Improved Confinement with Internal Electron Temperature Barriers in RFX-mod

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Abstract

In RFX-mod the feedback control on multiple magnetohydrodynamic modes allows to improve axysimmetry and to safely operate at high current. RFX-mod reliably operates at 1.5 MA, the highest current ever achieved on a Reversed Field Pinch (RFP).
In these high current discharges magnetic topology spontaneously self-organizes in an ohmic helical symmetry, quasi single helicity state (QSH), in which the magnetic dynamics is dominated by the innermost resonant mode, with the new magnetic axis helically twisting around the geometrical axis of the torus.
Inside the helical structure energy confinement is enhanced and electron temperatures exceeding 1 keV are measured, with steep gradients, which identify an internal transport barrier. Separatrix expulsion and symmetric Te profiles with high gradients are obtained for ratios between dominant mode and total B above about 4%. The measured electron temperature peak results nearly symmetric and involves a large fraction of the plasma cross section, corresponding to an improvement of the global electron energy confinement up to a factor 2. Transient strong QSH are reproducibly induced by oscillating poloidal current driven operation (OPCD), also at lower currents (Ip>500kA). The measured steep temperature profiles obtained on QSH conditions correspond to an electron thermal diffusivity diminution by more than one order of magnitude.
Perturbative experiments (pellets and impurity laser blow off injections) have been performed to study particle confinement inside and outside the thermal island. Experimental evidences of main gas confinement increasing inside the helical structure have been obtained, while for impurity during a QSH there are no evidences of confinement increase.
Plasma energy and particle transport properties are compared with the topological properties of the magnetic field both in standard, or multiple helicity (MH), and QSH cases and compared with numerical simulation result.

1. Introduction

The reversed field pinch (RFP) device RFX-mod (R/a =2 m / 0.459 m) is equipped with a actively controlled magnetic boundary which allows the compensation of error fields. The boundary control system is very flexible [1] with a full coverage mesh of 48×4 saddle coils, each equipped with a sensor for radial, toroidal and poloidal magnetic field, with independent power supplies supervised by a digital feedback system.
The recently developed control algorithm, dubbed clean mode control (CMC) [2] allows a real time correction of the aliasing of the sideband harmonics generated by the discrete saddle coils. Plasma operation in CMC mode leads to a smoother (i.e. more axisymmetric) boundary, tearing modes rotate (up to 100 Hz) and partially unlock. Plasma–wall interaction diminishes due to a decrease of the non axisymmetric shift of the plasma column. With the described ameliorated boundary control, plasma current has been successfully increased to 1.5 MA, the highest for an RFP.
At these high levels of the current, intermittently during the discharge, but for the main part of it, the magnetic dynamics is dominated by the innermost resonant mode and the internal magnetic field approaches a pure helix. The transition to this regimes corresponds to

confinement enhancement since it is accompanied by the formation of a thermal island covering a large part of the plasma core and featuring large gradients of electron temperature ($1/L_{Te}$ of the order of 20 m^{-1} is measured).

On the theoretical side, Visco-resistive MHD simulations [3,4] have predicted that the dynamo mechanism required to sustain the equilibrium fields in a RFP can be provided by a kink-like deformation of the plasma that attributes to the configuration a global chaos free helical symmetry: the single helicity (SH). This Ohmic helical state is not affected by the high level of magnetic turbulence, typical of an RFP in standard conditions (Multiple Helicity (MH) scenario) where many modes of comparable amplitude are simultaneously present. Abundant experimental evidences have been found in RFPs of a regime in which one mode, a saturated resistive kink instability, intermittently grows much higher than the others [5, 6]. This regime only approximates the theoretically predicted SH state, since the secondary mode amplitudes are low but not negligible and has been named Quasi Single Helicity (QSH).

The probability to develop QSH and its persistency, defined as the ratio between the total time in which the plasma stays in QSH and the flattop duration, increases with plasma current and above 1 MA QSH occupies a significant fraction of the current flat top, up to about 85% [7]. It has been found that QSH states are favored by high currents, low densities and high electron temperatures [8], or in other words by high Lundquist number (ratio of resistive to Alfven times) $S = 30 I_\phi T_e(0)^{3/2} / \left[(0.4 + 0.6 Z_{eff}) \ln \Lambda \sqrt{m_i \bar{n}_e}\right]$, as shown in Fig.1.

