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Issues in the plasma wall interactions in RFX

M. Valisa *, R. Bartiromo, D. Bettella, L. Carraro, S. Costa, P. Martin, S. Martini, R. Pasqualotto, M.E. Puiatti, P. Scarin, F. Sattin, G. Telesca, P. Zanca, B. Zaniol, RFX Team

Consorzio RFX, Corso Stati Uniti, Corso Stati Uniti 4, I-35127 Padova, Italy

Abstract

The standard intrinsic nature of transport in reversed field pinches entails that remarkable ohmic power input (20–80 MW) is involved in the all-graphite, MA level RFX device. MHD instabilities restrict the region of plasma-wall interaction (PWI), where power densities >100 MW m^{-2} may be locally reached. Means for handling such power have been successfully devised to avoid carbon bloom and allow reproducible experiments around 1 MA of plasma current. Improved confinement schemes (quasi-single helicity, pulsed poloidal current drive (PPCD)) corresponding to a more ordered magnetic configuration have opened new operational perspective in which PWI is a less severe problem. However, in general, plasma contamination is not a specific issue. Screening processes have been associated with low ionisation length to Larmor radius ratios and with the presence of an edge radial electric field. Impurities appear to have a role in the formation of the radial electric field by enhancing the ion prompt losses. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

RFX is a large ($a = 0.457$ m, $R = 2$ m) reversed field pinch (RFP) operated so far up to 1.2 MA of plasma current [1], with electron density n_e in the range $0.1–1 \times 10^{20}$ m^{-3}, electron temperature T_e between 150 and 400 eV and a pulse duration of the order of 150 ms.

The very rich MHD dynamics that is at the base of the self-generation processes characteristic of the RFP configuration [2] has two main consequences. First, a degraded transport which, in the RFX case, requires large ohmic input power (20–80 MW) to heat the plasma as well as large average particle fluxes ($>10^{23}$ s^{-1}) to sustain the density. Second, the resonant interference of several MHD modes determines toroidally localised kink-like deformations of the plasma column. These deformations concentrate the power exhaust onto a relatively narrow region of the wall, where power densities may locally depart from the average 1–2 MW m^{-2} and reach the remarkable level of 100 MW m^{-2}. RFX is an all graphite device with neither limiters nor divertors. Above approximately 0.9 MA the power density involved causes tiles overheating, carbon bloom, strong hydrogen desorption and ultimately the loss of the density control, becoming an operational limit.

The following paragraphs describe the progress that has been achieved to mitigate the PWI and perform reproducible discharges up to 1.2 MA. In addition, some considerations on the physics of the RFP edge directly connected to the PWI are presented. An emphasis is given to the screening mechanism that appears to contain the plasma contamination despite the large power applied and on the role of the impurities in generating the radial electric field that is measured at the edge.

2. Wall-mode locking

The CCD image of Fig. 1 is a tangential view of the torus in C II light showing a typical example of the effect

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* Corresponding author. Tel.: +39-49 829 5031; fax: +39-049 8700 718.

E-mail address: valisa@igi.pd.cnr.it (M. Valisa).

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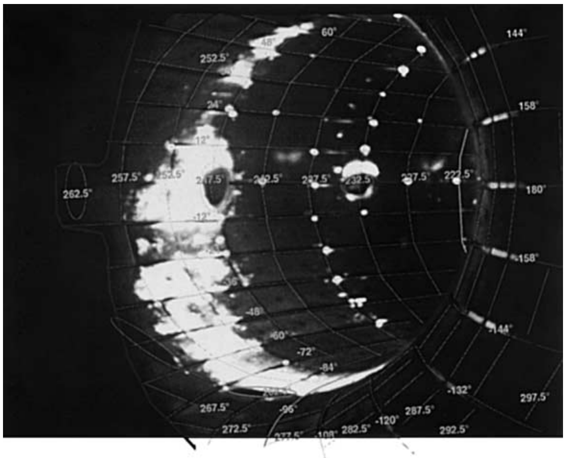

Fig. 1. Tangential view of the torus in C II light (515 ± 2 nm) showing the effects of wall locked modes. A portion of the helical footprint is clearly visible.

of the modes locked in phase and to the wall. Where the largest deformation occurs, the plasma is shifted outwards by several cm [3]. Estimates of the surface temperature at the hot spots have shown that above approximately 1600–1800°C, carbon bloom develops [4]. In general, in the region of the wall-locked modes the brightness of C II, O II and also H_α lines increases by about 50–100 times with respect to the rest of the wall. However, there is evidence that at the locking region, density is typically much higher ($> 1 \times 10^{20}$ m^{-3}) than in the rest of the plasma edge. Several arguments, as well as edge measurements carried out in regions, where the radial deformation is up to 1 cm, indicate that T_e at the locking region should decrease. Including the dependence of the effective atomic cross-sections on the plasma parameters [5] and considering the typical areas involved one can conclude that the wall-mode locking is responsible for approximately 20–40% of the total particle influx. Similar results are found in terms of radiated power.

