Modelling of plasma response to resonant magnetic perturbations and its influence on divertor strike points

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Abstract:
Resonant magnetic perturbations (RMPs) for edge localized mode (ELM) mitigation in tokamaks can be modified by the plasma response and indeed strong screening of the applied perturbation is in some cases predicted by simulations. In this contribution we use the spiralling patterns (footprints) appearing on the divertor to reveal information about the plasma response. We use two theoretical tools for investigation of the impact of plasma response on footprints: a simple model of the assumed screening currents, and the MHD code MARS-F. The former consistently predicts that footprints are significantly reduced when complete screening of the resonant perturbation modes is assumed, this result being independent on the parity of the applied perturbation (even or odd). MARS-F predicts a more significant reduction of footprints in odd parity than in even parity, explaining the results obtained on MAST. In the MAST experiments the footprints are correlated with the density pump-out, but appear later. Their sudden appearance is incompatible with the vacuum perturbation field approximation and can be explained by a decay of the plasma screening (the event of perturbation penetration).

1 Introduction

One of the key questions concerning the resonant magnetic perturbation (RMP) technique for edge localized mode (ELM) mitigation in tokamaks is the role of plasma response to the perturbation. The plasma response determines the actual perturbation field inside the plasma, which can be different from the value which the applied perturbation would have in vacuum. The plasma may screen the resonant modes of the perturbation in such a way that the generation of magnetic islands is prevented. If on the other hand there are magnetic islands close to those predicted by the vacuum perturbation approach, they would enhance radial transport, especially if several island chains overlap to produce a stochastic layer at the edge [1]. For this reason the question of whether the resonant perturbation in the RMP experiments penetrates or rather is screened is important for elucidating the ELM suppression mechanism and accompanying effects, such as the density pump-out.

Modelling has shown that significant screening can be expected in realistic cases [2, 3, 4]. In some scenarios the possibility of penetration can not be excluded because the total electron flow is not fast enough for screening. It is possible that the differences in results obtained in the RMP experiments in various tokamaks are partly due to differences in RMP penetration. Finding experimental signatures of RMP screening or penetration is thus highly desirable.

One accompanying effect of the application of RMPs in tokamaks with poloidal divertor(s) is the appearance of spiralling structures (footprints) of the flux patterns to the divertor target plates. Those can be observed e.g. by infrared or visible cameras or probes as a splitting of the strike point. The divertor footprints are thought to be manifestations of the homoclinic tangle which replaces the separatrix when the magnetic field is perturbed [5]. An important feature is its sensitivity to the resonant perturbation. Indeed we reported preliminary results, obtained using an ad-hoc model of screening currents, which showed that the screening of RMPs should significantly reduce the divertor footprints [6, 7]. This approach was then used in edge transport simulations and it improved their agreement with the DIII-D experimental results [8]. The divertor footprints thus are an essential diagnostic tool to discover whether the perturbation is screened or rather it penetrates. In this contribution we develop our approach towards more realism: we use the linear MHD model MARS-F [9] to calculate the plasma response to applied RMPs in addition to the ad-hoc model of screening currents. The perturbed field predicted by MARS-F is then used to calculate the divertor footprints.

A significant amount of data regarding the plasma reaction to RMPs has been obtained on the MAST tokamak in L-mode. While the eventual goal of the RMP studies is ELM suppression in H-mode, modelling the L-mode results is important for the understanding of the physics of RMP. The L-mode case is simpler to model than H-mode due to more moderate gradients and the absence of strongly sheared flows in the pedestal. No model of RMPs can thus be considered realistic without explaining the L-mode results correctly. The experiments performed in a scenario with a plasma current of 750 kA present a particular challenge to the theory. Different RMP coil configurations (even and odd) in otherwise similar discharges have in this scenario similar resonant components, leading to a similar profile of the Chirikov factor of island overlap [10]. Models based purely on resonant components of the perturbation field (and the resulting field line stochastization) would thus predict a similar effect on plasma for even and odd coil parity. This applies also to models of plasma response which include only the reduction of resonant components. Yet only the even parity case shows density pump-out [10] and divertor footprints [11] in the experiments. The MARS-F model is a candidate for explaining the difference between the two cases — as reported in [10, 12], MARS-F shows significant differences in plasma response. It is thus a question of if it can correctly reproduce the observed difference in divertor footprints. We will examine this problem in detail and compare MARS-F to results of the screening current model.

