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Active in-vessel coils and a conducting wall for MHD control in ASDEX Upgrade

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Introduction

Control of MHD instabilities will likely be a requirement for ITER and a fusion reactor to achieve high beta and benign wall erosion and co-deposition of tritium. The energy loss associated with Edge Localised Modes (ELMs) in ITER might exceed the tolerable limit of $\Delta W_{ELM} \approx 10$ MJ to avoid evaporation of C or W wall [1]. The extrapolation of ELM loss energy is not well understood, but present data suggests an unfavourable scaling with pedestal collisionality ν^* [2]. Techniques to avoid large ELMs are therefore being investigated, for example ELM loss reduction by injection of cryogenic pellets [3], small ELM regimes [4] and stationary ELM-free regimes [5]. It has early been observed in COMPASS-D that non-axisymmetric error fields can reduce the size of ELMs [6]. Recently, ELM mitigation is studied in DIII-D with more edge-localised $n = 3$ magnetic perturbations produced by a set of 2×6 in-vessel saddle coils [7]. Complete ELM suppression is obtained at low ν^* if a helical perturbation field of sufficient strength is applied which matches the plasma safety factor q ("resonant magnetic perturbation"). In a first interpretation [8], ELM suppression is attributed to ergodisation of the magnetic field in the pedestal region, causing additional radial heat transport and, for fixed heat source, a reduction of the pressure gradient to values below the MHD stability limit encountered at the ELM onset. Many open questions remain. In several experiments, application of a non-axisymmetric perturbation field is accompanied with a reduction of plasma density while the temperature is unchanged or even increases (e.g. [8]). The role of the resonance for complete ELM suppression is not clear. Because of the additional loss channel due to parallel transport one would expect that for sub-threshold error fields the ELM frequency is reduced, which is not observed. It is hence warranted to study the physics of ELM suppression with large configuration flexibility in detail in existing tokamaks. Here we present an overview of a system for MHD control with active saddle coils in ASDEX Upgrade. These coils offer large configuration flexibility for ELM suppression experiments and AC capability for feedback-suppression of resistive wall modes (RWM) and rotation control of neoclassical tearing modes (NTM, not discussed here).

Design of active coils and conducting wall

It is proposed to extend ASDEX Upgrade with a set of 24 (3×8) saddle coils (Fig. 1). The coils are mounted inside the vacuum vessel at the low field side and close to the plasma for fast response and flexible field structure. The enhancement will be carried out in several stages. First, 16 internal coils (2×8, dubbed `Bu` and `Bl` coils) will be installed which allow for DC and AC operation up to a frequency of $f_{\max} \approx 400$ Hz. The coils can be operated in series

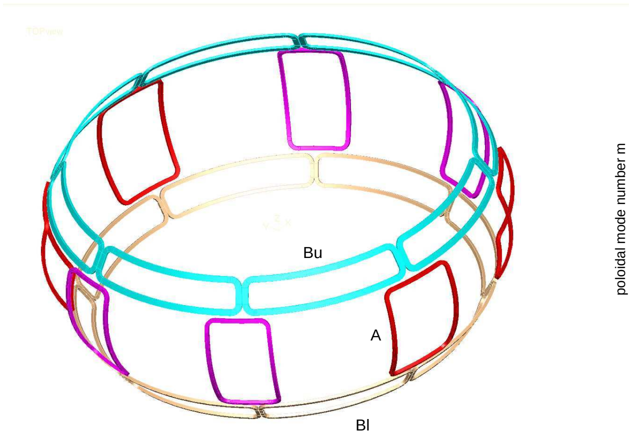

Figure 1: 3D view of active in-vessel coils

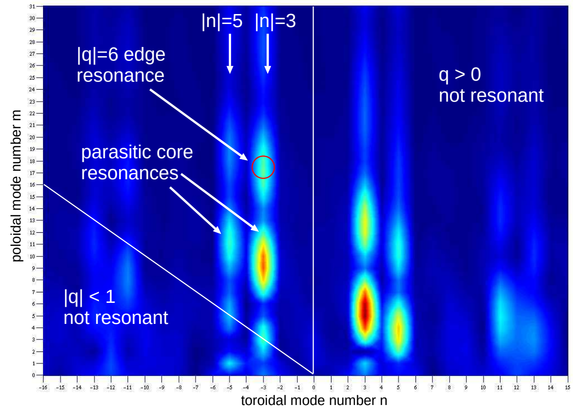

Figure 2: Mode number m, n spectrum perturbation (best fit to $n = -3$ at the $q = -6$ surface)

with an existing single power supply for ELM control experiments with toroidal mode number $n = 4$.

