LOCAL ENERGY BALANCE AND TRANSPORT IN RFX STANDARD AND ENHANCED PLASMAS

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In this paper we present the results of a systematic investigation of the radial electron temperature profiles $T_e(r)$ measured in a RFP experiment. T_e profiles, together with density and total radiation emissivity profiles, have been used to determine the effective heat diffusivity χ_{eff} by means of a steady-state power balance equation. We find that the scaling of core T_e gradients and χ_{eff} with current and density can be summarised in a scaling vs. the Lundquist number S (defined as in [1]) which is the ratio of the resistive diffusion time $\tau_R = \mu_0 a^2 / \eta$ to the Alfven time $\tau_A = a / v_a$ (a is the minor radius, η the plasma electrical resistivity and v_a the Alfven velocity). This leads to more peaked T_e profiles in regimes where core MHD fluctuations decrease. According to the resistive MHD theory of the RFP, in high S regimes the resistive dissipation effects get weaker on the MHD motion time scale so that the demand for dynamo magnetic field regeneration decreases: therefore, a reduction of magnetic fluctuations is expected [2]. The behaviour of magnetic fluctuations and their connection with transport is an active subject of research, both theoretically (see, e.g., [3]) and experimentally [1]. The experiments reported in this paper have been performed in RFX [4], a large RFP experiment whose major aim is the study of confinement in MA regimes (minor and major radius of RFX are a = 0.46 m and R = 2 m respectively). The analysis concerns either standard and enhanced confinements with Pulsed Poloidal Current Drive (PPCD) discharges. PPCD is a technique used to externally drive poloidal current in the plasma, by inducing a pulse in the toroidal field at the wall, and to alleviate the resort to spontaneous dynamo action [5,6].

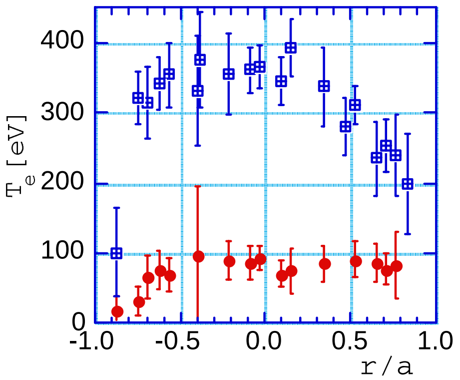

Fig. 1) Typical electron temperature profiles. Closed circles refer to I_ϕ=0.3, while squares to I_ϕ=0.85 MA.

Temperature profiles: The crucial diagnostic for this investigation has been a renewed Thomson Scattering system, which allows the measurement of electron temperature $T_e(r)$ in twenty radial points spanning a region from *r/a* = -0.94 to *r/a* = 0.84 [7] along the equatorial plane. The diagnostic is based on a Q-switched ruby laser with energy of 15J. The collection efficiency of the system permits reliable $T_e(r)$ measurement down to electron densities as low as $1.5x10^{19}$ m^{-3}, a lower limit which covers almost all the present operational range of RFX. Two typical examples of 20 point T_e profiles in different current regimes are shown in Fig. 1. For the measurements reported in this paper, a previous 10 points version of the instrument has been used. A statistical analysis of profile properties have been performed by considering the gradients in two radial regions: an internal region (between 0.3a and 0.8a) and an edge region. The edge gradient is determined by the last measured point and by the measurement obtained with a Langmuir probe [8]. The internal gradient $\nabla T_{e,\mathrm{int}}$ is obtained by a linear fit of the experimental points from the magnetic field reversal point r/a ≈ 0.8 to r/a ≈ 0.2. Typically the

