

## Suppression of large edge localized modes with a stochastic magnetic boundary in high confinement DIII-D plasmas

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### Introduction

Preventing the type I ELM heat pulses, in ITER Q~10 plasmas, from eroding the divertor target in a very short time will be a challenging, if not impossible task. This arises because high fusion power output requires a large plasma temperature near to the edge; around 4keV being a typical estimate. Thus, at density  $>10^{20}\text{m}^{-3}$ , as type I ELMs peel off the plasma edge they will take tens of megaJoules with them. In addition, present data indicates that the proportion of the plasma energy, lost with each ELM, increases as the collisionality decreases towards ITER values. Current estimates are that each ELM will eject as much as 40MJ towards the target plates, in a time of about one millisecond. Various operating regimes have been found in which type I ELMs are not present but these suffer from lack of scalability or do not overlap with the conditions of the standard ITER operating scenario.

This work started from the point of view that a robust way of actively suppressing type I ELMs is both mandatory and practical in ITER[1]. We report some considerable experimental success in exploring this proposition[2], using a magnetic perturbation generated by the I-coils in DIII-D. The hypothesis was tested that an external magnetic perturbation, whose toroidal and poloidal spectrum is in resonance with field lines at the edge, increases transport there, reduces the pressure gradient and, thereby, eliminates the drive for the mhd instabilities that cause ELMs. Holding the pressure gradient just below the threshold at which ELMs are triggered, should bring good fusion performance without the penalty of ELMs. JFT2-M [3] and Compass [4] had already made a start in this direction but neither obtained an unambiguous, robust suppression of type I ELMs.

### The Experimental Conditions

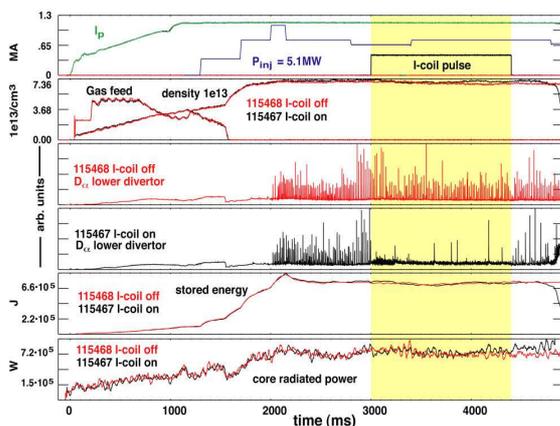
From the Tore-Supra Ergodic Divertor[5] experiments, it is known that good ergodisation and transport enhancement in the plasma edge is obtained with magnetic perturbations that have as high an n as possible, to limit core island formation, and have a broad poloidal spectrum, so that resonance with the field lines occurs with a range of magnetic surfaces.

The DIII-D I-coils are a set of rectangular coils, mounted inside the vacuum vessel in two toroidal strips, above and below the midplane. They were installed in order to perform stabilisation experiments on mhd instabilities; Resistive Wall Modes in particular. Since there are six coils in each strip, with alternating current sign, they have n=3 symmetry. Their

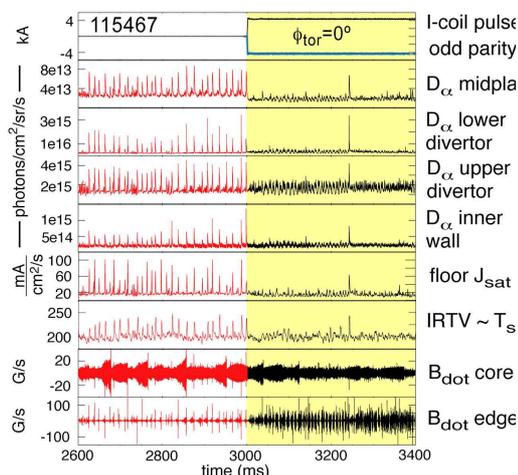
poloidal spacing is such that, when the strips above and below the midplane have opposite sign (“odd symmetry”), the maximum perturbing flux is obtained at  $q_{95} \sim 3.8$ .

At present, the I-coils have been commissioned to 4.4kAT, which produces a total perturbing radial field of the order of  $10^{-3}$ T at the plasma boundary. This is estimated to be enough to ergodise a few percent of the poloidal section, near to the separatrix, or, approximately, the whole of the pedestal gradient region. The components of the spectrum that resonate with  $q=1, 3/2$  and  $2$  are small and estimated island widths are calculated to be much less than their separation, so that core magnetic surfaces are still good.

The plasma chosen for the first experiment on ELM suppression using the I-coils was a 1.1MA/1.6T near double null plasma ( $\delta Z = -2$ cm), with good H-mode confinement and strong type I ELMs, with a frequency 70-75Hz. The neutral beam power was 5.1MW. The triangularity is relatively high ( $\delta_l = 0.73/\delta_u = 0.34$ ) for the configurational flexibility this allows in DIII-D. An experiment, using the I-coils for mhd control, with  $\delta_l = 0.38/\delta_u = 0.15$  has also demonstrated ELM suppression at half the density used in the first experiments. This data will not be described here but the observation encourages the belief that ELM suppression using magnetic perturbation can find application in a wide range of conditions.



