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Particle and energy transport analysis by means of pellet injection in the RFX reversed field pinch.

R. Lorenzini, L. Garzotti, P. Innocente, S. Martini, B. Pégourié*

Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy.
**CEA Cadarache, DRFC, 13108 Saint-Paul-lez-Durance, France.*

Introduction

Several pellet injection experiments have been performed in the last two years on the RFX reversed field pinch with the main aim to increase the plasma density and to improve the global confinement.

Pellet of mass m_p=1.5÷3· 10^{20} atoms and injection speed v_p=100÷500 m/s were injected in reversed field pinch (RFP) discharges with current I_p=600÷800 kA, electron density n_e=2÷3· 10^{19} m^{-3} and electron temperature T_e=250÷350 eV. Pellets were launched both in standard RFP plasmas and in combination with pulsed poloidal current drive (PPCD) [1]. The PPCD is a technique to stabilise internally resonant tearing modes that are responsible for magnetic field stochasticisation and for transport increase in the RFP core. Hence, pellet injection in superposition with PPCD could be an optimal scenario to obtain simultaneously efficient particle fuelling and good energy confinement. In the discharges presented here, PPCD is applied to the plasma from 32 ms to 42 ms.

A previous qualitative analysis [2] has already indicated that, in general, fast (v_p≈400 m/s) pellets aimed at the plasma centre trigger a dynamo relaxation event (DRE) enhancing the global transport in the plasma and preventing the temperature recovery after injection. However, in some rare cases, the DRE does not occur.

For pellets launched during the PPCD two phenomenologies are possible. If the mode stabilising effect of the PPCD is strong enough, a synergy between pellet injection and PPCD is possible. In this case the PPCD counteracts the perturbation induced by the pellet, the plasma confinement properties are maintained and a post pellet temperature increase is observed, leading to an enhancement of the global β.

On the other hand, if the PPCD is not sufficiently effective to stabilise the magnetic configuration, the transport reduction is lost. In this case the plasma temperature does not recover, remains low after the pellet injection and no increase of the total plasma energy content is obtained.

In this paper we present a transport analysis to estimate the transport coefficients for different injection scenarios. In particular we paid attention to the connection of the transport parameters with the behaviour of the magnetic configuration. The analysis has been performed using an interpretative transport code modelling the behaviour of both density and temperature profiles. The code has been used to analyse five different cases: two standard RFP shots (one of them with DRE triggered by the pellet and one without), two shots with pellet in combination with PPCD (one with pellet injection at the beginning of the PPCD and one with pellet injection at the middle of the PPCD), and one shot with injection of a low velocity (v_p=120 m/s) pellet.

Although the transport analysis presented is not directly extendible to unperturbed plasmas, because pellet injection represents a major perturbation of the equilibrium, it sheds some light on the transport modification induced by pellet injection, the robustness of the so-called improved confinement regimes and the possibility to perform effective plasma fuelling without spoiling global confinement properties.

Model description

The modelling of the plasma behaviour has been done by coupling a pellet ablation code [3], which computes the pellet ablation and trajectory according to the Neutral Gas Shielding (NGS) [4] scaling law properly averaged over the Spitzer and Härm [5] electron distribution function, with a 1-D transport code describing the plasma density and temperature evolution.

The equations for density and temperature are the following:

$$\frac{\partial n(r,t)}{\partial t} = -\nabla\cdot\Gamma(r,t) + S_p(r,t) + S_r(r,t)$$

$$n(r,t)\frac{\partial T(r,t)}{\partial t} = -\nabla\cdot Q(r,t) - = P_p(r,t) - P_r(r,t) - P_{rad}(r,t) + \eta(T(r,t))j^2(r,t)$$

where particle and energy fluxes are written as:

$$\Gamma(r,t) = -D(r,t)\nabla n(r,t) + V(r)n(r,t) \text{ and } Q(r,t) = -\chi(r,t)\nabla T(r,t) + \frac{5}{2}\Gamma(r,t)T(r,t)\,.$$

In the above equations the various particle and energy sources and sinks can be described as follows:

– $S_p(r,t)$ is the pellet particle source and is provided by the ablation code.

