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Book of Abstracts

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INSTITUTO DE PLASMAS
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Practical Information

1. **Invited speakers:** Make sure to upload the slides for your talk prior to your session. The slide desk is located on the lobby.

2. **Lunch options:** There are many options for lunch inside the IST campus and in its immediate vicinity. **On campus:** (i) canteen on the ground floor of the Civil Engineering Pavillion (the conference building); (ii) the cafeteria of *Complexo Interdisciplinar* (building 26 on the IST map); (iii) the post-graduate canteen (floor -1 of building 24); (iv) *Sena* restaurant (ground -1 of building 5). **Off campus:** on *Avenida Duque de Ávila*, heading towards *Saldanha*, you will find many small restaurants that offer reasonably priced lunch menus.

3. The **Conference Reception** will be held in *Museu da Cerveja*, located in *Terreiro do Paço*, on Monday, 18:30 – 19:30. This is easily accessible by underground (*"Terreiro do Paço"* stop on the blue line). If you prefer to be accompanied to the Reception you can join one of the designated guides, who will depart from the entrance to the conference building at 18:00

4. The **Conference Banquet** will be held in Casa do Alentejo, on Wednesday, from 20:00 onwards. The most convenient underground stops are *"Rossio"* (green line) and *"Restauradores"* (blue line). Again, if you prefer, you can join one of the conference guides who will be happy to take you. Guides will leave from entrance to the conference building at 19:30.

Hour/Date	5/10	6/10	7/10	8/10
08:00-08:30	Registration	-	-	-
08:30-09:00	Opening and welcome	-	-	-
09:00-09:50	Tutorial (50') *P. Catto* (MIT, USA) – Profile evolution and momentum transport in the core and pedestal	Tutorial (50') *F. Militello* (CCFE, UK) – Understanding density decay lengths and particle exhaust in tokamaks from a theoretical and an experimental perspective.	Tutorial (50') *A. Stockem* (Ruhr Univ., Germany) – Shock formation in astrophysics and laser-plasma interactions	Tutorial (50') *X. Garbet* (CEA-IRFM, France) – Interplay of turbulence, collisional and MHD transport processes
09:50-10:30	Topical (40') *E. Westerhof* (DIFFER, Holland) – Modeling of electron cyclotron current drive applied for neoclassical tearing mode stabilization	Topical (40') *F. Hariri* – EPFL, Switzerland The Flux-Coordinate Independent Approach for Plasma Turbulence Simulations	Topical (40') *A. Marocchino* (La Sapienza Univ., Italy) – Ablative Hydrodynamic Richtmyer-Meshkov and Rayleigh-Taylor instabilities at ablation front in direct-drive shock ignition scheme	Topical (40') *H. Doerk* (IPP Garching, Germany) – Turbulence stabilization due to high beta and fast ions in high-performance plasmas at ASDEX Upgrade and JET
10:30-11:10	Coffee break	Coffee break	Coffee break	Coffee break
11:10-11:50	Topical (40') *J. Ball* (CCFE, UK) – Intrinsic momentum transport in tokamaks with tilted elliptical flux surfaces	Topical (40') *M. Schneller* (IPP Garching, Germany) – Non-linear Energetic Particle Transport in the Presence of Multiple Alfvenic Waves in ITER	Topical (40') *L. Comisso* (Politecnico di Torino, Italy) – Formation of Plasmoid Chains due to Resonant Magnetic Perturbations	Topical (40') *A. Stegmeir* (IPP Garching, Germany) – The Field line map approach to plasma turbulence simulations
11:50-12:30	Plenary (60') *S. Cowley* (CCFE, UK) – Challenges for Fusion Theory	Topical (40') *F. Bombarda* (ENEA, Italy) – The High Density Approach for Fusion	Topical (40') *M. Kraus* (IPP Garching, Germany) – Towards Geometric Particle-in-Cell Schemes for Gyrokinetics	Topical (40') *A. Schekochihin* (Oxford Univ, UK) – Phase mixing vs. nonlinear advection in drift-kinetic plasma turbulence
12:30-14:00	Lunch	Lunch	Lunch	Closing(15' only)
14:00-14:40	Topical (40') *L. Vlahos* (Thessaloniki Univ., Greece) – Current fragmentation and particle acceleration in strongly turbulent plasmas	Topical (40') *I. Calvo* (CIEMAT, Spain) – Quasisymmetry far from the magnetic axis	Topical (40') *E. Hirvijoki* (Chalmers Univ., Sweden) – Gaussian Radial-Basis-Function solution of the non-linear Fokker-Planck equation	
14:40-15:20	Topical (40') *M. Muraglia* (PIIM, France) – Self-consistent interaction between MHD island and turbulence	Poster session 1	Poster session 2	
15:20-15:40	Coffee break	Coffee break	Coffee break	
15:40-16:20	Topical (40') *H. Lütjens* (LPP, France) – Effect of kinetic ions on internal kink modes with XTOR-K	Poster session 1	Poster session 2	
16:20-17:20	Topical (40') P. *Rodrigues* (IPFN, Portugal) – Predicting the stability of alpha-particle--driven Alfven Eigenmodes in burning plasmas	Poster session 1	Poster session 2	
18:30–19:15	Reception	-	-	
19:00-22:00	-	-	Banquet	

Invited Talks

Plenary

S. Cowley, *“Challenges for Fusion Theory”*

Tutorial

1. **P. Catto**, *“Profile evolution and momentum transport in the core and pedestal”*
2. **X. Garbet**, *“Interplay of turbulence, collisional and MHD transport processes”*
3. **F. Militello**, *“Understanding density decay lengths and particle exhaust in tokamaks from a theoretical and experimental perspective”*
4. **A. Stockem**, *“Shock formation in astrophysics and laser-plasma interactions”*

Topical

1. **J. Ball**, *“Transport in tokamaks with tilted elliptical flux surfaces”*
2. **F. Bombarda**, *“The High Density Approach for Fusion”*
3. **I. Calvo**, *“Quasisymmetry far from the magnetic axis”*
4. **L. Comisso**, *“Formation of Plasmoid Chains due to Resonant Magnetic Perturbations”*
5. **H. Doerk**, *“Turbulence stabilization due to high beta and fast ions in high-performance plasmas at ASDEX Upgrade and JET”*
6. **F. Hariri**, *"The Flux-Coordinate Independent Approach for Plasma Turbulence Simulations"*
7. **E. Hirvijoki**, *“Gaussian Radial-Basis-Function solution of the non-linear Fokker-Planck equation”*
8. **M. Kraus**, *“Towards Geometric Particle-in-Cell Schemes for Gyrokinetics”*
9. **H. Lütjens**, *“Effects of kinetic ions on internal kink modes with XTOR-K”*
10. **A. Marocchino**, *“Ablative hydrodynamic Richtmeyer-Meshkov and Rayleigh-Taylor instabilities at ablation front in direct-drive shock ignition scheme”*
11. **M. Muraglia**, *“Self-consistent interaction between MHD island and turbulence”*
12. **P. Rodrigues**, *“Predicting the stability of alpha-particle–driven Alfvén Eigenmodes in burning plasmas”*
13. **A. Schekochihin**, *"Phase mixing vs. nonlinear advection in drift-kinetic plasma turbulence"*
14. **M. Schneller**, *“Non-linear Energetic Particle Transport in the Presence of Multiple Alfvénic Waves in ITER”*
15. **A. Stegmeir**, *“The field line map approach to plasma turbulence simulations”*
16. **L. Vlahos**, *“Current fragmentation and particle acceleration in strongly turbulent plasmas”*
17. **E. Westerhof**, *"Modeling of electron cyclotron current drive applied for neoclassical tearing mode stabilization"*

Challenges for Fusion Theory

S. C. Cowley[1,2]

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[2] *Department of Physics, Imperial College, Prince Consort Road, London SW7 2BZ, UK*

Turbulence, beta limits and technology limits have driven fusion research to larger and larger size machines. Smaller, cheaper and simpler reactors are certainly preferable — and they require improvements in plasma performance. There is clear evidence for improved confinement regimes — but still no predictive theory. Reduced turbulence, while desirable, often results in explosive instability — but not inevitably. I will discuss the physics of these challenges.

Profile evolution and momentum transport in the core and pedestal

Peter J. Catto

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Abstract

Simulating radial profile evolution across the core of a tokamak plasma is one of the major challenges for gyrokinetic turbulence codes. The main complication is the evolution of the electrostatic potential profile [1], which along with the plasma density and temperature profiles enters the ion flow velocity. To evolve the potential the radial transport of angular momentum must be evaluated in the presence of turbulence in a weakly collisional plasma [2]. The off diagonal elements of the stress tensor determine the potential. In ITER and reactor relevant regimes the ion flow will be diamagnetic rather than sonic. In this diamagnetic regime, symmetries of the gyrokinetic equation [3] require that the ion distribution function be determined from a higher order gyrokinetic equation than is employed in local gyrokinetic simulations. In the near term, the only practical way to completely evaluate the required off diagonal stress tensor (including the residual stress needed to determine intrinsic rotation), is to solve a more accurate gyrokinetic equation to provide closure for the conservation of toroidal angular momentum equation [4], as well as for the number and energy conservation equations [5] (which do not normally require the added gyrokinetic accuracy). An additional challenge to gyrokinetic simulations is using a hybrid closure scheme in the pedestal [6], where the radial scale lengths of the density, ion temperature, and potential can become comparable to a poloidal ion gyroradius and strong poloidal variation can occur [7] and thereby remove the symmetries acting in the core. The tutorial will stress the need to deal with these important issues so that meaningful comparisons can be made between theory and experiment [8].

Work supported by the US Department of Energy grant DE-FG02-91ER-54109 at MIT.

[1] F. I. Parra and P. J. Catto, Plasma Phys. Control. Fusion **50**, 065014 (2008).
[2] F. I. Parra, M. Barnes and P. J. Catto, Nucl. Fusion **51**, 113001 (2011).
[3] F. I Parra, M. Barnes and A. G. Peeters, Phys. Plasmas **18**, 062501 (2011).
[4] F. I. Parra and M. Barnes, to appear in Plasma Phys. Control. Fusion.
[5] M. Barnes et al. Phys. Plasmas **17**, 056109 (2010
[6] G. Kagan and P. J. Catto, Plasma Phys. Control. Fusion **50**, 085010 (2008)
[7] C. Theiler et al. Nucl. Fusion 54, 083017 (2014).
[8] F. Nave poster this meeting.

TUTORIAL

Interplay of turbulence, collisional and MHD transport processes.

X. Garbet

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The question of impurity transport has gained a renewed interest with the decision to implement plasma facing components made of tungsten in several tokamaks, in view of a future implementation in Iter. Furthermore Helium will be produced in Iter by fusion reactions, and other impurities will come from edge plasma seeding. It turns out that impurity transport is a paradigmatic case where neoclassical and turbulent processes may not be additive, as usually assumed. Candidates for breaking the separability assumption are profile corrugations, poloidal asymmetries and shear flows. Moreover, MHD non linear processes such as sawteeth crashes or island profile flattening also affect particle transport. Profile relaxations due to MHD events do compete with collisional and turbulent particle transport. This synergy may come from the interaction between convective flow cells of various sizes or the modification of neoclassical transport because of helical magnetic perturbations. This overview will present the reasons why the common assumption of additivity of turbulence, collisional and MHD transport processes may fail. It will be illustrated by gyrokinetic and non linear MHD simulations that include neoclassical effects. Consequences for other transport channels will also be discussed.

Understanding density decay lengths and particle exhaust in tokamaks from a theoretical and an experimental perspective.

Fulvio Militello

CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK

As magnetic fusion research progresses towards reactor relevant conditions, it is becoming clearer and clearer that the plasma exhaust and its consequent surface interaction will strongly constrain the operational space and determine whether the next generation machines will be successful. The level of interaction of the plasma with the solid structures surrounding it is largely determined by the properties of the Scrape-Off Layer (SOL) and in particular by the decay lengths of relevant thermodynamic quantities such as density and temperature. Understanding the physical mechanisms determining the SOL profiles is therefore essential to predict and control the heat loads on the divertor plate and the heat and particle flux to the walls, which cause erosion and release impurities.

One important experimental observation in this respect is the formation of a flatter region in the density profile far from the separatrix (far SOL) as fuelling is increased. While the presence of this feature leads to enhanced plasma wall interactions, with harmful consequences to the material structures, a high core density is desirable from a performance point of view. Over the years, several theories were developed to explain this puzzling phenomenon, attributing its cause to enhanced wall recycling, divertor detachment or modifications of the parallel and perpendicular transport.

In this paper, all these theories are reviewed and compared with experimental findings from several machines. Particular focus will be given to recent MAST results that have shed some light on this problem, by falsifying the explanations involving wall recycling and divertor detachment as the SOL flattening was shown not correlate with the former and occur in the absence of the latter. While these theories might still explain part of the phenomenon and be relevant in particular conditions, and hence are interesting to study, they were proven to lack the generality of the transport based approach.

This approach is based on the physics of SOL filaments, which are coherent nonlinear density and temperature structures that erupt from the confined plasma and travel along field lines towards the solid surfaces of the machine. Their mechanics, still a field of active investigation, will be reviewed in the context of the interaction between fluctuations (the filaments) and profile formation (the decay lengths discussed above). The modelling of the intermittent, non-diffusive transport associated with the filaments, analysed with state of the art numerical simulations performed with the BOUT++ framework and with the ESEL code as well as with theoretical scaling laws, will also be discussed. It will be shown that even in the absence of divertor physics, simple filamentary transport models can explain the shoulder formation in the far SOL.

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/I501045]. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Shocks in astrophysics and laser plasma interactions

Anne Stockem Novo

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In collisionless shocks the interaction of charged particles and electromagnetic fields dominates over collisional effects. Such shocks occur in many different fields of physics. In the context of space and astrophysics they have been investigated since many decades, being a good candidate for explaining the origin of energetic cosmic rays. In fusion, shock waves are used for efficient compression of the target material and recently, collisionless shocks are discussed for acceleration of ions for medical physical applications.

The physical conditions are the key quantities for a controlled application, such that the shock is stable and directed with efficient energy transfer. In this context, plasma instabilities are important as mediators of the shock but also as undesired side effects.

This tutorial addresses these aspects for electromagnetic shocks as well as for electrostatic shocks. Electromagnetic shocks are of importance mainly in astrophysical environments. They are mediated by the Weibel or filamentation instability and accelerate charged particles via Fermi acceleration. Electrostatic shocks can be produced in the laboratory with the powerful state-of-the-art laser systems. They are characterized by a strong electrostatic field, which leads to electron trapping. Ions are efficiently accelerated by reflection from the electrostatic potential. An overview will be given over the shock formation and particle acceleration mechanisms in theory and simulations.