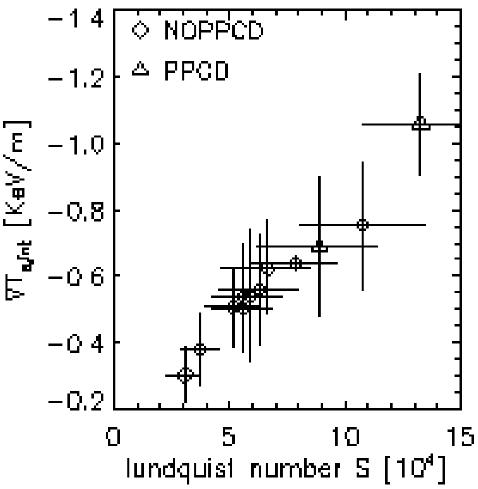

Fig. 2) Dependence of $\nabla T_{e,\mathrm{int}}$ on the Lundquist number S.

largest gradient in the T_e profile appears at the very edge, thus indicating that most of the energy confinement in RFX takes place there. Nonetheless the internal gradient exhibits some peculiar dependencies on plasma parameters, like density and current. In particular we observe a trend for $\nabla T_{e,\mathrm{int}}$ to increase in higher plasma current regimes and as electron density decreases, whereas the edge gradients do not change significantly with density, even if firm conclusions on this subject would need more detailed measurements. An example of this is displayed in Fig. 1, which shows two typical RFX profiles taken at similar values of I_Φ/N ($2\ 10^{-14}$ A m), (*N* is the cross section integrated density), but at two quite different level of plasma current, i.e. at I_ϕ=0.3 and at I_ϕ=0.85 MA. The trends with density and current can be summarised analysing the behaviour of $\nabla T_{e,\mathrm{int}}$ versus the Lundquist number S. The results are shown in Fig. 2, which reports the internal gradients as a function of *S* and indicates that stronger gradients, i.e. a better internal confinement, is obtained in high-*S* regimes as expected on the basis of 3D non-linear resistive MHD simulations [2] in the framework of a stochastic transport model [9]. Each point represents the ensemble average taken over similar discharges. It is interesting to note that a trend similar to that just mentioned, which concerns standard steady state plasmas, is also obtained when an increase of *S* is the result of a transient phenomenon such as during PPCD. The application of PPCD leads to a reduced fluctuation level, to hotter plasmas with much more core peaked T_e profiles and to a significant increase of the confinement time. Two points, corresponding to T_e measurements taken during the PPCD phase of two sets of discharges, at $I_\Phi \approx 0.6$ MA and $I_\Phi \approx 0.8$ MA respectively, are shown in Fig. 2. They fit reasonably well the scale law deduced from stationary conditions.

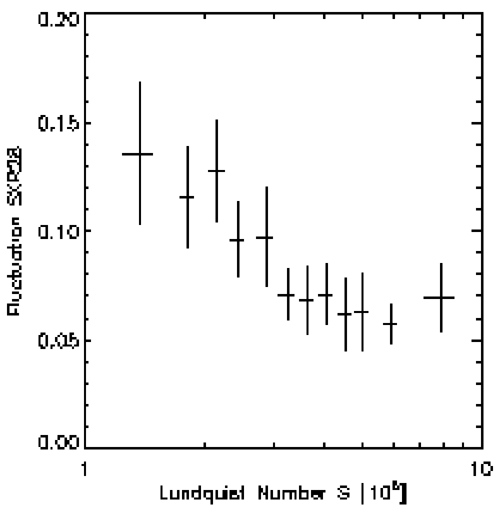

Fig. 3) RMS of the band pass filtered SXR brightness vs. S, normalised to the low pass filtered signal. Each points represent an ensemble average

