EFTC 2017

17th European Fusion Theory Conference

9-12 October 2017

Athens - Greece

Program & Book of Abstracts

The conference is organized by

National Program of Controlled Thermonuclear Fusion

Association EURATOM - Hellenic Republic

PCO CONVIN S.A.

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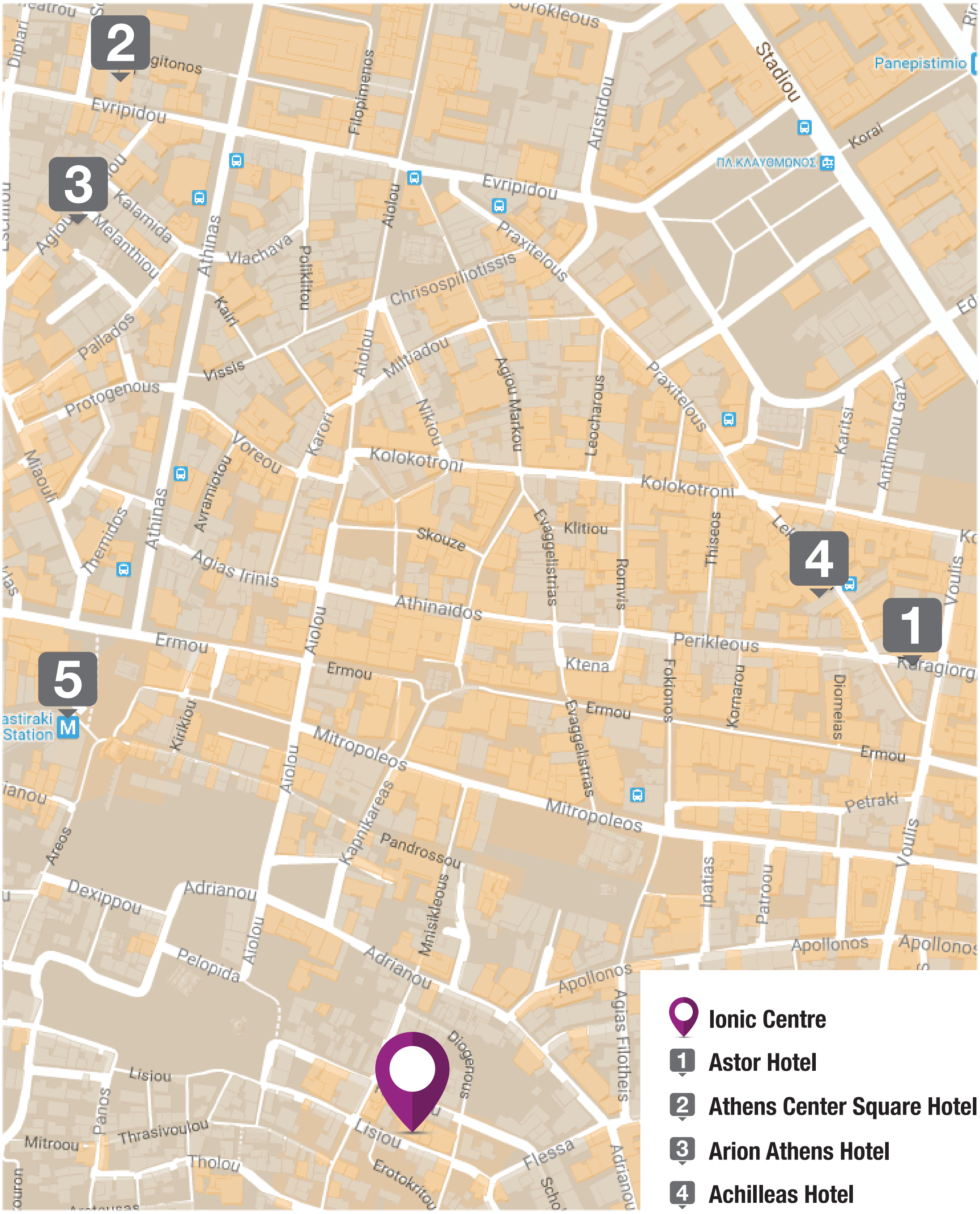
Professional Congress Organizer



Ionic Centre

1 Astor Hotel

2 Athens Center Square Hotel

3 Arion Athens Hotel

4 Achilleas Hotel

5 Metro Station Monastiraki

Contents

The *17th edition* of the *European Fusion Theory Conference* is held in *Athens*, *Greece*, between *9* and *12 October 2017*.

The conference is organized by the *Association EURATOM - Hellenic Republic*, in cooperation with *PCO CONVIN S. A.*

Conference Committees

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Outline of the main topics included in the EFTC

- Basic plasma theory
- Macro-instabilities and operational limits
- Alternative fusion concepts: stellarator, reverse-field pinches, spherical tokamaks, laser-induced ignition
- Turbulent transport and structures: theory and experimental evidence
- Neoclassical transport: theory and experimental evidence
- Burning plasmas and fast particles
- Heating, current drive and wave particle interactions
- Edge and scrape-off-layer/divertor physics
- Computational modelling in plasma physics

Conference venue

The Ionic Centre (www.ionic.gr)
Address: Lysiou 11, 105 56 Athens
Tel: (+30) 2103246614 – ***Fax:*** (+30) 2103214412

The Ionic Centre is located in a neo-classical style building in Plaka (historical centre of Athens), at a walking distance from *Syntagma Square (Athens' metropolitan hub of transport services*), surrounded by 3 *metro stations (Acropolis, Syntagma, Monastiraki)*.

Registration Desk

The Registration Desk for EFTC 2017 will be located on the ***main lobby*** (ground floor) and will be open the following hours:

Monday, October 9, 2017	08.00 - 16.30
Tuesday, October 10, 2017	08.30 - 17.00
Wednesday, October 11, 2017	08.30 - 17.00
Thursday, October 12, 2017	08.30 - 14.30

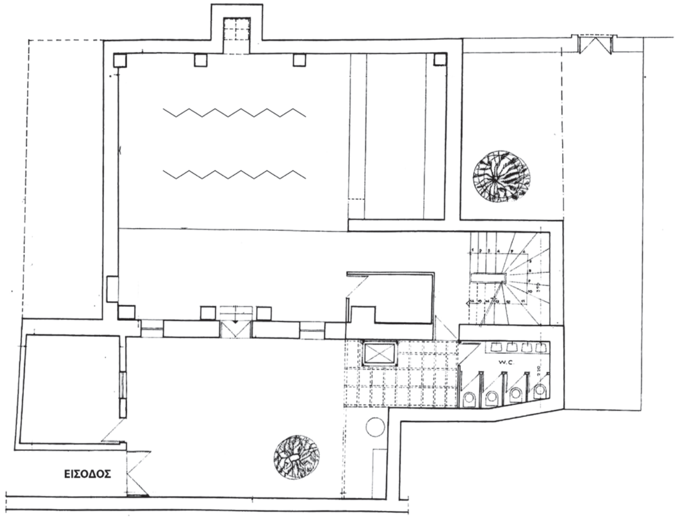
Conference Halls

The lectures will be presented at the ***Aerides*** room (Level 1), and the poster sessions will take place in the ***Apellis*** room (Level -1). The coffee breaks will be served at the main lobby (ground floor).

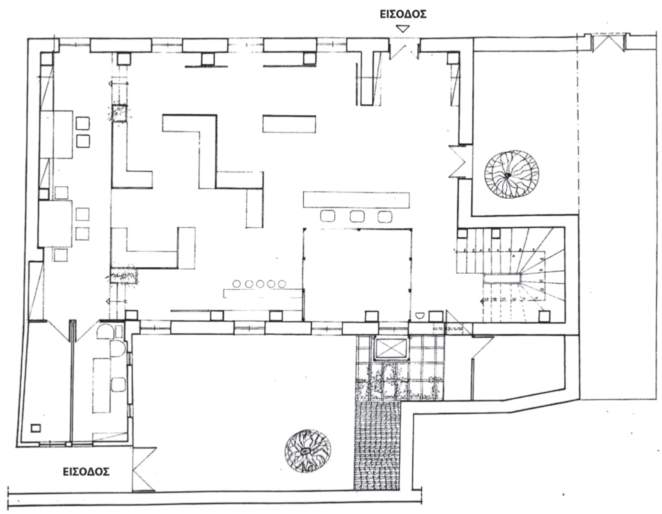
Wi Fi Internet access

Wi-Fi internet access will be available in the venue. The login credentials will be communicated to the participants upon registration.

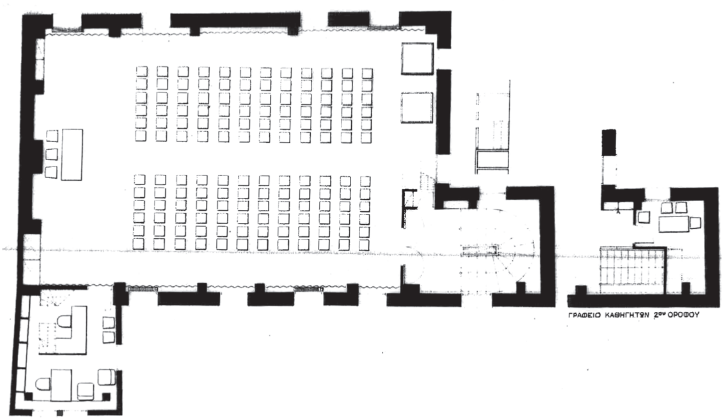
Plan of the Apellis room
(Level -1)



Plan of the main lobby
(ground floor)



Plan of the Aerides room
(Level 1)



Attendance policies

All speakers are kindly requested to bring their slides in electronic media form (CD/DVD-ROM, USB flash drive, external hard disk) to the volunteer in charge of all presentations inside the conference (***Aerides*** room) before the session of their presentation for uploading and technical check.

Each speaker is kindly requested to secure a 3 to 5 min of her/his presentation, for questions and discussion.

It is preferable that the speakers do not use their own computers for their presentations, in order to minimize technical connection problems and delays between the presentations.

Posters may be displayed on the day of the poster-session (Tuesday 10/10/17 or Wednesday 11/10/17) from 08.30 to 17.00. The mounting of posters should have been finilized by 14.00 on the day of the session, and the dismantling should be completed by 17.30 (after the end of the session). Any posters not collected by then, will be discarded. All necessary material for mounting the poster will be available at the poster area or can be collected by the registration desk. All posters will be allocated by their abstract ID number (*Px.yy*, where $x = 1 - 2$ and $y = 1 - 22$).

Certificates of attendance to the conference will be given upon request, after the completion of the conference. Each participant requiring a certificate may send an e-mail message of request to the Local Organizing Committee (eftc17@astro.auth.gr).

Persons with impaired mobility should notify the registration desk in order to accommodate any special requirements.

A special issue of the Journal of Plasma Physics (www.cambridge.org/core/journals/journal-of-plasma-physics) is scheduled to be published for the talks and posters presented at the conference. The submitted papers should reflect original (research or review/tutorial) work. The papers will be peer-reviewed by at least two referees, and the final decision on acceptance/rejection will be based on the scientific judgment of the editor. There is no limit to the length of the paper, as well as no page charges under the traditional publication scheme (i.e. not open access). Submission is expected to open right after the conference and will be announced on the conference webpage (www.astro.auth.gr/~eftc17).

The social events of the conference include the welcome reception, the conference dinner and an (optional) archaeological tour.

The ***welcome reception*** will be held on the first day of the conference (Monday, 9 October, 2017), starting at 18:30. The venue for the reception will be ***Theoreion*** (depending on the day's weather), which is located at the terrace of the conference venue (The Ionic Centre).

Open to all registered delegates and registered accompanying persons

The ***conference dinner*** will take place on Wednesday, 11 October, starting at 19.30. The venue for the dinner will be ***Thissio View*** (www.thissioview.gr), a club – restaurant which is located on Apostolou Pavlou street (pedestrian walkway surrounding Acropolis).

Open to all registered delegates and registered accompanying persons

A guided ***tour*** to the ***Acropolis Hill & Acropolis Museum*** will take place on Thursday, 12 October, 2017, after the end of the conference. The tour will begin from the Ionic Centre at 15.00, and its estimated duration is 4 hrs. Tickets may be purchased at the registration desk with a cost of 50 € per person.

Located at the crossroads of three continents, and with an overall population of close to four million people, the capital of Greece has often been the melting pot of many divergent cultures. Some of humanity's most exciting ideas, as well as democracy and philosophy were born in Athens.

The heritage of the classical era is evident in the city by its ancient monuments, the most famous of all being the Parthenon on the Acropolis. The city retains a vast variety of Roman, Byzantine and Ottoman monuments, projecting the city's long history across the centuries. Landmarks of the modern era are dating back to 1830 (establishment of the independent Greek state), and taking in the Greek Parliament and the Athens Trilogy (Library, University and Academy).

Athens is probably the only place in the world where you can discover a city more than 2.500 years old integrated into a modern metropolis. If you add to this city's lively nightlife and Mediterranean cuisine, you get some idea of how many different segments of the tourism market it can cater for.

Important landmarks to visit are:

- Acropolis
- Acropolis Museum
- Odeon of Herodes Atticus
- Ancient Agora
- Panathinaikon Stadium
- National Archaeological Museum
- Byzantine and Christian Museum
- Museum of Cycladic Art
- Benaki Museum

Time: Athens is at the time zone UTC/GMT +2 hours.
Climate: Warm, sunny, light rainfall. Temperature during October 16 – 24°C.
Emergency numbers: Ambulance – 166, Fire Department – 199, Police – 100.
Health: Emergency treatment is free to all visitors in public hospitals.
Telecom: 4 operators (Cosmote, Vodafone, Wind, CYTA) on GSM network.
Service charges: In restaurants and hotels, taxis or other services, tipping is optional and customized per case depending on whether you are pleased with the service. Approximately 5% of the bill is a good guideline.
Store hours: 9:00 – 15:00 on Monday – Wednesday – Saturday, 9:00 – 21:00 on Tuesday – Thursday – Friday (all major debit/credit cards are widely accepted).

Greek Gastronomy

Greek gastronomy has recorded a history of around 4,000 years, with especial characteristics based on pure and unique quality goods produced on Greek soil. In fact, it was Archestratos who wrote the first cookbook in history (330 B.C.). In truth Greek cuisine has four secrets: good quality fresh ingredients, correct use of flavorings (herbs) and spices, the famous Greek olive oil and simplicity.
Olive oil, honey, salt and cheese may be the signature tastes one remembers after having a meal here but there are many more ways to impress your palette and satisfy your cravings. Due to the ever generous Mediterranean sea, a Greek table is almost never complete without various delicious fresh fish.

Program at a glance

Aerides room				
TIME	Monday, October 9	Tuesday,October 10	Wednesday, October 11	Thursday, October 12
08:00-08:15	08:00-16:30 Registrations	08:00-17:00 Registrations	08:00-17:00 Registrations	08:00-14:30 Registrations
08:15-08:30				
08:30-08:45	Opening and welcome			
08:45-09:00				
09:00-09:15	Tutorial (50’) A. White [I.1]	Tutorial (50’) F. Pegoraro [I.2]	Tutorial (50’) F. Zonca [I.3]	Tutorial (50’) F. I. Parra [I.4]
09:15-09:30				
09:30-09:50				
09:50-10:00	Topical (40’) A. Mishchenko [I.5]	Topical (40’) G.N. Throumoulopoulos [I.9]	Topical (40’) X. Wang [I.12]	Topical (40’) J. A. Alonso [I.15]
10:00-10:15				
10:15-10:30				
10:30-10:45	Coffee Break	Coffee Break	Coffee Break	Coffee Break
10:45-11:00				
11:00-11:10				
11:10-11:30	Topical (40’) T. Puetterich [I.6]	Topical (40’) C. J. Ham [I.10]	Topical (40’) T. Kurki - Suonio [I.13]	Topical (40’) A. Geraldini [I.16]
11:30-11:50				
11:50-12:00	Topical (40’) C. Riconda [I.7]	Topical (40’) A. Zocco [I.11]	Topical (40’) Ye. O. Kazakov [I.14]	Topical (40’) R. Jorge [I.17]
12:00-12:15				
12:15-12:30				
12:30-12:45	Lunch break	Lunch break	Lunch break	Closing Ceremony
12:45-13:00				
13:00-13:15				
13:15-13:30				
13:30-13:45				
13:45-14:00				
14:00-14:20	Contributed (20’) H. Isliker [O.1]	Contributed (20’) V. Bandaru [O.5]	Contributed (20’) Z. X. Lu [O.8]	
14:20-14:40	Contributed (20’) M. Ottaviani [O.2]	Contributed (20’) N. Ohana [O.6]	Contributed (20’) M. Held [O.9]	
14:40-15:00	Contributed (20’) E. Fable [O.3]	Contributed (20’) F. Palermo [O.7]	Contributed (20’) C. V. Atanasiu [O.10]	
15:00-15:20	Contributed (20’) C. F. Beadle [O.4]	Poster session 1 [P1.1 – P1.22]	Poster session 2 [P2.1 – P2.22]	Tour to Acropolis Hill & Acropolis Museum*
15:20-15:40	Coffe Break	Coffe Break	Coffe Break	
15:40-16:00	Topical (40’) G. J. Wilkie [I.8]	Poster session 1 (cont.)	Poster session 2 (cont.)	
16:00-16:20				
16:20-16:30				
16:30-16:45				
16:45-17:00				
17:00-17:15				
17:15-17:30				
17:30-17:45				
17:45-18:00				
18:00-18:15				
18:15-18:30				
18:30-18:45	Welcome Reception			
18:45-19:00				
19:00-19:15				
19:15-19:30				
19:30-19:45			Conference Dinner	
20:00 - late				

* Optional tour

Monday 9 October 2017

08:00 – 08:30 Registration
08:30 – 09:00 Opening and welcome

09:00 – 09:50 **[I.1]** A. White (PSFC – MIT, USA)
Comparing turbulence measurements with simulation: an experimental, multi-machine tutorial on validation of nonlinear gyrokinetic transport models
09:50 – 10:30 **[I.5]** A. Mishchenko (IPP Garching, Germany)
Pullback approach for gyrokinetic electromagnetic simulations

10:30 – 11:10 Coffee break

11:10 – 11:50 **[I.6]** T. Pütterich (IPP Garching, Germany)
Impurities in a reactor
11:50 – 12:30 **[I.7]** C. Riconda (UPMC, France)
Relativistic electron acceleration in laser plasma interaction

12:30 – 14:00 Lunch break

14:00 – 14:20 **[O.1]** H. Isliker (AU Thessaloniki, Greece)
Fractional transport in strongly turbulent plasmas
14:20 – 14:40 **[O.2]** M. Ottaviani (IRFM – CEA, France)
Fast secondary reconnection and the sawtooth crash
14:40 – 15:00 **[O.3]** E. Fable (IPP Garching, Germany)
Integrated modelling of reactor scenarios and impact of core-SOL coupling on plasma performance
15:00 – 15:20 **[O.4]** C. – F. Beadle (SPC – EPFL, Switzerland)
Simulations of SOL turbulence in a double-null magnetic configuration

15:20 – 15:40 Coffee break

15:40 – 16:20 **[I.8]** G. Wilkie (Chalmers UoT, Sweden)
First-principles modelling of fast ion transport by microturbulence

Tuesday 10 October 2017

09:00 – 09:50 **[I.2]** F. Pegoraro (Universita di Pisa, Italy)
Stability criteria of magnetohydrodynamic plasmas and their underlying Hamiltonian structures
09:50 – 10:30 **[I.9]** G. Throumoulopoulos (University of Ioannina, Greece)
On equilibrium, stability and dynamics of ITER-like plasmas

10:30 – 11:10 Coffee break

11:10 – 11:50 **[I.10]** C. Ham (Culham CFE, UK)
Theory of nonlinear ballooning modes
11:50 – 12:30 **[I.11]** A. Zocco (IPP Greifswald, Germany)
Geometric stabilization of the electrostatic ITG driven instability

12:30 – 14:00 Lunch break

14:00 – 14:20 **[O.5]** V. – K. Bandaru (IPP Garching, Germany)
Implementation of a model for the non-linear interaction between runaway electrons and background plasma
14:20 – 14:40 **[O.6]** N. Ohana (SPC – EPFL, Switzerland)
The Particle-in-Fourier (PIF) approach applied to gyrokinetic simulations
14:40 – 15:00 **[O.7]** F. Palermo (IPP Garching, Germany)
Damping and propagation of geodesic acoustic modes in gyrokinetic simulations

15:00 – 15:20 **[P1.1 – P1.22]** Poster session 1

15:20 – 15:40 Coffee break

15:40 – 17:00 **[P1.1 – P1.22]** Poster session 1 (cont.)

