JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP ON

"THEORY OF FUSION PLASMAS"

Villa Monastero, Varenna, Italy

August 27-31, 2018

PROGRAMME AND ABSTRACTS

JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP

ON

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Organised by

Swiss Plasma Center
Ecole Polytechnique Fédérale de Lausanne

"Piero Caldirola"
International Centre for the Promotion of Science and International School of Plasma Physics

Istituto di Fisica del Plasma del CNR, Milano

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PROGRAMME

FOR THE

JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP

ON

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SUNDAY August 26, 2018

15:00 - 19:00 Registration in Villa Monastero

PROGRAMME

FOR THE

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Villa Monastero, Varenna, Italy

August 27-31, 2018

MONDAY, August 27, 2018

9:00		*Welcome*	*G. Gorini*
9:10	I-1	**N. Bonanomi**	Multi-scale interactions and role of fast ions and isotope mass in JET Plasmas
9:55	I-2	**J. Garcia**	A new mechanism for increasing density peaking in tokamaks: Improvement of inward particle pinch with edge ExB shearing
10:40		*Coffee break*	
11:10	I-3	**F. Rath**	Comparison of gradient and flux driven gyro-kinetic turbulence
11:55	I-4	**P. Donnel**	Synergies between neoclassical and turbulent impurity transport
12:40		*Group Photo in Villa Monastero's garden*	
12:50		*Lunch*	
15:00	I-5	**T. Stoltzfus-Dueck**	Intrinsic rotation in axisymmetric devices
15:45	I-6	**Z. Lu**	Theoretical studies and simulations of mode structure symmetry breaking in tokamak plasmas
16:30		*Coffee break*	
17:00	I-7	**J. Candy**	Spectral gyrokinetic implementation of rotation, rotation shear and profile shear
17:45		*End*	
18:50		Piano Concert (Hotel Villa Cipressi)	
20:00		Welcome Party (*Hotel Villa Cipressi*)	

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TUESDAY, August 28, 2018

9:00	I-8	**A. Ishizawa**	The study of multi-scale interaction and parity in turbulence/MHD system based on global flux driven simulation
9:45	I-9	**S. Lanthaler**	The spectral problem in kinetic-MHD and applications to beta-driven modes
10:30		*Coffee break*	
11:00	I-10	**B. Breizman**	The feeder pellets and the killer pellets in a plasma
11:45	I-11	**L. Hesslow**	Effect of partially ionized impurities and radiation on the effective critical electric field for runaway generation
12:30		*Lunch*	
15:00		**Poster session: P1 – P24 in Villa Monastero**	
16:00		*Coffee break*	
18:00		*End poster session*	

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WEDNESDAY, August 29, 2018

9:00	I-12	**O. Maj**	Interaction of electron-cyclotron beams with electron density fluctuations in turbulent plasmas
9:45	I-13	**R. Vann**	First-principles simulations of microwave beam propagation through edge turbulence
10:30	I-14	**R. Ragona**	Modeling in front of a plasma profile of a set of Traveling Wave Antenna (TWA) sections in view of the ICRF heating of DEMO
11:15		*Coffee break*	
11:35	I-15	**S. Henneberg**	Development of a novel quasi-axisymmetric stellarator
12:20	I-16	**A.D. Beklemishev**	New confinement concepts for Gas-dynamic linear traps
13:05		*Lunch*	
17:30		Meeting point for visit+conference dinner: main square (Piazza S. Giorgio, in front of the Hotel Royal Victoria)	
18:00		Arrival in Mandello del Lario and Visit to the Moto Guzzi Museum	
19:30		Social dinner at the Restaurant “Il Giardinetto” in Mandello del Lario	

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THURSDAY, August 30, 2018

9:00	I-17	**T. Hayward-Schneider**	Studying Alfvén eigenmodes in realistic conditions using a hierarchy of hybrid-gyrokinetic and fully gyrokinetic models
9:45	I-18	**C. Castaldo**	Nonlinear inverse Landau damping of ion Bernstein waves on alpha particles
10:30		*Coffee break*	
11:00	I-19	**F. Nabais**	Energetic ion losses “channeling” mechanism and strategy for mitigation
11:45	I-20	**H. Wang**	Simulations of energetic particle driven geodesic acoustic modes and the energy channeling in the Large Helical Device
12:30		*Lunch*	
15:00		**Poster session: P25 – P47 in Villa Monastero**	
16:00		*Coffee break*	
18:00		*End poster session*	

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FRIDAY, August 31, 2018

9:00	I-21	**M. Barnes**	Stellarator turbulent transport at low collisionalities
9:45	I-22	**B. Hnat**	Experimental constraint on the radial mode number of the Geodesic Acoustic Mode in MAST Ohmic plasma
10:30		*Coffee break*	
11:00	I-23	**M.J. Pueschel**	Instability and turbulence in the tokamak pedestal
11:45	I-24	**A.S. Kukushkin**	Bifurcations and oscillations in divertor plasmas
12:30		*Closing session*	
12:40		*End*	

MONDAY, August 27, 2018

Multi-scale interactions and role of fast ions and isotope mass in JET plasmas

N. Bonanomi[1,2], P. Mantica[2], J. Citrin[3], T. Goerler[4] , A. Di Siena[4], E. Delabie[5], C. Giroud[6], T. Johnson[7], E. Lerche[8], S. Menmuir[6], B.Teaca[9] , D. Van Eester[8] and JET contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1] *Università di Milano-Bicocca, Milano, Italy*
[2] *CNR - Istituto di Fisica del Plasma "P. Caldirola", Milano, Italy*
[3] *FOM Institute DIFFER, 5600 HH Eindhoven, The Netherlands*
[4] *IPP-Garching Garching bei Munchen, Germany*
[5] *Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA*
[6] *Culham Centre for Fusion Energy, Abingdon, OX14 3DB, UK*
[7] *KTH Royal Institute of Technology, Stockholm, Sweden*
[8] *LPP-ERM/KMS, TEC partner, Brussels, Belgium*
[9] *Applied Mathematics Research Centre, Coventry University, Coventry CV1 5FB, United Kingdom*
* See the author list of "X. Litaudon et al., 2017 Nucl. Fusion **57**, 102001"

Turbulent heat transport in tokamak plasmas is mainly driven by ion-scale (low-k) micro-instabilities such as ITG (Ion Temperature Gradient) modes and TEM (Trapped Electron Modes) and by electron-scale (high-k) micro-instabilities such as ETG (Electron Temperature Gradient) modes. These two scales are not separated but can strongly influence each other through multi-scale interactions. Few recent studies with multi-scale gyro-kinetic simulations revealed that high-k instabilities and multi-scale interactions can have a strong impact on electron and ion heat fluxes ($q_{e,i}$), especially when low-k instabilities are close to marginal stability [1-3] and in presence of high electron heating. As these will be the conditions in ITER plasmas, it is important to clarify in which conditions and to what extent these effects are important for the turbulent transport.

In JET C-Wall L-mode plasmas, a variety of experimental observations point to a significant role of ETG modes in determining q_e [4,5]. GENE linear, non-linear single-scale and a first non-linear multi-scale simulation of these plasmas indicate that low-k instabilities are not sufficient to explain the experimental heat fluxes [4,5] and predict a significant contribution from high-k instabilities to q_e and a key role of multi-scale interactions for the core turbulent dynamics. The theoretical finding being that low-k zonal flows are the main saturating mechanism for ETGs, it is expected that any mechanism stabilizing ITGs would in turn result in a destabilization of ETGs and increase of the high–k electron heat flux.

Indeed several observations on JET seem to confirm such opposite behavior of the two channels [6]. High NBI power scenarios, in which T_i peaking is enhanced by non-linear e.m. and fast ion stabilization of ITGs [7,8], feature flatter and stiffer T_e profiles with respect to ICRH electron heated plasmas. This may be associated to ETG destabilization due to decreased $\tau = Z_{eff} \cdot T_e / T_i$ and to ITG stabilization, which is also found when ITG stabilization is obtained by fast ions at high ICRH power in absence of NBI and rotation [9]. The ITG stabilization has been related, using gyro-kinetic simulations, to electrostatic [10] and electromagnetic [8] mechanisms, strongly dependent on the fast ions distribution function [9,11]. Another situation regards the changes observed in the core of JET ILW L-mode plasmas when changing isotope from D to H. Whilst at low power no significant deviation from the theoretically expected gyro-Bohm scaling is observed in the ion channel, at higher power a smaller stabilization of ITGs with an increase of ion stiffness has been observed in H plasmas, which has been related to the reduced NBI and ICRH fast ion pressure compared to D plasmas. In turn, the T_e peaking in H plasmas is significantly higher than in D plasmas for comparable values of $\tau = Z_{eff} \cdot T_e / T_i$, suggesting a reduced importance of ETGs due to more unstable ITGs.

Although gyro-kinetic models when used in their full complexity are found in good match with experimental results, they are computationally too heavy for scenario predictions in present and future machines. These findings point to the need of having quasi-linear models capable of accounting for such recently discovered mechanisms. Results from validation against these JET experiments of last generation quasi-linear models will be discussed.

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[10] Di Siena A. et al., 2017. Submitted to Nucl. Fusion.
[11] Di Siena A. et al., 2017, submitted to Physics of Plasmas.

A new mechanism for increasing density peaking in tokamaks: Improvement of inward particle pinch with edge ExB shearing

J. Garcia[1], H. Doerk[2], T. Görler [2] and JET contributors*
EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1]*CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*
[2]*Max Planck Institute for Plasma Physics,Boltzmannstr. 2, 85748 Garching, Germany*
(*) See the author list of X Litaudon et al. 2017 Nucl. Fusion 57 102001

The peaking of the electron density has significant consequences for tokamak plasmas. Whereas it can be an important source of bootstrap current, which can reduce the necessity of ohmic or external current drive current for achieving steady-state scenarios, it can also enhance the influx of high Z impurities, like tungsten, which can lead to significant core radiation.

Several mechanisms have been put forward for explaining such peaking. On the one hand, the core particle sources, mainly from the Neutral Beam Injection heating, play a significant role in plasmas from JET [1,2], however, such mechanism is unlikely to be relevant in ITER due to the low source contribution from NBI. On the other hand, the plasma collisionality has been identified as a key parameter from the analyses of experimental results, showing a significant increase of density peaking with lower collisionality [3]. Gyrokinetic analyses made mostly with the quasi-linear approach explain such behavior from the change of outward to inward pinch when the turbulence plasma characteristics change from mostly Trapped Electrons Mode (TEM) to Ion Transport Gradient (ITG) mode with decreasing collisionality [4]. This has significant consequences for future plasmas like the ones expected in ITER which will have very low collisionality and hence high density peaking is expected.

In this paper, a new mechanism contributing to the increase of density peaking has been found from extensive non-linear gyrokinetic simulations performed with the GENE [5] code for a JET hybrid discharge. The thermodiffusion part of the particle pinch becomes more inward with increasing ExB shearing and more outward with Parallel Velocity Gradient (PVG) by, otherwise, preserving the ITG nature of these plasmas. Dedicated analyses of the particle flux show that the ExB shearing reverses the higher ky part of the flux while the lower ky remains unchanged. The PVG has the opposite trend showing that the total pinch direction highly depends on the balance of ExB and PVG mechanisms. This effect becomes stronger the closer to the pedestal top leading to a very strong inward pinch in highly rotating plasmas.

Integrated modelling simulations performed with the CRONOS [6] suite of codes and different quasi-linear models for heat and particle transport show that such models are able to partially capture GENE results. Scans performed on the ExB shearing demonstrate that the density peaking significantly increases with edge ExB through a core-edge effect. This effect breaks the paradigm of density peaking mainly stablished by collisionality and have strong implications for ITER extrapolations as the ExB shearing is expected to be low in such device.

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Comparison of gradient and flux driven gyro-kinetic turbulence

F. Rath, A.G. Peeters, R. Buchholz, S.R. Grosshauser, F. Seiferling, and A. Weikl
University of Bayreuth, Physics department, 95440 Bayreuth, Germany

Flux and gradient driven ion temperature gradient turbulence in tokamak geometry and for Cyclone base case parameters are compared in the local limit using the same underlying gyrokinetic turbulence model.
Gradient driven approach: The gradient driven turbulence described, using the flux tube model with periodic boundary conditions, has a finite ion heat flux Qi $\approx 10 n_0 T_0 \rho_*^2 v_{th}$ (n_0 (T_0) is the background density (temperature), $\rho_* = \rho/R$ is the normalized Larmor radius, R is the major radius of the device, and vth is the ion thermal velocity) at the nonlinear threshold of the temperature gradient length for turbulence generation (hereafter termed finite heat flux threshold). Consequently, the gradient driven local transport model is unable to accurately describe heat fluxes below $Qi < 10 n_0 T_0 \rho_*^2 v_{th}$, since no stationary fully developed turbulent state can be obtained. This limitation of the gradient driven model is attributed to the generation of quasi-stationary structures in the radial profile of sheared zonal flows, known as staircases [Dif-Pradalier, Phys. Rev. E 82, 025401 (2010)]. Above the finite heat flux threshold staircases dissappear allowing for the development of a stationary turbulence state. The development of the staircases below $Qi = 10 n_0 T_0 \rho_*^2 v_{th}$ and the connected suppression of the turbulence involves very long time scales and is shown to be sensitive to the numerical dissipation scheme chosen. This possibly explains, why the finite heat flux threshold has been overlooked so far. The impact of collisions on the finite heat flux threshold is discussed and it is shown that this phenomenon persists for reactor relevant collision frequencies. Furthermore, possible mechanisms for the regulation of staircases as well as the development of the finite heat flux at the threshold are discussed. First, the damping of zonal flows through tertiary instabilities is shown not to be relevant, since zonal flows typically are situated in the stable parameter regime of this kind of instability. Second, the damping of zonal flows through turbulent transport of parallel momentum is advocated to be responsible for the development of a finite heat flux at the threshold.
Flux driven approach: The turbulence in the flux driven case shows intermittent behaviour and avalanches for $Qi < 10 n_0 T_0 \rho_*^2 v_{th}$. Isolated avalanches disappear for $Qi > 10 n_0 T_0 \rho_*^2 v_{th}$, and at higher heat fluxes, the statistics of the turbulence is the same for the flux and gradient driven case. The nonlinear upshift of the temperature gradient length threshold for turbulence generation is larger in the case of flux driven turbulence. This higher nonlinear upshift is related to the development of quasi-stationary corrugations in the temperature profile being related to the staircase structures. Avalanches are initiated at specific locations with respect to the staircase pattern and have roughly the same radial extent of 50-70 ion Larmor radii.

Synergies between neoclassical ant turbulent impurity transport

P. Donnel, X. Garbet, Y. Sarazin,V. Grandgirard, Y. Asahi, N. Bouzat,E. Caschera,G. Dif-Pradalier, P. Ghendrih, C.Gillot, G. Latu, C. Passeron

Impurity transport is an issue of utmost importance for fusion. One reason is the choice of tungsten for ITER divertor. Indeed high-Z materials are only partially ionized in the plasma core, so that they can lead to prohibitive radiative losses even at low concentrations, and impact dramatically plasma performance and stability. On-axis accumulation of tungsten has been widely observed in tokamaks. While the very core impurity peaking is generally attributed to neoclassical effects, turbulent transport could well dominate in the gradient region at ITER relevant collisionality. The transport of helium ashes and medium-Z impurities also results from both neoclassical and turbulent transport. Up to recently, first principles simulations of corresponding fluxes were performed with different dedicated codes, implicitly assuming that both transport channels are separable and therefore additive. One of the key questions is whether this assumption is valid.

Preliminary simulations obtained with the gyrokinetic code GYSELA have shown clear evidences of a neoclassical-turbulence synergy for impurity transport [1]. However no clear theoretical explanation was given. New simulations have been done using a new and more accurate collision operator [2], improved boundary conditions and more flexible sources. This new collision operator has been benchmarked against neoclassical theory. In particular, analytical predictions of the pinch velocity and screening factor are recovered. The new simulations confirm the neoclassical-turbulence synergy and allow identification of mechanism(s) that underly this synergy.

Several possible mechanisms to explain the observed synergies have been identified. First, turbulence is known to induce poloidal anisotropies which may modify significantly neoclassical flows [3]. This mechanism appears to be efficient to - at least partly - explain the observed synergies. An analytical prediction for turbulent generation of convective cells has been proposed [4] and is currently compared with results of GYSELA. Second, a mechanism was proposed in the context of bootstrap current modification by turbulence [5]: it relies on the fact that turbulence induces a diffusion both in radius and velocity. This diffusion may affect parallel flows and heat fluxes thus changing the neoclassical prediction of radial impurity transport. Finally, neoclassical transport can lead to density peaking of the impurity thus leading to a local breakdown of the trace assumption. The electric potential created can then act on turbulence. The respective role of these different mechanisms will be assessed and discussed.

References

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Intrinsic Rotation in Axisymmetric Devices

Timothy Stoltzfus-Dueck

Princeton Plasma Physics Laboratory

Toroidal rotation is critical for fusion, since it stabilizes instabilities that can otherwise cause disruptions or degrade confinement. Unlike present-day devices, ITER might not have enough neutral-beam torque to easily avoid these instabilities. We must therefore understand how the plasma rotates “intrinsically,” that is, without applied torque. Experimentally, torque-free plasmas indeed rotate, with profiles that are often non-flat and even non-monotonic. The rotation depends on many plasma parameters including collisionality and plasma current, and exhibits sudden bifurcations (“rotation reversals”) at critical parameter values.

Since toroidal angular momentum is conserved in axisymmetric systems, and since experimentally inferred momentum transport is much too strong to be neoclassical, theoretical work has focused on rotation drive by nondiffusive turbulent momentum fluxes. In the edge, intrinsic rotation relaxes to a steady state in which the total momentum outflux from the plasma vanishes. Ion drift orbits, scrape-off-layer flows, separatrix geometry, and turbulent intensity gradient all play a role. In the core, nondiffusive and viscous momentum fluxes balance to set the rotation gradient at each flux surface. Although many mechanisms have been proposed for the nondiffusive fluxes, most are treated in one of two distinct but related gyrokinetic formulations. In a radially local fluxtube, appropriate for $\rho_* \ll 1$, the lowest-order gyrokinetic formulations exhibit a symmetry that prohibits nondiffusive momentum flux for nonrotating plasmas in an up-down symmetric magnetic geometry with no $\boldsymbol{E} \times \boldsymbol{B}$ shear. Many symmetry-breaking mechanisms have been identified, but none have yet been conclusively demonstrated to drive a strong enough flux to explain commonly observed experimental rotation profiles. Radially global gyrokinetic simulations naturally include many symmetry-breaking mechanisms, and have shown cases with experimentally relevant levels of nondiffusive flux. These promising early results motivate further work to analyze, verify, and validate.

Intense ongoing research promises rapid progress in our physical understanding, as more detailed theory-experiment comparisons enable us to move towards a first-principles predictive capability allowing projection to ITER.

