

Spontaneous mitigation of anomalous transport in RFX-mod helical regimes.

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Introduction

The understanding of particle confinement of a thermonuclear fusion plasma is a critical issue: the fusion power increases as the square of density. In this work, a study of the particle transport in RFX-mod is presented. Besides the usual chaotic state, dubbed Multiple Helicity (MH) regime, the Reversed Field Pinch configuration shows a self-organized helical equilibrium named Single Helical Axis (SHAx) [1]. The SHAx state is characterized by an almost monochromatic MHD spectrum, where one mode (the dominant one) largely prevails against all the others (the secondary ones). The SHAx magnetic configuration has proved to develop internal energy transport barriers [2], leading to confinement time three times higher than in MH plasmas [3]. Perturbative transport studies have been performed in pellet injection experiments [4], highlighting a beneficial effect on particle confinement during the SHAx state. Moreover impurity transport has been studied, showing an outward velocity preventing impurity accumulation in the plasma core [5,6]. In this work we analyze the particle density radial profile in RFX-mod experiments above 1.2 MA in SHAx and MH state, varying the average density on the wide range $2\text{-}10 \times 10^{19} \text{ m}^{-3}$.

It turns out that the core transport is determined by the magnetic stochasticity: in SHAx state a spontaneous decrease of the central diffusivity has been observed as a consequence of the magnetic fluctuation damping with respect to the MH case, in agreement with the theory of transport in a stochastic magnetic field [7,8]. The edge region is ruled by a different mechanism: the electrostatic turbulence and in particular the presence of coherent structures drives edge particle transport. Its modification at different density levels is discussed.

Particle density influx and confinement time

The analysis has been carried out on a set of 20 discharges at different average plasma densities, in the range $2\text{-}10 \times 10^{19} \text{ m}^{-3}$ with plasma current from 1.2 to 1.8 MA. The Greenwald fraction varies from $n/n_G \sim 0.1$ to 0.6. Since the SHAx state usually develops in plasma where $n/n_G < 0.35$ [9], the database includes both SHAx and MH discharges.

The density profiles are obtained by means of the interferometer and the reflectometer. They result flat or hollow depending on the density level: the density peaking factor $pf = n_0 / \langle n_e \rangle$

(central density over average one), decreases when density increases, as shown in figure 1a.

In the figures, full dots refer to SHAx cases, the triangles to MH discharges.

The particle influx Γ , computed by considering the helically shaped PWI, scales linearly with the average density up to a threshold; above it, the flux becomes constant, as reported in figure 1b.

The particle confinement time computed in stationary case as $\tau_p = N / \Gamma_{\text{tot}}$, where N is the total number of particle and Γ_{tot} is the integral of Γ over the whole surface of the plasma, is shown

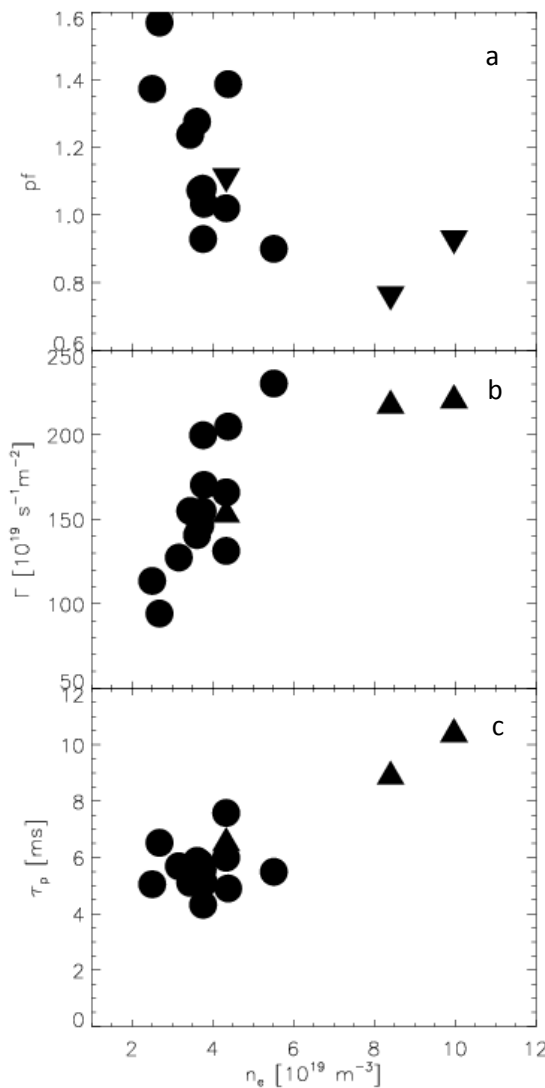


Figure 1: density peaking factor (1a), particle influx (1b) and particle confinement time as functions of the plasma density. Dots are used for SHAx discharges, triangles for MH cases.

