EFTC 2019

18th European Fusion Theory Conference

October 7—10, 2019

Ghent, Belgium

Programme

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Abstracts

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Gyrokinetic simulations: recent achievements and new opportunities

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Over the last decade or so, gyrokinetic simulations have become a workhorse for the description of turbulent transport in the core of tokamaks and stellarators. There exists a wide range of successful applications, from the prediction of plasma profiles via multi-channel flux matching to the interpretation of fluctuation characteristics via advanced synthetic diagnostics. Building on these recent achievements, the time is ripe to explore new opportunities in the decade ahead of us. Key themes include the self-consistent description of turbulence, MHD modes, and energetic particle physics within a single gyrokinetic framework, the application of gyrokinetic simulation techniques to the pedestal and SOL regions, and the realization of the "transport-by-design" concept for stellarators.

Isotope dependence of energy, momentum and particle confinement in tokamaks

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The isotope dependence of plasma transport has a significant impact on the performance of future D-T experiments in JET and ITER and eventually on the fusion gain and economics of future reactors. In preparation for future D-T operation on JET, dedicated experiments and comprehensive transport analysis were performed in H, D and H-D mixed plasmas. The analysis of the data has demonstrated an unexpectedly strong and favourable dependence of the global confinement of energy, momentum and particles in ELMy H-mode plasmas on the atomic mass of the main ion species, scaling as $\tau_{E,\phi,P} \sim A^{0.4\text{-}0.5}$ [1, 2], i.e. opposite to the expectations based only on local gyro-Bohm (GB) scaling, $\tau_E \sim A^{-1/2}$, and stronger than commonly used H-mode scaling for the energy confinement [3]. The scaling of momentum transport can be understood from its relation with ion heat transport $\chi_\phi/\chi_i \approx 0.8$, as reported for JET in [4]. Nonliner local GENE gyrokinetic analysis shows that the observed anti-GB heat fluxes are accounted for if collisions, $E\times B$ shear and plasma dilution with low-Z impurities (^{9}Be) are included in the analysis.

For L-mode plasmas a weaker positive isotope scaling $\tau_E \sim A^{0.15}$ has been found, similar to ITER97-L scaling [3]. Global quasi-linear gyrokinetic calculations using JETTO-TGLF in L-mode show that local GB scaling is overruled when stiff transport (as is the case for ITG's) is combined with an imposed boundary condition taken from the experiment, in this case predicting no isotope dependence. Dimensionless isotope identity experiments in JET L-mode plasmas confirm that transport physics is governed as expected by 4 dimensionless parameters (ρ^*, ν^*, β, q), consistently with global quasi-linear gyrokinetic TGLF calculations [5]. Good identity matches in H-mode have so far not been obtained in JET-ILW.

We compare findings in JET with those in different devices and discuss the possible reasons for the different isotope scalings reported from different devices, ranging from no scaling to fairly strong positive scaling, as in JET-ILW. The diversity of observations suggests that the observed differences may result not only from differences affecting the core, e.g. heating schemes, but may to a large part be due to differences in device-specific edge and wall conditions, pointing to the urgency of better understanding and controlling pedestal and edge processes.

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** See the author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018)*

Fully electromagnetic zonal flow residuals

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Turbulence driven zonal flow modes represent a major turbulence regulation mechanism at ion gyroradius scales in magnetic fusion devices. The analytic electrostatic zonal flow residual calculation by Rosenbluth and Hinton [1] was an important contribution to the way we think about zonal flows today, and it has become a standard test of gyrokinetic simulation codes. In this tutorial we discuss how the collisionless axisymmetric zonal flow residual calculation for a tokamak plasma can be generalized to include electromagnetic perturbations. We formulate and solve the complete initial value zonal flow problem by retaining the fully self-consistent axisymmetric spatial perturbations in the electric and magnetic fields [2]. Simple expressions for the electrostatic, shear and compressional magnetic residual responses are derived that provide a stringent, fully electromagnetic test of the zonal flow residual in gyrokinetic codes. We use the gyrokinetic code CGYRO [3] to demonstrate the use of these residual expressions. Unlike the electrostatic potential, the parallel vector potential and the parallel magnetic field perturbations need not relax to flux functions for all possible initial conditions.

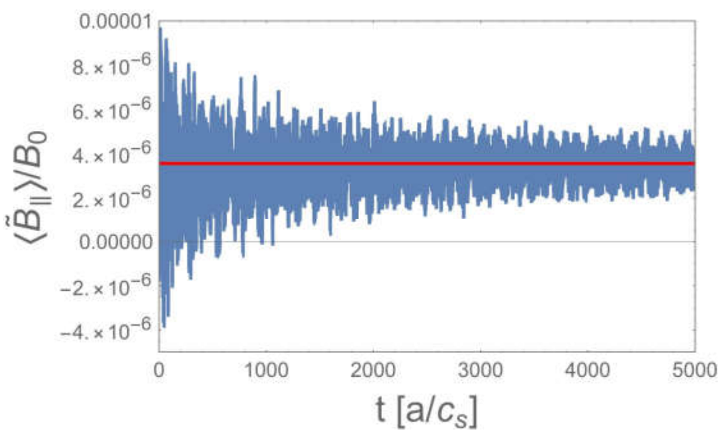

Figure 1: *Flux surface averaged compressional magnetic perturbation (blue) as a response to an initial electrostatic perturbation, converging slowly towards its theoretically predicted residual value (red).*

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Combining observations, models and numerical simulations for a better understanding of solar eruptions

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Solar flares are the most energetic events taking place in our solar system. They result from the conversion of magnetic energy stored in the Sun's atmosphere during magnetic reconnection. As a result, energetic particles and heat are released, and in some cases these flares lead to the launch of solar storms (or Coronal Mass Ejections - CMEs [1]) in the interplanetary space. Solar flares and CMEs are at the origin of space weather events [2]: on Earth, they lead to geomagnetic storms and can be responsible for disruptions of satellite systems, as well as electricity transport on large-scale national power grids. Auroras, atmospheric ion losses, and other effects of space weather also take place on other planets in the solar system. Therefore, understanding the underlying mechanisms of solar flares is of primary importance to better predict their evolution and influence on nearby planets.

The Sun's atmosphere, called the corona, is an invaluable space laboratory that allows us to test the behaviour of plasma during magnetic reconnection. Thanks to increased temporal and spatial resolutions of ground and space observatories, a standard model for eruptive flares has been refined throughout the years, which can explain most of the observed generic features. In particular, 3D MHD numerical modelling has provided us with some predictions on the magnetic field behaviour (e.g. instabilities) during the eruption, as well as on the electric current density layers where magnetic reconnection takes place. These predictions are nowadays well documented with the help of observations, e.g., those of the NASA mission Solar Dynamics Observatory [3].

On the other hand, CMEs are well monitored by space probes throughout the solar system [4]. However, these single spacecraft only give the local CME magnetic and plasma parameters. We will review how multiple spacecraft observations and analytical models can be used to retrieve some information about the propagation of ICMEs in the heliosphere, as well as their most generic features. Doing so at different heliospheric distances can inform us on the interplay between CMEs and the surrounding solar wind: new missions such as NASA's Parker Solar Probe and ESA's Solar Orbiter especially will help us explore the beginning of this interaction close to the Sun.

We will look at how these different diagnostics of solar eruptions help us understand their consequences, from the Sun's atmosphere to the interplanetary medium, and how observations, analytical and numerical modelling complement each other in finding standard models for the evolution of eruptive solar flares.

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A gyrokinetic model for the plasma periphery of fusion devices

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Understanding the turbulent dynamics of the plasma in the periphery of fusion devices - the region extending from the external part of the closed flux surface region to the scrape-off layer - is of crucial importance on the way to fusion energy. Indeed, this region largely controls the plasma heat exhaust, the plasma refueling, the level of fusion ashes and, also, the low-to-high (L-H) mode transition. In the present talk, a gyrokinetic model is presented that can properly consider the main elements at play in the periphery. These include the presence of strong flows, large and small amplitude electromagnetic fluctuations on scale lengths ranging from the electron Larmor radius to the equilibrium perpendicular pressure gradient scale length, and large deviations from thermal equilibrium. Due to the large range of collisionality present across the periphery, the model retains a nonlinear full Coulomb collision operator cast in a form suitable for implementation in a gyrokinetic code. The gyrokinetic equation and the associated equations for the electromagnetic fields are valid for arbitrary deviations from thermal equilibrium and are accurate at arbitrary perpendicular wavenumber values. The formulation of the gyrokinetic model is based on the single gyrocenter dynamics obtained from fully nonlinear second-order accurate electromagnetic gyrokinetic equations of motion, derived from Lie-perturbation theory where the fast particle gyromotion is decoupled from the slow drifts. Then, the collective behavior is obtained by the gyrokinetic equation including the collision operator. The gyrokinetic model takes the form of a set of coupled fluid equations referred to as the gyrokinetic moment (gyro-moment) hierarchy equation. To obtain the gyro-moment hierarchy, the gyro-averaged distribution function is expanded onto a velocity-space Hermite-Laguerre polynomial basis. By projecting the gyrokinetic equation, the gyro-moment hierarchy provides the spatial and temporal evolution of the Hermite-Laguerre expansion coefficients, which are velocity moments of the gyro-averaged distribution function referred to as gyro-moments. The Hermite-Laguerre projection of the full nonlinear Coulomb collision operator is performed using a multipole expansion of the Rosenbluth potentials, allowing us to derive a closed form of the Coulomb collision operator in terms of products between gyro-moments. Finally, the self-consistent evolution of the fields is described by a set of gyrokinetic Maxwell's equations derived from a variational principle. Linear results of the present model are illustrated and show that the Hermite-Laguerre decomposition provides an efficient framework for a numerical implementation with reasonable cost for the study of the turbulent dynamics in the plasma periphery.

This research was supported in part by the Swiss National Science Foundation, and has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014 - 2018 and 2019 - 2020 under grant agreement No 633053.

State-of-the-art modeling of collisional impurity transport in stellarators

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Accumulation of highly charged impurities in the plasma core can be one of the main obstacles to improve stellarator performance. This accumulation agrees in general with standard neoclassical theory. The lack of intrinsic ambipolarity of neoclassical transport in stellarators induces a radial electric field, E_r, which in a wide variety of relevant situations points radially inwards over broad regions of the core. This pushes impurities towards the plasma center more strongly as the charge state increases, and leads to a net inward convection unless the temperature and density gradients are sufficiently steep or $|E_r|$ is sufficiently small. However, some experimentally observed exceptions to these typical accumulation scenarios exist, see e.g. [1]. In recent years, interest in understanding such exceptions has motivated theory extensions and code developments beyond the standard approach. One such extension consists of including the electric field component tangential to the flux surface, φ_1. Its impact on the impurity radial transport has been numerically assessed for different machines and impurity species [2, 3]. The symmetry properties and size of φ_1 have been analytically derived at different collisional regimes, including the superbanana-plateau regime [4, 5]. Modern codes have generalized the usage of more accurate treatments of the impurity collisions, beyond pitch angle scattering models. Finally, the extended idea about the absence of impurity screening in stellarators has been analytically revisited in the so-called *mixed-collisionality* regime [6, 7]. As result of all this, stellarators count with new theoretical insight and codes, like EUTERPE, SFINCS, KNOSOS or FORTEC-3D, which can contribute to the understanding of neoclassical impurity transport including the aforementioned elements. In this talk this joint effort will be reviewed up to its most recent developments, results and experimental validation.

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HALO: nonlinear full-orbit modelling of fast particles driving bulk plasma eigenmodes

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The abundance of non-thermal 'fast' particles in the burning plasma regimes on ITER and DEMO represents both a key physics achievement and a new source of concern. It is well understood from current experiments that fast particles are responsible for driving instabilities in tokamak plasma, degrading performance and damaging the plasma-facing components through energetic ion redistribution and loss. Discrete wave eigenmodes are an important subclass of oscillation where the energy content of the mode is contained mainly in the thermal plasma response and the growth rate is much smaller than the mode frequency. The nonlinear dynamics are then characterised by the resonant fast particles and a perturbative treatment is suitable.

We present the new HALO code (HAgis LOcust) [1] which solves the initial value Vlasov-Maxwell problem perturbatively. It uses the same basic approach as the HAGIS code [2] for wave evolution but is built on the LOCUST-GPU full-orbit code [3] for computing the Hamiltonian fast particle motion in cylindrical coordinates. The wave amplitude and particle evolution include all fast ion finite Larmor radius effects. The code can model multiple eigenmodes and multiple fast ion species simultaneously and supports the general form of the fast particle distribution in equilibrium constants-of-motion space.

We will show that the formulation and numerical scheme are sufficiently general to allow straightforward implementation of a wide range of eigenmodes (for example compressional as well as shear Alfvén eigenmodes), and the adaptation of the scheme to other Hamiltonian particle descriptions will be discussed.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053 for the European Enabling Research Projects WP17-ENR-MFE-CCFE-02 and WP19-ENR-MFE-CCFE-05, and from the RCUK Energy Programme (grant number EP/P012450/1). The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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The properties of helium in tokamak plasmas, experimental studies and comparisons with theoretical predictions

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The presence of fusion-produced helium is fundamentally connected to the performance of a fusion reactor. In this light, the properties of He in tokamak plasmas are investigated from both experimental and theoretical points of view.

The accumulation of He "ash" needs to be avoided, as the fulfillment of the burn condition defines the tolerable effective confinement time for He [1]. For predictions, understanding of the He transport as well as experimentally validated modeling tools are needed. Experimental investigations of low-Z impurity transport in ASDEX Upgrade (AUG) provide insight and are an excellent testbed for comparisons to gyrokinetic modeling [2]. It is found that the modeled impurity density profile peaking does not always reproduce the experimental measurements.

Helium in reactor relevant concentrations (up to 10%) is observed to have a detrimental effect on the plasma performance and confinement in AUG and JET [3, 4]. Here, the modeling sheds light on the increased core transport in the presence of He. Furthermore, the observations of lower confinement in He plasmas (τ_{He}~$0.7\tau_D$ [5, 6]) are explained via gyrokinetic modeling and it is experimentally shown and theoretically explained to increase with the fraction of electron heating in ASDEX Upgrade, even reaching τ_{He}~τ_D [7].

Considering non-thermal He, Charge eXchange Recombination Spectroscopy measurements of energetic ^{3}He ions accelerated with a novel "three-ion" ICRH scheme [8] are shown to provide important information for the validation of fast ion and ICRH modeling codes [9].

Finally, insufficient exhaust of He will result in fuel dilution and decrease in fusion power. The experimental challenges and the need for validated modeling for He recycling and pumping, to be used for prediction and design of future machines, will be discussed.

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Multiscale, conservative hybrid kinetic-ion/fluid-electron algorithms for high-fidelity plasma simulation

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In the quest to describe fusion plasmas with improved fidelity, there is current emphasis in bridging the gap between electrostatic gyrokinetic descriptions and macroscopic electromagnetic models such as MHD and extended MHD. While various efforts are underway to develop electromagnetic global gyrokinetic algorithms, the asymptotic assumptions in the gyrokinetic formulation still present limitations in the fidelity of the simulations in regimes where large gradients are present (e.g., at the pedestal), and introduce fundamental inconsistencies between full MHD and the gyrofluid limit.

In this study, we have formulated a hybrid kinetic-ion/fluid-electron algorithm [1] that has the potential to bridge a significant gap in simulation capabilities. In our approach, ions are described by particles (PIC), while electrons are described by an extended Ohm's law (and therefore the model is fully electromagnetic). While many such formulations exist in the literature, our approach is unique in that it is fully implicit (converging particles and fields simultaneously), and enforces discrete conservation of mass, momentum, and energy in Cartesian geometry (see Fig. 1 for a demonstration on the GEM Challenge problem [2]). We have extended the formulation to curvilinear geometry (as is needed in fusion), along with conservation of mass and energy. Key to the efficiency of the scheme is the use of an efficient MHD-based preconditioner, which effectively accelerates the nonlinear iteration and renders the solver optimal in terms of mesh refinement.

