4th International Workshop on
Stochasticity in Fusion Plasmas

Programme

Book of Abstracts

Schedule for the 4th Workshop on Stochastic Fusion Plasmas, Jülich, March 02-04, 2009

Monday, March 02, 2009

	Time	Title	Name	Chair	Topic
	09:00-09:10	**Welcome**	Samm		
1	09:10-09:50	Invariant manifolds and magnetic barriers in a partially chaotic magnetic configuration	Schep	Karl-Heinz Spatschek	1
2	09:50-10:10	Generic magnetic field model in poloidal divertor tokamaks in the presence of resonant magnetic perturbations	Abdullaev		1
3	10:10-10:30	Numerical Estimations of Neoclassical Toroidal Vescosity due to Resonant Magnetic Perturbations Generated by ELM Suppression Coils.	Becoulet		2
	10:30-10:50	Coffee break			
4	10:50-11:30	Modification of the edge trasport barrier by resonance magnetic perturbations	Rozhansky	Andrew Kirk	2
5	11:30-11:50	ENERGY AND PARTICLE TRANSPORT IN THE PRESENCE OF NON-AXISYMMETRIC MAGNETIC FIELD PERTURBATIONS	Kominis		2
6	11:50-12:10	Modelling of density profile modifications by resonant magnetic perturbations	Tokar		2
7	12:10-12:30	Change of tokamak particle confinement by resonant magnetic perturbation	Yu		2
	12:30-14:00	Lunch break			
8	14:00-14:20	Particle Transport and Electron Density Relaxation due to Stochastic Magnetic Fields during Magnetic Reconnection	Brower		2
9	14:20-14:40	GENERALIZED SELF-SIMILARITY OF EDGE PLASMA TURBULENCE IN FUSION DEVICES	Budaev		2
10	14:40-15:00	Comparison of heat and particle transport of an ELMing versus an RMP H-mode*	Mordijck		2
11	15:00-15:20	Particle Transport in Stochastic Boundary Experiments at TEXTOR-DED	Schmitz		2
12	15:20-15:40	The Radial Electric Field during Improved Particle Confinement with the Dynamic Ergodic Divertor at the Tokamak TEXTOR	Coenen		2
13	15:40-16:00	On the change of the impurity transport due to a resonant magnetic perturbation on TEXTOR-DED	Greiche		2
	16:00-16:20	Coffee break			
14	16:20-16:40	Suppression of runaway electrons during TEXTOR disruptions by resonant magnetic perturbations	Lehnen		2
15	16:40-17:00	ELM Destabilization by Resonant Magnetic Perturbations during ELM-free H-modes in NSTX	Canik		2
16	17:00-18:00	General discussions on previous contributions			
	18:00	Bus transfer to Aachen			

Tuesday, March 03, 2009

	Time	Title	Name	Chair	Topic
17	09:00 - 09:40	Ballooning-like Structure of Edge MHD Modes Observed in the LHD Plasmas with Externally Applied Large m/n=1/1 Magnetic Perturbation	Watanabe	Todd Evans	3
18	09:40-10:10	Effect of Low m Magnetic Perturbations on LHD plasma with Highly Peaked Density Profile	Morisaki		3
19	10:10-10:30	Hydrogen recycling and transport in the helical divertor of TEXTOR	Clever		3
	10:30-10:50	Coffee break			
20	10:50-11:10	Plasma Response to Externally Applied Magnetic Perturbations in the range of Alfvén Eigenmode Frequency in the Compact Helical System	Ito		3
21	11:10-11:30	Plasma response currents induced by resonant magnetic perturbations	Reiser		3
22	11:30-11:50	Investigation of plasma edge structures imposed by the rotating Dynamic Ergodic Divertor at the Tokamak TEXTOR in comparison with the magnetic vacuum topology	Stoschus		3
23	11:50-12:10	Non-linear MHD modelling of the penetration of resonant magnetic perturbations into an H-mode plasma	Nardon		3
24	12:10-12:30	Sheared plasma rotation in stochastic magnetic fields	Wingen		3
	12:30-14:00	Lunch break			
25	14:00-14:20	Equilibrium responses on the stochasticity in non-axisymmetric torus	Suzuki		3
26	14:20-14:40	3D Monte Carlo Simulations of Edge Transport in RMP Scenarios at DIII-D	Frerichs		3
27	14:40-15:30	General discussions on previous contributions			
	15:30-16:00	Coffee break			
	16:00-18:00	Poster session			
	18:00	Departure of Bus to Aachen			
	19:00-21:30	Reception in Aachen, Rathauskeller			

Wednesday, March 04, 2009

	Time	Title	Name	Chair	Topic
28	09:00 - 09:40	ELM Control Coils for ITER: Progress in 2007–2008*	Schaffer	Marina Becoulet	4
29	09:40-10:10	ELM mitigation experiments on MAST	Kirk		4
30	10:10-10:30	Modification of ELM Power Deposition Patterns by Resonant Magnetic Perturbation*	Jakubowski		4
	10:30-10:50	Coffee break			
31	10:50-11:10	Vacuum Magnetic Field Modeling of High Field Side RMP ELM Suppression Coils in DIII-D*	Evans		4

32	**11:10-11:30**	Modeling of Plasma Pressure Effects on ELM Suppression With Resonant Magnetic Perturbations in DIII-D*	**Orlov**		**4**
33	**11:30-11:50**	Particle Exhaust During RMP ELM Suppression on DIII-D with an Open and Closed Divertor*	**E. A. Unterberg**		**4**
34	**11:50-12:10**	ELM Control with n = 1 and n = 2 External Perturbation Fields on JET	**Koslowski**		**4**
	12:10-13:00	General discussions on previous contributions			
	13:00-14:00	Lunch break			
	14:00-14:30	Summary session topic 1	**Spatschek**		
	14:30-15:00	Summary session topic 2	**Kirk / Unterberg**		
	15:00-15:30	Summary session topic 3	**Evans**		
	15:30-16:00	Summary session topic 4	**Becoulet**		
	16:00	Conclusions - end of workshop	**Unterberg**		
	Topic 1:	**Formation of stochastic magnetic layers**			
	Topic 2:	**Energy and particle transport in stochastic magnetic fields**			
	Topic 3:	**Plasma response to external, non- axis- symmetric perturbations**			
	Topic 4:	**Application of resonant magnetic perturbations for ELM control and implications for ITER**			

Invariant manifolds and magnetic barriers in a partially chaotic magnetic configuration

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The stable and unstable manifolds related to two intersecting island chains are calculated at subsequent points in time of a reconnecting sheared configuration [1,2]. The manifolds form barriers against transport of magnetic field lines.
The homoclinic and heteroclinic intersections are shown and the trajectory of one of the associated hyperbolic points is given [3].
The route to global stochasticity, when manifolds of different chains intersect, is discussed.
The spatial properties of the largest Lyapunov coefficient (FTLE) are also analyzed at those points in time.
Ridges in this coefficient form approximate transport barriers [4].
The barriers originating from these two different approaches are compared.

[1] D. Borgogno, *et al.*, *Phys. Plasmas.*, **12**, 032309 (2005).
[2] D. Borgogno, *et al.*, *Phys. Plasmas.*, **15**, 102308 (2008).
[3] K. Ide, *et al.*, *Nonlinear Processes Geophys*, **9**, 237 (2002).
[4] S.C. Shadden, *et al.*, *Physica D*, **212**, 271 (2005).

Generic magnetic field model in poloidal divertor tokamaks in the presence of resonant magnetic perturbations

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The study of transport of energy and particles in stochastic fusion plasmas became an important issue in the light of recent experiments on the suppression of large ELMs in high-confinement (H-mode) plasmas by applied external RMP in the DIII-D and JET tokamaks. At the present time the mechanism of ELM's suppression by RMPs is not well understood. The first important step in this complex nonlinear problem of plasma dynamics is to study the magnetic field structure at the plasma edge. It would be useful to have a generic model of magnetic near the magnetic separatrix of tokamaks which would allow fast and rigorously to study the structure and statistical properties of field lines in the presence of RMPs. We propose such a generic analytical model of magnetic field in poloidal divertor tokamaks. The model is based on the Hamiltonian description of magnetic field lines in tokamaks. The safety factor and the spectra of magnetic perturbations are chosen by the requirement to satisfy their generic behavior near the magnetic separatrix and at the magnetic axis. The field line equations are integrated by the construction of two symplectic and computationally efficient mappings of field lines. The first mapping iterates the poloidal angle, ϑ, and the toroidal flux, ψ, with the step $2\pi/n$ along the toroidal angle, where n is a fundamental toroidal mode. The second one, a canonical separatrix mapping, is a return map of the toroidal angle, φ, and the poloidal flux, ψ_p with a step of one poloidal turn. The effect of internal MHD modes is also studied. These modes are modeled by a function localized near the resonant surfaces. Diffusion and convection of field lines in stochastic layer are investigated. Analytical formulas for the quasilinear diffusion and convection coefficients of field lines are obtained and compared with the numerical calculated ones. It was found that in the presence of a single high $(m,n)-$ internal MHD mode localized at the plasma edge the diffusion coefficients of field lines are increased. However, the convection coefficient describing a directed transport of field lines can be completely modified near the magnetic surface resonant to the MHD mode, and even can change its direction. The latter means that in the presence of internal MHD mode the convectional flux of magnetic field may change its direction from outward to inward.

Numerical Estimations of Neoclassical Toroidal Vescosity due to Resonant Magnetic Perturbations Generated by ELM Suppression Coils.

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One of the promising methods to control Type I ELMs is the installation of dedicated coils producing Resonant Magnetic Perturbations (RMP) [1]. It is known from experiment that helical magnetic perturbations can significantly influence the toroidal rotation [2-3]. In most experimental cases slowing down of the global plasma rotation is observed potentially leading to core MHD and modes locking [3]. However, in some experiments an increase of the toroidal rotation at the pedestal was observed and, moreover, at weak co- and counter rotation an acceleration in the counter direction was demonstrated [4]. The Neoclassical Toroidal Viscosity (NTV), resulting from the toroidal drag force experienced by the plasma particles moving along field lines distorted by helical magnetic perturbations was proposed as a possible mechanism for the global plasma braking [5-6]. The helical perturbations can appear due to the intrinsic MHD activity or external magnetic perturbations such as RMPs. NTV is produced due to any helical magnetic perturbation including both resonant ($q=m/n$) the non-resonant part ($q \neq m/n$) of the perturbation spectrum. The understanding of the rotating plasma response on RMPs is important in the optimization of the ELM suppression coils spectrum in ITER. The loss of the plasma co-rotation due to NTV can be important in ITER, where the expected toroidal rotation is slow (*~1kHz*) compared to the existing experiments (*~10kHz*) [2,3]. The recent results on the estimations of Neoclassical Toroidal Viscosity due to applied RMPs in low collisionality regimes are presented for ITER, using modelling for DIII-D parameters as a benchmarking case. The counter with respect to the plasma current direction toroidal rotation ~1kHz is predicted for ITER at slow intrinsic rotation.

