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Interaction of pellets with plasma in standard and advanced regimes at TPE-RX reversed field pinch experiment.

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1. Introduction: A deuterium pellet injection campaign has been carried out in the reversed field pinch TPE-RX device (a=0.45m, R_0=1.72m) at Ip=300kA, $<n_e>=6x10^{18}$ m^{-3} and $T_e(0)\approx250$ eV, both in standard and Pulsed Poloidal Current Drive (PPCD) discharges. The PPCD system [1] was used for long action (more than 15 ms) on MHD dynamo modes. The pellets were produced by a cryogenic injector, with a mass of $1.0\text{-}8.0x10^{19}$ atoms and a velocity up to about 400 m/s, provided by a pneumatic system. The mass of the pellet is measured by means of a resonant microwave cavity and the velocity is computed by the time of flight between an optical detector and the cavity. The trajectory of the pellet in the plasma in the poloidal and toroidal directions is reconstructed by a 4 channels position sensitive device (PSD) [2], whereas the radial position is computed assuming constant radial speed during the ablation.

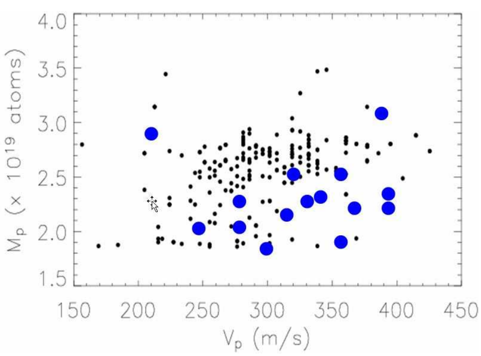

Figure 1 Complete pellet database. Blue dots represent the subset of 15 shots on which the analysis has been done.

In this work a characterization of the pellets behaviour entering a plasma has been carried out. Differences and similarity have been underlined between standard and PPCD discharges, both in confinement properties and in MHD activity after the pellet injection. The second major topic investigated is the study of the ablation of the pellets. The study of the penetration depth and the ablation scaling laws of pellets in TPE-RX is a topic of great interest in order to extend in the low plasma density region the ablation models that have been validated in the past [3]. In this paper the experimental penetration depth λ_d of a set of 15 pellets has been compared with the λ_d predicted by NGS [4] and NGPS [5] models.

2. Phenomenology of pellet injection: 150 pellets have been launched in TPE-RX plasma during the analyzed campaign. A subset of well diagnosticated 15 shots has been selected to perform the analysis on the ablation rate. The subset is representative of the whole database for pellet mass and velocity, as shown in figure 1. Figure (2a) and figure (2b) show the main plasma parameters respectively for a standard and for a PPCD discharge, compared with similar shots with pellet.

When a pellet is launched in a standard shot the density and the D_α line brightness increase in about 1 ms and the temperature drops. After the ablation, an enhanced recycling from the wall is observed, as highlighted by the D_α increase, that lasts for about 10 ms. Also the density recovers its original value in about 10 ms, therefore the particles deposited by the pellet are completely lost after that time. After a pellet injection, the MHD activity in standard discharges is enhanced, as observed in the experiment RFX [6]. Namely, the internally resonant m=1 tearing modes tend to increase as well as the m=0 and n=1 mode resonant at the reversal surface, producing a Dynamo Relaxation Event (DRE) [7]. It is to notice that an intensification of the global plasma column deformation is observed due to the increased mode amplitude, although the mode phase locked structure (generally also wall locked in these discharges) produced by the magnetic field fluctuations [8] is not affected by the pellet injection. The behaviour in PPCD shots is slightly different: without the pellet the density starts increasing at 18 ms (starting time of PPCD), the particle influx from the wall decreases and the temperature increases: the reduction of the MHD dynamo modes brings the plasma in an enhanced confinement regime. Concerning the shot with pellet, after the ablation the D_α signals decrease but the density stabilizes at a value about 3 times higher than the pre-injection level, confirming that the good confinement regime induced by PPCD is not destroyed by pellet injection, indeed MHD fluctuations remain low. From the point of view of MHD spectra, also the interaction between quasi single helicity states [9] and pellet was studied. Preliminary results show that according to the relative position between the thermal structure and the pellet, the plasma can survive in the QSH state (if the pellet does not reach the island) or change towards a multiple helicity state (when the pellet hits the island).

