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Pellet Injection from the High Field Side on FTU

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Introduction and Experimental set-up

Pellet injection from the low magnetic field side (LFS) had already been successfully performed on the Frascati Tokamak Upgrade (FTU: 8 T, 1.5 MA, R=93.5 cm, a=30 cm), a circular cross section device with a molybdenum high field side (HFS) toroidal limiter [1,2]. Recently the RFX pellet injector [3] has been installed for vertical HFS injection experiments. With the present set-up, pellets are injected vertically along a line that intercepts the equatorial plane at R=79.1 cm, and are delivered using a 13.7 m long, 4 mm diameter nylon guide tube with a minimum curvature radius of 2.5 m.

The injection system is equipped with a microwave cavity for measuring pellet mass and three optical detectors placed along the guide tube (two of them located close to the pipe gun and the third one at the end of the tube) for measuring pellet velocity and integrity. Due to the curvature of the guide tube, pellet formation was optimized for low velocity and Neon has been used as driver gas. Measured masses were around $1.5\cdot10^{20}$ atoms. The initial velocity, when in the range of 500-600 m/s, did not change significantly along the flight line. Given these parameters and optimising the ice quality, about 80% of delivered pellets reached the plasma intact.

With this set-up, experiments were carried out at plasma current of 0.8 and 1.1 MA and toroidal field of 7 T with target line average plasma density of the order of $1\cdot10^{20}$ m^{-3}. Plasma density is measured with a two-chord CO_2/HeNe interferometer (located at 30° toroidally from the injection port) able to track, without fringe jumps, the fast density rise due to the pellet. The central chord is located at the geometrical centre of the machine (R=93.5 cm), while the outer one is 20 cm from the centre towards the HFS (R=73.5 cm).

Experimental results

A first database of 10 intact pellets, and 9 broken in large pieces, has been analysed considering both single discharges behaviour and statistical results. This allowed us to perform a first comparison of HFS (vertical) with LFS (horizontal, from the outboard equatorial plane) injection. The point will be more carefully addressed in the future since the LFS set is made of the best performing cases, while the HFS one is still not optimised.

Regarding plasma density evolution, in figure 1 we show a comparison between vertical (left, V_p~490 m/s) and horizontal (right, V_p~1.4 km/s) injection for two pellets of comparable mass. Typically, the density rise time is three times faster in LFS with respect to HFS injection with similar plasma parameters. A sharp peak following the density jump is always present in the off-axis interferometer chord and is followed by a slower time evolution of the signal. This feature could be explained by the relative position of the injection line and the interferometer. Indeed, the pellet radial position when this peak occurs

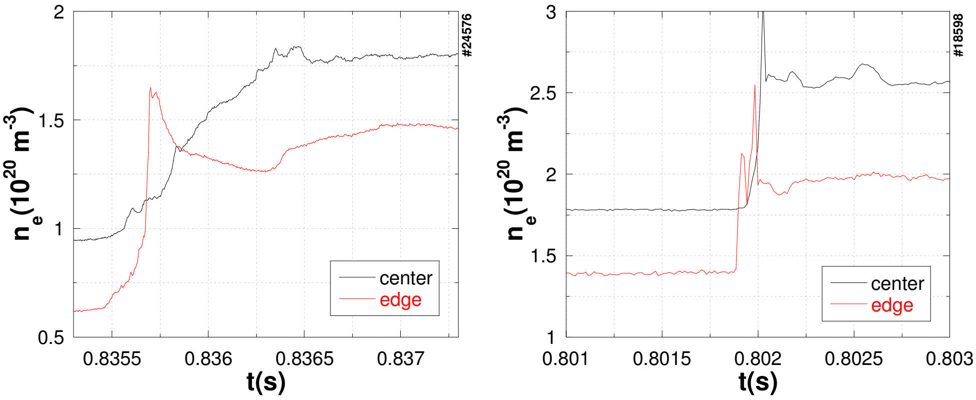

Figure 1. Plasma density measurements: HFS injection (left) and LFS injection (right).

is close to the magnetic surface tangential to the interferometer off-axis chord (impact parameter 20 cm). Therefore the sharp peak could be due to some ablated material that intercepts the chord before being homogenised in the bulk plasma. This could happen when the pellet is connected along a flux tube to the interferometer chord. An accurate modelling of this phenomenon can be found in [4].

