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On plasma startup using ECRH

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Abstract.
Electron Cyclotron Resonance Heating (ECRH) is the main plasma heating mechanism in the Wendelstein 7-X (W7-X) stellarator. The second harmonic heating at 140 GHz (X2- and O2-modes) is used for the startup and in a wide range of operation scenarios with magnetic fields of approximately 2.5 T. In further operation of the W7-X stellarator, it is desirable to use a lower magnetic field, which would allow access to a wider range of magnetic configurations. At lower magnetic field (1.7 T) the heating will rely on the higher harmonics, for example, X3. Regular quasi-linear theory predicts a minimal plasma temperature of 0.75 keV needed for sufficient absorption [1].

However, in the startup regime the quasi-linear theory is not valid, due to an ‘extended’ resonant wave-particle interaction. One instead needs to consider non-linear theory. The non-linear character of wave-particle interaction may also play a role in ECRH assisted start-up in tokamaks, such as in the start-up scenarios currently planned for ITER [2].

In this work, we seek to describe the non-linear wave-particle interaction. We derive the relativistic guiding-center Lagrangian for particles experiencing a fast oscillating electromagnetic wave. Contrary to the usual guiding-center Lagrangian, the magnetic moment is no longer conserved. The wave allows for the large energy excursions of the resonant particles. This guiding-center Lagrangian can be reduced to obtain results from, for example, [3] and [4].

The resulting guiding-center Hamiltonian is used to find both energy excursions inside the beam and the energy gain for electrons passing through the beam. These estimates provide scaling laws for the startup condition. The scaling laws are then compared with the experimental observations.

References
Modelling of magnetic islands in EUTERPE, a gyrokinetic PIC code

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Abstract.
Magnetic islands (MIs) — closed magnetic flux tubes isolated from the rest of the confinement region by a separatrix can be of two-fold nature. First, they may be derogatory, since they effectively short-circuit the plasma increasing the radial transport of heat and particles. Is is commonly the case in tokamaks that undesired MIs are created in regions of plasma prone to magnetic reconnection due to the tearing instability. This can only happen at finite resistivity and is therefore a non-ideal MHD effect.

On the other hand, when magnetic islands are localised close to the plasma edge, they can be used to extract waste material from the plasma, giving rise to the concept of island divertors. In the upcoming W7-X campaign, various fluctuation diagnostics will be used to investigate plasma flows and radial electric field at and around magnetic islands, for example the Doppler reflectometer and the correlation reflectometer. This calls for a theoretical investigation of transport properties in MIs.

Recent advances in computational power have allowed for the development of global gyrokinetic PIC codes, such as EUTERPE, which are capable of simulating the entire plasma volume. This also applies to stellarators which have an intrinsically 3D geometry. Nevertheless, most codes rely on the assumption that the magnetic field consists of nested magnetic flux surfaces, which is clearly not the case when MIs are present.

In this work discusses the implementation of an island model in EUTERPE. It is shown that magnetic equilibria obtained from ideal MHD codes give rise to island effects when the particles equations of motion are correctly modified. A set of appropriate magnetic coordinates in the vicinity of the island’s o-point is derived. Finally, preliminary numerical studies of particle transport in the presence of MIs are reported.
Linear ideal MHD modeling of plasma response to 3D magnetic perturbations in tokamaks

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Abstract. The class of plasma instabilities known as edge-localized modes (ELMs) is of special concern in tokamaks operating in high-confinement mode, such as ASDEX Upgrade and ITER. One strategy for ELM mitigation is the application of resonant magnetic perturbations (RMPs) via external coils. Kinetic modeling accurately describes the plasma response to these RMPs ab initio, particularly the parallel shielding currents at resonant surfaces. Away from resonant surfaces, ideal magnetohydrodynamics (iMHD) is expected to yield sufficiently accurate results, providing a computationally less expensive option that could complement kinetic modeling.