**Figure 1:** Time traces for shots 115467/8. (1) plasma current, neutral beam power and I-coil current; (2) gas injection rate and plasma density; (3) divertor  $D_\alpha$  with I-coils off; (4) divertor  $D_\alpha$  with I-coils on; (5) plasma stored energy; and (6) the power radiated from the core plasma.

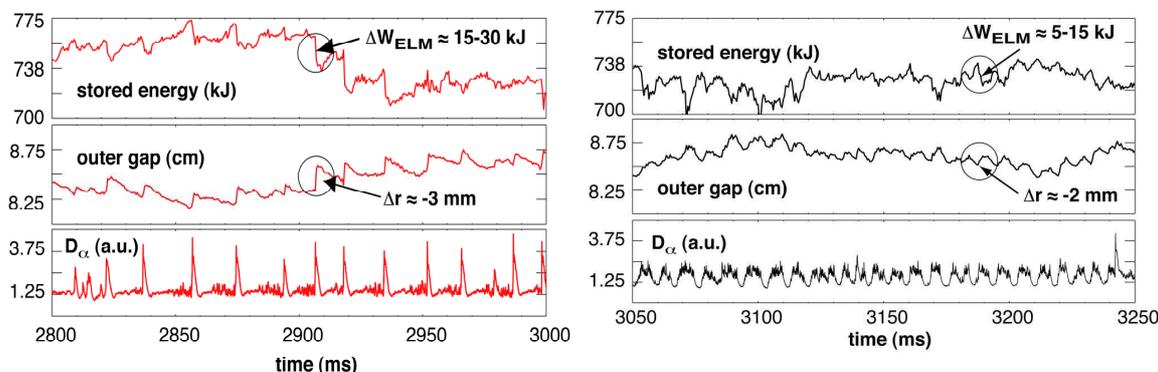


**Figure 2:** Close-up of 115467 (I-coils on). (1) I-coil current; (2-5)  $D_\alpha$  in various locations; (6) floor ion saturation current; (7) surface temperature; (8) low  $n$  pick-up coil signal; and (9) high- $n$  pick-up coil signal.

### The Experimental Results

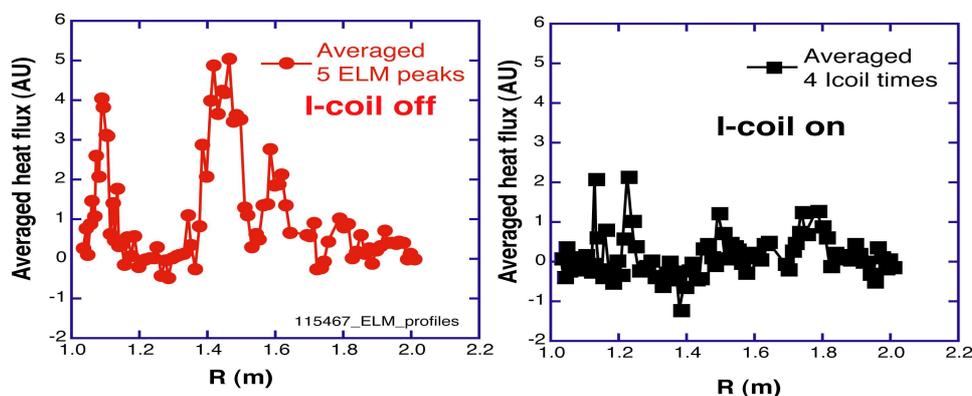
Figure 1 shows the principal time traces for the standard shot in the series, 115467, and its I-coils-off counterpart, 115468. The plasma current, neutral beam power, stored energy and radiated power traces are all overlaid for both pulses and show how little the energy confinement and power balance are affected by the application of the I-coil perturbation. In contrast, in the period, where 4.4kA is applied to the I-coils, the divertor  $D_\alpha$  emission is markedly different. The external perturbation eliminates the type I ELMs and replaces them with a 130Hz oscillation, which is just discernable in figure 1, and occasional ELM-like spikes. These latter have a different spatial structure to normal type I ELMs; in particular, they emanate from just inside the  $q=3$  surface. In figure 2, one sees a close-up of the transition from the ELMy to the non-ELMy phase of shot 115467. The  $D_\alpha$  traces show that

the ELMs nearly disappear everywhere, whilst the 130Hz oscillations are most apparent in the upper divertor. The low-n mhd is reduced, whilst the high-n activity, characteristic of edge mhd, shows a remarkable increase of an order of magnitude in power and a flattish spectrum out to 100kHz. As anticipated, scans of  $q_{95}$  showed that the effect is resonant, with a minimum in ELM amplitude around  $q_{95} = 3.6-4.0$ .



**Figures 3 and 4 :** (i) Plasma energy content; (ii) position of the outer surface; and (iii) the divertor  $D_\alpha$  light for ELMy periods(left) and periods with 130Hz oscillations(right).

