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Kinetic analysis of the collisional layer

M Abazorius[1*], F I Parra[2] and F Militello[3]

[1] Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, OX1 3PU, UK
[2] Princeton Plasma Physics Laboratory, Princeton, NJ 08540, USA
[3] United Kingdom Atomic Energy Authority, Culham Campus, Abingdon, Oxfordshire, OX14 3DB, UK

Abstract. In the scrape-off layer (SOL) of a tokamak, Braginskii fluid equations are used to model the plasma behaviour [1-3]. However, the fluid approximation breaks down near the wall. Separate layers develop perpendicular to the wall, their size is determined by 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 $\lambda_\perp$ and the device size L. Near the divertor the scale separation $\lambda_D \ll \rho_i \ll \lambda_\perp \ll L$ is valid, allowing analytical analysis of each layer separately. The plasma dynamics in the smallest scale layers (the Debye sheath and the magnetic presheath) are well understood [4-6]. In this work we focus on the collisional layer, its thickness is of order $\lambda_\perp$. It connects the collisionless magnetic presheath, where the distribution function is far from Maxwellian, with the fluid region of the SOL, where the collisionality is high. For the analysis of ion dynamics in the collisional layer, we solve the steady state drift kinetic equation in one spatial dimension with the full Fokker-Planck collision operator, together with the quasineutrality equation and the assumption of adiabatic electrons. For our boundaries we assume that all ions that reach the collisionless magnetic presheath are absorbed and we set the distribution function far away from the wall to be approximately Maxwellian. We show that at the boundary near the wall the Chodura condition [6] has to be satisfied, which is consistent with the magnetic presheath analysis [3]. We show that the scaling of the potential here is $\phi \sim \sqrt{x}$, where x is the distance from the wall, and the distribution function is exponentially small at small velocities parallel to the magnetic field. We also describe how the total potential drop across the layer depends on the electron temperature and the ion mean flow at the boundary far away from the wall. The predicted dependency is compared with the numerical simulations. The numerical equations are solved with a semi-Lagrangian code, which uses the Galerkin method together with quadratic finite element basis in velocity space.

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Comparisons of hybrid kinetic-MHD and gyrokinetic simulations of the fishbone instability using JOREK and ORB5

F. N. Antlitz[1*], X. Wang[1], M. Hölzl[1], G. T. A. Huijsmans[3,4], P. Lauber[1] and A. Mishchenko[2]

[1] Max-Planck-Institut für Plasmaphysik, Garching, Germany
[2] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
[3] CEA, Saint-Paul-Lez-Durance, France
[4] Eindhoven University of Technology, Eindhoven, Netherlands

[*] E-mail: felix.antlitz@ipp.mpg.de

Abstract. Investigating the impact of suprathermal energetic particles (EPs) is of great relevance for future burning plasma experiments as they will provide a large fraction of the total pressure and can strongly interact with the thermal bulk plasma. In this contribution we describe numerical simulations of the fishbone instability in tokamak plasmas – an n=1 internal kink mode driven unstable by EPs. Fishbones can lead to the redistribution and loss of EPs but may also suppress turbulence through the formation of internal transport barriers.

The nonlinear extended MHD code JOREK [1] and the global electromegnetic gyrokinetic code ORB5 [2] are run for the same simulation cases. JOREK evolves the MHD equilibrium in time and treats the bulk plasma as a fluid. The fast ions are modeled with a particle-in-cell (PIC) technique. A full-f formulation and an anisotropic pressure coupling scheme to the fluid are used [3]. On the other hand, ORB5 describes not only the fast ions but also the electrons and thermal ions gyrokinetically. Similarly, a PIC method is used but with a delta-f formulation.

Linear properties from the simulation runs like growth rates and mode frequencies are compared and the nonlinear behavior like frequency chirping of the mode, mode saturation and the effect of zonal flow are examined. Differences of the results obtained from the two codes are discussed.

