Investigation of the particle transport properties in RFX-mod SHAx state

F. Auriemma, L. Carraro, A. Fassina, P. Franz, P. Innocente, R. Lorenzini, W. Schneider[1], M. Zuin

Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione, 35127 Padova, Italy
1Max-Planck –Institut für Plasmaphysik, EURATOM Association, Teilinstitut Greifswald, Wendelsteinstraße 1, D-17491 Greifswald, Germany

Introduction

The density of a thermonuclear plasma is a critical parameter, since the fusion power increases as the square of density. Moreover particle transport contributes also to energy and momentum losses and plays a role in plasma-wall interaction processes. This is the reason why a significant deal of work of fusion science community is devoted to understanding particle transport.
A contribution to this research area comes from the study of particle transport in the self-organized, helical equilibrium named Single Helical Axis (SHAx[1]) which is observed in Reversed Field Pinch experiments. SHAx states appeared for the first time in high current discharges (up to 2MA) of RFX-mod experiment, thanks also to the good control of the magnetic plasma boundary obtained with the active control system peculiar of this machine.
When plasma enters the SHAx state is likely to develop electron internal transport barriers[2], which result in the formation of strong gradients in the electron temperature profile and in three-fold increase of confinement time with respect to standard plasmas[3].
Particle confinement studies in discharges where the plasma core is fuelled by means of pellet injection have shown a reduction of particle transport during SHAx states[4]. Preliminary transport analysis on plasma without pellet injection suggest that the particle diffusivity of SHAx states is reduced with respect to the standard case [5]. They also show that the theory of transport in stochastic magnetic field, which successfully describes the standard case, is not suitable in the SHAx case. Moreover impurity transport has been studied, turning out the presence of an outward velocity that prevents the impurity accumulation in the plasma core [6].
In this work we analyse the dependence on the average density of density profiles and we discuss the behaviour of particle transport coefficients in SHAx states of RFX-mod experiment. In particular we show that the convective particle flow predicted by the theory of transport in stochastic magnetic field [7][8] is systematically higher than that required to match the experimental data, the particle diffusivity at the edge results to be strongly dependent on the average density value.

Particle density profile

SHAx state usually develops in plasma with density $n/n_G < 0.30$, being $n_G = I_p/(\pi a^2)$ the Greenwald density, I_p the plasma current and a=0.459 m the minor radius. A database of 10 plasma pulses, with I_p between 1.6 and 1.8 MA has been selected, at different average densities, with good measurements of density profiles by the multi-chord interferometer and reflectometer and of temperature profile with the multi-point Thomson Scattering

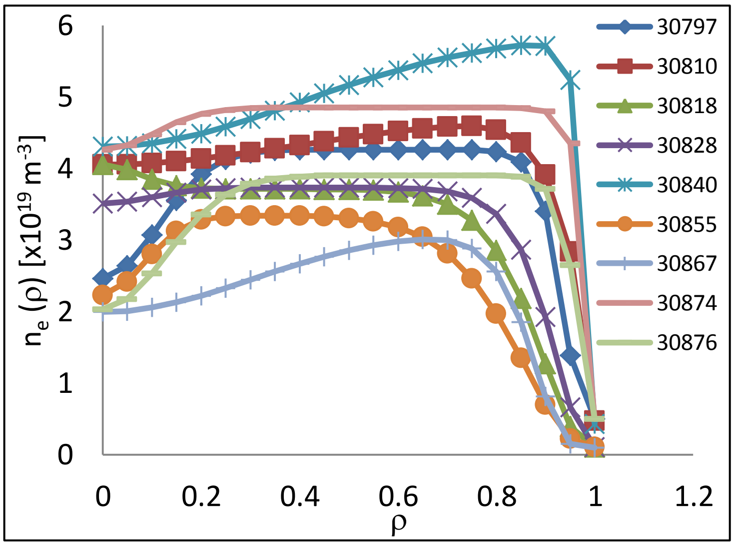

Figure 1: inverted density profiles as a function of the radial helical flux coordinate ρ.

Figure 1 displays the electron density profiles for each analyzed shot. The profiles are computed using both the interferometer and the reflectometer data. The latter helps the reconstruction of the edge profile giving information on the position of the 1.15 10^{19} m^{-3} layer. The profiles are plotted as a function of the normalized radial quantity $\rho = [(\chi-\chi_0)/(\chi_e-\chi_0)]^{0.5}$ being χ the helical flux (subscripts "0" and "e" refer to its central and edge value).

A direct relation between the edge gradient and the density level turns out. In particular the normalized average density gradient $\nabla n_{80}/\langle n_e\rangle$, computed from the edge up to the 80% of the maximum density value, scales with the Greenwald fraction. Moreover considering the normalized edge density gradient $\nabla n_{ed}/\langle n_e\rangle$ (computed about in the last 3 cm of the radius) the presence of a flat region at the very edge (∇n_{ed}~0) for density below [0.10-0.12] of the Greenwald fraction. The density value at which the transition occurs is not better identified because of the lack of points in the present dataset. It is important to notice that data are displayed as functions of n/n_G even if, since I_p is only slightly varying in the database, it is not clear if the shape of the edge density profile is ruled by the Greenwald fraction or by the average absolute density level. These results are summarized in figure 2, where the $\nabla n_{80}/\langle n_e\rangle$ is plotted in black dots and the $\nabla_n ed/\langle n_e\rangle$ is represent by red diamonds. This behavior can be explained by the presence of density coherent structures (blobs) at the edge of the plasma: it has been observed that their average perpendicular dimension is directly linked with the local electron pressure gradient [9].