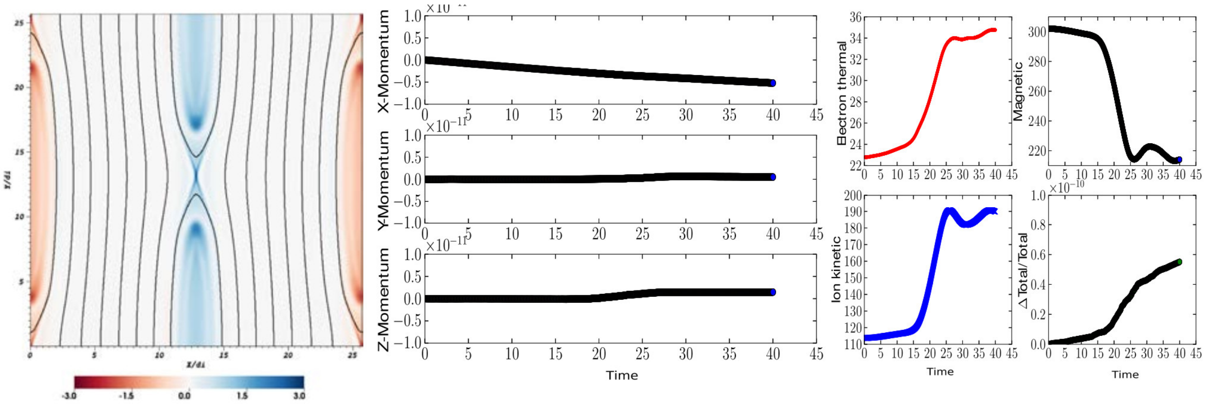

Figure 1: *Left: Current density j_z and contours of the magnetic potential A_z for the GEM Challenge reconnection problem [2]. Middle: Momentum errors in each direction vs time, demonstrating strict momentum conservation. Right: Traces of the electron thermal energy, magnetic energy, ion kinetic energy and the relative total energy error vs time, demonstrating strict conservation of energy.*

This work has been supported by the DOE Office of Applied Scientific Computing Research (ASCR), and performed under the auspices of the National Nuclear Security Administration of the U.S. Department of Energy at Los Alamos National Laboratory, managed by Triad National Security, LLC under contract 89233218CNA000001

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Progress in modeling the impact of ICRH heating on high-Z impurity transport and turbulence stabilization

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Application of ion-cyclotron-resonance heating (ICRH) in fusion plasmas has effects which go beyond the auxiliary heating and current-drive. In this perspective, we discuss recent progress in applying theoretical and numerical models to capture some aspects of the complex role of ICRH in present tokamak experiments.

An impact of ICRH on the behavior of high-Z impurities is commonly observed in tokamaks with a metallic wall. Theoretical and numerical modeling shed light on the key role played by anisotropies of the distribution function of the ICRH-accelerated ions on the neoclassical transport of high-Z impurities [1-4]. Moreover, in experiments done on ASDEX Upgrade (AUG), specifically designed to compare the efficiency of tungsten control with ICRH and electron cyclotron resonance heating (ECRH), the peaking of the tungsten density profiles in the plasma core decreased with increasing central heating power for both ICRH and ECRH. Analysis with numerical models made possible to explain this similarity with the role played by the electron-to-ion heat flux ratio in controlling tungsten accumulation in the plasma core [5].

Furthermore, we discuss possible mechanisms responsible for the observed stabilization of plasma turbulence and reduction of the anomalous heat transport by ICRH-generated energetic ions in the plasma core [6]. We address the possibility to exploit these mechanisms in future fusion devices.

Finally, we present recent developments towards a close comparison between the computed ICRH fast-ion distribution function and measurements on AUG [7,8].

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Suppression of the electron temperature gradient instability via cross-scale interactions with ion gyroradius scale turbulence

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Plasma turbulence in magnetic confinement fusion devices is driven by micro-instabilities at the distinct space-time scales associated with the gyroradii and thermal speeds of ions and electrons. The scale separation is determined by the electron-to-ion mass ratio $(m_e/m_i)^{1/2}$, which is approximately $1/60$ for a deuterium plasma. Such a large scale separation makes direct numerical simulations (DNS) that include both electron scale (ES) and ion scale (IS) turbulence extremely challenging. Nonetheless, a handful of DNS simulations have been performed, indicating that there can be significant cross-scale interaction between ES and IS turbulence; see, e.g., [1, 2]. To facilitate the study of this interaction, we have conducted an asymptotic analysis of the gyrokinetic equation, using $(m_e/m_i)^{1/2}$ as our expansion parameter. We find a system of coupled gyrokinetic equations for scale-separated IS and ES turbulence [3]. In the limit of vanishing $(m_e/m_i)^{1/2}$, the IS turbulence evolves independently of ES fluctuations. However, the ES fluctuations are modified by two cross-scale effects: the equilibrium gradient drive at ES is modified by the gradient of the IS electron distribution function; and ES fluctuations are advected by the IS $E \times B$ drift, the dominant effect of which is to shear the ES fluctuations in the parallel-to-the-field direction.

We have implemented the ES cross-scale terms in the δf gyrokinetic code `GS2` and have used it to conduct linear simulations of ES fluctuations . We present data showing that a strongly-driven electron-temperature-gradient (ETG) instability is suppressed in the presence of strongly-driven IS turbulence and only weakly modified when the IS turbulence drive is reduced to a near marginal level. We show that the primary mechanism for the suppression of the ES instability is the parallel-to-the-field shear introduced by the IS $E \times B$ advection. To give insight into this suppression mechanism, we present a simplified model of the effect of the parallel-to-the-field shear on the ES linear instability. The suppression mechanism that we describe here could explain why ES turbulence is often suppressed in a multi-scale DNS, in comparison to an ES-only simulation.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053 and from the RCUK Energy Programme [grant number EP/P012450/1]. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors acknowledge EUROfusion, the EUROfusion High Performance Computer (Marconi-Fusion), and the use of ARCHER through the Plasma HEC Consortium EPSRC grant numbers EP/L000237/1 and EP/R029148/1 under the projects e281-gs2.

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Optimized stellarators without optimization: Direct construction of stellarator shapes with good confinement

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Quasisymmetry, a remarkable property of some nonaxisymmetric magnetic fields that implies good confinement, has been the principle underlying stellarator designs such as HSX and NCSX. Historically, quasisymmetric magnetic field shapes have been found using numerical optimization. However a direct geometric construction of quasisymmetric fields, using equations derived by Garren and Boozer [1,2], is also possible. While the construction is limited to high aspect ratio, it has several advantages compared to optimization, such as orders-of-magnitude reduced computational cost, and opportunities for analytic insight [3,4]. For instance, the construction permits a precise understanding of how many unique quasisymmetric configurations are possible (close to the magnetic axis). We also demonstrate that the core regions of quasisymmetric fields obtained by optimization, including the HSX and NCSX experiments, match the construction [5]. We show that the construction can be modified for a more general confinement condition, omnigenity. The speed of the construction enables wide and high-resolution numerical searches to identify and map the interesting regions of parameter space.

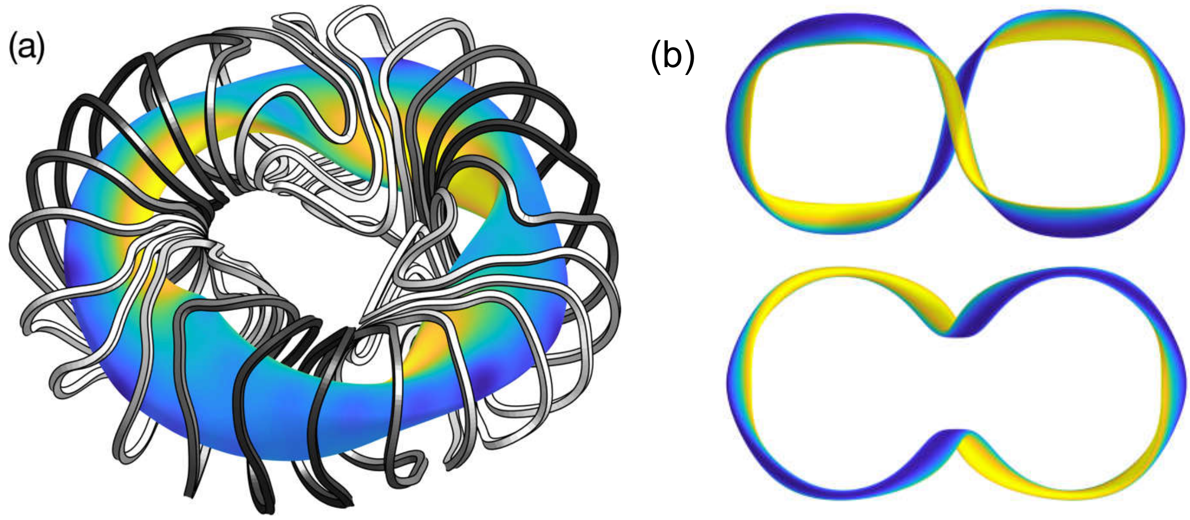

Figure 1: *A (a) quasi-axisymmetric and (b) quasi-helically symmetric stellarator configuration generated by the direct geometric construction of [4]. Color indicates |B|.*

This work was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Science, under award nos. DE-FG02-93ER54197 and DE-FG02-86ER53223. This work was also supported by a grant from the Simons Foundation (560651, ML).

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The impact of resonant magnetic perturbations on runaway electron dynamics

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Understanding runaway electron dynamics is among the highest priorities of the fusion roadmap. Dedicated campaigns on tokamak COMPASS with routinely generated runaway electron (RE) beams [1], together with controlled application of a strong magnetic perturbation (up to $B_{pert}/B_{T0} = 0.9*10^{-2}$ at plasma edge) allowed unique studies of the RE behavior. This work presents a study of impact of externally triggered resonant magnetic perturbation (RMP) on a formation of a layer of stochastic magnetic field lines at the plasma edge, MHD activity, radial transport (combination of diffusion and advection [2]) of RE. The study utilizes both detailed data analysis and modeling. Furthermore, the effect of the mentioned processes on a RE seed formation, dynamics of the fully developed RE population, and on the effectiveness of RE loss processes is evaluated. The RE population has been modeled with the combination of a transport simulation code METIS [3] and a Fokker-Planck code LUKE [4] for plasmas before application of the external perturbation field. Screening of the external perturbation due to plasma response as well as unscreened vacuum approximation have successfully been modeled with a resistive MHD code MARS-F [5]. The magnitude of the perturbed magnetic field has been implemented into an open-source python package for fast manipulation with equilibria PLEQUE [6] (developed at COMPASS) and into a particle tracking code, in order to quantify the degree of induced field line stochasticity as well as the effect of perturbed fields on the RE orbits. A significant impact of the magnetic perturbation on the RE dynamics is reported.

The work has been supported by the grant GA18-02482S of the Czech Science Foundation (GACR), the MEYS projects LM2015045, CZ.02.1.01/0.0/0.0/16_019/0000768 and carried out within the framework of the EUROfusion Consortium. It has also received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053 with the Co-fund by MEYS project number 8D15001. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Stability and nonlinear saturation of reconnecting current sheets in a helicity-conserving variational model

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The magnetic helicity is an exact invariant in ideal MHD and its conservation reflects the fact that the magnetic topology cannot be modified. In a plasma with finite resistivity, magnetic reconnection is possible and both plasma energy and magnetic helicity are dissipated. However, it is usually argued that for sufficiently fast reconnection events, or for sufficiently high wavenumber fluctuations, the magnetic helicity is a very good invariant in the sense that it is very well conserved on time scales over which the energy is dissipated [1]. The quasi-invariance of the magnetic helicity during such highly nonlinear processes thus stimulates the development of a variational principle with appropriate constraints capable of retrieving the nonlinear saturation of reconnecting instabilities without requiring a description of the dynamics leading to such saturated states.

Over a decade ago, the theory of multi-region relaxed magnetohydrodynamics (MRxMHD) was proposed [2] in an attempt to generalise Taylor's relaxation theory [3], which only preserves the global helicity and thus describes fully relaxed plasma equilibria with no pressure gradients. By conserving helicity in a number of sub-regions in the plasma, MRxMHD allows us to calculate three-dimensional, finite pressure, macroscopic equilibria in toroidal configurations, which generally exhibit regions of islands and magnetic field-line chaos encapsulated in between robust magnetic surfaces [4]. MRxMHD is based on a variational principle and equilibrium states are found as extrema of the plasma energy functional, i.e.they satisfy $\delta W = 0$. Their stability can also be investigated by studying the sign of δW for a finite perturbation around them. In this talk, we show that a stability analysis of MRxMHD provides information on potential instabilities that develop through spontaneous magnetic reconnection. In particular, we show that the stability boundary of a slab force-free current sheet is in exact agreement with linear tearing mode theory [5]. The nonlinear saturation of tearing modes is also investigated using the SPEC code [6] – a numerical implementation of MRxMHD – by seeking the lower-energy states with the same helicity as the initial unstable current sheet. We compare the obtained saturated island width with theoretical scalings (at small Δ') and numerical resistive MHD simulations (at large Δ').

This work was carried out within the framework of the EUROfusion Consortium and received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under Grant Agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was also partly supported by a grant from the Simons Foundation/SFARI (560651, AB).

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Theory and modeling of fusion alpha-driven TAEs in high magnetic field devices

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Next-generation tokamak experiments operating with deuterium and tritium fuel will have a significant population of energetic alphas from fusion. These alpha particles can destabilize Alfvén Eigenmodes (AEs), possibly causing loss of alpha heat and device damage. Recently-proposed tokamak concepts use magnetic fields up to 12 T, far higher than in conventional devices, to reduce size and cost [1,2]. We present recent theory and modeling of AE behavior focusing on such high field devices.

AEs are sensitive to device magnetic field via the field dependence of resonances, alpha particle beta, and alpha orbit width. We describe the origin and effect of these dependences on AE stability analytically and by using recently-developed numerical techniques [3]. The work suggests high-field machines where fusion-born alphas are sub-Alfvénic or nearly sub-Alfvénic may partially cut off AE resonances, reducing growth rates of AEs and the energy of alphas interacting with them. High-field burning plasma regimes have significant alpha particle beta and AE drive, but faster slowing down time, provided by high electron density, and higher field strength reduces this drive relative to low-field machines with similar power densities. The toroidal mode number of the most unstable modes will tend to be higher in high magnetic field devices. The work suggests that high magnetic field devices have unique, and potentially advantageous, AE instability properties at both low and high densities [4].

Alpha particles interacting with AEs may also be subject to ripple-induced loss. We present recent work on a drift-kinetic theory of transport of alpha particles capable of treating both AEs and ripple, revealing that the mechanisms for this transport have similarities with ripple transport. This similarity allows insight into transport in cases when ripple and AE transport simultaneously affect device alpha transport. Consequences for next-generation high-field tokamak experiment performance are considered.

The authors acknowledge support from the National Science Foundation Graduate Research Fellowship under grant No. DGE-1122374, US Department of Energy awards DE-SC0014264 and DE-FG02-91ER54109, and Fundação para a Ciência e a Tecnologia (FCT, Lisbon) project UID/FIS/50010/2013. This research used resources of the National Energy Research Scientific Computing Center (NERSC), a US Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231. The authors thank D. Borba of the Theory and Modelling group of Instituto de Plasmas e Fusão Nuclear for providing the code CASTOR-K, and S. Sharapov of Culham Centre for Fusion Energy for providing the codes HELENA and MISHKA.

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Recent Developments in the Studies of Plasma Self-Organization in the Reversed-Field Pinch and Impact on Transport Properties

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We will review key results from the 3D nonlinear MHD numerical modeling of Reversed-Field Pinch helical self-organization processes. Magnetic transport-barrier formation and nearly periodic reconnection events are found to be at play [1-4], akin to the experimental observation of thermal transport barriers and residual "back-transition" cycles when approaching helical regimes in high current discharges [4-7]. Similarities with Tokamak visco-resistive MHD snake/sawtooth–like phenomena will be discussed, as well as aspects at odds with the original Taylor's relaxation theory for the Reversed Field Pinch [8]. We will describe the recent successful technique to "channel" the system towards chosen "stimulated" macroscopic helical shapes by applying suitable (either Resonant or Non-Resonant) Magnetic Perturbations at the edge of the plasma, as predicted by nonlinear MHD modeling and observed in recent RFX-mod experiments [2]. In so doing, we are able to modify the transport properties of the configuration, with the two-fold objective of developing "handles" for the understanding of transport barrier formation processes and exploring new routes for optimization of pinch configurations. We have found that the magnetic chaos healing effect by helical structure development [9] appears to be more robust in the case of Non-Resonant helical regimes [2]. This line of research will be further explored in the upgraded RFX-mod2-device in Padova-Italy, expected to start operation in 2021.

