JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP

THEORY OF FUSION PLASMAS

Villa Monastero, Varenna, Italy

September 2-6, 2024

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 (ICPC)
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PROGRAMME FOR THE

JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP

"THEORY OF FUSION PLASMAS"

Villa Monastero, Varenna, Italy - 2 - 6 September 2024

SUNDAY September 1st, 2024

15:00 - 19:00	Registration in Villa Monastero

MONDAY, September 2nd, 2024

9:00		*Welcome*	*J.P. Graves and P. Helander on behalf of G. Gorini*

Session 1: Fundamental theory of turbulence

9:10	I-1	R. Nies	Turbulence saturation by propagating zonal flows
9:55	I-2	S. Mahajan	Transport Barriers in Magnetized Plasmas- General Theory with Dynamical Constraints
10:40		*Coffee break*	
11:10	I-3	A. Dudkovskaia	On electromagnetic turbulence suppression in steep gradient regions within the generalised gyrokinetic description of tokamak plasmas
11:55	I-4	Y. Zhang	Dimits transition in electromagnetic ITG turbulence
12:40		*Group Photo in Villa Monastero's garden*	
12:50		*Lunch*	

Session 2: Extended MHD

15:00	I-5	E. Balkovic	Direct prediction of nonlinearly saturated neoclassical tearing modes with SPEC
15:45	I-6	D. Borgogno	Mutual interaction of magnetic reconnection and runaway electrons in a postdisruption plasma
16:30		*Coffee break*	
17:00	I-7	F. I. Parra	Linear equations for stellarator local MHD equilibria around irrational and rational flux surfaces
17:45		*end*	
19:30		Welcome Party	Blanco Lounge Bar in Perledo, Via del Lido 2

TUESDAY, September 3rd, 2024

Session 3: Advanced gyrokinetic simulations and numerical methods

8:30	I-8	J. N. Sama	Ion temperature gradient mode mitigation by energetic particles, mediated by forced-driven zonal flows
9:15	I-9	J. Dominski	Whole device gyrokinetic simulations of ITER H-mode plasma with coupled core edge models
10:00		*Coffee break*	
10:30	I-10	T. Hayward-Schneider	Global gyrokinetic instabilities going to high plasma beta
11:15	I-11	E. Sonnendruecker	HPC implementation of structure-preserving geometric PIC models
12:00		*Lunch*	
14:00			Poster session 1: P1 - P13
16:00		*Coffee break*	
16:30			Poster session 2: P14 - P27
18:30		*End poster sessions*	
21:30		String quartet concert	Villa Monastero

WEDNESDAY, September 4th, 2024

Session 4: Design and optimisation of novel configurations

9:00	I-12	G. Plunk	A Neo-Spitzer stellerator
9:45	I-13	E. Sánchez	CIEMAT-QI4: compatibility of physics performance with coil and blanket requirements in an optimized magnetic configuration
10:30	I-14	F. J. Escoto	MONKES: a neoclassical code for fast evaluation of the bootstrap current and stellarator optimization
11:15		*Coffee break*	
11:35	I-15	S. D. Deshpande	A Strategy for Indian DEMO and Challenges in Bringing Fusion Electricity to Grid
12:20	I-16	S.A. Henneberg	A flexible, compact stellarator-tokamak hybrid concept
13:05		*Lunch*	
19:15		Departure for Conference diner (departure of bus at the entrance gate of Villa Monastero)	

THURSDAY, September 5th, 2024

Session 5: Plasmas in the pedestal, edge, SOL, sheath

8:30	I-17	W. Clarke	Electromagnetic interchange turbulence driven by temperature gradients
9:15	I-18	N. Chen	Drift wave soliton formation via beat-driven zonal flow and implication on plasma confinement
10:00		*Coffee break*	
10:30	I-19	A. Geraldini	Cross-field fluctuations in strongly ExB sheared plasmas near a solid target
11:15	I-20	T. Stoltzfus-Dueck	Intrinsic Rotation Drive by Neutrals and Scrape-off-Layer Flows
12:00		*Lunch*	
14:00			Poster session 3: P28 - P40
16:00		*Coffee break*	
16:30			Poster session 4: P41 - P53
18:30		*End poster sessions*	

FRIDAY, September 6th, 2024

Session 6: Energetic Particles and Heating

9:00	I-21	T. Barberis	Fast-ion-driven vertical displacement oscillatory modes in tokamak plasmas
9:45	I-22	C. A. Johansson	On electron cyclotron resonance start up in Wendelstein 7-X
10:30		*Coffee break*	
11:00	I-23	C. Sung	Gyrokinetic Analysis for Fast Ion Effects on Turbulence in KSTAR Plasmas
11:45	I-24	M. Hoppe	An upper neutral pressure limit for low Z benign termination of runaway electron beams in TCV
12:30		*Closing session*	
12:40		*end*	

Turbulence saturation by propagating zonal flows

R. Nies[1,2], F. Parra[1,2], M. Barnes[3], N. Mandell[2] and W. Dorland[4]

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Abstract. The energy confinement of tokamaks is limited by turbulent transport, making the understanding of turbulence saturation crucial. In previous work [1], tokamak turbulence was modelled using the critical balance conjecture [2], which posits that the turbulence parallel and decorrelation timescales are comparable. The theory does not however predict the radial length scale of the turbulence - which is required to obtain its saturation amplitude. Reference [1] made the assumption of perpendicular spatial isotropy to obtain a solution. We show using gyrokinetic simulations that the turbulence is in fact anisotropic in the radial and binormal directions, and follows the experimentally inferred grand critical balance [3]. The radial length scale is thus determined by the balance of the nonlinear, parallel, and magnetic drift timescales. Grand critical balance requires a revision of the scalings of [1], e.g. the heat flux scales linearly in the temperature gradient instead of cubically, which we show to be satisfied in gyrokinetic simulations using the stella [4] and GX [5] codes.

