficient than existing high fidelity codes. We do this by making use of novel stable finite difference discretizations combined with a multigrid method to solve the resulting linear system. Automatic differentiation is used to obtain derivatives for use in optimization. Applications are discussed including self consistent optimization of the bootstrap current and optimization of “electron root” plasmas [7].

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Advances in integrated modeling of burning plasmas in ARC

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Accurate and robust predictions of fusion performance in next-generation devices such as ARC [1,2] must rely on a combination of first-principles physics modeling as well as reduced models such as quasilinear transport codes and empirically-derived scaling laws. While 0D performance predictions are useful for scoping studies, experience with SPARC modeling has identified consistent over-prediction of fusion performance by confinement scaling laws due to stiff temperature profiles and unrealistic boundary conditions. We showcase the results of medium-fidelity ASTRA-TGLF-EPED [2-4] transport simulations which demonstrate the importance of optimizing FPP designs around pedestal performance, as well as highlighting the extremely stiff transport by showing a breakdown of the empirically-derived power degradation. We demonstrate the use of a new workflow, MAESTRO, to efficiently produce time-independent predictions of performance with a variety of different transport codes. We benchmark this new workflow against a large database of ASTRA simulations in order to test the sensitivity of fusion performance against various assumed quantities. Finally, we review high-fidelity gyrokinetic profile predictions carried out with PORTALS-CGYRO [5] and outline future work that is needed to understand the differences between medium- and high-fidelity transport modeling in ARC.
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Velocimetry analysis of apparent poloidal motion in the pedestal region for Type-I ELMs observed in MAST-U

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Measuring flow velocity is essential for characterizing edge plasma instabilities and turbulence. Based on measurements from the Beam Emission Spectrography (BES) diagnostic on MAST-U [1], we apply the dynamic time warping (DTW) algorithm previously proposed for estimating the flow velocity field from density fluctuation measurements [2, 3, 4]. The BES system on MAST-U provides 64 measurement channels, arranged in an 8×8 2D matrix, with 4 MHz temporal resolution, enabling the observation of fast transient structures.

By applying the DTW algorithm to the intensity fluctuations measured by the BES system, we estimate the apparent poloidal velocity of localised oscillations near the pedestal top. Based on recommendations from previous analyses [5], the estimated velocity near the edges of the field of view is neglected due to artefacts introduced by the DTW algorithm. Appropriate spatial and temporal averaging of the estimated 2D velocity field uncovers a clear reversal of the estimated poloidal velocity at the beginning of the precursor phase of Type-I edge localizes modes (ELMs) from the ion-diamagnetic direction to the electron-diamagnetic direction. We illustrate this behavior through the analysis of a Type-I ELM crash, while the estimated poloidal velocity during a non-developed precursor and in a Type-II ELM period is also given.

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Density Peaking in Next Generation Fusion Devices: Analysis of Performance and Transport in SPARC, ARC, and ITER

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Over a decade of research has focused on understanding the observed peaking of electron density in tokamak plasmas. Devices worldwide have observed a correlation between density peaking and effective collisionality, resulting in a well-known empirical scaling law [1]. However, recent work indicates that future fusion devices may deviate from observed trends. Surrogate modeling techniques implemented in PORTALS [2] has enabled routine profile predictions of SPARC, ITER, and ARC-like fusion devices utilizing high fidelity (4 gyrokinetic species, realistic geometry, collisions, electromagnetic turbulence), nonlinear gyrokinetic (CGYRO [3]) predictions. 20+ nonlinear gyrokinetic profile predictions (n_e, T_e, T_i simultaneously) have been performed for ~r/a < 0.95 for SPARC, ITER, and ARC plasma conditions that provide insight into the physics of density peaking and projections to fusion pilot plants (FPP). In projected SPARC L/I-mode plasmas, nonlinear gyrokinetic modeling reproduces empirical trends over 30x in effective collisionality. However, in conditions predicted for FPP-relevant conditions, modeling results are shown to deviate from empirical scalings. In addition to a reduction of peaking due to increase plasma beta [4][5], it is demonstrated that the presence of ITG dominated plasma transport in low collisionality conditions, results in a saturation of density peaking. The scaling of gyro-Bohm heat transport with temperature and the dependence of ITG driven particle flux on collisions is shown to result in a deviation from the empirical scalings that is independent of plasma beta. In this presentation we will cover nonlinear gyrokinetic predictions of performance in SPARC, ITER, and ARC and a detailed investigation into the density peaking that is predicted to be observed in FPP class devices.

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Kinetic modelling of runaway electron momentum distributions for the EU-DEMO tokamak

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In high-current devices, such as the planned EU-DEMO tokamak, a large fraction of the plasma current can be converted into runaway electron current, and the subsequent runaway beam can cause significant damage to the plasma-facing components. In this work, the momentum distribution of the runaway electrons is simulated in 3 dimensions: 1D in real space and 2D in momentum space. Self-consistent kinetic simulations with differing levels of approximations have been performed in DREAM [1] for EU-DEMO and are presented in this work. Our goal was to qualitatively describe the evolution of the runaway electron distribution function and relate the numerical results to previously published analytical models [2,3]. Results show that the high electric field during the thermal quench results in a monotonic distribution function in energy [2]. On a longer timescale, a bump forms in the distribution tail, as predicted by [3,4].