References:

[1]R. Hawryluk et al IAEA 2008, IT/1-2
[2]T.E. Evans et al Nucl. Fusion **48** (2008) 024002
[3]Y. Liang et al Phys Rev Letters **98** (2007) 265004
[4] A. Garofalo et al Phys Rev Lett, 101(2008)195005
[5]K. Shaing Phys. Plasm**15** (2008)082506
[6]A. Cole et al Phys of Plasm **15**(2008)056102

Subject 2

Modification of the edge trasport barrier by resonance magnetic perturbations

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The impact of resonance magnetic perturbations (RMP) on the structure of the edge transport barrier has been studied. A new model for the pump-out mechanism during the stochastization of the plasma edge will be proposed. In the present paper the observed phenomena are explained as a result of the impact of the ambipolar electric field, which is modified during RMP, on the particle fluxes in the pedestal region. It is demonstrated that the rise of the particle fluxes inside the transport barrier leads to the pump-out effect on density, while the pedestal temperature increases in spite of the big electron heat conductivity in the stochastic magnetic field. The analytical approach is supported by results from simulations with the B2SOLPS5.0 2D transport code which uses a full description of particle sources and transport phenomena in the pedestal region. Simulations are performed for ASDEX Upgrade and MAST configurations for various values of electron stochastic conductivity. The radial electric field with RMPs is predicted to be less negative than without. The density drop and temperature rise in the pedestal region are observed in accordance with the experimental observations. Generation of toroidal rotation in the co-current direction is predicted. The edge transport barrier control by RMP is discussed. Predictions for ITER based on the obtained results are made.

STOCHASTICITY IN FUSION PLASMAS (SFP)
March 2-4, 2009, Juelich, Germany

Subject 2: **Energy and particle transport in stochastic magnetic fields**

ENERGY AND PARTICLE TRANSPORT IN THE PRESENCE OF NON-AXISYMMETRIC MAGNETIC FIELD PERTURBATIONS

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ABSRACT

In toroidally confined fusion plasmas, non-axisymmetric magnetic perturbations lead to the formation of magnetic islands and the appearance of chaotic magnetic fields. These conditions lead to energy and particle transport which has important implications for plasma confinement. In our studies on energy and particle transport we utilize the Hamiltonian formalism and the Lie transform perturbation technique to determine the collective particle behavior, starting from single particle dynamics. We use an action-angle description and rigorously obtain a hierarchy of evolution equations for angle-averaged distribution functions. This can also include the collision operator in action-angle phase space For banana trapped ions, which are characterized by large banana widths compared to electrons, we carry out averaging over two angles leaving the dependence on the angle associated with the banana motion. The corresponding action diffusion equations are obtained from a hierarchy in which the distribution function is sequentially averaged over angles. In contrast to previous studies, our derivation makes no statistical assumptions on the underlying particle dynamics, such as the Markovian assumption or phase mixing. The resulting diffusion tensor is nonsingular and time-dependent so that transient transport phenomena, which can be either resonant or non-resonant, is included. The effects of internal and/or external non-axisymmetric perturbations, as well as their interplay, on energy and particle transport across flux surfaces can be carried out with this diffusion tensor. The effect of collisions on the energy and particle transport can also be included. A different perturbative scheme, where the velocity-like action subspace is averaged out, yields transport equations.

4th workshop on Stochasticity in Fusion Plasmas (SFP)
Subject 2): Energy and particle transport in stochastic magnetic fields

Modelling of density profile modifications by resonant magnetic perturbations

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The application of Resonant Magnetic Perturbations (RMP) for mitigation of type I Edge Localized Modes (ELM) in tokamaks DIII-D and JET has resulted in pronounced modification in the radial profiles of diverse plasma parameters such as densities and temperatures of charged particles, plasma rotation velocity, etc. Therefore as far as possibly self-consistent approach is required by modelling of the profile modifications with magnetic field stochastization. It has to account, in particular, for the transport changes due to non-ambipolar flows of electrons and ions both parallel and perpendicular to stochastic magnetic field lines and screening of RMP by currents in the plasma. Such an approach, treating in a coherent way in 1-D approximation the particle and energy transport, RMP penetration processes and recycling on the machine walls, will be presented in this contribution. This approach is applied to model changes in the density profile caused by magnetic field stochastization under diverse experimental conditions. It is demonstrated that both the particle pump out, normally observed in ELM mitigation experiments and being an important mechanism for the ELM suppression, and improvement of the particle confinement observed on TEXTOR with DED, can be reproduced in the framework of the model elaborated.

Subject 4   for oral presentation

Change of tokamak particle confinement by resonant magnetic perturbation

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The effect of an externally applied static resonant magnetic perturbation (RMP) of a single helicity on the tokamak particle confinement is investigated based on nonlinear two fluid equations. A sufficiently large RMP is found to flatten the local electron density profile around the rational surface as expected. With a small or moderate amplitude of RMP, however, the electron density is increased if the plasma rotates in the plasma current direction with a frequency being larger than the electron drift frequency. In the opposite limit the electron density is decreased, and its local gradient can changes from the usual negative value to a positive one. The effect of the applied RMP on the particle confinement is found to be more significant for plasmas with lower electron density, higher electron temperature and a large rotation frequency, being consistent with TEXTOR experimental results [K.H. Finken, S.S. Abdullaev, M.W. Jakubowski et al., Phys. Rev. Letts, **98**, 065001(2007)] and providing another possible explanation for the experimental results.

Our theoretical results also suggest that, an applied RMP of an appropriate frequency and amplitude can be utilized to either increase or decrease the local electron density gradient at the rational surface.

Topic: 2

Particle Transport and Electron Density Relaxation due to Stochastic Magnetic Fields during Magnetic Reconnection

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Particle transport resulting from stochastic magnetic fields has long been important in fusion research. Stochastic magnetic fields can arise from global tearing instabilities that often underlie the sawtooth oscillation and lead to density relaxation. Conversely, stochastic fields have also been externally imposed (resonant magnetic perturbation) to mitigate the effect of edge localized modes (ELMs) by locally enhancing edge transport in Tokamaks. Basic understanding of stochastic field driven transport processes is thus of great interest and possibly critical to ELM control in ITER. Progress to date is largely limited by the lack of measurements of the magnetic fluctuation-induced particle flux in hot plasmas. In this paper, we report the first measurements of stochastic magnetic field driven particle flux in the core of the MST reversed field pinch (RFP), particularly during the sawtooth crash when the stochastic field resulting from tearing reconnection is strongest. Direct measurements of the magnetic fluctuation-induced particle flux are made using a newly developed differential interferometer in combination with a fast Faraday rotation system. Measurements show that convective electron particle flux from stochastic magnetic field can account for the equilibrium density change at the magnetic axis.

GENERALIZED SELF-SIMILARITY OF EDGE PLASMA TURBULENCE IN FUSION DEVICES

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Turbulence is a natural state of plasma in fusion devices. Its statistical properties are essential for the understanding of the confinement in fusion devices. The fluctuations observed in tokamaks, stellarators and linear machines are intermittent and self-similar. They are responsible for the memory effects and large-scale correlation in space and time leading to substantial losses above the ones predicted by a classic diffusive scaling. In spite of a lot of experimental data obtained in fusion devices, our understanding of the turbulence and diffusive transport in magnetized plasmas is still rather limited. In this work, we review the comparative studies of the edge plasma turbulence in tokamaks (T-10, JT-60U, Hybtok-II), Large Helical Device (LHD), linear machine NAGDIS-II [1].

A generalized scale invariance (extended self-similarity - ESS) is observed for experimental data in fusion devices. Hidden statistical symmetries of the dynamics equations, hierarchy of moments, multifractality are behind the property of the ESS. The generalized self-similarity corresponds to the considering of the scaling in a turbulent cascade not with respect to the usual distance, but with respect to an effective scale defined by the third order moment of the velocity field.

Experimental turbulence scalings are compared with models of intermittent turbulence considered a stochastic cascade. Scalings of the structure functions strongly deviate from the Kolmogorov's K41 theory prediction. The data from the SOL plasma are deviated from the Iroshnikov-Kraichnan scaling as well. Experimental scalings are described in the frame of the log-Poisson model She-Leveque-Dubrull. One-dimension filament structures are likely the most intermittent dissipative structures. The similar behavior of the scalings has been observed in the edge of fusion devices with different magnetic topology and heating. It supports a view that the edge plasma turbulence displays universality. By using self-similarity indexes, transport scaling indexes are estimated.

1. V. P. Budaev et al, Plasma and Fusion Research 3, S1019 (2008)

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

Comparison of heat and particle transport of an ELMing versus an RMP H-mode*

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In this paper, we compare changes in the particle and electron heat transport between an ELMing and a Resonant Magnetic Perturbation (RMP) H-mode. RMPs in low collisionality H-mode experiments lead to a density pump-out, whereas the electron temperature remains nearly unaffected or increases slightly [1]. This does not agree with theoretical predictions based upon fully stochastic field lines [2]. In experiments, the pedestal density profile is reduced by RMPs across the entire plasma, which suggests a change in transport, whereas the electron temperature pedestal height increases and the gradient from the top of the pedestal inward decreases. The SOLPS5[3] code is being utilized[4] to quantify changes in the pedestal transport. SOLPS5 is a 2D axisymmetric transport code that typically uses an adhoc cross-field transport model to simulate the changes in the edge temperature and density profiles. The coefficients are determined by matching midplane density and temperature profiles.

We find that the cross-field particle transport needs to be increase by about a factor 2 in the transport barrier region (ψ_N between 0.9 and 1) when comparing an ELMing H-mode to an RMP H-mode. Although the code assumes axisymmetric flux surfaces, the ad hoc transport coefficient can be thought of as either due to cross-field processes (collisions or fluctuations) or the result of open field lines and free streaming of the electrons to the target plates.

We now calculate the magnetic diffusion created by the RMPs from non-axisymmetric field-errors and coils. We calculate the fraction of field lines that hit the divertor target plates within the free streaming limit and multiply the magnetic diffusion coefficient by this fraction. We observe that the increase in cross-field particle transport calculated by SOLPS5 matches the increase in the free streaming magnetic diffusion to within the uncertainty of the experimental profile data.

[1] T. E. Evans, et al., Phys. Plasmas **13** (2006) 056121.
[2] A.B. Rechester, M.N. Rosenbluth, Phys. Rev. Lett. **40** (1978) 38-41.
[3] R. Schneider, *et al.,* Contrib. Plasma Phys. **40** (2000) 328.
[4] S. Mordijck, et al., "Fluid Modeling of an ELMing H-mode and a RMP H-mode," 18th Intl. Conf. on Plasma Surface Interactions, Toledo, Spain, 2008, and to be published in *J. Nucl. Mater*.

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Particle Transport in Stochastic Boundary Experiments at TEXTOR-DED

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Control of particle transport and exhaust by a stochastic boundary is considered as an optimizing element in both stellarators as well as tokamaks. At TEXTOR, the Dynamic Ergodic Divertor (DED) allows for studying the impact of magnetic field stochastisation on particle transport with a flexible mode spectrum and therefore various magnetic topologies. In this contribution a systematic survey of the results from particle transport experiments at TEXTOR-DED is presented.

