Nucl. Fusion **46** (2006) S107–S112 doi:10.1088/0029-5515/46/4/S01

CONFERENCE SUMMARY

Summary of the second workshop on stochasticity in fusion plasmas (SFP) held in Juelich, Germany, 15–17 March 2005

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Received 14 July 2005, accepted for publication 20 February 2006
Published 15 March 2006
Online at stacks.iop.org/NF/46/S107

PACS numbers: 52.25.Gj, 52.25.Fi, 52.35.Vd

(Some figures in this article are in colour only in the electronic version)

In 2003 a biannual workshop on 'Stochastization in Fusion Edge Plasmas (SEP)' was initiated because of an increased interest in the effects of magnetic field ergodization within the magnetic confinement fusion community. In particular the role of ergodic magnetic fields for transport and stability is increasingly recognized. This interest is not only triggered by the hope to develop new methods for particle- and heat-exhaust in fusion reactors but also to gain a better understanding of transport around the stochastic tips of magnetic islands due to tearing mode instabilities. This is augmented by the very encouraging finding on DIII-D that the edge ergodization can reduce or even suppress large type I ELMs.

During the first workshop it was emphasized that the ergodization not only plays an important role in the edge of the plasma but also for transport over the whole cross-section. Therefore the title of the conference has been slightly changed to 'Workshop on Stochasticity in Fusion Plasmas (SFP)'. Details of the workshop including the author list and the presentations are found at http://www.fz-juelich.de/sfp/. The workshop was inspired by the recently installed dynamic ergodic divertor (DED) which has become the focal experiment of TEXTOR. By pursuing questions of ergodization, new contacts with colleagues from related fields were made bringing together different lines of fusion research.

The topics of the workshop were summarized under the following three headings:

- Mitigation of ELMs by ergodization of the edge magnetic field lines;
- Experimental results from ergodized plasmas;
- Theory development for ergodic systems.

1. Mitigation of ELMs by ergodization of the edge magnetic field lines

The type I ELMy H-mode is the standard operational scenario for ITER. Nevertheless, it is well known in the community that the frequent ELMs are a potential threat, in particular, to the divertor targets. Therefore means are investigated to mitigate the effect of the ELMs or even better to avoid them. Within the different methods of mitigating ELMs (pellet injection, movements of the vertical plasma postion, gas injection in the divertor region) the application of external resonant magnetic perturbations (RMP) in order to ergodize the magnetic field lines at the plasma edge was discussed at the workshop. The large number of contributions showed high interest in this question; the presentations were given by R.A. Moyer *et al*, T.E. Evans *et al*, M. Schaffer *et al* (DIII-D), P.R. Thomas *et al*, M. Bécoulet *et al*, E. Nardon *et al* (Tore Supra) and S.S. Abdullaev *et al* (TEXTOR).

On DIII-D, different plasma scenarios and perturbation coil configurations have been successfully investigated. Several plasma parameters are varied, e.g. the shape of the plasma, the collisionality and the edge safety value. Since ergodization is a resonant effect, the ELM suppression works only in a narrow q_{95}-range. Odd parity $n = 3$ I-coil (each coil is roughly centred 45° above and below the mid-plane) RMPs (pedestal islands) suppress ELMs at high collisionalities ($\nu* \sim 1.0$) while even parity $n = 3$ I-coil RMPs (pedestal stochasticity) produce QH-like conditions at low collisionality ($\nu* \sim 0.05$). The equatorially centred $n = 3$ C-coil RMP do not suppress ELMs and have no appreciable effect, to date, when combined with $n = 3$ I-coil RMPs (R. Moyer). The

