Energy confinement in high current RFX-mod plasmas


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In the modified Reversed Field pinch eXperiments (RFX-mod) [1], the radial profile of electron heat diffusivity ($\chi_e$) in stationary conditions was determined till now by adopting a 1D single fluid approach and solving the power balance equation [2]. This method proved RFX-mod improvements [3], [4], although it has various limitations. The stationary equation does not provide any information on heat transport properties time evolution, which is relevant as transient events take place in RFX-mod discharges (e.g., QSH or sawtooth-like activity). Then the power balance equation is solved through the current density profiles, which in turn is calculated using the mu&p model [5]. Hence, this cylindrical model can be applied to $T_e$ profiles measured during Quasi-Single Helicity (QSH) states only if the island is located at the plasma column center: the symmetry assumption is still holding, although estimation of current density profiles is still approximated [4]. Finally, in MH states the core $T_e$ gradient vanishes, and $\chi_e$ cannot be determined in that region, since heat transport is too fast to develop gradients. Using a power balance approach, $\chi_e$ diverges in the core ($\chi_e \sim 1/n_e \nabla T_e$), and can be defined only in the region $0.5 < r/a < 0.7$: here non null $\nabla T_e$ is still present and $\chi_e$ can exceed $1000 \text{m}^2/\text{s}$. Edge $\chi_e$ coincides with its profile minimum, is typically located at $r/a=0.9$ and is about $100 \text{m}^2/\text{s}$.

We partially overcome such limitations with two distinct approaches, which are described in the following sections. They both rely on $T_e$ profile measurements obtained through the main TS diagnostic [6]: the system measures $T_e$ at 50Hz repetition rate in 84 points with 7 mm resolution distributed along an almost entire diameter (-0.96 to 0.84 r/a).

2. $\chi_e$ modeling and $T_e$ simulation in MH states

An alternative method of determining $\chi_e$ during MH states is based on the above described RFX-mod $\chi_e$ profile shape and the experimentally observed correlation between RFP transport properties with magnetic fluctuations. The latter is used to simplify $\chi_e$ profile shape; the second allows determining $\chi_e$ from magnetic measurements.

The RFP core is dominated by magnetic stochasticity [7] and heat diffusivity in this chaotic region scales with the Rechester-Rosenbluth (RR) model, $\chi_e^{\text{core}} = k_1 (b/B)^\alpha$ with $\alpha \sim 2$ [8]; B
is the total magnetic field, \( b \) is the root mean square of the eigenfunctions of the \( m = 1 \) magnetic fluctuations with modes \( m = 1, n < -7 \) (the so called secondary modes) and \( k_1 \) is a constant. At the edge, \( m=0 \) magnetic islands exist around the reversal radius, and the transport is not chaotic: we assume a neoclassical diffusion, not related to magnetic fluctuations \( \chi_{e \text{ rev}}(r) = k_0 / B(r)^2 \). At the reversal radius, heat diffusivity is assumed quasi infinite, since transport is dominated by electrostatic fluctuations. The resulting modeled \( \chi_e(r) \), being independent from \( T_e \) measurements, was used for solving in cylindrical coordinates the one dimensional heat diffusion equation and obtaining \( T_e \) time evolution:

\[
\frac{\partial}{\partial t} \left( \frac{3}{2} n_e T_e \right) = \nabla \cdot (n_e \chi_e \nabla T_e) + P_{in}
\]

(1)

Here, \( n_e \) is the electron density and \( P_{in} \) the input power. The coefficient \( k_0 \) and \( k_1 \) are constant during a shot and are determined to obtain the best fit between simulated and experimental \( T_e \) profile; best fit is determined only for one \( T_e \) profile, generally during the flat-top of the discharge. The shape of \( n_e \) and \( P_{in} \) do not significantly affect simulated \( T_e \) profile since the latter is mainly determined by the large difference in the amplitude of \( \chi_{e \text{ rev}}(r) \) and \( \chi_{e \text{ core}}(r) \).

