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ICRH modelling of DTT reduced-field plasma scenarii by full wave codes

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Abstract. An in-depth analysis [1,2] on Ion Cyclotron Resonance Heating (ICRH) absorption in the Divertor Tokamak Test (DTT) plasma has been performed over the years following the evolution of the machine parameters: i.e. magnetic field, major and minor radii, etc. and in agreement with the prescription of the transport codes regarding expected kinetic profiles [3]. The use of the ICRH in DTT even with plasma parameters at reduced toroidal magnetic field [4] has recently reopened the analysis and modelling of the ICRH also in this context in order to evaluate whether the antenna setup (frequency range, coupled spectra etc.) is compatible with the scenario planned in the first years of DTT operations, in particular that characterized by an external magnetic field of 3 T, and plasma current of 2 MA. To this end, the numerical codes, DISEMAG, and TORIC-SSFPQL have been extensively used for a parametric analysis: minority or majority heating, frequency, spectra (parallel wave number, power, etc.). In this work the results of this extensive parametric investigation are summarized and prescriptions are also given for the correct use of ICRH in order to maximize ion heating.

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ICRH modelling of DTT plasma scenario by 1D semi-analytical model

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Abstract. An in-depth study of the Ion Cyclotron (IC) wave equation, which perturbatively includes the anti-Hermitian component of the dielectric tensor, was conducted after a thorough evaluation of the Hermitian and anti-Hermitian parts of the dielectric tensor [1]. This analysis was done in the context of cold, warm (first-order Larmor Radius Approximation $k_{\perp}\rho_i << 1$ (FLRA)), and hot plasma (all orders in $k_{\perp}\rho_i$). An ordinary differential equation in Cartesian geometry (slab) was derived in the complex parameter domain. By making further simplifying assumptions about the spatial dependence of density and magnetic field (e.g. DTT minority heating scenario[2]), and considering that the anti-Hermitian part is small compared to the Hermitian one, three types of second-order ordinary differential equations for the electromagnetic field were obtained and analytically solved: i) Homogeneous, ii) Airy, and iii) Weber equations. In this work, the three analytical forms were analysed, validating one case with the full wave electromagnetic simulator COMSOL Multiphysics.

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Integral dielectric kernel approach to modelling radiofrequency heating in toroidal plasmas

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Abstract. The realistic full-wave modelling of Ion Cyclotron Resonance Heating (ICRH) in tokamaks and stellarators traditionally relies on Fourier expansions of the radiofrequency (RF) fields along the toroidal and the poloidal angle. This approach allows convenient theoretical treatment of wave dispersion effects along the curved equilibrium magnetic field and leads to mixed spectral-finite elements numerical formulations of the wave equation, in which the plasma is described by a dielectric tensor formulated in Fourier space.

Recent theoretical and numerical treatments such as [1-3] have sought to express the plasma RF response as a nonlocal integral operator formulated in configuration space. This approach promises major advantages: *(i)* enabling the use of finite element methods (FEM) - in 2 or 3 space dimensions - to model wave propagation and absorption in hot inhomogeneous fusion plasmas; *(ii)* allowing for local mesh refinements which were ruled out with spectral methods; *(iii)* allowing straightforward connection of the plasma model with advanced descriptions of the RF antennas, themselves based on the FEM.

We report on the ongoing implementation of this integral approach to study RF wave propagation and absorption in tokamak and stellarator plasmas. As stressed above, its novelty lies in the treatment of non-locality in physical space, which is not typical of FEM. The numerical treatment of the nonlocal kernels requires due care, since these new special functions are logarithmically singular. Taking a gradual approach to validate our methods, we are initially implementing the theory to lowest order in the Larmor radius to study experimentally relevant ICRH minority RF heating scenarios. Geometrical complexity and additional wave physics will progressively be included. We are seeking to exploit already available open-source FEM libraries and the associated meshing, solving and postprocessing tools as much as possible.

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Chaotic features of charged particle dynamics in asymptotic tokamak-like equilibrium profiles

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Abstract. We construct thermodynamical kinetic equilibria of a plasma column in the fusion regime, see [1]. Upon making plasma bulk arguments, a steep density profile and an effective potential energy with an unstable point at thermal energy are obtained like in [2]. Seeing the column as an asymptotically large torus, we "bend it back" by taking finite, very large aspect ratio tori and investigate ensuing chaotic particle trajectories. A numerical integration shows chaos emerging around the unstable point and breaking of the conventional adiabatic invariant.

