The effect of ELM mitigation via RMP on divertor heat loads in the Mega Amp Spherical Tokamak and the implications for ITER

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Introduction

In high confinement mode (H mode) of tokamak operation, steep gradients in pressure and current form at the plasma edge. A critical gradient exists at the plasma edge, above which a peeling ballooning mode is driven unstable [1]. The instability leads to a collapse of the edge region and the emission of particles and heat from the plasma in an event known as an edge localised mode (ELM). ELMs could limit the lifetime of ITER, due to the large transient heat loads they generate on the plasma facing components [2]. A means of ELM mitigation is required to control the ELMs. One such mechanism is the application of resonant magnetic perturbations (RMPs) which act to perturb the plasma edge [3].

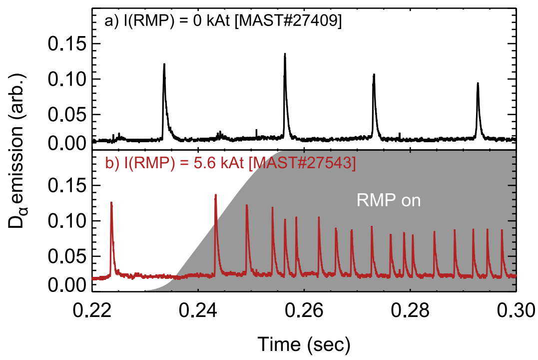

Figure 1: Effect of the RMP coils on an ELMing discharge. Panel a) shows the D_α emission without the coils applied and panel b) shows the effect of the coils.

ELM mitigation via RMP

Experiments on MAST [4] have shown that the application of the RMPs increases the ELM frequency as shown in figure 1. The product of the energy loss per ELM and the ELM frequency has been seen to be constant across a range of tokamaks. Therefore, the increase in ELM frequency seen when the RMP are applied produces a corresponding decrease in the ELM energy which in tern decreases the energy load to the divertor. The effect of the RMP on the peak divertor heat load can be seen in figure 2, which shows the energy loss per ELM (calculated using EFIT equilibrium reconstruction) and the peak divertor heat flux as measured by infrared (IR) thermography. Mitigation produces a nine fold increase in ELM frequency and a 3 fold reduction in the peak heat flux to the divertor. Mitigation also affects the area over which the energy is deposited during the ELM. The application of the RMP decreases the wetted area by 20% for a four fold reduction in the ELM energy which could act to limit the decrease in the peak heat flux with ELM energy.

Strike point splitting

The three dimensional field generated by the RMPs leads to the formation of X point lobes [5]. The lobes are formed as a result of the loss of toroidal symmetry and the break down of the last closed flux surface (LCFS) into two surfaces, known as the stable and unstable manifolds. The field lines on these manifolds approach the X point from opposite toroidal directions and oscillate about the location of the unperturbed LCFS. The oscillation of the stable and unstable surfaces is the process which generates the lobes.

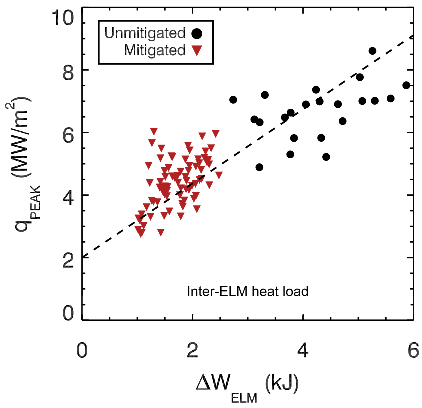

Figure 2: Peak divertor heat flux during ELMs for unmitigated ELMs (black circles) and mitigated ELMs (red triangles).

The lobes extend from the X point on the inboard and outboard sides of the plasma and intersect the divertor, giving rise to strike point splitting. The formation of strike point splitting offers insight into the penetration and screening of the applied RMP field into the plasma. The effect of the RMP on the divertor strike point can be seen in figure 3 which shows IR profiles taken before (black line) and after the application (red line) of the RMP in an L mode 950 kA double null discharge. The splitting can be modelled using the ERGOS vacuum code [6]. The strike point splitting is determined by following field lines from the target to the deepest point to which they reach inside the plasma in terms of square root normalised flux ($\Psi_{MIN}^{1/2}$). The field line excursion, which describes the depth to which a field line reaches, is then defined as $1-\Psi_{MIN}^{1/2}$ and plotted at the toroidal angle at which the IR measurement is made. Field line excursions of less than zero correspond to regions where the field lines are localised in the scrape off layer (SOL). The modelling, shown in figure 3 as the blue curve, shows good agreement in position for the majority of lobes in the profile. The final lobe at $\Delta R_{LCFS} = 0.12$ m is not seen in the measured profiles. The location of this lobe when mapped back to the midplane corresponds to a position 3 cm outside the LCFS. As the fall off length in density and temperature is typically 1 cm, it is expected that this lobe would not be seen.