Intrinsic momentum transport in tokamaks with tilted elliptical flux surfaces

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Recent work demonstrated that breaking the up-down symmetry of tokamaks removes a constraint limiting intrinsic momentum transport, and hence toroidal rotation, to be small.‡ We show, through MHD analysis, that ellipticity is most effective at introducing up-down asymmetry throughout the plasma. Using GS2, a local δf gyrokinetic code that self-consistently calculates momentum transport, we simulate tokamaks with tilted elliptical poloidal cross-sections and a Shafranov shift. These simulations illuminate both the magnitude and poloidal dependence of nonlinear momentum transport. The results are consistent with TCV experimental measurements§ and suggest that this mechanism can generate sufficient rotation to stabilize the resistive wall mode in reactor-sized devices. Furthermore, preliminary linear and nonlinear results indicate that tilting elliptical flux surfaces directly reduces the energy transport at low temperature gradients, but increases it at high temperature gradients.

This work has been carried out within the framework of the EUROfusion Consortium and J.B and F.I.P have received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053, as well as the RCUK Energy Programme (grant number EP/I501045). The views and opinions expressed herein do not necessarily reflect those of the European Commission.

‡ F.I. Parra, M. Barnes, and A.G. Peeters. Phys. Plasmas, 18(6):062501, 2011.

§ Y. Camenen, A. Bortolon, B.P. Duval, et al. Phys. Rev. Lett., 105(13):135003, 2010.

The High Density Approach for Fusion

F. Bombarda, *ENEA Frascati, Italy*

Demonstration of fusion ignition is a major scientific and technical goal for controlled fusion. Until the fundamental physics of fusion burning have been confirmed by experiments, the defining concepts for a fusion reactor must remain uncertain. Other factors would also have to be taken into account, such as the method for extracting fusion energy, self-breeding of tritium, and material technology. Nevertheless, the ignition process will be similar for any magnetically confined, predominantly thermal plasma. Heating methods and control strategies for ignition, burning, and shutdown all need to be establish in near term ignition experiments where pulse durations exceed all the plasma main characteristic time scales.

One of the key design criteria for compact, high field experiments comes from the observation that the scaling of the α-particle power density is, for the temperature range of interest, $P_\alpha = \varepsilon_\alpha n_D n_T \langle \sigma_F \mathrm{v} \rangle \propto n^2 T^2 \propto \beta_p^2 \bar{B}_p^4$, where $\bar{B}_p^4$ is the average poloidal field and β_p, in practice, takes values that are limited by stability considerations within a relatively small range. For this reason, as well as for reasons of confinement, for a given geometry of the machine, it is appropriate to operate with the highest plasma currents I_p possible. Furthermore, the high plasma density regimes discovered by the high magnetic field experiments (Alcator's, FT's) have both outstanding confinement characteristics and degree of purity: ignition can be reached at relatively low temperatures in regimes of relevance for future reactors, where $T_i \cong T_e$, and far from the known operational limits. At the same time, in regimes close to ignition, the thermonuclear instability can set in with all its associated non linear effects, and control methods can be experimented with the application of modest amounts of ICRH auxiliary heating.

Fusion creates more neutrons per energy released than fission or spallation, therefore DT fusion facilities have the potential to become the most intense sources of neutrons for material testing. Compact, high field, high density devices could be envisaged for this purpose making full use of the intense neutron flux that they can generate, without reaching ignition. The practical possibility of extending the duration of the plasma pulse by means of appropriately shaped magnet coils is discussed, and the requirements for a Neutron Source Tokamak are presented.

Quasisymmetry far from the magnetic axis

Iván Calvo[1], Félix I. Parra[2,3], José Luis Velasco[1] and J. Arturo Alonso[1]

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[2]*Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, UK*
[3]*Culham Centre for Fusion Energy, Abingdon, UK*

In tokamaks, rotation has been shown to quench turbulence and stabilize magnetohydrodynamic instabilities. It is reasonable to ask whether neoclassical flow damping in stellarators can be sufficiently weak to allow large plasma rotation. Recently, it has been proven [1] that flows are undamped if and only if the stellarator is quasisymmetric, and that quasisymmetry is equivalent to the vanishing of the flux surface averaged radial electric current for arbitrary plasma profiles. But perfect quasisymmetry throughout the whole plasma cannot be achieved [2].

Therefore, it only makes sense to think of quasisymmetry as approximate, and for that reason we need to study stellarators close to quasisymmetry. We do this rigorously by computing the scaling of the flux surface averaged radial electric current with the size of the deviation from quasisymmetry. We show that the effect of a deviation is very different depending on its helicity. For low helicity deviations, the current scales like the square of the deviation [3]. Large helicity deviations are more deleterious and, for low collisionality, the current scales linearly with the amplitude of the deviations [4, 5]. These results allow us to determine the maximum size of the deviations from quasisymmetry that are acceptable for the stellarator to admit large flows; i.e. for the stellarator to behave as quasisymmetric in practice.

Then, we address the question of how close to quasisymmetry can a stellarator actually be. More precisely, given a perfectly quasisymmetric flux surface, we would like to know how much one can separate from it before exact quasisymmetry fails. Garren and Boozer [2] answered the question in detail in a neighborhood of the magnetic axis. We will present the results for a generic flux surface. Since, at this point, we know the maximum size of the deviation from quasisymmetry that is admissible, and also the size of the region around a flux surface in which exact quasisymmetry can be imposed, we can estimate the maximum size of the region of the stellarator in which it behaves as quasisymmetric in practice. This should be useful to provide criteria for the design of future quasisymmetric stellarators.

References

[1] P. Helander and A. N. Simakov, *Phys. Rev. Lett.* **101**, 145003 (2008).
[2] D. A. Garren and A. H. Boozer, *Phys. Fluids B* **3**, 2822 (1991).
[3] I. Calvo, F. I. Parra, J. L. Velasco *et al. Plasma Phys. Control. Fusion* **55**, 125014 (2013).
[4] I. Calvo, F. I. Parra, J. A. Alonso *et al. Plasma Phys. Control. Fusion* **56** 094003 (2014).
[5] I. Calvo, F. I. Parra, J. L. Velasco *et al. Plasma Phys. Control. Fusion* **57** 014014 (2015).

Formation of Plasmoid Chains due to Resonant Magnetic Perturbations

Luca Comisso

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Recent studies have shown that the current sheets that typically characterize magnetic reconnection processes can be unstable to the formation of a large wavenumber chain of secondary islands, generally called plasmoids [1]. This phenomenon has fundamental importance since it leads to a novel nonlinear regime that allows for a large increase of the magnetic reconnection rate [2,3]. Here we present new results on the formation of plasmoid chains due to resonant magnetic perturbations, which can drive magnetic reconnection in laboratory fusion plasmas even if the equilibrium is tearing-stable. By considering a fundamental problem of forced magnetic reconnection, the so called Taylor problem [4], in which magnetic reconnection is driven by a small amplitude boundary perturbation in a tearing-stable slab equilibrium, we have derived an expression for the threshold perturbation amplitude required to trigger the development of plasmoids [5]. We have also derived an analytical expression for the reconnection rate in the plasmoid-dominated regime [5]. These analytical calculations are complemented by visco-resistive magnetohydrodynamic simulations, which confirm the analytical predictions [5,6]. The plasmoid formation may play a crucial role in allowing fast reconnection in laboratory fusion plasmas, and these results suggest that it may occur and have profound consequences even if the plasma is tearing-stable.

[1] N.F. Loureiro, A.A. Schekochihin, and S.C. Cowley, Phys. Plasmas 14, 100703 (2007).
[2] A. Bhattacharjee, Y.‑M. Huang, H. Yang and B. Rogers, Phys. Plasmas 16, 112102 (2009).
[3] N.F. Loureiro, R. Samtaney, A.A. Schekochihin, D.A. Uzdensky, Phys. Plasmas 19, 042303 (2012).
[4] T.S. Hahm and R.M. Kulsrud, Phys. Fluids 28, 2412 (1985).
[5] L. Comisso, D. Grasso and F.L. Waelbroek, Physics of Plasmas 22, 042109 (2015).
[6] L. Comisso, D. Grasso and F.L. Waelbroeck, J. Phys.: Conf. Ser. 561, 012004 (2014).

Turbulence stabilization due to high beta and fast ions in high-performance plasmas at ASDEX Upgrade and JET

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**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

For reaching high fusion performance, high plasma beta ($\beta = 8\pi p_0/B_0^2$) is desired. However, the dependence of the thermal confinement time τ_E on β is still unclear: dedicated experiments yielded inconclusive results [Petty PoP 2008] and most theoretical results are obtained in simplified setups (see e.g. [Doerk PoP 2015] for a summary. In this work, turbulent transport in the plasma core is studied by means of the gyro kinetic code GENE for plasma parameters and realistic geometry of recent ASDEX Upgrade and JET (with ITER-like-wall) discharges.

At ASDEX Upgrade we analyze a factor-of-two beta variation in H-Mode in which $\rho^\star$ and $\nu^\star$ are kept about constant. In these discharges, ion temperature gradient (ITG) modes linearly co-exist with microtearing modes (MTMs), but the transport associated with MTM magnetic flutter is found to be weak. Thus, we find strong reduction of the turbulence level in the core, as β is increased. However, the observed trend is within the experimental uncertainty of the temperature gradient. The measured weak degradation of the global confinement time is likely due to an interplay with edge physics.

For JET we have focussed on a power-scan in hybrid-configuration at low triangularity, which exhibits a weaker power degradation than that of the IPB98(y,2) scaling. Interestingly, the high-power JET case is very close to the transition from ITG to KBM turbulence. In nonlinear GENE simulations, high beta stabilizes ITG turbulence very efficiently, and additional turbulence reduction is observed, when the concentration of fast ions becomes large.

Overall, our results indicate that turbulence stabilization due to increased beta and/or fast particles contributes to improved plasma confinement, providing a tool for optimising future experiments.

The Flux-Coordinate Independent Approach for Plasma Turbulence Simulations

Farah HARIRI

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Field-aligned coordinates are necessary to optimize plasma turbulence codes. They are widely employed in today's codes allowing the number of grid points needed to represent structures elongated along the magnetic field to be greatly reduced. In this work, we present the development and implementation of a new approach to the problem of field-aligned coordinates in magnetized plasma turbulence simulations called the FCI approach, standing for Flux-Coordinate Independent.

The method exploits the elongated nature of micro-instability driven turbulence, which typically have perpendicular scales of the order of a few ion gyro-radii, and parallel scales of the order of the machine size. It is based on two concepts. The first is using an arbitrary mesh not based on magnetic flux coordinates; the second is computing the parallel gradient operator by tracing the magnetic field lines from one poloidal plane to the next and interpolating at end points.

The FCI approach, not based on magnetic flux variables, has been introduced and validated in [1]. It was also demonstrated, for the first time, in [3] that FCI can efficiently deal with X-point configurations and O-points such as the magnetic axis. The approach was also formulated to handle 3D magnetic configurations [3].

Employing FCI opens up the way for Plasma turbulence simulations with X-points and enables the study of important physical processes in complex geometries, such as turbulence and magnetohydrodynamical (MHD) instabilities in a tokamak plasma.

[1] F. Hariri and M. Ottaviani. A flux-coordinate independent field-aligned approach to plasma turbulence simulations. Computer Physics Communications, 184(11):2419{2429, November 2013.

[2] F. Hariri, P. Hill, M. Ottaviani, and Y. Sarazin. The flux-coordinate independent approach applied to X-point geometries. Physics of Plasmas, 21(8):082509, August 2014. ISSN 1070- 664X. doi:10.1063/1.4892405. URL http://scitation.aip.org/ content/aip/journal/pop/21/8/10.1063/1.4892405.

[3] F. Hariri, P. Hill, M. Ottaviani, and Y. Sarazin. Plasma turbulence simulations with X-points using the flux-coordinate independent approach. pages 1-20, September 2014. URL http://arxiv.org/abs/1409.2393. (accepted, to be published in PPCF 2015)

Gaussian Radial-Basis-Function solution of the non-linear Fokker-Planck equation

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The non-linear Fokker-Planck collision operator [1] that describes the collisional evolution of a plasma involves velocity-space friction and diffusion coefficients that are weighted integrals of the particle distribution function. Unfortunately, for a non-Maxwellian distribution function, these coefficients are difficult to compute. In this contribution, we present a completely new idea to address this difficulty and to solve the non-linear Fokker-Planck equation.

Observing that the friction and diffusion coefficients have analytical expressions for shifted Gaussian distributions motivates a Gaussian *Radial-Basis-Function* (RBF) approach – a method that is often encountered in interpolation of scattered multidimensional data. We express the distribution function as a sum of Gaussian RBFs and derive an exact expression for the full nonlinear collision operator. Further, using the RBF method, we demonstrate the solution of a non-linear relaxation problem both in the axisymmetric case, and in the full 3-D velocity space. The quality and conservative properties of the solution are also discussed.

[1] M. N. Rosenbluth, W. M. MacDonald and D. L. Judd, *Phys. Rev.* **107**, 1 (1957).

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Towards Geometric Particle-in-Cell Schemes for Gyrokinetics

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In this talk we will describe two lines of research towards geometric particle-in-cell schemes for gyrokinetics.

In the first part, novel integrators for guiding centre dynamics are presented. These methods are designed to respect momentum and energy conservation and exhibit superior long-time stability compared to conventional methods like explicit Runge-Kutta integrators. In addition to good energy behavior, which has already been reported in previous work [1], the advantages with respect to the conservation of toroidal momentum will be highlighted [2]. Previously presented integrators for the guiding centre system [1] are prone to the growth of parasitic modes [3] which eventually drive the simulation unstable. It will be shown how these issues can be resolved, thereby avoiding the appearance of such modes and allowing for extremely long time simulations.

In the second part, we will describe a novel technique for the derivation of particle-in-cell finite-element methods for the Vlasov-Maxwell system based on the discretization of the underlying Hamiltonian structure [4]. The resulting system is solved in a charge preserving way. Spline differential forms [5] ensure conservation of the divergence of the magnetic field and stability of the field solver.

The talk will be concluded with an outline of possible strategies to consolidate these techniques in order to obtain geometric particle-in-cell schemes for gyrokinetics.

References

[1] H. Qin, X. Guan, and W. M. Tang. Variational symplectic algorithm for guiding center dynamics and its application in tokamak geometry. *Physics of Plasmas*, 16:042510, 2009.

[2] M. Kraus. *Variational Intrators for Plasma Physics*. PhD thesis, Technische Universität München, 2013. arXiv:1307.5665.

[3] C. L. Ellison, J. W. Burby, J. M. Finn, H. Qin, and W. M. Tang. Initializing and stabilizing variational multistep algorithms for modeling dynamical systems. arXiv:1403.0890, 2014.

[4] P. J. Morrison. The Maxwell-Vlasov equations as a continuous Hamiltonian system. *Physics Letters*, 80A:383–386, 1980.

[5] A. Ratnani and E. Sonnendrücker. An arbitrary high-order spline finite element solver for the time domain Maxwell equations. *Journal of Scientific Computing*, 51:87–106, 2012.

Effects of kinetic ions on internal kink modes with XTOR-K

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The effects of kinetic ions on the dynamics of macroscopic extended MHD modes is known to be important, both from experimental measurements and previous theoretical / numerical works. To extend the understanding of the mechanisms in play, the XTOR-K code was developed at CPhT, Ecole Polytechnique. XTOR-K is a full 3D hybrid code, solving part of the plasma dynamics by a bi-fluid model and selected populations of ions by a PIC method, integrating their trajectories along the gyromotions: the method is 6D full-f for the kinetic ions, and based on the implicit code XTOR-2F [1] on the fluid side.