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Global gyrokinetic PIC simulations for stellarators and heliotrons with emphasis on experimentally relevant scenarios

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The global gyrokinetic particle-in-cell code EUTERPE is a versatile tool comprising models of different physical complexity, ranging from reduced MHD to full gyrokinetics. Building on algorithms and numerical improvements developed over the last years, it can now be applied to experimentally relevant scenarios including electromagnetic simulations in the MHD regime. Modern methods of signal processing allow deeper insights into simulation results as they reveal e.g. subdominant modes and the structure of the MHD continuum.

Based on the CKA-EUTERPE hybrid-model, we investigated nonlinear frequency chirping including collisional effects. In simulations taking into account realistic slowing down distribution functions, fast ion collisions are found to have a strong impact on the saturation level of Alfvén eigenmodes. A recently developed multi-mode model is ready to be applied to experimental cases of the last operational phase of Wendelstein 7-X.

With the kinetic electromagnetic version of EUTERPE, drift Alfvén instabilities in LHD have been calculated. It is shown that modes of the stable spectrum can be driven unstable by ambient pressure gradients. Fast particle driven instabilities for low mode-numbers are calculated in LHD and compared with earlier results. It is shown that the fully gyrokinetic calculations deviate considerably from fluid approximations.

Addressing the sawtooth-like behaviour found in current drive scenarios of Wendelstein 7-X we performed simulations for highly non-monotonic ι-profiles using a resistive fluid and a gyrokinetic model. Unstable modes could be found within both models. While the fluid model results in highly localised structures, the kinetic model predicts radially extended modes.

Linear electrostatic instabilities on the basis of realistic experimental Wendelstein 7-X profiles from the first operational phases including kinetic electrons have been performed. A simple model has been developed to analyse spatial mode structures and their relation to resonances of the rotational transform.

A three-dimensional reduced MHD model consistent with full MHD

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Reduced MHD, as first introduced by Greene and Johnson [1], and later developed by Kadomtsev, Pogutse and Strauss [2,3], relies on ordering in a small parameter, often taken to be the inverse aspect ratio. Such a reduction often has the effect of eliminating fast magnetosonic waves, which allows the use of larger time steps in numerical simulations [4,5]. Later, a new approach was introduced, where ansatz forms that eliminate fast magnetosonic waves are used for the velocity and magnetic field [6,7,8]. We systematically follow this approach, rigorously proving our claims, to derive a general reduced MHD model compatible with three-dimensional equilibria and possessing good conservation properties.

We begin with a viscoresistive MHD model that also includes anisotropic heat transport, mass diffusion across field lines and mass and energy source terms. Ansatz forms are then introduced for the magnetic field and velocity, and we show that any arbitrary magnetic and velocity fields can be expressed in the respective forms. Consequently, after their introduction we still remain within the scope of full MHD. The ansatz forms consist of a background vacuum field, a field line bending term and a field compression term for the magnetic field, and an ExB term, a field-aligned flow term and a fluid compression term for the velocity. Once the ansatz forms are inserted into the MHD equations, appropriate projection operators are applied to Faraday's law and the Navier-Stokes equation to obtain a system of scalar equations that is closed by the continuity and energy equations.

Importantly, we show that, if the background vacuum field is stronger than the bending and compression terms, and if the beta is sufficiently low, MHD waves are separated in the velocity ansatz, with Alfven waves contained in the ExB term, slow magnetosonic waves in the field-aligned flow term and fast magnetosonic waves in the fluid compression term. Thus, by setting the fluid compression term to zero, we eliminate fast magnetosonic waves, obtaining a reduced MHD model. We also show that the ExB and field-aligned flow terms do not compress the magnetic field, which allows us to set the field compression term in the magnetic field ansatz to zero within the same reduced model. As an optional further reduction, we also consider a model where the field-aligned flow term is set to zero. Finally, we derive a set of conditions under which the approximations made in the reduced models are valid, and also show that similar reduced MHD equations can be obtained with an ordering approach.

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Recent progress on kinetic-MHD modeling of the interplay between fast particles and macroscopic modes in tokamak plasmas using XTOR-K

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The non-linear hybrid code XTOR-K [1] self-consistently combines two-fluid magnetohydrodynamic (MHD) equations (XTOR-2F, [2]) with kinetic equations describing the 6D-movement of thermal and/or energetic particles [3]. This coupling allows us to accurately model the interplay between fast particles and macroscopic MHD modes evolving in tokamak plasmas. Understanding this interaction is a key issue for ITER, where fusion-born alpha particles will substantially affect the stability of MHD modes. In particular, alphas may partially stabilize sawteeth (thus resulting in "monster sawteeth" likely to trigger Neoclassical Tearing Modes [4]) and/or destabilize fishbone modes (whose growth can prevent the development of monster sawteeth [5]).

Towards a more accurate description of the non-linear interaction between MHD instabilities and kinetic populations, including relevant effects such as ion neoclassical effects and external heating induced fast-particles, the following two modules have been implemented in XTOR-K:

- Particle collisions in the kinetic module have been implemented using Langevin collisions for kinetic ion-fluid collisions and standard binary collisions for kinetic ion-ion collisions.

- A realistic ion source induced by the ionization of neutral-beam-injected (NBI) particles now reproduces the realistic experimental geometry and injection parameters.

In addition, a semi-analytical model [6-7] has been developed, solving the kinetic internal kink dispersion relation. This model was successfully compared with the linear phase of the growth of internal modes in XTOR-K, showing similar resonant conditions and highlighting the two - kink and fishbone - branches of modes depending on the fast-particle fraction.

These developments will be presented, as well as two original applications. First, for an ITER-like configuration where the internal kink mode is stable, the non-linear growth and chirping of fast-particle induced fishbones is observed, resulting in an enhanced particle transport near the q=1 resonant surface. The fishbone instability is triggered in simulations for a fast-particle pressure below the stability limit expected in ITER physics basis [8]. Second, first simulations of the impact of the realistic NBI-injected ions on the internal kink mode stability will be analysed.

This work has been carried out within the ANR project AMICI and within the framework of the EUROfusion Consortium and has received funding from the ANR and the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053.

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Tilt instability and formation of plasmoid chains

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The importance of plasmoids in fast eruptive events occurring in magnetically dominated plasmas like tokamaks and solar corona is now well accepted [1]. Indeed, a process of accelerated magnetic reconnection (compared to the usual Sweet-Parker regime) can be reached in two-dimensional Magnetohydrodynamics (MHD) approximation, with a fast rate that is nearly independent of the resistivity. However, the general theory based on the disruption of forming (shrinking in time) current sheets is not yet fully established, with some unsolved controversial points concerning the different phases of plasmoid dynamics [2-3]. On the other hand, most of the numerical simulations use the resistive tearing of an initially unstable current layer, or the ideal coalescence instability between two attracting current channels, in order to explore this mechanism [4]. We propose to adopt a much less commonly used setup of two repelling current channels, representative of an ideal MHD instability called the tilt mode, in order to form two quasi-singular current layers. We use a recently developed characteristic-Galerkin finite-element code, FINMHD, specifically designed to study this reconnection problem in a reduced MHD framework with a current-vorticity formulation [5]. Results obtained in the plasmoid-dominated regime (with high Lundquist numbers) are presented, compared to previous numerical simulations and to theoretical models. Finally, conclusions are drawn with perspectives to go beyond the pure resistive MHD model and include kinetic effects.

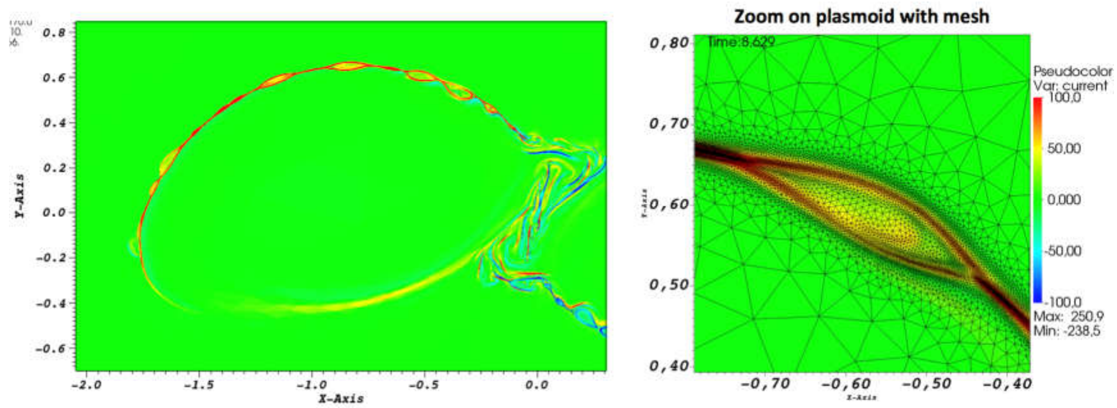

Figure 1: *A current layer with a plasmoid chain (left). Zoom on a single plasmoid overlaid with mesh (right).*

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Core-Edge-SOL interplay of turbulence in global and flux-driven gyrokinetic simulations

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Progress is required in the basic understanding of turbulent transport and will help offset risks when operating a future experiment as complex as ITER. The GYSELA code is developed and used in that perspective, emphasizing on the self-organized processes that take place across scales: from machine size down to the microscopic sizes of turbulent eddies as well as organization at intermediate mesoscopic scales. Because of its potential importance on global confinement, models must carefully treat the boundary layer that develops between the plasma and the material boundary. Contradictory results have been obtained, in particular regarding its width, its potential impact on the global organization of turbulence or its possible importance for the isotope transport problem.

A toroidally-symmetric limiter and a first wall have recently been implemented in GYSELA using penalized immersed boundaries. We mimic the transition between closed and open field lines as well as a simplified Scrape-Off Layer. The ion and electron temperatures are forced to a cold value within the immersed boundary and in the special case of adiabatic electrons the flux-surface averaged potential is bound to the electron temperature. With respect to heat transport, the limiter is a perfect heat sink; with respect to particle transport, several configurations have been studied to ensure particle conservation. Three types of computations have been conducted: in the simpler ones we test this penalization technique; in more advanced ones we impose axisymmetry, zeroing all main plasma instabilities and investigating the stability of a neoclassical SOL. At last, we run turbulent simulations in conditions as close as possible to experiments.

As expected, the introduction of a cold spot within the modeled volume generates a propagating parallel cold front whose characteristics are reproduced analytically. More interestingly, the modification of the electron response leads to the inversion of the radial electric field Er at the last closed flux surface and consequently the formation of an Er well in the confined region. Both effects lead to the onset of poloidal and/or parallel flows. We discuss how these flows modify the plasma equilibrium and lead to the spontaneous onset of a weak transport barrier. Global axisymmetric simulations show the development of instabilities for such steep profiles. Finally, turbulent simulations evidence the crucial role of the new boundary in recovering the proper behavior of the fluctuations level through most of the plasma volume, even deep in the confined core. Sensitivity to scanned parameters (especially to the Ti/Te ratio) and to the poloidal location of the limiter will also be presented.

Properties of plasma turbulence in the periphery of diverted tokamaks

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The turbulent plasma dynamics in the periphery of a tokamak plays a key role in determining its overall performances. In particular, it governs the confinement properties of the device, through the formation of a transport barrier associated with the L-H transition, and it controls the heat load on the vessel walls. GBS [1] is a three-dimensional two-fluid turbulence code, based on the drift-reduced Braginskii equations, which allows the simulation of plasma turbulence in this tokamak region. A non-field aligned algorithm has been recently implemented in GBS, to allow simulations in diverted configurations, such as the single- and double-null. Furthermore, simulations in innovative exhaust configurations, such as the snowflake, are being performed.

The results of GBS simulations in single-null configurations are used to investigate the processes determining the radial electric field at the plasma edge and the related formation of a transport barrier. In particular, we show the presence of two different turbulent transport regimes driven by Kelvin-Helmholtz and resistive ballooning instability, respectively. A transition between the two regimes is obtained by changing the power source, which leads to a strong ExB shear and to the onset of a transport barrier at the plasma edge. The ExB shear provides a saturation mechanism for the resistive ballooning instability while destabilising a Kelvin-Helmholtz mode that becomes the main drive for turbulent transport. The transition between the two regimes leads to a steepening of the pressure profile and improved plasma confinement. We derive an analytical expression for the pressure gradient length in both regimes. The simulation and analytical results are in good agreement. The analysis is then extended to the SOL where we highlight the effect of edge turbulence on the SOL width and therefore on the heat load on the vessel walls.

Finally, the results of simulations of alternative divertor configurations, which are considered for DEMO, are analysed. The analysis focuses on four different magnetic configurations: the ideal snowflake, the snowflake plus, the snowflake minus with the secondary X-point in the high field side and the snowflake minus with the secondary X-point in the low field side. For all the different geometries, the SOL width and the heat flux to the vessel walls are computed and the physics behind them analysed. A comparison between the single-null configuration and the four considered advanced configurations is shown.

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Theoretical and experimental studies of confinement in high field ST

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High field spherical tokamak ST40 (design parameters: R=0.4-0.6m, R/a=1.6-1.8, I_{pl}=2MA, B_t=3T, k=2.5, τ_{pulse}~ 1-5 sec, 2MW NBI, 2MW ECRH/EBW, DD and DT operations) is now operating and experiments and simulations are carried out to study transport properties in ST at high toroidal field, low collisionality and plasma parameters close to burning conditions.

Transport simulations with ASTRA, NUBEAM and TSC codes have been performed to model ST40 parameters and to support the physics basis of the compact high field ST path to Fusion. We show that high confinement regimes with just collisional (neoclassical) transport can be expected even when only ohmically heated. In an auxiliary heating regime, we find a hot ion mode with Ti in the 10keV range to be achievable with as low as 1MW of absorbed power. Issues connected with specific features of the high field ST are discussed, i.e. limitations of applicability of confinement scalings for prediction of performance of ST40. However, we show that if the performance achieved on other spherical tokamaks can be extended to ST40 conditions, up to 1 MW of Fusion power can be expected in DT operations. Studies of fast ions and alpha particle transport, heating and current drive, torque deposition and momentum transport have been performed using ASCOT, NUBEAM, Monte Carlo code NFREYA and the Fokker - Planck code NFIFPC. Different NBI energies and launch geometries have been studied and optimized. The confinement of thermal alphas in ST40 3T/2MA scenario is studied with full orbit following (which is necessary because of the large alpha particle gyro radius). The first orbit losses are seen to be almost 60% even in the high-performance scenario illustrating that the alpha confinement in a small device is very difficult even at the highest available fields. However, experiments on ST40 will provide useful information for verification of such simulations.

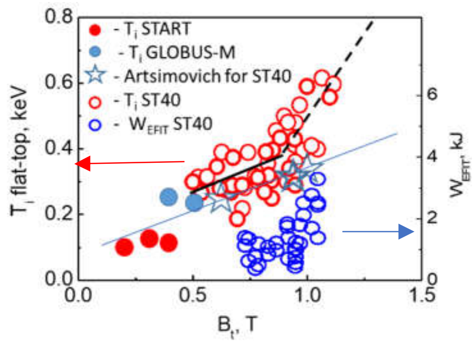

***Figure 1** Ion temperature T_i and thermal energy W_{EFIT} vs B_t, in STs.*

ST40 uses merging-compression plasma formation method [1] and ion temperatures in 1-2keV range have been achieved. Simulations of this start-up scenario have been performed using the TSC code and results are compared with experimental observations. After formation, at the flat-top, measured T_i increases with B_t, in agreement with START and Globus-M data [2,3] and also with Artsimovich formula, Fig.1. However, at B_t ~ 1T we observe sharp increase in T_i and W_{EFIT} which may suggest transition to better confinement at higher toroidal field.

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ECSim: Energy Conserving Semi Implicit Particle in Cell method

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Particle in cell (PIC) methods are a key tool for magnetic fusion energy research. Explicit PIC methods are severely limited in their applicability by stability constraints relative to grid spacing and time step. Often, for this reason, reduced methods like hybrid or gyrokinetic PIC are used to make the simulations accessible. An alternative approach that retains the full physical description is the use of implicit or semi-implicit PIC [1] that remove most of the stability conditions. Recently, a new approach to semi-implicit PIC that conserves energy - exactly has been proposed [2]. The method has three main features: 1) a new mover is proposed that allows to conserve energy exactly at the level of each particle; 2) a mass matrix formulation is used to express the current in terms of the electric field; 3) the fields formulated with the mass matrix can be solved with a linear iteration giving the overall method energy conservation for both fields and particle without requiring a non-linear iteration. For these reasons, the method is called Energy Conserving semi-implicit (ECsim). The main advantage of ECsim is the energy conservation leading to physical accuracy as well as enhanced numerical stability. The ECSim method has been implemented into a production code available in both cartesian [3] and cylindrical geometry [4]. The present abstract focuses on the applicability of this new method to different areas of plasma physics [5] and in particular fusion energy research [6].

