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Plasma wall interactions in RFX-mod with virtual magnetic boundary

P. Zanca *, D. Terranova, M. Valisa, S. Dal Bello

Consorzio RFX , Associazione Euratom ENEA sulla fusione, Padova, Italy

Abstract

A cross-check analysis of the plasma wall interaction in RFX-mod is presented. Different methods to determine the footprint of the interaction are compared. The issue is particularly important for the plasma performances, due to the presence of a quasi-stationary distortion of the plasma surface related to the phase locking of the dynamo modes. We show a good agreement between the different analysis and an important reduction of the phenomenon in the discharges with active feedback control of the magnetic boundary.

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1. Introduction

The new magnetic front end of RFX-mod [1] ($R = 2$ m, $a = 0.459$ m, $I \leqslant 2$ MA) features a full coverage of the torus with 192 independently powered saddle coils positioned outside a conducting shell (shell radius $b = 0.5125$ m) having a time constant $\tau b = 100$ ms, which is an order of magnitude shorter than the previous purely passive configuration with a thick aluminium shell of RFX. The system is very flexible and allows a number of possibilities in the direction of harnessing with feedback control techniques the modes that populate the rich MHD spectrum of a Reversed Field Pinch. Such a spectrum consists mainly of $m = 1$ tearing modes resonating inside the reversal surface and $m = 0$ modes resonating at the reversal surface. They are intrinsically part of the dynamo mechanism that in a RFP generates the toroidal flux and sustains the configuration [2]. The phase and wall locking of these modes [3] produces stationary deformations of the plasma column, the so called 'locked mode' (LM), that concentrate the power dissipation on limited areas of the first wall (fully covered by carbon tiles). Being the input power about 10–20 MW, the LM has represented in the past RFX discharges an operational limit, particularly at high current ($I \approx 1$ MA), accompanied by carbon blooming, high density and radiated power. In RFX-mod the carbon tiles have been designed with a new shape, which

* Corresponding author. Address: Corso Stati Uniti 4, Padova, Italy. Fax: +39 049 8700718.
E-mail address: paolo.zanca@igi.cnr.it (P. Zanca).

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minimizes the probability of local hot spots. Nevertheless an external magnetic control of the perturbation is required to avoid severe plasma wall interaction (PWI). In the past the problem has been overcome only by dragging toroidally the modes with externally applied magnetic torques [4], thereby spreading the PWI over a wider area. The new active feedback system of RFX-mod allows a better mitigation of the LM effects, because it is capable to compensate the radial magnetic field (associated to the plasma distortion) at the shell radius, therein providing an almost ideal magnetic boundary for the plasma. The operation, called 'Virtual Shell' (VS), has proved to be remarkably effective, decreasing by a factor 2–3 the amplitude of the MHD modes with a significant reduction of the radial extension of the deformation at the edge in the wall locking region. Moreover the VS suppresses all of the non-resonant resistive wall modes. In this paper we will discuss and compare three different methods to obtain the footprint of the PWI in RFX-mod: a reconstruction of the plasma surface distortion based on magnetic data, an estimate of the power deposition on the wall provided by a layout of thermocouples located on the outer surface of the vacuum vessel, and the wall images obtained by a CCD camera.

2. Analysis methods

The geometrical distortion ξ^r of the plasma surface in the radial direction is obtained from the radial b^r and equilibrium $\mathbf{B}_0$ magnetic field at $r = a$ exploiting the linear ideal-MHD Faraday–Ohm's law $b^r = \mathbf{B}_0 \cdot \nabla\xi^r$. In turn the radial magnetic field at $r = a$ is computed using the standard expressions in terms of the modified Bessel functions for the mth poloidal, nth toroidal Fourier harmonic $b_r^{m,n}(r) = A^{m,n} I_m'\left(\frac{|n|r}{R}\right) + B^{m,n} K_m'\left(\frac{|n|r}{R}\right)$, which are valid in the vacuum region adopting cylindrical geometry [3]. The arbitrary coefficients $A^{m,n}$, $B^{m,n}$ are obtained by matching the radial and toroidal magnetic field measurements, provided by four toroidal arrays of 48 probes each located nearby the inner surface of the shell. The phase-locked $m = 1$ modes give rise to a toroidally localized helical deformation, whose amplitude $\xi_1^r(\phi)$ has been reduced to less than 1 cm in the VS shots. The phase-locked $m = 0$ modes produce instead a toroidal variation of the plasma surface radius $\xi_0^r(\phi)$, which typically increases slowly with the toroidal angle, and undergoes a rapid shrinking nearby the $m = 1$ helical maximum distortion. In Fig. 1 the amplitudes of the $m = 1$ and $m = 0$ deformations are plotted as functions of the toroidal angle for a VS shot (# 18645) and for a shot without the active control of the magnetic boundary (# 17262). Note that the LM position is different in the two shots, and that in both cases the $m = 0$ shrinking occurs at higher toroidal angles with respect to the $m = 1$ peak. The significant reduction of the geometrical distortion of the plasma surface in the VS shot is apparent. The region of maximum PWI, inferred by this reconstruction, is confirmed by the analysis of the thermocouples signals. For easy of comparison with the thermal data, the geometrical distortion of the

