Turbulence measurements and local transport analysis in dedicated β scan in Tore-Supra L-mode discharges.

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The ITER H-mode scaling law written in dimensionless form [1] predicts a degradation of the energy confinement with β (the ratio of the kinetic to the magnetic pressure): $B_0\tau_E^H \propto \beta^{-0.9}$. However dedicated experiments on JET [2] and DIII-D [3] have shown a very weak dependence with β while the JT-60U [4] results are closer to the original ITER scaling law. This contradiction remains unexplained. One possible explanation comes from ELMs, which are likely MHD modes and thus depend on β. To clarify this question, a β scaling experiment has been achieved in L-mode plasmas on Tore-Supra. These experiments are not subject to ELMs, as these relaxation oscillations are not present in L-mode plasmas. In addition to global analysis, supported by transport calculations from the integrated modelling CRONOS code [6], turbulence has been studied with reflectometry. Thus, we will present the β dependence through global measurements (with τ_E) and local analysis (with the heat diffusivity χ and density fluctuations $\delta n/n$).

We consider here the usual form of the dimensionless scaling analysis, which assumes that normalised transport coefficients only depend on the local dimensionless parameters ρ_*, β and ν_* [5]. Moreover it is also assumed that the thermal diffusivity can be written as a power law:

$$\chi = \chi_B \rho_*^{\alpha} \beta^{\alpha_\beta} F(\nu_*, q, T_e/T_i, R/a, \ldots)$$

where $\chi_B = T/eB$ is the Bohm diffusivity, ρ_* is the normalised Larmor radius, ν_* the normalised collisionality, q the safety factor and T_e and T_i the electron and ion temperature. From this χ power law a similar power law can be deduced for the global confinement time

$$\tau_E \propto B^{-1}\rho_*^{(-2-\alpha)}\beta^{-\alpha_\beta}G(\ldots)$$

In a quasi-linear model, for electrostatic turbulence, $\chi = |k_\theta \delta\phi/B|^2 \tau_c$ where k_θ is the poloidal wavenumber of the turbulence, $\delta\phi$ the electric potential fluctuation and τ_c the turbulence correlation time. In an adiabatic model, the density fluctuations can be written $\delta n/n = e\delta\phi/T$. Finally, the density fluctuations should follow a power law:

$$\frac{\delta n}{n} \propto \frac{1}{k_\theta a}\rho_*^{\frac{\alpha-1}{2}}\beta^{\frac{\alpha_\beta}{2}}H(\ldots)$$

The aim of a β scaling experiment is to determine the exponent α_β from χ, τ_E and $\delta n/n$ evolutions.

	high β shots	**low β shots**
	(35900, 35873)	(36044, 36031)
B_0	3.8 T	3.2 T
I_p	0.95 MA	0.8 MA
$n_e(0)$	6.10^{19} m^{-3}	3.10^{19} m^{-3}
$T_e(0)$	4 keV	2.5 keV
P_{ICRH}	$7-8$ MW	$1.5-2$ MW
β_{th}	0.3 %	0.14 %
β_N	0.5	0.23

