Implications of X-point lobe structures due to resonant magnetic perturbations on MAST

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The Edge-Localised Mode (ELM) is a repetitive instability associated with a steep pressure gradient, which can form at the edge of a tokamak plasma in high confinement regimes. ELMs are explosive events, which can eject large amounts of particles from the confined region. In order to avoid damage to in-vessel components in future devices, such as ITER, a mechanism to suppress ELMs or reduce their size is required. One such amelioration mechanism relies on perturbing the magnetic field in the edge pedestal, enhancing the transport of particles or energy and keeping the edge pressure gradient below the critical value that would trigger an ELM, while still maintaining an edge transport barrier. This technique of Resonant Magnetic Perturbations (RMPs) has been employed on DIII-D, where complete ELM suppression has been possible [1] and on JET [2], AUG [3] and MAST [4] where ELM mitigation (i.e. an increase in ELM frequency and decrease in ELM energy loss) has been obtained.

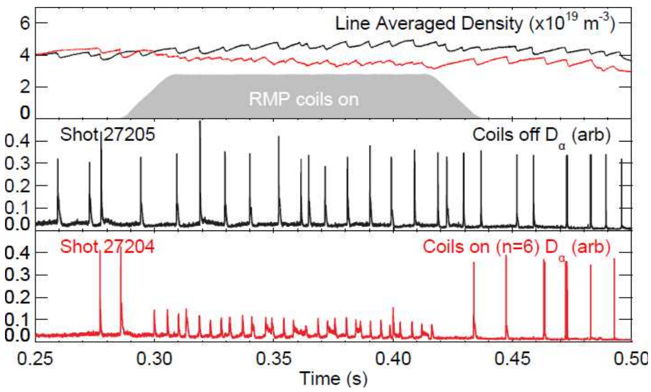

Figure 1: Time traces of a) the coil current (I_{ELM}), b) the line average density ($\bar{n}_e$) and the divertor D_α intensity for lower single null shots c) without and d) with RMP in an n=6 configuration.

MAST is equipped with a set of in-vessel ELM control coils consisting of six coils above the mid-plane and twelve coils below[5]. Different coil configurations allow toroidal mode numbers in the range n=1 to 6 to be applied. When the plasma is shifted downward to form a lower SND (Single Null Diverted) magnetic configuration the plasma is far from the upper row of RMP coils and hence the perturbation is predominantly from the lower row of coils, which produces a much broader spectrum of magnetic perturbation. If the RMPs are applied in an n=6 configuration with a current in the coils I_{ELM} = 5.6 kAt, a clear increase in the ELM frequency and decrease of the ELM size is observed (see Figure 1). For I_{ELM} < 3.2 kAt no effect is observed on the plasma, but above this threshold value the increase in ELM frequency is effectively linear. For the example shown in Figure , which has I_{ELM} = 5.6 kAt, the ELM frequency increases from 80 Hz (for I_{ELM} = 0 kAt) to 270 Hz while the energy lost from the core per ELM decreases from 16 kJ to 5 kJ. This is the first time that ELM mitigation has been observed on any device using a toroidal mode number greater than 3.

The radial pedestal profiles, obtained using Thomson scattering, show a drop in the pedestal density but little change in the electron temperature. The pedestal top pressure reduces but the peak pressure gradient remains either unchanged or is reduced. A stability analysis performed using the ELITE stability code [6] predicts that such a discharge would be stable to peeling-ballooning modes [7], contrary to the experimental observation of increased ELM frequency. Such a stability analysis assumes toroidally symmetric and smooth edge flux surfaces. However, as will be shown, during the application of RMPs the edge is anything but smooth and may be it is these deformations of the surface that lead to greater instability.

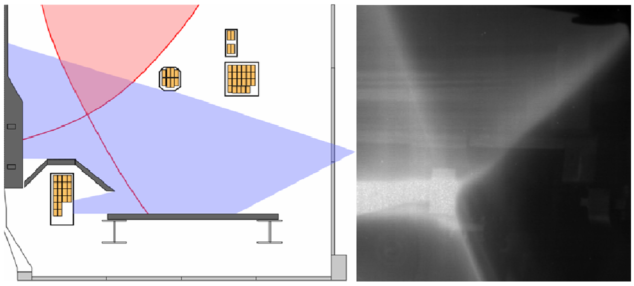

Figure 2: Left: Camera viewing geometry, right: unperturbed plasma boundary as seen by the camera