As a second stage, it is planned to complement this set with eight additional coils around midplane ports (A coils). These coils are more distant from passive conductors and are designed for $f_{\max} = 3$ kHz. For $n = 4$, toroidally neighbouring coils carry currents of opposite polarity. The upper and lower toroidal rings can have a 90^0 phase shift in clock-wise or anti-clock wise direction, leading to four different field configurations.

In a third step, 12 independent AC power supplies are installed, each of which is connected to two toroidally opposite coils in series. This allows for superposition of various modes, however, restricted to either all odd or all even n. In analogy to three phase current, $n = 3$ perturbations can be made which can be toroidally rotated. The phase between Bu and A coils, and between Bl and A coils can be varied independently. This allows to produce a resonance for any given plasma safety factor. Fig. 2 shows the m, n mode spectrum for a best fit to a $n = -3$ perturbation at the $q = -6$ surface in a typical ASDEX Upgrade H-mode plasma with monotonous q profile, in this case with $q_0 \approx 1.0$ and $q_{95} = 5$. Only the $m > 0$ half plane is shown. Modes with $n < 0$ and $|q| > 1$ are resonant in the plasma, $n > 0$ corresponds to opposite helical orientation of plasma field and perturbation. The spectrum is asymmetric in n because the best fitting field has neither odd nor even toroidal parity. In addition to the desired $n = 3$ mode, the finite number of toroidally distributed saddle coils leads to spatial aliasing, thus producing an $n = 5$ sideband. The finite toroidal extent of each coil causes deviations from a sinusoidal field variation, thereby creating higher n harmonics. The poloidal spectrum (m) is affected by the concentration of the coils at the low field side. Apart from the desired resonance at $m = 18$, there is a stronger, parasitic, resonance at $m = 9$ ($q = 3$). It should be stressed that spectral imperfections like those described above are unavoidable with this type of saddle coils. For an elongated and diverted tokamak plasma a full poloidal coverage (for a clean m spectrum) is unpractical because of the extremely high multipole moments required near the top and bottom of the plasma.

In a fourth stage, a conducting shell is added on the low field side, in between the existing upper and lower passive stabilising loops (PSL). While the PSL alone allows for induced currents that produce a radial field to reduce the vertical growth rate, the PSL branches and the new shell connected together allow helical currents. A feedback system consisting of

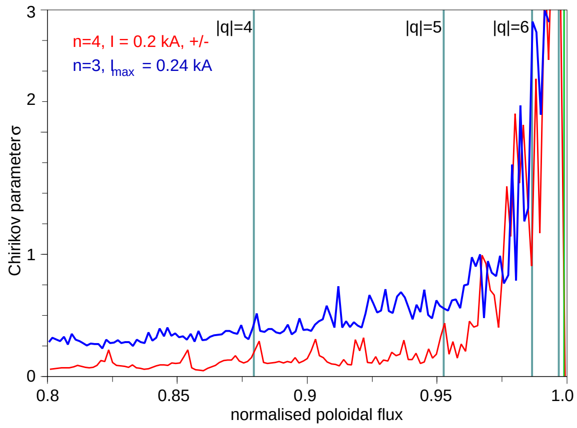

Figure 3: Chirikov parameter σ for $n = 3$ and $n = 4$ perturbations. The coil current is adjusted for slight ergodisation ($\sigma = 1 \ldots 3$) in the edge barrier region $\rho > 0.95$

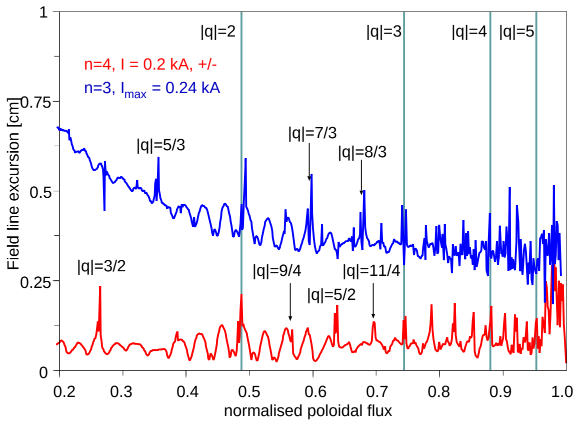

Figure 4: Field line excursion for the cases of Fig. 3 showing that for $n = 4$ the parasitic core island width is smaller than for $n = 3$.

distributed poloidal field sensors and a digital controller for $n = 1$ RWM control are envisaged at this stage.

