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Numerical studies of transport mechanisms in RFX-mod low chaos regimes

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Quasi Single Helicity in RFX-mod. In the Reversed Field Pinch (RFP) configuration the plasma can access regimes in which a single tearing mode dominates the magnetic perturbations spectrum (Quasi Single Helicity state, QSH) [1]. Thermal measurements performed in the RFX-mod experiment [2] (Padua, Italy) during QSH states have shown clear helical structures, identified by significant temperature gradient in the plasma core, which can reach a considerable size (25-50% of plasma radius) and temporal persistance up to 85% the flat top phase (~200ms) of the discharge [3]. In this work we study some aspects of the transport mechanisms relevant to these conditions: on the one hand the impact of residual magnetic chaos, on the other hand the effect of electrostatic micro-instabilities, the latter have been overlooked in the past when the RFP configurations where frequently dominated by turbulent chaotic regimes (so-called MH regimes). We shall here consider the best perfomance discharges (plasma current I_p *~1.0-1.3MA* and electron density $n_e \sim 2\text{-}4\cdot 10^{19}\ m^{-3}$) characterized by QSH regimes with separatrix expulsion from the helical core [4].

Helical flux computation in low chaos regimes. The magnetic field topology for the analyzed RFX-mod plasmas is obtained by the guiding center code ORBIT, given the magnetic field profiles (axi-symmetric plus helical components) reconstructed from the experiment [5]. Fig.1-(a) shows an example of magnetic topology during a QSH period of a discharge. A helical region with well conserved magnetic surfaces appears in the

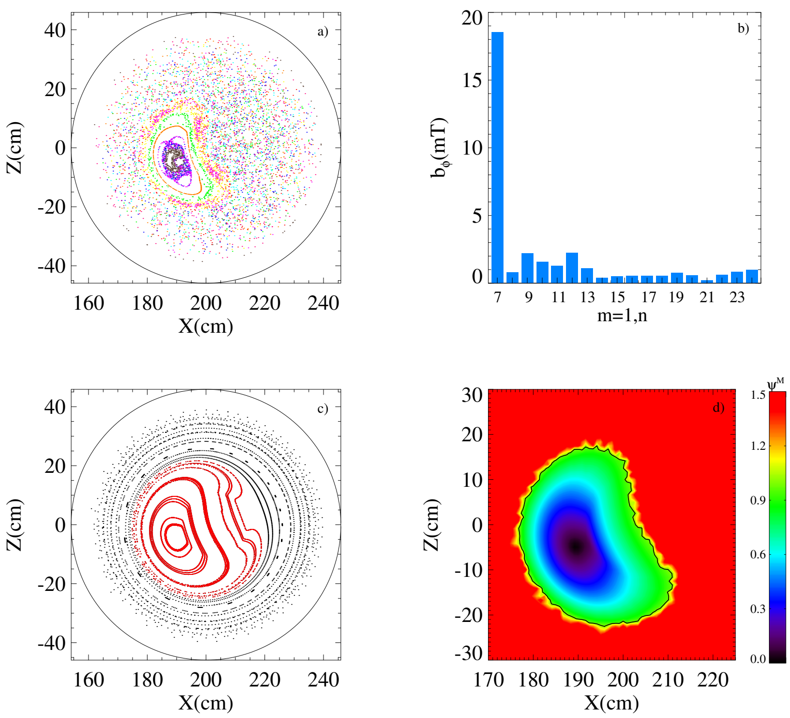

Figure 1 *(a) Magnetic field puncture plot by ORBIT in a QSH regime. (b) Magnetic spectrum of toroidal m=1 perturbation at the edge. (c) Single Helicity topology corresponding to the Poincarè plot in (a). (d) Helical magnetic flux reconstruction on a poloidal cross section. In black the loss helical surface* S_{out} *at* $\psi^M=1$.

core of the plasma, surrounded by a chaotic sea. This conserved structure is generated by the dominant mode (with poloidal number *m=1* and toroidal *n=-7*) whose amplitude at the edge is tenfold that of the secondary modes, as shown in the magnetic spectrum reported in Fig.1-(b). In Fig.1-(c) the same Poincarè of Fig.1-(a) is reported but neglecting all the secondary modes, obtaining in this way the underlying helical equilibrium (pure *Single Helicity*, *SH* [6]). The method described in [7] has been applied to determine the helical flux ψ^M associated to the computed magnetic surfaces. For a given coordinate assumed by a particle, the corresponding ψ^M univocally defines the helical surface crossed by that particle. A map of ψ^M on a poloidal cross section is shown in Fig. 1-(d). The helical flux normalization is such that it assumes the values *0* at the helical magnetic axis and *1.5* at the position corresponding to the edge of the region of conserved magnetic surfaces.