We posit that the validity of grand critical balance is predicated on the existence of a new propagating zonal flow mode. We characterise this mode through a generalised theory of the secondary instability [6], which considers the growth of zonal flows due to a streamer (the primary mode) driven by microinstabilities. Our generalised theory includes the effects of parallel streaming and magnetic drifts, and describes two new modes, the oscillating toroidal secondary and the purely growing neoclassical secondary, in addition to the classical secondary [6]. The latter is found to only be relevant at large primary amplitudes, above the values seen in gyrokinetic simulations or expected from grand critical balance. At relevant primary amplitudes, the zonal flow behaviour is instead governed by the neoclassical secondary, which relies on the transport of momentum in banana orbits, and the toroidal secondary, which involves up-down asymmetric fluxes balancing the compressibility of zonal flows induced by toroidicity. Good agreement is demonstrated between the analytical theory, gyrokinetic simulations of the secondary, and the zonal flow behaviour in fully nonlinear simulations. We also show numerical evidence of the role of the toroidal secondary on turbulence saturation.

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Transport Barriers in Magnetized Plasmas- General Theory with Dynamical Constraints

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A fundamental dynamical constraint - that fluctuation induced charge-weighted particle flux must vanish- can prevent instabilities from accessing the free energy in the strong gradients characteristic of Transport Barriers (TBs). Density gradients, when larger than a certain threshold, lead to a violation of the constraint and emerge as a stabilizing force. This mechanism, then, broadens the class of configurations (in magnetized plasmas) where these high confinement states can be formed and sustained. The need for velocity shear, the conventional agent for TB formation, is obviated. The most important ramification of the constraint is to permit a charting out of the domains conducive to TB formation and hence to optimally confined fusion worthy states; the detailed investigation is conducted through new analytic methods and extensive gyrokinetic simulations.

It is also shown how this constraint-based theory is a great help in categorizing and understanding the observed confinement trends in the ITPA data base. With this support from the current machines, one could extrapolate the theory predictions to future machines (in possibly uncharted physics domains) with greater confidence.

On electromagnetic turbulence suppression in steep gradient regions within the generalised gyrokinetic description of tokamak plasmas

A. Dudkovskaia

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Abstract. The tokamak plasma confinement is generally degraded by turbulence. In steep gradient regions of the finite beta plasma (beta is a ratio of thermal to magnetic energy), this turbulence arises from electromagnetic instabilities, e.g. kinetic-ballooning modes and micro-tearing modes [1, 2], typically described by the gyrokinetic theory. Generalised gyrokinetics is derived in [3] to ensure the effects of steep pressure gradients (and the associated neoclassical currents) are consistently incorporated within the gyrokinetic formulation. Coupled to the extended neoclassical equilibrium distribution function derived in [4], it allows one to investigate the impact of neoclassical effects on plasma turbulence and vice versa, while ensuring consistent ordering and being valid for a finite beta, arbitrary tokamak plasma with no restriction on the ratio of poloidal to toroidal magnetic field (important for spherical tokamaks). In particular, the local flux tube version of [3, 4] extends the low flow gyrokinetic theory of [5] to the finite beta, finite poloidal magnetic field limit. As one example, inclusion of these higher order corrections is found to suppress the kinetic-ballooning mode growth rate in strong gradient regions for lower toroidal mode numbers [6]. The latter is particularly important to model the nonlinear electromagnetic turbulence in a burning (power plant like) plasma, where the leading order, equilibrium flow shear is anticipated to be too low to influence nonlinear simulations.

Acknowledgments: J. Candy, J.W. Connor, D. Dickinson, F. I. Parra, H. R. Wilson

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Dimits transition in electromagnetic ITG turbulence

Yujia Zhang[1,2], Michael Barnes[1,3], Alexander A. Schekochihin[1,4], Toby Adkins[5], and Plamen G. Ivanov[1]

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A two-species (one main ion and electrons) fluid model for describing ion temperature gradient (ITG) turbulence in a Z-pinch magnetic geometry has been derived from gyrokinetics. First, we carry out a mass ratio expansion ($\sqrt{m_e/m_i} \ll 1$) similar to the procedure introduced in (Schekochihin et al., 2009). It is then followed by a subsidiary expansion in small $k_\perp \rho_i$, where $k_\perp$ is the typical wavenumber perpendicular to the mean field line and ρ_i is the ion gyroradius. Since we study ITG in the long-wavelength limit $k_\perp \rho_i \ll 1$, it requires shifting the driving scale of ITG also to long wavelength, leading to the cold-ion assumption, which is used in electrostatic ITG fluid models studied previously (Ivanov et al., 2020, 2022). The novelty of the model presented here is that it retains electromagnetic (EM) effects and aims to provide a physical mechanism by which the ITG turbulence transitions from a low-transport, zonally dominated state to a high-transport state with weak zonal flows. It is found that Maxwell stress tends to shift the Dimits transition to lower temperature gradients. Generally as β is increased, where β is the ratio between plasma pressure and magnetic pressure, Maxwell stress starts to erode the zonal flow, setting a threshold β above which the turbulence can no longer support a strong zonal flow and hence produces relatively large transport. Studying this model is an attempt to understand why many local gyrokinetic simulations of ITG turbulence lead to divergent heat fluxes at finite β(Pueschel et al., 2013).