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Theoretical studies and simulations of mode structure symmetry breaking in tokamak plasmas

Z. X. Lu[1], X. Wang[1], A. Bottino[1], E. Fable[1], W. Hornsby[1], Ph. Lauber[1], F. Zonca[2], C. Angioni[1]
[1]*Max-Planck-Institut für Plasmaphysik, Garching, Germany*
[2]*C.R. ENEA Frascati - C.P. 65, 00044 Frascati, Italy*

The symmetry breaking of the mode structure, as described by finite flux surface averaged parallel wavenumber $\langle k_{||} \rangle$ and poloidal angle $\langle \theta \rangle$, is important for estimating the off-diagonal component of momentum flux [1]. Energetic particles (EPs) bring in new features of symmetry breaking and in turn, the EP behaviors can be affected by symmetry breaking [2]. In this work, theoretical methods are developed and simulations are performed to study the symmetry breaking of the ion temperature gradient (ITG) mode and beta induced Alfvén eigenmode (BAE). The results are compared with ORB5 and GKW for ITG and XHMGC for BAE.

The Mode Structure Decomposition approach is developed for the symmetry breaking study of the ITG mode for which poloidal harmonics are strongly coupled [3,4]. A complex ballooning parameter is introduced to include the symmetry breaking due to the "profile shearing" [5] and the turbulence intensity gradient [6] on the same footing in tokamak geometry. The agreement with GKW and ORB5 simulation is shown. "Global-oriented local simulations" are suggested where global symmetry breaking properties are taken into account in the local model.

For the BAE problem, the weak coupling formula is adopted with EPs' non-perturbative effect taken into account. The theoretical global analysis and HMGC simulation demonstrate the essence of "boomerang" structures with/without asymmetric tails in the poloidal plane as well as the radial and parallel symmetry breaking [7]. Global effects and the non-perturbative EP response are important ingredients for the symmetry breaking and their effects on EP transport as well as the implications to experimental observations using ECEI are discussed.

Further studies based on theoretical analyses and ORB5/XHMGC simulations explore the symmetry breaking in broader parametric regimes, with the consideration of higher frequency AEs such as reversed shear Alfvén eigenmode (RSAE). The EPs effects on radial mode width, momentum transport, residual zonal flow and other nonlinear behaviors are discussed.

ZL appreciates input from A. Koenies, A. Mischenko, A. Biancalani, O. Maj and E. Poli, and T. Hayward-Schneider. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Spectral gyrokinetic implementation of rotation, rotation shear and profile shear

J. Candy and E.A. Belli

General Atomics, P.O. Box 85608, San Diego, CA 92186

Sonic toroidal plasma flow, on the order of the ion sound speed, arises in tokamaks due to external torque driven by neutral beam injection. This flow often has a profound effect on the intensity of drift-wave turbulence and corresponding levels of radial transport. In practice, gyrokinetic theory and simulation tend work almost exclusively in the weak rotation limit, retaining only the $\mathbf{E} \times \mathbf{B}$ flow, Coriolis drift and toroidal rotation shear. However, correct treatment of the sonic rotation regime requires the inclusion of centrifugal effects, which are quadratic in the Mach number. In 1998, Sugama worked out a complex but comprehensive formulation of gyrokinetic theory – including sonic rotation and associated centrifugal terms – which is valid in the case of general electromagnetic perturbations [1]. This formulation, importantly, includes the corresponding particle, energy, momentum and exchange transport coefficients which are required to obtain the correct equations for profile evolution. We show that the most general implementation is critically important for the study of heavy impurity transport. In particular, nonlinear turbulent fluxes for tungsten at finite Mach number are heavily modified by the new terms, even though the deuterium ions and electrons are relatively unaffected. To this end, we discuss the implications for detrimental core tungsten accumulation in a reactor, and remark that for realistic tungsten modeling, both turbulent and neoclassical transport must be considered. These claims are based on neoclassical simulations with NEO, together with quasilinear and nonlinear simulations with CGYRO.

In addition, we also discuss a new approach for the implementation of shear in the $\mathbf{E} \times \mathbf{B}$ flow. This shear is different than the previous rotation terms in that it cannot be treated simply or directly in a flux-tube. In the past, ExB shear is treated using either non-periodic boundary conditions, or in the case of flux-tube codes, using a discontinuous wavenumber shift method [2]. We report on the development of a new algorithm that is continuous and can treat the shear with spectral accuracy. Because the new algorithm may also be used to treat profile shear, it is well-suited to treat multiscale gyrokinetic simulations in the steep-gradient pedestal region.

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TUESDAY, August 28, 2018

The study of multi-scale interaction and parity in turbulence/MHD system based on global flux driven simulation

A. Ishizawa
Graduate School of Energy Science, Kyoto University, Uji, Janan

Turbulent transport is significantly influenced by the presence of magnetic island. The heat transport is enhanced inside the separatrix of the island, because meso-scale fluctuation is enhanced by the coexistence of the island and turbulence, while a steep temperature gradient is formed just inside the radius of the rational surface of the island, because strong flow shear suppresses the turbulence at the separatrix as shown by flux-driven global gyrofluid simulations [1]. This happens even if the growth rate of tearing mode is smaller than drift-wave instability, because the island suppresses drift-wave turbulence, so that the large eddy of tearing mode is stronger than the small eddy due to drift-wave instability, and dominates turbulence [1]. This dominance of the large eddy is a general feature of multi-scale interactions in magnetically confined plasmas. On the other hand, turbulence influences the threshold of the appearance of magnetic islands. Turbulence drives and sustains magnetic islands of width equal to multiples of the Larmor radius through the nonlinear multi-scale interactions [2]. These multi-scale interactions are recently observed by experiments in DIII-D, H2LA, and KSTAR.

The parity symmetry plays crucial role in these multi-scale interactions between turbulence and magnetic islands. This is because only the odd parity mode satisfies the nonlinear gyrofluid/gyrokinetic equations [3]. Here, magnetic islands belong to the odd parity mode and drift-wave turbulence normally belongs to the interchange/ballooning parity (even parity) mode. Since both modes satisfy the linearized equations, the parity of interchange/ballooning mode is conserved in its linear growth. However, when the amplitude of the mode becomes finite and nonlinear effects are dominant, the pure interchange/ballooning mode does not satisfy the nonlinear equations. Hence, the nonlinear energy transfer takes place from the even parity mode (interchange/ballooning mode) to the odd parity mode (magnetic islands). Through this process, the magnetic islands are produced by turbulence, this is called nonlinear parity mixture. A typical nonlinear parity mixture is presented in terms of modulational instability analysis of zonal flow production. In the modulational instability, zonal flow and a side-band mode grow with the same growth rate, and this side-band mode is actually magnetic islands produced by the pump mode representing turbulence in electromagnetic systems [3]. These are found by global gyrofluid simulations, and some global gyrokientic simulation results will be reported as well.

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THE SPECTRAL PROBLEM IN KINETIC-MHD AND APPLICATIONS TO BETA-DRIVEN INSTABILITIES

S. Lanthaler, J. P. Graves, W. A. Cooper
Ecole Polytechnique Ferale de Lausanne (EPFL),
Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

Analytical theory and numerical simulations have shown that the linear stability of beta-driven internal modes such as the 1/1 internal kink mode and interchange modes can be strongly influenced by kinetic effects due to suprathermal [1] and thermal ions [2, 3, 4], as well as centrifugal effects associated with toroidal rotation [5]. In rotating plasmas, centrifugal effects can lead to a strong coupling of perpendicular and parallel dynamics. This dependency on the parallel dynamics further motivates a kinetic-MHD approach [6]. In the present work, a hybrid kinetic-MHD model is derived based on the corrections to the guiding-centre equations given in [7], allowing for sonic plasma rotation. It is shown that in the limit of vanishing plasma rotation, the results of [1] are recovered. Higher-order finite Larmor-radius corrections to the pressure tensor are discussed. The derived model also recovers the quasi-neutrality equation in the form given in [2], and can be used to study the effects of a parallel electric field [3] in rotating plasmas. The model is implemented in a novel hybrid kinetic-MHD code, VENUS-KMHD. The solution of the kinetic equation is based on the exact integration of guiding-centre orbits with the VENUS-LEVIS code [8], which allows radial drifts and the associated corrections to the inertia [4] to be taken into account without further approximations. Combining this kinetic solver with a newly developed linear MHD stability code, also presented here, the linearized kinetic-MHD equations are then formulated as an eigenvalue problem. We apply VENUS-KMHD to study centrifugal and kinetic effects on internal beta-driven modes.

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The feeder pellets and the killer pellets in a plasma

B.N. Breizman[1], P. B. Aleynikov[2], A.K. Fontanilla[1], P. Helander[2],
H.J.C. Oliver[1, 3], S. E. Sharapov[3]

[1]*Institute for Fusion Studies, University of Texas, Austin, Texas, USA*
[2]*Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*
[3]*CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK*

breizman@mail.utexas.edu

Pellet injection is used to refuel the plasma, control edge-localized modes, and mitigate disruptions. This talk covers several aspects of pellet assimilation physics, potential benefits for MHD spectroscopy, pellet impact on electron-ion energy exchange, thermal quench and runaway electron suppression.

Heat flux from the ambient plasma causes pellet ablation. The ablated material flows away from the surface and partially shields the pellet. Calculation of the resulting ablation rate requires self-consistent solution of the fluid equations for the flow and the kinetic equation for the hot electrons. This problem simplifies a great deal in the case of high-Z pellet where hot electrons are nearly isotropic and diffuse spatially into the ablation cloud until they lose energy due to collisional friction. An outer part of the ablation cloud is governed by a self-similar solution in which the temperature scales as the two-thirds power of the radial coordinate.

Pellets typically disassemble on timescales of several millisecons. The ablated material breaks the toroidal and poloidal symmetry of the plasma density profile. This asymmetry modifies the Alfvén continuum and eigenmode structure significantly via coupling poloidal and toroidal harmonics, which is a likely scenario in JET experiments.

In a plasma with cold ions, ambipolar expansion of the dense ablation-produced plasma should convert electron thermal energy into the ion energy more efficiently then Coulomb collisions in a way similar to ion acceleration in laser-irradiated clusters.

In the case of high-Z pellet injection, radiative losses play an important role in energy balance. The pellet leaves a dense plume of impurity ions along its path through the plasma, which can enhance the radiative losses dramatically compared to the case of uniformly distributed impurities. This aspect is essential for proper modeling of the thermal quench as a prerequisite of runaway electron production.

Effect of partially ionized impurities and radiation on the effective critical electric field for runaway generation

L Hesslow[1], O Embréus[1], G J Wilkie[1], G Papp[2] and T Fülöp[1]

[1]Department of Physics, Chalmers University of Technology, 41296 Gothenburg, Sweden
[2]Max-Planck-Institute for Plasma Physics, D-85748 Garching, Germany

E-mail: hesslow@chalmers.se

Abstract. Unmitigated runaway electron beams can damage tokamaks so severely that every event must be successfully mitigated in large devices such as ITER. The currently envisaged mitigation method utilizes heavy-impurity injection, but existing models generally employ crude descriptions of the interaction between fast electrons and the partially ionized impurities in a cold, post-disruption plasma.

In this contribution, we describe an analytical formula for the effective critical electric field for runaway generation and decay that accounts for the presence of partially ionized impurities in combination with synchrotron and bremsstrahlung radiation losses. We show that the effective critical field is drastically larger than the classical Connor–Hastie field, and even exceeds the value obtained by replacing the free electron density by the total electron density (including both free and bound electrons). Using the kinetic equation solver CODE [1] with a self-consistent inductive electric field, we show that the runaway current decay after an impurity injection is expected to be linear in time and proportional to the newly derived effective critical electric field in highly inductive tokamak devices. This is relevant for the efficacy of mitigation strategies for runaway electrons, since the higher critical electric field significantly reduces the required amount of injected impurities to achieve a certain current decay rate.

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Penalized limiter configuration in GYSELA gyrokinetic global and flux driven simulations

E. Caschera[1], P.Ghendrih[1], G. Dif-Pradalier[1], V.Grandgirard[1], Y.Asahi[1], N.Bouzat[1], P. Donnel[1], C.Gillot[1], X. Garbet[1], G.Latu[1], C. Passeron[1], and Y.Sarazin[1]

[1] *CEA, IRFM, Saint-Paul-lez-Durance, F-13108, France*

To control and predict energy confinement in fusion plasmas is one of the current critical issues for ITER. The turbulent nature of heat transport from the core towards the edge makes analytical descriptions very complex. Numerical simulations support both theoretical and experimental analysis in understanding and charachterizing plasma energy transport. Global and flux-driven gyrokinetic simulations are one the most complete descriptions of the plasma system. In flux-driven frame a heat source located in the very core region builds plasma profiles, which are free to evolve and in turn give rise to turbulence, as it happens in experiments. The outer boundary layer of the simulation domain acts as a heat sink in which the heat flux is exhausted. The way this physics is implemented is of crucial importance for turbulence self-organisation. Including as much as possible of this physics in numerical simulations is part of the current challenges of fusion research.

In this presentation we show how boundary conditions of the code GYSELA have been improved towards limiter configuration. The presence of a solid object in contact with plasma, toroidally symmetric, is modeled as an immersed boundary inside the simulation domain. A mask function defines the geometry of the wall, poloidally symmetric but radially localized outer region, and limiter region, poloidally localized and protruding radially from the wall. Inside the mask, a restoring force drives the distribution function towards a target value at low temperature and acts as a heat absorber as the solid matter would do. Hence the limiter is a cold spot inside the plasma volume. With such geometry, a Scrape-off Layer (SOL) region, in which parallel transport competes with perpendicular one, is generated inside the simulation domain. A cold front propagation from the limiter is recovered in the SOL when only parallel transport is taken into account. The velocity of the cold front agrees with the theoretical value up to 10^{-3} relative error. This SOL layer provides a new and more realistic boundary for core turbulence development.

Furthermore quasi-neutrality equation has been modified to include the gap of electric potential arising in the sheath layer to confine electrons. A reversal of radial electric field is recovered at separatrix, as observed in experiments. Preliminary results of turbulent simulations show a cosinusoidal structure of electric potential developing at separatrix and increasing of the fluctuations level in the edge region. The shearing of the electric field appears to drive this effect, which would be consistent with Kelvin-Helmholtz instability. The impact of the new boundary condition on confinement is being addressed, including investigations on the size and poloidal location of the limiter.

Simulating background toroidal flow shear with the local gyrokinetic code GS2

N.Christen[1], M.A.Barnes[1], F.I.Parra[1]
[1]*Rudolf Peierls Centre for Theoretical Physics, University of Oxford, UK*

Microscale turbulence is a limiting factor for the core densities and temperatures that can be sustained in a tokamak. Experimental, theoretical and computational results have shown that the presence of shear in the background toroidal rotation can substantially affect turbulent transport: shear in the flow perpendicular to the mean magnetic field has been found to reduce transport, while a gradient in the parallel flow can enhance transport [1] [2]. Hence, flow shear is an important aspect to consider in simulations.

Local, δf gyrokinetic codes treat flow shear by approximating time-dependent radial wave numbers by their nearest neighbours on a fixed grid. For the moderate flow shear values observed in many experiments, the radial wave number evolves very slowly; this leads to long periods in which the flow shear has no effect interspersed with occasional, discontinuous jumps in wave number. In order to avoid this potentially unphysical behavior, we consider here an improved algorithm that treats flow shear continuously in time.

We present two alternative algorithms that have been implemented in the local, δf gyrokinetic code GS2. Linearly, GS2 is implicit in time and it uses a “response matrix” approach to solve the gyrokinetic equation. In the presence of flow shear, this large matrix becomes time dependent, and recomputing it at every time step is prohibitively slow. Our first algorithm relies on interpolation to approximate the time dependence. Our second algorithm removes the time dependence from the response matrix using the following trick. In the gyrokinetic equation, for each term that becomes time dependent due to flow shear, we add and substract that term evaluated at the nearest wave number on the grid. The difference between the exact time dependent term and the nearest neighbour term is small and can be treated explicitly, such that the remaining implicit term is now independent of time. We then present linear and nonlinear simulations comparing the two new approaches with the old code, focusing on cases that we expect to be challenging for the old implementation.

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Searching for the Secondary Instabilities in Magnetically Confined Plasmas

A.V. Dudkovskaia[1], X. Garbet[2], M. Lesur[3], H.R. Wilson[1,4]

[1] *York Plasma Institute, Dept. of Phys., University of York, Heslington, York YO10 5DD, UK*

[2] *CEA Cadarache,13108 St Paul Lez Durance, France*

[3] *IJL, Lorraine University, 34 Cours Leopold, 54000 Nancy, France*

[4] *CCFE, Culham Science Centre, Abington Oxon OX14 3DB, UK*

The particle-wave interaction plays a key role in a variety of applications and is essentially important in a burning tokamak plasma since alpha particles would provide the main heating source in a reactor. The energetic ion beams produced by NBI or ICRH as well as alpha particles can drive the Alfven modes and other instabilities of this type. These instabilities can lead to detrimental losses of the energetic particles. Thus, mitigation, control and the advanced prediction of the mode behaviour is crucial for a tokamak operation.

A population of high energy particles might drive a primary instability, which often evolve towards the formation of an island structure in phase space. The steepening of the distribution function at the edge of these phase space islands may excite a secondary instability, which in turn trigger the formation of a hole/clump pair. This hole/clump formation mechanism was advocated by Lilley et al.

In a tokamak, different nonlinear regimes can be gathered under the umbrella of the bump-on-tail instability. In our work, we intend to produce a generic model, able to address a variety of nonlinear problems in tokamaks, going from NTMs to instabilities driven by energetic particles. Using the Hamiltonian formalism allows us to extend our electrostatic problem to a tokamak case and to draw an analogy between phase space islands and the NTM magnetic islands that occur due to a plasma current density filamentation. Unlike other previous works [1-3], searching for the secondary instabilities, we start with a calculation of the fully nonlinear primary equilibrium that accounts for the presence of the phase space island. In our model we have found a full solution of the reduced kinetic equation in a presence of the effects of pitch angle scattering, velocity diffusion and dynamical friction. It is then considered as a new primary equilibrium state to search for the secondary instabilities. We refer again to the Fokker-Planck equation solving it perturbatively and deriving a dispersion function. The results of the stability analysis demonstrate an occurrence of the secondary modes in a certain range of plasma parameters and wave numbers.

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Why trapped electrons damp GAMs

C. Ehrlacher, X. Garbet, V. Grandgirard, Y. Sarazin, P. Donnel,

E. Caschera, G. Dif-Pradalier, P. Ghendrih, G. Latu, D. Zarzoso*

CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France.

**Aix-Marseille Université, CNRS, PIIM, UMR 7345 Marseille, France*

Gyrokinetic codes are often verified by applying the Rosenbluth-Hinton test, which consists in launching a zonal perturbation of the flow and characterizing its time evolution. This test provides the residual value of the flow, as predicted by Rosenbluth and Hinton [1], and also the pulsation and damping rate of the Geodesic Acoustic Mode (GAM). The GAM complex frequency is well documented in the particular case of a single ion species with adiabatic electrons [2,3]. It usually agrees well with simulations.