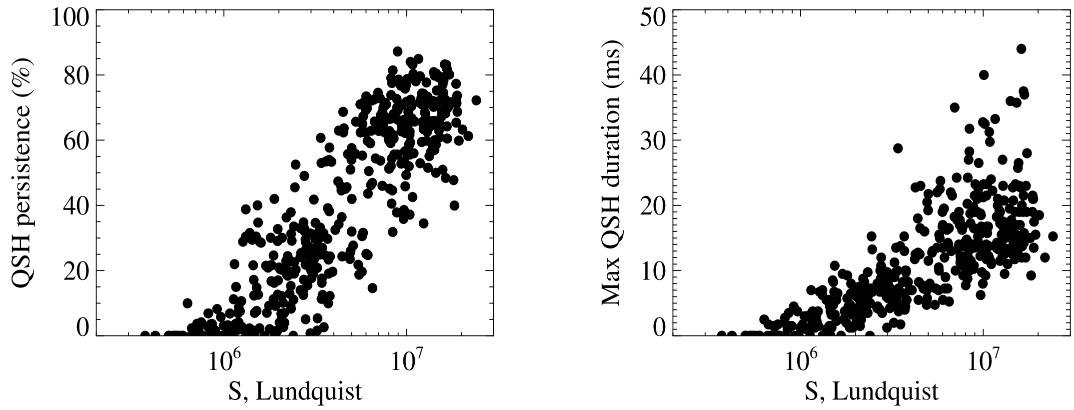


Fig.1 *QSH persistency and duration as a function of plasma current. For each pulse the QSH probability is computed as the ratio between the total time when QSH is present divided by the current flat-top period, the QSH duration is defined as the longest QSH time interval*

The paper is organized as follows:

In Section 2 the plasma conditions for QSH regimes establishment are analyzed and the corresponding plasma performances are described (electron temperature and conductivity profiles, energy confinement properties, density limits), the effect of microinstabilities on transport are then presented.

In section 3 recent results on particle confinement properties in QSH and MH conditions are presented and discussed and compared with prediction of numerical simulations. Conclusions are then drawn.

2. Plasma performances in QSH regimes

QSH regimes are systematically obtained in RFX-mod at higher plasma current (Ip ≥1 MA) while strong transient QSH are reproducibly induced by oscillating poloidal current driven operation (OPCD) [9] also at lower currents (Ip>500kA). During the OPCD the edge toroidal field is modulated in order to transiently induce a current profile modification in the plasma, concentrating the toroidal flux in the core. As an effect, secondary modes decrease while the resonant one increases and the electron temperature and energy confinement increase. During the QSH regimes, both spontaneous or induced by OPCD, the formation of a clear structure in the soft-X ray emissivity distribution is observed by the tomographic reconstruction [10], well correlated with the observed magnetic topology. Inside the helical structure energy confinement is enhanced and at higher plasma currents electron temperatures of the order of 1 keV are measured (Fig.2). In these cases the QSH effect on the electron temperature is very strong with steep gradients which identify an internal transport barrier ($1/L_{Te}$ of the order of 20 m^{-1} is measured).

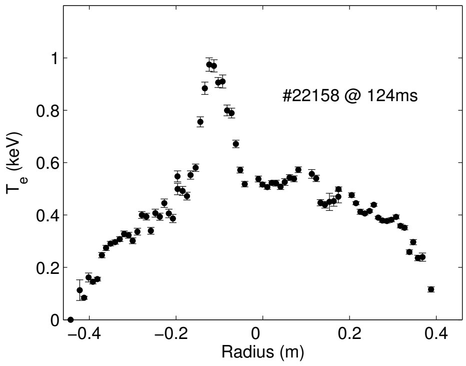


Fig.2 Electron temperature profile measured by Thomson Scattering in a QSH regime.