Wednesday 11 October 2017

09:00 – 09:50 **[I.3]** F. Zonca (ENEA Frascati, Italy)
Physics of energetic particles and Alfven waves
09:50 – 10:30 **[I.12]** X. Wang (IPP Garching, Germany)
Nonlinear dynamics of energetic particle driven Alfvenic fluctuations in fusion plasmas

10:30 – 11:10 Coffee break

11:10 – 11:50 **[I.13]** T. Kurki – Suonio (Aalto University, Finland)
Clearing the road for high-fidelity fast ion simulations in full 3D
11:50 – 12:30 **[I.14]** Ye. O. Kazakov (ERM/KMS Brussels, Belgium)
Recent advances in fast-ion generation and heating multi-ion plasmas with IC waves

12:30 – 14:00 Lunch break

14:00 – 14:20 **[O.8]** Z. X. Lu (IPP Garching, Germany)
Local and global analysis of symmetry breaking for ITG and BAE modes
14:20 – 14:40 **[O.9]** M. Held (University of Innsbruck, Austria)
Zonal flow generation by nonlinear polarization and high relative fluctuation amplitudes
14:40 – 15:00 **[O.10]** C. – V. Atanasiu (INFLPR, Romania)
Modelling of wall currents excited by plasma wall-touching kink and vertical modes during a tokamak plasma disruption with application to ITER

15:00 – 15:20 **[P2.1 – P2.22]** Poster session 2

15:20 – 15:40 Coffee break

15:40 – 17:00 **[P2.1 – P2.22]** Poster session 2 (cont.)

19:30 – 22:30 Conference dinner

Thursday 12 October 2017

09:00 – 09:50 **[I.4]** F. Parra (University of Oxford, UK)
Neoclassical and turbulent transport in stellarators
09:50 – 10:30 **[I.15]** J. A. Alonso (CIEMAT Madrid, Spain)
Zonal flow relaxation in stellarators: theory and first experimental observation

10:30 – 11:10 Coffee break

11:10 – 11:50 **[I.16]** A. Geraldini (University of Oxford, UK)
Kinetic solution of a collisionless magnetic presheath
11:50 – 12:30 **[I.17]** R. Jorge (SPC – EPFL, Switzerland)
Recent advances in fast-ion generation and heating multi-ion plasmas with IC waves

12:30 – 12:45 **Closing Ceremony**

15:00 – 19:00 Conference tour

[P1.1] I. Abel (Chalmers UoT, Sweden)
Kinetic modelling of the edge of fusion plasmas

[P1.2] E. Safi (University of Helsinki, Finland)
Plasma impurity co-bombardment effects on sputtering of Beryllium and Tungsten

[P1.3] D. Grasso (Politechnico di Torino, Italy)
ECCD magnetic island suppression as converse of a forced reconnection problem

[P1.4] A. Jayalekshmi – Chandrarajan (SPC – EPFL, Switzerland)
How non-adiabatic passing electron dynamics and density of mode rational surfaces affect turbulent transport in magnetic fusion plasmas

[P1.5] G. M. D. Hogeweij (FOM – DIFFER, Netherlands)
Separating the effects of heating and current drive on NTM evolution in TCV

[P1.6] D. Kaltsas (University of Ioannina, Greece)
Hamiltonian construction of translationally symmetric extended MHD with equilibrium applications

[P1.7] J. Parisi (University of Oxford, UK)
Extending critical balance to ITG-driven turbulence with flow shear in fusion plasmas

[P1.8] T. Fülöp (Chalmers UoT, Sweden)
Runaway dynamics in disruptions: sliding and screening

[P1.9] S. Lanthaler (SPC – EPFL, Switzerland)
Linear kinetic-MHD stability of internal modes in toroidally rotating plasmas

[P1.10] I. Calvo (CIEMAT Madrid, Spain)
Tangential magnetic drift, tangential electric field and their impact on stellarator radial neoclassical transport

[P1.11] P. Manas (IPP Garching, Germany)
Energy confinement in He and D plasmas: on the role of central electron heating

[P1.12] A. Papadopoulos (NTU Athens, Greece)
Propagation of radio frequency waves through spatially modulated interfaces in the plasma edge in tokamaks

[P1.13] A. Cardinali (ENEA Frascati, Italy)
Semi-analytical inspection of the quasi-linear absorption of RF in presence of alpha-particles in tokamak reactor

[P1.14] A. Kleiner (SPC – EPFL, Switzerland)
Ideal saturated 3D external kink structures in quiescent H mode plasmas

[P1.15] A. Evangelias (University of Ioannina, Greece)
Analytic anisotropic-pressure equilibria with incompressible flow in helically symmetric geometry

[P1.16] E. Lanti (SPC – EPFL, Switzerland)
An improved hybrid electron model for global gyrokinetic simulations using the ORB5 PIC code

[P1.17] Y. Sarazin (IRFM – CEA, France)
Multi-scale issues in fusion plasmas: synergy between turbulence and neoclassical transports

[P1.18] M. – S. Anastopoulos – Tzanis (University of York, UK)
3D perturbative ideal MHD stability in tokamak plasmas

[P1.19] H. Guillard (INRIA, France)
Grid generation for fusion applications

[P1.20] V. Baran (INFLPR, Romania)
Evolving the ion temperature gradient driven turbulence with test modes

[P1.21] S. Aleiferis (FORT Heraclion, Greece)
On the gradB and ExB drifts of alphas in burning plasmas

[P1.22] D. Borgogno (Politechnico di Torino, Italy)
Test-electron analysis of magnetic reconnection topology

[P2.1] P. Xanthopoulos (IPP Greifswald, Germany)
Gyrokinetic simulation of micro-turbulence in stellarators

[P2.2] D. Brunetti (IFP – CNR, Italy)
Analytic characterisation of infernal type instabilities in tokamak as with large edge pressure gradients

[P2.3] A. Rakha (Barcelona Supercomputing Centre, Spain)
Modelling of Alfvén modes properties in TJ-II plasmas

[P2.4] S. Buller (Chalmers UoT, Sweden)
Ion composition effects on neoclassical transport in density pedestals

[P2.5] L. Vlahos (AU Thessaloniki, Greece)
On the limits of the quasilinear evolution of ions interacting with Alfven waves in a magnetised plasma

[P2.6] K. Aleynikova (IPP Greifswald, Germany)
Quantitative study of kinetic ballooning mode theory in magnetically confined toroidal plasmas

[P2.7] F. Bairaktaris (NTU Athens, Greece)
Advanced homogenization approach for a plasma dielectric mixture: Case of a turbulent tokamak

[P2.8] H. de Blank (FOM – DIFFER, Netherlands)
Electromagnetically consistent model of complete reconnection

[P2.9] I. – G. Miron (INFLPR, Romania)
Modelling the effect of RMPs on neoclassical tearing modes

[P2.10] A. Biancalani (IPP Garching, Germany)
Nonlinear GK investigation of EP driven geodesic acoustic modes

[P2.11] E. Reiter (University of Innsbruck, Austria)
Full-F gyrofluid modelling of blob-impurity interaction in the tokamak SOL

[P2.12] L. Villard (SPC – EPFL, Switzerland)
Global features of gyrokinetic simulations with sources

[P2.13] F. Widmer (IRFM – CEA, France)
Neoclassical island control with stiff temperature model

[P2.14] N. Howard (PSFC – MIT, USA)
Multi-scale gyrokinetic simulation of L and H-mode plasma conditions in the Alcator C-Mod Tokamak

[P2.15] M. Hardman (University of Oxford, UK)
Modelling coupled ion and electron scale turbulence in magnetic confinement fusion plasmas

[P2.16] S. – I. Valvis (NTU Athens, Greece)
Scattering of RF waves by cylindrical blobs in the plasma edge in tokamaks

[P2.17] K. Särkimäki (Aalto University, Finland)
Mechanics of ELM control coil induced alpha particle transport

[P2.18] S. Mijin (Imperial College, UK)
A fully implicit kinetic code for parallel electron transport in the SOL

[P2.19] P. Donnel (IRFM – CEA, France)
A multi-species collision operator for gyrokinetic codes

[P2.20] K. Hallatschek (IPP Garching, Germany)
Study of collisional effects on GAMs and zonal flows

[P2.21] P. Rodrigues (IPFN – IST, Portugal)
Local, up-down asymmetrically shaped, analytical tokamak-equilibrium model

[P2.22] C. Dritselis (University of Thessaly, Greece)
Numerical modeling of dust transport in a tokamak plasma

List of Abstracts

Abstracts of invited lectures

Abstracts of oral contributions

Abstracts of poster presentations

I.1

Comparing Turbulence Measurements with Simulations: an Experimental, Multi - Machine Tutorial on Validation of Nonlinear Gyrokinetic Transport Models

A. White

Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Tokamaks and stellarators are used to confine and control plasmas for fusion energy research. Understanding heat, particle and momentum transport and the development of validated predictive transport models is critical for ITER operations and for design of other burning plasma devices. Validation of transport models, and especially of nonlinear gyrokinetic simulations, requires close coupling between experiment, computation, and theory. Recent advances in measurement capabilities at ASDEX Upgrade, C - Mod, DIII-D, JET, MAST, NSTX, TCV, W7-X and other fusion devices around the world, have opened the door to unprecedented, highly detailed, comparisons between experiments and nonlinear gyrokinetic simulations. This talk will explore the distinction between "comparing measurements to a simulation" and "validating a transport model". Synthetic diagnostics, models that mimic the spatial (or wavenumber) response of the turbulence measurements [1] and new international thrusts toward predictive experimental design [2] using nonlinear gyrokinetic simulations will be discussed, along with the role of reduced models (e.g. QuaLiKiz and TGLF) and prospects for machine - learning methods [3]. Open questions regarding multi-scale turbulence physics [4,5,6] and the challenges surrounding validation of nonlinear multi-scale gyrokinetic simulations will be assessed. Overall, this tutorial talk will explore both the history and present state of "comparison" and "validation" activities, from an experimental and cross-machine perspective.

References

[1] C. Holland et al. Implementation and application of two synthetic diagnostics for validating simulations of core tokamak turbulence, Phys. Plasmas, 16, 052301 (2009)
[2] S. Freethy et al. "The role of theoretical predictions in the design of correlation ECE and nT - phase diagnostics", invited talk, 21st EU - US Transport Task Force Meeting, Leysin, 5-8 September 2016
[3] J. Citrin et al. "Circumventing the conflicting constraints of speed and accuracy for tokamak turbulence modeling", invited talk, 21st EU-US Transport Task Force Meeting, Leysin, 5-8 September 2016
[4] T. Goerler and F. Jenko "Scale Separation between Electron and Ion Thermal Transport" Phys. Rev. Lett. 100, 185002 (2008)
[5] N. T. Howard et al. "Synergistic cross-scale coupling of turbulence in a tokamak plasma" Physics of Plasmas 21, 112510 (2016)
[6] S. Maeyama et al. "Cross - Scale Interactions between Electron and Ion Scale Turbulence in a Tokamak Plasma" Phys. Rev. Lett. 114, 255002 (2015)

I.2

Stability criteria of magnetohydrodynamic plasmas and their underlying Hamiltonian structure

F. Pegoraro[1], T. Andreussi[2], and P. J. Morrison[3]

[1]Physics Department, University of Pisa, Pisa, Italy
[2]Space Propulsion Division, Sitael S.p.A., Pisa, Italy
[3]Institute for Fusion Studies and Department of Physics, The University of Texas at Austin, Austin, TX 78712-1060, USA

Stability conditions of magnetized plasma flows are described by exploiting the Hamiltonian structure of the ideal magnetohydrodynamics equations using three kinds of energy principles that differ from each other being formulated either in Eulerian or Lagrangian variables and, most importantly because they impose different physical constraints on the allowed perturbations.

Specific features of the stability analysis are underlined and in particular:

1. the use of the time-dependent variable relabeling for equilibria with flows described in terms of Lagrangian variables, and
2. the relationship between the different classes of allowed perturbations and their implications on the stability conditions.

Two applications are presented: stratified convection and rotating pinch equilibrium configurations. The former example emphasizes the role played by entropy while the later demonstrates the utility of the relabeling transformation.

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I.3

Physics of Energetic Particles and Alfvén Waves

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Hydromagnetic Alfvén waves are fundamental low-frequency electromagnetic oscillations in magnetized plasmas, which are found to be prevalent in nature and laboratory. For example, they are often found to be excited by energetic charged particles in space and fusion plasmas.

Due to their lower frequency and near incompressibility, shear Alfvén waves are generally easier to be excited than compressional Alfvén waves. Furthermore, due to their anisotropic nature, the linear wave propagation and dispersiveness of shear Alfvén waves are affected by plasma nonuniformities and magnetic field geometries, such as the existence of continuous spectrum, spectral gaps, and discrete eigenmodes in toroidal plasmas.

This work reviews linear as well as nonlinear physics of shear Alfvén waves and their self-consistent interaction with energetic particles in toroidal fusion devices. More specifically, the linear analysis focuses on wave spectral properties and collective excitations by energetic particles via wave-particle resonances. Meanwhile, the nonlinear physics deals with nonlinear wave-wave interactions as well as nonlinear wave-energetic particle interactions. These topics are presented within a single unified theoretical framework [1], where experimental observations and numerical simulation results are referred to elucidate concepts and physics processes [2].

Work in collaboration with Liu Chen[2], Zhiyong Qiu[2] and the NLED Team [2].
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I.4

Neoclassical and turbulent transport in stellarators

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Due to the lack of a symmetry direction in stellarators, it is not necessary to drive current in the plasma to achieve a stable MHD equilibrium. Thus, stellarators do not need costly current-drive systems and do not suffer from current-driven instabilities. These advantages come at a cost: expensive magnets, islands at rational flux surfaces, large energetic particle losses, large neoclassical transport... Of all the aspects of active research in stellarators, this talk will focus on the transport of thermal particles (both neoclassical and turbulent).

First, we will consider the neoclassical transport of particles, energy and momentum in the low collisionality regime relevant in the core of stellarators. In an unoptimized stellarator, there are direct orbit losses and understanding confinement requires a global treatment. However, when stellarators are sufficiently optimized [1], orbit losses are minimized, and neoclassical transport can be treated as a radially local problem [2,3]. We will emphasize that the problem takes a very simple form when expressed in terms of the map of the second adiabatic invariant. Surprisingly, neoclassical fluxes are well above the gyroBohm level and larger than turbulent fluxes. We will describe the processes that lead to this large neoclassical fluxes, making connections with tokamaks with ripple [3].

After discussing neoclassical transport, we will consider the most recent efforts to model turbulent transport in stellarators. We will emphasize the fundamental differences between tokamak and stellarator turbulence: the complicated zonal flow response of stellarators [4] and the problems of the flux tube treatment in systems without symmetry [5,6].

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I.5

Pullback approach for gyrokinetic electromagnetic simulations

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Recently, the pullback approach has been suggested for gyrokinetic electromagnetic simulations [1]. It has been verified in global tokamak and stellarator particle-in-cell simulations, where various kinds of Alfvenic instabilities have been considered. It has been found that the pullback scheme is a very powerful mitigation technique for the so-called cancellation problem appearing in the conventional formulation of the gyrokinetic theory. The mixed-variable formulation of the gyrokinetic theory [2] used in the pullback approach is tailored in such a way that the cancellation problem is minimised through the choice of the phase-space coordinates. Recently, the pullback scheme has been further developed to be applicable for fully-nonlinear simulations [3] and to include collisions into the electromagnetic simulations. A consistent field-theoretical formulation of the mixed-variable gyrokinetics using a variational principle based on the phase-space Lagrangian has been developed. This formulation provides explicit expressions for the energy and momentum conservation laws appearing as Noether's invariants of the theory.

In my talk, I will briefly review the cancellation problem and the conventional mitigation techniques. I will describe the mixed-variable formulation of the gyrokinetic theory and introduce the pullback mitigation scheme. Finally, I will present the state of the art of our work on this subject.

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I.6

Impurities in a Reactor

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In a future fusion reactor the occurrence of plasma impurities pose a challenge as they lead to dilution and increased energy losses via radiation. However, for power exhaust the impurity radiation including that in the main plasma may be a crucial ingredient. The fact that impurities may be beneficial and detrimental for the plasma implies that in a reactor a compromise needs to be found.

In order to evaluate the appropriate impurity level, an important ingredient is a set of high quality atomic data, which can be used to evaluate the cooling efficiency, i.e. the cooling factor L_Z, of an impurity. For the present work, a unique set of cooling factors for 35 elements from hydrogen (Z = 1) to bismuth (Z = 83) was available. All data has been calculated using the same codes and approximations for all elements. On these grounds the ensemble may be labelled 'consistent'.

Using these data, the optimal impurity level is evaluated with four reactor models varying in complexity. The simplest model is a 0D power balance and is quickly applicable to all sorts of fusion reactors. The most complex model is focusing on the EU DEMO1 2015 design. The comparison between the models yields insights into the effect of various simplifications and demonstrates the following:

- The consideration of plasma profiles instead of a 0D model (Lawson criterion) always reduces the concentration of the optimal impurity level.
- The radial profiles of impurities and electrons including the divertor compression are sensitively influencing the operational window of a reactor.
- Low-Z impurities - intrinsic or seeded - should be avoided because the related dilution is significantly diminishing the performance of a power plant.
- For core temperatures above 20 keV, the cooling factors of high-Z radiators support optimized power exhaust at good core performance.
- The transport and confinement of helium may reduce the fusion yield of a reactor plasma and requires attention.

