RECENT PROGRESS IN RFP RESEARCH ON THE RFX EXPERIMENT

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Abstract

This paper presents an overview of recent experimental results obtained on the RFX device. We succeeded in obtaining and study RFP plasma with a plasma current up to 1 MA with negligible radiation losses and low effective charge. The local power and particle balance shows that in standard operation the plasma core is dominated by magnetic turbulence and that the global confinement is mainly provided by the edge region where a strongly sheared radial electric field is present. With poloidal current drive the amplitude of magnetic fluctuation and the thermal conductivity of the plasma core are reduced leading to improved confinement. Reduced heat transport is also observed when the width of the n spectrum of magnetic fluctuations is reduced.

1. INTRODUCTION

With its dimensions (R=2m, a=0.46m) RFX is one of the three large RFP experiments in the world. It is unique in its volt-second capability and power supply system that allow for a plasma current up to 2 MA and a pulse duration up to 0.25 s with full control of current and field waveforms [1]. The overall goal of the RFX project is to study the physics of the RFP configuration at high plasma current to assess its potential for reactor application.

In RFX the magnetic configuration can be reliably produced for a pulse duration much longer than the resistive decay time with a variety of setting up, showing that the dynamo mechanism driving the poloidal current in the plasma is quite robust[1-2]. On the contrary the thermal behaviour of the discharge and its plasma resistivity show a remarkable dependence on the fine tuning of the configuration with respect to field errors at the gaps of the conductive shell and to the plasma horizontal position. Indeed with its ohmic power input exceeding the level of 20 MW, RFX relies on the possibility to distribute smoothly the heat load on its graphite first wall. However it has become increasingly evident that the possibility to minimise the radial magnetic field at the first wall is limited by a natural tendency of a RFP plasma to break symmetry due to mode locking phenomena: unstable MHD modes, saturated at finite amplitudes, lock in phase and to the wall already during the setting up of the configuration and produce a helical deformation of the magnetic surfaces which causes enhanced plasma-wall interaction [3].

In the recent years the experimental programme of RFX has been confronted with the issue of understanding the limitations on plasma performances caused by localised plasma-wall interaction and of finding operational ways to overcome them or ameliorate their consequences. In parallel the nature of the helical deformation has been addressed and clearly related to the mechanism driving the magnetic dynamo. Finally the best performing discharges have been diagnosed in details to gain information on the mechanisms driving energy and particle transport in a RFP and to identify possible routes to improve the properties of the configuration with respect to plasma confinement.

Correspondingly this paper is structured in four parts: in section 2 we discuss our measurements of radiation losses and effective charge under various operating conditions. In section 3 our present understanding of the dynamo mechanism and of its relation with mode locking is discussed. In section 4 we summarise the results of our transport studies. Enhanced confinement regimes are discussed in section 5 and our conclusions are presented in the last section.

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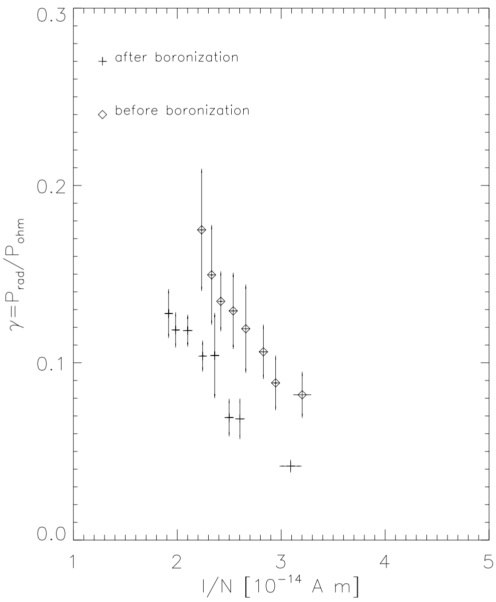

FIG. 1 Radiated power fraction as a function of the ratio I/N (N being the surface integrated electron density) for plasma discharge with I_p=0.6 MA. Open dots (crosses) were obtained before (after) boronization.

