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Impact of electromagnetic fluctuations on turbulent transport in the two-fluid drift-reduced Braginskii model

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Abstract. To understand the role EM fluctuations have on transport we performed a parameter scan in collisionality, heat source and beta, using the two-fluid flux-driven GBS code, which solves the drift-reduced two-fluid Braginskii model. Our results show that EM effects are vital for accurately describing edge turbulence. While transport is mainly due to electrostatic fluctuations, EM fluctuations significantly impact turbulence, especially in the drift-wave regime, enhancing particle confinement time by up to 1.8 times. Our simulation results are validated by an analytical scaling for the pressure gradient length in an EM-active drift-wave regime.

There has been some debate in the literature as to the importance of electromagnetic (EM) effects on turbulent transport in the boundary region of tokamak devices. In [1] for instance, the authors attribute the LH transition to an inherently EM phenomenon of turbulence suppression, while [2] found that EM effects have virtually no impact on edge turbulence, which for tokamak edge conditions are found to be dominated by ballooning mode and drift-wave turbulence. To assess the impact of EM fluctuations on edge turbulent transport we performed a parameter scan (collisionality, heat source and beta) using the two-fluid flux-driven code GBS, which solves the drift-reduced two-fluid Braginskii model. We found that, in general, EM effects are crucial to simulate turbulence in typical edge conditions. To correctly capture the dynamics it was vital to self-consistently model the nonlinear coupling between turbulence and the mean component of the perturbed magnetic potential, which was previously missed [2]. We observed that the transport is still predominantly due to electrostatic fluctuations, but that EM fluctuations can significantly impact turbulence, especially in the drift-wave regime. In fact, in conditions of low collisionality and steep pressure gradient, where turbulence is mostly dominated by drift-waves, EM fluctuations increased the particle confinement time by up to a factor of 1.8. It is known that the linear stability of drift-waves is impacted favourably by the presence of EM fluctuations [3], and we demonstrate that this suppression is strengthened by a nonlinear roll-down mechanism, leading to progressively lower growth rates. We validate our simulation results by deriving an analytical scaling for the pressure gradient length in an EM-active drift-wave regime.

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Turbulent transport reduction in negative triangularity tokamaks: non-local, finite size and collisional effects

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Understanding and controlling transport phenomena is notoriously one of the most challenging tasks in fusion plasmas: turbulent behavior accounts for the anomalous transport of heat, momentum, and particles in tokamak devices. One critical parameter affecting confinement performance is plasma shaping and in particular the triangularity δ. Negative triangularity ($\delta < 0$) configuration has gained significant interest in last decade since it has been shown, through intensive experimental campaigns (e.g. [1, 2, 3]), to increase the confinement time compared to the traditional positive triangularity configuration in L-mode operation.

Here, we address a systematic comparison between the transport levels in these two triangularities. To do so, we employ global gyrokinetic simulations performed with the ORB5 PIC code in both gradient-driven and flux-driven modes of operation.

Our findings reveal the significant influence of global effects in these simulations and that long-range phenomena, both in time and space, govern the turbulent dynamics. Significant avalanches, as well as the corrugation of profiles, do affect the simulation results. A local approximation of the heat flux would be incorrect in this case, and long averages in space and time have to be taken for a meaningful comparison. The data indicate a Hurst exponent larger than 0.5, suggesting a super-diffusive process hidden in the turbulence. Interestingly, this exponent does not converge to 0.5 (i.e. diffusive process) when the system size increases.

Our analysis sheds some light on the differences between positive and negative triangularity, and predicts that the relative improvement, $(\chi_{NT} - \chi_{PT})/\chi_{PT}$, is not limited to small machines. Our ρ^* scan shows that the relative improvement *does not* scale with the system size, at least up to the range we covered ($\rho^*_{min} = 1/350$). The simulations have been performed in a turbulent regime of interest: a mixed ITG-TEM regime. Given this context, collisional effects are likely significant and we evaluated their impact on the turbulence for both triangularities. Our observations align with Y. Camenen et al.'s [1] experimental work, which noted the stabilizing effect of collisions on the TEM, with consequent reduction of the difference in electron heat diffusivity between positive and negative triangularity. On the other hand, the ion heat flux does increase with collisionality, and the negative triangularity configuration maintains its advantage over the positive triangularity configuration.