The code MEPHIT has been developed to solve the linearized iMHD equations in a way that is compatible with existing kinetic modeling approaches. We consider an axisymmetric iMHD equilibrium in realistic tokamak geometry under the influence of a non-axisymmetric external perturbation from ELM mitigation coils with infinite impedance. The plasma responds to this external magnetic perturbation with a current perturbation, which in turn produces a magnetic field perturbation. The resulting fixed-point equation can be solved in a self-consistent manner by preconditioned iterations in which Ampère’s equation and the magnetic differential equations for pressure and current are solved in alternation until convergence is reached. After expansion in toroidal Fourier harmonics, these equations are solved on a triangular mesh in the poloidal plane using finite elements. These results are then benchmarked against established codes.
RF heating mode transition, hysteresis, and applications of inductive discharges

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Abstract. Fundamental understanding of the radio-frequency (RF) heating mode and hysteresis is essential in both the high temperature fusion reactor and the low temperature plasmas and history-dependent huge hysteresis has been observed in inductive discharges, which are in the widespread use, such as nuclear-fusion operation, spacecraft propulsion, gas reformation, and nanostructure/material fabrication [1]. Here, we present the RF heating mode transition, hysteresis, and material applications of the inductive discharges. When the external RF power increases, the plasma parameters (especially, plasma density) suddenly changes from a low-density mode (called capacitive heating mode, E mode) to high-density mode (called inductive heating mode, H mode). With decreasing the external RF power, there is a significant plasma hysteresis in the inductive discharge. Here, we provide a new theory for the hysteresis mechanism that evolution of the electron energy distribution creates such a huge plasma hysteresis. This theory is supported by the experimental evidence and the theoretical calculation based on the plasma balance model. We also applied the RF discharge modes of the inductive discharge to the nano-material/device surface treatment process, such as nanoparticle creation and two-dimensional transition metal dichalcogenide material etching and the results will be presented in this conference.

References
2D full-f gyrofluid magnetic reconnection

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Abstract. We introduce a 2D full-f gyrofluid magnetic reconnection model and outline the applicability to different parameter regimes. The linear tearing mode stability parameter is derived from the model to discuss the initial evolution of a typical X-point equilibrium situation. After introducing the numerical framework briefly, we discuss the status of our 2D simulations of magnetic reconnection in a turbulent environment under various conditions with a focus on tokamak geometry including finite Larmor radius (FLR) effects for a temperature ratio \( \tau = T_i/T_e > 0 \). The linear transport is compared to the turbulent situation to obtain insight on the respective stability of the X-point geometry. We compare our results with recent publications from delta-f gyrofluid, gyrokinetic and MHD simulations.
Implementation of gyrokinetic electromagnetic models using cubic spline and C1 finite elements

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Abstract. Finite element methods using unstructured meshes have been applied to the gyrokinetic studies of edge physics [1]. C1 finite elements (quintic polynomials) in combination with an unstructured mesh have not been adopted widely in gyrokinetic simulations except a few cases [2]. The aim of this work is the implementation of the gyrokinetic electromagnetic model with the use of C1 finite elements in unstructured meshes, in order to achieve high numerical accuracy in whole volume simulations. By following the previous work [3], the mixed variable (MV) and pullback (PB) schemes have been implemented in TRIMEG-GKX (with concentric circular flux magnetic surfaces and structured meshes) based on its early version [4]. The MV/PB scheme shows its superior performance in noise reduction for the kinetic simulations of energetic particle driven Toroidicity induced Alfvén eigenmode (TAE). While the solver is fully parallelized, shared memory MPI has been adopted to store the three dimensional fields on each computational node, which leads to different features and performance of the code. In order to handle more realistic tokamak geometry, the original TRIMEG code (with unstructured meshes) [5] has been upgraded using C1 finite elements [6]. Cubic splines in toroidal direction and C1 elements in poloidal planes have been adopted. High accuracy in the field solver is observed. The deposition and gathering processes between markers and fields show reasonable computational performance for cases in moderate size (>millions of markers, moderate n mode numbers). The progress of the development of TRIMEG-C1 and its possible application for studies of energetic particle activities in AUG experiments [7] will be introduced. The possible implementation of the gyrokinetic electromagnetic model in the JOREK code [8] will also be discussed.

