Outward impurity convection in the RFX-mod Reversed Field Pinch

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Introduction

Impurity behavior is a growing topic in fusion science studies, as proved by the recent experimental, theoretical and modeling efforts. Radiation, transport, plasma-wall interaction and first wall conditioning are indeed key aspects – where impurities play important roles – which need to be controlled and understood. The headline of this paper is the evidence that impurity core penetration is prevented in Reversed Field Pinch plasmas. The experimental evidence is based on nickel Laser Blow Off (LBO) injection, on neon gas puffing experiments and on the behavior of intrinsic impurities (carbon and oxygen). It is robust in various experimental conditions [1], including the improved confinement self-organized helical regimes, Quasi Single Helicity (QSH), occurring at high plasma current (I>1.2 MA), where strong internal transport barriers for energy and for particles are observed [2]. The impurity flux convective term is positive (outward) over the whole plasma radius: the pinch velocity profile shows a barrier that is stronger and wider in the helical regime. Such a barrier opposes the impurity penetration preventing core plasma contamination. Impurities behave differently with respect to the main gas: in QSH conditions, the reconstruction of the electron density profile time evolution during the transients produced by H$_2$ pellet injection shows lower particle diffusion inside the helical structure, without a significant outward pinch [3]. With the present knowledge of the ion temperature profile, the impurity outward velocity cannot be ascribed to a classical effect. Gyrokinetic calculations (GS2) of turbulent transport performed to evaluate the effect of electromagnetic and electrostatic turbulences on the impurity fluxes found that microtearing modes are associated to outward directed impurities convection.

Impurity transport in RFX-mod QSH high current discharges

The diffusion coefficient D and the convection velocity v are estimated by a 1-dim impurity transport code [4]. The impurity behaviour is reconstructed both in QSH plasmas, where   the magnetic dynamics is dominated by the innermost resonant mode (m=1,n=-7), and in Multiple Helicity (MH) states, characterized by the superposition of many m=1 tearing modes. In both regimes the analysis reported in Ref. [1] for Ni transport after Ni LBO injection indicates the presence of a spatial region with strong outward convective velocity. However such a velocity barrier, opposing impurity penetration into the core, is found to be more effective in the QSH case, resulting in

more hollow steady state extrapolated impurity profiles. The same conclusions have been drawn also from analysis of neon gas puffing experiments, indicating that there is not a significant mass/charge dependence of impurity transport parameters.

In this work we focus in particular on the simulation of the time evolution of the experimental radiation pattern, including SXR prof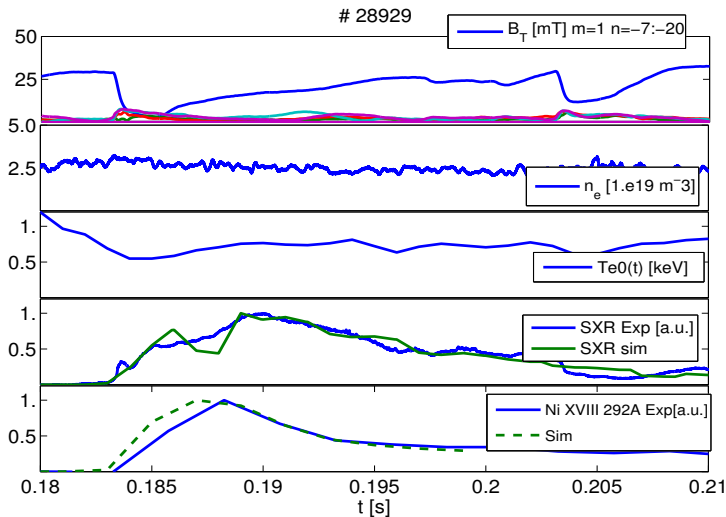iles and impurity line emission, in discharges in which during the LBO pulse the periodic transitions from QSH to MH occur (fig.1, top). The QSH to MH transition, associated to magnetic reconnection events, intermittently occurs in all RFX-mod discharges.

Fig 1 Top to bottom:time evolutions of dominant(m=1,n=-7 ,blue) and secondary toroidal magnetic field components, , experimental and simulated central SXR brightness, Ni XVIII 292 A line brightness.

