JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP

THEORY OF FUSION PLASMAS

Villa Monastero, Varenna, Italy

September 12 - 16, 2022

PROGRAMME and ABSTRACTS

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Organised by

Swiss Plasma Center
Ecole Polytechnique Fédérale de Lausanne

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

Istituto di Fisica del Plasma del CNR, Milano

Scientific Committee

PROGRAMME FOR THE

JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP

"THEORY OF FUSION PLASMAS"

Villa Monastero, Varenna, Italy
12 - 16 September 2022

SUNDAY September 11th, 2022

15:00 - 19:00		Registration in Villa Monastero	

MONDAY, September 12th, 2022

9:00		*Welcome*	*G. Gorini*

Session 1: design and optimisation of novel configurations

9:10	I-1	F. Casson	The challenge of integrated scenario design for the STEP reactor
9:55	I-2	R. Jorge	The direct construction of an exceptionally quasi-isodynamic stellarator
10:40		*Coffee break*	
11:10	I-3	A. Tinguely	Modeling of runaway electron suppression with a passive 3D coil in SPARC
11:55	I-4	E. Rodriguez	Space of quasisymmetric configurations: a topological view
12:40		*Group Photo in Villa Monastero's garden*	
12:50		*Lunch*	

Session 2: plasma turbulence: edge, SOL and separatrix

15:00	I-5	G. Dif-Pradalier	Transport in Fusion Plasmas: Is the Tail Wagging the Dog?
15:45	I-6	A. J. Coelho	Global fluid simulations of plasma turbulence in stellarators
16:30		*Coffee break*	
17:00	I-7	T. Body	In-depth validation of divertor turbulence simulations in TCV and ASDEX Upgrade
17:45		*end*	
19:30		Welcome Party	

TUESDAY, September 13th, 2022

Session 3:extended MHD

8:30	I-8	X. Wang	Nonlinear Dynamics of a nonadiabatic chirping-frequency Alfvén mode in Tokamak Plasmas
9:15	I-9	Yi-Min Huang	Current singularities on rational surfaces including pressure effects
10:00		*Coffee break*	
10:30	I-10	G. Bustos Ramirez	Advanced modelling and existence conditions for edge harmonic oscillations
11:15	I-11	M. Sato	Kinetic-MHD hybrid simulations of MHD instabilities in toroidal plasmas with kinetic thermal ion effects
12:00		*Lunch*	
14:00		Poster session 1: P1 - P15	
16:00		*Coffee break*	
16:30		Poster session 2: P16 - P31	
18:30		*End poster sessions*	
21:30		Harp concert	

WEDNESDAY, September 14th, 2022

Session 4: turbulence and gyrokinetics

9:00	I-12	T. Adkins	Electromagnetic instabilities and plasma turbulence driven by electron-temperature gradient
9:45	I-13	A. Banon Navarro	GENE-3D/KNOSOS-Tango: A New Transport Model for Stellarators
10:30	I-14	K. Imadera	Full-f gyrokinetic simulation of plasma turbulence and transport barrier under ion/electron heating
11:15		*Coffee break*	
11:35	I-15	G. T. Roberg-Clark	Modeling the onset of toroidal ion temperature gradient modes in general toroidal geometry
12:20	I-16	R. J. J. Mackenbach	Available energy and its relation to turbulent transport
13:05		*Lunch*	
18:00		Boat tour on the lake and social dinner	

THURSDAY, September 15th, 2022

Session 5: Energetic particles and heating

8:30	I-17	P. Rodrigues	Energetic particles and coupled Alfvén-acoustic eigenmodes in tokamaks: theoretical insight and modelling
9:15	I-18	E. Paul	Confinement in 3-dimensional magnetic fields: Loss mechanisms and optimization strategies
10:00		*Coffee break*	
10:30	I-19	E. Gospodchikov	Electron-cyclotron heating and kinetic instabilities of a mirror confined plasma
11:15	I-20	Y. Li	Physics of Drift Alfvén Instabilities and Energetic Particles in Fusion Plasmas
12:00		*Lunch*	
14:00		Poster session 3: P32 - P47	
16:00		*Coffee break*	
16:30		Poster session 4: P48 - P63	
18:30		*End poster sessions*	

FRIDAY, September 16th, 2022

Session 6: Advanced simulations of tokamak transport and scenarios

9:00	I-21	E. Belli	Hydrogenic isotope mass scaling of multiscale turbulent transport in the H-mode pedestal
9:45	I-22	D. Dickinson	Microstability and transport in high beta spherical tokamaks
10:30		*Coffee break*	
11:00	I-23	S. Van Mulders	Full-discharge simulation and optimization with the RAPTOR code, from TCV and AUG to ITER and DEMO
11:45	I-24	E. Serre	Advanced modelling of cross-field turbulent transport
12:30		*Closing session*	
12:40		*end*	

The challenge of integrated scenario design for the STEP reactor

F.J. Casson, H. Meyer, F. Eriksson, S. Freethy, F. Koechl, S. Marsden, F. Palermo, B. Patel, E. Tholerus, T. Wilson, S. Bakes, Y. Baranov, D. Brunetti, C.D. Challis, T.C. Hender, M. Henderson, S.S. Henderson, M. Lennholm, K. McClements, D. Moulton, S.L. Newton, R.T. Osawa, C.M. Roach, S. Saarelma, and STEP team

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Abstract: The STEP (Spherical Tokamak for Energy Production) programme has settled on a reactor concept following a design space exploration phase integrating physics, technology and engineering. The reactor is designed to generate net electricity, breed its own tritium and run fully non-inductively. The spherical tokamak allows higher beta and elongation than in conventional devices but also presents additional challenges of limited space: The exhaust solution is likely to be double null with an exacting vertical control requirement; even a small distance between the two separatrices in double null can lead to significant loads on the inner divertor. A compact spherical design also limits the size of a central solenoid. A spherical tokamak reactor will rely on high bootstrap current fraction and non-inductive current drive, even during the ramp up. The STEP concept has R=3.6m, B_T = 3.2 T, Ip ~ 20 MA, A=1.8, κ=2.8, P_{fus}~1.5 GW, β_N ~4.4, f_{bs} > 70%, and fully non-inductive current drive provided by electron cyclotron and electron Bernstein systems.