2 Methods and results

2.1 Experimental results from MAST

A series of shots in a MAST double-null divertor (DND) scenario with 750 kA plasma current was performed in L-mode using the RMP coils with dominant toroidal mode number $n = 3$ in both parities (even and odd) and both possible phases (0° and 60°). The odd parity shots show no change in density due to the RMP [10]. In some of the even parity shots a lower current in the RMP coils was used in order to determine the threshold for the density pump-out (see the lower graphs in FIG. 1). We can see that the pump-out does not occur for 0.5 kA coil current, but it does for 0.8 kA, although in this case it is delayed until after the coil current has reached the flat-top phase. With larger coil current this delay does not appear. The divertor strike points were observed with one infrared (IR) camera and six arrays of Langmuir probes [11]. The camera has a time resolution of 1.25 ms. The probes are being swept every 1.04 ms. However the power flux estimate from the probes has a significant noise which must be eliminated by averaging over longer time windows by using the method described in [11]. We use two windows, with a boundary at 0.22 s, which is the time when the coils are near their flat-top current. This method allows us to observe the difference due to the perturbation, but it can not determine precisely at what instant the structures appear. The resulting profiles of averaged power flux at four of the probe arrays in the even parity, 60° phase perturbation are shown in FIG. 3. We see that clear strike point broadening or splitting appear when the perturbation is applied. For 0.8 kA coil current it is less pronounced than for larger coil currents and for 0.5 kA there is almost no effect. In addition the probes are measuring the floating potential V_{float}. Those data do not require time averaging, so their time trace of (FIG. 1) allow us to determine how the structures appear during the coil ramp-up, as do the IR data (FIG. 2) which have a similar time resolution. The figures also show the evolution of density in the same shots for comparison of the timing.

The appearance of significant splitting in the IR data (at 0.221 s in the shot 25965) and of the strongly negative spike of V_{float} (at 0.223 s in the shot 25941) is a sudden, not continuous event, and the comparison reveals that the density pump-out starts earlier. FIG. 2 shows two clear peaks and a very weak and broad third peak of heat flux outside the original strike point, those peaks appear all at the same time.

2.2 Modelling results

To see if the data can be explained by a vacuum model we prepared a synthetic trace simulating the experimental heat flux profile in FIG. 2. The logarithm of the heat flux was simulated by the distance to the perturbed separatrix at the outboard midplane, which was then mapped along field lines to the divertor at the toroidal location of the actual IR camera view. This method was used to take into account the finite thickness of the SOL, which is deformed by the magnetic perturbations and produces longer footprints of flux compared to the footprints of connection length [13, 8]. This function was estimated using a Melnikov integral method [14], taking into account the actual evolution of the RMP coil current. The synthetic trace shown in FIG. 4 agrees