However kinetic electrons change drastically this picture. While the residual flow and the GAM frequency are mostly unchanged, the GAM damping rate increases significantly [4,5] . This is due to a resonance between the GAM and trapped electrons that is responsible for a transfer of energy from the mode to particles, hence a mode decay. In principle such a resonance is not possible since the electron bounce frequency is much larger than the ion sound frequency. However barely trapped electrons spend a long time near the bounce point, so that their bounce pulsation is low enough to match the GAM frequency. Hence trapped electrons are mostly responsible for GAM damping [4,5].

The analytical calculation of the GAM damping rate due to trapped electrons does not seem to be available in the literature. The present work provides a detailed expression, and an explicit upper bound. This expression recovers the scaling in electron to ion mass ratio obtained in simulations. However the scaling with the safety factor and ratio of electron to ion temperature disagree with numerical findings. These results will be discussed and commented.

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Flux-driven simulations and profile stiffness investigation using the global gyrokinetic code ORB5

E. Lanti[1], B. F. McMillan[2], S. Brunner[1], N. Ohana[1], L. Villard[1]

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

[2] Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry, UK

E-mail: `emmanuel.lanti@epfl.ch`

Abstract.
ORB5 is a global gyrokinetic code being developed by many scientists over the last 20 years. It relies on the δf technique which assumes a scale separation between the background and perturbed quantities and allows to perform so-called gradient-driven simulations. In this paradigm, background profiles such as density and temperature are assumed to be constant in time and an adaptive source is used to relax the zonal component of the perturbed distribution function so that the total distribution function does not deviate too much from the equilibrium background.

Even though the gradient-driven model is useful due to its relatively low numerical cost (there is no need to perform simulations over transport time scales) it does not reflect the experimental reality where fluxes are prescribed by the actual heat sources. Furthermore, comparison between experimental and gradient-driven numerical predictions of the heat fluxes is a challenging task because of the profile stiffness: a small change, within experimental error bars, in the imposed temperature gradients leads to a large variation of the computed heat fluxes.

To address the stiffness problem, the ORB5 code has been adapted to be able to run flux-driven simulations. In this model, fluxes are prescribed by a radially localized heat source and sink and the background profiles slowly evolve toward a quasi-steady state. As a first step toward complete flux-driven simulations, a mixed-mode is used, in which the run is started in the gradient-driven mode and then continued in flux-driven mode. This allows us to keep the numerical cost relatively low as a quasi-steady state is more quickly reached.

In this work, we present the heat source implemented in ORB5 to perform the flux-driven simulations as well as the numerical technique used to ensure that no other moment is injected by the source up to machine precision. Furthermore, simulation results illustrating the mode switching between gradient- and flux-driven as well as results of an L-mode pedestal and core profiles ITG power scan similar to [L. Villard *et al.*, 2014, *JPCS* **561**] will be shown. Preliminary results of TEM dominated cases will be also presented.

Linear and non-linear gyrokinetic simulations of zonal structures

I. Novikau[1], A. Biancalani[1], A. Bottino[1], P. Manz[1], E. Poli[1], A. Di Siena[1], T. Görler[1], L. Villard[2], and E. Lanti[2]

[1]*Max-Planck-Institut für Plasmaphysik, 85748 Garching Germany*
[2]*Ecole Polytechnique Fédérale de Lausanne, Swiss Plasma Center, Switzerland*

Turbulence in tokamaks generates radially sheared zonal stuctures (ZSs). Two kinds of ZSs exist, that is zero-frequency zonal flows (ZFs) and finite frequency geodesic acoustic modes (GAMs). Understanding the interactions of the ZSs with the plasma micro-instabilities and their role in the turbulence regulation is of a high importance for the improvement of the plasma confinement.

In the first part of this work, the linear dynamics of the ZSs is studied with gyrokinetic (GK) particle-in-cell code ORB5. One of the main advantages of a GK code, with respect to fluid codes, is to include the wave-particle interaction in the dynamics. In order to investigate the location and importance of the resonances in the phase space, which are responsible for the Landau damping of a mode, a dedicated diagnostics has been developed in ORB5. This diagnostics is crucial for understanding the role of each species (thermal ions, thermal electrons, impurities, energetic particles, etc) in driving or damping a mode. It has been used to show the resonance between the GAMs and the electrons.

In the second part of this work, we investigate the excitation of the GAMs and ZFs and their radial structure in non-linear GK simulations. A weakly driven regime, where GAMs manifest their properties close to the linear ones, is identified. In particular, the GAMs show a continuous spectrum, and in a good agreement with linear predictions. The radial structure of the ZFs is also discussed. Comparison with other regimes is done, and a realistic AUG case is chosen as an application. Furthermore, comparisons with the GK eulerian code GENE are also shown. The final goal of this study is to understand the formation of the radial structure of these modes and its influence on the radial particle and heat fluxes.

Fundamental global properties and frequency shift of geodesic acoustic modes in shaped axisymmetric toroidal plasmas

C. Wahlberg[1] and J. P. Graves[2]

[1] *Department of Physics and Astronomy, P.O. Box 516, Uppsala University, SE-751 20 Uppsala, Sweden*
[2] *École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Association EURATOM-Confédération Suisse, 1015 Lausanne, Switzerland*

The study of geodesic acoustic modes GAMs) in tokamak plasmas is not solely academic. Global goedesic modes are observed in experiments, the structure of which associated with improved plasma properties. The advantage of gyro-kinetic approach for the modelling of GAMs is that causality and sustainment of GAMs can in principle be self-consistently included. In contrast, the advantage of a linear development using the ideal MHD model is that higher order geometric effects can be included analytically, and the results verified easily against experimental observation. Naturally encompassing magnetic fluctuations, global effects, and extensions beyond the plasma-vacuum interface, the MHD model has been used [1] to model the mode spectrum of magnetic fluctuations measured in TCV. The effects of toroidicity and shaping being manifest in the poloidal mode spectra. In the current contribution we calculate the GAM frequency to yet higher order in a smallness parameter associated with the metric tensor, and obtain a new triangularity dependence that appears to agree with new TCV experimental results [2]. Perhaps more importantly, we solve for the global structure of the GAM flows, reconciling the generic singularities $[1/(\psi-\psi_0)$ and $\log(\psi-\psi_0)]$ of continua in an up-down symmetric torus [3], and extending those local perturbations from the axis to the plasma edge. It is hoped that these advances will be used not only for further empirical comparison, but for the verification of advanced gyro-kinetic codes.

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Gyrokinetic analysis of global effects on the zero particle flux condition in a TCV plasma

A Mariani*[1], S Brunner[2], G Merlo[3], and O Sauter[2]

[1] *Istituto di Fisica del Plasma IFP-CNR, Via R. Cozzi 53, 20125 Milano, Italy*
[2] *École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), 1015 Lausanne, Switzerland*
[3] *University of Texas at Austin, Austin, TX 78712, USA*

In small-sized tokamaks, finite ρ^* effects could lead to a significant discrepancy between gyrokinetc local flux-tube results and global ones. This has been shown in previous turbulent transport studies of TCV discharges using flux-tube models, addressing internal transport barriers [1] and plasma shaping effects [2]. The impact of such effects on the zero particle flux condition is investigated here. The zero particle flux condition is useful to reduce the uncertainty on physical input parameters derived from experimental measurements, for cases where the particle source is negligible. This constraint had already been applied to the analysis of a particular TCV discharge, where a detailed reconstruction of the zero particle flux hypersurface in the multidimensional physical parameter space at fixed radius had been presented in [3]. Here, we extend these results, investigating their radial dependence, together with the possible impact of global effects. The ρ^* effects are analysed by simulating a plasma annulus corresponding to the stiff region $0.4 < \rho_{\mathrm{tor}} < 0.8$. Because of the computational cost of the non-linear global gyrokinetic simulations, we restrict to a two species plasma in the collisionless regime, with heavy electrons and simplified density and temperature radial profiles. Making use of an iterative approach for modifying the profiles, it has been possible to identify a density profile that, including global effects, verifies the condition of zero particle flux at each radii. The current results are based on gradient driven simulations. With these simplifications, for the case considered, the results seem to point out that the global effects on the zero particle flux could be less significant then originally expected from related studies [1, 2].

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*mariani@ifp.cnr.it

Nonlinear simulations of ELM cycles and inter-ELM activity in comparison to experimental results

A. Cathey*[1], M. Hoelzl[1], M. G. Dunne[1], F. Mink[1], E. Wolfrum[1], G.T.A. Huijsmans[2,3], and S. Günter[1]

[1] *Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany*
[2] *CEA, IRFM, 13108 Saint-Paul-Lez-Durance, France*
[3] *Eindhoven University of Technology, Eindhoven, The Netherlands*
**acathey@ipp.mpg.de*

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Abstract

Edge Localized Modes (ELMs) are peeling-ballooning instabilities driven by large pressure gradients and current densities in the edge of high confinement regime (H-mode) plasmas which cause high heat and particle fluxes to the divertor tiles. They have been extensively studied due to their unfavourable (particularly type-I ELMs) and beneficial properties in tokamaks. Type-I ELM crashes expel $\sim 10\%$ of the plasma thermal energy typically within several hundred microseconds to a few milliseconds. After the crash, the pressure gradient and current density at the edge have decreased and in tens of microseconds they rebuild to their pre-ELM crash values. Single ELM crashes have been well described and reproduced using numerical simulations, but their characteristic periodicity still needs to be simulated consistently.

Using equilibrium reconstructed profiles immediately after an ELM crash occurs in an ASDEX Upgrade discharge, the nonlinear reduced MHD code JOREK is used to simulate the inter-ELM phase and the ELM onset. This allows to compare to recent experimental observations which show that specific toroidal harmonics show increased levels of activity at different stages of the inter-ELM phase. We will study the distinct relevant modes throughout the inter-ELM phase and their coupling as the ELM onset approaches. This aims to provide the validation for obtaining later-on realistic type-I ELM crashes.

Study of Ion Cyclotron Heating (ICRH) scenarii and fast particles generation in DTT

A. Cardinali[1], C. Castaldo[1], S. Ceccuzzi[1], G. Granucci[2], R. Maggiora[3], D. Milanesio[3], F. Mirizzi[4], G. L. Ravera[1], A. A. Tuccillo[1]

[1]ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy
[2] Istituto di Fisica del Plasma- CNR, Via R. Cozzi 53, Milano, Italy
[3] Politecnico di Torino, Dipartimento di Elettronica, Torino, Italy
[4] Consorzio CREATE, Via Claudio 21, I-80125 Napoli, Italy

In this study we are establishing the physics of ICRH plasma interaction in the Divertor Tokamak Test facility (DTT) to be realized by Italy, and the most efficient scenarii for bulk ion (or electron) heating and/or fast particle generation. It has been demonstrated that ICRH is a very flexible tool in order to transfer energy to the plasma and to generate fast particles at very high energies. On the basis of the plasma and tokamak parameters, as well as of the antenna design, an assessment of the ICRH scenarii which involves i) frequency choice, ii) power spectrum, iii) minority H and/or ^{3}He heating, iv) Deuterium 2nd harmonic heating, v) fast particles energies, have been investigated by using the well assessed numerical tools: "DISEMAG"[1], "TORIC5"[2] and SSQLFP[3]. Preliminary studies based on minority heating scenarii, being the most efficient scheme for plasma heating, have identified that the most suitable frequency range for DTT is 60-90 MHz. Within this range, the design of ICRH system benefits from a mature technology with reference to the transmission line and its components. Regarding wave generators, both diacrodes or tetrodes are valid candidates, respectively allowing an output power of 1 and 2 MW per tube at 90 MHz for the required pulse length of 100 s. Two antennas, providing a total coupled power of at least 3 MW, are envisaged for the first plasma of DTT with additional launchers to be possibly commissioned during the first years of operation. TOPICA [4] is the reference tool for the launcher design in presence of a plasma load. Simulation results include coupling performance and power spectra that have been used as input parameters for the numerical codes of wave propagation and absorption.

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Simulation study of toroidal flow generation by ECH in non-axisymmetric toroidal plasmas

S. Murakami[1], Y. Yamamoto[1], C. Chang[1], H. Yamaguchi[2],
H. Takahashi[2], K. Nagaoka[2], K. Ida[2], and LHD experiment group[2]
[1]*Department of Nuclear Engineering, Kyoto Univ., Kyoto 615-8540, Japan*
[2]*National Institute for Fusion Science, 322-6 Oroshi, Toki 509-5292, Japan*

Many experimental observations suggest the important role of the plasma flow and its shear in the transport improvement. Spontaneous toroidal flows with no direct momentum input have been observed in many devices with various heating methods such as Ohmic heating and ICRF (ion cyclotron range of frequencies) heating. Among them, spontaneous flows have been observed during ECH (electron cyclotron heating) with no direct momentum input in DIII-D[1], JT-60U[2], KSTAR[3] and LHD.

In LHD, when we applied ECH to the NBI heated plasma, the toroidal velocity profile changed drastically and turned over in the core region. ECH generates a radial flux of supra-thermal electrons in non-axisymmetric plasmas[4]. We assume that the energetic electron current enhances the bulk ion current to cancel the electron current, and this ion cancel current generates the $\mathbf{j} \times \mathbf{B}$ torque, which would play an essential role in causing a toroidal flow. On the other hand, there is another toroidal torque due to the collision of the supra-thermal electrons, which direction is opposite to the $\mathbf{j} \times \mathbf{B}$ torque.

In this study, we investigate the roles of the $\mathbf{j} \times \mathbf{B}$ torque due to the radial current of supra-thermal electrons and the collisional torque by the supra-thermal electrons in the LHD. We solve the 1D diffusion equation of the toroidal flow with NBI torque and two torques by ECH and compare with the LHD experiment results. As a result, the $\mathbf{j} \times \mathbf{B}$ torque generated by ECH is several times larger than the collisional torque of the supra-thermal electrons. The total torque by ECH is the same order as the NBI torque, and its direction is opposite (same) direction to NBI torque in the inner (outer) region.

Also, we evaluate the torque by ECH in the non-axisymmetric tokamaks (finite toroidal field ripples and magnetic perturbations). We find that the significant torque by ECH is obtained in the case the toroidal field ripple > 0.2%.

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Mode excitation by an antenna in global gyrokinetic simulations

N. Ohana[1], L. Villard[1], E. Lanti[1], S. Brunner[1], B. F. McMillan[2], N. Tronko[3], A. Bottino[3], A. Biancalani[3], I. Novikau[3], A. Mishchenko[4]

[1] École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland
[2] Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry, UK
[3] Max Planck Institute for Plasma Physics, Garching, Germany
[4] Max Planck Institute for Plasma Physics, Greifswald, Germany

E-mail: `noe.ohana@epfl.ch`

Abstract.
In order to get a better understanding of the linear and non-linear plasma interaction of microinstabilities and associated turbulence with different specific modes, an antenna is implemented in the global gyrokinetic code ORB5. It consists in applying external charge and current density perturbations or, alternatively, external electrostatic and magnetic potentials, to the system. The contributions of the antenna and plasma perturbed fields are considered separately and, optionally, the plasma response can be linearized by neglecting the perturbed plasma field contribution in the particle orbits.

In a first step, we will use this antenna to excite zonal structures. As a proof of principle, we will start by scanning the shearing rate of the applied $E \times B$ flow and measure its effect on the linear growth rate of electrostatic instabilities such as ion temperature gradient (ITG) instabilities or trapped electron modes (TEMs). Second, we will consider time-dependent antenna excitations to address the effectiveness of corresponding non-stationary $E \times B$ sheared flows in stabilizing such modes. Third, the nonlinear plasma response will be included so as to study the effectiveness of oscillatory sheared flows to saturate turbulence. The antenna will also be used to excite geodesic acoustic modes (GAMs) and study their coupling with microinstabilities. We will then address the question of the origin of non-linear zonal structures (avalanche-like features) observed to propagate at a frequency close to the one of GAMs.

Future work may also include toroidal Alfvén eigenmodes (TAEs) excitation by the antenna.

$\boldsymbol{E} \times \boldsymbol{B}$ and diamagnetic equilibrium flows effects on pedestal localised MHD infernal stability

D Brunetti*[1], J P Graves[2], E Lazzaro[1], A Mariani[1], S Nowak[1], W A Cooper[2], and C Wahlberg[3]

[1] *Istituto di Fisica del Plasma IFP-CNR, Via R. Cozzi 53, 20125 Milano, Italy*
[2] *École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), 1015 Lausanne, Switzerland*
[3] *Department of Physics and Astronomy, P.O. Box 516, Uppsala University, SE-751 20 Uppsala, Sweden*

Quiescent high confinement (QH) tokamak plasmas share with the standard high confinement regime (H-mode) large edge pressure gradients and high energy confinement times but avoiding the dangerous presence of Edge Localised Modes (ELMs). ELM activity is replaced by long lasting low-n (~ 1) pedestal localised magnetohydrodynamic perturbations called Edge Harmonic Oscillations (EHOs).

The EHOs driving mechanism on which we focus our attention is associated with the so called *infernal* instability. Infernal modes are characterised by toroidicity induced coupling between a fundamental nearly resonant mode and its neighbouring sidebands. They can be driven unstable when β is sufficiently large and the magnetic shear becomes small over a fairly extended region. These two conditions are naturally met at the plasma edge in QH regimes. A vacuum gap separating plasma and the ideal metallic vessel is needed for the existence of such perturbations. Because of the large edge pressure gradient, strong diamagnetic flows are expected. In addition experimental observations indicate that the $\boldsymbol{E} \times \boldsymbol{B}$ flow shear is a key ingredient for EHO generation.

To take these effects into account, we extend the results previously obtained in [1, 2] by including equilibrium poloidal flows and diamagnetic rotation. A Frieman-Rotenberg Lagrangian formalism is adopted for the stability analysis with poloidal flows, while diamagnetic effects are studied within the Eulerian frame. These two effects, first treated separately, are then phenomenologically combined together in order to produce a general dispersion relation. As in [1] the analysis focuses on the particular class of step profiles both for equilibrium density and pressure. This simplification is sufficient to capture the underlying physics while having the macroscopic parameters (q, β, ϵ, wall position etc.) close to JET-like experimental conditions [3]. A bell shaped poloidal flow profile leads to a stabilisation for low m modes, while high m modes simply experience a Doppler shift in their eigenfrequency. If the diamagnetic frequency ($\propto p'$) is assumed to have a δ-like behaviour (consistent with the choice of step equilibrium pressure and density profiles), it is found that high m modes are suppressed.