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Direct prediction of nonlinearly saturated neoclassical tearing modes with SPEC

E. Balkovic[1], J. Loizu[1], J. P. Graves[1], Y.-M. Huang[2], J. Salm[1], C. Smiet[1], M. Kong[1]

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Abstract.

We demonstrate, for the first time, that the nonlinear saturation of neoclassical tearing modes (NTM) in slab geometry can be found directly with an MHD equilibrium code, without needing to simulate the intermediate, resistivity-dependent dynamics. As in previous investigations of classical tearing mode saturation [1, 2], we make use of SPEC [3], an equilibrium solver based on the variational principle of Multi-Region relaxed MHD, featuring stepped pressure profiles and arbitrary magnetic topology. We use a simple bootstrap current model $J_{bs} = C\,\nabla p$ [4] to study NTMs in slab geometry, scanning over the asymptotic matching parameter Δ' (related to linear stability) and bootstrap current strength C. Saturated island widths, w_{sat}, produced by SPEC agree very well with the predictions of an initial value resistive MHD code [5], while being orders of magntiude faster. Additionally, we observe good agreement with a simple Modified Rutherford Equation. The same approach is then attempted in realistic tokamak geometry and we show initial results for the prediction of NTMs in the TCV tokamak. This involves reconstructing a TCV equilibrium unstable to NTMs and finding a nonaxisymmetric SPEC equilibrium with a 2-1 island, which we compare to experimatal observations [6]. Finally, we discuss the future steps involving application of this method to general resistive insabilities in stellarators.

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Mutual interaction of magnetic reconnection and runaway electrons in a post-disruption plasma

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Abstract. Runaway electrons are considered a major issue for future fusion devices. These particles, that are produced during disruptions, have velocity close to the speed of light and represent an important part of the electron population, due to collisions between relativistic electrons and low-energy electrons. The thermal load deposited by runaway electrons on the device components facing the plasma is therefore expected to be too high to be handled by the current materials. However, contrary to pessimistic scenarios, recent studies have highlighted the role of magnetic field line stochasticity in inducing benign termination of the runaway electron beams [1]. In this case, in fact, the region of runaway electron deposition broadens, both poloidally and toroidally, avoiding the formation of dangerous hot-spot on the wall. The magnetic field stochastization results from the onset of magnetic reconnection instabilities resonating at different radial position of the torus. Theoretical and numerical analysis based on a resistive MHD plasma description in 2D geometry [2,3], when magnetic surfaces are preserved, have shown that magnetic reconnection can be effectively induced by a runaway current. More recently, these results have been extended by considering the contribution of microscopic collisionless effects, such as the electron skin depth [4]. It has been shown that also in a low temperature, post disruption plasma collisionless effects can be relevant when realistic runaway electron velocities are considered. In this work we present new results on the generation of magnetic chaos induced by the runaway current through magnetic reconnection in 3D configurations and how this stochasticity affects the spatial distribution of thermal and runaway currents.

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Linear equations for stellarator local MHD equilibria around irrational and rational flux surfaces

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Abstract. Global MHD models provide the magnetic field within a volume enclosed by a flux surface given the shape of that flux surface and the radial profile of pressure and rotational transform. In contrast, local MHD equilibrium equations determine the magnetic field and its radial derivatives on a flux surface of interest given the flux surface shape, the shape of the contiguous flux surfaces and several flux functions. These local MHD equilibria are useful for transport studies (both neoclassical and turbulent) because they can be used to determine how changes in the flux surface shape affect fluxes across that flux surface. In the case of stellarators, local MHD equilibria can also be used to study rational flux surfaces, where the MHD equilibrium equations are expected to fail.

Building on previous work [1, 2, 3], we develop a new set of linear equations to determine the magnetic geometry coefficients needed for local gyrokinetic simulations on a flux surface of interest. Unlike previous local MHD equilibrium models, our equations are linear because they are derived for general angular coordinates.

Most neoclassical and turbulent transport models only need the magnetic field and its radial derivative on the flux surface of interest. The inputs required to determine the magnetic field and its radial derivative are the shape of the flux surface, the radial derivative of that shape and four constants. One possible choice for these four constants is the pressure gradient, the gradient of the toroidal flux, and the rotational transform and its radial derivative at the flux surface of interest. Higher order radial derivatives of the magnetic field require higher order derivatives of the pressure and the rotational transform.

When we apply our equations to rational flux surfaces, we find that, for rational flux surfaces to exist, two conditions must be satisfied. One of the conditions is the well-known Hamada condition [4], but the other has not been discussed in the literature to our knowledge. This new condition arises when one calculates the second order radial derivative of the magnetic field, and it constrains the value of the flux surface curvature on rational flux surfaces.

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Ion temperature gradient mode mitigation by energetic particles, mediated by forced-driven zonal flows

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Abstract. Zonal flows are axisymmetric perturbations in tokamak plasmas, and they are believed to be crucial in the self-consistent saturation of turbulence and the generation of nonlinear equilibrium. Recent numerical simulations and analytical theory have shown that Alfvén modes, driven unstable by resonant interaction with energetic particles, can generate zonal flows through a forced-driven process [1]. It has been conjectured that zonal flows can significantly mitigate drift wave instabilities. Recent research has extended the concept of zonal structures to phase space, known as phase space zonal structures (PSZS). In this context, PSZS are defined as the nonlinear distortions of the plasma reference distribution function. More generally, developing a gyrokinetic theory for EP phase-space transport led to a renormalization of the usual plasma equilibrium in the presence of finite electromagnetic fluctuations named Zonal State [2].