A spherical reactor will face the same reactor integration challenges as DEMO, with additional challenges for predictive modelling, due to the fact the design space is less well explored: The anomalous transport is likely to be dominated by the electron channel. To predict the confinement, nonlinear gyrokinetic simulations of microtearing turbulence will be needed, and a reliable reduced transport model for microtearing turbulence needs to be developed. Since the plasma will operate at a high bootstrap fraction, the current profile may be self-organised but still needs to be optimised for MHD stability; for this we use a genetic alogrithm. The plasma will also need a high seeded radiation fraction, another territory not yet well validated in integrated modelling.

A non-inductive ramp up at reactor temperatures is also quite novel; due to Faraday's law the ramp up timescale cannot be accelerated just by adding additional current drive, and due to the required heating the timescale is very long. The increase of non-inductive current drive must be carefully managed to avoid the formation of current holes. To reach fusion conditions, the plasma must transition from a hot electron, low density plasma optimised for current drive efficiency to a high density plasma with hot ions and high bootstrap current.

Integrated modelling is embedded in a wider plant architecture integration programme which seeks to reconcile assumptions and constraints from different areas of plasma physics, technology and engineering into a self-consistent burning plasma. These plasmas form the basis more more detailed modelling of heating and current drive, exhaust, MHD, fast particle losses, and technology selection.

This talk will summarise and discuss the current status of many of the key theory and modelling challenges discussed above that are facing the design of STEP.

The direct construction of an exceptionally quasi-isodynamic stellarator

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Abstract. Conventional stellarator design is largely based on finding a boundary shape that allows for good plasma performance and realisable coils. This process requires substantial computational time as there is a large number of degrees of freedom and the optimization targets need to be adjusted iteratively. We present here a novel framework for optimizing stellarator shapes that requires significantly less time based on the coupling of SIMSOPT [1], a stellarator optimization code, and pyQSC, a near-axis expansion code. This framework is based on the near-axis expansion [2,3], which allows for the direct construction of neoclassically optimized configurations. This framework is able to find new stellarator configurations orders of magnitude faster than conventional codes due to the small number of degrees of freedom. Using this procedure, we have obtained an exceptionally quasi-isodynamic stellarator [4], meaning that the relative error between the idealised near-axis solution and the final design at an aspect ratio equal to eight is smaller than any previously found near-axis solutions. Furthermore, its resulting transport at low collisionality is much smaller than the corresponding transport at W7-X. Being a single field period configuration, it needs significantly less coils than other optimized configurations with a higher number of field periods.

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[2] Jorge, Sengupta, & Landreman, JPP 86 (2020)
[3] Landreman, Sengupta, & Plunk, JPP 84 (2018)
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Modeling of runaway electron suppression with a passive 3D coil in SPARC

R A Tinguely[1], V A Izzo[2], I Pusztai[3], K Särkimäki[4], D T Garnier[1], A Sundström[3], T Fülöp[3], R S Granetz[1], M Hoppe[3,5], C Paz-Soldan[6], R Sweeney[1]

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Abstract. In [1], state-of-the-art modeling of disruption MHD coupled with a self-consistent evolution of runaway electron (RE) generation and transport showed that a non-axisymmetric (n = 1) in-vessel coil can passively prevent RE beam formation during disruptions in SPARC, a compact high-field tokamak projected to achieve a fusion gain Q > 2 in DT plasmas. However, this analysis assumed a tightly fitting ideal wall, unconstrained coil current (up to 590 kA), and an artificially triggered thermal quench (TQ) with no MHD-driven losses. In this talk, we present the results of extended modeling [2] which captures additional physics compared to the reference case: A longer current quench (CQ) is achieved with a more realistic wall location or higher CQ temperature, each leading to higher RE loss than avalanche growth rates. Exploring the effect of the coil current, we find that a limit of 250 kA can allow a RE plateau to form with current ~2 MA depending on the choice of other model parameters. Finally, the TQ and coil work together to enhance RE loss early on, but the resulting late-CQ safety factor (q) profile is non-resonant with the coil, leading to a RE plateau ~1.5 MA. Importantly, the contribution of RE current to the safety factor is not yet included, but this could reduce q, regain resonance, and induce further MHD and transport.

References

[1] Tinguely et al. 2021 Nucl. Fusion 61 124003
[2] Izzo et al. 2022 In preparation.

Space of quasisymmetric configurations: a topological view

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Abstract. Optimisation plays a central role in the pursuit of viable stellarator designs. Customarily, designs are a result of a search in large configuration spaces. Although this approach has proven useful providing many designs, its complexity makes it, to a large extent, a 'black box'.

We present an alternative view on the space of configurations, with a focus on those of the quasisymmetric type. The central idea is to describe configurations inside-out, starting with a shape of a closed curve (the magnetic axis), along with a few additional shaping parameters. The resultant approximate description confers configuration space a topological structure (quasisymmetric phases and phase transitions) and each point in phase space a measure of their desirability as quasisymmetric designs. This description can be leveraged to frame typical quasisymmetric designs as well as explore the space of possibilities in a more exhaustive way.

Transport in Fusion Plasmas: Is the Tail Wagging the Dog?

