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Electron transport model applied for STEP reactor prediction

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Abstract. Spherical tokamaks appear to have several practical advantages (compactness, low magnetic field, stability for plasma and so on) with respect to the traditional tokamaks and for this reason have attracted attention and generated strong interest in recent years. This interest led to the construction of different spherical tokamaks such as NSTX, MAST, MAST-U and most recently to the development of the STEP project in which a reactor concept with major radius \( R=3.6 \) and an aspect ratio \( A=1.8 \) is assessing. STEP is designed to operate in a fully non-inductive regime and to generate a net electricity starting from a fusion power \( P_f \sim 1.5 \) GW.

The design of the reactor can rely on the experience gained from the existing compact spherical tokamaks that have shown how the problems and challenges differ from those in conventional tokamaks.

Concerning this, one of the most important challenges is to understand the anomalous electron transport observed in spherical machines [1] and that can have a big impact on the STEP design. A relevant mechanism responsible for the electron transport seems to be the microtearing instability that, due to the lower magnetic field value in a spherical tokamak, saturates at high amplitude values [2]. This instability can conduct to a global stochastic behaviour of the magnetic field lines with a strong impact on particles and heat transport. It is important to note that there is no existing exhaustive theory able to describe the turbulent diffusion of plasma in a stochastic magnetic field. However, the electron thermal conductivity \( \chi_e \) in the presence of a stochastic magnetic field can be predicted on the basis of a basic model developed by Rechester and Rosenbluth (RR) [3]. This model assumes that decorrelation effects are due to the stochastic instabilities and not to the collision of particles whose random walk plays the role of a seed diffusion. Consequently, the transverse diffusion coefficient is related to a magnetic diffusion and to a longitudinal correlation length \( L \).

The RR model has been implemented in the integrated modelling JINTRAC tool and tested together with TGLF transport code in order to predict the electron thermal conductivity \( \chi_e \) in MAST and STEP. Thus, by using selected MAST shot cases we have calibrated the model and we have investigated various possible configurations of the STEP flat-top scenario. Moreover, by taking into account effects of temperature and density length scales, we have studied various stochastic regimes with different models for \( L \). In particular, we have focused attention on effects related to the Kadomtsev and Pogutse assumption [4]. This latter differs from that of the RR model for the importance given to the collisional diffusion in determining the decorrelation distance travelled by a particle between two magnetic field lines.

References
Saturation mechanisms of core micro-tearing modes in spherical tokamaks

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Abstract. Spherical tokamaks (STs) have shown improved confinement at lower electron collisionalities $\nu_{ee}$ such that the product of magnetic field and energy confinement time, $B\tau_E$, is proportional to $\nu_{ee}^{-0.67}$ on NSTX [1] and $\nu_{ee}^{-0.82}$ for MAST [2]. Micro-tearing modes (MTMs) potentially explain this behaviour, with linear gyrokinetic simulations finding these modes in both MAST [2] and NSTX [3], as well as future reactor relevant STs such as STEP [4]. However, converged nonlinear simulations with MTMs are notoriously difficult to achieve [5], with nonlinear STEP relevant simulations not saturating when using the CGYRO gyrokinetic code [6]. Recent nonlinear simulations for the NSTX case using CGYRO could only achieve saturation when ExB shear was included: without this the heat flux is seen to “blow up”. In STEP-like simulations, a similar blow up is seen, however the MTMs found here were not stabilised by ExB shear, and therefore it was not possible to obtain saturated results. Unstable MTMs that are entirely robust to ExB shear have been found in a MAST equilibrium: nonlinear simulations for this case saturate at modest amplitudes, with a strong zonal component. Miller local equilibrium parameters were individually varied to match the local parameter values for STEP. This study revealed that saturation was sensitive to the radial derivative of the Shafranov shift. Changing this parameter to its large STEP value, resulted in considerably higher fluxes, where the large zonal component is not seen. Higher magnetic shear in the NSTX case, is found to be responsible for the class of MTMs which are susceptible to ExB shear stabilisation. Specifically, it was how the magnetic shear impacted Ampere’s Law. With this knowledge it was possible to determine a metric from geometric quantities alone to determine when an MTM can be stabilised by ExB shear.