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Edge radiation dynamics during the attachment-detachment transition in Wendelstein 7-X

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Detachment is a key operational scenario in magnetically confined fusion plasmas, enabling significant thermal power dissipation via radiation before it reaches the divertor targets. This reduces heat and particle loads, making detachment a promising candidate for power exhaust control in future fusion power plants. On Wendelstein 7-X (W7-X), stable detachment has been reliably achieved in certain conditions — the longest demonstrated duration was 110 seconds — during which the heat flux to divertor targets was almost negligible [1].

To optimize operational scenarios and deepen our understanding of detachment physics, it is crucial to investigate changes in transport processes occurring during the transition from attached to detached states.

The EDICAM overview camera system has a large coverage of the W7-X vacuum vessel, with a view of the inner wall where visible edge radiation can be spatially localized after calibration. By overlaying the magnetic topology, including X- and O-points, onto the camera images, the evolution of edge emission patterns can be studied with a good temporal and spatial resolution.

During detachment, the overall divertor radiation decreases compared to the attached phase. Simultaneously, field-aligned, poloidally localized structures tend to brighten around certain X-points and inside magnetic islands, especially on the inboard side. In this work, we compare the spatiotemporal dynamics of these structures across different magnetic configurations, with particular attention to their intensity profiles, including their peak brightness, spatial extent and evolution in time.

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Exploring spectral energy transfer in nonlinear gyrokinetic simulations to understand zonal flow drive

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Zonal flows (ZFs) are radially-sheared **E**×**B** poloidal flows that are believed to play a role in the L-H transition. The zonal potential $\phi_{\mathrm{ZF}} = \phi(k_x, k_y = 0)$ is constant on a flux surface, so it does not drive radial transport; on the contrary, the variation of ϕ_{ZF} across flux surfaces causes differential rotation that shears apart turbulent structures, causing transport to saturate at lower levels. ZFs are linearly stable but are driven nonlinearly through the Reynolds-Maxwell stress arising from the fields caused by drift wave turbulence. Energy transferred into zonal flows from drift wave turbulence naturally leads to reduction in energy in non-zonal ($k_y \neq 0$) turbulence. Previous attempts to measure this energy transfer during the L-H transition have been limited by the poloidal extent of typical turbulence diagnostics [1, 2]. To facilitate comparisons with experimental data, and to probe ZF dynamics numerically, diagnostics have recently been added to the gyrokinetic codes GS2 [3, 4] and GX [5, 6] that resolve the nonlinear spectral energy transfer as a function of (t, θ, k_{xs}, k_{ys}, k_{xt}); that is, time, poloidal angle, source k_x and k_y, and target k_x ($k_y = 0$ for ZFs). The work presented here builds on this existing electrostatic ($\delta\phi$) diagnostic [7, 8] by including electromagnetic fluctuations ($\delta A_\parallel$ and $\delta B_\parallel$). It has been observed in electromagnetic gyrokinetic simulations that above a critical β, electrons stream across flux surfaces and short-out ϕ_{ZF}, leading to enhanced transport levels [9]. This is known as the non-zonal transition (NZT). Recent work by Rath and Peeters [10] has shown that it's possible to access saturated states above this critical β, provided persistent mesoscale ZF patterns can develop. This work aims to probe this further and provide insights into the effects of shaping on ZF drive and access to improved-β regimes.

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Investigating the pedestal intrinsic torque at the ASDEX Upgrade tokamak

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Accurate methods for predicting toroidal plasma rotation in magnetically confined tokamak plasmas are of great interest due to the effect rotation has on MHD stability, impurity transport, and turbulence suppression. Predictive capabilities for the toroidal rotation have been challenging to develop due to the complexities of momentum transport; in addition to the convective and diffusive components present in heat or particle transport, momentum transport includes a residual stress component, which is neither proportional to the rotational velocity nor its gradient, and causes an intrinsic, turbulence-induced torque that can spin up the plasma from rest. To develop predictive models for the plasma rotation, this phenomenon must be better understood.

A momentum transport analysis methodology was recently developed at ASDEX Upgrade to analyze the contributions of the different transport components [1], including intrinsic torque. This is done by using the ASTRA code [2, 3] to solve the momentum transport equation [4] and infer a set of momentum transport coefficients to best match experimental rotation profiles. While this analysis framework was mainly applied to study the plasma core, in this work it is adapted for application in the pedestal region of the plasma. In particular, a neoclassical correction was added to experimental profiles to account for the relatively greater impact of the neoclassical effects in the pedestal. For the first time at AUG, the effective intrinsic torque in the pedestal region can be radially resolved and studied. Analysis of the effects of different transport mechanisms in the edge indicates the dominance of diffusion and intrinsic torque over convection inside the pedestal top. This workflow is applied to a database of AUG discharge phases to allow for the determination of corresponding parametric dependencies of the intrinsic torque. Furthermore, the radially resolved transport coefficients enable the characterization of the shape of the intrinsic torque in the pedestal region, as well as the identification of a maximum value and it's location. Ultimately, this study should lead to a more complete picture of the formation of plasma rotation profiles and facilitate the construction of self-consistent rotation models for integrated modeling of future fusion devices.