Particle dynamics in QSH regimes. Particle transport is studied by extending to *QSH* the algorithm described in ref. [7], originally developed for the *SH* cases. A set of test particles with random pitch angle $\lambda = cos(\theta)$, being θ the angle between the particle velocity $\boldsymbol{v}$ and the field $\boldsymbol{B}$, are deposited inside the helical structure and diffuse out of it subject to collisions. Particles are considered lost when they cross the helical loss surface labeled by $\psi^M=1$ of area S_{out}; they are then injected back in the helical axis position, in such a way to keep constant the particles number during the whole simulation. Information on transport are obtained from the stationary spatial distribution, computed with respect to the helical poloidal flux ψ^M relative to the topology of the reference helical equilibrium. In Fig.2-(a) the ion and electron density distributions for *T=800eV* are reported. They are not characterized by a linear trend, as at lower temperature (and similarly to what happens in the *SH* cases described in [7]): thus, a constant global diffusion coefficient cannot be defined. This non-diffusive behavior at high temperatures is mainly a consequence of the reduced plasma collisionality (which is proportional to $T_e^{-3/2}$). In fact, above *800-1000 eV* the plasma is in a very low collisionality regime (about 0.03 collisions per toroidal transit). In such conditions, trapped and passing particles are subject to different transport mechanisms, as shown in the following. As indicator for the quality of confinement in the hot helical region, we consider the *particles flux* across its boundary, $\Gamma = N^{lost}/(S_{out} \cdot t)$, (N^{lost} is the total number of ions/electrons flowing outside S_{out} during the time interval [0,*t*]). Simulations at different plasma temperature, but with the same magnetic topology, have been performed; results are reported in Fig.2-(b) both for ions and electrons. In Fig.3-(a) the pitch angle distribution for the ions of Fig 2-(a) with a

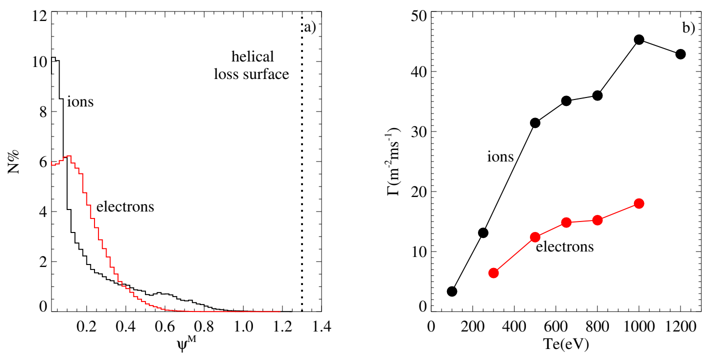

Figure 2 *(a) Ions (black) and electrons (red) density distribution inside the helical structure for Ti=Te=800eV. (b) Particles flux for ions (black) and electrons (red) at several electron temperatures.*

value of helical flux greater than ψ^M=0.8 is displayed. Since the curve is peaked around the value λ=0, this means that the tail of the ion distribution is mainly composed of trapped ions which may be rapidly lost, because of their banana orbits. On the contrary, passing ions (or electrons) are mainly affected only by the secondary modes and are not moved far away from the initial helical surface on which they are deposited. This is shown in Fig. 3-(b) where transport simulations for only passing (black, λ=0.7-0.9) and only trapped ions (red, λ=0-0.2) have been performed at T=800 eV. Even in a low collisionality regime trapped particles diffuse across the helical magnetic surfaces and their density distribution is almost linear. Trapped and passing particles are thus described by different transport properties. Charge separations due to the non-uniformity density of trapped and passing particles, and to the different rate of transport for ions and electrons, are expected to generate an electric field E which would ensure a global ambipolar transport. The definition and the implementation of E is still a work in progress, very important to have a more complete description of high temperature QSH regimes. At present, only a rough estimate of the ambipolar diffusion coefficient D for trapped particles can be given. This is achieved by performing the geometric average [5] between the electron (D_e) and ion (D_i) diffusion coefficients which are separately computed from the ratio $\Gamma/\nabla n$, being the flux Γ and the particle density gradient ∇n the outputs of the numerical simulations; we obtain: $D_{trap} \leq 5m^2/s$ at $T_e=T_i=800eV$. It is worth noting that similar simulations performed in a SH topology are characterized by values of Γ and D only about a factor 1.5 lower than in the QSH cases; this confirms that the residual chaos in QSH does not strongly affect the good confinement properties of the helical core. Moreover these estimates for D in QSH are much lower than those experimentally measured in Multiple Helicity configuration ($D_{MH} \simeq 30m^2/s$).