Two test problems were used to validate the code. The first one is the so-called Hinton Rosenbluth test [2], where an initial m=n=0 velocity perturbation is Landau damped by a thermal kinetic deuterium population. In this example, the electrons are handled as a fluid and the ions are 100% kinetic. We found an excellent agreement between the theoretical and the numerical damping rates. The second test case is the so-called fusion alpha fishbone branch [3]. Coppi et al. demonstrated that increasing kinetic alpha pressure firstly stabilizes the internal kink and secondly destabilizes the fishbone branch. We have reproduced this result with an excellent agreement with XTOR-K.

XTOR-K is then used to study the impact of a 100% kinetic thermal ion bulk on the dynamics of internal kinks, thus including trapped ion and all ion FLR effects. Linear theory predicts a stabilization of the kink [4]. However, the picture from existing numerical results [5] and first simulations with XTOR-K seems more complicated. For instance, the kink stabilization predicted by theory seems much weaker with first XTOR-K simulations. These issues will be clarified by a parameter study.

The last issues addressed in the present work are first nonlinear simulations of the internal kink with kinetic ions. In particular the behavior of kinetic thermal ions and alphas during the kink saturation will be investigated.

[1] H.Lütjens, J.F.Luciani, Journal of Comp. Physics **229** (2010) p.8130.

[2] M.N. Rosenbluth, F.L. Hinton, Phys Rev. Lett. **80** (1998) 724.

[3] B. Coppi et al., Phys.Fluids **B2**, (1990) 927.

[4] M.D. Kruskal, C.R. Oberman, Phys.Fluids **1**, (1958) 275.

[5] T.M.Antonsen and A. Bondeson, Phys. Fluids **B5**, 4090 (1993).

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ABLATIVE HYDRODYNAMIC RICHTMYER-MESHKOV AND RAYLEIGH-TAYLOR INSTABILITIES AT ABLATION FRONT IN DIRECT-DRIVE SHOCK IGNITION SCHEME

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Shock Ignition (SI) [1,2] is a promising approach to Inertial Confinement Fusion. The strength of SI relies in decoupling the phase of fuel compression from the phase of ignition. The compression stage of a spherical millimetre target is driven by a ramped nanosecond laser pulse that causes shell implosion at about 300 km/s. Ignition is triggered by a second intenser laser pulse (spike) launched toward the end of the first laser pulse. The spike is tailored to produce an inward shock that reaches the rebouncing one coming from the centre causing the additional heating and fuel compression needed to ignite.

The continuous shock launching as well as the shell implosion are a natural place where both hydrodynamic ablative Richtmyer-Meshkov instability (RMI) and ablative Rayleigh-Taylor instability (RTI) are seeded and grow [3,4]. Hydrodynamic instabilities quickly degenerate, e.g. hot-cold material mixing, causing fuel degradation and so aborting ignition.

Our numerical investigation begins assuming that the outer target surface is corrugated. Simulations are carried out with the 2D radiative hydrodynamic code DUED. Our studies show that during the first phase of the ramped profile surface, the perturbations below a given threshold are damped by vorticity, above the RMI is excited [3]. Most importantly the RTI develops toward the end of the pulse, when the shell takes up moving, and its initial amplitude conditions are given by the late phase of the RMI. The two instabilities are sequential (one follows and seeds the other) and thus they are strictly correlated. We deduce that instability control can be traced back up to the original surface manufacturing perturbations. For this reason we have investigated techniques such as an 'adiabat shaping picket', giving promising results. Simulations verify that RMI and RTI behave similarly if we impose shell density inhomogeneity [3] or whether we consider target positioning error [4,5].

Non-local electron transport effects [6,7] are also included, they become important in ablative regions to reproduce all the thermal flow features. Nonetheless we showed that for very intense lasers ($I > 10^{16}$ W/cm^2) non-local transport smooths out pressure profiles reducing dis-uniformities [7].

During the RTI the involved geometry, density and electron temperatures ranges are suitable to self induce a magnetic field. The underlying physics is investigated adding the magneto hydrodynamic induction equation with the baroclinic source term to our model (DUED-B). A toroidal magnetic field forms around the sinusoidal density profile slightly changing the overall evolution, modifying the evolution times and influencing the non linear phase.

[1] Betti et al. *Phys. Rev. Lett. 98 155001*
[2] Atzeni S, Marocchino A, Schiavi A *Plasma Physics and Controlled Fusion* ***57*** *014022* (2014)
[3] Marocchino A, Atzeni S, Schiavi A, *Physics of Plasmas* **17** 112703 (2010)
[4] Atzeni A, Schiavi A, Marocchino A, *Plasma Physics and Controlled Fusion* **53** 035010 (2011)
[5] Schiavi A, Atzeni S, Marocchino A, EPL *Europhysics Letters* **94** 35002 (2011)
[6] Marocchino A, Atzeni S, Schiavi A, *Physics of Plasmas* **21** 012701 (2014)
[7] Marocchino A. et al. *Physics of Plasmas* **20** 022702 (2013)

Self-consistent interaction between MHD island and turbulence

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Magnetic reconnection can be problematic for tokamak plasmas: tearing modes (neoclassical or otherwise) grow slowly expelling energetic particles from the plasma core and possibly lead to disruption phenomena that can terminate the discharge and cause damage to the plasma facing components. However, the neoclassical tearing modes (NTMs) are not associated to a linear instability (the so-called Δ' parameter is negative) and require pre-existing seed islands to grow [1]. In experiments, precursors as sawtooth oscillations, fishbones instabilities or edge localized modes could appear before a NTM. These precursors are supposed to trigger the requested seed island. However, sometimes, a NTM can grow without any noticeable MHD event [2]. Thus, the question of the origin of the seed magnetic island is still an open question for fusion reactor. Moreover, in tokamaks, macro-scale MHD instabilities (magnetic islands) coexist with micro-scale turbulent fluctuations and zonal flows [3], and some recent works have shown the microturbulence impact on the island dynamics [4, 5]. In [4], 2D nonlinear simulations show that the nonlinear beating of the fastest growing small-scale interchange modes on a given rational surface drives a magnetic island located on the same surface. Here, we show that such turbulent driven seed island can be amplified by the current bootstrap leading to a self-consistent generation of a NTM. Moreover, such turbulence driven NTM presents a significant signature : the pressure flattening inside the island is partial, *i.e.* the pressure gradient inside the island is finite and constant in space and in time.

[1] R.J. La Haye and O. Sauter, *Nucl. Fusion*, **38**, 7 (1998)

[2] A. Isayama *et al*, *J. Plasma Fusion Res.*, **8**, 1402013 (2013)

[3] B.J. Ding *et al*, *Plasm. Phys. Control. Fusion*, **46**, 1467 (2004)

[4] M. Muraglia *et al*, *Phys. Rev. Lett.*, **107**, 095003 (2011)

[5] A. Ishizawa *et al*, *Nucl. Fusion*, **53**, 053007 (2013)

Predicting the stability of alpha-particle–driven Alfvén Eigenmodes in burning plasmas

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Plasma heating in the burning regime of tokamak reactors will be provided mainly by an isotropic population of fusion-born alpha-particles with energy in the MeV range. However, their free energy can drive Alfvén eigenmodes (AEs) unstable. If destabilized, AEs may enhance alpha-particle transport away from the fusing core, thereby eliminating the dominant heating source and causing damages to the vessel walls. Therefore, understanding and predicting the complex interplay between supra-thermal particles and AEs has emerged as one of the most significant research topics in support of the fusion effort in magnetic-confinement devices.

In future tokamak reactors, for which no experiments have been performed yet, there is no experimental guidance about which AEs interact most with fusion alpha-particles. To address this issue, a systematic approach was recently developed to intensively scan a parameter-space range (frequency and wave number) in order to find all AEs allowed by a given magnetic equilibrium and rank them by their linear growth rate [1]. Numerical simulations carried out for an ITER baseline scenario [2] found that the most linearly unstable modes expected are core-localized Toroidicity-induced AEs with a large toroidal mode number ($n \approx 30$) [1]. It was also found that alpha particles in resonance with such modes were strongly passing ones, with large parallel velocity and small (but not vanishing) pitch angle. In these circumstances, the drift-velocity term $k_\perp v_\perp$ becomes comparable with the AE's angular frequency and the wave-particle resonance condition must be revisited.

In this talk, new developments concerning the resonance mechanism between AEs and fusion-born alpha-particles with large parallel velocity are discussed. In particular, the effects of the drift-velocity contribution to the resonance condition are addressed in order to explain the results of recent numerical simulations. The new elements brought into the discussion will aid one to understand why specific AEs pair with the most energetic alpha-particles available in the population, becoming thus the most unstable ones. The consequences of the gained insight for stability predictions of alpha-particle–driven AEs in burning plasmas are also discussed.

References

[1] P. Rodrigues *et al.*, Nucl. Fusion **55**, 083003 (2015).

[2] S. D. Pinches *et al.*, Phys. Plasmas **22**, 021807 (2015).

Phase mixing vs. nonlinear advection in drift-kinetic plasma turbulence

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A scaling theory of long-wavelength electrostatic turbulence in a magnetised, weakly collisional plasma (e.g., drift-wave turbulence driven by ion temperature gradients) is proposed, with account taken both of the nonlinear advection of the perturbed particle distribution by the fluctuating $\mathbf{E} \times \mathbf{B}$ flows and of its phase mixing, which is caused by the streaming of the particles along the mean magnetuc field and in a linear problem would lead to Landau damping. It is found that it is possible to construct a consistent theory in which very little free energy leaks into high velocity moments of the distribution function, rendering the turbulent cascade in the energetically relevant part of the wave-number space essentially fluid-like. The velocity-space spectra expressed in terms of Hermite-moment orders are steep power laws and so the free-energy content of the phase space does not diverge at inifinitesimal collisionality (like it does for a linear problem). The partitioning of the phase space between the (energetically dominant) region where this is the case and the region where linear phase mixing wins its competition with nonlinear advection is governed by the "critical balance" between linear and nonlinear timescales. The ability of the free energy to stay in the low velocity moments of the distribution function is facilitated by the "un-phase-mixing" effect, whose presence in the nonlinear system is due to the stochastic version of the plasma echo (the advecting velocity couples the phase-mixing and un-phase-mixing perturbations). It is argued that at low collisionality, Landau-fluid closures that retain a sufficient but finite (collisionality-independent) number of moments may be sufficient for a full characterisation of kinetic turbulence, with phase mixing terms serving only to regularise the problem in the energetically subdominant part of the wave-number space.

Non-linear Energetic Particle Transport in the Presence of Multiple Alfvénic Waves in ITER

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The interplay of fast ions with Alfvénic instabilities is an important topic in fusion research, since future fusion devices will exhibit large fractions of highly energetic particles (EP). Strong EP transport might reduce the heating and current drive efficiencies, while losses could even damage the first wall. The aim of the here presented work is to enhance the understanding of interaction mechanisms between EP and multiple Alfvén waves in a realistic ITER case.
The focus lies on the 15 MA baseline scenario, where a "sea" of small-amplitude perturbations is expected to be marginally unstable [1]. Based on quasi-linear estimates [2], the EP transport would be rather low. The question of interest here is, whether the EP population can drive linearly stable or weakly unstable modes non-linearly unstable – and if so, under which EP conditions. As a consequence, domino-like transport can occur. Such behavior has been found already in realistic ASDEX Upgrade double-mode simulations [3], which could explain experimentally found EP losses [4]. Basis of the simulations is a non-linear hybrid model, the driftkinetic HAGIS code [5]. As crucial new elements of a realistic scenario, the perturbation structures, frequencies and damping rates are taken as obtained from the gyrokinetic eigenvalue solver LIGKA [6].
Although the non-linear wave-particle interaction is calculated self-consistently within the HAGIS-LIGKA model, at the present status, other non-linearities such as the evolution of wave structure are not included yet. Before extending the model in this direction, the expected effect of the radial wave structure evolution is investigated: HAGIS-LIGKA results are compared to those of a different hybrid code, HMGC [7], which already contains wave structure evolution. For that comparison, a newly implemented phase space diagnostic, the so called Hamiltonian Mapping Technique [8] is used. It allows for a detailed study of wave-particle interaction processes, especially in the view of non-linear saturation mechanisms, including the newly implemented effect of a parallel electric field.

References

[1] PH. LAUBER. Plasma Physics and Controlled Fusion, **57** (5):054011 (2015).
[2] K. GHANTOUS ET AL. Phys. Plasmas, **19** (9):092511 (2012).
[3] M. SCHNELLER ET AL. Nucl. Fusion, **53** (12):123003 (2013).
[4] M. GARCÍA-MUÑOZ ET AL. Phys. Rev. Lett., **104**:185002 (2010).
[5] S. PINCHES ET AL. Comput. Phys. Commun., **111** (13):133 (1998).
[6] PH. LAUBER ET AL. J. Comp. Phys., **226** (1):447 (2007).
[7] S. BRIGUGLIO ET AL. Phys. Plasmas, **5** (9):3287 (1998).
[8] S. BRIGUGLIO ET AL. Phys. Plasmas, **21** (11):112301 (2014).

—Abstract for EFTC 2015—

The Field line map approach to plasma turbulence simulations

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Abstract

The complex geometry in the edge and scrape-off layer poses a challenge to simulations of magnetically confined plasmas. The usually employed field/flux-aligned coordinates become singular on the separatrix/X-point. In the field line map approach these problems are avoided and a separatrix can be treated [1, 2, 3, 4] (see also FCI approach [5, 6, 7]). The approach is based on a cylindrical grid, and the characteristic flute mode property ($k_{\|} \ll k_{\perp}$) of structures is exploited computationally via grid sparsification in the toroidal direction. A field line following discretisation for parallel operators is then required, which includes field line tracing and interpolation or integration. The drawback of the approach is that there arises a numerical erroneous perpendicular coupling among distinct field lines, which causes numerical diffusion. Based on the support operator method [8] a numerical scheme was constructed for the parallel diffusion operator, which exhibits only very low numerical diffusion. The numerical concept was applied to a simple plasma turbulence model, the Hasegawa-Wakatani equations [9], which were implemented in the new code GRILLIX. Extensive benchmarks show the validity of the field line map approach in general and GRILLIX in particular. Finally, first geometrical effects of the X-point on turbulent structures have been identified.

References

[1] A.Stegmeir, D.Coster, O.Maj, and K.Lackner. *Contributions to Plasma Physics*, 54:549, 2014.

[2] Andreas Stegmeir. *GRILLIX: A 3D turbulence code for magnetic fusion devices based on a field line map.* PhD thesis, Technische Universität München, 2015.

[3] A.Stegmeir, D.Coster, O.Maj, K.Hallatschek, and K.Lackner. The field line map approach for simulations of magnetically confined plasmas. *Journal of Computational Physics*, Submitted, 2015.