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Nonlinear Saturation Mechanism of Toroidal Alfvén Eigenmodes driven by Trapped Particles

Farah Atour[1], Xin Wang[1] and Sergio Briguglio[2]

[1] Max-Planck-Institute for Plasma Physics, Garching, Germany
[2] C.R. ENEA Frascati, Frascati, Italy

E-mail: farahatour@ipp.mpg.de

Abstract. In controlled fusion devices, shear-Alfvén waves can be driven unstable by resonant interactions with energetic alpha particles. This results in significant issues regarding particle confinement. This study presents a series of numerical simulation experiments aimed at illustrating the fundamental physical processes underlying the saturation mechanism of Toroidal Alfvén Eigenmodes (TAE), specifically for trapped particles within the framework of the ITPA benchmark. Due to the presence of trapped particles, many interesting phenomena were observed using the Hamiltonian mapping technique, such as multiple harmonics within the resonance structure, with the most dominant harmonic located at the outer radial position. At this location in the equatorial plane, no mode is present for the energetic particles to interact with, making this initially a surprising result. This phenomenon is attributed to the relatively wide orbit width, which cannot be neglected as it has been in previous studies that focused on passing particles. Therefore, quantities such as the power transfer and the effective field should be considered as the average values perceived by trapped particles along their entire orbit, noted at the equatorial plane, rather than their instantaneous contributions, to ensure more accurate comparisons. In terms of saturation, previous research has established that two distinct regimes - namely radial decoupling and resonance detuning - exhibit specific scaling between the saturation amplitude and the linear growth rate [1]. According to this nonlinear pendulum model [2], the width of the island covers the region of power transfer, typically limited by either resonance detuning or radial decoupling regimes [3]. However, in the cases presented in this study, the situation deviates from this general rule. It was observed that when the harmonic with the highest power transfer covers the region where power transfer occurs (resonance detuning), a sudden drop in power transfer is observed over time. Following this, the islands from different harmonics begin to overlap, leading to a residual but much weaker drive. Saturation is reached when the overlap of all harmonics encompasses the region where the effective field is located, indicating a transition to the radial decoupling regime. Consequently, the system is not exclusively in one regime or the other but exhibits characteristics of both regimes simultaneously.

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Construction of an invertible mapping to boundary conforming coordinates for arbitrarily shaped toroidal domains.

Robert Babin[1,2], **Florian Hindenlang**[1], **Omar Maj**[1] **and Robert Köberl**[1,2]

[1]Numerical Methods in Plasma Physics, Max Planck Institute for Plasma Physics, Garching, Germany

[2]School of Computation, Information and Technology, Technical University of Munich, Munich, Germany

E-mail: robert.babin@ipp.mpg.de

Abstract. In state-of-the-art 3D MHD equilibrium codes (VMEC, SPEC, DESC, GVEC), the equilibrium solution is found by iteratively moving surfaces of constant magnetic flux, starting from an initial guess. The flux surfaces are represented by the inverse of a map, defining boundary conforming coordinates on the considerate toroidal domain. For a successful simulation it is crucial that the initial coordinates are well defined. For fixed boundary equilibria, often only the boundary shape of the domain is known, and thus finding a valid initial guess can be challenging, especially when considering the non-convex boundaries from recent developments in stellarator optimization [1].

In [2] a minimization approach is proposed and successfully applied to strongly shaped 3D domains. Inspired by this work, we propose a new algorithm to construct such a mapping, by solving two Laplace problems using a boundary integral method. We can prove that the generated continuous mapping is always invertible. Furthermore, we can find a discrete approximation of the mapping which preserves this property.