in panel 1c. It turns out to be about 6 ms at density between 2 and 6x10¹⁹ m⁻³, whereas it increases linearly at higher density.

Hence, a study has been performed to identify the transport mechanisms acting in the core and in the edge of the plasma and to understand the processes responsible for the longer particle confinement time at higher density.

Transport analysis: results and discussion

The transport analysis has been carried out with ASTRA[9], using as input the experimental electron temperature profile $T_e(\rho)$, the particle influx Γ and the ion temperature profile $T_i(\rho)$, according to the Neutral Particle Analyzer data. The diffusivity has been parameterized as the sum of a core term $D_c(\rho) = D_0(1-\rho^\alpha)^\gamma$ and an edge one $D_e(\rho) = D_a \rho^{15}$ in order to separate the study of transport in such regions. The velocity is $V(\rho) = V_{\text{ExB}} + V_H$, where V_{ExB} is the usual inward pinch and V_H is the ambipolar velocity computed according to the Harvey theory [8], namely

$$V_H(\rho) = -0.5 * D_c(\rho) \nabla T_i / T_i.$$

For each shot, at least 10⁴ simulations have been performed, varying the set $(D_0, D_a, \alpha, \gamma)$ in order to widely cover the free parameters space. The agreement among the numerical and experimental density profile has been evaluated computing the $\chi^2 = \sum (N_{\text{exp}} - N_{\text{num}})^2 / \sigma_{\text{exp}}^2$, 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 as computed by ASTRA. The sum is taken over the number of lines of sight of the interferometer.

Figure 2 shows the diffusivity profile for a SHAx plasma. The shaded area represents the uncertainties, estimated considering the free parameters datasets within the 110% of the best χ^2 . The core and edge term, $D_c(\rho)$ and $D_e(\rho)$, are plotted respectively in dashed and dot-dashed lines. The $D(\rho)$ profile shows a value of about $0.75 \text{ m}^2/\text{s}$ on a large portion of the core region, an intermediate layer around $\rho=0.85$ where its value reaches the minimum and the external part dominated by the edge term, for $\rho>0.9$.

In a stochastic magnetic field the particle diffusivity is proportional to $(b/B)^\beta v_{i,\text{th}}$, where B is the equilibrium magnetic field, b is the amplitude of the MHD modes responsible for the stochasticization of B and $v_{i,\text{th}}$ is the thermal ion velocity [7]. The β value ranges between 1 and 2, respectively for sub-diffusive transport and full ballistic trajectories. In previous studies [10,11] on MH plasmas $\beta=1.5$ -1.6. Figure 3 shows $D_c^* = \langle D_c(\rho) \rangle / v_{i,\text{th}}$ as a function of the ratio of the energy of the secondary $m=1$; $n=8$ -22 modes b_{sec} over the dominant mode b_7 ($\langle D_c(\rho) \rangle$ is the volume averaged core diffusivity). The best core confinement is reached when the secondary modes are damped and the dominant mode is large. Even if no particle transport barriers are visible, the core transport in SHAx turns out to be reduced because of the magnetic chaos healing achieved in such configuration [1]. It is interesting to notice that the reduction of

the energy of b_{sec} in SHAx state is a spontaneous process that brings the plasma in a better transport regime, with core diffusivity damped with respect to the MH case.

