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# High current plasmas in RFX-mod Reversed Field Pinch

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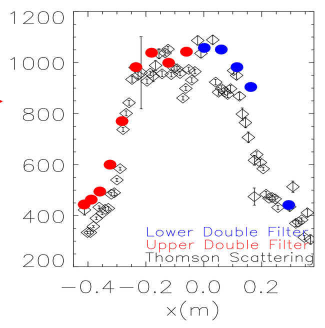
## Introduction

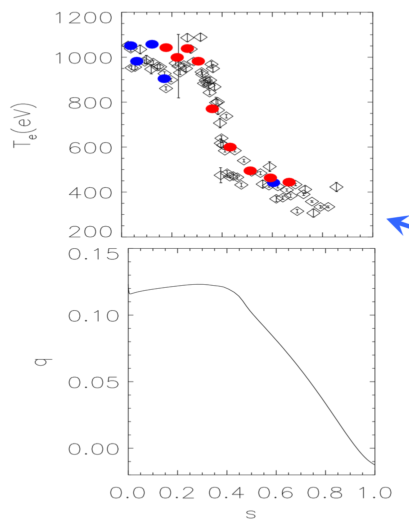
In RFX-mod the feedback control on multiple magnetohydrodynamic (MHD) modes allows to improve axisymmetry and to safely operate at high current (Ip=1-2 MA). In these high current discharges, only for $n_e/n_G \lesssim 0.3$, magnetic topology spontaneously self-organizes in a Quasi Single Helicity state (QSH), in which the magnetic dynamics is dominated by the high amplitude of the innermost resonant mode (the dominant mode), with a low amplitude of the other MHD modes (secondary modes). For a ratio between dominant mode and total B above about 4%, the separatrix is expelled and the Single Helical Axis (SHAx) regime is obtained, with the new magnetic axis helically twisting around the geometrical axis of the torus. Inside the helical structure electron temperatures exceeding 1 keV are measured, with steep gradients, which identify an internal transport barrier. The transition to this regime corresponds to confinement enhancement, since it is accompanied by the formation of a thermal island covering a large part of the plasma core.

## Equilibrium reconstruction and temperature evolution in helical states

The helical nature of the equilibrium reached when RFX-mod approaches the SHAx state sets a strong similarity with the Stellarator topology. The equilibrium and transport analysis codes developed for the Stellarator has been applied to the RFP: the equilibrium codes VMEC and V3FIT have been successfully adapted to reconstruct RFX-mod equilibria with the inclusion of diagnostics and these equilibria have been used to perform stability and transport analysis .



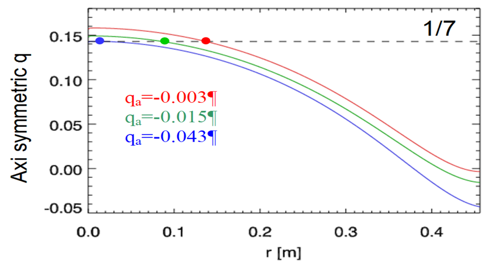
Typical SHAx $T_e$ profile along the major radius on a poloidal section is not symmetric relative to the geometric axis.



The asymmetry vanishes if the $T_e$ is remapped as function of the normalized helical flux coordinate.

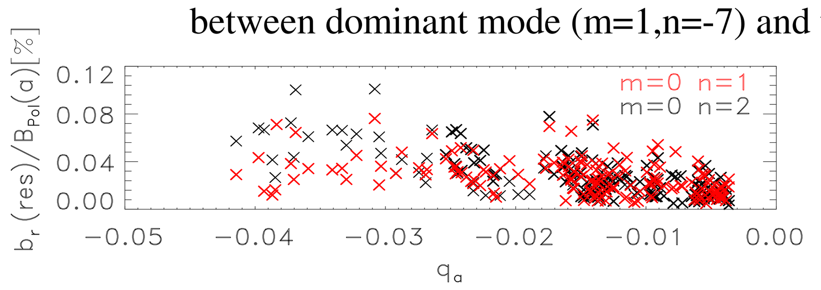
**The safety factor q profile is non-monotonic**; the existence of a point of null in the q derivative results to be a necessary condition for building a helical equilibrium (VMEC): if the reversed shear is lost, the helical state disappears and an axisymmetric case is recovered. The foot of the internal transport barrier is found on the shear q null position