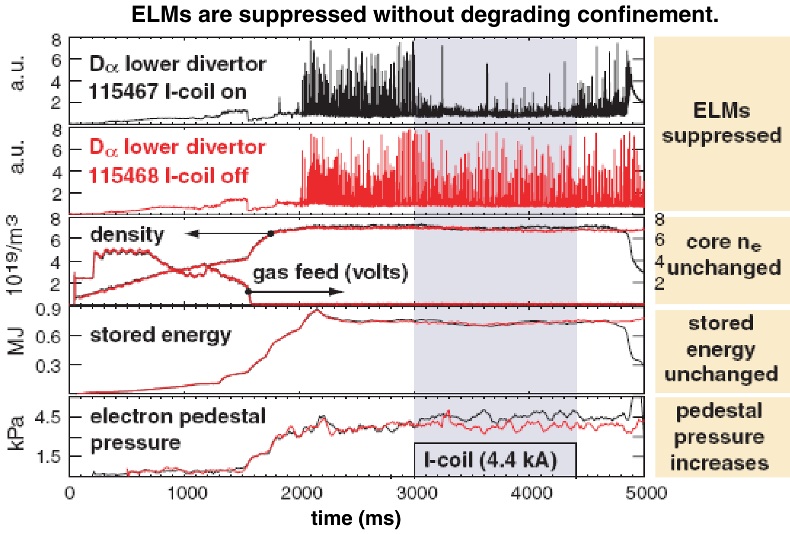

Figure 1. Example of DIII-D on the ELM development with applied ergodization coils (black) and for reference without perturbation current (red). The perturbation field resulting from currents in the I-coils reduces the ELMs in the grey part of the figure; density, stored energy and electron pedestal pressure remain practically unchanged (R. Moyer).

experiments on DIII-D showed that edge ergodization offers a unique opportunity to modify the boundary of axisymmetric divertor tokamaks, both to understand ELMs and, potentially, to eliminate them. It is so far the only method that eliminates ELMs while maintaining good confinement. An example of the ELM mitigation at DIII-D is shown in figure 1.

The other contributions in the session treated the possible transfer of the encouraging DIII-D results to JET and ITER taking into account realistic locations for external coils. One aspect is also the applicability to JET which includes a realistic coil geometry which can be implemented on ITER. Such a proposal for JET is shown in figure 2. The main discussions concentrated on the question of the possible coil location, namely, whether a set of equatorial coils will produce a suitable perturbation field spectrum or whether a more complicated set of coils will be required. The choice of the coil geometry is most likely linked to the competing effects of the perturbation field on the plasma edge and the plasma core: the edge perturbation is related to the beneficial ELM reduction while the perturbation of the plasma core may trigger undesired seed islands of neoclassical tearing modes. These modes reduce plasma confinement and may inhibit the toroidal plasma rotation to a level which endangers the plasma stability in high performance discharges with high toroidal momentum input (resistive wall modes).

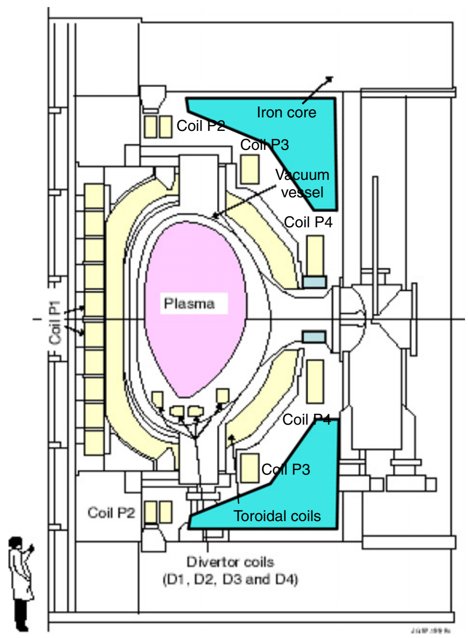

Figure 2. Proposal of the location of perturbation coils for JET in the blue areas (R.P. Thomas).

2. Experimental results from ergodized plasmas

In the experimental sessions, different experiments and different aspects of field line ergodization were presented; therefore, this block is less coherent than the first one. Data were obtained from the Large Helical Device (LHD) in Toki, Japan, from HYBTOK-II, University Nagoya, Japan and a larger block from the TEXTOR DED, Juelich, Germany. K. Toi *et al* (NIFS) reported the formation of a steep pressure-gradient region in the ergodic field layer of LHD. The role of closed, ergodic and open magnetic field lines was discussed, in particular, with respect to the particle and energy transport. At high temperature and low collisionality, the transport channel is dominated by the detailed structure of the magnetic field lines with a dominant transport along the ergodic field lines from deep inside the plasma. At high collisionality, the transport along open field lines becomes more important. The formation of an edge transport barrier at an L to H transition is observed and coherent modes are found at the edge of the plasma.

