Characterization of eITBs in high current deuterium and hydrogen helical shaped plasmas

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Helical regimes in deuterium and hydrogen plasmas. High current plasmas ($I_p > 1.2MA$) in the RFX-mod experiment [1] are often characterized by a 3D helical shape with internal electron transport barriers (eITBs) occurring when a single saturated resistive kink mode dominates the perturbation spectrum (Quasi Single Helicity state, QSH [2]). An example is shown in Fig.1-(a): the helicity of the dominant mode has poloidal and toroidal numbers $m=1$, $n=-7$ respectively and during QSH states the amplitude of the toroidal component of the magnetic field ($b_\phi^{1,-7} \approx 20\text{-}30\ mT$) at the edge ($a=0.459m$) is up to ten times higher than that of secondary modes (b_s is the mean square root of $b_\phi(a)$ for $m=1,n=-8,-9,\ldots.-15$) and corresponds to 3-4% of the total axisymmetric field component. The analysis reported in this paper have been performed using experimental data from the high time resolution (10kHz) soft-x-ray (SXR) diagnostic DSX3 which allows to follow the electron temperature T_e profiles dynamic and its gradient, as described in [3] and reported for a plasma discharge in Fig1.(b)-(c); in (b), the black line corresponds to the core T_e evolution while the blue one to T_e in the middle region of the plasma ($r/a= 0.6$ i.e. the outer DSX3 measurement available). Fig. 1-(c) shows the corresponding maximum T_e gradient time evolution.

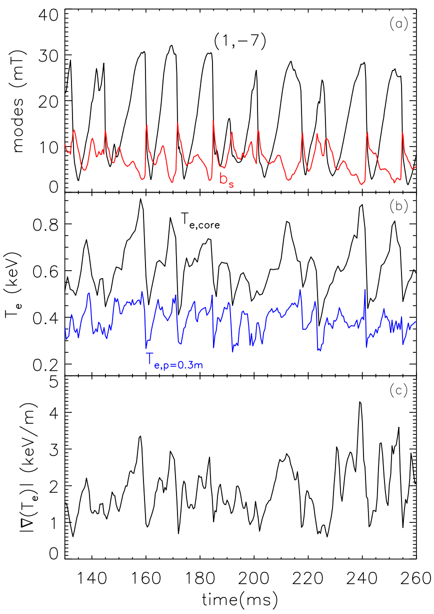

Figure 1. (a) *Evolution of the dominant mode (1,-7) in black and of the square root of secondary modes (b_s) in red for a typical RFX-mod high current discharge. (b) Corresponding evolution of core (black) and middle region (blue) electron temperature. (c) Maximum gradient time evolution* (*shot* #35095).

Experiments performed in deuterium (D) and hydrogen (H) plasmas have shown peculiar features both in terms of magnetic and thermal characterization. This paper is focused on QSH states since they exhibit improved performances and higher confinement times. An attempt to reinforce the helical shape of the plasma is carried on by using the set of 192 saddle coils available in RFX-mod for active control [4]. This technique, already exploited for H plasmas in the past [5], has been applied only recently to D discharges.

Magnetic QSH and eITBs fraction. The parameter which best describes the quality of a QSH plasma is N_s defined as:

$$N_s = \frac{1}{\sum_{n=-7}^{n=-15} \left(b_{1,n}^2 / \sum_{n=-7}^{n=-15} b_{1,n}^2 \right)} \qquad (1)$$

where $b_{1,n}$ is the toroidal component amplitude of the mode $(1,n)$ at the edge of the plasma. N_s increases when many magnetic modes coexist and decreases to 1 for a pure Single Helicity (SH) state (magnetic spectrum with only one mode). A comparison between the *total time* spent by H and D plasmas in QSH regimes has been performed for an ensemble of #80 discharges, with I_p in the range 1.2-1.6MA, and is shown in Fig.2 (a). The y-axis reports the average fraction of total time during a discharge in which the plasma is characterized by N_s<1.6 at several Greenwald fraction levels (n/n_G). The black points are relative to H shots while the red diamonds to those in D. The empty black circles / red diamonds still accounts for hydrogen / deuterium shots respectively with a weak non-zero (1,-7) radial perturbation ($b_r^{1,-7}(a)$ ~ *2-8mT*) imposed by the control system. About 60% of the average discharge duration in D plasmas is in a QSH state, especially at n/n_G < 0.15. This fraction falls under 50% for hydrogen but increases when a finite amplitude of the (1,-7) mode is imposed by the control system (50-60%). A similar analysis has been performed for thermal quantities from DSX3 diagnostics. Fig. 2-(b) shows the average fraction where the maximum gradient of T_e is above 1.5keV/m (which generally defines the presence of an eITB), while Fig.2-(c) reports the average fraction where the core T_e is greater than 700eV. Also for these thermal parameters the performances improve in D plasmas with respect to those in H. The non-zero $b_r^{1,-7}(a)$ perturbation application seems