Following the discussion of the above models, modifications of the operational window due to impurity transport are discussed. For comparison, experimental findings on impurity transport in today's fusion experiments are extrapolated to a reactor plasma.

I.7

Relativistic electron acceleration in laser plasma interaction

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The availability for the scientific community of compact sources of intense, high-power, ultrashort laser pulses, allowed a rapid growth of studies on laser driven electron accelerators. Different laser plasma acceleration mechanisms have been explored. A by now well know scheme involves the generation of huge acceleration gradients, up to 10 to 100 GV/m, due to the propagation of a TW-class laser pulse in a diluted plasma. GeV scale and very short duration (some fs) electron beams produced in this way are a natural candidate as drivers for a free-electron laser or to be coupled into undulators to produce radiation in the visible and X-ray domain.

In this talk we present an alternative approach: the generation of fast electron beams in relativistic laser-solid interaction. The studies in this domain are mainly stimulated by the possibility of having higher electron currents due to the high density. In laser-solid interaction the energy coupling between the laser beam and the target is mainly localized at the surface and the coupling efficiency needs to be optimized in order to get an energetic electron distribution. One way is to use properly-structured targets whose surface characteristics match with the laser parameters, so that surface plasma waves are excited [1].

As will be discussed, the surface plasma wave excitation on solid grating target enhances drastically the laser absorption in ultra-high intensity interaction regime ($I\lambda^2 > 1018\ \mathrm{Wcm^{-2}\mu m^2}$) and generates large currents of relativistic electrons. Theoretical, numerical (via the Particle-in-Cell method) and experimental studies of fast electron generation will be presented. Recently, a simple scaling for the conversion of surface wave field energy into electrons kinetic energy has been identified by our group by considering the interaction of test electrons with the evanescent high frequency field of a surface wave [2]. We were able to show that the most energetic relativistic electrons are accelerated parallel to the plasma-vacuum interface to velocities larger than the wave phase velocity. These results have been confirmed by Particle-in-Cell simulation and experiments [3].

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I.8

First-principles modelling of fast-ion transport by microturbulence

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Electrostatic microturbulence is a ubiquitous and deleterious phenomenon in every current and hypothesised fusion device. However, its effects upon energetic particles have previously been thought to be small. We have recently developed an efficient method of studying these effects by post-processing local nonlinear gyrokinetic simulations. Through these analyses, we have discovered a profound effect of turbulence on the energetic particle distribution function. This affects both the plasma heating profile and the stability of Alfven eigenmodes, which are sensitive to the phase space distribution of fast particles. These are both key issues for ITER.

Our result relies upon the passive-tracer approximation. The dominant departure from the passive approximation is through dilution of the main ions by adiabatic energetic particles. We thus developed a theoretically-motivated prescription to successfully model this effect. This was benchmarked by performing full nonlinear simulations including the energetic species. We found it to be valid up to an energetic particle concentration of 20%, easily including the parameter regime of both ITER and future reactors. In order to provide a heuristic tool for quickly estimating these turbulent effects, we performed detailed analysis of our results. We show that we can, in fact, characterise the effect of turbulence on the energetic species through one dimensionless parameter. This allows an order-of-magnitude estimate to be made prior to performing any detailed calculations. Unifying all of these results, a model distribution function, which takes turbulence-induced corrections into ac- count, will also be presented. We conclude with a brief application of this to the differing behaviours of NBI- and ICRH-generated energetic particles in current experiments.

I.9

On equilibrium, stability and dynamics of ITER-like plasmas

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Research results of the local Plasma Physics group and external collaborators on ITER pertinent Physics will be presented. The presentation will consist of three parts. The first one will concern the construction of equilibria with sheared flow of arbitrary direction, in connection with transitions to advanced confinement modes in tokamaks, as solutions of a generalized Grad-Shafranov equation and

the extension of the HELENA equilibrium code for flows parallel to the magnetic field. In the second part the linear stability of equilibria with parallel flows will be examined and potential methods of stabilization of the resistive wall mode will be discussed. Finally, the third part will refer to the development of a multifluid code describing the dynamics of a burning plasma with first applications to JET and ITER-like plasmas.

I.10

Theory of Nonlinear Ballooning Modes

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It is important to develop and control plasma scenarios which maximize the confined pressure in tokamak plasmas as these reduce the size and cost of a potential power plant. Instabilities limit the pressure in tokamak plasmas. This limit can be a hard, disruptive, limit or a soft limit which may result in a critical pressure profile. It is well known that transport barriers allow tokamaks to achieve much higher fusion performance but they have the disadvantage of hard, nonlinear ballooning, instabilities: such as the ELM for the edge transport barrier [1], and high plasma beta related disruptions for internal transport barriers, as seen experimentally in TFTR [2] or numerically in nonlinear MHD calculations [3]. An improved understanding of nonlinear ballooning stability will help us design configurations that have a soft limit, for example by staying below the critical pressure gradient for nonlinear stability. It may also explain experimental observations of ELMs and high plasma beta related disruptions on TFTR [2].

We review nonlinear ballooning theory and the MHD modelling of nonlinear ballooning modes, e.g. [3]. We then describe recent analytic work [4] on the nonlinear stability of a large aspect ratio tokamak plasma to finite ballooning displacements of thin elliptical magnetic flux tubes in the presence of a large pressure gradient region i.e. a transport barrier. We use a generalized form of Archimedes' principle to derive a differential equation which models the dynamics of such an ideal MHD flux tube. We solve this equation to find the equilibrium states of these flux tubes and calculate the energy of these equilibria. Above a critical pressure the energy stored in a tokamak plasma may be lowered by finite displacements of such tubes but not by infinitesimal displacements – i.e. they are metastable. Above a higher critical pressure such tubes become unstable to linear and nonlinear displacements. The distance the flux tubes are displaced in these states can be as large as the pressure gradient scale length. Triggering eruptions into these lower energy states leads to explosive dynamics, as seen in ELMs. We discuss how plasma transport is enhanced by displaced flux tubes and how this results in rapid loss of confinement. We describe a scan of pressure gradient and magnetic shear profiles looking at nonlinear stability, and, finally, how this work is extended to experimental tokamak geometries.

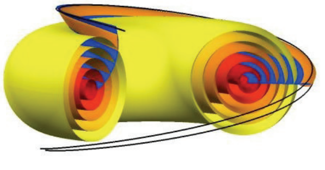

Figure 1: *Elliptical (orange) flux tube with $r \sim \delta_2 \gg S \sim \delta_1$ sliding along (blue) surface $S = 0$ parting surrounding (black) field lines. Note the tube's displacement is larger on the large R part of the flux surfaces – the tube balloons. The magnetic shear ($s = rq'/q$) causes the twist and narrowing of the tube on the inside.*

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I.11

Geometric stabilization of the electrostatic ion-temperature-gradient driven instability

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The effects of a non-axisymmetric (3D) equilibrium magnetic field on the linear ion temperature-gradient (ITG) driven mode are investigated. We study the strongly driven, toroidal branch of the instability in a global (on the magnetic surface) setting. Non-axisymmetry is included explicitly via the dependence of the magnetic drift on the field line label, i.e. across the magnetic field, but within the magnetic flux surface. We consider the limit where this variation occurs on a scale much larger than that of the ITG mode, and also the case where these scales are similar. Close to axisymmetry [1], we find that an averaging effect of the magnetic drift on the flux surface causes global (on the surface) stabilization, as compared to the most unstable local mode. In the absence of scale separation, we find destabilization is also possible, but only if a particular resonance occurs between the magnetic drift and the mode, and finite Larmor radius effects are neglected. We discuss the relative importance of surface global effects and known radially global effects. Far from axisymmetry, a non-perturbative analysis is introduced. Surface-global effects are described by using a matrix formalism that couples local eigenvalue problems via a lattice equation. It is found that finite Larmor radius effects can suppress the global (on the surface) instability and shift its poloidal location from the position of the greatest local instability, in accordance with numerical global (on the surface) simulations [2]. Spectra of the unstable global eigenfunction whose width grows for increasingly non-axisymmetric systems are predicted and observed numerically. The application of the lattice matrix formalism to other instabilities that require flux-tube coupling is also discussed.

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I.12

Nonlinear dynamics of energetic particle driven Alfvénic fluctuations in fusion plasmas

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Understanding the properties of EP confinement largely depends on the insights into Alfvén mode dynamics, regarding both the linear stability properties and the nonlinear dynamics. The latter one have recently attracted significant interests both on theoretical and numerical analysis sides. In general, the nonlinear dynamics of Alfvén eigenmodes (AEs) can be classified into two major categories: mode-mode coupling and nonlinear wave-particle interactions. Although the former can play a crucial role in multi-scale dynamics of burning plasmas, we will focus, in the current talk, on the latter category, motivated by the relevance of the resonant drive on the Alfvénic fluctuation spectrum in fusion devices.

In our work, the nonlinear dynamics are investigated by means of the nonlinear hybrid magnetohydrodynamics gyrokinetic code (XHMGC) [1,2] with emphasis on beta induced Alfvén eigenmodes (BAE) and energetic particle modes (EPM). A detailed analysis of resonant interactions between the mode and particles is performed by using phase space numerical diagnostics based on the Hamiltonian mapping [3].

First, saturation mechanism for a single-toroidal-mode-number-gap mode due to resonance detuning and/or radial decoupling are discussed [4,5,6]. We show that the radial width of the single poloidal harmonic sets an upper limit to the radial displacement of resonant particles produced by a single toroidal number gap mode in the large n limit, irrespectively of the possible existence of a large global mode structure formed by many harmonics.

Then, multi modes simulations, retaining only wave-particle nonlinearities, are performed to investigate the synergic effect of different toroidal mode numbers on fast-ion transport. Last, chirping-frequency EPMs are investigated [7]: it shows that, for specific resonant particles, a radial displacement larger than both linear-phase mode and resonance widths is possible, but this does not necessarily imply a large fast-ion density flattening.

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

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I.13

Clearing the road for high-fidelity fast ion simulations in full 3D

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High-energy ions, such as fusion alphas and ions from NNBI, can be very sensitive to any nonaxisymmetric features in the confining magnetic field due to their collisionless nature. Such nonaxisymmetries can be introduced externally by coils (ELM mitigation) or ferritic components (TBMs and ferritic inserts), and internally by various MHD modes. Since understanding the confinement properties of these ions is crucial for ITER and beyond, it is of ultimate importance that the predictive simulations are free of numerical distortions. Such can be produced by artificial features in the magnetic background and/or inaccuracies in the particle following. In this contribution we discuss both of these error sources and present some results on 3D effects.

When calculating the magnetic field, the contribution from discrete coils can be obtained very accurately using the Ampere's law. An approximate 3D field is usually obtained by combining this with a 2-dimensional equilibrium. As for the ferritic components, for large machines like ITER the problem doesn't render itself to using standard FEM solvers, but a multi-step procedure had to be devised in order to obtain the total field at desired accuracy.

Another source of uncertainty comes from including the plasma response. In the vacuum approximation described above, external perturbations are exaggerated. For ITER simulations, the plasma response has been evaluated by two different methods: with the fast, linear MARS-F code, and with the non-linear resistive MHD code JOREK.

When simulating energetic ions in large devices, typically the guiding-center (GC) approach is used. However, for high-energy ions the gyro orbits (GO) are substantial and, therefore, when calculating the power distribution on material structures, a hybrid GC-GO method has been developed. To check the validity of such simulations, complementary GO-simulations for the entire slowing-down time were carried out with somewhat surprising results: the power loads obtained with GO-following gave loads that were 25 – 50 % lower than those given by hybrid simulations. The validity of the guiding-center approach in non-axisymmetric magnetic fields thus calls for re-examination.

ASCOT simulations have been carried out not only for ITER and DEMO, but also for both regular-NBI and NNBI for JT-60SA, the device that will be paving the way for successful operation of ITER. With plasma response, none of the known 3D effects is found to jeopardize the fast ion confinement in these devices. The simulations address also the observed differences between GC and GO simulations. In the end, based on the simulation results, the role of the device size for the 3D effects is discussed.

I.14

Recent advances in fast-ion generation and heating multi-ion plasmas with ion cyclotron waves

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**See X. Litaudon et al., "Overview of the JET results in support to ITER", Nucl. Fusion 57,102001 (2017)*

Plasma heating with waves in the ion cyclotron range of frequencies (ICRF) is a powerful method to increase temperatures in magnetic fusion devices. A new technique of resonant wave absorption in multi-ion plasmas was recently theoretically predicted [1] and later successfully confirmed in dedicated experiments on Alcator C-Mod and JET tokamaks [2]. One of the unique features of the so-called 'three-ion' minority ICRF scenarios is the possibility to reduce the concentration of resonant ions, which absorb RF power, to the level of a few per mille (‰), if needed. As a result, the absorbed RF power per resonant ion is increased and an effective acceleration of minority ions to high energies is possible. In this work, we discuss the physics behind three-ion ICRF scenarios and explain how the plasma composition has to be chosen to observe this phenomenon. Theoretical and modelling results will be supported with illustrations of the experimental observations.

We also outline the application of three-ion scenarios for the experimental programmes of W7-X and ITER. W7-X requires a source of energetic ions to validate the predicted improvement of fast-ion confinement at high β. Energetic ^{3}He ions can be generated in high-density H plasmas of W7-X, which also naturally include ^{12}C and ^{16}O impurities. Three-ion scenarios are also relevant for the non-activated and activated phases of ITER operation. As an example, intrinsic ^{9}Be impurities were computed to absorb efficiently RF power in D-T plasmas. This method was proposed for heating bulk D and T ions in ITER [3].

Finally, we discuss the synergetic ICRH+NBI heating scenario, which was recently developed and successfully tested on JET as a part of isotope mixture studies in summer 2016 [4]. This method was shown to be very effective in heating H plasmas, including a small amount of D ions. The role of D-NBI system is to provide a seed of fast ions, which can absorb RF power in the vicinity of the mode conversion layer in H-D plasmas through the Doppler-shifted cyclotron resonance $\omega = \omega_{cD} + k_{||}v_{||}$. In agreement with theoretical predictions, acceleration of D-beam ions to high energies $E_D > 0.5$MeV was confirmed by neutron spectroscopy and gamma-ray measurements.

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I.15

Zonal flow relaxation in stellarators: theory and first experimental observation

J. A. Alonso[1], I. Calvo[1], E. Sánchez[1], J. L. Velasco[1], S. Perfilov[2], P. Monreal[1], F. I. Parra[3,4], and the TJ-II team

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Turbulence simulations in both tokamaks and stellarators show that the formation of zonal flows (i.e. flows due to radially localised electrostatic potential perturbations that are constant on flux surfaces) is an ubiquitous non-linear saturation mechanism with favourable transport regulation effects [1]. These electrostatic potential structures are robustly generated by drift-wave turbulence, yet their saturated level and their effectiveness in regulating transport depends on the damping they undergo in the toroidal magnetic surfaces. The collisionless relaxation mechanisms, associated to neoclassical polarisation currents or the finite radial excursions of the particle orbits, were first studied in tokamaks by Rosenbluth and Hinton in [2]. Their results showed that zonal structures are not completely damped in axisymmetric systems and highlighted the importance of properly modelling, via kinetic theory, this damping in turbulence codes to obtain meaningful non-linear energy fluxes. The kinetic treatment of the problem of the collisionless, linear relaxation of an initial zonal electrostatic perturbation has become a standard test of gyrokinetic codes.

During the last decade, the Rosenbluth-Hinton analysis has been extended to general three-dimensional geometry [3,4,5,6]. First, it has been found that the collisionless relaxation of long-wavelength zonal perturbations has a stronger damping at infinite time (or lower residual level) compared to tokamaks. Second, the relaxation exhibits a low frequency oscillation as a specific feature of stellarator geometry. The characteristics of this oscillation, besides arguably more relevant for turbulence regulation, lend themselves to more straightforward experimental approaches. Recently, pellet injection experiments in the TJ-II stellarator have shown that the sudden perturbation of the distribution functions caused by the injection triggers a transient evolution of the zonal electrostatic potential with the oscillation predicted by kinetic theory [7]. This constitutes the first experimental observation of the basic zonal flow damping mechanisms.

In this talk we will review the basic theory of the collisionless relaxation of zonal electrostatic perturbations, as well as these pioneering experiments, and will discuss their implications and prospects for further research.

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I.16

Kinetic solution of a collisionless magnetic presheath

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Magnetic presheaths, first studied by Chodura [1] are boundary layers present in the edge region of a tokamak, where the Scrape-Off Layer (SOL) plasma reaches the divertor or limiter target. They are present if the magnetic field impinges with an oblique angle a on the target surface. In that case, there
is a small region of size a typical ion Larmor orbit ρ_i in which ions may intersect the wall during an orbit. The physics of this region is crucial for determining boundary conditions to impose on SOL plasmas at the wall [2].

We develop a gyrokinetic model of the magnetic presheath of a typical magnetic fusion device, in which the magnetic field is at grazing incidence with the wall, $a \sim 0.1 << 1$ [3]. Across the magnetic presheath, the electrostatic potential drop is so large that ion orbits are distorted. In addition to large gradients normal to the wall, our ordering allows weak turbulent gradients parallel to the wall. These gradients are due to the presence in the SOL of turbulent structures, which are elongated along the magnetic field and have a characteristic size across the field $l = \rho_i / d \sim 10$ mm $>> \rho_i \sim 1$ mm, where $d \sim 0.1 << 1$ is another small parameter. We use $a \sim d << 1$ to solve the ion equations of motion perturbatively. Exploiting the solutions to the phase space trajectories of the ions [4], we find that the ion distribution function is independent of the gyrophase angle of the orbit and we derive the lowest order ion gyrokinetic equation, which has a simple solution in a collisionless magnetic presheath. The density of ions in closed orbits is obtained by numerically integrating the ion distribution function in velocity space.

We further demonstrate that an additional piece of the ion density is required in order to solve correctly for the magnetic presheath potential and density profiles. This piece is the density of ion orbits whose trajectory intersects the wall over a gyroperiod. We derive an equation for the lowest order density of such open orbits. Assuming adiabatic electrons, which is justified provided $a >> \sqrt{m_e/m_i} \sim 0.02$ radians, the electron density is known. Because the Debye length is small, $\lambda_D \sim 0.02$ mm $<< \rho_i$, the quasineutrality equation can be used to solve for the electrostatic potential. Using our model, we obtain numerical results for the density and electrostatic potential profiles in a collisionless magnetic presheath with no turbulent gradients parallel to the wall. The results obtained from our model provide boundary conditions for gyrokinetic codes of the SOL.

