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Parametric Dependence of Turbulent Particle Transport in high collisionality plasmas on the Frascati Tokamak Upgrade FTU

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Understanding the mechanisms which control particle transport in non homogenous high temperature magnetized plasmas is of crucial importance for addressing the issue of fuelling in a fusion reactor. Electrostatic drift waves destabilized by the ion temperature gradient (ITG) drive an inward flow of particles (thermo diffusive pinch) proportional to $\nabla T_e/T_e$ as it was shown by Coppi [1]. Numerical simulations including modes driven by trapped electrons (TEM) and toroidal geometry confirmed the presence of the thermo diffusivity and led to a more accurate quantitative estimate of the phenomena [2]. Another mechanism driving particle pinch is related to the precession drift frequency of trapped electrons in the presence of TEM and is proportional to the normalized gradient of the safety factor q, $\nabla q/q$ [3]. By taking into account all these pinch mechanisms, the ion and electron flux Γ can be written as [4] $\Gamma = -D\,[\nabla n + C_q \nabla q/q\, n - C_T \nabla T_e/T_e\, n + C_n n] + V_{Ware} n$ (1) where D is a turbulent diffusion coefficient (typically one order of magnitude large than the collisional diffusion coefficient), the C's are numerical parameters, n is the electron-ion density, q the safety factor, T_e the electron temperature and V_{Ware} the Ware pinch velocity proportional to E_ϕ. In the absence of a toroidal electric field, particle sources and in stationary conditions, the density gradient is $\nabla n/n = - C_q \nabla q/q + C_T \nabla T_e/T_e - C_n$ (2). In order to extend the study of the parametric dependence of turbulent particle transport carried out on other Tokamaks [5] and in particular on Tore Supra [6], we have carried out on FTU [7] (B up to 8 T, I up to 1.6 MA, R=0.973 m, r=0.3 m) an experimental campaign studying radio frequency electron heated plasmas at the

Lower Hybrid resonant frequency in the current drive scheme (LHCD) [8]. The discharges analysed here are 21636, 22424, 26476, 26477, 26480, 26481, 26659, 26671 covering the following range of parameters *I*=360-500 kA, B=5.3-7 T, P_{LH}= 0.8-1.8 MW, P_{ECRH}= 0-1.2 MW, q_{95}=7-9, n_e=0.7-1×10^{20} m^{-3}, T_{e0} = 3-6 keV, ν_{eff}=0.14-2.0 ($\nu_{eff}=\nu/\omega_{de}$ where ν is the electron ion collision frequency and ω_{de} the electron vertical drift frequency) and ion temperature T_{i0} = 1.5-2 keV. An important difference between FTU and Tore Supra plasmas is the duration of the LHCD phase in terms of resistive time, being much shorter on FTU; however according to the evolution of the local toroidal electric field calculated by the JETTO [9] transport code, a good level of non inductive current drive is reached in the central region of the plasma up to half the minor radius in approximately one resistive time (less than 0.1 s) and the toroidal electric field remains zero during the rest of the LHCD phase for several particle confinement times. Neutral penetration for the set of discharges analyzed here has been estimated numerically and the ratio between neutral density and electron density at mid radius does not exceed 10^{-5}.

The density gradient decreases in the central region (*r/a*≤0.3) when the LH power is switched on and during the LH phase the density profile remains constant within the error bars. In Fig 1 we reported the time traces of the toroidal electric field at *r/a*=0.4 (r=12cm), the normalized density gradient measured by interferometer, the temperature gradient measured by Thomson Scattering and the safety factor gradients for shot #26481. The Ware pinch at t=0.5 s and r/a=0.4 is -0.3 ms^{-1}, particle diffusivity is estimated by assuming it equal to the thermal diffusivity around 0.4 m^{2}s^{-1}, the change in the normalized density gradient due to the suppression of the Ware pinch is 1 m^{-1}. By subtracting expression (2) calculated at t=0.6 s and the same expression calculated at t=0.5 s using the data reported in Fig. 1 taking the variation of the temperature gradient as negligible we find C_q=0.3 (Γ/Dn=-0.35, -0.92, -0.19 m^{-1} at t=0.5, 0.6, 0.7 s respectively). By