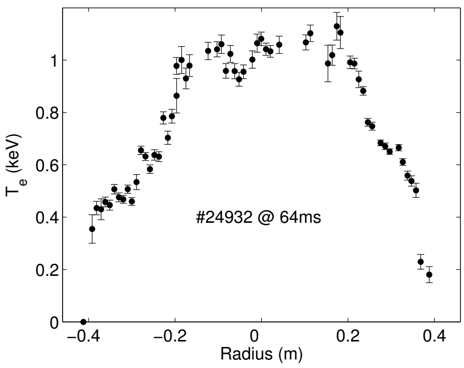


Fig.3 Electron temperature profile measured by Thomson Scattering in a SHAx regime.

The best results in terms of plasma energy content are obtained when the chaos reduction involves also the plasma outside the island; in these cases a significant region of the plasma

core is occupied by a rather large n = −7 helical structure, very likely without a separatrix [11], as predicted by the theory [12]. This Single Helical Axis regime (SHAx) is the closest ever achieved to the predicted Single Helicity regime and the volume affected by the ameliorated condition represented by QSH is large enough to have an impact on global confinement (see Fig.3). The SHAxs states are obtained for ratio between dominant mode and total B greater than about 4%, as can be seen in Fig 4. It is worth of notice that for ratio between dominant mode and the total B greater than about 4.5% every QSH corresponds to a SHAx.

Electron density profiles are essentially flat in RFX-mod [13], except at the edge of the plasma, in either standard or QSH regimes and SHAxs , in virtue of their broader temperature profiles, have confinement times that can be a factor 2 higher than that of a QSH that has developed an island [14]: as reported in Fig 5.

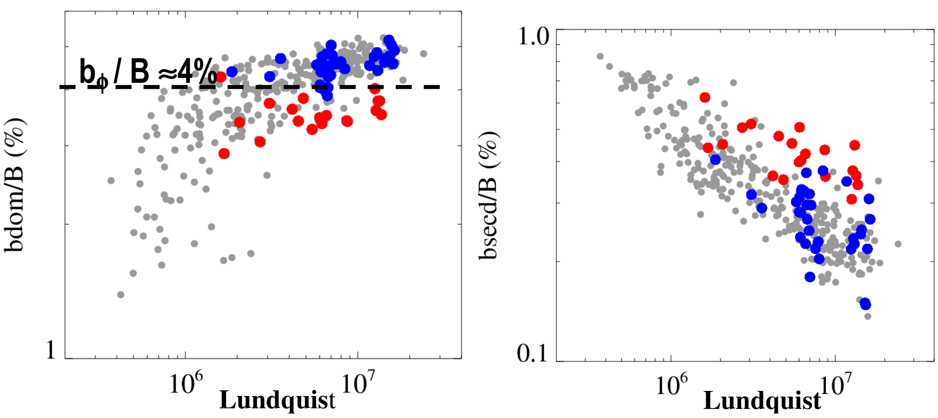


Fig.4 Top: dominant (left) and secondary (right) mode amplitude versus the Lundquist number. The electron temperature profiles corresponding to the discharges indicated in red are represented by that in Fig.2, the electron temperature profiles corresponding to discharges indicated in blue are represented from that in Fig.3