In fig.1 we show results. In frame a), an example of \( \chi_e(r) \) is shown; the \( \chi_e(r) \) obtained with the power balance equation (dashed blue line, \( \chi_e = \int P_{in} dV/n_e \nabla T_e \)) agrees within error bar uncertainty (dashed blue lines). In frame b) the time evolution of the root mean square of the secondary \( m = 1 \) modes is compared to (c) \( \chi_{e \text{ core}}(r) \). In frame c) \( \chi_e(r) \) time evolution at the reversal is reported as well, \( \chi_{e \text{ rev}}(r) \). The simulated \( T_e \) is compared to experimental results in frame d) and e). Spatial profiles are similar to those measured by the main TS diagnostic: the first order discontinuity in simulated \( T_e \) profile is ascribable to discontinuity Fig.1: Temperature simulation for shot 18490. Radial profiles of the modeled \( \chi_e \) (red) and \( \chi_e \) from the power balance heat equation (blue), frame (a). Time evolution of (b) the root mean square of the secondary \( m = 1 \) modes, (c) \( \chi_e \) in the core and at the reversal (d) simulated and experimental \( T_e \) in the core. Simulated and experimental \( T_e \) profiles at \( t = 134ms \) are shown in frame (e).
in the modeled $\chi_e$ profile; the TS profile is folded on the magnetic axis since the poloidal symmetry of the model. Core $T_e$ time evolution reproduces that measured with the double filter technique with an uncertainty of about 10% (core $T_e$ from the average of core measurements in TS profiles are superposed for completeness, blue dots).

3. $\chi_e$ modeling and $T_e$ simulation in QSH states

During QSH states in the RFP, strong $T_e$ peaking is commonly observed inside the magnetic island [4],[9] (see fig.2). The typically MH state chaotic magnetic field leaves place to closed flux surfaces inside the island, so that $\chi_e$ decreases, being almost no more driven by magnetic fluctuations. To prove this, a pre-existing code, M1TeV [10],[11], has been adapted to RFX-mod to estimate $\chi_e$ value. This 2D numerical code was originally developed to describe the evolution of a $m=1$ kink mode in a Tokamak, taking into account both magnetic reconnection (helical flux surfaces reconnect following Kadomtsev model [12]) and diffusion. It has been adapted to RFX-mod, where during QSH state a thermal island typically develops around the $m/n=1/7$ rational surface with an almost constant density. When the island reaches a width $w$ comparable to the experimental one, the topological picture is frozen and only the diffusion is left to evolve, according to the diffusion equation (eq.(1)). Comparison between experiment and the M1TeV code demonstrates that the peak in $T_e$ is essentially due to the fact that $\chi_e$ is strongly reduced inside the island and that the difference between the peak and external temperature ($\Delta T_e$) is proportional to $w$ and the power density deposited inside the island. Furthermore, the model predicts that experimental peak $T_e$ measured during advanced operations, such as OPCD, can be obtained for $\chi_e$ ranging between 10m/s$^2$ and 30m/s$^2$ ($\Delta T_e \approx 80-300$eV), comparable to Tokamak values of particle diffusivity (see fig.3 frame a) [13].

A direct comparison with $\chi_e$ from the power balance equation can not be presently done, due to the lack of a power balance model based on flux surface reconstruction. The input power contribution is the most uncertain value: the current radial profile is still based on the mu&p model, since it is not directly
measured. Nevertheless, as stated in Section 2, \( \chi_e \) is expected to be correlated to secondary modes, which are low but non negligible in presence of a QSH island. This is demonstrated in OPCD operations: here the periodic oscillation of magnetic fluctuations is correlated to the thermal structure appearance in the core without influencing background thermal properties [14]. As a consequence, predicted and experimental \( \Delta T_e \) are compared respectively to simulated \( \chi_e \) (frame a) and measured magnetic fluctuation level (frame b): as expected, they both show the same dependence.

A further comparison with the experiment is given in frame c. The measured electron temperature profile is used to calculate the island \( \nabla T_e \), so that the relation \( \chi_e \sim 1/ \nabla T_e \) is verified. For this preliminary stage of the work, an appropriate agreement is found also for the dependence between simulated \( \chi_e \) and experimental \( \nabla T_e \).

Fig.3: a) \( \Delta T_e \) plotted against the simulated \( \chi_e \). Open triangles: results from the M1TeV code, full line: \( T_e \sim 1/\chi_e \). b) Island \( \Delta T_e \) vs. normalised secondary modes. c) Island \( T_e \) gradient vs. predicted \( \chi_e \) with the M1TeV code for the measured \( \Delta T_e \).