VERTICAL PELLET INJECTION EXPERIMENTS ON TORE SUPRA

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1. Introduction

Like on other tokamaks [1], pellet injections carried out on Tore Supra from the low magnetic field side (LFS), using either a centrifugal injector or two-stage pneumatic guns, showed generally a fast outward displacement of the ablated material. The recent high field side injections (HFS) performed on Asdex-U [2] and a model [3] accounting for the enhanced pellet penetration and fuelling efficiency observed on this machine, have motivated us to attempt vertical injection experiments on Tore Supra. Indeed the model, based on a drift towards LFS of the ablated matter driven by the inhomogeneous magnetic field, also predicts a better fuelling efficiency for such a configuration. This scheme was relatively easy to implement through a vertical port using a guide-tube with large radii of curvature allowing to inject pellets from the Tore Supra Centrifugal Pellet Injector (CPI) at velocities in the 500 m/s range. Results of the first vertical injections into ohmically and LH heated plasmas are presented.

2. Breaking limits modeling and experimental setup

A curved guide-tube and a cone to funnel into it pellets exiting from the CPI had to be studied and installed between the injector and a top port of Tore Supra. The design of the guide-tube, a stainless steel tube of 10m long, 8mm of inner diameter and curved with a minimum radius of curvature of 1m, is consistent with a model allowing to calculate the breaking limit for pellets of different sizes and velocities. This model [4] is based on a ballistic propagation in the guide-tube and a strain accumulation in the pellet, resulting from successive impacts whose effect is calculated from the mechanical properties of deuterium ice [5]. It leads to a limit lower than that due to the centrifugal force which is generally considered [6]. The predictions of the model for the limit of the pellet integrity versus pellet velocity and radius of curvature of the tube are presented in Figure 1. When applied to the CPI, the sum of strains resulting from ice cutting, impact at the spinning arbor entrance and pellet

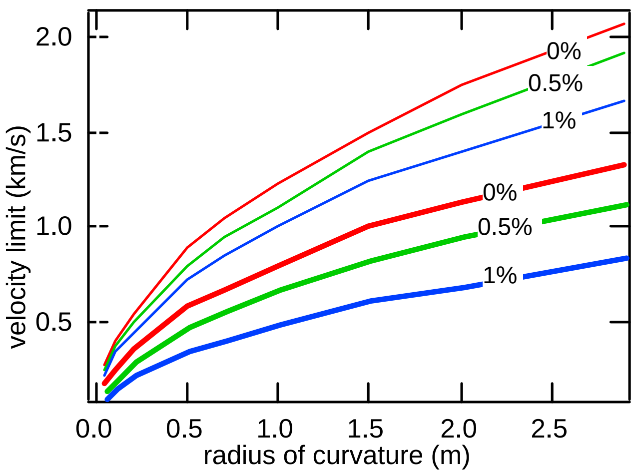

Fig. 1 : overall velocity limits (thick curves) and limits for the first impact (thin curves) for different pellet predeformation (without, 0.5% and 1%), calculated for pellet of 3.10^{20} atoms and T=9K without erosion

collection after acceleration must be taken into account, although if not precisely known. It is shown in Fig. 1 that working at 500 m/s and with a radius of curvature of 1m would allow 1% of predeformation to be accepted.

In the experiments, the initial pellet velocity was known by the rotation frequency of the spinning arbor (60 Hz) and a microwave cavity gave the pellet mass at the CPI exit before the funnel. Velocity and mass were also measured at the end of the guide-tube in a diagnostic chamber in which another microwave cavity, two light barriers and photodiodes for Hα emission measurements in the plasma were installed. In fact this second cavity, which was the most useful, did not allow accurate measurements owing to both its initial design for bigger pellets and its location very close to the plasma which was source of parasites, in particular when lower hybrid waves (LH) at 3.7 GHz were applied. The guide-tube being rather smooth and coherent with the model, the main breaking component was the funnel, which was not optimized due to time and manufacturing limitations. It was made up by a stainless steel cone (half-angle of 2°) mounted after a short free flight section connected to a pumping tank. A baratron gauge on the tank was used to estimate the pellet mass loss after the first microwave cavity, assuming that the losses occur mainly in the cone. The direction of injection into the plasma could be varied from -10° to 10° relatively to the vertical by tilting the guide-tube. For the reported experiments, we used a line of sight of 5°, i.e. 95° relatively to the LFS horizontal injection, corresponding to a radial injection. Pellets ($2\text{-}6.10^{20}$ D atoms) have been fired mainly into ohmically (Ip=1.5 MA) plasmas with an initial velocity of 520 m/s. The effect of the guide-tube on the velocity is weak, the maximum of the distribution at the end being around 480 m/s (-9%). In order to increase the database towards low penetration depths, for which a clearer effect is expected, some pellets have been injected during LH current drive experiments (P_{LH} up to 4 MW).