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Gyrokinetic Electromagnetic Particle Simulations in Triangular Meshes with C1 Finite Element

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Abstract. The triangular mesh-based gyrokinetic scheme enables comprehensive axis-to-edge studies across the entire plasma volume. Our approach employs a triangular finite element with first-derivative continuity (C1) [1], building on the previous work [2,3,4] to facilitate gyrokinetic simulations. Additionally, we have adopted the mixed variable/pullback scheme [5,6] for gyrokinetic electromagnetic particle simulations. The filter-free treatment in the poloidal cross-section with triangular meshes introduces unique features and challenges compared to previous treatments using structured meshes [7]. Our implementation has been validated through benchmarks using ITPA-TAE parameters, showing its capability in moderate to small electron skin depth regimes. Additional examinations with experimental parameters confirm its applicability to realistic plasma conditions. Furthermore, we analyzed the phase space zonal structure of energetic particles (EPs) to highlight key features of EP transport in the constant of motion space [8,9], aiding in the prediction of burning plasma behaviors.

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Optimising for bounce-averaged quantities on a flux-surface

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Abstract. Here we present numerical routines for evaluating the bounce-average of any function on a magnetic flux surface, which allows for novel optimisation strategies for bounce-averaged quantities on the flux surface of a general stellarator. We shall focus on optimising for minimal bounce-averaged radial drift (related to neoclassical transport and omnigeneity) without specifying a symmetry class of the magnetic field. Similarly, we target bounce-averaged binormal drift, closely related to the maximum-$\mathcal{J}$ property that is important for trapped-electron-mode stability [1]. There is freedom in how one weighs the different trapped particle classes, and we investigate how this freedom affects the outcome of various optimisations. Overall, this exercise shows that bounce-averaged drifts can be directly targeted in optimisation routines, resulting in favourable transport properties. We finally prove various convergence properties of bounce-averaging operations (near magnetic maxima, for example), as these are important for numerical stability of the optimisation routines.

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Full-f gyrokinetic model for simulating turbulence in a linear plasma device based on the gyromoment approach

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Abstract. A gyrokinetic model for simulating turbulence in a linear plasma devices in the electrostatic limit is proposed and the challenges for its numerical implementation are discussed. The proposed model relies on an expansion of the ion distribution function on a orthogonal polynomial basis allowing for evolving distribution functions arbitrarily far away from a Maxwellian [1].

Building upon precious investigations of the drift-kinetic limit [2], and the δ-f limit [3, 4] of the gyromoment model, this work relies on a splitting of the distribution function and electrostatic potential in a large-scale, drift-kinetic, slowly-varying part and a small-scale, gyrokinetic, rapidly-varying part. The regimes of validity for this scheme is explored, and it is shown that a δ-f approach is retrieved in the limit where the drift-kinetic distribution function is a fixed Maxwellian, while a drift-reduced Braginskii model can be retrieved in the highly-collisional limit, neglecting the gyrokinetic part of the distribution function. The model is finally expanded on a Hermite-Laguerre polynomial basis, giving rise to a coupled equation for the expansion coefficients denoted as gyromoments (GMs) associated with the gyrokinetic part of the distribution function, and drift-kinetic GMs associated with the drift-kinetic part of the distribution function. The closure problems of such a scheme are discussed. Finally, the initial steps in the numerical implementation of this model in a linear plasma device are presented along with an advised numerical scheme for evolving the system.

Linear plasma devices such as LAPD [5] or RAID [6] offer an ideal test bed for studying turbulence and are the ideal starting point when developing codes for studying plasma turbulence. Due to the absence of magnetic curvature and sheer, an electrostatic gyrokinetic model significantly simplifies, however, turbulence is still an inherent feature of these devices giving rise to interesting analyses and conclusions.

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Solution space and effective model for plasma turbulent transport

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Abstract. We discuss an effective transport model of magnetized turbulent plasma based on first-principle gyrokinetic simulations. If the time evolution of dynamical systems can be regarded as solution trajectories in theoretical phase space, physical phenomena in saturated stable phase are realized in the *solution space* formed by these trajectories in the long time limit. The *renormalized trajectory* in quantum field theory, for example, is a kind of the solution space in infra-red low energy limit formed by the solutions of the renormalization group equation [1], and the space can be understood as an effective theory of the fundamental theory. Therefore, if the solutions effectively form a finite-dimensional solution space, the physical system can generally be represented in reduced form [2]. Here, we try to apply the above discussion to develop a transport model of turbulent plasma in first-principle gyrokinetic simulations. Based on the reduced transport model [3, 4, 5], the solution space due to the trajectory of the simulation can be represented by a certain functional form [6]. The obtained solution space is, of course, given in the effective functional form containing some errors. By evaluating the errors in a parameter space redefined by the coefficients and other parameters employed in the model functions, we determine a plausible functional form and construct an effective transport model.