The experiments resolved for the TEXTOR perturbed boundary the existence of a laminar and a stochastic domain. Both are distinguished by the field line properties and their corresponding impact on transport. The short connection length, laminar field lines form magnetic flux tubes, which act as a helical scrape off layer (SOL) [1]. These field lines are surrounded by stochastic field lines causing an enhanced outward transport due to field line diffusion which is related for example to non-ambipolar flows [2] and resulting changes of the radial electric field E_r [2,3]. It was shown that fine tuning of the extensions of these domains - predicted by vacuum magnetic field line modelling - allows for control of the particle confinement in measures of the particle confinement time τ_p. The impact on τ_p and the exhaust properties was analyzed with both, a basic single reservoir particle balance model as applied also at DIII-D [4] and an extended three reservoir model. Initial results from He plasmas will be discussed to inspect the role of wall pumping.

This analysis shows that three topological domains and two particle confinement regimes can be distinguished. A thin stochastic layer with a small fraction of laminar field lines results in an increase of τ_p while in contrast a wide extend of the stochastic layer and in particular of the laminar zone induces a net de-confinement of particles, an effect referred to as stochastic particle pump out. The connected reduction in τ_p is even enhanced by a magnetic island positioned in the plasma edge layer (r/a~0.9) [5], i.e. in the plasma source region which indicates the magnetic island potentially acts as a convective cell inducing enhanced outward transport. These results suggest that the laminar field lines form the SOL and steer the fuelling characteristics while the stochastic field lines determine if either an enhanced or a reduced particle confinement is observed. Both, E_r as well as the E_r shear rate Ω_{Er} [3] and the turbulence properties measured as turbulent driven diffusion coefficient $D_{RW}=\lambda^2{}_n/\tau_{DC}$ (with turbulence correlation length λ_n and de-correlation time τ_{DC} [6]) react in a correlated way. For the improved particle confinement Ω_{Er} increases on the innermost perturbed resonant flux surface with increasing DED current and D_{RW} on this flux surface is reduced. However, as soon as for increasing perturbation amplitude this resonance surface becomes stochastic, the transition to particle pump out with a decrease of Ω_{Er} and an increase in D_{RW} is observed. These findings will be correlated to the manipulation of τ_p and plasma profiles in these regimes to study on an experimental basis the feasibility of magnetic field stochastisation as a tool to control the plasma edge transport, particle confinement and exhaust at TEXTOR-DED.

[1] M. Clever et al., "Hydrogen Recycling and Transport in the Helical Divertor of TEXTOR" (2008), submitted as contribution to this conference
[2] M. Tokar et al., "Modelling of Density Profile Modifications in Experiments with Resonant Magnetic Perturbations" (2008), submitted as contribution to this conference
[3] J.W. Coenen et al., "The Radial Electric Field during Improved Particle Confinement with the Dynamic Ergodic Divertor at the Tokamak TEXTOR" (2008), submitted as contribution to this conference
[4] E.A. Unterberg et al., "Particle Exhaust during RMP ELM Suppression on DIII-D with an Open and Closed Divertor" (2008), submitted as contribution to this conference
[5] H. Stoschus et al., "Investigation of Edge Structures Imposed by the Rotating Dynamic Ergodic Divertor at the Tokamak TEXTOR in Comparison with the Magnetic Vacuum Topology" (2008), submitted as contribution to this conference
[6] A. Kraemer-Flecken et al., Nuclear Fusion **46** (2006) S730 | A. Kraemer-Flecken et al., TTF Workshop (2008), Kopenhagen

Subject: (2) Energy and particle transport in stochastic magnetic fields, talk

The Radial Electric Field during Improved Particle Confinement with the Dynamic Ergodic Divertor at the Tokamak TEXTOR

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Resonant Magnetic Perturbations (RMP) are a powerful method to control the plasma edge properties. It was shown that external resonant magnetic perturbations can be used to influence edge instabilities in Fusion devices such as ITER (ELM mitigation). Understanding the transport changes caused by RMPs is thus a potential key to improve transport in future tokamaks. One of the quantities connected to plasma transport is the radial electric field, hence a detailed picture of the influences of RMP can facilitate a deeper understanding of edge transport properties and changes in confinement.

At TEXTOR the influence of RMPs is investigated by means of the Dynamic Ergodic Divertor (DED) which can be operated at different toroidal(m) and poloidal(n) mode configurations, m/n= 3/1, 6/2, 12/4. The 12/4 mode leads to a very shallow stochastic zone, while for 3/1 operation a deeper penetration is anticipated. Charge exchange recombination spectroscopy (CXRS) on C^{5+} with a hydrogen diagnostic beam, is used at TEXTOR for the measurement of the impurity rotation v and ion temperature T_i. The diagnostic setup consists of two observation systems,measuring the poloidal (v_{pol}) and toroidal ion velocity (v_{tor}) with a resolution of < 1 km/s and $\sim$ 5km/s respectively to deduce the E_r from the radial force balance [2].

The DED can influence the global confinement parameters: The Improved Particle Confinement (IPC) [2–4] is an increase in confinement observed during application of the DED. It is characterized by an increase in density, particle confinement time as well as a significant change in the poloidal and toroidal rotation ($\mathcal{O}(1 \text{ km}, 10 \text{ km})$). This manifests in the strong changes in the radial electric.

A chain of arguments can be deduced from the recent experiments: A scan of the perturbation current has been performed where at $I_{DED} = 2.5$ kA a strong increase in density (N_{tot}) and particle confinement time τ_P is observed. This is connected to a local steepening of the edge density gradient outside the q = 5/2 surface[3]. From vacuum topology calculations it can than be seen that at a value of 2.5 kA the x-points of the 5/2 island chain are ergodized and the connection to the target is established causing a pattern on the DED target. This evidently establishes the existence of the 5/2 island chain and connects the step in particle confinement and changes E_r to the magnetic topology.

Apart from this evidence connecting IPC and topology local changes in E_r ($\Delta E_r \sim 7$ kV/m) are observed when ergodizing the q=5/2 island chain, changing it towards more positive values and subsequently increasing the $E \times B$ - shear rate ($\Delta\Omega \sim 1.5 \cdot 10^5 s^{-1}$) [2]. The increase in shear at the plasma edge evidently suggests localized turbulence suppression connected to the IPC scenario [5] and hence may be one of the contributions to the improved confinement.

As a conclusion to the in detailed discussed IPC the transition into the low confinement scenario , Particle Pump Out (PO) [6] will be shown. The PO is achieved simply by increasing the perturbation ampitude and completely ergodizing in this case the q=5/2 surface in contrast to the small dose of x-point ergodisation during the IPC.

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On the change of the impurity transport due to a resonant magnetic perturbation on TEXTOR-DED

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The impurity transport in TEXTOR plasmas during a resonant magnetic perturbation is studied with the help of intrinsic impurities which are in transport equilibrium (net flux = 0) and additionally with the help of transient impurity puffing experiments. Latest experiments on TEXTOR with the application of the DED in static and dynamic operation show a reduction of the central concentration of intrinsic iron. This phenomenon is observed in several plasma scenarios, including steady state plasmas, pumped out plasmas and plasmas with an excited tearing mode.

In the case of dynamic DED application a correlation between the DED frequency and the amount of the iron reduction has been found.

During static DED application, the ratio between the intensities of the ionization stages of iron in the core and at mid minor radius reduces. Simulations of the iron ion density distribution in transport equilibrium with the transport code STRAHL in all of the above mentioned plasma scenarios cannot reproduce the reduction of the intensity ratio without changing the radial anomalous transport coefficients. Therefore, a change of the radial anomalous iron transport is induced by the resonant magnetic perturbation.

Except for the plasmas with an excited tearing mode the measurements of intrinsic carbon as well as transient impurity transport experiments with extrinsic argon do not show significant changes of the anomalous transport. A possible explanation is a Z-dependent transport mechanism which is induced by the resonant magnetic perturbation.

Suppression of runaway electrons during TEXTOR disruptions by resonant magnetic perturbations

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Disruptions in ITER are supposed to generate runaway electrons which can impose extreme heat loads to plasma facing components. Suppression of these runaway electrons is thus mandatory. Beside massive gas injection, a technique proposed is the application of external magnetic perturbations. The dynamic ergodic divertor in TEXTOR was used to suppress runaway electrons in TEXTOR disruptions. The runaway current can be reduced by $n = 2$ and even completely suppressed by $n = 1$ perturbations. The mechanism is thought to be a compensation of the runaway avalanche by enhanced losses caused by ergodisation.

ELM Destabilization by Resonant Magnetic Perturbations during ELM-free H-modes in NSTX

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The destabilization of edge-localized modes (ELMs) by the application of resonant magnetic perturbations (RMPs) has been observed on the National Spherical Torus Experiment. The perturbation is applied using a set of midplane coils external to the vacuum vessel, in an n=3 configuration. When the external field is applied during an otherwise ELM-free period of a discharge, ELMs begin within 50 ms, with an apparent threshold perturbation level necessary for the triggering to occur. Calculations assuming vacuum perturbation fields show that a strongly stochastic edge layer is formed by the RMP, with a width of $\Delta\psi_N \sim 0.4$. Simulations of the plasma response using the Ideal Perturbed Equilibrium Code (IPEC), however, indicate a strong shielding of the RMP in the plasma core, so that the width of the stochastic layer is reduced to $\Delta\psi_N \sim 0.1$. Although no strong changes are observed in the core temperature and density profiles, the pedestal electron temperature increases modestly when the RMP is applied, leading to an increased pressure gradient. In addition, the toroidal rotation shows a global reduction due to braking by the applied field, which is qualitatively consistent with neoclassical toroidal viscosity. The characteristics of the triggered ELMs are dependent on plasma shape, with ELMs being smaller and more frequent at higher elongation. This magnetic triggering has been used as an ELM-pacing technique to reduce impurity accumulation in the high-confinement, ELM-free H-modes that occur with lithium conditioning.

4) Plasma response to external, non- axis- symmetric perturbations

Ballooning-like Structure of Edge MHD Modes Observed in the LHD Plasmas with Externally Applied Large *m*/*n*=1/1 Magnetic Perturbation

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In high beta and/or L-H transition discharges of the Large Helical Device (LHD), resistive interchange modes having lower mode numbers, i.e. m/n = 1/1, 3/4, 2/3, 1/2 etc. (m: poloidal mode number, n: toroidal mode number) are excited noticeably by the formation of steep pressure gradient at the plasma edge, because the edge region has high magnetic shear but in the magnetic hill [1-4]. We have investigated the effects of a sizable m/n = 1/1 static island generated by the externally applied magnetic perturbation on these edge MHD modes in LHD plasmas at the low toroidal magnetic field (B_t = 0.9T) [5, 6]. It has been found that the m/n = 3/4 edge MHD mode detected by soft X-ray detectors has a ballooning structure that the fluctuation amplitude in outboard side of LHD plasma (larger R) is larger than that in inboard side. This structure is obviously different from the interchange mode observed in LHD plasmas without the m/n = 1/1 magnetic perturbation, of which the structure has comparable amplitude in inboard and outboard sides or even anti-ballooning character. Recently, dependences of edge MHD modes on plasma beta β, $d\beta/d\rho$ (ρ: normalized minor radius) and magnetic Reynolds number have been investigated in the LHD plasmas with the sizable m/n = 1/1 static island. These parameters are controlled by the toroidal magnetic field strength, the electron density and magnetic axis position in the vacuum field. These experimental results will be reported in this workshop.