3. Experimental results

A lot of pellets have been found broken in two or more pieces in the plasma from the Hα emission signal (time resolution Δt=1 µs), even if several of them looked intact as far as the plasma density increase is concerned (measured by IR interferometer, Δt=2ms). The fuelling efficiency is defined as $\eta = dNe/(M - N_{loss})$ where dNe is the increase of the total number of electrons in the plasma , M the pellet content measured by the injector microwave cavity and N_{loss} the number of atoms lost in the funnel. This experimental η is plotted versus the normalized pellet penetration depth in Fig. 2, where it is compared to the experimental curve fitting the LFS experiments and to the prediction of the Pégourié's model [2]. It is clear that the accuracy of the pellet size measurement at the plasma entrance is too low to

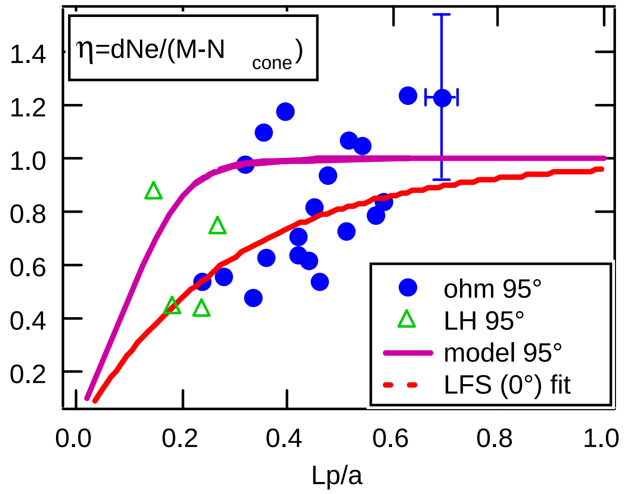

Fig. 2 : Experimental and calculated fuelling efficiency versus the pellet penetration depth

conclude about a possible difference LFS-95°. Then another approach has been considered, based on a potential link between the ExB drift of the model and the fast outward displacement of the deposited pellet material generally observed when the Δne profile (ne 1 to 3 ms after ablation - ne before) is compared to the Hα profile considered as the instantaneous matter deposit profile.

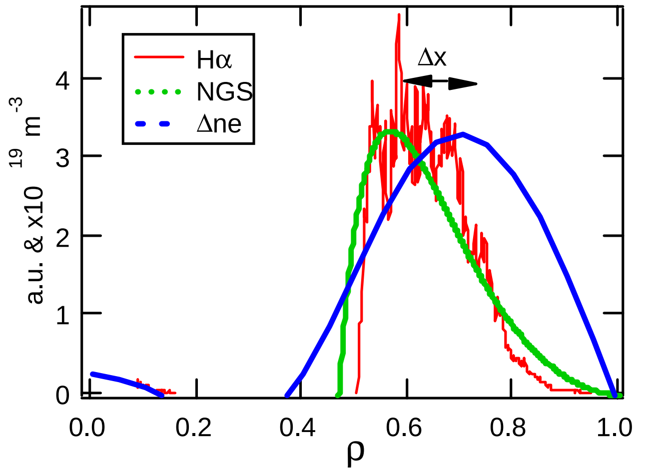

Fig. 3 : Hα and Δne profiles for a pellet injected at 95° into an ohmic plasma *(TS22416)*. The displacement Δx is defined as the distance between the maxima of Hα and Δne. Also presented is the NGS model prediction.

An example is presented in Fig. 3 for a pellet injected vertically, showing a weak displacement Δx of the ablated material. It has been possible, in particular, to compare directly two pellets, one injected from LFS and the other one vertically and radially into ohmic plasmas, giving the same instantaneous deposit (Fig. 4 Hα) profile. The measured deposition (Fig. 4 Δne) is found to be exactly the same in the two experiments with the same outwards displacement Δx. Before concluding definitely, this result has to be confirmed by a statistical analysis. As the experimental conditions were very variable, the analysis has been undertaken with the following start point: In the LFS injection experiments on Tore Supra, the outwards displacement has been observed to rise roughly linearly when the pellet penetration depth increases. This evolution is seen whatever heating methods (ohmic, LH up to 3 MW or ICRH

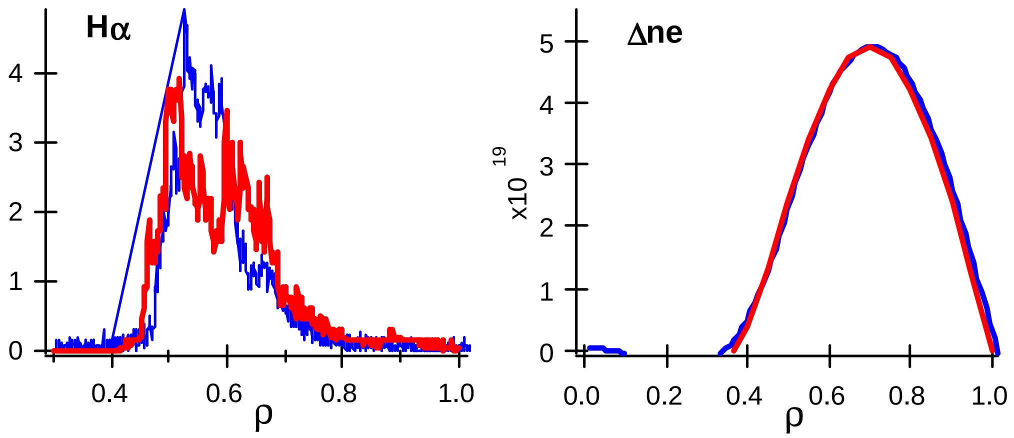

Fig. 4 : Comparison of the Hα and Δne profiles for a pellet injected from LFS (dashed curves TS4150, v=600m/s) and a pellet injected vertically and radially (solid curves TS22424, v=500m/s)