2. PLASMA-WALL INTERACTION

Plasma wall interaction in RFX can lead to intolerable impurity influx. This is clearly shown in standard discharges with plasma current at the MA level, where carbon blooming at the toroidal location of the helical deformation and consequent discharge termination are usual features. We had therefore to assess the effect of impurities in terms of radiation losses and increased resistivity, when documenting RFX discharges for physics studies, and to identify viable strategies to improve its performance. Due to the non uniformity of the power deposition to the wall, a good diagnostic coverage of the plasma surface has been necessary to evaluate quantitatively impurity influxes and radiation losses.

Radiation losses have been routinely measured by an integrated SXR and bolometric tomographic diagnostic. A considerable effort has been dedicated both to the study of the emissivity distributions and to their dependence on plasma parameters. Maximum entropy reconstruction of tomographic measurements confirm that most of the radiation comes from an outer layer whose width is 0.15-0.3 of the plasma minor radius. The radiated fraction increases with the electron density, ranging typically between 5% to 20% of the input power, Fig. 1, and reaches a minimum when the first wall is freshly boronized. Therefore radiated power is usually a negligible loss channel except at very high densities, where it could be responsible for the observed saturation of global confinement with density, and in discharges where carbon blooming is observed. Analysing in more detail the space structure of total radiation losses it has been observed that they are localised in the edge and asymmetric both in the toroidal and in the poloidal directions. In the toroidal direction strong enhancement of radiated power is observed in the region of the helical deformation. A careful analysis [4] has shown that this region may be responsible of approximately 30 to 50% of the total power lost by radiation. Similarly, the impurity influx from this region is of the order of 50% of the total one. Far from the helical distortion, poloidal asymmetries are observed in the emissivity profiles which correlate with plasma horizontal position. A displaced plasma equilibrium leads to a larger localised influx of impurities, which in their lower ionisation states are mostly responsible for radiation. This kind of asymmetry has been found to change with plasma density, the radiating layer being more symmetric at higher densities.

Despite the large power load to the graphite and provided carbon blooming is avoided, the plasma effective charge is relatively low and similar to that found in tokamaks for the same electron densities. The main contribution to Z_{eff} comes from oxygen and carbon, while metals have only seldom shown up in the spectra. The result of a density scan performed with Ip = 0.6 MA is displayed in Fig. 2. We observe Z_{eff} values and a density dependence identical to those of an equivalent ohmically heated tokamak with values close to unity at high density and with boronized walls. On the contrary, we observe that Z_{eff} doe not increase when plasma current is increased at constant plasma density, despite the increased ohmic power. A consistent picture of the

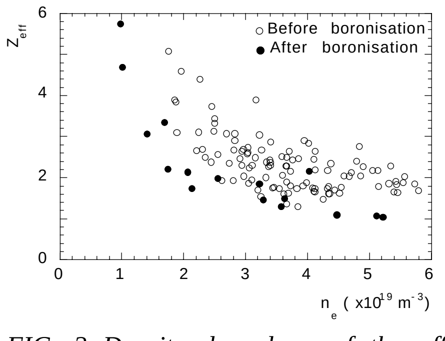

FIG. 2 Density dependence of the effective charge, as deduced from continuous visible emission for plasma discharge with I_p=0.6 MA. Open (closed)dots were obtained before (after) boronization.

impurity content in RFX has been obtained with a diffusion code which can satisfactorily reproduce bolometric losses, visible bremsstrahlung, impurity influxes and soft X-ray emission profiles [5]. A study of the mechanisms behind the observed impurity behaviour is presented in a companion paper at this conference [6]. It turns out that the value of effective sputtering coefficient in RFX is similar to the value reported in tokamaks and this in turn is due to similar values of temperature in the SOL. Screening of impurities, as deduced with the help of a Montecarlo code, can be very effective due to the steep gradient of density at the edge [7].