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Study of the beta dependence of confinement and transport for H-mode plasmas in EAST

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Dimensionless parameter scanning experiments are widely utilized to compare transport and confinement properties across diverse devices [1,2], serving as a cornerstone for extrapolating results from existing devices to future reactors like ITER and CFETR. Among these, investigating the interplay between energy confinement, transport, and β is fundamental to unraveling the operational regimes of future burning plasma devices. In this work, β was scanned across three plasma current platforms with multiple heating, yielding a variation range of β_N = 0.8–1.3 while ρ^*, ν^*, q and other magnetic geometrical parameters were kept fixed. Global analysis reveals a strong negative correlation between the energy confinement time and β, quantified as $B\tau_E \propto \beta^{-1.32}$, which is stronger than that predicted by the IPB98(y,2). Meanwhile, turbulence diagnostics in EAST revealed enhanced magnetic fluctuation with β, which is associated with the enhanced electromagnetic effects at high β [3]. The TRANSP code combined with CQL3D and NUBEAM will be used to analyze the thermal heat and particle transport of the discharges, confirming the results of the global analysis. The TGLF code will be used to explain the experimentally observed phenomena and clarify the mechanisms behind the influence of β on turbulence. Additionally, the findings will be discussed and compared with experimental results from other current devices [4-6] to further validate β dependence of confinement and transport.

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Dynamics of plasma fluctuations and confinement properties during I-phase in ST40 plasmas

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The transition from L-mode to H-mode in tokamak plasmas can occur through either a direct, one-step transition or through an intermediate oscillatory phase, characterised by limit-cycle oscillations (LCOs), also known as I-phase. Understanding of the transition, the phenomena involved and the plasma parameters affecting it is crucial for predicting confinement in future fusion reactors. The interaction between turbulence and zonal flows is believed to play a crucial role in governing the LCOs [1-4].

This work presents results from the analysis of the dynamics during the I-phase on the ST40 tokamak. Transport analysis using ASTRA [5] indicates an improvement in confinement in H-mode compared to the I-phase. Transitions from I-phase to H-mode, as well as back-transitions, were observed.

Poloidal magnetic field and electron density fluctuations in the range of 1-10 kHz were studied using magnetic probes and a sub-millimetre interferometer. These oscillations were identified as LCOs and hence a signature of I-phase. In some cases, multiple low-frequency modes (harmonics) - with frequencies up to 20 kHz - were detected. The higher-frequency modes appear closely linked to the burstiness of LCO dynamics.

Bursts of high-frequency turbulence activity, as seen in both magnetic and density fluctuations, were found to occur at the LCO frequency. The amplitude envelope of the LCO was observed to correlate with the envelope of high-frequency turbulence in both poloidal magnetic field and electron density oscillations. The low-frequency mode lags the turbulence envelope. The dynamics are consistent with periodic suppression of turbulent transport and enhancement of edge confinement, in line with predator-prey dynamics and limit-cycle oscillations.

Statistically significant nonlinear interactions between the broadband high-frequency fluctuations and the modes at LCO frequency were identified, indicating the presence of zonal flows during I-phase. The magnetic component of the LCO exhibited a mode structure of m=1, n=0. Additionally, the frequency scaling with edge sound speed suggests that the observed modes may correspond to a geodesic acoustic mode.

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Physics-informed neural networks for electron density reconstruction in the plasma edge

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Neural networks (NNs) have been shown to tackle various challenges in magnetically confined fusion research [1][2], particularly when large amount of high-quality data is available. Experimental data is, however, rarely abundant and data quality is usually limited by several other factors. NNs can be sensitive to noise, incomplete data, and data bias. To address these limitations, one approach is to inject physical laws into the loss function, allowing the network to learn the underlying physics while trying to fit the data. Physics-informed neural networks (PINNs) gained a lot of attention recently in solving differential equations [3]. A key advantage of NNs is their fast inference time, often outperforming traditional methods. This is because the heavy computations are performed in the training phase, while the inference phase is quick. For real-time plasma control, several studies [4][5][6] have proposed using NNs as surrogate models of complex simulations or to reconstruct plasma parameters from diagnostic data. Our study explores PINNs to reconstruct electron density from alkali beam emission spectroscopy (A-BES) data. A-BES is typically limited to diagnose plasma edge and the SOL, measuring the light yield of de-excitation of injected alkali atoms, which depends on the local electron density. The underlying physics is well described by the rate equations that capture interactions between alkali atoms and plasma particles. We investigate two approaches for incorporating these equations into the NN's loss function: one is called the Bayesian PINN [7] that maximizes the prior-weighted likelihood to simultaneously find network and physics parameters (the electron density in this case). The other approach is to transform the rate equations to directly describe the physical loss due to the mismatch between light and density profiles and build a NN for a light profile – density profile inference. As a first attempt using PINNs for this problem, we restrict our studies to synthetic data and vary noise levels artificially to observe PINN robustness.

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On the use of toroidally-averaged triangularity as a proxy for optimizing compact stellarators with respect to electrostatic ITG turbulent transport*

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By targeting negative values of the toroidally averaged triangularity in the optimization of a compact stellarator configuration [1] we demonstrate a significant reduction in radial turbulent heat transport for ion- temperature-gradient (ITG) modes with adiabatic electrons. Importantly, this reduction is achieved while preserving other desirable properties such as ballooning stability, neoclassical confinement, magnetic field quasi-symmetry and plasma volume. These findings are reminiscent of previous observations in tokamaks, where negative toroidal triangularity has been shown to yield the largest reductions in turbulence-driven transport [2]. They further suggest that toroidally averaged triangularity –a quantity that can be computed very fast and easily in stellarators – could serve as an effective proxy for guiding the optimization of stellarator configurations towards more favorable ITG turbulence characteristics, thereby reducing the computational cost of full-scale numerical optimization.