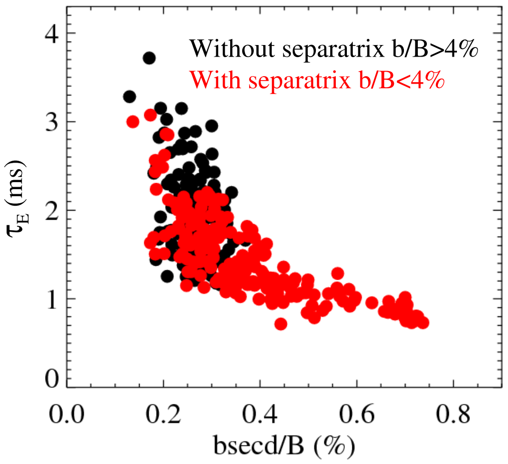
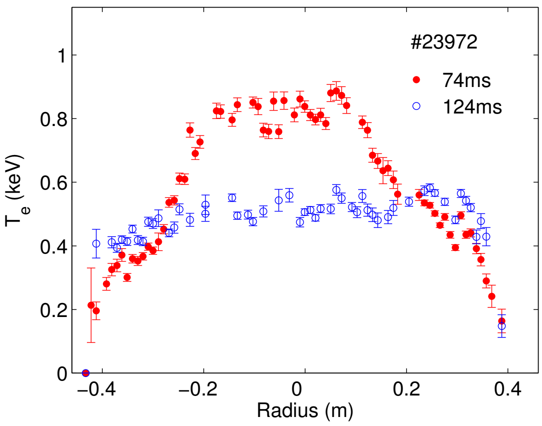
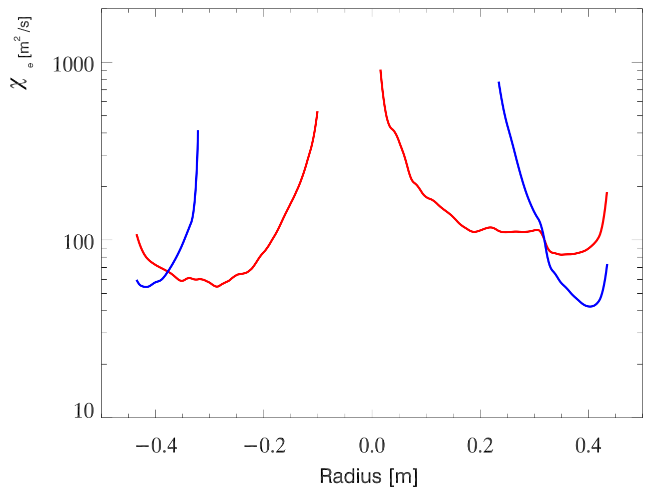


Fig. 5 Energy confinement time (assuming equal ion and electron temperatures) towards the secondary modes total amplitude

The radial profile of electron heat diffusivity χ_e in stationary conditions has been determined by adopting a 1D single fluid approach and solving the power balance equation [15]: during QSH states χ_e strongly decreases in correspondence of the thermal transport barrier of the thermal structure. The χ_e improvement during a SHAx state in the best cases involves about one half of minor radius and can be more than one order of magnitude (as an example, Fig.6 shows χ_e profiles calculated during MH and SHAx states in the same discharge). It has to be mentioned that the 1D power balance equation can be applied to approximately estimate the heat diffusivity during a QSH if the island is nearly symmetric with respect to the centre [15].





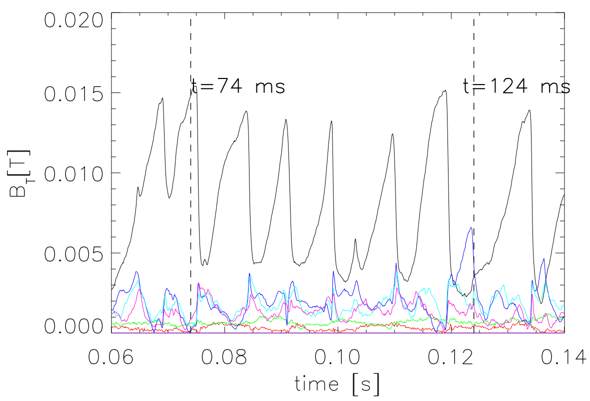


Fig. 6 Top: Electron temperature obtained by Thomson Scattering diagnostics and thermal diffusivity profiles (calculated in the region of not-vanishing electron temperature gradients) for the same high current discharge during QSH (a SHAx state) and MH phases. Bottom: Time evolutions of the m=1,n=.-7 dominant mode and secondary ones in the same discharge.

The heating of the magnetic island of a QSH state in RFX-mod has been analyzed with the M1TEV [16] two-dimensional transport code. The simulated time evolution of electron temperature inside the island during a QSH regime and the values of the thermal conductivity are consistent with the peak temperatures measured in RFX-mod, indicating that the essential cause of the heating of the magnetic island is the reduction of the thermal diffusion coefficient inside it.