[4] A.Stegmeir, D.Coster, K.Hallatschek, and K.Lackner. Grillix: A 3d turbulence code based on a field line map. *Computer Physics Communications*, Submitted, 2015.

[5] M.Ottaviani. *Physics Letters A*, 375:1677, 2011.

[6] F.Hariri and M.Ottaviani. *Computer Physics Communications*, 184:2419, 2013.

[7] F.Hariri, P.Hill, M.Ottaviani, and Y.Sarazin. *Physics of Plasmas*, 21:082509, 2014.

[8] Mikhail Shashkov. *Conservative Finite-Difference Methods on General Grids.* CRC Press, 1996.

[9] Akira Hasegawa and Masahiro Wakatani. *Physical Review Letters*, 50:682, 1983.

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Title: Current fragmentation and particle acceleration in strongly turbulent plasmas

Abstract

Numerous recent studies demonstrate that a relatively large number of current sheets may be formed during the evolution of strong ($\delta B/B$) turbulence. A large fraction of the current sheets present in strongly turbulent environment will be forced to reconnect and will further be fragmented or will interact with their close neighbours. The subset of the current sheets that are forced to reconnect will be associated with a statistical distribution in space and time of relatively strong electric fields. Fragmented electric fields (associated with reconnecting current sheets) may be spread over large volumes and are associated with coronal heating, or they may be compressed into relatively smaller volumes due to the emergence of new magnetic flux, and in this case they may be associated with intense explosive acceleration and heating correlated with the magnetic topology. Based on the above scenario, two main lines of research are currently in progress and will be outlined in my tutorial: (1) we may start on data-driven 3D magnetic field which is perturbed by a turbulent driver. A relativistic test-particle simulation traces each particle's guiding center within these configurations. Using the simulated particle-energy distributions, we test our results against experimental data. (2) We may consider 3D nonlinear MHD simulations of a turbulent system. We first analyze the statistical nature and spatial structure of the electric field, calculating histograms and making use of isocontour visualizations. Then test-particle simulations are performed for electrons, in order to study heating and acceleration phenomena, as well as to determine the high energy emission. This study is done by comparatively exploring quiet, turbulent explosive, and mildly explosive phases of the MHD simulations. Also, the importance of collisional and relativistic effects is assessed, and the role of the integration time is investigated. Particular aim of this project is to verify the quasi- linear assumptions made in standard transport models, and to identify possible transport effects that cannot be captured with the latter. In order to determine the relation of our results to Fermi acceleration and Fokker-Planck modeling, we determine the standard transport coefficients. In different MHD time-instances we find heating to take place, and acceleration that depends on the level of MHD turbulence. Also, acceleration appears to be a transient phenomenon, there is a kind of saturation effect, and the parallel dynamics clearly dominate the energetics.

Modeling of electron cyclotron current drive applied for neoclassical tearing mode stabilization

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A consistent model of electron cyclotron current drive (ECCD) in the presence of a neoclassical tearing mode (NTM) is set up. The plasma equilibrium is perturbed by the NTM changing in particular the topology of the magnetic field: a region around the resonant surface is broken up into a helical set of closed magnetic surfaces known as the magnetic island, while outside this island the toroidal magnetic surfaces remain closed but are helically deformed. The wave beam propagation in this perturbed equilibrium is described by ray tracing. The power absorption and current drive are then calculated on the sets of closed magnetic surfaces both inside and outside the island. Because of the small volume of the surfaces near the O-point of the magnetic island, the EC power density near the O-point can become very large and exceed the threshold for the appearance of nonlinear effects. Flux surface averaged quasi-linear Fokker-Planck code calculations are performed to quantify these nonlinear effects. The modeling is done for locked islands and for rotating islands. In the case of a rotating magnetic island, the results show a large phase delay between the maximum in the driven current density on a particular magnetic surface and the phase during which this surface is heated. This is a consequence of the highly non-local character of the ECCD and it's dominant origin in the Fisch-Boozer current drive effect.

In the case of MHD modeling of NTMs, the EC driven current density is described by a closure relation. Based on the Fokker-Planck code calculations and the origin of the ECCD in the Fisch-Boozer effect a new closure relation for the EC driven current is derived. The predictions of this closure relation are shown to compare well with the full Fokker-Planck calculations.

List of Poster Presentations

Poster Session 1 – Tuesday, 6th Oct., 15:40h – 17:20h

P1.1	**A. Bottino**	Gyrokinetic Monte Carlo - finite element simulations of Alfvenic modes
P1.2	**P. Zestanakis**	A full-orbit treatment of collisionless transport of energetic particles in axisymmetric toroidal plasmas.
P1.3	**A. Figueiredo**	Comprehensive evaluation of the linear stability of Alfvén eigenmodes driven by alpha particles in an ITER baseline scenario
P1.4	**M. Raghunathan**	Single Particle Confinement in 2D and 3D Rotating Tokamak Equilibria
P1.5	**I. Abel**	Free Energy and Adjoints in Gyrokinetics
P1.6	**C. di Troia**	Equilibrium distribution functions for gyrokinetic studies of realistic tokamak Scenarios
P1.7	**E. Highcock**	Preliminary Trinity Simulations of JET DT
P1.8	**W. W. Lee**	Recent Progress on Finite-beta Gyrokinetics
P1.9	**V. Naulin**	Turbulence Spreading and Rotation Reversal in Ohmic L Modes
P1.10	**F. Parra**	Non-local effects on neoclassical flows and fluxes in transport barriers
P1.11	**I. Predebon**	ITG turbulence in finite-beta helical and axisymmetric reversed field pinch plasmas
P1.12	**E. Startsev**	Gyrokinetic simulation of the collisional micro-tearing mode instability
P1.13	**F. van Wyk**	Investigation of the effect of flow shear and the ion temperature gradient on marginally unstable turbulence in MAST using gyrokinetic simulations
P1.14	**F. da Silva**	Synthetic reflectometry probing of gyrofuid edge turbulence
P1.15	**M. Held**	Full-F gyrofluid edge turbulence computations
P1.16	**H. Isliker**	Identification of magnetic reconnection in the edge region of the RFX plasma
P1.17	**A. Merle**	Pedestal structure and stability of different H-mode regimes in the TCV tokamak
P1.18	**G. Anastassiou**	Relativistic particle and momentum transport under interaction with a localised EM wave in a magnetized plasma
P1.19	**A. Cardinali**	Modeling of Lower Hybrid Current Drive in Tokamak Reactors
P1.20	**S. Khan**	Kinetic full wave analysis of electron cyclotron wave mode conversion in tokamak plasmas

Poster Session 2: – Wednesday, 7th Oct., 15:40h – 17:20h

P2.1	**J. Bizarro**	Growth estimates, control and structures in a two-field model of the scrape-off layer
P2.2	**A. Geraldini**	Solving the kinetic equation of a magnetized ion gas close to a fully absorbing wall
P2.3	**R. Jorge**	Simulation of SOL turbulence in the ISTTOK tokamak
P2.4	**F. Riva**	Effects of plasma shaping on tokamak scrape-off layer turbulence
P2.5	**N. Dubuit**	Remote Generation of Magnetic Island by Turbulence
P2.6	**P. Maget**	Viscosity effect on tearing modes in toroidal geometry
P2.7	**C. Marchetto**	Modelling the effects of NTM islands On the transport of heavy impurities in a tokamak
P2.8	**C. Tsironis**	Test-particle simulations of wave-particle interaction in the presence of magnetic islands
P2.9	**E. Fable**	Impact of the choice of core/pedestal transport modeling assumptions on the performance of a DEMO fusion reactor
P2.10	**D. Grasso**	Transport processes characterizing the Quasi-Single-Helicity states in RFX-mod
P2.11	**D. Hogeweij**	Tracer transport with multiple W charge states in ASDEX Upgrade
P2.12	**A. Teplukhina**	Current ramps optimization study with the RAPTOR code
P2.13	**M. Fox**	Extracting physical quantities from BES data
P2.14	**C. Silva**	Experimental investigation of geodesic acoustic modes on JET using Doppler Backscattering
P2.15	**N. Loureiro**	Viriato: a Fourier-Hermite spectral code for strongly magnetised fluid-kinetic plasma dynamics
P2.16	**C. Smiet**	Self-organizing knotted magnetic structures in plasma
P2.17	**E. Tassi**	Hamiltonian fluid reduction of drift-kinetic equations for non-dissipative plasmas

Gyrokinetic electromagnetic Monte Carlo - finite element simulations of Alfvenic modes

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The Particle-In-Cell (PIC) algorithm is the most popular method for the discretisation of the general 6-D Vlasov-Maxwell problem and it is widely used also for the simulation of the 5D gyrokinetic equations. In this paper we derive a Monte Carlo Particle In Cell Finite Element model starting from a gyrokinetic discrete Lagrangian. The variations of the Lagrangian are used to obtain the time continuous equations of motion for the particles and the Finite Element approximation of the field equations. The Noether theorem for the semi-discretised system, implies a certain number of conservation properties for the final set of equation. Moreover, the PIC method can be interpreted as a probabilistic Monte-Carlo like method, consisting of calculating integrals of the continuous distribution function using a finite set of discrete markers. The nonlinear interactions along with numerical errors introduce random effects after some time. Therefore, the same tools for error analysis and error reduction used in Monte-Carlo numerical methods can be applied to PIC simulations of Alfvenic modes in tokamak geometry.

A full–orbit treatment of collisionless transport of energetic particles in axisymmetric toroidal plasmas.

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The significant drift of energetic particle orbits makes it necessary to abandon the fixed flux surface assumption. Instead, it is essential that both resonance conditions and unperturbed distribution functions are written as functions of the exact integrals of motion, when developing a transport model for energetic particles.

Making use of the symmetries of the unperturbed dynamical system, the semi–analytical Orbital Spectrum Analysis (OSA) method transforms the equilibrium into an Action Angle (AA) phase space, where the actions are integrals of motion and the analytical study of the dynamics is significantly simplified. OSA requires no assumptions about the particle orbits and treats both energetic and non–energetic particles on equal footing. It is applied once per equilibrium and makes it remarkably easy to construct resonance charts for different perturbations, determine the conditions for stochastic transport or confinement loss, study the effects of synergy between different modes, as well as construct a reliable quasilinear transport model.

Comprehensive evaluation of the linear stability of Alfvén eigenmodes driven by alpha particles in an ITER baseline scenario

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In ITER, the performance of burning plasmas will depend on the population of alpha particles being well confined within the plasma core, as the heating of the DT plasma will then rely mainly on the energy of these suprathermal particles, which are produced by core fusion reactions. A phenomenon that can potentially hinder the successful operation of ITER is therefore the destabilization of Alfvén eigenmodes (AEs) by alpha particles. An increased alpha-particle radial transport due to destabilized AEs would degrade the conditions necessary to sustain the fusion reactions, and it could carry damaging heat loads to the tokamak wall [1]. In this work we systematically address the stability of AEs in an ITER baseline scenario [2] making use of a recently introduced framework [3] based on a suite of numerical codes. These codes are HELENA [4] to calculate equilibria, MISHKA [5] to identify AEs, and the hybrid MHD drift-kinetic code CASTOR-K [6], which assesses the stability of eigenmodes by computing their linear growth rates due to alpha-particle drive, and to damping by the DT ions and electrons and by the thermalized alpha particles (helium ashes). AEs are extensively considered in our methodical approach, which is appropriate to predict, rather than interpret experimental results. In a previous study [3] it has been found that the most unstable AEs had toroidal mode numbers around $n = 30$. Here we focus our attention on values of n ranging from 1 to 50 in order to stay within the limits of the drift-kinetic ordering [3]. The main differences between the ITER scenario that we now consider and the one in [3] are the safety factor, which has a lower on-axis value and a flatter radial profile at the plasma core; the temperatures that are higher at the edge pedestal (roughly by a factor of 2) and lower at the core; and the much lower density of alpha particles and helium ashes. The results of the linear-stability analysis are presented and conclusions are drawn. A comparison with previous results is made, particularly with those obtained in [3].

Acknowledgments

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References

[1] S. E. Sharapov *et al.* Nucl. Fusion **53** (2013) 104022. [2] A. R. Polevoi *et al.*, J. Plasma Fusion Res. SERIES **5** (2002) 82. [3] P. Rodrigues *et al.* "Systematic linear-stability assessment of Alfvén eigenmodes in the presence of fusion α-particles for ITER-like equilibria", submitted to Nucl. Fusion (2015). [4] G. Huysmans *et al.*, Int. J. Mod. Phys. C **2** (1991) 371. [5] A. Mikhailovskii *et al.*, Plasma Phys. Rep. **23** (1997) 844. [6] D. Borba and W. Kerner, J. Comput. Phys. **153** (1999) 101.

SINGLE PARTICLE CONFINEMENT IN 2D AND 3D ROTATING TOKAMAK EQUILIBRIA

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Strong toroidal rotation is an important element of plasmas in toroidal fusion devices such as spherical tokamaks. Using the Variational Moments Equilibrium Code (VMEC)[1] under fixed and free boundary conditions, we first obtain ideal MHD equilibria for 2D axisymmetric rotating cases . Next, a class of 3D equilibria explored would be 3D equilibria with an unsheared flow profile. VMEC is then also used to generate 3D equilibria having helical cores with strong sheared toroidal rotation in the helical core region but with a sharply axisymmetric mantle surrounding the helical core.

We aim to follow single particle orbits using guiding-centre Hamiltonian formulation using the particle orbit-following code VENUS-LEVIS[2], with added modifications incorporating toroidal flows[3]. Full-orbit simulations are also undertaken, and benchmarked against drift-orbit simulations for both axisymmetry and the above-mentioned 3D cases.

Under strong rotation, the next-order electric field produced by the contrasting effect of the centrifugal force on the ions and electrons, becomes an important component of quasi-neutrality. A distribution of particles is used to verify the quasi-neutrality of the rotating plasma for both the axisymmetric and 3D cases, and thereby verify the consistency of the equilibrium.

Having a consistent model for toroidal rotation in tokamaks lets us explore certain important applications. For example, Neutral Beam Injection (NBI) simulations are performed in order to study the kinetic distributions and thermal properties of such toroidally rotating plasmas, for a MAST-like tokamak with strong rotation and long-lived modes. Also of interest are the trajectories of heavy impurities leaving the wall and entering the plasma for the toroidally rotating equilibria, which would be applicable to JET and ASDEX-U experiments with metal walls.

References

[1] Hirshman, S.P., et al, Comput. Phys. Commun. **43**, 143 (1986).

[2] Pfefferlé, D., et al, Comput. Phys. Commun. **185**, 3127 (2014).

[3] Brizard, A.J., Phys. Plasmas **2**, 459 (1995).

Free Energy, Norms and Inner Products in Gyrokinetics

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Generalized Free Energy has long been used as a measure of the size of deviations of kinetic systems from a static equilibrium and in studies of kinetic turbulence[1,2]. We demonstrate that it provides a formal norm for solutions of the gyrokinetic equation, and moreover that there is a compatible inner product arising from this norm. This extra structure is useful in that it allows us to import extremely powerful ideas from other fields. We demonstrate two such algorithms.