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References
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Abstract. Fluid models are yet the workhorse for plasma edge turbulence simulations (e.g. [1], [2], [3]). Whereas they are computationally less intense than kinetic edge codes (e.g. [4], [5]), they come with certain limitations in their predictive capabilities. Important effects that are not contained in fluid models are primarily kinetic effects due to the missing velocity space.

The heat flux is most susceptible to kinetic effects in fluid models, e.g. Landau damping, as it represents usually the highest order fluid moment. Fluid models are mostly based on collisional closures (e.g. Braginskii) using the Spitzer-Härm [6] expression for the parallel heat conductivity. Towards lower collisionalities, that can already be present in the near SOL of present day experiments, the Spitzer-Härm formula vastly overestimates the parallel heat conductivity. A common method to deal with this issue is to introduce ad-hoc artificial limiters, based e.g. on a harmonic average of the collisional and free-streaming heat flux [7]. But these limiters need to be tuned by comparing either with an experiment or with gyrokinetic simulations.

An approach to introduce Landau damping ab-initio into fluid models is given in [8]. This approach is formulated solely in k-space and is therefore not well suited for computer codes that act in configuration space. A method to translate this approach into configuration space is presented in [9].

In this work the Landau-fluid closure is implemented into the edge plasma turbulence code GRILLIX [2]. Theoretically this requires solving an infinite set of elliptic problems along magnetic field lines. In practice a closed set of elliptic equations is obtained by truncation at a reasonable order. Simulations in an Alcator C-Mod like setup are performed to compare the Landau-fluid closure with the Braginskii closure and with the above mentioned heat-flux-limited model. The aim is to find out whether this model is capable of predicting the parallel heat conductivity self-consistently and to investigate if non-local effects of the Landau-fluid closure can be seen in the turbulence simulation. Finally, the performance of the Landau-fluid closure in comparison to the other heat flux models is assessed.

References
Abstract. Magnetic divertors are a common feature of present-day tokamak experiments. For these configurations, the last closed flux surface is a magnetic separatrix with, typically, either one (single-null) or two (double-null) X-point(s). These are points on the plasma poloidal cross-section, or magnetic field-lines when viewed in three dimensions, where the poloidal magnetic field vanishes, and the confining magnetic field is purely toroidal. Vertical displacements, on the other hand, are axisymmetric perturbations with toroidal mode number $n = 0$. Therefore, a vertical displacement is resonant at the X-point(s) of a magnetic divertor configuration, in the sense that this perturbation, regardless of its poloidal modulation, is constant along the toroidal field-line going through the X-point. Mathematically, the resonance condition is represented by the criterion $B_{eq} \cdot \nabla \chi = 0$, where $\chi$ is a generic axisymmetric perturbation and $B_{eq}$ the equilibrium magnetic field. Because of the X-point resonance, axisymmetric current sheets localized along the separatrix are likely to form. This process, which leads to current sheet formation in the proximity of magnetic X-points, has been studied in the context of astrophysical plasmas, as well as in connection with fundamental laboratory plasma experiments, and is well known to researchers working in magnetic fusion. However, as far as we are aware, Refs. [1, 2] are the first articles where the resonant interaction between modes and the X-point(s) of a magnetic divertor configuration was addressed analytically within the framework of a tokamak plasma. Current sheets are observed in numerical simulations of the vertical instability in tokamaks, with advanced numerical codes that can correctly treat the X-point geometry, such as M3D-C$^1$, NIMROD and JOREK [3]. However, analytic understanding of why these current sheets form, and more importantly, the impact they have on the stability of vertical displacements, was not clarified in those numerical works. The main result of Refs. [1, 2] is that current sheets that form along the tokamak divertor separatrix can suppress the vertical instability on the ideal-MHD time scale, thus providing effective passive stabilization of these modes, even in the absence of a nearby wall and/or ad hoc plasma facing components. The purpose of this presentation is to review the work of Refs. [1, 2], and to provide additional insight on the mechanism leading to the ideal-MHD stabilization of vertical modes associated with the X-point resonance. We will also briefly discuss the possibility that vertical displacements, oscillating at about the poloidal Alfvén, and weakly damped by wall resistivity, can be driven unstable by the resonant interaction with energetic ions, as reported in Ref. [4] and observed experimentally on JET [5].