The research leading to these results has received funding from the European Community's Horizon 2020 (H2020) Funding Program under Grant Agreement No. 754304 (Project DEEP-EST) and has been supported by R&D Agreement between Energy Matter Conversation Corporation, United States (EMC2) and KU Leuven R&D, Belgium (Contract # 2017/771). Computations were carried out at the Flemish Supercomputer Centre (VSC). This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of the Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Data Driven Theory to Support Model Formulation and the Design of New Experiments

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Until recently, science has progressed mainly in a hypothesis driven way: based on already established theories, new models have been developed mathematically and have been falsified with specifically designed experiments. This methodology has been very successful in the study of deterministic linear phenomena but its limitations are evident in the case of complex systems such as high temperature plasmas. In particular, when dealing with complex non-linear phenomena, the interpretation of the experimental evidence is a quite delicate task. The high complexity and uncertainties of Tokamaks, for example, increase dramatically the difficulties of traditional analysis techniques, due to their rigidity and poor exploratory capability. Consequently, a lot of untapped knowledge remains buried in the large collected databases, which could profitably be used to formulate models and plan experiments. The present contribution is indeed meant to provide an overview of recent developments in machine learning (ML) and statistics, to address some two of the most challenging issues in data analysis for the science of complex systems: data driven model building and the design of new experiments.

The <u>extraction of mathematical models directly from cross sectional data</u> is a great challenge in case of large database such as the one of JET, which is now approaching 0.5 Petabytes. A new approach to data driven theory, called Symbolic Regression (SR) via Genetic Programming (GP), has been recently developed to address problems, for which it is difficult to develop models based on first principles. It is based on the manipulation of symbols, namely mathematical expressions, with genetic algorithms. Typical examples of SR via GP applications are the extraction of scaling laws and the identification of dimensionless quantities. The deployment of this approach to study large databases (devoted to the investigation of the energy confinement time, the L-H power threshold etc) has shown that the traditional power laws are not necessarily the best mathematical forms to represent the data of and has helped clarifying the limitations of the most widely used non-dimensional parameters. Traditional ML and statistical tools are predicated on the assumption that the data are independently sampled form the same distribution function in the training set and the final application. Their results are therefore strictly valid only for data acquired in absolutely stationary conditions. A typical violation of these hypotheses is <u>the planning of new experiments</u>; the available models have to be applied to new regions of the operational space, not represented in the previous data. A new genetic programming procedure has been developed to extract from past data the most appropriate candidate models and to identify the best region of the operational space to falsify theories and plan new experiments.

In addition to exhaustive numerical tests to prove the generality of the techniques, specific applications to ITPA databases and data of metallic Tokamaks will be provided.

**See the author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018)*

Proposal Abstract for Oral at the 2019 EFTC

Ion cyclotron resonance heating modeling of JET, ITER and DEMO scenarios within the EUROfusion Integrated Modeling (EU-IM) framework

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Ion cyclotron resonance heating (ICRH) is a reliable and versatile tool routinely used in conjunction with neutral beam injection (NBI) to heat plasmas to fusion relevant temperatures in tokamaks (see e.g. [1,2]). Understanding the wave-particle interaction underlying wave-induced plasma heating requires looking at the problem from two complementary venture points, each requiring solving a dedicated equation. The wave equation describes the propagation of waves excited by the antennas and their absorption by the various plasma species, including intrinsic impurities and neutral beam injected ions. The Fokker-Planck equation describes the fate of the energy transferred to the heated particle populations accounting for Coulomb collisional relaxation. Since the various plasma components absorb different amounts of power in different regions of the plasma, this equation has to be solved for all the plasma species simultaneously. Furthermore, because the heated distribution functions impact on the wave propagation and in particular the wave absorption, the wave and Fokker-Planck equations have to be solved iteratively in a self-consistent loop for a reliable inter-species power flow – to be used by transport solvers - to be obtained.

The EUROfusion Integrated Modeling (EU-IM) [3] framework offers a standardized infrastructure for integrated modeling and provides flexible workflows, encompassing a variety of interchangeable models with various physics descriptions and different levels of sophistication, hereby allowing to highlight specific aspects of physics lying outside the scope of some of the codes while available in others. Moreover this provides an immediate tool for code benchmarking [4], ensuring all codes use the same equilibrium, plasma kinetic profiles, particle sources and machine specific parameters.

Within the EU-IM framework, various wave equation solvers and Fokker-Planck solvers are available. They provide the power sources needed to solve the transport equations, and provide the populations' distribution functions required e.g. to estimate the neutron yield and to cross-check against experimental data of fast particle diagnostics such as TOFOR [5] and NPA [6].

Fokker-Planck solvers often implicitly assume the population studied is a minority while the majority ions are untouched and hence in thermal equilibrium. However, experimentally relevant scenarios typically involve various heated populations, some of which having large concentrations and several of which have distributions deviating significantly from Maxwellians. To bridge this gap, dedicated Fokker-Planck solvers were developed for the EU-IM heating and current-drive workflows. Specifically, the StixReDist code [7] solves a set of coupled Fokker-Planck equations exploiting the non-linear collision operator [8] to incorporate the effect of self-collisions crucial for non-minority populations. This collision operator for arbitrary distribution functions relies on iteratively solving linear equations, the solutions of which asymptotically approach the solution to the non-linear problem. Stix [9] proposed a fast yet accurate method to solve the Fokker-Planck equation, particularly suited in generalized form for integrated modeling. To allow studying neutral beam injection (NBI) as well as the synergy of ICRH and NBI, the FoPla code [10] has also been developed and deployed on the EU-IM framework.

The ICRH modeling tools developed within the EU-IM framework are now ready for exploitation. As practical illustrations, the present paper discusses modeling of scenarios relevant for the upcoming JET D-T campaign as well as for future machines ITER and DEMO. In particular the role of various control parameters such as the minority concentrations, the plasma density, the beam energy and power, and the total applied power on the overall deposition profile and power distribution among the various populations, on the formation of fast ion tails and thermal subpopulations as well as on the fusion reactivity will be discussed.

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**See http://www.euro-fusionscipub.org/eu-im

On the performance of future tokamak devices based on scaling law predictions

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The main design parameters of a fusion reactor have to be determined through an optimization which takes into consideration both the technological possibilities and constraints as well as the plasma physics properties, in order to maximize the electric power. Therefore, from the plasma physics standpoint there is the need of developing models which can be easily and quickly applied in order to test the compatibility of different plasma configurations with the technological side.

These models can be obtained by running theory-based models in a transport code, like the coupled ASTRA / TGLF package [1,2,3], over a wide range of reactor engineering parameters, then deriving appropriate regressions which can be used as practical scaling laws at the interface with the technology requirements.

In this way, it is also possible to explore performances of the future reactors in terms of fusion power, confinement time H-factor and so on, in different relevant regimes such as *H*-mode, *I*-mode and *L*-mode (see *Figure 1*).

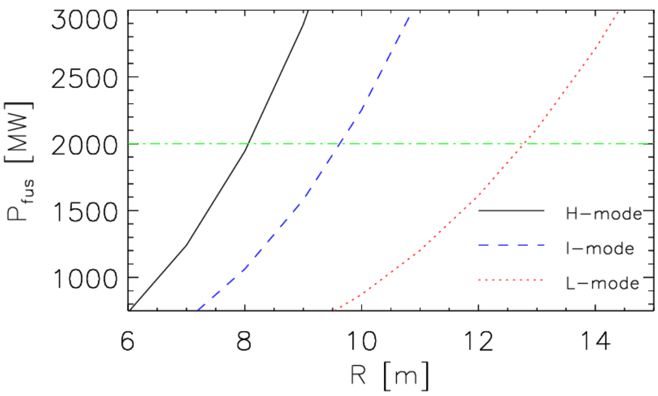

Figure 1: *Fusion power as a function of size of the machine for H-, I-, L-mode. The quantities in common to the regimes considered for the plot are B = 6 T, q_{95} = 3.5, A = 3, P_{aux} = 50 MW and P_{rad} = 200 MW.*

The approach, the results and the insights, obtained on the priorities from the plasma physics standpoint, have been developed in Ref. [4] and provide important key points for the establishment of the best physical and technological solutions for the future tokamak scenarios. In particular the work shows that it is possible to move towards an *I*-mode avoiding the problems of ELMs related to the *H*-mode regime, obtaining at the same time very good performances for tokamak devices in terms of fusion power, *H*-factor and *Q*.

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https://doi.org/10.1088/1741-4326/ab276f

Shear Alfvén wave continuum spectrum with bifurcated helical core equilibria

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Three dimensional effects in the magnetic field geometry occur in both axisymmetric and non-axisymmetric fusion devices. In tokamaks, which are inherently axisymmetric devices, resonant magnetic perturbation (RMP) coils are often used to optimize the magnetic field geometry [1] and saturated internal-ideal-kink modes self-consistently generate a helical core around the q = 1 rational surface, which leads to 3D magnetic configurations [2, 3]. The bifurcated MHD equilibria formed by the helical core and axisymmetric boundary equilibrium affects Alfvénic instabilities in tokamak plasmas as predicted by kinetic calculations including the diamagnetic frequency (ω^*) [4, 5].

In this work, the radial structure of the continuum spectrum of shear Alfvén and Alfvén-acoustic waves in the beta-induced Alfvén eigenmode (BAE) frequency range is modeled for tokamak plasmas in the presence of 3D effects obtained from the bifurcated MHD equilibrium reconstruction. Plasma compressibility and geodesic curvature effects responsible for the low-frequency continuum spectrum calculations are invoked in the extended STELLGAP code [6, 7]. In the equilibrium calculations we find that the helically distorted MHD equilibria may exist in the axisymmetric devices if q = 1 rational surfaces are present. Equilibrium reconstruction has been achieved using 3D VMEC equilibrium solver [8], which is commonly used in stellarator devices under the assumption of closed magnetic flux surfaces. The continuum calculations with the bifurcated equilibria lead to the frequency splitting via coupling to adjacent n = 1 continuum around an accumulation point. Our modelling including 3D effects correctly reproduces the phenomenon of continuum frequency splitting and provides a possible solution for the differences of few kHz in frequency splitting, which remained unexplained with the 2D kinetic calculations [4]. The pressure scaling confirms the increase of helical excursion of the magnetic axis in equilibrium reconstruction and hence the range of continuum frequency splitting. In our calculations, the existence of low-frequency continua is in agreement with the experimentally observed low-frequency modes.

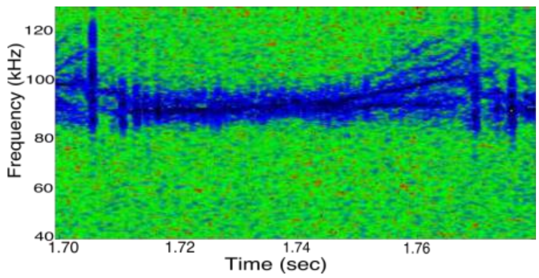

Figure 1: *Frequency spectrogram for AUG discharge 20488 from t = 1.72 to 1.78 seconds. Strong BAE mode activity during monster saw-tooth crashes is measured with Mirnov coils.*

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. We also acknowledge Severo Ochoa (SO) mobility grant to support a research stay by Allah Rakha at Max Planck Institute for Plasma Physics (IPP) Garching, Germany.

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Spatiotemporal analysis of the runaway current from synchrotron images in a tokamak disruption

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Understanding runaway electron dynamics during tokamak disruptions is of utmost importance for future reactor-sized tokamaks, such as ITER. Before any theoretical model is applied to future reactor scenarios, it should be validated against existing experimental data, which is often difficult to do in disruptions due to the notoriously hard-to-diagnose nature of the rapid thermal quench. However, when the fast electrons acquire sufficiently high energies, non-intrusive synchrotron diagnostics can be used. In this contribution we apply the recently developed synthetic diagnostic tool SOFT [1] to obtain information about the spatiotemporal evolution of a runaway current that exhibits a spike resulting from magnetic reconnection.

During the post-disruption runaway plateau phase of certain discharges at ASDEX Upgrade, which were deliberately triggered by injecting argon [2], a sudden transition of the synchrotron spot from an elliptical to a crescent shape was observed, as shown in Fig. 1. The spot shape transition is temporally correlated with a small current spike, and the magnetic pick-up coils show a strong $n = 1$ MHD fluctuation. SOFT simulations show that the spot shape transition is consistent with a flattening of the runaway current profile, and allow the time evolution of the electron beam radius to be estimated. Combined with kinetic simulations, these results can be used to validate theoretical models for the runaway electron distribution function and stability of the runaway beam.

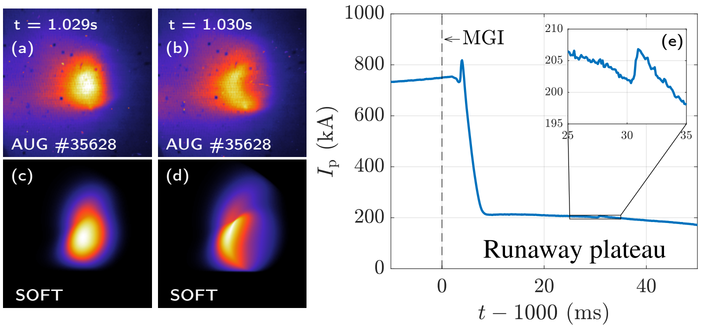

Figure 1: *(a/b) Synchrotron images from ASDEX-Upgrade shot #35628, (c/d) simulated synchrotron images from SOFT [1], (e) Post-disruption plasma current evolution, with small spike around* $t = 1.030\,\mathrm{s}$ *in the same shot.*

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Toroidal and slab ETG instability dominance in the linear spectrum of JET-ILW pedestals

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Electron temperature gradient physics is shown to dominate the linear gyrokinetic spectrum in JET-ILW pedestals where the ion temperature is measured. Local linear gyrokinetic simulations of JET pedestal shots 82550, 92167, and 92174 demonstrate that with the exception of kinetic ballooning modes (KBMs), all other microinstabilities are driven mainly by the electron temperature gradient — many of these instabilities exist at transport-relevant scales. The ion temperature gradient (ITG) instability is subdominant, and both KBMs and ITG are shown to be suppressed by $\mathbf{E}\times\mathbf{B}$ shear. Electron temperature gradients are particularly large in all shots, causing electron temperature gradient (ETG) instabilities to be driven at perpendicular scales larger than in the core by a factor of $R_0/L_{Te} \gtrsim \sqrt{m_i T_{0i}/m_e T_{0e}}$. Here R_0 is the major radius of the last closed flux surface, L_{Te} is the electron temperature length scale, m_i and m_e are the ion and electron masses, respectively, and T_{0i} and T_{0e} are the equilibrium ion and electron temperatures, respectively. Results show ETG instability dominating at $k_y\rho_i \gtrsim 0.5$, which is mainly toroidal at low k_y and slab at larger k_y. Here, k_y is the perpendicular wavenumber in the direction perpendicular to both the magnetic field and the radial direction, and ρ_s is the gyroradius for a species s. Instabilities at all scales are much more sensitive to L_{Te} than L_{Ti}. The toroidal ETG mode has a small parallel wavenumber, $k_{\|}$, and a sufficiently large radial wavenumber that electron finite Larmor radius (FLR) effects become important; that is, $k_y\rho_i \sim 1$, but $K_x\rho_e \sim 1$, where K_x is the effective radial wavenumber. At larger $k_y\rho_i$, the fastest growing mode is a slab ETG mode. Both types of ETG modes are surprisingly well-described by simple local dispersion relations. It is also shown that electron collisions, $T_i \neq T_e$, and $L_{Ti} \neq L_{Te}$ break the isomorphism in the linear spectrum between ITG and ETG, and that R_0/L_{Ti} is often below the critical threshold. A prescription for calculating the ETG stability boundary is also found for general perpendicular and parallel wavenumbers.