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I.17

An analytical model for scrape-off layer plasma dynamics at arbitrary collisionality

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The lack of an appropriate model to describe the plasma dynamics in the tokamak scrape-off layer (SOL) has undermined our ability to reliably predict the heat flux to the vessel wall of future fusion devices, one of the most important issues on the way to fusion energy. Because of large fluctuations, the plasma properties in the SOL vary significantly, resulting in an extremely large range of collisionality values. Commonly used SOL descriptions are based on a fluid Braginskii-like description, which is valid only at high collisionalities; gyrofluid and gyrokinetic SOL models are also used, but these rely on linearised collision operators, which cannot be justified for the SOL, where deviations from a thermal distribution function might be large.

We have recently developed a drift-kinetic analytical model for SOL plasmas that overcomes the limitations of fluid and kinetic models. Our model is based on a full-f approach, and employs a full Coulomb collision operator. By porting the Coulomb collision operator from pitch angle to a guiding center coordinate system, a moment hierarchy is obtained. This allows the inclusion of kinetic effects while retaining a correct description of collisional effects. By separating between parallel and perpendicular directions, the model is suitable for being implemented in a turbulence code. In fact, it can exploit the large difference present between the parallel and perpendicular scale lengths, allowing therefore the use of coarse numerical grid in the direction of the magnetic field.

The newly-developed model has been analysed in the large collisionality limit, and shown to retrieve, and improve, the widely-used drift-reduced Braginskii equations. The linearized version has also been studied and shown to capture well known collisional and collisionless modes. Finally, the derivation of the present model illustrates how a fully gyrokinetic model for the SOL might be obtained.

O.1

Fractional Transport in Strongly Turbulent Plasmas

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We analyze statistically the energization of particles in a large-scale environment of strong turbulence that is fragmented into a large number of distributed current filaments. The turbulent environment is generated through strongly perturbed, 3D, resistive MHD simulations, and it emerges naturally from the nonlinear evolution, without a specific reconnection geometry being set up. Based on test-particle simulations, we estimate the transport coefficients in energy space for use in the classical Fokker-Planck (FP) equation, and we show that the latter fails to reproduce the simulation results. The reason is that transport in energy space is highly anomalous (strange), the particles perform Levy flights, and the energy distributions show extended power-law tails. Newly then, we motivate the use and derive the specific form of a fractional transport equation (FTE), we determine its parameters and the order of the fractional derivatives from the simulation data, and we show that the FTE is able to reproduce the high energy part of the simulation data very well. The procedure for determining the FTE parameters also makes clear that it is the analysis of the simulation data that allows to make the decision whether a classical FP or a FTE is appropriate.

O.2

Fast secondary reconnection and the sawtooth crash

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The sawtooth cycle is an almost periodic oscillation of temperature in a tokamak plasma, characterized by a slow growth and a fast collapse [1]. The internal kink mode instability is typically considered an ingredient of this cycle, although in resistive MHD theory its growth rate is found too slow to account for the observed fast sawtooth collapse, especially in weakly collisional plasmas. For these reasons, non-collisional effects are usually called for to explain experimental observations [2].

In this work, we approach this problem from a different point of view, by performing an analysis of secondary reconnecting instabilities in thin current sheets with both resistive and electron inertia effects. We show that when the current sheet is generated by a primary instability of the internal kink type (large Δ′ regime), reconnection proceeds thanks to a secondary tearing-mode developing on a time scale much shorter than the primary instability characteristic time. By applying these results to the purely resistive reconnection regime, we obtain estimates in agreement with the numerical results obtained by Yu et al. [3] for the nonlinear dynamics of the internal kink instability in a cylindrical tokamak.

By extending the analysis to include electron inertia terms, we find that non-collisional physics becomes important for the sawtooth crash when the Lundquist number exceeds a value which scales like $S\sim(R/d^e)^{12/5}$ in terms of the tokamak major radius R and of the electron skin depth d^e. This value is commonly achieved in present day devices. By comparison, the criterion for the transition to the collisionless regime of the internal kink is $S\sim(R/d^e)^3$, hard to achieve except in JET. As collisionality is further reduced, the characteristic rate increases, approaching Alfvénic values when the primary instability approaches the collisionless regime. One finds that the overall minimum normalized growth rate of the secondary instability scales like $g\sim(d^e/R)^{2/5}$, corresponding to a crash time in the tens of microseconds range as observed in experiments. One can conclude that taking into account secondary instabilities in the sawtooth mechanism provides an explanation of both fast crashes and of their broad range of occurrence in experimental devices [4]. Further results of the ongoing work aimed to assess the above picture with numerical simulations will also be presented at the conference.

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O.3

Integrated modeling of tokamak reactor scenarios and impact of core-SOL coupling on plasma performance

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To design a tokamak reactor scenario, including optimization and external plant elements down to the electrical output, a key ingredient is the plasma performance. The core and the edge of the plasma act together in a highly non-linear way to dictate the final fusion output and the received divertor heat loads.

Integrated modeling is thus required to get the full performance of the plasma, including divertor protection requirements. Of the latter, the most basics are: divertor temperature below the W (or say metal coating) sputtering limit, and divertor heat fluxes below the melting limit. The detached regime is the most favorable to get these conditions, and it is thus used as a "constraint" in searching for the design parameters. It is also mandatory to use 1D transport codes since 0D core scalings are often leading to unrealistic values of some parameters.

In the present work, 1D transport code ASTRA [1], coupled to a newly developed SOL model [2] is used to perform parameter scans in major radius R, magnetic field B_T, safety factor q, aspect ratio A, and confinement quality H(Iter 98y,2) to find where the plasma performance is maximized in terms of net production of electrical power (assuming some thermal/wall-plug efficiencies). Several constraints are also imposed on each scan point, including separatrix power above L-H threshold, divertor protection, and some assumptions on MHD limits ($\beta_N < 3\text{-}4$, $q_{95} > 3$).

The main result of this work is to show that the curves of constant net electrical power in the R-B_T plane are closed and have a well-defined shape determined by the plasma core/edge physics [3]. Other collateral implications for the choice of machine parameters are discussed, with the focus on the physics more than the engineering aspect.

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O.4

Simulations of SOL turbulence in a double-null magnetic configuration

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Different magnetic geometries are being considered for handling the power exhaust in DEMO, among which is the double-null. In addition to doubling the exhaust area, experiments have found stark differences in the SOL on the HFS and LFS in this configuration [1], allowing the possibility of efficient heating from the HFS in addition to doubling the exhaust area. The contrast between the LFS and HFS calls for theoretical investigation. In fact, the asymmetry can help to disentangle the different driving mechanisms of the turbulence.

Since the temperature in the SOL is relatively low, the plasma is sufficiently collisional for a fluid model, such as the drift-reduced Braginskii, to be used. This model has been implemented in the GBS code [2,3]. Focusing on limited geometries, the SOL width – a crucial quantity to determine the heat load on the plasma facing components – was estimated by identifying the driving linear instability and turbulence saturation mechanism [4]. The analytical and simulation results were validated against a large number of experiments, showing good agreement [5].

Recently, a non-field aligned coordinate system has been implemented in GBS. This avoids the coordinate singularity present for field-aligned coordinates at the X-point, thus allowing any toroidally symmetric magnetic field configuration to be simulated. We will introduce GBS, discuss the implementation of the new coordinate system and show results of the first simulations in a double-null magnetic configuration. We will present the first insights on the nature of SOL turbulence and the SOL width on the HFS and LFS.

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O.5

Implementation of a model for the non-linear interaction between runaway electrons and background plasma

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Disruptions in tokamaks are caused by large scale instabilities, that eventually lead to the loss of plasma confinement. During a disruption, the plasma cools down significantly over a short timescale, leading to the generation of a large electric field along the toroidal direction. This leads to the free acceleration of electrons to relativistic speeds, giving rise to a significant runaway electron (RE) current. Understanding the dynamics of runways interacting with the disruption is essential to enable robust disruption mitigation strategies for reactor size tokamaks like ITER.

The goal of this work is the numerical simulation of the non-linear effects of runaway electron currents in the course of a disruption. This is done by extending the non-linear MHD code JOREK [1,2]. Runaway electrons are currently modelled in JOREK as a seed particle population, that evolves spatially in a passive manner [3]. However, in the present work, in order to include the effects of a back-reaction on the background plasma, a fluid model for runway electrons is implemented. The model describes the evolution of the runaway electrons as a fluid species interacting with the background plasma. It includes the generation of REs due to the Dreicer mechanism [4] and their subsequent growth through the secondary avalanche [5] process. A self-consistent primary generation mechanism is important, as the location of initial RE seed could determine the final profile of the current in an RE dominated plasma [6]. Preliminary results of the JOREK simulations will be presented along with first comparisons to one-dimensional runaway electron codes [7] for validation purposes.

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O.6

The Particle-In-Fourier (PIF) Approach Applied to Gyrokinetic Simulations

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A widespread method for gyrokinetic simulations relies on the discretization of distribution functions with numerical markers. The electromagnetic field is typically represented on a grid by finite differences or finite elements (Particle-In-Cell, PIC). When simulating large-sized systems, this method encounters performance losses, both locally (intra-CPU) and globally (inter-CPU) because the amount of communicated data increases. Another approach, Particle-In-Fourier (PIF), takes advantage of the anisotropy of the field by representing it in Fourier space, where data is much smaller. One can scale up the system size keeping the number of particles per mode constant, and removing the subdomain decomposition, resulting in a better parallel scalability. The price to pay is the computation of transcendental functions at marker positions instead of low-order polynomials. We show that GPUs are well suited to such high arithmetic intensity.

PIF versus PIC accuracy and performance comparisons are performed. Applications to physical cases involving mode coupling of high wave numbers are shown, for which the PIF approach performs faster than the PIC.

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O.7

Damping and propagation of geodesic acoustic modes in gyrokinetic simulations

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Geodesic acoustic modes (GAMs) [1] play a fundamental role in the self-regulation of turbulence in toroidal plasmas. In fact, GAM oscillations can transfer energy from the zonal flow (ZF) to the pressure perturbation [2] and can radially propagate the ZF, with important consequences on the energy transport. Moreover, GAMs are considered to be potential key players in the dynamics of the transition from low confinement (L-mode) to I- and to H-modes.

Because of the multitude of manifestation of GAMs, several of their properties are not established or not completely understood. Although most of experiments show a radial propagation toward the edge of the tokamak device, some observations show an inward radial propagation of GAMs [3]. Moreover, the role played by temperature and density gradients needs to be elucidated. In spite of the fact that a well-grounded theoretical framework exists to formulate a complete description of GAMs, only a qualitative agreement between the experimental results and the linear theory has been obtained. Thus in the last years the research has been focused in particular on the nonlinear description.

The present work, based on a theoretical and numerical gyrokinetic analysis, reveals a fundamental effect which has been neglected so far, namely that the different GAM oscillations at different radial positions lead by phase mixing [4], to the generation of higher and higher radial spectral components, which are more effectively damped. As a consequence, neglecting this effect leads to damping rates and radial propagation speeds that are largely underestimated. Analytical calculations concerning damping [5,6] and radial propagation [7] support the numerical findings. A comparison of drive and damping rates leads to a possible explanation for the disappearance of GAMs in H-mode. The propagation direction as a function of temperature gradient and electron-to-ion temperature ratio is investigated, finding a good agreement between simulations and theory. Finally, a detailed analysis of the influence of dissipative and dispersion effects on the temporal spreading of the GAM signal allows us to provide a complete new picture of the GAM behavior.

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O.8

Local and global analysis of symmetry breaking for ITG and BAE modes

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The mode structure symmetry breaking such as flux surface averaged parallel wavenumber $\langle k_{||} \rangle$ and poloidal angle $\langle \theta \rangle$ is important for estimating the momentum transport due to its connection to the corresponding off-diagonal component [1]. It is also a key concept to demonstrate the non-perturbative effect of energetic particles on Alfvén eigenmodes and to study the interaction between low frequency Alfvén eigenmodes and thermal/energetic particles [2]. In this work, the symmetry breaking of the 2D structure of the Ion Temperature Gradient (ITG) mode and Beta-induced Alfvén Eigenmode (BAE) is studied based on local and global analysis. The Mode Structure Decomposition (MSD) approach [3] is developed with the complex envelope phase variation (θ_k) [4] and global effects taken into account. The results are compared to ORB5, GKW for ITG and XHMGC for BAE.

For the ITG problem, a theoretical method for the calculation of parallel mode structure has been developed [4,5]. It is shown that the radial symmetry breaking is intimately coupled to the parallel symmetry breaking [5]. For local simulations, in addition to the "tilting angle" ($\mathrm{Re}\{\theta_k\}$), the intensity gradient described by $\mathrm{Im}\{\theta_k\}$ affects the local eigenvalue and the symmetry breaking. "Global-oriented local simulations" are suggested where global corrections are taken into account in the local model and its importance for the study of turbulent momentum transport is discussed.

For the BAE problem, the wave-packet calculation technique for weakly coupled poloidal harmonics is proposed to demonstrate the BAE mode structure symmetry breaking, with the non-perturbative effect of the energetic particles (EPs) included. The theoretical global analysis identifies the essence of "boomerang" structures with/without asymmetric tails in poloidal plane as well as the radial and parallel symmetry breaking. The agreement between the wave-packet calculation and XHMGC is achieved. Global effects and non-perturbative EP response are important ingredients for the symmetry breaking and their effects on EP transport as well as the implications to experimental observations are discussed.

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O.9

Zonal flow generation by nonlinear polarization and high relative fluctuation amplitudes

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Zonal flows are of central importance for transport regulation in fusion plasmas [1,2]. The importance of the Reynolds stress for zonal flow generation is indisputable [1-3], but also other stresses like the Maxwell or diamagnetic stress can be significant in magnetized plasmas. Recent theoretical and experimental studies of poloidal mean flow in edge turbulence indicate that unresolved mechanisms beyond the Reynolds stress exist and that steep density gradients and large fluctuations affect the poloidal mean flow dynamics.

In this contribution we generalize the theory of poloidal ExB mean flows to nonlinear polarization and high fluctuation amplitudes. To this end, we decompose the density and electric potential of a full-F gyro-fluid model [4] with the help of a density weighted Favre average, a well-known decomposition strategy in compressible fluid dynamics, to derive the evolution equation for the density weighted poloidal mean flows. This allows us to identify novel agents in the mean flow dynamics, which become significant either for high relative density fluctuations or steep density gradients. We confirm the derived mechanism for radial advection of zonal flows (cf. Figure 1) with the help of fully nonlinear numerical simulations of drift wave-zonal flow dynamics, which are accomplished by the presented extension of the Hasegawa-Wakatani model to the full-F framework. Additionally, we show how the density weighted mean flow dynamics are distributed among the proposed actors when we vary the collisionality or initial gradient length.

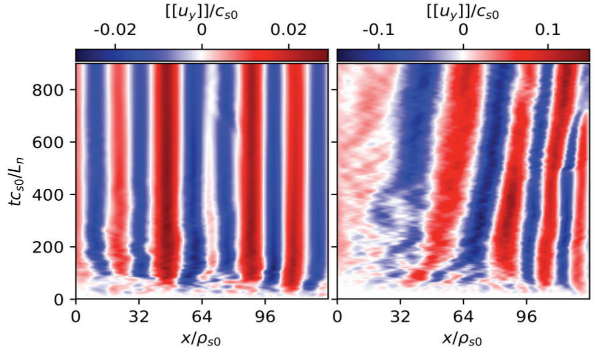

Figure 1: *The spatio-temporal zonal flow evolution of the density weighted mean poloidal velocity is shown for two different density gradient lengths. The radially outward advection of zonal flows for the four times smaller gradient length (right) is clearly visible.*

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O.10

Modelling of wall currents excited by plasma wall-touching kink and vertical modes during a tokamak disruption, with application to ITER

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To understand plasma disruptions in tokamaks and predict their effects, realistic simulations of electric current excitation in three-dimensional vessel structures by the plasma touching the walls are required. The Wall-Touching Kink Modes are frequently excited during vertical displacement events and cause large sideways forces on the vacuum vessel which are difficult to withstand in large tokamaks like ITER [1]. The amplitude and localization of the sideways force are determined by the sharing of electric current between the plasma and the wall.

The present paper describes a wall model that covers both eddy currents, excited inductively, and source/sink currents due to current sharing between the plasma and the thin conducting wall of arbitrary three-dimensional geometry [2,3]. The developed ***ssec*** code (standing for "source/sink and eddy current" code) calculates the electromagnetic wall response to perturbation of magnetic fields and to current sharing between the plasma and the wall. The code accepts the vector $\mathbf{j}_{perp}$ of values of current density entering/exiting the wall surface from the plasma at each vertex and the time derivative of the magnetic vector potential $\partial \mathbf{A}^{pl}/\partial t$ at each vertex. The third input vector is the set of space points in which ***ssec*** returns the magnetic field $\mathbf{B}^{wall}$ and its vector potential $\mathbf{A}^{wall}$ from the wall currents. The numerical results have been checked against analytical examples [2,4] and for a high-resolution mesh (16384 triangles on the wall surface) a relative accuracy of 0.001 has been found. Figure 1 presents the results of calculation of eddy and source/sink currents in the tokamak wall.

Using this approach, JOREK-STARWALL [5,6] presently limited to eddy currents, will be extended to self-consistent non-linear MHD simulations including eddy and source/sink currents.

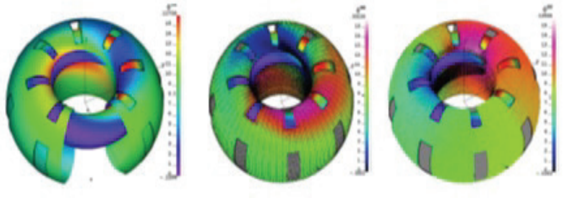

Figure 1: *Left: Wetting zone created by a vertically shifted plasma with a m/n=1/1 surface perturbation, Middle: Eddy currents excited by the plasma. Colours corresponds to their stream function, Right: Total surface current with the Sink/Source current as the dominant component.*

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P1.1

Kinetic Modelling of the Edge of Fusion Plasmas

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A hybrid fluid-kinetic framework for studying large-amplitude fluctuations in the edge of tokamak plasmas is presented. We derive equations for the behaviour of a spatially-anisotropic plasma in the presence of both large fluctuations and steep gradients. The system of equations consists of kinetic equations for electrons and ions, supplemented with fluid equations for the electromagnetic fields. In this way, it builds upon both kinetic MHD [1] and upon the use of vorticity equations in gyrokinetics [2].

This framework, by including both Alfvénic (including current-driven modes [3]) and drift wave dynamics, can handle fully nonlinear perturbations such as erupting ELM filaments and blob-based turbulence. The relationship between this framework and existing collisional edge models is made clear [4,5].