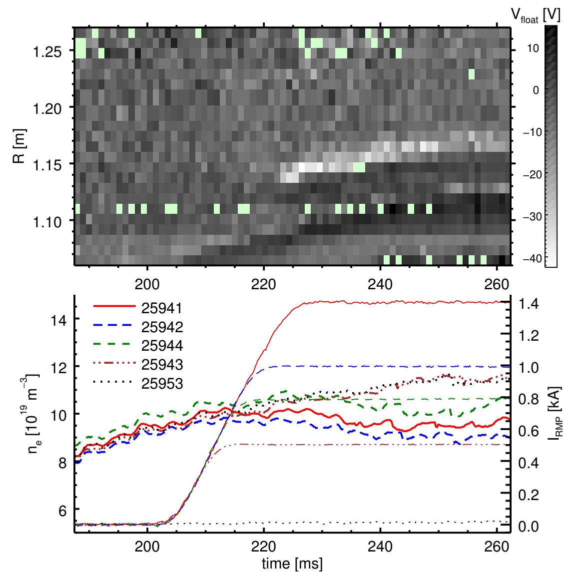

FIG. 1: Time dependence of V_{float} in even parity 60° phase shot 25941 (top) and the RMP coil current and electron density evolution in a series of shots in the same RMP coil configuration (bottom). The green points in the top graph represent unavailable data.

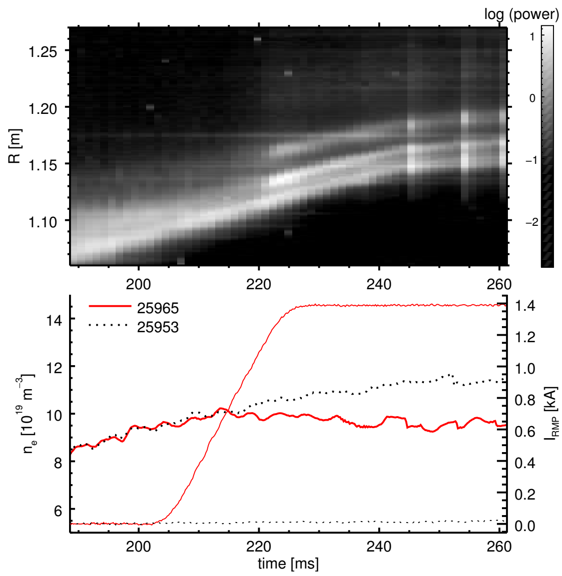

FIG. 2: Time dependence of the profile of the logarithm of the heat flux calculated from the IR camera data in even parity 0° phase shot 25965 (top) and the RMP coil current and electron density evolution in this shot compared with a reference shot (bottom).

very well with the experimental trace after the footprints have appeared[1]. In the synthetic trace the footprints however appear gradually and the peaks closer to the unperturbed strike point appear earlier.

Another disagreement between vacuum modelling and experiment is found by comparing even and odd parity shots. We used the MARS-F linear MHD model to calculate the plasma response for even and odd parity perturbation, as described in detail in [10, 12]. The magnetic field computed by MARS-F was then used to trace field lines and calculate divertor footprints. In the even parity case the coil current was set to 0.8 kA, as this yields similar size vacuum footprints to the 1.4 kA odd case and allows a better comparison. MARS-F was used in ideal and resistive regimes including the plasma rotation. The results are shown in FIG. 5 together with the vacuum footprints and those predicted by the ad-hoc screening currents model [7] assuming a complete screening of resonant modes in the plasma up to the $q = 6$ rational surface. The screening current model reduces the footprints in a similar way for odd and even cases, while MARS-F predicts a stronger reduction for the odd case, the reduction assuming an ideal response being stronger than for a resistive response.

[1] except for the fine structure of footprints very close to the strike point, which can be expected to merge into a single peak in reality due to the perpendicular transport

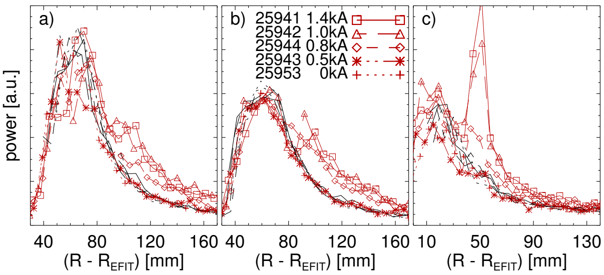

FIG. 3: Comparison of heat flux profiles measured by the divertor probes for varying perturbation coil current in even parity, 60° configuration. a), b) upper sectors, c) lower sector. Black lines without symbols: time window before $t = 0.22$ s, red lines with symbols: time window after $t = 0.22$ s.