Not all of the strong PWI events cause blooming phenomena. In many events Z_{eff} does not increase and the large density increase suggests that an amount of hydrogen be released from the wall. The left side of Fig. 2 shows some relevant time traces of a 1 MA shot (#13245) with a remarkable density increase at about 40 ms, an even higher increase of the CV emissivity but just minor effects on Z_{eff}.

The uncontrolled strong hydrogen and carbon release cool the plasma, lead to the loss of density control and also compromise the feasibility of the following pulses, since too a high plasma density during the RFP formation phase hampers the magnetic field reversal. The problem worsens at high currents due to an increase of the power input and above ~0.9 MA it becomes a severe operational limit. One solution has been that of forcing the plasma bulge associated to the locked modes to rotate around the torus so as to distribute the power on a larger surface. This has been accomplished by applying a toroidally rotating $m = 0$ field error with proper amplitude and frequency [6]. Discharge reproducibility has been achieved also at the highest currents (1.2 MA) experimented. On the right side of Fig. 2 it is shown a discharge in which the induced rotation of the perturbation avoids blooming and the current is relatively well sustained. Fig. 3 shows an example of the time behaviour of the impurity monitors in a shot in which the modes have been made rotating: when the magnetic bulge crosses the diagnostic section indeed the C II brightness increases by 50 times. The duration of the event allows an independent estimate of the toroidal extension of the intersection between plasma and wall (about 50 cm in the specific case of Fig. 3). The emission is typically characterised by bursts, which might be an indication of the presence of some dynamics in the modes interference or in the wall response.

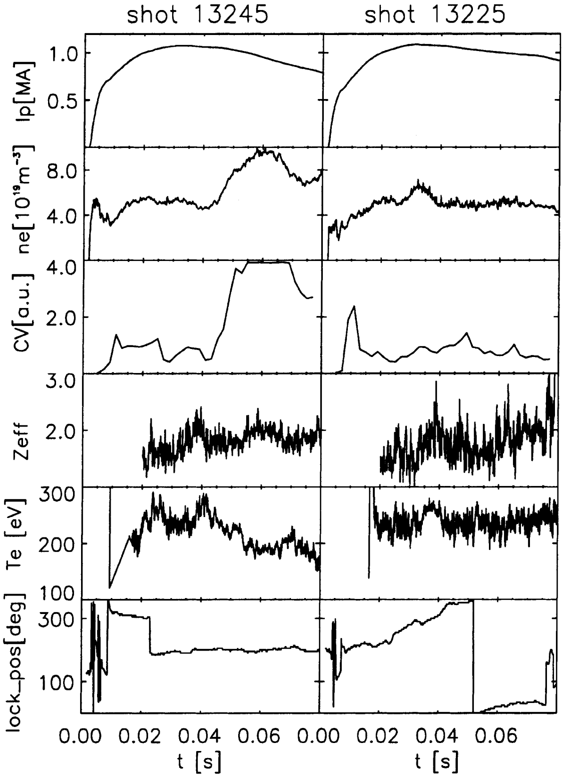

Fig. 2. Comparison between one shot with wall-locked modes (13 245) and one with induced mode-locking rotation (13 225). From top to bottom: plasma current, n_e, CV line emission, Z_{eff}, T_e and the toroidal position of the locked modes.

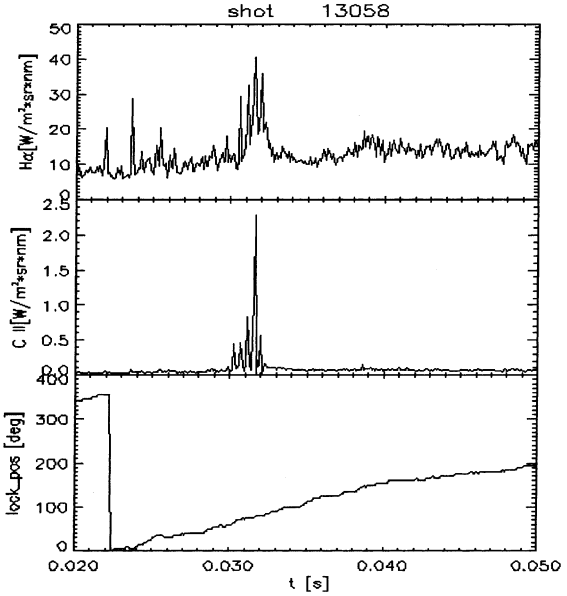

Fig. 3. Time evolution of the H_α (top), C II (middle) emission and locked mode toroidal position (bottom). When the perturbation transits in front of the diagnostic section line, brilliance increases by several factors.