Among the various conditioning procedures, boronization with diborane has produced the most beneficial effects. In fact, after wall boronization Z_{eff} value approaches unity and the radiation barrier moves towards higher densities, i. e. in the parameter region where the best confinements are found. Boronization together with carefully dosed glow discharge cleaning in helium and hydrogen has been particularly effective in improving the control of the hydrogen recycling, otherwise essentially determined by the graphite wall. Further recycling control capability has been gained with hot wall operations (T=280 °C) especially at high currents. The beneficial effect of the boronization procedure however lasts for about fifty shots when the plasma current exceeds the MA level. The reduced capability of oxygen trapping has been associated to the formation of hydrogenated carbon-rich layers, originated by erosion phenomena due to localised plasma-wall interaction [8]. The analysis of the time evolution of vessel temperature between shots has shown that more than 40% of the input power is deposited in the region of the locked deformation. This information has been used to evaluate the temperature distribution on tiles located in the locking region. Calculations show that carbon blooming at the edge of such a tile is reached after 40 ms in discharges with 1 MA plasma current as indeed observed. In these conditions carbon bloom is avoidable if the helical deformation can be reduced or shifted toroidally during the discharge as recently achieved, see next section.

3. DYNAMO PHYSICS AND LOCKED MODES

Studies conducted in this area have addressed the issue of the influence of boundary conditions, and notably of the plasma-shell distance, on the dynamo mechanism and its relation with the phenomenon of mode locking. More recently we have focused our efforts on the possibility of controlling the position of the helical deformation with external means. All mechanisms proposed to explain the dynamo rely on the non linear interaction of low-m resistive MHD modes resonant inside the reversal surface, usually referred to as dynamo modes.

The poloidal electric field generated by the dynamo is found also in three-dimensional numerical simulations [9-10-11] and has been experimentally measured [12]. Both simulations and experiments show that periodical discrete relaxation events (DRE) are involved in the mechanism and generate at least a fraction of the plasma toroidal flux. Marginal stability to dynamo mode seems to be a natural requirement to sustain the RFP configuration in inductively driven toroidal discharges and indeed the analysis of magnetic measurements has shown that the current profile in RFX is consistent with the requirement of marginal stability to internal resistive m=1 modes [13].

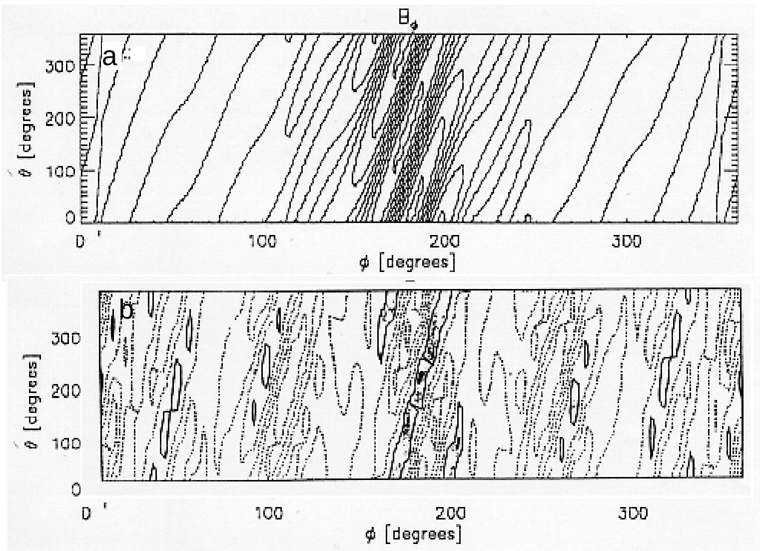

FIG. 3 a) Measured pattern of the toroidal component of the magnetic field as measured on the inner surface of the conductive shell. b) the same pattern as computed in three dimensional MHD simulations. .

Numerical simulations also predict that the dynamo modes in their non-linear interaction have a natural tendency to lock in phase among themselves [9]. We gathered clear experimental evidence that the helical deformation of the plasma column is caused by dynamo modes. A Fourier analysis in real space shows that the helical deformation is composed of modes resonant inside the reversal layer [14].