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Category 4) Plasma response to external, non- axis- symmetric perturbations

Effect of Low *m* Magnetic Perturbations on LHD plasma with Highly Peaked Density Profile

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A superdense core (SDC) plasma develops when a series of pellets is injected into the neutral beam heated plasma in the outward shifted configuration in LHD. The central density more than ~ 1×10^{21} m^{-3} and the central temperature about 0.3 keV are maintained by an internal diffusion barrier (IDB) formed in the core region, where the steep density gradient is seen. The critical ingredients for the IDB formation are strong edge pumping to reduce particle recycling and multiple pellet injection to ensure strong central fuelling. From the wide range magnetic configuration study, it has been found that the IDB-SDC mode can be obtained only in the outward shifted configuration where the ergodic layer surrounding the confinement region is very thick. During the IDB-SDC discharge, the large Shafranov shift due to the high central plasma pressure takes place, which strongly modifies the magnetic field structure. According to the HINT2 code which can deal with the three-dimensional equilibrium, the ergodization develops from the edge region to the core region with the increase in the central beta value. In the ergodic layer, it is expected to have different heat and particle transport properties from the region with perfectly nested flux surfaces. It is surely observed in the experiment that the region where the density and its radial gradient are low spreads outside the SDC. In order to see the relation between the magnetic field structure and the profile formation, resonant perturbation field was applied to the IDB-SDC plasma to modify the magnetic field structure. An interesting phenomenon was observed in the experiment, i.e., the low *m* (=1 or 2) islands generated by the perturbation field seem to be healed or ergodized during the density increasing phase. At the conference, the effect of ergodization on the IDB-SDC formation is discussed.

Hydrogen recycling and transport in the helical divertor of TEXTOR

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In the tokamak TEXTOR the Dynamic Ergodic Divertor (DED) is used to selectively influence the particle transport in the plasma edge and by that control the energy and particle exhaust from the plasma. The perturbation fields imposed by the DED lead to a formation of a magnetic field topology which is very similar to helical divertor structures in stellarators [1, 2]. This similarity is expected to lead to comparable physical mechanisms in high density divertor scenarios such as detachment. The detached divertor regime is the envisaged divertor scenario not only for helical devices such as Wendelstein 7-X and LHD but also for ITER, as it is characterized by a reduced power flux to the target plates of the divertor and therefore a reduced erosion of the mostly loaded wall components.
Understanding the physical properties of such a divertor like hydrogen recycling, detachment and the screening of impurities in different plasma scenarios is a major goal of the current research at TEXTOR. A numerical tool to model plasma transport in 3-dimensional geometries is the 3-dimensional Monte Carlo code EMC3/Eirene. Our experimental studies can now be used to validate this code for its application to future helical devices like Wendelstein 7-X and also tokamaks like ITER with resonant magnetic perturbations applied.

In this contribution we will present results from first dedicated experiments to characterize the helical divertor in the $m/n = 3/1$ and $6/2$ base mode configuration of the DED (with m and n being the poloidal and toroidal mode number resp.), which are characterized by a different penetration of the resonant magnetic perturbations into the plasma and therefore different extents of the divertor volume. For these studies an optical detection system consisting of four digital CCD cameras has been build, allowing a spectrally selective, two dimensional observation of the divertor target plates and the plasma edge at the high field side of TEXTOR. The base technique applied is optical emission spectroscopy of neutral atoms and molecules. Such techniques have been proven successful to determine both the characteristics of the recycling processes on plasma facing components [4] and local plasma parameters [3, 5].

In order to study high density scenarios, the plasma density was ramped up while recording the emission of different Balmer lines at the target plates. From these, local electron densities and temperatures as well as the penetration depths of the observed species can be determined. For quantifying the carbon source, methane was injected locally into the plasma and the carbon line emission was recorded. By comparing the light intensity from this artificial carbon source and the intensity without methane injection, the carbon flux can be estimated. Local injections of molecular deuterium were used for an in-situ calibration of the system and to determine the molecular break-up.
This experimental sequence allowed for the first time detailed studies of hydrogen recycling and transport in the helical divertor of TEXTOR and a survey of the first promising results will be presented in this contribution. With rising electron density in the plasma at first a nonlinearly rising particle flux in front of the divertor target was observed, followed by a roll over into a decreasing particle flux when reaching a critical plasma density. At that moment a movement of the ionization front away from the target surface can be seen. This behavior was found in two of the four divertor legs that form on the target plates in the $6/2$ base mode configuration. They were also confirmed by Langmuir probe measurements, which showed a manipulation in the ion flux at the DED target with rising plasma density compared to the limiter case. The onset of detachment is observed at higher electron temperatures compared to those typical to tokamak divertors, which was also seen at the stellarator W-7AS [2] and is therefore an indication for the topological similarity of the helical divertor in TEXTOR to divertor structures in helical devices.

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Plasma Response to Externally Applied Magnetic Perturbations in the range of Alfvén Eigenmode Frequency in the Compact Helical System

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Alfvén eigenmodes (AEs) would be destabilized by energetic alphas in a burning plasma and in turn enhance radial transport and/or loss of these alphas. Therefore, it is of great importance to evaluate the damping rate of AEs experimentally, in not only tokamaks but also helical/stellarator devices. A powerful technique to do so is to measure plasma response to externally applied magnetic perturbations of which frequency range is in that of Alfvén eigenmodes[1].

In the Compact Helical System(CHS), stable low-n Alfvén eigenmodes were excited by application of alternating magnetic perturbations which are generated by external electrodes at the edge region of neutral beam heated plasma. A pair of electrodes was installed in CHS for excitation of magnetic perturbations driven by alternating currents which are extracted along the magnetic field line by AC biased electrodes[2]. The frequency of applied magnetic perturbations was swept to excite stable AEs. A frequency response function, so-called transfer function was derived as the ratio of Fourier transform of the excited magnetic fluctuations to that of the alternating electrode current. The resonant peaks in the frequency range of Toroidal Alfvén eigenmode (TAE) were clearly observed in the transfer function. The eigenmode frequency of excited resonant mode and the damping rate can be directly obtained from the shape of the peak. The experimentally obtained resonance frequencies f_o agree well with those of TAE gaps located near the plasma edge, where fast ion drive of AEs is sufficiently low. The damping rates γ derived from the width of the resonance peak are fairly large, i.e., γ/f_o~10 to 20%[3].

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Plasma response currents induced by resonant magnetic perturbations

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Resonant magnetic perturbations (RMP) are known to have a strong impact on several aspects of plasma transport in the tokamak plasma edge [1,2]. Experiments at TEXTOR-DED [3] proved that small scale turbulence, blobby density transport and Geodesic Acoustic Modes (GAM) are strongly affected simultaneously by the RMPs [4,5,6]. Also it has been found that a certain screening of the RMP fields is present in the plasma at least for some operational windows of RMP field strength and collisionality.
In this work we focus on the generation of plasma currents in the presence of RMP fields for TEXTOR-DED like geometry. The analysis is based on three-dimensional non-linear drift-fluid simulations performed with the ATTEMPT code. It is shown that resonant plasma currents appear due to the impact of RMP fields providing screening and that these currents are always accompanied by out-of-phase components which are coupled to the GAMs. Due to non-linear interaction of currents of different mode structure the screening drops at a certain RMP field strength such that the so called vacuum field approximation for the analysis is justified for particular collisionalities. In addition these induced plasma currents provide a suppression of the intermittent radial particle transport. The interplay of the plasma currents with zonal flows and toroidal rotation is adressed and the simulation results are compared with experimentally found trends.

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Abstract for SFP workshop 2009
(preferred type/category: talk for subject 4)

Investigation of plasma edge structures imposed by the rotating Dynamic Ergodic Divertor at the Tokamak TEXTOR in comparison with the magnetic vacuum topology

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For future fusion devices such as ITER resonant magnetic perturbation fields (RMP) are considered as a method to suppress edge localized modes (ELMs). Up to now, the plasma response of those RMPs is not fully understood – especially plasma feedback, such as both screening or field amplification may change the magnetic topology and hence the plasma structure. At the tokamak TEXTOR those RMPs are imposed by the Dynamic Ergodic Divertor (DED), which result in a sophisticated magnetic topology with e.g. laminar zone and regions with stochastic field lines and remnant islands in the plasma edge (r/a>0.8). These structures can be generated statically (DED-DC) or rotated (DED-AC). Hence the relative rotation between RMP and plasma rotation is varied.

This talk will focus on measurements to investigate the plasma edge structure (r/a>0.8) in comparison to the vacuum topology of the external RMP field. All experiments shown were performed in the m/n=3/1 DED base mode configuration because of the deep penetration of the RMP field in vacuum.

To investigate the plasma structure, the electron density (n_e) and temperature (T_e) were measured with a supersonic helium diagnostic (SHE), which allows to resolve these quantities with a high spatial and temporal resolution of Δr=2mm and Δt=40µs, respectively.
When rotating the DED field in both directions and hence having different relative rotations between plasma and RMP field no changes in the global plasma parameters were observed, but three observations in the local edge structure were done. First a clear modulation of n_e and T_e in the edge measured with the SHE is observed. Second, the analysis of the modulation depth and the phase between n_e and T_e show that both are a function of the tokamak's minor radius. Third observation is that modulation depth and phase change for different relative rotations. This was related to locally different pronounced plasma structures due to a changed magnetic topology for both DED rotation directions. This gives hints for different plasma response to the external RMP field, which in a first approach was investigated by comparing the measured plasma structure with the topology of the perturbed magnetic field under vacuum assumption without screening effects. These initial experiments indicate that the local RMP field at the resonant surface is weaker, when the relative rotation between the plasma fluid and the perturbation field is larger.

In addition experiments were performed to investigate the rotating edge island structure with respect to its dimensions in comparison to the results known from DED-DC experiments. Here in the global parameters particle pump out was observed. In the plasma edge an inversion of the T_e modulation at the q=3 surface was seen. For visualization a fast framing camera (f_s=50kHz) was available, which showed a rotating structure at the q=3 surface. In this talk the size of the 3/1 edge island will be determined and compared to the theoretical expected size calculated with the field line tracing GOURDON code without plasma response and to former results from DED-DC measurements to assess further plasma feedback.