The lower, X-point region of the plasma, shown in Figure 2 was monitored using a toroidally viewing camera with a spatial resolution of ~1.6mm at tangency plane. The light entering the camera has been filtered for He^{1+} (468 nm) emission and the images obtained using an integration time of 500-1000μs. Due to atomic physics considerations, the He^{1+} line is visible over a relatively narrow temperature range around 10eV, so that the observed light emission is localised to the plasma boundary. Figure 2 shows an image obtained using a He II filter in a shot with I_{ELM}=0 kAt during an inter-ELM period. The image shows a smooth boundary layer associated with the Last Closed Flux Surface (LCFS). In contrast, Figure 2 shows an image obtained at the same time during an inter-ELM period for the shot with an n=6 perturbation applied and I_{ELM}=5.6 kAt. Clear lobe structures are seen near to the X-point [8]. Whilst these structures are clearest on the low field side (LFS) they are also visible on the high field side (HFS). These lobe structures only exist when the RMP coil current is above the threshold required to give an effect on the ELM frequency. These lobe structures have been observed in both L-mode and H-mode discharges with n=3, 4 or 6 but only when there is an accompanying effect of the RMPs on the plasma i.e. a density pump out in L-mode or an increase in ELM frequency in H-mode. Examples of these lobe structures in ELM mitigated H-mode discharges where the RMPs are applied in an n=6, n=4 and n=3 configuration are shown in Figure 3. While clear lobe structures are observed in each case, the location and poloidal separation of the lobes is different. For the same toroidal mode number of the perturbation the position of the lobes

Figure 3: Enhanced images of He^{1+} emission from the plasma boundary, where RMPs of toroidal mode number n = 6 (a), n = 4 (b) and n = 3 (c) are applied.

depends on the phase of the applied field (i.e. it depends on the sign of the current in the first coil).

The idea that so-called “Manifold” structures could exist was probably first introduced to the tokamak community by Evans et al., [9]. In an ideal axi-symmetric poloidally diverted tokamak the magnetic separatrix (or LCFS) separates the region of confined and open field lines. Non-axi-symmetric magnetic perturbations split this magnetic separatrix into a pair of so called “stable and unstable manifolds”. Structures are formed where the manifolds intersect and these are particularly complex near to the X-point. The manifolds form lobes that are stretched radially both outwards and inwards. RMP screening is expected to reduce the radial extent of the lobes (i.e. how far they extend from the LCFS), and therefore lobe images provide quantitative information to test plasma response models. In reference [10] it is shown that the radial extent of the lobes sets a minimum value on the radial extent of the stochastic layer, i.e. the stochastic layer has to be at least as broad as the lobes.

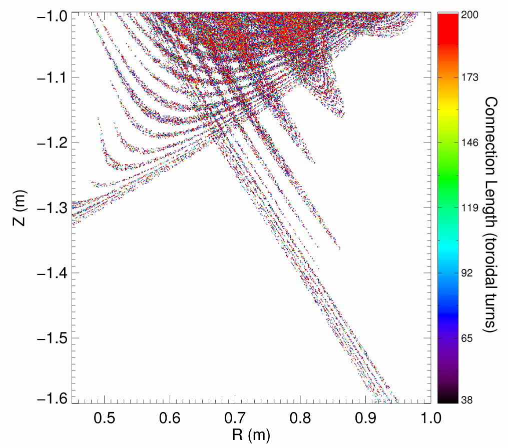

Figure 4: Laminar plot of X-point lobes due to the application of an n=6 perturbation.

Calculations of what these lobes should look like have been performed based on numerical field line tracing using the ERGOS code [11] with external magnetic perturbations (from the in-vessel coils, intrinsic error field and ex-vessel error field correction coils) superimposed on the equilibrium plasma. Field lines are traced in both directions until they hit the divertor plate or complete 200 toroidal turns. A plot is then made in the poloidal plane of the location of each field line at a given toroidal location. The number of turns that they perform before hitting the plate is denoted by the colour of the dot. The pattern is independent of where the field lines started but is dependent on the toroidal location used for the plot. Figure 4 shows the resulting laminar plot at a toroidal angle (ϕ) of 322 degrees for simulations with an n=6 coil configuration. The toroidal angle is chosen as the average toroidal location where the camera viewing chords are tangent to the unperturbed magnetic flux surface. The toroidal angle representing the tangency location varies from 350 degrees for pixels viewing the HFS of the plasma, through 322 degrees for pixels close to the X-point and up to 305 degrees for pixels at the far right hand side of the image.