V.P. Budaev (Kruchatov Institute) *et al* have analysed the effect of the rotating helical fields (RHF) on the plasma edge in the HYBTOK-II tokamak using a wavelet technique on multi-pin Langmuir probes. As indicated in figure 3, they observed during the RHF operation at 5 kHz that density perturbations rotate in the same direction as the RHF one, producing large

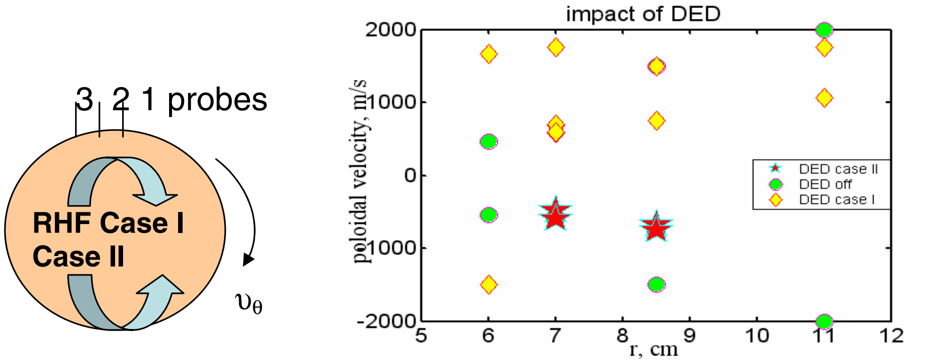

Figure 3. Induced rotation as measured by the set of Langmuir probes (indicated in the figure, left). Three cases are indicated: the green circle symbols represent a non-rotating perturbation field while the red star and yellow diamond symbols stand for opposite senses of rotation (see figure, left) (V.P. Budaev).

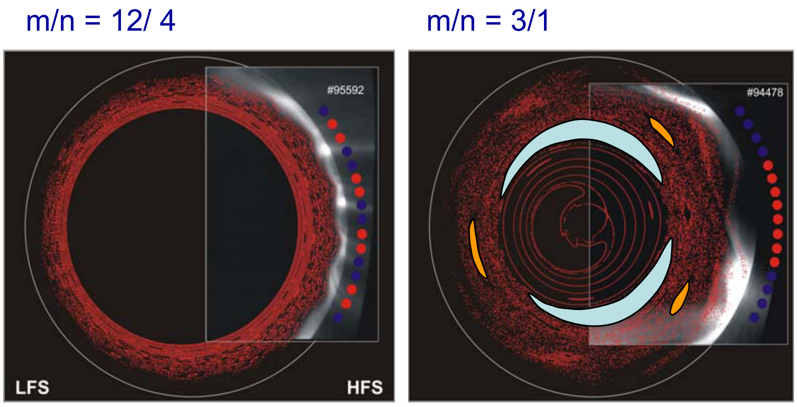

Figure 4. Poncaré plot of the magnetic field lines in a poloidal cross-section for the $m/n = 12/4$ (left) and $m/n = 3/1$ (right) base modes of the DED. The DED coils and the directions of the electric currents (red/grey and blue/black) are indicated on the right-hand side of each sub-figure. Overlaid is also the CIII light of the plasma recorded by a tangential CCD camera (B. Unterberg).

events on $\sim$200 μs scale. The effect of the RHF is essential up to $r/a = 0.55$ ($r = 6$ cm) and the toroidal rotation of density perturbation is estimated of $\upsilon_\varphi \sim 20\,\mathrm{km\,s^{-1}}$.

In a second contribution they treated the superdiffusion and multifractal statistics of edge plasma turbulence in fusion devices. They showed that burst radial propagation in magnetized plasma is a non-diffusive process. The plasma edge turbulence in fusion devices demonstrates multifractal statistics with long-range correlation and non-trivial scale invariance. The waiting time is not a Poisson process; no clear signature of the SOC paradigm is observed. Universality of multifractal properties observed in edge fusion plasmas is one of the key moments for the prediction of transport losses in large-scale fusion devices. M. Okamoto *et al* have investigated the dynamic behaviour of internal magnetic field during disruptions in HYBTOK-II. They stressed the importance of the overlap of the $m/n = 2/1$ and 3/1 islands for the development of disruptions on HYBTOK-II.

An overview on the results on the TEXTOR DED was given by B. Unterberg (TEXTOR). The results and the physics questions depend strongly on whether the base mode $m/n = 12/4$ of the DED (figure 4, left) is applied or whether the coarse and deeply reaching $m/n = 3/1$ base mode (figure 4, right) is used. The $m/n = 12/4$ base mode influences only the plasma edge and therefore investigations on the divertor play a dominant role.

