Partially-relaxed, topologically-constrained MHD equilibria with chaotic fields

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The commonly used equation of ideal force balance, $\nabla p = \mathbf{j} \times \mathbf{B}$, is pathological when the magnetic field, $\mathbf{B}$, is chaotic. This is because $\mathbf{B} \cdot \nabla p = 0$ implies that any continuous pressure, p, will have a gradient everywhere discontinuous or zero. Recently [1], formulation of the three-dimensional equilibrium problem has been proposed that combines elements of both ideal MHD, and thus allows non-trivial pressure profiles, and Taylor relaxation, so that the magnetic field may reconnect. A key element of this model that allows some a-priori control of the pressure (an input quantity) while making minimal assumptions regarding the topology of the chaotic field is to specify the pressure and rotational-transform profiles discretely.

Consider a plasma region comprised of a set of N nested annular regions which are separated by a discrete set of toroidal interfaces, $\mathcal{I}_l$. In each volume, $\mathcal{V}_l$, bounded by the $\mathcal{I}_{l-1}$ and $\mathcal{I}_l$ interfaces, the plasma energy, U_l, the global-helicity, H_l, and the "mass", M_l, are given by the integrals:

$$U_l = \int_{\mathcal{V}_l} \left(\frac{p}{\gamma - 1} + \frac{B^2}{2\mu_0} \right) dv, \qquad H_l = \int_{\mathcal{V}_l} \mathbf{A} \cdot \mathbf{B} \, dv, \qquad M_l = \int_{\mathcal{V}_l} p^{1/\gamma} \, dv, \tag{1}$$

where $\mathbf{A}$ is the vector potential, $\mathbf{B} = \nabla \times \mathbf{A}$.

The equilibrium states that we seek minimize the total plasma energy, subject to the constraints of conserved helicity and conserved mass in each annular region. We allow arbitrary variations in both the magnetic field in each annulus and the geometry of the interfaces, except that we assume the magnetic field remains tangential to the interfaces which we consider to act as ideal barriers. The Euler-Lagrange equations show [1] that that in each annulus the magnetic field satisfies $\nabla \times \mathbf{B} = \mu \mathbf{B}$ and the pressure is constant, and across each interface the total pressure is continuous, $[[p + B^2/2]] = 0$.

We have implemented this model in a code, the Stepped Pressure Equilibrium Code (SPEC), and numerical results will be presented. The SPEC code uses a mixed Fourier-Finite element representation for the vector potential. Quintic polynomial basis functions give rapid convergence in the radial discretization, and the poloidal angle is adjusted to minimize a "spectral-width". For given interface geometries the Beltrami fields in each annulus are constructed in parallel, and a Newton method (with quadratic-convergence) is implemented to adjust the interface geometry to satisfy force-balance.

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On the W7-X island divertor

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W7-X will be equipped with ten divertor modules of the same type as the island divertor (ID) tested on W7-AS. Nevertheless the divertor islands are much larger and the poloidal mode number of the island chain is smaller because of the increased operational rational-transform in W7-X. Divertor transport studies using the EMC3-EIRENE code clearly show different transport behaviour between W7-AS and W7-X. Using W7-AS as reference, this paper shows how and to what extent the island divertor transport characteristics in W7-X in terms of power load, particle exhaust, neutral screening and compression, impurity radiation and transport and detachment transition are expected to change. β-induced stochasitization and finite plasma current effects are also discussed.

NON-NESTED MAGNETIC SURFACES IN TOKAMAKS

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We present stream function analytical solutions of the Grad-Shafranov equation, for arbitrary aspect ratio tokamaks with reversed toroidal currrent. The solutions are obtained in terms of non-orthogonal toroidal polar field line coordinates, introduced in previous works to evidence toroidal effects in the equilibrium geometry. We expand the solutions in terms of the inverse aspect-ratio and analyze the first two terms in this expansion. In the toroidal polar coordinates, the zero order stream function already contains toroidal effects; it depends only on the radial coordinate and describes nested toroidal magnetic surfaces with a null stream function gradient in one of these surfaces. However, the first order correction introduces a poloidal angle dependence on the stream function and gives rise to a field lines reconnection around this especial surface. Consequently, for toroidal reversed current profiles, one magnetic island chain arises around this surface. Moreover, we use our analytical stream function to derive an approximate expression for the magnetic island width.

Internal transport barriers in non-twist magnetic configurations with monotonous safety factor

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We study the existence of the internal transport barriers in zones where the twist property of the magnetic field configuration is violated, even if a monotonous safety factor is considered. We study the influence of the safety factor on the position and on the width of the transport barrier (when it exists). We also show how a transport barrier can be (theoretically) built in a prescribed position using slight modifications of the safety factor.

Impact of Fast Rotating Resonant Magnetic Perturbation Fields on Edge Electron Density and Temperature at TEXTOR-DED

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The understanding of the plasma edge (r/a>0.9) transport under the impact of externally applied Resonant Magnetic Perturbation (RMP) is key to extrapolate suppression of large type-I edge localized modes (ELMs) to future fusion devices.

We show for highly resistive L-mode plasmas at the TEXTOR-DED tokamak by means of highly radially and temporally resolved electron density n_e and temperature T_e measurements that a fast rotating RMP field imposes a poloidal and toroidal modulation to the $n_e(r,t)$ and $T_e(r,t)$ fields. This shows that a 3D plasma boundary structure is imposed and rotates with the RMP rotation frequency of $|\nu_{RMP}|=974$ Hz applied. In the far plasma edge (r/a>0.98), a simultaneous drop of both n_e and T_e is found, consistent with observations with static RMP fields indicating the existence of a 3D scrape-off layer (SOL).

At smaller radii (r/a<0.98), a shift of the n_e modulation relative to the T_e waveform is detected and the actual magnitude of the phase between both depends on the relative rotation f_{rel} between the rotating RMP field and toroidal plasma rotation. The phase between n_e and T_e grows approaching the next inward rational flux surface showing at low relative rotation of f_{rel}=-200Hz, an in-phase modulation while at high relative rotation of f_{rel}=+1800Hz, counter-modulating n_e and T_e waveforms are measured. An explanation for the measured phase shift is extracted from stationary EMC3-Eirene fluid plasma transport and kinetic neutral modelling. In the far edge coherent SOL flux tubes represent an effective loss channel for energy and particles inducing a simultaneous modulation of n_e and T_e. At the next rational surface a magnetic island is formed which connects radial regions over the island extension at the O-point. This causes a quasi-isothermal distribution around the island with small cross-field heating of the island interior. The island interior as region with increased density display low temperature, consistent with the phase shift between n_e and T_e.

Both waveforms are shifted toroidally with respect to the one modelled by EMC3-Eirene and this shift increases for high relative rotation. This indicates that the local magnetic island topology and the induced transport depend on the resonant amplitudes and the relative rotation. This is in agreement with recent results of a 4-field drift fluid modelling with self-consistent internal plasma response.

Comparisons between the trends predicted by this code and the measurement will be discussed highlighting the importance of measurement of local transport features in the plasma edge for development of self-consistent plasma response and transport models with RMP fields.

Spatiotemporal Chaos in Rotation Profiles near Separatrix of Tokamak Plasma

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Toroidal and poloidal rotations of plasma at the edge region of tokamak devices have long been known to play an important role, such as enhancing the confinement properties by suppressing turbulent behaviour, improving tolerance to error fields and increasing stability to neoclassical tearing modes [1]. This behaviour is seen in many tokamaks with different regimes. Imparting momentum to the plasma is also possible intrinsically as well as through the external sources such as, for example, the neutral beam injection. Several mechanisms has been suggested to explain the reason for spontaneous toroidal rotation of plasmas. The gradients of temperature and density have also an effect on plasma rotation. Therefore, the bifurcations and chaos in temperature profiles caused by a periodically driven impurity injection in edge region of toroidal devices [2] are also likely to influence the rotation phenomena. Hence, understanding of creation and evolution of rotation has a great importance, since external momentum would not be enough or could not be even realized especially for future large fusion devices [3].

In this study, the flux surface averaged toroidal and poloidal plasma rotation equations in edge region of tokamak have been investigated numerically by using a discretization method described in Ref. [4] within the context of collisional neoclassical theory revised to include the effects of steep gradients [5-8] with nonchaotic magnetic fields. For the temperature and density evolutions the multi-time scale quasilinear energy and particle conservation equations were considered conjointly with the toroidal and poloidal rotation velocity equations derived from the conservation of angular momentum. These equations were solved in a radial boundary layer of the magnetic separatrix under the Dirichlet boundary conditions.

It is shown that the approach of the inital gradient of temperature and density to a steady-state is much faster than those of the rotation velocities. Under some boundary values, however, it is observed that, in particular the poloidal rotation has a tendency for spatiotemporal chaotical oscillations. This is due to the weakening of the stability of the system of equations considered. It is observed that as the initial steepness of the temperature and density gradients grows, the velocity profiles exhibit bifurcative behaviour as shown in steady state solutions [9]. A special diffusively coupled map lattice was also applied as a model for the chaotic solutions of the PDE system considered.

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POLOIDAL DIVERTOR MODEL TO INVESTIGATE MAGNETIC FIELD LINE ESCAPE PATTERN IN TOKAMAKS

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We use a model consisting of five parallel infinite wires conducting electric currents to reproduce a single-null magnetic surface similar to divertor tokamaks surfaces. This simple model reproduces quite well ITER like magnetic topologies being capable to capture some aspects of the magnetic field lines dynamics of the plasma region near the separatrix, but not in the plasma core. To study the field line escape patterns near the separatrix we include resonant magnetic perturbations associated to error fields, which appear due to asymmetries on the machine. We compare the obtained escape pattern with the observed particle deposition on the tokamak wall and how this comparison is improved by taking into account particle collisions inside the plasma.