A good quantitative agreement is observed between the number and separation of the lobes in the image and the modelling. Comparison has been carried out by calculating the lobe locations at the camera tangency plane for the case where the RMPs are in the n=6 configuration. A curve representing the boundary of the lobe structures produced is then superimposed on the image shown in Figure 5Figure . As can be seen the number and location of the lobes, particularly at the LFS, are in good agreement between the image and the modelling. At the HFS the agreement is less good and is possibly due to the effects of viewing through a greater volume of plasma and increased sensitivity to camera misalignment. There appears to be a discrepancy in the poloidal width of the lobes and their radial extent. This could be due to several effects: 1) the visible extent of the lobes is determined by the extent of the HeII emitting region, 2) impurity light emission from elsewhere other than the tangency

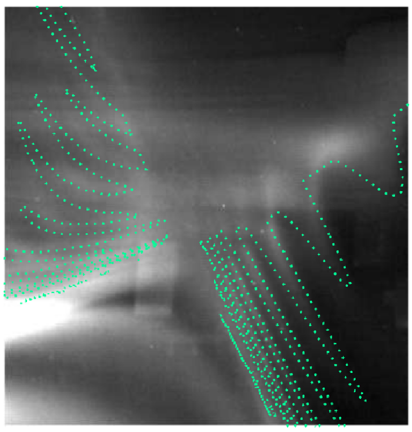

Figure 5: Comparison between measured camera data and lobe locations predicted by ERGOS.

location, 3) cross field diffusive transport, 4) plasma screening of the applied fields and 5) plasma response to the RMP.

The effects of plasma screening have been approximated by reducing the applied value of I_{ELM} used in the vacuum field simulations until the radial extent of the filaments in the simulations match those observed in the images. A value of I_{ELM}= 1.4 kAt, i.e. one quarter of the actual current, is found to be a good approximation with experiment, both in terms of the position and extent of the lobes. The lobes are only observed for coil currents above a threshold RMP coil current I_{THR}. Furthermore, for $I_{ELM}>I_{THR}$ the radial extent of the lobes increases approximately linearly with $I_{ELM}-I_{THR}$.

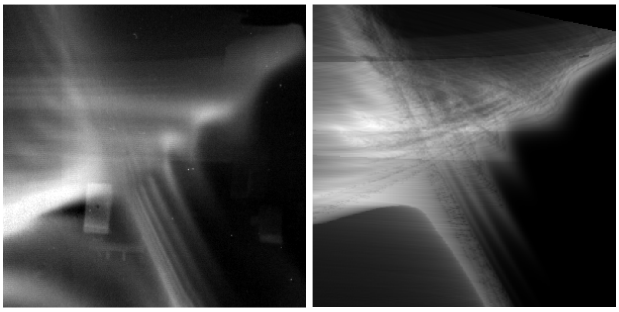

Figure 6: Left: raw camera image of X-point lobes due to the application of an n=6 perturbation with I_{ELM} = 5.6kAt. Right: forward modelled image using He^{1+} light emission distribution determined prior to the application of RMPs and a factor of 3 reduction in RMP coil current.

The sensitivity of these measurements to the distribution of the He^{1+} light emitting region was investigated by forward modelling the camera data taken during inter-ELM H-mode periods. Camera data recorded from whilst the plasma was in H-mode but before the RMPs were applied were used to generate synthetic images by assuming that the He^{1+} light is a flux surface quantity, and finding a light distribution function that provided a good match between the experimental and synthetic camera data. The ERGOS code was used to follow field lines in the 3D region monitored by the camera to determine the average magnetic flux along these field lines, which was used to determine the light emission within the lobes. It was found that in order to get a good agreement between the synthetic and experimental data, the applied RMP coil current needed to be reduced by a factor of 3 (Figure 6).

References

[1] T. Evans *et al.*, Phys. Rev. Lett. **92**, 235003 (2004)
[2] Y. Liang et al., Phys. Rev. Lett. 98, 265004 (2007)
[3] W. Suttrop et al., Phys. Rev. Lett. **106**, 225004 (2011)
[4] A. Kirk et al., Plasma Phys. Control. Fusion **53**, 065011 (2011)
[5] A. Kirk et al., Nucl. Fusion **50**, 034008 (2010)
[6] H. R. Wilson et al., Physics of Plasmas **9**, 1277 (2002)
[7] I. T. Chapman et al., Submitted to Nucl. Fusion.
[8] A. Kirk et al., Phys. Rev. Lett. **108**, 266003 (2012).
[9] T. E. Evans et al., Contrib. Plasma Phys. **55**, 235 (2004)
[10] S. S. Abdullaev et al., Physics of Plasmas **15**, 042508 (2008)
[11] E. Nardon et al., J. Nucl. Mater, **363-365**, 1071 (2007)

Acknowledgement

This work was funded by the RCUK Energy Programme under grant EP/I501045 and the European Communities under the contract of Association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was carried out within the framework of the European Fusion Development Agreement.