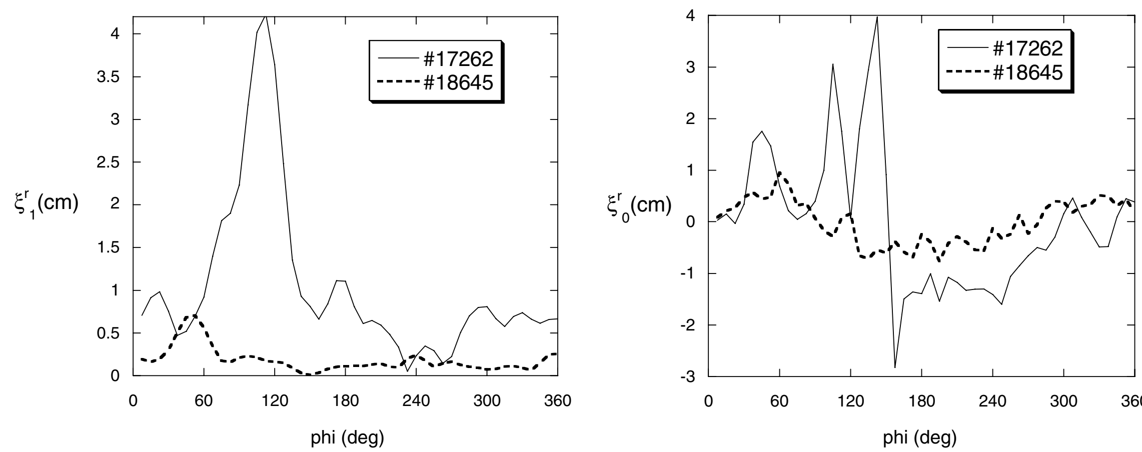

Fig. 1. Plasma surface distortions as a function of the toroidal angle for the shot 18645 at $t = 140$ ms, and for the shot 17262 at $t = 100$ ms. Left: radial helical displacement due to the $m = 1$ perturbations. Right: variation of the radius due to the $m = 0$ modes.

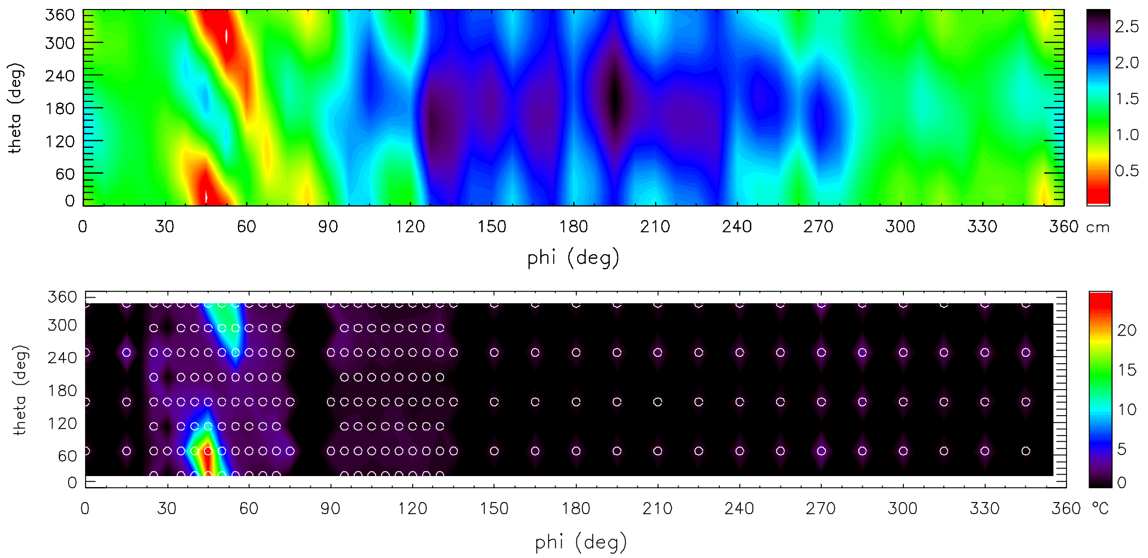

Fig. 2. Top: distance (cm) from the wall of the surface touching it only in the point of maximum outward displacement, for the shot 18 645 at $t = 140$ ms. Bottom: wall temperature variation during the shot 18 645.