These modes increase during DRE [15] while they decrease systematically when the dynamo action is reduced by external poloidal current drive, see section 5. Moreover magnetic measurements of this deformation are well described by a model where helical currents are added to an axisymmetric current profile on the corresponding resonant surfaces of the main dynamo modes seen in RFX and the toroidal flux generated during DRE is well accounted for by the variation of these helical currents [16]. Finally the observed pattern of the toroidal field on the inner side of the conductive shell is very similar to the results obtained by three dimensional numerical simulations [11] as shown in Fig. 3. The influence of shell proximity on the dynamo mechanism has been studied using discharges with shifted equilibria and by a comparison of RFP devices with different shell proximity. The analysis shows that with increasing shell distance the current distribution evolves toward a fully relaxed Taylor profile where the ratio of parallel current to the total magnetic field remains constant over the plasma cross-section [16]. This is consistent with the marginal stability requirement but entails a larger toroidal field generation for larger plasma-shell separation. Although this increase of field is only of the order of 20% for RFX parameters, the question arises of whether the stronger action required to the dynamo does not imply an increase in the mode amplitude which can badly affect plasma performances. For this reason we have carried out a careful comparison of similar discharges obtained in RFX and MST, where a closer distance between shell and plasma exists. The results of this analysis have shown that during standard operation similar macroscopic behaviour and confinement properties are obtained in the two devices [17]. Although the shell proximity does not seem to have a strong influence on plasma behaviour, a conductive shell close to the plasma brings the benefit of reducing the radial component of the magnetic field at the wall due the helical deformation, thereby alleviating the problem of localised heat deposition. Also a good magnetic design of such a shell, where errors due to gaps and portholes are minimised, helps to reduce the electromagnetic torque on the dynamo modes, thereby avoiding the locking of the helical deformation to the wall, as observed in some circumstances in MST. Strict limits on shell proximity are dictated by linear MHD stability theory for modes not directly involved in the dynamo mechanism, namely for m=0 modes and for modes resonating outside the reversal layer. Since they are located in the good confinement region of a standard RFP, they can have a strong impact on the confinement properties of the configuration. However m=0 modes, predicted to be usually unstable for RFX conditions, become relevant only during dynamo relaxation events while modes resonant outside the radius of reversal, also predicted unstable, are never observed. Because of the need of minimising localised heat deposition to operate RFX with a plasma current above the MA level, a large fraction of the experimental effort in this field has been devoted to the issue of wall locking. Minimising the error at the gaps through feedback systems was instrumental in achieving a uniform distribution over different discharges for the toroidal position of the helical deformation. We were also successful in influencing the locking position by applying a toroidally localised perturbation to the toroidal field. This produces a m=0 radial field which interacts with the m=1 dynamo modes through non linear effects. In a series of discharges with static perturbation we could localise the deformation with almost 100% reliability. These results have motivated a modification of the toroidal field power supply to

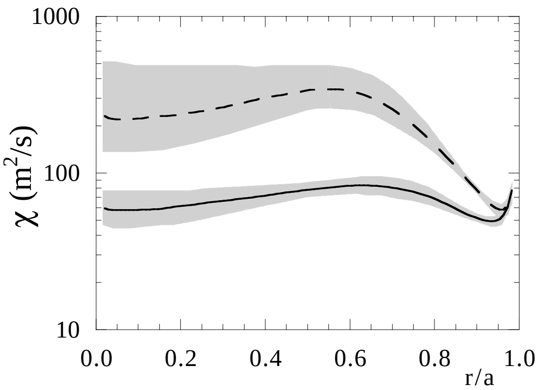

FIG. 4 The radial profile of thermal conductivity during standard operation (dashed line) and during poloidal current drive (solid line). The dashed region around each profile corresponds to 25%-75% confidence interval, as estimated with a Montecarlo code.

sweep the perturbation toroidally during the discharge. With this method we were able to shift the region of high heat load on the first wall during the discharge allowing operation at high current without carbon bloom. More details are given in a companion paper at this conference [18].