In this work, we use the global electromagnetic and electrostatic gyro kinetic approaches to investigate the effects of forced-driven zonal flows on the dynamics of ITG instabilities. We consider the equilibrium of the 92416 JET tokamak shot. We investigate the linear and nonlinear Alfvén modes and zonal flow dynamics and report their respective radial structures and saturation levels. We also report the phase space structures (PSZS) in a simplified magnetic equilibrium resulting from the plasma reference state nonlinear distortion in simulations with unstable Alfvén modes or ITGs.

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Whole device gyrokinetic simulations of ITER H-mode plasma with coupled core edge models

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Abstract. Whole device gyrokinetic simulations of ITER H-mode relevant plasmas with a new core-edge coupled model [1] will be presented. In the core, the new delta-f model maintains the profiles fixed and acts as a source of heat at the pedestal top. To balance this input of power, the modeling of a sink of energy related to tungsten radiation in the edge is discussed [2]. Pedestal turbulence, which is influenced by the power coming from the core and the heat radiated in the edge, is modeled with the usual flux driven total-f model of XGC. The core delta-f and edge total-f models are continuously coupled in an overlap region of a single simulation. A new coupled core-edge background optimized for the core and edge regions enables XGC's system of equations to behave as a delta-f / total-f model in which the turbulence is saturated over the whole device volume. A similar technique was employed when coupling the field [3] and particle distribution function [4] of XGC-XGC simulations and later applied to the field coupling of GEM-XGC [5] and GENE-XGC [6]. The coupling of the slowly saturated core model with a time telescoping technique will be discussed.

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Global gyrokinetic instabilities going to high plasma beta

T. Hayward-Schneider[1,*], and the ORB5 and EUROfusion TSVV10 and "ATEP" Project Teams

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Abstract. A lot of effort has been spent in the past on (primarily local) gyrokinetic modelling of electrostatic turbulent transport in tokamaks, typically dominated by Ion Temperature Gradient (ITG) modes. In this context, there is some previous understanding of the various effects that bulk-plasma beta may have, namely that with increasing plasma beta the ITG is initially stabilized before the Kinetic Ballooning Mode (KBM) branch becomes unstable for large enough values of the plasma beta. There is also a somewhat more complex picture regarding the effect of energetic particle (EP) beta, which in some cases may stabilize ITG turbulence [J. Citrin et al., PPCF, 2023], but can also drive large scale Alfvén Eigenmodes unstable.

We aim to elaborate on this issue with global electromagnetic gyrokinetic simulations using the particle-in-cell and finite-element code ORB5 [A. Lanti et al., CPC, 2020]. We start from some previous works, one focussed on the effect of electromagnetic turbulence in simplified geometry [A. Mishchenko et al., PPCF, 2022], and the other looking at ITER plasmas [T. Hayward-Schneider et al., NF, 2022]. In the former, the transition from ITG to KBM (or similar electromagnetic modes) was observed, although a detailed analysis of the linear phase was not presented. In the latter, meso-scale (between EP-driven Alfvén eigenmodes and ITG) Alfvénic-Ion-Temperature-Gradient [F. Zonca et al., PPCF, 1998] instabilities with flute-like structures were observed on rational surfaces in a zero-shear region. Similar observations of AITGs were made with both the ORB5 and the GENE codes for JET-like plasmas [A. Di Siena et al., NF, 2023].

We have extended the analysis of the simplified case to include a study of the effect of several factors which we want to decouple: thermal plasma beta, energetic particle beta (and the separate effects of temperature and density), and energetic particle temperature and density gradients. In general, in the absence of energetic particles, we recover the results that with increasing beta the high-n ITG modes are stabilized while the low-n electromagnetic modes are destabilized. We observe that this low-n branch is accompanied by a move of the instability to rational surfaces, warranting a global approach. We discuss the nature of these electromagnetic modes, discussing whether the moniker "KBM" or "AITG" is appropriate, and what effects energetic particles have on these electromagnetic modes, as well as the electrostatic ITG modes.

Finally we discuss how robust some of these observations are as we go from the linear to the nonlinear regime.

HPC implementation of structure-preserving geometric PIC models

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Abstract. Many plasma physics models have been proved to possess a non-canonical hamiltonian structure. Invariants like the hamiltonian or Casimir invariants like the Gauss law and div B = 0 follow immediately from this structure. Adequate conservation of these quantities has been proven to be essential for well behaving numerical solutions. Many numerical methods have been devised to this aim. Geometric numerical methods achieve this by discretizing the Hamiltonian structure, i.e. Poisson bracket and Hamiltonian, rather than the resulting PDEs. This approach approximates the infinite dimensional original hamiltonian system by a Finite Dimensional hamiltonian system and in this way guarantees the conservation of the appropriate discretised invariants.

We will present our implementation of these geometric Particle in Cell models in a new HPC code GEMPICX, based on the C++ AMReX framework, which offers performance portable parallel data structures and iterators suitable for Adaptive Mesh Refinement that will be considered in the future. In this new code, we replaced the initial Finite Element discretisation of the fields [4, 2, 5, 1] by a generalised mimetic Finite Difference version [3] better suited to the new framework. In addition to the initial fully kinetic Vlasov-Maxwell, we have implemented new electrostatic models with kinetic or adiabatic electrons and a gauge invariant field based electromagnetic drift-kinetic model.