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Generalized Multi-Temperature Zhdanov Closure for Scrape-Off Layer/Edge Applications

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Abstract. The challenge of power exhaust is a key area of research in next step fusion devices, particularly tokamaks. Reducing the peak heat fluxes on the plasma facing components to tolerable levels, relies on impurity radiation in the boundary layer of the tokamak to a large extent. The impurity radiation pattern in turn depends on parallel and perpendicular plasma transport. This problem is generally addressed by solving 2D plasma fluid models coupled to kinetic neutrals (e.g. with the Soledge3x-EIRENE, SOLPS code packages). One such model is a closed set of fluid equations for a collisional plasma derived from taking moments of the Boltzmann collision operator for a multi-species plasma, i.e. electrons, main ions, and impurities in multiple charge states, along the lines given by Zhdanov et al\cite{1}. In fact, a number of versions of this closure have been implemented in B2/SOLPS, EDGE2D, Soledge3x-EIRENE, and GBS. The thus-named Zhdanov closure prescribes the friction and thermal forces, and the viscous-stress tensor of each species, however it does so assuming that the temperatures of all colliding species are near each other. Among the aforementioned code, Soledge3x solves an energy equation of each species, permitting the temperatures of each species to differ. In order to address this, we generalize the Zhdanov closure for the multi-temperature case, by first deriving and providing a general derivation method for the multi-temperature collisional coefficients\cite{2, 3}, identifying the assumptions behind the closure, and verifying the formulae in Ref.\cite{1} in the process, providing ranges of validity for it\cite{4}. We find that the single-temperature coefficients are generally valid for small temperature differences (∼ 10%) for multi-species plasmas with ions of comparable mass like deuterium-tritium plasmas and for heavy ions such as tungsten in trace density levels. However, for light impurities like argon and neon, significant differences are found to persist between the single-temperature and multi-temperature Zhdanov closure for values of transport coefficients (up to 80%) and friction/thermal forces very different (up to 40%) even for small temperature differences. These key results, along with a general overview of the Zhdanov closure and its assumptions, will be presented in this contribution.

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Simulation of radio-frequency heating and fast-ion generation in Wendelstein 7-X

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Abstract. Modelling of radio-frequency (RF) heating and fast-ion generation using the SCENIC code package\cite{Jucker2010} shows that fast-ion wall loads will not be a danger in the upcoming experimental campaign of Wendelstein 7-X (W7-X). This next scientific operation phase is scheduled to begin in late autumn of 2022 and will, for the first time, include experiments in which the ICRH (ion-cyclotron-resonance heating) antenna will be used.

The two purposes of this system are to heat the plasma, but also to generate fast ions. Therefore this system offers a new way to assess fast-ion confinement which is important for studying the reactor relevance of W7-X. The first plasmas that will be used for the upcoming ICRH operation will be Helium-4 plasmas with a small Hydrogen minority on the order of about 10%. Plasmas of such a composition typically offer good power absorption in tokamaks and are thus considered a safe way for gaining first experiences with the new antenna in W7-X.

This assessment is confirmed by the SCENIC simulations carried out in this contribution that use realistic profiles foreseen for the upcoming campaign as input. The usage of more realistic profiles is one of the main differences compared with earlier works (e.g.\cite{Faustin2017,Machielsen2021}) and is of course only possible now that experimental experience has become available at W7-X.

The simulations are carried out in the standard configuration of W7-X in low-beta ($\langle \beta \rangle \lesssim 1\%$) plasmas. However, also scans over minority concentration and background-plasma density, taking into account the range expected experimentally, are performed. We find that the power absorbed by the Hydrogen minority directly from the RF wave is typically (provided that the minority concentration is not too high) on the order of about 90\% with the rest going to the electrons. Very little power goes to the Helium-4 ions. With the regular minority heating scheme only fast-ion energies up to about $E \approx 50$ keV can be reached. The so-called 3-ion scheme or neutral-beam-assisted schemes are known to perform much better in this respect\cite{Kazakov2015, Hirvijoki2014}.

SCENIC only models the energetic particles up to the last-closed flux surface. In order to ensure the safe ICRH operation, data of particles leaving the plasma during the simulation is recorded. This data is used in a second step which uses ASCOT\cite{Hirvijoki2014} to follow particles drawn from the pre-computed distribution of lost particles to the 3D wall. The results show that the wall loads that can be expected from ICRH under the first operating conditions are benign.