Interplay of magnetic shear and resonances in magnetic fusion devices

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The dual impact of low magnetic shear is shown in a unified way with extension to non-axisymmetric states. Away from resonances, it induces a drastic enhancement of magnetic confinement that favors robust internal transport barriers and turbulence reduction. When low-shear occurs for values of the winding of the magnetic field lines close to low-order rationals, the amplitude thresholds of the resonant modes that break internal transport barriers by allowing a radial stochastic transport of the magnetic field lines may be quite low. This analysis puts a constraint on the tolerable mode amplitudes compatible with internal transport barriers and is shown to be consistent with diverse experimental and numerical signatures of their collapses.

Screening of RMPs by flows in tokamaks.

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The application of RMPs with the aim of ELM control in tokamaks demonstrated a variety of ELM responses at similar a priory edge ergodisation estimated using vacuum modelling without plasma response: ELM suppression, ELM mitigation, ELM triggering or no effect at all were observed on different machines at different plasma parameters with RMP *[M Fenstermacher et al 23rd IAEA Conference, Daejon, Korea, 11-16 October, 2010]*. This indicates the importance of plasma response for the reliable extrapolations of RMP method of ELM control to ITER.

In the present work MHD rotating plasma response to RMPs is studied using non-linear reduced four-field MHD model with neoclassical poloidal viscosity tensor and two fluid diamagnetic effects for electrons and ions. It was demonstrated that RMPs can be screened due to the large poloidal *ExB* rotation for the pedestal region or penetrate into the plasma depending on plasma parameters such as toroidal rotation, temperature, density, resistivity and RMP amplitude. ITER H-mode scenario equilibrium, plasma profiles and RMP coils spectrum were used for estimations of RMP screening in ITER using cylindrical version of the code RMHD.

First results of the implementation of toroidal rotation, neoclassical viscosity tensor and ion-ellectron diamagnetic effects in non-linear MHD code JOREK in toroidal geometry will be presented. It is demonstrated that very specific structure of the parallel and poloidal flows are formed in the region of the separatrix and strong pedestal gradients, which is important for physics of RMP screening by rotating plasma.

This work, supported by the European Communities under the contract of Association between EURATOM and CEA, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work has benefitted from financial support from the Fusion For Energy grant F4E-GRT-055(PMS-PE).

Impact of RMP screening on tokamak poloidal divertor footprints

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One of the major unsolved questions of the RMP technique of ELM control is the importance of plasma screening by RMPs. The empirical criterion of island overlap in the edge region is based on the vacuum field, however the plasma response may modify the applied RMP field substantially, possibly leading to elimination of magnetic islands and the edge stochastic region that the vacuum models predict. ELM control experiments on different tokamaks yield very different results and one may speculate that an underlying reason might be differences in the plasma response. It is therefore important to develop models of the plasma response to RMPs and at the same time experimental methods to detect the plasma response and validate the models.
The present work addresses both issues. The plasma response is modelled using the four-field reduced MHD code RMHD, which includes diamagnetic effects and neoclassical poloidal viscosity. The diamagnetic effects are important because, together with the ExB rotation in the pedestal, they can lead to almost complete screening in the pedestal. A more detailed explanation of the model is given in another contribution in this workshop [Becoulet SFP2011]. The main focus of the present work is the possibility of detection of screening using the splitting of divertor strike points (the so-called divertor footprints). We already predicted that for MAST, JET and COMPASS the footprints should be significantly reduced if complete screening is assumed, which can explain the MAST and JET experimental results. Here we make similar predictions for DIII-D and compare with the abundant experimental observations of strike point splitting during the RMP experiments on this device. The RMHD modelling results are used in addition to the ad-hoc assumption of complete screening in order to give a more realistic profile of screening and possible impact of X-point geometry on the screening is discussed.

This work was supported by the Academy of Sciences of the Czech Republic IRP #AV0Z20430508, the Ministry of Education, Youth and Sports CR #7G09042 and European Communities under the contract of Association between EURATOM/IPP.CR No. FU07-CT-2007-00060. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Analysis of NSTX RMP ELM-triggering experiments using stellarator tools

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The application of non-axisymmetric magnetic perturbations has been demonstrated to destabilize edge-localized modes (ELMs) in the National Spherical Torus Experiment [1]. The magnetic spectrum of the dominantly n=3 perturbation contains strong resonant components, sufficient to cause stochasticity assuming fully penetrated fields, although the non-resonant terms are also strong. In initial experiments, it was observed that the pedestal electron temperature increased when the n=3 field was applied, leading to an increase in the edge pressure gradient sufficient to cause edge instability according to MHD stability calculations [1]. However, later experiments—notably those that used lithium coatings on the plasma facing components—showed a flattening of both the electron temperature and density profiles in the region $\psi_N = 0.8$-0.9, with no increase in the pressure gradient [2]. ELMs were also triggered in this case, leaving the underlying cause of the change in edge stability due to the presence of 3-D fields unclear.

A model 3-D equilibrium has been calculated for these experiments using the VMEC code [3], which assumes nested flux surfaces and therefore that resonant perturbations are shielded. First, a free-boundary equilibrium is calculated using the NSTX coil set, with pressure and current profiles matched to a standard 2-D reconstruction, but with up-down symmetry enforced (in experiment the plasma is biased slightly downward, with $d_r^{sep} \sim 0.5$ cm). A new equilibrium is then calculated with the n=3 field applied at a level consistent with experiment. This equilibrium is then used as the basis of further calculations using codes developed for analysis of stellarator plasmas. The neoclassical transport is calculated using the DKES [4] and NEO [5] codes, and compared both the experimental transport rates and that expected if the perturbation fully penetrates and the field is stochastic. A new 3-D equilibrium is also calculated using the SIESTA code [6], which allows for the formation of islands and stochastic regions. A comparison of the field structure between the SIESTA calculation and the assumption of fully penetrated vacuum perturbations, as well as the expected stochastic transport rates under the two models, will be presented.

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*Supported in part by U.S. DOE Contracts #DE-AC05-00OR22725, DE-AC02-09CH11466, and DE-FG02-99ER54524

5th International Workshop on Stochasticity in Fusion Plasmas,Julich, Germay 2011

Topic: Plasma response, Particle and Energy Transport in 3D magnetic perturbation, RMP penetration

Oral presentation requested

Kinetic Simulation of RMP Penetration, Plasma Transport, and Pedestal Response in Diverted Tokamak Geometry*

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The XGC0 guiding center particle code has been used to study resonant magnetic perturbations (RMP) penetration and pedestal response physics in diverted DIII-D magnetic field geometry. The plasma response (including current response) to external RMPs is evaluated in XGC0 and the magnetic field perturbation, consistent with the plasma response, is calculated using a solver in the M3D code in a mathematically strongly coupled manner. Monte Carlo neutral atoms, kinetic ions, kinetic electrons, heat and torque inputs are considered together. The simulation results are compared, with noticeable success, to DIII-D experimental results; these include radial profiles of plasma density, ion temperature, electron temperature, radial electric field, toroidal rotation, and electron perpendicular flow. Comparison of the results with other tokamaks (especially, the tight aspect ratio devices NSTX and/or MAST) is to be performed and presented. A new understanding of RMP field penetration physics and the stochastic plasma transport physics has emerged from these simulations and will be presented. Similarities with and differences between ideal and resistive MHD results will be discussed. In response to a recently elevated interest in the response of the turbulence to RMP fields, an XGC1 gyrokinetic simulation study of RMP effects on ITG turbulence in diverted magnetic field geometry will be presented, using the XGC0-M3D plasma response to the RMP fields. Future plans for further validation and for predictive ITER simulation will also be discussed.

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*This work was supported in part by the U.S. Department of Energy under DE-FG02-06ER54845, DE-FG02-86ER53223, DE-FG02-07ER54917, and DE-FC02-04ER54598.

Density Fluctuation-Induced Transport in a Stochastic Magnetic Field

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Abstract:

Stochastic magnetic fields in a reversed field pinch play a very important role in particle and momentum transport. The magnetic fluctuations resulting from tearing instabilities are coupled with current and pressure fluctuation leading to profile relaxation. Direct measurements of the stochastic field driven particle and momentum flux are made using a high-speed, laser-based, differential interferometer and Faraday rotation system. Measurements show (1) particle and momentum flux from stochastic magnetic field can account for the equilibrium density and flow change at the magnetic axis and plasma edge during reconnection, and (2) nonlinear interactions play an important role in the fluctuation-induced transport. Both particle and momentum transport arise from finite radial magnetic field correlation with density fluctuations. The origin of these density fluctuations is also identified experimentally. Work supported by US DOE and NSF.

Edge Monte Carlo 3D - Eirene simulations of the ASDEX Upgrade edge plasma under the influence of resonant magnetic perturbations and their comparison with the experiment

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The high confinement regime in tokamaks is accompanied by the appearance of so called edge localized modes (ELMs), quasi-periodic expulsions of particles and energy from the edge plasma to the surrounding plasma facing components (PFCs). Due to the limited capability of the PFCs to withstand the enormous heat loads expected in particular in large devices, ELMs have to be controlled or even suppressed in ITER. An important success to provide such a control tool was reported from DIII-D [1] and other devices where resonant magnetic perturbations (RMPs) were applied. Presently, a new set of 24 in-vessel RMP coils with an even further enlarged operational space is being installed at ASDEX Upgrade (AUG), of which a set of eight coils started operating in December 2010. Since the RMP coils break the toroidal symmetry of the tokamak, the edge plasma transport should be described by a 3D model. Recently, the Edge Monte Carlo 3D (EMC3) – Eirene code package was implemented successfully at AUG to simulate limiter [2] and divertor discharges [3]. EMC3 solves Braginskii's equations and is self consistently coupled to Eirene, which solves the kinetic equation for neutral particles. Since both EMC3 and Eirene are 3D codes this package is well suited to simulate the impact of the RMP coils on the AUG edge plasma. An indispensable prerequisite for EMC3-Eirene is the computational grid, which contains all the information about the magnetic geometry. Since the plasma parameters and in particular the neutral density vary over several orders of magnitude, different spatial scales are involved in the simulation and so an optimized grid is strongly required in particular in the case of ITER. In our presentation we will report on the details of the grid generation – now fully automatic for AUG – as well as first runs of EMC3-Eirene for AUG conditions with RMPs. The simulations will furthermore be compared to various edge and divertor diagnostics like the divertor and main chamber Langmuir/Mach probes, IR and visible cameras and the Li-beam and ECE diagnostics that acquired data during the first AUG H-mode discharges with applied RMPs.