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Differential Cross-Phase Modulation as a Control Knob for I-Mode Transport: New Reduced-Model and Non-linear GENE Results with Insights

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Enhanced-confinement regimes such as the I-mode promise H-mode-like energy confinement without large particle and impurity retention, but the mechanism that decouples energy and particle transport remains an open question. We extend our previously proposed differential cross-phase modification hypothesis, where multiple micro-instabilities shift the relative phase between fluctuating fields, altering their transport weights, by combining first-principles gyrokinetic simulations with a validated reduced dynamical model.

1. **Reduced-model exploration.** Embedding these cross-phase responses in a six-field transport model reproduces continuous L → I transitions, including the weak E×B shear layer. The model predicts robust I-mode windows when the H-mode is suppressed.
2. **Gyrokinetic simulations**. Linear scans with GENE incorporating ITG, TEM and ETG drives confirm that modest adjustments to ion- versus electron-heating profiles can shift the dominant instability mix. This shift in the instability mix is shown to lead to different changes in the phases for the thermal vs particle channel. Fully non-linear runs at machine I-mode–relevant parameters show similar results.
3. **Control strategy**. Simulated heating sweeps (modulated ICRH + ECH) suggest that relatively low frequency modulation can nudge discharges back and forth from the I-mode to the L-mode window providing a practical transport control knob for current and future devices.

These results support differential cross-phase as a viable explanation for I-mode's channel-selective transport and offer concrete control guidelines. Upcoming experiments could investigate these mechanisms.

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Study of SOL plasma turbulence on Wendelstein 7X with synthetic reflectometry

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Diagnostics that are able to observe fast density fluctuations near the Scrape of Layer (SOL) are crucial measurements to map the behaviour of the plasma on a microsecond timescale. A synthetic diagnostic framework is designed, to explore the study of SOL turbulence on the Wendelstein 7-X stellarator. The framework includes two different diagnostic setups, poloidal correlation reflectometry [1], and Doppler reflectometry [2]. These diagnostic systems rely on the injection of an O-mode wave into the plasma and collect its backscattered form in different ways. The methods are used to examine density fluctuations in the plasma edge region. Both measurement method were modelled using the FW2D reflectometry code [3] and adopted to their respective W7-X configurations.

A comparative study was conducted between the two synthetic diagnostic setups performed on an artificially generated 2D transient density field coupled to the framework. The density field is derived from relevant measurement data of W7-X in the SOL. The properties of the density fluctuations, namely the amplitude, size, velocity and occurrence density, were in the main focus of the sensitivity analysis, to identify the potential and the capabilities of the system in the region of the SOL.

The synthetic diagnostic framework furthermore quantitively explores any positive complementary nature of both measurement systems for SOL density fluctuations.

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Time dependent ASTRA-TGLF predictive modelling of the DTT Hybrid scenario

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Hybrid scenarios in tokamak experiments represent a major advancement toward achieving optimized plasma performance. This scenario operates at high normalized beta (βN) with a tailored current profile and a central safety factor (q_0) greater than one, which helps mitigate MHD instabilities and improves overall plasma stability.

In this study, we use the ASTRA-TGLF(SAT2)-NCLASS [1,2] transport code to design and study the time evolution of the hybrid scenario in the Divertor Tokamak Test facility (DTT) from the plasma formation to its end. The profile of electron temperature and density, the ion temperature, the main impurities density, the plasma current, and the equilibrium, along with additional heating profiles, are self-consistently computed. The focus is on the most challenging hybrid configuration, known as Scenario E, which operates in a Single Null (SN) divertor setup with a magnetic field B_T=5.85 T, plasma current I_p=3.8 MA at the flat-top, and total auxiliary heating power of approximately 45 MW.

The study of the current ramp-up (RU) phase compares the I_p overshoot (OS) technique, with the standard current RU, assisted by additional heating: both approaches aim at tailoring the q profile. On one hand the OS demonstrates is effectiveness in enlarging the low shear region but the constrained current ramp rates achievable in DTT implies that the OS ends at about 13.5s, when the q_0 has dropped below 1 (q=1 arrival time t_{q1}= 10s). On the other hand, with the standard RU the flat-top (FT) starts at t=6s, saving time, magnetic flux and, thanks to a proper ECRH scheme, entering the FT with the q profile above 1, despite a less pronounced flat q core region. The effects of pure EC heating and the additional impact of EC current drive (ECCD) on q-profile shaping is also studied, showing how the high plasma density limits the CD efficiency. The trajectory of the internal inductance results always below 1, being within the DTT control system capabilities and the flux consumption turns out to be about 9Vs at the beginning of the FT. The FT phase is simulated in L-mode for about 1s and the additional input is increased at t=7s, bringing the plasma in H-mode. Different techniques for computing the pedestal of the kinetic profiles are exploited, providing the confidence intervals for such quantities. The large input power rockets the $T_e(0)$ to 20keV, freezing the core current profiles. To keep also the off-axis q profile ($0.2<\rho_t<0.4$) above 1, the optimal location for ECCD is studied. The consequent low resistivity entails a low flux consumption in H-mode and the foreseen theoretical maximum FT length (21.6Vs available for RU+FT) turns out to be about 100s, with a hybrid-like q profile that lasts for more than 15s. Moreover, a low-density route, with early X-point formation, is also explored, highlighting the pros and cons of this alternative approach.