4. ENERGY AND PARTICLE TRANSPORT

The energy and particle local balance were studied in standard discharges by the analysis of density and temperature profiles. A clear variation of temperature profiles with plasma parameters has been found with more peaked profiles being observed at low plasma density and high plasma current. Edge and core region show different behaviour [19] . In fact the edge gradient does not show any appreciable density dependence, whereas the slope of the profile in the intermediate region increases as density is lowered (i.e. when the ratio I/N is higher, N being the surface integrated electron density). The density profiles are flat or slightly peaked in the centre at low density and become hollow at high density, with large density gradients only in a region of a few centimetres from the edge [20]. A detailed transport analysis of density profiles indicates that an outward convective velocity, V, is required to explain the stationary and hollow profiles observed at high density. An interpretative analysis [20] suggests that the density dependence of the shape of the profiles could be explained by the same core transport mechanism coupled to changes in the source profiles and edge diffusivity. Experimental profiles can be satisfactorily reproduced by the V and D values derived by the Rechester Rosenbluth's theory of diffusion in a stochastic magnetic field [21]. In the framework of this theory, the global convective velocity would be composed of the inward $\mathbf{E}_\phi \mathrm{x} \mathbf{B}_\theta$ drift (the main classical term in RFPs), and of an additional outward particle flux proportional to the temperature gradient [22]. The differences found in the outer region ($r/a \geq 0.9$) cannot be explained in term of stochastic transport. In fact the estimate of D in this region for the low and the high density case cannot be justified since neither large differences in the temperature (a factor ≥ 10 would be necessary), nor a dependence of the magnetic fluctuation on density is seen in that region. Some other mechanism seems to be responsible for transport in the $r/a > 0.9$ region [20]. The local power balance in RFX shows that most of the energy loss is due to transport and that in standard operation the profile of thermal conductivity χ has a minimum very close to the edge, as shown in Fig. 4. The signature of magnetic turbulence on core transport is seen from the ratio χ/D, which is consistent with the square roots of the ion mass, and from the reduction of conductivity with increasing Lundquist number [19]. The value of χ at the edge has been found to decrease with increasing density while an increase is observed in the core. This implies that the observed increase of the global confinement time with density is due to the properties of the edge region. Particle diffusivity in this region also shows a favourable dependence with increasing density [20]. The most interesting feature of the edge region of RFX consists of a sheared radial electric field with shearing rate comparable to tokamaks [23]. The resulting $\mathbf{E}\times\mathbf{B}$ velocity is in agreement with direct measurements of the plasma flow velocity, as measured by Langmuir probes, which have given for 0.5 MA discharges a velocity shear of the order of 10^6 s^{-1} across the last closed magnetic surface (LCMS). This is comparable to the naturally occurring velocity shear observed across LCMS in tokamaks and stellarators and has a similar origin related to the different dynamics of ions and electrons along open field lines. A remarkable feature of RFX is the presence of a spontaneous second velocity shear region just inside the LCMS where the gradient of the radial electric field is negative. The velocity shear in this second region increases almost linearly with the plasma current and its width scales with the Larmor radius. A mechanism based on ion losses on unconfined gyro-orbits can explain the generation of plasma flow [24].The fluid velocity associated with the radial field has been also studied by spectroscopic measurements of Doppler shift of impurity lines. It is essentially perpendicular to the local magnetic field at the edge and becomes nearly parallel to it moving toward the core [25]. Once again two different mechanisms of flow generation seem to be acting in the core and in the edge region.

The value of the flow measured in the region outside the reversal layer is consistent with stabilisation of external resistive mode when the presence of the liner is taken into account.

Probe measurements and reflectometry have been used to characterise the edge turbulence as reported in more detail in a companion paper at this conference [26]. These studies have shown that energy and particle transport driven by magnetic turbulence becomes negligible in this region, thus confirming MST results [27]. Electrostatic turbulence is responsible for particle transport and the particle diffusivity is in agreement with the results of the analysis of density profiles reported above. Only a fraction of about 30% of the total energy flux can be accounted for by electrostatic turbulence and the driven flux is almost convective in nature [28]. These measurements have also shown that a reduction of particle diffusivity is associated with the shear layer mainly caused by a decrease of coherence between density and velocity fluctuations. The BDT criterion for shear decorrelation of turbulence has been tested and found to be marginally satisfied [29].

