PLASMA-WALL INTERACTIONS IN RFX

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Abstract

Plasma wall interactions become a crucial issue in the Reversed Field Pinch RFX at high current (>0.7 MA).Wall-Mode Locking (WML) leads to carbon bloom, enhanced recycling and makes the density control very difficult to achieve. Several wall conditioning techniques have improved the capability of controlling recycling, especially boronisation with diborane, but at 1 MA of plasma current removal of the WML becomes mandatory. Encouraging results have been achieved by rotating an externally induced perturbation that can unlock the WML. The strong impurity screening mechanism found at intermediate current does not degrade significantly at 1 MA. Modification of the tiles geometry could further reduce the power density dissipation and mitigate the PWI.

1. INTRODUCTION

In Reversed Field Pinch (RFP) experiments the plasma-wall interaction (PWI) is a subject of considerable interest for three main reasons: 1) the input power in a RFP (10-50 MW in RFX [1]) is typically ten times higher than in an ohmically heated tokamak of similar dimension, and due to a number of asymmetries, first of all the locking in phase and to the wall of MHD modes, may result in local power depositions of 100 MW m^{-2} [2,3]. 2) The resistivity enhancement associated to PWI hampers the dynamo, i.e. the fundamental mechanism that drives the large poloidal currents characteristic of the RFP configuration [4]. 3) PWI affects directly the edge region that plays an important role in the RFP confinement, where in fact large pressure gradients, high shears of flow velocity and of radial electric fields are measured.

It is finally important to note that the several improved confinement regimes found in the recent past in RFP's, such as the externally driven Pulse Poloidal Current Drive or the spontaneous High-Θ Mode and α-Mode [5], whose common feature seems to be the reduction of the turbulent dynamo and therefore of the radial transport in the plasma core, all require among other requisites a low plasma contamination.

RFX is a toroidal device of 2 m in major radius and 0.46 m in minor radius whose aim is to experiment the RFP configuration up to 2 MA. The first wall is made of an armour of graphite tiles that covers almost completely the Inconel vacuum vessel.

Up to 700 kA discharges the effect of the PWI has been documented to be of little influence on the plasma performance. Despite the presence of a large area of graphite tiles (36 m^2) and the high particle outflux, of the order of 10^{23} s^{-1}, control of recycling is feasible by minimising the magnetic field errors and by means of a careful wall conditioning. Z_{eff} may reach values close to one at intermediate and high densities (4-9 $10^{19} m^{-3}$) [6] and, with the exception of the high density regimes, radiated power is typically a negligible loss channel [7].

When plasma current is increased the input power generally increases as well. The PWI close to the WML position shows an increase of the fraction of total energy dissipated (up to 40-50%)[2,3], an increase of the radial error field at the wall and an enlargement of the area of the wall affected by the perturbation. The tile edges show an excessive overheating that beyond a threshold, i.e. when the temperature of the hot spots exceeds approximately 1800 °C, degenerates into carbon blooming or in enhanced recycling and eventually in a current decay [2].

In the following we describe the several actions that have been undertaken to mitigate the PWI effects at high current, namely the wall conditioning techniques for controlling recycling and the attempts to control wall-mode locking position (WML). In addition we analyse the screening mechanism that allows a low contamination despite the large PWI and finally we consider whether alternatives to graphite as the first wall material may be conceived for future experiments.

2 1 MA OPERATION

2.1. Effects of wall conditioning procedures

Fig. 1 shows some relevant time traces of a 1 MA pulse. In the first 35 ms the WML is stuck at one position of the wall and the density increases. The external chord (solid line) increases more than the central one (dashed line), i.e. the density profile becomes hollow. C VI and O VII emissions increase as well but Z_{eff} remains constant. At about 35 ms the modes change their locking position: density recovers, the discharge continues and the temperature increases.

Without mode unlocking, WML at high currents thwarts the efforts of controlling the recycling whatever method is used: either He GDC, boronisation or hot wall. In any case there are relevant differences in the effectiveness of the three methods: He GDC alone allows depleting the H inventory at the wall for just a few discharges. A boronised wall instead displays a good capability of pumping hydrogen during the discharge for about 50 pulses and reduced effects remain for approximately 200 shots**;** loss of effectiveness is accompanied by the formation of a hydrogenated carbon layer on the top of boron [8] and is the faster the higher the current. Hot wall operations (up to 280 °C) feature strong hydrogen desorption after the shot; the hysteresis effect on recycling is reduced but the pumping capability during the discharge is less effective compared with the other two methods. Once boronisation has lost its effects, hot wall operation does not lead to specific improvements in the control of recycling, presumably because of the dominant role of the WML in regulating the particle inventory at the wall.