plasma surface is represented as a contour plot in the (θ, ϕ) co-ordinates in Fig. 2 (top) for the shot 18 645. Here the colour[1] scale indicates the distance from the wall of the surface touching the vacuum vessel only in the point of maximum outward distortion. The Shafranov equilibrium shift is taken into account, even if in RFX-mod it is kept at small values (less than 0.5 cm) by a real-time equilibrium control system. The region of maximum PWI corresponds to the red area where the $m = 1$ and $m = 0$ deformations combine to produce the maximum outward displacement. This region wraps helically following the $m = 1$ perturbation. In Fig. 2 (bottom) a contour plot of the local wall temperature increase $\Delta T(\theta, \phi)$ (°C) during the same shot is reported. Since heat must diffuse from the interaction region on the graphite wall to the thermocouples outside the vessel, ΔT is computed from the difference of the signals measured 1 min before the shot 18 645 and 12 min later. Note that the sensors (indicated by the empty circles) are not evenly distributed around the torus. A region of high PWI interaction is evident also in this figure, following a helical path that corresponds very well to the red area of Fig. 2 (top). The same quantities are reported for the shot 17 262 in Fig. 3, and again a good agreement between the thermal data and the magnetic reconstruction is obtained (the greater temperature increase in the previous VS shot is due to more than double pulse length and higher current level). The images provided by the CCD camera confirm the magnetic reconstruction reliability. A detailed description of the RFX viewing system is given in [5]. Typically, the observations are carried out in the CI light, that is by interposing an interfering filter centred around 907.7 ± 2 nm, which makes the observation sensitive to the carbon influx. This is in fact a good indicator of the PWI since, as shown by both fluid and Monte Carlo modelling [6], neutral carbon atoms should exist mainly in the first 1–2 cm layer close to the wall. Fig. 4 (left) shows the PWI interaction seen by the CCD camera for the VS shot 18916; Fig. 4 (right) shows the same type of contour plot represented in Figs. 2 and 3 (top) wrapped along the portion of the torus seen by the camera. The poloidal white circles 1 in the contour plot corresponds to the lines of the ports clearly visible in the CCD image; the circle 2 is traced 15° toroidally apart, a distance that on the CCD image corresponds to three tiles (each tile covers 5° in the toroidal direction). We can therefore infer that the red area in the contour plot corresponds exactly to the region of maximum PWI interaction seen by the CCD camera.

3. Discussion and conclusions

A sensible indicator of the PWI intensity is the ratio $\Delta T_{max}/(\Delta t_{pulse}\Delta E_{pulse})$ between the maximum

[1] For interpretation of colour in Fig. 2, the reader is referred to the web version of this article.

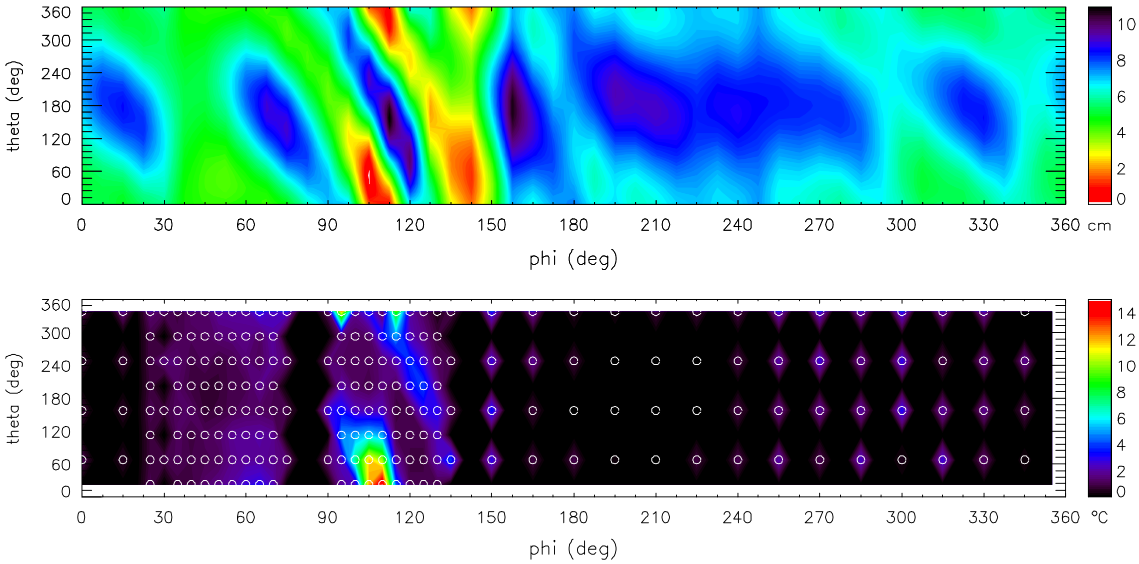

Fig. 3. Same quantities reported in Fig. 2 for a shot (# 17262) without the VS boundary.