We not only present equations for such fast behaviour, but also develop higher order equations that describe pedestal equilibria and slow scrape-off-layer dynamics. The large-aspect-ratio limit of this system of equations is explored, producing simplified models of edge equilibria.

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P1.2

Plasma impurity co-bombardment effects on sputtering of Beryllium and Tungsten

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In future fusion reactor, ITER, plasma facing materials (PFMs) will consist of tungsten (W) and beryllium (Be). Ions from the plasma as well as injected noble gas impurities (argon (Ar) and neon (Ne) here) as a coolant for the plasma, will lead to sputtering of PFMs. To study the effect of plasma impurities on the erosion and surface morphology of wall materials, molecular dynamics simulations were carried out. Therefore, we modeled irradiation of both W and Be surfaces with Ar-deuterium (D) and Ne-D mixtures, varying the fraction of Ar and Ne impurities from 0 to 20 percent with impact energies of 10-100 eV at 500 and 800 K surface temperatures for W and impact energies of 30-200 eV at 400, 600 and 800 K surface temperatures for Be. In both materials, after a few hundred bombardments the sample surface was damaged and cell structures changed from crystalline to amorphous at lower ion energy and blistering-like effect was observed due to D2 accumulation in the Be cells at higher energies. In W only the noble gas impurities were responsible for surface erosion in the energy range studied here and the sputtering mechanism was in physical region. For Be at impact energies higher than 100 eV, total Be sputtering yield, in the presence of Ar and Ne impurities is around three times higher than pure deuterium irradiations. The effect of surface temperature on the results is negligible here.

P1.3

ECCD magnetic island suppression as converse of a forced reconnection problem

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The effect of ECCD is investigated as a converse of the Hahm Kulsrud Taylor (HKT) [1,2] forced reconnection problem, where the current drive plays the role of the drive force. We present analytical calculations which show the relation between the peaking value of the ECCD on the rational surface and the final island width [3]. Then the transition between the constant-ψ and non-constant-ψ regimes under the effect of a ECCD control is analyzed through highly accurate numerical simulations. It is shown that if the deposition width is below a critical value this transition occurs generating the X-point collapse and entering a plasmoid formation phase.

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P1.4

How non-adiabatic passing electron dynamics and density of mode rational surfaces affect turbulent transport in magnetic fusion plasmas

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The non-adiabatic response of passing electrons near low order Mode Rational Surfaces (MRSs) leads to fine radial structures on ion-scale microinstabilities (Ion Temperature Gradient and Trapped Electron Mode instabilities). It has been shown that these structures persist in the non-linear turbulent regime driven by these instabilities and lead to the corrugation of radial density and temperature profiles, as well as zonal flows. This effect may significantly affect the turbulent fluxes of heat and particles as was shown using both local (flux-tube) and global gyrokinetic simulations [1,2]. It is indeed well known that the shearing rate associated to zonal flows plays an important role in regulating transport levels. The generation of fine zonal flow structures centered at lowest order MRSs, which are separated by a distance $L_{LMRS} = r_0 / n_{min} q_0\, s$ (where s is the magnetic shear, n_{min} the minimum considered toroidal mode number and q_0 the safety factor at a given radial position r_0), leads to higher time averaged shearing rates at these radial positions. By varying n_{min} or the magnetic shear s one can vary L_{LMRS} and therefore the density of zonal flow shearing layers associated to lowest order MRS. Using the flux-tube version of the gyrokinetic code GENE, we show that through this mechanism, turbulent transport tends to increase with decreasing density of lowest order MRSs.

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P1.5

Separating the effects of heating and current drive on NTM evolution in TCV

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Neoclassical Tearing Modes (NTMs) are widely observed in tokamak plasmas. They have a detrimental effect on plasma confinement and may even lead to disruptions. Therefore it is important to understand the evolution of NTMs, which is influenced by several effects. These effects are summarized in the modified Rutherford Equation (MRE), see e.g. [1,2].

The birth of NTMs can be prevented, and existing NTMs can be stabilized by localized heating (H) and current drive (CD) near the location of the NTM. An important question is the relative importance of the H and CD terms in the evolution of the NTM.

The TCV tokamak is equipped with a very flexible ECRH/ECCD system [3], and is therefore very suited to address this question. In a series of dedicated experiments the m/n = 2/1 NTM was triggered by central co-ECCD using 2 gyrotrons, and then it was tried to stabilize this NTM with a third gyrotron whose deposition location was swept from the centre towards the q = 2 surface. In otherwise similar discharges, this third gyrotron was delivering either co- or counter-ECCD, or pure ECRH. In the experiment a clear difference in NTM stabilization was observed between these discharges.

The main aim of the present work is to model the evolution of the NTMs, and reproduce these different time evolutions. For this purpose the Rapid Plasma Transport simulator (RAPTOR) is used [4,5]. It has a module that solves the NTM evolution based on the MRE. RAPTOR self-consistently calculates the simultaneous evolution of electron temperature (Te) profile, q profile and NTM width. The effect of an NTM on plasma confinement is modelled by assuming an increase of the thermal diffusion coefficient over the width of the NTM; an increase by a factor of $\simeq 2$ gives a good reproduction of the observed confinement degradation.

It is shown that the triggering and suppression of the m/n = 2/1 NTM in TCV by varying the ECCD deposition and by varying the sign of the CD, can be described well by the MRE. Moreover, it is shown that the H term in the MRE is essential to fully capture the observed dynamics.

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P1.6

Hamiltonian construction of translationally symmetric extended MHD with equilibrium applications

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The noncanonical Hamiltonian structure of translationally symmetric extended MHD (XMHD) [1-3] with barotropic ion and electron fluids, is obtained by employing a method of Hamiltonian reduction [4] on the three-dimensional noncanonical Poisson bracket of XMHD [2]. The existence of the continuous spatial translation symmetry allows the introduction of the so-called poloidal representation for the magnetic field and an analogous Clebsch-like representation for the velocity field, consistent with the Helmholtz decomposition theorem. Upon employing the chain rule for functional derivatives, the 3D Poisson bracket is reduced to its translationally symmetric counterpart. Using this symmetric version of the noncanonical Poisson bracket, the families of symmetric Hall, Inertial, and extended MHD Casimir invariants are identified and used to obtain Energy-Casimir variational principles for generalized XMHD equilibrium equations with arbitrary macroscopic flows. The obtained set of equilibrium equations is cast into one of the Grad-Shafranov-Bernoulli (GSB) type. Then the following special cases of equilibria are investigated: static plasmas, equilibria with flows parallel to the axis of symmetry, and Hall MHD equilibria with finite ion flow but neglected electron inertia. The barotropic Hall MHD equilibrium equations are derived as a limiting case of the XMHD GSB system and they are consistent with those derived for axisymmetric plasmas in [5] via direct projection of the 3D equilibrium equations. In addition, we present a numerically computed equilibrium with D-shaped boundary, that plausibly shows the separation of ion flow from electron-magnetic surfaces, since in the framework of Hall MHD the magnetic field is frozen into the electron fluid.

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P1.7

Extending Critical Balance to ITG-Driven Turbulence With Flow Shear in Fusion Plasmas

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Scaling laws derived from the critical balance conjecture are substantiated with numerical results for a range of temperature gradients and flow shear. These scalings are tested using spatial and temporal correlation analysis. In the presence of flow shear, we observe how flows hear-independent scaling laws are modified. Analytic modifications are made to the critical balance scalings, incorporating the effects of flow shear. Additionally, we analyze an asymmetry in how the system responds to a flow shear; preliminary results suggest that the system changes in its parallel and temporal scales, but remains invariant in the perpendicular plane.

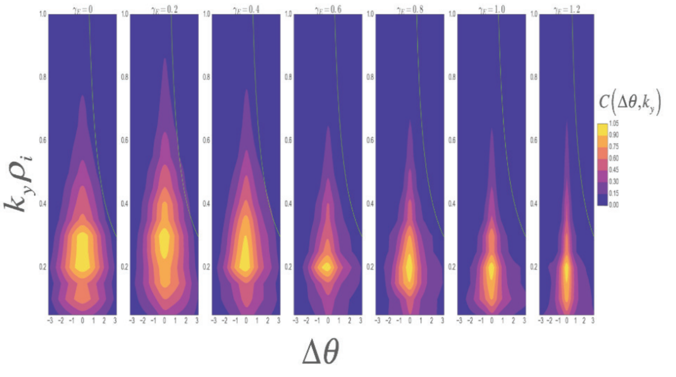

Figure 1: *Parallel density correlation function as a function of k_y and $\Delta\theta$, the distance along the field line. Each subplot is for a fixed flow shear, γ_E, where γ_E ranges from 0 to 1.2, left to right. The narrowing of the correlation function indicates a shortening of the parallel turbulent length scales.*

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P1.8

Runaway dynamics in disruptions: sliding and screening

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Runaway electrons (REs) are a pressing issue for ITER due to their significant potential to cause damage. Improved knowledge of RE formation mechanisms, their dynamics and characteristics, as well as transport or loss processes that may contribute to RE suppression and control, will benefit the fusion community and contribute to a safe and reliable operation of reactor-scale tokamaks.

We review recent results on runaway electron dynamics obtained with the relativistic finite-difference Fokker-Planck code CODE [1] and its nonlinear counterpart NORSE [2]. The latter includes a fully nonlinear relativistic collision operator, making it possible to consider scenarios where the electric field is comparable to the Dreicer field (or larger), or the electron distribution function is otherwise far from a Maxwellian, which can be the case already in present-day runaway experiments. Using NORSE, the transition to a regime where the entire electron population experiences continuous acceleration, so-called electron slide-away can be investigated. We will show that Ohmic heating and the rate of heat loss play an important role in the transition to slide-away, with the latter affecting the average energy reached by the runaways by several orders of magnitude.

We will also describe the dynamics of fast electrons in plasmas containing partially ionized impurity atoms, where the reduced-screening effect of bound electrons must be included [3]. We show that the enhancement of both collisional drag and pitch-angle scattering due to reduced screening lead to significant runaway current decay. This has important implications for the understanding of important phenomena, such as the energy spectrum of runaways and the effective critical electric field for runaway electron generation.

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P1.9

Linear kinetic-MHD stability of internal modes in toroidally rotating plasmas

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Analytical theory and numerical simulation have shown that the linear stability of internal modes such as the 1/1 internal kink mode can be strongly influenced by kinetic effects due suprathermal [1,2] and thermal ions [3-5] and by centrifugal effects associated with toroidal rotation [6-9]. For an accurate description of the kinetic effects, radial drifts and the resulting finite orbit width of particles need to be taken into account accurately [1,5]. Based on analytical theory, it has been suggested [7,8] that the stabilization of internal kink modes due to toroidal rotation is due to coupling of this mode with zonal modes. The strong dependence on parallel, in addition to the perpendicular, dynamics in rotating plasmas motivates a kinetic-MHD approach [8], including a parallel electric field.

In the present work, some aspects of the problem of the kinetic-MHD stability in toroidally rotating plasmas are addressed. First, a kinetic equation, suitable for inclusion in a kinetic-MHD code and allowing for sonic plasma rotation as well as finite Larmor-radius effects is derived. To this end, a link between the linear gyrokinetic description [10] and the description adopted in [1], and used in many hybrid kinetic-MHD codes, is established. We show that in the long-wavelength limit and in the limit of vanishing plasma rotation, the results of [1] are recovered. We also show that our results are consistent with [3]. In particular, the quasi-neutrality equation in the form given in [3] is obtained.

To study the combined influence of toroidal rotation and kinetic effects on internal modes, a numerical code for the self-consistent computation of the linear kinetic-MHD stability of toroidally rotating plasmas is currently under development. The VENUS-LEVIS code [11] is extended and used to solve the kinetic equation in the long-wavelength limit. The integration of the kinetic equation along unperturbed guiding-centre orbits, utilizing a decomposition into bounce-harmonics employed in the analytical work [1], allows full finite orbit width effects to be retained. We report on progress in the numerical implementation and first results using this new code.

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P1.10

Tangential magnetic drift, tangential electric field and their impact on stellarator radial neoclassical transport

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In general, the orbit-averaged radial magnetic drift of trapped particles in stellarators is non-zero due to the three-dimensional nature of the magnetic field. Stellarators in which the orbit-averaged radial magnetic drift vanishes are called omnigeneous [1,2], and they exhibit neoclassical transport levels comparable to those of axisymmetric tokamaks.

In the 1/n regime of non-omnigeneous stellarator neoclassical transport (and in higher collisionality regimes), the piece of the electrostatic potential that is non-constant on the flux surface (equivalently, the component of the electric field that is tangent to the flux surface) is irrelevant for the radial transport of the main ions, and so are the tangential drifts. However, for lower ion collision frequencies (below the values that define the 1/n regime), the situation is different. Using recently developed techniques [3], we treat such low-collisionality regimes. These techniques rely on an asymptotic expansion in which the small expansion parameter is the size of the deviation of the magnetic configuration from an exactly omnigeneous one.

First, we prove that closeness to omnigeneity allows to rigorously derive a radially local, bounce-averaged drift-kinetic equation for collisionalities below the 1/n regime, and we give the correct way to incorporate the tangential drifts in this equation, and in particular the tangential magnetic drift. Then, we show that radial neoclassical transport is determined by two small layers at different regions of phase space; one of them corresponds to the $\sqrt{\nu}$ regime and the other one to the superbanana-plateau regime.

We explain why, under these conditions, the tangential component of the electric field has to be correctly calculated in order to compute the radial neoclassical fluxes of the main ions (at least if no large aspect ratio assumption is made), and why resolving the superbanana-plateau layer is fundamental for working out the tangential electric field. The role of the tangential electric field is essential for the emergence of a new subregime of superbanana-plateau transport when the radial electric field is small, and therefore when the tangential magnetic drift is more important. Strikingly, in this subregime a large tangent electric field appears at the bounce points of certain resonant trapped-particle trajectories.

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P1.11

Energy confinement in He and D plasmas: on the role of central electron heating

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Helium is one of the gas foreseen for the non-nuclear phase in ITER [1], in part due to a H-mode power threshold close to deuterium plasmas [2]. However, energy confinement times in He plasmas have been consistently observed to be lower by approximately 30% [2,3] than those in D plasmas, which is in contradiction with the gyro-Bohm scaling of the turbulent transport, where He is expected to have better confinement than D.

To explore these discrepancies, companion discharges in helium and deuterium at ASDEX Upgrade are compared and analysed with theory-based modelling tools. Plasmas in both H and L-mode regimes with various combinations of electron cyclotron resonance and neutral beam heating powers are considered, producing different ratios of electron and ion heating fractions. In contrast to several previous results [2,3], regimes are identified in which helium plasmas have the same good confinement properties as the corresponding deuterium plasmas.

The stored energy or equivalently the energy confinement time (matched input powers) in helium is found to be comparable to that of deuterium when ECRH provides the dominant fraction of heating power, at comparable electron density profiles. In this regime, the ion temperature profile in helium is higher than that in deuterium due to a reduced ion density. Concurrently, and interestingly, also the electron temperature is higher in these conditions, where electrons are significantly hotter than ions. The increased temperatures are shown to be related to a change in the equipartition (energy exchange between electrons and main ions), which, in the presence of dominant electron heating, allows a strong increase of the ion (and electron) temperature in He, large enough to compensate the reduction by a factor 2 of the main ion particle content in helium plasma, at the same electron density of a deuterium plasma.

Consistently with previous observations [2,3], low energy confinement times are instead recovered in helium (compared to deuterium) when the neutral beam heating is dominant. In these conditions, the electron and ion temperature profiles are very close in both D and He plasmas. The He temperature is hindered to significantly exceed the electron temperature, despite the factor 2 reduction of the total number of main ions, resulting in an overall reduction of the total stored energy. This reduction of the core stored energy in helium is attributed to a concomitant destabilisation of the electron temperature gradient instability and to a reduced background core rotation and ExB shearing. Such mechanisms are investigated via local gyrokinetic simulations using the gyrokinetic code GKW [4].

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P1.12

Propagation of radio frequency waves through spatially modulated interfaces in the plasma edge in tokamaks

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In tokamaks, radio frequency waves are used to control the temperature and the current in the plasma core. Before the waves reach their target in the core, they are being scattered by density fluctuations that exist in the plasma edge, known as blobs [1,2] or turbulent interfaces. The propagation of RF beams through interfaces are studied numerically using the finite difference frequency domain method (FDFD) in conjunction with the Total-Field Scattered Field (TFSF) method and the Perfect Matching Layer (PML) absorbing boundary condition [3]. For that purpose, the interfaces are considered to have a harmonically spatially modulated shape and the incident beam is approximated by a plane wave of wavelength comparable to the interface modulation period. Results will be compared to the COMSOL commercial numerical solver and the semi-analytical Rigorous Coupled Wave Analysis (RCWA) [4] solver for anisotropic media that is under development. The frequency range of the RF waves studied is the electron cyclotron and lower hybrid frequency range for ITER-like and Medium Size Tokamak applications (such as TCV, ASDEX-U, DIII-D, etc). The study covers for a variety of density contrasts between across the interfaces and a wide range of interface modulations.

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P1.13

Semi-Analytical inspection of the quasi-linear absorption of RF in presence of alpha-particles in tokamak reactor

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In reactor plasma (like DEMO), which uses the RF heating or current drive [1], a large fraction of the ion population (the continuously born alpha-particle, and/or the NBI injected ions) is characterized by a non-thermal distribution function. The interaction (propagation and absorption) of the wave both in the ICRH and/or LH domain of frequencies must be reformulated by considering the quasilinear approach for each species separately. The collisional slowing down of such an ion population in a background plasma is balanced by a quasi-linear diffusion in velocity space due to the propagating electromagnetic wave. In this paper both the propagation (related to the hermitian part of the dielectric tensor) and the absorption (related to the anti-hermitian part) are reconsidered by including the ion distribution function solution of the Fokker-Planck equation, which describes the collisional dynamics of the particles, including the effects of frictional slowing down, energy diffusion, and pitch-angle scattering. Analytical solutions of the Fokker-Planck equation at the steady state are included in the calculation of the dielectric tensor and a novel dispersion relation is obtained. In the lower hybrid frequency domain, for example, the analytical ray tracing (including the quasi-linear damping), can be solved by iterating with the Fokker-Planck solution, and the interaction of the LH wave with alpha-particles and NBI ions can be accounted self-consistently and the lost of the CD efficiency can be evaluated.

