Particle transport analysis of L-mode pellet fuelled plasmas in JET

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Introduction

After pellet injection many phenomena take place in the target plasma on different time scales. Pellet ablation and ablated mass redistribution occur in a time-interval of few milliseconds immediately after injection and determine various aspects of the particle source due to the pellet as, for example, penetration depth and fuelling efficiency. After the faster phenomena immediately following pellet injection, slow diffusion and relaxation of the post injection profile take place on a time scale of the order of the confinement time (hundreds of milliseconds in JET). They are determined by the global transport regime in the target plasma and, from the perturbative analysis of this longer phase, transport information can be extracted provided that profile behaviour is known with high enough time resolution.

Pellet fuelling experiments of both L-mode and H-mode plasmas have been performed at JET during the May 1999 campaign [1], by means of both low field side (LFS) and high field side (HFS) injection, to characterise pellet injection in different scenarios. The main purpose was the investigation of how pellet penetration and fuelling efficiency change switching from LFS to HFS injection and how they scale with varying target plasma and pellet parameters.

However for a set of L-mode pellet fuelled discharges the profile measurements were suitable also for particle transport analysis. In this paper we concentrate on these shots and present a study of particle transport and density profile behaviour aimed to understand the basic characteristics of the transport regime in pellet fuelled plasmas. The analysis has been conducted to investigate the differences between this transport regime and the conventional one and to clarify two main points:

i) establish the variation of the particle diffusion coefficient in the plasma;
ii) assess the effects of the introduction of an inward pinch velocity.

The analysis tool employed is the JETTO transport code, coupled with a Neutral Gas and Plasma Shield (NGPS) ablation code to calculate the pellet particle source. The two coupled codes have been used to perform a statistical analysis by varying the principal diffusion parameters.

Experiment description

In the experiments considered in this paper, pellet trains were fired in JET L-mode plasmas from t_s=58 s to t_e=61 s. Pellet parameters were: nominal mass $3.84\cdot10^{23}$ atoms, velocity 160 m/s and injection frequency 5 Hz. Target plasma characteristics were: plasma current 2.5 MA, magnetic field 3.2 T, on axis density and temperature before pellet injection $2\cdot10^{19}$ m^{-3} and 3 keV respectively. 1 MW of neutral beam injection was applied for diagnostic purpose and ion cyclotron radio frequency heating (ICRH) varied from 2.6 MW to 7.7 MW.

During the experiments electron density and temperature profiles were measured by the LIDAR Thomson scattering with a sampling frequency of 4 Hz. Therefore the relative delay between pellet and LIDAR profile increased by 50 ms per successive pellet. Assuming periodic behaviour, which seems reasonable since between two pellets both plasma electron density and temperature relax to the pre-pellet profiles, this technique is equivalent to a profile sampling after pellet injection with 50 ms time resolution.

In these experiments the density profile evolution exhibits some features that cannot be reproduced by the standard diffusion model describing particle transport in JET plasmas [2]. In particular the experimental evidence shows that the relaxation and the peaking of the post-pellet hollow density profile take place on a time-scale which is two to three times shorter than that predicted by the conventional model.

Results and discussion

In order to perform a quantitative study of the density profile behaviour a pellet ablation code has been coupled with the JETTO transport code. The ablation code employed is the NGPS model described in [3, 4]. The model has been tested on the IPADBASE [5], a database of pellet fuelled discharges from several machines and is able to reproduce the pellet penetration in different experimental conditions.

To obtain the density and temperature profiles needed to calculate the pellet ablation, the JETTO profiles have been mapped onto the pellet trajectory and used in the ablation code as the effective profiles seen by the pellet. This allows the simulations of pellet injection from any position on the plasma boundary, in particular of pellet injection from the plasma high field side.

The model in its present state is not able to calculate the fuelling efficiency and the effective particle source profile due to the pellet taking into account the post-ablation drift of the ionised cloud [6, 7]. Therefore the effective pellet mass has been inferred from the plasma density rise and the particle source profile associated with pellet injection has been assumed coincident with the ablation profile. This does not affect dramatically the results because the pellet penetration depth is small compared with the plasma minor radius and therefore relative modifications of the source radial shape have little relevance on the profile evolution. Also the time during which the drift is effective is much shorter than the duration of the simulation.