The action of the DED is strongly resonant and dominant areas with either short connection lengths of the magnetic field lines (laminar zone) or with large connection lengths can be selected by an appropriate choice of the edge safety factor. The largest divertor effect on the plasma edge structure is observed at $2.8 < q(a) < 3$; in this range one also observes a slight increase in the plasma confinement. The relatively complicated 3D edge structure is visualized by 2D ECE imaging (radial and poloidal directions of the T_e-measurement) as shown in figure 5. The ergodization generates an edge electric field which accelerates the plasma in the co-direction of the plasma current. The results of the $m/n = 3/1$ base mode operation of the DED are dominated by the excitation of a strong $m/n = 2/1$ tearing mode which influences the plasma confinement, the plasma rotation and the impurity transport; at $r < r(q = 2)$ the transport is enhanced while further outside it is reduced.

The overview was complemented by the individual contributions of M. Jakubowski, C. Busch, K.H. Finken, Y. Liang, O. Schmitz, O. Zimmermann (TEXTOR), F. Dubois (Tore Supra) and T. Van Rompuy (University of Ghent) and specific investigations such as the comparison of calculated magnetic structure to measured heat flux pattern, of the

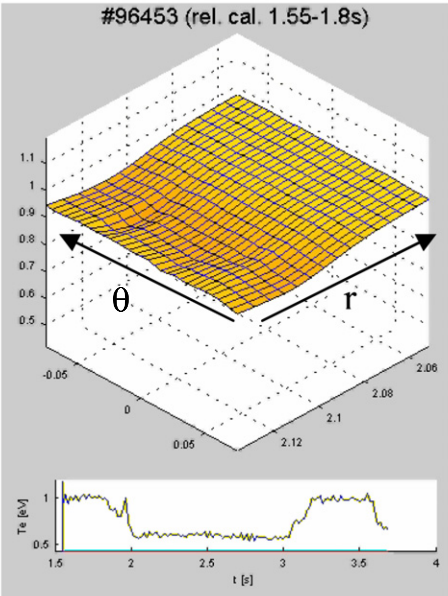

Figure 5. Radial and poloidal temperature profile recorded by ECE imaging. The figure clearly shows the 3D character of temperature in the laminar zone (B. Unterberg).

impact of the DED on the plasma rotation, of the plasma properties in the magnetic flux tubes at the plasma edge, of the characterization of the edge plasma by Langmuir probes, of the penetration of carbon impurities, of the excitation of the Alfvén-like modes, and from losses of energetic runaway electrons and on MARFE formation by the DED-field.

The experiments with DED on TEXTOR were accompanied by modelling efforts of H. Gerhauser *et al*, D. Harting *et al*, Y. Kikuchi *et al*, X. Loozen *et al* and M.Z. Tokar *et al* (TEXTOR) using different codes such as the 3D fluid code EMC3, or the 2D fluid code TECXY. The following topics were addressed: the rather complex 3D plasma transport including the recycling neutrals and impurities, the transport characteristics in a stochastic magnetic field with anomalous perpendicular transport and recycling and the enhancement of the density limit by the DED. Finally, the stability and growth of the magnetic islands induced by the DED were studied.

3. Theory development for ergodic systems

The theoretical presentations are subdivided into the following four categories:

- mapping of magnetic field lines;
- particle and heat transport coefficients;
- numerical modelling (simulations);
- perturbation field penetration and ponderomotive force transfer to the plasma.

New *mapping* ideas for tokamaks have been introduced by R. Balescu and were continued by B. Weyssow *et al* (Université Libre, Brussels) who treated order and chaos in some Hamiltonian systems in plasma physics. In particular he investigated non-twist mapping methods and plasma systems with a reversed safety factor profile. I.L. Caldas (University

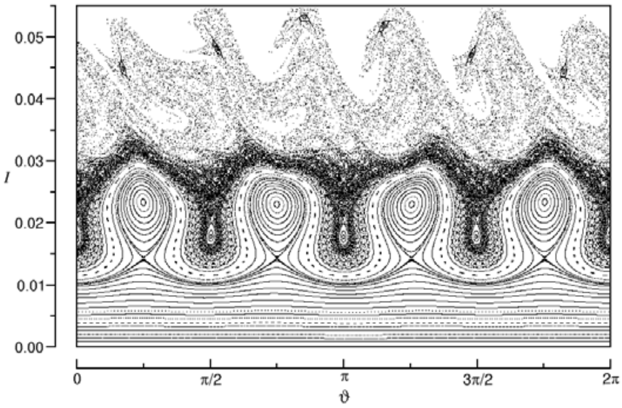

Figure 6. Poincaré plot of EML perturbation with $m/n = 5/1$ and $4/1$ islands, $I_h/I_p = 0.02$, where I_h is a helical current and I_p the plasma current. Lines escape uniformly (I.L. Caldas).

of São Paulo, Brazil) introduced non-twist maps to describe analytical tokamak plasma equilibria, with non-monotonic current profile, perturbed by ergodic magnetic limiters as shown in figure 6. Examples of high concentration of magnetic field lines escaping and the robustness of internal invariant curves on the shear-less region are given.