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K-epsilon modelling of turbulent transport in the edge-SOL boundary layer

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Confinement performance remains a challenging issue for ITER and alternative projects of magnetically confined plasmas. Of particular importance is the boundary layer where one aims at securing both enhanced performance on the closed flux surface and lowered confinement on the open field lines in order to spread the heat outflux and reduce the peak heat load.
The K-epsilon models offers a means to address turbulent transport [1] by capitalising on the important simulation effort of plasma turbulence using a reduced model that can address key tasks such as scenario optimisation and uncertainty propagation.
To address turbulent transport in the boundary layer encompassing the edge, SOL and divertor plasma, one must determine regions that drive turbulence and those governed by spreading. For that purpose the growth rate used in the K-epsilon model must account for the stabilising and possibly destabilising effect of the electron current. Stepping from the linear analysis of the growth rate in Fourier space [2] to turbulent energy generation and damping is performed by selecting relevant wavevectors and therefore multiple K-epsilon couples of turbulent energy K and turbulent energy predator *epsilon* [3].
Analytical work on the K-epsilon model is completed by simulations of competing K-epsilon dynamics with simplified settings. Comparison to turbulent transport in the SOL is performed and first results in WEST geometry are presented.

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Boundary turbulence simulations of an induced H-mode RFX-mod discharge in the presence of edge biasing

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Abstract. The $\boldsymbol{E} \times \boldsymbol{B}$ flow shear is believed to play a key role in suppressing plasma turbulence in the edge of magnetic confinement fusion devices. Experimental observations show that the onset of edge transport barriers, and the subsequent transition to a high-confinement (H-mode) regime, is accompanied by the formation of an edge radial electric field [1]. Experiments carried out in RFX-mod, operating as a tokamak, have shown the possibility to access H-mode by inducing an edge radial electric field by means of an external polarized electrode, providing further and direct evidence of the impact of the radial electric field on edge turbulent transport [2]. In this work, a set of boundary turbulence simulations of a RFX-mod discharge [3] is performed by using the GBS code [4]. Turbulence simulations are carried out by applying different values of edge electric field through the presence of an external polarized electrode that has been recently implemented in GBS. By leveraging these simulations, we investigate here the direct impact of the induced edge radial electric field on turbulent transport as well as its role played on turbulence regime transitions, extending therefore previous works where such transitions have been obtained by varying the heating source and the plasma resistivity [5, 6]. GBS simulations performed at high density in the presence of an edge voltage biasing are leveraged to investigate the effect of an induced radial electric field on plasma turbulence in the proximity of the edge density limit transition caused by large turbulent transport [7]. Finally, the results of these simulations are exploited to inform the design of new boundary turbulence diagnostics [8], which will be installed in RFX-mod2.

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Non-linear saturation of non-resonant ideal long wavelength instabilities with application to sustained hybrid operational regimes and NTM seeding

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Abstract. A new theory is presented unifying the non-linear saturation of non-resonant $n = m = 1$ internal kink modes with reverse shear [1], and non-linearly saturated $n = m = 1$ quasi interchange modes with an extended region of very low shear [2]. The generalised set of equations also describes $n = m > 1$ modes [3] with arbitrary non-resonant q-profiles. By explicitly evaluating the non-linear effect of these modes to, and on, the magnetic flux, it is possible to analytically quantify the effect of the 3D magnetic structures on the q-profile. Over the initial phase of the resistively diffusing plasma scenario, the associated growing 3D magnetic perturbations are assumed to cause strong cross-field transport. Under these conditions the plasma will cease to resistively diffuse, and the modes cease to grow, so that the hybrid regime can in principle be sustained, thereby providing a simpler explanation than the magnetic flux pump model [4]. The picture remains robust to potential kinetic corrections of core instabilities in the weakly collisional regimes of future tokamak reactors. The non-linear equations presented here are also shown to agree with the expected non-linear saturated amplitude of current driven external kink modes [5], thus proving to encompass the salient physical properties of the most important long wavelength instabilities in near-axisymmetric machines. An important extension of this work is the linear and non-linear seeding and saturation of NTMs by core pressure driven modes, a risk always present for a plasma regime that relies on sustained long-living ideal perturbations.