We are grateful for useful conversations with T. Adkins, J. R. Ball, N. Christen, W. Dorland, M. R. Hardman, Y. Kawazura, J. C. Hillesheim, A. Mauriya, S. Saarelma, and A. A. Schekochihin. JFP is supported by EPSRC Scholarship No 3000207032. FIP, MB, and CMR are supported in part by the RCUK Energy-Programme (grant number EP/EPI501045). PGI is supported by an EU H2020 grant, agreement No 3000207035. Computational time provided by Plasma HEC Consortium EPSRC (grant number EP/L000237/1). This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053 and from the RCUK Energy Programme (grant number EP/P012450/1).

Zonal Flow — Drift-Wave Interactions in two-dimensional curvature-driven fluid ITG turbulence

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Numerical simulations have shown that turbulence in tokamaks is regulated by the interaction of zonal flows (ZF) and drift waves (DW) [1, 2]. The latter are wave-like fluctuations in the plasma, driven by gradients in the equilibrium plasma parameters. Zonal flows are Larmor scale shear flows in the poloidal direction, which are generated nonlinearly by the drift-wave turbulence itself. Starting from the gyrokinetic equation [3] for ions, we derive equations for a 2D 2-fluid system of ion density and ion temperature perturbations of an equilibrium of constant magnetic curvature and constant background temperature gradient. These equations are numerically integrated to explore the turbulent state of the model. We report results on the interplay of zonal and nonzonal perturbations in saturated turbulence. The transition from a saturated, low transport state ("Dimits regime") to a strongly turbulent regime with stiff transport is controlled by the ratio of normalised background temperature gradient and collisionality. The low-collisionality Dimits state is found to be dominated by quasi-steady zonal flow and temperature in an arrangement, which suppresses the ITG instability. This arrangement is reminiscent of the "**E**x**B** staircase" seen in global gyrokinetic simulations [4]. This quasi-steady zonal background is periodically disturbed by bursts of travelling localized coherent structures, which significantly enhance the radial heat flux. Similar structures have been observed in local gyrokinetic simulations with imposed background flow shear [5].

P.G.I. is funded through an EU H2020 grant, agreement No 3000207035. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Advanced Power Exhaust Studies in EAST and DIII-D

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Divertor is one of the key components in Tokamak. The design, construction and operation of advanced divertors have been the main topics of tokamak research during the last decade. In general, developing an advanced divertor configuration requires: 1) Optimizing magnetic configuration to extend the plasma wetted area through flux expansion, and increasing the divertor volume by increasing the field line length; 2) Increasing divertor closure by divertor baffling to improve divertor screening for recycling neutrals and impurities, hence increasing divertor neutral pressure, thus enhancing divertor particle and power exhaust [1].

Some advanced divertor solutions have been developed and validated in EAST and DIII-D respectively. In EAST an alternative advanced divertor configuration, i.e., quasi snowflake (QSF), aka X-divertor and in DIII-D an alternative advanced divertor coupling divertor closure with advanced magnetic configuration(X-divertor) have been attempted respectively. In EAST SOLPS predicts that the quasi snowflake configuration significantly reduces the peak heat flux at the lower divertor outer target, by a factor of 2–3, owing to the magnetic flux expansion. Furthermore, the density threshold for detachment is much lower for QSF, compared to LSN under the same upstream conditions. This indicates that QSF provides a promising tool for controlling heat flux at divertor target while maintaining a lower separatrix density, which is highly desirable for current drive, thus greatly facilitating long-pulse operation in EAST [2]. The SOLPS modeling for a high confinement plasma in DIII-D finds that increasing divertor closure with standard divertor (SD) reduces the upstream separatrix density at the onset of detachment from $1.18 \times 10^{19} m^{-3}$ to $0.88 \times 10^{19} m^{-3}$. Moreover, coupling the divertor closure with X-divertor(XD) further promotes the onset of divertor detachment at a still lower upstream separatrix density, down to the value of $0.67 \times 10^{19} m^{-3}$, thus, showing that divertor closure and advanced magnetic configuration can work synergistically to facilitate divertor detachment.

This work has received funding from the National Natural Science Foundation of China under Contracts No. 11505234, 11347113 and National Key Research and Development Program of China under Contracts No. 2017YFA0402500, 2017YFE0300402.

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How the self-interaction mechanism affects zonal flow drive and convergence of flux-tube turbulent transport simulations with system size

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We use gyrokinetic flux-tube simulations to report a decrease, in the shearing rate of ExB zonal flows, with increasing system size measured by $1/\rho^*=a/\rho_i$, where a is the tokamak minor radius and ρ_i is the ion Larmor radius. In practice, this is done by decreasing $k_{y,min}\rho_i$ ($\sim\rho^*$), where $k_{y,min}$ is the minimum wavenumber along the direction y, bi-normal to the magnetic field. The corresponding gyro-Bohm normalised heat and particle fluxes also increase with decreasing $k_{y,min}$. We find that this is an effect of the non-adiabatic passing electron dynamics and the resulting fine structures at mode rational surfaces of each k_y [1,2]. The associated strong self interaction mechanism [3] disrupts resonant 3-wave interactions involving the zonal modes. As a consequence, the different k_y contributions to Reynolds Stress driving the zonal flow tend to get decorrelated, which results in the shearing rate level developing a statistical dependence on $k_{y,min}$. In adiabatic electron simulations, the scaling is not as severe, owing to a weaker self interaction mechanism at play.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Computations were performed on Piz Daint, CSCS (CH) and Marconi, CINECA (Italy).

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Hall-MHD Modelling of CAEs and their interaction with fast ion populations

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Fusion-born alpha particles and Neutral-beam injected (NBI) particles are important to the initial and continuous heating of a fusion plasma. However, these supra-thermal particles can drive plasma instabilities that may lead to significant losses - measurements in DIII-D during NBI showed that up to 70% of the beam power could be lost due to fast-particle driven instabilities [1]. The Alfvén Cyclotron Resonance between fast ions and Compressional Alfven Eigenmodes (CAEs) is one of the first loss mechanisms that fast ions encounter as they slow down [2].

To better understand this a linear Hall-MHD stability code called Whales2 is being used to solve for CAEs in an axisymmetric toroidal geometry. This code is based on ideal MHD equations using a non-variational Hermitian approach, with straightforward extension to Hall-MHD. The code is being benchmarked against known analytical and numerical results from cylindrical to toroidal geometries. The spectrum of calculated CAE modes for low-aspect ratio equilibria will be used to simulate the impact on fast ion populations as test particles, measuring particle and energy flux.

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1D description of transport in TCV ECRH plasma

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The TOMATOR 1D hydrogen helium plasma simulator numerically describes the evolution of currentless magnetised RF plasmas in a tokamak based on Braginskii's standard continuity and heat balance equations. Since no consistent theoretical model exists to describe particle and heat transport in ECRF plasmas, a study of the transport coefficients used in the diffusion-convection-reaction equation of the simulation is necessary.

The inhomogeneous magnetic field in a tokamak leads to a vertical electric field, by virtue of particle drifts, resulting in a convective flow due to the $\boldsymbol{E}\times\boldsymbol{B}$ drift. Diffusion of charged particles due to random collisions in the plasma results in an additional radial motion. Early experiments indicate though that diffusion occurs at a faster Bohm rate with respect to classical theory. To estimate these diffusion and convection coefficients in ECRF plasmas, the code is benchmarked with experimental data from TCV.

The implementation of a vertical magnetic field reduces the $\boldsymbol{E}\times\boldsymbol{B}$ drift, favoring particle confinement and resulting in an increasing plasma density. However, a further increase of this vertical magnetic field favors the parallel particle loss and reduces plasma density. An optimal value of this magnetic field for particle confinement can be deduced using experimental data and verified through modeling.

Benchmarking the TOMATOR 1D code with other machines will help to determine the influence of the machine parameters on the transport coefficients and on the optimal value for the applied vertical magnetic field.

A well-founded prediction of the transport coefficients and a valid estimation of the optimal value for the vertical magnetic field can help to determine the optimal conditions for ECRF plasma production in a tokamak and to develop advanced scenarios for ITER operation.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commision.

Stellarator impurity transport driven by main ion pressure anisotropy

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Accumulation of highly charged impurities in the plasma core of stellarators is commonly observed, leading not only to fuel dilution but also to unacceptable energy losses by radiation [1]. Since heavy metals like tungsten are the preferred materials for the plasma-facing components of magnetic confinement fusion devices, impurity accumulation becomes an obstacle in the path towards stellarator reactors. This is why impurity transport is one of the most active research areas in the stellarator community. In particular, significant effort is being made on its theoretical understanding, to which the present work aims to contribute.

The radial neoclassical impurity flux in a stellarator can be written as a sum of two terms [2]. The first term is driven by parallel friction between impurities and main ions. The second term is driven by impurity pressure anisotropy and, for impurities in the Pfirsch-Schlüter regime, is typically neglected. The reason is that the impurity-ion collision operator C_{zi}, when expanded to lowest order in $\sqrt{m_i/m_z} \ll 1$, only involves the component of the main ion distribution that is odd in the parallel velocity, h_-, and gives very small impurity pressure anisotropy. Whereas keeping only the lowest order term in the expansion of C_{zi} is correct in tokamaks, its correctness is not obvious in stellarators because higher-order terms in the $\sqrt{m_i/m_z}$ expansion involve the component of the main ion distribution that is even in the parallel velocity, h_+. If the main ions have low collisionality, h_+ can be large [3] and one cannot automatically ignore higher-order terms in the mass ratio expansion of C_{zi}. The component h_+ produces pressure anisotropy in the main ions, which through the impurity drift kinetic equation generates impurity pressure anisotropy. These higher-order terms can actually be relevant not only in the Pfirsch-Schlüter regime, but also in other regimes.

In this conference contribution we analytically calculate the radial neoclassical impurity flux including the effect of main ion pressure anisotropy when the impurities are in the Pfirsch-Schlüter (extending the techniques of [4]), plateau or $1/\nu$ regimes and the main ions have low collisionality. The derived expressions have been implemented in a numerical code, which allows for a fast evaluation of neoclassical impurity transport in any of these regimes. We identify regions of plasma parameter space where, in principle, pressure anisotropy can modify or even dominate impurity transport.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This research was supported in part by grant ENE2015-70142-P, Ministerio de Economía y Competitividad, Spain and grant PGC2018-095307-B-I00, Ministerio de Ciencia, Innovación y Universidades, Spain.

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Multi-species collision operator for Particle-In-Cell gyrokinetic code

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The collision frequency is often weak compared to other typical frequencies in the core of tokamaks. It is nevertheless important to correctly describe various effects on tokamak plasmas. For example, the presence of collisions is known to directly modify the level of TEM turbulence. Collisions are also a key ingredient for neoclassical physics which is important for large scale flows and impurity transport.

In this context, a new collision operator has been implemented in the gyrokinetic code ORB5 (1). This operator, which is based on a moment approach for the back reaction term, is valid for arbitrary species (mass, charge and concentration). The collision operator implemented in ORB5 is similar to the one used by GYSELA (2) but its numerical treatment is totally different due to distinct plasma descriptions (grid versus particles).

The PIC method implies large uncertainties of velocity derivatives of the distribution function which are used by the collision operator. To circumvent this problem, different numerical techniques are used. In particular, the test-particle part of the operator is solved via a Langevin approach which is known to increase the noise via weight spreading (3). A noise control scheme adapted for both collisional and collisionless simulations (4) has therefore been implemented and tested.

The new collision operator has been successfully verified. Conservation properties (mass, total momentum and energy), exchange rates between species and the isotropization rate were found in excellent agreement with theoretical prediction. A benchmark against neoclassical physics was also performed. The results of these tests will be presented.

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Dynamics and Spectral Properties of Turbulence-Driven Magnetic Islands

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Neoclassical tearing modes (NTM) are metastable magnetic islands in tokamaks; however, they appear frequently in experiments without any noticeable triggering event. In order to understand this, it has been numerically shown that turbulence can create a seed island by mode coupling [1-3], even remotely [4] ; such a seed island can indeed be large enough to further grow from the NTM mechanism [5].

However, this amplification only happens for islands larger than a critical size. Therefore, the definition and determination of the size of turbulence-driven magnetic islands is of crucial importance.

First, the definition of island size is more ambiguous in a turbulent and/or stochastic context than in a quiescent, tearing mode context. Different definitions of the island size are discussed, as well as the associated diagnostics that can be implemented in numerical codes.

Next, we use 3D reduced-MHD simulations of flux-driven ballooning turbulence to study the seed island creation in regimes where the classical tearing mode is linearly stable. A localized pressure source is used to control the radial position and strength of the turbulence, and allows to radially separate turbulent region from q=2 island resonant surface.

We show that the onset of the magnetic island on the q=2 surface follows complex dynamics that can be split into several distinct phases : as a first step the nonlinearly dominant mode in the turbulent region drives a weak harmonic island on the q=2 surface. Subsequently the spectrum on the q=2 surface evolves towards larger scales. The final dominant island mode depends on the power source that feeds the turbulent region; this can lead to an oscillating behaviour when the peak of the final island spectrum lies between integer harmonics.

This work was performed using HPC resources from GENCI-CINES (Grant 2019-A0060510146)

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Questioning the quasilinear nature of turbulent transport by means of gyrokinetic flux-driven nonlinear simulations

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Efficiently operating a nuclear fusion device requires understanding and predicting turbulent transport processes. Reduced quasilinear models, backed on gyrokinetic gradient-driven nonlinear simulations, reveal extremely powerful in recovering experimentally measured steady state fluxes at low cost. However, flux-driven nonlinear simulations as well as experimental measurements reveal new features, such as transient and non-local dynamics like avalanches and turbulence self-organization close to marginal stability. We perform gyrokinetic simulations with GYSELA code [1] and focus on the impact of such forcing on turbulence properties. In particular, we study numerically the effect on stationary zonal flow on turbulent structures, and access the quasilinear nature of fluctuations.

The angular rotation of electric potential structures is computed as the best-fitting non-linear registration of 3D images. This results in a mostly toroidal rotation. Its projection against $\nabla\varphi - q\nabla\theta$, i.e. the direction transverse to B and contained on magnetic surfaces, agrees well with the same projection of the stationary zonal flow velocity. This suggests that the parallel dynamic compensates the poloidal ExB drift on average, so as to yield a mostly toroidal motion. This explains why the ballooning character is preserved despite significant poloidal flows. The sign of the computed radial velocity correlates well with that of the stationary zonal flow shear rate, as already reported [2, 3]. This leads to either converging or diverging layers at local extrema of zonal flows. Most surprisingly, turbulent correlation time and length are affected differently in these 2 different layers, hence questioning the universal picture of turbulence decorrelation by zonal flows. Finally, the complex temporal dynamics of inferred velocities suggest a different role for zonal flow fluctuations.

Quasilinear framework assumes that the linear relationship between perturbations hold in the non-linear regime. Phase relations between electric potential and pressure are investigated numerically. The heat flux is decomposed into the product of pressure and radial ExB velocity fluctuation amplitudes times the sine of the phase shift. Statistical analysis shows that the phase distribution is radially-uniform over the whole radial domain $0 \leq r/a \leq 1$ and narrow around $0.3^{rad} \pm 0.1^{rad}$. The majority of the flux variance appears to be governed by the amplitude fluctuations. Those phase relations have been compared to the expected linear properties computed with the quasilinear code QuaLiKiz [4], run with time-averaged profiles. QuaLiKiz prediction for the phase shift is higher, around 0.6^{rad}, and exhibits a stronger radial dependency. The possible roles of nonlocal features and of the proximity to marginal stability are currently explored and will be reported.

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Finite-Orbit-Width Effects in the Orbital Spectrum of Guiding Center Motion

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The Guiding Center (GC) description of particle motion is of fundamental importance in studying particle, momentum and energy transport in fusion plasmas. The Hamiltonian description of GC motion directly implies integrability of the underlying system for axisymmetric magnetic field configurations. In such cases, particles are either trapped in banana orbits or circulate along the toroidal direction [1]. Commonly to all nonlinear systems, the orbital frequencies of all degrees of freedom depend strongly on the particle energy and momentum. This dependence determines the effect of the presence of any non-axisymmetric perturbation, either due to MHD instabilities or to propagating plasma waves, on transport phenomena, through resonance conditions. The conditions are fulfilled locally rendering the phase space of the system strongly inhomogeneous with regions of regular or chaotic motion [2]. So far, the orbital frequencies involved in the resonance conditions have been calculated analytically only under specific restrictions for the particle momentum and position and under the approximation of Zero-Orbit-Width (ZOW) assuming that the particle motion is restricted on a specific magnetic flux surface [1, 3-5].