The spontaneous transitions to a QSH regime are observed in RFX-mod only for electron densities normalized to the Greenwald density $n/n_G \leq 0.3 \div 0.4$ [17, 18]. This corresponds to the observed behavior of QSH persistency towards Lundquist number, since high current plasmas at relatively high density ($n/n_G > 0.4$) display a lower Lundquist number and consistently a lower dominant to residual modes ratio. When a transition to a multiple dynamo mode occurs confinement degrades by approximately a factor two and for this reason RFX-mod high current discharges have been run mainly at low densities, typically below n/n_G=0.3. Moreover, at high current the input power increases and therefore the requirements for a low recycling wall become more stringent. A still open question is if the QSH low persistency at higher densities reflects a fuelling problem which could be overcome by depositing particles in the plasma centre with pellets injection. In this respect many promising experimental evidences of dominant mode sustainment by pellet in a phase in which the QSH was disappearing have been found (see Fig.7)

Finding suitable conditions for high current high density discharges will be matter of future investigations.

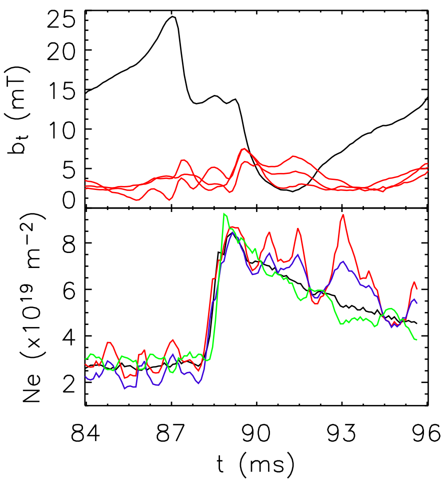


Fig.7 Example of sustainment of the dominant mode by pellet: time behavior of the toroidal component of dominant and secondary modes (top) and interferometer central chords measurements (bottom).

In SHAxs regimes with large gradients of the electron temperature the magnetic turbulence could become so small that drift modes, of electrostatic nature, may become important. Both gyrokinetic and fluid approaches have been adopted to study Ion Temperature Gradient (ITG) modes in RFP plasmas. The result is that these instabilities are in general more stable in a RFP than in a Tokamak, due to the shorter connection length in RFP, but could be excited in the RFX-mod regions where experimentally very high Te gradients are found, namely at the edge of the islands associated to a QSH and at the edge of the plasma [19, 20]. Note that the SHAx states are characterized by steep temperature gradients which enclose a core region where, on the contrary, the temperature profile is rather flat: an ITG turbulence which originates in the gradient regions and nonlinearly propagates nearby (turbulence spreading), might explain this flattening. Also, the presence of a residual magnetic chaos in the interior of the transport barrier might be the cause for this observation. The presented analysis hold on the assumption that ion and electron temperatures have the same normalized gradient $\nabla T/T$. Ion temperature profile measurements are not available on RFX-mod yet. Line of sight integrated Doppler broadening measurements on OVIII, OVII, CV and simulation of impurity emission profiles indicates that $T_i \sim (0.6\text{-}0.7)\ T_e$: suitable ion temperature profile measurements will therefore clarify if the scenario of a RFP core dominated by electrostatic instability is plausible. It is worth mentioning that tools developed to study drift turbulence in Tokamaks such as TRB [21] and GS2 [22] are also being adapted to investigate RFP plasmas

3. Particle transport

Perturbative experiments (pellets and impurity laser blow off injections (LBO)) have been performed to study particle confinement inside and outside the thermal island. Given the flatness of electron density profiles in RFX-mod and the transient nature of the QSH regimes, the presence of a particle source inside/outside the thermal island is very useful to emphasize any modification of the particle transport parameters and makes suitable its estimate.

The multi pellet injector of RFX-mod [23] was used to inject pellets with a nominal mass of 1.5×10^{20} particles and velocity around 600 m/s; faster pellets (velocity up to 1200 m/s) deeper penetrating the QSH hot structure, were also recently injected in RFX-mod, by using Hydrogen launch gas instead of Neon. An 8–chords CO2 interferometer is used to measure the time evolution of the electron density [24].