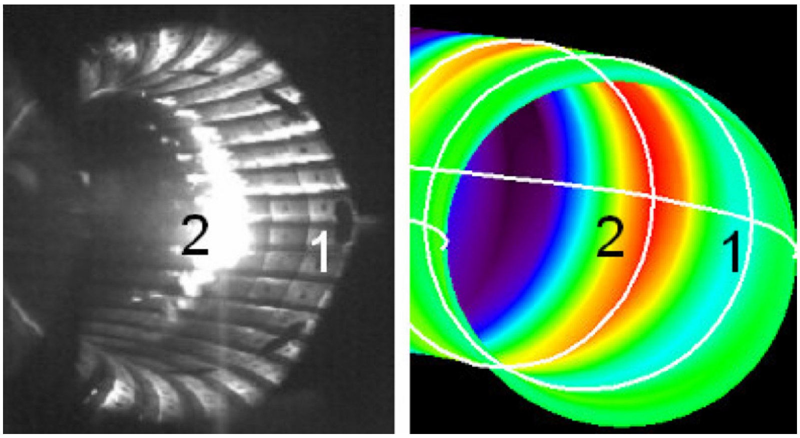

Fig. 4. PWI for shot 18916. Left: CCD image of the first wall. Right: magnetic reconstruction of the plasma surface distortion along the torus.

temperature increase, the total energy input and the duration of the shot. It quantifies the wall-heating rate due the localized geometrical distortion. The magnetic quantity showing the best correlation with this indicator is the toroidal maximum (located nearby the LM) of the $m = 0$ radial field. This correlation is shown for some shots with and without the VS boundary in Fig. 5. While Figs. 2 and 3 indicate that the region of maximum PWI wraps along the torus following the $m = 1$ helical displacement, Fig. 5 shows that the intensity of this interaction is related to the $m = 0$ radial field. This could imply a dependence of the edge transport on the $m = 0$ mode, fact not surprising since these modes are resonant at a radius about 0.8–0.9a. Recent analysis has put into evidence the crucial role of the $m = 0$ modes in the edge transport of RFPs [7]. On the other hand, Fig. 5 clearly shows a decrease of the PWI intensity in the VS shots. One should consider that in the plot ΔT_{max} is likely to be underestimated for the shots without VS, since the major part of them have the maximum PWI in the region where the thermocouples are sparse, while the major part of the VS shots have the maximum PWI in the well-covered region. In the experiment the improvement brought by the VS is confirmed by a better

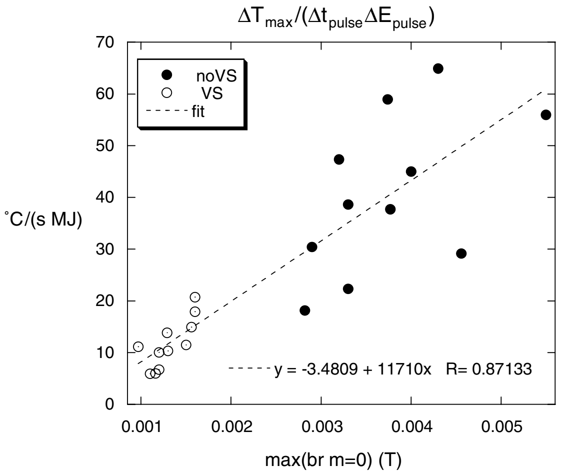

Fig. 5. $\Delta T_{max}/(\Delta t_{pulse}\Delta E_{pulse})$ as a function of the toroidal maximum of the $m = 0$ radial field in some shots with the VS boundary (empty circles) and without VS boundary (black circles). The maximum is averaged during the shot.

control of the density and by more than doubled pulse duration. Due to the increased pulse length, ΔT_{max} remains high in the VS discharges, so techniques to further mitigate the PWI, such as the forced toroidal rotation of selected modes, are being experimented. In conclusion a good agreement between the different analysis and a reduction of the PWI in the VS shots have been shown.

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