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Investigations of tungsten temperature screening in the periphery of ASDEX Upgrade plasmas

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Keeping high-Z impurities such as tungsten out of fusion plasmas is crucial for the success of future fusion reactors, to avoid excessive radiation levels or even plasma collapse. This may be achieved through temperature screening, which requires a steep ion temperature gradient relative to the electron density gradient at the pedestal (outward neoclassical convection).

This effect has been experimentally observed at the periphery of optimised, high performance hybrid scenario pulses at JET [1, 2] with high pedestal ion temperature, and was enhanced by the strong rotation and low collisionality [3]. Motivated by these results, significant effort has recently been invested to achieve similar conditions in ASDEX Upgrade, a full W-wall device, with the aim of answering open questions and providing improved diagnostic measurements.

To access the required plasma conditions – strong edge T_i gradient, low edge n_e gradient, low collisionality and strong rotation – the "improved H-mode" plasma scenario with high β and a current overshoot [6] was chosen (I_p=1MA with overshoot up to 1.2MA) and optimised by tuning the heating and gas waveforms. The pulses exhibit very high performance; H_{98}~1.3 (up to 1.5), β_N approaching 3.5. The radiation is maintained at low levels (f_{rad}~0.3) despite the very high stored energy W_{MHD}~1.3MJ. Despite a substantial W source, W concentrations remain relatively low, and bolometry measurements indicate a significant reduction of impurities in the 'mantle' region, strongly suggesting that tungsten is effectively kept out at the plasma edge. Preliminary transport modelling using FACIT [7] and NEO [8] codes supports the presence of tungsten temperature screening inside the pedestal top.

Additionally, neon was injected in selected pulses to study neon transport in these conditions using CXRS, via the method outlined in [9]. This analysis also provides information on the effectiveness of impurity seeding for power exhaust in these plasma conditions.

We will present the scenario development efforts, the experimentally observed W and Ne transport and the comparison with the theoretical predictions.

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Parametric study of Ion Temperature Gradient and Parallel Velocity Gradient instabilities and 5D gyrokinetic transport simulations in cylindrical geometry

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The understanding of the dynamics of turbulent transport in tokamaks, as well as the study of the associated microinstabilities, remain open problems. Notably, the interplay between Ion Temperature Gradient (ITG) and Parallel Velocity Gradient (PVG) instabilities [1, 2] still requires further research, even in cylindrical configurations. A Water-bag approach [3], which consists of discretizing the ion velocity distribution, is used. Then, a linear analysis of ITG and PVG instabilities in cylindrical geometry is performed. From an analytical dispersion relation for ITG and PVG modes, key parametric dependencies are highlighted. In particular, temperature gradients are shown to stabilize or destabilize PVG modes, depending on their strength, while parallel flow shear is found to enhance ITG-PVG hybrid modes. These properties are likely to impact the turbulent regime in NBI heated plasmas, and therefore reactors like ITER for example.

Furthermore, nonlinear simulations are performed to study transport properties in cylindrical devices such as SPEKTRE [4] with a modified version of the 5D nonlinear gyrokinetic code GYSELA [5], whose applicability to cylindrical systems was recently validated [6].

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New model for runaway transport in chaotic Hamiltonian systems

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Motivated by the presence of runaway electrons during disruptive events in present and future tokamaks like ITER, we investigate the transport in mixed phase space Hamiltonian systems. That is, we consider the case where both magnetic islands and chaotic (ergodic) regions are present. We are interested in the regime where the remnants of the disintegrated invariant transport barriers (i.e. the outermost invariant curves in an island), the so-called sticky regions, form layers in the phase space separated by partial barriers to transport. We show that the survival probability from the internal region can be thought of as the resultant of a radial passage from layer to layer. We show, based on considerations from chaos theory, that, besides an exponential decay (as described by Rechester and Rosenbluth), a power-law component is present at the same time, but described by an independent effective time-scale. We successfully apply our model in the standard map, the Ullmann-Caldas nontwist map, and in a JOREK simulation of a JET disruption.

Efficient dataset construction using active learning and uncertainty-aware neural networks for surrogate model generation

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This study applies uncertainty-aware neural network architectures in combination with active learning (AL) techniques [1] to construct efficient datasets for data-driven surrogate model generation. The ADEPT [2] framework, previously demonstrated on static pre-labelled datasets, was adapted and re-applied to the tokamak plasma turbulent transport problem, specifically using the QuaLiKiz code [3], generating surrogates aimed at accelerating profile predictions in transport solvers such as PORTALS [4]. Despite the speed of QuaLiKiz, this exercise focuses on small datasets as a proxy for using more expensive gyrokinetic codes, e.g. CGYRO [5], which can be bootstrapped by leveraging gyrokinetic simulation databases. The newly implemented workflow uses the SNGP [6] and the BNN-NCP [7] models for the classification and regression components, respectively, and trains single-output models for all turbulent modes (ITG, TEM, ETG) and all transport fluxes (Q_e, Q_i, Γ_e, Γ_i, and Π_i) provided by QuaLiKiz.