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*brunetti@ifp.cnr.it

Drift kinetic response of ions to magnetic island perturbation and effects on NTM threshold

K Imada[1], H R Wilson[1,2], J W Connor[2], A Dudkovskaia[1] and P Hill[1]

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

[2] CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, United Kingdom

The evolution of a magnetic island characterising a neoclassical tearing mode (NTM) can be described by the modified Rutherford equation. The transport along perturbed magnetic field lines reduces the radial pressure gradient ($\boldsymbol{\nabla}p$) across the island width, and the resulting hole in the $\boldsymbol{\nabla}p$-dependent bootstrap current profile typically enhances the island width [1]. Not only does this lead to a significant confinement degradation, but it can also lead to a disruption. Therefore, the control of the NTM is essential for successful operation of future tokamaks.

Experimental evidence suggests the presence of a threshold mechanism that stabilises sufficiently small seed islands. One possible source for the threshold is the finite banana width effect [2], which not only modifies the bootstrap current, but also gives rise to the neoclassical polarisation current. If these contributions to the modified Rutherford equation are stabilising, then they can provide the threshold when the island width, w, is comparable to the ion banana width, ρ_{bi}.

Considering a small island, $w \ll r$, where r is the minor radius, but crucially retaining the ordering $\rho_{bi} \sim w$, we have developed a new drift kinetic theory for the ion response to the magnetic island. It leads to a 4D orbit-averaged kinetic equation in toroidal geometry, the solution of which depends on: the toroidal canonical momentum, p_ϕ, representing the poloidal flux, ψ; helical angle ξ labelling the field lines at the rational surface; pitch angle λ and kinetic energy v^2. We solve for the perturbed ion distribution function, taking into account momentum conservation and quasineutrality, both of which are crucial for accurately determining the bootstrap and neoclassical polarisation current perturbations.

We present our latest results for the ion response to the magnetic island perturbation and its influence on the bootstrap current contribution to the island evolution. We find that the finite particle orbit effects are significant, even for a moderately small ratio of $\rho_{\theta i}/w$ ($\rho_{\theta i}$ is the ion poloidal Larmor radius; $\rho_{bi} = \epsilon^{1/2}\rho_{\theta i}$). When $w \sim \rho_{\theta i}$, the flattening of the pressure gradient across the island is substantially restored, implying that the bootstrap current drive for the island growth is suppressed. Moreover, we find that for sufficiently small island, $w \ll \rho_{\theta i}$, the bootstrap current contribution (Δ'_{bs}) can be negative, meaning that it can stabilise the small seed islands, providing threshold [3] (see Figure). This will have significant impact on our understanding of the NTM threshold physics.

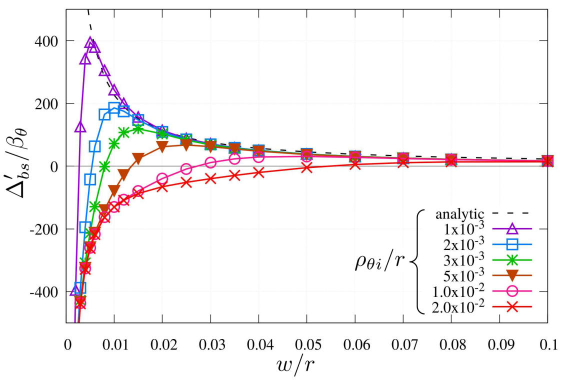

Figure 1. Plot of Δ'_{bs} normalised to β_θ as a function of w/r, for various values of $\rho_{\theta i}/r$. Analytic limit corresponds to $\rho_{\theta i} \ll w$ [2].

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Size of Turbulence-Driven Magnetic Islands

N. Dubuit[1], O. Agullo[1], M. Muraglia[1], S.Benkadda[1], X. Garbet[2]
[1] Aix-Marseille Université, CNRS, PIIM UMR 7345, Marseille, France
[2] CEA, IRFM, F-13108 St.Paul-lez-Durance cedex, France

Abstract.

Neoclassical tearing modes (NTM) are metastable magnetic islands in tokamaks; however, they appear frequently in experiments without any noticeable triggering event. In order to understand this, it has been numerically shown that turbulence can create a seed island [1, 2, 3] by mode coupling, even remotely [4] ; such a seed island can indeed be large enough to further grow from the NTM mechanism [5].

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

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

Next, we use 3D reduced-MHD simulations of flux-driven ballooning turbulence to study the seed island creation in regimes where the classical tearing mode is linearly stable. A localized pressure source is used to control the radial position and strength of the turbulence. Although the energy of the seed island mode grows with the turbulence level, it is shown that from the point of view of NTM seed island generation, stronger turbulence may not be favorable to NTM generation.

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Self-consistent numerical calculation of neoclassical effects of 3D MHD geometry on heavy impurity transport in the presence of strong rotation

E. Neto[1], J. P. Graves[1], M. Rhagunathan[1], S. Lanthaler[1], D. Pfefferlé[2]

[1]École Polytechnique et Fédéral de Lausanne, Lausanne
[2]University of Western Australia, Crawley

Abstract. Heavy impurity transport is an important subject in present day tokamaks. Observations in JET and ASDEX show that an inward radial flux of tungsten ions can cause early termination of the plasma. Only recent investigations have been made into understanding the effects of 3D background rotation profiles and 3D MHD equilibria on the transport of heavy impurities. In [M. Raghunathan et al. 2017 Plasma Physics and Controlled Fusion, 59] the VENUS-LEVIS PIC code has been used to follow heavy impurities in the presence of a 1/1 kink saturated 3D MHD equilibrium and strong toroidal rotation. However, no temperature gradients were considered and only an axisymmetric approach to the calculation of the centrifugal effects and electrostatic potential correction was made. In the present work, a self consistent approach to calculate these quantities for arbitrary 3D flow field and 3D magnetic geometry is presented based on the neoclassical 3D flow theory in [K.C. Shaing et al. 2015 The Physics of Fluids, 26] and the guiding center theory in [A. J. Brizard 1995 Phys. Plasmas 2]. A numerical scheme is implemented and verified to obtain the 3D flow field in both Pfirsch-Schlüter and banana regimes with finite temperature gradients. The electrostatic potential correction and density corrections due to centrifugal effects are obtained for these 3D flow fields. A study is performed on how these quantities change between axisymmetric and 3D equilibria, as well as between different collisional regimes. Heavy impurity transport studies are then performed by following these particles in the background conditions calculated.

An analytical model for the scrape-off layer width when the anomalous transport of plasma is considered

S. Baschetti[a,*], P. Ghendrih[a], H. Bufferand[a], G. Ciraolo[a], N. Fedorczak[a], E. Serre[b], P. Tamain[a]

[a]*CEA, IRFM, F-13108 St-Paul-Lez-Durance, France*
[b]*M2P2, Aix-Marseille Université, CNRS, F-13451 Marseille, France*

*serafina.baschetti@cea.fr

Increasing the confidence in empirical scaling laws of the SOL [1] is crucial in view of preparing ITER operation.

From a dimensional analysis approach, the SOL width λ must be proportional to a length scale, either macroscopic device scales such as the minor radius, or microscopic scales related to collision such as the Debye scale, or scales related to transport, typically the Larmor radius ρ_L. The experimental evidence, and transport properties both collisional and turbulent indicate that the latter is the appropriate length scale. To be complete such a scale can me multiplied by any dimensionless parameter: aspect ratio, safety parameter q. Again, based on the empirical scaling [1], $q\ \rho_L$.provides an appropriate dependence.
To support this approach, an analytic model for the plasma scrape-off layer width λ/a is introduced taking into account anomalous transport. A variational form of the particle equilibrium with fluctuating electric field is considered. The equation for the energy of the fluctuations K is used. We then recover the above scaling. This approach based on turbulent transport thus yields a scaling law that agrees with that of [1], which was understood in the neoclassical framework as the neoclassical step of collision induced diffusion [1].
A key issue is then determining the pre-factor of the scaling. It is known to depend on confinement regime, L and H mode, as well as configuration, limiter versus divertor [2]. Other hidden parameters could explain the existing spread in the data. First theoretical calculations of the pre-factor have been obtained and are in qualitative agreement with experimental evidence.

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Numerical simulations of plasma fuelling in tokamaks using the GBS code

Coroado A.[1], Beadle C.[1], Paruta P.[1], Ricci P.[1], Riva F.[2], Wersal C.[1]

[1] École Polytechnique Fédérale de Lausanne, Lausanne
[2] Culham Center for Fusion Energy, Oxford

Abstract. The tokamak periphery determines the fuelling of a tokamak as the result of a complex interplay of neutral and plasma dynamics, perpendicular turbulent transport, and losses to the vessel walls. In the present work, results from first-principles numerical simulations are used in order to study the tokamak fuelling, aiming to assess the neutral penetration length, the ionization region, and the mechanisms that regulate plasma transport in the edge and Scrape-Off Layer (SOL) regions of a tokamak. Ultimately, these simulations aim at understanding the role played by the neutrals in the formation of the critical density gradient near the Last Close Flux Surface (LCFS) and the impact of neutral dynamics on cross-field transport at different plasma densities. The numerical simulations are carried out with the GBS code, which has been developed in the past years in order to simulate the tokamak edge dynamics. GBS is a 3D flux-driven code that solves the drift-reduced two-fluid Braginskii equations to simulate the plasma dynamics and a self-consistent neutral kinetic equation. Neutrals and plasma models are coupled by the presence of ionization, charge exchange, and recombination processes. Based on the simulation results, we develop a 1D radial model for plasma and neutrals balance, thus enabling a quantitative evaluation of the different mechanisms determining the tokamak fuelling.

Turbulence spreading from the SOL into the edge plasma and generation of large poloidal convective cells in GYSELA and TOKAM3X flux driven simulations

P. Ghendrih[1], Y. Asah[1]i, E. Caschera[1], G. Dif-Pradalier[1], P. Donnel[1], X. Garbet[1], C. Gillot[1], V. Grandgirard[1], G. Latu[1], Y. Sarazin[1], S. Baschetti[1,2], H. Bufferand[1], T. Cartier-Michaud[2], G. Ciraolo[1], P.Tamain[1], R. Tatali[2], E. Serre[2]
1 CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
2 M2P2, Aix-Marseille Université, CNRS, F-13451 Marseille, France

Due the geometry of the eigen modes, to changes in linear stability conditions, as well as spreading effects, turbulence is observed to depend on boundary conditions. This is especially the case in the so called flux driven regime that yields response regimes with maximum self-organisation capability. In the gyrokinetic code GYSELA, ion heat absorbing conditions have been implemented with versatile poloidal geometry, e.g. poloidally symmetric wall or localised akin to a limiter configuration.
Qualitative comparison with the Mistral base case [1] where the limiter poloidal position is changed can be performed. Such simulations have already been achieved with the fluid turbulence code TOKAM3X for isothermal plasma, which provides an interesting point of comparison.
An important feature of the GYSELA heat transport simulation in such a configuration is the development of turbulence in the SOL that appears to spread in the poloidal direction and in the radial direction modifying the fluctuation level in the edge. This effect is readily observable on the electric potential field. Striking features of the latter are a polarisation of the plasma superimposed to fluctuating convective cells elongated in the poloidal direction and relatively narrow in the radial direction. Such structures are important contributors to the edge fluctuation level. These potential structures seem to be specific of the GYSELA kinetic simulations with weak signatures in the TOKAM3X simulations. Two issues appear to be importance in this effect:

i) the development of instabilities in the SOL that could be related to the Kelvin-Helmholtz instability, with some common trends in the two types of simulations,
ii) spreading that sustains transport in regions that are linearly stable.

Both features develop in time, which offers consequently means to identify their respective signatures and importance. It is also interesting to remark that simulations with both codes exhibit ubiquitous electric field wells at the separatrix, but these are found too weak to generate marked pedestal features. The large poloidal structures also have a shearing capability that might play a role. However, the overall effect is the development of fluctuations when compared to a case with poloidally symmetric absorbing conditions. These results provide a novel means to address the short-fall of simulations in the edge region in global flux driven simulations. Indeed a shortfall is observed in the case of poloidally symmetric wall and not in the limiter case.

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Scrape-off-layer current loops and floating potential in limited tokamak plasmas

J. Loizu[1,2], J. A. Morales[3], F. D. Halpern[4], P. Ricci[1] and P. Paruta[1]

1. Swiss Plasma Center, Ecole Polytechnique Fédérale de Lausanne, Switzerland

2. Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

3. Commissariat à l'Energie Atomique IRFM, Saint Paul Lez Durance, France

4. General Atomics, San Diego, California, USA

We investigate the question of how plasma currents circulate and close in the scrape-off-layer (SOL) of convection-limited tokamak plasmas [1]. A simplified analytical two-fluid model describes how currents must evacuate charge at the sheaths due to cross-field currents that are not divergence-free. These include turbulence-driven polarization currents and poloidally asymmetric equilibrium diamagnetic currents. The theory provides an estimate for the radial profile of the floating potential that, in good agreement with experimental observations, reveals a dipolar structure and has an amplitude that scales linearly with toroidal plasma current [2]. Simulations with a fluid turbulence code provide further evidence for the predicted behaviour of the floating potential and points out the limitations of the analytical model.

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Corresponding author: J. LOIZU *joaquim.loizu@epfl.ch*

Analytical finite-Lamor-radius and finite-orbit-witdth model for the LIGKA code and its application to KGAM and EGAM physics

Ph. Lauber[1]

[1]MPI für Plasmaphysik, Boltzmannstr. 2, D-85748 Garching, Germany

E-mail: philipp.lauber@ipp.mpg.de

Abstract.

The physics of kinetic geodesic acoustic modes (KGAMs) and their energetic particle (EP)-driven counterpart (EGAMs) is known to be an important ingredient for the understanding of the self-regulation of a fusion plasma. In recent years it was shown that not only kinetic effects of both thermal ions and electrons influence the local and global properties of these modes, but also the geometry, in particular ellipticity, electromagnetic effects and the details of the anisotropic EP distribution function play a crucial role for the linear and non-linear mode behaviour.

In this paper, the linear gyrokinetic code LIGKA [1] is used to investigate the local and global properties of KGAMs and EGAMs for parameters given by recent experiments at ASDEX Upgrade [2]. In order to include finite Larmor radius effects (FLR) and finite orbit width effects (FOW) and to compare to analytical theory, an extended model of the LIGKA codes is derived and benchmarked. The model is based on a consistent expansion in $k_\perp \varrho_i$ up to fourth order. Assuming Maxwellian distribution functions and using the fast circulating ion approximation $\omega \gg \omega_t$ where ω is the mode frequency and ω_t the transit frequency of the the background ions, analytical expressions for the non-adiabatic response in the quasi-neutrality (QN) and the gyrokinetic moment equation (GKM) are derived. It is shown how these expressions valid for arbitrary mode numbers can be connected to results in the literature for $n = 0$. Benchmarks with analytical literature [3] are carried out for mode frequency, damping and radial mode propagation. For finite n, the model can be used to estimate the local radiative damping consistently, which is of great value for the fast evaluation of AE stability required for energetic particle transport models. Further, the analytical expressions are compared to fully numerical evaluations for circular and elongated equilibria. Finally, the roles of electrons and anisotropic distributions functions for fast ions are investigated.

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Ion losses driven by Alfvén ion-cyclotron instability in mirror machine with skew neutral beam injection

Ivan S. Chernoshtanov

Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia

E-mail: `I.S.Chernoshtanov@inp.nsk.su`

Neutral beam injection (NBI) is one of the methods of heating and maintaining plasma in the mirror machines. Injection results in formation of population of fast anisotropic ions and can provoke excitation of kinetic instabilities, in particular the Alfvén ion-cyclotron (AIC) instability [1, 2, 3]. This is electromagnetic instability, which is driven by inverse population of ions with velocity satisfying the cyclotron resonance condition [4] $v_\parallel = v_r \equiv (\omega - \Omega)/k_\parallel$, here ω and $k_\parallel$ are frequency and longitudinal (along external magnetic field) wave vector of perturbation and Ω is the ion cyclotron frequency in the minimum of magnetic field. Excitation of the AIC instability results in generating quasi-monochromatic circularly polarized waves with frequency being satisfied condition $\omega < \Omega$. Such a waves provoke angle scattering of fast ions so the AIC instability can drive anomalous losses of ions. This work is devoted to investigation of spatial structure of unstable perturbations and anomalous losses of fast ions in the axisymmetric mirror machine with skew NBI.

The Wentzel-Kramer-Brillouin approximation is used for calculation of spatial structure of perturbations [1, 2, 3]. The perturbations have the following longitudinal distribution: standing wave near trap center and traveling waves propagating toward mirrors of trap. The cyclotron resonance condition can be satisfied in the central region only. Velocity of the resonant ions approximately equals the longitudinal velocity of the injected atoms $v_{\parallel inj}$ in the case of skew NBI. The methods developed in the papers [5, 6] are used for investigating non-linear dynamic of ions. Fast sloshing ions are scattered by perturbation at the intersection of the central region. Such scattering can essentially change ions velocity if ion makes an integer number of ion-cyclotron circulations during bounce-oscillation, i.e. the resonance condition $\omega - \langle\Omega\rangle = n\Omega_b$ being satisfied, here Ω_b is the bounce frequency, $\langle\Omega\rangle$ is the ion cyclotron frequency averaged over period of bounce oscillation and n is integer. The interval between resonances decreases with decreasing transverse particle energy, so resonances overlap if longitudinal particle velocity of the order of $v_{res} \approx v_{\parallel inj}$ and transverse velocity is small in comparison with transverse velocity of injected atoms. Overlapping of resonances results in magnetic moment diffusion and longitudinal losses of ions. The analytical expressions for diffusion coefficient and boundary of area of chaotic motion are found and compared with results of numerical simulation of particle dynamic [7].

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Effects of island chains on transport through changes in the radial electric field (TJ-II stellarator)

D. López-Bruna[1], B. Momo[2], A. López-Fraguas[1], I. Predebon[2], F. Auriemma[2] and R. Lorenzini[2]

[1] Laboratorio Nacional de Fusión–CIEMAT, Avda. Computense 40, Madrid 28040, Spain
[2] Consorzio RFX, Corso Stati Uniti, 4, Padova 35127, Italy

E-mail: `daniel.lopezbruna@ciemat.es`

The opening of island chains in magnetically confined fusion plasma is a natural, quite common process. The effects on transport, however, are difficult to assess because of the complexity of the phenomenon, which often happens in a dynamic way. In this work we investigate a basic way in which transport may be altered due to the presence of magnetic islands: the modification of the ambipolar radial electric field E_r due to the distortion of the flux surfaces and the presence of a separatrix. For the latter, we modify the flux-surface averaged metric coefficients of an ideal magnetic configuration consisting of nested tori. The new radial coordinate excludes the island region. Once the geometry is modified, we also perturb the original E_r with a neoclassical scaling taken from Shaing's theory [Phys. Plasmas **9** 3470 (2002)]. Figure 1 shows an example application to TJ-II plasmas in a configuration-scan discharge where the 5/3 low-order rational of the rotational transform moves through the plasma minor radius. From the experimental data, the variations of electron temperature with respect to the mean indicate an increment around the resonant location (left), while the model indicates a decrement (right). It is suggested that a more profound modification of transport properties is necessary in order to explain the experimental results.