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Measurement and modeling of divertor heat and particle fluxes in NSTX during RMP field application

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All magnetic confinement devices have, to some degree, a 3-D magnetic field structure. In tokamaks, asymmetry in the axisymmetric field is caused by plasma effects (such as neoclassical tearing modes), intrinsic error fields from a finite number or misalignment of coils, and intentional application of perturbative fields, e.g., for ELM suppression on DIII-D [1] and ELM triggering on NSTX [2]. As the 3-D structure exists in any case, the beneficial and detrimental effects must be understood, particularly in the divertor region where large heat and particle fluxes are deposited to the plasma facing components. In NSTX one effect of the applied external magnetic perturbations is to modify divertor heat and particle fluxes by directing formerly closed field lines to the targets, resulting in a striated pattern of field line intersections. These striations are observed in the NSTX divertor heat and particle fluxes, measured by infrared and D_α emission, respectively [3]. Without perturbation, the divertor profiles usually show a single peak localized to the intersection of the separatrix and target. After the perturbation is applied, this single peak is split into multiple locations at different radii. This strike point splitting is observed, to a lesser degree, due to intrinsic error fields. In both cases, the locations of the modified patterns are well described by field line following calculations performed using a superposition of 2-D equilibrium and vacuum applied and/or error fields. Comparisons of vacuum modeling and calculations from the IPEC code [4] indicate that plasma response does not have a large effect on the locations of the lobe structure formed by the stochastic field. More direct comparisons of both the patterns and magnitudes of the divertor fluxes can be made using the EMC3-EIRENE code [5], which self-consistently handles cross-field and parallel transport, with prescribed anomalous radial transport coefficients, in 3-D stochastic fields. The code also includes the effects of neutrals and complicated divertor geometries. Strike point patterns from field line following, as well as progress towards obtaining and particle fluxes from EMC3-EIRENE will be presented and compared to 2-D infrared and visible D_α camera measurements.

This work is supported in part by Magnetic Fusion Energy Postdoctoral fellowship from the Oak Ridge Institute for Science and Education and DOE contracts DE-AC05-00OR22725 (ORNL), DE-AC02-09CH11466 (PPPL), DE-AC52-07NA27344 (LLNL).

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ESCAPE PATTERNS OF MAGNETIC FIELD LINES IN ELONGATED TOKAMAKS WITH POLOIDAL DIVERTOR

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Integrable maps describing plasmas with a single null poloidal divertor with elongated cross sections are presented. The methodology proposed by Abbamont and Morrison [1] was used choosing a potential that produces a topology with an X-point. Hamilton´s equations are transformed in a discrete map, where the discrete time step depends on the safety factor $q(\psi)$. To study the escape patterns of the magnetic field lines and their footprints, a resonant perturbation was introduced by using a Martin Taylor ergodic magnetic limiter map. These effects of the ITER like elongated cross section were studied introducing a choosen potential. With these maps we show how the escape patterns and the footprints change with the plasma cross section.

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5th International Workshop on Stochasticity in Fusion Plasmas,Julich, Germay 2011

Topic: Energy and particle transport in stochastic magnetic fields
Oral presentation

Impact of Resonant Magnetic Perturbations (RMPs) on Turbulence Drives, Damping, and Transport*

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Edge localized mode (ELM) suppression by resonant magnetic perturbations (RMPs) is one of the possible options for mitigating the erosion of the divertor targets due to ELM-induced impulsive heat fluxes in ITER. RMPs have been used successfully to suppress ELMs in DIII-D H-modes with ITER-similar shape and pedestal collisionality by reducing the pedestal pressure gradient below the linear peeling-ballooning stability limit found using the ELITE code. A significant contribution to this pressure gradient reduction is the pedestal density reduction ("density pump-out") that occurs over a relatively broad range of edge safety factor q_{95}. Broadband density fluctuation increases in RMP ELM-suppressed discharges suggest that electrostatic turbulence may play a role in the increased transport caused by the magnetic perturbations, similar to the effect of the edge harmonic oscillation in QH-modes or the quasi-coherent mode in enhanced D_α (EDA) H-modes in Alcator C-Mod. Because this enhanced particle transport reduces core plasma performance, it is important to understand its causes in order to optimize RMP ELM control for ITER.

Normalized ion-scale ($k_\theta \rho_i \approx 0.2$) fluctuations $\tilde{n}/n$ increase across a rather wide radial extent ($0.5 < \psi_N < 0.9$) where the $E \times B$ shearing rate decreases. This increase in ion-scale turbulence may explain the difficulty in recovering the core density pump-out with high-field-side fueling pellets in these discharges. However, in the edge, the changes in ion-scale fluctuations $\tilde{n}/n$ and $E \times B$ shearing rate are more complex and not always correlated. In addition, the $E \times B$ shearing rate doesn't scale with increasing RMP-coil current as the density pump-out does, suggesting that RMP-induced changes to the turbulence drives or to intermediate-scale ($k_\theta \rho_i \approx 1$) turbulence may also be important. Density fluctuations $\tilde{n}$ at higher $k_\theta \rho_i \approx 0.5 - 0.7$ increase at $\psi_N \sim 0.93$, even though the inverse scale lengths for the profiles (n, T_e, T_i) drop significantly at this radius when the RMP is applied. The difficulty in assembling a consistent picture from these edge turbulence, shearing rate, and drive measurements may mean that other transport mechanisms are dominant in the edge. The observation that a/L_n decreases a factor of 2 while a/L_{Te} decreases a factor of 5–10 at the top of the pedestal is consistent with stochastic transport and supports the observation of windows in q_{95} for which the pedestal T_e decreases during q_{95} ramps coincident with ELM suppression.

*This work was supported by the U.S. Department of Energy under DE-FG02-05ER54809, DE-FG02-07ER54917, DE-FG02-94ER54235, DE-FG02-89ER53296, DE-FG02-08ER54984, and DE-FC02-04ER54598.

Analysis of stochastic magnetic fields formed by the application of resonant magnetic perturbations on MAST and comparison with experiment

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Suppression of type-I edge localized modes (ELMs) on DIII-D has been achieved using resonant magnetic perturbations (RMPs) produced by the internal coils (I-coils). This is thought to be due to the formation of a stochastic layer in the plasma edge, which enhances transport and keeps the edge pressure gradient below the critical value required to trigger an ELM.

MAST is equipped with a set of in-vessel coils similar to those on DIII-D, and the application of RMPs produced by these coils to MAST discharges has resulted in a density pump-out being observed in a range of L- and H-mode plasmas. An analysis of three-dimensional vacuum magnetic field structures formed in MAST RMP experiments, including various methods of quantifying the degree of edge stochasticity, are presented and compared with experimental values such as the magnitude of density pump-out.

The first of these methods involves the Chirikov parameter σ_{Chir}. It is found that, although the width of the region for which the vacuum σ_{Chir} exceeds unity, $\Delta\psi_{\sigma>1}$, must be greater than ~0.15 for pump-out to occur, this is not a sufficient condition. Further methods include the magnitude of the resonant harmonics of the applied field and figures of merit based thereon, as well as the field line loss fraction and the widths of the stochastic and laminar layers as calculated using vacuum field line tracing. The final method, and the one that shows the strongest correlation with experiment, is the displacement at the X-points relative to that at the mid-plane as calculated using the MARS-F code, which includes the plasma response to the applied RMPs. In this presentation, the predictions from each of these methods will be compared to a range of MAST experimental observations.

This work was funded by the Engineering and Physical Sciences Research Council under grant EP/G003955 and the European Communities under the contract of Association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Influence on Plasma Rotation by Resonant Magnetic Perturbation field

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Influence of resonant magnetic perturbation (RMP) fields on the plasma rotation is important for the application of plasma instability control using RMP in the next fusion devices, i.e. ITER. On TEXTOR, the Dynamic Ergodic Divertor (DED) can produce either a static or a rotating field with different configurations of m/n=3/1, 6/2 or 12/4, where m and n are the poloidal and toroidal mode numbers. Poloidal correlation reflectometry has been applied to measure plasma perpendicular velocity ($v_\perp$, perpendicular to the magnetic field line). These provide powerful tools to study the major effects of RMP on the plasma rotation including *i*) the edge stochastic torque; *ii*) Neo-classical toroidal viscosity (NTV) and *iii*) the electral magnetic torque. Recently, experimental studies of the influence of RMP on the plasma rotation have been carried out on TEXTOR.

When a static 6/2 RMP field is applied in an Ohmic plasma, $v_\perp$ is reduced by ~50% toward the ion diamagnetic drift (IDD) direction with a DED coil current (I_{DED}) of 2.5 kA. However, when the plasma current is reversed, where the DED field is not aligned with the pitch angle of the background field (non-resonance), the plasma rotation is not influenced. This result indicates that the change of plasma rotation towards IDD direction with a static 6/2 DED field is produced by the resonant part of the perturbation field. This has been considered to be due to generation of the boundary stochastic torque by charging of the plasma edge electric field to a more positive value due to larger losses of electrons than ions with an ergodic boundary [1, 2].

When an m/n = 3/1 RMP field, rotating in the electron diamagnetic drift (EDD) direction with a frequency (f_{DED}) of 5 kHz is applied to the same Ohmic target plasma, $v_\perp$ measured over the whole radii are spin-up in EDD direction before an m/n = 2/1 mode is excited. Further increase of I_{DED} up to 0.38 kA, an m/n = 2/1 mode is excited and the $v_\perp$ near the q=2 surface increases by a factor of 2 while no clear change of $v_\perp$ at the plasma edge (r/a~0.8) is observed. This results in a very large velocity peak appearing at the q=2 surface and a strong velocity shear near the boundary of the 2/1 island. When the rotating direction of the 3/1 RMP field is changed over from EDD direction to IDD direction, no clear influence on the plasma rotation is observed. These experimental observations can not be explained by either the boundary stochastic torque or the NTV theory. Theory suggests that the shielding current induced on the rational surface by the RMP field produces a force on the plasma such that the plasma is accelerated or decelerated, which depends on the difference between the plasma rotation and the RMP rotation [3]. This electromagnetic torque could explain the experimental observation.