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Abstract. Advanced experimental scenarios exploit the fascinating yet uncommon ability of magnetically confined plasmas to bifurcate into states of enhanced performance upon application of additional free energy sources. Self-regulation of small-scale turbulent eddies is essential to accessing these improved regimes. Several decades after initial observations, basic principles for these bifurcations and comprehensive understanding from first principles is still largely debated. The near-separatrix edge region is a cornerstone of fusion research and our focus here. We discuss the following conundrum: experimentally, the edge is measured to be turbulent, with fluctuations increasing with proximity to the separatrix whilst local profile analysis predicts linear stability. The edge would thus appear as unfit to produce or sustain a turbulent state. This opposes the experimental trend and precludes possibility for turbulence-induced bifurcations to improved confinement. We show a possible resolution for this problem from flux-driven gyrokinetic analysis of Tore Supra based experimental parameters. We show self-consistent development of a near-separatrix transport barrier. What we establish is threefold: (i) plasma—boundary interaction deeply modifies edge linear stability. Edge turbulence activity is found to require interplay between closed and open field lines. Magnetic connection to the material boundaries deeply modifies global stability at the separatrix. An additional source of free energy arises there. We describe whereby fluctuations, initially localised in a narrow peripheral area of the plasma (the 'tail') expand beyond their region of instability drive and spread throughout the stable edge (the 'dog'). Whilst expanding, (ii) locally-borne eddies spread out and destabilise distant regions of the edge and core. The plasma transitions to a globally-organised state of improved confinement, 'nonlocally' controlled by fluxes of turbulence activity. (iii) Causality is assessed using the information theoretic 'Transfer Entropy' measure, applied to the primitive kinetic data. Flow shear builds as eddies (vorticity) are advected, primarily through pressure inhomogeneities. The expanding interface organises into a stable peripheral transport barrier and the plasma transitions into improved confinement. This lays the groundwork for elucidation of dynamically pertinent feedback loops in transport barrier onset, highly relevant to the fusion programme.

References

[1] This work is currently under consideration: G. Dif-Pradalier, et al., "Transport in Fusion Plasmas: Is the Tail Wagging the Dog?", DOI : 10.21203/rs.3.rs-879691/v1 (2021)

Global fluid simulations of plasma turbulence in stellarators

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Abstract. We present the results of the first 3D, flux-driven, global, two-fluid electrostatic turbulence simulations in stellarators with different configurations, one with an island divertor and another one corresponding to the TJ-K stellarator. The numerical simulations are carried out with the GBS code [1], which solves the two-fluid drift-reduced Braginskii equations and has been extended to simulate plasma turbulence in non-axisymmetric magnetic equilibria.

The vacuum magnetic field of the island divertor configuration corresponds to a 5-field period stellarator and was carefully constructed using Dommaschk potentials [2] in order to describe a configuration with a central region of nested flux surfaces, surrounded by a chain of magnetic islands. In a similar way to the diverted configurations of W7-AS [3] and W7-X [4], particles and heat, transported radially outwards from the core region, reach the island region, which effectively acts as a scrape-off-layer (SOL) with the open field lines striking the walls at specific toroidal locations of the device wall. In this configuration, we find that the radial particle and heat transport is mainly driven by a field-aligned mode with low poloidal wavenumber, whose origin is investigated theoretically. The equilibrium radial electric field in the core is found to be in the ion-root regime, $E_r < 0$. Transport is observed to be larger on the high-field-side of the device, where the amplitude of fluctuations is larger, despite the cross-phase between density and potential being smaller. A very good agreement is obtained when comparing the radial ExB flux of the simulation with the one predicted theoretically due to a single (dominant) coherent mode. In contrast to tokamak simulations [5] and experiments [6], we do not observe radial propagation of coherent filamentary structures (blobs) that usually contribute to intermittent transport events in axisymmetric configurations, thus shedding light on the surprising differences between transport mechanisms in stellarator and tokamak configurations.

Simulations are also carried out by using the vacuum field of TJ-K [7], a six-field period stellarator with torsion that operates with low temperature plasmas. In this configuration, the plasma is limited by the vessel and the heat is exhausted non-axisymmetricallly. We present the first comparisons with experiments.

This work, supported in part by the Swiss National Science Foundation, has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053.

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[7] N. Krause et al., Review of Scientific Instruments **73**, 10 (2002)

Towards realistic divertor turbulence simulations with GRILLIX

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Abstract. Self-consistent turbulence models for the edge and divertor could play a crucial role in helping to understand and control fusion plasmas. Recently, it has been shown that edge turbulence models are able to accurately describe the edge and upstream scrape-off-layer, while in the divertor, turbulence models are not yet able to quantitatively reproduce experimental measurements.

This talk details recent work to validate and improve turbulence modelling of divertor plasmas with the GRILLIX fluid-turbulence model [2]. We first consider the TCV-X21 validation case where significantly better agreement is found at the outboard midplane than at the divertor targets [1]. The divertor results are found to be strongly affected by the resistivity and heat conductivity in the simulations, as this changes the balance of parallel-to-perpendicular transport and the size of scrape-off-layer filaments. We also compare simulations using insulating, ad-hoc and conducting sheath boundary conditions and show that, due to compression associated with terminating internally generated currents, insulating boundary conditions lead to unphysical dynamics. Comparing simulations with and without neutral dynamics, we show that neutrals lead to a localised density source and temperature sink near the X-point, which in turn changes the generation and size of scrape-off-layer filaments.