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A framework for integrated transport modelling and validation

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Abstract. The predictive capability of theory-based transport models has improved steadily over the last 25 years, capturing trends and increasingly new features. Integrated transport modelling is now strongly envisaged, especially concerning the core-edge integration, which allows a predict-first approach (e.g. for future devices). Moreover, integrated modelling relies on modular workflows, which are powerful for benchmarking and validating new codes. This is now feasible thanks to significant progress in the transport community:

a) A universally accepted data environment (IMAS-IDS) is now available and portable. This is the basis for modular workflows, where a modeller can choose between several modules to solve specific tasks, such as the equilibrium, the source profiles or transport.

b) The experimental data from several devices are now easy to access with user-friendly tools, facilitating codes' validation and cross-machine studies.

In this paper we discuss some new milestones on the way towards user-friendly and efficient integrated modelling of ASDEX Upgrade plasmas, achieved within the TSVV11 activity, on top of the established IMEP (Integrated Modelling with Engineering Parameters) core-edge integration workflow [1]:

1) Completion of the TRVIEW package, a GUI-based tool for fast and flexible manipulation of ASDEX Upgrade data. It includes several profile regularisation algorithms, Fourier moments fit for the separatrix and multiple output options: ASTRA, TRANSP and RABBIT input formats. Most importantly, TRVIEW features IMAS output, with all relevant IDS branches. Due to its modularity, TRVIEW could be ported to other devices, such as JET, with moderate effort.

2) Comprehensive refurbishment of the ASTRA suite of codes (v8.0), a tool optimised for flexible and fast simulations with theory-based transport models: fully fortran90, with modules replacing COMMON blocks; NetCDF output; version-tracking for the coupled modules; fully new python parser for code-preprocessing.

As an example we present a time-dependent modelling workflow of a pellet discharge. We use TRVIEW for input collection and ASTRA-8.0 for the plasma evolution, with TGLF and QuaLiKiz as transport models.

Future plans include further ASTRA development, such as the implementation of IMAS I/O and the coupling of an ICRF module like TORIC and of the impurity transport code STRAHL.

Gyrokinetic modelling of the Alfvén mode and EGAM activity in ASDEX Upgrade

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Abstract. Energetic particles (EPs) present in tokamak machines can drive through resonant wave-particle interaction different plasma instabilities, e.g Alfvén modes (AMs) and EP-driven geodesic acoustic modes (EGAMs). While the former are potentially detrimental as they can enhance the EP transport and damage the machine wall, the latter are axisymmetric, possibly benign modes that can act to regulate turbulence. A unique scenario, the so-called NLED-AUG case [1], has been developed in ASDEX Upgrade by tuning the plasma parameters so that the EP kinetic energy is 100 times higher than that of the background plasma, like in ITER. An intense EP-driven activity is observed, most prominently various AM bursts triggering chirping EGAMs.

The present work reports studies on the AM and EGAM dynamics showing, for the first time, many toroidal mode gyrokinetic simulations with ORB5 [2] where the NLED-AUG case scenario is considered. We study the mode dynamics modelling the EPs with different equilibrium distribution functions, such as: isotropic slowing-down, double-bump-on-tail and equivalent Maxwellian. We retain, at the beginning, the nonlinearities only in the EP dynamics. Later also the background plasma species nonlinearities are taken into account. The nonlinear interaction between EGAM and AM is investigated in post-processing using the newly implemented python bicoherence diagnostics. The results obtained extending the electrostatic power-balance diagnostics already present in ORB5 [3] to the electromagnetic version are here shown and discussed. The use of this newly implemented diagnostics allows the localization of the velocity domains of maximum wave-particle energy exchange.

Intrinsic rotation drive in tokamaks: the competition between turbulence and magnetic braking.

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Controlling the flows in large size magnetized plasmas is hardly achievable with external momentum sources. They are rather determined by intrinsic physics that combine turbulent and collisional effects in presence of 3D magnetic perturbations, here magnetic ripple. The underlying loss of axisymmetry is responsible for a toroidal torque leading to magnetic braking (1). This constraint lifts the degeneracy of the standard neoclassical theory between the mean toroidal velocity and the radial electric field. This magnetic braking then imposes a finite value for the plasma rotation, analytically predicted in the low collisionality limit, which acts as an intrinsic drive.