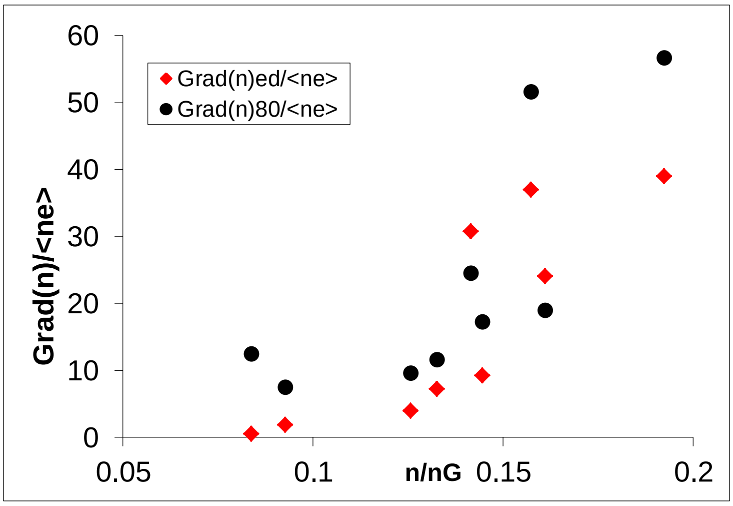

Figure 2: density gradient normalized to the average density plotted as a function on the Greenwald fraction. The red series refers to the very edge portion of the density profile, whereas the black dots represent the average gradient.

Looking at the global shape of the density profiles, going towards the center of the plasma, after the external gradient region there is a flat part and eventually a central reduction of the density is observed. The hollow region corresponds roughly to the radial position of the electron temperature gradient (see figure 3,where the dashed vertical line identify the steepest part of the temperature profile). A stationary density profile with a hollow region cannot be described only by a diffusion process but requires the presence of an outward velocity associated with the positive density gradient. To investigate the central and edge behavior of the density and the magnitude of the outward velocity, transport simulations have been performed.

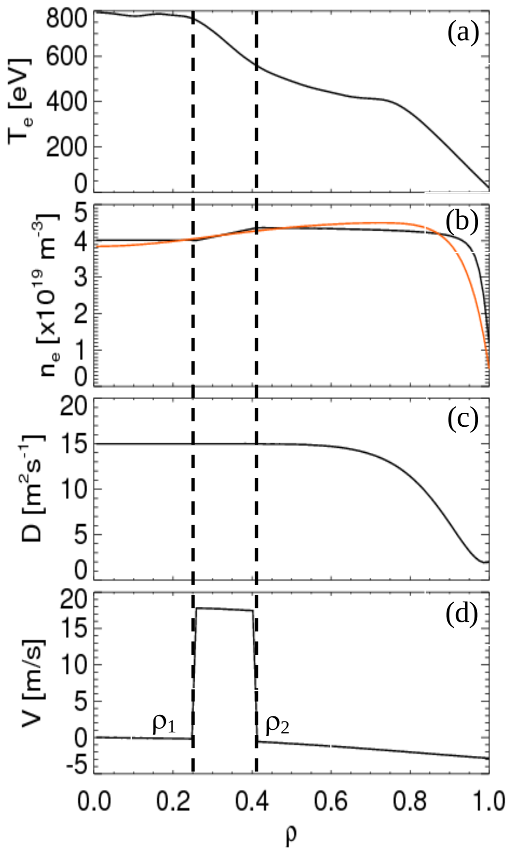

Figure 3: (a) experimental temperature profile and (b) density profile (red inversion, black ASTRA simulation) for pulse 30810. Plot (c) and (d) display the diffusivity and velocity term. The dashed lines highlight the region where Vout ≠0, corresponding to the location of the steepest temperature gradient.