In this work we utilize a canonical transformation to rigorously define a ZOW Hamiltonian which retains all the terms of the original GC Hamiltonian without any restrictions on particle's energy and momentum that are questionable for energetic particles. For the case of a circular Large Aspect Ratio (LAR) equilibrium, this Hamiltonian is more accurate than the standard pendulum-like one that is widely used in the literature [3-5]. Moreover, the canonical formulation of the problem allows for the natural introduction of FOW effects that take into account deviations from a fixed flux surface in a perturbative fashion. The perturbed system is analyzed in terms of Canonical Perturbation Theory and the FOW effect on the orbital frequencies is analytically calculated. It is shown that for specific particle energies and momenta the FOW effects significantly modify the orbital frequencies of the GC motion and therefore the location where resonant interactions with non-axisymmetric perturbations take place resulting in modification of particle and momentum transport properties in comparison to the ZOW approximation.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053 as well as from the National Programme for the Controlled Thermonuclear Fusion, Hellenic Republic. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Alfvén waves in nonlinear 3D MHD modelling of RFP plasmas

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A variety of Alfvénic eigenmodes have been observed in the magnetic spectra of reversed-field pinch (RFP) plasmas in past years, in machines like RFX-mod [1] and MST [2]. In particular, in the RFX-mod device two branches of long-wavelength Alfvén eigenmodes have been observed. On the one hand, a high-frequency branch (in the range 500−1500 kHz) with two discrete eigenmodes is present during the whole discharge and interpreted as global Alfvén eigenmodes [1]. On the other hand, a lower frequency branch ($f < 500$ kHz) with three coherent peaks is detected only during helical RFP states, which spontaneously emerge at high plasma current (above 1 MA) and are associated with improved confinement [3].

Here, we report the investigation on the modelling study of Alfvén waves in reversed-field pinch plasmas, and the comparison with experimental findings in the RFX-mod device. The nonlinear 3D MHD cylindrical code SpeCyl [4,5] has been used to analyze configurations with increasing level of complexity. First of all, numerical solutions have been compared with analytical ones in the simplest case of a uniform axial magnetic field: an excellent agreement is obtained for both the shear Alfvén wave (SAW) and the compressional Alfvén eigenmodes (CAEs). Then, the RFP configuration has been studied by assuming perturbations with a single space periodicity. Phenomena such as phase mixing of SAW, resonant absorption of CAEs and the appearance of the global Alfvén eigenmode (GAE) are reported. Finally, the fully 3D RFP case with realistic magnetic reconnection events [6] has been investigated, showing for the first time in nonlinear RFP simulations the excitation of Alfvén waves by magnetic reconnection. Modelling results are in good quantitative agreement with the experimental characterization of the Alfvénic activity observed in RFX-mod [1]. In particular, the two high-frequency eigenmodes observed experimentally are reproduced in nonlinear MHD modelling, and identified as a global and a compressional Alfvén eigenmode. Overall, these findings suggest that reconnection processes can destabilize global Alfvén eigenmodes, as well as compressional Alfvén eigenmodes (normally disregarded in Tokamak plasmas, because of the associated very high frequency).

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Optimized Phasing Conditions to Avoid Coaxial Mode Excitation by ICRH Antennas

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Ion Cyclotron Resonance Heating (ICRH) is one of the key heating schemes for tokamaks. The antenna system must launch the Radio Frequency (RF) power with a wave number spectrum which maximizes the coupling to the plasma and should ensure good absorption while minimizing the wave interaction with the edge of the plasma. Such interactions lead to impurity release, the effect of which has been measured far from the antenna location [1] and can involve the entire Scrape-Off Layer (SOL).

Possible mechanisms causing the deposition of RF power in the edge region are the excitation of coaxial and surface modes [2], bad central absorption and the occurrence of a wave confluence in the low-density region near the antenna [3]. The first two mechanisms can be avoided by the exclusion of the low $|k_{\parallel}|$ excitation, in particular the coaxial modes satisfying $|k_{\parallel}| < k_0$ which propagate in the edge. The present study shows that canceling the excitation and the derivative of the excitation with respect to $k_{\parallel}$ at $k_{\parallel}$=0 is very effective to avoid the coaxial modes. For example, this condition is fulfilled by the 3-strap antenna of ASDEX Upgrade [4] which has been shown to reduce the release of heavy impurities into the main plasma.

The paper also presents modeling results of the ITER antenna coupling and its extrapolation to DEMO with comparison between optimized and non-optimized phasing cases.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Influence of the normalised gyroradius on neoclassical transport in global gyrokinetic simulations using the code GT5D

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The use of tungsten in plasma facing components, as will be the case for ITER, inevitably leads to the pollution of the fusion plasma by heavy impurities. Several tokamaks (ASDEX Upgrade, JET) have reported on-axis accumulation of tungsten – which would be detrimental to fusion efficiency. However, the transport of high-Z impurities is not yet fully understood. Furthermore, recent numerical results using global gyrokinetic simulations showed large differences in neoclassical impurity particle fluxes compared with commonly employed estimates based on local theory [1].

The gyrokinetic full-f Eulerian simulation code GT5D [2] which uses a multi-species linear Fokker-Plank collision operator [3], was recently upgraded to enable simulations with very large mass ratios, as is needed to study the transport of heavy impurities. A prior neoclassical benchmark for bulk ions between GT5D and the Hirschman-Sigmar (HS) theory [4] was extended to various impurities spanning over all transport regimes.

While the impurity particle fluxes in our simulations showed good agreement with the HS estimates in the case of flat temperature profiles, the addition of a temperature gradient led to large differences. The thermal screening factor, which quantifies this dependence on the thermal gradient, was found to be reduced by 30% at $\rho_*=1/150$ while good agreement was recovered for smaller values. This result is in agreement with the results found in [1] and explains the discrepancy. Furthermore, our results suggest that larger machine size should favor the outward transport of heavy impurities such as tungsten.

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Scrape-off layer turbulence with STORM: overview of recent physics studies and upgrade of staggered grids in BOUT++

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Turbulence in the scrape-off layer (SOL) plays a key role in regulating the heat and particle loads to the divertor and first wall. These loads must remain within stringent operational limits in a fusion reactor. We present the latest updates to the STORM code [1], which is a BOUT++ [2,3] module developed at CCFE to simulate SOL turbulence via a system of fluid equations, and the supporting upgrades to BOUT++.

First we present some highlights of recent physics studies with STORM. Simulations in slab-like geometry allow the analysis of key features of SOL behaviour. A study of turbulent transport in a divertor leg identified the instability drives governing spreading of plasma into the private flux region [5]. Electromagnetic effects were included in STORM and their influence on filament motion investigated [6]. Moving from slab to diverted tokamak geometry, the STORM model was generalised with full curvature operators and radial boundary conditions adapted to long-time simulations with strong fluctuations; the first simulations of saturated turbulence in a double-null tokamak SOL have been completed and validated by comparison with experimental results from MAST [7].

The main part of the presentation concerns support for staggered grids in BOUT++. The standard BOUT++ treatment of toroidal geometry uses a 'quasi-ballooning' scheme [4]: a grid aligned to $\nabla\psi$ is used for radial derivatives, while parallel derivatives are field-aligned. The 4.x series of BOUT++ has an implementation of this scheme optimized for collocated grids: the values of a fluid variable are stored in toroidal (ψ, θ, ϕ) coordinates and values at the points along the magnetic field from each grid point at the next and previous perpendicular planes are calculated by interpolation. However, STORM uses a staggered grid in the parallel direction to avoid the checkerboard instability, which has twice as many grid point positions – so that the standard BOUT++ implementation of parallel derivatives would require twice as many interpolations. It is more efficient to transform to a globally field-aligned grid where a single transformed fluid variable can be used to calculate parallel derivatives for both centred and staggered locations; the results are transformed back to the (ψ, θ, ϕ) grid. We have implemented this method in the latest v4.3 release of BOUT++, as well as fully integrating support for staggered grids throughout the BOUT++ code-base, resolving many minor inconsistencies which previously limited the order of convergence in simulations with staggered grids. The availability of staggered grids in toroidal geometry together with the many optimizations in the 4.x series of BOUT++ delivers a significant increase in the performance of STORM, around a 20-40% speed-up, compared to the earlier version based on BOUT++ v3.1.

This work has been funded by the RCUK Energy Programme [grant number EP/P012450/1].

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Scattering of radio frequency waves by randomly modulated density interfaces in the edge of fusion plasmas

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The optimization of heating and current drive by radio frequency (RF) waves in fusion plasmas necessitates the need for understanding the propagation of RF waves through the turbulent plasma that is encountered in the edge region and the scrape-off layer. The same is also relevant for RF related diagnostics in fusion devices. The turbulent plasma modifies the propagation characteristics of RF waves which, in turn, can affect the heating and current profile. We have developed a full-wave, three-dimensional electromagnetic code ScaRF [1] that is being used to study the propagation of RF waves through turbulent plasma. ScaRF is based on the Finite-Difference Frequency-Domain method, and includes the anisotropic cold plasma permittivity tensor for a magnetized plasma. It is configured (but not limited) for RF waves in the electron cyclotron frequency range. It is used to study scattering in ITER-type plasmas and in medium-sized tokamaks (TCV, ASDEX-U, DIII-D). Experiments [2] show the presence of drift waves and rippling modes in the edge region of medium-sized tokamaks. Consequently, the RF scattering by periodic density interfaces (plasma gratings) is analyzed [1]. Here we represent the periodic density interfaces as a superposition of spatial modes with varying periodicity (comparable to the incident RF wavelength) but with random amplitudes. With ScaRF we calculate the power reflection coefficient (R). R is now a random variable whose uncertainty is quantified using the method of Polynomial Chaos Expansion (PCE) [3], in conjunction with the Smolyak sparse grid integration [4]. In Fig. 1, we plot the mean value (**MV**) and the standard deviation (**Std**) of R for 5 randomly selected amplitudes using ~ 50 calls of ScaRF per angle (orders of magnitude less than a direct Monte Carlo calculation).

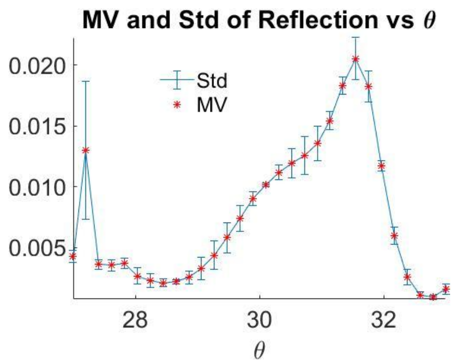

Figure 1: *MV & Std of Reflection as a function of the angle of incidence (θ) of the RF wave.*

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053.A.K.R. is supported by the US Department of Energy grant numbers DE-FG02-91ER-54109 and DE-FC02-01ER54648.

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Effective constitutive parameters of the turbulent tokamak plasma in the scrape-off layer with homogeneous distribution of filamentary structures

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It has been established both theoretically [1], [2] and experimentally [3], that radio frequency (RF) waves used for heating and/or current drive in a tokamak fusion device, can be severely affected by the filamentary structures (blobs) developed by turbulent density fluctuations at the scrape-off layer (SOL). The Gaussian beams that are launched from the antennas system at the edge of the device, are subjected to shape deformations, dissipation of their power and even misalignment of the predicted beam path due to their passage from the turbulent layer. One can facilitate the computation of such a behavior if the complex structured scrape-off layer is replaced by an equivalent layer with an effective dielectric tensor that on average can have the same effect on the propagating fields.

We attempt in this work to implement an effective medium description of the scrape-off layer incorporating the presence of blobs using the two-scale expansion, averaging methodology, that is commonly applied in many areas of physics and composite materials [4] as well as in the description of anisotropic electromagnetic media [5]. The corresponding technique is rigorous and is adapted to the requirements of the magnetized plasma in the SOL layer for frequencies spanning from tens of megahertz to hundreds of gigahertz. The distribution of the cylindrically elongated filamentary structures is considered homogeneous in order to use the periodicity conditions of the two-scale expansion scheme.

We describe and solve the corresponding cell problem, calculate the effective parameters and use the convergence conditions of the method to establish the range of validity. Comparisons are given with the recently developed generalization of the depolarization/Green function method [6] that gives also an effective medium description beyond the-long wavelength regime for the same medium configurations.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053 as well as from the National Programme for the Controlled Thermonuclear Fusion, Hellenic Republic. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Toward reliable non-linear gyrokinetic PIC simulations in stellarators with the code EUTERPE

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Particle-in-cell simulations of plasma turbulence have the important drawback that the numerical noise grows with the simulation time. This numerical noise is not critical for linear simulations; however, the quantification of physically relevant quantities in a turbulent state requires nonlinear simulations covering a simulation time beyond the non-linear saturation of linearly unstable modes and reaching a quasi-steady nonlinear regime in which statistical averages can be extracted. The noise accumulation not only reduces the accuracy of any measured quantity but it also makes difficult to reach quasi-steady conditions. A side effect of the numerical noise is the generation of a spurious unphysical contribution to the zonal flow component of the turbulent potential. This noise is known to grow due to the increase in the variance of the markers weights. A brute force solution consists of reducing it by increasing the number of markers, which, however, increases notably the computational cost and, furthermore, it still does not provide a quasi-steady state, but a slowly decaying one, instead. Smarter solutions have been proposed to mitigate this problem, such as the use of a Krook operator which introduces a long-time decay of the markers weights [1] compensating their intrinsic growth, or the use of coarse-graining techniques [2] and smoothing of the markers weights [3]. Both smoothing and the Krook operator were previously successfully implemented in the tokamak code ORB5 [4]. An ad hoc corrected Krook operator was also implemented which preserves the zonal flow residual close to the Rosenbluth-Hinton level. However, in stellarators, the linear evolution of zonal flows is more involved than in tokamaks [5,6,7] and implementing such a correction is more difficult. Weight smoothing and a simple Krook operator have been implemented in EUTERPE, a global code for stellarators. In this work, we present a detailed characterization of the effect of these tools for the control of numerical noise in global PIC simulations. We first study a tokamak configuration and compare linear and nonlinear simulations with ORB5 and EUTERPE using ideal profiles. Next, we study how these tools can improve the quality of the simulation and their effect over the zonal flow evolution in a set of linear and non-linear simulations in stellarator configurations. Both tools allow improving the simulation quality at the expense of affecting the zonal flow; however, the Krook operator is more effective to reach a quasi-steady state than the weight smoothing. Finally, we will present the application to a non-linear gyrokinetic simulation in a W7-X stellarator configuration.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Isotope Mass Impact on the Electromagnetic Stabilization of ITG

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One of the great challenge in the comprehension of plasma turbulent transport is the experimentally observed improvement of magnetic confinement as the isotope mass increases from hydrogen to deuterium, the so-called *isotope effect* [1]. Knowledge of the isotope mass impact on turbulent transport is necessary to properly extrapolate experimental results from actual devices, running mainly with deuterium, to future reactors such as ITER or DEMO that will operate with a mixture of deuterium and tritium.

We aim to clarify the role of the isotope mass on the stabilization of turbulence by electromagnetic effects. For that, we consider the stabilization of the Ion-Temperature-Gradient (ITG) by the plasma beta (ratio of the kinetic to magnetic pressure) which has been observed experimentally [2] and recently shown numerically to bear isotopic dependencies [3]. The fact that the isotope mass affects electromagnetic effects is not well documented yet since it has been only very recently identified [3].

We perform electromagnetic linear numerical simulations of ITG using the gyro-kinetic code GKW in the local approximation [4] varying the isotope mass and plasma beta values as well as other parameters such as the density and temperature gradient scale length, the magnetic shear or the safety factor. We numerically obtained the ITG growth rate as a function of the plasma-beta for different species as shown in *Figure 1* for helium (H), deuterium (D) and tritium (T). We chose to focus first on the direct impact of beta on $A_{\|}$ fluctuations. In these simulations the plasma beta was therefore varied keeping the pressure gradient and the magnetic equilibrium constant, and $B_{\|}$ fluctuations were neglected. To interpret the gyro-kinetic simulation results, we derived a simple model for the dispersion relation of a purely toroidal ITG. The model takes into account the kinetic response of main ions and electrons coupled to the quasi-neutrality and Ampère equation. In our derivation we neglect trapped electrons and assume that the current density is only driven by these electrons.