S.S. Abdullaev (TEXTOR) concentrated in his presentation on mapping developments for the separatrix mapping and showed details of the laminar zone in such a system. A. Wingen *et al* (University of Duesseldorf) treated transport in incomplete chaotic systems, discussed stable and unstable manifolds and transport. C. Chandre *et al* (University of Marseille) reported on the control of stochasticity in magnetic field lines. In this method a second order control function is introduced which cures the chaotic motion introduced by a first order perturbation. The method is rather general but has not yet been applied to a plasma system.

The stochastic theory of test-particle *transport* in perturbed magnetic flux structures using the A (accelerated)—Langevin formalism was studied by M. Neuer (University of Duesseldorf). The method is very powerful and many limiting cases discussed earlier in the literature are reproduced such as the Kadomtsev and Pogutse approximation, the Rechester–Rosenbluth regime, or the Corrsin approximation at high Kubo-numbers. H. de Blank *et al* (FOM) treated the temperature gradient effects on magnetic stochastization. It was shown that reconnection in collisionless plasmas can accelerate in the nonlinear phase. It was found numerically that this fluid model of reconnection has singularities; a kinetic description of electrons resolves the singularities (thermal broadening). In the kinetic model, nonlinear processes remain tractable and exact nonlinear reconnection solutions are obtained. A current layer equilibrium is constructed the instabilities for which (tearing modes) are found in exact form. D. Reiser *et al* (TEXTOR) discussed the effect of static stochastization fields on electromagnetic fluid drift turbulence in the TEXTOR-DED. He uses a model for electromagnetic turbulence which includes the various electrostatic and electromagnetic modes. Of particular interest are the energy flow paths in turbulence for the different modes.

In contrast to the previous more general section on transport, *numerical modelling* is very specifically related to

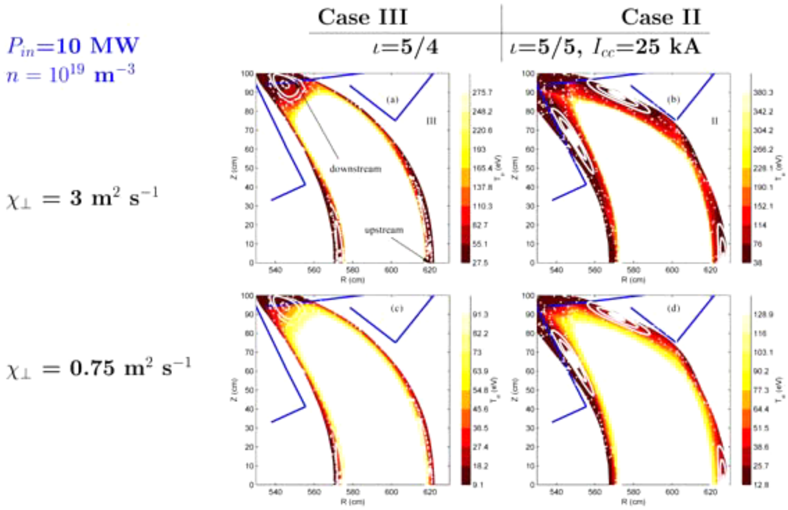

Figure 7. 3D modelling of the W7-X island divertor (D. Shama). The axes are the major radius R and the vertical coordinate z.