– $S_r(r,t)$ is the recycling source and is written in the form $S_r(r,t)=R(t)F(r)\Gamma(a,t)$ where the recycling R(t) is time dependent and is tuned to track the evolution of the total plasma particle content, the profile factor F(r) is calculated once for all for a typical pellet fuelled RFX discharge by mean of the recycling code EDCOLL [6] and $\Gamma(a,t)$ is the particle outflux at the plasma wall. This degree of approximation would be sufficient since the behaviour of the plasma core is affected primarily by the pellet source and not by the details of the plasma edge where the recycling source is important. The particle sink is the total particle outflux.

– ηj^2 is the ohmic power deposition where η is the Spitzer resistivity.

– $P_p(r,t)=S_p(r,t)\varepsilon_i$ and $P_r(r,t)=S_r(r,t)\varepsilon_i$ are the energy sinks represented by the power necessary to ionise and heat the pellet and recycled particle respectively (ε_i=25 eV is the energy lost per hydrogen ionisation).

– $P_{rad}(r,t)$ is the radiated power which has been assumed of the form $P_{rad}(r,t)=W_{rad}(t)G(r)$ where $W_{rad}(t)$ is the total power radiated by the plasma (for RFX typically 5-10% of the total power input) and G(r) is a fit of the experimental profile of the radiation sink [7].

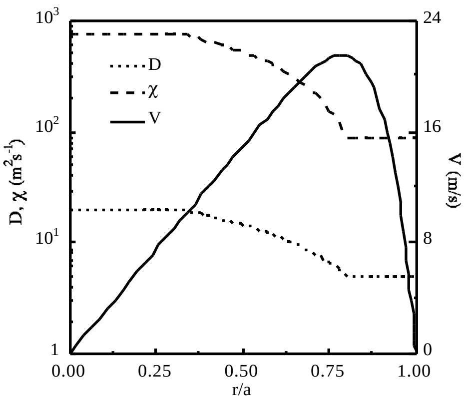

Figure 1: example of the transport coefficient profiles.

Typical profiles [8] of the transport coefficients D, V and χ are given in Figure 1.

The model uses the experimental time evolution of current profile computed by the μ and p equilibrium model [9].

Results and discussion

All the simulations start at the pellet injection, from values of D, V, and χ consistent with the stationary density and temperature profiles.

The central and edge values of D and χ may be varied in time to track the experimental behaviour of the line integrated density profile measured by a 13-chords interferometer and the central electron temperature measured by a double filter diagnostic. No time evolution of the temperature profile is available because the RFX Thomson scattering diagnostic provides only one 20-points profile per shot.

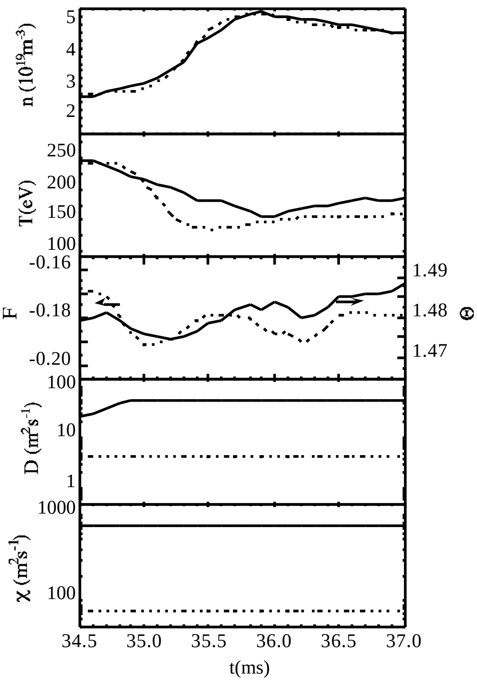

Figure 2: experimental (solid line) and simulated (dashed line) central density and temperature, experimental F and Θ, central (dashed line) and edge (solid line) values of D and χ for shot 8066.