The 130Hz oscillations have an interesting structure, as seen by comparing Figures 3 and 4. The ELMs that precede the application of the I-coils show, in  $D_\alpha$ , a sharp spike and a decay with a timescale of 1ms. The oscillations, on the other hand, show almost continuous, low-level spikes, on an elevated background, except for a marked minimum, with a duration of about 2ms. During ELMs, the density profile, measured with reflectometry, extends out 8cm from the separatrix to the wall, whilst during the oscillations there is a 1-2cm broadening. Similarly, as seen in figs. 3 and 4, the ELMs typically cause a loss in plasma energy content of 15-30kJ, whilst oscillations produce sporadic energy drops of 5-15kJ. The effect on the divertor target infra-red pictures is even more marked, as seen in Figure 5.

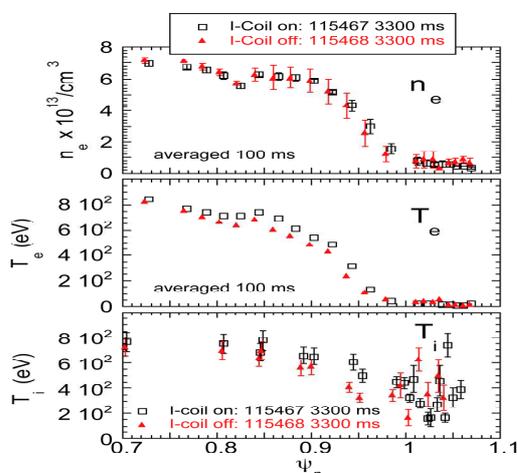


**Figure 5 :** Power heat-flux to the divertor target, deduced from IR images, for(left) average over ELM peaks and (right) during the 130Hz oscillations.

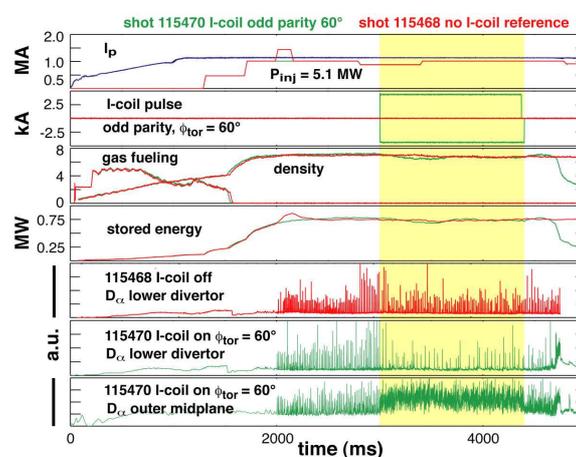
A startling result of these first experiments concerns the density and temperature profiles in the pedestal regions. Instead of showing the anticipated reduction of the edge pressure gradient, the electron density and temperature profiles move outwards slightly and the ion temperature profile by 2-3cm, as shown in figure 6. The movement of the ion temperature profile is entirely compensated by a drop, and even a slight reversal around the separatrix, of the toroidal rotation velocity, such that the radial electric field profile is unchanged.

Figure 7 shows some data from a shot in which the I-coil current was inverted, thus effecting a toroidal shift of  $60^\circ$ . Now the effect on the plasma is very much as originally expected,

with a reduction in the pressure gradient in the pedestal region, increased mid-plane transport, as evidenced by the bottom  $D_\alpha$  trace and an associated reduction in ELM frequency, expected with type I ELMs if the SOL power flow to the divertor is reduced.



**Figure 6 :** (i) Thomson scattering  $n_e$ ; (ii)  $T_e$ ; and (iii) the CERS  $T_i$  with I-coils on ( $\square$ ) and I-coils off ( $\blacktriangle$ ). Note  $\psi_n$  has an error of 2-3% (shift profiles to right).



**Figure 7:** Similar set of time traces to fig. 1, for #115470 with the perturbation toroidally shifted by  $60^\circ$ . Note ELMs in the next to last and increased background in last  $D_\alpha$  traces.

### Discussion:

Robust type I ELM suppression, except for a few infrequent ELM-like “events”, has been obtained using a magnetic perturbation from DIII-D’s I-coils, carrying 0.4% of the plasma current. With the standard  $0^\circ$  phasing, the ELMs nearly disappear and are replaced with complex 130Hz oscillations. However, none of the associated phenomenology seems consistent with the effects anticipated of edge ergodisation and the resulting increased edge transport. In contrast, shifting the phase of the perturbation by  $60^\circ$  produces a drop in ELM frequency, and increase in edge transport and an inward movement of pressure profiles, consistent with expectations.

These experiments were done with the compensating C-coils off. Thus there was an error field present, which is of the same order as the perturbation produced by the I-coils. Evidently, the different phasing of one relative to the other produces an entirely different total perturbation. Investigations are under way of the idea that this is due to the presence of an extra island chain in the  $0^\circ$  phasing that is not present in the  $60^\circ$  case. Experiments to be carried out during 2004 will investigate the physics behind the suppression and the potential for the method to be applied to ITER.

### Acknowledgments:

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