*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-5.160 (2009)*

Analysis of pellet fuelling, ablation and particle deposition at JET

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* *See the appendix of F. Romanelli et al., Proc. 22nd IAEA Fus. En. Conf., Geneva, 2008*

1. Introduction

Pellet injection is expected to be used to raise and control the density in a reactor-grade plasma. The viability and the efficiency of this method need to be investigated in large tokamaks in order to gain confidence in extrapolation to ITER. The JET pellet system, which already included a centrifuge injector, has recently been upgraded with a new high frequency pellet injector (HFPI) designed to deliver pellets both for fuelling purposes and for ELM pacing [1]. The new HFPI system has been successfully used in the fuelling mode (design mass range 2.2-3.8 x 10^{21} D atoms), delivering pellet trains (~30) through the low field side track (LFS) which reached the plasma with mass losses of about 40% up to a speed of 200 m/s and a repetition rate up to 10 Hz. Due to technical problems, the vertical high field side line (VHFS) has not been fully exploited while the high field side one (HFS) is still to be tested. Since the last pellet experiments at JET [2, 3], new diagnostics, including a fast visible camera, High Resolution Thomson Scattering and Polarimetry, have become fully operational thus improving the accuracy of the analysis.

2. Experimental data and Statistical analysis

One of the most important information, for pellet injection studies, is the evolution of the electron density profile following the pellet perturbation. This can be obtained at JET using three diagnostics whose capabilities have been continuously upgraded. A laser interferometer, relying on mechanical stability for the four vertical channels and on the 'two color' correction technique for the four horizontal ones, can provide, after inversion, a profile every 1.5 ms. On request, implying fast data acquisition and fast equilibrium reconstruction, the resolution time can be enhanced to 10 μs. A conventional LIDAR system (50 points, 4 Hz) and a new High Resolution Thomson Scattering (HRTS, 50 points, 20 Hz) give a direct measurement of density and temperature profiles which can also be applied for corrections of interferometer fringe jumps occurring during pellet ablation.

A statistical analysis has been performed using a routine able to detect the entrance of pellets into the plasma and calculate the difference between the HRTS profiles before and immediately after the pellet induced density jump. Only pellets followed by a HRTS pulse within 30 ms have been considered in order to limit the contribution of particle diffusion effects. In the cases considered, the pellet speed was in the range 180-200 m/s and the nominal mass was of the order of 3x10^{21} Deuterium atoms (D). Figure 1a) shows particle deposition profiles averaged over 26 pellets injected from LFS (blue) and over 9 pellets from VHFS (red) in L-mode. Fig 1.c shows the same comparison (22 pellets from LFS and 6 from

VHFS) in H-mode (P_{NBI}< 10 MW). There is no significant difference in the location of the maximum pellet particle deposition in L-mode for both launch positions. In H-mode, pellets injected from VHFS deposit particles slightly deeper. This is what is expected due to radial drift effects [4]. Using the same database, figure 1b) and 1d) show the averaged density jump evolution measured by the interferometer central chord. Compared to the L-mode, in H-mode plasmas the pellet density enhancement vanishes faster for both launch positions.

3. Ablation and Particle Deposition

Best target plasmas to study ablation and particle deposition are L-modes since in the presence of an edge pedestal (H-mode, Hybrid) other phenomena such as ELM induced losses and associated edge instabilities add up to ablation and drift effects. However, due to lower temperatures and temperature gradients, L-mode plasmas are expected to show less pronounced drift effects. Hence, high temperature L-mode phases are regarded most adequate for these studies. Within the statistical analysis illustrated above, we have examined a few cases with very similar plasma and pellet parameters and HRTS density profiles available a few ms after the injection. In figure 2a) and 2b) , particle deposition profiles taken within 5 ms after the pellet injection for two similar L-mode plasmas are displayed. Pellets comparable in launch size and speed were injected from LFS in shot 76411 and from the VHFS in shot 76570. A comparison of the measured particle deposition (black line) with ablation simulations based on a NGPS [5] code shows a modest displacement to the outboard for LFS and to the inboard for VHFS. Drift effects were not included in the simulations.

With an edge pedestal present, as already pointed out, the difference between the two injection lines remains marginal at moderate power. However, at higher power (>15 MW) the difference becomes dramatic. Injection from LFS was only hardly detectable on the peripheral interferometer line (R~3.75 m) while no significant change on the HRTS density profile was visible. Injection from VHFS provides much more fuelling efficiency: figure 2c) displays the particle deposition of a VHFS pellet (160 m/s, $3x10^{21}$ D) in a Hybrid plasma heated with 21 MW of NBI. The particle deposition, though more peripheral than in L-mode, was clearly visible and in agreement with the prediction of the ablation code.