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Theoretical and Computational Plasma Physics for Fusion Energy in Singapore

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Nanyang Technological University has launched an ambitious program aimed at bringing Singapore into the international community of magnetic fusion plasma science and engineering for clean energy. This program has got substantial funding from Temasek Holdings and the National Research Foundation. To catch up quickly, we have focused the project on Computational and Theoretical Plasmas physics for MCF and established a joint research center with the French CEA. Dr Xavier Garbet from CEA has been appointed as a full Professor at NTU to lead this program. The research topics rely on three pillars: large scale kinetic modeling of fusion plasmas and surrogate models for turbulence and instabilities, production of large data bases and use of data based and physics-informed deep learning to uncover transport features and improve the control of instabilities; and an experimental project to be carried out at the WEST Tokamak facility to diagnose runaway electrons. Produced during a disruption. I shall present the ongoing progress on these topics.

Reducing the intercoil forces by penalizing the vacuum energy

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Abstract. Being "three-dimensional", stellarators have the advantage that plasma currents are not essential for creating rotational-transform;[1] however, the external current-carrying coils in stellarators are usually not planar. Reducing the inter-coil electromagnetic forces acting on strongly shaped 3D coils while preserving the favorable properties of the "target" magnetic field is a design challenge. In this work, we recognize that the inter-coil $\mathbf{j} \times \mathbf{B}$ forces are the gradient of the vacuum magnetic energy, $E := \dfrac{1}{2\mu_0} \displaystyle\int_{R^3} B^2 \, dV$. We introduce an objective functional, $\mathcal{F} \equiv \varphi_2 + \omega E$, built on the usual quadratic flux on a prescribed "target surface", $\varphi_2 \equiv \displaystyle\int_{\mathcal{S}} (\mathbf{B} \cdot \mathbf{n})^2 \, dS$, and the vacuum energy, where ω is a "weight" penalty. The Euler-Lagrange equation for stationary states is derived, and numerical illustrations are computed using the SIMSOPT code.[2]

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Designing stellarators with a transport barrier

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Abstract. We draw attention to an interesting possibility in the design and operation of stellarator fusion reactors, which has hitherto been considered unrealistic under burning-plasma conditions [1]. Thanks to recent advances in stellarator optimisation theory, it appears possible to create a positive (outward-pointing) radial electric field in the plasma core by carefully tailoring the geometry of the magnetic field in such a way that shallowlly trapped particles are better confined than more deeply trapped ones [2]. A positive radial electric field is likely to expel highly charged impurities from the centre of the plasma through neoclassical transport and thus eliminate, or at least mitigate, a long-standing problem in stellarator physics. Further out, the electric field is predicted to suddenly change sign from positive to negative, thus creating a region of strongly sheared flow. The latter appears strong enough to locally suppress turbulent transport and could thus enhance overall energy confinement.

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A generalized Frenet frame for computing MHD equilibria

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Abstract. For the representation of axi-symmetric plasma configurations (tokamaks), it is natural to use cylindrical coordinates (R, ϕ, Z), where ϕ is an independent coordinate. The same cylindrical coordinates have also been widely used for representing 3D MHD equilibria of non-axisymmetric configurations (stellarators), with cross-sections, defined in (R, Z)-planes, that vary over ϕ.

Stellarator equilibria have been found, however, for which cylindrical coordinates are not at all a natural choice, for instance certain quasi-isodynamic stellarators obtained using the near-axis expansion (NAE) [1,2], defined by a magnetic axis curve and its Frenet frame. An example of such a configuration is depicted in Fig.1, showing highly shaped cross-sections if (R, Z)-planes are used, as opposed to simple ellipses when using the Frenet frame.

In this contribution, we propose to solve the 3D MHD equilibrium using an axis-following frame that we call a 'generalized Frenet frame'. We see two advantages: 1) the capability to easily represent configurations where the magnetic axis is highly non-planar or even knotted. 2) a reduction in the degrees of freedom needed for the geometry, enabling progress in optimization of these configurations.

The generalized Frenet frame is defined by the position of a closed curve (axis) and the normal and bi-normal vectors (N, B), as a function of the position along the curve. This definition circumvents some deficiencies of the Frenet frame, such as being undefined at points of zero curvature and the related sign flips that occur at such points. Furthermore, the generalized Frenet frame allows to effectively undo the twist of a conventional Frenet frame that comes about in cases of non-zero self-linking number.

In this work, we discuss the definition of the generalized Frenet frame, and details of the implementation of the new frame in the 3D MHD equilibrium solver GVEC [3]. Furthermore, we demonstrate for a highly shaped configuration that far fewer degrees of freedom are necessary to find a high quality equilibrium solution, compared to the solution computed in cylindrical coordinates.