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Energy flux balance in the 6D kinetic description of plasmas with adiabatic electrons

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This contribution showcases an innovative description of the particle and energy fluxes the 6D kinetic Vlasov system. Previous research [3, 4] has demonstrated that the fully kinetic system displays behaviors beyond gyrokinetics in scenarios with large density and temperature gradients, akin to the edge of a tokamak during transition phases.
To make sense of these findings, it is crucial to understand the particle and the energy flows within the 6D kinetic system. We introduce a novel method for calculating particle and density transport, enabling the determination of the fluxes directly from other moments of the distribution function. This approach offers significant advantages, allowing us to discern various contributions to the energy flux. Consequently, we can pinpoint both the gyrokinetic $\boldsymbol{E} \times \boldsymbol{B}$ heat flux and additional non-gyrokinetic contributions. Furthermore, this novel description reduces the gyro-oscillations inherently present in the energy and particle flux [6]
With the increased computational capabilities in recent years, it has become possible to simulate increasingly complex and accurate physical models. Gyrokinetic theory was introduced in the 1960s and 1970s to describe plasmas with more accuracy than with fluid models, while eliminating the complexity of the fast gyration of the particles around magnetic field in 6D kinetic models. Although current gyrokinetic simulations show fair agreement with experimental results in core physics, crucial assumptions made in the derivation make it unreliable in regimes with higher fluctuations and stronger gradients, such as the tokamak edge.
We have developed an advanced and scalable semi-Lagrangian solver tailored for the 6D kinetic Vlasov system. This solver incorporates a highly efficient scheme to address the $\boldsymbol{v} \times \boldsymbol{B}$ acceleration resulting from the strong background magnetic field [1, 2]. This allows us to simulate the excitation of plasma waves and turbulence with frequencies extending beyond the cyclotron frequency, without being limited by gradient strength or fluctuation levels [3]. The solver has undergone rigorous testing in the low-frequency regime, consistently providing accurate results for dispersion relations and energy fluxes in both linear and non-linear scenarios [5]. Having a tool that captures the full 6D distribution function allows us to compute all velocity moments directly. This enables us to confirm the analytical description of the energy and particle flux and demonstrate the differences in energy fluxes between gyrokinetic and non-gyrokinetic simulations.

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Progress in modeling low n pressure driven modes in W7-AS and W7-X

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Abstract.

Low n pressure driven modes enforce an operational limit on future stellarator designs, typically prescribed by the Mercier stability criterion. This is because the triggered nonlinear MHD activity is considered to lead to an intolerable degradation in confinement. At the same time, past experimental evidence suggests that stellarators can be nonlinearly robust against pressure driven MHD activity [2]. The extent to which this experimental observation applies to current and future optimised stellarator configurations is unclear. For this reason, it is important to establish a detailed understanding of when soft MHD activity can be expected, such that the operational space of such devices can be extended to reach higher reactor performance.

The following contribution aims to apply the recently implemented stellarator capable nonlinear MHD model in JOREK [3] towards understanding these modes. Three separate cases are considered. First, building on previous work [4], experimental reconstructions of finite β W7-AS discharges at intermediate β are studied in order to determine if the experimentally observed $(2,1)$ mode can be reproduced numerically. In particular, it is tested whether the introduction of a background $\mathbf{E}\times\mathbf{B}$ flow will modify the dominant nonlinearly saturated mode. A second case is then considered, based on prior linear MHD analysis during the design of the W7-X operational space [5]. A low ι, high mirror W7-X-like configuration unstable to an ideal $(m,n)=(3,2)$ interchange mode is studied. The nonlinear dynamics are quantified in order to determine whether this mode will lead to a core crash according to the single temperature MHD fluid model. Finally, preliminary analysis of the UFM (low ι, very large mirror) W7-X configuration, intended for study in experimental campaigns OP2.2 and OP2.3, will be presented in an attempt to inform future experimental studies.