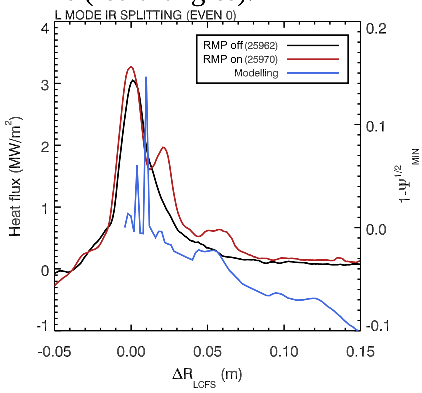

Figure 3: IR profiles showing strike point splitting. The RMP off (black line) shows no splitting. With the application of the RMP the strike point splits into three lobes (red curve). The location of the lobes matches with vacuum modelling (blue trace).

The plasma may act to screen out the applied RMP field, which is not accounted for in the vacuum modelling calculations. In order to take into account the plasma response, two approaches have been taken.

The first approach uses an ideal MHD response [7] to screen the currents on rational surfaces and does not account for plasma rotation. The second method uses MARS-F [8] to calculate the full linear plasma response to the applied field. The effect of the plasma response on the field used for determining the strike point splitting can be seen in figure 4 which shows the poloidal mode spectrum of the total magnetic field at the location of one of the rational surfaces in the plasma. The q=2 surface is located at the m=12 surface for the RMP field (n=6) used in the modelling to illustrate the screening. The effect of the screening can be seen at the m=12 surface, where both screening models show a reduced amplitude compared to the vacuum case. The ideal MHD model (red dashed line) m=12 component amplitude decreases to approximately zero and the MARS-F resistive plasma response shows a significant reduction in the amplitude.

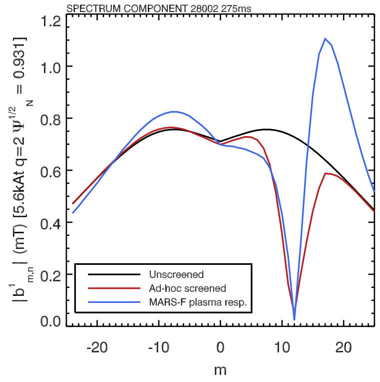

Figure 4: Poloidal mode spectrum at the location of the q=2 surface for the vacuum case (black), ideal MHD response (red) and MARS-F (blue) cases.

The effect of the plasma response on the strike point splitting is shown in figure 5. The plasma response decreases significantly the depth to which the field lines at the LCFS ($\Delta R_{LCFS} = 0$ m) penetrate into the plasma and decreases the amplitude of the outer lobe at $\Delta R_{LCFS} = 0.05$ m, but does not completely remove them. The reduced penetration shown in the modelling suggests that the plasma response will act to decrease the heat flux seen in the lobes of the splitting. The effect of the plasma response could explain why the large lobe at $\Delta R_{LCFS} = 0.01$ m is not seen in the measured profiles. It is likely that cross field transport also plays a role in determining the splitting measured at the divertor. In order for the SOL lobes to show heat flux, particles must be carried into them before they are conducted down to the divertor. Therefore, the missing outer lobe in the measured profiles could simply be due to the particles not reaching the field lines upstream of the target which form this lobe on the divertor. Splitting measurements during inter-ELM phases and during ELMs support this observation. In the inter-ELM case, where the cross field

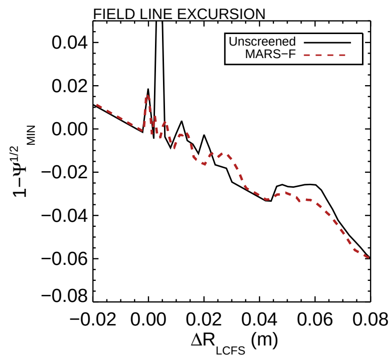

Figure 5: Modelled divertor strike point splitting with (red dashed line) and without (black solid line) the plasma response.

transport is reduced over the L mode cases shown above, the splitting extends over a smaller area and the lobes are less clearly defined. In the ELM case, the number of lobes seen increases as a function of time through the ELM; profiles taken at the onset of the ELM show one extra lobe and profiles taken at the peak of the heat flux show three lobes which is consistent with the toroidal mode number of the perturbation applied.

Conclusions

The effect of RMPs on ELMs has been investigated on MAST and shown to be effective at increasing the ELM frequency. The observed nine fold increase in the ELM frequency results in a corresponding decrease in the energy loss per ELM. The decreased energy loss per ELM produces reduced divertor heat loads in the mitigated ELMs compared to the unmitigated ELMs, with a 3 fold decrease in the peak divertor heat load for a nine fold reduction in the ELM energy. The reduction in the peak heat flux is not as large as would be expected from the fall in the ELM energy, this could be partially due to the decrease in the wetted area between mitigated and unmitigated ELMs limiting the reduction. Strike point splitting as a result of the applied RMP field has been measured and compared with vacuum modelling. The vacuum modelling predicts lobes which are not experimentally measured. Inclusion of the plasma response, via an ideal MHD model and MARS-F, reduces the size of the outer lobes, but does still predict they should be present. The suggestion is that the plasma response and cross field transport determine the magnitude of the heat flux seen in the measured profiles.

References

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