We have chosen shot 49030 as a typical shot representative of the set of discharges under consideration. In this shot inboard pellets where launched and 5.1 MW of ICRH were present. The basic features to reproduce are the decay of the total plasma particle content following each pellet injection and the relaxation of the density profile.

The decay of the plasma volume averaged density can be reproduced by modifying either the recycling coefficient after the pellet injection or the particle flux at the plasma edge. In the simulations performed we have lowered the recycling from 1.0 to 0.9 after the injection of the first pellet and kept it constant during the injection of successive pellets. Moreover we have modified the diffusion coefficient at the plasma edge. In the standard transport model in use at JET the particle diffusion coefficient is given by the following expression:

$$D(r) = S(r)\frac{\chi_i(r)\chi_e(r)}{\chi_i(r)+\chi_e(r)}$$

where S(r) is a form factor monotonically decreasing from the plasma centre to the plasma edge with S(0)=1.0 and S(a)=0.3. $\chi_{i,e}(r)$ are linear combinations of the Bohm and gyro-Bohm ion and electron thermal diffusivities.

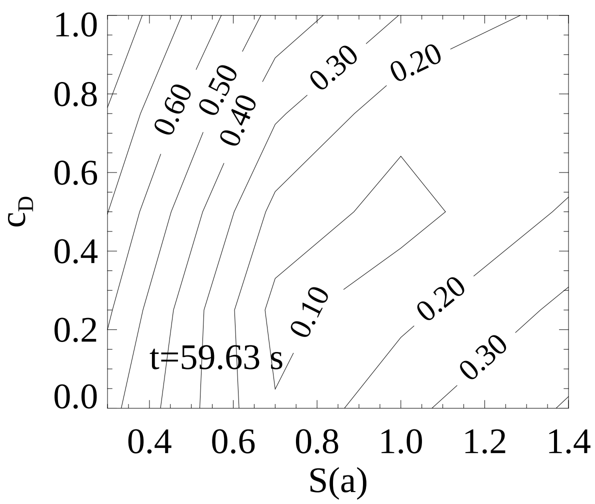

Figure 1: contour plot of Δ^2 at t=59.63 s for the case $V=c_D r\cdot D/a^2$.

It is worth noting that the Bohm contribution to $\chi_{i,e}(r)$ is proportional to $\nabla T/T_{edge}$ so that lowering the edge temperature enhances the global transport. Therefore it is important to correctly impose the boundary condition on the electron temperature. In all the simulations performed we have prescribed T_{edge} in order to track the plasma edge cooling measured by the outermost channel of the ECE. The initial value for T_{edge} is obtained by extrapolating the LIDAR profiles to the plasma edge.

As to the relaxation and the peaking of the density profile they can be determined either by the pellet penetration depth or by the diffusion of the ablated material toward the plasma centre driven by the negative density gradient of the hollow profile created by the