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A coarse-grained model for critical ion temperature gradients in general toroidal geometry

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Abstract. We present an improved model to predict the critical gradient that determines the linear onset of the ion temperature gradient (ITG) mode in general magnetic geometry. The onset of the well-known slab and toroidal branches of the ITG mode play central roles in this model, which combines the effects of parallel Landau damping, finite-Larmor-radius (FLR) stabilization, and phase mixing as a result of magnetic field line curvature. The model is leveraged via numerical optimization to find a quasi-helically-symmetric stellarator with an unusally large ITG threshold, basic MHD stability, and a smaller number of field periods than a previously published result.

Interaction of turbulence, Alfvén modes and zonal structures in Tokamak plasmas

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Abstract. The nature of turbulent transport in burning plasmas and its effects on energetic particle confinement, present a challenging open question for future reactors. Moreover, the presence of global, MHD-like, modes may have an effect on turbulence, in particular through coupling via zonal structures. Burning plasmas are characterized by fast ions born in fusion reactions. Alternatively, neutral beam injectors (NBI) can be used to introduce fast ions directly into the plasma. Gradients in the fast ion distribution can drive Alfvénic instabilities such as toroidal Alfvén eigenmodes (TAEs). Typically, these are low toroidal number ('n') modes that can have a radial extent over the whole plasma domain. On the other hand, drift waves, which are ubiquitous in tokamak plasmas, are driven by high 'n' modes, such as ion temperature gradient (ITG) or trapped electron modes (TEM). Both these low and high n types of instabilities are known to generate zonal structures, either in real or phase space, thus allowing for a possible nonlinear coupling channel. In addition, recent work suggests that a drift wave can disperse a TAE by generating (through direct nonlinear wave-wave coupling) short-wave kinetic Alfvén waves (KAWs), which are subsequently Landau damped.[2]

Herein, we present an investigation of the nonlinear interplay between Alfvén eigenmodes driven by fast ions, self-generated zonal flows, and the onset of turbulence due to micro-instabilities. We use ORB5 [1], a gyrokinetic, particle in cell (PIC) code, to perform global electromagnetic simulations of both circular (Cyclone Base Case [3] (CBC)) and shaped (TCV) magnetic equilibria. We study the low-n Alfvén and the high-n ITG spectra. The Alfvénic instabilities are induced by a small fraction of fast ions introduced as a third species into the system. We linearly and non-linearly investigate the effects of zonal flows, system size, density gradient profiles, and the ratio of Alven to thermal speed, on the fast ion drive. We identify the instability thresholds and characterize the resulting Alfvén eigenmodes. In addition, we explore the effects of self-generated zonal flows on the growth rates and saturation levels of an electromagnetic ITG in a CBC. Finally, we investigate the nonlinear coupling between the ITG and the Alfvén eigenmodes (AE) with and without zonal flows.

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Measurement of three-wave coupling between Alfvén modes and a zero-frequency fluctuation in the JET tokamak

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Abstract. We report on the first experimental confirmation of a zero-frequency fluctuation that is pumped by an Alfvén mode in a magnetically-confined plasma. Alfvén modes can be destabilized by energetic particles issued from auxiliary heating schemes, or by fusion born-alpha particles in a burning plasma. Alfvén eigenmodes have traditionally been regarded as detrimental to plasma confinement because they can give rise to strong transport of the energetic particles [Heidbrink PoP 2020]. Recent theoretical advances [Chen PRL 2012, Qiu Pop 2016] and numerical simulations [Biancalani PPCF 2021, Mazzi Nat Phys 2022] have suggested that unstable Alfvén eigenmodes can have a stabilizing effect on the background turbulence by generating a zero-frequency zonal flow. To date, the coupling of a zonal-flow component to the Alfvén eigenmodes lacks experimental demonstration, and is the object of this presentation. In the experiment in the JET tokamak, a trace minority of 3He ions accelerated to MeV energies are shown to destabilize core-localized Alfvén modes. Most of the heating is ultimately absorbed by the thermal electrons as the 3He ions slow down. Despite negligible direct heating of the thermal ions, the thermal-ion temperature is shown to increase and equalize the electron temperature when Alfvén modes are observed, as is the ion temperature gradient and the L-mode confinement factor $H_{89,P}$. Bicoherence analysis of the Doppler-backscattered signal shows that Alfvén modes of frequency inside the toroidicity-induced-gap (and its harmonics) exhibit nonlinear three-wave coupling interactions with a zero-frequency fluctuation. We will show how the coupling between Alfvénic and a zero-frequency zonal mode is reproduced by direct nonlinear gyrokinetic simulations using the CGYRO code. The overall confinement improvement suggests a stabilizing effect of the turbulence by the zero-frequency zonal mode, which can balance the deleterious energetic particle transport driven by the Alfvén mode.