Concerning statistical results, we estimated the pellet penetration depth along its trajectory using the measured pellet speed and the density rise time of the central chord. This is a good approximation of the actual penetration depth, except for fragmented pellets. All the intact pellets injected from the HFS in 800 kA discharges travelled in the plasma for about 30-40 cm. This means that most pellets reached or even went beyond the FTU equatorial plane, up to the maximum radial penetration of 15.6 cm allowed by the injection geometry. On the contrary in the cases of injection at 1 MA they stopped after 15-20 cm, due to the higher temperature, that corresponds to a radial penetration length of about 10 cm. The same analysis for the set of shots with LFS injection showed a radial penetration of about 15 cm.

A qualitative analysis of density profiles evolution was carried out taking the ratio between the central and edge interferometer chord measurements as an indication of the peaking. Since density profiles prior to pellet injection are in a similar range for HFS and LFS injection, we compare their variation normalised to the pre-pellet value. Immediately after complete pellet ablation, we obtained an average value 0.87±0.03 for the HFS set of shots and 1.04±0.02 for LFS set. This suggests that the particle deposition for LFS pellets is concentrated closer to the centre with respect to that obtained with HFS injection. This result can be explained as due to the different deposition profile of vertical and horizontal pellets (see numerical simulations in the following section). On the other hand, we also considered the same ratio 50 ms later and obtained factors of 1.11±0.03 for the HFS set and 1.13±0.01 for the LFS set, which indicates that, on time scales determined by transport, the peaking level is comparable.

Since HFS injection on FTU is actually a vertical injection, in the absence of a significant radial drift of the ablated material towards the centre, one cannot expect to deposit any material beyond the injection impact parameter. At the same time, given the large penetration depths observed for HFS injected pellets, it seems that some drift of the ablated

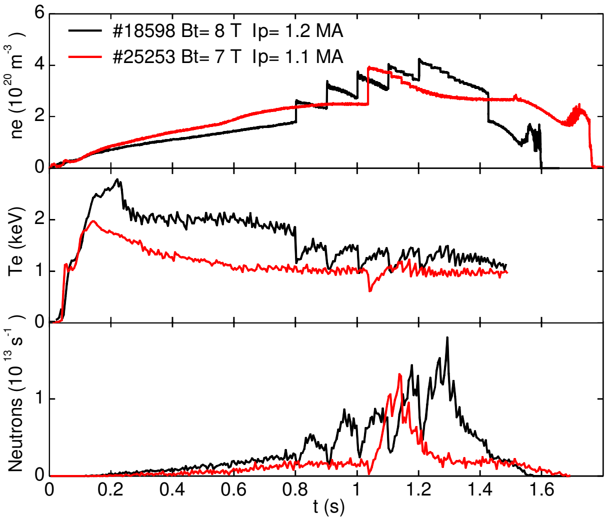

Figure 2. LFS injection (black) and HFS injection (red).

material is present and, by pre-cooling the plasma toward the magnetic axis, the pellet is able to reduce the ablation rate and survive longer. This picture is confirmed by numerical simulations. The effect does not seem to be strong enough in 1 MA discharges, where pellet penetration is small, and density profiles become hollow, inducing a disruption in many cases. Nevertheless, recent experiments indicate that, when plasma is particularly clean and the pellet timing is optimised, high performances can be obtained also at high current in spite of the pellet low velocity and the off-axis injection line.

Concerning plasma performances, we were able to compare the two best shots of the data sets considered. In figure 2 we show the density, temperature and neutrons time evolution for a LFS injection (5 pellets, V_p~1.4 km/s) [1] and a HFS injection (single pellet V_p~490 m/s). As can be seen results are comparable and for slower HFS pellets indicate a high fuelling efficiency (higher than 80%). Also neutron performances are comparable indicating that we are close to an optimised setting-up for HFS injection.