3. Improved regimes

An underlying rich MHD dynamics is not the only possible regime for sustaining an RFP. New operational regimes have been explored in which the intrinsically stochastic magnetic field is either naturally or by active means modified towards a higher order and correspondingly, to an improved transport.

In some circumstances [7,8] states of nearly single helicity may develop, in which the amplitude of one internal mode dominates over all the others. The plasma column deformation features a helical pattern with the shape imposed by the dominant mode (in the RFX case the mode $m = 1$, $n = 7$–9), thus wetting the wall surface over a helical region that spans a portion of the wall much larger than the 40–60 toroidal degrees of the multiple helicity case.

A method for significantly improving transport in RFPs consists of driving poloidal current at the edge. The idea is to help the configuration to produce the toroidal flux and minimise the detrimental effects on transport quality associated with the self-generation mechanism. This can be done inductively with the pulse poloidal current drive (PPCD) [9,10]. The detailed physics of the process triggered by PPCD is matter of debate, however it is found that confinement improves by a factor two, power input decreases, the amplitude of the destabilised modes is reduced with beneficial effects on PWI. Besides the reduction of the plasma column deformation, it is directly found that during PPCD the H_α brightness at the locking region reduces significantly. Because of the intrinsic transient nature of the experiment, PPCD does not represent an immediate solution to the PWI issue in RFX; means to drive continuously poloidal current at the edge of an RFP are currently being investigated.

4. Edge radiative layers

A well-known method to tackle the power exhaust problem is to increase the power radiated at the edge via impurity seeding. Neon seeded plasmas have demonstrated on RFX the compatibility of the RFP configuration with the presence of a radiative layer. At high density the radiated fraction $P_{\mathrm{rad}}/P_{\mathrm{ohm}}$ may change from the typical value of 5–20% to 40–60%, Z_{eff} from 1.5–2 to 3, confinement time may decrease by 10–20% and $P_{\mathrm{ohm}} - P_{\mathrm{rad}}$ can decrease from 40–50 MW to less than 20 MW. Neon injection has the further advantage of reducing both poloidal and toroidal asymmetries of the radiation pattern especially at high densities. This fact may be due to both a slightly larger radial extension of the radiative layer and to the high recycling coefficient of Ne. In RFX, in general, values for the neon radiation efficiency $P_{\mathrm{rad}}/(Z_{\mathrm{eff}} - 1)n_e^2$ in the range of 1–2×10^{-39} MW m^6 are found, i.e., a factor 3–5 higher than predicted by the tokamak scaling [11]: a difference that has been correlated with differences in particle transport in the two confinement systems [12].

5. Impurity screening

Despite the large power involved, impurity concentration is not a particular issue on RFX. Values of Z_{eff} close to 1.5 and a power radiative fraction close to or less than 10% can be obtained at all the plasma currents so far investigated [13].

Monte Carlo simulations of the carbon behaviour have shown that a screening mechanism can be associated to the fact that the ratio ρ between the impurity ionisation length and the Larmor radius of the first ionised stage of carbon is low (between 0.1 and 1) in all the experimental situations, especially due to the relatively low magnetic field at the edge [14]. The above ratio does not change significantly with current, mainly as a consequence of the increase of the edge T_e with current for any given density [15]. Increasing density, which in RFX entails higher edge density gradients, reduces ρ.

The energy with which the carbon atoms are released from the wall is probably largely affected by chemical sputtering. However, the influx of chemically produced carbon (deduced from C_2 molecular spectra at 516.2 nm [16]) results to be 2–5 times the carbon influx deduced form the C II emission lines, suggesting that only a small fraction of the chemical production enters the plasma. Moreover, the average carbon yield is seen to be a decreasing function of the hydrogen flux, as expected in case of chemical sputtering [17] and as it is documented in Fig. 4. The scatter of the data in Fig. 4 can be ascribed to the fact that the data have not been selected according to edge density and temperature or to the wall surface temperature. The analysis of the H_α emission line, see Fig. 5, shows that hydrogen also seems to enter the plasma with relatively low energies ($\sim$1 eV) and that only in the region of the wall mode locking a small component of reflected atoms with energies up to 20–40 eV appears.

Another term relevant to the screening mechanism is the presence at the edge of a radial electric field E_r. In fact, sputtered atoms are shifted inward or outward according to whether they are ionised in the region of the negative or positive field. E_r, measured by inserted probes and consistently estimated by impurity flow velocity spectroscopically evaluated, is negative (inward directed) close to the wall (≈ -3–7 kV/m), and becomes positive further inside the plasma ($\approx$1.5 kV/m). The origin of the negative E_r can be predicted by the Monte Carlo code in a self-consistent way as the result of the balance between the plasma momentum losses-prompt ion losses and charge exchange processes, – the momentum input in the form of a return current that compensates for the ionic losses, and the diamagnetic term.