Firstly, following well-trodden paths in fluid dynamics, access to a physical inner product enables more formal studies of systems in which transient growth is present[3,4], including the calculation of instantaneous and finite-time optimal perturbations. In particular, this framework allows us to distinguish transient growth that might lead to nonlinearly sustained fluctuations from those perturbations which must inevitably decay. This procedure has been performed for fluid systems[5,6], and we extend it to the more general gyrokinetic system. We also show that the gyrokinetic system is generically susceptible to transiently growing perturbations.

Secondly, we demonstrate the use of the inner product by importing adjoint methods from seismology[?] to potentially accelerate transport and sensitivity calculations based on gyrokinetic turbulent fluxes. We outline an implicit transport solver algorithm based on these ideas with $O(1)$ scaling in the number of implicit variables.

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1 K. Hallatschek, Phys. Rev. Lett. **93**, 125001 (2004).

2 A. A. Schekochihin, S. C. Cowley, W. Dorland, G. W. Hammett, G. G. Howes, G. G. Plunk, E. Quataert, and T. Tatsuno, Plasma Phys. Control. Fusion **50**, 124024 (2008).

3 B. Farrell, J. Atmos. Sci. **42**, 2718 (1985).

4 M. Landreman, G. G. Plunk, and W. Dorland (2015), http://arxiv.org/abs/1501.02980.

5 B. Friedman and T. A. Carter, Phys. Rev. Lett. **113**, 025003 (2014).

6 B. Friedman and T. A. Carter, Phys. Plasmas **22**, 012307 (2015).

Equilibrium distribution functions for gyrokinetic studies of realistic tokamak scenarios

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abstract
A class of parametric distributions has been proposed in [1] as equilibrium distribution functions (EDFs) for particle description in slowly evolving tokamak plasmas. Such EDF depends on $(\mathcal{P}_\phi, w, \mu)$, the toroidal canonical momentum, the energy and the magnetic moment, respectively. In addition to the latter constants of unperturbed motion (COMs), the EDF depends on control parameters as in the following functional form:

$$\begin{aligned} f_{\rm eq}(\mathcal{P}_\phi, w, \mu) = \quad & \mathcal{N}\frac{[1+(\mu/w)/\lambda_0](w/T_w)^{\alpha_w}}{\sqrt{2\pi}}\frac{\mathrm{H}(w_b - w)}{w^{3/2}+w_c^{3/2}} \times \\ & \times \exp\left[-\frac{(\mathcal{P}_\phi - \mathcal{P}_{\phi 0})^2}{\Delta^2_{P_\phi}}\right] \exp\left\{-\frac{w}{T_w}\left[\frac{(\mu/w)-\lambda_0}{\Delta_\lambda}\right]^2\right\}. \end{aligned}$$

Here, the probabilistic derivation of such EDFs is discussed, making use of the Bayes' theorem and of general assumptions concerning the gyro-center transformation [2]. For the given dependence on COMs, a Landau collision operator is constructed with the corresponding Fokker-Planck equation that yields the system relaxation towards the proposed EDF. A realistic plasma in ASDEX Upgrade, where an energetic Deuterium population is produced by tangential Neutral Beam Injection, is chosen to illustrate the choice of EDF control parameters and for realistically representing off-axis deposited supra-thermal particles in anisotropic equilibria. Gyrokinetic and hybrid simulations with NEMORB [3], LIGKA[4] and (X)HMGC [5], are discussed to illustrate the simple use of the present EDF in non-linear studies of shear Alfv́en waves.

[1] C. Di Troia, Plasma Physics and Controlled Fusion, 54, (2012)
[2] C. Di Troia Physics of Plasmas, 22, (2015) 042103
[3] A. Bottino, et al., Plasma Physics and Controlled Fusion, 53, (2011) 124027
[4] P. Lauber et al, Journal of Computational Physics, 226, (2007), 447
[5] S. Briguglio, et al., Physics of Plasmas, 2, (1995) 3711; X. Wang, et al., Physics of Plasmas, 18, (2011) 052504

Preliminary Trinity Simulations of JET DT experiments

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The Trinity transport solver [1] has been upgraded to include multiple ion species, self-consistent evolution of the equilibrium [2,3], and additional flux models including the nonlinear gyrofluid code GRYFX [4]. As part of the JET 2015 programme, Trinity is being used to model the effects of combining deuterium and tritium in a future JET experiment. We present preliminary results from the study and discuss implications for future work.

[1] M. Barnes, I. G. Abel, W. Dorland, T. Görler, G. W. Hammett, and F. Jenko, Phys. Plasmas **17**, 056109 (2010).
[2] E. Highcock, M. Barnes, G. Colyer, J. Citrin, D. Dickinson, N. Mandell, F. van Wyk, C. Roach, A. Schekochihin, and W. Dorland, in *Bull. Am. Phys. Soc.* (2014).
[3] J. Lee and A. Cerfon, Comput. Phys. Commun. **190**, 72 (2015).
[4] N. Mandell and W. Dorland, in *Bull. Am. Phys. Soc.* (2014), p. Abstract CP8.039.

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Recent Progress on Finite-β Gyrokinetics*

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The governing gyrokinetic Vlasov-Maxwell system of equations can be derived from the Lagrangian of $L = mv^2/2 - q\phi + q/c\mathbf{v} \cdot \mathbf{A}$, using the usual gyrokinetic ordering and gyrophase-averaging, and be written in simple geometry as

$$\frac{\partial F_\alpha}{\partial t} + \left[v_\parallel \mathbf{b} - \frac{c}{B_0} \nabla(\overline{\phi} - \frac{1}{c}\overline{\mathbf{v}_\perp \cdot \mathbf{A}_\perp}) \times \hat{\mathbf{b}}_0 \right] \cdot \frac{\partial F_\alpha}{\partial \mathbf{x}} - \frac{q}{m} \left[\nabla(\overline{\phi} - \frac{1}{c}\overline{\mathbf{v}_\perp \cdot \mathbf{A}_\perp}) \cdot \mathbf{b} + \frac{1}{c}\frac{\partial \overline{A}_\parallel}{\partial t} \right] \frac{\partial F_\alpha}{\partial v_\parallel} = 0, \quad (1)$$

where the associated field equations in the low frequency and small Larmor radius limit are

$$\nabla^2 \phi + \frac{\omega_{pi}^2}{\Omega_i^2} \nabla_\perp^2 \phi = -4\pi \sum_\alpha q_\alpha \int \overline{F}_\alpha dv_\parallel d\mu \quad (2)$$

and

$$\nabla^2 \mathbf{A} = -\frac{4\pi}{c} \sum_\alpha q_\alpha \int \mathbf{v} \overline{F}_\alpha dv_\parallel d\mu, \quad (3)$$

where $\overline{\cdots}$ denotes gyrophase average. A new treatment by calculating $A_\parallel$ and $\partial A_\parallel/\partial t$, but without $\mathbf{A}_\perp$, has been devised recently [1], which, along with the toroidal effects, has enabled us to study tearing physics [2] using our global gyrokinetic particle code, GTS [3]. Details will be reported.

In the fluid limit, this set of equations can be reduced to pressure balance, vorticity equation and collisionless Ohm's law, respectively,

$$\mathbf{J}_\perp = \frac{c}{B} \mathbf{b} \times \nabla p, \quad (4)$$

$$\frac{d}{dt} \nabla_\perp^2 \phi - 4\pi \frac{v_A^2}{c^2} \nabla \cdot (\mathbf{J}_\parallel + \mathbf{J}_\perp) = 0, \quad (5)$$

$$E_\parallel \equiv -\frac{1}{c} \frac{\partial A_\parallel}{\partial t} - \mathbf{b} \cdot \nabla \phi = 0, \quad (6)$$

with $d/dt \equiv [\partial/\partial t - (c/B)\nabla\phi \times \mathbf{b}]$, $\nabla^2 \mathbf{A} = -(4\pi/c)\mathbf{J}$ and $\mathbf{B} = \nabla \times \mathbf{A}$, where v_A is the Alfven speed and $\mathbf{b} \equiv \mathbf{B}/B$. With a equation of state of $dp/dt = 0$, we then obtain a simple set of gyrokinetic MHD equations with normal modes of $\omega = \pm k_\parallel v_A$. When $\phi \to 0$, which gives $\partial A_\parallel/\partial t \to 0$ from Eq. (6), then from Eq. (5) we obtain

$$\nabla \cdot (\mathbf{J}_\parallel + \mathbf{J}_\perp) = 0. \quad (7)$$

Thus, the gyrokinetic equations exhibit the quasi-neutral, static property in the absence of the fluctuating potential. It is this connection between the time-dependent, micro system to the time-independent, macro system, which we will explore. Note that Eq. (5) is more complete that Eq. (32) in Ref. [4].

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[1] E. A. Startsev and W. W. Lee, Phys. plasmas **21**, 022505 (2014).
[2] E. A. Startsev, W. X. Wang and W. W. Lee, "Gyrokinetic simulation of the collisional micro-tearing mode instability", International Sherwood Theory Conference, New York (2015).
[3] W. X. Wang et al., "Gyrokinetic simulation of glob al turbulent transport properties in tokamak experiments", Phys. Plasmas 13, 092525 (2006).
[4] W. W. Lee and H. Qin, Phys. Plasmas **10**, 3196 (2003).

Turbulence Spreading and Rotation Reversal in Ohmic L Modes

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In momentum input free L-mode plasmas rotation is a complex issue, with many different effects having been observed. In general the L-mode rotation behaviour in this case is far less well understood than the rotation of H-mode discharges. H-mode rotation seems to be more robust, either because the H-mode is usually achieved at high heating power including external momentum input by beams or due to high rotation at the pedestal, which allows for a robust boundary condition for the rotation.
For plasmas with no obvious external momentum source spontaneous spin up poses a problem to transport theory as without initial rotation velocity or seed flow the momentum flux is zero everywhere and so no build-up of rotation, neither of net plasma rotation nor of differential plasma rotation can take place.
It has been suggested that turbulent momentum transport can lead to a differential rotation source, which can lead to spin up. This local momentum flux, which is generated in the plasma itself, cannot be expressed in terms of a transport term, as it is neither proportional to the gradient of the velocity profile, e.g. to be expressed as a diffusion like term, nor to the velocity itself, e.g. a convective or pinch velocity like term and thus termed residual stress. Its appearance in a transport equation is like a localised source which integrates to zero.
We here propose a 1D transport model which includes plasma spin-up by residual stress, with the residual stress driven by the gradient in the turbulence amplitude profile.
The model is used to investigate the rotation sign reversal observed at some internal position and its disappearance with the transition from a subcritical to a saturated Ohmic confinement, as observed in Alcator C-MOD [1]. This is inherently coupled to potential sign reversal for cold pulse propagation, an effect earlier described with a similar model [2,3].

[1] Rotation Reversal Bifurcation and Energy Confinement Saturation in Tokamak Ohmic L-Mode Plasmas; J.E. Rice, I. Cziegler, P.H. Diamond, et al., Phys. Rev. Lett. **107**, 265001, 2011

[2] Turbulence spreading, anomalous transport, and pinch effect, V. Naulin, A.H. Nielsen, J. Juul Rasmussen, Phys. Plasmas **12**, 122306, 2005

[3] Fast Heat Pulse Propagation by Turbulence Spreading, V, Naulin, J. Juul Rasmussen, P. Mantica, D. del-Castillo-Negrete, and JET-EFDA contributors. J. Plasma Fusion Res., Vol. 8, 2009

Non-local effects on neoclassical flows and fluxes in transport barriers

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The neoclassical flows and the neoclassical radial fluxes in transport barriers with gradient scale lengths comparable to the ion poloidal gyroradius are calculated analytically by expanding in small aspect ratio. Utilizing the smallness of the inverse aspect ratio, it is possible to formulate a delta-f theory with an ion temperature gradient comparable to the pressure and electrostatic potential gradients, thereby generalizing the results of [1] and subsequent references. The resulting neoclassical flows and fluxes depend on the poloidal electric field that must be calculated self-consistently. Importantly, the neoclassical radial fluxes are non-local. The non-locality is a result of a new condition to determine the ion poloidal flow that is obtained from a rigorous asymptotic expansion in the inverse aspect ratio, instead of by imposing momentum conservation for a model collision operator. In transport barriers, the standard neoclassical formula that relates the ion poloidal flow to local gradients fails, and the ion poloidal flow depends on the density, temperature and electrostatic potential profile throughout the transport barrier. A result of this non-locality is that one needs to reexamine the standard results for the neoclassical ion particle flux. Due to turbulence, the neoclassical ion particle flux need not be equal to the electron particle flux. The interaction between neoclassical physics and turbulence will be discussed.

[1] G. Kagan and P.J. Catto, Plasma Phys. Control. Fusion 52, 055004 (2010)

ITG turbulence in finite-beta helical and axisymmetric reversed field pinch plasmas

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In the reversed field pinch (RFP) device RFX-mod, good confinement properties are achieved when the magnetic surfaces become helical. This condition causes on overall reduction of the magnetic chaos, but, at the same time, creates the physical conditions mostly favoring the onset of electrostatic/electromagnetic turbulence, e.g., the occurrence of large pressure gradients.

In particular, a helical core imposes an unfavorable effect in terms of ion-temperature-gradient (ITG) stability and related turbulent transport[1]. ITG modes turn out to be localized where the magnetic surface compression is higher: here the local temperature gradients become larger, with a consequent growing instability and higher ion heat transport. Moreover, while an axisymmetric RFP presents a very high zonal flow residual level, the helical states of the plasma exhibit a lower zonal flow residual and a stellarator-like oscillating behaviour of the zonal potential.

In this contribution we revisit these findings, obtained in simplified conditions of the plasma. Due to the importance of electromagnetic effects in the RFP, we focus on the role of a finite plasma β on ITG stability, turbulence and zonal flow response. The occurrence of microtearing modes in high-β plasmas is also evaluated.

[1] I. Predebon and P. Xanthopoulos, Phys. Plasmas **22**, 052308 (2015).

Gyrokinetic simulation of the collisional micro-tearing mode instability*

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Abstract

An application of recently developed perturbative particle simulation scheme for finite-β plasmas in the presence of background inhomogeneities is presented. Originally [1], using similar scheme, we were able to simulate shear-Alfven waves, finite-β modified drift waves and ion temperature gradient modes using a simple gyrokinetic particle code based on realistic fusion plasma parameters. Recently, we have successfully used the scheme for simulation of linear tearing and drift-tearing modes, in both collisionless semi-collisional regimes in slab geometry with sheared magnetic field. Here, we present further development of this scheme for the simulation of linear collisional micro-tearing mode driven by electron temperature gradient [2] in high-aspect ratio cylindrical cross-section tokamak using the modified turbulence code GTS.

[1] E. A. Startsev and W. W. Lee,*Phys. Plasmas* **21**, 022505 (2014). [2] J. F. Drake and Y. C. Lee, *Phys. Fluids* **20**, 1341 (1977).