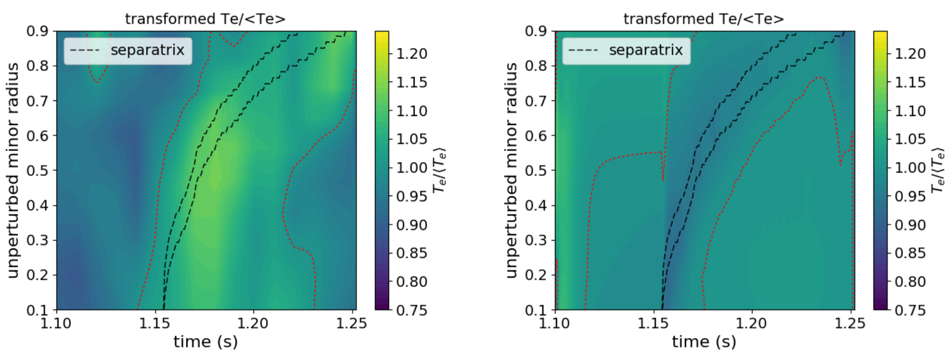

Figure 1. Left: Representation of the electron temperature profile, T_e, normalized to its mean in the time interval shown, $\langle T_e\rangle$, for TJ-II discharge No. 21658 with dynamic configuration scan (data from Electron Cyclotron Emission). The $\iota/2\pi = 5/3$ rational moves between the black dashed lines. Red dotted lines indicate $T_e = \langle T_e\rangle$. Right: the same for a transport calculation based on magnetic island effects, where opposite effects are observed.

Wednesday 29 August, 2018

Interaction of electron-cyclotron beams with electron density fluctuations in turbulent plasmas

O. Maj[1], A. Snicker[2], A. Köhn[3], E. Poli[1], H. Weber[1], L. Guidi[1], S. Alberti[4], O. Chellaï[4], I. Furno[4] T. Goodman[4], L. Figini[5] and D. Ricci[5]

1. Max Planck Institute for Plasma Physics, D-85748 Garching, Germany.
2. Department of Applied Physics, Aalto University, FI-00076 AALTO, Finland.
3. Institute of Interfacial Process Engineering and Plasma Technology, University of Stuttgart, D-70569 Stuttgart, Germany.
4. Swiss Plasma Center (SPC), EPFL Lausanne, Switzerland.
5. Istituto di Fisica del Plasma CNR, 20125, Milano, Italy

e-mail: `Omar.Maj@ipp.mpg.de`

For large tokamaks such as ITER the effects of electron density fluctuations on electron-cyclotron beams have been identified as a potential source of degradation of the beam quality [1, 2]. This concern has sparked a volume of research aiming to better understand wave propagation in turbulent plasmas as well as to quantify such effects. Numerical [3, 4] and analytical [5] studies have been presented addressing basic physics mechanisms along with indirect experimental measurements of beam broadening [6]. Dedicated experiments have been designed to directly measure the transmission of a beam through a turbulent plasma [7]. A complete description of the beam propagation in tokamak plasmas including the statistically averaged effects of fluctuations on power deposition can be achieved by means of the wave-kinetic-equation solver `WKBeam` [8], which has been recently applied to ITER-like scenarios [9, 10]. Validation of the `WKBeam` code by experimental data from dedicated experiments on the TCV tokamak is in progress within the EUROfusion Enabling Research project RFSCAT (Swiss Plasma Center, EPFL, Lausanne). In this talk, the theory of waves in turbulent plasmas is developed from the point of view of the wave-kinetic equation, thus interpreting the interaction of the wave field with density fluctuations as a scattering process. `WKBeam` predictions for the dedicated experiments on TCV as well as for ITER are presented and discussed in terms of scattering processes and their link to the underlying wave physics. The relationship between the wave-kinetic theory and wave physics is also addressed through a series of benchmarks against both beam-tracing and full-wave solutions that, in addition to testing the `WKBeam` code, allow us to understand the limitations of the physics assumptions underlying the wave-kinetic equation.

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

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First-principles simulations of microwave beam propagation through edge turbulence

R. G. L. Vann[1], M. W. Brookman[2], A. Köhn[3], J. Leddy[1] and M. B. Thomas[1]

[1] *York Plasma Institute, Department of Physics, University of York, York, YO10 5DD, UK*
[2] *Institute for Fusion Studies, University of Texas at Austin, 1 University Station C1500, Austin, USA*
[3] *Max Planck Institute for Plasma Physics, D-85748 Garching, Germany*

It is not fully understood how electromagnetic radiation interacts with plasma perturbations whose size is comparable to the radiation wavelength. Yet the use of microwave radiation in magnetic confinement fusion plasmas is widespread for heating, current drive and both passive and active diagnostics, including in regimes for which there exist wavelength-scale plasma perturbations. Of particular interest is the broadening of electron cyclotron heating beams due to their propagation through regions of turbulence; this is potentially a particular problem when the localisation of the heating location is important – for example when localised electron cyclotron current drive is used to destroy neoclassical tearing modes: this is a standard technique on both current and future devices, including ITER.

In this work we present simulation results using the full-wave cold plasma finite difference time domain codes EMIT-3D [1] and IPF-FDMC [2] developed independently at York and Stuttgart, respectively. First we present a novel systematic study of the scattering of microwaves through Hasegawa-Wakatani turbulence [3]: we quantify the relationship between the normalised turbulent correlation length and the scattered power. Additionally we find a quadratic relationship between the scattered wave power and the turbulence amplitude.

We then proceed beyond the idealised case to consider scattering by turbulent profiles generated by the more realistic Hermes [4] model that adds temperature gradients and curvature effects, and we fit equilibrium profiles to experimental data from DIII-D. We find that there is good agreement between our first-principles simulations and the experimentally-observed beam broadening. By validating this new predictive capability, our investigation provides renewed confidence in the community's ability to design & operate present & future tokamaks in such a way that microwave heating schemes achieve their intended objectives.

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Modeling in front of a plasma profile of a set of Traveling Wave Antenna (TWA) sections in view of the ICRF heating of DEMO

A. Messiaen [a] and R. Ragona [a,b]

[a] *Laboratory for Plasma Physics LPP-ERM/KMS, B-1000 Brussels, Belgium*
[b] *Applied Physics Department, Ghent University, B-9000 Gent, Belgium*

Abstract

An upgraded version of the fast semi-analytical code ANTITER II is used to model the refueled TWA sections of any arbitrary number of radiating straps facing a low coupling plasma profile. The code computes the **Y**, **Z** and **S** matrices of the antenna array from which the performances of the TWA sections and of their feeding system are deduced as a function of the geometrical parameters of the TWA. The model incorporates the feeding of each section by a resonant ring circuit that re-circulates its output power. The cases of straps grounded at one of their ends (*L grounding*) or in their center (*T grounding*) are also compared.

This model is extended to a number n_B of TWA sections of n_s straps each, with arbitrary positions in the *y,z* plane (i.e. machine wall). The full matrices of the resulting array of $n_s\, n_B$ straps are derived and connected to resonant ring circuits feeding each TWA section independently, to incorporate consistently the feeding circuit in the model.

Examples of toroidal and/or poloidal arrays of sections with T or L grounding and symmetric or asymmetric $k_{//}$ spectra are analyzed. First conclusions for the design of a set of TWA sections for the reactor are already drawn.

Development of a novel quasi-axisymmetric stellarator

S.A. Henneberg, M. Drevlak, C. Nührenberg, C.D. Beidler, Y. Turkin, J. Loizu, P. Helander

Max-Planck-Institut für Plasmaphysik, 17491 Greifswald, Germany

Email: Sophia.Henneberg@ipp.mpg.de

The magnetic field for a new quasi-axisymmetric, two-field-period stellarator has been developed following an extensive design study utilizing ROSE (Rose Optimizes Stellarator Equilibria) – an optimization code for 3D magnetic plasma equilibria. The results of this design study and the characteristics of the new configuration are presented.

A quasi-axisymmetric magnetic field approximately fulfills: $B \approx B(s,\theta)$ where $s \approx r^2/a^2$ is the normalized flux and θ is the poloidal Boozer coordinate. One can show that such a magnetic field reduces the radial drift of particles and corresponding particle losses. Because of the toroidal symmetry of the magnetic field strength, quasi-axisymmetric stellarators share many neoclassical properties of tokamaks, such as a comparable bootstrap current which can be employed to simplify the coil structure. Along with the reduced particle losses, the potentially simplified coil structure, and a potential steady state, there is experimental evidence that sufficient vacuum rotational transform can prevent certain types of disruptions – a major challenge for tokamaks.

Although no quasi-axisymmetric stellarator yet exists, quasi-axisymmetric designs have been studied previously e.g., NCSX [1], CHS-qa [2], and ESTELL [3]. In this talk, new Pareto-optimal stellarator configurations are presented and compared to previous work. To the best of our knowledge, we have obtained better fast-particle loss-fraction rates than any previous quasi-axisymmetric configuration. The ROSE code optimizes the plasma boundary calculated with VMEC based on a set of physical and engineering criteria. Various aspect ratios, number of field periods and iota profiles are investigated. As an evaluation of the design, the bootstrap current [4], the ideal MHD stability [5], the fast-particle losses [6], and the existence of islands [7] are examined.

Results of this broad study which has culminated in the design of a compact, MHD-stable, two-field-period stellarator with small fast-particle loss fraction will be discussed.

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New Confinement Concepts for Gas-dynamic Linear Traps

A. D. Beklemishev
Budker Institute of Nuclear Physics, Novosibirsk, Russia, bekl@bk.ru

The idea of gas-dynamic trap, realized in GDT [1] in the Budker Institute of Nuclear Physics, is surprisingly successful. The trap itself recently reached high plasma parameters, surpassing its original goals and most historic peers [2]. After more than 20 years of research our understanding of its physics became sufficient for planning future development.

This talk reviews two new theoretical concepts for improved confinement in linear systems that build upon the legacy of gas-dynamic and multiple-mirror traps. The first one is the helical-mirror trap [3], realizing the pinch-era idea of "peristaltic" plasma confinement. Its theory states that the plasma rotation in a solenoidal section with helical corrugation of the magnetic field will cause axial and radial plasma flows that can be used for effective reduction of losses. Existence of the effects is already confirmed in the recent dedicated experiment SMOLA.

The second concept is the "diamagnetic confinement" regime that predicts possibility of quasi-stable $\beta=1$ equilibrium in gas-dynamic traps satisfying specific requirements [4]. Due to drastic increase of the effective mirror ratio of the trap at high beta the energy confinement time surpasses standard estimates, allowing fusion in relatively compact devices. The diamagnetic confinement regime would be similar to FRCs in confinement quality but without necessity of a current drive. Verification experiment is planned.

The two concepts are mutually compatible and may have multiplicative effect on confinement. In case of successful realization in full-scale experiments any one of them may be sufficient to build a fusion reactor based on a linear trap. Theoretical description of the proposed confinement schemes poses many new and interesting problems and needs a lot of development.

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THURSDAY, August 30, 2018

Studying Alfvén eigenmodes in realistic conditions using a hierarchy of hybrid-gyrokinetic and fully gyrokinetic models

Thomas Hayward-Schneider **
Philipp Lauber, Alberto Bottino

Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany
** *E-mail: thomas.hayward@ipp.mpg.de*

Abstract: Alfvén eigenmodes, driven unstable by energetic particles, have the capability to transport particles and energy in a fusion reactor via resonant wave-particle interaction. Whilst it is not expected that the amplitudes of individual saturated Alfvén eigenmodes will be sufficiently large to cause significant transport, in future machines (and especially in burning plasmas) we can potentially expect large numbers of toroidal Alfvén eigenmodes (TAEs) to be driven unstable, and studying the interaction between these modes is of importance, as it can lead to significantly increased transport.

In order to study the effects of TAEs, we value models which include complete physical descriptions, but we also value fast and robust reduced models, in particular for exploratory parameter scans, especially relevant when investigating systems with large numbers of modes present. To this end, we aim for a hierarchy of models, ranging (in this work) from various hybrid-kinetic models to fully gyrokinetic (GK) models against which the simpler models can be verified.

In this work, we focus on two model paradigms, firstly the coupled HAGIS-LIGKA model [1] (linear GK eigenvalue solver/nonlinear perturbative hybrid code), and secondly, the nonlinear gyrokinetic electromagnetic particle-in-cell code ORB5 [2, 3].

In the coupled HAGIS-LIGKA model, the TAE eigenvalues (mode frequency and damping) and eigenvectors (radial mode structure) are calculated using the linear gyrokinetic code LIGKA [4], and evolved with the hybrid HAGIS [5] code. Depending on the physics required, the LIGKA model can perform local or global, MHD or kinetic mode calculations.

In this work, we look at the ITER standard 15MA scenario [6], with three levels of increasing mode-structure fidelity from HAGIS-LIGKA: a gaussian mode structure model combined with analytical estimations for the mode width together with a local ideal MHD calculation, a global eigenvalue calculation in the limit of ideal MHD, and the global kinetic eigenvalue calculation. In the case of the former two non-kinetic models, we estimate the mode damping using a fast local kinetic eigenvalue calculation. We show that the simpler models match well under certain restrictions, with the simplest model allowing for a surprisingly good measurement of the linear growth rate when the mode is well localized as is true for larger toroidal mode numbers. In this study, we not only focus on the linear properties of large numbers of modes but also assess the validity of analytical estimates for resonance broadening by monitoring the relation between linear growth rates and saturated amplitudes. With this information, the validity of quasi-linear models can be checked with nonlinear multi-mode simulations.

We also present efforts in studying this ITER scenario, also with a realistic equilibrium, using linear runs of ORB5. By applying both paradigms to the same case, we can draw inter-level comparisons across the hierarchy of models.

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Nonlinear inverse Landau damping of ion Bernstein waves on alpha particles

C. Castaldo[1], A. Cardinali[1]

[1] ENEA, C.R. Frascati, Via E. Fermi 45, I-00044 Frascati, Italy

Ion Bernstein waves (IBW) coupled by mode conversion of fast magnetosonic waves in D-H(T) tokamak plasmas were suggested as a tool to achieve enhanced fusion reactivity [1]. In such scenario, T ions are accelerated in the 50-100 keV energy range by IBW linear Landau damping at second harmonics cyclotron resonant layers $\omega = 2\Omega_T$. Here we investigate, in the same scenario, the occurrence of IBW nonlinear inverse Landau damping on the fusion alpha particles. This effect might be observed at Doppler-shifted half-integer resonant layer $\omega = (3/2)\Omega_\alpha + k_\parallel \mathrm{v}_\parallel$. The nonlinear RF-induced diffusion tensors in both velocity and physical space are derived in the frame of single-particle dynamics. We then discuss numerical solutions of the relevant Fokker-Planck equation, taking into account also the collisions of the alpha particles with the plasma background as well as the source and sink terms. During the time evolution of the alpha particle distribution function towards the steady state, α power channeling [2] into IBW can be produced.

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Energetic ion losses "channeling" mechanism and strategy for mitigation

F. Nabais[1], D. Borba[1], R. Coelho[1], J. Ferreira[1], A. Figueiredo[1], V. Kiptily[2], F. Portugal[1], P. Rodrigues[1], and JET Contributors[§]

[§] *See the author list of "X. Litaudon et al 2017 Nucl. Fusion,* ***57****, 102001"*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[1]*Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal.*

[2]*CCFE, Culham Science Centre, Abingdon OX14 3DB, UK*

Abstract

In future fusion reactors, the loss of highly energetic ions from the plasma may cause severe damage to the reactors first wall and plasma facing components. Thus, the understanding of the mechanisms leading to energetic ion transport and losses is of critical importance. Toroidal Alfvén eigenmodes (TAE) are known for its capability to interact with energetic ions and transport them radially. TAE may exist either in the plasma core or in the outer region of the plasma. We show that when the core-localized TAE have the same frequencies and toroidal mode numbers than the outer TAE, a "channeling effect" exists, with core-localized TAE transporting energetic ions from the plasma core to outer regions of the plasma and the outer TAE kicking these ions out of the plasma. Thus, when these conditions are verified, the combined effect of modes at different locations cause enhanced losses. On the other hand, when these conditions are not verified, no enhanced losses are expected even if core-localized and outer TAE are both simultaneously present in the plasma. We present experimental evidences from the JET tokamak showing that enhanced losses are observed only when the mentioned conditions are verified. In addition, since the frequencies of TAE depend on the *q*-profile and on the mass density profile, it is shown that these profiles may be tailored in order to reduce the number of losses.

Simulations of energetic particle driven geodesic acoustic modes and the energy channeling in the Large Helical Device

H. Wang[1,*], Y. Todo[1,2], M. Osakabe[1], T. Ido[1], and Y. Suzuki[1,2]

[1]*National Institute for Fusion Science, National Institutes of Natural Sciences, Toki 509-5292, Japan*
[2]*SOKENDAI (The Graduate University for Advanced Studies), Toki 509-5292, Japan*
[*]wanghao@nifs.ac.jp

Energetic particle driven geodesic acoustic modes (EGAMs) in the Large Helical Device (LHD) plasmas are investigated using MEGA code[1]. MEGA is a hybrid simulation code for energetic particles (EPs) interacting with a magnetohydrodynamic (MHD) fluid. In the present work, both the EPs and the thermal ions are described by the kinetic equations. The simulations are conducted based on realistic experimental parameters[2]. The energy of injected neutral beam is 170 keV, and a Gaussian-type pitch angle distribution is assumed to model the energetic ions. A realistic 3-dimensional equilibrium generated by HINT code is used. A global electrostatic mode is reproduced and identified as low frequency EGAM for the slowing-down EP distribution. The dominant mode number is m/n = 0/0 for poloidal velocity and 1/0 for pressure perturbation. The linear frequency is around 40 kHz, and it decreases with increasing EP pressure. The energy transfer of various species is analyzed and shown in Fig. 1. The bulk ion heating during the EGAM activity is observed. The ions obtain energy when the EPs lose energy, and this indicate that an energy channel is established by EGAM. The EGAM channeling is reproduced by simulation for the first time. From t = 0 to t = 0.36 ms, the energy transferred from EP is 63 J. About half of this energy (51%) is transferred to bulk ions (34%) and electrons (17%), while another half is dissipated. The heating power of bulk ions around t = 0.1 ms is 3.4 kW/m^3 which is close to the value 4 kW/m^3 evaluated from the experiments[2].

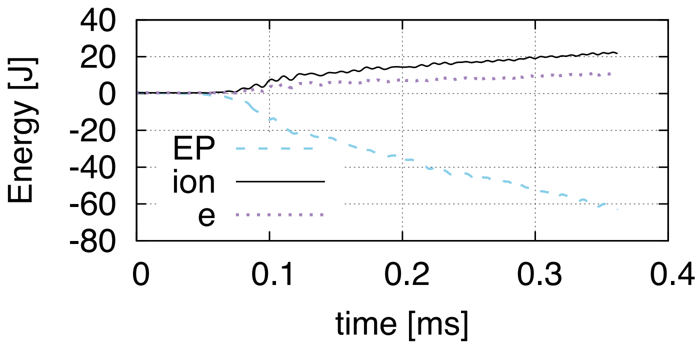

Figure 1: Energy transfer of various species.