In 45 iterations, moving from an initial training data set of 10^2 to a final set of $\sim 10^4$, the resulting models obtained a F_1 classification performance of $\sim$0.8 and a R^2 regression performance of $\sim$0.8 on an independent test set across all outputs. This extrapolates to reaching the same performance as the previous ADEPT pipeline at $\sim 10^5$ data points, although on a problem with 1 extra input dimension. Additionally, the overall technique can be generalized to create surrogate models beyond the chosen domain, as demonstrated by applying this pipeline on the EPED pedestal stability model [8]. This obtained a R^2 of $\sim$0.85 after 22 iterations with a final data set of $\sim 10^3$ points. From these trials, it is strongly suspected that additional improvements to the underlying NCP model training pipeline can further increase the AL efficiency.

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Global fluid turbulent simulations in W7-AS and HSX stellarators

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Abstract*:* We present results from three-dimensional, flux-driven, global two-fluid electrostatic turbulence simulations performed with the GBS code, recently extended to handle arbitrary 3D magnetic configurations [1]. GBS recently allowed the first validation of fluid turbulence simulations against experiments in the TJ-K stellarator, successfully reproducing the fluctuation spectrum and the observed dominant mode driving radial transport [2]. In this work, we extend the validation to more fusion-relevant devices. We focus on W7-AS, both in limited and island-diverted configurations, and HSX, in its quasi-helically symmetric (QHS) configuration.

In the W7-AS limited simulations, turbulence is found to be field-aligned and driven by pressure gradients and magnetic curvature. The simulations reveal the emergence of coherent modes within the last closed flux surface and a broadband fluctuation spectrum in the scrape-off layer. The turbulence cascade exponent agrees reasonably well with experimental edge measurements [3]. The radial electric field falls in the ion-root regime, and the Pfirsch-Schlüter current modulation follows theoretical predictions [4]. Consistently with experiments [5], turbulent eddy inclinations in the radial-poloidal plane are invariant under magnetic field reversal except in regions where local ExB shear exceeds local magnetic shear. Simulations of the island-diverted W7-AS configuration exhibit an increased SOL width with respect to the limited configuration.

The simulations of the QHS configuration in HSX enable, for the first time, the validation of a turbulence code with local turbulence edge measurements [6], including the comparison of power spectra, radial correlation lengths, turbulent fluxes and ExB flows. Our work, highlights the differences between the considered configurations in terms of turbulent transport and SOL width, providing general predictions of the turbulent properties in fusion-relevant devices.

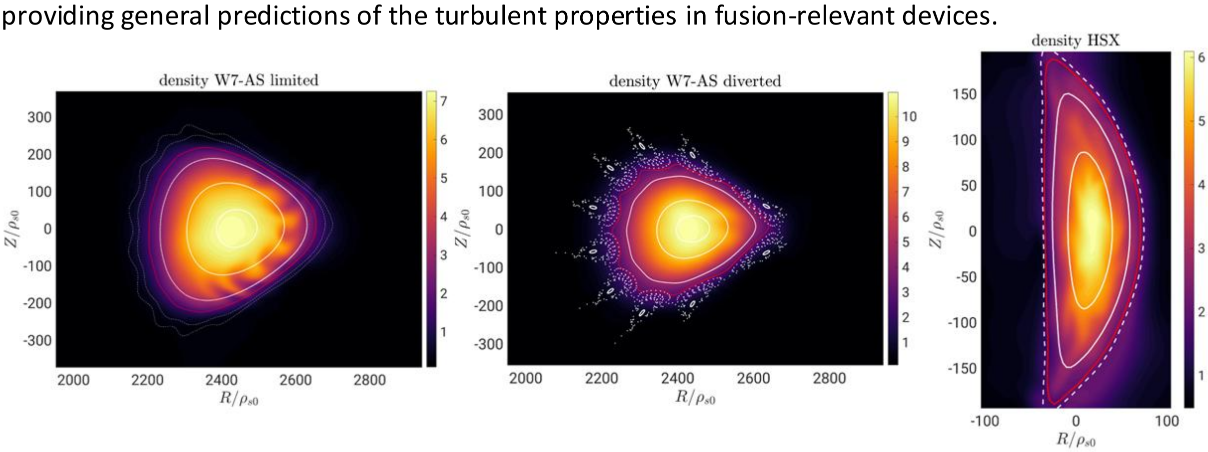

Figure 1: density snapshot for the three different simulations. White full lines are the closed flux surfaces. Dashed white lines are open flux surfaces. The red full surface is the last closed flux surface.

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Variation of the Number of Field Periods for Symmetric Stellarators

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Numerical optimization of the design of stellarator fusion reactors is ongoing. These devices have many symmetries, including a symmetry of the geometry defined by the number of field periods and often an underlying quasi-symmetry of the magnetic geometry. There are many numerical codes that are used in this effort, including the SIMSOPT code [1]. These codes allow for the variation of the shape of the geometry of the device and often target a particular quasi-symmetry. These codes do not vary the number of field periods during the optimization process. In this work, a study is done varying the number of field periods and optimizing for each value of the number of field periods. The impact on the optimization, the quasi-symmetry, transport and stability of the configurations is explored.