References
GX: a GPU-native gyrokinetic turbulence code for tokamaks and stellarators

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Abstract. The GX code [1] is a GPU-native radially-local delta-f gyrokinetic turbulence code that uses pseudo-spectral methods in both configuration and velocity space. At high resolution GX is a standard gyrokinetic code, but it can also be successfully run at low resolution (particularly in velocity space) in lieu of uncontrolled approximations, since in the lowest-resolution limit the system corresponds to established gyrofluid models [2]. GX requires, for example, less than 30 seconds to compute the correct Cyclone base case heat flux for ITG turbulence on a desktop computer with an appropriate graphics (GPU) card. We present this and other linear and nonlinear turbulence benchmarks against standard gyrokinetic codes from the community, for both tokamak and stellarator configurations. GX has recently been coupled to the Trinity transport solver [3]. Trinity uses a multi-scale approach to solve for the time-dependent radial profiles of density, temperature, etc, with turbulent fluxes obtained from GX calculations, neoclassical fluxes obtained from a drift kinetic solver, external sources, and edge boundary conditions supplied by the user. Using the Trinity+GX system, we demonstrate the ability to solve for the time-dependent evolution of core fusion reactor profiles in approximately real time, without resorting to reduced models. This also enables the realistic prospect of using GX and Trinity+GX inside the optimization loop of design frameworks for tokamaks and stellarators such as SIMSOPT [4].


Global ‘zero particle flux’-driven gyrokinetic analysis of the density profile for a TCV plasma, compared with gradient-driven and quasi-linear results

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Abstract. TCV is a small-sized tokamak, where finite $\rho^*$ effects could significantly impact the heat and particle fluxes, leading to discrepancies between gyrokinetic local flux-tube results and global ones [1, 2, 3]. The impact of such effects on the density peaking has been investigated in the past by our research group for a particular TCV discharge with negligible particle source, satisfying the zero particle flux condition. A flux-tube analysis, reconstructing the zero particle flux hyper-surface in the multidimensional physical parameter space at fixed radius $\rho_{\text{tor}} = 0.6$ [4], has been followed by a global analysis [5], where the plasma annulus corresponding to the stiff region $0.4 < \rho_{\text{tor}} < 0.8$ has been simulated comparing local quasi-linear and nonlinear results with global simulations, showing small $\rho^*$ effects. Because of the computational cost of the nonlinear global gyrokinetic simulations, we restricted to a two species plasma in the collisionless regime, with heavy electrons and simplified density and temperature profiles. However, these gradient-driven global runs considered Krook-type heat and particle sources to keep temperature and density profiles fixed on average, which differ from the experimental sources. To remove this possible bias on the obtained results, a different evaluation of the density peaking for the same case is performed, based on global nonlinear hybrid simulations where the temperature profiles are [still] kept fixed with the Krook-type sources, however the density profile relaxes in a flux-driven way (with zero particle source). The results show a good agreement with the old ones from [5]. A global quasi-linear model is also developed and applied to global linear results, showing a good agreement with the global nonlinear gradient-driven simulations. The effect of collisions on the quasi-linear and nonlinear flux-tube results of [5] is also investigated. Finally, all the results are invoked to try to re-interpret the experimental density profile fits.

Deep neural networks for physics-informed modelling of edge turbulence based upon gas puff imaging in fusion plasmas

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Abstract. To robustly diagnose edge turbulence, we develop and demonstrate a technique to translate brightness measurements of HeI line radiation into local plasma fluctuations via a novel integrated deep learning framework that combines neutral transport physics and collisional radiative theory for the $^3\text{D} \rightarrow ^3\text{P}$ (587.6 nm line) transition in atomic helium. Based upon fast camera data on the Alcator C-Mod tokamak, we present 2-dimensional time-dependent experimental measurements of the electron density, electron temperature, and neutral density on turbulent scales using a single spectral line. The electron density and temperature are then further compared against independent probe measurements. With this experimentally inferred data, we calculate initial estimates of the 2-dimensional turbulent electric field consistent with drift-reduced Braginskii theory under the framework of an axisymmetric fusion plasma with purely toroidal field. The inclusion of atomic helium effects on particle and energy sources are found to strengthen correlations between the electric field and electron pressure while broadening turbulent field fluctuation amplitudes which impact edge $\mathbf{E} \times \mathbf{B}$ flows and shearing rates.
Effect of turbulence on current drive in up-down asymmetric tokamaks

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Abstract. Up-down asymmetric geometries enable turbulence to redistribute toroidal momentum in the radial direction [1]. The bulk toroidal rotation generated by this phenomenon can improve MHD stability, motivating recent work to optimise the magnetic geometry in order to maximise the plasma rotation [2]. However, the impact of this turbulent effect on the plasma current had not yet been studied.