This work concerns both subject 4 (plasma response to external, non-axisymmetric perturbations) and subject 5 (application of RMPs for ELM control)

Non-linear MHD modelling of the penetration of resonant magnetic perturbations into an H-mode plasma

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The design of the presently considered ELM control coils for ITER is based on vacuum calculations, where the plasma response to the magnetic perturbations from the coils is neglected [1,2]. On DIII-D, the vacuum approach shows a correlation between ELM suppression and the width of the stochastic layer [3]. However, it is unlikely that the vacuum approach is sufficient and some effect of rotational screening from the plasma would be expected. Generally speaking, the helical currents that prevent a resonant external field from penetrating into the plasma (i.e. magnetic islands from being formed) are induced by the motion of the electrons perpendicularly to the equilibrium field lines on the resonant surface, across the perturbed field. This motion is a sum of ExB (v_E) and diamagnetic (v_{*e}) motions:

$$v_{e,perp}^{tot} = v_E + v_{*e} \quad (1).$$

The ExB rotation is associated to the radial electric field E_r which can be written as:

$$E_r = v_{\varphi i}B_\theta - v_{\theta i}B_\varphi + (\partial_r P_i)/(Z_i e n_i) \quad (2).$$

In the “classical” case [4] where the resonant surface is in the core plasma (for instance for m/n=2/1 external perturbations), the diamagnetic effects are small and the screening comes essentially from the toroidal rotation because the first term on the right hand side of equation (2) dominates the others. But when the resonant surface is in the pedestal of an H-mode plasma, the diamagnetic effects become essential. The results from non-linear reduced MHD cylindrical modeling, which takes into account diamagnetic effects, will be presented. Simulations made for DIII-D parameters show that field penetration may be expected at the very edge of the plasma (over ~1% of the radius) because of the low rotation and large resistivity. In contrast, a strong screening is expected in the middle of the pedestal, due to the large v_E and v_{*e}, which add up. Interestingly, there is a location towards the top of the pedestal where v_E and v_{*e} cancel out, meaning that some field penetration can take place again. This suggests a new interpretation of the DIII-D results, which will be presented and discussed. An attempt to generalize the results to other machines, in particular JET, MAST and ITER, will be discussed.

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Sheared plasma rotation in stochastic magnetic fields

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Abstract

The presentation considers a plasma response to external non-axis-symmetric perturbations and is part of subject 4.

Motion of electrons and ions in stochastic magnetic fields is considered. The analysis starts from a Hamiltonian formulation of the drift motion including electric fields. For an efficient statistical evaluation of the resulting particle transport, a symplectic mapping technique is applied. Compared to previous considerations, the ion and electron test particle motion are investigated simultaneously, allowing calculations of the ambipolar electric field and its influence on stochastic transport. The predictions based on the relativistic drift model are applied to the magnetic perturbations in the TEXTOR-DED [A. Wingen et al., Nucl. Fusion **46**, 941 (2006)].

Space charge fields are generated by the differential drifting of electrons and ions in collisionless plasmas with stochastic magnetic fields. The spatial structure within a poloidal cross-section of the resulting electric field is shown. The influence of the magnetic coil arrangement on the poloidal plasma rotation, caused by the generated radial electric field, is discussed. It is shown that a sheared poloidal plasma rotation can be induced by the radial part of the electric field. The effects of a varying plasma current on the so induced poloidal rotation is presented.

Equilibrium responses on the stochasticity in non-axisymmetric torus

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The stochasticity of edge field lines by finite-β effects is an intrinsic property in stellarator/heliotron and it affects the confinement. The stochasticity is driven by overlaps of pressure-induced perturbed field. In the conventional analysis of the magnethydrodynamic (MHD) equilibrium [1], the gradient of plasma pressure ∇p in stochastic and islands regions is specified as zero. Since some field lines in edge stochastic region, which are called to 'open field lines', are achieved to the vacuum wall, the plasma pressure p in that region is also specified as zero. Up to now, many studies ignored the role of finite pressure p and finite gradient ∇p in edge stochastic region. However, in experiments, finite pressure gradient was observed [2] and this indicates a possibility that stochastic field lines can sustain finite pressure gradient. This means the finite pressure p strongly affects the stochasticity on the field topology because the perturbed field is produced by the equilibrium current along the field line. Thus, the study of the stochasticity and its impact on the confinement is one of aim in the stellarator/heliotron research.

On the other hand, in some tokamak experiments [3,4], the Resonant Magnetic Perturbations (RMP) superposed to the magnetic configuration to eliminate the Edge Localized Mode (ELM). In those magnetic configurations, the field topology becomes stochastic and the equilibrium current flow along stochastic field leads the distortion of flux surfaces. In order to model the stochastic field superposed the RMP field, self-consistent 3D MHD calculation is necessary.

In this study, equilibrium responses on the stochastic field lines are studied in a high-β heliotron and tokamak with the RMP. As a first step, we study properties of finite-β MHD equilibrium in those configurations. In order to consider equilibrium response on stochastic field lines, we use a three-dimensional (3D) MHD equilibrium calculation code without the assumption of nested flux surfaces, HINT2 [5]. Using experimental conditions obtained from diagnostics, we reconstruct MHD equilibrium with high accuracy. In the next, we study the stochasticity of field lines. In order to investigate the stochasticity quantitatively, we estimate the diffusion coefficient of field lines $D=\langle(\Delta\rho)^2\rangle/L_C$, where $\Delta\rho$ is the mean square of radial displacements from the averaged flux surface and L_C is the correlation length of field lines. We also study other parameters like the Kolmogorov length to measure the stochasticity of field lines.

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3D Monte Carlo Simulations of Edge Transport in RMP Scenarios at DIII-D

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Resonant magnetic perturbations (RMPs) are a candidate for ELM control in ITER. Modelling of the perturbed magnetic field structure during RMP application in the vacuum approach suggests that an open chaotic system in the plasma edge layer is induced, leading to a complex three-dimensional (3D) magnetic field structure. In order to investigate the resulting impact on plasma and neutral gas transport, the 3D edge transport code EMC3-EIRENE has been extended to be capable for modelling in poloidal divertor geometry. In particular, a fast field line reconstruction method has been advanced from structured to block-structured grids in order to achieve a uniform discretization of domains with asymmetric radial and poloidal extension. This is of particular importance in the edge layer of tokamaks with a poloidal divertor due to the remoteness of divertor plates from the last closed flux surface. Therefore, this code extension allows for the first time for a 3D numerical transport analysis of ELM control experiments at DIII-D in a self-consistent, fluid treatment of particle, parallel momentum and energy transport, as well as kinetic recycling neutrals.

In this contribution the first results from modelling of RMP ELM-suppressed H-mode plasmas in ITER similar shape (ISS) and low electron pedestal collisionality ν_e^* will be presented. A significant 3D modulation of electron density n_e and temperature T_e is predicted, reflecting the underlying perturbed 3D magnetic topology. In particular the existence of laminar flux tubes — expected to act as a mesh of 3D scrape off layer (SOL) flux tubes — and their complex trajectory and 3D shape was revealed including the parallel n_e, T_e and Mach number M_N profiles. This analysis shows that a treatment of transport in a simple SOL model is not sufficient and that already the very edge of the perturbed boundary — likely to be existing even in case screening takes place in the deeper plasma regions — manipulates the plasma edge and leads to a 3D plasma boundary.

This 3D boundary causes helical, toroidally spiraling lobes in the heat and particle flux patterns which were observed in experiment and can be used as a mean for basic validation of the code and first transport studies. The comparison of modelling results for different anomalous radial particle $D_\perp$ and heat $\chi_\perp$ diffusion coefficients to the experimental observation allows for deducing an upper limit for $D_\perp$ and $\chi_\perp$. We found that a clear striation pattern as observed in experiment is only obtained in modelling with a low, H-mode like level for $D_\perp \sim 0.25\ \mathrm{m}^2\ \mathrm{s}^{-1}$ and $\chi_\perp=3*D_\perp$. This low level of radial transport parameters needed to reproduce the experimental pattern also indicates that open, perturbed field lines must exist in the perturbed boundary to channel the heat and particle fluxes into the 3D target load pattern.

However, while the particle target pattern is found to be in qualitative agreement to the experimental observations, the heat target pattern significantly is more pronounced and higher absolute values are obtained in modelling than in experiment. Ad hoc kinetic corrections ("flux limiters") of the parallel electron heat flux are investigated as one candidate for resolving this discrepancy. Also screening of the magnetic perturbation – possibly leading to a much shallower extent of the perturbed field line region – is considered. All of these modelling results were obtained with assumptions of radially constant cross-field transport coefficients, which work well in the EMC3 model for plasmas without an edge transport barrier as demonstrated in application at TEXTOR-DED. However, for poloidal divertor H-mode plasmas $D_\perp$ and $\chi_\perp$ are known to be strongly dependent on the radial coordinate in particular in the pedestal region. Therefore, advancements of the cross-field transport model in EMC3-EIRENE for the application in simulations of H-mode plasmas will be discussed as an outlook on future code extensions.

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Category: Application of RMPs for ELM control and implications for ITER
Oral Contribution

ELM Control Coils for ITER: Progress in 2007–2008*

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Type-I ELM heat pulses in ITER are predicted by empirical scaling to severely limit divertor target lifetime. Suppression of Type-I ELMs by weak ($dB/B_0 < 10^{-3}$) non-axisymmetric, resonant magnetic perturbations (RMPs) is demonstrated on DIII–D. The ITER Organization decided in 2008 to provide for an ELM control array of 3 toroidal rows of 9 coils each on the plasma-facing surface of the vacuum vessel. This paper summarizes scientific progress for ITER ELM suppression since the work reported at the 3rd Workshop on Stochasticity in Fusion Plasmas and in the proceedings [Schaffer et al., Nucl. Fusion **48** (2008) 024004].

ELM suppression in DIII–D correlates with reduction of pedestal pressure gradients that reduce the peeling and ballooning ELM drive terms. However, the pressure change in ITER-like low collisionality experiments comes from reduced density, not temperature, contrary to expectations for stochastically opened magnetic surfaces. Numerical calculations are studying magnetic island width reduction by plasma rotation ("screening") and RMP-induced transport, but so far models do not reproduce the experimental level of effects. Without an understanding of RMP-induced transport, ITER decisions are still guided by extrapolation from experiment and incomplete theory.

New DIII–D data validated the concept of adjusting coil currents to match the RMP harmonic spectrum to the plasma q. However, other data approximately doubled the resonant field magnitude recommended for reliable ELM suppression from that in 2007. ELM suppression by a single toroidal row of six poloidally short, near-plasma coils, in contrast to long poloidal period fields that make locked modes first, implies competing ELM suppression and plasma braking effects. Resonant braking was found to depend on the plasma-amplified internal magnetic field at both low and high β; thus, error correction should counter the error field coupling to the least stable kink mode. Neoclassical toroidal viscosity (NTV) braking of toroidally rotating plasmas by non-resonant perturbations was quantified in NSTX and DIII–D experiments, and the theoretically predicted NTV offset rotation was detected and measured in DIII–D. Much progress was made in numerically challenging calculations of NTV effects across the two collisionality regimes important to ITER. Helically deformed surfaces are important and must be included. Calculations predict large NTV braking in ITER. They also predict that the offset rotation should dominate and rotate the plasma counter to the plasma I_p direction. Such rotation might provide the necessary benefits of rotation to ITER. Calculation shows that ITER's selected three-row array offers an ability to adjust core NTV torque.