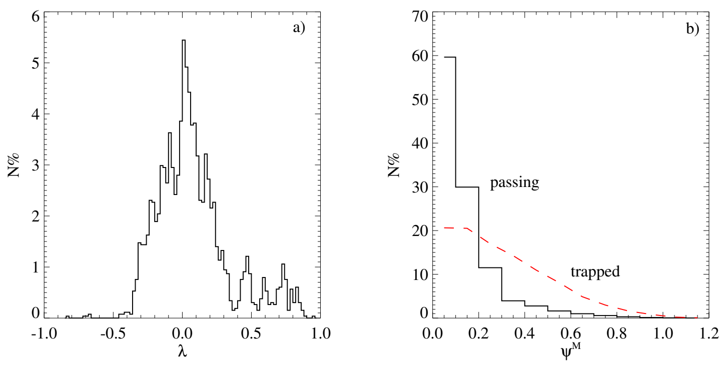

Figure 3 *(a) Pitch angle distribution of ions near the helical loss surface of the magnetic island (b) Density distribution for passing (black) and trapped (red) ions.*

Microinstabilities effect on transport. A linear stability analysis on ITG (Ion Temperature Gradient) driven modes has been currently carried out and revealed that, due to a shorter connection length, ITGs are more strongly Landau damped, and thus the instability requires much more peaked temperature profile than in tokamaks [8]. Such temperature profiles may only exist in the edge of the plasma or the region close to the border of hot helical core in QSH states introduced above. In Fig.4 the temperature profile $T_e(r)$ and the corresponding gradient scale length $\varepsilon_T = L_T / R$ at several radial locations are plotted for a typical QSH discharge of RFX-mod. Based on the parameters provided by data analysis on the profiles of q and density n_e, the profile of ITG stability threshold L_{Tc}

is plotted by assuming $L_{Te} \approx L_{Ti}$. It shows the ITG instability might be excited in the regions with the strongest temperature gradients. A further investigation is now being performed by the TRB code [9]. This is a 3D fluid code developed to study the transport of density, heat, velocity and electric potential due to electrostatic instabilities (ITG and TEM) in the core of Tokamaks. A modified version of the code has been developed to deal with RFP equilibria. The major modifications of the code are related to the fact that - in a RFP - poloidal and toroidal magnetic fields have comparable magnitude. This implies a straightforward modification to all terms in the equations that depend upon the safety profile, as well as taking into account into the curvature operators of terms of higher order in B_{pol}. As first tests, we investigated the stability of the modes under different conditions, from flat MH profiles to mildly peaked ones. In all of these preliminary cases growth rates turned out to be negative, in agreement with analytical predictions obtained in the corresponding cases.

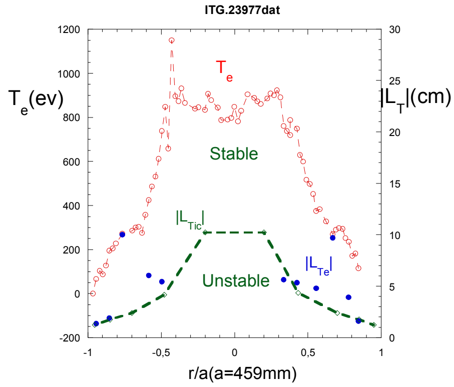

Figure 3 *The blue solid circles denote the temperature gradient scale length L_{Te} for the sample Te profile (red). The green curve is the critical ion temperature gradient length L_{Tic} predicted by the theory.*

Summary. In conclusion, when RFP enters the low-magnetic chaos high-temperature regime, the contribution to transport by electrostatic and neoclassical effects eventually overrides the residual magnetic diffusivity. The relative weights of the two contributions appear to be different from the Tokamak case: our particle code highlights the relevant role of trapped particles in collisional transport. On the other hand, first results from kinetic and fluid codes suggest that electrostatic (ITG) modes could provide a supplementary drive to transport, but only in some limited regions of space characterized by very strong gradients as experimentally observed for electron temperature profiles in QSH (without mode separatrix). The magnetic configuration is found to affect in an interesting way the neoclassical transport, that does not appear to be describable as a simple diffusive process.

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References

[1] P. Martin, L. Marrelli, A. Alfier et al., Plasma Phys. Controlled Fusion **49**, A177 (2007)
[2] R.Paccagnella *et al*., Phys. Rev. Lett. **97**,075001 (2006)
[3] M.Valisa, this conference (invited); P.Piovesan et al., this conference O4.029; F.Bonomo et al., this conference P2. 054
[4] D.F.Escande et al. Phys. Rev. Lett. Lett. **85** 3169 (2000); R. Lorenzini et al., to be published in Phys. Rev. Lett.
[5] R.B.White and M.S.Chance, Phys. Fluids **27**, 2455 (1984) ; I.Predebon *et al.*, Phys. Rev. Lett. **93**, 145001 (2004)
[6] S. Cappello, D. Bonfiglio, D.F.Escande, Physics of Plasmas **13**, 056102 (2006)
[7] M.Gobbin *et al*., Phys. Plasmas **14**, 072305 (2007)
[8] S.C. Guo, Bull. Am. Phys. Soc. 52, p.178 (2007), S. C. Guo submitted 2007
[9] X. Garbet, *et al*, Phys. Rev. Lett. **91**, 035001 (2001)