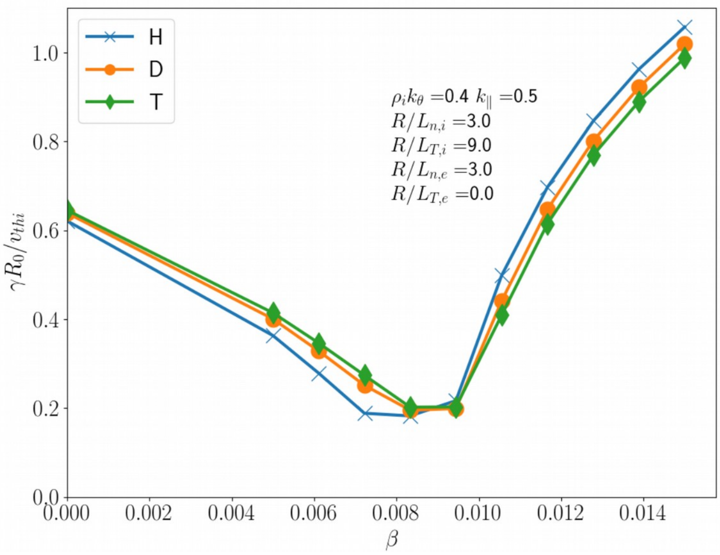

Figure 1: ITG growth rate as a function of the plasma beta β for the hydrogen (H), deuterium (D) and tritium (T). GKW simulations

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Kinetic Analysis of the Collisional Layer

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To understand plasma behaviour in the scrape-off layer (SOL), we need to know the boundary conditions for the plasma and electromagnetic fields near a divertor. At the boundary, in the direction perpendicular to the wall, there are four length scales of interest. These are the Debye length λ_D, the ion gyroradius ρ_i, the projection of the collisional mean free path in the direction normal to the wall $\lambda_{MFP}\sin\alpha \approx \lambda_{MFP}\alpha$ and the device size L. Assuming that the plasma near the divertor satisfies the scale separation $\lambda_D \ll \rho_i \ll \alpha\lambda_{MFP} \ll L$, we can split the plasma-wall boundary into three separate layers, the Debye sheath, the magnetic presheath and a collisional layer of width $\alpha\lambda_{MFP}$. Plasma dynamics in the magnetic presheath and the Debye sheath are well understood [1-3]. We will analyse the collisional layer. In the SOL at distances much greater than $\alpha\lambda_{MFP}$ from the wall, Braginskii fluid equations are used to model the plasma behaviour [4-7], that is, the ion and electron distribution functions are assumed to be close to Maxwellians. The collisional layer connects this region of high collisionality with the magnetic presheath where the ion distribution function is far from Maxwellian.

The ion gyro radius ρ_i satisfies the ordering $\rho_i \ll \alpha\lambda_{MFP}$, therefore the drift kinetic approximation can be used. We will use a continuous Galerkin method to solve the drift kinetic equation in one spatial dimension (direction perpendicular to the wall) with the full Fokker-Planck collision operator together with the quasineutrality equation and the assumption of adiabatic electrons. The drift kinetic approximation means that, to lowest order in $\rho_i/\alpha\lambda_{MFP}$, the distribution function f is independent of the gyrophase. As a result we can analytically integrate over the gyrophase in the Fokker-Planck collision operator. We use a quadratic finite element basis to approximate the logarithm of the distribution function f, thus ensuring positivity of f independent of the weights of the basis functions. Using this numerical model, we will discuss the boundary conditions that Braginskii fluid equations need.

This work was part funded by the RCUK Energy Programme [grant number EP/P012450/1]. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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The long-time behavior of electrostatic, collisionless plasmas

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We consider the long-time behaviour of collisionless plasmas described by the Vlasov equation with a Poisson electrostatic response and external forcing. Exploiting the natural timescale separation between the dynamics associated with the mean and fluctuating parts of the particle distribution of each species, we derive a Fokker-Planck-type equation for the long-time evolution of the mean. In the quasilinear approximation, an unforced system relaxes towards a universal class of steady-state equilibria of Lynden-Bell type [1] (similar to Fermi-Bose statistics), with the long-time asymptotic evolution governed by (a generalised version of) the effective collision integral derived by [2]. We show that the more general, nonlinear regime is also described by an effective collision integral, whose form depends on the correlation properties of plasma turbulence in time and in phase space. The theories of phase-space granulation [3,4] correspond to a particular set of assumptions about these correlations. We then examine the implications of the recent results on the suppression of phase mixing in plasma turbulence [5] for the long-term evolution of the mean distribution and the effective collisionality of a collisionless plasma.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under Grant Agreement No. 633053, and from the RCUK Energy Programme [Grant Number EP/P012450/1]. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Effect of a refined magnetic boundary on MHD modelling of helical self-organization in the RFP

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The reversed-field pinch (RFP) is a configuration for the magnetic confinement of fusion plasmas, in which most of the toroidal field is generated by the plasma itself through a self-organized dynamo process, instead of being produced by external coils as in the tokamak. In the RFP, the nonlinear saturation of resistive-kink/tearing modes brings to the spontaneous emergence of helical states with improved confinement. This is observed both in nonlinear magnetohydrodynamics (MHD) modelling [1] and in RFP experiments, especially at high current [2,3]. A major advance in the predictive capability of nonlinear MHD modelling for RFP plasmas was made possible by allowing helical perturbations of the radial magnetic field at the plasma boundary, as suggested by analytical calculations based on helical equilibrium equations [4]. A proper use of helical magnetic perturbations (MPs) in MHD modelling allowed to obtain experimental-like helical states [5] and to predict new helical states with chosen helical twist, successfully produced in RFX-mod [6].

Here, we describe a further refinement of the magnetic boundary modelling. We study the helical self-organization in the presence of a thin resistive shell at the plasma boundary r=a, surrounded by a vacuum layer and an ideal shell at r=b. The new magnetic boundary is implemented in the SpeCyl code [7] in a similar way as in Refs. [8,9]. Two main results are discussed. On the one hand, by varying the distance between the plasma and the ideal shell it is possible to provide a nonlinear estimate for the decrease of secondary modes by increased shell proximity to the plasma. This is of interest in view of the upgraded RFX-mod2 device (starting operation in 2021), in which the shell proximity will change from b/a=1.11 to b/a=1.04 [10]. Based on nonlinear MHD modelling, a factor of 2 reduction of the edge radial magnetic field is expected going from RFX-mod to RFX-mod2, with the beneficial consequence of a milder plasma-wall interaction. On the other hand, it is observed that with a proper choice for the resistive diffusion time of the thin shell at r=a, helical states do emerge in a spontaneous and systematic way, as in the experiment, without the need to impose a fixed helical MP. Finally, further extensions of the realistic boundary implementation, in order to take into account a double resistive shell and a feedback control system, will be discussed.

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Dynamic generation of velocity shear at the edge of plasma during NBI

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We examine the effects induced by the expansion of the orbits of trapped NBI-originated ions. At counter-injection about half of the new ions are lost [1], but we are interested in those that though are close to the edge, still remain inside the plasma. Each new trapped NBI generated ion has a transitory part of evolution before reaching its periodic motion on the banana orbit [2]. In this transitory part, which represents an expansion of the orbit, the outer half of the banana penetrates a narrow layer at the edge of the plasma. This represents a flow (which is equatorial by symmetry arguments) sustained by NBI, toward this layer. In the narrow layer of plasma, the new ions transfer momentum to the circulating electrons, generating a parallel current. This mechanism is similar to the bootstrap current mechanism [3], but does not necessarily involve the gradient of the density of the new NBI ions. By successive collisions, the new ion, with a very wide banana orbit (with the outer half inside the layer), loses energy and progressively returns to smaller radii deeper inside plasma, i.e. it becomes similar to the background ions. The outer half of its banana orbit leaves the narrow edge layer. The geometry of a banana trajectory does not conform to the geometry of the magnetic surface. The distribution function of trapped particles shows a variation with the θ angle, through a term of the form $\sqrt{\kappa^2 - sin^2(\theta/2)}$, where κ defines the orbit. It follows that the transfer of the momentum varies along the magnetic field line, having a maximum at the equatorial region and lower values in regions (symmetric with respect to the equatorial plane) where the banana departs from the line. The parallel current is therefore dependent on the distance along the line.

The line derivative of the parallel current is a source of vorticity, implicitly of the radial derivative of the poloidal velocity. The latter is the *shear* with an essential role in the control of instabilities. We will discuss the quantitative aspects of this physical picture.

This work was supported by the contract PN 19 15.

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Tokamak disruption prediction using different machine learning techniques

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Tokamak is a promising technology in attaining commercially viable fusion energy. However they suffer from disruptive events which cause lasting damage to the reactor. Disruption prevention is therefore key in the development of tokamaks. Disruptions can be averted using energy dissipating methods if they are predicted in advance. A very promising method to accurately predict disruptions is by using machine learning. In this work [1], a variety of different machine learning techniques have been tested to compare their performances. These include support vector machines (SVM), two-tiered SVM [2], random forest (RF) and long short-term memory (LSTM). A device-independent SVM model was also designed based on Tang et al (2016) [3]. Such models can be used across different tokamaks, and could therefore be used in the next generation of experimental reactors like ITER, for which no training data is available yet.

The different models were trained using data from JET, where the ITPA disruption database [4] was used to locate the disruptive events. The final performance results were very similar between the different methods. Performance across all models was also limited by a low temporal resolution of the input data and frequently missing data, so methods to combat this [5] would be very valuable. The RF model performed slightly better overall than the others, but had a significant bias towards minimizing the false alarm rate over minimising the miss rate. The two-tiered SVM had near identical performance to the standard SVM even though an improvement in performance was expected [2]. The LSTM model had slightly lower performance compared to the other models. This was also not the expected result, as this method is more suited for analysing time dependent data. However, this method does perform better when analysing performance on individual time steps, rather than overall predictive capabilities in a window of time. Potentially better performance could be attained through different implementations of the LSTM method, like a many-to-one systems.

The portable SVM predictor showed a significant loss in performance compared to its non-portable counterpart. This was expected due to a loss of information in converting the inputs to their portable counterparts.

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Kinetic Modeling of Runaway Generation in Argon-induced Disruptions in ASDEX Upgrade

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Disruptions in tokamak plasmas may lead to the formation of a strong current carried by relativistic so-called runaway electrons, which threatens to damage plasma-facing components. Massive material injection – increasing the collisional drag experienced by the electrons - is proposed for mitigating the problem. Current experimental data suggest that this mitigation scheme is effective in present tokamaks, but uncertainty remains regarding its effectiveness in future, larger ones, such as ITER. Numerical modeling of the electron dynamics helps to develop mitigation schemes for reactor scale devices. For this purpose, the relativistic finite-difference Fokker-Planck solver CODE [1] has been developed.

In the current work, we use CODE to investigate how injections of different quantities of argon affect the formation of a runaway electron beam. CODE includes a model for the reduced-screening effect of bound electrons of partially ionized impurities – an effect which has been shown to have a strong impact on the runaway electron dynamics [2]. We investigate how the final runaway current density is affected by the assimilation and change in ionization states of the argon atoms injected into the plasma. The most notable result is that the runaway current immediately after the current quench decreases with increasing amounts of assimilated argon.

To validate the results, we compare them with experimental data from ASDEX Upgrade and perform sensitivity scans in the most influential physics parameters (e.g. assimilation rate, ionization states). Comparisons are mainly made between measured and calculated plasma current.`

Our simulations and their comparison with the experimental runaway electron generation data suggest that including the interaction of relativistic electrons with partially ionized impurities is essential in order to accurately capture the dynamics of runaway electrons in present and future tokamaks, such as ITER.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Nuclear Fusion Reaction Process in Nonideal Plasmas

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The nuclear fusion reaction process [1] is investigated in partially ionized nonideal plasmas. The effective pseudopotential model taking into account the collective and plasma shielding effects [2] is applied to describe the interaction potential in nonideal plasmas. The analytic expressions of the Sommerfeld parameter, the fusion penetration factor, and the cross section for the nuclear fusion reaction in nonideal plasmas are obtained as functions of the nonideality parameter, Debye length, and relative kinetic energy. It is found that the Sommerfeld parameter is suppressed due to the influence of collective nonideal shielding. It is also found that the fusion penetration factors in nonideal plasmas represented by the pseudopotential model are always greater than those in ideal plasmas represented by the Debye-Hückel model. In addition, it is shown that the collective nonideal shielding effect on the fusion penetration factor decreases with an increase of the kinetic energy.

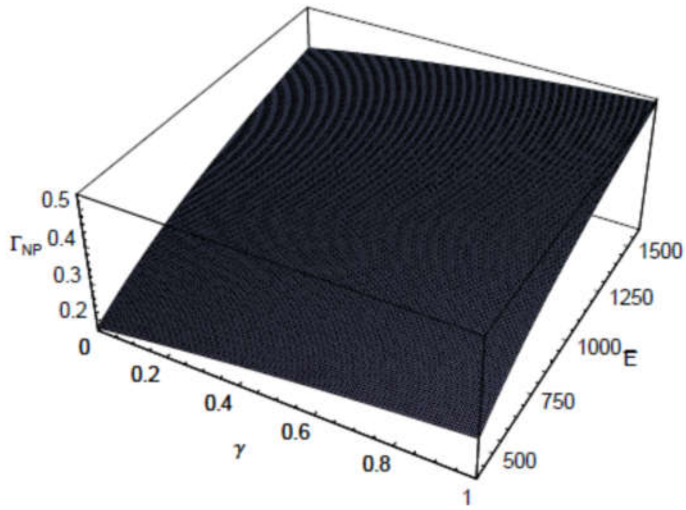

Figure 1: *The surface plot of the fusion penetration factor Γ_{NP} in nonideal plasmas as a function of the nonideality parameter γ and the scaled energy of the reactive motion $\overline{E}$ when $\overline{\lambda}_D = 10$.*

The work was supported by the National Research Foundation of Korea (NRF) (2019M1A7A1A03088471).

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Temperature screening of impurities in stellarators and tokamaks deviating from symmetry

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Quasisymmetric stellarator configurations aim to combine the stability of stellarators with the confinement of tokamaks, making them particularly interesting for optimization efforts. However, perfect quasisymmetry can only be achieved on a single flux surface at best, making it useful to study configurations with small deviations from perfect quasisymmetry, a regime in which devices will have to operate. A particular neoclassical phenomenon that occurs in tokamaks, which are naturally quasisymmetric, is a favorable outward radial flux of highly charged impurity ions, commonly referred to as impurity temperature screening. Conversely, stellarators generally display an *inward* impurity flux, causing an impurity accumulation in the core that can be detrimental to performance. In this work, we use the SFINCS drift-kinetic solver to explore how the impurity particle flux is influenced as the degree of symmetry-breaking is varied between realistic levels and perfect quasisymmetry, over various reactor-relevant parameter regimes and configurations. We aim to answer the question of exactly how much symmetry-breaking a particular configuration can tolerate before impurity temperature screening is lost.

Effect of up-down asymmetry on the plasma current

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Up-down asymmetric geometries enable turbulence to redistribute toroidal momentum in the radial direction [1]. The bulk toroidal rotation generated by this phenomenon can improve MHD stability, motivating recent work to optimise the magnetic geometry in order to maximise the plasma rotation [2]. However, the impact that this asymmetric turbulence has on the plasma current had not yet been studied.

To this end, we have coupled a δf local gyrokinetic code (STELLA [3]) and a neoclassical code (SFINCS [4]). Capturing the effect of turbulence on neoclassical transport requires second order terms in ρ_* [5] which are usually dropped in gyrokinetic codes. These terms are computed in STELLA and subsequently employed in SFINCS when measuring the plasma current. We show that the elongated asymmetric geometries found to maximize intrinsic rotation yield higher plasma currents than symmetric configurations. Nevertheless, the asymmetric turbulence produces a negligible effect on the current when compared to the total increment observed. The up-down asymmetric configuration also affects the balance of trapped and passing particles. Scans in elongation and elongation tilt suggest that the trapped particle population can be increased, yielding potential enhancements to the current of the order of 10% in originally symmetric geometries.