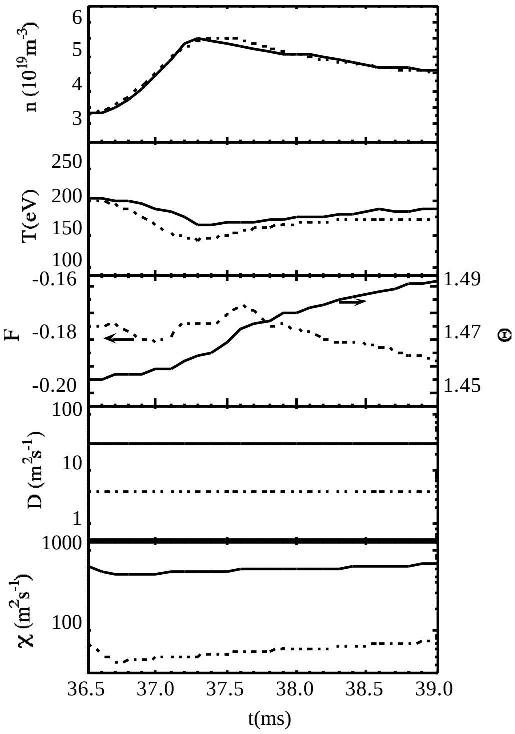

Figure 3: same as Figure 2 for shot 7274.

The results are summarised in Figures 2-6 where for each pulse we plot the simulated and experimental central density and temperature, the experimental reversal $F \equiv B_\phi(a)/\langle B_\phi \rangle$ and pinch $\Theta \equiv B_\theta(a)/\langle B_\phi \rangle$ parameters, the centre and edge values of the diffusion coefficient and thermal diffusivity.

The oscillations of the F parameter for pulse 8066 indicate that after the pellet injection, a DRE is immediately triggered and a sawtooth activity sets on.

To reproduce the experimental data, the diffusion coefficient has to be increased from its stationary value, which is 20 m^2/s, to 60 m^2/s, while a constant profile of thermal diffusivity can be used. However this does not rule out the possibility of a similar increase of the central χ made less evident by a favourable scaling of the edge χ with density [8].

In the case of shot 7274 the pellet is injected during a spontaneous transition of the plasma toward an improved confinement state, which has previously been identified as an α-mode [10]. F was increasing, Θ decreasing and the dynamo mode amplitude was globally decreasing. In this condition the pellet does not affect the transport. This is reflected by the fact that, in order to reproduce the plasma parameter behaviour, there is no need to increase the diffusion with respect to the pre-pellet phase and the thermal diffusivity has to be decreased.

The pellet of shot 8059 is injected in correspondence with the start of the PPCD, and the most evident feature of the plasma behaviour is the recovering of the central temperature which is faster than in the case without PPCD. To reproduce the plasma central temperature a reduction from 800 m^2/s to 200 m^2/s in 2 ms has been applied to the central value of χ, whereas the edge value is kept nearly constant. The density behaviour is compatible with a central value of D, averaged over the duration of the phase when the density profiles are strongly peaked, of about 25 m^2/s. These results confirm that in the initial phase the PPCD induces an improved DRE-free confinement regime.

When the pellet enters the plasma at the middle of the PPCD phase (shot 8040) the dynamo mode amplitude starts to increase and no recovery of the central temperature is observed. This suggests that the mode stabilising effect of the PPCD diminishes after its initial phase and its effectiveness in maintaining an improved plasma confinement in spite of pellet injection is lost.

Indeed the transport parameters, which have been reduced in the same way as for shot 8059 to reproduce the effect of the PPCD on the plasma confinement before the pellet injection, have to be increased after the pellet injection. The rapid increase of central value of D up to a value of 50 m^2/s is very similar to the value of shot 8066 in presence of a DRE.

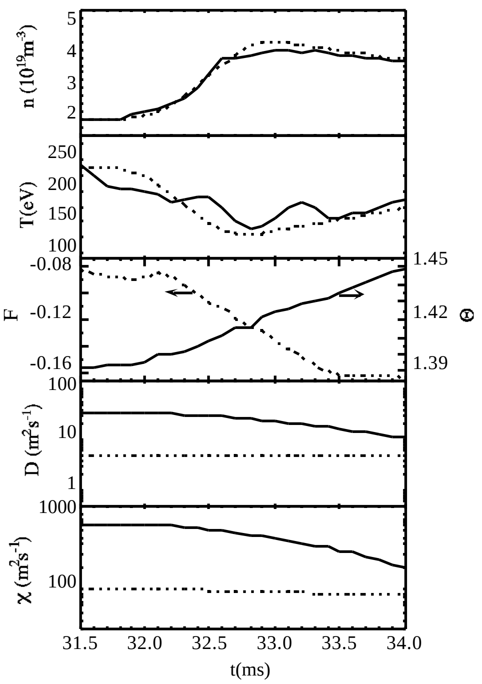

Figure 4: same as Figure 2 for shot 8059.