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Core turbulent transport in negative triangularity tokamak power plants

Justin Ball[1*], Alessandro Balestri[1], Stefano Coda[1], and Stephan Brunner[1]

[1] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

*E-mail: justin.ball@epfl.ch

Abstract. In this work we will present a set of studies to assess core turbulent transport in a potential Negative Triangularity (NT) power plant, relative to the standard Positive Triangularity (PT) flux surface shaping. First, using standard local gyrokinetic simulations, we will compare the heat transport in EU DEMO equilibria. This reveals that NT substantially increases the critical gradient needed to drive turbulence, while barely changing the profile stiffness. Second, through a set of parameter scans we will investigate how the confinement benefits of NT (relative to PT) depend on aspect ratio, safety factor, magnetic shear, elongation, and the driving gradient. In particular, the scan in aspect ratio displays a surprising dependence and motivates a simple physical picture for why NT typically stabilizes Ion Temperature Gradient (ITG) turbulence [1]. Third, we will perform electromagnetic gyrokinetic simulations to determine if the electromagnetic instabilities that can be present in high-performance plasmas (e.g. kinetic ballooning modes, microtearing modes) are also stabilized by NT. Lastly, we will employ a novel flux tube domain that includes non-uniform magnetic shear [2] in order to introduce profile shearing effects into flux tube gyrokinetic simulations. This allows us to extrapolate the performance of NT from small machines (where profile shearing is substantial) to large machines (where profile shearing is negligible).

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Investigation of the tearing instability with the gyrokinetic code GYSELA

R. Bigué[1,2], P. Donnel[2], Y. Sarazin[2], X. Garbet[2,3], V. Grandgirard[2], K. Obrejan[2], G. Dif-Pradalier[2], Z. Qu[3], L. De Gianni[2], Y. Munchy[2], M. Muraglia[1]

[1]PIIM Laboratory, UMR 6633 CNRS-University of Provence, Marseille
[2]CEA, IRFM, F-13108 Saint Paul-lez-Durance, France
[3]School of Physical and Mathematical Sciences, NTU, 637371 Singapore

E-mail: romeo.bigue@univ-amu.fr

Abstract. Hot magnetized plasmas in tokamaks machines are subject to magnetic reconnection that can dramatically degrade the confinement. In particular, Neoclassical Tearing Modes (NTMs) drive radially large magnetic islands which modify the magnetic equilibrium structure. This lead to confinement degradation and potential disruptions that can damage the device. Although the control of NTMs has benefited from recent key advances [1], fundamental questions remain in particular regarding the prediction of their saturated radial width [2].
Over the past few years, gyrokinetic codes have started to contribute to this topic and improved our general understanding of magnetic reconnection processes in tokamak plasmas. In this contribution, we successfully benchmark the electromagnetic version of the flux-driven GYSELA code [3] against GENE and ORB5 recently published results on the linear collisionless tearing instability [4] for a wide range of scanned parameters, both in terms of growth rate and mode structure. Linear simulations in the collisional regime will also be presented and compared to the collisionless case.

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Multiscale approach to the derivation of the quasilinear Fokker-Planck equation for radiofrequency heating in fusion plasmas

Roberto Bilato, Omar Maj, Marco Brambilla, Emanuele Poli
Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany
E-mail: roberto.bilato(at)ipp.mpg.de

Abstract. The modeling of radiofrequency (RF) heating in magnetically confined plasmas involves coupling the Maxwell equations to a kinetic equation with a quasilinear diffusion operator for the long-term evolution of the distribution function. In his seminal paper [Phys. Fluids **15**, 1063 (1972)], Kaufman proposed an elegant derivation of the quasilinear equations using action angle variables as appropriate for the motion of the particles in the equilibrium fields. This derivation is based on two approximations, namely the linearized Vlasov equation for the fast plasma response, and the "usual Markov assumption" for the quasilinear operator of the kinetic equation. To better understand the validity range of these approximations, we present here an alternative derivation of Kaufmann's quasilinear equations based on the explicit separation of the different time scales involved. This shows that the condition justifying these approximations is the decorrelation between the wave and the motion of the resonant particles in a time shorter than the time in which the nonlinearity of the response of the particles to the waves would manifest itself.