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Screening of resonant magnetic perturbations with account of self-consistent electric field

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Screening of resonant magnetic perturbations (RMP) in a tokamak is analyzed with account of self-consistent electric field. On one hand, the self-consistent radial electric field is determined by the balance of the electron radial conductivity in a stochastic magnetic field screened by the plasma and by the neoclassical ion conductivity. On the other hand, the parallel current of electrons, radial projection of which is balanced by the ion current, determines the screening of RMP. In the present work the self-consistent electric field and RMP screening are calculated. Two different regimes of screening are found: the 'ion' branch which corresponds to the negative radial electric field and the 'electron' branch for which the electric field is positive. Predictions of the model are compared with the experimental data and results of simulation with various codes. Corresponding toroidal rotation and pump-out effect are discussed.

5th International Workshop on Stochasticity in Fusion Plasmas,Julich, Germay 2011

Topic: Formation of Stochastic Magnetic Layers at the Plasma Edge
Poster or short contributed oral presentation

Stochastic Edge in Poloidally Diverted Tokamaks*

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This work relates topological features of poloidally-diverted, tokamak magnetic line strike patterns on divertor surfaces to the magnetic field topology in the upstream tokamak edge plasma region. Plasma divertor strike patterns, visualized experimentally by light emitted by electron-excited atomic species just before the divertor target surface, as well as by other diagnostics, have been used to infer edge features [1–4].

The intent of this paper is to clarify aspects of ITER, JET, DIII-D and ASDEX low collisionality plasmas that might be stochastic near the plasma edge, i.e., neoclassical electron and ion collisionalities ν_e^*, ν_i^* << 1, but still slightly resistive and flowing slowly enough that magnetic lines reconnect under the influence of the 3D perturbation.

The present work studies the mapping of the last poloidal circuit (last “flight”) of diverted magnetic lines, from the neighborhood of the divertor saddle point to the target, during which the lines may exhibit mixed regular and stochastic behavior. Only conventional, poloidally elongated and diverted tokamak geometry with aspect ratio $A = R_0/a \approx 3$ is considered here, and the perturbations are limited to externally-sourced resonant magnetic perturbation (RMP) fields applied from the low field side of the plasma with amplitudes $<0.01\ B_0$. In this weakly perturbed system, the hyperbolic fixed point that governs containment or loss of magnetic lines is still nearly a geometric circle. The divertor target magnetic strike pattern is split into a discontinuous spiral pattern. Magnetic lines are integrated numerically with high accuracy by the TRIP3D code. New mapping results will be presented and will be discussed in the context of RMPs used for edge localized mode suppression.

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*This work was supported by the U.S. Department of Energy under DE-FC02-094ER545698.

Numerical Modelling of Plasma Response to Externally Applied Resonant Magnetic Perturbations

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The response of tokamak plasmas to applied resonant magnetic perturbations (RMPs) is studied numerically by using the nonlinear two-fluid equations. It is found that either the plasma rotation frequency or the local electron temperature and density gradient (diamagnetic drift frequency) can be significantly changed by RMPs. Depending on plasma parameters, the RMP amplitude and the original equilibrium plasma rotation direction and frequency, the RMP can either speed up or slow down plasma rotation or even change the rotation direction. Similarly, the RMP can either increase or decrease the local electron density gradient. The electron temperature changes in a different way from the electron density due to the parallel heat diffusion. The particle transport in stochastic magnetic fields is also studied, which is found to be similar to that across a single magnetic island.

β dependent changes of divertor heat and particle fluxes at LHD

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Abstract

A helical experiment like the Large Helical Device (LHD) can be operated in configurations resulting in a significant amount of stochastic field lines in the plasma boundary [1]. A comparison between particle fluxes measured with Langmuir probes [2] and heat flux pattern determined with a simple semi-infinite model [3] shows similarities to the magnetic edge structure, which leads to the assumption, that the heat and particle flux patterns are strongly depending on the magnetic topology of open field lines [2]. Similar effects have been observed at the tokamak TEXTOR with an externally created ergodized magnetic edge [4]. The magnetic edge topology changes drastically with plasma from the vacuum field due to the nonlinear response to perturbing plasma currents. This response was shown to be dependent on the plasma β in the stellarator W7-AS [5]. Therefore, it is assumed that the heat and particle flux pattern can be used to study not only the magnetic edge structure but also the nonlinear interaction of the plasma with external fields at different β.

In this comparative study the finite β effects on the magnetic field structures calculated with a numerical equilibrium code (HINT2 [6]) are verified by a systematic investigation of the heat flux pattern on the helical divertor at different plasma conditions in LHD. Heat fluxes are derived from temperature measured by an infra-red camera observing the surface of the helical divertor. In addition to the infra-red data, time correlated measurements of CIII and H_α emission were conducted at the very same location.

The correlation of the evolution of the calculated magnetic topology and the observed structural changes of the heat and particle flux pattern serves as an experimental reference to the equilibriums and provides further insight in the particle and energy transport in the stochastic edge.

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Formation of particle transport barriers in small-scale turbulent fields in tokamaks

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The turbulent transport of particles and energy in magnetized plasmas induced by small-scale turbulent fields (drift–wave turbulence or magnetic fluctuations) is believed to be the main cause of poor confinement in magnetically confined plasmas. The experiments show that the high confinement operational (H-mode or ITB) regimes are achieved by the heating plasma. It is believed that in theses regimes the turbulent transport is locally suppressed by the creation of transport barriers at certain radial positions of the plasma, the edge transport barrier (ETB) at the plasma edge and the internal transport barrier (ITB) in the plasma core. There are several important issues of the transport barrier formation in turbulent plasmas, such as a determination of dominant mechanisms of the ETB and ITB formation and the role of integer and rational magnetic surfaces.

The aim of this work is to study the formation of turbulent transport barriers of test particles near low-order rational magnetic surfaces. The transport of passing particles in a small-scale turbulent field is directly simulated using a fast-running mapping. The local radial transport (diffusion) coefficients of passing particles are numerically calculated. It is found that for the turbulent field amplitude causing the stochastic transport due to overlapping small-scale resonant islands the radial profiles of diffusion coefficients in average follow the quasilinear approximation. However, in the small neighborhood of low-

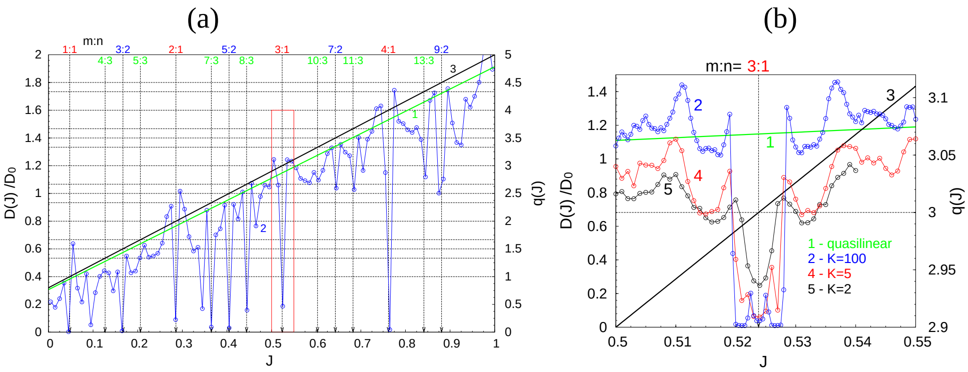

Figure 1: (a) Typical radial profile of diffusion coefficient $D_J = \langle(\Delta J)^2\rangle/2\Delta\varphi$, ($J$ is the radial flux coordinate, φ is the toroidal angle) for the Kubo number $K = 100$. Curve 1 (green) – the quasilinear prediction, curve 2 (blue) – numerical results, curve 3 – the effective safety factor profiles, $q(J)$ (right axis). The low–order resonant surfaces J_{mn}, ($q(J_{mn}) = m/n$), are shown by vertical straight lines. (b) Zoom of rectangular area near the $q = 3$. Curves 2, 4, and 5 correspond to the Kubo numbers $K = 100$, 5, and 2.

order rational magnetic surfaces the diffusion coefficients drops forming transport barriers. The typical radial profiles of diffusion coefficients and the transport barriers for the different Kubo numbers K are illustrated in Fig. 1 for the simple model of a passing particle motion in a tokamak with the background small-scale turbulent field. The depth and width of the transport barrier depend on the mode spectrum and the Kubo number of fluctuating turbulent field. A possible role of this phenomenon on the formation of the ITB and ETB triggering the high confinement regimes (H-mode) is discussed.

Universal asymptotics of poloidal spectra of magnetic perturbations created by saddle coils in tokamaks

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Many modern fusion devices, tokamaks are equipped with the external coils to control MHD instabilities in plasmas to suppress the ELMs in high-confinement (H-mode) regimes. Control coils are also planned to install in the ASDEX-U tokamak and ITER to control the resistive-wall modes and to mitigate the ELMs. The external coils are typically installed inside or outside of a plasma vacuum vessel as a set of toroidally distributed saddle coils. The effect of the magnetic perturbations is mainly determined by their toroidal and poloidal spectra given by the $(m,n)-$ components of a Fourier expansion of the perturbation field in straight field line coordinates, ϑ and φ, i.e., poloidal and toroidal angles. Calculations of the spectra of magnetic perturbations are the important first step in studies of the effect of magnetic perturbations on various properties of plasmas in tokamaks.