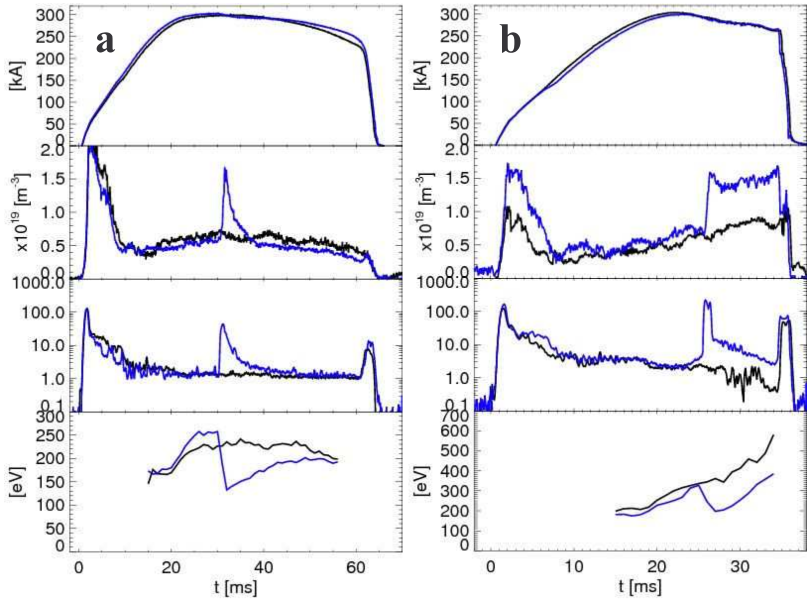

Figure 2 Plasma current , mean line density, Dα line brigthness (a.u.) and electron temperature for standrd shots (a) (#46803, #46830) and PPCD shots (b) (#46950, #47342). Shots without pellet are represented in black whereas shot with pellet in blue.

3. Ablation models: A complete description of the penetration of a cryogenic pellet in a hot, magnetized plasma takes into account mechanisms related to neutral gas dynamics around the pellet, atomic physics processes, charging of the ablated cloud and diamagnetism of the cold plasma cloud (plasmoid) surrounding the pellet.

The NGS model considers only the shielding of the neutral cloud expanding spherically from the pellet surface. The other mechanisms are considered by a global reduction of the electron heat flux, hence of the ablation rate. Moreover, the Maxwellian distribution of the incident electrons is approximated by a monoenergetic beam. In spite of this simplified scheme, the penetration depths predicted by the NGS model are generally in good agreement with the experimental measurements for a wide range of plasma (density and temperature) and pellet (mass and velocity) parameters [10]. The pellet surface regression velocity predicted by NGS model is:

$$\left.\frac{dr_p}{dt}\right|_{NGS} = 10^{-16/3} \times 1.72 \times 10^{-8} \times n_e^{1/3}\left[\mathrm{m}^{-3}\right] \times T_e^{5/3}\left[\mathrm{eV}\right] \times r_p^{-2/3}\left[\mathrm{m}\right] \qquad (1)$$

where n_e and T_e are the plasma density and temperature and r_p is the equivalent spherical pellet radius.

Under the name of NGPS scaling law, a numbers of more sophisticated models are included. In general the NGPS describes the ablation considering the interaction of the plasmoid with the magnetic field and the local Maxwellian distribution of the energy of bulk electrons, hence relative to NGS, it provides a more physical description of the heat flux on the pellet. The NGPS model gives the following law for the ablation rate:

$$\left.\frac{dr_p}{dt}\right|_{NGPS} = 5.286 \times 10^{-18} \times B^{-0.02}\left[\mathrm{T}\right] \times V_p^{0.05}\left[\mathrm{m/s}\right] \times n_e^{0.57}\left[\mathrm{m}^{-3}\right] \times T_e^{1.61}\left[\mathrm{eV}\right] \times r_p^{-0.48}\left[\mathrm{m}\right] \qquad (2)$$

