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1. INTRODUCTION

The application of resonant magnetic perturbation fields is a promising technique to control transient heat loads due to large type-I Edge Localised Modes (ELM) in tokamaks. Previous experiments have shown that $n > 4$ (n is the toroidal mode number) magnetic field perturbation were able to trigger small ELMs during otherwise ELM-free H-mode phases on JFT-2M [1]. Magnetic perturbations with $n = 1$ and $m = 4$–5 were able to increase the repetition frequency of type-III ELMs in COMPASS-D [2]. Recent results from DIII-D using $n = 3$ magnetic perturbation fields have shown that type-I ELMs can be completely suppressed in collisional and collisionless plasmas [3]. All of these experiments have in common that the applied coil systems were built into the vacuum vessel and had only a small separation to the plasma. For next-step fusion devices, such as ITER, it may not be feasible to use internal coils due to technical constraints. ELM mitigation using magnetic perturbation fields generated with external coil systems (which are further away from the plasma than coils build into the vessel) and having low toroidal mode numbers (which have less radial decay of field strength than higher n modes) needs to be explored for ITER-relevant plasma conditions with high triangularity and high beta.

This paper summarizes recent experiments on the JET tokamak where it has been shown that type-I edge localised modes can be controlled by an externally generated perturbation field using a set of four Error Field Correction Coils (EFCC) [4] which allows one to apply perturbation fields with toroidal mode numbers $n = 1$ or $n = 2$.

2. GENERAL OBSERVATIONS WHEN ELM MITIGATION WITH EXTERNAL $N = 1$ FIELDS IS APPLIED

The first experiments applying the EFCCs with $n=1$ for ELM mitigation on JET were carried out in a low triangularity configuration [5]. It was found that the ELM frequency could be increased by a factor of 4, accompanied by a strong reduction in D_α intensity. The energy loss per ELM $\Delta W/W$ (where W is the total stored energy in the plasma) decreased from about 7% (which would cause too strong erosion of ITER plasma facing components) to values below 2%. This value is less than an estimated upper limit for ELM energy losses in ITER which is compatible with the envisaged tungsten divertor plates [6]. The application of the perturbation fields caused a reduction of the edge and core density, the so-called pump-out effect, which is an indication of increased transport due to edge ergodisation. An increase in the edge and core electron and ion temperatures partly compensated the reduction in stored energy, which was between 0 and 20%, depending on the discharge parameters.

In a recent series of experiments using the $n = 1$ configuration, ELM control was achieved in ITER-like high triangularity ELMy H-modes. Again, like in the low triangularity case, it was found that the mitigation worked in a wide range of edge safety factor q_{95}. Stationary ELM mitigation was achieved for times up to 3 s ($> 10\tau_E$), limited only by the power supply for the EFCCs [7].

3. ADDITIONAL FEATURES OF EDGE ERGODISATION

By chance the perturbation field was applied to a discharge which had a very low ELM frequency (few Hz) and showed clear signs of density peaking between ELMs. The application of the perturbation field during an ELM-free H-mode phase triggered small ELMs and increased particle transport prevented the density peaking.

Another important feature observed when ELMs were mitigated by the EFCCs is the improved coupling of the ICRH. The perturbations of the edge plasma from large ELMs deteriorate the coupling between the antenna and the plasma and lead to strong modulations of the ICR heating power. In phases with mitigated ELMs the coupled ICRH power was almost constant and no drop-outs were observed.

4. APPLICATION OF *N* = 1 FIELDS FOR ELM MITIGATION AT HIGH BETA

Advanced tokamak steady state scenarios operate at a normalised beta close to or above the no-wall beta limit. In this scenario ELM mitigation is needed to keep ELM amplitudes small which otherwise may erode the internal transport barrier and reduce the confinement [8].

Figure 1 shows an example where the EFCCs have been applied for ELM mitigation in a high beta discharge. The time traces from top to bottom are: NBI heating power (real-time controlled to achieve constant beta); the current in the error field correction coils; D_α signals from outer and inner divertor; line-integrated electron densities in the core (blue) and at the edge (red); ion temperature in the plasma core (blue) and at the pedestal top (red); angular frequency of toroidal plasma rotation in the core; stored plasma energy; normalised beta (blue) and approximate no-wall beta limit $4\times li$ (red); thermal energy confinement time (from TRANSP).

When the current in the EFCCs is ramped up the D_α spikes show a strong decrease and the ELM frequency increases. Although the density drops due to the pump-out effect caused by the edge ergodisation, the thermal energy stays almost constant. This is due to the fact that the temperature increases, as has been observed in the standard ELMy H-modes. Another indication for the constant energy content is given by the unchanged heating power request from the real-time beta control.

It is important to note that no locked modes were seeded by the perturbation field, in some contrast to an earlier report from DIII-D where error field mode thresholds were significantly reduced at high beta [9]. It is quite likely that the strong beam heating keeps the toroidal plasma rotation high enough to prevent the field from penetration.