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On the existence of a stable stationary state solution of toroidal drift mode structures in the presence of self-consistently calculated flows

A Bokshi[1,2], Y Camenen[3], D Dickinson[1], B D Dudson[1], P Hill[1], C R Roach[2], S Saarelma[2], H R Wilson[1,2]

[1]York Plasma Institute, Univ. of York, Heslington, York YO10 5DD, UK; [2]CCFE Culham Science Centre, Abingdon, OX14 3DB, UK; [3] CNRS Aix-Marseille Univ., PIIM UMR7345, Marseille France

Email: arka.bokshi@york.ac.uk

The ballooning formalism when applied to toroidal drift microinstabilities (such as ITGs, KBMs) predicts *two distinct classes* of global eigenmodes [1]: the strongly unstable Isolated Mode (IM) that exists under certain special conditions, and the relatively benign General Mode (GM) that is more easily accessible to the plasma. In a previous work [2], the linear transition between the GM and IM branches of a fluid-ITG mode, under the influence of a *critical* equilibrium flow shear, has been shown to occur on a characteristic *O(*ms) time scale – this we speculate may be the physical mechanism underlying certain small-ELM regimes.

In building towards such a model of ELMs, a key piece of physics to consider is the intrinsic torque that poloidally asymmetric modes such as the GM generate through Reynolds stresses [3]. (The IM on the other hand is symmetric and not expected to produce any torque.) This necessitates a treatment wherein the intrinsic flow generated by the mode modifies the equilibrium flow profile and contributes to the self-consistent flow shear. To understand this, we study the momentum flux Π: around the $\Pi = 0$ working point, with increasing $-\partial\, u_\varphi / \partial\, r$ if Π is radially outwards and increasing, the mode structure and flow profile corresponding to the $\Pi = 0$ stationary state are stable.

The linear, electrostatic version of the GEM model [4] with adiabatic electrons has been implemented in the BOUT++ framework [5]. At this meeting we will present first physics results showing how the momentum flux varies with equilibrium flow shear u'_φ as the latter is varied to obtain the GM and IM. The stability of the $\Pi = 0$ stationary point, in particular if one exists corresponding to the GM, is of fundamental importance since we speculate that preceding/following a small-ELM crash, the plasma profiles are pinned to gradients set by the GM. We will also compare results from the global implementation of the GEM model in BOUT++ with gyrokinetic simulations in GKW [6] for the cyclone base case, and discuss numerical challenges in performing local/global gyrofluid simulations using the BOUT++ framework.

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Verification of turbulent simulations using PoPe: quantifying model precision and numerical error with data mining of simulation output

T. Cartier-Michaud[1], P. Ghendrih[2], V. Grandgirard[2], G. Latu[2], Y. Sarazin[2], E. Serre[1]
1 M2P2, Aix-Marseille Université, CNRS, F-13451 Marseille, France
2 CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

With the increasing computing capability, simulations are playing a growing role in research and innovation. Consequently, reliability of High Performance Computing must be addressed and quantifying each simulation quality becomes mandatory. Verification is usually performed on a small set of test cases, as in the Method of Manufactured Solution, which can depart from actual production runs. Projection on Proper elements (PoPe [1]) is a novel framework developed to quantify the simulation error, potentially for each simulation used in publications. It requires typically 1% CPU and is a powerful and versatile tool for verification: checking the implementation of models, determining the numerical convergence, and characterizing the residual error. The basic idea is to measure the departure from the expected bijection between the code data output and the set of equations that are considered to generate it.

As an illustration PoPe is used to verify the 1D-1V VOICE code dedicated to investigating kinetic plasma physics [2]. In a standard fashion the VOICE code has been verified confronting the code output with analytical results on Landau damping, resonant interaction with an external electric field and collisional relaxation towards equilibrium temperature. Furthermore, each part of the code has been verified with the reference Method of Manufactured Solution. Kinetic problems have a unique feature insofar that they depend on precise description of the phase space, including in particular challenging computation of the high velocity tail of the distribution function, while standard quantities used for the physics, typically the electric field, are projections based on velocity integrals. Using Pope for VOICE has proven that very significant error can then be tolerated in the high velocity tail of the distribution function while achieving precise comparison in the linear response of the electric field. More generally, one can use PoPe when investigating procedures to reduce the impact of the numerical errors, such as changing (i) the order of the numerical method, (ii) the mesh resolution or (iii) filtering the solution to only retain the contributions which are consistent with the precision of the numerical scheme. Cost and benefit of each improvement scheme can be analyzed.

Present development of PoPe in VOICE is focused on verification of the code on the fly, then providing a figure of merit of accuracy for each run of the code. This absolute criterion allows one to check that aspects (i) and (ii) are fulfilled. We now further analyze the case when the figure of merit of a particular simulation is degraded to discuss what simulation information can still be regarded as significant, hence developing the analysis according to (iii). However, in that case the universality of the verification is lost. Precise investigation of the code output is then required to assess the level of confidence for each particular observable.

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Lagrangian Coherent Structures as a new frame to investigate the particle transport in highly chaotic magnetic systems

G. Di Giannatale[1], M.V. Falessi[2], D.Grasso[3] , F.Pegoraro[4], T. Schep[5], M. Veranda[1] , D. Bonfiglio[1], S. Cappello[1]

[1] *Consorzio RFX, Corso Stati Uniti 4 - 35127 Padova, Italy*
[2]*Dipartimento di Matematica e Fisica, Roma Tre University, Roma, Italy*
[3]*ISC - CNR and Politecnico di Torino Dip. Energia, Torino, Italy*
[4]*Dipartimento di Fisica "Enrico Fermi", Universita' di Pisa, Italy*
[5]*Fluid Dynamics Lab., Eindhoven Univ. Techn., The Netherlands*

In recent years the use of Dynamical system techniques[1,2] to investigate the transport features in magnetized plasmas took a very important role, especially in plasmas with low collisionality. At low collisionality the transport is highly anisotropic, collisions are no longer the main actor and, as has been shown (e.g. in Stellarator studies[3]) magnetic topology plays a very important role: this means that, neglecting effects due to finite Larmor radius and drifts, in this regime particles move essentially along magnetic field lines.
In these situations, a common practice is to study the topological properties of the magnetic field by means of the Poincaré map technique. A Poincaré map is best used when a periodic magnetic field is considered and, for an evolving 3D magnetic configuration, this means to study the confinement properties at a fixed time instant. The goal of the present work is to go beyond this limit applying Lagrangian Coherent Structures (LCS) [4] to magnetic field configurations. This technique allows to underline coherent magnetic structures having a role in transport processes and thus to detect regions of the system having different transport characteristics.
In particular, we introduce a simplified model, in Cartesian geometry, that allows us to consider explicitly the case where the magnetic configuration evolves in time on timescales comparable to the particle transit time through the configuration. In contrast to the previous articles on this topic[5,6], in the framework of our simplified approach, this analysis requires that a system that is aperiodic in time be investigated. We investigate, by means of a numerical procedure, the LCS in the case of a two-dimensional magnetic configuration with two island chains that are generated by magnetic reconnection and evolve nonlinearly in time. We first focus on a particular time in which the magnetic configuration is fixed, and then we consider a time dependent magnetic field. The first part allows us to show the analogies between Poincaré map and LCS, while the second part enables us to investigate when and how particles with different transient time see different transport barriers[7,8].
Finally, following previous studies[6], we extend our analysis to a realistic numerical representations of a quasi single helicity state of a Reversed Field Pinch configuration.

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Study of wavenumber resolution convergence in turbulent transport simulations including kinetic electron dynamics

Ajay C. J.[1], **S. Brunner**[1], **B. McMillan**[2], **J. Dominski**[3], **J. Ball**[1]

[1]Swiss Plasma Center, EPFL, Station 13, Lausanne 1015, CH

[3]Centre for Fusion Space and Astrophysics, University of Warwick, Coventry, CV4 7AL, UK

[2]Princeton Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, New Jersey 08543-0451, USA

E-mail: `ajay.chandrarajanjayalekshmi@epfl.ch`

Abstract. This work reports on the non-trivial convergence of gyrokinetic flux-tube simulations of turbulent transport in tokamak plasmas with respect to wavenumber spectral resolution. Such a study involves increasing the simulation box in the toroidal direction, *i.e.* in practice decreasing $k_{y,\min}\rho_i$, where $k_{y,\min}$ is the minimum wavenumber along the direction y, binormal to the magnetic field, and ρ_i is the ion Larmor radius. Given that the true flux-tube limit corresponds to $k_{y,\min}\rho_i \sim \rho^* \to 0$ ($\rho^* = \rho_i/a$ with a being the minor radius of the tokamak), this study is relevant to the question of physical scaling with tokamak size.

It is observed that transport levels in simulations assuming adiabatic electron dynamics are nearly converged as $k_{y,\min}\rho_i$ is decreased within practical achievable limits. These flux levels however increase significantly with decreasing $k_{y,\min}\rho_i$ in the case of kinetic electron simulations. These increasing fluxes develop in conjunction with decreasing shearing rates associated with the zonal flows, well understood to play an essential role in saturating turbulence. A novel diagnostic tool has thus been developed for analyzing the statistical properties of the contributions from the different k_y modes to the Reynolds Stress (RS) driving the zonal flows. The picture that appears to emerge from this study is that, in the case of adiabatic electron simulations, the different k_y mode contributions to the RS, resulting in this case mainly from multiple resonant 3 wave interactions (∼modulational instabilities), are correlated with each other. In the case of kinetic electron simulations however, additional contributions to the RS drive are provided by fine radial structures formed as a result of non-adiabatic passing electron dynamics, and localized at the Mode Rational Surfaces (MRSs) of each k_y mode [1, 2]. Except around lowest order MRSs, these latter contributions to the RS are essentially decorrelated, thus leading to a drive of the zonal flows that become less effective as $k_{y,\min}\rho_i \to 0$.

The current state of this study will be presented, including simulation results in different geometries (slab & tokamak), different electron models (adiabatic & kinetic), as well as different turbulent regimes (Ion Temperature Gradient & Trapped Electron Mode).

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Stability of kinetic microtearing modes

M.Hamed[1,2], M.Muraglia[2], Y.Camenen[2], and X.Garbet[1]

[1]IRFM, CEA, F-13108 St-Paul-Lez-Durance, France
[2]Aix-Marseille Université, CNRS, PIIM UMR 7345, Marseille, France

In H-mode plasmas, the modelling of the pedestal dynamics is an important issue to predict temperature and density profiles in the tokamak edge and therefore in the core. The "EPED" model [1] , based on the stability of large and small scales MagnetoHydroDynamic (MHD) modes, is most commonly used to characterize the pedestal region. The EPED model has been quite successful until now. However some recent analysis of JET plasmas [2] suggest that another class of instabilities, called microtearing modes, may be responsible for electron heat transport in the pedestal, and thereby play some role in determining the pedestal characteristics.

Microtearing modes belong to a class of instabilities where a modification of the magnetic field line topology is induced at the ion Larmor radius scale. This leads to the formation of magnetic islands, which can enhance the electron heat transport. Although the stability of MTMs has been theoretically studied in the past [3], the destabilization mechanism at play in the pedestal region is not yet well understood owing to the number of parameters (electron temperature gradient, magnetic field curvature, magnetic shear, ...) that control the strength of the instability. This lack of understanding leads to apparent disagreement between the linear analytical theory and gyrokinetic simulations. Indeed, past linear theories show that a slab current sheet is stable in the absence of collisions [3] whereas, in collisionless regimes, recent gyrokinetic simulations in toroidal geometry found unstable MTMs [4, 5]. The purpose of our work is to reconcile theory and numerical simulations to improve the understanding of MTM destabilization mechanisms.

A linear theory of a slab microtearing mode using a kinetic approach has been etablished and compared with linear gyrokinetic simulations [6]. The linear stability of the collisionless MTMs predicted by the theory is found consistent with numerical simulations using the gyrokinetic code GKW [7]. A new analytical calculation including the magnetic field curvature and the collisionality frequency in ballooning representation is also formulated and compared with numerical results. It appears that the magnetic drift velocity and electric field fluctuations are destabilizing when combined with collisions. However, this destabilization effect disappears at low collisionality and no unstable MTM is found so far in collisionless plasmas.

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Cross Scale Interaction Mechanisms for Coupled Electron and Ion Scale Turbulence

M.R.Hardman[1,2], M.Barnes[1,2], C.M.Roach[2]
[1]*Rudolf Peierls Centre for Theoretical Physics, University of Oxford, UK*
[2] *CCFE, Culham Science Centre, Abingdon, Oxon, UK*

Turbulent transport is a limiting factor in the performance of magnetic confinement fusion devices. Evidence suggests that this turbulence is driven at the scales of the ion and electron Larmor radii, that ions at ion Larmor scales and electrons at electron Larmor scales can make a comparable contribution to the heat transport, and that there is an interaction between the turbulence at the different Larmor scales [1, 2]. To gain insight into the sources of electron scale heat transport, and the mechanism for cross scale interaction, we exploit the scale separation between the ion and electron Larmor radii, and the electron and ion thermal speeds, to asymptotically expand the gyrokinetic equation in the large ion to electron mass ratio following the method of multiple scales. We derive coupled gyrokinetic equations for the ion scale and electron scale turbulence which contain novel cross scale interaction terms. We propose and justify a parallel to the field boundary condition for the electron scale equations which is consistent with the usual flux tube boundary condition for the ion scale [3]. This boundary condition, which resembles the 'flux tube train' approach [4], respects the difference between rational and irrational flux surfaces for electron scale physics in a flux tube model. Using the local gyrokinetic code GS2, with the recently implemented cross scale interaction terms, we present results from a numerical study where we consider the effect of the ion scale turbulence on the electron scale linear instability, for both weakly and strongly driven ion scale turbulence.

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

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Global and local turbulence features near and far from marginality and nonlocal pedestal-core interactions

L. Villard[1], B.F. McMillan[2], E. Lanti[1], N.Ohana[1], A. Bottino[3], A. Biancalani[3], I. Novikau[3], S. Brunner[1], O. Sauter[1], N. Tronko[3], A. Mishchenko[4]

[1] Swiss Plasma Center, EPFL, lausanne, Switzerland
[2] Center for Fusion, Space and Astrophysics, University of Warwick, UK
[3] Max-Planck Intitute for Plasmaphysik, Garching, Germany
[4] Max-Planck Intitute for Plasmaphysik, Greifswald, Germany

E-mail: `laurent.villard@epfl.ch`

Abstract. Turbulent transport in magnetically confined fusion plasmas is often characterized by intermittent events which appear as avalanche-like phenomena. In this work, we examine the statistical properties of various fluctuating quantities obtained from global gyrokinetic simulations using the ORB5 code. The PDFs of density, temperature, temperature gradient and potential are found to have nearly Gaussian distributions, whereas the heat flux can have, in the presence of avalanches, a more or less strongly positiveley skewed PDF, which could be fitted by a log-normal distribution. The skewness is found to be radially dependent, and non-locally dependent, in the sense that, for example, in the plasma core it also depends on the gradients in the pedestal. Comparing simulations with different background gradients, the skewness is generally higher as marginality is approached. The local, instantaneous flux vs gradient relation shows a hysteresis behaviour during an avalanche. The same is also true of the relation between flux and Zonal Flow shearing rate $\omega_{E\times B}$. When time-averaged over many avalanche events, and calculated locally at different radii, the heat diffusivity χ can be a decreasing function of $|\nabla T|$, contrary to the usual local behaviour. This is due to the plasma self-organization in radial zones, mediated by turbulence-generated ZFs, which results in corrugated profiles: transport is locally maximal where the time-averaged $\omega_{E\times B}$ is minimal and results in a local flattening of the temperature profile. Only when averaged radially over several zones, and for series of simulations with different background gradients, the effective 'global' χ vs the 'global' $|\nabla T|$ shows a behaviour which qualitatively 'looks like' the familiar local relation, i.e. an offset by a critical gradient, and then a more or less fast increasing transport. One of the goals of this study is to understand which aspects of turbulent transport are essentially non-local and therefore system-size dependent.

Radial transport studies in magnetized plasmas with islands

B. Momo(1), D. Lopez-Bruna(2), I. Predebon(1), A. Lopez-Fraguas(2), F. Auriemma(1), R. Lorenzini(1), Y. Suzuki(3,4)

(1) Consorzio RFX, Corso Stati Uniti, 4, 35127, Padova, Italy
(2) Laboratorio Nacional de Fusion, CIEMAT, Avda. Complutense 40, 28040 Madrid (Spain)
(3) National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Gifu 509-5292, Japan
(4) SOKENDA, The Graduate University for Advanced Studies, Toki, Gifu 509-5292, Japan

barbara.momo@igi.cnr.it

Abstract

One dimensional (1D) energy and particle diffusion in a magnetized plasma rely on the presence of nested flux surfaces, which, from the geometrical point of view, provide a monotonic radial coordinate from the magnetic axis to the plasma edge. Resonant layers in the plasma may lead to the growth of magnetic islands, with the consequent breaking of the magnetic flux surfaces in that region of the plasma. This brings to multiple magnetic axes in the plasma domain, and to an intrinsically three dimensional (3D) nature of the transport problem.

Since 1.5 transport codes need a monotonic radial coordinate, they cannot manage topologies with more than one magnetic axis; on the other side a proper fully 3D treatment of the problem is difficult and CPU-time demanding. In order to preserve a 1D geometrical description, a piecewise treatment where different radial coordinates are defined in different domains around their own magnetic axes has been developed [1].

In this contribution we present an alternative method [2] based on the idea that the presence of magnetic islands does not impede making 1D transport calculations if the island region is *excluded* and then, eventually, treated separately. We present a simple way to modify the geometry (radial coordinate and related metric coefficients) in order to exclude the island region from the 'principal' plasma, where 1D transport is considered. The method would equally apply to a fully chaotic region, excluded from the conserved plasma.

Comparison with the metrics obtained from Poincaré plots (in presence of magnetic islands) are shown, as well as applications to two types of plasma using the ASTRA transport shell [3] with appropriately modified metrics: Heliac (TJ-II, CIEMAT, Spain), and Heliotron (LHD, NIFS, Japan).