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P1.14

Ideal saturated 3D external kink structures in quiescent H mode plasmas

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Future tokamak devices like ITER are designed to operate in high confinement mode (H mode), but the associated deleterious effects of ELMs are well known. The quiescent H mode (QH mode) [1] was first discovered in DIII-D and was subsequently observed in other machines, e.g. ASDEX-U and JET. Instead of edge-localised modes (ELMs), the QH mode shows benign edge harmonic oscillations (EHOs), which can enhance both energy and impurity exhaust. In the peeling-ballooning stability diagram, the QH mode is thought to be located around the kink/peeling edge. EHOs are argued to correspond to saturated 3D external kink states [2] and saturated edge corrugations have been previously observed in VMEC equilibrium simulations [3]. Since experimental measurements show that EHOs could be saturated modes, a comparison to theoretical predictions can be made in terms of the saturated amplitude of the edge perturbation. Neglecting the phase of the mode, the problem can be described by a time-invariant force balance equation. Such saturated peeling structures, which have features similar to infernal modes, are modeled in the current work by three different approaches. First, by using free-boundary simulations with the ideal MHD equilibrium code VMEC. The non-linear saturated external kink mode amplitude is evaluated from the edge perturbation in the converged equilibrium state. Second, neighbouring equilibria are identified and non-linear external kink stability is determined from free-boundary simulations with the full-MHD initial value code XTOR-2F [4]. Third, the non-linear amplitude of saturated external kink modes is also calculated according to an analytical model valid for poloidal mode numbers $m > 2$ and arbitrary current density profiles [5]. A study is presented that compares the saturated non-linear external kink amplitude obtained numerically by equilibrium computations, MHD stability simulations and from an analytical theory.

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P1.15

Analytic anisotropic-pressure equilibria with incompressible flow in helically symmetric geometry

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It is shown that the equilibrium states of an MHD helically symmetric plasma with incompressible flow and pressure anisotropy are governed by a generalized Grad - Shafranov equation for the helical magnetic flux containing six surface quantities together with a Bernoulli equation for an effective isotropic pressure defined as $\bar{p} = (p_{||} + p_{\perp})/2$, where $p_{||}$ and $p_{\perp}$ are the CGL pressure tensor elements parallel and perpendicular to the magnetic field [1]. This equation recovers the respective ones that govern both axisymmetric and translationally symmetric equilibria, either with pressure anisotropy and flow or not, as particular cases [2-4]. The form of the generalized equation indicates that the parallel flow, expressed by a poloidal Alfénic Mach function and the pressure anisotropy measured by the function $\sigma_d = \mu_0(p_{||} - p_{\perp})/B^2$ assumed to be uniform on the magnetic surfaces, have a cumulative impact on equilibrium in agreement with [3] for the axisymmetric case. In addition, through the most general linearizing ansatz for the free functions included in the derived Grad - Shafranov equation, we construct equilibrium solutions and study their properties. It turns out that the pressure anisotropy has a paramagnetic effect for $\sigma_d > 0$ and a diamagnetic one for $\sigma_d < 0$, irrespective of the shape of the helical current density profile, though the latter profile is noticeably affected by the pressure anisotropy. Also, the parallel flow induces paramagnetism, while the nonparallel one associated with the electric field induces diamagnetism. The generalized equation and its solutions obtained in the present study, being two-dimensional in connection with configurations of constant torsion and without toroidicity, consist a first step approximation to the actual steady states of stellarators. In this respect, they can contribute to modeling such a large aspect ratio device, as that described in [5].

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P1.16

An improved hybrid electron model for global gyrokinetic simulations using the ORB5 PIC code

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Gyrokinetic simulations are extensively used as a tool to describe various phenomena in magnetically confined plasmas. Among others, turbulent transport induced by drift-wave type instabilities such as Ion Temperature Gradient (ITG), Trapped Electron Mode (TEM) and Electron Temperature Gradient (ETG) plays a central role in fusion research. While the ITG mode in first approximations can be modeled using a reduced adiabatic electron model, the TEM and ETG modes require a kinetic description.

The global delta-f PIC code ORB5 [1] currently implements three electron models: in the first, all the electrons are treated adiabatically, in the second they are all treated as kinetic and finally, in the so-called hybrid model the trapped electrons are treated as kinetic while the passing ones are considered to have an adiabatic response. Although the hybrid model is very useful to simulate electron driven modes such as the TEM at a lower numerical cost as compared to the fully kinetic electron model, in its standard form it does not ensure the ambipolarity condition and toroidal angular momentum conservation, which is clearly problematic for long nonlinear simulations.

Recently, an improved hybrid electron model was proposed [2] to solve the ambipolarity problem while avoiding the electrostatic limit of the shear Alfvén mode (so-called ω_H mode) that constrains the time step to small enough values so as to resolve this high frequency mode. This new model treats the trapped electrons as kinetic but separates the passing contribution into a zonal contribution that is treated kinetically and a non-zonal contribution that has an adiabatic response. Finally, all the zonal modes with a poloidal mode number $m \neq 0$ are filtered out. Although this model clearly satisfies the ambipolarity condition, it affects the GAM frequency, which is problematic, for example for comparisons with the experiment [3].

In this work, we propose a further improved hybrid electron model based on [2]. This version considers the zonal contribution of the passing electrons as kinetic but contrarily to the reference, it also includes the zonal modes with $m \neq 0$ as an adiabatic response. In addition to verifying the ambipolarity condition, it affects less the GAM frequency. Zonal flows damping (Rosenbluth-Hinton) tests are used to validate the linear regime of this improved hybrid electron model and comparison with other models and theory will be shown to assess the GAM properties. Nonlinear simulations confirm the ambipolarity condition and show a richer physics that will be discussed. In particular, the zonal flow dynamics is affected by the proximity of mode rational surfaces.

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P1.17

Multi-scale issues in fusion plasmas: synergy between turbulence & neoclassical transports

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In tokamak plasmas, the radial transport of matter, momentum and energy, governed by collisions and turbulence, is intrinsically multi scales. While neoclassical transport results from stationary large scale structures, namely static (m,n) = (1,0) modes (m,n = poloidal, toroidal Fourier wave numbers), turbulence develops fluctuating small scale modes m,n >> 1. Here, neoclassical refers to the collisional transport driven by axisymmetric modes (n = 0), turbulent transport being governed by non-axisymmetric modes ($n^{1}0$). On the basis of this apparent scale separation, it is usually assumed that both contributions are additive. In turn, these two transport channels are often modelled with different dedicated codes. Yet, on the one hand, turbulence is long known to generate meso- to large-scale structures such as zonal flows or avalanches, or the more recently reported staircases. On the other hand, neoclassical coefficients can exhibit small-scale variations, e.g. due to strong variation of the collisionality at the edge. A key question is therefore whether this assumption is valid or neoclassical/turbulent transports exhibit synergetic effects.

This fundamental issue has been recently addressed by means of self-consistent nonlinear simulations of both turbulent and neoclassical transports with the full-f and flux-driven gyrokinetic code GYSELA [1]. There, a simplified version of the multi-species collision operator – valid for trace thermal impurities – has been implemented and successfully benchmarked against neoclassical theory [2,3]. A clear example of this synergy comes from the observation that the tungsten impurity flux is not the sum of turbulent and neoclassical fluxes computed separately [3], as usually assumed. Actually, it is found that the synergy partly results from the turbulence-driven in-out poloidal asymmetry of tungsten density. Indeed, large scale poloidal structures of the impurity density are generated by turbulence large scale (m,n) = (1,0) modes of the electric potential. These add-up and/or compete with those governed by neoclassical physics, so that neoclassical and turbulent transports are not additive. Interestingly, it is also found analytically – dedicated numerical simulations are in progress, with scrape-off layer like boundary conditions – that these poloidally asymmetric large scale convective cells also impact momentum transport [4]. Last but not least, evidence of flow poloidal asymmetries was found in measurements on the Tore Supra tokamak [5].

The conditions for the onset and sustainment of these turbulence-driven m=1 cells have been clarified and will be exposed. It turns out that Landau damping is small at low frequency, so that the amplitude of quasi-steady cells is mainly dictated by shielding polarization effects. It is also found that poloidal asymmetries of the distribution function driven by these cells produce a flux of toroidal momentum via the magnetic drifts of particle guiding-centers. This flux partially balances the contribution of ExB drift velocity fluctuations to the turbulent residual stress. Also the resulting poloidal asymmetries of the density modify deeply the neoclassical flux of impurity. It will be shown that the neoclassical thermal screening of heavy impurities is reduced because of this effect. Finally turbulence self-regulation through the generation of poloidal convective cells and feed-back via vortex shearing will be discussed.

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P1.18

3D Perturbative Ideal MHD Stability in Tokamak Plasmas

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High confinement tokamak plasmas are characterised by a large edge current density and pressure gradient leading to destabilisation of edge localised modes (ELMs) [1] that are responsible for large heat loads on the divertor. In ITER, uncontrolled type-I ELMs are anticipated to produce power fluxes that are above melting point of tungsten [2] and active ELM control will be necessary for the safe operation of the reactor. One method for active ELM control uses non-axisymmetric resonant magnetic perturbations (RMPs) that result in mitigated [3] or even suppressed [4] ELM plasmas. The physics mechanisms responsible for the access of a suppressed or mitigated state still remains an unanswered question. RMPs create current layers at rational surfaces that potentially lead to formation of magnetic islands and relaxation of the profiles at the edge. However, island formation is suppressed if sufficiently strong flows or pressure gradient exists at the rational surfaces. In addition, the 3D nature of the external field has an impact on the plasma equilibrium and may change MHD stability boundaries directly affecting the onset of ELMs. In this work, the 3D ideal MHD stability is studied employing linear perturbation theory to examine the change in peeling-ballooning boundaries [5]. Preservation of nested flux surfaces is required for the validity of the perturbative approach, motivating our study of an ideal plasma response as a model for strong plasma shielding of the RMPs. The simulation of the non-axisymmetric part of the equilibrium for an applied external field is performed using a linear ideal stability code ELITE [6,7] and a non-linear ideal fluid model implemented with BOUT++ [8] for a circular large aspect ratio plasma. The ideal and incompressible plasma response produces large normal and divergent binormal plasma displacement localised around rational surfaces that create singular Pfirsch-Schluter currents. The axisymmetric toroidal modes are coupled due to geometrical effects and calculation requires information from the 3D part of the plasma equilibrium (see Fig.1). Future work will use this information to quantify the impact of RMPs to ideal MHD stability.

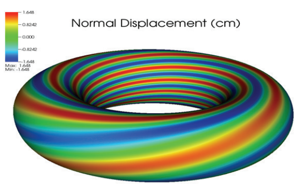
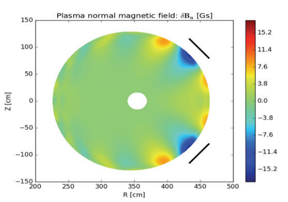


***Figure 1:** Equilibrium plasma normal (A) displacement, (B) magnetic field for an "even" (n = 3) RMP magnetic field configuration evaluated using the modified ELITE code.*



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P1.19

Grid generation for fusion simulations

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Due to the very large anisotropic character of strongly magnetized plasma, the use of flux aligned grid is generally believed to be highly useful (or even mandatory) to obtain accurate and reliable simulations for fusion applications. For real geometries, the magnetic geometry can only be computed by the use of specialized equilibrium solvers (e.g [1]) solving the non-linear Grad-Shafranov equation. The output of these solvers then have to be used as input to construct flux aligned meshes that respect the magnetic topology. This process usually require some manual input and expertise from the final users to identify the relevant features of the magnetic topology (X points, magnetic axis). Here, we will describe an original method for the automated construction of flux aligned grids. This method assumes that the magnetic flux is a Morse function [2] and consequently that the results of Morse theory can be applied: the topological set of the iso-contours of the flux function consists of finite connected components that are either (1) Circle cells which are homeomorphic to open disks, (2) Circle bands which are homeomorphic to open annulus and (3) Saddle connections. The construction of flux aligned grid then can relies on the analysis of the singularities of the magnetic flux function and the construction of a graph known as the Reeb graph [3] that encodes the segmentation of the physical domain into sub-domains that can be mapped to a reference square domain. We will present several examples taken from existing tokamaks to illustrate this grid generation process.

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P1.20

Evolving the Ion Temperature Gradient driven turbulence with test modes

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The analytical treatments of turbulence are severely outnumbered by the numerical simulations, due to the complexity of this strongly nonlinear process. In the case of magnetically confined plasmas, the particle and energy transport properties are directly influenced by the low frequency drift type turbulence, whose nonlinear evolution exhibits large scale correlations and generation of zonal flow modes.

The first semi-analytical methods capable of reaching beyond the quasi Gaussian transport stage are the decorrelation trajectory method and the nested sub-ensemble approach [1,2], being able to naturally account for the trajectory trapping leading to quasi coherent structures. On this basis, it is possible to perform a study of the test modes on top of a turbulent plasma background [3].

In this work we investigate, within the framework of the test modes approach, the evolution of the ion temperature gradient (ITG) driven turbulence in slab geometry. Starting from a drift kinetic picture, the growth rates of the test modes are obtained from a dispersion relation altered with respect to the quiescent plasma case by the statistical averaging procedure of the ion propagator over the background turbulence configurations. In turn, the growth rates indicate the tendencies of evolution of the spectrum of the background fluctuations. Through this kind of self-consistent iterative procedure [4] we gain new insights into the nature of the emerging complex nonlinear processes. The effects of the density gradient are also studied.

A new mechanism of generation of zonal flow modes (zfm) was found. It does not involve the Reynolds stress of the electric drift velocity fluctuations, nor the combined action of ion eddying and potential drift, but is due to the ion diffusion along the ion temperature gradient. The radial diffusion has dual role on zfm. Besides the damping effect produced by ion spreading, the background turbulence determines the amplification of these modes. The amplification effect yields from the advection of the temperature gradient with the stochastic ExB velocity of the background turbulence modulated by the potential of the mode. More precisely, the Lagrangian correlation of the stochastic velocity with the trajectory leads to a radial average Lagrangian velocity that adds to the diamagnetic velocity and yields unstable modes with zero poloidal wave numbers. The zfm turbulence contributes to the damping of the ITG turbulence through the increase of poloidal diffusion coefficient.

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P1.21

On the gradB and ExB drifts of alphas in burning plasmas

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A two-dimensional time depended model based on the two-fluid approach, where the electrons, the reacting ions, and the generated alphas, are treated as separated interacting fluids has been developed. The model computes the conservation equations for the electrons the reacting ions (D-T) and alphas, supplemented with Maxwell's equations in two-dimensional Cartesian geometry, which represents the poloidal plane of a tokamak fusion reactor, with uniform flows in the 3rd direction. The fluid equations for each plasma species are derived by taking moments in velocity space of Boltzmann's equation. We remain in the two-fluid description because in the MHD approximation the plasma is invariant for a broader class of transformations. In addition a zero dimensional multi-fluid plasma burning model has been developed for alpha heating of plasma in a fusion reactor. The model is based on the conservation of the various plasma species particles (electrons, reacting ions and alphas generated by nuclear reactions) and on the energy balance of these plasma species. Using this model we compute the power output of the reactor, the reacting ions and alpha particle density and temperature, and under what initial conditions the reactor will be operating in a steady state.

Here we study: (a) the production of alphas and their drifts, in the very early stages of the burning process by placing high pressure plasma blob in the center of the two-dimensional grid and have an initial magnetic field which has a gradient (f/r) ITER like. And (b) by coupling the zero-dimensional model to the two-dimensional model, we study the drifts of the alphas when the production of alphas is in steady state.

P1.22

Test-electron analysis of magnetic reconnection topology

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Three-dimensional (3D) investigations of the magnetic reconnection field topology in space and laboratory plasmas have identified the abidance of magnetic coherent structures in the stochastic region that develop during the nonlinear stage of the reconnection process [1-4]. Further analytical and numerical analyses highlighted the efficacy of some of these structures in limiting the magnetic transport [5-6]. The question then arises as to what is the possible role played by these patterns in the dynamics of the plasma particles populating the chaotic region. In order to explore this aspect, we provide a detailed description of the nonlinear 3D magnetic field topology in a collisionless magnetic reconnection event with a strong guide field [7]. In parallel, we study the evolution of a population of test electrons in the guiding-center approximation all along the reconnection process [8]. In particular, we focus on the nonlinear spatial redistribution of the initially thermal electrons and show how the electrons dynamics in the stochastic region depends on the sign and on the value of their velocities. While the particles with the highest positive speed populate the coherent current structures that survive in the chaotic sea, the presence of the manifolds calculated in the stochastic region define the confinement area for the electrons with the largest negative velocity. These results stress the link between the magnetic topology and the electron motion and contribute to the overall picture of a non-stationary fluid magnetic reconnection description in a realistic geometry.

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P2.1

Gyrokinetic simulation of micro-turbulence in stellarators

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Most magnetic confinement fusion devices come in two shapes: the "plain-donut" tokamak and the "curly-donut" stellarator. Owing to its technological simplicity, the tokamak line has been enjoying popularity for the past several decades. However, the recent commissioning of the Wendelstein 7-X stellarator experiment in Greifswald (Germany) has rendered the stellarator an important contender for the next fusion reactor. Thanks to great strides in the computational efficiency of simulation codes at the peta-scale level [1], we now understand that turbulence could play a key role, limiting the confinement and thus the performance of an optimized (with respect to neoclassical transport) stellarator. As shown in Figure 1, turbulence in stellarators is typically localized poloidally, contrary to tokamaks where the structures are distributed evenly over the entire outboard side. This localization is found to be responsible for a number of favorable features. For instance, 3D shaping tends to create locations where adjacent magnetic surfaces are dense, and therefore the local pressure gradients are strong, exacerbating turbulent heat fluxes. This effect is found, however, to be alleviated significantly thanks to localization, since the transport calculated through the entire magnetic surface is much smaller than the increased local one [2]. In addition, localization in stellarators is found to impede the decay of zonal flows in stellarators [3], which act as a stabilizing mechanism for turbulence. Despite these positive inherent features of stellarator turbulence, there seems to exist enough room for further optimization of the magnetic field towards lower levels of turbulent transport. Genetic algorithms have been implemented which are able to perform global search in the vast space of stellarator configurations, and novel stellarator designs have emerged from this effort, improving on the existing ones [4].

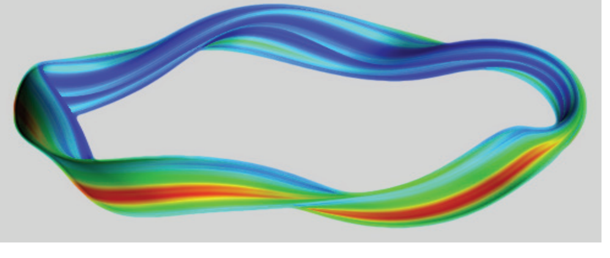

Figure 1: *GENE simulation of the density fluctutations caused by ion temperature gradient turbulence on a magnetic flux surface of the Wendelstein 7-X stellarator.*

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P2.2

Analytic characterisation of ideal infernal type instabilities in tokamaks with large edge pressure gradients

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The quiescent high confinement mode (QH-mode) tokamak regimes share with the H-mode a large edge pressure gradient and a high energy confinement time. Experimental observations in QH-mode conditions showed the appearance of low-n magnetohydrodynamic oscillations which replace the ELM activity (ELMs have n >> 1). The associated energy loads on the plasma facing components are much lower compared to regimes where ELMs are present. The appearance of these benign low-n oscillations has been linked with kink/peeling modes.