In this work the toroidal and poloidal spectra of magnetic perturbations created by a single set of saddle coils in tokamak plasmas are studied in a vacuum approximation. It is found that the poloidal mode spectra with a high–accuracy are described by a linear combination of three universal asymptotical formulas corresponding to the two horizontal and vertical segments of a saddle coil set, respectively. They depend only on the safety factor $q(\psi)$ of the equilibrium plasma and the geometry of perturbation coils. The each of components of perturbation poloidal fluxes corresponding to the toroidal mode number n are described by the following expressions

$$H_{mn}^{(j)}(\psi) = \exp\left(-\frac{mC_j(\psi)}{q(\psi)}\right) e^{i\chi_{mn}^{(j)}} \begin{cases} A_j(\psi)/q(\psi), & j=1,2, \\ nA_3(\psi,m)/m, & j=3, \end{cases}$$

where $(j=1,2)$ correspond to the horizontal segments and $j=3$ to the vertical $(j=3)$ segments of a set of saddle coils. The functions $A_j(\psi)$ and $C_j(\psi)$ are functions of the magnetic flux ψ with a finite values at the separatrix ψ_s, $A_j(\psi_s)\neq 0$, $C_j(\psi_s)\neq 0$. Near the magnetic axis $\psi\to 0$ the function $C_j(\psi)$ grows as $C_j \approx -\alpha q(\psi)\log\psi$, which corresponds to the asymptotics $H_{mn}^{(j)}(\psi)\sim\psi^{m\alpha}$. The numerical calculations show that $\alpha\approx 1/2$. The amplitudes $A_j(\psi)$, $(j=1,2)$, corresponding to the horizontal segments of saddle coils change very weak with ψ in the whole plasma region. The dependence of A_j on the toroidal mode number n is close to the exponential law, $A_j\sim\exp(-Bn)$ for $n>1$ $(B\neq 0)$. The phases $\chi_{mn}^{(j)}(\psi) = \chi_n^{(j)} - m\vartheta_j(\psi)$, $(j=1,2,3)$ are linear functions of the poloidal mode number m where $\vartheta_j(\psi)$ are angles at which the magnetic perturbation functions corresponding to each segments attain their extrema. The angle $\vartheta_j(\psi)$ has the following asymptotics near the separatrix $\vartheta_j(\psi)\approx c/q(\psi)$, $(c\neq 0)$.

The asymptotical formulas are confirmed by numerical calculations of the mode spectra of I-coils in the DIII-D plasma and of the EFC in the NSTX plasma. Their accuracy improves with increasing the toroidal mode number n. It is more pronounced in low aspect-ratio tokamaks. The asymptotical formulas can be useful in installations and a technical design of saddles coils in modern tokamaks to obtain a desired spectra of magnetic perturbations.

On the confinement of passing alpha particles in a tokamak-reactor with resonant magnetic field perturbations shielded by plasma currents

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The effect of external resonant magnetic field perturbations (RMPs) on passing α-particle orbits in a tokamak is studied numerically for typical parameter values of the tokamak-reactor with additional coils for ELM mitigation. The size of magnetic islands can be strongly reduced due to shielding of RMPs by plasma currents in the vicinity of resonant surfaces up to two orders of magnitude as compared to their size in vacuum. The analogous reduction of islands formed by α-particle drift orbits is usually much weaker because α-particles depart from the resonant magnetic surfaces by distances which are much larger than the Larmor radius of thermal ions. As a result, the ergodization of α-paricle orbits at the plasma edge is stronger than the ergodization of magnetic field lines. Nevertheless, in the presence of shielding, the region with stochastic orbit losses is noticeably smaller as compared to the size of this region computed in the vacuum approximation for the perturbation field.

Spectral Measurements of the Influence of Resonant Magnetic Perturbation on Runaway Electron Loss

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Abstract

At TEXTOR the Dynamic Ergodic Divertor, DED, is an excellent tool to create a well defined ergodization of the magnetic field. The DED can be operated with different connections of the coils, namely in the m/n = 12/4, m/n=6/2 or m/n=3/1 modes. Here we chose the m/n=6/2 mode because it provides a radially rather deep ergodization without exciting a tearing mode.

In order to measure the effects of the ergodization, we utilize runaway electrons in the MeV range produced in low density discharges for which TEXTOR has a long tradition. Because runaways move nearly with the speed of light and because they are practically collisionless, they are immediately lost when their orbit intersects a wall component. The orbits of the runaways resemble the ones of the magnetic field lines. However, they are not identical because the runaways are displaced from the magnetic surfaces depending on their energy such that the orbits of the low MeV electrons are close to the field line structure while the ergodic effect on high MeV runaways is strongly reduced. A new theory is developed for the mapping of the runaway orbits including the additional diffusive loss effect of magnetic turbulence.

A new scintillator probe is developed for measuring the runaways which leave the plasma. The probe is mounted on a drive mechanism which inserts it to the plasma edge shortly before the DED is switched on and leaves it there until the end of the discharge. The probe is covered with a graphite mantle which shields it from electrons with energies lower than 4 MeV. The active parts of the probe are 9 crystals which scintillate when hit by runaways. The emitted light is fed via glass fibres to 9 photomultipliers. The crystals are placed behind layers of stainless steel of different thicknesses such that the first crystal detects all runaways passing the graphite mantle and the last one only runaways beyond 22 MeV. By this construction, the energy spectrum of the runaways leaving the plasma is measured.

With the onset of the ergodization, the probe signal increases; the increase grows non-linearly with the ergodization level. Also details of the spectrum of the lost runaways change from low to high ergodization level. The details of the observed effects are topic of the ongoing analysis.

Turbulence in the Vicinity of Magnetic Islands: Their Impact on Long Range Correlations of Potential Fluctuations in the WEGA Stellarator

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Abstract.

The role of the magnetic field topology for the complex interplay between turbulence and zonal flows leading to the formation of transport barriers is a recent topic in fusion research. Gaining knowledge on their relation in experiments requires a flexible magnetic configuration and a good diagnostic access with high temporal and spatial resolution. WEGA as a small classical stellarator with moderate plasma parameters is well suited for such experiments.

A systematic study of the impact of low order magnetic islands on electrostatic fluctuations has been performed in the WEGA stellarator. Stationary islands with a toroidal mode number $n = 1$ caused by coil misalignments can be modified in size by external error field compensation coils. The results presented here were performed in magnetic configurations with $m/n = 5/1$ islands of different size at the plasma edge, with m being the poloidal mode number. The results are compared to configurations showing no major $n = 1$ resonances leading to the formation of islands in the rotational transform profile. The spatio-temporal structure of fluctuations can be studied with Langmuir-probe arrays installed at different toroidal and poloidal positions.

In low density discharges finite frequency zonal flow like potential fluctuations were observed. A characteristic feature of these oscillations is a long range correlation with fluctuations being in phase on a flux surface and thus indicating an $m = 0$, $n = 0$ mode structure. In magnetic configurations without islands these low frequency ($f < 5$kHz) fluctuations appear in the edge region about two cm inside the last closed flux surface. The phase relation between radially separated probes shows a continuous increase with increasing probe distance which indicates a distinct radial phase velocity.

However, the presence of magnetic islands at the plasma edge alters the structure of these low frequency fluctuations. At $r < r_{island}$ the long range correlations are still observed. Inside the islands the fluctuations show up more like large scale structures with finite poloidal wave number. The radial phase shows, within the available spatial resolution, a discontinuity at the inner island separatrix which in turn indicates the radial electric field fluctuations of the zonal flow to be localized at the island separatrix.

Further on, a distinct localized increase of the turbulent radial $\mathbf{E} \times \mathbf{B}$ flux, estimated from $\tilde{I}_{sat}$ and $\tilde{\Phi}_{fl}$, depending on the island width was observed in WEGA.

On the effects of pumping, recycling and re-fuelling in 3D edge transport simulations of ITER similar shape plasmas

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Resonant magnetic perturbations (RMPs) are a candidate for ELM control in ITER. Modelling of the magnetic field structure during RMP application in the so called vacuum approach suggests that an open chaotic system in the plasma edge layer is induced. In order to investigate the resulting impact on plasma and neutral gas transport, the 3D edge transport code EMC3-EIRENE has recently been extended to poloidal divertor configurations [1]. This code includes a self consistent fluid treatment of particle, parallel momentum and energy transport for the edge plasma, as well as recycling and kinetic neutral particle transport.
For the present contribution, the code has been advanced to include the effect of neutral gas pumping and particle re-fuelling (e.g. by neutral beam injection or gas puffing) in order to reflect the experimental setup more realistically. The interface between EMC3 (charged particles) and EIRENE (neutral particles) has been further enhanced to better accomodate the EIRENE gas circulation options (puffing and pumping) in the overal integrated model. This allows to study the RMP induced particle pump-out effect e.g. observed at the DIII-D tokamak [2], and it will be shown that a reduction of density in the presence of RMPs is found in the simulations as well.
In this contribution we investigate the impact of these additional model features on an ITER similar shape plasma, using the DIII-D tokamak as example. Depending on the pump efficiency, a reduction of neutral gas density and recycling strength of more than one order of magnitude is found.

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Ideal and Non-ideal Plasma Responses to 3D Magnetic Perturbations in Tokamaks

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A small non-axisymmetric (3D) magnetic perturbations can greatly change tokamak performance, and thus the plasma responses to 3D magnetic perturbations have been actively studied in tokamaks. Fundamental level of understanding can be achieved by solving perturbed tokamak equilibria. The calculations of ideal perturbed equilibria, such as IPEC or MARS-F computations, and their applications to tokamak experiments have been largely successful to explain the observed plasma responses. However, a number of observations indicating the limitation of the ideal method have been also found, especially when a tokamak is in an advance operational regime. A critical physics required to improve the inconsistency is the non-ambipolar transport at the non-resonant flux surfaces, and the inner-layer dynamics including magnetic island opening at the resonant flux surfaces. The two different physical processes can be separated but still can be combined into a self-consistent solutions, if the kinetic forces associated with the non-ambipolar transport are included in solving perturbed force balance with appropriate jump conditions across the resonant surfaces. The development of the so-called General Perturbed Equilibrium Code (GPEC) is being planned and studied, and the presentation will cover the progress for GPEC, but also the progress in the understanding for the kinetic forces, for instance, the understanding for the Neoclassical Toroidal Viscosity (NTV) torque. Independently of the physics inside the plasma, the information in magnetic measurements for plasma responses are practically only the amplitude and the toroidal phase. Since the modifications for each by plasmas represent the energy and the torque required for producing the perturbation in the plasma, the external magnetic measurements are very useful to validate a model for the 3D plasma responses. The progress and the future work in experimental validations will be also presented.