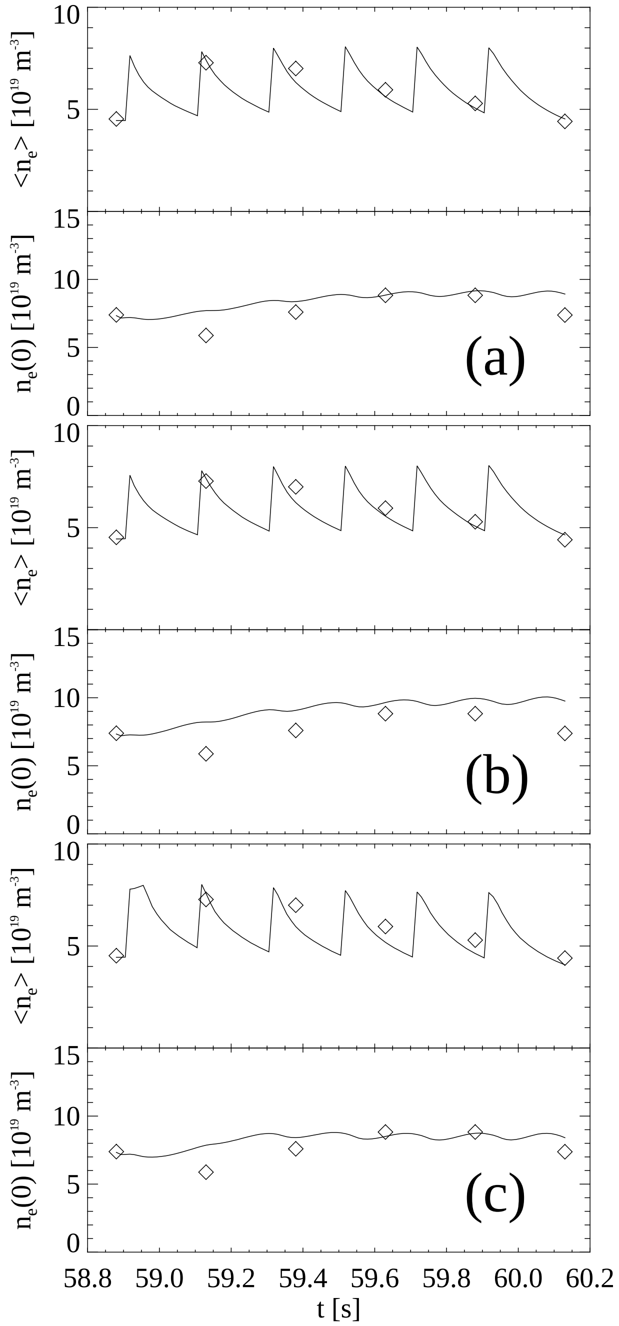

Figure 2: experimental and simulated time behaviour of average and on-axis plasma density. ***(a)*** *$V=c_D r\cdot D/a^2$ ($c_D=0.5$),* ***(b)*** *$V=-c_T D\cdot \nabla T_e/T_e$ ($c_T=0.15$), and* ***(c)*** *$V=c_q D\cdot \nabla q/q$ ($c_q=0.25$) (diamonds: LIDAR measurements, solid line: simulation). In all cases S(a)=1.0.*

pellet injection or to the presence of an inward pinch velocity or to a combination of these three phenomena.

To analyse this point with particular regard for the presence of a pinch velocity we have introduced in the code an inward convection. Three forms for the convective velocity V have been tested: an empirical model with $V=c_D r\cdot D/a^2$, and two theory based models with either $V=-c_T D\cdot\nabla T_e/T_e$ or $V=c_q D\cdot\nabla q/q$ [8, 9, 10]. The sign convention is such that V>0 represents an inward pinch.

In order to perform a statistical analysis of the simulated profiles we have varied the value of S(a) and the value of the coefficients c_D, c_T, and c_q. The grid over which the coefficient have been varied is S(a)=(0.3, 0.7, 1.0, 1.4) and c_D, c_T, and c_q=(0.00, 0.25, 0.50, 0.75, 1.00). In practice we have systematically increased S(a) in order to quantify the diffusion enhancement in the target plasma and introduced a pinch velocity in the model.

To evaluate the quality of the simulation we have calculated [11]:

$$\Delta^2 = \frac{\sum_{j=1}^{N}\left[\left(n_{exp}(x_j)-n(x_j)\right)/n(x_j)-m\right]^2}{N}$$

with:

$$m = \frac{\sum_{j=1}^{N}\left[\left(n_{exp}(x_j)-n(x_j)\right)/n(x_j)\right]}{N}$$

where x_j is the j-th point of the spatial grid and we have determined the regions in the parameter space where Δ^2 was minimum.

An example of the result is given in Figure 1, showing the contour plot of Δ^2 for the case $V=c_D r\cdot D/a^2$. It can be seen that Δ^2 reaches its minimum value of 9% for $0.7<S(a)<1.0$ and $0.1<c_D<0.6$. Moreover it can be noticed that the highest values of S(a) minimising Δ^2 correspond to the highest values of c_D and that therefore the two parameters cannot be chosen independently.

A similar analysis has been conducted for the $V=-c_T D\cdot\nabla T_e/T_e$ and $V=c_q D\cdot\nabla q/q$ cases and gives similar results. In particular, for the $\nabla T_e/T_e$ velocity, a minimum Δ^2 of 12% is obtained for $0.7<S(a)<1.0$ and $0.0<c_T<0.25$ whereas, for the $\nabla q/q$ velocity, the minimum Δ^2 was 11% and was obtained for $0.7<S(a)<1.0$ and $0.0<c_q<0.5$. The optimum values of c_T and c_q are significantly smaller than those predicted by theory which are 0.5 and 1 respectively.