The steep edge pressure gradient in the low collisionality regime is associated with a significant bootstrap current contribution which reduces locally the magnetic shear. When the magnetic shear is allowed to become small, infernal modes can be driven unstable by an increase of the pressure gradient. These instabilities are characterised by toroidicity induced coupling between a main Fourier mode and its neighbouring sidebands. Numerical studies of low-n MHD instabilities in the QH-mode regime with a plateau in the safety factor near the edge found infernal-like features.

We focus our attention on the analytic description of low-n edge localised infernal-type instabilities with the inclusion of the equilibrium toroidal rotation and a vacuum region that separates plasma and the metallic wall (ideal or resistive).

P2.3

Modelling of Alfvén modes properties in TJ-II plasmas

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Alfvén modes are a low-frequency electromagnetic class of instabilities, which degrade the fast ion confinement and result in poor performance. In burning plasma devices, i.e. ITER and beyond, it is expected that energetic alpha particles will heat the bulk plasma; therefore good confinement and the interaction of energetic particles with background plasmas are of the most important interest in fusion research. The study of Alfvén Eigenmodes (AE) in tokamak plasmas [1] and in 3D non-axisymmetric devices like TJ-II [2,3] demands detailed investigations and modelling of these structures for the optimization of fusion devices. The study of the properties of AE modes and their effect on fast ion confinement is deemed necessary for the enhanced performance of next step burning plasmas [4]. In this work, we take advantage of TJ-II flexibility and present modelling of the observed behavior of Alfvénic modes in a configuration scan of TJ-II, shown in Figure 1 from [5], and compare these results with the experimental ones for the different properties of Alfvén Eigenmodes in TJ-II plasmas. Simulations of selected instabilities [5] are performed by using STELLGAP [6] and AE3D [7] codes for the three-dimensional flexible Heliac TJ-II. Simulation results for the properties of observed AE modes i.e. frequency and radial location are consistent with the experimental observations. Additionally, in our simulations, the mode with same poloidal and toroidal mode numbers appears with the small variations in on-axis iota values. In next step, we will investigate the transition of AE modes between chirping and steady at different iota values.

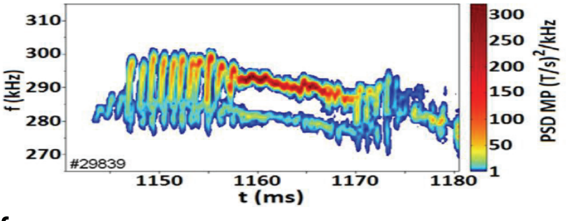

Figure 1: *Experimental observations of Alfvén Eigenmodes (AE) in TJ-II Stellarator.*

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P2.4

Ion composition effects on neoclassical transport in density pedestals

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Orbit-width scale profile variations, as found in tokamak pedestals, qualitatively change the nature of neoclassical transport, as the radial fluxes no longer can be expressed by Fick's law-like relations that relate the local fluxes to local gradients. Instead, the profile values at nearby flux-surfaces are needed to calculate the fluxes on a given surface – the transport is said to be radially global. The fluxes nevertheless tend to decorrelate over distances longer than an orbit-width, which has implications for impure plasmas or isotope mixtures, as the different species will have different correlation lengths, but are coupled through collisions.

We study such effects in density pedestals using the global δf drift-kinetic solver PERFECT [1]. We focus on sharp density and electrostatic potential variations, with weak temperature T and pseudo-density $\eta = ne^{Ze\Phi/T}$ variations, as this allows the problem to be linearized around a flux-surface Maxwell-Boltzmann distribution, and thus provides a simple context for the study of global effects. We find that global effects tend to reduce the heat flux by about 10 – 20%, depending on the pedestal profile and isotope. The convective contribution to the ion heat flux can be comparable to the conductive one for sharp electron profiles. In the middle of the pedestal in local simulations, both contributions vary linearly with the local logarithmic density gradient, while in global simulations they become less sensitive to that parameter for sharper pedestals. The global fluxes have qualitatively different poloidal structure, as these fluxes are no longer divergence free on flux-surfaces, which allows complicated radial-poloidal flow patterns to emerge, as illustrated in Figure 1.

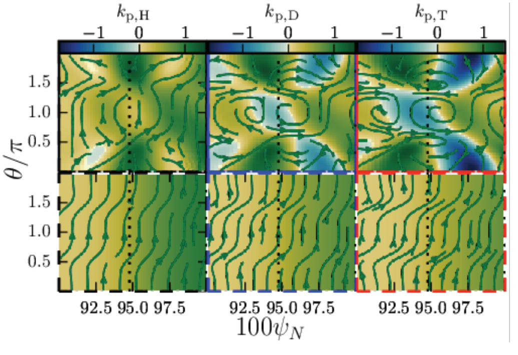

Figure 1: *Streamline plot of radial-poloidal fluxes superimposed over poloidal flow coefficients, from local (top row) and global (bottom row) simulations, for H, D and T isotopes (columns 1, 2 and 3). The flow coefficients are defined to be flux-functions in the local limit, but can even change signs in the global simulations, as is found here. Note that the flow structures extend from the pedestal top (black dotted line) into the core, for a distance that scales with the orbit width.*

The authors thank M. Landreman for developing the PERFECT code. SB and IP were supported by the INCA grant from Vetenskapsrådet (Dnr. 330-2014-6313), JO and SN by the Framework grant for Strategic Energy Research (Dnr. 2014-5392). This work used high-memory nodes at Kebnekaise at the Swedish national computing center HPC2N [2], Dnr. 2017-3-29.

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P2.5

On the limits of the quasilinear evolution of ions interacting with Alfven waves in a magnetised plasma

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We analyse the transport properties of ions in the presence of a spectrum of Alfven waves. Assuming that the ambient magnetic field is $B = B_0 e_z$ and the amplitude of the waves is small ($\delta B/B_0 << 1$, weak turbulence), we attempt to estimate the transport in energy space of an initial thermal distribution inside the turbulent spectrum of MHD waves by presuming that the Fokker Planck equation is valid and by using the Quasilinear approximation to estimate the transport coefficients. We repeat the above experiment using test particle simulations and try to confirm the analytical results. Keeping the above setup, we gradually increase the amplitude of the waves till the strong turbulent regime is reached ($\delta B/B_0 = 1$). Our goal is to search for the breakdown of the Quasilinear theory and, correspondingly, the inability of the Fokker Planck transport equation in energy space to reproduce the results derived from our numerical simulations.

P2.6

Quantitative study of kinetic ballooning mode theory in magnetically confined toroidal plasmas

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In this work, we report a systematic quantitative comparison of analytical theory and numerical gyrokinetic (GK) simulations of kinetic ballooning modes (KBMs) in a magnetically confined toroidal plasma. A physics-based ordering for beta (the ratio of kinetic to magnetic plasma pressure) with small asymptotic parameters is found. This allows us to derive several simplified limits of previously known theories [1] and to identify regimes where quantitative agreement between theory and numerical simulations can be achieved. We introduce a variational approach which provides explicit dispersion relations in terms of integrals of quadratic forms constructed from numerical eigenfunctions.

For the axisymmetric case, in simple s-α geometry, it is found that, for large pressure gradients, the growth rate and frequencies computed by the gyrokinetic codes GS2 and GENE show excellent agreement with those evaluated by using, in the quadratic forms, a diamagnetic modification of ideal MHD. This is true only if geometric drifts are kept consistent with the equilibrium pressure gradient. For moderate pressure gradients, a new finite-beta formulation of KBM theory is proposed. Also in this case, good agreement between numerical simulations and analytical theory is found.

The theory is also extended to treat the stellarator device Wendelstein 7-X (W7-X) [2]. We show results of finite-beta electromagnetic GK simulations of ion-temperature-gradient-driven modes and KBMs for various W7-X configurations with different ideal MHD stability properties. This is important since, at present, it is not clear how the KBM and the ideal MHD ballooning mode thresholds relate to each other in stellarator geometry.

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P2.7

Advanced homogenization approach for a plasma dielectric mixture: Case of a turbulent tokamak

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Homogenization methods for dielectric mixtures have been used extensively in the past for a wide range of complex media. In this study the case of interest is a magnetized plasma medium, which by default is a subcategory of gyrotropic media. Embedded in an ambient plasma of a given density profile are turbulent structures at a different density (blobs) of various shapes from long filamentary structures to ellipsoids aligned to the local magnetic field lines. The classical homogenization approach is very limited in our case, strongly depended on low volume fractions for the blobs and wavelengths of the incident radio frequency waves. In our study we use Fourier space components for the electric and magnetic fields (scattered and excited within the blobs) that, in turn, are seen as eigenvectors of the dispersion relation matrix. Using Green's function approach for the ambient plasma leads to an equation for the homogenized dielectric tensor. The parameters used are those implemented for a series of experiments performed on devices such as TORPEX and TCV.

This work was supported in part by the Hellenic National Programme on Controlled Thermonuclear Fusion associated with the EUROfusion Consortium.

P2.8

Electromagnetically consistent model of complete reconnection

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The internal kink mode, with principal poloidal and toroidal mode numbers m=n=1, is thought to underlie the sawtooth crashes in tokamak plasmas. The expulsion of thermal energy from the core may be caused by magnetic reconnection in several ways, e.g. through stochastization of magnetic field lines, or complete magnetic reconnection of the plasma core [1]. Complete reconnection amounts to a heat loss mechanism simply by mixing of two plasma temperatures on reconnected flux surfaces. However, energetic particles in the core (from fusion or additional heating) can behave differently from the bulk plasma during a sawtooth crash. These particles are almost collisionless on the timescale of the crash and have drift orbits that deviate significantly from the field lines. These orbits are affected by the internal kink mode via the time-dependent magnetic field an electric field, with contributions specific to the m=1 kink motion and to the reconnection.

This point was made in [2] which presented a model for these magnetic and electric fields. In [3] that model was used to compute energetic particles orbits during sawtooth crashes. In [2,3], the magnetic and electric fields are computed self-consistently, satisfying Maxwell's and Ohm's laws. However, the model is short of a full MHD model: the plasma motion, while consistent with the electric and magnetic fields, is prescribed instead of based on the MHD force balance. This is evident from the fact that the mode has single helicity and hence magnetic surfaces exist in the nonlinear phase (full MHD dynamics in a torus produces multiple helicities and hence at least some level of field stochasticity).

The present paper uses the same assumptions, but adds to the earlier research by presenting explicit analytic expressions for the electric and magnetic fields. The model gives an electromagnetically self-consistent description of complete reconnection of a single-helicity m=1 mode in an arbitrary axisymmetric equilibrium with arbitrary q-profile (with q=1 surface, of course). It is shown that the single-helicity restriction gives rise to two distinctive phases in complete reconnection: first the m=1 shift of the core and reconnection, which leads to an m=1 deformed shape of the reconnected magnetic surfaces. The second phase is a reconnection-free m=1 motion that restores axisymmetry. Generally, these two phases cannot be mixed: reconnection cannot immediately yield an axisymmetric state.

The application to the modelling of energetic particle orbits during reconnection, to be published separately, will be briefly outlined. In particular, comparison with full-MHD simulations can reveal the specific role of magnetic stochasticity in the full MHD case.

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P2.9

Modelling the effect of resonant magnetic perturbations on neoclassical tearing modes

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**See the author list of "Meyer et al, Overview of progress in European Medium Sized Tokamaks towards an integrated plasma-edge/wall solution, accepted for publication in Nuclear Fusion"*

A 3D time dependent quasi-analytic model is built to describe the NTM perturbations evolution under the effect of the external resonant magnetic perturbations (RMPs). The model applies to the ASDEX-Upgrade tokamak with its system of B-coils generating magnetic perturbations, having a sufficiently close realistic description of the experimental installation. A clear, quasi-analytic expression of the neoclassical perturbation calculated by solving the magnetic island resistive equations [1] is obtained, compulsory linked via the matching conditions at the magnetic island-ideal plasma boundary with a general time dependent solution satisfying the perturbed equations outside the magnetic island, separately derived [2]. The latter solution is compulsory to be derived because contains all the information about the plasma column external structures, such as the B-coils generating RMPs. Based on both solutions, the perturbation stability index is obtained to be used to solve the modified Rutherford equation. The stability index is also a measure of the influence of the RMPs on the NTM evolution, hence is has been point out the RMPs role as a trigger for the NTM onset and magnetic island seeding process. The RMPs effect on the mode frequency and phase is shown along with the influence of the B-coils arrangements effect. The results are compared to some ASDEX-Upgrade disruptions experimental results in order to assess plasma stability performance and stability control in high-beta and advanced tokamak regimes. Despite the limitations involving a model describing the small perturbations evolution, good results are obtained concerning the RMPs effect on the NTMs at least before important perturbed model equilibrium quantities significantly change.

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

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P2.10

Nonlinear gyrokinetic investigation of energetic-particle-driven geodesic acoustic modes

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Geodesic acoustic modes (GAM) are axisymmetric perturbations of the radial electric field, oscillating in tokamaks with the characteristic acoustic frequency [1]. Their importance is linked to the nonlinear interaction with turbulence, present in tokamak plasmas due to temperature and density gradients. GAMs can also interact with fast ions in tokamaks, taking the name of energetic-particles (EP) driven GAMs (EGAM) [2]. Understanding the nonlinear dynamics of EGAMs is crucial for predicting their relevance in present tokamaks and future reactors.

The nonlinear dynamics of EGAMs is investigated here by means of numerical simulations with the global gyrokinetic particle-in-cell code ORB5 [3,4]. A bump-on-tail distribution function for the energetic particles is considered. Axisymmetric modes only are investigated. In previous works, ORB5 has been successfully verified and benchmarked for the linear dynamics of EGAMs [5,6]. In this work, we extend the previous linear investigation to the nonlinear saturation phase. The nonlinear modification of the frequency and mode structure is described. A special effort is dedicated to understanding the saturation mechanisms. In particular, when wave-particle nonlinearity only is considered, a quadratic scaling of the saturated electric field on the linear growth rate is found, defining a saturation due to wave-particle trapping. Differences with wave-wave nonlinearity (i.e. EGAM self-coupling) are discussed. Comparisons and benchmarks with analytical theory [7] and with other gyrokinetic codes are also shown.

This work is supported by the EUROfusion Consortium under grant agreement number 633053, in the framework of the NLED project.

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P2.11

Full-F gyrofluid modelling of blob-impurity interaction in the tokamak scrape-off layer

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In two-dimensional gyrofluid simulations of filament evolution in the tokamak scrape-off layer show a slowdown of radial blob propagation, dependent on concentration, mass and charge of impurity ions present.

A better understanding of non-trace non-fuel ion effects on edge turbulent transport is of uttermost rel- evance for reactor operations because of two partially interlinked issues. First, the distribution of im- purities, originating from plasma-wall interaction or deliberate seeding, throughout the reaction volume determines positive and negative effects on confinement alike; Heat mitigation at the divertor or plasma dilution and increased radiation losses at the core, respectively [1]. With the plasma edge as a natural boundary between plasma volume and impurity sources, transport processes at the SOL significantly influence impurity penetration deeper into and impurity distribution in the plasma.

The assessment of a parameter-scan on cold isothermal seeded blob evolution with constant impurity background focuses on the second aspect of importance. Between the last closed flux surface and the first wall propagating filaments dominate particle and heat transport. Quantification is provided by the maximum center of mass velocity of a blob. This parameter is computationally accessible and results are comparable to a suitable linearised analytical scaling law.

Derived in the full-F gyrofluid model [2], the presented equation set self-consistently evolves multiple ion species while making no distinction between background and fluctuations which are known to be of comparable amplitude at the scrape-off layer [3]. Calculations remain far less computationally expensive than operating kinetic codes used for similar purposes [4].

This work was partly supported by the Austrian science fund (FWF) Y398. The computational results presented have been achieved in part using the Vienna Science Cluster (VSC2/3).

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P2.12

Global features of gyrokinetic simulations with sources

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Gyrokinetic simulations of turbulence are now routinely used for various physics studies. Gyrokinetic theory as such can be considered as based on first principles. However, virtually all codes add some elements which are, strictly speaking, not first-principle based. Examples of these are the source terms, which are introduced in global gradient-driven or flux-driven simulations, typically in order to avoid the system to relax their gradients to the marginal state. The simulations can thus reach a quasisteady-state, with average gradients above marginality and finite fluxes of heat, particles or momentum.

The main objective of this paper is to examine in more detail, and from a pragmatic point of view, the consequences on the transport level and turbulent structures of the application of different types of source terms. Source terms have been designed [1] to conserve selected momenta of the distribution function in a flux-averaged sense: density, parallel flows, kinetic energy or Zonal Flow (ZF) residuals.

Using the ORB5 code [2], ITG turbulence properties with various choices of source terms are shown to depend crucially on the type of conservation, respectively non-conservation, imposed on the sources. The effect is particularly marked in the vicinity of the critical gradient, where a Krook source not flow-conserving is shown to lead to the destruction of radially coherent regularly repetitive avalanches, in which ZFs play an essential role, and which have been observed in the TCV experiment near or below the GAM frequency [3]. Furthermore, the time- and radially averaged heat transport is overestimated as compared to a source term with appropriate conservations. The flow structures are also affected.

This speaks in favour of a more systematic assessment of how sources are applied to gyrokinetic codes, with the goal of designing source terms that have a 'benign' effect on the physics.

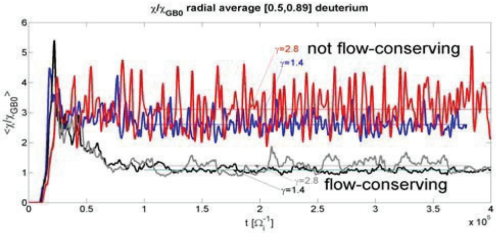

Figure 1: *Ion heat effective diffusivity for flow-conserving (black, grey) and non-conserving (blue, red) sources, for two values of the Krook relaxation rate, in global, gradient-driven ITG simulations.*

This work was partly supported by the Swiss National Science Foundation and by the EUROfusion Work Programme.