Table 1: *Main plasma parameters used for the β scaling*

By adjusting the plasma parameters and the Ion Cyclotron Resonance Heating (ICRH) power, the value of β profiles has been increased by a factor of 2 while keeping ρ_*, ν_* and q profiles constant. In order to keep, these profiles constant, attention has been paid to maintain homothetical profiles for the electron density n_e and temperature T_e in the gradient zone ($0.2 < \rho < 0.8$). 4 shots have been realised: 2 at low β ($\beta_N = 0.2$) and 2 at high β ($\beta_N = 0.5$). The main plasma parameters are detailed in Table 1 and Figure 1 shows a comparison of the radial profiles of the dimensionless parameters. The profile matching is good in the gradient area. In the plasma centre ($\rho < 0.2$), a slight mismatch is noticeable due to a warmer core temperature for the high β shots. The ratio between electron and ion temperature, not shown on the figure, does not change during the β-scan: T_e/T_i from the Bragg spectrometer does not evolve during the β scan and is close to 1. One of the high β shots had a different impurity composition from the other shots ($Z_{eff} \approx 4.5$ instead of 2) and was not used for the local analysis. Hydrogen minority ICRH heating, in a deuterium plasma is the only additional heating used in this experiment and the ICRH frequency has been adapted in order to have a central power deposition in both case. Finally, the plasma shape has been kept constant during the experiment.
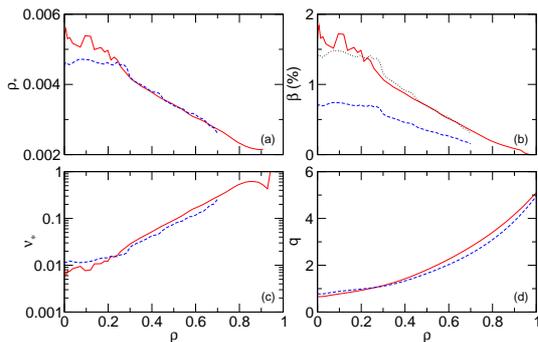

Figure 1: *Radial profiles of (a) ρ_*, (b) β, (c) ν_* and (d) q at low β (solid curves) and high β (dashed curves). The (b) dotted curve is a scaling of the the low β curve by a factor of 2.*

The first analysis has been done for the global confinement time of the energy τ_E. The ITER L-mode scaling law exhibits a strong dependence with β: $B_0\tau_E^L \propto \beta^{-1.4}$. The figure 2 shows the weak dependence found in this set of 4 shots : $B_0\tau_E \propto \beta^{-0.2\pm0.2}$. Global values of β and τ_E are given by magnetic probe measurements. For the high β shots, the error bars take account of a 10 % systematic error in the magnetic measurements due to fast ions contributions. However, the weak dependence found ($\alpha_\beta = 0.2 \pm 0.2$) is largely lower than the predicted one by the ITER L-mode law.

The CRONOS code has been used to evaluate the effective thermal diffusivity $\chi_{eff} = (q_e + q_i)/(n_e\nabla T_e + n_i\nabla T_i)$ where q_e and q_i are the electron and ion heat flux. Figure 3 shows a comparison between 2 shots for χ_{eff} in the gradient

zone ($0.3 < \rho < 0.7$). From this profile evolution, radial profile of the β dependence has been evaluated. We have also found a weak dependence in β for for χ_{eff} ($\alpha_\beta = 0.31 \pm 0.36$ at $\rho = 0.5$). This dependence is in good agreement with the scaling of the confinement time.
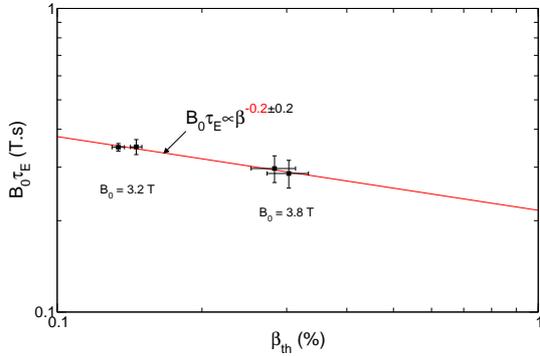
Finally, density fluctuation measurements have been done with 2 reflectometers. The D-band fast-hopping fluctuation reflectometer [7] allows us to have an overlap of fluctuation profiles in the area $-0.5 < \rho < 0.5$. Figure 4 shows the profiles of the fluctuation level for 2 shots. We have observed that outside the $q = 1$ surface ($|\rho| > 0.25$) the fluctuation level does not change with β. The β exponent has been evaluated at mid-radius: $\alpha_\beta = 0 \pm 0.6$. Inside $q = 1$, a clear increase of the density fluctuations is observed. This change could be due to the mismatch of the ρ_*, ν_* and ∇T profiles in this very central region. A change in the MHD activity cor-

