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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 (χ_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 χ_e cannot be determined in that region, since heat transport is too fast to develop gradients. Using a power balance approach, χ_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 ∇T_e is still present and χ_e can exceed 1000m^2/s. Edge χ_e coincides with its profile minimum, is typically located at r/a=0.9 and is about 100m^2/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. χ_e modeling and Te simulation in MH states

An alternative method of determining χ_e during MH states is based on the above described RFX-mod χ_e profile shape and the experimentally observed correlation between RFP transport properties with magnetic fluctuations. The latter is used to simplify χ_e profile shape; the second allows determining χ_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, $\chi_e^{core} = k_1 (b/B)^\alpha$ 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 $\chi_e^{rev}(r) = k_0 / B(r)^2$. 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 Te time evolution:

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_e T_e\right) = \nabla \cdot n_e \chi_e \nabla T_e + P_{in} \qquad (1)$$

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 $\chi_e^{rev}(r)$ and $\chi_e^{core}(r)$.

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, $\chi_e \sim \int P_{in} dV / n_e \nabla T_e$) 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) $\chi_e^{core}(r)$. In frame c) $\chi_e(r)$ time evolution at the reversal is reported as well, $\chi_e^{rev}(r)$. 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

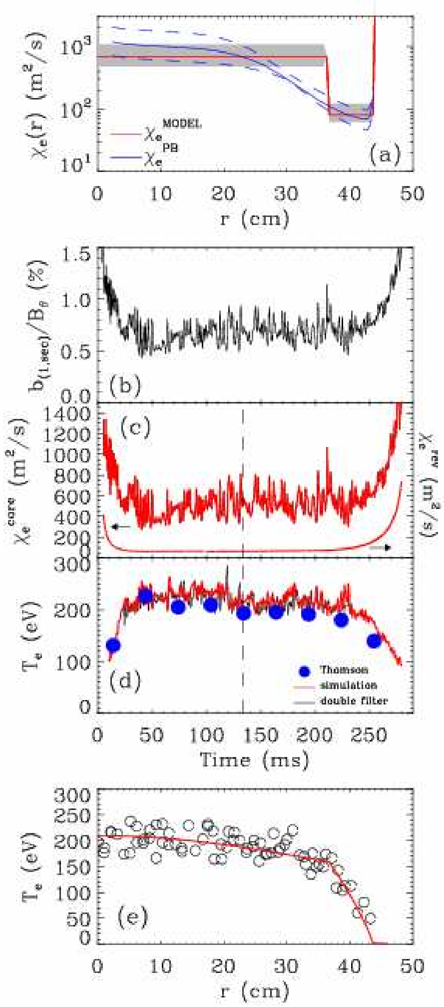

Fig.1: *Temperature simulation for shot 18490. Radial profiles of the modeled χ_e (red) and χ_e from the power balance heat equation (blue), frame (a). Time evolution of (b) the root mean square of the secondary m = 1 modes, (c) χ_e in the core and at the reversal (d) simulated and experimental T_e in the core. Simulated and experimental T_e profiles at t = 134ms are shown in frame (e).*

in the modeled χ_e profile; the TS profile is folded on the magnetic axis since the poloidal symmetry of the model. Core Te 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. χ_e modeling and Te simulation in QSH states

During QSH states in the RFP, strong Te 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 χ_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 χ_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 χ_e is strongly reduced inside the island and that the difference between the peak and external temperature (ΔT_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 χ_e ranging between $10 m/s^2$ and $30 m/s^2$ (ΔT_e ~80-300eV), comparable to Tokamak values of particle diffusivity (see fig.3 frame *a*) [13].

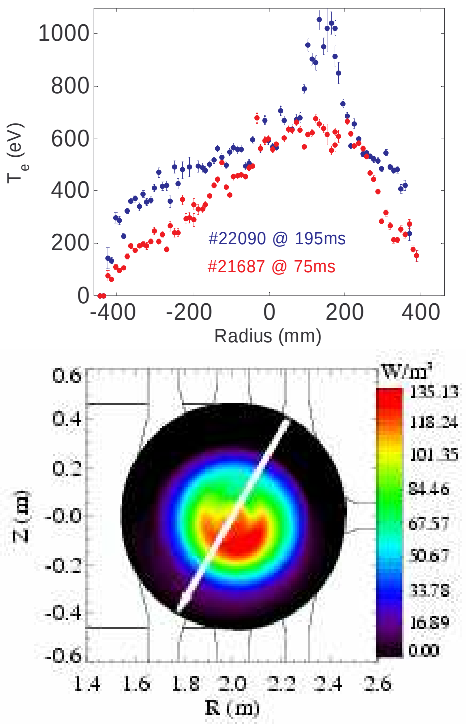

Fig.2: *Example of T_e profiles during two QSH states. The tomographic image of soft x-ray emission for shot # 21687; the arrow represents the TS measurement section.*

A direct comparison with χ_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, χ_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 ΔT_e are compared respectively to simulated χ_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 ∇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 χ_e and experimental ∇T_e.

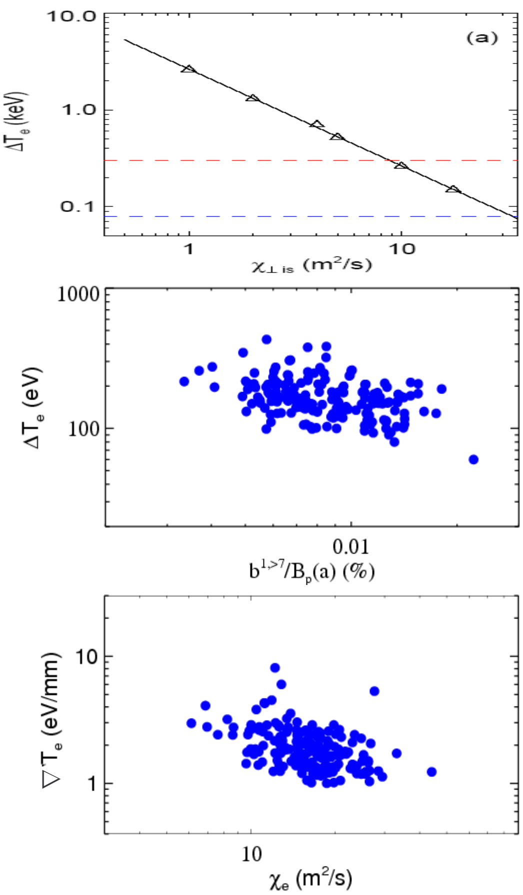

Fig.3: *a) ΔT_e plotted against the simulated χ_e. Open triangles: results from the M1TeV code, full line: $T_e \sim 1/\chi_e$. b) Island ΔT_e vs. normalised secondary modes. c) Island T_e gradient vs. predicted χ_e with the M1TeV code for the measured ΔT_e.*

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