This highly collaborative research informed the ITER Organization of its decisions and yielded advances in many topics of plasma physics.

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Subject 5

ELM mitigation experiments on MAST

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In order to avoid damage to in-vessel components in future devices, such as ITER, a mechanism to ameliorate the size of type-I ELMs is required. One such amelioration mechanism relies on perturbing the magnetic field in the edge plasma region, enhancing the transport of particles and keeping the edge pressure gradient below the critical value that would trigger an ELM. This technique has been successfully employed on DIII-D using two up-down symmetric sets of 6 in-vessel coils and more recently on JET using external error field correction coils. MAST is equipped with both a set of four ex-vessel error field correction coils (EFCCs), similar to JET, which can be configured to give n=1 or n=2 fields and with a set of 12 in-vessel coils, similar to those used in DIII-D, which can be configured to give n=1,2 and 3 fields.
ELM mitigation experiments have been performed using n=1 and n=2 fields from the ex-vessel coils. With an n=1 configuration of the coils a delay in the L-H transition was observed with increasing error field. Further n=1 experiments were performed by delaying the application of the field until after the L-H transition, however, it was difficult to find an operational window where sufficient current could be applied without either causing a back transition H-L or locked mode. In experiments with an n=2 configuration, in a low pedestal collisionality (ν_e*=0.3) discharge, the EFCCs were observed to increase the ELM frequency by typically 50 %. The evolution of the line integrated density shows that the EFCCs enhance the rate of density drop, which is reminiscent of the density pump-out observed in experiments on DIII-D and JET.
The internal coils have recently been commissioned. The application of these coils to L-mode plasmas has shown a clear density pump-out but only when the coils were in the configuration (even versus odd parity) predicted to be on resonance with the plasma. These experiments have also revealed a large change in the edge turbulence due to the applied fields. Preliminary H-mode experiments have begun. Initial results have shown how the coils can modify an ELM free discharge into one that contains regular small ELMs. Experiments are continuing and the results from application of the coils to ELMng discharges will be presented and, in particular, the importance of being on resonance will be highlighted.

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Category: 5) Application of resonant magnetic perturbation for ELM control.
Oral Contribution

Modification of ELM Power Deposition Patterns by Resonant Magnetic Perturbation*

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As reported from many machines, Type-I ELMs create helical footprint patterns of heat flux on the divertor surface. This was found on ASDEX-Upgrade and later confirmed on other machines like DIII-D, MAST and JET. On DIII-D, recent experiments in low collisionality ITER Similar Shaped plasma result in Type-I ELMs with a splitting of target heat flux patterns on the inner and outer target plates. We have performed measurements of the power deposition patterns to the inner target of the lower divertor with two toroidally separated (by 100 degrees) fast infrared cameras, which gives a unique opportunity to resolve the filamentary structure of Type-I ELMs in time and space and to study toroidal asymmetries. During an H-mode, Type-I ELMs typically create dynamically evolving structures for a few hundred microseconds, which later on decay over a few milliseconds. Some of the ELMs show hints of toroidally rotating structures. We find that the width of the deposition profile coming from an ELM, expressed as an inverse peaking factor, increases linearly with the energy deposited per ELM to the inner target. These findings are consistent with a hypothesis in which the separatrix is dynamically perturbed due to thermoelectric currents induced within ELM filaments. At DIII-D, application of resonant magnetic perturbation with sufficiently high amplitude leads to complete ELM elimination. However, in the initial RMP phase, there is still a short period of time (~200 ms) when we do observe some remaining ELMs with amplitudes at least two times smaller than in the non-RMP phase of the discharge. During this initial RMP phase when small, higher frequency ELMs are present the target heat load patterns seem to follow the magnetic topology driven by the interaction of RMP with magnetic equilibrium as predicted by the TRIP3D code. We do not observe any dynamic changes in the ELM structure and the ELMs appear to lock to the RMP field. Here, the widths of the ELMs do not depend on their size, which suggests that the exhaust channels are defined by the magnetic topology of the stochastic boundary.

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Category 5: Application of Resonant Magnetic Perturbations for ELM Control and Implications for ITER
Prefer Poster

Vacuum Magnetic Field Modeling of High Field Side RMP ELM Suppression Coils in DIII-D*

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Resonant magnetic perturbations (RMPs) are used in DIII-D to eliminate Type-I edge localized modes (ELMs) in H-mode plasmas while maintaining good edge transport barriers. In these experiments, it is found that the width of the q_{95} ELM suppression operating window can be increased by more than a factor of 4 when RMPs from two independent coil sets are mixed. This increases the width of the edge stochastic layer and the fraction of field lines connected from the pedestal plasma to the divertor target plates. Here, n=1 vacuum field RMPs from a single-row coil centered on the equatorial plane are coherently combined with n=3 RMPs from a double-row coil set with one row above and one below the equatorial plane. These results suggest that it may be possible to expand the q_{95} operating window farther by adding either n=2 or n=4 spectral components from another RMP coil set. Thus, a new RMP coil with this capability is being designed for installation inside the DIII-D vacuum vessel. A high priority goal for this new coil is to test whether the ELM suppression window can be expanded well beyond a factor of 4. A key element of this goal is to determine how well the properties of the q_{95} window can be understood in terms of the vacuum field model. If it is found that the vacuum field model is unable to capture the essential features required to understand the scaling of the q_{95} window with the addition of the spectral components from the new coil then a more sophisticated model, that includes the plasma response to the RMP, will need to be developed.

Although understanding the physics of the ELM suppression window is of prominent importance for developing reliable RMP ELM control coils for ITER it is not the only issue driving the design of this new RMP coil set. It is also highly desirable to build a coil that has sufficient spectral flexibility to study a wide range of fundamental stochastic boundary layer physics issues that may generally be more useful for improving the performance of poloidally diverted H-mode plasmas. With these objectives in mind, we have developed a set of tools that use a 2D EFIT reconstruction of a DIII-D RMP H-mode discharge to generate a 3D VMEC equilibrium. This is then fed into an automated spectral optimization code, VACISLD/ELM_NLP. Here, VACISLD/ELM_NLP is used to minimize the current required to obtain a specified stochastic layer metric using a variety of RMP coil configurations. Optimized coil configurations, with various toroidal mode numbers, are then modeled with the TRIP3D and SURFMN codes in order to quantitatively compare properties, such as magnetic diffusivity and field line loss fraction profiles, of the resulting stochastic layer. This procedure and results for the optimized n=2, 3 and 4 high field side DIII-D RMP coil set will be discussed.

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Category 5: Application of Resonant Magnetic Perturbations for ELM Control and Implications for ITER
Prefer Poster

Modeling of Plasma Pressure Effects on ELM Suppression With Resonant Magnetic Perturbations in DIII-D*

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Small edge resonant magnetic perturbations (RMPs) are used to control the pedestal pressure gradient without destroying the H-mode transport barrier in low ν_e^* ITER relevant, DIII-D plasmas. During this process the pedestal pressure gradient drops below the linear peeling-ballooning stability limit as calculated by ELITE, which leads to stabilization of edge localized modes (ELMs). The work discussed in this presentation concentrates on modeling the effects of β_N on the structure of the vacuum magnetic field during ELM suppression using *n*=3 RMPs in the DIII-D tokamak. Previously, low-triangularity ($\langle\delta\rangle = 0.30$) ELM suppression experiments showed a dependence on the NBI power for the presence of ELMs, indicating that certain power threshold needs to be reached for ELMs to be suppressed. Here, several high-triangularity ($\langle\delta\rangle = 0.51$) discharges with different neutral beam injection power levels and β_N's ranging from 1.5 to 2.3 are modeled and compared to low-triangularity discharges with a similar range of β_N's. Kinetic equilibrium fits are used for a reconstruction of bootstrap current and energetic ion population. Changes in the pedestal profiles and vacuum magnetic structure are compared for ELMing and ELM suppressed phases during the RMP pulse. The field line integration code TRIP3D is used to model the magnetic perturbation produced by the intrinsic and externally applied error fields in the DIII-D experiment and to quantify the loss of edge poloidal magnetic flux due to stochastic magnetic fields. Changes in the vacuum field structure are analyzed along with magnetic diffusion coefficient, filed line lengths, and Kolmogorov lengths.

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Category: 5) Application of resonant magnetic perturbations for ELM control and implications for ITER.
Oral Contribution

Particle Exhaust During RMP ELM Suppression on DIII-D with an Open and Closed Divertor*

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A common feature in many edge stochastic experiments is a reduction of plasma density ("pumpout"). Pumpout precedes the suppression of ELMs during the application of resonant magnetic perturbations (RMPs) in most DIII-D plasmas. The magnitude of the pumpout of electrons has a ~30% variation for discharges with similar applied RMP field strength and q_{95}. This large variation in pumpout magnitude motivated a more detailed study of plasma sources and sinks during RMP experiments on DIII-D. Recent analysis using a global particle balance and measurements of the D_α poloidal distribution shows that the wall inventory can be strongly affected by changing the average triangularity ($\langle\delta\rangle$) of the plasma (primarily due to changes in δ_{low}). Lower single null (LSN) discharges with similar plasma characteristics (e.g. n_e and electron collisionality) with different $\langle\delta\rangle$ were realized in DIII-D with a significant modification to the lower divertor baffling structure during a vessel upgrade in 2005. In particular, the analysis shows that at $\langle\delta\rangle \sim 0.3$ the integrated plasma efflux during the RMP is greater than the total number of particles removed by the cryopump system, indicating active wall pumping. Conversely, at $\langle\delta\rangle \sim 0.5$ in a scaled ITER-like shape, the plasma efflux during the RMP is balanced by the cryopump exhaust, i.e., no wall pumping is inferred. Additionally, the D_α intensity in the $\langle\delta\rangle \sim 0.5$ discharges increased by ~ 50-100% when compared to the $\langle\delta\rangle = 0.3$ discharges. The observations at $\langle\delta\rangle \sim 0.5$ imply an increase in the scrape-off layer neutral density. This overall result is significant, because it demonstrates density pumpout and ELM suppression without significant wall pumping, a feature that is essential in long-pulse reactors with saturated walls.

Three factors in the discharges at different $\langle\delta\rangle$ have been identified as possibly contributing to the observed difference in the particle balance and recycling characteristics: (1) the significant modification of the lower divertor baffling structure and subsequent change in pump-plenum-entrance vacuum-conductance during the 2005 upgrade; (2) a more closed divertor geometry with reduced leakage to the main chamber; and (3) the changes in the plasma triangularity itself. Lower divertor pumping speed and conductance measurements indicate that the baffle modification should not have a significant effect on the observed difference in wall pumping and recycling. DEGAS2 calculations are being used to quantify the change in divertor closure on the measured result. Finally, changes in the plasma $\langle\delta\rangle$ have been assessed with the ELITE stability code, which show a reduction in the region of stability as $\langle\delta\rangle$ increases, and the TRIP3D field line following code is being used to assess changes in the open field line connection length, L_c, to the graphite wall. In summary, we have found that varying the plasma shape from $\langle\delta\rangle \sim 0.3$ to an ITER-like shape of $\langle\delta\rangle \sim 0.5$ the increased plasma efflux due to the RMP is completely compensated by the cryopumps in DIII-D. It is suggested that this change in cryopump exhaust capability is due to changes in the divertor geometry, namely going from a more open configuration at $\langle\delta\rangle \sim 0.3$ to a more closed divertor configuration $\langle\delta\rangle \sim 0.5$ and/or to particle transport near the plasma edge.