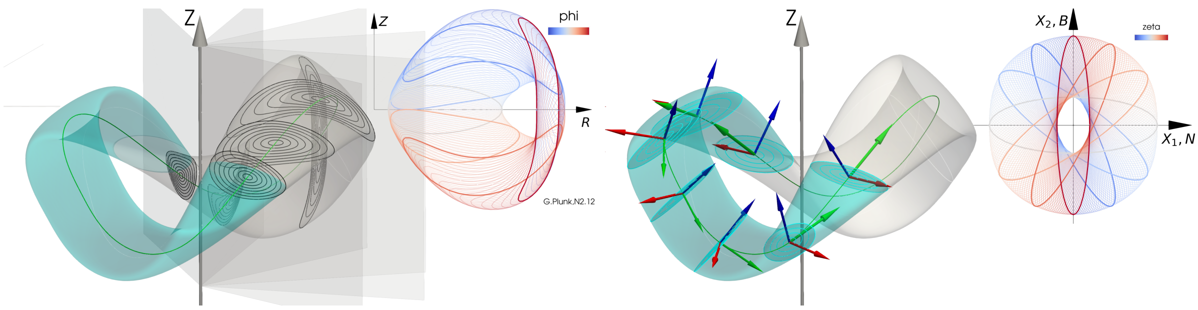

Figure 1: Two-field periodic QI-configuration from NAE. Left: (R, Z)-planes, with strongly-shaped cross-sections, Right: Frenet frame (N red, B blue) and elliptical cross-sections in (N, B)-planes.

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Modeling Upper Hybrid Waves for RF Heating and Current Drive Applications using Metaplectic Geometrical Optics

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Abstract. Ray tracing codes based on geometrical optics (GO) are widely used when designing diagnostics and heating and current drive systems. However, the WKB approximation underpinning GO theory breaks down at focal and turning points of rays, collectively known as caustics, where the field amplitude within GO diverges. Caustics are prolific in fusion plasmas and often occur in critical regions for mode coupling and potential non-linear wave interactions. This work presents results from a first-of-its kind unsupervised numerical implementation of the recently proposed metaplectic geometrical optics (MGO) theory. MGO [1] is a reduced wave modeling framework capable of reconstructing the electric field close to caustics where traditional WKB theory breaks down. We validate our 1D numerical implementation against exact analytical solutions to two simple equations in the form of Airy's and Weber's equation. In both cases we find good agreement between the MGO and exact solutions. Furthermore, we use the MGO code to model linear conversion between X-mode waves and electron Bernstein waves (EBW) at the upper hybrid (UH) layer of a gyrotron source relevant for EBW heating and current drive schemes [2]. There is a finite amplification at the UH layer where the ray turns and the XB mode conversion takes place. We find that MGO is capable of predicting this finite amplification whereas traditional WKB theory erroneously predicts an infinite amplification at the UH layer. Finally, we find good agreement between the MGO fields and results from fully kinetic particle-in-cell (PIC) simulations. Our results and the numerical implementation pave the way for further reduced modeling of nonlinear wave interactions such as parametric decay instabilities.

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Application of Lagrangian integration to the magnetic axis

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Abstract.
Lagrangian variational methods are applied to the magnetic axis of stellarator vacuum fields. The *magnetic fieldline action* [1] is given by $\mathcal{S}[\mathcal{C}] \equiv \oint_{\mathcal{C}} \mathbf{A}(\mathbf{x}) \cdot d\mathbf{l}$, where $\mathbf{A}(\mathbf{x})$ is a magnetic vector potential and $\mathcal{C}$ is a smooth, closed *trial curve*, which we represent as $\mathbf{x}(\zeta)$. For a given vector potential, the first variation resulting from a variation, $\delta\mathbf{x}$, in the trial curve is $\delta\mathcal{S} = \oint_{\mathcal{C}} \delta\mathbf{x} \cdot \mathbf{x}' \times \mathbf{B}\, d\zeta$, which shows that stationary curves are magnetic fieldlines, $\mathbf{x}' \times \mathbf{B} = 0$. The behavior of fieldlines *nearby* the magnetic axis are governed by the *second* variation of the action. By exploiting periodicity and using Floquet theory, the on-axis Floquet exponent is shown [2] to coincide with the on-axis rotational transform and an expression for the rotational transform is derived, which agrees with Mercier's [3]. Allowing for changes in the vector potential, the second *mixed* variation of the action determines the sensitivity of the geometry of the magnetic axis to variations in the magnetic field, and singular value decomposition can be used to identify the important "error fields" that drive deformations to the axis. The Lagrangian integration methods can be applied to any closed, periodic fieldline; including for example, the unstable periodic fieldline at the separatrix or at the island island divertor.

