Access conditions for ELM mitigation with non-axisymmetric magnetic perturbations in ASDEX Upgrade

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Introduction

In 2010, the ASDEX Upgrade tokamak has been extended with a set of in-vessel saddle coils that are capable of producing non-axisymmetric magnetic perturbations (MP) for a variety of physics applications [1]. These coils are mounted close to the plasma, at the magnetic low field side above and below the mid-plane. Initial experiments with 2×4 coils have shown that with MP of toroidal $n = 2$ symmetry type-I Edge Localised Modes (ELMs) can be replaced by a benign form of ELMs with much reduced energy loss per ELM from the plasma [2]. A main access requirement appears to be that the plasma edge density exceeds a minimum value which can be expressed as a constant fraction of the empirical Greenwald density limit, $n/n_{\mathrm{GW}} = 0.65$ [3]. Recently, the coil set has been extended to $2 \times 8 = 16$ coils. The additional coils fill the toroidal gaps in between the previously installed coils. For the first time, $n = 0$ and $n = 4$ perturbation fields can be made, while $n = 1$ and $n = 2$ configurations benefit from the additional coils in terms of reduced spectral sidebands. We report here ELM mitigation results of a perturbation field configuration scan in otherwise similar plasmas.

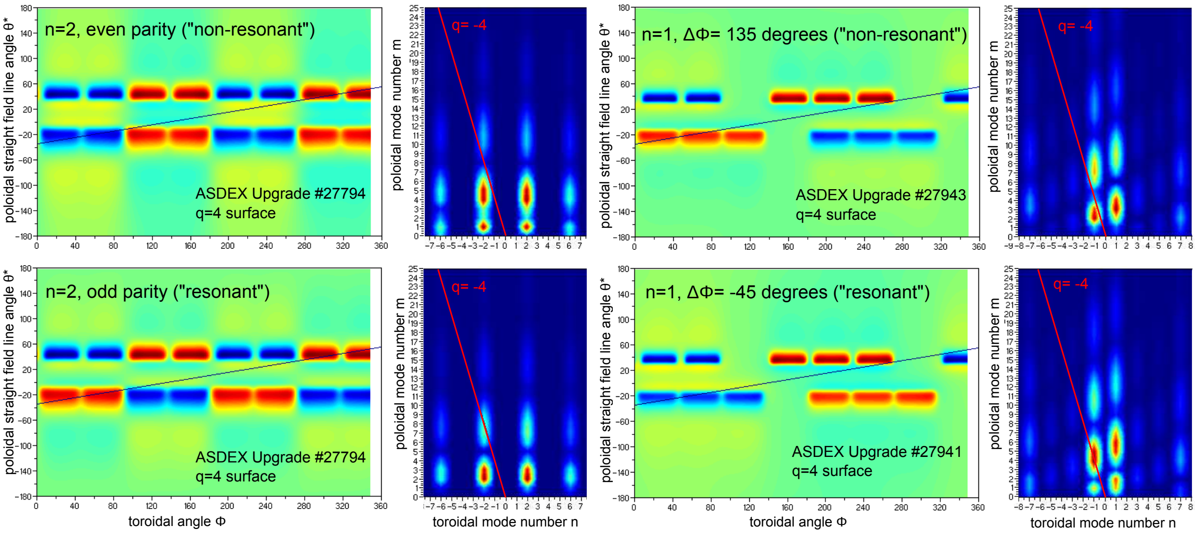

Figure 1: Structure of $n = 2$ (left) and $n = 1$ (right) magnetic perturbations (Biot-Savart vacuum field calculation). Green background: Normal field on the $q = -4$ surface in straight field line coordinates; Blue background: Poloidal and toroidal mode number spectra. The field line inclination and resonant spectral components are indicated by straight lines.

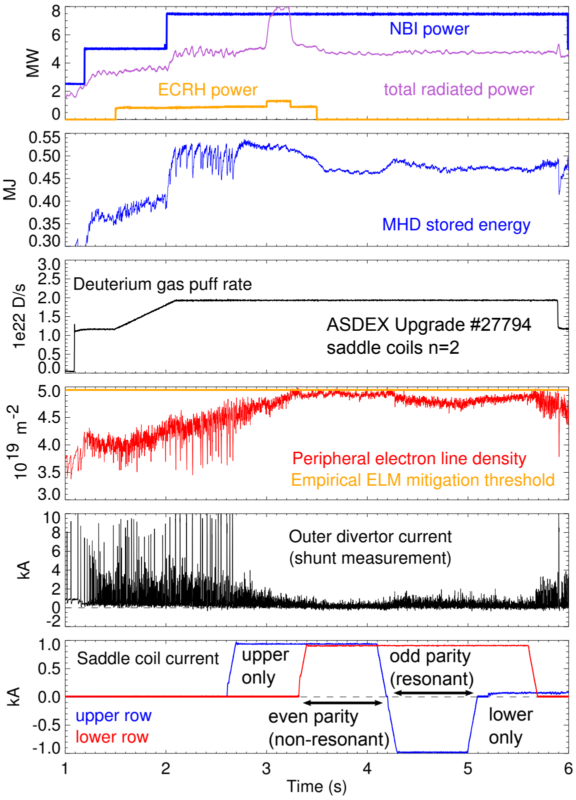

Figure 2: ELM mitigation with $n = 2$ MP comparing even (non-resonant) and odd (resonant) coil parity with single (upper and lower) row operation.