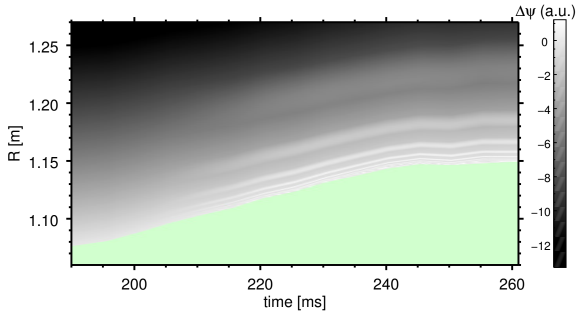

FIG. 4: Time evolution of the radial distance to the perturbed outboard midplane separatrix, mapped to the divertor, using the conditions in shot 25965.

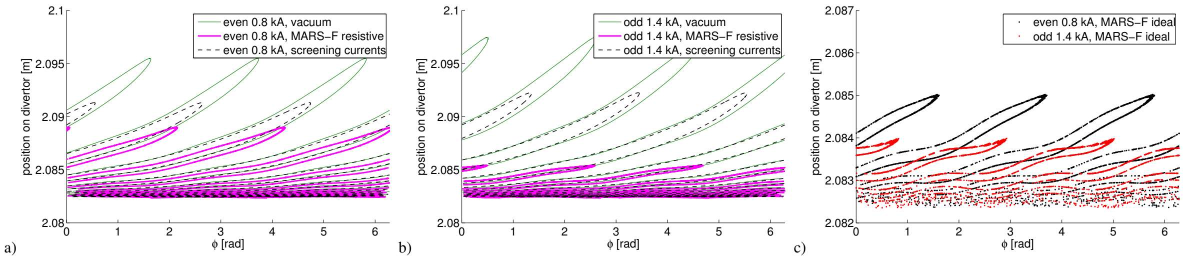

FIG. 5: The unstable manifold (boundary of the magnetic footprint) on the divertor calculated in the magnetic field of the vacuum perturbation, MARS-F resistive plasma response and the model of screening currents for the even parity, 0.8 kA perturbation coil current (a) and odd parity, 1.4 kA perturbation coil current (b). (c) shows a comparison using MARS-F ideal plasma response.

3 Discussion and conclusions

The appearance of footprints during the ramp of the RMP coil current is sudden and can not be explained by the gradual change of footprint length as the coil current is being increased. Especially the simultaneous appearance of multiple peaks on the heat load profile rules out this possibility — the peaks closer to the primary strike point appear for lower perturbation amplitude acording to the modelling, so during the current ramp up they should appear earlier, as shown in the synthetic time evolution (FIG. 4). This sudden and simultaneous appearance of footprints must thus be explained by a corresponding sudden change of the plasma response. We may suppose that before this event the plasma behaves in an ideal manner — the resonant component of the perturbation is screened inside the plasma, while this event represents penetration of the perturbation at the edge and after the event the field is closer to the vacuum solution. This hypothesis is supported by modelling of the footprints using the model of ad-hoc screening currents, which show that the footprints can be indeed substantially reduced by screening inside the plasma. This result is actually very general and has been found in all cases where the ad-hoc model has been tested - JET, COMPASS [7], ITER and DIII-D [8]. The screening always results in shortening of the footprint lobes, with their positions remaining unchanged. Reducing the perturbation coil field has a similar effect. This is confirmed by the perturbation coil current scans, where the experimentally observed peaks remain at the same position for the same coil configuration and different current.

Footprints in the ideal plasma response field calculated by MARS-F show qualitatively the same result — they are substantially shortened compared to the vacuum result. The longer footprints in the ad-hoc model compared to MARS-F are likely explained by the fact that the ad-hoc screening current model can include less resonant surfaces at the edge for numerical reasons, so it actually can not represent full screening everywhere[2]. It is known that inclusion of more surfaces with the screening currents leads to shorter footprints in the ad-hoc model [7].