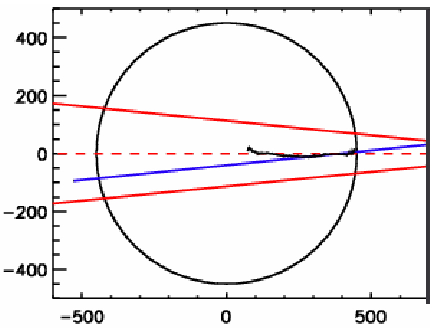

Figure 3 Trajectory of the pellet in the poloidal plane for shot #47050. The blue line represent the projection of the launch line inside the plasma, the red lines are the angle of view of the PSD. Dimension of the axis are in millimetres.

where B is the magnetic field and V_p is the pellet velocity. In Tokamak experiments NGS and NGPS models, despite the more accurate description given by the NGPS, provide comparable results on pellets penetration depth and ablation rate.

The analisys has been carried out matching the experimental penetration depth with the λ_d predicted by the two models. An *Enhancement Ablation Factor* (EAF) is used to increase (EAF >1) or decrease (EAF <1) the ablation rate. For the NGS model the penetration depth is computed with the following relation:

$$\int_{R_pMAX}^{0} r_p^{2/3}\, dr_p = \int_{a}^{\lambda_{dEXP}} \mathrm{EAF} \times 10^{-16/3} \times 1.72 \times 10^{-8} \times n_e^{1/3} \times T_e^{5/3} \times \frac{dr}{v_p}$$

where R_{pMAX} is the pellet radius before entering the plasma and λ_{dEXP} is the experimental penetration depth. Figure (3) shows the trajectory of the pellet in the poloidal plane for shot #47050. The pellet shows a small poloidal deflection (suggesting the presence of a low fraction of suprathermal electron) and it reaches almost the plasma centre: the experimental penetration depth is λ_{dEXP}=40cm. The EAF for this pellet, for the NGS model is 1.15. This means that the model can predict the penetration depth within the 15% of accuracy, comparable with the error of other measured quantity. Figure (4a) summarizes the EAF values for the NGS model, for the 15 pellets analyzed as a function of the pellet mass. The average value is 1.5 and only very small pellets (blue dots in fig.4) need a bigger value of EAF, suggesting that a different physics description must be considered for small pellets: the ablation time is of the same magnitude of the time of formation of the shielding cloud so no stationary state between pellet surface and plasma heat flux can be achieved. No differences have been observed between standard and PPCD shots, despite the different density and temperature level: the NGS model gives a description of ablation process which is better than the NGPS paradigm also at typical TPE-RX density and temperature regimes.

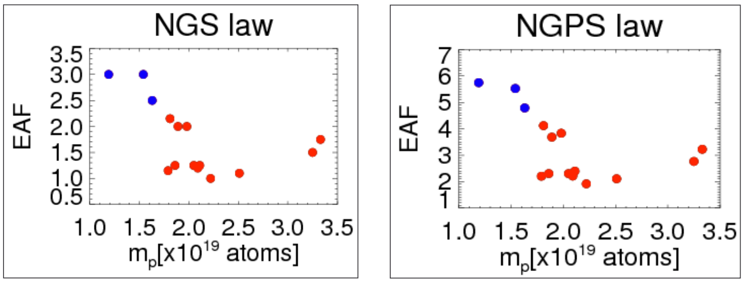

Figure 4 EAF values for NGS (a) and for NGPS (b) ablation scaling law as function of the pellet mass. The blue dots represent small pellets which show an anomalous behaviour.

4. Conclusion: The combination of pellet with PPCD allows TPE-RX to enter high density plasma regimes, not achievable in other ways. The good confinement properties induced by the PPCD are not destroyed by the enhanced MHD activity after the pellet injection. The ablation of the pellet in standard and PPCD discharges has been studied by means of NGS and NGPS model. The NGPS model needs bigger values of EAF (generally twice the value found for NGS) therefore we can conclude that the description given by the NGPS model does not suit the physics of the ablation of pellet in RFP plasma. As discussed in [11], the presence of the magnetic field, inducing the formation of the plasmoid, should supply an additional shield from the heat flux on the pellet core but the typical high magnetic shear of the RFP configuration and the magnetic stochastization prevent the formation of an elongated plasmoid. So, according to the NGS model, the shielding of the pellet core is supplied only by the neutral cloud.

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