### The best plasma performances in QSH states have been achieved with shallow reversal

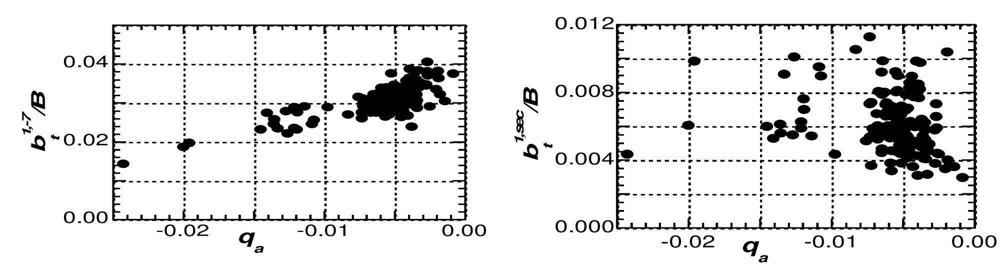



At small values of the safety factor q at the edge :$-0.01<q_a<0$, the shear q null point moves toward the edge, thus increasing the volume involved by the helical structure and the plasma thermal content. The helical equilibrium, ruled by the m=1, n=-7 mode, is no more achieved at deeper reversal configuration, when the mode is no more resonant

The transition to the helical state is linked to the suppression of the m=0 low n(=1,2) number, responsible for the coupling between dominant mode (m=1,n=-7) and the secondary higher order (m=1, |n|>7) modes.



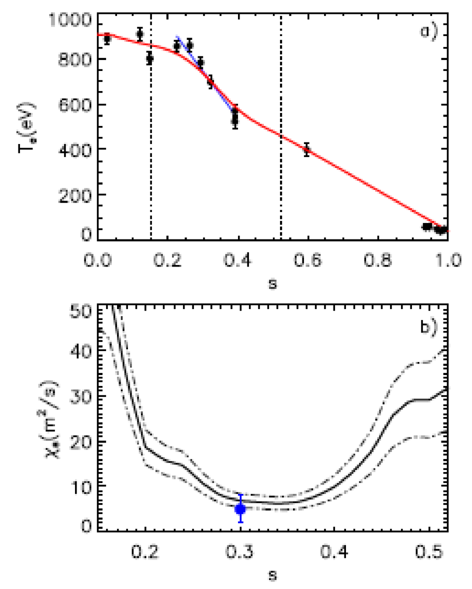

*m=0 resonance amplitude normalized to the poloidal field at the wall towards $q_a$*



*Dependence of the dominant m=1, n=-7 and of the sum of the secondary (m=1, n<-7 modes) on $q_a$*

In very shallow configurations:

- the (m=0,n=1,2) amplitude drops, stabilized by the shift of their resonance (the q=0 surface) closer to the external conducting shell.
- The nonlinear mode coupling is then reduced, the dominant mode (m=1,n=-7) is free to grow up to form the helical equilibrium without dragging the secondary modes amplitude.
- The low level of secondary modes reduces the magnetic chaos, as expected from the non linear 3D MHD modeling and gives rise to the QSH enhanced confinement

