ELSEVIER

Journal of Nuclear Materials 290–293 (2001) 729–732

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Study of edge plasma properties comparing operation in hydrogen and helium in RFX

M. Spolaore [a,*], V. Antoni [a,b], M. Bagatin [a,b,c], D. Desideri [a,b,c], L. Fattorini [a,b], E. Martines [a], G. Serianni [a], L. Tramontin [a], N. Vianello [a,b]

[a] *Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy*
[b] *INFM, Unita'di Padova, Sez. A, Italy*
[c] *Dipartimento di Ingegneria Elettrica, Universita'di Padova, via Gradenigo 6/A, Padova, Italy*

Abstract

The properties of the edge plasma in the reversed field pinch RFX have been investigated by comparing the operation in helium with those normally performed in hydrogen. It has been found that a spontaneous velocity shear layer takes place in the edge region also in helium discharges. The edge structure of hydrogen and helium discharges have been interpreted using a momentum balance equation, which takes into account anomalous viscosity and friction with neutrals. The electrostatic turbulence properties are also compared: it is found that electrostatic turbulence drives most of the particle losses and a small fraction of the energy losses also for the He discharges. The modifications of the mean profiles, including the $\mathbf{E} \times \mathbf{B}$ velocity, during PPCD are briefly discussed and compared with the results obtained in hydrogen.

Keywords: RFX; Plasma edge; Helium

1. Introduction

In most reversed field pinch (RFP) experiments it has been observed that a radial electric field builds up in the outer region of the plasma. This field gives rise to a toroidal $\mathbf{E} \times \mathbf{B}$ drift velocity which in RFX, for standard discharges in hydrogen, is of the order of 10^4 m/s and exhibits a double shear with values of around 10^6 s^{-1}. At the edge, the negative radial electric field is similar to that established in tokamaks and stellarators. The radial electric field in RFP's changes sign in the outer region, becoming positive in the plasma core [1]. The $\mathbf{E} \times \mathbf{B}$ velocity shear has been found to play an important role in controlling the electrostatic turbulence at the edge being high enough to marginally fulfill the turbulence decorrelation criterion [2]. This feature, originally observed in standard discharges, has been confirmed by edge biasing experiments in RFX in which an electrostatic transport reduction was measured by increasing the velocity shear [3]. In order to clarify the origin of the radial electric field at the edge, RFX has been operated using hydrogen and helium as filling gas and modifying the radial electric field by pulsed poloidal current drive (PPCD). In this paper, the results of these experimental campaigns are presented and discussed in terms of a fluid model.

2. Experimental setup

RFX is an RFP device with minor radius $a = 0.457$ m and major radius $R = 2$ m. The outer region is defined as the region between the wall and the $B_\phi = 0$ surface.

Two types of diagnostics based on Langmuir probes have been used to measure the profiles of temperature, density, electrostatic particle and energy fluxes and radial electric field. The first probe, called 'rake' probe [3], measures the floating potential V_f in seven radial positions equally spaced by 8 mm and it has been placed at 217° toroidal position. The plasma potential is related to

* Corresponding author.
E-mail address: spolaore@igi.pd.cnr.it (M. Spolaore).

0022-3115/01/$ - see front matter
PII: S 0 0 2 2 - 3 1 1 5 (0 0) 0 0 5 3 1 - 6

the floating potential through $V_p = V_f + \alpha T_e$, where $\alpha = 2.5$ for a H plasma [1]. Using the same procedure described in [1] α results 3.3 for He discharges. The radial electric field has been approximated by the floating potential gradient, since this is much larger than the temperature gradient in the explored region. The second diagnostic, named fluctuation insertable probe (FLIP) and described in [4], has been used to measure the electrostatic fluctuations, density and temperature profiles. In this experimental campaign a five-pin balanced triple Langmuir probe and a pin measuring the floating potential are used. The two measurements are aligned in the toroidal direction, orthogonal to the edge magnetic field, at a distance of 44 mm from each other. The FLIP probe has been inserted at 247° toroidal position and it has been moved on a shot-by-shot basis up to $r/a = 0.91$ to scan the region where the electrostatic particle flux has a maximum [5].

During the (PPCD) operation a poloidal electric field is generated in the outer region of the plasma by a sudden increase of the reversal of the toroidal magnetic field [6]. This process has been found to slow down the $\mathbf{E} \times \mathbf{B}$ velocity in the outer region [7].

3. Results and discussion

3.1. Comparison between hydrogen and helium radial profiles

The measurements have been performed in low plasma current discharges ($I_p = 300$–350 kA), both for H and He. The average H plasma density was $n_e = 3 \times 10^{19}$ m^{-3} and the pulse had a typical duration of 80 ms. For He discharges the density was higher, $n_e \sim 4$–6×10^{19} m^{-3}, and the pulse duration was shorter (40–50 ms).