5. ENHANCED CONFINEMENT REGIMES

Reducing the impact of magnetic turbulence on core transport has become one of the major challenges of the RFP research. This requires to interfere with the dynamo mechanism to reduce the stochastic region created by internal tearing modes. External poloidal current drive is an useful tool since it reduces the need of the dynamo and/or can modify the current density profile, stabilising modes and reducing the associated particle and energy transport. Tests of this concept performed on the MST reversed field pinch with a technique named Pulsed Poloidal Current Drive (PPCD) supported this hypothesis showing strong reduction of magnetic fluctuations measured at plasma edge and suppression of sawteeth MHD activity [30]. We adopted this technique in RFX by applying a series of one to five poloidal voltage pulses on the toroidal field winding and obtained reduction of magnetic fluctuations at various plasma current levels. Results of a 0.8 MA PPCD experiment are shown in Fig. 5. In a range of I/N and F, we can reproducibly obtain improvements in many plasma parameters lasting, in the best cases, for several milliseconds, i.e. for a time greater than the energy confinement time which is of the order of 1 ms for standard RFX discharges. We always find a strong increase of soft X ray emission and a peaking of its profile, confirming that PPCD is able to drive changes in the whole plasma configuration and not only at the edge. The time evolution of on-axis T_e reveals an increase up to 75% with respect to the pre-PPCD value in the best cases (Fig. 5). Electron temperature radial profiles have been measured near the maximum of the soft X ray emission: a clear evidence has been obtained of a peaking of T_e profiles during PPCD while electron density shows a little decrease without profile modification. Reduced plasma wall interaction is usually observed during PPCD and is attributed to the decreased amplitude of locked mode perturbation. Z_{eff} and total radiation losses decrease, particularly in the outer equatorial edge region, where the main interaction with the wall is concentrated because of the Shafranov shift of the plasma. A careful comparison with the performance of stationary discharges with high Θ values, comparable to the post-PPCD ones, shows that amplitude of magnetic fluctuations is lower and peaking of the T_e profiles is larger during PPCD. These features can therefore be interpreted as due to the reduction of dynamo action induced by PPCD and not simply as an effect of a transition to higher values of Θ. An increase of poloidal beta by 30-40% has been evaluated from the integration of profiles, assuming T_e=T_i. For the calculation of the energy confinement time, τ_E, the ohmic input power has been estimated using the equilibrium μ&p model to compute the contribution from the variation of the plasma internal magnetic energy: τ_E can double during the period of poloidal voltage application, reaching a value of 2 ms which can be maintained for more than 5 ms in the best cases. As an alternative approach we have estimated the ohmic input power by mean of the ohmic dissipation taking into account the Spitzer resistivity, the measured electron temperature and Z_{eff} and again modelling the current profile with the μ&p model obtaining results in good agreement with the previous calculation. The beneficial effects of PPCD on the core plasma are best shown by the analysis of local power balance [31]. The improved confinement during PPCD is due to a reduction

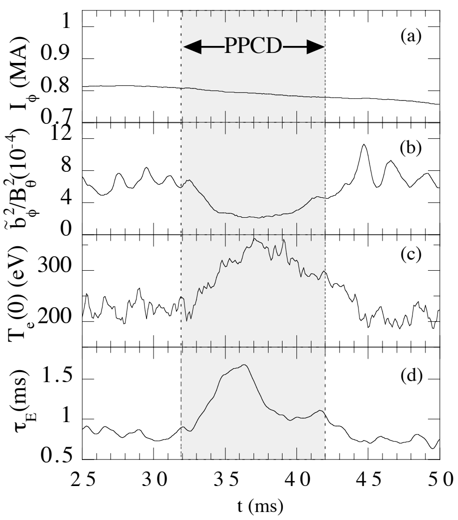

FIG. 5. Waveforms of (a) plasma current, (b) normalised mean square of the toroidal component of the fluctuating magnetic field, (c) on-axis electron temperature (d) energy confinement time during pulsed poloidal current drive experiments.

of χ in the core to a value similar to the edge as depicted in Fig. 4. This reduction is consistent with the Rechester-Rosenbluth expression for magnetically driven transport and the observed reduction in the amplitude of magnetic fluctuations. Recently some spontaneous transitions to an improved confinement regime have been seen in RFX during normal operation. This regime is associated to a peaking of the current profile and has been dubbed α-mode. It is observed during the current ramp-down and can last for several ms. Its typical signature is a slowing down of the current decay accompanied by a decrease of loop voltage and an increase of SXR emission. In the α-mode we systematically observe a remarkable modification of the n spectrum of m=1 modes which becomes sharply peaked around n=8-9 with all modes with n>9 being reduced to a value much below their normal amplitude. Such single helicity states are expected to have a reduced stochastic region and seem to be at the origin of many diverse observations of enhanced confinement in RFPs [32]. In this respect it is useful to note that often our best PPCD pulses evolve toward a single helicity magnetic spectrum.