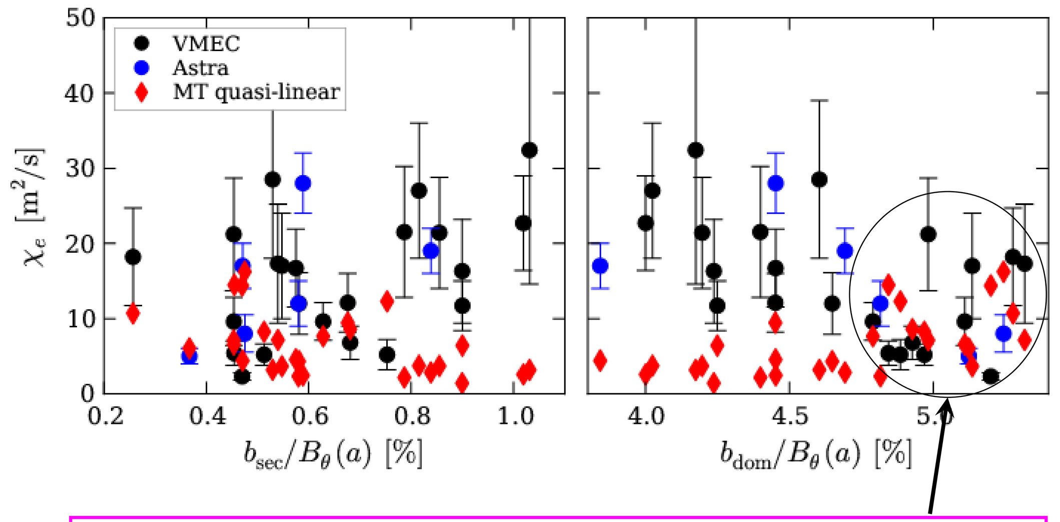


## Electron heat diffusivity

$\chi_e$ has been evaluated for several SHAx by solving the energy transport equation in helical geometry, using the helical equilibrium calculated by VMEC and the experimental $T_e$ profiles At the barrier the thermal confinement improves significantly, $\chi e$ decreases to 5-10 $m^2/s$ well below ~40-100 $m^2/s$ typical of the outer regions

The ASTRA transport code, coupled to the RFX-mod helical equilibrium (perturbative code SHEq), has been applied to calculate $\chi_e$ time evolution, by solving the heat transport equations during the time rising phase of the dominant mode (and of the electron temperature gradients).

The ASTRA prediction averaged in the barrier region (blue dots) agrees with the 'VMEC' evaluations (black dots) and shows a progressive improvement of thermal confinement in the barrier region. Both calculations show a weak increasing/decreasing trend of $\chi_e$ with the secondary/dominant mode amplitude. **linear gyrokinetic calculations show that Micro Tearing (MT) modes are usually unstable during SHAx states, driving transport across the thermal barrier in agreement with the experimental estimate of $\chi_e$(red)**. It has to be remarked that for the presented comparison MTs have been assumed to be unstable in all the cases, without performing gyrokinetic simulations, an exact evaluation of ( $\chi_{MT}$ ) would require not available non-linear gyrokinetic calculations



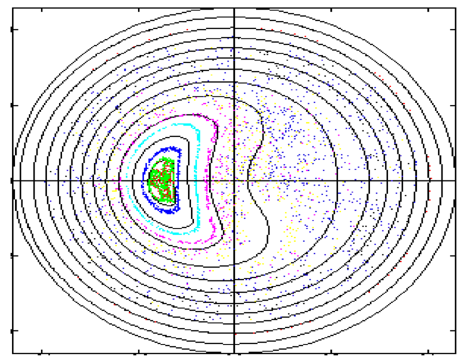

$\chi_e$ lowest values are greater than the neoclassical estimates of about $\chi_{e,neo}$<1 $m^2/s$: other mechanisms are still deteriorating the confinement

**To make more clear the effect on the magnetic surfaces of the m=0,1 secondary mode activity on the magnetic surfaces, the Poincarè plot has been drawn, by the field line tracing code FLiT**

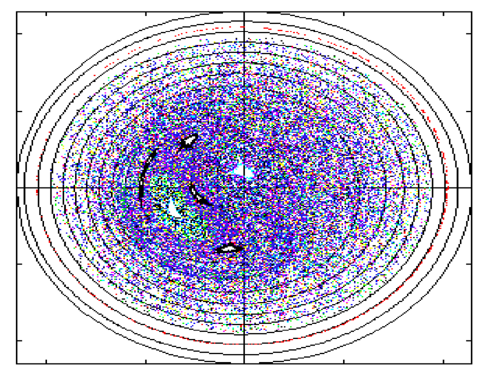
To explain the anomalous transport and the flat electron temperature profile observed inside the transport barrier a model for self-consistently generated vortical drift motion due electrostatic turbulence has been proposed. More recently the effect of magnetic chaos produced from m=2 modes has also been evaluated. It is worth to be noted that errors affecting the evaluation of the m=2 tearing mode eigenfunctions from external measurements are typically twice those affecting the m=1, with one order of magnitude amplification of the edge measurement error. Only after the recent correction of Bt-Bp edge probes crosstalk an acceptable uncertainty in the evaluation of m=2 eigenfunctions has been reached.