To properly simulate the experimental emission after the Ni LBO pulse, the transport parameters D and V are changed in time, according to the time behavior of the magnetic spectral index Ns=[Σ_{-n}(W$_n$ / $\Sigma_{-n'}$W$_{n'}$)^2]$^{-1}$, where W$_n$ is the magnetic energy of the (-1,n) mode (Fig. 3, left) , Ns=1 corresponding to a pure SH state and Ns ≤ 2 indicates the presence of a QSH regime

As shown in figs. 1 and 2, the time evolution of both the emission line brightnesses and of the SXR profiles following the LBO pulse has been well reconstructed by the model. In both the MH and QSH scenario the convective flux is outward directed, with a radial region where the velocity increases significantly; such region in the MH phase is more external and less extended than in QSH (fig.3 right).
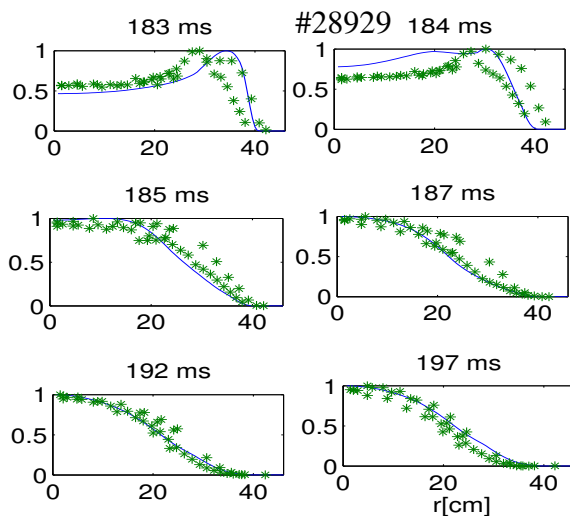

Fig.2 Experimental and simulated SXR profiles during the Ni LBO (0.182s)

A good simulation of emission patterns of intrinsic impurities C and O [5] is also obtained in high currents plasma discharges by varying transport parameters in MH and QSH phases, as shown in Fig 4 and 5. The H-like ion C VI features a hollow brightness profile consistent with the measurements

performed on different viewing chords. The evolution of the ratio between CVI and CV resonant lines, measured by a XUV grazing incidence spectrometer, and of the SXR profiles is also well reproduced. The diffusion coefficient and the convection velocity found for C and O in MH and QSH conditions are similar to what found for Ni and Ne, with a lower outward velocity (fig.6). However, in order to better evaluate the existence of a mass/charge dependence of the peaking factor (*aV/D)* experiments and transport analysis of different impurities in the same discharge are needed.

The deduced transport parameters have been compared with the neoclassical theory applying the DKES-PENTA codes [6,7]. Contrary to the experimental findings, according to neoclassical transport the impurity convection is inward ($\cong$1m/s at r/a=0.3-0.4) and the diffusion coefficient is at least one order of magnitude lower than the experimental evaluation (0.1 instead of 2-10 m^2/s). Impurity transport parameters have been also evaluated for a stochastic magnetic field [8], with electron temperature and density profiles of a QSH discharge; finding a small D (D$\cong$0.1m2/s) and a small outward V, increasing at the edge (r/a>0.85) to V $\cong$10 m/s [1]. Impurity behavior in RFX-mod is then not consistent with particle transport in a stochastic magnetic field [1].
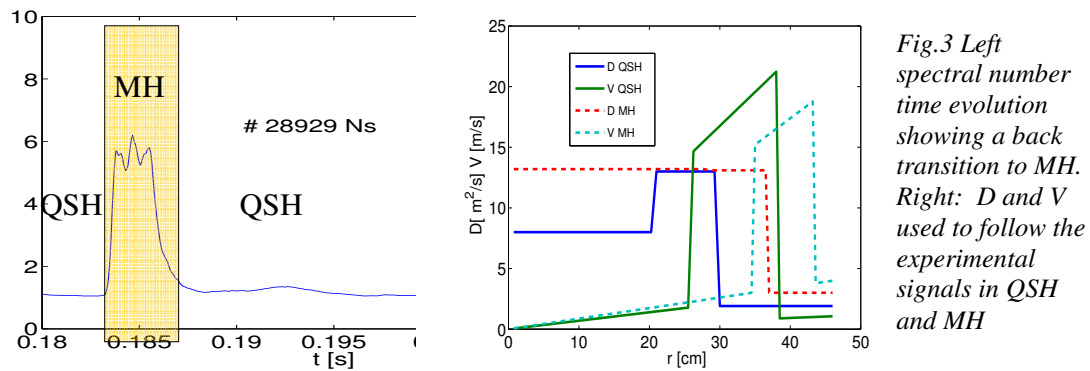