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Study of kinetic effects on MHD instabilities in cylindrical geometry using a spectral hybrid kinetic MHD code

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Abstract. Machine-scale instabilities in fusion devices must be avoided. They are well described and commonly studied using magnetohydrodynamics (MHD). Kinetic effects can significantly affect MHD instabilities through wave-particle interactions. Such perturbations of MHD-like modes can be studied using a hybrid kinetic MHD model, obtained by adding kinetic effects in the MHD description. Many previous efforts trying to estimate these kinetic effects using this hybrid approach rely on a semi-analytical solution of the drift-kinetic equation, which implies limitations on the type of orbits that can be studied. Alternatively, particle orbits can be time-stepped numerically. This does not necessarily require assumptions on the considered trajectories but significantly increases the numerical cost and usually restricts the types of instabilities that can be investigated. We use a recently developed hybrid kinetic MHD code that solves the model proposed by [1] using a spectral method. It is formed by extending the MHD momentum equation with moments from a drift-kinetic equation, the latter expressed in the Case-Van Kampen formalism [2]. The resulting equations can be written as a standard linear generalized eigenvalue problem. The associated eigenvector is composed of the MHD displacement as well as the kinetic correction to the perturbed distribution function. Kinetic effects on MHD-like modes in simplified cylindrical geometry are studied and specific limits are explored. Benchmarks against semi-analytical relations are presented.

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Advanced modelling of heavy impurity tokamak transport in rotating 3D magnetic fields with numerically resolved neoclassical equilibrium

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Abstract. Future tokamaks such as ITER are considering tungsten as the first-wall armour material. Accumulation of metallic impurities in the core plasma is a concern due to associated performance degradation [1]. Thus, core tungsten accumulation must be minimised which means that it is crucial to develop a theoretical and numerical framework to understand the transport processes for heavy impurities. Tokamaks are often heated with unbalanced neutral beam injection which induces rotation in the plasma. The associated rotation of the tungsten population is typically super-sonic. Another common feature of tokamaks is the existence of long-living non-axisymmetric magnetic fields, such as those due to long-living modes [2], edge harmonic oscillations (EHOs) [3, 4] and magnetic islands. We investigate the behaviour of impurities in the presence of EHOs and strong plasma rotation.

To trace the heavy impurities, we use a code called VENUS-LEVIS [5], an advanced guiding center code which computes the evolution of plasma charges in arbitrary 3D MHD equilibria. For accurate simulations, the interaction of tungsten with the background plasma needs to be considered. A custom Coulomb collision operator is used which relies on neoclassical transport coefficients of both impurities and main light ions. These coefficients can be obtained in various ways, e.g. analytically in ideal MHD equilibria [2, 6], or with the drift-kinetic solver SFINCS [7]. A new numerical method for calculating these coefficients has been developed using VENUS-LEVIS. This method is crucial for extending the transport code beyond ideal MHD, and we present it here for EHO applications.

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Hybrid kinetic-MHD model of RMP interaction with tokamak plasmas

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Abstract. In this report, we present results of a kinetic–MHD approach to the plasma response of resonant magnetic perturbations (RMPs) in tokamaks. Suppressing edge-localized modes (ELMs) with help of RMPs is an experimentally proven technique for the reduction of tokamak first wall damage by large, type-I ELMs. Linear and nonlinear modelling of the interaction of RMPs with tokamak plasma is presently developing on the basis of MHD and kinetic theory. The latter [1] accounts for kinetic effects like Landau damping and, most importantly, the finite Larmor radius effects which lead to dependence of RMP penetration on isotope contents of plasma ions and which are not properly accounted for in MHD models. Recent experiments on ELM suppression actually show strong dependence of ELM mitigation on isotope contents [2]. The present developments have been recently realised within the code MEPHIT [3, 4]. Via an iterative approach, the bulk plasma is described by the ideal MHD equations, but the resonant layers are treated using a kinetic approximation utilising the finite Larmor radius expansion up to second order. This order is already sufficient to qualitatively describe the isotope effects. The hybrid kinetic–MHD version is applied to ASDEX Upgrade and compared to the results of the ideal MHD code GPEC [5]. It is shown that in cases where shielding of perturbations by plasma response currents is strong, the results of these codes agree, as should be expected.

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