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A Neo-Spitzer Stellarator

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Abstract. The original idea of Lyman Spitzer demonstrated that three-dimensional shaping of a topollogically toroidal magnetic field can provide the needed rotational transform for plasma confinement. Yet Spitzer's figure-8 "stellarator" bears little resemblance to the modern intricately sculpted designs that are found via computational optimization. In recent years the near-axis theory of quasi-isodynamic (QI) stellarator equilibria [1] has revealed exotic classes of solutions, for instance with broken symmetries and distinct topological properties of the magnetic axis, but has also lead to renewed interest in simpler solutions, especially those with only one or two field periods, reminiscent of Spitzer's design. These solutions hint that it may be possible to overcome limitations in existing QI designs, like compactness or coil-to-plasma distance, by going "back to the basics" – if only they could be further developed into mature concepts (with stability, etc). Paradoxically, the further development of such simple designs has proved to be a technical challenge with existing optimization methods. In this work, we explore the underlying reasons for this difficulty, and demonstrate how it can be overcome, as exemplified by the intriguing case of a figure-8 QI stellarator. We show how this design has certain attractive properties, made uniquely possible by its simple geometry. Finally, we present the results of the first optimizations using new capabilities developed with the GVEC code [2], showing that it may indeed be possible to realize Spitzer's original concept in the form of a modern optimized QI stellarator.

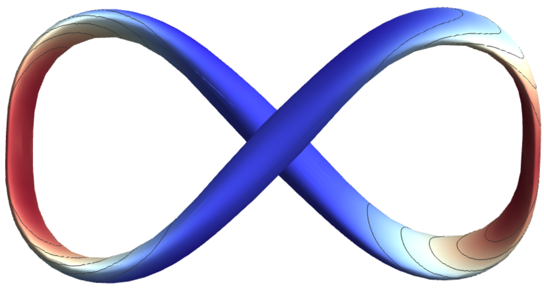

Figure 1: A figure-8 QI stellarator: colors correspond to magnetic field strength.

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CIEMAT-QI4: compatibility of physics performance with coil and blanket requirements in an optimized magnetic configuration

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Abstract. The stellarator is an attractive concept for magnetic confinement fusion reactors. Its main advantage over the tokamak is that the magnetic field is generated by external coils, without relying on a large (typically inductive) plasma current, thus avoiding the risk of current-driven instabilities and making steady-state operation easier. However, the lack of axisymmetry of the stellarator implies that careful tailoring of the magnetic configuration, usually called optimization, is required to ensure confinement quality comparable to the tokamak and, in particular, sufficiently low neoclassical transport. Wendelstein 7-X (W7-X) is the first large stellarator whose magnetic configuration has been designed using numerical optimization, and reduced neoclassical transport of thermal species has been recently demonstrated experimentally [1]. Nevertheless, some critical aspects for a reactor, prominently good confinement of energetic particles and reduced turbulent transport, need further optimization beyond W7-X [2]. Recently, a quasi-isodynamic configuration (the family of optimized configurations to which W7-X also belongs), called CIEMAT-QI4, has been obtained [3] that keeps the good properties of W7-X (low neoclassical transport of thermal particles, MHD optimization, and iota profile suitable, in principle, for an island divertor) and, in addition, exhibits smaller bootstrap current, very good fast-ion confinement at low and high b, and reduced turbulent transport. CIEMAT-QI4 is robustly optimized in the sense of [4] and, therefore, is expected to be resistant to field errors. A reactor design based on the stellarator concept requires magnetic coils that can accurately generate the optimized magnetic configuration and, at the same time, are compatible with technology and engineering constraints. In this talk, we provide a preliminary study of this compatibility for CIEMAT-QI4. A set of filamentary coils will be presented that faithfully generate the configuration, and have sufficiently large coil-coil distance and tolerable coil curvatures. It will also be shown that plasma-coil distance is compatible with a breeding blanket with large enough Tritium Breeding Ratio (TBR), even for moderate reactor size as compared to previous designs [5].

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MONKES: a neoclassical code for fast evaluation of the bootstrap current and stellarator optimization

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Stellarator magnetic fields must be optimized to achieve the confinement quality required for fusion reactors. Specifically, in order to exhibit radial neoclassical transport at low collisionality as small as tokamaks, stellarators need to be approximately omnigenous [1]. A magnetic field is omnigenous if, for all particles, the radial component of the drift velocity averages out to zero over the lowest-order orbits. Although radial neoclassical transport has typically been minimized indirectly by means of figures of merit such as the effective ripple [2], recent developments have enabled to carry out this minimization using accurate calculations of radial neoclassical transport at low collisionality [3]. However, not only neoclassical transport across flux-surfaces is important for stellarator optimization. In general, parallel transport produces a net electric current, known as bootstrap current, that can modify the magnetic field and, therefore, needs to be evaluated during the optimization process. This is particularly important if the goal is the design of approximately quasi-isodynamic fields (quasi-isodynamicity is the concept in which the magnetic configuration of Wendelstein 7-X is based on), a subclass of approximately omnigenous fields that have the additional property of giving small bootstrap current [4] and are compatible with island divertors. However, precise calculations of the bootstrap current were too slow to be included in a stellarator optimization loop so far.

In this talk we present MONKES (MONoenergetic Kinetic Equation Solver) [5], a new neoclassical code that solves the same monoenergetic drift-kinetic equation as DKES [6], the workhorse of neoclassical transport calculations in stellarators. MONKES was conceived, among other things, to satisfy the need for fast and accurate calculations of the bootstrap current. By exploiting the tridiagonal structure of the drift-kinetic equation in a Legendre basis, it is possible to obtain accurate results for all monoenergetic transport coefficients (i.e. those giving radial as well as parallel transport) at low collisionality using a single core in approximately one minute. These features make MONKES ideal for its inclusion in stellarator optimization suites for direct optimization of the bootstrap current. Apart from optimization, MONKES can be used for the analysis of experimental discharges and be integrated into predictive transport frameworks.