Poincarè plots of magnetic field lines at pellet and interferometer port toroidal positions (which are 120° apart) have been obtained by means of the magnetic field line tracing code FLiT in toroidal geometry [25] and are used to analyze pellet ablation and density behavior with respect to magnetic topology. When the pellet enters the hot structure the ablation increases due to the higher electron temperature and the helical magnetic topology reflects in a m=1 asymmetry in the density measurements along different chords [26]. In some cases when pellet enters the island the time evolution of interferometer central chords does not decrease just after pellet ablation and stays constant for a short time, indicating that the thermal structure can confine particles. As a general remark, FLiT reconstruction and experimental observations after a pellet injection agree, but due to the poor statistic available it was not possible to get a suitable evaluation of particle confinement times inside the island. Attempts to deduce the main gas transport parameters indicate that the global particle confinement in non-axisymmetric states seems to improve in the best cases by a factor around 2 to 3 with respect to a MH state.

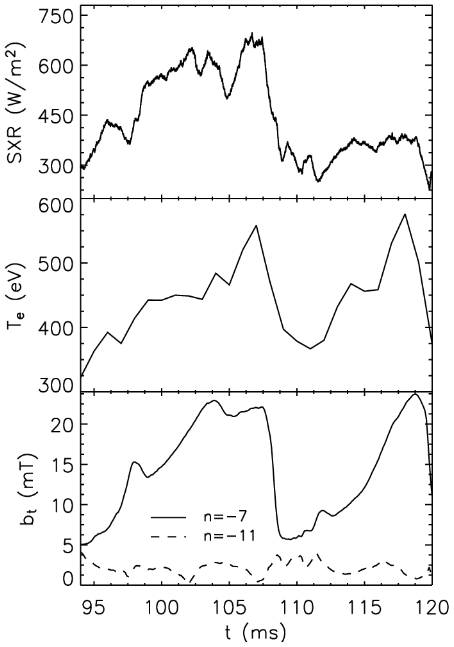


Figure 8: Shot #24073 at 1.2 MA. Top: line integrated SXR brightness. Centre: Te measured with a double filter diagnostic. Bottom: bt of dominant mode m=1,n=-7 and m=1,n=-11 (representative of the secondary modes).

In addition to pellet injection Ni LBO was also attempted for the first time in RFX-mod as a way to provide a traceable particle source inside the island present in QSH states [26]. The injection into the hot structure was successful since the emission lines Ni XVII 249 Å and Ni XVIII 292 Å have been observed, indicating that the impurity reached the high temperature regions inside the helical structure. Fig.8 shows an example of the SXR signals following Ni injection (by a single laser pulse) when a QSH was developing: the SXR signal (and also Ni lines, not shown) lasts for the whole QSH phase clearly following the time evolution of the electron temperature.

Due to the strongly varying plasma conditions (including poloidal and toroidal asymmetries in the Te profile due to the helical geometry) the Ni transport parameters evaluations obtained by reproducing the emission pattern by a 1D collisional-radiative impurity transport code [27] are not fully reliable. However, the simulations indicate that the observed time evolution depends more on the electron temperature evolution (i.e. on the energy content of the island) rather than on strong differences in the Ni transport properties inside the thermal island. Ni emission data have been reasonably reproduced using for both the MH and QSH phases the same transport parameters (D~10-20 m^2/s in the plasma centre) [28].

Summarizing, experimental evidences seem to indicate a different behavior between impurities and main gas diffusion mechanisms in QSH: transport of main gas appears to be positively influenced in some case by QSH while impurity transport seems not to strongly depend on QSH. The ion and electron diffusion coefficients inside the helical magnetic island in a QSH plasma have been numerically calculated by a Monte Carlo approach with the ORBIT code [29]: the average diffusion coefficients obtained for hydrogen ions and electrons inside the helical structure in stationary simulations result lower than those found in MH plasmas.