Experimental investigation of density regimes in the helical divertor at TEXTOR

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Control and efficient exhaust of particles and energy using divertors with chaotic magnetic field structures are a field of major interest in stellarator research and also for tokamaks due to the application of resonant magnetic perturbations (RMPs). In particular the accessibility of favourable divertor density regimes such as *high recycling* and *detachment* [1], largely determined by the recycling of the hydrogen plasma at the divertor target plates, is still under investigation.

Using the capabilities of the Dynamic Ergodic Divertor [2] in the limiter tokamak TEXTOR, we have experimentally investigated the hydrogen recycling in such a complex, three-dimensional (helical) divertor structure similar to divertor structures found in stellarators [3], and compared the observations to results from modelling with the three-dimensional transport code EMC3-EIRENE [4]. The measurements showed that the recycling flux at the divertor target increases linearly with increasing plasma density, a high recycling regime is not observed. The radial penetration depth of the neutral hydrogen particles ($\lambda_\mathrm{n} \approx 3 - 4\,\mathrm{cm}$) estimated from spectroscopic measurements was found to be often larger than the varying radial extent of scrape-off layer of the helical divertor (few mm up to $6\,\mathrm{cm}$) which leads to convective heat transport reducing parallel temperature gradients and inhibiting flux amplification. The detailed comparison of the experimental observations and the modelling results showed agreement in this high density behaviour (in particular absence of a high recycling regime) as well as in the absolute values of the calculated and measured target particle fluxes. Simulations using different cross-field transport coefficients showed, that this agreement is only found above a certain level of cross-field transport ($D_\perp = 1\,\mathrm{m}^2\mathrm{s}^{-1}$). These findings, together with the proven capability to produce typical high recycling features in other configurations [4], support the use of the EMC3-EIRENE code for predictive modelling for divertors with similar chaotic magnetic field structures.

This work is part of a PhD thesis at the Heinrich Heine University Düsseldorf and included in the activities of the Research Training Group GRK 1203.

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Modeling of ELM with a current relaxation model

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Using a Taylor relaxation theory, initialised by an external peeling mode, the radial widths and frequencies of Edge Localised Modes (ELM) can be modeled. From this the dependence of the ELM frequency on the edge safety factor is investigated and a development of multiple resonances at lower values of the normalised edge current density is observed. The addition of small deviations of the plasma current leads to a possible explanation for the range of ELM frequencies experimentally observed. A comparison of experimental observations taken from the TEXTOR Limiter H-mode plasma is found to have good agreement with the modeling results. The basic assumptions and the range of validity of the model are discussed. The extensions to an application of this concept to scenarios with Resonant Magnetic Perturbations are sketched.

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First observations of ELM mitigation with new active in-vessel saddle coils in ASDEX Upgrade

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Edge Localised Modes (ELM) present a high risk for excessive wall erosion and co-deposition of tritium with hydrocarbon layers. It is therefore urgent to devise ELM mitigation techniques for ITER. Among the most interesting candidates, application of non-axisymmetric error fields has lead to full ELM suppression while maintaining stationarity of the H-mode [1]. However, experimental results from tokamaks have been very diverse so far. More intense studies are needed to resolve discrepancies and to build a physics basis for extrapolation to ITER. ASDEX Upgrade is currently being enhanced with a set of 24 in-vessel saddle coils for ELM mitigation, MHD mode rotation control and resistive wall mode feedback stabilisation [2]. The first set of eight in-vessel saddle coils, four toroidally spaced coils at the low field side above mid-plane and four coils below midplane, have now been installed and started to operate. The present coil configuration allows for $n = 1$ and $n = 2$ perturbation fields with odd or even parity between upper and lower arrays.

Initial H-mode experiments show that type I ELMs can be mitigated with stationary $n = 2$ perturbations (DC saddle coil current). The configuration chosen (odd parity) is resonant in the pedestal of discharges with edge safety factor $q_{95} = 5.5$. Plasma parameters used so far are $P_{\mathrm{NBI}} = 7.5$ MW neutral beam power and $P_{\mathrm{ECRH}} \geq 0.8$ MW centrally deposited electron cyclotron heating power. Medium gas bleed of $\Phi \geq 6 \times 10^{21}$ D/s is applied. The total heating power is more than three times the H-mode threshold power, and without operation of saddle coils ELMs are of type I as seen from the power dependence of the ELM frequency. The stored energy loss per ELM ranges from 30 to 100 kJ. The peak divertor power, as measured by infrared thermography, reaches up to 10 MW (total) in the inner divertor. After switching on the saddle coils (coil current 4.5 kA$\times$turns), the frequency of these large ELMs gradually decreases. In many cases they completely disappear for the entire remaining duration of the saddle coil pulse. In between or instead of these large ELMs intermittent high frequency transport events are observed, with similarities to small ELMs in type II or type III ELMy regimes. The power load on the divertor becomes more stationary, with peak levels not exceeding 2 MW in the outer divertor and lower power in the inner divertor, which remains detached. The plasma density and stored energy with coils on is not reduced compared to unmitigated type I ELM phases. Spectroscopic measurements of both tungsten lines and the quasi-continuum indicate that the tungsten concentration is lower in ELM-mitigated phases than in unmitigated type I ELM phases. First pellets have been injected into an ELM-mitigated phase: No large ELMs are triggered, however a moderate increase of density and stored energy is achieved. The presentation will describe these experimental results, characterising the mitigation effects on ELMs, and parameter ranges encountered so far. It is planned to widen the range of plasma parameters and to systematically scan access conditions to ELM mitigation. Any such new results obtained will be discussed.

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Topic: Energy and particle transport in stochastic magnetic fields
Oral contribution

Modeling Experimental Changes in Particle Transport from Resonant Magnetic Perturbations (RMPs) in DIII-D Using SOLPS5*

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Resonant magnetic perturbations (RMPs) are the most successful technique at suppressing the edge localized modes (ELMs) that will reduce divertor target plate lifetimes in future tokamaks such as ITER due to high impulsive heat loads. RMPs reduce the edge pedestal pressure gradient below the peeling-ballooning limit in part by increasing particle transport and reducing the density by 5%–30% [1], although this density reduction is a necessary but not sufficient condition for ELM suppression [2], Limiting the density pump-out to minimal levels to achieve ELM suppression is critical to achieve high performance in ITER.

In this paper, we compare the experimental changes in particle transport measured by using gas puff modulation for both ITER similar shape L- and H-mode experiments in DIII-D where the RMP was applied. The gas puff modulation experiments are initially interpreted assuming no particle source, which will affect the calculated transport changes towards the plasma edge. In both L- and H-mode, density pump-out is observed, but the magnitude of the pump-out is much larger in H-mode than in L-mode. Puff modulation experiments show that in H-mode, the inward pinch is reduced over the whole profile and the diffusive transport increases towards the edge. Together with the fact that the ExB shear decreases at $\Psi_N \sim 0.7$–0.9 and $\tilde{n}/n$ fluctuations in this same region measured by beam emission spectroscopy (BES) increase, this is consistent with an increase in turbulent transport in the core. At the plasma edge ($\Psi_N \sim 0.9$–1), $\tilde{n}/n$ ($k_\theta \sim 1$ cm^{-1}) decreases and no clear trend in ExB measurements is observed. However, in L-mode, two types of density pump-out are observed. There is an initial density pump-out, which correlates with the applied I-coil current. This initial density pump-out coincides with an $n = 3$ locked mode, which slows the rotation. For applied RMP currents from the I-coil above a threshold of 5.8 kA, even parity, 60 deg phasing, the rotation drops low enough for the RMPs to penetrate and create a stochastic edge, that is associated with the disappearance of the $n = 3$ locked mode and a spin-up of the edge rotation. Contrary to the H-mode results, $\tilde{n}/n$ decreases significantly and the puff modulation does not penetrate, when compared to L-mode without RMP. Experimental analysis (that does not incorporate the fueling source) shows that the inward pinch becomes outward in RMP L-mode plasmas. We use SOLPS5 to investigate if the changes in D and V result in the altered RMP density profile or if an additional change in neutral fueling is required.

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*This work supported in part by the U.S. Department of Energy Cooperative Agreement under DE-FG02-07ER54917, DE-FG02-08ER54984, DE-AC05-00OR22725, DE-FG03-97ER54415 and DE-FG02-04ER54761.

Plasma Response Models for Non-Axisymmetric Perturbations*

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The plasma response is a key to determining the consequences of 3-D perturbations arising from external non-axisymmetric coils, or saturated instabilities. This problem can be treated using various linear and nonlinear models, none of which are fully satisfactory. Linear models cannot provide the full response and the result can depend on the detailed physical model used, for example, ideal or resistive, single or two fluid, or a rotating or static plasma. For nonlinear models, there is no guarantee that the final state is the one chosen dynamically by the plasma among possible multiple states, or is even accessible. Studies have been performed using a number of the possible approaches and the results are compared. For a rotating dissipative plasma, the plasma behaves nearly ideally in the linear regime. In the quasi-linear regime, the response leads to the development of magnetic islands. The linear response is also calculated using the initial-value, finite-element code M3D-C1, which includes two-fluid effects, and rotation, as well as open field line regions and a resistive wall. Results of these calculations are compared with the ideal response and the response observed in DIII-D. In particular, two-fluid effects appear to reduce the screening of low rotation perturbations. The nonlinear response can be treated as a dynamic stability problem or from a nearby perturbed equilibrium approach. The nearby equilibrium approach aims to bypass the detailed evolution and search for the appropriate final state. The key is to assure accessibility of the final state. The simplest implementation is to add a perturbation from a stability code or external field to the equilibrium and solve for 3-D force balance. This is an example of the “Almost Ideal MHD” idea [1], where one looks for invariants relating the 2-D and nearby 3-D system; the invariants are buried in the numerical details of the equilibrium code. For example, calculations with VMEC can only yield solutions with, nested surfaces. An appropriate set of constraints is not presently known. However, the constraints can be informed from linear calculations. The linear calculations, for example yield the direction of steepest descent in a general sense.