In terms of impurity concentration and radiated power the boronised wall guarantees the best performances at all currents and regardless of the wall temperature(Z_{eff}≈1.5, Prad/Pohm<10%)

One of the main effects of a wall saturated with hydrogen is the formation at the plasma edge of large density gradients; they increase with the average density and are almost independent on current [9], although the highest densities are reached mainly at high currents. Fig. 2 shows the density gradients measured by the thermal He beam diagnostic as a function of the average density: the data confirm the results found by the interferometer in [9] and in addition show large hysteresis effects especially at high density, as indicated by the three contiguous 1 MA shots 10790, 10791, 10792: despite the filling gas was progressively reduced, in these three shots the density gradient doubles while the average density is practically constant, meaning that the density profiles become more and more hollow.

2.2. Impurity screening

Remarkably, high current operation do not necessarily mean a higher plasma contamination. Fig. 3 shows that Zeff does not increase with current for shots with selected density and a comparable degree of wall conditioning. This behaviour has been justified on the basis of Monte Carlo simulations of the carbon behaviour at the edge [6] as due to several possible causes: 1) the ratio between the impurity ionisation length and the Larmor radius of the first ionised stage is typically low (between 0.1 and 1) and does not change significantly with current, mainly as a consequence of the increase of the edge electron temperature with current, as it is shown in Fig. 4 for density selected pulses**.** 2) High currents are typically associated to high densities and therefore to higher density gradients that also reduce the ionisation length. 3) The fraction of chemical sputtering is relatively large, that is ≈ 50% of the total, in agreement with the observation of molecular emission [6]. 4) At the edge of RFX the radial electric field Er is negative (≈ -3 kV, inward directed) in the first 0.5 to 3 cm close to the wall and positive (≈ 1.5 kV) further inside the plasma [10,11]. The origin of the negative electric field has been ascribed to the prompt losses associated to the finite Larmor radius [12] while the internal and positive one has been thought to be of ambipolar nature, as a consequence of the stochasticity of the internal magnetic field [10]. The radial dependence of E_r may significantly affect the impurity screening since sputtered atoms are shifted inward if ionised in the region of the negative field, the opposite in case of ionisation in the positive field. Data available up to 0.5 MA show that the region where Er is negative shrinks when current is increased while keeping I/N constant.

2.3. Wall-mode unlocking

Recently a method for controlling the wall-mode locking position has been envisaged and brought into operation. A more detailed description is reported in [13]. Basically the idea was to produce an artificial error and to make it rotating toroidally in order to hook and drag the locked modes around, thus spreading the power losses on a larger area. A reproducible effect on the

WML, with movements accompanied by changes in the phase locking among the modes and in a reduction of their amplitude, has been obtained at intermediate plasma current (0.6 MA)[13]. However several successful events have been already obtained also in 1 MA pulses; indeed in these cases the typical sudden increase in the density is stopped when the WML position is moved. Fig 5 shows the evolution of the toroidal distribution of the perturbation amplitude for the same shot as in Fig. 1. At about 35 ms the WML moves toroidally by about 200° and prevents a premature quenching of the current: density recovers and the electron temperature increases reducing the emission of the highly ionisation states of carbon and oxygen.

3. FIRST WALL MATERIALS AND TOPOLOGY

At low current level (< 0.7 MA) the experience from different RFP experiments shows that the first wall material is not an issue since the effect of different first wall materials and configurations on the plasma performance is negligible. In RFX the experience has demonstrated that at 1 MA the enhanced power exacerbate the PWI and the power handling is much more critical for both materials and first wall topology.

The excessive plasma edge temperatures advise against the use of high Z materials, especially if the locking of the modes cannot be avoided.

For the high current and high performance operation only graphite seems to be the suitable material. Improvements could instead derive from an optimised shaping of the tile profile in particular in the poloidal direction in order to minimise the power density and avoid the formation of the hot spots where blooming is likely to occur [14].

4. CONCLUSIONS

The recent experience on RFX shows that the severe problems induced by the PWI at high currents may be overcome. Positive impacts are expected from the optimisation of the unlocking of the modes at 1 MA and beyond. Mitigation of the PWI should improve the effectiveness of boronisation and therefore the density control, which is a necessary means for trying to access the regimes of improved confinements at high currents. A strong impurity screening at the edge that does not degrade with current plays favourably in the same direction. Finally further optimisation of the PWI should come from modifications of the tile geometry aimed at reducing the local power density.