Despite its elegance, the numerical implementation of the quasilinear equation in action angle variables is out of the question for realistic RF heating problems. In contrast, more traditional derivations, such as that of Bernstein and Baxter [Phys. Fluids 24, 108 (1981)], are suitable for realistic implementation in numerical codes, although the evaluation of the resonance integrals requires some careful treatment. We discuss the differences between the two approaches and how to efficiently evaluate the resonance integrals of the wave-particle interaction.

Particle-in-cell methods in edge plasma physics: the PICLS code

A. Bottino[1], **A. Stier**[1], **M. Boesl**[2], **T. Hayward-Schneider**[1], **A. Bergmann**[1], **D. Coster**[1], **S. Brunner**[3] **and L. Villard**[3]
[1]Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany
[2]Spark e-Fuels GmbH, Berlin, Germany
[3]Swiss Plasma Center, Ecole Polytechnique Fédérale de Lausanne, Switzerland

E-mail: `alberto.bottino@ipp.mpg.de`

Abstract. Over the past decades, multiple gyrokinetic codes have shown to be able to simulate turbulence and associated transport in the core of tokamak devices. However, their application to the edge and scrape-off layer (SOL) region presents significant challenges. To in particular study the SOL region with its steep temperature and density gradients as well as large fluctuation amplitudes, the full-f particle-in-cell code PICLS has been developed. PICLS is based on a full-f gyrokinetic model with linearised field equations, considers kinetic electrons and uses logical sheath boundary conditions. In the past, PICLS was verified by applying it to a well-studied 1D parallel transport problem during an edge-localized mode (ELM) in the SOL under both collisionless [1] and collisional conditions, for which a Lenard-Bernstein collision operator was implemented [2]. PICLS recently was extended towards three spatial dimensions [3] to study turbulence in open-field-line regions in slab and closed-field-line toroidal geometries. In this work, we will focus on the models and methods we used for extending the code towards three spatial dimensions, including validation efforts and comparisons with other existing codes in closed-field-line geometry.

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Edge intrinsic rotation with finite-step charge-exchange neutrals and self-consistent ion distribution

R. Brzozowski III[1] **and T. Stoltzfus-Dueck**[1]

[1]Theory Department, Princeton Plasma Physics Laboratory, Princeton, USA

E-mail: rbrzozow@pppl.gov

Abstract. Toroidal rotation is a stabilizing mechanism for tokamak plasmas, preventing locked modes and potential resulting disruptions. ITER and future fusion reactors will operate in regimes where neutral-beam injection cannot apply sufficient torque to significantly affect the toroidal rotation. Instead, the toroidal rotation will largely be set by intrinsic torques, the largest of which is driven by turbulent transport, is typically co-current, and scales with T_i/I_p [1, 2]. However, not all observed low-torque rotation fits this pattern. Unexplained counter-current shifts in intrinsic rotation have been observed, which, together with the usually counter-current torque applied by 3D fields, will unfavorably decrease the toroidal rotation magnitude in ITER and other future devices. Some experimentally observed scalings of these shifts suggest that neutrals could play an important role, motivating our investigation.

We present a new theory for momentum transport by neutrals in the plasma edge by extending the Modulated Transport Model [1, 2] to include a single neutral species. First, we show that local neutral transport terms (taking the infinitesimal charge-exchange step limit) are unable to drive significant toroidal rotation with a self-consistent treatment of the plasma edge [3]. We then relax the approximation to include finite-neutral-step transport in the boundary-layer solution procedure, including the contribution of cold neutrals that charge exchange in the transport-driven Scrape-Off-Layer flows. When coupled with these ion flows to the targets, poloidally asymmetric neutrals can transport a strongly imbalanced momentum, with sign corresponding to those of the local ion flows, into the pedestal.