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*This work supported by the US Department of Energy under DE-FG02-95ER54698, DE-AC05-06OR23100, and DE-AC05-00OR22725.

Edge topology and flows in the reversed-field pinch

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Edge topology and plasma flow deeply influence transport in the RFX-mod reversed field pinch, playing an important role in many practical aspects of plasma performances, such as access to enhanced confinement regimes [1], the impact on global power balance and operative limits, like the density limit[2].

In our analysis a central role is played by the edge electric field, which is determined by the ambipolar constraint guaranteeing quasi-neutrality in a sheath next to the plasma wall. Its radial component is experimentally determined in RFX over the whole toroidal angle by means of a diagnostic set measuring edge plasma potential and flow with different techniques [1]. The measured radial electric field is a guess for describing the potential in the form $V(\psi_p, \theta, \zeta)$ (ψ_p radial coordinate, θ, ζ angles), by means of the Hamiltonian guiding center code ORBIT[3]. In numerical simulations we included a schematic treatment of a realistic wall with recycling. Simulations show that a proper functional form of the potential, worked out from the experimental guess, is sufficient to balance the differential radial diffusion of electrons and ions subject to magnetic island O- and X-points. These islands are naturally present in the RFP edge, due to the vanishing of q at the reversal surface[4]. Electrons spend more time in the X-points of such islands than in O-points; ions have comparatively larger drifts and their radial motion is more uniform over the toroidal angle. The final spatial distribution of $V(\psi_p, \theta, \zeta)$ results in a complex 3D pattern, with convective cells that close onto the wall. This condition, for some threshold values of parameters as $q(a)$ and n/n_G (n_G Greenwald density), as well as of the boundary electron density and temperature (that depend on wall conditioning), can degenerate to more pathologic situations, such as the development of a stagnation point for electron density (precursor of the density limit[2]).

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Description of magnetic field lines without arcanes

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The description of magnetic field lines (MFL's) is at the core of the theory of magnetic confinement. It is also of paramount importance to tackle several issues of this workshop: stochastic magnetic layers, transport in stochastic magnetic fields, and resonant magnetic perturbations for ELM control. The need to deal with these issues has generated a huge literature where technical aspects are heavy and have required a considerable amount of analytical and numerical work. Although there have been since 1983 fundamental results about MFL's which might have alleviated this kind of work, as well as the training of beginners in the field, unfortunately, as yet these powerful results have been used by a small fraction of the magnetic fusion community only. This talk aims at reviewing these results and at proposing a methodology in order to minimize the work necessary to answer a theoretical problem about MFL's, either analytically or numerically.

The standard rigorous derivation of the Hamiltonian description of MFL's requires first the introduction of general coordinate systems involving the covariant and contravariant representations of vectors in physical space, and the derivation of orthogonality properties of their respective basis vectors. This tedious preliminary step may be avoided altogether by following the elegant and straightforward derivation by Cary and Littlejohn [1]. It relies upon the analogy between the stationary action principle ruling Hamiltonian mechanics and the one ruling MFL's. The latter gives the leading role to the *vector potential A,* while the standard derivation focuses on the magnetic field *B,* a pseudo-vector.

Working with *B* instead of *A* has induced repeated errors. A recent paper [2] quotes three theoretical and five experimental papers where a resonant Fourier harmonic of *B* was mistakenly considered as almost invariant when going from "natural" to magnetic coordinates, while it has a strong dependency on these coordinates. On the contrary the resonant flux is invariant in this process. This is proved in the literature by using *B* and the formula for the area element on magnetic surfaces in general coordinate systems. However working with *A* provides a much simpler proof that does not appeal to such coordinate systems. Indeed *magnetic flux and vector potential are strongly connected*.

Using *A* clarifies the nature of the *change of magnetic coordinates:* it boils down to a *change of gauge of the vector potential*. As shown by Elsässer, this change of gauge is a change of canonical coordinates [3]. No Hamiltonian needs to be invoked in the process, a natural consequence of the symplectic structure underlying MFL's dynamics. Working with the vector potential, avoiding as much as possible to use generalized coordinates, and substituting heavy approximate analytical calculations by simple numerical estimates or drawings provided by any validated computer code computing MFL's: this brings other simplifications which will be described, as well as new results.

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Overview of 3D heat flux in DIII-D RMP discharges

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As shown on DIII-D edge localized modes (ELMs) can be either completely eliminated or mitigated with Resonant Magnetic Perturbation (RMP) fields. Application of RMP results in a 3D magnetic topology that affects heat loads for ELM-suppressed discharges as well as the smaller ELMs seen during mitigated scenarios. One of the key questions is in how far these scenarios are compatible with ITER operational regimes and divertor design. In this contribution we aim to present overview of DIII-D results on heat loads to the divertor during RMP scenarios. We concentrate on the structure and distribution of the energy deposition in ELM suppressed and mitigated scenarios. This will also include recent experiments, where two infrared cameras, separated 105 deg toroidally, were used to make simultaneous measurements of ELM heat loads with high frame rates.
Depending on the plasma conditions and amplitude of the RMP fields one gets either full suppression of Type-I ELMs or mitigated ELMs. Interestingly it is possible to achieve a configuration with very small and very frequent transient heat loads to the plasma facing components and a very good confinement at the same time. Strong enough amplitude of RMP fields helps to control Type-I ELMs, but introduces three-dimensional patterns of heat loads with small toroidal asymmetries.

Toroidal Plasma Flow Generated from the Neoclassical Toroidal Plasma Viscosity in Tokamaks

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As one of the most important 3D effects in tokamaks, the theory of the Neoclassical Toroidal Plasma Viscosity (NTV) induced by the Non-Axisymmetric Magnetic Perturbation (NAMP) in different collisionality regimes has been well developed in the last few years, and it has been summarized in [1]. The numerical results showed a good agreement with the analytic solutions in different asymptotic limits [2]. The experimental observations of the non-resonant magnetic braking induced by NAMP on different tokamaks emphasized the importance of the NTV theory. The NAMP cannot be avoided and it is even applied for the control of the Edge Localized Mode (ELM) and Resistive Wall Mode (RWM) in tokamaks. Because of the importance of the toroidal flow, it is necessary to estimate the toroidal flow induced by the NTV without additional momentum input. Depended on the collisionality, the steady state flow will be in the counter-current direction if the ion NTV is dominant, while it is possible to be in the co-current direction if the electron NTV is dominant. The toroidal plasma flow induced by the NAMP for different plasma parameters will be self-consistently calculated according to the NTV theory in this paper. It will be discussed as well the prediction of the steady state flow induced by the NTV on ITER.

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Field Penetration and Shielding of Resonant Magnetic Perturbation Fields

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Plasma response to resonant magnetic perturbation fields (RMPs) is important for understanding the physical mechanism of instability control using RMP fields in the next generation of fusion devices, i.e. ITER. To date, many attempts to explain ELM suppression/control using RMP fields have focused on the idea that the edge thermal and particle losses are enhanced due to formation of an outer ‘ergodic’ zone with RMP fields. [1, 2] The ‘ergodic’ boundary would reduce the edge pressure gradients, and thus stabilise the peeling-ballooning modes thought to underlie ELM formation [1]. However, either bulk plasma or diamagnetic rotation [3, 4, 5] can screen the RMP fields from the resonant magnetic flux surface. Many calculations of the Chirikov parameter [6] or overlapping of resonant magnetic islands employ a vacuum assumption, which neglects the plasma response due to rotational screening and modification of the underlying equilibrium.

On TEXTOR, investigation of plasma response to RMP fields has been carried out under different dynamic ergodic divertor (DED) configurations. The perturbed magnetic field is measured by the Fast Movable Magnetic Probe (FMMP) installed at the outer equatorial plane (low-field side). Preliminary results show that the perturbed plasma edge magnetic topology is different from the case simulated with a vacuum assumption. Plasma response to RMP depends strongly on both the location of the resonant rational flux surface and the frequency difference between the drift of the rational surface in the plasma and the external perturbation.

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Edge Soft X-ray Imaging and Inversion Techniques for Measurement of Magnetic Topology from External 3-D Magnetic Perturbations*

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A new tangential 2D soft x-ray imaging system (SXRIS) has been designed for DIII-D to directly measure the edge island structure in the lower X-point region [1]. Plasma shielding and/or amplification of applied resonant magnetic perturbations (RMPs) may play a role in the suppression of edge localized modes (ELMs). Measurements of the actual island structure inside the plasma are needed to validate models for the effects of RMPs on ELM stability. Soft x-ray (SXR) imaging yields information on the magnetic topology of the plasma and this diagnostic is well placed to advance 3D tokamak physics, especially during RMP ELM suppression. This diagnostic targets the capability to image islands with widths >2 cm near the X-point where the flux expansion is large and island sizes are increased. Core MHD studies have used tangential viewing with visible cameras, pinhole optics and a scintillator plate [2] on both tokamaks and stellarators, but interpretation of the images is complicated by the 3D chordal integration, and requires advanced inversion techniques [3].

The image inversion is ill-posed and is inherently composed of limited-angle measurements. Therefore, it requires a regularization method. This problem has similarities to medical imaging, where high spatial resolution from limited-angle measurements is needed. Bayesian-statistics are often used to determine information at the desired level of accuracy to make useful diagnosis. Our approach is to exploit advances in this field along with more standard techniques used in SXR data of high temperature plasmas, e.g. Phillips-Tikhonov and maximum entropy methods. These techniques add a tailored “cost function” in the minimization functional, which apply criterion during the minimization.