The main ingredients that define E_r over a radial shell of a few Larmor radii close to the wall are the neutral density, which reduces the absolute value of the negative electric field, and the impurities, which deepen E_r by dominating the ion prompt losses due to their large Larmor radius [18]. The electron density acts in the sense of deepening the electrical field by increasing the ion Larmor losses through an increased collisionality, while an increasing plasma current tends to shrink the shell, where the electrical field is negative by reducing the Larmor radii.

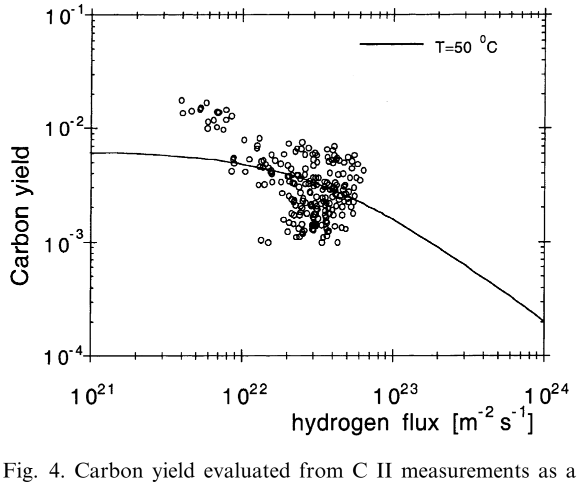

Fig. 4. Carbon yield evaluated from C II measurements as a function of the hydrogen influx. The continuous curve is the expected chemical erosion yield according to [18].

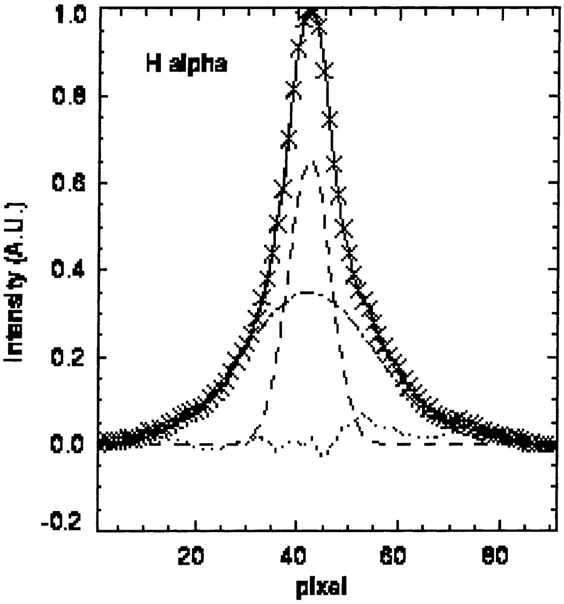

Fig. 5. H_α spectral line fitted with two Gaussian curves. The narrow component corresponds to a temperature of $\sim$1 eV, the large one to $\sim$10 eV (charge exchange) while the asymmetric feature, residual of the fit and interpretable as due to reflected particles, extends to energies of $\sim$40 eV. Zeeman effect has been verified to be negligible. Instrumental dispersion is 0.1 Å/pixel.

Impurities appear to have an important role in creating the radial electrical field shear at the edge, which is in general associated to stabilising effects on turbulent modes. Indeed in RFX the edge is the region where the highest pressure gradients are observed.

6. Conclusions

In RFX, large densities of exhausted power (>100 MW m^{-2}) can be successfully handled on the time scale of the discharge. By introducing proper field errors, localised PWI associated with the locking in phase of several MHD modes can be forced to rotate toroidally, thus smearing the power over a large portion of the wall.

Improved regimes of operation have to some extent relaxed the issue of the PWI. Quasi-single helicity states increase the surface of the wall wetted by the plasma. Although of transient nature, PPCD improves transport, reduces the power input and the amplitude of the modes, thus suggesting that active reduction of the toroidal magnetic field self-generation would largely be beneficial in mitigating the PWI.

Neon seeded discharges have shown that the RFP configuration is compatible with a highly radiative layer at the edge at least in high density regimes, and have been effective in reducing the convection losses on to the wall with only minor degradation of confinement.

Impurity screening mechanisms have been associated with the relatively small ratio between ionisation length and Larmor radius, and to the presence of a radial electric field at the edge. Impurities themselves appear to have a role in determining the radial electric field shear at the edge, in a region where indeed the largest pressure gradients are observed.

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