up to 5 MW) and pellet velocities (from 500 to 3300 m/s) were used and provided that pellets do not reach the q=1 surface. A similar study has been done for the outwards displacement in the vertical injection case. The result is presented in Fig. 5 together with the LFS observations. It is clear that, except perhaps for two pellets, the outwards displacement presents exactly the same behaviour for the two experimental configurations. This result can be interpreted as an indirect evidence of no fuelling efficiency improvement for the vertical scheme. For the experiments on Tore Supra, the critical parameter remains the pellet penetration depth (see Fig. 2). This penetration depth and the deposition profile deduced from the Hα measurement have been compared to the prediction of the simple NGS scaling law ($dr_p/dt=C.ne^{1/3}.Te^{1.64}.r_p^{-2/3}$ with $C=5.7\ 10^{-14}$ in m, m^{-3} and eV), and with the one of the Tore Supra NGPS scaling law [7] which both fit well the LFS ablation data on Tore Supra. As it can be seen in Fig. 3 and Fig. 6, the ablation of pellets injected vertically is still correctly described by the same NGS or NGPS scaling laws.

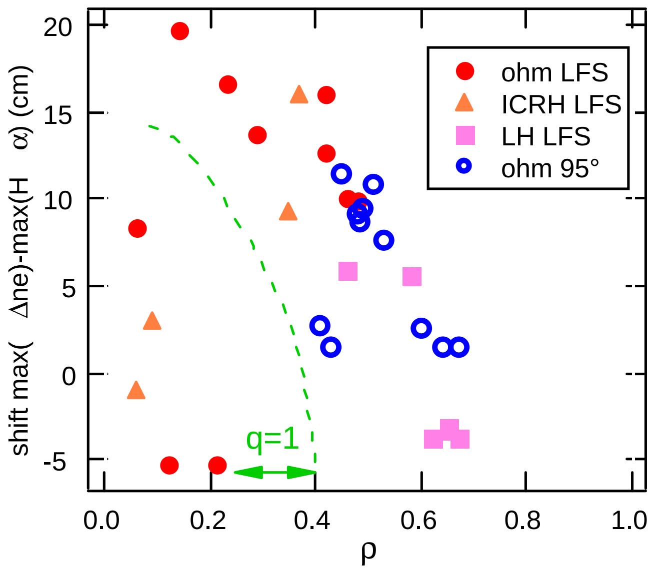

Fig. 5 : Outwards displacement Δx for LFS and vertical injection versus the minimum normalized radius reached by the pellets. Symbols on the left of the dashed curve corresponds to pellets penetrating inside the q=1 surface.

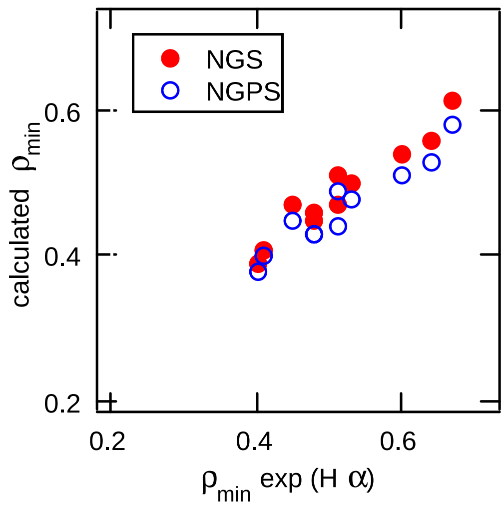

Fig. 6 : Comparison of the experimental and calculated (NGS and NGPS) penetration depth for injection at 95°

4. Conclusion

Pellets have been injected radially with an angle of 95° relatively to the LFS standard configuration into ohmic and LH Tore Supra plasmas. With a velocity of 500 m/s, allowed by the large radii of curvature of the guide-tube, penetration around mid-radius were obtained in ohmic plasmas. For these conditions, no difference concerning ablation and fuelling efficiency can be deduced from the experiment. Nevertheless, since the vertical injection configuration allows higher velocity than the HFS one, thanks to the possibility to use higher radii of curvature for the guide-tube, it should be interesting to complete the present results by widening the experimental conditions. In particular a vertical but not radial injection or an injection towards the inner wall from a vertical port as well as experiments with high additional power (≈ 10 MW of ICRH available on Tore Supra) have to be checked.

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