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The effect of the plasma position control system on the three-dimensional distortion of the plasma boundary when magnetic perturbations are applied in MAST

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Abstract
When resonant magnetic perturbations are applied in MAST, the plasma edge boundary experiences a three-dimensional (3D) distortion, which can be a few percent of the minor radius in amplitude, in good agreement with ideal 3D equilibrium modelling. This displacement occurs in plasmas both with radial position feedback control applied, and without feedback. When position feedback control is employed, an applied non-axisymmetric field can lead to an exacerbated edge displacement due to an ancillary axisymmetric position correction, with the direction of the correction dependent upon the phase of the applied field with respect to the toroidal position of the sensors used in the controller. This suggests that future machines reliant upon resonant magnetic perturbations for controlling ELMs should consider using a plasma control system capable of applying a position correction which accounts for the non-axisymmetry of applied magnetic perturbations.

Keywords: RMPs, MAST, corrugation

(Some figures may appear in colour only in the online journal)

1. Introduction

Non-axisymmetric fields are routinely applied in tokamak plasmas for various reasons: correction of intrinsic error fields [1], enhancement of neoclassical viscous torques [2], or perhaps most routinely, for control of edge localized modes (ELMs) [3]. Indeed, three-dimensional (3D) resonant magnetic perturbations (RMPs) have been used to completely suppress ELMs in DIII-D [4, 5] and KSTAR [6], or to mitigate ELMs—that is to say increase their frequency and reduce their amplitude—in ASDEX Upgrade [7, 8], MAST [9–11] and JET [12, 13]. Here, RMPs are defined as small perturbations to the magnetic field such that the non-axisymmetric field has the same helicity as the equilibrium magnetic field at a rational flux surface near the edge. However, as well as affecting the behaviour of the ELMs, such non-axisymmetric fields have also been shown to lead to a significant distortion of the plasma boundary [14–21, 24]. This displacement has been shown to scale with the applied field strength [16, 21] and predicted to give rise to displacements of the order of 3 cm at the midplane in ITER [21]. Such toroidal corrugation of the plasma boundary affects many things, notably the coupling of ion cyclotron resonance heating (ICRH), the minimum values of wall gaps assumed for safe operation, the plasma position control, and (*de facto*) the control of ELMs. Whilst this scale of midplane perturbation is likely to be tolerable, the interaction with the plasma control system (PCS) may exacerbate the problem. As an example, it has been shown in JET that the plasma position and current controller (PPCC) can lead to a reversal of the direction of the boundary displacement depending upon which magnetic sensors are used for the radial position feedback [20].

For any given RMP, there are toroidal positions where the plasma boundary is displaced inwards, and others where it is displaced outwards closer to the plasma facing components. Under the assumption of axisymmetry, if the phase of the RMP is such that the plasma boundary is displaced inwards in the toroidal position where the sensors used in the control system are located, the resultant $n = 0$ correction will correct in such a way that other toroidal positions where the RMP has induced an outward-displacement will have an additional outward movement resultant from the PCS. This is particularly pertinent for the application of RMPs in ITER, where the non-axisymmetric fields will be rotated at $<$5 Hz to avoid hot-spots on the divertor plates [25, 26]. Here we present measurements of the 3D corrugation of the plasma boundary when an $n = 3$ magnetic perturbation is applied in MAST in section 2, following the procedure used in [17]. We then compare this displacement with numerical modelling of an ideal 3D equilibrium using numerical tools developed for stellarator applications. Finally, measurements of the edge displacement in MAST are also made when the radial position is not in feedback control, and the difference between the cases with and without the influence of the radial position control within PCS are assessed in section 3, before the implications for future application of RMPs, notably in ITER, are discussed in section 4.