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Effects of Modulated Heat Source on Non-local Transport

Y.W. Cho[1*], X. Garbet[1,2], R. Varennes[1], Z. Qu[1], P. Donnel[2], K. Obrejan[2], G. Dif-Pradalier[2], Y. Sarazin[2], V. Grandgirard[2]

[1] School of Physics and Mathematical Science, Nanyang Technological University, Singapore, Singapore
[2] CEA, IRFM, F-13108 St. Paul-lez-Durance, France

[*]E-mail: youngwoo.cho@ntu.edu.sg

Abstract. Recent study in LHD has shown a correlation between the period of modulated electron cyclotron heating (MECH) and non-local transport events. Moreover, when an avalanche is induced by a minor collapse of electron internal transport barrier, turbulence pulse propagates faster than heat pulse [1]. Inspired from the observations, we utilize the global full-F gyrokinetic code, GYSELA [2] to analyze non-local transport in the presence of modulated heat source, the period of which is in the range of transport timescale. In the near marginal stable case, it is observed that the localized and modulated heat source can establish temporal $E \times B$ staircase and trigger an avalanche-like transport. When heat source-stimulated avalanche occurs, propagation speed of turbulent fluctuations is faster than that of heat transfer. To understand these effects, an analytic study was done to model turbulence spreading forced by modulated source using a two-field critical gradient model [3]. The propagation speed of turbulent fluctuations was found to be inversely proportional to the local pulse length. Since the growth of burst-like fluctuations is higher than the frequency of source, radial propagation of turbulent fluctuations is faster than that of heat transport.

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Gyrokinetic Investigation of TAE Damping Channels with Comparison to Theory and Application to MAST-U

Noah Chulu Chinn[1,2], Ben McMillan[1] and Francesco Palermo[2],Colin Roach[2],Michael Fitzgerald[2], Ken McClements[2],Sam Gibson[2],Mykola Dreval[2],Alexey Mishchenko[3],Thomas Hayward-Schneider[3]

[1]CFSA, University of Warwick, Coventry, United Kingdom
[2]CCFE, Culham Science Centre, Abingdon, United Kingdom
[3]IPP Garching, Max-Planck-Institut für Plasmaphysik, Garching, Germany

Abstract. The Toroidal Alfvén Eigenmode (TAE) is an Alfvenic gap mode which can lead to anomalous Energetic Particle (EP) transport and can have a detrimental effect on plasma heating efficiency. The global gyrokinetic code ORB5 has been used to study linear TAE phenomena with a focus on investigating individual damping and drive channels which determine whether a TAE will be driven unstable. Newly developed code diagnostics that measure the energy transfer per-species and in terms of specific (e.g. parallel and perpendicular) components of particle motion have been used to separate the individual channels. Circular geometry scenarios such as the ITPA-TAE and CYCLONE case were used to verify the correct modelling of the damping mechanisms; ITPA as it is a standard test case when bench-marking codes, and CYCLONE as it has parameters close to those found on real tokamaks. Qualitative indications of radiative damping were also demonstrated by radial oscillations of the TAE eigenmode. Thus, ORB5 has also been used to study the physics of Alfvén Eigenmodes in specific MAST-U shots, where high beta and inverse aspect ratio mean the drive regimes alter the damping of TAEs compared to conventional tokamaks and theory-based estimates. The results from these simulations can then be used to extrapolate and provide predictions of TAE phenomena in future machines such as STEP.

Physics of core MHD instability spectra in advanced tokamak regimes

M. Coste-Sarguet[1], J. P. Graves[1,2]

[1]Swiss Plasma Center (SPC), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, 1015, Switzerland

[2]York Plasma Institute, Department of Physics, University of York, YO10 5DD, Heslington, York, United Kingdom

E-mail: margot.coste-sarguet@epfl.ch

Abstract.