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Impact of bootstrap current and resistivity on a turbulent driven NTM

M. Muraglia[1,2], O. Agullo[1,2], N. Dubuit[1,2], S. Benkadda[1,2], , X. Garbet[3] and A. Sen[4]
[1] *France-Japan Magnetic Fusion Laboratory, LIA 336 CNRS*
[2] *Aix-Marseille Université, CNRS, PIIM UMR 7345, Marseille, France*
[3] *IRFM, CEA, 13108, St-Paul-Lez-Durance, France*
[4] *Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
*e-mail: magali.muraglia@univ-amu.fr

Magnetic reconnection is a physical process involving conductive plasma flows and leading to a topology modification of the magnetic filed. It can be a major break to the good realization of fusion experiments. In particular, large magnetic island (with a size of the order of centimeter) can lead to the destruction of the plasma confinement. This phenomenon, known as Neoclassical Tearing Mode (NTM), requires a seed island, which will be nonlinearly amplified by the so-called bootstrap current. A lot of studies [1] are devoted to the crucial question of the NTM control in fusion reactor. However, few studies exist on the seed island origin and on NTM triggering mechanism whereas these questions are still fully open. Moreover, in fusion experiments, large magnetic island coexist with micro turbulence. In [2, 3, 4, 5], it has been underlined that a Turbulence Driven Magnetic Island (TDMI) can be generated thanks to a nonlinear beating of small-scale interchange modes. Recently [6], by means of numerical simulations of a 2D Reduced-MHD model, we have shown that a TDMI can be amplified by the bootstrap current. Here, we investigate the impact of the bootstrap current strength and of the resistivity on the dynamic of a turbulent driven NTM. We also compare such dynamic with the dynamic of a NTM driven by a numerical seed island.

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Modeling of LHCD in high magnetic field, high density tokamak configuration

A. Cardinali, R. Cesario, C. Castaldo, F. Santini, L. Panaccione, A. A. Tuccillo

ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy

The project ARC [1] and, more recently, the project SPARC [2] by MIT as compact, high magnetic field and high-density tokamaks have re-launched the Lower Hybrid Current Drive (LHCD) concept as method for actively and efficiently generating current in the outer radial half of plasma. In particular, driving current near the pedestal layer of H-mode regimes could help preventing the onset of MHD instabilities detrimental for confinement. The idea relies essentially on the injection of the wave from the high-field side of the tokamak [3,4], which enables the wave to better penetrate in the plasma, although its practical realization in a reactor needs to be investigated. We present new modeling results performed by the Ray^{star} code with the aim of assessing the radial LH-driven radial current profiles as function of plasma and antenna parameters that include: the n|| peak and the width of the launched RF power spectrum, the coupled power, the launched position of the antenna in the poloidal direction and the kinetic profiles. Moreover by launching LH antenna spectra with a suitable n|| width the power spectrum propagating in the plasma is weakly modified by quasi-linear broadening effects. Non-linear interactions with plasma density fluctuations of the thermal background are also negligible. The LHCD efficiency has been calculated and correlated to these parameters.

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Paraxial expansion of the wave kinetic equation for electron cyclotron beams in turbulent plasmas

Hannes Weber, Omar Maj, Emanuele Poli

E-mail: hannes.weber@ipp.mpg.de

Abstract. The paraxial WKB (beam tracing) method [1] has proven to be very powerful for the computation of EC beams for heating, current-drive and diagnostics applications in smooth plasma equilibria. However, fluctuation-induced beam broadening with possible concerns for ITER application [2], [3] has raised interest on the effect of edge density fluctuations. The averaged effect of these is considered in a new approach based on the wave kinetic equation (WKE) and description of the beam in phase space. This method has been implemented in the WKBeam code [4].

In this work we propose to apply the paraxial technique to the wave kinetic equation [5]. On the one hand this allows comparison to the pWKB approach on the level of equations, clarifying the physical meaning of the WKE in phase space and the limitations of a standard Gaussian beam in physical space. On the other hand, we achieve a remarkable speed-up compared to WKBeam: Evolution of the beam is a direct result of a system of 11 ordinary differential equations whereas in WKBeam typically 10^5 rays are traced (Monte-Carlo approach).

The paraxial method applies to situations in which turbulence conserves the Gaussian beam shape, which is the case in the diffusive scattering regime. For beam and turbulence parameters chosen in accordance with this requirement we achieve good agreement with the well-benchmarked WKBeam code.

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Numerical tool based on FEM and wavelets for modeling wave propagation in spatially dispersive media

P. Vallejos, T. Johnson, T.Hellsten

June 15, 2018

KTH Royal Institute of Technology
School of Electrical Engineering
Dept. of Fusion Plasma Physics
Teknikringen 31, SE-100 44 Stockholm
Sweden

E-mail: pablova@kth.se

Abstract

Modeling RF-heating in tokamak plasmas is a challenging task due to spatial dispersion. The finite element method (FEM) is a numerical tool for modeling electromagnetic waves in plasma and can be applied on complex geometries of the plasma domain, scrape off layer and the antenna. To include spatial dispersive effects in FEM codes is a challenging task, e.g. finite-Larmor radius effects or up- and downshift in the parallel wave number. Fourier spectral methods can handle spatial dispersive effects, but is not suitable for calculations outside the plasma domain, in particular for complex geometries.

Recently, a new numerical method for treating spatial dispersive effects has been developed that is based on wavelets [1-5]. The method was successfully applied to a case of one-dimensional fast-wave heating in an inhomogeneous medium [5], including reflection on the high field side. However, the convergence was slow. This was a consequence of using the wavelet spectral method to invert the curl-curl operator in the wave equation.

In the present study, we investigate the potential of a hybrid numerical method based on operator splitting using FEM and wavelets. In this method, the curl-curl operator and non-dispersive terms in the wave equation are treated with FEM, while the spatial dispersive terms are evaluated using wavelets and included as an inhomogeneous term in the wave equation. The system is solved using Anderson iterations [4]. The objective is to show that convergence can be reached in fewer iterations and that the method is capable of handling spatial dispersive effects.

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Relaxation to a magnetohydrodynamics equilibrium via collision brackets

C ressan[1,2], M Kraus[1,2], Morrison[3] and Maj[1,2]

[1] Max-Planck-Institute for Plasma Physics, Garching, Germany
[2] Technische Universität München, Zentrum Mathematik, Garching, Germany
[3] The University of Texas at Austin, Physics Department and Institute for Fusion Studies, USA

E-mail: camilla.bressan@ipp.mpg.de, michael.kraus@ipp.mpg.de, pjmorrisonjr@gmail.com, omaj@ipp.mpg.de

Abstract. The computation of general 3D MHD equilibria (considering the presence of islands, ripples and chaotic regions) is increasingly important. Existing codes propose different numerical approaches. Variational codes [1] assume the existence of nested flux surfaces and minimize the energy of the system in order to obtain an equilibrium. Iterative solvers [2] on the other hand do not impose topological restrictions, and compute the MHD equilibrium through an iterative procedure. General relaxation methods do not assume nested flux surfaces but allow for little control over the relaxed profiles, e.g. pressure profile and rotational transform.
Recently methods from geometric mechanics have attracted some interest as means to improve relaxation methods for the computation of equilibrium states of both fluid and kinetic theories ([3] and references therein). Here a novel relaxation method is proposed. Its theoretical foundation relies on the Boltzmann's H-theorem [6]: the equilibrium points of the system can be understood in terms of local extrema of an entropy functional. This method fits into the framework of metriplectic dynamics, developed by Morrison ([4], [5]), in which the energy-preserving dynamics is combined with entropy dissipation.
The new approach has been numerically tested. Results for the Euler ideal fluid equations in two dimensions and Grad-Shafranov MHD equilibria are presented. A three dimensional proof of concept for Taylor-relaxed states (Beltrami fields) is also provided.

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Multicomponent fluid model for two-temperature plasmas derived from kinetic theory and applied to the simulation of magnetic reconnection in the sun chromosphere

Quentin WARGNIER, CMAP, Ecole Polytechnique, FRANCE

Benjamin GRAILLE, LMO, Université Paris-Sud, FRANCE

Thierry MAGIN, AR Dept., von Karman Institute, BELGIUM

Marc MASSOT, CMAP, Ecole Polytechnique, FRANCE

Key words : Kinetic theory, Solar physics plasma, Magnetic reconnection, Modeling, Simulation.

This contribution deals with the modeling of multicomponent magnetized plasmas in thermo-chemical non-equilibrium from the partially- to fully-ionized collisional regimes aiming at the simulation and prediction of magnetic reconnections in the chromosphere of the sun [2].

The first objective is to develop an asymptotic fluid model based on a kinetic theory approach, yielding a rigorous description of the dissipative effects, which inherits a well-identified mathematical structure [1]. The system of equations has been derived using a multiscale Chapman-Enskog perturbative solution method, based on a non-dimensional analysis accounting for the mass disparity between the electrons and heavy particles, as well as the influence of the magnetic field. The transport properties have been computed using a spectral Galerkin method based on a converged Laguerre-Sonine polynomial approximation. The multicompoment one-fluid model allows us to describe partially ionized plasmas as well, beyond the multi-fluid model of Braginskii [3], for the Sun chromosphere conditions [4].

The second goal is to develop an accurate and robust numerical strategy based on CanoP, a massively parallel code with adaptive mesh refinement, which is able to cope with the full spectrum of scales of the magnetic reconnection process. We also propose a numerical method to investigate the influence on shock solutions of a nonconservative product present in the electron energy equation [5].

Finally, we will show that the model and related numerical strategy, is able to properly reproduce the physics of magnetic reconnection in the sun chromosphere conditions. The validation of the approach through a series of test-cases relevant for the application to the dynamics of solar atmosphere in connection with the heliophysics team of NASA Ames Research Center [2].

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Quentin WARGNIER, CMAP, Ecole Polytechnique, CNRS, Université Paris-Saclay, FRANCE
`quentin.wargnier@polytechnique.edu`
Benjamin GRAILLE, Laboratoire de Mathématiques d'Orsay, Université Paris-Sud, CNRS, Université Paris-Saclay, FRANCE
`benjamin.graille@u-psud.fr`
Thierry MAGIN, Aeronautics & Aerospace Department, von Karman Institute for Fluid Dynamics, BELGIUM
`thierry.magin@vki.ac.be`
Marc MASSOT, CMAP, Ecole Polytechnique, CNRS, Université Paris-Saclay, FRANCE
`marc.massot@polytechnique.edu`

Free boundary 3D equilibrium calculations for non-linearly saturated current and pressure driven external kink modes

A Kleiner[1], J P Graves[1], D Brunetti[2], W A Cooper[1], T Nicolas[3] and C Wahlberg[4]

[1] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland
[2] Istituto di Fisica del Plasma IFP-CNR, I-20125 Milano, Italy
[3] Centre de Physique Théorique, Ecole Polytechnique, CNRS, F-91128 Palaiseau Cedex, France
[4] Department of Physics and Astronomy, PO Box 516, Uppsala University, SE-751 20 Uppsala, Sweden

E-mail: andreas.kleiner@epfl.ch

Abstract. The quiescent H mode (QH mode) [1] is interesting for future tokamak operation due to the absence of ELMs. Here, benign edge harmonic oscillations (EHOs) with low toroidal mode number (n=1,2,3) are observed instead, providing both energy and impurity exhaust with much lower energy deposits on surrounding components. Non-linearly saturated kink/peeling modes were proposed as a possible explanation of EHOs [2, 3]. In QH mode plasmas, low collisionality and large pressure gradients at the edge pedestal produce a considerable bootstrap current causing a flattening of the q profile close to the plasma boundary. Recent analytical modelling predicts linearly unstable external kink modes driven by coupling to infernal modes in the low shear region [4]. Such work provides a natural explanation for the corrugation of the last closed flux surface. In the current work we model non-linearly saturated external kink modes using free-boundary 3D computations with the ideal MHD equilibrium code VMEC. The saturated mode amplitude is evaluated from the edge corrugation in the converged equilibria. First, we present simulations of baseline tokamak scenarios where standard current-driven external kink modes are expected to be linearly unstable and non-linearly stable. A comparison [5] with an analytical model demonstrates that VMEC is capable of capturing the features of non-linear saturated current-driven external kink modes [6]. In JET-like QH mode plasmas, current-driven modes are found to be stable, but at high β_N infernal modes coupling to external kink modes can be identified in the resulting VMEC equilibrium states, in general agreement with the mechanism of Ref. [6].

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The effect of parallel magnetic field fluctuations on pressure driven MHD instabilities in toroidal plasmas

J. P. Graves[1], D. Brunetti[2], S. Lanthaler[1], C. Wahlberg[3]

[1] *École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Association EURATOM-Confédération Suisse, 1015 Lausanne, Switzerland*

[2] *Istituto di Fisica del Plasma IFP-CNR, Via R. Cozzi 53, 20125 Milano, Italy*

[3] *Department of Physics and Astronomy, P.O. Box 516, Uppsala University, SE-751 20 Uppsala, Sweden*

Analytic derivation and numerical calculation of pressure driven MHD instabilities in toroidal plasmas is notoriously difficult. Instability is determined by apparently weak effects in the toroidal metric tensor. A classic example being the case of the $m = n = 1$ internal kink mode, where previous numerical and analytic results obtained in a cylinder were shown [M. N. Bussac *et al*, Phys. Rev. Lett. **35**, 1638 (1975)] to be exactly cancelled by toroidal corrections, even in the limit of infinite aspect ratio. With such lessons well learned by many MHD code and analysis developers, there are now new generations of gyro-kinetic codes (e.g. EUTERPE [1], GTC [2], LIGKA [3], ORB5 [4]) that are being deployed to model MHD instabilities. Many of these codes are, or have been, only partially electromagnetic, usually assuming that the perturbed vector potential is parallel to the equilibrium field. Such reduced models are assumed in some non-linear MHD codes deployed for the study of edge localised modes (e.g. JOREK [5]), and non-linear kinetic-MHD codes (e.g. HXMGC [6]) that have for example been used to investigate fishbones. The present contribution investigates the effect of neglecting parallel magnetic field fluctuations on pressure driven instabilities in cylindrical and axisymmetric toroidal equilibria, and provides analytic benchmarks for codes that are not yet fully electromagnetic. Neglecting parallel field fluctuations allows the drive for pressure driven instabilities to be artificially absorbed by the energy required to perturb the magnetic curvature. While ballooning modes in tokamaks are only weakly affected by the neglect of the parallel magnetic field, the internal kink mode, infernal modes and interchange modes are strongly, or entirely, stabilised by neglecting $\delta B_{\|}$. For example, for interchange modes, the effect is dominant if the ballooning parameter $\alpha > 4\varepsilon(1-q_r^2)$, where $q_r = m/n$ is the rational safety factor of the main mode, and ε is the local inverse aspect ratio. The effect in a cylinder, reverse field pinch, and the core of the tokamak is seen to be particularly important.

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Kinetic treatment of ions in the magnetic presheath

A. Geraldini[1,2], F.I. Parra[1,2], F. Militello[2]

[1] Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, OX1 3PU, UK
[2] CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK

Boundary layers are present in the thin region of a tokamak where the Scrape-Off Layer (SOL) plasma reaches the divertor or limiter target. In order to obtain boundary conditions for SOL plasmas, these boundary layers must be studied [1]. Extending a few Debye lengths from the target, there is a non-neutral region of plasma with strong electric fields that repel the fast-moving electrons from the target. This region is known as the Debye sheath. The magnetic field usually impinges with a grazing angle $\alpha \ll 1$ (measured in radians) on the target surface. Hence, a boundary layer in which ions may intersect the wall during a gyro-orbit is also present, which extends a few typical ion Larmor radii from the wall and is much larger than the Debye sheath. This layer is called the magnetic presheath [2]. The large size and distortion of the ion gyro-orbits in the magnetic presheath makes a kinetic treatment necessary when the ion temperature is non-zero.

We present numerical solutions for the electrostatic potential across a collisionless magnetic presheath for several values of α. The electron density is assumed to be a Boltzmann distribution, valid if most of the electrons entering the thin Debye sheath bounce back from it. The ion distribution function is constant in the magnetic presheath when expressed in terms of the conserved quantities of ion motion for $\alpha \ll 1$ [3,4]. An expression for the ion density which includes the non-trivial contribution due to ions in their last gyro-orbit is obtained [5]. The solution for the electrostatic potential across the magnetic presheath is obtained by solving the quasineutrality equation using an iteration scheme. We obtain the ion distribution function entering the Debye sheath, and find that it is much thinner at smaller values of α. The ion temperature dependence of the magnetic presheath is studied, and the results of Chodura's fluid model are recovered when the ion temperature is zero.

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Non-linear modeling of the threshold between ELM mitigation and ELM suppression by resonant magnetic perturbations in ASDEX Upgrade

F.Orain,[1,2] M.Hölzl,[2] F.Mink,[2] M.Willensdorfer,[2] M.Dunne,[2] E.Viezzer,[2]
M.Bécoulet,[3] G.T.A.Huijsmans,[3,4] W.Suttrop,[2] S.Pamela,[5] S.Günter,[2]
K.Lackner,[2] the ASDEX Upgrade Team,[2] and the EUROfusion MST1 Team[6]

[1]CPHT, Ecole Polytechnique, CNRS, Université Paris-Saclay,
Route de Saclay, 91128 Palaiseau, France
[2]Max-Planck-Institut für Plasmaphysik, Garching, Germany
[3]CEA, IRFM, 13108 Saint-Paul-Lez-Durance, France
[4]Eindhoven University of Technology, Eindhoven, The Netherlands
[5]CCFE, Culham Science Centre, OX14 3DB, UK
[6]See author list of "H. Meyer *et al* 2017 Nucl. Fusion 57 102014

Instabilities occurring at the edge of tokamak plasmas, called Edge Localized Modes (ELMs), induce large heat loads on divertor targets and must be imperatively controlled. The application of Resonant Magnetic Perturbations (RMPs) is capable to mitigate or suppress ELMs in existing tokamaks and will therefore be used in ITER. In order to define an ELM-suppression criterion ensuring the safety of ITER divertor, the mechanism behind ELMs mitigation or suppression by RMPs needs to be better understood. With this aim, non-linear modeling of the interaction between ELMs and RMPs has been performed with the extended MHD code JOREK, using experimental data from ASDEX Upgrade discharges.

An $n = 2$ magnetic perturbation similar to experiments is applied in simulations, varying the applied RMP amplitude, the applied spectrum (more or less resonant depending on the phasing between RMP coils) and the plasma rotation. Depending on these parameters, plasma response can either screen RMPs or allow the formation of poloidally coupled tearing-kink modes at the edge (RMP partial or total penetration). Therefore, RMPs can either have no effect on ELMs, or mitigate or suppress them.

ELM mitigation or suppression is not only due to the degradation of the pedestal pressure gradient by RMPs, but can be explained by the non-linear toroidal coupling of medium n modes with the edge $n = 2$ modes induced by RMPs. When RMPs are screened, this coupling is too low to affect the ELM growth, dominated by medium toroidal modes $n = 4 - 8$. When RMPs partially penetrate, the mode coupling forces the medium n modes to reach a saturation level lower than the ELM crash level, resulting in rotating saturated modes and mitigated energy reaching the divertor. Above a penetration threshold, the braking of the perpendicular electron rotation is observed, inducing the locking of medium n modes, which saturate to a low level: hence, ELMs are fully suppressed. The detailed suppression mechanism will be described.