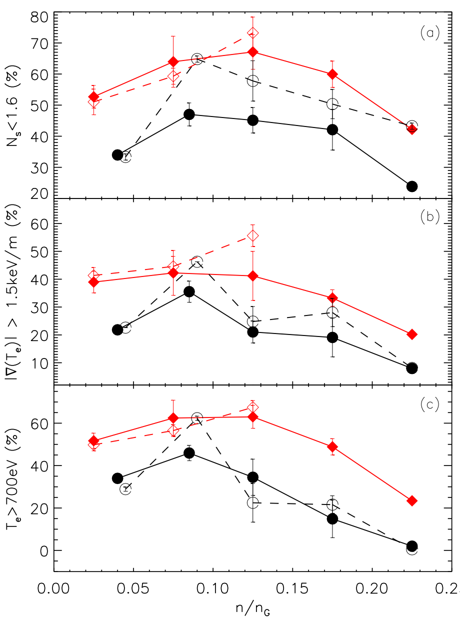

Figure 2. *(a) Average fraction spent by plasma in QSH state with N_s<1.6 for H (black-dots) and D (red-diamonds) without and with (1,-7) active control finite references (H - black empty circles, D - red empty diamonds) vs n/n_G. With the same colors code: (b) average fraction of discharge with T_e gradient greater than 1.5keV/m and (c) with T_e >700 eV.*

not to have a strong impact on D plasmas while, on the contrary, they increase the frequency of eITBs and the total magnetic QSH duration in H discharges.

Main parameters in D and H discharges. Differences between H and D plasmas arise also in terms of absolute value of the magnetic mode amplitudes and of the thermal quantities averaged during the flattop phase of the discharges and when N_s<1.6, as reported in Figure 3. In (a) and (b) the data show the mean values of the dominant and of the secondary modes amplitude vs n/n_G. Deuterium plasmas are characterized by a ~20% reduction of b_s with respect to hydrogen. No relevant effects for the dominant mode are observed. Panels (c) and (d) report the average T_e measured by the DSX3 diagnostic relative to the central ($T_{e,core}$) and to the middle ($T_{e,mid}$) region of the plasma respectively. T_e in D plasmas is systematically greater of about 10-30% at all n/n_G; such a phenomenology holds both for the central and for the middle region of the plasma suggesting that the full T_e profile is shifted upward with respect to the H cases. On the other side, the average maximum T_e gradients in panel (e) do not show relevant differences between H and D plasmas. Concerning the role of (1,-7) non-zero perturbation imposed by the control system on the performances, the results are not univocal: in fact, while the core T_e increases for D plasmas, no clear effects are visible for H discharges. Nevertheless, at n/n_G <0.2, both H and D plasmas with imposed finite (1,-7) radial perturbation show an increase of the T_e gradient suggesting that T_e profiles are slightly steeper.