4. Particle Transport

Fully predictive simulations performed with the JETTO code showed that the profile evolution was compatible with the Bohm/gyro-Bohm transport model [6]. Figure 4 shows the results of the simulation of a pellet injected from the LFS into an Ohmic target plasma. It was necessary to enhance the calculated Bohm/gyro-Bohm diffusion coefficient by a factor of 6-8 in the ablation region during the pellet transient in order to explain the observed fast particle redistribution. Nevertheless, the diffusion coefficient was lower than 1 m/s^2 in this phase (fig 6). Similar results were found in the case of VHFS injection in Ohmic plasmas. The density evolution after pellet injection in H-mode targets could also be reasonably well described with the Bohm/gyro-Bohm transport model. In this case however the particle diffusivity enhancement factor required to simulate the density decay after the pellet ablation was in the range 3-4. No evidence of an anomalous inward pinch was observed. However, in the analysed discharges the effective collisionality was relatively high and strong inward convection should not be expected. Moreover, for the Ohmic targets, sawteeth were present during pellet injection and this might have contributed to mask the effect of an anomalous pinch.

5. Fuelling

In spite of the limited performance achieved so far, the new pellet injector has shown good fuelling capabilities when used in repetitive mode. Figure 5a) shows the case of a LFS injected pellet train raising the average density by 50% in an L-mode discharge. The NBI power applied was of about 5 MW, pellets were of medium size (4x4 mm, $3x10^{21}$ D) with an average speed of about 100 m/s. The injection frequency was 10 Hz. It was estimated that the average particle flux injected by pellets was of $\Phi=2.4x10^{22}$ D/s which gives, at an average total particle content of N= $8x10^{21}$ D, a fuel retention time (N/Φ) of 330 ms.

Figure 5b) shows the effect of LFS pellet injection on an H-mode target (#77732, P_{NBI}~13MW). In this case, although the effect of single pellets was hardly visible, the average density was raised by 25% accompanied by a 13% confinement reduction.

Gas-pellet fuelling comparison studies were performed in H-mode at low (LT) and high (HT) triangularity plasma shapes. In LT configuration, where gas puffing is usually less effective in raising the density and more deleterious for the confinement, pellets performed similarly to gas at about half the particle flux. In HT, pellets were able as well to raise the density but the optimized gas performance was not reproduced. For more details, see ref. [7]

Dedicated fuelling experiments were also performed in the Hybrid scenario [8] and in combination with Error Field Correction Coil (EFCC) technique for ELM control [9]. In the latter case, pellets were able to compensate for density reduction (pump-out) normally observed during the application of low n magnetic perturbations. As for the other cases, pellets proved to be more efficient than gas in terms of particle flux required for achieving the performance.

7. Conclusion

The new pellet injector, recently installed at JET, has been successfully applied in the fuelling mode. Only the LFS and VHFS tracks were used, the latter being limited in delivery efficiency. Intact pellets reached the plasma from LFS up to a speed of 200 m/s and 10 Hz. Ablation studies have shown good agreement with model predictions and, as expected from radial drift theories, the VHFS has proven to be more effective than LFS track in depositing particle deeper into the plasma. New results confirm that transport coefficient need to be increased by a factor of 3-8 with respect to BgB level in order to explain the density profile evolution in the ablation region during the transient. The fuelling capabilities of the system need further enhancement and exploitation. For improving particle drift studies it would be desirable to use suitable L-mode targets with as high electron temperature as possible in order to maximize the expected particle displacement but avoiding additional edge effects.

References

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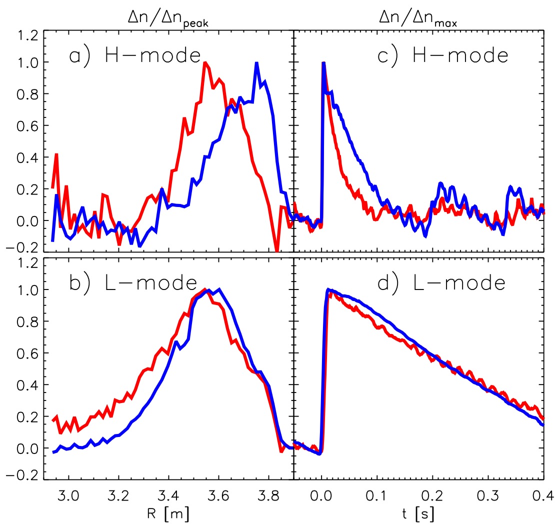

Fig 1: Normalised particle deposition (left) and density decay (right). Top row: H-mode. Bottom row: L-mode. Blue: LFS. Red: VHFS.