5. ELM control with $n = 2$ fields

The results with $n = 1$ fields from JET have shown that an operational window for ELM mitigation exists below the error field mode threshold for type-I ELMy H-modes and high beta steady-state discharges, i.e. the EFCC current required for ELM mitigation is less than the current which would seed a locked mode. The $n = 1$ field penetrates deeply into the plasma and in all discharges a quite substantial braking of the core rotation has been observed. Using higher toroidal mode numbers would be an advantage, because (i) they will most likely cause less core rotation braking, thus preventing the field to penetrate and excite a locked mode, and (ii) result in an even better ergodisation of the edge due to the higher density of resonant magnetic surfaces.

The EFCCs allow to be configured in $n = 2$ configuration. Figure 2 shows a discharge where the $n = 2$ configuration has been applied to mitigate ELMs. Due to limitations of the power supplies the maximum coil current was limited to lower values as compared in the $n = 1$ configuration, therefore yielding less perturbation field at the plasma edge. Nevertheless, similar to the results in $n = 1$ configuration a quite strong reduction in electron density due to the pump-out effect, which is a signature for ergodisation of the plasma edge, is observed. The ELM amplitudes become much smaller, and the ELM frequency rises from 12Hz to 28Hz. The electron temperature in the core increases. The observed braking of the plasma core rotation was about 40% and very similar to the braking observed with the $n = 1$ field.

SUMMARY AND CONCLUSION

JET results show that low n perturbation fields generated by an external coil system can be used to control frequency and energy loss of type-I ELMs. ELM mitigation using the EFCCs has been investigated in standard ELMy Hmodes at low and ITER-like triangularity and in a high beta steady-state scenario. With $n = 1$ fields the ELM frequency could be increased by a factor of 4 and the ELM energy loss became less than 2%, compatible with the upper limit of acceptable ELM losses for ITER. The application of $n = 2$ fields shows similar features, although the maximum perturbation field strength was limited. An operational window for ELM mitigation was always found below the threshold for locked modes excited by the $n = 1$ perturbation field. The small $n = 1$ component of the $n = 2$ field make it even more unlikely to seed a locked mode in the plasma and offers an additional advantage for low plasma rotation as anticipated in ITER. This offers an attractive solution for ITER where type-I ELM energy losses are predicted to be too large and control or mitigation of ELMs will be required.

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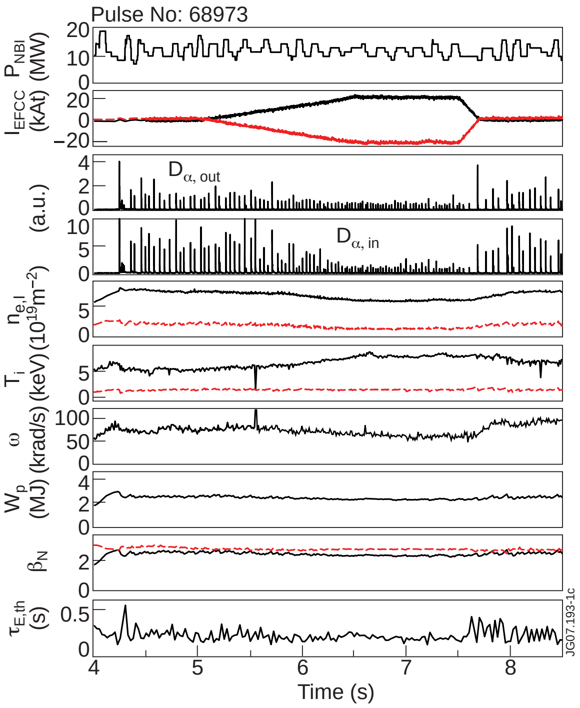

Figure 1: Overview of ELM control with n = 1 magnetic perturbation in a high beta discharge.

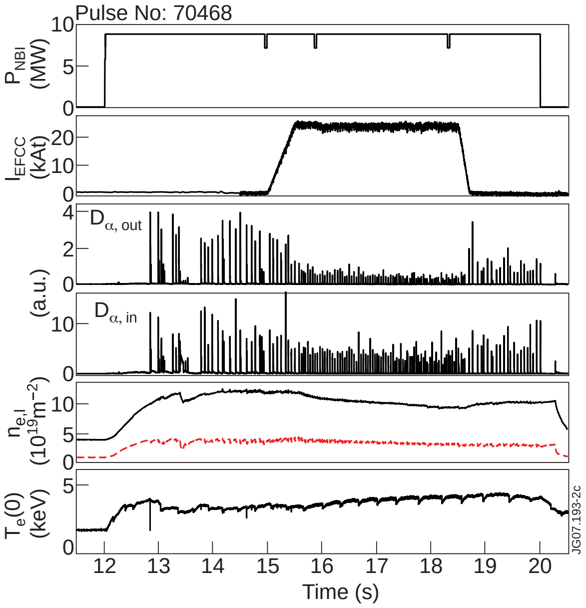

Figure 2: ELM mitigation with n = 2 field.