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ELM Control with $n = 1$ and $n = 2$ External Perturbation Fields on JET

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The tolerable energy losses associated with Edge Localised Modes are likely to be restricted to values of the order of 1 MJ/ELM in ITER. The operation in baseline H-mode requires either a substantial increase in ELM frequency ("ELM control") or even a complete suppression of ELMs. The application of magnetic perturbation fields is a promising method to achieve this goal.

Experiments on DIII-D [1] have shown that an $n = 3$ perturbation field generated by a coil set mounted close to the plasma inside the vacuum vessel could completely stabilise ELMs within a certain range of global plasma parameters (shape, heating power, collisionality, edge safety factor). On the contrary, JET has no internal ELM control coils but is equipped with a set of four error field corrections coils (EFCCs) located far away from the plasma. These coils were utilised to apply $n = 1$ and $n = 2$ magnetic perturbations. Both were found to be able to increase the ELM frequency (up to a factor of 4) [2].

A recent paper [3] proposed a set of plausible criteria to design an ELM control system for ITER which should be capable to completely suppress ELMs. These criteria describe demands to minimise unwanted plasma rotation braking due to resonant and non-resonant effects (in order to avoid locked modes and NTMs), and quantify the required perturbation strength. The Chirikov parameter has to be ≥ 1 for normalised flux $\Psi_N \geq 0.85$. A recent series of experiments on JET aimed to test this criterion. The limited capabilities of the present EFCC system required to develop a specifically tailored plasma in order to maximise the Chirikov parameter, but complete ELM suppression was neither in $n = 1$ nor $n = 2$ configuration obtained.

This talk will give a detailed report on the JET ELM control experiments during the last two years comprising (i) determination of the operational window, (ii) compensation of density pump-out, (iii) effect on plasma rotation, (iv) influence on ELM behaviour in plasmas with increased toroidal field ripple, and (v) application in high beta discharges.

Helpful discussions with M. Fenstermacher, T. Evans and A. Kirk are acknowledged.

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*See the Appendix of F. Romanelli et al., Fusion Energy Conference 2008 (Proc. 22nd Int. Conf. Geneva) IAEA, (2008)

Poster contributions to the 4th Workshop on Stochastic Fusion Plasmas, Jülich, March 02-04, 2009

1	**Roberto**	Marisa	Symplectic Maps for Tokamaks with Poloidal Divertors	**1**
2	**Guimarães-Filho**	Z.O.	Dynamical Characteristics of Plasma Turbulence with High MHD Activity in TCABR Tokamak	**1**
3	**Isliker**	H.	A self-organized criticality model for the magnetic field in toroidal confinement devices	**1**
4	**Isliker**	H.	A Self-Organized Criticality model for Ion Temperature Gradient (ITG) mode driven turbulence	**2**
5	**Isliker**	H.	The combined random walk in position and momentum space as a model for anomalous particle transport	**2**
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Topic 1: **Formation of stochastic magnetic layers**

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Topic 4: **Application of resonant magnetic perturbations for ELM control and implications for ITER**

Subject: 1. **Formation of stochastic magnetic layers**

Abstract

Symplectic Maps for Tokamaks with Poloidal Divertors

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A symplectic mapping method to study magnetic field lines near the separatrix of poloidal divertor tokamaks, proposed by Morrison and Abbamonte, is applied to describe the magnetic field lines near the separatrix of a tokamak with a single-null divertor. For this application, the canonical time step required by the method is initially chosen to be uniform with a value adequated to roughly reproduce the equilibrium safety factor profile near the separatrix. To improve this fitting a nonuniform time step profile is numerically calculated to simulate the considered equilibrium safety factor profile near the separatrix. The map control parameters were varied to study the structure of field lines and the positions of the hyperbolic point and the divertor plate. The obtained integrable map is perturbed by helical resonances due to an ergodic limiter described by the Martin-Taylor map. This perturbed map is used to follow magnetic field lines initialized on the divertor plate until they again intersect the plate. Thus, the field line connection lengths are determined as a function of their initial position on the plate. Moreover, the field line structure is used to obtain their footprints, i. e., the line deposition patterns on the plate.

Subject: Formation of stochastic magnetic layers

Dynamical Characteristics of Plasma Turbulence with High MHD Activity in TCABR Tokamak

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In some TCABR discharges MHD activity may increase and drive the plasma edge electrostatic turbulence. For these discharges, spectral linear analyses of electrostatic turbulence, measured by the Langmuir probes, and magnetic fluctuations, measured by Mirnov coils, present several common features with a noticeable dominant peak in the same frequency. Nonlinear dynamical analysis reveals other common characteristics between these fluctuations. Thus, their bicoherence spectra show a strong nonlinear coupling involving the MHD frequency. Moreover, a spectral version of order parameter reveals that the turbulence fluctuations are synchronized with the Mirnov fluctuations in the MHD frequency. In addition, these two nonlinear effects are both mainly concentrated inside the plasma near the edge. Furthermore, the recurrence quantification analysis of these fluctuations shows that their determinism increases with the MHD activity. In conclusion, all these results indicate that coupled nonlinear equations should be applied to describe the reported influence of the high MHD activity on the turbulence.

Subject 2 (or 1)

A self-organized criticality model for the magnetic field in toroidal confinement devices

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Abstract:

We present a Self-Organized Criticality (SOC) model for the magnetic field in toroidal confinement devices. The model is in the form of a Cellular Automaton (CA), where the temporal evolution is determined by local rules. A main aim in the construction of the model is that the usual physical variables are used, and that they are physically interpretable in a consistent way.

The core of the model is formed by a two-dimensional cellular automaton (CA) for the evolution of the magnetic vector-potential in the poloidal plane, with a driving mechanism and an instability criterion that allow the CA to reach the SOC state. The CA is embedded in a set-up that allows to have access to the magnetic field and the current in a way fully compatible with MHD and Maxwell's equations, e.g. the divergence-freeness of the magnetic field is guaranteed. This is achieved by interpolating the vector-potential in 2-dimensional space, which makes it possible to calculate its derivatives at any point inside the simulation box of the else discrete CA model. The magnetic field and the current are thus continuously defined spatial vector-fields and are calculated in the usual MHD way.

In the application to toroidally confined plasma, we first implement a typical magnetic topology as initial condition, with prescribed radial safety factor profile. The system is driven by the toroidal current, which occasionally triggers local resistive instabilities that are relaxed in local diffusion events. The system reaches the SOC state, with a characteristic magnetic SOC topology, around which the magnetic field fluctuates, staying though very close to it and exhibiting thus a high degree of stiffness. The magnetic SOC topology is qualitatively in agreement with the topologies realized in magnetic confinement devices such as the reversed field pinch.

Subject 2

A Self-Organized Criticality model for Ion Temperature Gradient (ITG) mode driven turbulence

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Abstract:

We present a Self-Organized Criticality (SOC) model for Ion Temperature Gradient (ITG) mode driven turbulence. The model is in the form of a Cellular Automaton (CA), with the temporal evolution determined by local rules. Our purpose is to model the evolution of the ion temperature on global spatial scales, i.e. the evolution of the temperature profile along the entire minor radius, with the ion temperature itself as the physical variable, and where the local (micro-)physical processes are consistent with the physics of ITG mode driven turbulence.

We use a one-dimensional grid along the minor radius, with grid variable the ion temperature. The system is heated by systematically increasing the temperature locally, following a specified spatial heating pattern (e.g.\ central heating, off-axis heating, etc.). Instabilities are defined to occur if the inverse ion-temperature gradient-length locally exceeds a threshold, exactly as in ITG driven turbulence, whereby the temperature profile is interpolated in order to calculate its gradient. Local instabilities are relaxed in local diffusion events, which basically cause a local smoothing of the temperature profile.

The system reaches the SOC state, with ion temperature profiles that are qualitatively in agreement with those seen in tokamaks, e.g. in JET (in the L-mode). The temperature profiles exhibit very high stiffness, their shape is largely independent of the applied loading pattern. Thus, despite the normal character of the diffusive processes that act at local scales, the model exhibits anomalous diffusive behaviour on global scales, in particular we find that heat is systematically transported 'up-hill' (against the driving gradient).

Subject 2

The combined random walk in position and momentum space as a model for anomalous particle transport

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Abstract:

We introduce the combined Continuous Time Random Walk (CTRW) in position and momentum space, in the form of two coupled integral equations that describe the evolution of the probability distribution for finding a particle at a certain position and with a certain momentum as a function of time. The integral equations are solved numerically with a pseudospectral method that is based on the expansion of the unknown functions in terms of Chebyshev polynomials. In parallel, Monte-Carlo simulation are performed.

Through the inclusion of momentum space, the combined CTRW is able to yield results on the evolution of particle densities and kinetic energy distributions, and, in confined plasmas, on density profiles, as well as on particle fluxes and diffusivities. The combined CTRW is non-local in position-space, in momentum-space, and in time (non-Markovian), and it is able to model phenomena of anomalous transport in position as well as in momentum space.

An application is made to a toroidally confined plasma that undergoes off-center injection of cold plasma (off-axis fueling), with the momentum space representing the ensemble of stochastically evolving drift velocities.
We address the phenomenon of density profile stiffness, and we show that it can be reproduced by the combined CTRW with varying success.
The particle confinement times are determined, and their dependence on the applied intensity of plasma heating is discussed. Finally, we derive and analyze the particle fluxes in the combined CTRW and discuss them in comparison with the classical approach of Fick's law for particle transport.

Subject 2

Test-particle simulations of ion drift in stochastic magnetic fields

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Abstract:

We study the influence of stochastic magnetic fields on ion diffusion, using a drift approximation in slab geometry, and applying a stationary stochastic magnetic field on top of a uniform background field. The stochastic magnetic field follows a Gaussian in its distribution function, and it obeys a prescribed auto-correlation function with given correlation length. The running diffusion coefficients of the ions are determined with the use of test-particle simulations in the three dimensional environment, for different levels turbulence (varying Kubo number). Particular focus is on the effects of particle trapping on diffusion. The results of the test-particle simulations are compared to and used to validate the results as obtained for the same physical system by the semi-analytical Decorrelation Trajectory (DCT) method.