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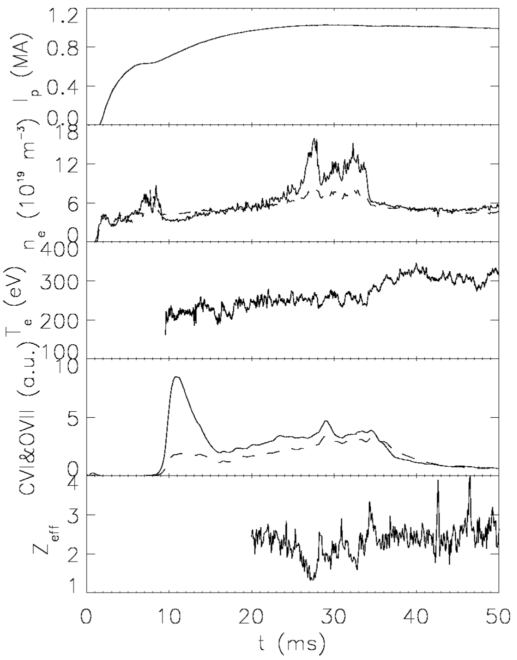

FIG. 1. Shot 10661. At 35 ms the modes are unlocked by an externally induced error. Density recovers, Te increases, he emission of C VI (dashed line) and O VII (solid line) decreases, while Zeff displays the usual density dependence.

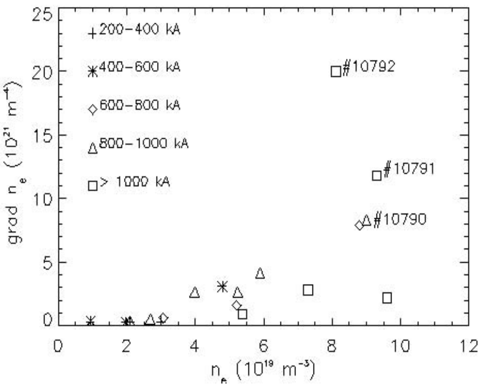

FIG. 2. Density gradients as a function of the average density. The sequence of shots outlined shows the effect of a hydrogen saturated wall. The density gradient increases from shot to shot while the average density remains about constant, indicating a density profile more and more hollow.

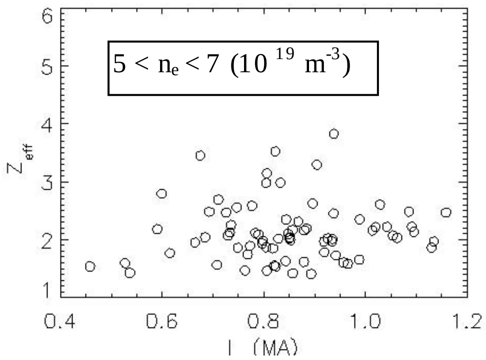

FIG. 3. Zeff versus plasma current for density selected pulses. The estimated error is ±10%.

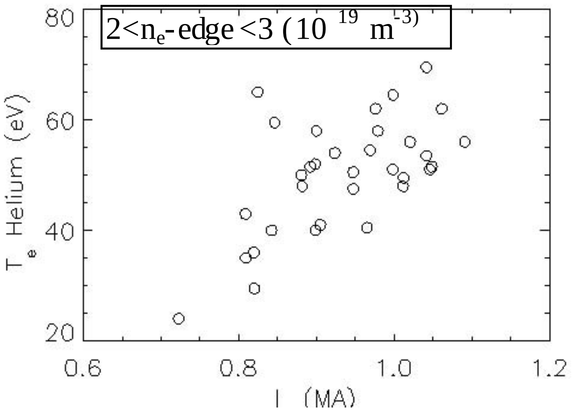

FIG. 4. Edge Te from the He beam diagnostic versus plasma current.

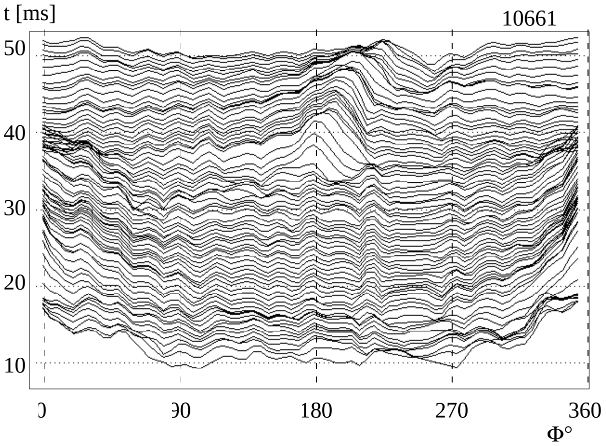

FIG. 5. Evolution of the radial amplitude of the perturbation versus the toroidal angle for the same shot as in Fig. 1. The modes unlock at ≈ 35 ms.