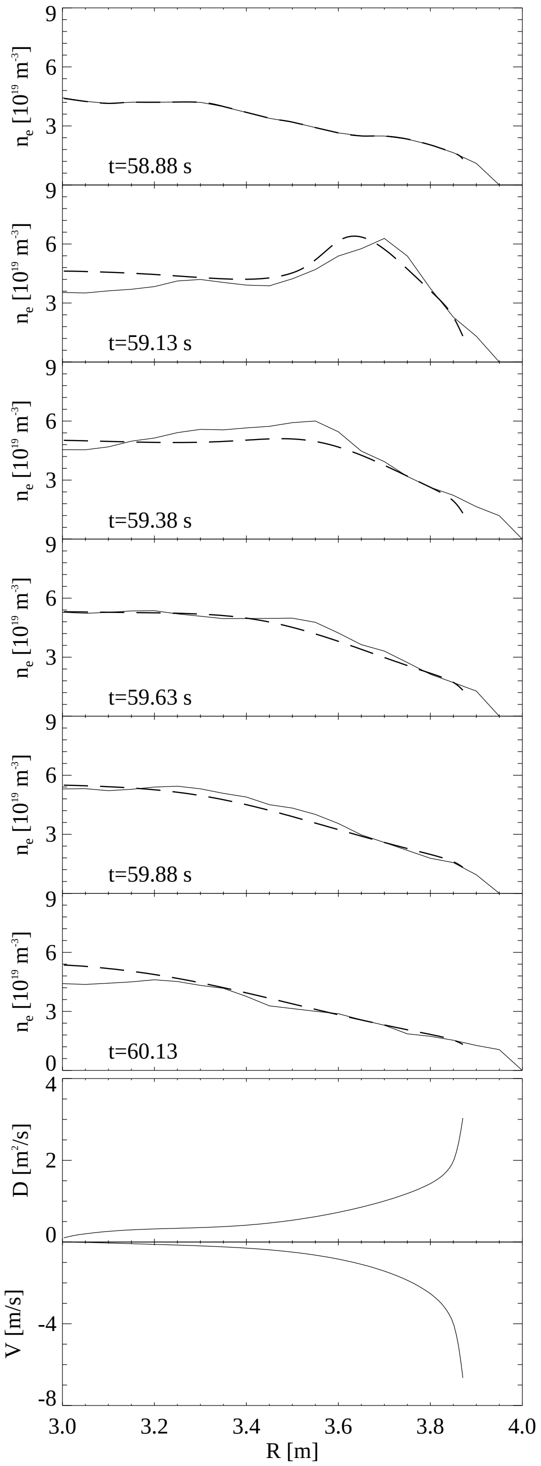

Figure 3: time evolution of plasma density profile for the case $V=c_D r \cdot D/a^2$ (c_D=0.5, S(a)=1.0). Simulated density profiles (dashed lines) are compared with LIDAR measurements (solid lines). The last two frames show the particle diffusion coefficient D(r) and the pinch velocity V(r) at t=59.63 s.

The results of the simulations are plotted in Figure 2 and 3. In Figure 2 we compare the experimental and simulated time evolution of the average and central plasma density for the three cases. The first six frames of Figure 3 display the experimental and simulated evolution of the density profiles for the case $V=c_D r \cdot D/a^2$, whereas the remaining two frames show the diffusion coefficient and the pinch velocity at t=59.63 s. Beside the good agreement between experiment and simulation, it should be observed that the pinch velocity used in the simulation is less than 2 m/s for r/a<0.8 and increases up to 6 m/s at the edge.

Conclusion

A study of particle transport in JET during L-mode pellet fuelled discharges has been done. In order to reproduce the density profile behaviour we found that it is essential to take into account the edge cooling induced by the pellet and the resulting increased diffusion. Nevertheless this is not sufficient to explain the fast relaxation and peaking of the post-pellet hollow density profile. Some other mechanism should be at work and an extra enhancement by a factor of 2 to 3 of the particle diffusion at the plasma edge has to be invoked. Finally we found that the presence of an inward pinch velocity may help in reproducing the peaking of the density profile. However if such a velocity exists, it is weak (<6 m/s) and tends to be overestimated by theoretical predictions.

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