The average radial profiles of electron density and temperature measured by the FLIP probe are shown in Fig. 1. For He plasma the electron density and its gradient (Fig. 1(a)) are higher than those in H plasma (Fig. 1(b)), while the temperatures are comparable with a shallow gradient in both cases.

The data have been linearly interpolated to deduce the radial profiles of the diamagnetic drift velocity, $\mathbf{v}_D = \nabla p \times \mathbf{B}/(enB^2)$ and are shown in Figs. 2(a) and (b) for H and He, respectively. In the same figures also the electric drift velocity $\mathbf{v}_{E\times B} = \mathbf{E} \times \mathbf{B}/B^2$ profiles are shown. The magnetic field, which is mainly poloidal in the external region, was about 0.15 T. For He and H discharges, the $\mathbf{E} \times \mathbf{B}$ flow velocities are comparable showing two $E \times B$ velocity shear layers [1]. In proximity of the wall surface, the first velocity shear is $\sim 10^6$ s^{-1} for both H and He discharges, whereas in the second layer is $\sim 0.3 \times 10^6$ s^{-1} for H and much lower for He. A lower value of the second velocity shear layer has also been observed by spectroscopic measurements, in He discharges, at higher plasma current ($I_p \sim 800$ kA). It is worth noting that the $\mathbf{E} \times \mathbf{B}$ term prevails over the diamagnetic term for $r/a < 0.97$, while the diamagnetic term dominates close to the first wall ($r/a = 1$).

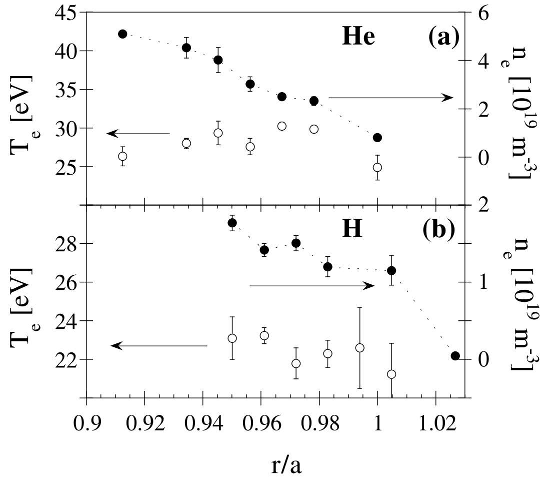

Fig. 1. Average density and temperature radial profiles measured for He (a) and H (b) RFX discharges.

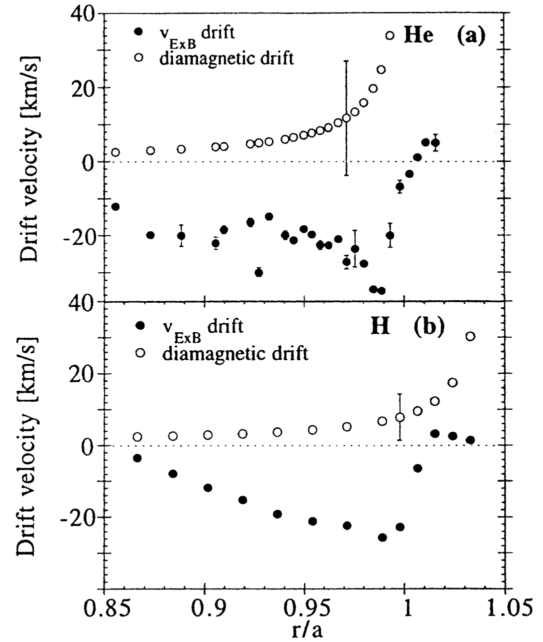

Fig. 2. Average diamagnetic and $\mathbf{E} \times \mathbf{B}$ drift velocity radial profiles obtained for He (a) and H (b) discharges.

The particle and energy fluxes driven by electrostatic turbulence have been deduced from fluctuation measurements of density and plasma potential. The elec-

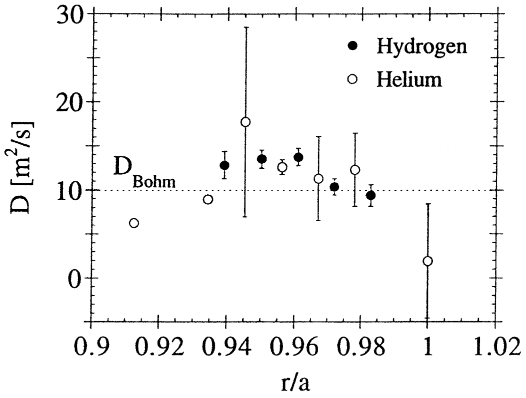

Fig. 3. Particle diffusion coefficient radial profile: comparison between H and He discharges, the dotted line represents the average D_{Bohm}.