There is however a substantial difference between MARS-F and the ad-hoc screening currents model. For 0.8 kA current in the even configuration of the perturbation coils a vacuum case has shorter footprints and smaller resonant field components than for 1.4 kA in the odd configuration, hovewer the MARS-F resistive response case has significantly longer footprints in the even configuration with 0.8 kA current, and also larger resonant components. The difference is present even in the ideal response case. Although here the footprints are so shortened that the difference is not experimentally relevant, it is still important from the theoretical point of view, as it shows that the result is not due to resistive effects. In the ad-hoc model with full screening this result is not reproduced and even parity 0.8 kA configuration has shorter footprints than odd parity 1.4 kA. The disagreement between models is surprising as the ad-hoc screening current model is based on the ideal assumption of vanishing resonant components, which is also implicitely present in the ideal MARS-F model. We have yet to identify what physics missing from the ad-hoc model is responsible for the difference — there are several candidates:

- the screening currents are not infinitely narrow sheets and are not localized exactly on resonant surfaces, as the ad-hoc model assumes. There are theoretical reasons to suppose that the screening current sheets are radially displaced from the corresponding resonant surfaces,
- the MARS-F perturbed current is not exactly aligned with the equilibrium field, unlike the assumption of the ad-hoc model,
- MARS-F in addition to the formation of screening currents which suppress the opening of islands also predicts excitation of a mode coupled to the RMP coil field [12]. (See also [15].) The structure of this mode is very different for even and odd configurations of the coils. In the odd case, it is a core kink mode, while in the even case it is an edge peeling-tearing mode. The result is a different shape of the plasma edge displacement: localized at the midplane in the odd case, near the X-points in the even case.

To test the latter possibility the MARS-F simulations were repeated for other plasma scenarios on MAST to verify that the density pump-out remains correlated with the X-point vs. midplane

[2] This would require an infinite resolution at the edge.

displacement, with a positive result [10, 12]. A study of divertor footprints, analogous to the one presented here for the 750 kA scenario, should be performed for those other scenarios.

It should be stressed that MARS-F results do not take the penetration of the RMP into account. It is possible that the difference apparent in the MARS-F results leads to the penetration of the field in the even configuration but not in the odd one, which would further amplify the difference between the two. Nonlinear MHD simulations in a toroidal geometry, which are numerically difficult, are required to solve this question and we intend to use the code MARS-Q for the present case in the future.

The comparison of footprints and density pump-out in a series of shots with varying RMP coil currents reveals that in the 60° phase the threshold for appearance of footprints and density pump-out is the same — 0.8 kA. On the other hand the data indicate that during the shots the density pump-out appears earlier than footprints, although a better time resolution would be needed to confirm this result with certainity. If the appearance of footprints marks the instant where the perturbation ceases to be screened, the pump-out shall be explained by a mechanism which works even in a screened perturbation field, such as the one proposed in [16]. This type of density pump-out is related to the torque which the perturbations exert on the plasma. This would explain the correlation of the density pump-out with the footprint presence in the 60° phase shots, as for the penetration the torque must be at a certain minimum level to stop the plasma rotation, which at the same time sets a minimum limit on pump-out. The torque — thus the pump-out — comes before the penetration in this model, in agreement with the experimental findings. The findings in [16] were however derived for a H-mode pedestal and may be different for L-mode conditions. An alternative explanation is offered in [1], however it relies on a formation of a stochastic layer, so is incompatible with complete screening. We would have to suppose that there is a thin layer at the edge where the perturbation penetrates immediately, before the appearance of footprints. This is not implausible as the low temperature and rotation at the edge indeed facilitates penetration, but it is a question if such a narrow stochastic layer can generate sufficient transport. These possibilities should be evaluated quantitatively for the present parameters to see which one matches the observed pump-out.

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