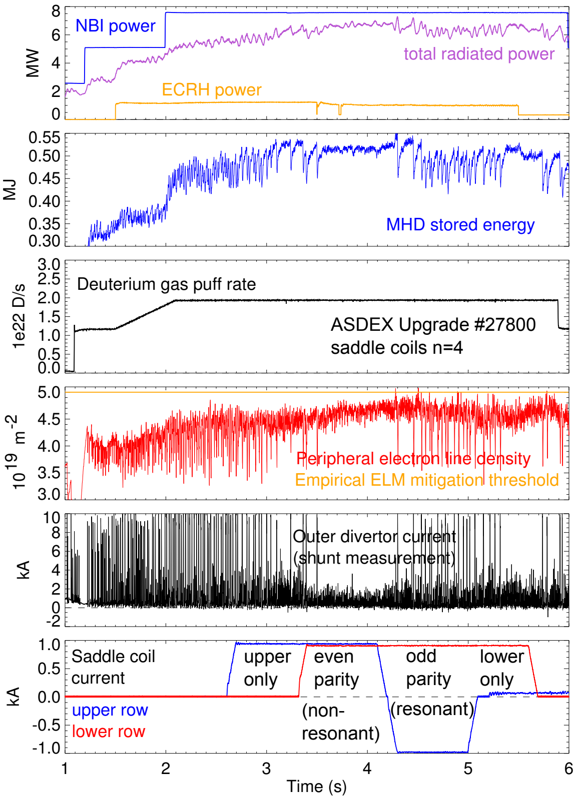

Figure 3: ELM mitigation with $n = 4$ MP and similar parity permutations as in Fig. 2.

Perturbation field configuration and experimental setup

The existence of two poloidally separated rows allows us to select their phase to maximise or suppress perturbation field components that are aligned (“resonant”) with the magnetic field of the plasma for certain values of the plasma safety factor q. With eight toroidally spaced coils, there are two possible phasings for $n = 4$ (“odd” or “even” parity), four phasings for $n = 2$ and eight for $n = 1$. It should be noted that due to the low magnetic shear around the outboard midplane (between the coil positions) the resonance condition is met or not met simultaneously for a number of rational surfaces in a large radial range. Hence, the choice of resonant or non-resonant field is global. We select a plasma configuration with $I_p = 0.8$ MA, $B_t = -2.5$ T and low triangularity, resulting in an edge safety factor $q_{95} = -5.5$. In this configuration there is, for all $n > 0$, one accessible phasing that minimises the resonant components. Flipping the sign of the coil current in one row then produces the maximum resonant field. Axi-symmetric perturbations ($n = 0$) are entirely non-resonant.

Figure 1 shows the $n = 2$ and $n = 1$ configurations used in this study (normal field on $q = -4$ surface and mode number spectra). In contrast to the $n = 2$ fields, the $n = 1$ configurations lack odd and even up/down symmetry and hence the spectra are not mirror-symmetric in n. Due to the geometrical constraints on the saddle coils, their field is in poor alignment with the plasma field structure and hence the spectrum is heavily polluted with toroidal and poloidal sidebands (harmonics and aliasing).

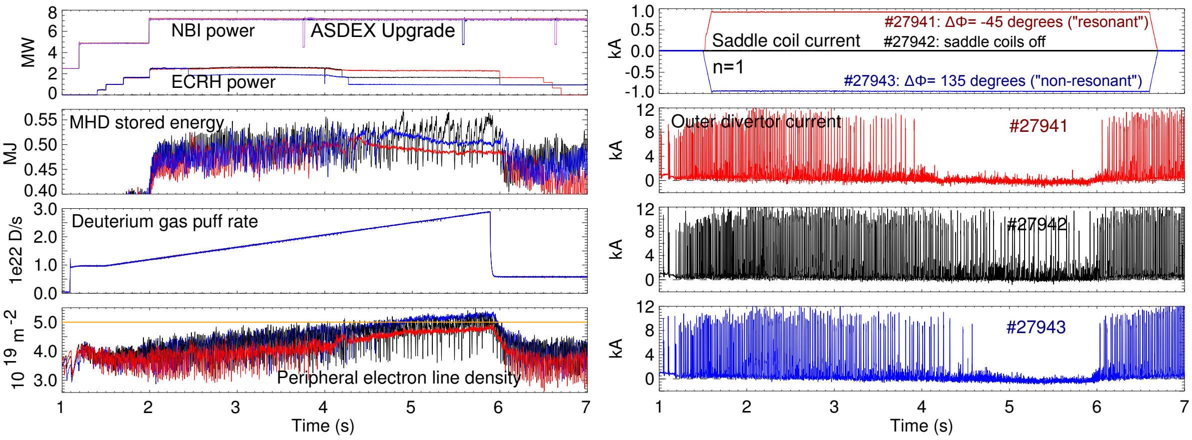

Figure 4: ELM mitigation with $n = 1$ MPs comparing resonant (#27941, red) non-resonant (#27943, blue) coil configurations and saddle coils switched off (#27942, black).