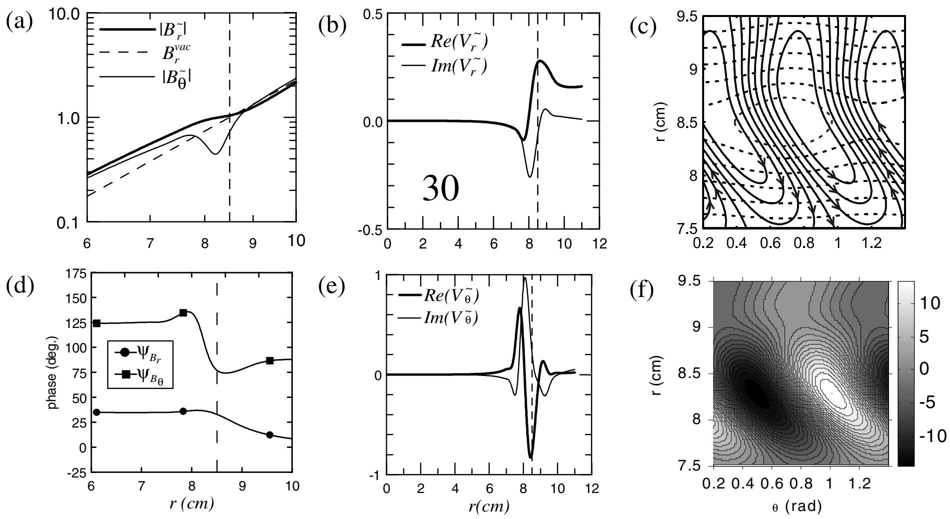

Figure 8. Structure of the magnetic field, flow velocity and flow pattern near (vortex structure) the resonance generated by a rotating perturbation pattern similar to that of the DED (I.M. Pankratov).

experiments. Besides the already mentioned TEXTOR DED related modellings, two further contributions were presented in the workshop both of which stem from Stellarator groups.

D. Sharma *et al* (W7-X) discussed the W7-X island divertor transport for different magnetic configurations by means of the EMC3-EIRENE code and A. Runov (MPI-Greifswald) presented the transport modelling with E3D. Both codes are very powerful Monte Carlo-based fluid codes and are designed for 3D modelling. The W7-X part continues work of the island divertor of the previous Wendelstein-AS and transfers the knowledge to the modelling of the new W7-X island divertor as shown as an example in figure 7. A. Runov applies his code to the divertor plasma of DIII-D which is perturbed by the I- and C-coil currents. The imposed ergodization leads to a splitting of the heat deposition pattern on the divertor target plates in good agreement with the observations.

A specific aspect of theoretical consideration stems from the dynamic action of the DED. The relative rotation between plasma and the external perturbation field imposes questions on the mechanism of the *perturbation field penetration* into the plasma; since the problem is linked with induced shielding currents flowing at the resonance layers, the *force transfer* due to $j \times B$ forces is immediately linked with the penetration problem. E.R. Rondan *et al* (University of San Paulo, Brazil) discussed plasma rotation by the interaction of low frequency fields with plasmas at the rational surfaces in tokamaks and applied their calculations to the presently operational tokamaks with dynamic options TCABR (Brasil), TEXTOR and HYBTOK. M.F. Heyn *et al* (University of Graz) studied pressure gradient effects on the interaction of a rotating magnetic field with the plasma in the kinetic approximation. The separation of the work of the electric field on the plasma currents allows three relatively independent methods to calculate the absorbed (generated) power: as a total power flux (Poynting plus material flux) towards the antenna, as an integral of the absorbed power density over the plasma volume and as the work of the antenna currents on the wave electric field. Two contributions are presented by I.M. Pankratov *et al* (Kharkov): one on toroidal considerations of the plasma response to penetration of an external low frequency helical magnetic perturbation into a tokamak edge plasma and a second one on plasma vortexes induced by an external rotating helical magnetic perturbation as illustrated in figure 8. The toroidicity effects lead to the generation and coupling of poloidal modes with different *m* numbers in the plasma. Plasma vortexes are predicted near the resonant layer and are driven by the shielding current.

Finally A. Nicolai *et al* (TEXTOR) modelled the plasma rotation induced by error fields. In particular they calculated the braking forces of the error fields and applied their theory to the TEXTOR DED and ALCATOR C Mod.

It is planned to continue the workshop series 'Workshop on Stochasticity in Fusion Plasmas (SFP)' in February/March 2007 in Juelich. As important information on the community it has been proposed to encourage presentations on the following topics which have not been treated so far:

- self-consistent reconstruction of the 3D equilibrium. By methods presently available (e.g. VMEC-code) the equilibrium would be described by a set of 3D flux functions; the method would probably strengthen the role of the near field; however, the Ergodic aspect (Poincaré plot technique) would be reduced;
- the role of the electric field, radial currents in the ergodic layer and shielding currents on the induced plasma rotation should be clarified and be compared with the experimental data;
- the effect of plasma transport in the ergodic and laminar zones should be more elucidated by modelling and experiments.