We then consider an ASDEX Upgrade simulation which is closer to reactor-relevant conditions [3]. We show that neutral dynamics significantly improve the match to experiment for both the target and confined-region profiles by changing the location of the density source and the subsequent turbulence drive. These results are compared to gyrokinetic modelling performed with GENE-X [4] to investigate which kinetic effects are most important for accurate modelling at low collisionality, to guide the development of the fluid model. Through continued comparison against experiment and high-fidelity gyrokinetic modelling, we show that fluid turbulence simulations can interpret existing experimental results across the edge and divertor with increasing accuracy and that predictions of reactor-relevant plasmas are within reach.

References

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Nonlinear dynamics of nonadiabatic chirping-frequency Alfvén modes in Tokamak plasmas

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Abstract. Frequency chirping is a common phenomenon in both space and laboratory plasmas. Chirping Alfvén modes are thought to be detrimental to the confinement of energetic particles (EPs) in a burning Tokamak plasma and enhancing EP transport. The nonlinear dynamics of this chirping behaviour has been one of the long-studied physics problems for decades. For weakly-driven modes near marginal stability, this phenomenon has been explained based on a 1-D bump-on-tail model with sources and sinks, which predicts an adiabatic chirping; that is, a chirping characterised by a frequency variation, in the bounce time of wave-trapped particles, much smaller than their bounce frequency. A more general model has been developed by Zonca and co-workers without time scale separation between nonlinear mode evolution and phase space transport. In the weak drive regime, it reproduces the Berk-Breizman paradigm. In the opposite limit, in which energetic particle effects have a non-perturbative character, it predicts a nonlinear dynamic characterised by phase-locking and non-adiabatic frequency chirping, indeed observed in both laboratory and space plasmas. In this work, the nonlinear evolution of a single-toroidal-number chirping mode is analysed by means of numerical simulations. Both hybrid MHD-gyrokinetic simulations by XHMGC and fully gyrokinetic simulations by ORB5 show that such a mode can chirp in a wide frequency range along the shear Alfvén continuum. It is worth mentioning that frequency-chirping studies, by means of the fully gyrokinetic simulations, offer the possibility to study such nonlinear behaviors of all plasma species with fully self-consistent kinetic dynamics. In addition, the Hamiltonian-mapping test particle approach is used to investigate the phase space dynamics. Nonadiabatic frequency chirping dynamics, such as the mode saturation scaling, the density flattening, the broadening of the resonance region, the self-consistent modified mode radial structure, and the trapping-detrapping process of the resonant particles will be discussed in detail.

Current singularities on rational surfaces including pressure effects

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Abstract. Non-axisymmetric ideal magnetohydrodynamic equilibria with a continuum of nested flux surfaces and a continuous rotational transform generically exhibit singular currents on rational surfaces. These currents have two components: a surface current (δ-function in radius) that prevents the formation of a magnetic island and an algebraically divergent Pfirsch-Schlüter current when a pressure gradient is present across the rational surface. At an adjacent flux surface of the rational surface, the traditional treatment gives the Pfirsch-Schlüter current density to scale as $j \sim 1/\Delta\iota$, where $\Delta\iota$ is the difference of the rotational transform between the two flux surfaces. If the distance x between flux surfaces is proportional to $\Delta\iota$, the scaling relation $j \sim 1/\Delta\iota \sim 1/x$ will lead to a paradox that the Pfirsch-Schlüter current is not integrable. In this work, we investigate this issue by considering the pressure-gradient-driven Pfirsch-Schlüter current in the Hahm-Kulsrud-Taylor problem, which is a prototype for singular currents arising from resonant perturbations. We show that because of the δ-function current at the resonant surface, the neighboring flux surfaces are strongly packed with $x \sim (\Delta\iota)^2$. Consequently, the Pfirsch-Schlüter current $j \sim 1/\sqrt{x}$, making the total current finite, thus resolving the paradox.

Advanced modelling and existence conditions of Edge Harmonic Oscillations

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Abstract. Advanced scenarios which retain H-mode-like confinement properties but are intrinsically ELM-free offer a safe alternative to the operation of ITER and future devices. Edge Harmonic Oscillations (EHOs), which are long-wavelength MHD instabilities that saturate at the plasma edge, replace ELMs during QH-mode operation by enhancing particle transport just enough to avoid the instability threshold of peeling-ballooning modes [1]. Recent work [2] has theorised EHOs to be the nonlinear saturated state of exfernal modes. The usual route to numerically model EHOs is by taking an equilibrium which is linearly unstable, then evolve it using an initial value code until nonlinear saturation is achieved. Meanwhile, in this work it is demonstrated that an equivalent final saturated exfernal mode obtained by nonlinear initial value simulations can be recovered using the nonlinear 3D equilibrium VMEC code [4]. Such proof of principle eases the load on the required numerical computations, allowing then for extensive parameter scans. This talk presents the conditions to obtain both linearly unstable exfernal modes and non linearly saturated EHOs. It is first shown using a linear analytical approach that the parameter space for exfernal modes increases with pedestal pressure gradient, and decreases with edge magnetic shear. [2, 3]. The same dependency on these parameters is also observed in the nonlinear phase using the VMEC free-boundary code. The resulting parameter space can be modified by the plasma shape, decreased by the presence of a separatrix, and expanded by the use of internal RMP coils or external EFCCs for generating non-axisymmetric external magnetic perturbations. Finally, and in accordance to previous analytical modelling and experimental data analysis [2, 5], it is found in linear numerical simulations that toroidal rotation only weakly modifies the excitation of exfernal modes, but defines the frequency at which EHOs are measured in experiments. The obtained parameter space for excitation and saturation of exfernal modes might offer possible routes to robustly access QH-mode.