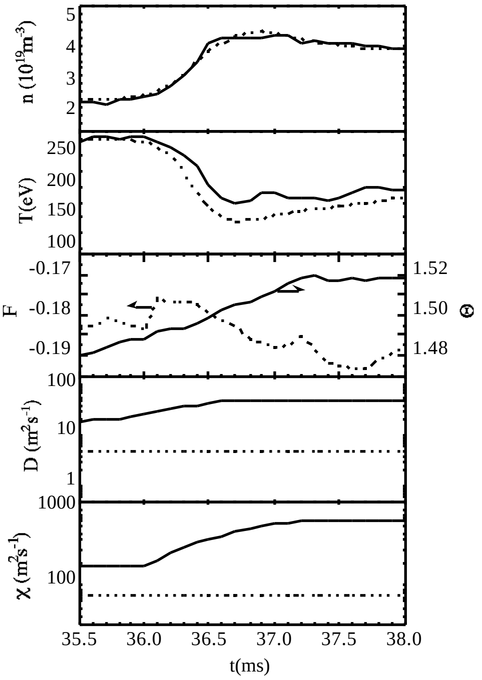

Figure 5: same as Figure 2 for shot 8040.

The low speed pellet (shot 8092) misses the centre and completely ablates at r/a > 0.7. As previously noted [10] as long as the core plasma region is untouched even a strong cooling of the outer region does not excite a DRE. This could be due to the fact that the pellet does not reach the plasma region where the dynamo tearing modes are resonant. The particle diffusion coefficient maintains the pre-pellet values of about 20 m^2/s at the centre, whereas the fast recovering the central temperature requires a reduction of edge value of χ that can be related to the average density increase.

Conclusions

Pellet injection experiments have been performed on the RFX reversed field pinch and analysed by means of a transport code to investigate the transport modifications induced by the pellet and to ascertain the possibility of effective plasma fuelling avoiding excessive confinement deterioration. The experimental results indicate that deep pellet injection affects the plasma confinement. The precise cause of this transport increase is under investigation but its evident that the pellet triggers a DRE followed by an increased magnetic activity.

For pellet injection to be effective and to fuel the plasma without reducing the confinement it should therefore be coupled with a confinement improvement that can counteract the pellet injection negative effects. This improvement can be spontaneous (α-mode) or induced (PPCD). However, the PPCD has proved itself effective in counteracting the natural confinement degradation induced by the pellet only in its first phase.

The simulation results confirm these experimental evidences. It is not possible to well reproduce the experimental data by means of the same D and χ profiles. When an improved confinement regime inhibits the onset of the DRE, the central value of D is 20-30 m^2/s, otherwise values of about 50-60 m^2/s are requested. Similar considerations apply also to χ profiles, which undergo significant differences during the transition from a standard confinement regime to an improved one and vice-versa.

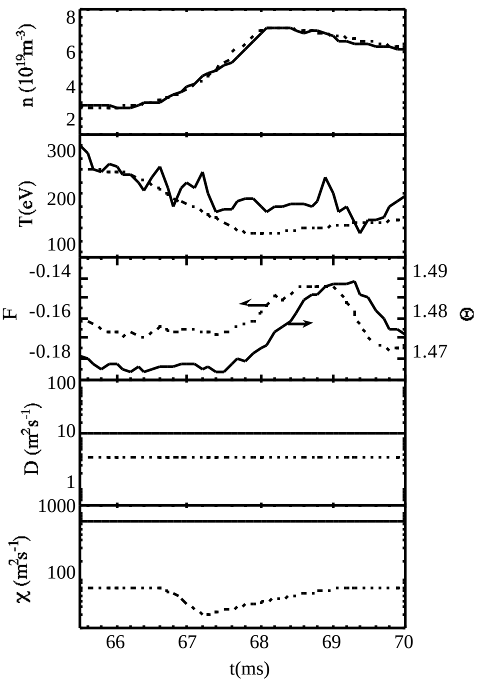

Figure 6: same as Figure 2 for shot 8092.

As a final remark we point out that in all the simulations performed the χ/D ratio is always between 10 and 20 and is compatible with a transport regime determined by the magnetic field lines stochasticity as described by Rechester and Rosenbluth in [11].

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