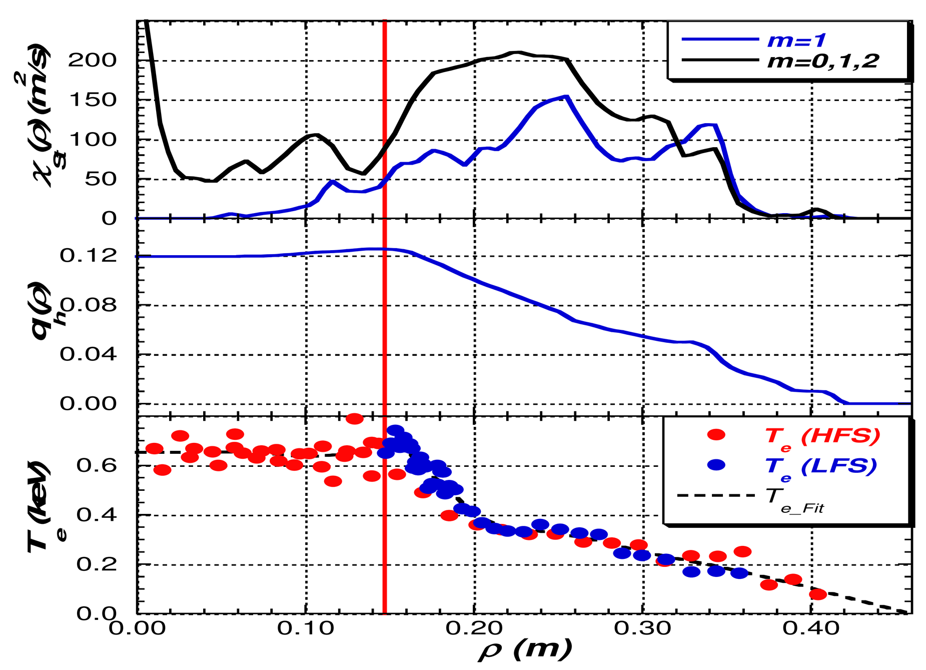
***#24599, t=0.098 s***

The residual magnetic chaos in the external region can still provide the anomalous transport observed in such region, while in the plasma centre the m=0,1 modes provide good nested magnetic surfaces



With the inclusion of m=2 modes, the core magnetic surfaces are nearly completely destroyed

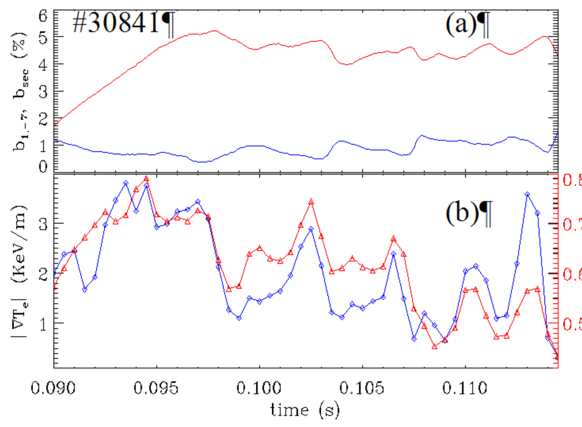





*From top to bottom: Magnetic thermal diffusion computed with and without m=2 modes, computed safety factor and experimental Te profile*

The evaluation of $\chi_e$, according to the Rechester-Rosenbluth (RR) relation $\chi_e$=$D_M$vth provides values close to those coming from the energy balance but at the position of the transport barrier, that is no more present. The discrepancy could be ascribed to the errors on the evaluation of m=2 modes and/or on the evaluation of thermal diffusion from magnetic diffusion since, as seen with ORBIT simulations, the RR relation between DM and $\chi_e$ could be not suitable to the experimental situation

**The QSH magnetic states are not stationary all over the plasma discharge. They show back transitions to Multiple Helicity (MH) regime, however their duration at Ip>1.5 MA can cover more than 90% of the plasma current flat-top.**




The high $T_e$ gradients do not persist for all the magnetic QSH cycle

- The rising phase of the QSH (increase of the dominant mode and decrease of the secondary ones) corresponds to a continuous increase of the Te gradients
- The magnetic QSH flattop phase correspond to oscillations of Te gradients with values lower than the maximum reached at the end of the rising phase.
- The overall time in which a certain threshold in the normalized gradient ($\nabla Te/Te,core = 2\ m^{-1}$) is exceeded (even in non consecutive time frames) is different in the rising (75%) and flattop phase (50%) of the dominant mode.