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Kinetic-MHD hybrid simulations of MHD instabilities in toroidal plasmas with kinetic thermal ion effects

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Abstract. One of the critical issues in the confinement of the Large Helical Device (LHD) plasmas is to suppress the pressure driven magnetohydrodynamic (MHD) instabilities such as ballooning modes and interchange modes. In the LHD experiments, about 5% of the volume averaged beta value is achieved without large MHD activities. However, the nonlinear simulations based on the MHD model for the high beta LHD plasmas showed that the MHD instabilities induce the core crash decreasing the central pressure, which is inconsistent with the LHD experimental results[1]. For solving the inconsistency between the theoretical predictions based on the MHD model and the LHD experimental results, the kinetic effects of thermal ions on the MHD instabilities for the high beta LHD plasmas have been investigated by using the kinetic MHD simulations[2-4]. From the kinetic MHD simulations, it is found that the linear growth rate and the saturation level of the pressure driven MHD instabilities are significantly reduced by the kinetic thermal ions so that the high beta plasmas can be maintained. This results from the fact that the response of the trapped ions to the instabilities is weakened by the precession drift motion in the three-dimensional magnetic field. In the LHD, the ions trapped in the helical ripple have the precession drift motion not only in the toroidal direction but also in the poloidal direction. The poloidal precession drift motion enables the trapped ions to move through both positive and negative perturbed regions of the instabilities in the growth phase of the instabilities. Thus when the precession drift frequency of the trapped ions with respect to the mode phase is comparable with, or larger than, the growth rate of the instabilities, the response of the trapped ions to the instabilities is weakened, which leads to the suppression of the instabilities.

The ions trapped by the helical ripple do not exist in axisymmetric configurations such as tokamaks. However, since the essence of the suppression mechanism shown for the LHD plasmas lies in the fact that ions move across the magnetic field line due to the curvature and gradient B drifts, the same suppression mechanism may exist for slowly growing pressure driven instabilities in the axisymmetric configurations. In addition to the analysis for the LHD plasmas, we have applied the kinetic MHD simulations to study an infernal mode limiting the beta value in tokamak plasmas[5]. The kinetic thermal ion effects on the beta limit due to the infernal modes in tokamak plasmas will be also reported.

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Electromagnetic instabilities and plasma turbulence driven by electron-temperature gradient

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Abstract. Electromagnetic (EM) instabilities and turbulence driven by the electron-temperature gradient are considered in a local slab model of a tokamak-like plasma, with constant equilibrium gradients (including magnetic drifts, but no magnetic shear). The model describes perturbations at scales both larger and smaller than the flux-freezing scale (d_e, the electron skin depth), and so captures both electrostatic and EM regimes of turbulence. The well-known electrostatic instabilities — slab and curvature-mediated ETG — are recovered, and a new instability is found in the EM regime, called the Thermo-Alfvénic instability (TAI). It exists in both a slab version (destabilising kinetic Alfvén waves) and a curvature-mediated version, which is a cousin of the (electron-scale) kinetic ballooning mode (KBM). The curvature-mediated TAI is shown to be dominant at the largest scales covered by the model (greater than d_e but smaller than ρ_i), its physical mechanism hinging on the fast equalisation of the total temperature along perturbed magnetic field lines (in contrast to KBM, which is pressure balanced). A priori critical-balance estimates suggest that the TAI-driven heat-flux scales more steeply with the temperature gradient than that due to electrostatic ETG turbulence, giving rise to stiffer transport. Numerical results on the saturation of the resultant electromagnetic turbulence and the role of zonal flows and zonal fields are presented.

GENE-3D/KNOSOS-Tango: A New Transport Model for Stellarators

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Abstract. Due to advancements in stellarator optimization with respect to MHD stability and neoclassical transport, turbulence has become one of the limiting factors, if not the main one, for stellarator confinement. This has recently been confirmed by the results of the first experimental campaigns of Wendelstein 7-X (W7-X) [1], which showed that ion-temperature-gradient (ITG) driven turbulent transport exceeds its neoclassical counterpart and controls the behavior of the temperature profiles. More specifically, it has been observed that the ion temperature is clamped around 1.5 keV in electron heated plasmas, regardless of the heating power, plasma density, and magnetic configurations [2]. It has been proposed that the clamping is due to an increase in Te/Ti ratio on the ITG turbulence [2]. However, to date, there is not a valid transport model able to capture this effect for stellarators. Indeed, only recently, using some of the world's most powerful supercomputers, it is possible to study turbulence in the whole plasma volume of stellarators. One code capable of performing such simulations is GENE-3D, the extension of the GENE code [3] to fully three-dimensional magnetic field geometries [4]. However, those simulations are still limited to turbulence time scales and, therefore, not be suitable to capture the profile evolution needed to study the clamping of the ion temperature. For this reason, a recent effort has been spent on extending GENE-3D and allowing simulations from the turbulent to the transport timescales. For this purpose, we have adopted a multiple-time scale approach, which simulates turbulence and transport phenomena only on their natural timescales [5]. We have achieved this by coupling the turbulence code, GENE-3D, and the neoclassical code, KNOSOS [6], to the transport code Tango [7]. In this contribution, we present this novel tool, GENE-3D/KNOSOS-Tango, and use it for the first time to study the ion temperature profile evolution for electron heated plasmas in W7-X, where we reproduce the ion temperature clamping. In addition, we discuss how different effects might affect the ion temperature profiles, namely, the radial electric field, neoclassical transport, and the Te/Ti ratio, to investigate the main mechanisms causing the ion temperature clamping.