Fig.3 Left spectral number time evolution showing a back transition to MH. Right: D and V used to follow the experimental signals in QSH and MH
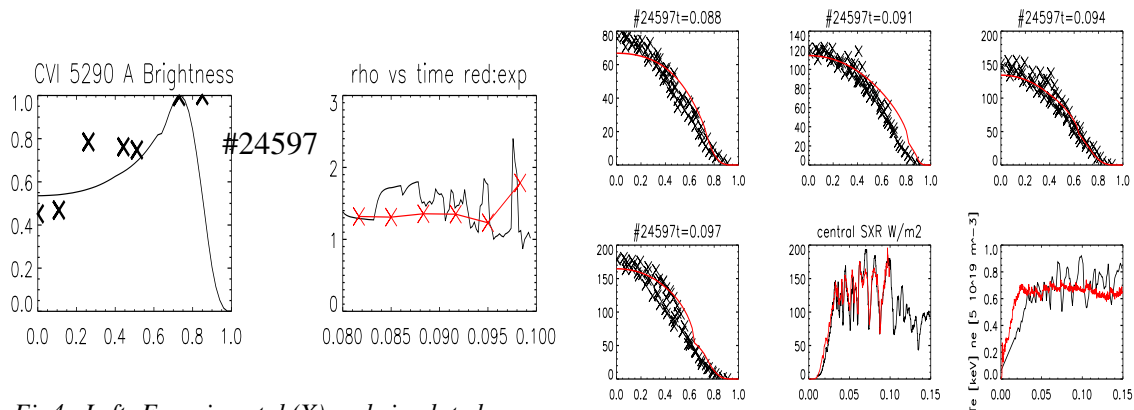

Fig4. Left: Experimental (X) and simulated brightness profile of CVI 5290 A emission line Right: Experimental and simulated time behavior of the ratio between CVI (33A) and CV (40.27A) resonance lines

Fig5 From top- left to bottom-right: Experimental and simulated SXR profiles at 4 times during a MH-QSH transitions. Experimental and simulated central SXR brightness time evolution. Measured Electron temperature and density.
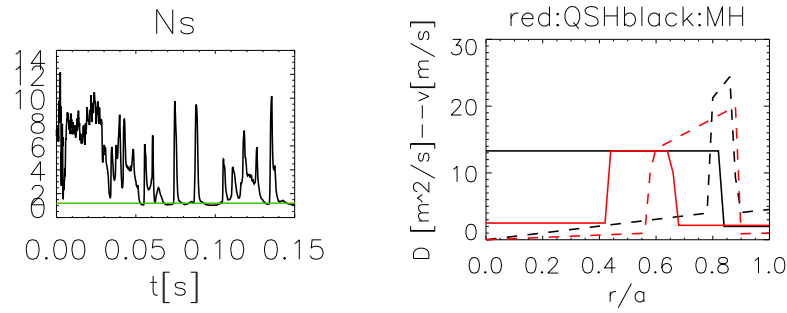
Fig 6 Left spectral number time evolution.the green line is the threshold (Ns<1.2 QSH) Right: D and V used to simulate experimental C and O emission:black curves are relative to the MH phase (Ns>1.2), the red ones are assumend during the QSH phases (Ns<1.2)

Gyrokinetic simulations of impurity transport

As a possible drive of outward impurity fluxes in QSH states the occurrence of microtearing instabilities, recently found to be unstable across the electron temperature barriers of RFX-mod [9], has been investigated. Microtearing modes are high *m* drift tearing modes, excited by large electron temperature gradients, non-vanishing collisionality and plasma beta [10]. As usual, tearing modes developed across radially extended regions are associated with magnetic island overlapping, which produce magnetic surface breaking and a consequent increase of transport.

Following the procedure described in [11], we have calculated the peaking factor *aV/D* for fully stripped trace impurities for a shot in QSH state (#23977) at mid radius, see
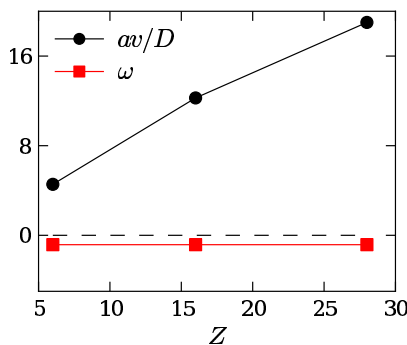

Fig7: aV/D and mode frequency for a GS2 scan over the impurity charge Z.

Fig.6. An outward flux is produced, larger for increasing impurity charge. In the ratio *aV/D* the ExB contribution turns out to be dominant over the flutter component from fluctuations of the parallel vector potential. The large value of the impurity flux compared to the main ion flux is one of the aspects to be understood in the future. The sign of the quasilinear impurity flux agrees with the experimental one, but the strong dependence on Z does not: the experimental peaking factor of C and O is only slightly (a factor 1.3) lower than the peaking factor of Ni in the same discharge; furthermore, the peaking factor of Ni and Ne in similar discharges is very similar. Thus with the present technique based on gyrokinetic linear calculations we cannot ascribe the impurity flux to microtearing instabilities. For a more meaningful and correct comparison we should make use of nonlinear 3-species simulations of microtearing turbulence, a still computationally demanding effort.

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