Core thermal fluctuations. In the high S regimes a decrease of the core MHD-related thermal turbulence amplitude, as indirectly determined by SXR measurements, has also been observed. Thanks to a tomography system [10], plasma emissivity in the continuum soft x-ray range can be measured. The rms of the brightness signal, measured along a line of sight passing through the plasma core, is a "thermal-like" fluctuation amplitude and may be considered related to the internal MHD fluctuation level, at least qualitatively and in the approximation that emissivity is constant over magnetic flux surfaces. The rms is calculated over a 10 ms interval during the discharge flat top, in the frequency range [0.1-3] kHz (to exclude any contribution due to slow variation of the equilibrium) and normalised to the low pass filtered signal. Fig. 3 shows the normalised rms $\tilde{s}_{sxr}$ of the line integrated core emissivity versus *S*. A trend for $\tilde{s}_{sxr}$ to decrease with S can be noted; this evidence confirms, to our opinion, that the level of internal MHD turbulence, which is driving dynamo, is decreasing when S increases, i.e. in hotter plasma regimes.

Local Energy Balance: The measured T_e profiles, together with measured density profiles [11], total radiation emissivity ε(r) [10], and ohmic power deposition profile Ω(r), allow to study the steady-state local power balance, on the basis of the equation:

$$\nabla \cdot \mathbf{q}(r) = \Omega(r) - \varepsilon(r) \qquad (1)$$

where **q** is the heat flux, Ω(r) is given by Aη(r) j(r)^2, η(r) is the classical resistivity [12], and the parameter A is determined by matching the volume integral of Ω(r) to the experimental ohmic input power. The equilibrium current profiles are reconstructed with an equilibrium model [13], with boundary conditions derived from magnetic external measurements. From Eq. (1) the heat flux perpendicular to magnetic surfaces $q_\perp$, in steady-state conditions, can be calculated, and it is possible to derive the effective thermal diffusivity coefficient χ_{eff}, defined as follows:

$$\mathbf{q}_\perp(r) = -n_e \chi_{eff} \nabla T_e \qquad (2)$$

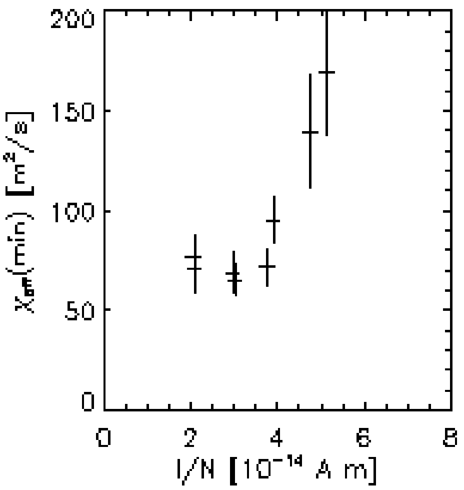

Fig. 4) Minimum value of the conductivity χ_{eff}(min) vs. the I/N parameter at I_ϕ=0.65MA

Due to experimental uncertainties in the T_e profile measurement, a direct calculation of the gradient needed for χ_{eff} determination may be affected by large errors. In order to minimise such errors, T_e profiles are regularised by fitting them with sixth order polynomial functions. The sensitivity to errors is obtained by varying randomly the temperatures within the error bars and using the regularised T_e profiles to determine $q_\perp$ and χ_{eff}. The 50% confidence intervals for $q_\perp$ and χ_{eff}, delimited by the continuous and the dashed lines respectively, are shown in Fig. 5. χ_{eff} shows a minimum in proximity of the edge region, whose absolute value is lower at the highest densities (Fig. 4) and does not scale with S. This indicates that in standard RFX discharges global energy confinement is controlled by the plasma edge and is weakly affected by the reduction of internal fluctuations. Moreover, this results confirms previous investigations showing that global energy confinement time in RFPs is mainly controlled by density. On the other hand, the heat diffusivity in the internal region (averaged from 0.4a to 0.6a) scales with the Lundquist number (Fig. 6), suggesting a correlation with the reduction of internal thermal fluctuations.