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Full-f gyrokinetic simulation of plasma turbulence and transport barrier under ion/electron heating

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Abstract. Transport barrier, which acts as the shielding layer of particle and heat transport by suppressing turbulence, has a crucial key to achieve high-performance plasma confinement. In the NBI modulation tests in JT-60U reversed magnetic shear discharge, they found that after the change from balance-NBI to co-NBI, internal transport barrier (ITB) is suddenly collapsed, because mean flow shear in outer half ITB region becomes weak in addition to the change of toroidal rotation shear [1]. This indicate that not local but global pattern of mean E_r, which satisfies the radial force balance, is crucial for ITB formation. For the comprehensive study of such global effects, we have investigated the effect of momentum injection for ITB formation by means of our 5D full-f gyrokinetic code GKNET [2-4]. We found that co-current toroidal rotation in outer region can change mean E_r shear through the radial force balance, leading to ITB formation [5]. However, enough external momentum injection was required for ITB formation in our previous work based on adiabatic electron model.

In this study, we have introduced kinetic electron process based on hybrid electron model and then performed flux-driven ITG/TEM simulation for reversed magnetic shear configuration. We newly found that enhanced ITG mode by kinetic electron dynamics can provide robust net co-current intrinsic rotation around q_{min} surface. In addition, once electron heating steepens electron temperature gradient, TEM is selectively destabilized in negative magnetic shear region, leading to opposite intrinsic rotation, because the ballooning angle of TEM is opposite to that of ITG mode. Such intrinsic rotations with different direction can provide steep rotation shear and resultant strong E_r shaer through the radial force balance, decreasing the ion turbulent thermal diffusivity around q_{min} surface to the neoclassical transport level. This indicates that the co-existence of different modes can trigger the discontinuity near q_{min}, leading to spontaneous ITB formation. These new findings can contribute to ITB formation in ITER and DEMO plasmas.

We will also address the effect of ion/electron heating and momentum injection, which make ITG, TEM and Parallel Velocity Gradient (PVG) modes unstable, on particle transport.

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Modeling the onset of toroidal ion temperature gradient modes in stellarator geometry

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Abstract. We present a coarse-grained gyrokinetic theory to describe the linear onset of ion-temperature gradient (ITG) modes in toroidal fusion plasmas, based on a separation of scales in the spatial variation of magnetic geometry. The coarse graining is implemented by smoothing of the "drift curvature" profile at local minima, with the most unstable result yielding an estimate for the onset gradient of ITG modes. The result agrees surprisingly well with linear gyrokinetic simulation results for a number of stellarator designs. Drawing insight from the theory, we propose a novel magnetic configuration, based on a simple modification of the Wendelstein 7-X stellarator, which has double the critical gradient, in support of the model predictions.

Available energy and its relation to turbulent transport

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Abstract. Any collisionless plasma possesses some available energy" (AE), which is that part of the thermal energy that can be converted into instabilities and turbulence. Here, I present an investigation into the AE carried by trapped electrons in tokamaks and stellarators. For tokamaks, the investigation focuses on how AE varies with the various parameters found in equilibria discussed by Miller *et al* [1]. This nonlinear measure remarkably captures many known phenomena; negative shear, high Shafranov shift, and negative triangularity all tend to be stabilizing as indicated by a reduction in AE. Next, a comparison is made between AE and saturated turbulent energy fluxes resulting from collisionless trapped electron modes in both stellarator and tokamak devices. A close correlation is found, resulting in a power law, which can furthermore be explained by a simple argument. This highlights that AE accurately captures the effects of geometry on turbulence. Finally, I investigate the AE of ions in slab geometries. The turbulent heat fluxes are found to scale with the ion temperature gradient the the third power, which corresponds to the prediction from critical balance [2].

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Energetic particles and coupled Alfvén-acoustic eigenmodes in tokamaks: theoretical insight and modelling

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Abstract. Research on the resonant interaction between energetic particles and Alfvén waves in tokamaks has mostly focused on incompressible waves from the shear-Alfvén branch of the MHD spectrum and, in particular, on toroidicity-induced eigenmodes (TAEs). Eigenmodes resulting from the coupling between shear-Alfvén waves and acoustic (or ion-sound) waves are not a new subject [1, 2], but have recently attracted attention due to observations of MHD activity below the TAEs characteristic frequency ω_{TAE} in high-β plasmas [3, 4] and to a series of theoretical developments [5, 6, 7]. Of particular interest, is the prediction of coupled shear-Alfvén and acoustic eigenmodes at frequencies below but close to ω_{TAE} and, simultaneously, significantly above the typical ion-sound frequency. In these conditions, such eigenmodes may interact with energetic particles in a fashion similar to TAEs and play a still unexplored role in the stability of fusion plasmas.

In this talk, the properties of coupled shear-Alfvén and acoustic continua are discussed with the aid of an analytical equilibrium model, highlighting the role of plasma shape (mainly elongation and shift) to open frequency gaps close to ω_{TAE} [7], which are a generalisation to shaped equilibria of previous analytical results obtained in the limit of circular magnetic surfaces and finite toroidicity [2, 5]. Global eigenmodes inside such frequency gaps are found unstable to energetic-particle populations typical of tokamak operation, while fundamental resonances with passing ions are shown to take place for velocities between the Alfvén and sound speeds [7]. This theoretical insight is then employed to explain the properties of recently reported Alfvénic activity just below ω_{TAE} in tokamak plasmas [4].

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Confinement in 3-dimensional magnetic fields: Loss mechanisms and optimization strategies

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Abstract. Magnetic confinement reactors must confine both the thermal and energetic particle populations. Excessive losses of fusion-born alpha particles can inflict damage to material structures and reduce heating of the bulk plasma. When 3D magnetic fields are introduced, such as in a stellarator or rippled tokamak, collisionless particle orbits are no longer confined and collisional transport is generally enhanced. Using new optimization strategies [1,2], we demonstrate that excellent collisional and collisionless confinement can be obtained by achieving precise quasisymmetry on one surface or throughout a volume. To gain further insight into the nature of energetic particle confinement in 3D magnetic fields that deviate from quasisymmetry, we perform a classification of loss mechanisms in a set of magnetic configurations. We identify the relative impact of banana diffusion, super-banana orbits, ripple trapping, transitions between particle classes, and complex periodic orbits. We propose optimization strategies to mitigate each loss type.