Finally, we explain the first two problems to which we have applied MONKES. Taking advantage of its speed, the first application of MONKES has been the evaluation of a large dataset of partially optimized configurations obtained during the design of CIEMAT-QI4 [7]. The results allow us to discuss the suitability of targeting indirect proxies for the minimization of the bootstrap current. In addition to massive evaluation of typical stellarator magnetic configurations, MONKES allows to investigate, at reasonable computational cost, neoclassical transport in magnetic configurations whose accurate description requires an unusually large number of Fourier modes. As a second application of MONKES, we explore the configuration space of piecewise omnigenous stellarators, recently introduced in [8].

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A Strategy for Indian DEMO and Challenges in Bringing Fusion Electricity to Grid

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Abstract

A staged approach to Indian DEMO envisions a reactor-park consisting of multiple moderate-sized reactor units and is developed taking advantage of developments in understanding of tokamak physics, experience from ITER construction, technology advances in magnets, materials and manufacturing [1]. Critical decisions for the strategic requirement of change in industrial perspective are developed. We define targets for directed-R&D and parameter options for an integrated test facility followed by a compact pilot plant that demonstrates steady-state gross electricity generation. One of the outcomes of our analysis is that the advantages of high bootstrap scenarios are outweighed by high transport losses due to dependence of separatrix power loss on β, leading to degraded Q in a moderate sized reactor. Combined with the fact that the space constraints do not permit extended Ohmic operation, the non-inductive current-drive becomes very crucial step to success. This makes it necessary to have an integrated test facility where high current (5-7 MA) plasmas with about 50% bootstrap fraction can be operated in steady-state along with blanket concepts testing and advanced magnets based high temperature superconductors. This step will lead to a technical foundation for building the pilot plant. In order to build such devices a crucial requirement is the ability to carry an entire device/ power plant simulation that can give rapid design convergence consistent with physics requirements and engineering constraints. In this direction, a workflow based multi-physics simulator called SARAS is being developed [2]. The architecture of SARAS and its requirements will be presented. Challenges in the incorporation of physics aspects of burning plasmas, current-drive and confinement with certain key engineering constraints in whole device simulators will be discussed. It is argued that an early demonstration of gross electricity production will have a positive impact on the next step – at all levels, cost, risk, policy, and industrial partnership.

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A flexible, compact stellarator-tokamak hybrid concept

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Abstract. A natural and compelling question is whether the advantages of stellarators and tokamaks can be combined in a single machine. Such a device would have a compact design, simple coils, good confinement and easily achievable steady state operation. In addition to combining the strengths of stellarators and tokamaks it would be interesting to be able to have a flexible hybrid machine that could continuously switch between tokamak and stellarator operation.

A novel compact quasi-axisymmetric stellarator-tokamak hybrid concept will be presented [1]. Its coil set consists of standard tokamak coils, augmented by three or four (depending on the selected parameter) simple stellarator coils, all of identical shape. Such a machine is capable of operating as a tokamak, a quasi-axisymmetric stellarator, or anything in between.

Additionally, flux surfaces in vacuum are demonstrated to exist. This could be exploited, instead of the expensive central solenoid, as a novel start-up scenario. To illustrate the flexibility of the concept, a number of additional examples of low-aspect-ratio, high-field-period quasi-axisymmetric equilibria are presented, which were numerically found by optimizing with a novel target [2]. The new optimization efforts ensure that the levels of quasi-axisymmetry are sufficient for good fast-particle confinement and that enhanced stability can be achieved.

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Electromagnetic interchange turbulence driven by temperature gradients

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Abstract. A fluid model of interchange-mode electromagnetic turbulence is proposed, being a long-wavelength extension of the class of models introduced by Adkins et al. [1]. This describes the basic physics of the kind of turbulence and transport that might occur in open-field-line systems like mirror devices or scrape-off layers in tokamaks. A 3D Alfvenic (electromagnetic) secondary instability is identified as the principal disruptor of unstable 2D electrostatic interchange structures. By this mechanism, energy is transferred from these structures into a turbulent cascade that is shown to be very similar to the standard MHD critically balanced cascade familiar in many astrophysical and space-physical contexts. The effective heat diffusivity associated with such a saturated state is shown to be dramatically larger than its electrostatic counterpart (and only accessible in simulations that resolve both sufficiently large and sufficiently small scales parallel to the ambient magnetic fields as well as sufficiently large scales in the direction of the ambient temperature gradient; in simulations underresolved in any of these three senses, seemingly real but in fact unphysical states emerge). Thus, interchange turbulent transport is shown to be fundamentally electromagnetic and frighteningly efficient.

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Drift wave soliton formation via beat-driven zonal flow and implication on plasma confinement

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Abstract. Understanding the triggering and regulation mechanisms of anomalous transport is a significant issue for magnetically confined plasmas. Drift waves (DWs) turbulences [1], driven by plasma pressure gradient intrinsic to confined plasmas, are considered as important candidates for inducing anomalous transport. Numerical simulations have found that zonal flow (ZF) generated by DWs can significantly reduce turbulence amplitude and associated transport [2]. Previous analytical theories on ZF generation by DWs have been focused on the spontaneous excitation via modulational instability [3], in which DWs are scattered into linearly stable short radial wavelength domain by the nonlinearly excited ZF. The ZF growth rate, meanwhile, is determined by the DW amplitude. However, it is very often found in numerical simulations that ZF grows at twice the DW instantaneous linear growth rate [4,5], which is the typical characteristics of the beat-driven process [6].