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Investigation of the effect of flow shear and the ion temperature gradient on marginally unstable turbulence in MAST using gyrokinetic simulations

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In this work we study the effect of flow shear γ_E and ion temperature gradient a/L_{Ti} on L-mode turbulence in the Mega-Ampere Spherical Tokamak (MAST). These parameters have been identified in recent computational [1] and experimental [2] work as playing a crucial role in regulating and driving turbulence. Together with the ratio of the safety factor to the inverse aspect ratio, q/ε, these parameters can be used to define a "zero-turbulence manifold" (ZTM) that represents the critical values needed to sustain turbulence.

We have used the experimental parameters for MAST shot #27268 at *r/a* = 0.7 and modelled the plasma using the local gyrokinetic code GS2, varying γ_E and a/L_{Ti} while keeping all other equilibrium parameters constant. The nominal parameters from the experiment were $\gamma_E = 0.16 \pm 0.02$ and $a/L_{Ti} = 5.5 \pm 1$.

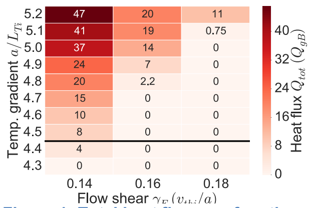

Figure 1: Total heat flux as a function of ion temperature gradient and flow shear showing the ZTM.

Nonlinear simulations show that by varying γ_E and a/L_{Ti} within experimental errors the turbulence crosses the ZTM (see diagram), implying that the experiment operates close to marginality. In particular, we find that flow shear is very effective at regulating turbulence and that increases in γ_E of only 10% are enough to drastically change transport properties from strongly driven to complete suppression of the turbulence. We are able to achieve the experimental heat flux for γ_E = 0.16 (v_{thi}/a) and a/L_{Ti} = 4.8 which are within the experimental errors.

Linear and nonlinear simulations also showed that the plasma exhibits subcritical behavior [3]. The important consequence is that small changes in the transient linear behaviour causes large changes in the transport properties, meaning that full nonlinear simulations are needed to study the resulting turbulence.

Finally the structure of the turbulence was studied by performing a correlation analysis that extracted statistical parameters such as radial, perpendicular and parallel correlation lengths ℓ_x, ℓ_y, and $\ell_\parallel$, and the correlation time τ_c. We compared these with results from the Beam Emission Spectrometer and found reasonable agreement, showing GS2 and gyrokinetics are good representations of experimental turbulence in the outer-core.

[1] Highcock E G *et al*., PRL. **109** 265001 (2013).
[2] Ghim Y.-c. *et al*., PRL **110** 145002 (2013).
[3] Schekochihin *et al*., PPCF (2012)

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Synthetic reflectometry probing of gyrofuid edge turbulence

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An important tool for the progress of reflectometry is numerical simulation. It enables to assess the measuring capabilities of existing systems and to predict the performance of future ones in machines such as ITER and DEMO. To exploit this concept, one should use sophisticated models for the plasma turbulence. A framework has been implemented to enable the usage output data from a 3D gyrofluid turbulence code as input for a 2D full-wave finite-differences time-domain code (REFMUL) [1], thus yielding a comprehensive synthetic diagnostic capable of coping with the complex signature of turbulence. The turbulence code used is a six moments gyrofluid electromagnetic model with global geometry (GEMR) [2, 3]. This two-dimensional synthetic reflectometer is applied to three-dimensional numerical simulations of edge plasma turbulence. Two cutoff densities are considered, corresponding to the regions inside and outside the last close flux surface, respectively. The electron density fluctuations' frequency spectra, accessible directly from the numerical turbulence data, are compared to the reflecting layer displacements' spectra measured by reflectometry in fixed frequency regime. This approach to a synthetic diagnostic contributes to a better understanding of the complexity associated with reflectometry measurements.

References

[1] F. da Silva, S. Heuraux, S. Hacquin, M. E. Manso, Journal of Computational. Physics **203** 467-492 (2005).

[2] B. D. Scott, Phys. Plasmas **12**, 102307 (2005).

[3] S. J. Zweben, B. D. Scott, J. L. Terry, B. LaBombard, J. W. Hughes, and D. P. Stotler, Physics of Plasmas **16**, 082505 (2009).

Full-F gyrofluid edge turbulence computations

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We present numerical simulations of an isothermal electromagnetic full-F two field gyrofluid model in twodimensional slab geometry or threedimensional axisymmetric X-point geometry. The gyrofluid model is derived from the full-F gyrokinetic theory [1]. This yields evolution equations for the gyrocenter densities and parallel velocities, which are closed by the nonlinear polarization and induction equations and by parallel resistivity. The presented model equations retain ion FLR effects up to 1st order. We incorporate all nonlinear, parallel and curvature terms consistently so that an exact energy theorem follows. The discretization of the parallel derivatives is based on a flux-coordinate independent field aligned approach [2, 3, 5], which fits best into the numerical implementation. This casts the perpendicular operators into a minimal form while allowing the treatment of an axisymmetric X-point geometry. The discretization of perpendicular derivatives is undertaken by discontinuous Galerkin methods, which are very versatile in the choice of the desired order of accuracy, while retaining a high degree of parallelism in the resulting algorithm. We exploit this in an implementation for GPUs and CPUs on shared and distributed memory systems [4].

We present also the extension to a thermal twodimensional full-F gyrofluid model, which accounts for ion FLR effects due to variations in temperature or magnetic field.

Our 2D and 3D numerical experiments concentrate on blob propagation and turbulent structure formation in the edge and scrape off layer.

References

[1] J. Madsen, Physics of plasmas 20, 072301 (2013)

[2] F. Hariri, M. Ottaviani, Computer Physics Communications (2013)

[3] A. Stegmeir, D. Coster, O. Maj, K. Lackner, Contributions to Plasma Physics 54, 4-6, p. 549–554 (2014)

[4] M. Wiesenberger, J. Madsen, A. Kendl, Phys. Plasmas 21, 092301 (2014)

[5] M. Held., M. Wiesenberger, A. Stegmeir, submitted to Computer Physics Communications (2015), arXiv:1505.05383

Identification of magnetic reconnection in the edge region of the RFX plasma

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The global 3D magnetic field in the RFX device is reconstructed using Newcomb's solution. We show that the calculation of the current density in toroidal coordinates (as the rotation of the magnetic field) is an efficient tool to identify magnetic structures, such as magnetic islands. It thus is an alternative to field line tracing and Poincare plots, with generally less noise in its results, and with the advantage of allowing to explore straightforwardly structures in 3D space, in contrast to the method of the Poincare plots. In an application, we show how the current density allows to identify a reconnection event, where an m=1, n=7 island chain merges into a single m=0 current-layer.

Pedestal structure and stability of different H-mode regimes in the TCV tokamak

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The type-I ELMy H-mode is the operational standard scenario chosen for ITER. This scenario is characterized by the presence of an edge transport barrier known as the pedestal which greatly enhances the global energy confinement thanks to the profile stiffness in the core plasma. Hence the performance of H-mode scenarios heavily relies on the achievement of a sufficiently large temperature pedestal in the plasma edge. It is therefore crucial to be able to predict the pedestal height within reasonable accuracy when designing experiments on actual machines or on a new machine such as ITER. A first constraint on the pedestal structure is the appearance of Edge Localized Modes or ELMs. They have been identified as a type of MHD instabilities called peeling-ballooning modes. The constraint on the pedestal structure by peeling-ballooning stability has been confirmed by linear MHD computations on many machines including the TCV tokamak [1]. However the peeling-ballooning stability of the pedestal only provides a limit on the pedestal height for a given width and one needs an additional constraint to predict both of them. The EPED model [2] uses the assumption that this other constraint could be linked to the onset of Kinetic Ballooning Modes turbulence. This model has been successful in predicting the pedestal width and height on several machines such as DIII-D, Alcator C-Mod or JET [2].
This work will report on the development of a similar predictive model using the equilibrium codes CHEASE and CAXE and the MHD stability code KINX [3] to compute the peeling-ballooning stability limit as well as the infinite n ballooning stability which can be used as a proxy for the onset of KBM turbulence. Results of peeling-ballooning stability and pedestal structure prediction will be presented for 2 different H-mode regimes observed in the TCV tokamak. The first one is a regime with large ELMs where the temperature collapse is observed up to the plasma core hinting at coupling of edge modes to core modes. The second one is the quasi-stationary ELM-free H-mode observed during third harmonic electron cyclotron heating [4].

References

[1] A. Pitzschke, et al., *Plasma Phys. and Contr. Fusion* **54**(1), 015007 (2012)
[2] P. Snyder, et al., *Nucl. Fusion* **51**(10), 103016 (2011)
[3] L. Degtyarev, et al., *Comp. Phys. Comm.* **103**(1), 10 (1997)
[4] L. Porte, et al., *Nucl. Fusion* **47**(8), 952 (2007)

Relativistic particle and momentum transport under interaction with a localised EM wave in a magnetized plasma

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We investigate the interaction of a spatially and temporally localised EM wave with charged particles in a magnetized plasma for the general case of a Gaussian wave-packet and relativistically moving particles, allowing the consideration of applications related to energetic ions and runaway electrons in fusion as well as in space plasmas. The EM wave-packet can have an arbitrary polarization, angle of propagation with respect to magnetic field lines, phase and group velocity, temporal and spatial width along and across the magnetic field and is introduced as a perturbation to the relativistic Guiding Center (GC) particle motion.

Using the Lie-perturbation method for the non-integrable Hamiltonian system that describes the wave-particle interaction, we obtain all the essential information of the collective characteristics of the interaction in terms of ensemble-averaged variations of the particle's momentum, energy and position, due to the interaction with the EM wave-packet. Significant interaction is shown to be associated with either resonant or ponderomotive effects, with the two mechanisms being treated on equal footing. Finite Larmor Radius (FLR) effects are also shown to introduce an additional interaction mechanism. The critical dependence of particle and momentum transport on the wave-packet characteristics is investigated for a wide range of parameters.

Modeling of Lower Hybrid Current Drive in Tokamak Reactors

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The role of the power spectrum in the localization of the quasi-linear absorption of the LH wave in tokamak reactors (first pass absorption) has been demonstrated in a recent paper (Ref. 1). In this work, the role of 2D power spectra as calculated by grill3D code [2] describing the finite dimensions of the grill (toroidal and poloidal extension) as well the effects of the tilt angle of the external magnetic field is accurately studied by means of the "LH^{star}" code which solves the wave propagation and damping of LH waves in the framework of quasi-linear (QL) theory. The governing system of coupled ordinary differential equations has been solved, for each Fourier component of the launched antenna spectrum by considering the finite dimensions of the antenna. A radiated power spectrum P(m,n) in the poloidal and toroidal components of the wavenumber is obtained which allows to reconstruct the quasi-linear diffusion coefficient inside the plasma, and to compute the 2-D electron distribution function by means of the Fokker-Planck solver. Radial profile of LH wave-driven current density has been obtained for expected typical plasma parameters of ITER and DEMO. The results demonstrate the key role of the $n_{||}$ antenna spectrum in determining the radiofrequency power penetration to the core of thermonuclear plasmas. An antenna spectrum with sufficiently narrow principal peak (in toroidal and poloidal mode number) moderates the strong absorption expected in reactor high temperature plasmas (which however remains single-pass), and allows the wave to reach more internal layer. A fine control of the radial deposition profile can be got by opportunely changing the power spectral width. PAM (passive-active multi-junction) antennas realistically designed for ITER and foreseen for DEMO have been considered. The results are discussed and represent a breakthrough evidencing that the LHCD concept should represent a robust tool capable of efficiently driving current in the outer radial half of thermonuclear reactor plasma column.

[1] A. Cardinali et al. , Proceedings of the 21st Topical Conference on Radiofrequency Power in Plasmas, AIP, Lake Arrowhead, CA (2015).
[2] M. A. Irzak, and O. N. Shcherbinin, Nuclear Fusion 35, 1341 (1995).

Kinetic full wave analysis of EC wave mode conversion in tokamak plasmas

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For heating and current drive in high-density core plasmas of tokamaks, electromagnetic waves with electron cyclotron (EC) range of frequencies have been extensively studied theoretically and experimentally. The propagation and absorption of EC waves are usually analyzed by the ray tracing method based on geometrical optics for waves with short wave length. In a plasma with high density or low magnetic field, however, the presence of cutoff layer may prevent the waves from penetrating into the central part from the low field side. In this case, the full wave analysis of EC waves is required for evaluating the absorption profile and optimizing the wave launching conditions. In the present analysis, two schemes of the full wave analysis in which the boundary value problem of Maxwell's equation is solved are presented. The first one is a one-dimensional kinetic analysis of the X-O-B mode conversion using the TASK/W1D code. The finite gyroradius effects are represented by an integral form of the dielectric tensor derived by integrating along particle orbits and introducing variable transformation from velocities to spatial coordinates. The mode conversion to the electron Bernstein waves and the absorption near the cyclotron harmonic resonance are successfully described. Parameter dependence of the absorption rate and the deposition profile is discussed. The second one is a two-dimensional analysis near the cutoff-resonance layer using the TASK/WF2D code. Using the collisional cold plasma model, reflection, transmission, and absorption of an EC wave beam is calculated, and compared with the results of a combination of the ray tracing method and the one-dimensional estimate of absorption and transmission. Finally using the integral formulation of the dielectric tensor, the mode conversion to the electron Bernstein wave is demonstrated. Quantitative comparison of three models will be presented.

Growth estimates, control and structures in a two-field model of the scrape-off layer

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Transport in the plasma boundary is one of the main issues in the design and operation of future fusion machines. Anomalous transport, turbulence and generation of large scale structures are the main questions controlling machine performance and the life expectancy of the materials facing the plasma. Here one tries to achieve some understanding of these questions through the study of a reduced two-dimensional fluid model [Sarazin and Ghendrih *Phys. Plasmas* **5** 4214 (1998); Ghendrih *et al.*, *Nucl. Fusion* **43**, 1013 (2003); Izacard *et al.*, *Phys. Plasmas* **18**, 06215 (2011)]. The emphasis is on obtaining nonlinear growth estimates for the physical quantities described by the equations and the eventual control of fluctuations by polarization as well as magnetic modulations. Finally, focusing on the conservative part of the equations, we obtain some exact solutions which might be the conservative ancestors of the collective structures observed in experiments as well as in numerical simulations.

Solving the kinetic equation of a magnetized ion gas close to a fully absorbing wall

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We will provide an overview of the different boundary layers in a typical tokamak divertor target (non-neutral sheath, magnetic presheath and collisional layer), and of a model that aims to solve the ion kinetic equation in all these layers. The magnetic presheath layer, of a width of the order of the ion gyroradius, can be solved using a generalized version of gyrokinetics valid for grazing angles between the wall and the magnetic field lines. For the collisional layer, with a width of the order of the mean free path, we will present numerical kinetic results. An outline of future work will be given, and will include a multispecies (ion and electron) model and transition between positive and negative sheath at grazing angles.