We base our work on a form of the gyrokinetic equation which can account for characteristic eddy sizes ranging from the ion gyroradius to the ion poloidal gyroradius [3]. This renders the equation self-consistent for neoclassical formulations and allows us to produce analytical predictions for the plasma current.

Our model has been implemented into a code that couples stella [4], a local δf gyrokinetic code, to SFINCS [5], a drift kinetic solver. With this code, we show that the elongated asymmetric geometries found to maximize intrinsic rotation yield higher plasma currents than symmetric configurations. The examination of the evolution of the phase space under scans of the turbulent characteristics gives an intuitive understanding of the phenomena involved.

References

Acknowledgments
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Non-linear simulations of the plasma response to resonant magnetic perturbations in ASDEX Upgrade plasmas

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Abstract. Large uncontrolled Type-I Edge Localized Modes (ELMs) are not acceptable in future fusion devices, since the associated high transient heat loads would damage plasma facing components. A variety of ELM control methods have been developed to mitigate or suppress ELMs. One of the most promising approaches is the application of Resonant Magnetic Perturbations (RMPs), where small helical field perturbations are introduced into the plasma via a set of external coils. While RMPs are used routinely both for suppression and mitigation of ELMs in many present-day tokamaks, the mechanisms that lead to RMP-ELM control are still subject of debate. Numerical models are a helpful tool to advance the understanding of the underlying physical processes that are caused by the penetration of the perturbation fields into the plasma and the subsequent response of the plasma.

Here, we use the non-linear MHD code JOREK to investigate these dynamics in ASDEX Upgrade (AUG) plasmas. The presented simulations performed in realistic geometry and with realistic plasma parameters and flows are based on reconstructions of experimental AUG equilibria. We present an extension of the coupled JOREK-STARWALL code suite, that allows to replace the commonly used fixed boundary treatment (Dirichlet boundary conditions for the poloidal flux and plasma current at the computational boundary) with a free boundary treatment (natural boundary conditions). This allows a fully self-consistent development of the plasma response and the magnetic perturbation in the whole computational domain. Via direct comparisons, we investigate the differences between both approaches.

The RMP-induced corrugation of the separatrix is compared to lithium beam emission spectroscopy measurements showing excellent agreement, which suggests an accurate depiction of the plasma response. Based on this validation, first preliminary results of the penetration of RMPs into ELM unstable plasmas are presented. The use fully realistic plasma parameters makes the simulations particularly challenging, but allows direct insights into the underlying mechanisms and quantitative comparisons to the experiment. In particular, the experimentally observed density threshold for the transition between suppression and mitigation regimes is approached in the modeling.
Reduced Transport Models for a Tokamak Flight Simulator

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Abstract. A tokamak flight simulator is a numerical tool which predicts the plasma behavior using the discharge program editor as input. It can ensure that either actuator trajectories or plasma parameters satisfy the experimental goals and reduces the probability of plasma disruptions and of exceeding operational limits. It is based on the interaction between control system, plasma equilibrium and transport. The transport models have to be physics based to be realistic, but also fast enough to be used as an inter-discharge prediction tool. This compromise can be reached employing analytical models which are derived from first principle theories. In this work an integrated model including every plasma region has been developed. The confined region is modeled in 1.5D, while the scrape-off-layer has a 0D structure. For the core region a physics based analytical regression based on a set of TGLF [G. M. Staebler, Phys. Plasmas 12, 102508 (2005)] runs has been produced. For the H-mode regime, an average ELM model is applied in the pedestal region. In the SOL a 2-point model for electron temperature (exhaust) and a particle balance for the species density at the separatrix have been implemented. All the models have been first validated individually in standalone setting. Finally, a fully integrated simulation in Fenix flight simulator [F. Janky et al., Fusion Engineering and Design (2019), E. Fable et al., Plasma Physics and Controlled Fusion (2021)] framework including transients (ramp-up + flattop + ramp-down) has been performed, matching the experimental trajectories. A broader validation including more discharges is planned for the near future and will be presented at the conference.
Multi-scales physics of magnetic reconnection: From basic mechanisms to instability