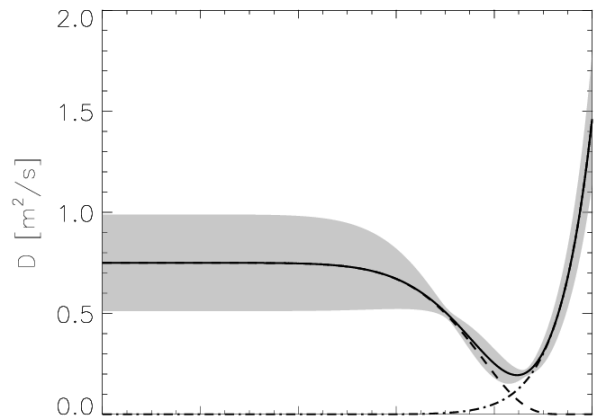


Figure 2: Radial profile of the particle diffusivity as computed by ASTRA. The shaded area represent the error bar. The dashed line refers to $D_c(\rho)$, the dot-dashed line represents the $D_e(\rho)$.

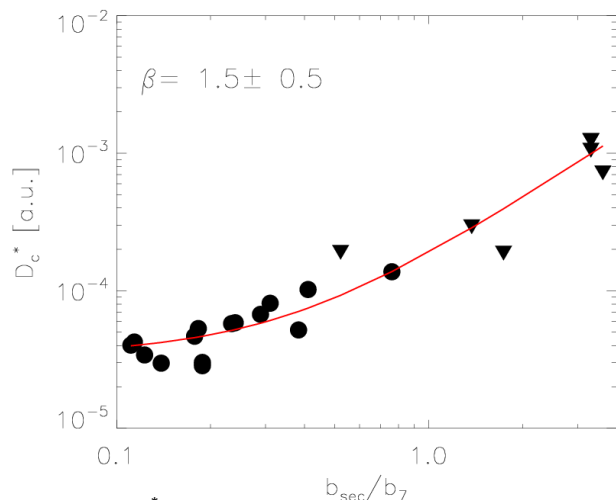


Figure 3: D_c^* as a function of the ratio of the secondary modes and the dominant one. The higher b_{sec}/b_7 values imply an enhanced transport state, mainly present in MH discharges. The line is the data fit

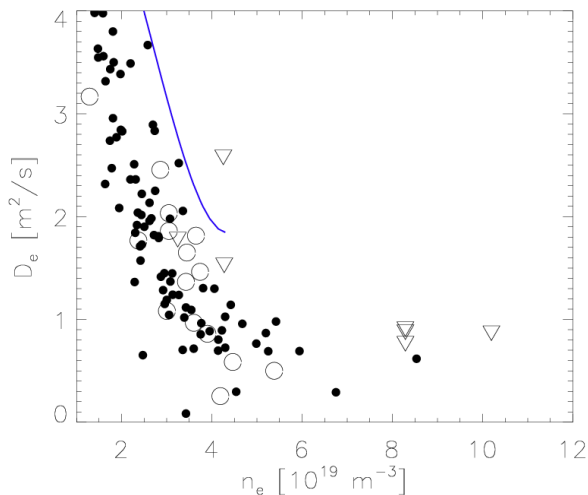


Figure 4: Edge diffusion coefficient D_e versus density. Empty symbols are the result of ASTRA simulations (circle for SHAX, triangle for MH). The black small dots are the blobs effective diffusivity D_p . The blue line represents the Bohm diffusivity level

The transport mechanism acting at the plasma edge is still matter of study: the absence of large $m=1$ modes and the presence of a $m=0$ island chain [12] resonating next the wall reduce the magnetic diffusion. Indeed, in the plasma external region (about last 10%) the diffusivity is likely to be ruled by coherent pressure structures, called “blobs”. The interaction between blobs generates an effective particle diffusion coefficient estimated as $D_p = f_p^2 v \Delta s$ [13,14], where f_p is the packing fraction (i.e. the fraction of edge area occupied by the coherent structures), v is

the relative velocity of the edge structures and Δs their average dimension. Figure 4 shows the magnitude of the edge diffusivity as a function of the average density. The result of the transport analyses D_e (empty symbols) and the effective diffusivity due to blobs D_p (full symbols) are shown. Both quantities have a similar trend and magnitude, with a linear decrease at lower densities and an almost constant value when $n_e > 6 \times 10^{19} \text{ m}^{-3}$. The trends can be interpreted as a reduction of transport associated to blobs at higher density due to the decrease of v and Δs [15]. Edge transport is also compatible with Bohm diffusivity (blue line). The D_e behaviour as a function of the density is the principal responsible for τ_p increase at high n_e (figure 1c): the global particle confinement is likely to be guided by edge transport.

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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