26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 1141 - 1144

Scaling of pellet ablation and trajectory deflection in RFX

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1. INTRODUCTION

In the RFX reversed field pinch experiment (a=0.5 m, R=2 m, I=1 MA) several pellet injections experiments have been performed with H pellets.

The pellet experiments in RFX are characterised by penetration depths shorter than predicted by the commonly accepted ablation models and poloidal and toroidal deflections larger than what observed in Tokamak experiments. Both these differences have been already observed in previous experiments [1,2], but a quantitative analysis has been never performed.

This paper presents a pellet ablation and trajectory statistical analysis. The scaling of various pellet characteristics, such as the penetration depth and the trajectory deflection, with pellet and plasma parameters is investigated and compared with the predictions of existing models. Establishing the scaling laws for the penetration depth and deflections provide a basis to investigate which of the RFPs plasma characteristics, such as low magnetic field, large shear rate, large magnetic fluctuation, large electric field or non Maxwellian electron energy distribution, cause the observed phenomena.

2. EXPERIMENTAL RESULTS

In RFX the H_α total emission and the 3-D pellet trajectory are diagnosed by an absolutely calibrated multiple Position Sensitive Detector (PSD) looking at the H_α radiation coming from the pellet ablation cloud [3]. Four PSD cameras are installed at the pellet injection section. Two cameras look at the pellet trajectory from behind, thus providing a measurement of the poloidal and toroidal deflections. The other two cameras look at the pellet trajectory from below, thus getting a good view of the radial motion and, again, of the toroidal deflections.

With this system the 3-D trajectory is computed from the intersection of the pellet viewing angle measured by at least one of the horizontal and one of the vertical PSD cameras. This allows obtaining the trajectory without any other information. In figs. 1a,1b the typical H_α total emission and the poloidal and toroidal trajectories measured by the system are drawn.

It is possible to see from fig. 1a that the time evolution of the H_α total emission is qualitatively similar to what observed on Tokamaks with a sharp maximum obtained before the pellet end of ablation. However an important difference is observed for the pellet penetration: while in the Tokamak case the emission stops whenever the pellets go beyond the plasma axis, this does not happen in RFX where the emission does not show any appreciable decrease.

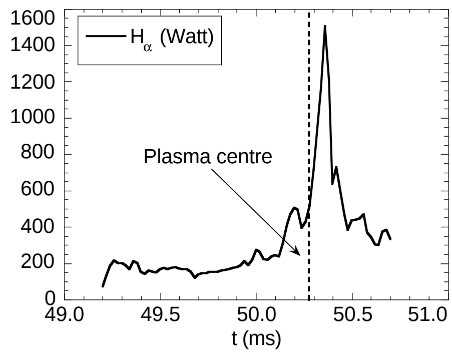

Fig. 1a H_α total emission measured by the PSD system.

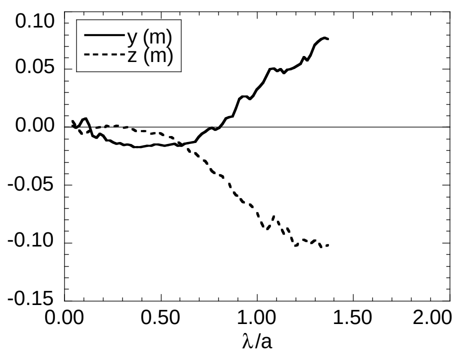

Fig. 1b Toroidal (z) and poloidal (y) trajectory measured by the PSD system.

The trajectory is also different from the Tokamak case (fig. 1b), since it is characterised by large poloidal and toroidal deflections that are typically of the order of 0.05÷0.15 m (Δ/a = 0.1÷0.3).

3. SCALING OF PENETRATION DEPTH

We have examined the dependence of the penetration depth on pellet and plasma parameters that are most likely to be involved in the ablation physics, such as pellet mass and speed and plasma electron density and temperature. The results have been then compared with the ablation models already validated by the Tokamak experiments.

The range of pellet injection experimental parameters covered in the database for RFX is rather limited with respect to m_p and v_p, with the majority of pellets having a mass in the range between $1.5\cdot10^{20}$ and $2\cdot10^{20}$ atoms and injection speed velocities in the range of 400-500 m/s, while it is sufficiently large for plasma parameters ($n_e=2\cdot10^{19}\div5\cdot10^{19}$ m^{-3}, $T_e=200\div350$ eV).

Various ablation models have been proposed for the physics of pellet ablation. The Neutral Gas Shielding NGS [4,5] is the simplest one: it only considers the shielding of the neutral cloud expanding from the pellet surface, uses a simple 1-D ablation geometry and assumes monoenergetic incident electrons. With these simplified approximations the NGS is able to predict pellet penetration depths in good agreement with a number of experiments [6,7], for this reason it has become the most widespread and accepted one. More sophisticated models have been developed to remove the above approximations. For instance the monoenergetic incident electrons approximation has been replaced with a correct Maxwellian electron distribution and some additional shielding effect have been considered. One of the most developed model is the Neutral Gas Plasma Shielding NGPS [8,9] which, using the correct Maxwellian electron distribution and considering also the shielding of the plasma expanding along the field lines from the cloud surface, predicts pellet penetration depths in agreement with the experiments. Still, due to fortuitous approximations, the NGS provides a simple scaling law for the ablation rate which is equivalent to that of the more complete and realistic models. Therefore in Tokamak experiments the NGS is used as a reference. For the same reason we will also start comparing initially our data with the NGS model.