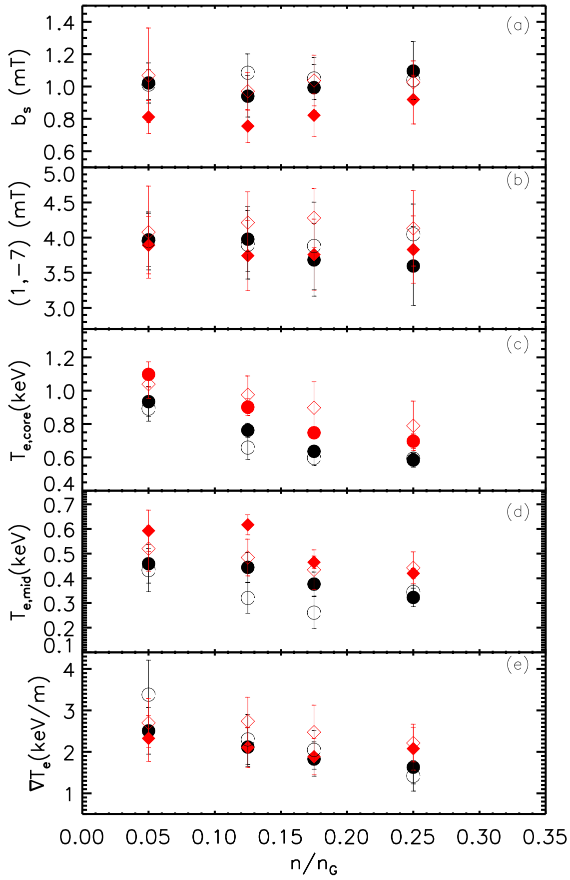

Figure 3. *(a) Average values of secondary modes amplitude vs n/n_G for H (black-dots) and D (red-diamonds) without and with (1,-7) finite references (H-black empty circles, D-red empty diamonds). With the same colors code, mean values of: (b) dominant mode amplitude, (c) core T_e, (d) T_e at r/a=0.3, (e) T_e gradient.*

Test particles diffusion simulations. The Hamiltonian guiding center code ORBIT [6], modified to deal with the helical geometry defined by the dominant mode (1,-7), has been used to analyze the magnetic field influence on transport for mono-energetic ions (H and D) taking into account the collision mechanisms too. Simulations are performed by considering average density, maximum core temperature and magnetic modes amplitudes from several experimental cases. Results are reported in Fig.4: in panel (a) the averaged (over the region with *r/a<0.6*) ion diffusion coefficients $D_{i,SH}$ vs the (1-7) mode amplitude are shown in the ideal Single Helicity scenario (no secondary modes) for hydrogen (*i=H*) and deuterium (*i=D*). For most the cases $D_{D,SH} \geq D_{H,SH}$ which can be explained in terms of stronger neoclassical effects for the ion with greater atomic mass. The implementation of secondary modes substantially changes this picture as illustrated by panel (b) reporting the diffusion coefficients vs the secondary modes amplitude in QSH regimes: $D_{D,QSH} \leq D_{H,QSH}$. This is basically related to transport in a stochastic magnetic field where diffusion mainly occurs along the field lines, so that the thermal velocity v_{th} term dominates over collisions and neoclassical mechanisms. For a given thermal energy in fact:

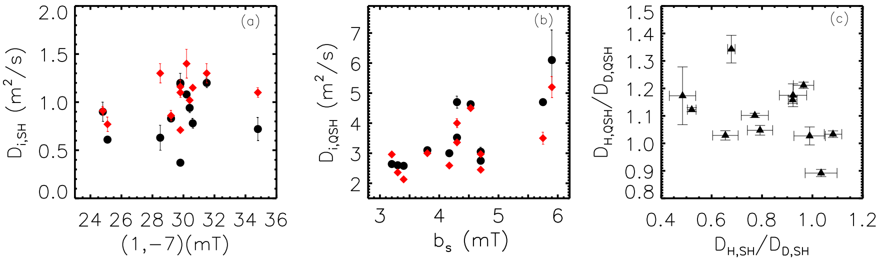

Figure 4. *D (red) and H (black) ion diffusion coefficients by ORBIT in SH (a) and QSH (b) regime. (c) Ratio of H and D diffusion coefficients in SH and QSH states.*

$$\frac{v_{th,H}}{v_{th,D}} = \sqrt{\frac{M_D}{M_H}} = \sqrt{2} \qquad (2)$$

with M_H and M_D the atomic mass of hydrogen and deuterium. In Fig.4-(c) the ratio of the two isotope diffusion coefficients in QSH and SH is reported; in the magnetic topology typical of QSH RFX-mod plasmas, on average, $D_{H,QSH}/D_{D,QSH} \approx 1.11 \pm 0.12$ which is lower than the value predicted by Eq. (2) since the field is only partially stochastic. These results will be compared with those obtained with the 1.5D transport code ASTRA [7] which takes into account the full temperature/density profiles and their gradients.

Conclusions. In conclusion, D plasmas in RFX-mod states show a partial improvement of performances under many aspects: a greater frequency of helical states, increased T_e profiles, reduced secondary modes amplitude. Simulations in QSH states confirm a better confinement for deuterium test particles. More experiments are required to deeper investigate the effect of applying (1,-7) finite amplitude radial perturbation on eITBs formation and evolution.

Acknowledgment. *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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