2. Measuring 3D displacements with RMPs

MAST is equipped with 18 in-vessel coils, with six in an upper row and twelve in the lower row, meaning that RMPs with mode numbers $n = 1$–6 can be applied [10, 27]. As well as meaning that $n = 3$ fields with 30° phase differences can be applied, MAST also has a number of diagnostics with spatial resolution of sub-cm at the plasma boundary, meaning that it is possible to discern the corrugation of the plasma boundary when RMPs are employed. Previous experiments in MAST have demonstrated that sizeable displacements of the plasma boundary are measured when non-axisymmetric fields are applied [17]. Displacements of up to five percent of the minor radius can be observed when an $n = 3$ RMP field is applied [21]. In order to explicate the role of the PCS in determining the distortion to the plasma boundary in the presence of RMPs, we firstly demonstrate a boundary corrugation when the plasma boundary is nominally kept in radial position feedback by the control system (which assumes axisymmetry in MAST), in the same way as done in [17]. The primary diagnostics used to measure the radial position of the edge of the plasma are the linear D_α camera which sees the edge of the plasma, the phantom colour camera, the charge exchange recombination spectroscopy diagnostic, the RGB camera, a charge-coupled device (CCD) camera viewing both sides of the plasma, and the Thomson scattering diagnostic, all of which measure the boundary position in different toroidal locations. An example of the plasma boundary displacement observed when the RMP field is applied is given in figure 1, which shows the plasma boundary as determined by a linear CCD camera at two times, just before the non-axisymmetric field is applied, and just as the current in the in-vessel coils reaches flat-top. Linear CCD cameras measure D_α light from the plasma boundary [22], generated by plasma electron impact excitation of the neutral deuterium gas in the vessel. A singular value decomposition algorithm is applied to the camera data and the geometry matrix in order to calculate the plasma D_α emissivity as a function of major radius [23]. The camera location and field of view are then used to calculate the radius at which camera lines of sight are tangent to flux surfaces to give the local plasma brightness as a function of major radius. A demonstrable shift of the plasma boundary is observed in figure 1 despite the fact that the plasma boundary is in radial feedback control since the sensors used for the feedback control are in a different toroidal position to the plane at which the camera view is tangent to the boundary. The plasma position controller uses sensors located at $\phi = \pi$ which means that the plasma boundary is kept at a constant radial position at this toroidal location.

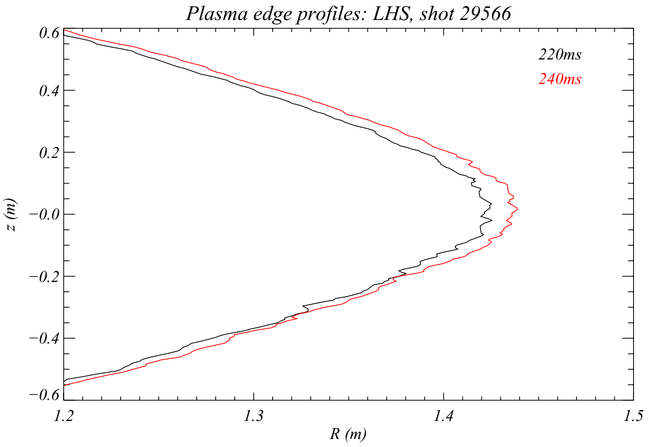

Figure 1. Plasma edge profiles of shot 29566, produced by calculating the position of the brightest pixels from the right-hand-side black-and-white CCD camera. The 220 ms trace (black) is found using the filtered image. Even after image processing, approximately ±0.5 cm of noise remains in the plasma edge position.

By measuring the boundary position on a number of different diagnostics around the vessel, a toroidal map of the plasma boundary position can be made, as illustrated in figure 2. It is evident that the plasma becomes corrugated with $n = 3$ periodicity, with the amplitude of the perturbation being 1 cm (or 2 cm peak-to-peak) in this case, which equates to about 2% of the minor radius. (Note here that the plasma used in this study is further from the in-vessel coils to facilitate studies without radial feedback, has lower injected power—hence lower plasma amplification of the fields since the plasma beta is lower—and a lower applied field than those studied in [17], hence the smaller radial corrugation amplitude, and the $n = 0$ correction applied by the plasma position control has been

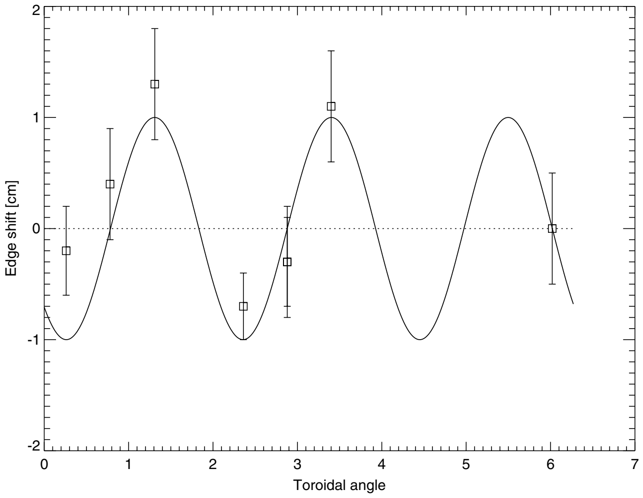

Figure 2. Toroidal map of the plasma edge displacements determined using the five diagnostic methods. An ideal $n = 3$ perturbation with 1 cm amplitude is plotted and good agreement with the measurements is seen, except for the RGB filtered camera. Here the $n = 0$ correction applied by the position controller is subtracted and will be discussed later in section 3.