In realistic plasmas though, turbulence is also an intrinsic rotation drive that competes/synergizes with these neoclassical effects. Usually these mechanisms are handled separately in numerical simulations. In this work (2), they are treated on an equal footing for the first time, using both analytical theory and gyrokinetic simulations. The methodology sums up in three stages. First, gyrokinetic simulations, performed with the GYSELA code (3), without turbulence and including ripple are successfully compared to the neoclassical theory (4). Secondly, in simulations of Ion Temperature Gradient driven turbulence without ripple, turbulent momentum transport is analyzed and compared with available models of turbulent transport (5; 6). Finally, all effects are self-consistently accounted for to assess the resulting flow. These numerical simulations demonstrate that magnetic braking prevails over turbulence above a critical amplitude of ripple, determined analytically. Moreover, interplay mechanisms between magnetic braking and turbulent momentum drive are addressed. The main mechanism is the enhancement of the rotation-driven radial electric field shear \( E'_r \) when magnetic ripple is present. This effect indirectly results in a significant change in magnitude of the turbulent stress tensor – quite sensitive to \( E'_r \). Conversely, the turbulent intensity is only mildly affected in our simulations.

References
Localized spontaneous compressional heating in magnetic islands

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Abstract. A spontaneous heating process is found to arise in a system where a magnetic island is present due to a linearly unstable tearing mode. The parity, the relative phases and the structure of the fields determined linearly by the tearing mode [1] cause the compression of the plasma in the direction parallel to the magnetic field to heat the plasma in the vicinity of the separatrix in the non-linear phase. The process is, however, of much broader interest than the specific case of linearly unstable tearing modes. Firstly, because the parity of the fields in the presence of a magnetic island is independent of the mechanism that originated said magnetic island [2], so this study is relevant even for scenarios like Turbulence-Driven Magnetic Islands [3]. Secondly, since the heating is given by the correlation of regions of parallel compression to regions of positive pressure fluctuations, any situation where such an overlap is produced should give place to a similar effect. Indeed, using a 6-field electromagnetic fluid model, the process is found to be present in both 2D single-helicity and 3D multi-helicity simulations with both symmetric and a-symmetric magnetic equilibrium profiles, thus showing a resilience to changes in geometry and inclusion of parallel fluctuations. The feature of said model that allows the observation of the heating effect is the higher order compression terms that are retained in the equations, as is the case in other models (e.g. [4]). The process is believed to be linked to experimental observations of localized hot-spots on externally induced magnetic islands [5].

References
Kinematic viscosity estimates in reversed-field pinch fusion plasmas

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Abstract. In the magneto-hydrodynamic (MHD) modelling of fully ionized plasmas, a “neutral fluid like” viscosity term is introduced in the momentum balance equation to represent momentum transport in the plasma. Viscosity determines, together with resistivity, the dimensionless Hartmann number \[1\], which quantifies the plasma ‘slipperiness’ and rules some important aspects of plasma dynamics \[2\]. This is more evident in the reversed-field pinch (RFP), a toroidal configuration used for confinement in nuclear fusion research. In the RFP, non-linear MHD simulations \[3\] have successfully described the rise of quasi-periodical helical self-organized states \[4\], considering low visco-resistive dissipation and finite edge radial magnetic field \[5\].

Despite the key role played by the viscosity in the RFP, no unique consensus on either the form of the viscous term or the viscosity coefficient evaluation in RFP plasmas still exists \[1\]. In fact, the experimental estimates \[10-15\] carried on according to classical \[6\] or turbulent transport theory \[7-9\] display orders of magnitude differences, motivating further studies to assess a viscosity estimate in RFP plasmas.

In this work, we first perform a sensitivity study in SpeCyl non-linear MHD simulations \[3\] to test the effect of ‘Braginskii-like’ viscosity profiles – resulting in a slight reduction of the velocity field and a consequent increase of magnetic field amplitude - and the effect of a preliminary self-consistent evolution of the Hartmann number - resulting in a slowdown of the RFP sawtoothing activity. Despite significant differences, both the modifications do not qualitatively modify the plasma helical regime.