Perturbation field configuration scan

A side-by-side comparison of different $n = 2$ configurations is made in a single discharge (#27794) shown in Fig. 2. This plasma (as all others discussed here) is predominantly heated by neutral beam injection (NBI), with sufficient power to maintain type-I ELMy H-mode. Additional central electron cyclotron resonance heating (ECRH) can be used to avoid density peaking and impurity accumulation in view of the fully tungsten-cladded first wall, but is not essential in these plasma because of a significant gas puff rate of 2×10^{22} D/s. Unmitigated type-I ELMs show about $\Delta W_{ELM} = 50$ kJ energy loss. In this example, odd and even parity configurations as well as single rows of upper or lower coils succeed in mitigating ELMs. The edge density (in Fig. 2 the peripheral line density measured by the DCN interferometer is shown) remains slightly below the empirical threshold found with eight saddle coils [2], and decreases as the resonant component is maximised (odd parity).

A direct comparison can be made to $n = 4$ perturbation field (Fig. 3), using the same plasma parameters. In this case, ELM mitigation is obtained only during shorter time intervals, and not for the entire duration of the applied error field. Also, the effect of the MP on the edge density is weaker than for $n = 2$. Attempts to raise the edge density by higher gas puff rate (3×10^{22} D/s) resulted in a spontaneous (i.e. not MP-induced) transition to small ELMs.

For the first time, ELM mitigation with $n = 1$ MP has been attempted in ASDEX Upgrade. Fig. 4 shows time traces of three discharges with the same NBI heating power and identical gas puff ramp that were performed to detect the ELM mitigation edge density windows with resonant (#27941) and non-resonant (#27943) MP, and a control experiment without saddle coil current (#27942). With saddle coils on (resonant or non-resonant) there is a window during which type-I ELMs are completely suppressed while with saddle coils off type-I ELMs occur throughout. However, at gas rates $> 2.5 \times 10^{22}$ D/s the type I ELM frequency is reduced and small ELMs occur in between large ELMs. Similar to the $n = 2$ case, the plasma edge density for identical fueling is lower with resonant field than with non-resonant field. Also, the edge density at the onset of type-I ELM suppression is lower with resonant than with non-resonant MP.

Finally, $n = 0$ MP have been tested in plasmas conducted similarly to those shown in Fig. 2, 3 (constant gas puff, coil current in only upper and lower row of coils, and same and opposite coil current in both rows) and Fig. 4 (gas ramp with constant opposite currents in upper and lower rows). No ELM mitigation effect of the applied MP was found in comparison

	Shot	Configuration	B_{res} (μT)	
$n = 1$	27941	$\Delta\Phi = -45°$	264	“resonant”
	27943	$\Delta\Phi = 135°$	89	“non-resonant”
$n = 2$	27794	$\Delta\Phi = 0°$	22	“non-resonant”
		$\Delta\Phi = 180°$	154	“resonant”
		upper coils only	88	
		lower coils only	66	
$n = 4$	27800	$\Delta\Phi = 0°$	21	“non-resonant”
		$\Delta\Phi = 180°$	47	“resonant”
		upper coils only	34	
		lower coils only	13	

Table 1: Amplitude B_{res} of fundamental resonant normal field component ($m = q/n$) on the $q = -4$ surface. The perturbation field is calculated for a vacuum; the fundamental toroidal mode number n is given in the first column.

to the control experiments without saddle coil currents.

Conclusions and Discussion

ELM mitigation at high plasma density is observed with $n = 1$, $n = 2$ and $n = 4$ magnetic perturbations in ASDEX Upgrade. For $n = 1$ and $n = 2$ there is a window in edge density or gas puff rate in which both resonant and non-resonant MP lead to complete suppression of type I ELMs in favour of benign small ELMs with negligible power loss and power load onto the divertor. The effect of MP is marginal with $n = 4$ perturbations and limited to high gas puff close to the “spontaneous” transition to small ELMs, presumably of type III. The nature of the MP-induced mitigated ELMs and their relationship to high-density type-III ELMs is unclear at present and will be investigated further. The lack of ELM mitigation at $n = 0$ indicates that a helical perturbation is required, however, there is no apparent correlation with the amplitude of the resonant field component (see table 1). However, the effect of MP on the plasma density seems to depend on field structure in that with resonant MP the edge density tends to drop and with non-resonant MP it tends to increase. This effect is reminiscent of the “density pump-out” observed in JET [4], DIII-D [5] and MAST [6]. Further experimentation in ASDEX Upgrade aims to map out the parameter range of ELM mitigation, in particular at higher I_p and lower density, and document the MHD and edge pedestal behaviour for the newly accessible MP configurations.

References

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