This work was part funded by the RCUK Energy Programme [grant number EP/P012450/1]. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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1D study of target particle flux dependencies with SOLPS-ITER

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Following the work presented in [1], we have studied aspects of detachment physics in a simplified 1D SOL geometry with the SOLPS-ITER code. Specifically, we have considered the change in the momentum and power lost along the domain when various reactions, such as charge exchange or elastic molecular collisions, are retained or excluded in EIRENE. These losses are characterised through f_{mom} and f_{pow} factors, typical of the two point model, with the impact on the particle flux to the target of most interest. We find good agreement with the interpretation presented in [2] to understand the onset temperature of the rollover in the flux. We have looked at the sensitivity of the results to choices of the wall boundary conditions, flux limiters and grid resolution.

An edge fluid model for the limit of strong collisional coupling between the plasma ions and neutrals through charge exchange was presented in [3]. We have formed analytic expressions from this model for the expected momentum loss along the domain and compared to the modelling results. A similar procedure was carried out in [4] for comparison to the simpler isothermal Self-Ewald model. We find that the two analytic models bound the values of f_{mom} obtained in the simulations, though the bounds are too widely separated to be predictive, as the simulation parameter regimes of interest do not satisfy well the restrictions of the models. Building on the model of [3], an expression for the particle flux to the target was given in [5], which captures the behaviour of the simulation results. The discrepancy appears to be due to the reduction of target temperature by energy transfer to the walls via the neutrals, which is a parameter in the model we fit to represent the kinetic neutral behaviour modelled with EIRENE. We have considered the change produced by altering the wall temperature.

This work has been funded by the RCUK Energy Programme [grant number EP/P012450/1].

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Decorrelation PDF Method for stochastic transport in strongly turbulent plasmas

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Energy and particle turbulent transport in magnetically confined plasma is one of the important problems in fusion research. In this context, test particle stochastic transport can evaluate the diffusion coefficients, provided that the characteristics of the turbulence are known.

The test particle motion is determined by the ExB drift which, being divergence-free, imposes two constrains: a) the invariance of the potential along trajectories and b) the statistical invariance of the Lagrangian velocities. A standard (semi-analytical) method to approximate the turbulent trajectories is the decorrelation trajectory method (DTM) [1]. While it is able to give good qualitative results regarding the transport coefficients and its trajectories obey the first constrain (a), it does not reproduce the statistical invariance of the velocities (b). Moreover, it predicts average periodic trajectories, which in reality must have a helical character.

For these reasons, we propose an extension of the method, capable to correct (at least partially) DTM's inaccuracies. The new method endows each DTM subensemble with internal structure. The PDF of the turbulent trajectories evolves in accordance with a convection-diffusion equation. The results are tested against Direct Numerical Simulations.

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Impact of Asymmetries and Anisotropy on Transport

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Large scale poloidal asymmetries of the plasma are inherent to tokamak configurations due to the in-out inhomogeneity of the magnetic field. It is well known that the ballooning character of turbulence and of the associated transport derives from them. Our recent results have unraveled new drives for these asymmetries and their subsequent critical impact on turbulent heat and neoclassical impurity transport in core plasmas. Interestingly, these discoveries confirm and highlight the multi-scale nature of transport. They have been permitted by the use of the flux-driven gyrokinetic GYSELA code [Grandgirard 2016], where fluctuations and equilibrium profiles are self-consistently solved on an equal footing, as well as turbulence and neoclassical physics [Donnel 2018].

The standard neoclassical predictions for impurity transport are strongly modified, both regarding magnitude and sign, when the impurity density exhibits poloidal asymmetries [Angioni 2014]. We have recently shown that turbulence can efficiently drive poloidal convective cells, which in turn contribute to generating density asymmetries of trace impurities when they follow a Boltzmann response [Esteve 2018, Donnel 2018]. Our new results push forward the dominant role of the asymmetry of the impurity pressure, coupled to its anisotropy (perpendicular vs. parallel): this synergy mostly controls the neoclassical flux of impurities in the banana-plateau and Pfirsch-Schlüter regimes, the former being relevant for ITER. We will show how both pressure asymmetry and anisotropy modify the neoclassical flux on the one hand, and detail the mechanisms by which turbulence is responsible for these effects. It turns out that, depending on the oscillating frequency of these features, they are driven either by transverse compressibility (high frequency) or the ballooned character of the Reynolds stress (low frequency). The former mechanism, also at the origin of geodesic acoustic modes, leads to up/down asymmetry, while the latter exhibits in/out asymmetry. GYSELA simulations show qualitative agreement with these analytical predictions. Both of these effects are signatures of the synergy between turbulent and neoclassical transports. Accounting for them reveals critical for any reliable prediction of core plasma pollution by impurities.

Besides, the consequences of both anisotropy and poloidal asymmetries on heat and momentum transport will also be discussed and quantified, partly with the help of artificial filters implemented in nonlinear simulations.

Effects of edge density fluctuations to ECCD used for NTM stabilization

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In this work we study the undesired effects of electron density fluctuations (turbulent structures such as blobs and filaments), which may exist in the edge region of tokamak plasmas [1], to the electron-cyclotron (EC) wave propagation and current drive (CD) [2], in connection to the efficiency of neoclassical tearing mode (NTM) stabilization [3]. Our model involves the evaluation of the ECCD in the presence of turbulent structures, by using a combination of a wave solver based on the generalized Electromagnetic Homogenization (gEMH) method [4] for the propagation part prior to and inside the region of these structures (where standard asymptotic propagation methods may not be valid due to the short-wavelength limit breakdown [5]), with a ray tracing code including island geometry effects and ECCD computation for the propagation past the turbulent region [6]. The computed ECCD is input to the modified Rutherford Equation (MRE) [7] in order to estimate the consequences of the wave deformation driven by density fluctuations to the NTM stabilization.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053.

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Test Particle Simulations for non-Maxwellian plasma transport: Discretized Collision Operator

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The strongly non-Maxwellian distribution is the key characteristic of plasma observed in modern fusion devices. The transition from Maxwellian to non-Maxwellian distribution takes place due to reconnection of the magnetic field lines followed by formation of either magnetic islands or magnetic stochastic layers. Besides that, the neutral beam injection (NBI) together with ion/electron cyclotron resonance frequency (ICRF/ECRF) heating induce the non-Maxwellian fast ions, which interact with bulk and thermal ions. These phenomena significantly modify the plasma parameters in general that is clearly observed on fusion device Tokamak JET [1, 2]. Many different numerical techniques to simulate such transition from Maxwellian to non-Maxwellian distribution are developed [3-5]. To obtain the comprehensive description of plasmas one should take care of plasma particles interaction, i.e. Coulomb collisions in non-Maxwellian environment. Hence, the approach describing the non-Maxwellian plasma relaxation through collisions should be introduced. That could be done via discretized collision operator developed for the test particle tracing approach. This operator was introduced in the paper [6] for the pitch-angle scattering and the energy slowing down and scattering. Later it was extended to different plasma species [7] and its validity to trace heavy impurities in fusion plasmas was shown in [8]. The significant limitation of this operator is the assumption that the distribution of bulk plasmas is isotropic Maxwellian.

The objective of our work is to extend the applicability of the discretized collision operator and to simulate self-collisional relaxation of non-Maxwellian fusion plasma with an arbitrary initial shape of distribution function. Starting from the Fokker-Planck collision operator, which includes Rosenbluth potentials, we derive new expressions for the discretized operator of a general Monte Carlo equivalent form in terms of expectation value and standard deviation including an arbitrary shape of distribution function for bulk plasma. The preliminary test of the operator was performed for simulation of fast ions relaxation on bulk ions with δ-function distribution [9]. To simulate self-collision relaxation of non-Maxwellian plasma the initial distribution functions for each test fraction are chosen of highly peaked shifted Gaussian shapes. The applicability of the presented collision operator to reproduce the time scale for fusion non-Maxwellian plasma relaxation is shown.

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Effects of poloidal flow on resistive wall mode in toroidally rotating plasmas

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Understanding and controlling the resistive wall mode (RWM) [1] is a key issue for the optimization of plasma pressure and improving the economic benefit of a potential fusion power plant. So far, most previous work on passive stabilization of the RWM only assumes toroidal plasma flow, neglecting any effects from the poloidal and/or parallel flow of the plasma. This is partially due to the fact that the poloidal flow is usually strongly damped in a tokamak device due to neoclassical effects [2]. On the other hand, recent experiments in JET (Joint European Torus) have shown that the poloidal flow velocity of the plasma can be one order of magnitude higher than the neoclassical prediction [3, 4].

Effects of parallel and poloidal flows, as well as the flow shear, on the RWM instability have been numerically investigated in toroidally rotating plasmas, utilizing a recently updated version of the MARS-F code [5]. A significant difference between these flows is that the background toroidal flow frequency is symmetric with respect to the poloidal angle, whilst both the poloidal and toroidal projections of the additional parallel flow are functions of both the plasma minor radius and poloidal angle.

It is found that the stability of the resistive wall mode is hardly modified by the parallel flow, as a consequence of cancellation of the stabilizing effect provided by the poloidal projection of the parallel flow from one side, and the destabilizing effect provided by the toroidal projection from the other side. The destabilizing effect of the toroidal projection comes predominantly from the m=1 poloidal Fourier harmonic of the flow contribution. The shear of the parallel flow is found to generally weaken the stabilization/destabilization effect on the RWM, as compared to the case of uniform parallel flow.

This work is supported by NSFC with Grant No. 11605046 and the Royal Society K. C. Wong International Fellowship. The work is also supported by U.S. DoE Office of Science under Contract Nos. DE-FG02–95ER54309 and DE-FC02–04ER54698. The project is also partly funded by the RCUK Energy Programme [grant number EP/P012450/1].

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Kinetic Infernal Modes for Wendelstein 7-X-like iota-profiles

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We show analytically that for ι-profiles similar to the one of the Wendelstein 7-X stellarator, where ι is the rotational transform of the equilibrium magnetic field, a highly conducting toroidal plasma is unstable to kinetically mediated pressure-driven long-wavelength reconnecting modes, of the infernal type [1-2-3]. The modes are destabilized either by the electron temperature gradient or by a small amount of current, depending on how far from unity is the average value of ι, which is assumed to be slowly varying. We argue that, for W7-X, a broad mode with toroidal and poloidal mode numbers (n,m)=(1,1) can be destabilized due to the strong geometric side-band coupling of the resonant kinetic electron response at locations where ι is rational for harmonics that belong to the mode family of the (n,m)=(1,1) mode itself. In many regimes, the growth rate is insensitive to the plasma density, thus it is likely to persist in high performance W7-X discharges. For a peaked electron temperature, with a maximum of $T_e = 5\,keV$, larger than the ion temperature, $T_i = 2.5\,keV$, and a density $n_0 = 10^{19} m^{-3}$ instability is found in regimes which show plasma sawtooth activity, with growth rates of the order of tens of kiloHertz. Frequencies are either electron diamagnetic or of the ideal magnetohydrodynamic type, but sub-Alfvenic. The kinetic infernal mode is thus a good candidate for the explanation of sawtooth oscillations in present-day stellarators and poses a new challenge to the problem of stellarator reactors optimization.

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A **Journal of Plasma Physics (JPP) student poster prize** competition is organized during the conference, open to MSc and PhD students. Two poster prizes will be awarded, in the form of a book prize kindly offered by the Journal of Plasma Physics.

If you have a poster contribution at the conference and you wish to enter the competition, please inform the Scientific Programme Committee or a member of the Local Organizing Committee before the start of your session.

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Social programme

Welcome reception

Monday, October 7, 2019
18:30 – 20:00
Conference venue (“Het Pand”),
Room “Kapittelzaal”

Guided walking tour “small stories”

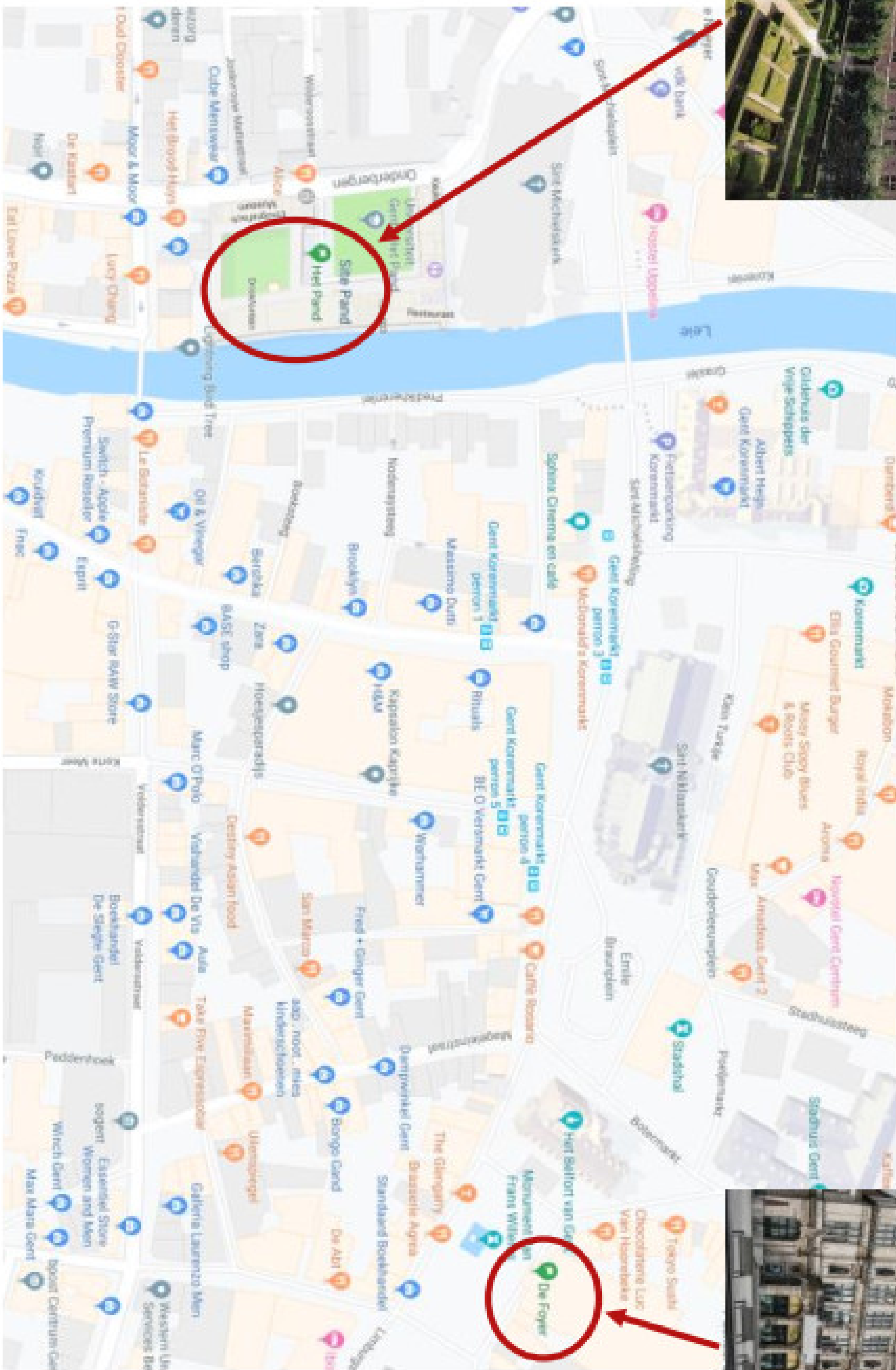
Wednesday, October 9, 2019
18:30 – 20:00
We meet outside the conference venue
at 18:20

Conference banquet

Wednesday, October 9, 2019
20:00 – 23:00
The walking tour ends at the restaurant, brasserie “De Foyer”, around 20:00.
Address: Sint-Baafsplein 17, 9000 Gent
Website: http://www.foyerntgent.be

Map

"Het Pand"
Conference venue



Brasserie "De Foyer"
Conference banquet

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Acknowledgements

Financial support from ITER Belgium is greatly acknowledged.

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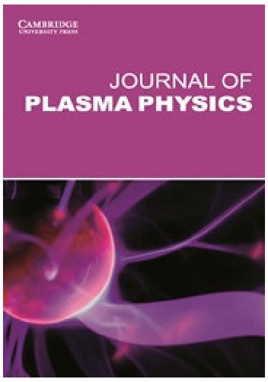
The Journal of Plasma Physics student poster prize has been kindly donated by the Journal of Plasma Physics.



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