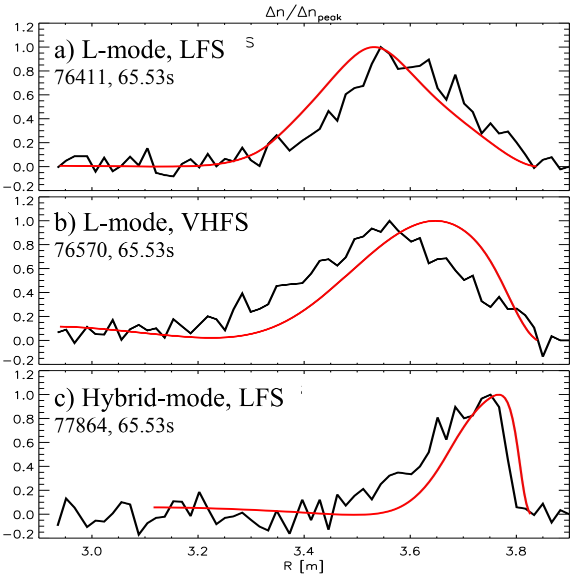

Fig 2: Normalised particle deposition (black) compared with ablation predictions (red, NGPS model without drift).

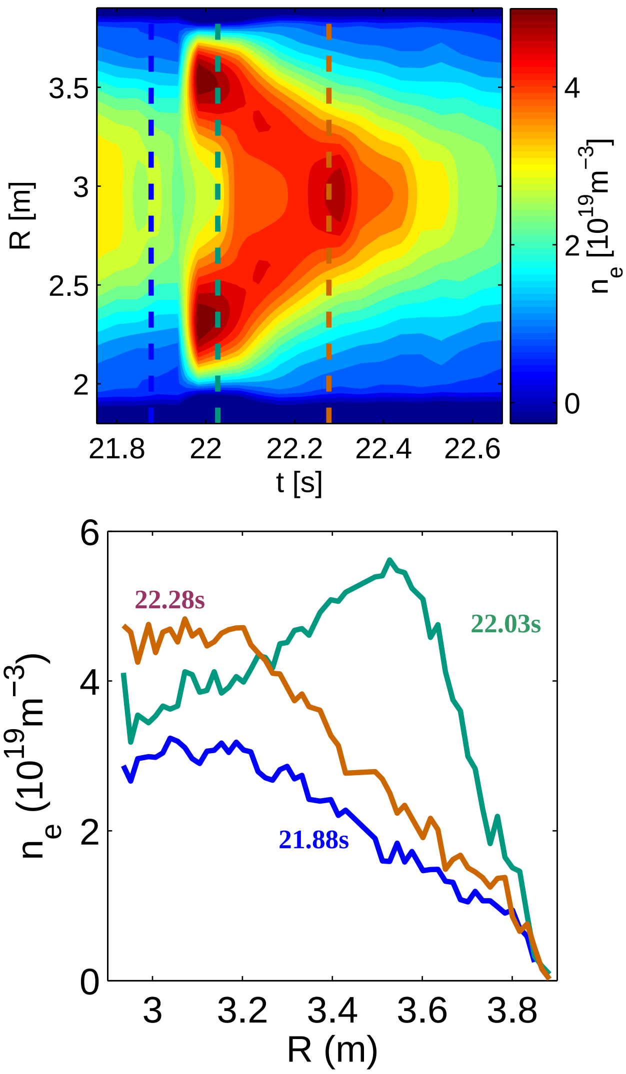

Fig 3: Density profile evolution (#77421). Top: contour plot. Bottom: HRTS profiles before, immediately after injection and after particle diffusion (times of vertical lines in the top box)

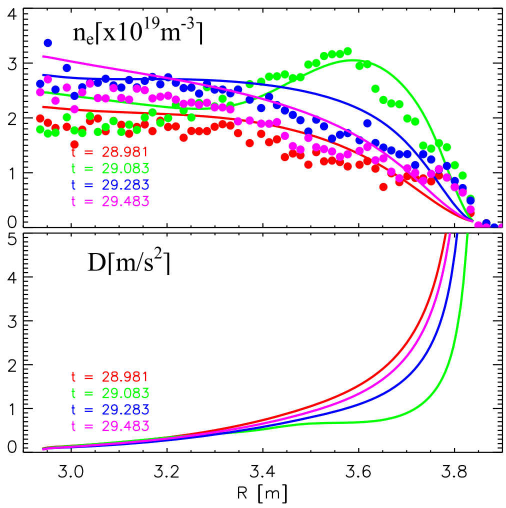

Fig 4: Fully predictive JETTO simulation of density profile evolution in the vicinity of a LFS pellet injected into Ohmic plasma (#76570). Top: density profiles (lines: JETTO. points: HRTS.). Bottom: particle diffusivities

Fig 5: Density integrated along a central chord. Blue line: Interferometer. Red crosses: HRTS. Top: LFS, L-mode (#76924). Bottom: LFS, Hybrid (#77732) ⟶