*(a)Time evolutions between 90 and 114.5 ms of the dominant normalized toroidal mode amplitude (in red) and of secondary normalized toroidal mode amplitude (in blue). (b) Time evolutions of $\nabla T_e$ estimation in blue and Te core in red*

There is not a strict correlation between the $T_e$ oscillations and the amplitude of the dominant and/or secondary modes. To investigate the reason of the oscillations a more detailed analysis of the MHD activity is in progress, such as 3D analysis of the phase relation among the secondary modes. Suggestions in interpreting the observed oscillations of the helical thermal structure could come from the 3D nonlinear simulation of the effect of helical boundary conditions on the MHD dynamics in RFP. The simulations highlight that the chaos resilience of the helical configuration rely on peculiar phase states of the dominant and secondary Fourier components, and it is not explainable in terms of magnetic island overlap.

## MHD control optimization

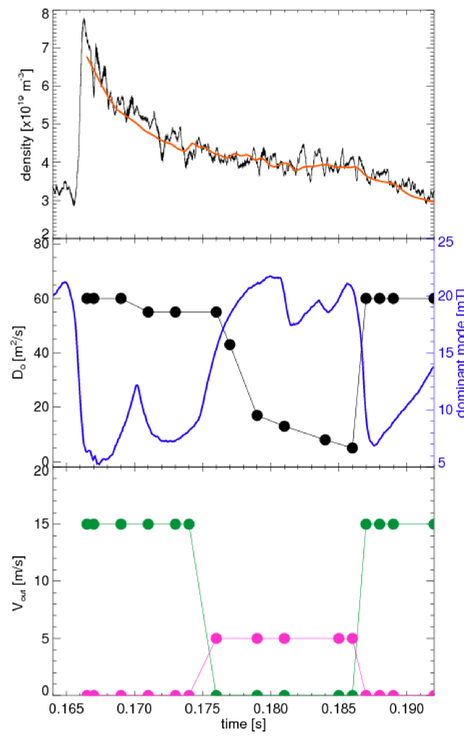
To improve the feedback effectiveness, both the field measurements and feedback algorithms have been optimized.

The magnetic field measurements at the edge, used by the feedback system, have been ameliorated. The cross talk of the (higher) poloidal field on the (smaller) toroidal field measurement at the edge has been measured for each of the 192 probes, and it resulted about 1%, giving an error on the toroidal field harmonics estimation at the edge of the order of 10%. The real-time correction of the cross-talk has allowed to remove localized field errors. Possible optimization has been recently identified in the correction of systematic errors in the edge field measurements and of the fields induced by the presence of a conductive wall with 3D structures. A dynamic decoupler (DD) algorithm has been developed to reduce the radial field harmonic distortion due to the 3D wall structures, through the production of radial magnetic field harmonics inside the wall. A reduction of the error field harmonics at the edge is observed and internal radial field evaluation with the Newcomb equation shows that the m=0, n=7 harmonic is significantly reduced at the edge, but it is not changed in the core, where most of it is due to toroidal coupling, and not to 3D wall effects; the m=1, n=7 plasma response, which corresponds to a non-resonant, stable mode is reduced over the whole radius. The effects of DD application on plasma performances is under investigation.

To extend the QSH persistence and effectiveness several experiments have been performed with different magnetic boundaries. During the QSH the plasma boundary shows a helical pattern with the dominant mode helicity, which is counteracted by the feedback control system. To support the plasma helical self organization and to distribute all over the wall the plasma wall interaction (PWI), an active rotating n=-7 perturbation has been applied to the edge. The promising result was the extension of the magnetic QSH persistence and the increased density range where it exists up to $ne/n_G$=0.4.