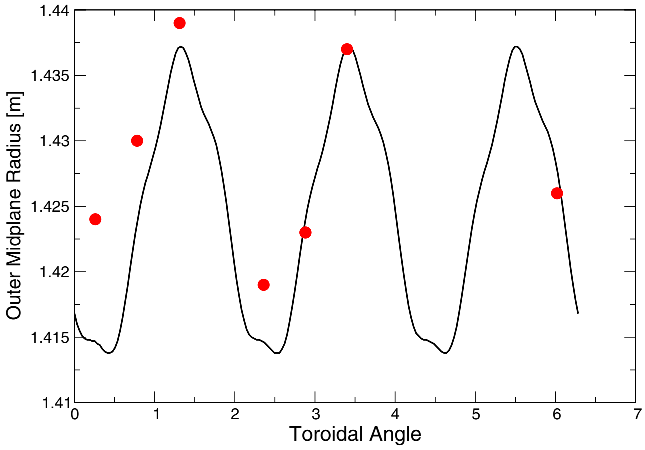

Figure 3. The plasma edge radius at the midplane as predicted by VMEC (solid line) compared to the experimental data from figure 2 (circles) giving an edge displacement of approximately 1 cm with the same phase.

subtracted.) The size of the displacement is in good agreement with ideal three-dimensional equilibrium modelling using the VMEC code [28]. Figure 3 shows the measured displacements in various toroidal positions plotted against the boundary position as modelled using VMEC when an $n = 3$ field is applied in addition to the toroidal field ripple [29]. This good agreement between measurements and a linear ideal equilibrium model which does not account for magnetic islands suggests that, at least for determining the position of the plasma *boundary* (though not necessarily inside the pedestal region) in these low-beta MAST plasmas, neither resistivity nor nonlinear plasma screening or amplification effects are leading order.

3. Position feedback control and RMPs

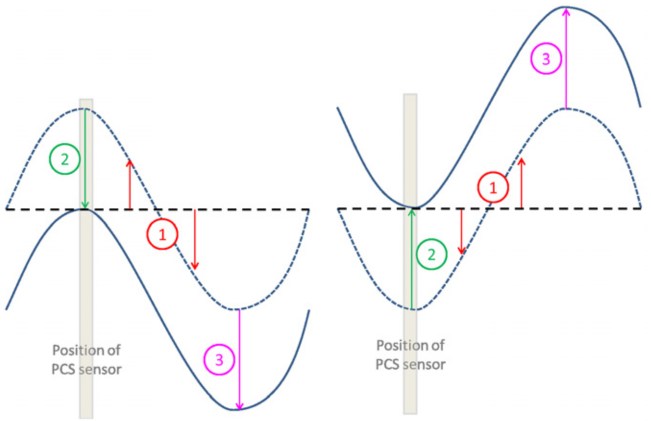

Figure 4. A sketch showing the time evolution of how radial feedback control can exacerbate RMP induced boundary distortions, dependent upon the phase of the applied field with respect to the toroidal position of the sensors used for the radial position feedback. (1) When the RMP is applied, it causes the plasma to move outwards at the position of the PCS sensors; (2) the controller applies an $n = 0$ correction to rectify this perturbation, which (3) causes twice as large a perturbation in a different toroidal position, either inwards (left) or outwards (right).

Figures 2 and 3 do not, however, illustrate how the plasma is displaced from the nominal position used in the feedback control system. The fact that the boundary clearly takes a 3D corrugated structure means that whether or not the average boundary position is inside, at, or outside the reference value used in the controller depends on the phase of the applied field with respect to the toroidal position of the sensors used in PCS. This is illustrated by the sketch in figure 4: When the applied field is such that the plasma boundary is moved outwards in the toroidal position of the PCS sensors, the control system applies an axisymmetric correction moving the plasma back to its set-point in the local position of the sensors, which has the effect of exacerbating an inward shift half a period of the applied perturbing field toroidally around the plasma. Conversely, if the RMP causes an inward displacement in the sensor toroidal position, the resultant $n = 0$ correction means that the outward shift of the plasma boundary in other toroidal positions is effectively doubled by the control system. MAST uses the PCS developed at DIII-D [30], with the radial position control using optical plasma edge detection in MAST as described in [23].

Plasmas have been executed in MAST in the absence of radial feedback control to exemplify this. Whilst the vertical position feedback is retained (since this is necessary to avoid rapid plasma termination due to vertical displacement events caused by transient perturbations, such as ELMs), the currents in the poloidal field coils are pre-programmed to replicate a plasma in radial position feedback. As before, the displacement due to the RMP field is measured in various toroidal positions. Since the plasma is no longer in position control, there is a small radial drift (less than 1 cm) over the period at which the RMPs are applied. However, this radial drift is reproducible, and therefore can be subtracted from the plasmas with non-axisymmetric fields applied in order to ascertain the RMP-induced boundary distortion. Figure 5 shows the same toroidal map of the boundary position in the case with radial position feedback as shown in figure 2. In