trostatic particle fluxes have a maximum at $r/a \sim 0.96$, with values 0.6×10^{22} m^{-2} s^{-1} for H [3] and $(1.5–2) \times 10^{22}$ m^{-2} s^{-1} for He. By comparison with the H_α emission, measured by a multichord spectrometer, it was found that the electrostatic particle flux account for about 100% of the particle flux in H discharges [5]. The same conclusion holds also for He discharges where the influx value at the edge was estimated from a single chord and taking the same space distribution measured in H discharges [8].

The particle diffusion coefficient has been estimated applying Fick's law and it is shown in Fig. 3. In the same figure is also shown the Bohm diffusion coefficient estimated for $T_e = 24$ eV, a value close to the average experimental values both for He and H. The diffusion coefficient results comparable for H and He discharges, despite the different mass and density, proving that it is anomalous.

3.2. Interpretative model: momentum balance equation

The experimental radial profiles of the total toroidal drift velocity are given by the sum of the diamagnetic and the $E \times B$ drift terms as shown in Fig. 2 for H and He, respectively. These data have been interpreted by a model based on the toroidal momentum balance, which in cylindrical coordinates becomes [9]

$$J_r B = nMvu_z - nMD\frac{1}{n}\frac{dn}{dr}\frac{du_z}{dr} + (\nabla \Pi_i)_z, \qquad (1)$$

where J_r is the radial current density, n the plasma density, M the ion mass, v the ion neutral collision frequency, u_z the toroidal component of the flow velocity and Π_i is the ion viscosity tensor. The $nMvu_z$ frictional term is due to momentum exchange between ions and neutrals, which results to be larger than the electron–neutral momentum exchange. In the H case, the collision frequency has been taken as $v = 10^{-14}T^{0.318}n_n$, where n_n is the neutral density (m^{-3}), and the ion temperature T is expressed in eV, as in [10]; for the He case, in the hypothesis of singly charged ions at $T_e \sim 20$ eV, the collision frequency has been estimated to be $v \sim 6 \times 10^{-15}n_n$ [11].

Eq. (1) has been solved for stationary condition by assuming azimuthal and axial symmetry, with $B = B_\theta$, and with the radial velocity $u_r = -D(dn/dr)/n$, where D is the anomalous particle diffusion coefficient [9]. The term depending on J_r is related to the ion losses at the wall due to the finite ion Larmor radius. A J_r profile of the type $J_r = J_0 \exp[-((r-a)/\sigma)^2]$ has been assumed, according to the result of a Monte Carlo simulation [12]. J_0 is the current at the wall ($r/a = 1$) and σ gives the J_r radial extension.

The velocity profile has been computed by using the experimental profiles of plasma density, temperature and particle diffusion coefficient, while for neutrals an exponentially decaying profile has been assumed, with decay length equal to 7 cm for H and 9 cm for He.

An example of experimental u_z profile measured in H discharges with a plasma current of 300 kA is shown in Fig. 4(a) and compared with the numerical result. In this case the neutral density at the wall was 0.35×10^{18} m^{-3}, while $\sigma/r_{L,H}$ (where $r_{L,H}$ is the hydrogen Larmor radius) was 5 and $J_0 = -250$ A/m^2.

An example of experimental u_z profile and its simulation for He discharges is shown in Fig. 4(b). In this

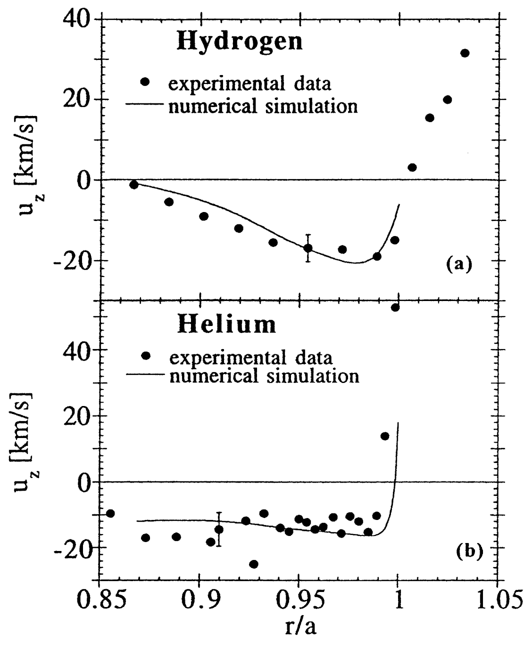

Fig. 4. Toroidal drift velocity radial profile measured for H discharges (a) and He discharges (b): numerical simulation and experimental data.