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Simulation of SOL turbulence in the ISTTOK tokamak

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Understanding scrape-off layer (SOL) turbulence is crucial for the success of the fusion program. SOL dynamics determines the overall confinement and performance of future tokamaks (such as ITER), governs the heat load on the vessel wall, and regulates the impurity dynamics, the plasma refueling, and the removal of fusion ashes. While the use of numerical simulations has recently allowed some important advancements in the understanding of the plasma SOL dynamics, such as the identification of the mechanisms regulating the turbulence amplitude and the SOL width and the main turbulent regimes [1-2], our theoretical understanding still needs to be completely assessed by comparing it with a large set of experimental results.

In some cases, the collision frequency in the SOL is sufficiently large to justify the use of a fluid model. In addition, the amplitude of the fluctuations is comparable to that of the background profiles, and occurs on scale lengths that are larger than the ion Larmor radius. This suggests that a good description of the SOL region is provided by the drift-reduced Braginskii equations [3], which we solve by using the GBS code [4]. GBS evolves the SOL plasma dynamics in three-dimensions, without separation between perturbations and equilibrium.

Through GBS simulations, the evaluation of the linearly unstable modes and analytical investigations, we have studied the turbulent regimes, the saturation mechanisms and the formation of the SOL profile in ISTTOK, where our theoretical predictions have then been compared with the ISTTOK experimental measurements. The gradient removal hypothesis [5] provides an estimate for the SOL width which is in good agreement with the one obtained from the GBS code, thus suggesting that even in tokamaks with a poloidal limiter, the SOL width is set by the non-linear flattening of the driving plasma gradients. We also show that the inclusion of a perpendicular component to the wave number introduces a poloidal shift in the maximum of the typical pressure radial gradient length scale.

The measure of the phase-shift and cross-coherence between density and electric potential fluctuations demonstrates that the drift-wave instability is the main drive for the observed turbulence profiles, which is confirmed by the linear results. A parabolic relationship between the skewness and kurtosis of the electric potential at the low-field side is found (cf. [6]), lying in the range of a beta distribution function. Moreover the computed PDF of the *ExB* flux from the GBS code agrees with the experimental one, demonstrating that fluctuations have a more intermittent character at the low-field side than at the high-field side.

[1] P. Ricci, et. al., *Phys. Plasmas* **20** 010702 (2013)
[2] F.D. Halpern, et. al., *Nuclear Fusion* **53** 122001 (2013)
[3] A. Zeiler, et. al., *Phys. Plasmas* **4** 2134 (1997)
[4] P. Ricci, et. al., *Plasma Phys. Control. Fusion* **54** 124047 (2012)
[5] P. Ricci, et. al., *Phys. Plasmas* **20** 010702 (2013)
[6] B. Labit, et. al., *Phys. Rev. Lett.* **98** 255002 (2007)

Effects of plasma shaping on tokamak scrape-off layer turbulence

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The understanding of the plasma dynamics in the scrape-off layer (SOL) of tokamaks is of crucial importance as we approach the ITER era. In this region, particles and heat coming from the core, through turbulent transport, flow along the magnetic field lines and are exhausted to the vessel. The processes taking place in the SOL govern the performance of the entire device, as they determine the impurity dynamics, the recycling level, the peak heat loads at the vessel, and have an important role in setting the overall plasma confinement. In the recent past, a large effort has been devoted to improve the knowledge of plasma turbulent dynamics in the tokamak SOL, achieving significant progress. In the simplest circular limited configuration, electromagnetic fluid turbulence simulations carried out with the Global Braginskii Solver (GBS) [1] have pointed out the mechanisms that regulate the SOL width, the plasma toroidal rotation, and the turbulence regime transition.

In the present work we generalize the magnetic geometry of GBS, to perform simulations with elongated plasmas and non-zero triangularity, and we investigate the effects of plasma shaping on tokamak SOL turbulence. Nonlinear simulations are performed, with different values of elongation and triangularity. The turbulence properties are analyzed, and the gradient removal theory [2] is used to estimate the SOL width. Thanks to a linear study, we elucidate the mechanisms through which the plasma shaping affects the SOL turbulence.

[1] P. Ricci, F. D. Halpern, S. Jolliet, J. Loizu, A. Mosetto, A. Fasoli, I. Furno, and C. Theiler, "Simulation of plasma turbulence in scrape-off layer conditions: the GBS code, simulation results and code validation," *Plasma Physics and Controlled Fusion*, vol. 54, p. 124047, Dec. 2012.

[2] P. Ricci and B. N. Rogers, "Plasma turbulence in the scrape-off layer of tokamak devices," *Physics of Plasmas*, vol. 20, no. 1, p. 010702, 2013.

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Remote Generation of Magnetic Island by Turbulence

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Large magnetic islands have been observed on several occasions in tokamak plasmas, even without any triggering event that could create a seed island large enough to overcome the threshold for NTM growth [1]. Small-scale interchange-type turbulence has been proposed as an explanation for such seed islands, tapping free energy from the pressure gradient and releasing it as electromagnetic fluctuations which are then nonlinearly coupled to larger scales; this has been confirmed by 2D numerical simulations [2].

Recently, a more detailed model for remote $(2, 1)$ magnetic island excitation has been proposed in 3D cylindrical geometry. It is based on the nonlinear coupling of unstable interchange modes, through intermediate-scale radially extended modes, to the large scale magnetic island [3]. This has shown that magnetic island may be generated by interchange turbulence, even when the resonant surface is far from the turbulent zone. We further study this mechanism by using a more elaborate fluid turbulence model, using toroidal geometry. This introduces an additional linear coupling between modes, in addition to the nonlinear coupling due to advection.

References

[1] A. Isayama et al, J. Plasma Fusion Res., 8, 1402013 (2013)

[2] M. Muraglia et al, Phys. Rev. Lett., 107, 095003 (2011)

[3] A. Poye et al, Phys. Plasmas 22, 030704 (2015)

Viscosity effect on tearing modes in toroidal geometry

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Two nonlinear regimes, depending on the magnetic Prandtl number Prm, are identified for magnetic islands described by resistive MHD equations in toroidal geometry, computed with XTOR [1]. The frontier between these two regimes is sharp, with a critical Prm of about unity, and has the characteristics of a phase transition controlled by plasma viscosity. In the low Prm regime, a new form of the so-called flip instability, consisting of a sudden change of the island phase, is identified. Already known in the context of a forcing by external magnetic perturbations and localized current drive [2, 3], it occurs spontaneously at low Prm, in particular close to marginal stability. The main characteristics of this structural instability can be described by a static exchange of the O and X-points of the island. The island dynamics is trapped into a limit cycle of such flips until finally it escapes and reaches saturation. The period of the cycle has a finite time singularity as Prm approaches its critical value. The low Prm regime is well described by the slab visco-resistive model in the linear phase [4], with a linear stability for Prm above few units, and its dynamical features are similar to what has been already observed in simpler geometries [5, 6]. Conversely, curvature physics strongly impacts the viscous regime, due to the widening of the pressure perturbation associated to a lower coupling to adjacent poloidal harmonics. The critical width above which curvature effects are damped increases therefore with Prm. This translates into an increasing linear growth rate as Prm increases, and a saturation that increases similarly. Toroidal geometry therefore introduces a new viscous regime for Prm values above unity.

References

[1] LÜTJENS H. ET AL. *Journal of Computational Physics* **229** (2010) 8130 .

[2] LAZZARO E. ET AL. *Physics of Fluids (1958-1988)* **31** (1988) 1623.

[3] BORGOGNO D. ET AL. *Physics of Plasmas (1994-present)* **21** (2014) 060704.

[4] GRASSO D. ET AL. *Physics of Plasmas* **15** (2008) 072113.

[5] COELHO R. *Physics of Plasmas (1994-present)* **14** (2007) 052302.

[6] POYÉ A. ET AL. *Plasma Physics and Controlled Fusion* **56** (2014) 125005.

Modelling the effects of NTM islands

On the transport of heavy impurities in a tokamak

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In tokamaks, magnetohydrodynamic (MHD) instabilities are frequently observed to have a strong impact on the evolution of the plasma discharge. It is, therefore, important to properly account for MHD activity when modelling the tokamak plasma behaviour.

In 2011 the inner wall of JET was covered with Tungsten and Beryllium tiles, replacing the previous Carbon wall with the ITER Like Wall (ILW). In some discharges with ILW, Tungsten accumulates in the core of the plasma, leading to plasma radiation collapse and ultimately disruption. This accumulation seems exacerbated by the presence of a magnetic island [1].

Among the various MHD instabilities, a magnetic island can be detected by magnetic coils placed within the torus wall and by temperature measurements provided by Electron Cyclotron Emission (ECE) diagnostic. The island appearance time and position can be measured by exploiting the correlation between the fluctuations of coil and ECE signals. The island width can be determined by comparing the first and the second harmonic of ECE fluctuations [2].

We use JETTO (a one-and-a-half-dimensional transport code calculating the evolution of plasma parameters in a time dependent axisymmetric MHD equilibrium configuration) in interpretive mode and its impurity component SANCO in predictive mode with transport coefficients calculated by the codes NEO and GKW [1]. We model a discharge with both an initially off-axis Tungsten peak and a (3, 2) island. The island is modelled enhancing Tungsten diffusion, in a position, time instant and with a width determined by diagnostics as previously detailed [3]. The output of the simulations is studied in different ways: reconstructed SXR emissivity, line integrated emissivity profiles, time evolution of SXR channels intensity, Tungsten density and radiation. When opportune, comparison between simulated and experimental data is performed.

Although not reproducing quantitatively the experimental result, the simulated emissivity at the final state reproduces qualitatively the trend of the experimental one. In particular if the island is situated in the inner, convex part of the Tungsten density gradient, the impurity is channelled toward the inner core as observed in experiments [4].

[1] Angioni C. et al., Nucl. Fusion 54, 083028 (2014)
[2] Baruzzo M., et al., *Plasma Phys. Control. Fusion* **52** 075001 (2010)
[3] Marchetto C., et al., 41st EPS Conference on Plasma Physics, ECA Vol. 38, P1.018 (2014)
[4] Hender T. C., et al., 41st EPS Conference on Plasma Physics, ECA Vol. 38, P1.011 (2014)

*See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

Test particle simulations of wave-particle interaction in the presence of magnetic islands

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We study the relativistic motion of charged particles in toroidal plasma configurations, under the influence of a perturbed equilibrium magnetic field as well as of external drivers. We particularly focus on NTM-related perturbations, exhibiting magnetic islands, and we consider the presence of electromagnetic waves in the island region, in the context of plasma heating and current drive. Collisions with background plasma particles are also taken into account, and the fully nonlinear test particle simulations are performed for ITER-relevant parameters. Using large numbers of test particles, for the need of which the code has been parallelized, particle trajectories are tracked and statistical results concerning transport coefficients in velocity space (both diffusive and convective terms), as well as the current drive and absorbed power densities, are obtained. The results will be compared with other methods used to solve this problem, such as the linear and quasilinear theories of wave-particle interaction.

Impact of the choice of core/pedestal transport modeling assumptions on the performance of a DEMO fusion reactor

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DEMO is foreseen as the next–step fusion device in the European programme, after ITER, that should demonstrate net electricity production in the worth of $\sim$ 500 MW [1, 2]. The pulsed device ($\sim$ 2 hrs discharge duration) will operate, during the flat–top phase, in H–mode, to allow for a reasonable size. However, the two main ingredients of a H–mode plasma, pedestal height and core profiles peaking, have to be predicted to assess if the margin of operation is possible inside the allowed constraints (separatrix power above L–H threshold, relevant fusion power, seeded impurity concentration not diluting in a dramatic way).

In this work, the pedestal is used as a boundary–condition, which height will be scanned. Together with the modeling of the core profiles, the predicted performance will give rise to the pool of operational possibilities in which the plasma can live. Critical are of course assumptions on the core transport model, as these impact not only the temperature and density of the main plasma, but also the confinement time of the intrinsic (undesired) and seeded impurities.

The ASTRA transport code [3, 4], coupled to turbulence quasi–linear model TGLF [5], is used to perform theese investigations. The predicted diffusivities will be then modified (based on existing knowledge and probable interactions) to give rise to i.e. improvements/loss of core confinement and the resulting performance will be computed, allowing to draw conclusions on what is the actual sensitivity of the foreseen scenario on unforeseen confinement characteristics.

In particular, the impact on He ash and seeded impurities of these confinement changes will be addressed, as they feed–back on the plasma through dilution, radiation, and turbulence modifications.

References

[1] R. Wenninger *et al.*, *Nucl. Fusion* **55**, 063003 (2015)

[2] G. Giruzzi *et al.*, *Nucl. Fusion* **55**, 073002 (2015)

[3] G. V. Pereverzev and Y. P. Yushmanov, IPP Report 5/42 (August 1991)

[4] E. Fable *et al.*, *Plasma Phys. Control. Fusion* **55**, 12402 (2013)

[5] G. M. Staebler *et al.*, *Phys. Plasmas* **12**, 102508 (2005)

Transport processes characterizing the Quasi-Single-Helicity states in RFX-mod

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Abstract

The fluid-dynamical approach developed in Refs. [1, 2] and based on the behavior of the Finite Time Lyapunov Exponent (FTLE) field, associated to the magnetic configuration is applied to investigate a real situation [3]. We consider the magnetic field characterizing the emergence of self-organized quasi-helical states [4], predicted by magnetohydrodynamic (MHD) simulations [5] and observed in high current experiments in the reversed field pinch configurations. The associated FTLE field shows the presence of ridges, that can be recognized as Lagrangian Coherent Structures (LCSs) for the magnetic field. These structures actually limit the field lines motion and provide a chaos healing effect, by influencing the transport properties of the system.

References

[1] D. Borgogno et al., *Phys. Plasmas* **18** 102307 (2011)

[2] D. Borgogno et al., *Phys. Plasmas* **18** 102308 (2011)

[3] G. Rubino et al., submitted to *Plasma Phys. Control. Fusion*.

[4] Lorenzini R. et al. *Nature Physics*, 14 June 2009.

[5] D. Bonfiglio, M. Veranda, S. Capello, L. Chacón, G. Spizzo, *Journal of Phys.: Conf. Series* **260** 012003 (2010)

Tracer transport with multiple W charge states in ASDEX Upgrade

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Under certain conditions AUG and JET, the largest present devices with high-Z PFC components, suffer from considerable W influx. This can even lead to a radiative collapse of the plasma. In view of future ITER operation, it is important to assess tolerable W levels in the core plasma [1], and to understand which transport mechanisms are dominant in the different parts of the plasma.

It is known that transport coefficients may depend on Z. E.g. for neoclassical transport, to first order convection $V \sim Z$, whereas diffusion D is not dependent on Z; rotation and minority heating make this picture more complicated [2]. Also the various turbulent transport mechanisms have different dependencies on Z.

The impurity transport module as developed within the European Integrated Modelling (EU-IM) framework [3] solves the time evolution of each charge state separately, and has been coupled to the European Transport Simulator (ETS). This allows to implement charge state dependent transport coefficients, as prescribed by theory or by gyrokinetic modelling.

In this contribution, we start from typical kinetic profiles from AUG in L- and H-mode, for cases where a significant W influx was observed. The quasi-linear gyrokinetic turbulence code QuaLiKiz [4] is used to determine the Z dependent turbulent transport coefficients for these given profiles. QuaLiKiz now treats an arbitrary number of ion species, and includes poloidal asymmetry effects on heavy impurities [5].