Density transport analysis: results and discussion

The transport analysis has been carried out with ASTRA[10], providing to the code the experimental electron temperature $T_e(\rho)$, the particle influx from the wall Γ_H as the average over all the available H_α lines of sight, and the central ion temperature $T_i(0)$ measured by the NPA diagnostic (the profile is assumed equal to the electron one). The time instant for the analysis has been selected regarding the presence of the internal energy transport barriers, as measured by the TS. The density profile has been computed by ASTRA according with the diffusion term $D(\rho)=D_0(1-\rho^{\alpha})^{\beta}+D_a\rho^{15}$, and a velocity given by $V(\rho)=V_{ExB}+V_{out}[\rho_1,\rho_2]$, where V_{ExB} is the inward pinch velocity and $V_{out}[\rho_1,\rho_2]$ is equal to 0 everywhere a part between ρ_1 and ρ_2 (first and last point of the internal temperature gradient) where its value V_{out} can assume values in the range [0-50] m/s. The 5 free parameters D_0, D_a, α, β and V_{out} have been determined, in order to match the experimental data, minimizing the $\chi^2=\Sigma(N_{exp} - N_{num})^2/\sigma_{exp}^2$, where N_{exp} and σ_{exp} are respectively the experimental line average density and its measurement error and N_{num} is the numerical line density of the profile computed by ASTRA. The sum is taken over the number of lines of sight of the interferometer. Figure 3 displays the electron temperature profile (a) and the resulting density profile in black (b) for plasma pulse 30810 (the red line represents the inverted density profile). Plot (c-d) shows respectively the diffusivity term and the total velocity. The χ^2 of the output density profile (~2.32) is comparable with the χ^2 of the density inversion (~2.97).

The global results of the transport analysis are reported in figure 4. Plot 4(a) shows the central and edge diffusion coefficients: the D_a value (blue square) decreases at higher n/n_G, according with the observation that the steepest edge gradient are obtained in higher density regime. Moreover D_a values shows a strong decrease, with a step dependence versus the density, for n/n_G=0.12, that turns out to be compatible with the density regime at which the edge density gradient has its transition from flat to steep. The D_a values in the transition region are affected by larger error bars, highlighting the fact that for density in the range [$0.10n_G$ - $0.12n_G$] there is a change in the transport regime. Anyway to clarify this point a larger dataset will be analysed.

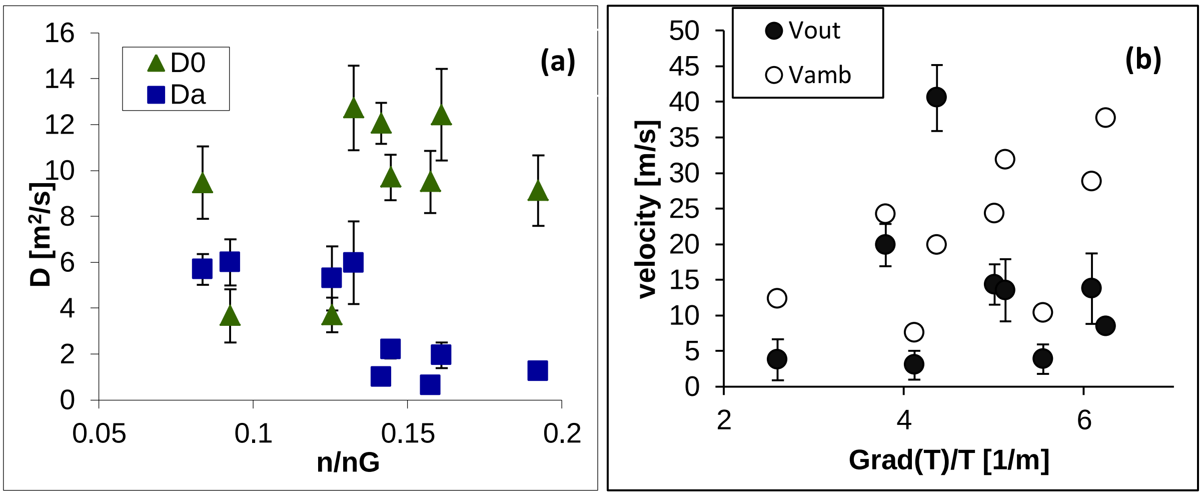

Figure 4: central (green full triangle) and edge (blue full squares) diffusion coefficients as a function of the Greenwald density fraction. (b) outward velocity in the region of the internal energy transport barrier(black full circle) compared with the outward velocity computed with the Harvey model, in the assumption of a stochastic transport regime.

The D_0 values (green triangle) are more scattered, not showing any clear dependence on the density level: this is mainly due to the lack of particle source in the core and to the flat central gradient that increases the uncertainty on this parameter, stated also by the larger error bars. This fact does not means that the central energy transport barrier is not acting on particles, but it is just showing that the stationary analysis is not able to resolve the central transport level with sufficient accuracy: transport simulation following the density plasma time evolution will be carried out to better determine the diffusivity in the core. Anyway the average D_0 value are more than halved with respect to the diffusion coefficients computed in standard regimes [11], confirming the global beneficial effect on particle confinement of the SHAx configuration. Plot 4(b) displays the outward velocity as a function of the normalized temperature gradient on the energy transport barrier. The outward velocity, in full black circle, does not show a dependence from the normalized temperature gradient, having an average value of about 10 m/s, a part one cases that has an anomalous behaviour, with V_{out} = 40 m/s. On the same plot is over imposed also an estimation of the ambipolar outward velocity V_{amb} computed in the assumption of transport in a stochastic magnetic field. It turns out that V_{amb} is larger (beyond the error bar) than the actual outward velocity, confirming that the transport due to stochasticization of the confining magnetic field does not describe the RFP plasma in SHAx state.

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