In this work, a paradigm model of DW self-beating, i.e., beat-driven process, to generate zero frequency ZF is derived using nonlinear gyrokinetic theory. The obtained nonlinear DW equation is a nonlinear Schrodinger equation (NLSE), in which the linear dispersiveness, linear growth rate, plasma nonuniformity and cubic nonlinearity induced by feedback of beat-driven ZF to DW are self-consistently included. In uniform plasmas, soliton structures, given by balancing the linear dispersion and cubic nonlinearity, can form after DW amplitude reaching certain threshold; and, thereby, enhance turbulence spreading. More importantly, the threshold on DW amplitude for soliton formation is within experimentally relevant parameter regime. In nonuniform plasmas, the evolution of the corresponding linear eigenstates is investigated. It is found that the extent for wave propagation is the same for linear and nonlinear cases, which implies that in nonuniform plasmas, solitons can not extend beyond the range bounded by the turning points of the wave packet.

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Cross-field fluctuations in strongly ExB sheared plasmas near a solid target

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Abstract. In magnetised plasmas where the magnetic field is obliquely incident with a solid target, the "magnetic presheath" region within a few ion Larmor radii from the target is characterised by a large and inhomogeneous electric field directed towards the target [1]. The presence of non-circular ion gyro-orbits, open orbits, and strong sheared ExB flows tangential to the target implies that fluid and gyrokinetic theories are inaccurate in this region, and require appropriate boundary conditions. In fusion devices, the magnetic field is at such grazing incidence with the target that even the ExB drift from a small electric field tangential to the target can substantially affect the ion outflow and the boundary conditions [2]. To illustrate this, we present a set of analytical constraints posed by the magnetic presheath, which include a "turbulent" kinetic Bohm-Chodura condition, as well as a new intrinsically kinetic polarisation condition and a constraint on the tangential electric field [3]. The cold-ion limit of our constraints are consistent with previously derived fluid boundary conditions [4].

We also present kinetic, steady-state, 2-dimensional (2D) numerical solutions of the electrostatic potential in the magnetic presheath. Our numerical method hinges on an iterative scheme to find the steady state. At every iteration, the ion density is numerically calculated from an analytical expression valid for small magnetic field angle at the target [5, 6] and small tangential electric field. This approach is attractive because it bypasses the dynamical evolution of the system, which is simulated in particle-in-cell codes at a huge computational cost due to the wide range of length and time scales involved (electron *vs* ion thermal speed, Debye length *vs* ion gyroradius). From our solutions, we characterise the propagation of turbulent fluctuations across the last few ion Larmor radii before reaching the target.

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Intrinsic Rotation Drive by Neutrals and Scrape-off-Layer Flows

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Abstract. Toroidal rotation is key for the performance of present-day tokamaks, stabilizing resistive wall modes that can otherwise lead to disruptions. As ITER and future devices grow in size and transition to alpha heating, they will not be able to strongly drive such rotation with neutral-beam injection. To keep these devices in stable regimes, we need first-principles understanding of the plasma's self-driven "intrinsic" rotation. In the edge, the modulated-transport model (MTM) has explained basic intrinsic-rotation scalings and predicted a strong dependence of rotation on X-point position [1], subsequently observed on TCV [2]. However, neither the MTM nor other models have self-consistently explained the sometimes-observed dependencies of rotation on plasma density and on favorable- vs unfavorable-∇B magnetic configuration [3]. The contribution of strong, transport-driven scrape-off-layer (SOL) flows, although intuitively plausible, sums to zero in a self-consistent plasma transport formulation. However, the influx of neutral particles provides an alternate mechanism to carry this momentum back into the confined plasma, especially with poloidally asymmetric neutrals.

Although small in number, neutral particles move freely across the magnetic field, enabling a larger-than-expected contribution to the momentum flux. In charge-exchange (CX) reactions, a neutral donates its electron to an ion, allowing that newly-neutralized ion to carry its momentum freely across the field until the next CX event. In the short-CX-length limit, this appears as a neutral-mediated momentum diffusivity, as each temporarily neutralized ion takes a drunkard's step in a direction randomized by its gyrophase. Previous works have developed an expedient formalism to evaluate the resulting momentum flux, but are restricted to the context of a specified background neoclassical plasma [4].

We exploit a new boundary-layer-analysis-based generalization of the MTM [5] to self-consistently model an axisymmetric edge plasma, retaining wide ion drift orbits and a global geometric topology, together with turbulent- and neutral-mediated diffusive momentum transport [6]. Although this model contains both transport-driven flows and an influx of neutrals, the resulting momentum flux is usually weak in the short-CX-length limit, so we relax that assumption too, using a Green's function method to allow finite-length steps between CX events. The intrinsic momentum flux is then determined by the interaction of strong transport-driven SOL flows with incoming charge-exchanging neutrals, allowing experimental manipulation through actuators including magnetic geometry, divertor closure, and poloidally localized gas puffing.