Secondly, we estimate the kinematic plasma viscosity (and, consequently, the Hartmann number \(H\)) on a wide database of RFX-mod shots \[16, 17\] according to the main existing theories of momentum transport \[6, 8, 9\]. We show that the tearing mode amplitude and sawtoothing frequency scaling in SpeCyl MHD simulations match the scaling of RFX-mod data if the Braginskii perpendicular viscosity estimate \(H \propto B^3 T_e^{3/4} T_i^{1/4} / n\) with \(B, T_e, T_i, n\) the magnetic field, the electron and ion temperature and the density respectively) is chosen, whereas the other estimates yield lower correlations. Nevertheless, the matching procedure shows that the absolute value of viscosity \((0.7 - 4 \cdot 10^2) m^2/s\) is two orders of magnitude higher than the Braginskii estimates \((3 \cdot 10^{-3} - 2) m^2/s\), a value closer to the one predicted by turbulent theories \[8, 9\].

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Ultra long turbulent eddies, magnetic topology, and the triggering of internal transport barriers

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In this work, we use local nonlinear gyrokinetic simulations of tokamaks to demonstrate that turbulent eddies can extend along magnetic field lines for hundreds of poloidal turns when the magnetic shear $\hat{s}$ is very weak or zero. Their length is limited only by critical balance — the distance that electrons can travel along the field line within the lifetime of a turbulent eddy. Such “ultra long” eddies can have significant consequences on turbulent transport due to parallel self-interaction [1]. Moreover, it makes correctly treating the field line topology, in particular whether a flux surface has a safety factor that is integer, rational, near rational, or irrational, all the more important, which is accomplished by carefully choosing the simulation domain length as well as the phase factor in the parallel boundary condition for $\hat{s} = 0$ simulations. To this end, we will show that field line topology can cause transitions between different turbulent modes and completely stabilize Ion Temperature Gradient (ITG) turbulence, both linearly and nonlinearly. Using Floquet-Bloch theory, we show how linear results from a domain that is one poloidal turn long can be used to calculate growth rates for any number of poloidal turns. Empirically, very weak or zero $\hat{s}$ has been identified as being one of the key conditions for facilitating Internal Transport Barriers (ITBs) [2]. We present standard local gyrokinetic simulations that exhibit weak ITBs caused by the magnetic topology, which may inform a long-standing experimental observation that it is often easier to trigger ITBs where the safety factor has a low-order rational value [3]. Lastly, we observe a novel physical effect termed “poloidal eddy squeezing” — when eddies become ultra long they can cover the full flux surface and, for specific values of the safety factor, strongly interact with themselves in the perpendicular direction. This can squeeze them, reducing their perpendicular size and ability to transport energy, thereby embodying an intriguing new strategy to improve confinement in tokamaks.

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Long-wavelength closures for collisional and neutral interaction terms in gyro-fluid models

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Abstract  Gyro-fluid models are known to have difficult and often impractical expressions for collisional inter-species interaction terms and little work exists on plasma-neutral interaction terms. The result is that practical implementations of gyro-fluid models largely ignore collisions and plasma neutral interactions altogether. Drift-fluid models are preferred for that purpose even though these models do not share many advantages of gyro-fluid models: finite Larmor radius corrections, consistent particle drifts, an energy and momentum theorem based on variational methods in the underlying gyro-kinetic model and an inherent symmetry in moment equations with regards to multiple ion species. It is known that drift-fluid models can be obtained in the long-wavelength limit of gyro-fluid models when the gyro-radius is small compared to the typical length-scales. The central argument for a long-wavelength closure of gyro-fluid models is that this correspondence extends to the collisional (scattering and reacting) terms: they are such that their long-wavelength limit corresponds to the drift-fluid terms. In that way a gyro-fluid model can be built based on the extensive literature on fluid collisions [1,2]. Our goal is to derive a practical four-moment, multi-species model that in particular can be used in the TSVV3 project for edge plasma fluid simulations. We will therefore focus on numerical “implementability” avoiding infinite sums, strongly coupled equations or intricate operator functions. We further highlight the impact of the derived collision terms on the conservation of currents “vorticity” equation [3] as well as the impact on rotation [4].