We use both synthetic modeling of the DIII-D design and the wide-field SXR camera on NSTX to test inversion schemes. The synthetic DIII-D diagnostic calculation is based on 3D SXRIS emissivity estimates calibrated against the NSTX SXR camera [4]. The inversion methods are examined in the context of noise, spatial sensitivity and symmetry assumptions. Models of typical DIII-D discharges indicate integration times >1 ms with accurate equilibrium reconstruction are needed for small island (<3 cm) detection. Inversions of core NSTX 2/1 islands provides a basis to test these methods on less complicated data. These modes are much larger and have clear signatures on other diagnostics. Island sizes measurements are compared to modeling.

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*This work was supported in part by the US Department of Energy under DE-AC05-00OR22725 and DE-FC02-094ER545698.

Influence on Plasma Rotation by Resonant Magnetic Perturbation field

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Influence of resonant magnetic perturbation (RMP) fields on the plasma rotation is important for the application of plasma instability control using RMP in the next fusion devices, i.e. ITER. On TEXTOR, the Dynamic Ergodic Divertor (DED) can produce either a static or a rotating helical field with different configurations of $m/n = 3/1$ and $6/2$, where m and n are the poloidal and toroidal mode numbers. Poloidal correlation reflectometry has been applied to measure plasma perpendicular velocity ($v_\perp$, perpendicular to the magnetic field line). Experiments have been carried out on TEXTOR in order to study the major effects of RMP on the plasma rotation, including i) the edge stochastic torque, ii) Neo-classical toroidal viscosity (NTV) and iii) the electromagnetic torque.

In an ohmic plasma, $v_\perp$ is in the electron diamagnetic drift (EDD) direction and gets smaller when a static RMP field with $m/n = 6/2$ is applied. However, when the plasma current is reversed, where the DED field is not aligned with the pitch angle of the background field (non-resonance), the plasma rotation is not influenced. This result indicates that the reduction of plasma rotation is produced by the resonant part of the perturbation field. This has been considered to be due to the generation of a stochastic torque in the edge ergodic region, where a positive radial electrical field is produced due to a larger transport of electron than ion [1, 2].

When an RMP field with configuration of $m/n = 3/1$, rotating in the EDD direction with a frequency of 5 kHz, is applied to the same Ohmic target plasma, $v_\perp$ gradually increases with the increase of the field amplitude over the whole measurement radii. Further increase of the field amplitude excites an $m/n = 2/1$ mode and $v_\perp$ near the $q = 2$ surface increases by a factor of 2 while no clear change of $v_\perp$ at the plasma edge ($r/a \sim 0.8$) is observed. This results in a very large velocity peak appearing at the q=2 surface and a strong velocity shear near the boundary of the 2/1 island. When the rotating direction of the field is changed from the EDD to IDD (ion diamagnetic drift) direction, no clear influence on the plasma rotation is observed. These experimental observations can not be explained by either the edge stochastic torque or the NTV theory. Theory in [3] suggests that the shielding current induced on the rational surface by the RMP field produces a force on the plasma such that the plasma is accelerated or decelerated, which depends on the difference between the plasma rotation and the RMP rotation. This electromagnetic torque could explain the experimental observation.

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Current filaments in the plasma edge with non-axissymmetric magnetic fields

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A numerical model of the nonlinear evolution of edge localized modes (ELMs) in tokamaks is presented. It is assumed that thermoelectric currents flow in short connection length flux tubes [1], initially established by error fields or other non-axisymmetric magnetic perturbations.

Peeling-ballooning theory predicts that a Type-I ELM cycle is initiated when an edge ideal MHD mode is destabilized. This produces an initial pulse of heat and particles which is conducted towards the target plates. The heat pulse instantaneously increases the electron temperature T_e on the outer target relative to the inner target plate. Thus, a thermoelectric current is driven between the targets [2]. Magnetic perturbations resulting from the current are incorporated into the magnetic topology.

The model consists of two steps. In the first step an initial current of a few hundred A is assumed in an initial flux tube. Several new effects appear [3]. A connection to the upper target plates is established. Corresponding experimental observations are discussed. Also new flux tubes appear which are very large in area compared to the initial tube. The area of these tubes formerly belonged to the scrape-off layer. The formation process is discussed. In the second step it is assumed that thermoelectric current flows through the newly created flux tubes. A multiple current filament distribution is compared to the single current filament case of Ref. [3]. The resulting topology shows ELM like structures at the vessel wall. Excellent agreement between the calculated magnetic structures and camera observations during an ELM cycle is shown.

This work was supported by the US Department of Energy under DE-FC02-04ER54698 and DE-AC52-07NA27344 as well as the Deutsche Forschungsgemeinschaft (DFG) under project SP229/1-1.

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ITER ELM control requirements and required physics R&D

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ITER operation in its high fusion performance DT scenarios (inductive, hybrid and steady-state) relies on the achievement of the H-mode confinement regime with H_{98}=1 and a significant plasma pressure gradient at the plasma edge which is expected to lead to the quasi-periodic triggering of ELMs. Requirements to control the energy loss by repetitive ELMs in ITER have thus been defined for ITER on the basis of experimental results to avoid enhanced ELM erosion associated with surface overheating of plasma facing components (PFCs) and it is therefore expected that these limits will be will be exceeded for H-mode plasmas with uncontrolled ELMs with I_p larger than 6.5-9.5 MA; the precise value depending on the possible broadening of the power footprint at the divertor during uncontrolled ELMs.

Control of ELMs in ITER is presently foreseen to be performed on the basis of two schemes : resonant magnetic field perturbations by in-vessel coils and pellet injection. The ELM control coil system consists of 27 coils (3 for each of the 9 vessel sectors) which are powered independently and with a maximum current capability of 90 kAt [1]. Assuming a sinusoidal waveform in coil current with n=4 periodicity, 90kAt provides a 20% margin on the coil current required to satisfy the empirical criterion derived from the achievement of ELM suppression in ITER-like conditions in DIII-D [2, 3]. In order to prevent toroidally localised erosion or overheating of PFCs this perturbation can be rotated toroidally at a frequency of ~ 1 Hz. More details of the system and its foreseen use will be described in the paper. Although the design parameters for the ELM control coils in ITER have now been fixed, a series of physics-related issues remain uncertain with regards to their application in different phases of ITER scenarios, the effects that an edge magnetic field resonant perturbation will have on ELMs in ITER and the effects that such perturbations will have on the plasma performance. The paper will describe the present understanding of these issues for ITER and the modelling and experimental R&D required to address them.

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Heat and particle flux profiles compared to the edge magnetic topology in a n=2 perturbation field at JET

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Abstract

At JET the Error Field Correction Coils (EFCC) can be used to generate an n=1 or n=2 magnetic perturbation field. A lot of experiments at JET have already been carried out to investigate the mitigation of ELMs by Resonant Magnetic Perturbations (RMP) generated with the EFCCs. However, the typical formation of a secondary strike point (strike point splitting) by RMPs has never been observed at JET before.

At the end of campaign C27 a plasma scenario was found, which for the first time at JET showed a strike point splitting induced by RMPs. Under these plasma conditions ($B_T \approx 2.1$T, $I_P \approx 2.2$MA, $P_{NBI} \approx 0$-1.6MW, $q_{95} \approx 3.2$, I_{EFCC}=3kA) the strike point splitting was robust and reproducible. In this work, the divertor heat and particle flux profiles from the KL9 infrared camera and the KY4D langmuir probe measurements were analysed and compared to the footprint of the vacuum magnetic topology obtained by field line tracing. This comparison was carried out at four different toroidal positions in a range of 45° and showed that the toroidal asymmetry of the magnetic footprint from field line tracing is well reflected in the experimental measurements.

Additionally two q_{95}-scans have been carried out experimentally, varying q_{95} from 3.6 to 3.1 and vice versa, which showed an appearing and disappearing strike point splitting in the KL9 infrared camera measurements. For these experimental q_{95}-scans the magnetic footprint on the divertor tiles has also been modelled by field line tracing, showing the same appearing and disappearing strike point splitting. The fact that the strike point splitting could only be observed in a small window around $q_{95} \approx 3.2$ is a geometrical effect. The magnetic lobe, which is responsible for the strike point splitting, hits the divertor target for different q_{95} at different toroidal positions and thus making the strike point splitting appear and disappear at the fixed toroidal position of the infrared measurement. A similar effect can also be observed during the ramp up phase of the perturbation current running through the EFCCs. The magnetic lobe evolves radially and toroidally with increasing perturbation current. This leads to a spontaneous appearance of the strike point splitting in the infrared measurements when the lobe cuts the fixed toroidal position of the camera.

The good agreement of the measurements and the calculated magnetic footprints suggests that under these very low (and even none) NBI heating conditions no relevant shielding of the magnetic perturbation field is happening and the vacuum field line tracing is here a good approximation.

Magnetic barriers and their possible role in the q95 dependence of ELM control by RMPs at DIII-D

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It is well known that externally generated resonant magnetic perturbations (RMPs) can form islands in the plasma edge. In turn, large overlapping islands generate stochastic fields, which are believed to play a role in the avoidance and suppression of edge localized modes (ELMs) at DIII-D. However, large coalescing islands can also generate, in the middle of these stochastic regions, KAM surfaces effectively acting as “barriers” against field-line dispersion and, indirectly, particle diffusion. It was predicted in [H. Ali and A. Punjabi, Plasma Phys. Control. Fusion **49** (2007), 1565-1582] that such magnetic barriers can form in piecewise analytic DIII-D plasma equilibria. In the present work, the formation at DIII-D of n=1 magnetic barriers and n=3 “semi-permeable” magnetic barriers is corroborated by field-line tracing calculations using experimentally constrained EFIT DIII-D equilibria perturbed to include the vacuum field from the internal coils utilized in the experiments. According to these calculations, magnetic barriers only form for certain values of the edge safety factor q_{95}. Some degree of anti-correlation is found between this q_{95} dependence, and the q_{95} dependence of ELM suppression by RMPs. It is thus suggested that magnetic barriers might contribute to narrowing the edge stochastic layer and, indirectly, to RMPs failing to control ELMs for those values of q_{95}.