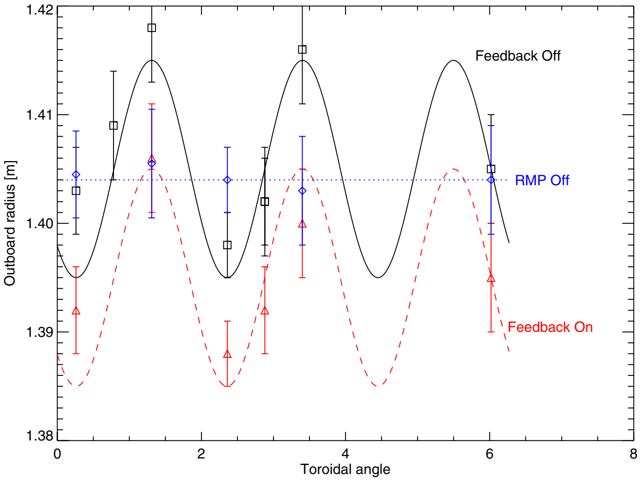

Figure 5. The plasma edge perturbations with radial feedback (dashed line, triangles) and without feedback (solid line, squares) compared to the axisymmetric case without RMPs applied (dotted line, circles). The effect of the feedback control is to pull the plasma in by 1cm everywhere, while leaving the edge corrugation due to RMPs unchanged.

addition, a similar boundary shape is mapped out for a plasma with RMPs applied when radial position control is disabled. It is immediately clear that whilst the amplitude of the boundary corrugation is identical in the cases with or without position control, the average position of the plasma boundary is strongly affected by the control system. The sensors used for position feedback are approximately at $\phi = \pi$. In the plasma without radial position feedback, the boundary was displaced outwards at this toroidal location. As illustrated in the sketch in figure 4, the PCS responded accordingly with an axisymmetric correction to bring the plasma edge back to its reference set-point. However, the assumption of axisymmetry results in an ancillary inward displacement in other toroidal positions which had already experienced a 1cm inward corrugation due to the RMPs. By performing a feed-forward plasma in this way, the role of the PCS in determining the plasma boundary position in a 3D plasma configuration is just as important as the displacement caused by the non-axisymmetric field itself. (It should be noted that there are not measurements in every toroidal position for all cases, primarily due to the restrictions from short time-windows of some diagnostics meaning that they cannot collect data in both the RMP on and off phases of the discharge.)

4. Discussion and conclusions

MAST plasmas can exhibit sizeable boundary corrugations of the order of a few percent of the minor radius when RMPs are applied. Such distortions of the plasma edge can be replicated by ideal 3D equilibrium modelling. When plasma radial position feedback is disabled, the plasma boundary is ‘naturally’ corrugated by the applied non-axisymmetric field. However, when position feedback is utilized, if the ‘natural’ distortion is finite in the toroidal location of the sensors used for radial position feedback, then the plasma controller applied an ancillary axisymmetric correction to the plasma boundary position.

Future machines are likely to rotate the RMPs used to control ELMs in order to avoid localized erosion damage on the divertor plates. This means that the non-axisymmetric field will have an oscillating phase at any given toroidal position. Consequently, it is important that the plasma control system utilizes a radial position feedback scheme which accounts for a non-axisymmetric boundary shape to avoid exacerbating the distortion caused by the RMPs. This could be as simple as choosing a set of toroidal locations for magnetic sensor arrays to be at different phases of the applied field, so that their average is insensitive to the non-axisymmetric field. The set of magnetic diagnostics envisioned for ITER [31, 32] will include 72 saddle loops as well as four full loops in nine sectors. In total there will be more than 1700 magnetic diagnostics (compared to ∼500 in JET for instance). In principle, this coil set provides sufficient toroidal coverage to take into account nonaxisymmetric perturbations with a strongly dominant toroidal mode number such as those from the RMPs. In order to keep flexibility in the spectra of allowable applied fields, as well as redundancy in case some of the sensors fail during operation, these multiple sets of sensors will be needed. In order to optimize the minimum number (in the event of coil failure for instance) and toroidal locations of these coils, detailed forward-modelling is needed and will be the subject of future work.

It should also be borne in mind that, in this work we study the effect of the applied field on distortions of the outboard plasma in the midplane. However, detailed numerical studies [21] shows that sizeable displacements also arise near the top of the plasma, which would lead to concerns about melting the upper dump plate in ITER. The distortions predicted for ITER in [21] are of the order of 5–8 cm near the upper X-point, they are likely to stay within the tolerable limits for heat loads to the plasma facing components [33]. However, since the diagnostic coverage in present-day machines is primarily on the geometrical mid-plane, there are fewer, less well-resolved measurements for comparison of off-midplane distortions with the numerical predictions, meaning that extrapolation to ITER has a larger uncertainty. Nonetheless, this modelling suggests that such an optimization should also take into account distortions of the plasma off mid-plane.

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