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Using Reynolds/Maxwell stress to predict the drive of Alfvénic turbulence by drift waves

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Abstract. We investigate the nonlinear energy exchange between high frequency Alfvén waves and lower frequency drift waves. We are particularly interested in seeing whether this interaction will lead to a mechanism for damping the drift wave turbulence or produce observable Alfvén modes. Our expectation is that both Alfvén eigenmodes and the Alfvén continuum can serve as a sink of turbulence energy and provide a saturation mechanism for turbulence. One aim is to see how much of this interaction can be captured by a simple scaling laws where the forcing of the MHD waves by drift-wave turbulence is captured by the Reynolds/Maxwell stress nonlinear term in reduced MHD. Part of the aim is to understand the correspondence between nonlinear MHD phenomena in tokamaks and slab theory relevant to astrophysics, like weak-turbulence MHD.

Using the nonlinear gyrokinetic code GENE [1], we study the interaction between Alfvénic modes including Toroidal Alfvén Eigenmodes (TAEs) [2], and drift waves. We ultimately aim to model the Reynolds/Maxwell stress drive of the Alfvénic wave equations as arising from the drift wave turbulence we observe in the simulations. Nonlinear gyrokinetic simulations in slab geometry have already been performed to examine Alfvén wave coupling, in preparation for tokamak-relevant simulations in toroidal geometry. In these studies we have observed a coupling in the gyrokinetic simulation that is forbidden from the MHD theory, namely co-propagating Alfvén waves. We believe this to be because the Alfvén waves we see in the gyrokinetic simulations are the Kinetic Alfvén Waves (KAWs). Additionally we have numerically solved the MHD equations self-consistently and with the gyrokinetic simulation output as the driving term in slab geometry. We hope to extend this numerical model to toroidal geometry in the near future. We will then be interested in seeing how this behaviour is modified by scaling against relevant plasma parameters such as the plasma beta, density and temperature gradients, and the presence of fast ions.

Quantifying the role of higher order neoclassical corrections to gyrokinetics

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Abstract. Bootstrap current is known to be important in the pedestal region of tokamak plasmas, and arises due to a finite $\rho_0$ correction to the Maxwellian equilibrium distribution function, where $\rho_0$ is the poloidal Larmor radius. This correction provides the neoclassical flows. In the limit that the poloidal component of the magnetic field is small compared to the toroidal component, this correction can be accommodated in a linear electromagnetic gyro-kinetic equation [1]. Using a large aspect ratio approximation of the tokamak geometry, together with a momentum-conserving collision operator that retains pitch-angle scattering, we present results quantifying the impact of the neoclassical correction to the equilibrium distribution function, finding its effect is generally small. We will also present progress in calculating whether the results become more important in realistic tokamak geometry, and employing a more accurate collision operator.

While the approximation of small ratio of poloidal to toroidal components of the magnetic field is generally a good one, it can break down in a spherical tokamak, for example. We have therefore extended the higher order gyro-kinetic theory to accommodate the situation when $\rho_0$ and $\rho$ are comparable, with $\rho$ the Larmor radius evaluated using the full magnetic field. The results of this higher order theory will be presented, and the challenges associated with implementing in gyrokinetic simulation codes assessed.

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Statistical mechanics with non-Hermitian Hamiltonians and its applications for zonal flow of plasma interacting with drift waves

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Abstract. Non-Hermitian Hamiltonian operators readily occur not only in open quantum systems, but also in various non-quantum systems whose description allows a Schrödinger equation mapping and wave-mechanical representation. For such systems, multiple mode solutions occur, which satisfy same boundary conditions but correspond to different eigenvalues of a Hamiltonian operator, which is somewhat analogous to the one in quantum (wave) mechanics. These solutions form a Hilbert space, which requires a probability-based selection of modes. In order to describe this selection properly, one needs to go beyond the state-vector formalism and consider a density operator formalism. We adopt this approach to non-Hermitian Hamiltonian operators and derive the corresponding master equation in a general case.

As an application example, we study dissipations in plasma with the large-scale zonal flow interacting with small-scale drift waves representing turbulence, which appear in various phenomena in astrophysics, such as planetary atmospheres, protoplanetary disks, as well as in fusion plasmas. The creation of zonal flows is attributed to self-organization processes. We demonstrate that these waves are indeed can be described in terms of wave-mechanical non-Hermitian Hamiltonian operators and adopt a density operator approach.

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