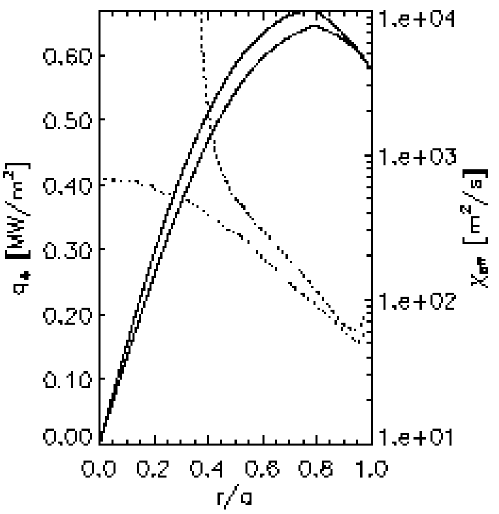

Fig. 5) Radial profile of the heat flux (continuous line) and of the effective heat diffusivity (dotted line).

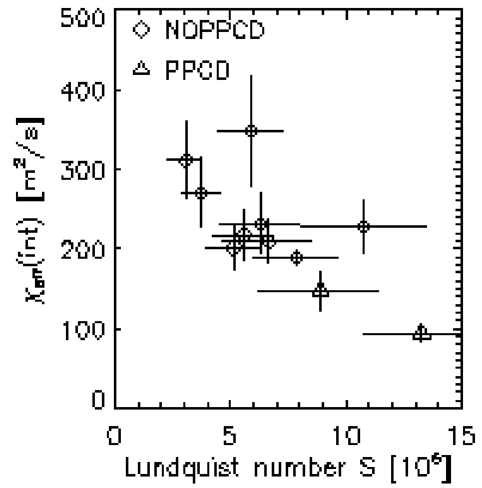

Fig. 6) Heat diffusivity χ_{eff} in the internal region of the discharge, vs. the Lundquist number S.

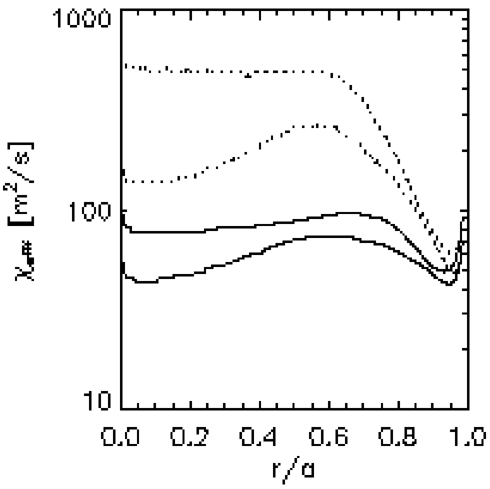

Fig. 7) χ_{eff} profiles before (dashed lines) and during (continuos line) PPCD.

During PPCD experiments, the χ_{eff} profiles substantially decrease over the whole plasma radius and χ_{eff} in the internal region become similar to χ_{eff} at the edge (Fig. 7).

Discussion: Measurements presented in previous paragraphs confirm that spontaneous MHD dynamo activity is correlated to energy transport in the internal region of a steady state RFP discharge. In fact, the Lundquist number seems to be a relevant parameter to summarise the behaviour of electron temperature gradients and of energy transport. In regimes characterised by high values of S, a steepening of T_e profiles and an improvement of internal transport are observed and, simultaneously internal thermal fluctuations are found to decrease. This is consistent with the picture in which anomalous transport in the core is due to the stochasticity of the magnetic field lines [9], caused by dynamo related MHD fluctuations: when the demand for dynamo (i.e. magnetic fluctuations) is reduced, either in standard or in enhanced confinement regimes, then core confinement improves. The main distinction between standard and enhanced plasmas concerns the extent of the reduced transport region. In fact, the global confinement in standard regimes occurs mainly in the edge region: it is weakly affected by the reduction of internal magnetic fluctuations (and consequently internal energy transport) and scales with the density. On the other hand, PPCD plasmas are characterised by a reduced transport over the whole cross section, leading to an improved global confinement, where turbulent dynamo suppression is exploited to its greater extent.

1) References

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