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Electron-cyclotron heating and kinetic instabilities of a mirror confined plasma

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Abstract. In this paper we focus on electron-cyclotron interaction of electromagnetic waves and plasma confined in laboratory mirror traps. Such studies are usually associated with electron-cyclotron resonance plasma heating used to achieve a high electron temperature in open magnetic configurations of various scales, from relatively compact technological ion sources to large-scale plasma traps used in fusion researches. These applications have a long history but still remain topical, mostly due to a progress in the development of high-power sources of microwave radiation, such as gyrotrons, followed by essential increasing the rf-power load and thereby by increasing the population of non-equilibrium resonant electrons. The interaction of rf waves with resonant electrons leads to a specific transport of electrons in a momentum space that ends with their falling into the loss-cone and precipitation from a trap. Such electrons may result also in the development of electromagnetic electron-cyclotron instabilities in a wider frequency range then those used for the resonant plasma heating. If this occurs, suprathermal electrons act as an amplifying medium for its own electromagnetic noise while bulk plasma and vacuum chamber serve as a cavity providing positive feedback for unstable modes. In many cases this mechanism determines the losses of excess energy stored in accelerated electrons, thereby limiting the achievement of peak plasma parameters in applications. Recent advance in the basic theory helps to optimize the ECR heating [1-4] and suggests approaches for the control of unwanted plasma turbulence caused by the strong ECR heating [5-10]. We review these new ideas aimed at achievement of better plasma performance in different applications, and discuss its experimental verification available at present.

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Physics of drift Alfvén instabilities and energetic particles in fusion plasmas

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Abstract. Shear Alfvén wave (SAW)/drift Alfvén wave (DAW) fluctuations can be destabilized by energetic particles (EPs) as well as thermal plasma components, which play a key role in the EP energy and momentum transport processes in burning fusion plasmas. The drift Alfvén energetic particle stability (DAEPS) code, which is an eigenvalue code using the finite element method (FEM), was developed to analyze Alfvén instabilities excited by EPs [1]. The model equations, consisting of quasi-neutrality condition and Schrödinger-like form of vorticity equation, are derived within the general fishbone-like dispersion relation (GFLDR) theoretical framework [2,3], which is widely used to analyze SAW/DAW physics. The mode structure decomposition (MSD) approach and asymptotic matching between the inertial/singular layer and ideal regions are adopted. Therefore, the DAEPS code can provide not only frequency and growth/damping rate, but also the parallel mode structure as well as the asymptotic behavior corresponding to the singular layer contribution. Thus, it fully describes fluid and kinetic continuous spectra as well as unstable and damped modes. The model equations have been extended to include general axisymmetric geometry, and to solve for the response of circulating and trapped particles by means of the action angle approach [5]. In this work, we discuss linear dispersion relation and parallel mode structure of drift Alfvén instabilities excited by EPs, computed by the DAEPS code with realistic experimental plasma profile and magnetic configuration. Based on this information, we adopt the Dyson-Schrödinger Model (DSM) [4] to further analyze EP energy and momentum flux. We will also briefly discuss how the parallel mode structure of the drift Alfvén instabilities can be used in the DSM to calculate the nonlinear radial envelope evolution and the EP transport [4-6].

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Hydrogenic isotope mass scaling of multiscale turbulent transport in the H-mode pedestal

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Abstract. The hydrogenic isotope mass scaling of multiscale turbulent transport in the edge region of tokamaks is studied. In the L-mode edge, the nonadiabatic electron drive can play a key role in favourably reversing simple gyroBohm mass scaling, toward agreement with experimental observations, for ion-scale ion temperature gradient (ITG)-driven and trapped electron modes (TEM) [1]. However, in the H-mode pedestal, multiscale turbulence (coupling ion and electron scales) often dominates. Nonlinear, multiscale gyrokinetic simulations are used to study the particle and energy transport of mixed deuterium-tritium (D-T) plasmas in the pedestal using parameters based on a DIII-D ITER baseline H-mode experiment, where neoclassical ion transport and electron temperature gradient (ETG)-driven turbulent transport are needed to match the total experimental power balance for the energy flux [2]. The influence of the ion-electron coupling on the isotope mass scaling of ETG turbulence and the role of electron-scale turbulence in breaking the gyroBohm isotope mass scaling are characterized. The isotope mass dependence of electromagnetic pedestal turbulence and the kinetic ballooning mode (KBM) threshold, which can have an impact on pedestal structure, is also explored. For mixed D-T plasmas, the influence of non-trace thermalized and non-thermalized helium ash can further affect the turbulent energy isotope scaling, including through electromagnetic stabilization of the bulk ion turbulence, as well as unfavourable D-T particle flow separation [3]. Overall, these results have implications for global energy and particle confinement and power threshold requirements for achieving H-mode regimes in the transition from D to D-T plasmas.

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Microstability and transport in high beta spherical tokamaks

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Abstract. Compact fusion reactor designs can offer several attractive advantages in the pursuit of commercially viable fusion energy, leading to ongoing interest alongside more conventional approaches. Reactor designs based on the spherical tokamak (ST) approach must operate at high plasma beta, β, which in turn requires sufficiently low turbulent transport such that steep pressure gradients can be maintained in steady-state operation. Such a regime sits outside the operational limits of existing tokamaks, limiting the utility of existing confinement scalings and motivating the use of first-principles simulation to explore the compatibility of confinement properties with candidate operating scenarios.