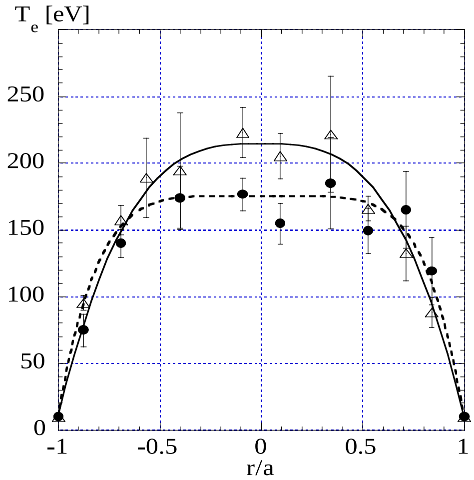

FIG. 6. T_e profiles from Thomson scattering: triangles -> pre-pellet data, circles ->post pellet data

Enhanced energy confinement has also been observed in set of H pellet injection experiments in discharges with I_p= 0.6-0.8 MA. The RFX 8-pellet injector was used to fire mainly ‘small’ pellets of $1.5 \cdot 10^{20}$ atoms at velocity of 400÷500 m/s, which were generally completely ablated in the plasma core. Pellet injection proved to be useful to peak the density profiles, allowing to achieve transient improvements of the plasma β and confinement time, and as a diagnostic tool for particle and energy transport analyses. When a pellet is injected in the RFX plasma, despite the relative large perturbation in the density profile and central value, very little effects are produced on the plasma current, loop voltage, total radiated power, H_α emission, reversal and pinch parameters F and Θ. A drop in the central electron temperature in the range 50÷130 eV is generally observed with a transient flattening of the profile as shown in Fig. 6. The temperature recovers the pre-pellet central value and profile in 2-4 ms. The initially flat or slightly hollow density profile, which is typically found in the medium/low density regimes where the pellet are injected, becomes centrally peaked with a maximum peaking factor $n_0/\langle n \rangle$ which ranges between 1.5 and 2. The profile then diffuses back to the original one in a time of 1-5 ms. The faster diffusion times are generally due to a MHD Dynamo Relaxation Event (DRE), which is triggered when the pellet reaches and cools the plasma core. In DRE-free cases, obtained more frequently by injecting pellets during the improved confinement phase produced by PPCD, a fast re-heating is seen and τ_E is found to increase by a factor about 1.5 for a few confinement times.

6. CONCLUSIONS

The experience gained with RFX has shown that a RFP configuration can be maintained for times longer than resistive diffusion time by the dynamo mechanism. However the resort to the dynamo implies a breaking of the toroidal symmetry with a consequent localisation of the heat flux to the wall. The use of a conductive shell near to the plasma helps to overcome this problem but for long pulses an active control of the position of the helical deformation is required. We have shown that such a control is achievable by using the toroidal winding of the device and this has allowed for the first time to run 1 MA discharges with reduced Z_{eff} and radiation losses. Beside breaking symmetry, the need of the dynamo also causes a deterioration of magnetic surfaces in the plasma core leading to high values of thermal conductivity there. Thermal insulation is therefore provided mainly by a thin layer at the plasma edge. The nature of thermal transport in this layer is still unclear and it is expected that a better understanding will offer the possibility to increase its extension and/or to reduce its thermal conductivity. However, to continue to consider the RFP as a viable option for a fusion reactor, it is necessary to recover an acceptable level of thermal insulation also in the plasma core. Pulsed poloidal current drive constitutes the first step in this direction and experimental results show that it is indeed capable to improve core confinement. Additional improvement could be offered by the possibility to run a RFP discharge in a nearly single helicity state. By combining these two approaches and with the support of good plasma diagnostics, we aim to improve confinement properties in a wide current range and to give better insight into the physics of low field magnetically confined plasmas. Further progress in the direction of reactor application can be expected if effective tools to modify and interact actively with the plasma are identified and deployed in the experiment. This requires a shift in plasma engineering from an approach based on an optimised passive control through conductive elements to a new one based on the adoption of active control techniques for magnetic configuration, current profile, plasma rotation and mode spectrum. The results presented in this paper indicate that this is a valuable and viable approach.