The NGS model gives the following law for the pellet surface regression velocity:

$$\frac{dr_p}{dt} = 5.58\cdot10^{-14}\,\frac{n_e^{1/3}\cdot T_e^{5/3}}{r_p^{2/3}} \qquad (1)$$

where r_p is the equivalent spherical pellet radius.

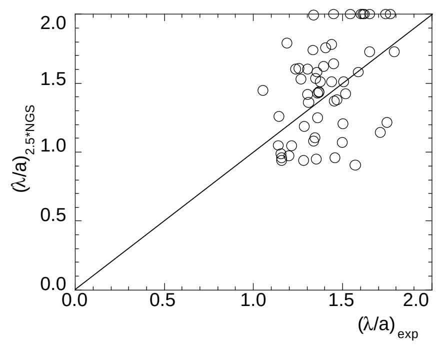

Fig.2. Penetration depths computed with 2.5 times the ablation rate of the NGS model versus the measured penetration depths.

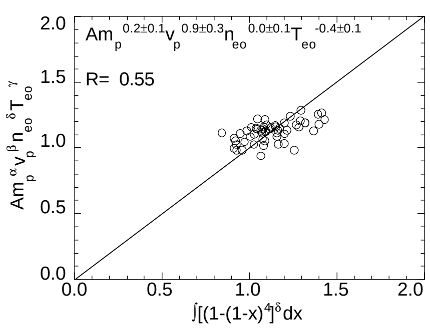

Fig.3. Comparison of penetration depth with regression analysis for RFX pellets database.

As a first analysis of the pellet ablation, we compared the measured penetration depths with the theoretical ones obtained from the NGS model by integrating the previous equation. The computed penetration depths appear to be larger with respect to the measured ones. Quantitatively it seems that a multiplicative factor of the order of 2.5 is needed to reproduce the experimental penetration depths (fig.2). This value is close to that one obtainable with the NGS replacing the monoenergetic incident electrons approximation with a correct Maxwellian electron distribution and no additional shielding effect. This seems to indicate that a modified NGS model with Maxwellian electron distribution and no additional shielding, like the Kuteev model [10], could be a better approximation in our case. Indeed using the Kuteev model we obtain penetration depths very close to the experimental ones. The reason why none of the additional shielding effects is present in RFX is not completely understood, but probably it depends from the low magnetic field in the RFPs experiments.

Although the experimental absolute value of the ablation rate is not well described by the NGS model, it is useful to compare the experimental scaling law to that of the NGS model, which on the other hand is very similar to that one obtained from models that considered the electron Maxellian distribution.

Usually in the Tokamak experiments the scaling law found for the normalised penetration depth is compared with the NGS model integrating the equation (1) over a flat density profile and a linear [6] or power [7] temperature profile. Since the theoretical scaling law found in this way is valid only if the pellet penetration depth is lower than the minor radius, this method could not be applied to our data because in RFX most of pellets have a penetration depth larger than plasma minor radius. Due to the previous reason, to evaluate correctly the profiles effect we preferred to integrate the equation (1) with the RFX density and temperature experimental profiles. In RFX the density profiles are very close to flat while the temperature profiles could be expressed as $T_e(r)=T_{eo}(1-r^4)$. In this way after integration the equation (1) becomes:

$$\int_0^{\lambda/a}\left[1-(1-x)^4\right]^{5/3}dx = 5.58\cdot 10^{-14}\cdot a^{-1}m_p^{5/9}\cdot v_p\cdot n_{e0}^{-1/3}\cdot T_{e0}^{-5/3}$$

where λ/a is the normalised penetration depth. To compare the experimental data with the theoretical models we performed a multivariable power regression of the left hand integral computed from the measured penetration depths:

$$\int_0^{\lambda/a}\left[1-(1-x)^4\right]^{\delta}dx = A\cdot m_p^{\alpha}\cdot v_p^{\beta}\cdot n_{e0}^{\gamma}\cdot T_{e0}^{\delta}$$

Since the integral depends from the temperature exponent, which is a result of the regression analysis, we proceeded in an iterative way until the exponent used in the integral becomes equal to the computed temperature exponent.
In this way we obtained α=0.23±0.08, β=0.85±0.30, γ=0.02±0.06 and δ=-0.41±0.10 (fig. 3). Comparing the previous exponents whit the NGS exponents it is possible to see that they are similar for pellet mass and velocity (α_{NGS} = 0.55, β_{NGS} = 1.00) although their validity is low due to the limited range covered by the experimental data. Conversely, the dependence of penetration depth from the electron temperature and density is very small compared to the NGS and similar models (γ_{NGS} = 0.33, δ_{NGS} = 1.50). Various hypotheses could be formulated to explain this difference:

- Due to the low radial confinement in the RFPs and the low pellet velocity, the perturbation in the density produced by the pellet itself could precede the pellet and cool the plasma, so that the density and temperature the pellet encounters are different from unperturbed conditions.
- The presence of suprathermal electrons in an RFP can affects not only the trajectory but also the ablation rate which, in this case, depends, not only from the bulk plasma parameters, but also from the fraction and the energy distribution of the suprathermal.
- The NGS has been studied and confirmed extensively only at temperatures larger than 1 KeV, but a few theoretical and experimental confirmations exist in the 200-500 eV range, so it is likely that this model could not describe correctly the low temperature range explored in the RFX device. For example, the temperature dependence we have found is in agreement with the theoretical result of Milora and Foster [11], which neglected the elastic scattering.

4. ANALYSIS OF PELLET DEFLECTIONS

As already studied for the smaller toroidal deflection observed in Tokamaks [12] also for the RFPs the large deflections are most likely due to the presence of a distortion in the electrons Maxwellian distribution function that enhance the pellet ablation on the electronic drift side. Because of the momentum conservation, the asymmetry of the ablation process causes a ‘rocket effect’ which accelerates the pellets along magnetic field lines in the direction of the electron drift.
For the RFPs, with regard to the origin of the Maxwellian distortion, two different hypothesis can be made: the production in the plasma centre of suprathermal electrons that diffuse radially thanks to the magnetic field stocasticity (Kinetic Dinamo Theory [12]), or, as for the Tokamak case [13], a Spitzer-Härm distortion of the electron distribution function due to the electrical field.
In RFX the toroidal and poloidal deflections are found to be an increasing function of the plasma temperature, plasma current and a decreasing function of the plasma density. It seems in particular that the deflections are strongly affected by the plasma current, so we have chosen to

estimate the power law dependence of the deflection from the plasma current, the electron density and the average ablation rate (m_p/τ_p, τ_p=pellet ablation time).
Performing a regression analysis at the plasma centre we found for the toroidal deflection a nearly linear dependence from the plasma current while for the poloidal deflection a nearly quadratic dependence again for the plasma current (figs. 4,5). Due to the RFP magnetic configuration the toroidal deflection is mainly originated in the centre, while the poloidal deflection is originated in the outer plasma region. We can observe that the linear toroidal deflection dependence from the current is in agreement with Spitzer-Härm Maxwellian distribution distortion [13]. As for the poloidal deflection dependence on density and current the interpretation is more difficult and calls for a detailed modelling of the large density and temperature profile variation at the edge. Indeed the shot to shot profile variation could explain also the lower regression correlation for the poloidal deflections.

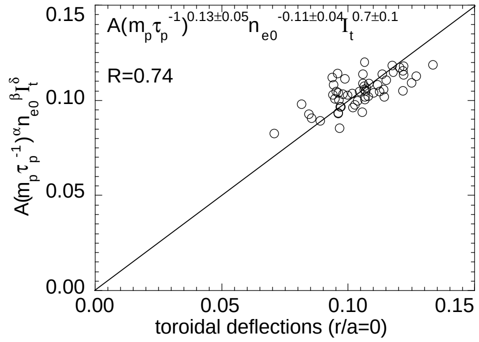

Fig.4. Comparison of toroidal deflections at r/a=0 with regression analysis for RFX pellet database.

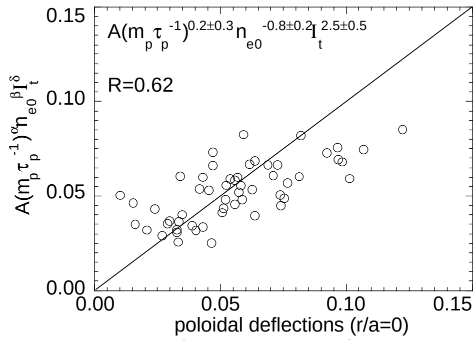

Fig.5. Same of Fig.4 but for poloidal deflections.

5. CONCLUSIONS

We have studied the ablation rate and the trajectory for about 60 pellet injected in RFX. We found an ablation rate 2.5 times larger than that predicted from the monoenergetic NGS model. It seems that in the RFPs plasma are not present the shielding effects that in the Tokamaks reduce the ablation rate computable considering the full electron Maxwellian distribution. The ablation scaling law has been also studied, in this case while exponents close to the theoretical values have been found for the pellet mass and velocity, exponents much lower than that of the NGS model have been found for the density and temperature. It is not clear if this result is correlated to that one on the absolute ablation rate or if this means that the physics of the ablation is different in the RFPs plasma.
The poloidal and toroidal deflections are well correlated with the plasma current; the power dependence of the toroidal deflection from current is in agreement with Spitzer-Härm Maxwellian distribution distortion. The scaling law for the poloidal deflection is different but this could be due to profile effects.

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