Numerical simulations

Pellet deposition has been modelled with the code PelDep2D, which is an improved version of the model described in [5] also used in the past to simulate ASDEX-U HFS injection experiments. The model takes into account the two-dimensional geometry of the injection, the adiabatic cooling of the plasma due to the pellet deposition and the drift of the ablated material along magnetic field gradient. The only free parameter is the length Λ along which the drift takes place. From the simulated density profile evolution during pellet ablation we reconstructed the density line integrals and compared them with the experimental values. An example of results for a pellet injected from the HFS in an 800 kA plasma is shown in figure 3. The general agreement with the experiment is acceptable. We are not able to simulate the sharp peak on the edge chord, due to the fact that the parallel expansion and the connection between the pellet cloud and the interferometer chords is not taken into account in the model. On the other hand, we are able to simulate the pre and post-

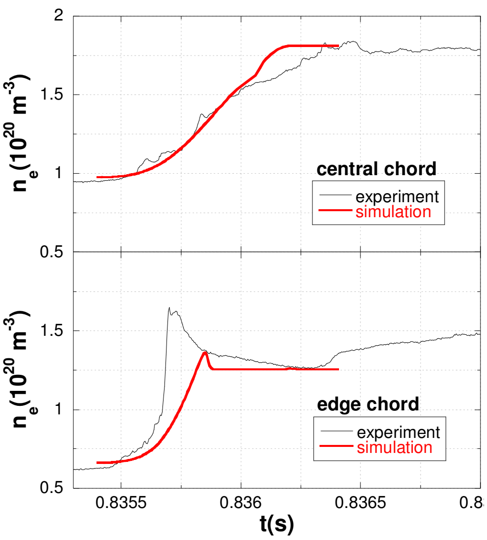

Figure 3. Experimental data and numerical simulation of chords measurement.

pellet values of both signals and the rise-time of the central chord. Moreover the simulation gives a penetration depth of about 40 cm in good agreement with the estimated value. This result was obtained with a value of Λ=7.5 cm, in agreement with the result of independent simulations reported in [6]. Increasing this value beyond 10 cm leads to a significantly worse agreement with the experimental data. This shows that in FTU the drift is too small for the ablated material to reach the centre. The enhanced penetration compared to the LFS case is due to the cooling of the plasma in front of the pellet. The same agreement and the same value for the drift were obtained when we simulated HFS pellets in a 1 MA plasma and LFS pellets.

The numerical analysis of the deposition profile provides a possible explanation of the experimental peaking time evolution mentioned above. Indeed LFS pellets show a deposition profile more concentrated towards the plasma centre, though do not have a large penetration. On the other hand, HFS pellets undergo a smoother ablation, thus depositing particles both at the edge and towards the plasma centre. These particles then diffuse towards the core on longer time scales, in such a way that the final result is similar to the one for LFS injection.

Conclusions

LFS and HFS pellet injection experiments were performed in FTU ohmic plasma in the range 0.8-1.1 MA achieving. good pellet quality and reproducibility. Plasma performances (neutron yield and plasma density) were comparable for LFS and HFS injection. Efficient plasma fuelling and deep particle deposition were obtained for HFS injection in spite of a moderate pellet speed (450-500 m/s) and an off-axis injection line. Instead, for LFS injection, a pellet speed of 1300 m/s had been used for achieving similar performances. The experimental data show evidence of a relatively small ∇B drift of the ablated material towards the low field side. However all these tests were performed in ohmic, low beta plasmas where this drift effect is expected to be small. Numerical simulations are compatible with a characteristic drift length between 5 and 10 cm. The drift has mainly the effect of adiabatically cooling the plasma in front of the pellet thus facilitating its deeper penetration. Different deposition profiles are obtained for HFS and LFS injection, showing different density behaviours on ablation time scales, whereas a similar result is produced on transport time scales. Enhanced central fuelling by magnetic reconnection, had already been found for LFS pellets. More accurate analysis is in progress to assess whether the same phenomenon enforces drift effects in the HFS case [7].

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