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Non-inductive ramp-up and burning plasma access for STEP

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The STEP (Spherical Tokamak for Energy Production) prototype powerplant is designed to generate net electricity, breed its own tritium, and run fully non-inductively. The ST allows higher beta and elongation than in conventional devices but also presents additional challenges of limited space, which limits the size of a central solenoid. A spherical tokamak reactor will rely on high bootstrap current fraction (f_{bs}) and non-inductive current drive, even during the current ramp up. The initial concept has toroidal field B_T = 3.2 T at geometric major radius R=3.6m, with plasma current Ip ~ 20 MA, aspect ratio A=1.8, elongation κ=2.8, fusion power P_{fus}~1.7 GW, normalised beta β_N ~4.4, toroidal beta β ~18%, bootstrap fraction f_{bs} > 70%, and fully non-inductive steady state current drive provided by electron cyclotron and electron Bernstein systems STEP [Tholerus et al. NF 2024]. The small solenoid (~9Vs) is used only for plasma initiation, and up to 150 MW of ECCD is used to ramp from 2MA to 20 MA. Given the high electron heating and low resistivity, Faraday's law dictates that the ramp-up must take place over a very long resistive timescale (>1000s).

We present integrated modelling and transport analysis of a non-inductive current ramp-up scenario from 2-20MA, followed by a densification and fusion power ramp to 1.7GW. The main actuators for optimisation are the density trajectory and ECCD heating during ramp up; to maximise ECCD efficiency the density is kept low until maximum current is reached. To reach fusion burn conditions, the plasma must then transition from a hot electron, low density plasma to a high density plasma with hot ions and high bootstrap current. The required auxiliary power to reach the flat top operation depends sensitively on current drive efficiency, pedestal assumptions, and transport. The current drive efficiency assumptions have been validated with GRAY modelling, and we use JETTO-TGLF to simulate the scenario for the first time with a predictive core transport model. The flat top confinement relies on β' stabilisation of electromagnetic turbulence.

Optimising the ramp up pathway while remaining within all the required constraints requires an accurate and fast reduced transport model across a large parameter space, so a neural network surrogate of TGLF has been built for the STEP parameter space. The non-inductive current drive must be carefully managed to maintain vertical stability and avoid the formation of current holes, transport barriers, and MHD instabilities, which presents a delicate optimisation and control problem well suited to automation and machine learning.

Effect of Tungsten Impurity Concentration on Core Transport in DIII-D with the Proposed Tungsten First Wall

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We report on the results from a new study investigating the impact of tungsten (W) impurity concentration on core transport in DIII-D, which is being carried out in anticipation of a planned transition from the current graphite first wall to tungsten (or tungsten-coated) tiles. As tungsten is a leading plasma-facing component (PFC) candidate for future fusion pilot plants (FPPs), understanding its influence on plasma performance is critical for guiding scenario development. Assessing these impacts is doubly important given the significant changes to scenario performance observed in other machines, such as JET or WEST, when PFC materials were changed [1].

To help quantify the potential impacts of this wall change-out, the PORTALS (Physics-based Optimization and Regression Tool for Advanced Low-dimensional Simulations) [2] framework was installed on the DIII-D Omega computing cluster. A dedicated OMFIT module was developed to support the execution and analysis of these simulations. The starting scenario parameters and profiles for this study were taken from a DIII-D ITER Baseline Scenario (IBS) discharge with elevated toroidal rotation carried out as a part of a recent impurity transport experiment [3].

For these initial simulations, the intrinsic carbon and trace lithium impurities are first replaced with varying concentrations of tungsten, with the thermal deuterium density adjusted accordingly to maintain quasineutrality at fixed electron density. Core temperature and density profiles were then predicted using the TGLF SAT2 and NEO models to calculate the turbulent and neoclassical fluxes, including self-consistent calculations of radiative losses and collisional coupling. A scan of W concentrations corresponding to $1.0 \leq Z_{eff} \leq 1.5$ was performed in order to quantify of the sensitivity of core profiles and transport to tungsten content. This assessment includes quantifying changes in heat fluxes, radiation losses, and profile stiffness. At a higher level, these results will provide key constraints on allowable W impurity levels to preserve core confinement in DIII-D IBS plasmas with the future tungsten wall.

In addition to tungsten, we are extending this study to assess the impact of alternative materials under consideration for the initial stages of the DIII-D wall replacement, such as stainless steel and Inconel. These materials, while not intended as final PFCs, may introduce distinct impurity sources that must be evaluated to ensure scenario viability and inform operational planning. The implications for core-edge integration and future steps will also be discussed.

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Island divertor studies in 3D with GRILLIX

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Understanding and predicting heat exhaust properties is a key challenge on the path toward a stellarator power plant. The island divertor [1] is a key feature in the Scrape-Off Layer of most current stellarator reactor designs, and it is also experimentally investigated in the Wendelstein 7-X (W7-X) stellarator. Such a concept leverages a magnetic island chain formed at the plasma edge, which is intersected by divertor targets to enable effective power exhaust. Numerical modeling of island divertors usually relies on transport codes. However, discrepancies between these predictions and experimental data highlight the need for more sophisticated approaches. Three-dimensional turbulence simulations potentially enable deeper insights, but they face numerical and computational challenges due to the complex geometry.