Finally, with 24 independent AC power supplies, odd and even n perturbations can be made simultaneously, and the full voltage swing (maximum frequency) is available for each coil. This allows for multi-mode RWM control ($n = 1, 2, \ldots$) and, simultaneously, high n DC components for ELM suppression in a combined high performance plasma scenario.

Resonant Magnetic Perturbation for ELM suppression

The objectives of investigating the effect of error fields on ELMs in ASDEX Upgrade are to test the role of a resonance between external field and q profile, study edge transport and stability for varying degrees of edge ergodisation (which implies diagnosis of the H-mode edge pedestal and ELM behaviour) and investigate different perturbation field configurations that may be useful in ITER.

The degree of ergodisation is described by the “Chirikov parameter” [9], $\sigma = (\psi_{\max} - \psi_{\min})/(\psi_{q_{\rm in}} - \psi_{q_{\rm out}})$, which is defined here as the radial field line excursion in terms of the minimum and maximum unperturbed poloidal flux, normalised by the flux difference between nearest neighbor rational surfaces $q_{\rm in}, q_{\rm out}$, where $m = q/n$ and n is the fundamental of the harmonic. From inspection of Poincaré plots and the Lyapunov exponent we find as a practical threshold for edge ergodisation, $\sigma_{crit} = 1$, which corresponds to the picture of onset of radial “overlap” of magnetic island chains created by the perturbation. With increasing perturbation field, ergodisation sets on always at edge, in the strong magnetic shear region.

Fig. 3 shows σ as a function of normalised flux for an $n = 3$ and an $n = 4$ external field. The coil current (maximum current for $n = 3$) is chosen to obtain $\sigma \approx 3$ and turns out to be similar in both cases ($I_{\rm coil} = 0.24$kA$\times$turns (kAt) max. for $n = 3$, and 0.2 kAt for $n = 4$). The field line excursion in cm (outboard midplane) is shown in Fig. 4. For same pedestal σ, the core excursions are much smaller for $n = 4$ than for $n = 3$. The island width ($2\times$ max. excursion) is to be compared with a typical NTM seed island width of 1 cm. Rotational shielding will reduce the perturbation field in the plasma core, but will not much affect the ergodisation in the edge pedestal region. The present saddle coil design allows up to $I_{\rm coil} = 5$ kAt, providing headroom to compensate for shielding of the perturbation field.

RWM control

The active coils, in combination with the conducting wall and a feedback system, can be used to stabilise resistive wall modes. The effectiveness of the non-axisymmetric shell to reduce the RWM growth rate is studied with the 3D stability code CAS3D [10]. The current distribution in the shell is modeled using finite elements. A hypothetical H-mode equilibrium with steep edge pressure gradient, q_0 just above 2 and $q_{95} = 3.8$ is used. This case has a no-wall beta limit of $\beta_{N,nowall} = 1.9$. The ideal wall (realistic geometry) is stabilising at $\beta_N = 2.7$. Stability calculations with a resistive wall (same 3D wall model) are performed with the STARWALL [11] code. Without feedback, two non-degenerate eigenmodes are unstable, with $\lambda_1 = 2.07$ m^{-1} and $\lambda_2 = 1.97$ m^{-1} ($\lambda = \gamma\mu_0\sigma d$), corresponding to growth rates of $\gamma_1 = 5.55$ s^{-1} and $\gamma_2 = 5.29$ s^{-1} with a 5 mm copper layer on the shell. With feedback-controlled coil voltages, and optimised proportional gain, all roots are stable. Further work is devoted to include a more detailed model (transfer function) of the sensors, the controller, power supplies, cables and active coils circuitry in the stability assessment.

Summary and Discussion

The proposed set of 3×8 in-vessel saddle coils allows flexible perturbation field configurations. For ELM control experiments, $n = 4$ resonant magnetic perturbations can be produced (and compared to lower n perturbations) that can show the advantages of high n for core mode avoidance. Three poloidally distributed toroidal sets of coils can produce four different phasings for $n = 4$, resonant at different q, which allows to test the importance of a resonance for complete ELM suppression. For $n = 3$, the spatial phase can be varied quasi-continuously. This can be used to rotate toroidally the perturbation field with respect to the sightlines of the edge diagnostics, and hence achieve quasi 2D resolution of the existing measurements similar to measurements obtained with the TEXTOR Dynamic Ergodic Divertor [12]. In addition, the toroidal phase can be "detuned" from a resonance, which radially shifts and/or broadens the ergodised layers. These studies will allow to prepare operation of similar coils (internal or external) or ferritic inserts for ELM suppression in ITER. Together with a conducting shell and suitable feedback system, the proposed active coils can stabilise the RWM well above the no-wall limit, a further step in preparation of advanced scenarios towards steady-state operation.

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