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P2.13

Neoclassical Island Control with Stiff Temperature Model

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A major problem for plasma confinement in Tokamak devices is the appearance of non-ideal Magnetohydrodynamics (MHD) instabilities such as Neoclassical Tearing Modes (NTM). They allow for the formation of metastable magnetic islands driven by the perturbation of the bootstrap current, leading to a degradation of energy confinement. The nonlinear growth of these magnetic islands can be controlled by Electron Cyclotron (EC) wave injection. While the role of the RF current inside the island is known to efficiently reduce the magnetic island size by counterbalancing the island current perturbation, the contribution of the heating associated to these waves is not clear. In fact, such an heating adds a stabilizing mechanism to the current drive and makes it sensitive to the turbulent transport properties, in particular to the dependence of the transport coefficient $\chi\perp$ on the temperature gradient leading to stiff temperature profiles [1]. As a result, the effect of heating is restricted and limits its effect on island stabilization. This mechanism can be modeled through $\chi\perp$ as a temperature gradient power law where the power represents the stiffness (σ). A Rutherford equation is derived that integrates this effect. We implemented our model into the XTOR-2F code [2] and we consider an ITER-like plasma with and without a (3/2) NTM. We test the implication of the σ parameter on temperature gradient using σ=1 and 8 [3]. We verified the limitation of temperature increase with σ. Usually, the RF stabilization efficiency is increased taking into account the heating, but this increase is lower as anticipated with a stiff gradient model. On short time scale, we found that RF heating (PRF) enhances significantly the stabilization by RF current (JRF) (Figure 1, left panel). This seems to be due to the effect of heating on the ohmic contribution of the total plasma current. This fast response enhances the advantage of modulated injection even though the width of the RF current and power profile is smaller than the island size. On longer time scale, the island stabilization is mainly due to the RF current contribution.

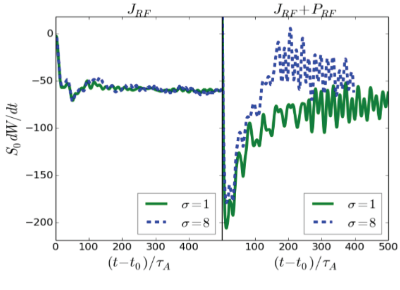
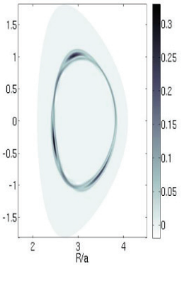


Figure 1: *Left Panel: Magnetic island width time derivative as (left) RF current and (right) combined RF current and heating is applied with and without stiffness. Right Panel: spatial distribution of the RF current density.*



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P2.14

Multi-Scale Gyrokinetic Simulation of L and H-mode Plasma Conditions in the Alcator C-Mod Tokamak

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Referred to as the, "great unsolved problem of tokamak transport physics" [1], electron thermal transport is often anomalous in the tokamak core. It has been speculated that short wavelength ETG turbulence plays a key role, but due to extreme computational requirements this hypothesis has only recently been tested quantitatively using a model that captures coupling between long wavelength ITG/TEM and short wavelength ETG. In Alcator C-Mod, simulations of long wavelength turbulence often fail to explain experimental electron heat fluxes [2], suggesting that electron-scale turbulence and cross-scale coupling may play an important role. Dedicated experiments have been performed in Alcator C-Mod L-mode plasmas and ITER-relevant, ELM-y H-mode plasmas to validate nonlinear gyrokinetic simulations. Building off of previous work [3] full-physics, multi-scale simulations of tokamak plasmas have been performed using the GYRO code. The simulations capture coupled ITG/TEM/ETG turbulence ($k_q r_s < 48.0$), use experimental inputs, impurities, real geometry, electromagnetic effects, ExB shear, collisions, and realistic electron mass (mi/me = 3600) while pushing the limits of high-performance computing. These multi-scale simulations reveal the complex interplay between ion and electron-scale turbulence in real plasma conditions. ETG streamers are found to coexist and strongly interact with ITG turbulence, modify the direction of energy cascades, and nonlinearly couple with zonal flows in the core tokamak plasmas. This nonlinear cross-scale coupling enhances both ion and electron heat flux, resulting in simulations that quantitatively reproduce experimental ion and electron heat flux levels and measured values of electron profile stiffness. In some experimental conditions, multi-scale simulation is found to predict heat fluxes up to a factor of 10 greater than corresponding ion-scale simulation, which may call into question existing ITER predictions based solely on long wavelength simulation. To begin to probe the importance of cross - scale coupling in ITER, multi-scale simulations of high performance, Alcator C-Mod, H-mode conditions were performed. These simulations predict extremely stiff transport and demonstrate that cross-scale coupling plays a critical role in reproducing experimental heat fluxes and electron profile stiffness in ITER-like conditions as well. The role of multi-scale plasma turbulence in real experimental conditions and the implications of cross-scale coupling on predicting turbulence and transport in current and future experiments will be discussed.

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P2.15

Modelling Coupled Ion and Electron Scale Turbulence in Magnetic Confinement Fusion Plasmas

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The turbulent transport of particles, momentum, and energy limits confinement in magnetic confinement fusion devices. Theoretical, numerical, and experimental evidence suggests that turbulent ion transport is primarily caused by turbulence with characteristic spatial scales comparable to or larger than the ion Larmor radius. In addition to these ion Larmor scale transport mechanisms, it is known that there can also be significant transport of heat by electrons due to turbulence driven at the electron Larmor scale.

Due to the largeness of the ion to electron mass ratio direct gyrokinetic simulations of turbulence including both the ion and electron Larmor scales have only recently become possible, with most work to date treating the ion and electron scales separately or using a reduced mass ratio [1]. Simulations involving both ion and electron scales indicate that the cross-scale coupling can be important for matching anomalous transport levels with experiment [2]. However, the extreme expense of a realistic mass ratio direct simulation limits the usefulness of multiscale direct simulations for fully understanding the physics of the cross-scale interaction and its consequences. A reduced, less expensive, gyrokinetic model would help shed light on the physics of the interaction and when we can expect it to be important.

We present such a reduced set of coupled gyrokinetic equations for the ion and electron scales. These equations are derived asymptotically from the full gyrokinetic equation using a multiscale method, with the expansion parameter being the square root of the electron to ion mass ratio. This expansion exploits the separation between ion and electron Larmor scales in the plane perpendicular to the magnetic field line, and the separation between the ion and electron thermal speeds. We discuss the new cross scale coupling terms appearing in these equations, and present results from preliminary simulations using these new terms which have been implemented in the local gyrokinetic code GS2.

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

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P2.16

Scattering of radio frequency waves by cylindrical blobs in the plasma edge in tokamaks

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In tokamaks, radio frequency waves are used to control the temperature and the current in the plasma core. Before the waves reach their target in the core, they are being scattered by density fluctuations that exist in the plasma edge, known as blobs. The propagation and scattering processes of RF beams with transverse Gaussian intensity distribution by blobs are studied analytically and numerically (COMSOL). For that purpose, the blobs are considered to have cylindrical shape and in general, the cylinder axis is not aligned with the externally applied magnetic field. The results are compared to the ones from the study of the aligned case [1,2]. The frequency range of the RF waves studied is the electron cyclotron (EC) frequency range for ITER-like and Medium Size Tokamak applications (such as TCV, ASDEX-U, DIII-D, etc). The study covers for a variety of density contrasts between the blobs and the ambient plasma and a wide range of blob radii.

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P2.17

Mechanics of ELM control coil induced alpha particle transport

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We model alpha particle transport in ITER under the influence of all major externally induced perturbations, namely ELM control coils (ECCs), toroidal field ripple, and test blanket modules, with emphasis on how the plasma response (PR) modifies the transport mechanisms and fast ion loads on the divertor. The modeling is done with an orbit-following code ASCOT.

Earlier studies have shown that PR shields the plasma by healing the flux surfaces broken by ECCs which leads to reduction of passing particle losses compared to vacuum approximation [1,2,3]. However, we found that PR also opens a new loss channel for marginally trapped particles: PR causes strong toroidal variation of the poloidal field near the X-point which leads to de-localisation of banana tips and collisionless transport as illustrated in Figure. 1.

The reduction in passing particle losses and the increase in marginally trapped particle losses shift divertor loads from targets to the dome and under-the-dome structures. The shift is undesired as the under-the-dome structure cannot endure heat loads as high as the main divertor components.

The plasma response was calculated independently by both MARS-F and JOREK codes. We compared the alpha particle loss mechanisms between these cases, and found them to be qualitatively similar. However, the new transport mechanism was stronger for PR calculated by JOREK which, unlike MARS-F, explicitly includes the X-point.

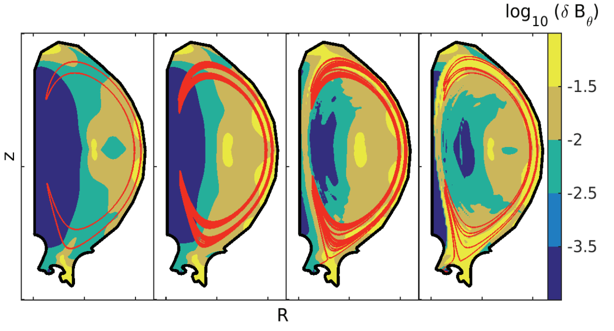

Figure 1: *Illustration of the collisionless motion of an alpha particle in different cases which are, from left to right: without ECCs, ECCs present but without PR, ECCs present with MARS-F calculated PR, ECCs present with JOREK calculated PR. The contours show toroidal variation of the poloidal field.*

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P2.18

A fully implicit kinetic code for parallel electron transport in the Scrape-Off Layer

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Modeling of transport in the edge region of tokamaks has relied traditionally on either a hydrodynamic two-fluid approach backed up by transport coefficients calculated by Braginskii [1], or kinetic approaches based on PIC (particle-in-cell) or Monte Carlo methods. These approaches suffer from the inability to easily capture non-local effects (due to varying collisionality in the plasma edge), as well as noise inherent to particle methods. A third approach is to solve kinetic equations using a finite difference method and to obtain particle distribution functions. While codes employing the finite difference method have been used and reported in the Scrape-Off Layer transport literature [2], their use up to now appears to be limited.

Kinetic codes capable of capturing non-local effects have been used in simulations of laser-plasma interactions [3,4]. Those codes employ a spherical harmonic decomposition of the electron distribution function (EDF), which allows for efficient treatment of transport and the effects of anisotropy. On the other hand, the same decomposition of the EDF has been used in electron swarm models [5], where electron-neutral interactions are dominant. For simulations involving detached plasmas as well as steep temperature and density gradients (such as those during ELM bursts), a novel combination of these two approaches appears to be natural. This has been the motivation for developing a new fully implicit kinetic 1D3V code using the combination of the above approaches to model plasma of highly varying collisionality.

Here we present our new fully implicit 1D3V code for the treatment of parallel electron transport in hydrogen plasmas of varying collisionality and with any level of distribution function anisotropy. The code includes models for both Coulomb collisions of charged species, as well as models for several electron-neutral collision processes. Self-consistent fields are calculated using a combination of Ohm's law and Maxwell's equations. Presented are tests of various aspects of the model used for benchmarking the code, from individual collisional terms to 1D transport.

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P2.19

A multi-species collision operator for gyrokinetic codes

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Core fusion plasmas are almost collisionless as the plasma density and temperature in the core of fusion devices are extremely small and high, respectively. Nevertheless, accounting for collisions remains essential for three main reasons. First, to a large extent, collisions govern the level of large scale flows – both the mean ion poloidal flow and turbulence-driven zonal flows – via the friction on trapped particles. Second, neoclassical transport can reveal dominant (or at least competitive) with respect to turbulent transport in certain regimes such as transport barriers, or for certain classes of particles such as heavy impurities like tungsten. Third, and more fundamentally, collisions ensure the relaxation of the distribution function towards a Maxwellian. In turn, they are critical for gyrokinetic simulations since they smooth out small scale structures in velocity space, contributing to numerical stability.

We report here on the numerical implementation of a new linearized multi-species collision operator in the full-f gyrokinetic code GYSELA. It is based on the model operator developed by Estève *et al.* [1]. This new operator alleviates two important assumptions which were made previously. First, the operator now accounts for the velocity derivatives along the parallel *and* the transverse (new) directions. The adopted method to keep good parallel scalability – despite m is no longer an adiabatic invariant – makes use of projections on Laguerre polynomials. Second, the deflection and velocity relaxation frequencies are properly discriminated, so that the novel operator is valid for any multi-species collisions, regardless of their mass, charge and concentration. So far, this operator does not include finite Larmor radius effects, although these corrections could be added if the resulting classical transport should be retained.

The conservation properties of the new collision operator (particles, total momentum and energy) have been tested successfully. The relaxation towards a Maxwellian, which is a part of the H-theorem, is recovered. Also, the exchange rates of parallel momentum and energy agree with theoretical predictions. Neoclassical transport can then be addressed when accounting for trajectories. In this framework, the collision operator has been successfully benchmarked against neoclassical theory in banana and plateau regimes. The Pfirsch-Schlüter regime is under investigation. The Zonal Flow damping will also be compared with predictions made by Hinton and Rosenbluth [2].

Finally, neoclassical benchmarks with two species will be shown, with particular focus on the thermal screening factor, which is expected to play a critical role in preventing core plasma pollution by heavy impurities. As part of future work, comparison with other collision operators will be performed in the frame of the Enabling Research project "TNT" (Turbulent & Neoclassical Transport).

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P2.20

Study of collisional effects on GAMs and zonal flows

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Using the gyrokinetic code CGYRO [1] employing the model collision operator of Sugama [2], essentially the gyro averaged lowest order Hirshman-Sigmar operator the transition between the fully kinetic and the fully fluid regime has been mapped for GAMs and zonal flows. The collision operator is sufficiently accurate to reproduce the two-fluid damping of the GAMs and residual zonal flows in the limit of large collision number. Some surprises are found for the GAMs: A small number of collisions reduces the collisionless damping, possibly due to the destruction of resonant orbits. After reaching a minimum, the damping rate grows again for increasing collision frequency. Eventually, for edge typical safety factors, a maximum occurs in the damping rate at $\nu_{ii} \sim \omega_{GAM}$. The maximum damping is relatively small (much smaller than the one of the zonal flows) so that the worst quality factor of the GAM resonance is still of the order ~ 100 – which would allow, e.g., its external excitation. Finally, at very high collision numbers the damping rate decreases again, while the frequency approaches the fluid value [3,4].

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P2.21

Local, up-down asymmetrically shaped, analytical tokamak-equilibrium model

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Although magnetic equilibria are at the basis of almost every phenomena in tokamak plasmas, accurate numerical solutions of the Grad-Shafranov equation are not always the best way to gain insight into such complex processes. Often, a simplified description is preferable, either to achieve analytically tractable expressions or to perform parameter scans without the need to recompute a numerical equilibrium at every scan step. Therefore, it is not surprising that several local equilibrium models have seen wide application in tokamak plasmas, ranging from analytical studies on stability (e.g., ballooning modes, Alfvén eigenmodes, zonal flows) and charged-particle orbits, to simplified magnetic-field descriptions on large-scale numerical simulations with gyrokinetic codes.

Most of these local equilibrium models are built by expanding the poloidal-field flux in powers of some radial coordinate around a magnetic surface of prescribed shape, which may range from shifted circles [1] to more sophisticated parametrizations written in terms of the conventional shaping parameters: shift, elongation, and triangularity [2]. Despite the elegant magnetic-surface description achieved by such approaches, they usually result in non-trivial curvilinear coordinates and yield complicated expressions for the magnetic-field components [2,3], which turn analytical work into a difficult task.

To ease these difficulties, a local magnetic-equilibrium model is presented, with finite aspect ratio and up-down asymmetrically shaped cross section, where the poloidal-field flux is expanded as a series of Solovev solutions [4,5] with radially changing coefficients. Here, the focus changes from simple magnetic-surface parametrizations to a more convenient flux description, accurate to fourth-order terms in the inverse aspect ratio. It depends on eight free parameters, one for each of the four independent poloidal-angle harmonics (even and odd), of which three can be related with the conventional shift, elongation, and triangularity. In contrast with other local equilibrium approaches, the proposed model is intentionally built to afford tractable analytical expressions for the magnetic-field components. Therefore, it is particularly suitable for analytical assessments of equilibrium-shaping effects on a variety of tokamak-plasma phenomena. A couple of example applications are provided to illustrate this ability.

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. IST activities also received financial support from "Fundação para a Ciência e Tecnologia" through project UID/FIS/50010/2013. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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P2.22

Numerical modeling of dust transport in a tokamak plasma

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One of the most serious challenges faced by the fusion community at present is addressing the material related issues in the next generation of fusion experiments. The discussion on the role of dust in magnetic fusion devices started long time ago, but it is still not clear what is the impact of dust on the edge plasma parameters and plasma contamination by impurities [1]. More recently, several studies have clearly indicated the occurrence of transient impurity events in plasma discharges following a disruption [2]. These events result in intense radiation spikes in the JET plasma discharges that can be explained by a possible injection of tungsten (W) ions as an outcome of full ablation of W dust particles. Consequently, the problem of dust production, mobilization and interaction both with the plasma and the vessel plasma-facing components is of great importance, and requires the development of accurate numerical tools. In this frame, dedicated tools for the calculation of dust trajectories are useful for predicting the transport and dynamics of dust grains in tokamaks. The present work describes the physical and numerical models implemented in a recently developed dust dynamics code SOLPDUST. The new code is robust, flexible, and computationally inexpensive, which includes the essential physics of modeling the trajectories of dust grains in realistic tokamak plasma environments (see Figure 1). It implements several high-level algorithms for the computation of dust orbits, dust charging, inter-collisions and breakup, dust collisions with micro-turbulence, and dust-chamber wall interactions. Several approaches for modeling dust micro-turbulence collisions and for reconstructing dust trajectory from mean plasma backgrounds are also presented. The main features of the present and previous dust transport codes, such as DUSTT [3], DTOKS [4], DUSTTRACK [5], MIGRAINe [6] are outlined and compared. Finally, representative results are shown from comparisons of the numerical predictions of the new code with the aforementioned codes in selected examples.

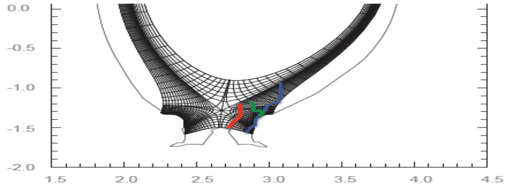

Figure 1: *Representative trajectories of carbon dust predicted by using the new dust transport code.*

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<http://stasy.gr/fileadmin/pages_material/metakinitheite/maps/Diktyo_Astikon_Sygkinonion_Athinon_en.pdf>
(Accessed 28 December 2013)

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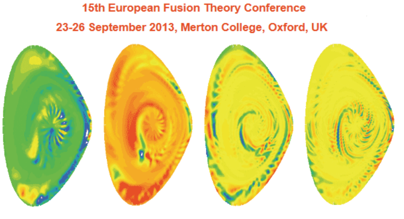

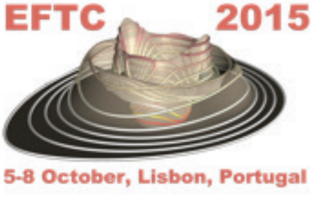

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7	1997	Jülich – Germany
8	1999	Como – Italy
9	2001	Helsingør – Denmark
10	2003	Helsinki – Finland
11	2005	Aix en Provence – France
12	2007	Madrid – Spain
13	2009	Riga – Latvia
14	2011	Frascati – Italy
15	2013	Oxford – United Kingdom
16	2015	Lisboa – Portugal
17	2017	Athens – Greece