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Fast-ion-driven vertical displacement oscillatory modes in tokamak plasmas

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Abstract. Axisymmetric modes in elongated plasmas are normally associated with a well-known ideal instability resulting in a vertical shift of the whole plasma column. This vertical instability is stabilized by means of passive feedback consisting of eddy currents induced by the plasma motion in a nearby wall and/or in plasma-facing components. When a thin resistive wall is considered, the n=0 mode dispersion relation can be studied analytically with reduced ideal MHD models and is cubic. Under relevant conditions, two roots are oscillatory and weakly damped. These oscillatory modes present Alfvénic frequency and are dependent on plasma elongation and on the relative position of the plasma boundary and of the wall. The third root is unstable and represents the so-called resistive wall mode (RWM). We focus on the two oscillatory modes, that can be driven unstable due to their oscillatory character. A drive arising from resonant interaction with MeV ions may overcome dissipative and resistive wall damping, leading to fast-ion-driven vertical modes (FIDVM). The effects of energetic particles are added within the framework of the hybrid kinetic-MHD model. An energetic ions distribution function with $\partial F/\partial E > 0$ is required to drive the instability, achievable with pitch angle Λ anisotropy or an isotropic distribution with regions of positive slope in the velocity space. The latter situation can be achieved by considering losses of fast ions or due to fast ion source modulation [1,2]. The theory presented here is partly motivated by the observation of saturated n=0 fluctuations reported in [2,3], interpreted in terms of a saturated n=0 Global Alfvén Eigenmode (GAE). Modeling of recent JET discharges using the NIMROD MHD code will be presented, focusing on mode structure, frequency dependence, and preliminary hybrid kinetic-MHD results. It is early for us to conclude whether, in fact, the mode observed at JET is a FIDVM rather than a GAE, nevertheless, we discuss the main points of distinction between GAE and FIDVM that may facilitate the experimental identification.

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On electron cyclotron resonance start up in Wendelstein 7-X

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Abstract.

The plasma in Wendelstein 7-X (W7-X) is routinely created using electron cyclotron resonance heating at the second harmonic with a polarisation corresponding to the extraordinary mode. Experiments aiming at high plasma β plan to use a lower magnetic field, implying third-harmonic start-up. However, so far all attempts using third-harmonic heating for this purpose have failed. Similarly, in Ref. [1] it was concluded that startup using the third harmonic is impossible in ITER too.

Regardless of whether the second or third harmonic is employed, however, the 3D nature of the stellarator magnetic field offers a potential advantage for the nonlinear electron-wave interaction during plasma startup, thanks to the magnetic-field gradient [2]. The possibility of resonant interaction, which occurs when $n\frac{qB}{m\gamma} + k_\parallel v_\parallel - \omega = 0$, is extended if the electron energy increases in step with the background magnetic field strength along the trajectory. This effect is prominent for third-harmonic interaction. Here $qB/m\gamma$ is the relativistic gyrofrequency, $k_\parallel v_\parallel$ the Doppler shift from the motion parallel to the magnetic field, ω the wave frequency, and n the number of the harmonic.

The magnetic-field gradient also allows for "resonance overlap" if several waves of the same frequency are present but do not all occupy the same spatial region. It is possible to arrange the waves in such a way that large energy gains are possible since the resonant energy is equal to $mc^2\gamma_r = n\frac{qB}{\omega - k_\parallel v_\parallel}c^2$ and a small increase in B thus results in a large increase in resonant energy. Several waves thus enable much larger energy gains in a multi-stage process than would result from simply adding the power of the individual waves.

In this work, we discuss the impact of magnetic-field inhomogeneity on energy gain and the implications of resonance overlap during start up of Wendelstein 7-X.

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Gyrokinetic Analysis for Fast Ion Effects on Turbulence in KSTAR Plasmas

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Abstract. An internal transport barrier (ITB) was observed in the neutral beam heated discharges with a significant fast ion population in KSTAR[1]. The correlation between ITB foot location and fast ion population observed in these discharges motivated us to investigate the effects of fast ions on turbulence in these plasmas through gyrokinetic analysis. Utilizing the gyrokinetic code CGYRO[2], we examined the impact of fast ions on both ion and electron scale turbulence inside ITB region. For ion-scale turbulence simulations, the gyrokinetic code predicted a significant reduction in energy flux with the addition of fast ions, qualitatively consistent with experimental observations. Further analysis indicated that the primary physical mechanism for this reduction was the dilution effects[3]. In addition, a long-wavelength mode was destabilized with the inclusion of fast ions. While this fast ion relevant mode was not critical for the reduction in energy flux, we found that it generated a substantial level of zonal flow[4]. Simulations for electron scale turbulence revealed that the energy flux driven by electron scale turbulence also decreased with the addition of fast ions. This reduction was attributed to the enhanced Shafranov shift caused by the increased total pressure gradient due to the addition of the fast ion pressure. Furthermore, the electron energy flux level driven by electron scale turbulence was higher than the flux level driven by ion scale turbulence, suggesting that the electron scale turbulence can play a significant role in these KSTAR discharges. In this presentation, we will discuss the detailed effects of fast ions on turbulence as revealed by our gyrokinetic analysis.

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An upper neutral pressure limit for low-Z benign termination of runaway electron beams in TCV

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Abstract. In recent years, simulations have highlighted the difficulty of simultaneously mitigating all adverse consequences of a tokamak disruption during nuclear operation [1, 2, 3]. Hence, future reactor-scale devices should have a range of mitigation techniques at their disposal. One such technique for mitigating beams of runaway electrons (REs) is known as "benign termination", whereby the bulk plasma is recombined to facilitate fast MHD mode growth, and the edge safety factor is reduced until a large-scale MHD instability occurs. If successful, the REs are then spread broadly across the wall, instead of depositing their energy locally. As shown in Ref. [4], the vessel neutral pressure (NP) is an indicator for successful RE beam termination. A sufficiently high NP is required for the plasma to recombine, but a too high NP results in the plasma re-ionizing.

In this contribution we present a model for the upper NP limit, above which the plasma re-ionizes. We show that this effect is due to the enhanced ionization by REs, and we quantify the sensitivity to the RE density and energy. The model is applied to interpret data in the large benign termination database available at TCV.

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