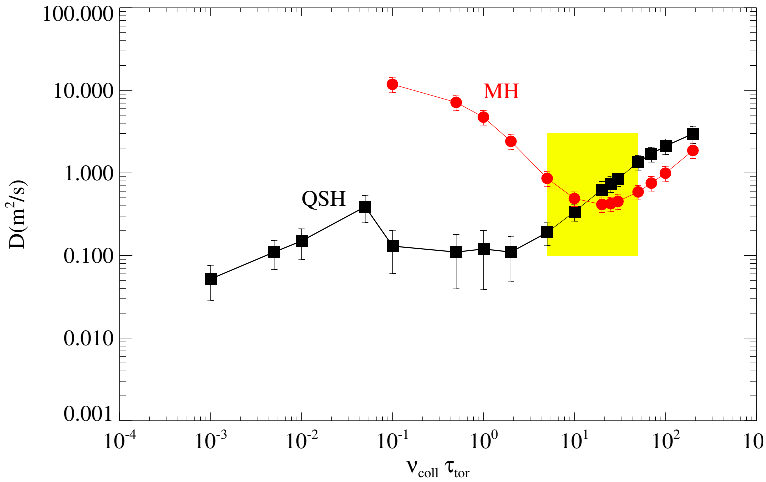


Figure 9: Nickel diffusion coefficients as function of collisions for toroidal transit both in MH and QSH plasmas. The yellow shaded region refers to typical collisionality of RFX-mod high temperatures plasmas.

For Ni, Fig. 9 shows the ORBIT evaluation of the diffusion coefficients as a function of collisionality both in MH (red-circle) and QSH (black-squares) regimes. The typical range of Ni ions collisionality for recent RFX-mod plasmas (with T_i~*400eV-600eV*) is computed by taking into account their interaction with the main gas, other Nickel ions, Oxygen and Carbon ions. This interval is marked with a yellow box in Fig.10 and shows that, due to high collisionality, Ni ion transport is little influenced by the magnetic field topology. In fact, Ni diffusion coefficients are found to be about the same (D~0.5-2m²/s) in MH and QSH regimes. This is in agreement with the described experimental findings, however the quantitative evaluation of the N_i diffusion coefficient performed with ORBIT is about an order of magnitude smaller than the mentioned experimental estimate. This mismatch is currently being investigated and may be due to mechanisms actually not included in ORBIT which could be relevant in particle transport, such as: turbulence or collective phenomena (blobs) which are obviously beyond a single-particle approximation, underestimation of the effective collisionality or to numerical approximation (for example, in ORBIT only mono-energetic test particle have been used up to now).

Conclusions

Thanks to improved feed-back control and to advanced operation techniques, RFX-mod displays clear and robust transitions to QSH regimes which were predicted by simple MHD modeling. The synergic interplay between the growth of the dominant mode and the reduction of the secondary modes provides enhanced confinement properties with steep gradients in the electron temperature profiles and an enhanced energy confinement time up to a factor of two. The higher energy content and steeper gradient measured during QSH regimes correspond to an electron thermal diffusivity diminution which in the best cases can be more than one order of magnitude.

Microstability analysis indicates possible destabilization of ITG modes in the region of steep temperature gradients, the associated turbulence could limit the electron temperature inside the island. The scenario of a core dominated by electrostatic instability would be a change of perspective for the RFP physics, where urgency on healing magnetic turbulence is gradually substituted by the emerging electrostatic turbulence, entering a field well known to the Tokamak community.

Experiments with pellet injection and Nickel LBO in MH and QSH regimes have been performed in RFX-mod to study particle transport inside and outside the hot helical structure. Even if more experiments are needed to properly evaluate the particle transport parameters, there are evidences of an improvement by a factor 2÷3 of the main gas confinement time. As far as impurities are concerned no clear evidence of strong transport modifications in QSH states with respect to MH has been found. Impurity diffusion coefficient obtained by ORBIT Monte Carlo model simulations confirms that impurity transport is not strongly influenced by magnetic field topology, by virtue of their higher collisionality, also if it results lower than that deduced by reproducing the experimental impurity emission data with a 1-dim collisional-radiative code. Further experiments with pellet and impurity injection and further theoretical enquires will allow to establish QSH particle confinement properties.

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