For neoclassical transport, known to be dominant in the inner core, we follow the formulas of [2]. We then establish whether a charge state dependent W transport description, as dictated by the dominant transport mechanism, gives a better match to the observed W density time evolution compared to the normally applied single charge state description (where it is assumed that all W has the same charge, typically ~ 40 in the hot core of AUG or JET).

Fully self-consistent modelling of all transprot channels, using QuaLiKiz and a neoclassical transport code such as NEO [6], is a future step in this work.

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[1] G.M.D. Hogeweij *et al* 2015 *Nucl. Fusion* **55** 063031
[2] F. Casson *et al* 2015 *Plasma Phys. Contr. Fusion* **57** 014031
[3] D. Kalupin *et al* 2013 *Nucl. Fusion* **53** 123007
[4] C. Bourdelle *et al* 2007 *Phys. Plasmas* **14** 112501
[5] J. Citrin, C. Bourdelle *el al, ITPA Transport and Confinement Topic Group Meeting, October 2014, Cadarache; paper to be submitted*
[6] E. Belli *et al* 2012 *Plasma Phys. Contr. Fusion* **54** 015015

*See http://www.euro-fusionscipub.org/mst1
†See http://www.euro-fusionscipub.org/eu-im

Current ramps optimization study with the RAPTOR code

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Optimization of the plasma discharge is related to the determination of the optimal time evolution of the plasma parameters to reach a specific plasma state taken into account certain physical and technical constraints. The set of plasma parameters which should be optimized consists of the parameters significantly changing the plasma state and can be defined from the different tokamak actuator inputs: plasma current, EC, NBI heating or current drive power, density, etc. An optimization of the ramp-up phase of the plasma discharge with plasma current and EC heating as actuators has already been carried out with the RAPTOR code [1,2]. It is a light and fast transport code with a simplified transport model which includes transport equations for electron temperature and poloidal flux. In particular, the simulation showed that a plasma current overshoot with early heating allows to get a voltage profile close to the stationary state and a safety factor profile appropriate for a hybrid scenario operation [3].

In this work we carry out the optimization study of the current ramps. Phases of the plasma discharge like current ramp-up and ramp-down are of particular interest for optimization because of the rapid changes in the plasma state. For example, numerical optimization of the current ramp-up phase of the plasma discharge provides knowledge about the optimal way (the fastest or the most economical trajectory) to reach stationary state. Numerical optimization of the current ramp-down can prescribe evolution of the plasma parameters to terminate plasma as fast as possible and in the same time to avoid disruptions in the real experiments. The simulation is performed with the RAPTOR code. However, this code was constructed assuming a fixed plasma equilibrium, whereas plasma geometry might change both during the ramp-up and ramp-down phases. Therefore to expand area of the code applicability, RAPTOR has been extended to include time varying terms. In this way, time varying plasma geometry can be used in the optimization procedure and for example plasma elongation can be an additional parameter for the trajectory optimization. The results of the simulation with the extended transport model and optimization procedure of the ramp-up and ramp-down phases of TCV- and AUG-like plasma parameters will be presented.

References

[1] F. Felici et al, Nucl. Fusion **51** (2011) 083052.
[2] F. Felici, PhD thesis (2011), Lausanne, Switzerland: EPFL: http://infoscience.epfl.ch/record/168656
[3] F. Felici, O. Sauter, Plasma Phys. Control. Fusion **54** (2012) 025002.

Extracting physical quantities from BES data

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We propose a method for extracting the underlying physical properties of turbulent density fluctuations from measurements made using Beam Emission Spectroscopy (BES) diagnostics.

BES systems record fluctuating time series of photon counts, which are related to the fluctuating density field in the plasma via the Point-Spread Functions (PSFs) of the instrument and the atomic excitation rate of the neutral-beam. The correlation properties of the photon counts can then be calculated: the radial and poloidal correlation lengths and wavenumbers, the correlation time and the fluctuation amplitude. These then have to be related to the correlation properties of the density field.

In order to determine these relationships we have constructed a toy model of the turbulent structures, to which model PSFs have been applied. Thus, expressions have been derived that relate the correlation parameters of the density field to the correlation parameters of the intensity field measured by the BES. These expressions are easily inverted and can then be used to determine physical quantities from BES measurements.

The assumptions of our toy model have been tested by convolving PSFs with a density field generated by non-linear gyrokinetic simulations (using GS2) of MAST, from which correlation parameters have been extracted. The inversion equations have then been used to successfully recover the correlation function of the simulated density field. Therefore, this method can facilitate comparisons between plasma theory and experiment.

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Experimental investigation of geodesic acoustic modes on JET using Doppler backscattering

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Geodesic acoustic modes (GAMs) are characterized by a symmetric potential structure in the poloidal and toroidal directions and a rapidly varying radial structure with finite wavelength. Because of their small radial structure, the E×B shearing rate due to GAMs can be important before and during the L-H transition when the mean shear flow is modest [1]. Recently, the influence of isotope mass on the GAM amplitude has been studied [2] showing a systematic increase in the GAM amplitude during the transition from H to D dominated plasmas. Consequently, understanding GAMs may yield important implications for the dynamics of the L-H transition.

This contribution focuses on the characterization of GAMs in the JET edge plasma using mainly Doppler backscattering (DBS). Experiments were performed in Ohmic and NBI heated vertically-shifted plasmas (where a correlation reflectometer works for DBS) for different values of plasma current ($1.5 < I_p < 2.75$ MA) and line-averaged density ($1.5 < n < 4\times10^{19}$ m^{-3}). GAMs are generally most intense in the edge density gradient region in a radial region of about 2 cm, coinciding with the location of the radial electric field well. The GAM has a constant frequency with radius, not varying with the local temperature. The GAM RMS E×B flow velocity is up to 1.5 km/s, corresponding to about 50% of the local mean value.

There are two factors that determine the magnitude of the GAM: its drive and damping. The GAM amplitude is observed to decrease with the edge safety factor, in contradiction with the expected reduction due to collisionless damping. GAMs on JET appear to be regulated by the turbulence drive – the density fluctuation level, as well as the density and temperature inverse scale lengths, increase with plasma current and line-averaged density, concurrent with the enhancement of the GAM amplitude.

[1] G. D. Conway et al., Phys. Rev. Lett. 106 (2011) 065001

[2] Y. Xu et al., Phys. Rev. Lett. 110 (2013) 265005

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* See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

`Viriato`: a Fourier-Hermite spectral code for strongly magnetised fluid-kinetic plasma dynamics

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We report on the algorithms and numerical methods used in `Viriato`, a novel fluid-kinetic code that solves two distinct sets of equations: (i) the Kinetic Reduced Electron Heating Model equations [Zocco & Schekochihin, 2011] and (ii) the kinetic reduced MHD (KRMHD) equations [Schekochihin *et al.*, 2009]. Two main applications of these equations are magnetised (Alfvénic) plasma turbulence and magnetic reconnection. `Viriato` uses operator splitting to separate the dynamics parallel and perpendicular to the ambient magnetic field (assumed strong). Along the magnetic field, `Viriato` allows for either a second-order accurate MacCormack method or, for higher accuracy, a spectral-like scheme. Perpendicular to the field `Viriato` is pseudo-spectral, and the time integration is performed by means of an iterative predictor-corrector scheme. In addition, a distinctive feature of `Viriato` is its spectral representation of the parallel velocity-space dependence, achieved by means of a Hermite representation of the perturbed distribution function. A series of linear and non-linear benchmarks and tests are presented, with focus on 3D decaying kinetic turbulence.

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Self-organizing Knotted Magnetic Structures in Plasma.

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Understanding the types of structures that a plasma forms spontaneously is of fundamental importance for fusion applications. We perform full-MHD simulations on various helical initial conditions consisting of linked rings of magnetic flux, and see that a free, unconfined, helical plasma invariably forms a localized magnetic structure. This relaxed state is roughly axisymmetric and consists of nested toroidal magnetic surfaces with a nearly constant rotational transform. We analyze this state and show that it is not a Taylor state, but a state where the Lorentz force is balanced by the hydrostatic pressure. The field exhibits complex dynamics, such as the emergence of magnetic islands at rational magnetic surfaces. We finally show that such a field can be approximated by a simple analytical expression derived from the Hopf map.

Hamiltonian fluid reduction of drift-kinetic equations for non-dissipative plasmas

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Drift-kinetic models (see, e.g. Ref. [1]) are commonly adopted to describe the dynamics of plasmas in the presence of an intense magnetic field. Also, from drift-kinetic equations, fluid models can be derived, which describe the evolution of a finite number of moments of the drift-kinetic distribution function. For plasmas where dissipative effects are negligible, such as the essentially collisionless plasmas of the magnetosphere or of the core of tokamak fusion devices, drift-kinetic equations are supposed to possess a Hamiltonian structure. Their reduction to a finite set of fluid equations, however, might in general violate the Hamiltonian structure of the parent drift-kinetic model, depending on the adopted closure relation. An uncontrolled closure could in particular lead to the introduction of unphysical dissipation in the resulting fluid model.

In this contribution I will describe a closure relation that leads to a Hamiltonian fluid model, starting from a Hamiltonian drift-kinetic model. In the two-dimensional (2D) limit, where translational invariance is imposed along the direction of the dominant component of the magnetic field, the Poisson bracket of the fluid model is obtained from a non-trivial extension of the Lie algebra associated with the Lie-Poisson bracket of the 2D Euler equation for an incompressible fluid. The extension to the 3D case can be carried out by means of a procedure described in Ref. [2], which allows to extend to 3D a 2D Poisson bracket from plasma fluid models assuming a strong magnetic field along a spatial direction. Alternatively, the Poisson structure of the fluid model can be obtained by carrying out a change of variables which unveils the direct sum structure of the Poisson bracket. In terms of the new set of variables, the existence of conserved quantities for the fluid model (Casimir functionals), which turn out to be associated with Lagrangian invariants, can also be shown.

References

[1] R.D. Hazeltine, J.D. Meiss. Plasma Confinement. Dover Publications, New York (2003).

[2] E. Tassi, P.J. Morrison, D. Grasso, F. Pegoraro. Hamiltonian four-field model for magnetic reconnection: nonlinear dynamics and extension to three dimensions with externally applied fields. Nucl. Fusion 50 (2010), 034007.

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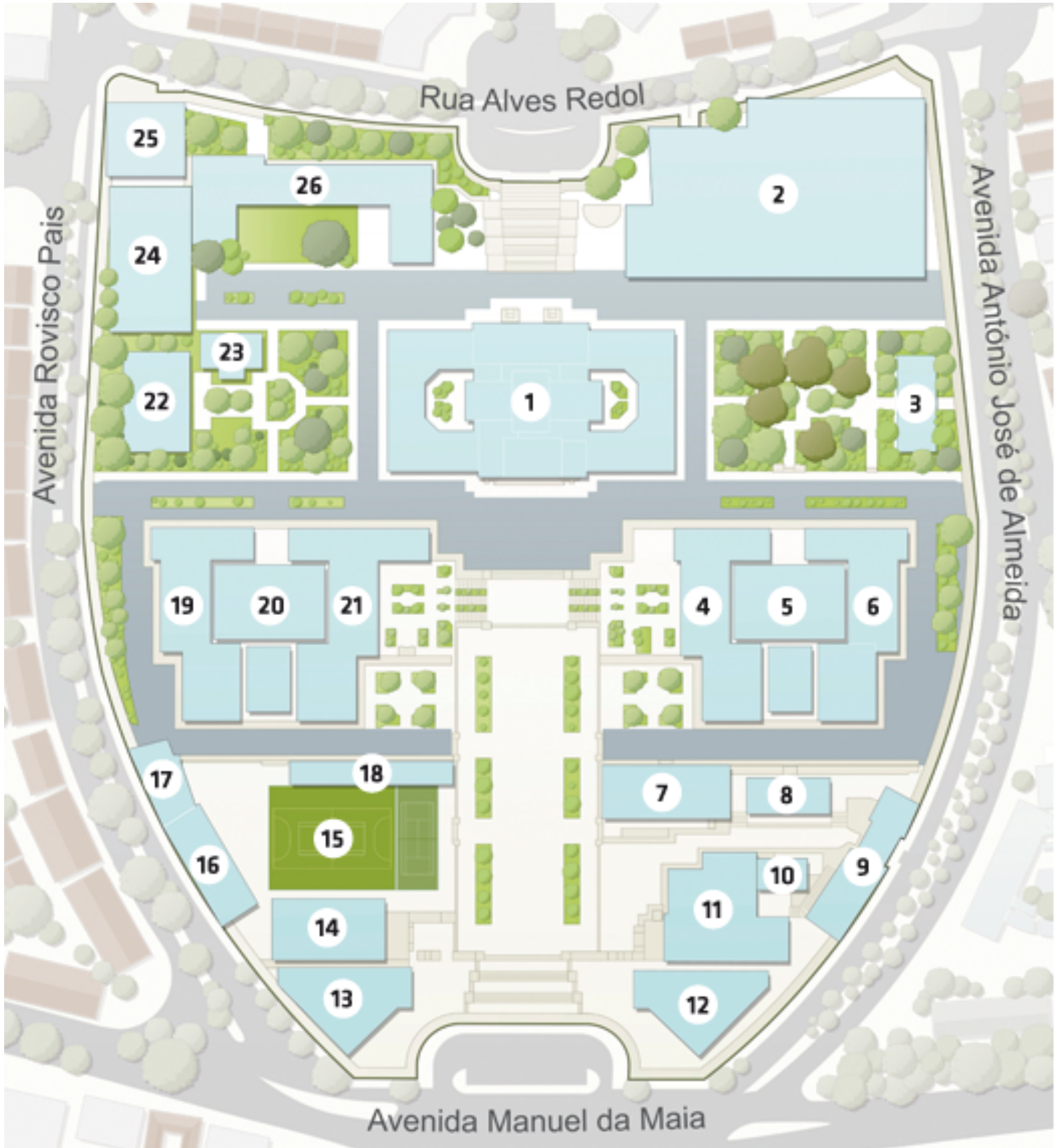

1 Main Building
2 Civil Building
3 North Garden Building
4 Mechanics Building I
5 North Tower
6 Electrical Engineering Building
7 Information Technologies Building II
8 Mechanics Building IV
9 Information Technologies Building I
10 Information Technologies Building III
11 Mechanics Building II
12 Mechanics Building III
13 Canteen
14 Students Association Building
15 Playing Fields
16 Swimming-Pool
17 Social Action Building
18 Copy Section
19 Mining Building
20 South Tower
21 Chemistry Building
22 South Garden Building
23 Kindergarden
24 Mathematics Building
25 Physics Building
26 Interdisciplinary Building


transportes de Lisboa
Rede de transportes de Lisboa
Network diagram
Coroa 1
Zone 1
Coroa L
Zone L
Amadora Este
Alfornelos
Pontinha
Carnide
Colégio Militar/Luz
Alto dos Moinhos
Laranjeiras
Jardim Zoológico
Sete Rios
Praça de Espanha
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Anjos
Intendente
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