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Abstract. Magnetic reconnection consists in a modification of magnetic field topology leading to the formation of island-shaped magnetic structures. Magnetic reconnection is ubiquitous in magnetized plasmas. It is found in space plasmas (with the well-known example of sunspots of the solar flares[1]) as well as in fusion plasmas on earth[2]. The idea of the non-conservation of magnetic connectivity during the movement of a plasma emerged over the years[3]. Since then, many works based on theoretical and/or numerical models have given estimates of the growth rate of reconnected structures in disagreement with experimental observations (in space plasma in particular). In fusion plasmas, it is commonly accepted that the collisionality is too low to explain the existence of magnetic reconnection phenomena at large-scales[4] and at small-scales[5]. Thus, magnetic reconnection still raises many open questions. The work presented here falls within the context of hot fusion plasmas and aims to improve the fundamental knowledge about the life of a magnetic island. In the literature, studies mainly focus on how a reconnected structure (magnetic island) can grow, the phenomenon at the origin of magnetic reconnection being not distinguished from the phenomenon of growth. This leads generally to the disagreement between theory and experiences. However, there is no fundamental reason that the non-ideal mechanism at the origin of the reconnection is also the one that will allow the island to grow. Here, in the light of the many works of the last 70 years, a new paradigm for understanding and studying the magnetic reconnection in fusion plasmas is proposed. The life of a magnetic island (whatever its scale) follows 3 phases: the origin, the growth and the saturation. And, each of these 3 phases can be governed by different physical mechanisms.

The example of TDMIs[6] (i.e. Turbulent Driven Magnetic Islands) will be highlighted to illustrate this magnetic island recipe and the distinction between the mechanism which originates magnetic reconnection and that which drives the instability growth. Then, in the light of this new paradigm, an investigation on the origin (and not the drive) of magnetic reconnection in 3 tokamaks of different sizes (TCV, WEST and JET) will be presented in order to verify if magnetic reconnection is such an unexplained phenomenon in fusion plasmas.

References

Gyrokinetic simulations of turbulence and zonal flows driven by steep profile gradients using a delta-f approach with an evolving background Maxwellian

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Abstract. Delta-f Particle-in-Cell (PIC) codes have been successful in simulating gyrokinetic turbulence in the plasma core. This scheme is limited when simulating the plasma edge characterized by strong gradient regions, as large deviation and fluctuation from the background distribution render results unreliable as noise accumulates, especially in the zonal flows at quasi-stationary state. To alleviate this problem, under simplified physics [1], an adaptive delta-f scheme characterized by the use of a control variate which is a flux-surface-averaged Maxwellian with a time-dependent background temperature profile has been implemented, which demonstrated reduced noise accumulation in the zonal flows, prolonged heat flux, and increased signal-to-noise ratio. Efforts are now focused on implementing the adaptive scheme in the ORB5 [2] code with realistic geometry and stronger turbulent drive.

References
Shafranov shift correction to the Furth-Yoshikawa scaling of tokamak adiabatic compression

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Abstract. In 1970, Furth and Yoshikawa\cite{Furth1970} introduced the scalings of adiabatic plasma compression. Basically, if the shape of the external boundary of the plasma and the aspect ratio are preserved during the compression, then the density, kinetic pressure, beta and current scale respectively as $n \sim C^3$, $p \sim C^5$, $B \sim C^2$, $\beta \sim C$, $I \sim C$, where $C$ is the compression ratio, that is, the ratio between initial and final major radius. In the 1980s, some numerical simulations of tokamak adiabatic compression revealed discrepancies with respect to this scaling\cite{Albert1980, Holmes1980}, but the explanations remained vague. Even recent works on adiabatic compression relating to General Fusion plasmas appear to be unaware of a definitive explanation of the modification with respect to the FY scaling\cite{Brennan2020, Brennan2021}. In this work, we show analytically, by expanding the Grad-Shafranov equation in terms of $C$, that the deviation to the FY scaling is related to the Shafranov shift that arises when beta increases at large compression ratios. There is an obvious effect of the Shafranov shift, and an indirect effect, the latter adding to the first, and being the same order of magnitude. The result is that the pressure increases less than the $C^5$ scaling, which can have a significant impact on the fusion power achieved at maximum compression. The analytical results are backed up by equilibrium simulations carried out with the CHEASE code. Equilibria are obtained for different values of $C$, with conservation of the total flux, $q$ profile, and entropy of the plasma. The agreement of the theory and simulations is very good when the boundary of the plasma is circular and the aspect ratio small. When the aspect ratio is close to 1, and the boundary not circular, the analytical result gives the gist of the reduction of compression.

References:
\begin{itemize}
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