Recent breakthroughs in fusion energy have been achieved through several record-breaking DT pulses at the Joint European Torus (JET), utilising a hybrid scenario. These advanced tokamak regimes, characterised by an extended region of low magnetic shear, are a promising scenario choice for ITER and European DEMO. Unfortunately, they are also more prone to specific kinds of MHD instabilities due to the central flattening of the q profile. The proximity to a rational surface with very low magnetic shear significantly reduces field line bending stabilisation and amplifies the effects of toroidal coupling between modes. This fosters the development of long-wavelength perturbations known as infernal modes, which can displace the plasma over a wide radial extent.

It has also been found that these modes can grow collectively as a spectrum, leading to a cascade of different perturbations for single mode numbers m, n. Subdominant modes with lower growth rates have distinct radial structures, oscillating more (they can be characterized by Bessel functions). These spectra of fast-growing modes are significant for developing stable scenarios for future reactors, and for the understanding of global reconnection events like sawteeth, motivating a deeper investigation into their fundamental physics. Considering resistive diffusion, compressibility, toroidal effects, shaping and non-linear saturation, we explore the critical regions and parameters which influence the stability of the hybrid mode scenario.

This led to the development of a new resistive modular MHD eigensolver [1], based on a unified and global description of pressure and current driven internal instabilities [2]. This tool allows to identify a novel resonant resistive spectrum of infernal modes, with quite high linear growth rate values even for the subdominant modes. For the non-resonant case, we derive an analytic dispersion relation with higher-order corrections in $q-q_s$, allowing the first correct description of a non-resonant kink mode spectrum with $q_s = 1$. Basic shaping effects are included for odd and even parity modes. We also initiated a study on the saturation of these spectra in the ideal case, including nonlinear terms using a quasi-linear approach presented in [3].

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Effect of the magnetic geometry on Trapped Electron Modes instability: an analytical model

L. De Gianni[1], X. Garbet[1,2], P. Donnel[1], Y. Sarazin[1], Z. Qu[2], Y. Melka[1], V. Grandgirard[1], K. Obrejan[1], E. Bourne[3], G.Dif-Pradalier[1], Y. Munschy[1], R.Bigué[1,4]

[1] CEA, IRFM, F-13108 Saint Paul-lez-Durance, France
[2] School of Physical and Mathematical Sciences, NTU, 637371 Singapore
[3] SCITAS, EPFL, CH-1015 Lausanne, Switzerland
[4] PIIM Laboratory, UMR 6633 CNRS-University of Provence, Marseille

E-mail: ludovica.degianni@cea.fr

Abstract. Good plasma confinement is crucial to harness fusion energy. Experiments on the TCV [1] and DIII-D [2] tokamaks have shown that negative triangularity (NT) reduces the turbulent transport, hence improving confinement. Trapped Electron Modes (TEM) are suspected to play an important role in the process, since they are stabilized when decreasing triangularity. However, a clear understanding of the underlying physics is still lacking, preventing from extrapolation.

In order to identify the key mechanisms for the stabilization of TEM at NT, a reduced analytical model has been recently derived, focusing on their linear stability[3]. The geometry-dependence of the kinetic response of trapped electrons to perturbations of the electrostatic potential is retrieved, passing electrons and ions response being assumed adiabatic. With this model, NT is found stabilizing only when the poloidal localization of the linear modes – ballooning character – is accounted for, leading to a "Finite Mode Width" effect. It gives more weight to the electrons trapped at small bounce angles, whose precession frequency is lower for NT than for positive triangularity (PT). However, critical gradients predicted with this model are larger than those found in gyrokinetic simulations [4]. When taking into account a kinetic response of the ions in the model, the gyrokinetic predictions for the critical gradients can be recovered.

In this case, however, the stabilization of TEM by negative triangularity is called into question. Indeed, the stabilization trend is found to be much sensitive to the shape of the ballooned electro-static potential. This points towards the need of an accurate estimation for this quantity to conclude on stabilization of TEM by NT. An improved analytical prediction of Finite Mode Width effects will be presented and compared with gyrokinetic simulations.

References

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