## Particle transport

The experimental electron density profiles (from $CO_2$ multi-chords interferometer) have been very reproduced with the ASTRA code by varying the particle diffusion coefficients D in the centre, at the edge and the pinch velocity V as input to the code in a minimization procedure. The diffusion coefficient is assumed to be $D(\rho)=D_0(1-\rho^{a})^{b}+D_a\rho^{15}$, and the velocity is given by $V(\rho)=V_{ExB}+V_{out}[\rho1,\rho2]$, where $V_{ExB}$ is the inward pinch velocity and the term $V_{out}[\rho1,\rho2]$ is not zero only in the region $[\rho1,\rho2]$ of the internal temperature gradient. D and V are varied until the difference between the measured and simulated density profile is minimized .




The analysis has been done in stationary conditions for a database of 10 SHAx states, with Ip=1.6-1.8 MA, at different average densities, with the results that, inside the thermal barrier, the average value of the particle diffusion coefficient results smaller by a factor about 2-3 with respect to the MH regimes, the pinch velocity is outward, of the order of 10 m/s and lower than the velocity required by a transport in a stochastic field; the outward velocity does not show a dependence on the normalized temperature gradient confirming that particle transport in RFX-mod in QSH regimes is no more ascribable to stochasticization of the confining magnetic field .

Transient phenomena allow to better quantify the diffusion and convection terms in the electron transport equation and ASTRA code has been recently used to simulate the density time evolution after pellet injection in SHAx regime The experimental density profiles have been satisfactorily reproduced by assuming that the outward velocity be external (r/a□0.9) during the MH phase (green curve) and at the position of the internal temperature gradients in the SHAx phase ( pink curve). The outward velocity in the SHAx phase is lower than what expected for particle transport in a stochastic field , in analogy with the simulations of the stationary cases. In the central region, the average value of the particle diffusion coefficient during the SHAx phase results smaller by a factor about 5 with respect to the previous and following MH ones

*Top to bottom:*
*Central line-integrated density as measured by the CO2 interferometer and simulated with ASTRA (red)*
*Time evolutions of central $D_0$ and of the dominant MHD mode amplitude*
*Time evolutions of $V_{out}$: green in MH phase ($\rho$/a=0.9), pink in SHAx phase (at the ITB location).*

## Summary and Conclusions

A self-consistent 3D helical RFP equilibrium, taking into account both magnetic and kinetic experimental data, has been obtained for RFX-mod to describe the SHAx regime.

The time evolution of the thermal structure associated to the SHAx has been analyzed in detail, thanks to the high time resolution $T_e$ profile measurements done with the double filter soft-x ray (SXR) diagnostics, recently installed. The thermal gradient at the barrier is not stable during the magnetic phase, it shows oscillations without strict relation with the dominant/secondary mode amplitudes.

$T_e$ profiles and helical equilibrium have been used to evaluate the value of $\chi_e$ during several SHAx, confirming that at the internal barrier position the heat confinement improves significantly (by a factor at least 5-10, with respect to the outer region). A weak increasing/decreasing trend of $\chi_e$ with the secondary/dominant mode amplitude has been observed, meaning that a relevant fraction of heat transport is provided by magnetic stochasticity. Linear gyrokinetic calculations have been applied to the same experimental data and Micro Tearing (MT) modes are found to be unstable. At the highest value of the dominant mode MT drive of transport across the thermal barrier is in agreement with the experimental estimate of $\chi_e$.

The chaos produced by m=2 tearing modes has been taken into account, resulting quantitatively in agreement with the anomalous heat transport observed inside the thermal barrier.

Particle transport analysis showed that in the plasma centre the value of the particle diffusion coefficient is smaller by a factor about 2-5 with respect to the MH regimes, the pinch velocity is outward, of the order of 10 m/s and lower than the velocity required by a transport in a stochastic field, confirming that particle transport in RFX-mod in QSH regimes is no more ascribable to stochastization of the confining magnetic field.

The properties of the RFX-mod plasma core in the helical regimes have been presented. The large plasma volume external to the barrier is however crucial to improve the global confinement. Lithium wall conditioning experiments are ongoing aiming at producing higher edge temperature and temperature gradients through a reduced radiation and recycling: promising experiments with good density control up to $n/n_G$=0.5 have been produced.