IMPACT OF COLLISIONALITY ON TURBULENCE IN THE EDGE PLASMA AND SCRAPE-OFF LAYER (SOL)

R. Tatali[1], G. Ciraolo[2], D. Galassi[1, 3], Ph. Ghendrih[2], F. Nespoli[1], E. Serre[1], P. Tamain[2], C. Baudoin[1, 2], H. Bufferand[2], T. Cartier-Michaud[1], N. Nace[1, 2], F. Schwander[1]

[1]M2P2, UMR7340 Centrale Marseille Plot 6, 38 rue Joliot-Curie 13451 Marseille, France
[2] CEA, IRFM, F-13108, Saint-Paul-lez-Durance, France
[3]École Polytechnique Fédérale de Lausanne(EPFL), Swiss Plasma Center(SPC), CH-1015 Lausanne, Switzerland

A better understanding of how turbulent transport influences the scrape-off layer width and more in general the confinement of the plasma itself is required in sight of the design of future fusion reactors, as ITER. State of the art modeling tools can provide a deeper understanding of these phenomena.

The TOKAM3X code [1, 2] has been developed between M2P2 and IRFM. This is a 3D fluid turbulence code which can simulate self –consistently the plasma turbulence in full torus geometry (both open and closed field lines) in limited and diverted configurations. Including energy balance equations in TOKAM3X opens the way to consistently take into account variations of collisionality and its direct impact in heat and charge conductivity, in the edge and SOL [3, 4].

To study those effects a set of TOKAM3X simulations have been run using COMPASS characteristic parameters with different value of resistivity. All simulations are performed with high field side limiter in circular plasma geometry. This analysis shows that the size and the amplitude of turbulent structures are sensitive at the changes of collisionality, especially the lower is the resistivity and the smaller the structures become. This opens numerical issues on the code resolution and therefore it gives a constraint on the value of collisionality that we can use in our simulation. Moreover heat conductivity is found to have the same qualitative impact.

To assess these results, the impact of resistivity has been analyzed in a simplified model that allows us to determine analytical growth rates and investigated some of non-linear properties. Here we have found analytically that reducing the resistivity leads to a larger typical wave length and therefore generate smaller turbulent structures. The scaling is weakly sensitive on the resistivity (power 1/4). Based on this model the amplitude of the fluctuations exhibits a maximum with two branches. Thus, at larger resistivity the amplitude tends to increase and vice versa. The dependence of wave vector with thermal energy is typically T^(3/8). A balance argument between the damping and drive terms indicates that for the large resistivity branch the amplitude tends to decrease when decreasing the resistivity. This analytical work is consistent with simulations from TOKAM2D [5], a 2D version of TOKAM3X. The discrepancy of 2D simulation and 3D is further discussed.

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Parametric study of fast-ion-driven modes in Wendelstein 7-X

C. Slaby[1], A. Könies[1], R. Kleiber[1], S. Äkäslompolo[1], and J. Kontula[2]

[1] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
[2] Aalto University, Aalto, Finland

E-mail: `christoph.slaby@ipp.mpg.de`

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Abstract. In the upcoming operation phase 1.2b (Summer 2018), fast ions in the stellarator Wendelstein 7-X will be generated by neutral beam injection (NBI). Later operation phases will also include ion cyclotron resonance heating (ICHR). In order to effectively heat the plasma, the particles generated by those systems need to be confined for a time period that is on the order of the slowing-down time. The fast ions may, however, excite instabilities in the plasma which can lead to enhanced fast-ion transport and can, in severe cases, cause damage to plasma-facing components [1].

We present a numerical study of fast-ion-driven Alfvén eigenmodes (AEs) in a Wendelstein 7-X high-mirror equilibrium using the non-linear CKA-EUTERPE code package [2]. This model is perturbative, since a fixed mode structure – computed by the ideal-MHD code CKA – is used throughout the calculation. The non-linear gyrokinetic code EUTERPE computes the power transfer of the fast particles to the mode which defines the growth rate of the instability.

We show that having a fast-ion collision operator present in the simulations is required to accurately predict the non-linear saturation levels of the modes. The scaling of the saturation levels with respect to fast-ion drag and the pitch-angle collision frequency is investigated.

Furthermore, we study the impact of several other actuators that might be of experimental relevance for finding operation windows that show AE activity. Examples are the effects of a radial electric field on the mode dynamics and the composition of the background plasma (hydrogen versus helium).

The background-plasma temperature and density profiles used in the simulations are close to their expected values for operation phase 1.2b. For such plasmas, the fast-ion density profile and parameters of the fast-ion slowing-down distribution function are calculated using the ASCOT code [3, 4].

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Equilibrium β-limits in classical stellarators and beyond

J. Loizu[1,2], S. R. Hudson[3], C. Nührenberg[2], J. Geiger[2] and P. Helander[2]

1. Swiss Plasma Center, Ecole Polytechnique Fédérale de Lausanne, Switzerland

2. Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

3. Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA

A numerical investigation is carried out in order to understand the equilibrium β-limits in classical stellarators [1]. The SPEC code [2, 3] is used in fixed-boundary in order to assess whether or not magnetic islands and stochastic field-lines can emerge at high β. Two modes of operation are considered: *fixed-current* and *fixed-iota*. Despite the fact that relaxation (magnetic reconnection) is allowed, the former is shown to maintain good flux surfaces up to the equilibrium β-limit predicted by ideal MHD, above which a separatrix forms. The latter, which has no ideal equilibrium β-limit, is shown to develop regions of magnetic islands and chaos at sufficiently high β, thereby providing a "non-ideal β-limit". We compare our results to the High-Beta-Stellarator theory of Freidberg [4] and derive a new analytical prediction for the non-ideal equilibrium β-limit above which chaos emerges. Following the same approach, we examine the effect of β and net-toroidal-current I_φ on the degradation or healing of magnetic surfaces in experimentally-relevant geometries.

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Corresponding author: J. LOIZU *joaquim.loizu@epfl.ch*

Electron temperature gradient driven instabilities in helical reversed field pinch plasmas

I. Predebon[1], **P. Xanthopoulos**[2], **M. Gobbin**[1]
[1] Consorzio RFX, Padova, Italy
[2] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

Abstract. Helical states have, in general, beneficial consequences on the reversed field pinch plasma performance. Good confinement properties are achieved due to an overall reduction of magnetic chaos. On the other hand, this physical condition favors the onset of radially localized electrostatic/electromagnetic turbulence due to the simultaneous formation of large pressure gradients in the region surrounding the helical core.

In a previous work, ion-temperature-gradient (ITG) turbulence has been investigated with a realistic geometric description of the 3D configuration*. The core displacement turns out to have an unfavorable effect in terms of ITG turbulent transport: in the region of higher magnetic surface proximity, the local temperature gradients become larger with consequent growing instabilities, weaker zonal flows, and, in general, larger ion heat fluxes.

Since the transport barriers are usually observed in the electron heat channel, in this contribution we mainly focus on the occurrence of instabilities driven by the electron temperature gradient. Due to the importance of electromagnetic effects in the reversed field pinch, we include finite β and collisionality, using realistic geometry and plasma profiles. The occurrence of low wavenumber microtearing modes (MTMs) and high wavenumber electron-temperature-gradient (ETG) modes is discussed, with their possible role in the determination of the electron heat conductivity. The role of the geometric coefficients is also explicitly analyzed, making a comparison with the corresponding axisymmetric configurations.

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BSTING: fluid turbulence simulations in stellarators

B Shanahan[1], B Dudson[2] and P Hill[2]

[1]*Max-Planck Institute für Plasmaphysik, Teilinstitut Greifswald, Germany*

[2]*York Plasma Institute, Department of Physics, University of York, UK*

The recent implementation of the Flux Coordinate Independent (FCI) [1] method for parallel derivatives in BOUT++ [2] has allowed for simulations in nonaxisymmetric geometries [3,4]. Here we present the most recent results for the BSTING project, which seeks to modify the **B**OUT++ framework to **S**imulate **T**urbulence **I**n **N**on-axisymmetric **G**eometries.

To allow for fully three dimensional turbulence simulations, the metric tensor components in BOUT++ have been extended to vary in three dimensions. Following this extensive modification, we present the results of several tests to ensure the accuracy and stability of the framework have been maintained. Of particular importance are the tests of the parallel derivatives and the associated parallel boundary conditions. These methods have been examined qualitatively by tracing non-axisymmetric flux surfaces and quantitatively via the Method of Manufactured Solutions [5], the results of which will be presented.

A fully three dimensional framework furthers the flexibility of BOUT++, and therefore several new features to exploit this flexibility will be presented here. Modifications to the Zoidberg grid generator which allow for Wendelstein 7-X geometries and a newly-implemented FCI curvilinear grid generation system are discussed in detail.

Finally, initial investigation of plasma filaments in non-axisymmetric geometries using an isothermal model which evolves electron density, vorticity, electromagnetic potential and parallel momentum is presented. Among other results, filaments propagating in the closed-field-line region of a low-field-period, rotating-ellipse equilibrium are characterized as inertially-limited via examination of the velocity scaling and currents associated with the filament propagation. The implications of these simulations for future experiments will be explored.

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FRIDAY, August 31, 2018

Stellarator turbulent transport at low collisionalities

M. Barnes[1,2], M. Landreman[3], F.I. Parra[1,2], J.A. Alonso[4], I. Calvo[4], J.M. García-Regaña[4] and J.L. Velasco[4],
[1]*Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, UK*
[2]*Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, UK*
[3]*Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, MD, USA*
[4]*Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain*

Turbulent transport limits energy confinement in axisymmetric magnetic field configurations and is also expected to limit confinement in stellarators optimized to reduce neoclassical transport. Much effort over the last two decades has gone into characterizing – and to some extent, understanding – turbulence in tokamaks, but there has been comparatively little work on studying turbulence or even microinstabilities in stellarators. The relatively few studies of turbulence in stellarators (see, for example, [1, 2]) have assumed a Maxwellian velocity space distribution for the plasma equilibrium. However, at reactor-relevant temperatures the collisional mean free path should be sufficiently long that particles trapped in the non-axisymmetric magnetic field diffuse radially outward with a characteristic step size much larger than the ion gyroradius. These large radial excursions lead to significant deviations of the equilibrium velocity distribution from a Maxwellian. In the limits of large aspect ratio [3] or approximate omnigeneity [4], it is still possible to define a small parameter so that these deviations can be treated as perturbations to a Maxwellian. However, due to the sensitivity of turbulent heat fluxes to gradients, the non-Maxwellian corrections may nonetheless impact turbulent transport.

In this talk we present results for microstability and turbulent transport in the low collisionality regime, with these non-Maxwellian features taken into account. The deviation from a Maxwellian is calculated using the drift kinetic code SFINCS [5]; the turbulent fluctuations are computed using a new gyrokinetic code called `stella`. In particular, we present results on the dependence of microstability on collision frequency and on the ratio of gyroradius to system size, and we compare these results with the low-collisionality neoclassical transport. A discussion of the implications of these results for optimized stellarator core confinement will also be given.

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Experimental constraint on the radial mode number of the Geodesic Acoustic Mode in MAST Ohmic plasma.

B. Hnat[1], S. Gadgil[1], A. Kirk[2], F. Militello[2], N. Walkden[2] and the MAST Team

[1] Physics Department, University of Warwick, Coventry, CV4 7AL, UK.
[2] EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK.

Reciprocating Mach probe data is used to estimate the radial wave number of oscillatory zonal flows in Ohmic MAST plasma. An intermittent ~10 kHz mode, previously identified as a Geodesic Acoustic Mode (GAM), is detected in the wavelet decomposition and windowed spectra of plasma potential fluctuations of the MAST tokamak edge plasma. Two-points phase differencing technique is then applied to probe pins with radial and poloidal separations giving an estimate of the radial wave number at the desired range of frequencies. The phase velocity of propagation and an estimate of the shearing rate of the GAM is obtained. We measure the radial mode number range $k_r \sim 0.3\text{-}1.0\ \mathrm{cm}^{-1}$ and a radial propagation speed of up to ~1 km/s. The GAM shearing rate is an order of magnitude smaller than the growth rate of drift-like turbulence. These results are consistent with the estimates obtained previously from multi-fluid numerical simulations of GAM in MAST.

Instability and Turbulence in the Tokamak Pedestal

M.J. Pueschel[1], D.R. Hatch[1], M. Kotschenreuther[1], X. Liu[1], S. Mahajan[1], J. Citrin[2], P.W. Terry[3], J.W. Connor[4], D.R. Ernst[5], and W. Guttenfelder[6]

[1]Institute for Fusion Studies, University of Texas at Austin, Austin, Texas 78712, USA
[2]FOM Institute DIFFER, 5600 HH Eindhoven, The Netherlands
[3]University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
[4]Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[5]MIT Plasma Science and Fusion Center, Cambridge, Massachusetts 02139, USA
[6]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA

Abstract. Transport barriers are a key component of high-performance discharges in tokamak experiments. Much of the theoretical understanding of plasma microturbulence, however, has been developed based on core parameters. We show how at steep normalized gradients, higher eigenstates of typical microinstabilities can be excited. In the nonlinear, quasi-stationary state, these new mode branches affect turbulence both by imprinting mode structures and by boosting fluxes. Thus, if shear-flow suppression is insufficient to stabilize such eigenstates, it may become difficult to accurately predict transport using standard quasilinear transport models.

Microtearing turbulence in the pedestal is shown to play an important role in present-day experiments, breaking the symmetry between transport channels common to MHD-like instabilities. Using nonlinear modeling to extrapolate to future fusion devices at small ρ^*, however, one finds that electrostatic modes can no longer be stabilized by flow shear, with the adiabatic-electron slab-ITG mode predicted to have a central role. Approaches to maintaining a pedestal-like region in such a regime are discussed, invoking magnetic geometry as well as the relative position of the density and temperature pedestal.

Bifurcations and oscillations in divertor plasmas

A.S. Kukushkin[1], S.I. Krasheninnikov[2]
[1] NRC "Kurchatov Institute", Moscow, Russia
[2] UCSD, La Jolla, CF, USA

It is generally assumed in divertor modelling that the solution relaxes to some steady state that depends on the input parameters, such as the power input to the SOL and the plasma density there. However, this is not always the case. The non-linear nature of the plasma transport equations can render the steady state solution impossible in some parameter range, which drives the solution to a regular or irregular oscillation pattern or to a sharp transition to a different steady state (bifurcation). Such evolution patterns are not uncommon in divertor modelling [1, 2] and they can be identified in experiment [3, 4]. The modelling results for the reactor (e.g., ITER) parameters show that this effect can cause a factor 2 modulation depth of the divertor target loading, which can exacerbate the problem of target survival.

In the present paper, we consider different mechanisms that can lead to the bifurcations and regular oscillations in the divertor plasma and check them against the modelling results. We feel that the effort devoted to studying these phenomena in the edge physics community is far too weak and we want to attract more attention to this area of the edge plasma physics.

[1] S.I. Krasheninnikov, et al., *Nucl. Fusion* **27** (1987) 1805
[2] R.D. Smirnov, et al., *Phys. Plasmas* **23** (2016) 012503
[3] A. Loarte, et al., *Phys. Rev. Letters* **83** (1999) 3657
[4] S. Potzel, et al., *J. Nucl. Mater*. **438**, S285

List of Contributed papers
(Posters)

Contributed papers (posters)

	Last Name	First Name	Laboratory	Title
P-18	Baschetti	Serafina	CEA, IRFM, F	An analytical model for the scrape-off layer width when the anomalous transport of plasma is considered
P-25	Bokshi	Arka	Uni. York, UK	On the existence of a stable stationary state solution of toroidal drift mode structures in the presence of self-consistently calculated flows
P-37	Bressan	Camilla	IPP-Garching, D	Relaxation to a magnetohydrodynamics equilibrium via collision brackets
P-13	Brunetti	Daniele	CNR Milano, I	ExB and diamagnetic equilibrium flows effects on pedestal localised MHD infernal stability
P-19	Calado Coroado	André	EPFL-SPC, CH	Numerical simulations of plasma fuelling in tokamaks using the GBS code
P-10	Cardinali	Alessandro	ENEA, I	Study of Ion Cyclotron Heating (ICRH) scenarii and fast particles generation in DTT
P-34	Cardinali	Alessandro	ENEA, I	Modeling of LHCD in high magnetic field, high density tokamak configuration
P-26	Cartier-Michaud	Thomas	CNRS, F	Verification of turbulent simulations using PoPe: quantifying model precision and numerical error with data mining of simulation output
P-1	Caschera	Elisabetta	CEA, IRFM, F	Penalized limiter configuration in GYSELA gyrokinetic global and flux driven simulations
P-9	Cathey Cevallos	Andres	IPP-Garching, D	Nonlinear simulations of ELM cycles and inter-ELM activity in comparison to experimental results
P-28	Chandrarajan J.	Ajay	EPFL-SPC, CH	Study of wavenumber resolution convergence in turbulent transport simulations including kinetic electron dynamics
P-23	Chernoshtanov	Ivan	Budker Inst., RU	Ion losses driven by Alfvén ion-cyclotron instability in mirror machine with skew neutral beam injection
P-2	Christen	Nicolas	Univ. Oxford, UK	Simulating background toroidal flow shear with the local gyrokinetic code GS2
P-27	Di Giannatale	Giovanni	Consorzio RFX, I	Lagrangian Coherent Structures as a new frame to investigate the particle transport in highly chaotic magnetic systems
P-15	Dubuit	Nicolas	Univ. Marseille, F	Size of Turbulence-Driven Magnetic Islands
P-3	Dudkovskaia	Alexandra	Uni. York, UK	Searching for the Secondary Instabilities in Magnetically Confined Plasmas
P-4	Garbet	Xavier	CEA, IRFM, F	Why trapped electrons damp GAMs
P-41	Geraldini	Alessandro	CCFE, Culham, UK	Kinetic treatment of ions in the magnetic presheath
P-20	Ghendrih	Philippe	CEA, IRFM, F	Turbulence spreading from the SOL into the edge plasma and generation of large poloidal convective cells in GYSELA and TOKAM3X flux driven simulations
P-7	Graves	Jonathan	EPFL-SPC, CH	Fundamental global properties and frequency shift of geodesic acoustic modes in shaped axisymmetric toroidal plasmas
P-40	Graves	Jonathan	EPFL-SPC, CH	The effect of parallel magnetic field fluctuations on pressure driven MHD instabilities in toroidal plasmas
P-29	Hamed	Myriam	CEA, IRFM, F	Stability of kinetic microtearing modes

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P-5	Lanti	Emmanuel	EPFL-SPC, CH	Flux-driven simulations and profile stiffness investigation using the global gyrokinetic code ORB5
P-16	Lascas Neto	Eduardo	EPFL-SPC, CH	Self-consistent numerical calculation of neoclassical effects of 3D MHD geometry on heavy impurity transport in the presence of strong rotation
P-22	Lauber	Philipp	IPP-Garching, D	Analytical finite-Lamor-radius and finite-orbit-witdth model for the LIGKA code and its application to KGAM and EGAM physics
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P-6	Novikau	Ivan	IPP-Garching, D	Linear and non-linear gyrokinetic simulations of zonal structures
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