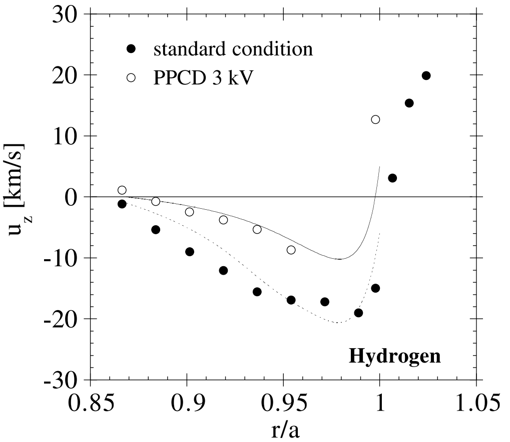

Fig. 5. Toroidal drift velocity radial profile measured for H discharges during standard condition and during PPCD operation at 3 kV, compared with the respective numerical simulation.

case $\sigma/r_{L,He} \sim 6$ and J_0 is -350 A/m^2. It is worth noting that the velocity profiles in He discharges are well simulated with a wider σ and a larger J_0 consistent with the larger He Larmor radius and experimental particle flux.

3.3. PPCD experiments

During PPCD operation, the plasma in the outer region undergoes important modifications. In particular the electrostatic flux decreases as well as the edge density [7]. As pointed out in the same reference, the PPCD technique constitutes a tool for studying the edge physics and then for validating the modeling of edge radial electric field. For these reasons, PPCD has been applied to H and He discharges. The drift velocity radial profile measured during the PPCD operation and compared with standard condition profile for H discharges is shown in Fig. 5. The effect of PPCD, in the time in correspondence to the maximum value of the induced poloidal electric field, is a reduction of the $\mathbf{E} \times \mathbf{B}$ velocity and of its shear. The two profiles have been interpreted on the basis of the same momentum balance model described in the previous section. The numerical simulations of the u_z standard profile (dotted line) and of the u_z profile modified by PPCD (continuous line) are also shown in Fig. 5. All simulations have been obtained by taking into account the modification of the experimental profiles of n_e, T_e and D. The temperature gradient did not show substantial variations during PPCD [7]. It is worth noting that the return current due to the ion losses decreases during PPCD as expected by the measured reduction of the electrostatic particle flux profile, $\Gamma_{es}(r)$.

It is worth mentioning that a similar behavior has been observed for PPCD operations in He plasmas although it has been observed that $\Gamma_{es}(r)$ and $n_e(r)$ are less affected than in H discharges. The different behavior have been related to the higher values of density in He discharges, confirming that in general PPCD is more effective at lower plasma densities.

4. Conclusions

The edge plasma properties have been studied in He discharges and compared with H discharges. The radial electric field exhibits a high shear close to the wall in both cases, whereas the innermost shear is lower for He discharges. The particle diffusion coefficient is found to be anomalous and in agreement with Bohm estimate in both cases.

The toroidal plasma flow radial profiles measured in the outer region have been simulated using a single fluid model, based on the momentum balance equation, which includes the ion losses to the wall due to finite Larmor radius effects.

The PPCD operations in He and H discharges induce similar modifications of the electric field profiles and electrostatic particle fluxes and these effects have been simulated by the same momentum balance model.

References

[1] V. Antoni et al., Phys. Rev. Lett. 79 (1997) 4814.
[2] H. Biglari P.H. Diamond, P.W. Terry, Phys. Fluids B 2 (1990) 1.
[3] V. Antoni et al., Plasma Phys. Control. Fus. 42 (2000) 83.
[4] V. Antoni et al., J. Nucl. Mater. 266–269 (1999) 766.
[5] V. Antoni et al., Phys. Rev. Lett. 80 (1998) 4185.
[6] J.S. Sarff et al., Phys. Rev. Lett. 78 (1997) 62.
[7] V. Antoni et al., Plasma Phys. Control. Fus. 42 (2000) 893.
[8] L. Carraro et al., Rev. Sci. Instrum. 66 (1) (1995) 610.
[9] D. Desideri et al., Czech. J. Phys. 49/S3 (1999) 119.
[10] J. Cornelis et al., Nucl. Fus. 34 (1994) 171.
[11] R.A. Phaneuf, Nucl. Fus. Suppl. 2 (1992) 75.
[12] V. Antoni et al., Experimental measurements and modeling of the structure of the radial electric field in RFX, presented at the Third Europhysics Workshop on the role of Electric Fields in Plasma Confinement and Exaust, Budapest, 18–19 June 2000.