Figure 2: *Normalised confinement time of energy as a function of the average β. The best fit is represented by a line.*

related with ICRH heating is also noticeable. It has been observed on Tore-Supra that around the $q = 1$ surface the particle transport is largely modified by the magnetic surface. However, the density fluctuations have a very weak β dependence in the gradient area. Figure 5 from the Doppler reflectometer [8] shows the power spectrum of the density fluctuations versus $k_\perp$. This measurement, localised at $\rho = 0.7$, has been done for the two same shots. No visible evolution of the turbulence spectrum in $k_\perp$ can be observed.
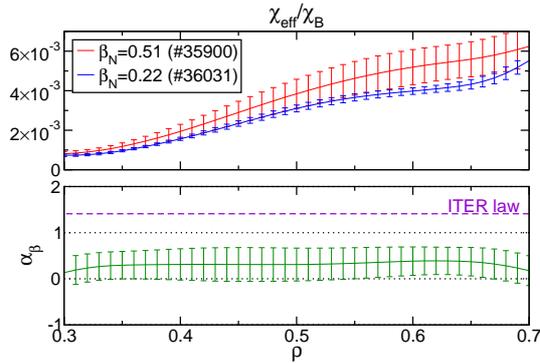

Figure 3: *Radial profiles of the effective thermal diffusivity normalised to the Bohm diffusivity. From these data, the β scaling exponent is deduced.*

We have found a weak β-dependence of the global confinement time. This observation is supported by transport analysis and for the first time by fluctuation measurements. In the gradient region ($|\rho| > 0.25$), the heat diffusivity presents a weak dependence and the turbulence level and spectrum do not change when β is increased. This result is in contradiction with the ITER L-mode scaling law which exhibits a strong dependence on β, as in H-mode. An increase of the fluctuation level is observed in high β discharges inside the $q = 1$ surface ($|\rho| < 0.25$). This increase could be due to a slight mismatch of the other dimensionless parameters in the plasma centre or to a change of the MHD activity associated to high ICRH power. An explanation of the contradiction between experiments and scaling laws, for both L and H modes, could be a bias in the extraction of dimensionless scaling laws from databases [9].

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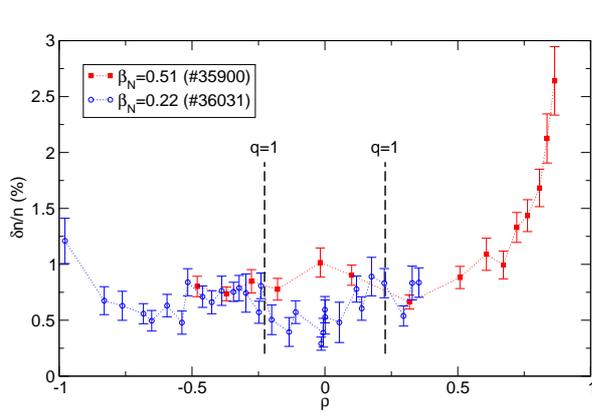[9] D. Elbèze *et al.*, *Proceedings 32nd EPS on Plasma Physics*, Tarragona (2005)

Figure 4: *Profiles of the density fluctuations from the fluctuation reflectometer.*
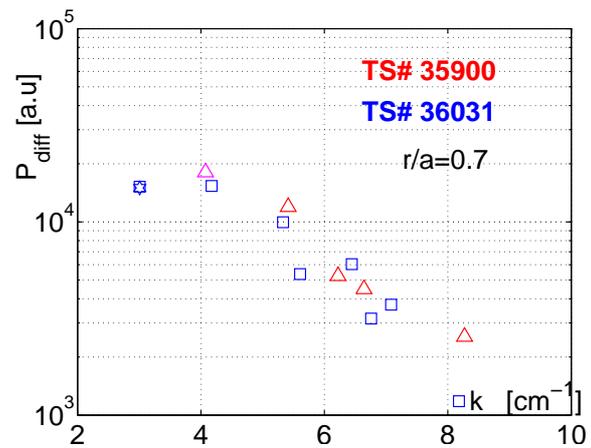

Figure 5: *Power spectrum of the density fluctuations in $k_\perp$ from the Doppler reflectometer.*