REFERENCES

[1] G. Rostagni, Fusion Engineering. and Design **25**, 301 (1995)
[2] V. Antoni et al., in Proc. 15th IAEA Conf. on Fusion Energy 1994 Vol II, 405 (1995)
[3] V. Antoni et al., in Proc. 16th IAEA Conf. on Fusion Energy 1996 Vol II, 711 (1997)
[4] L. Marrelli et al, Edge localized asymmetric radiative phenomena in RFX, in Proc. 13th Plasma Surface Interaction Conference, to be pubblished in Journ. Nucl. Mat.
[5] L. Carraro et al, in Proc. 24th EPS Conf. on Controlled Fusion and Plasma Physics, Vol I, 329 (1997).
[6] P. Sonato, M. Valisa et al, paper EXP3/14 at this conference
[7] F. Sattin et al., Modelling of carbon behaviour in the edge plasma of RFX, to be pubblished in Proc. 25th EPS Conference on Controlled Fusion and Plasma Physics.
[8] L. Tramontin et al, Erosion, redeposition and boronization lifetime in RFX, in Proc. 13th Plasma Surface Interaction Conference, to be pubblished in Journ. Nucl. Mat.
[9] K. Kusano and T. Sato, Nucl. Fusion **30**, 2075 (1990)
[10] Y. l. Ho, S. C. Prager and D, D. Schnack, Phys. Rev. Lett. **62**, 1504 (1989)
[11] S. Cappello and D. Biskamp, Nucl. Fusion **36**, 571 (1996)
[12] D. J. Den Hartog et al, in Proc. 16th IAEA Conf. on Fusion Energy 1996 Vol II, 83 (1997)
[13] R. Paccagnella, Nucl. Fusion **38**, 1067 (1998)
[14] A. Buffa et al., in Proc. 22th EPS Conf. on Controlled Fusion and Plasma Physics, Vol I, 458 (1994).
[15] L. Marrelli et al., Proc. 1996 ICPP Conf., vol I, pag. 974.
[16] S. Martini et al., Sponteneous and driven reduced turbulence modes in the RFX Reversed Field Pinch, to be pubblished in Plasma Phys. and Control. Fusion
[17] T. Bolzonella et al, Comparison of plasma confinement properties in the RFX and MST experiments under similar stationary conditions, to be pub. in Proc. 25th EPS Conf. on Contr. Fusion and Plasma Physics.
[18] S. Martini, R. Piovan et al, et al, paper EXP3/13 at this conference
[19] P. Franz et al, Local energy balance and transport in RFX standard and enhanced plasmas, to be pub. in Proc. 25th EPS Conf. on Contr. Fusion and Plasma Physics.
[20] D. Gregoratto et al Nucl. Fusion **38**, 1199 (1998)
[21] A. B. Rechester and M. N. Rosenbluth, Phys. Rev. Lett. **40**, 38 (1978)
[22] S. Hokin, Nucl. Fusion **37**, 1615 (1997)
[23] Antoni V. *et al*. Phys. Rev. Lett. **79**, 4814 (1997)
[24] R. Bartiromo Physics of Plasmas **5** 3342 (1998)
[25] Carraro L. *et al.*, Plasma Phys. and Control. Fusion **40**, 1021 (1998)
[26] V. Antoni, P. Martin et al, et al, paper EXP3/15 at this conference
[27] G. Fiksel et al. Phys. Rev. Lett. 72, 1028 (1994)
[28] E. Martines et al, Energy flux driven by electrostatic turbulence in the RFX edge plasma, sub. Nucl Fus.
[29] V. Antoni et al. Phys. Rev. Lett. 80, 4185 (1998)
[30] S. Sarff et al Phys. Rev. Lett. 78, 62 (1997)
[31] R. Bartiromo et al. Core transport improvement during pulsed poloidal current drive in the RFX Reversed Field Pinch, submitted to Phys. Rev. Lett.
[32] P. Martin, Magnetic and thermal relaxation in the reversed field pinch, to be pub. in Plasma Phys. and Control. Fusion