RAY TRACING AND ELECTRON MOTION IN A STOCHASTIC MAGNETIC FIELD ARISING FROM THE PRESENCE OF MULTIPLE NTMs

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ABSTRACT

We study the propagation and absorption of electron cyclotron (EC) waves in tokamak plasmas in the presence of a number of magnetic islands. The purpose of EC waves is to drive currents (ECCD) for controlling plasma instabilities, such as the neoclassical tearing mode (NTM), and/or providing plasma current for confinement and for controlling the current profile. The general idea for the stabilization of a single NTM is to raise the current in the vicinity of the island's O-point by ECCD [1]. The usual analysis of EC propagation and absorption is done in an axisymmetric magnetic topology, ignoring the presence of the islands [2,3]. We assume the existence of several NTM magnetic islands which could be overlapping in configuration space. The motion of electrons within this magnetic configuration is studied using the tools of Hamiltonian dynamics. This is subsequently used to study the propagation and absorption of EC waves near the reconnection layers. We include the effect of island topology and the chaotic magnetic fields generated by island overlap in determining the efficiency of the EC wave absorption and ECCD. The plasma response determined from linear theory is compared with the response obtained by using the detailed particle dynamics in the prescribed magnetic topology. The presence of magnetic islands and of spatially chaotic magnetic surfaces affects the propagation and damping of the EC waves and the transport of electrons in the presence of these waves.

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Subject : 1 Energy and particle transport in stochastic magnetic fields

Secondary instabilites and turbulent regimes in a Hamiltonian four-field model for magnetic reconnection in collisionless plasmas

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Abstract

Magnetic reconnection (MR) is a process that allows to convert magnetic energy into kinetic and thermal energy of a plasma through a rearrangement of the topology of the magnetic field. This phenomenon is of great relevance for both laboratory and astrophysical plasmas [1,2]. In high temperature plasmas such as tokamak plasmas, where particle collisions are infrequent, MR can be effectively caused by electron inertia, which is capable to violate the frozen-in condition for the magnetic field.
In this contribution we present results concerning a nonlinear model [3] for MR in collisionless plasmas. After reviewing the noncanonical Hamiltonian structure of the model, we present results [4], based on numerical simulations, showing how the formation of a magnetic island as a consequence of an initial reconnective instability, can in turn trigger the formation, in the vorticity field, of a secondary instability of Kelvin-Helmholtz type, caused by the formation of steep velocity gradients. The secondary instability can lead to the formation of a turbulent regime that might affect plasma transport. The onset of the secondary instability, seems however, to depend on the value of the beta parameter (with beta indicating the ratio between the plasma pressure and the magnetic pressure exerted by the guide field) and of the electron temperature. A qualitative interpretation of the observed nonlinear dynamics of the vorticity field, in terms of the Casimir functionals of the model, is provided.

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Abstract for 4th International Workshop on Stochasticity in Fusion Plasmas
(preferred type/category: talk for subject 4)

3D MHD Equilibrium Calculations for Tokamaks with the HINT2 Code

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Tokamaks are often considered to be two-dimensional and consequently, their equilibrium is treated by solving the Grad-Shafranov equation. In real devices, the toroidal field ripple, error fields due to coil misalignments and deliberate application of resonant magnetic perturbations lead to a three-dimensional structure. To study the effect of the deviations from axisymmetry on the equilibrium the application of complex numerical tools is necessary.
For the calculation of 3D MHD equilibria a number of numerical codes are available (VMEC, PIES, HINT2, IPEC). Some assume nested flux surfaces (VMEC, IPEC), while others allow for magnetic islands (PIES, HINT2).
In this study the HINT2 code [1] is used to compute numerical 3D equilibria. Some issues concerning the pressure distribution within an ergodic region as well as the treatment of the net toroidal current density will be discussed. Examples will mainly be shown for TEXTOR with DED.
Furthermore, first calculations of 3D equilibria for diverted tokamaks with HINT2 will be presented for a JET discharge using the error field correction coils for ELM control and discussed in comparison with the vacuum superposition approach.

Part of this work was performed with the support of a "Pre/Postdoctoral Scholarship for North-American and European Researchers (Short Term)" of the Japan Society for the Promotion of Science, which is gratefully acknowleged by one of the authors (C.W.).

[1] Y. Suzuki et al., Nucl. Fusion **46** (2006) L19-L24

*See the Appendix of F. Romanelli et al., Fusion Energy Conference 2008 (Proc. 22nd Int. Conf. Geneva) IAEA, (2008) Category: 4) Plasma response to external, non- axis- symmetric perturbations

Screening of magnetic perturbations by the electron diamagnetic drift

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As it was shown in the last years resonant magnetic perturbations (RMPs) are an important tool to manipulate the edge of magnetically confined tokamak plasmas. It is planned to use RMP in ITER to minimize the negative effects of Type-I ELMs on plasma facing components. An exhaustive and appropriate description of the RMP tool and especially its interaction with the tokamak plasma is necessary to understand the physical processes behind this system. We concentrate in this contribution on the properties of the shielding currents induced by interaction of external perturbations with the plasma and their influence on the stochastization of magnetic field lines. To study this effect theoretically a linearized two fluid model was used. The modeled fluid quantities are: particle density, vorticity, ion velocity, electron temperature and magnetic vector potential. One of the results of the modeling is a rather sharp resonant window in which the shielding currents affect the plasma stochastic boundary. Namely the strongest plasma response on external perturbations happens when the electron diamagnetic drift frequency is varied around the external perturbation frequency. In principle the electron diamagnetic drift frequency depends on many quantities and parameters. Here we have chosen to vary it by changing the electron temperature.

This effect was also studied experimentally on TEXTOR with the Dynamic Ergodic Divertor (DED). A scan of the diamagnetic drift frequency has been performed by changing the electron temperature profile by a variation of the heating power using neutral beam injection. Balanced beam injection was chosen in order to keep the plasma rotation constant. The poloidal and radial magnetic field was measured by a Hall probe located on the low field side outside of the plasma and by Mirnov coils. At different plasma temperatures the Hall probe measures different strengths of the magnetic perturbation for the same DED current. From this we can deduce information about the plasma response on the RMP. At small levels of perturbation we observe a linear increase of the magnetic perturbation with the DED currents as predicted by the model. However, at higher amplitude of the external perturbation a non-linear behavior is observed, which can not be described. This non-linear behavior appears at around 400A to 800A of AC DED current depending on the heating power. Our present understanding is that this behavior is related to a significant reduction of the shielding currents as soon as ergodization sets in.

Planning of RMP experiments on COMPASS

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We have done calculations of resonant magnetic perturbations (RMPs) that can be produced by the set of saddle coils on the COMPASS tokamak, recently transferred from UKAEA Culham to IPP Prague. Studies of RMPs are planned to be an important part of the future experimental programme of COMPASS, especially in view of their application as an ELM control mechanism and their planned use in ITER. To demonstrate the suitability of COMPASS for such a research we computed the islands and the resulting stochasticity which can be created by the saddle coils for several typical operating regimes. We have developed methods for optimizing the coil spectrum to create a stochastic region at the edge (in a vacuum approximation). We will discuss the possibility of upgrading the COMPASS coil system, for example to produce higher toroidal mode numbers (currently the toroidal mode number can be 1 or 2) and possible impact of the coils on plasma parameters accessible by diagnostics. As the amount of perturbation screening by plasma is an important question, we will estimate the possibility of indirect detection of plasma screening currents by available diagnostics, which would help to resolve this problem experimentally.

[4]

EXCITATION AND SUPPRESSION OF ALFVEN EIGENMODES (AEs) BY USING DED COILS

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Alfven eigenmodes (AEs) excited by high energy particles are predicted to play an important role on the confinement of particles in nuclear fusion reactors. In order to study a stability of AEs and develop the method to suppress them, we excite AEs on TEXTOR tokamak plasma by using the dynamic ergodic diverter (DED) coils as an external antenna.

DED coils are wound inside the vacuum vessel at the high field side. The field modes of m/n=12/4, 6/2 and 3/1 can be excited by changing the coil configuration, where m and n are poloidal and toroidal mode numbers, respectively. The rf current of ≤4A with frequencies swept from 100kHz to 1MHz was applied on the DED coils. The coil impedance was measured as a function of frequency for Ohmic plasmas (Ip = 400 kA, Bt = 2.25 T, n_e~2x10^{19} m^{-3}). The wave magnetic fields were detected by the Mirnov coils installed around the torus. The effects of the ergodization of edge magnetic fields on AEs were studied by superimposing the DC current on the DED coils. The reduction of AEs excited by the rf was observed by applying the small DED current (~0.5kA) which does not give notable effects on plasma parameters at periphery.

Magnetic field parameters relevant for the ELM - mitigation at ITER by the designed EFCCs and proposed coils

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RMP - coils in DIIID and the error field correction coils (EFCCs) at JET, mounted at a significantly larger distance d_c ($d_c \approx 2R_0$) than the RMP - coils in DIIID, were both effective in ELM suppression. Thus the proposed near plasma coils /1/ and the designed EFCCs ($d_c \approx 2.2R_0$), similar to the EFCCs at JET, are investigated here and compared. The efficacy of these coils depends on a sufficient width W_e of the ergodized layer at the edge and on the screening of the plasma interior by plasma rotation at sufficiently large slip frequencies thus avoiding mode locking and disruptions due to resonances at the singular surfaces.

Since the ITER - plasma (with the parameters given in /1/) is in the 'visco - resistive' regime, the Fitzpatrick expression (e. g. in /1, 2/) can be used to compute the screening factor S_f. The toroidal speed is obtained from a generalized neoclassical theory /2/.

To estimate the vacuum island widths W_v, the radial magnetic field is Fourier analyzed (using 'intrinsic' coordinates). The total field is used for field line tracing thus obtaining the radial extension W_e of the ergodic layer at the edge.

Like the RMP configurations at DIIID or JET the perturbation coils at ITER have a preferential toroidal mode number ($n_{rmp} = 3$, for all coil configurations). Thus the 3d - distribution of the perturbing radial field can be described by the two dimensional poloidal and radial distribution of the Fourier component $\bar{B}_{n_{rmp}}(r,\theta) \sim \int d\phi B_r \sin(n_{rmp}\phi)$. By Fourier analyzing $\bar{B}_{n_{rmp}}(r,\theta)$ with respect to θ the radial dependence of the spectrum $\hat{B}_{n_{rmp},m}(r)$ can be derived and by means of $S_f(r)$ the screening can be accounted for.

The main results can be summarized as follows:

In the even configuration of the EFCCs (n_{rmp}=3) and at their maximum current ($\approx$ 280 kA in the side coils) the peaked maximum of the distribution of $\bar{B}_{n_{rmp}}(r,\theta)$ at θ=0 is roughly the same as that of the 'external' coils, of the '6 coils on PFCs', and of the 'internal coils' (currents given in /1/) . The Fourier decomposition of $\bar{B}_{n_{rmp}}(r,\theta)$ generates a spectrum in $-25 < m < 25$ which is narrower in the case of the EFCCs then in the case of the other coils. The Fourier components ergodize the edge at the x - point with a width $W_e \approx 30$ cm (obtained by field line tracing). The dangerous islands at the q=3 and q=2 surface can be shown to get a small extension (compared to W_v) if the plasma rotates with a maximum speed $v_t \approx 40\frac{km}{sec}$ (in rough agreement with /1/) due to $\approx$ 50 MW NBI.

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