Local microstability analysis of a range of high beta spherical tokamak designs demonstrate a near complete suppression of typical electrostatic instabilities. Instead, a mixture of weakly unstable tearing and twisting parity electromagnetic instabilities, similar to those found in pedestal simulations of existing tokamaks, are found to dominate across the plasma. The instability mix includes multiple classes of microtearing mode (MTM), hybrid ion temperature gradient - kinetic ballooning modes (ITG-KBM) and zero frequency extended electrostatic instabilities. Access to second stability is shown to be vital for accessing high pressure gradients whilst avoiding strongly unstable, long wavelength, KBMs. This access is sensitive to the plasma shaping and current profile, through q and $\hat{s}$, and it is shown that negative triangularity is incompatible with this requirement. This leads to the identification of a "*high* q_0" positive triangularity equilibrium as a candidate for further investigation. In the presence of sheared flows, linear analysis suggests that this case will be dominated by a collisionally driven MTM which exists at the ion scale in the binormal direction and the electron scale in the radial direction. Such anisotropic instabilities are computationally expensive to simulate due to substantial resolution requirements.

Nonlinear simulations of such high beta STs are challenging, due both to the extreme resolution requirements imposed by the unstable MTM, the long time scales associated with modes near marginality and the physics impact parallel streaming along perturbed field lines. Here we examine a number of nonlinear simulations, with multiple gyrokinetic codes, in order to shed light on the expected confinement properties of the ST reactor designs considered. Transitions from pseudo-saturated states to higher heat flux are observed and the relation between this transition and the known non-zonal transition is explored.

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Full-discharge simulation and optimization with the RAPTOR code, from TCV and AUG to ITER and DEMO

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Abstract. Full-discharge modeling and optimization prior to experiments is necessary for reliable operation of future tokamak devices like ITER and DEMO, to achieve high-performance plasma regimes and maintain the plasma state within stability limits at all times, even in the absence of extensive real-time measurements. Combining fast numerical schemes and semi-empirical physics modules, the RAPTOR core transport solver achieves rapid simulations of the time evolution of the plasma profile dynamics. Fast inter-discharge optimization of the different phases of tokamak operation allows for model-based optimized strategies for ramp-up, flat-top and ramp-down [1, 2].

To achieve advanced scenarios on AUG, early heating is applied during the plasma current ramp-up, allowing for the fast formation of an elevated q profile [3]. Applying a model-based approach, the available actuators are optimized to develop a reproducible scenario, aiming to access an early stationary phase, while avoiding the onset of deleterious NTMs.

Optimal operating points during the flat-top phase can be explored by directly solving for a stationary transport solution. Applying the QLKNN-hyper-10D transport model [4], the performance of the ITER hybrid scenario is optimized for different combinations of plasma current, plasma density, pedestal height and heating mix, tailoring the q profile to maximize the fusion gain Q [5].

An optimized ramp-down strategy is critical for safe and fast termination of plasma discharges in a pulsed DEMO, both in planned and emergency shutdown scenarios, avoiding plasma disruptions and excessive heat loads to the first wall. Plasma stability limits and machine specific technical requirements constrain the achievable ramp-down rate. We will present how optimizing the time evolution of plasma current, plasma shaping, auxiliary heating and impurity gas injection can ensure a safe ramp-down scenario, avoiding radiative collapse and vertical instability. The DEMO predictions will be backed up with dedicated ramp-down experiments on TCV and AUG.

We will discuss along this work the role of simplified transport models and more advanced physics ones, as well as the interaction with experiments and more complete plasma integrated simulators.

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Advanced modelling of cross-field turbulent transport for core and edge plasma

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Abstract
Cross-field turbulent transport is a key player to determine the tokamak operation constraints governed by the exhaust limitations. Indeed, combined with large-scale drifts, and collisional transport it competes with the SOL parallel conductive/convective transport to determine the width of the heat and particle channels impinging onto the target plates. In the current fluid transport modelling, the transverse fluxes are assumed to be driven by local gradients, and consequently defined by effective diffusion or conductivity coefficients which are tuned to match experimental radial profiles usually known at a single poloidal location, typically in the midplane. It is then a critical issue to provide accurate input values of these transport coefficients in the simulation codes to determine the SOL width, and thus accurately take into account plasmawall interaction. In this talk, we will introduce a new model that allows a self-consistently determination cross-field fluxes in the edge and scrape-off layer (SOL) region of diverted plasma [1]. A two-equation model based on the local evolution of two characteristic turbulent quantities, at this step the turbulent kinetic energy $\kappa = \frac{1}{2} < \tilde{v}^2 >$ and its dissipation rate (interpreted here as the loss via the energy cascade to the energy dissipation scale), provides the values of the diffusion/conductivity coefficients as κ^2/ϵ. This model is inspired by the work done from the 70s in hydrodynamics turbulence numerical modelling [2]. In this model using the Boussinesq assumption, the turbulent stresses and the deformation speeds of the mean flow are proportional that defines the eddy viscosity ν_t. Two additional transport equations algebraically derived provide the local evolutions of κ and ϵ, governed by a linear term driving exponential transients with the interchange-like growth rate and a quadratic saturation term. The theoretical analysis shows that both predatorprey models [3] and quasilinear theory [4] classically used to describe plasma turbulence provide a theoretical background to this $\kappa-\epsilon$ description of turbulent transport. Finally, comparing scaling laws behaviors and experimental data with 1D and 2D plasmawall simulations performed with SOLEDGE2D, we will show the ability of the model to capability to generate changes of the transport regimes in a self-consistent manner as well as to predict equilibrium profiles. The model is shown to predict self-consistently the radial and poloidal dependencies of turbulent transport and the ballooning aspect reported in experiments.

References

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