In this work, we employ the transcollisional fluid turbulence code GRILLIX [2] to simulate a simplified island divertor geometry. The configuration involves a helically perturbed circular toroidal magnetic field, generating a magnetic island chain at a rational surface. These islands are intersected by discrete target plates aligned with the island chain, mimicking the divertor architecture of W7-X. Such simplified yet versatile model enables the investigation of general island divertor phenomena, including the structure of the electrostatic potential [3], electron temperature distribution [4], and the influence of sheared poloidal flows [5]. By analyzing these fundamental features, we advance our understanding of island divertor physics in tractable geometries - an essential step before tackling more complex geometries like W7-X.

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Fast bootstrap current evaluation in devices close to omnigeneity

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In advanced modern, omnigenous (quasi-symmetric/isodynamic) stellarator configurations, global magnetic field maxima tend to be aligned on the magnetic surface. Some of these devices rely on the island divertor on the edge for proper operation. This requires a very accurate control of the rotational transform ι. Optimisation therefore often aims at minimising the bootstrap current. For that purpose, a fast and accurate measure of this current is necessary. Such an accurate measure can be provided by drift kinetic equation solvers like DKES [1], NEO-2 [2] and MONKES [3]. At the same time, the fastest way to compute bootstrap current is to use asymptotical formulas for the long mean free path regime such as the Shaing-Callen formula [4] which describes the ideal omnigeneous configurations well. Recently [5], a formula for the deviation "offset" of the bootstrap current from its asymptotic Shaing-Callen limit for such aforementioned nearly aligned quasi-poloidal symmetric configurations has been derived and an algebraic solution for a simple example has been found. In this report we present an extension of this "offset" formula to general quasi-symmetry, as well as its numerical evaluation for devices close to omnigeneity. The computation time of the "offset" does not exceed the computation of the Shaing-Callen expression as it only requires the evaluation of double integrals on the magnetic surface. The accuracy of the results is checked against direct evaluation by NEO-2.

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Recent Progress in divertor-SOL-edge studies for advanced and alternative confinement in spherical tori

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We report a coordinated effort of theory, improved metrics in computation for the support of experimental diagnostics, recent experiment, and both fluid and gyrokinetic modelling to understand the complex interactions of turbulence and transport between divertors and the pedestal region. The goal of this series of studies is to establish advanced, ELM-mitigated scenarios along with the understanding required to predict if the conditions so necessitated could be extrapolated to reactor-relevant scales.

As turbulence-flow interactions are relevant on most known scales and decidedly important for some of the confinement regimes (H-mode, I-mode, likely QH-mode) either for access or sustained performance, we report on new results on the gyrokinetic modelling of the nature and poloidal distribution of zonal flow drive. We show significant dependence on shaping and new results on the most ST-relevant electromagnetic version of the coupling mechanisms.

Impurity transport across the SOL is addressed in a Hasegawa-Wakatani model for studying the effect of zonal contribution on the scaling of charge-to-mass ratios, as this is an important component of stability in radiative divertors. Recent studies of the robustness of the latter against transients are shown.

Furthermore, new experiments on MAST-U have been conducted for expanding the operational space to include the quasi-coherent exhaust as well as the I-mode. Modelling of the pedestal stability using ELITE show each to be close to the ballooning limit, and beam emission spectroscopy has been employed to study both the increased activity in candidate QCE discharges in the vicinity of the LCFS, as well as employing the group's improved nonlinear metrics and flow detection for both QCE and I-mode.

Optimization of MAST-U Beam Emission Spectroscopy diagnostics for edge turbulence measurements

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The turbulence imaging Beam Emission Spectroscopy (BES) diagnostic on MAST-U is a key tool for characterizing turbulence and fast transient events [1], [2]. The BES system utilizes an 8×8-pixel APDCAM-10G detector camera to measure local density fluctuations, offering a 500 kHz analogue bandwidth and 4 MHz temporal resolution.

Originally optimized for core turbulence measurements, a major goal of the BES upgrade for MAST-U operation was to enhance signal quality in the edge region. This was pursued by carefully optimizing the transmission characteristics of the installed interference filter. A new filter was procured by the University of York and installed in a custom-designed, temperature-controlled filter holder manufactured at HUN-REN Centre for Energy Research.

During the MU01 and MU02 experimental campaigns, the BES signal exhibited an excessive background component, significantly reducing the signal-to-background ratio (SBR). This background was observed across all radial positions and appeared to originate from the plasma edge. Its relatively high amplitude and large fluctuation levels prevented meaningful turbulence analysis.

Light collected near the APD detectors is transmitted to the backplate of the APDCAM-10G cameras via large-diameter optical fibres. A high-resolution spectrometer was employed to spectrally resolve the BES signal. This analysis revealed that the dominant background component was a CII doublet at 658 nm, originating from a localized layer in the plasma edge.

The filter's transmission passband is thermally tuneable, shifting by 0.017 nm/°C at the operational wavelength to allow for spectral background rejection. This optimization was not utilized during the MU01 and MU02 campaigns as the filter heater was non-operational. Signal quality improved during the MU03 campaign with active heating [2], though a detailed background analysis was only completed before the MU04 campaign. It revealed that optimal SBR and signal quality were achieved near the maximum allowed filter temperature.

It was also found that the measured CII background strongly depends on the fuelling location. Low-field side fuelling introduced increased background, suggesting elevated carbon impurity density. In addition to evaluating the background's impact on turbulence measurements, a comparison of edge turbulence under high-field side and low-field side fuelling is briefly presented.

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