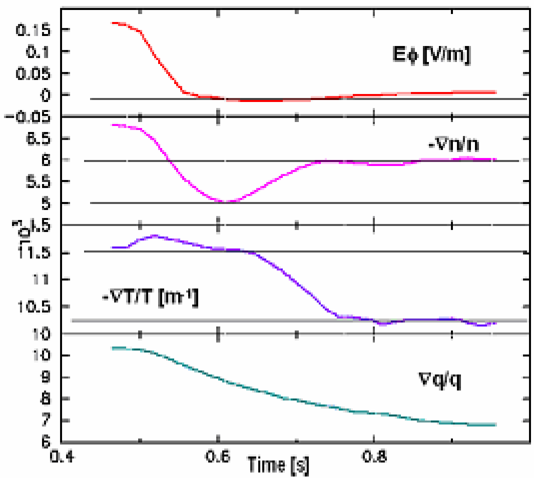

Fig. 1: *FTU #26481. Toroidal electric field, normalized density, temperature and q gradients (in m^{-1}) versus time at r/a=0.4*

repeating the same calculation using t=0.7 s and t=0.6 s (no Ware pinch) we find C_T= -0.6 and C_N=10.3. An independent evaluation of the C parameters is obtained by studying the data base in the stationary phase, the results are reported in Fig 2a,b and Fig 3a: C_T= -0.4, Cq=0.2, C_N=8.

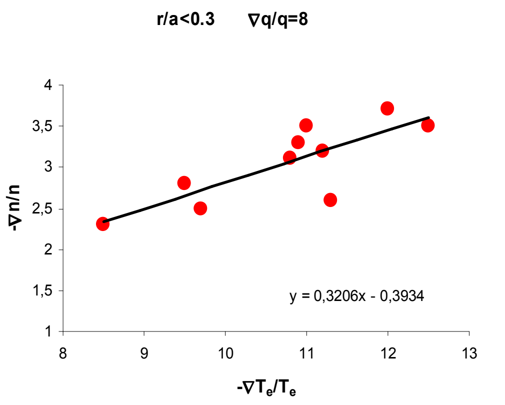

Fig. 2a: *density gradient scale versus temperature gradient scale during stationary LHCD phase taken at constant* $\nabla q/q$ *in the r/a<0.3 region;* $\nabla T_e/\nabla T_i$ *>4.*

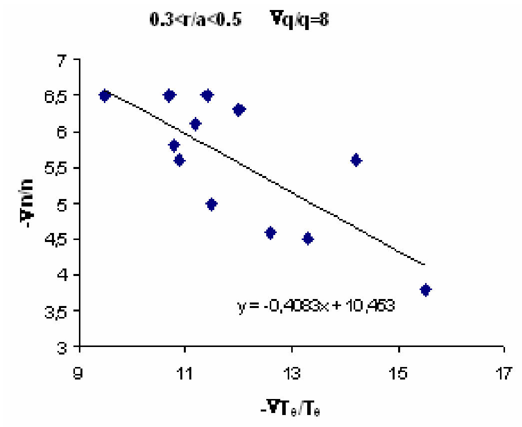

Fig. 2b: *density gradient scale versus temperature gradient scale during stationary LHCD phase taken at constant* $\nabla q/q$ *in the 0.3<r/a<0.5 region;* $\nabla T_e/\nabla T_i$ *<4.*

As result of the analysis we find that the thermo diffusive flow is inward in the inner region either dominated by ITG turbulence or by collisional transport and outward in the gradient region dominated by TEM, in agreement with Tore Supra results [6]. However the flux driven by ∇q/q in the gradient region is smaller than the thermodiffusion whereas in Tore Supra is found to be larger. An extra flux independent of temperature gradient and magnetic shear needs to be introduced to explain the experimental profiles; this term is one order of magnitude larger than the corresponding term of equation 5, ref. [4] due to the magnetic field curvature. This difference could be ascribed to the FTU high collisionality. Increasing collisionality has a stabilizing effect on TEM [10] while it can have a destabilizing effect on ITG and ETG also via the interaction with zonal flows [11]. The change in the dominant type of turbulence due to increased or decreased collisionality leads to the observation of a different particle transport. Collisionality effects on particle transport and density peaking have been investigated experimentally in several Tokamaks, among which Asdex Upgrade (AUG) [12], JET [13] and Alcator C-mod [14]. Both in JET and AUG H-mode plasmas (with dominant ion heating) the density peaking is found to decrease with increasing collisionality, while the dependence of density peaking with collisionality in L-mode plasmas is not clear. The role of collisionality in changing the stability of increased density gradient has been discussed for FTU PEP mode plasmas [15]. By using the dataset described above, we have found the dependence of density peaking versus the effective collisionality $\nu_{eff}=\nu/\omega_{de}$ reported in Fig 3b.

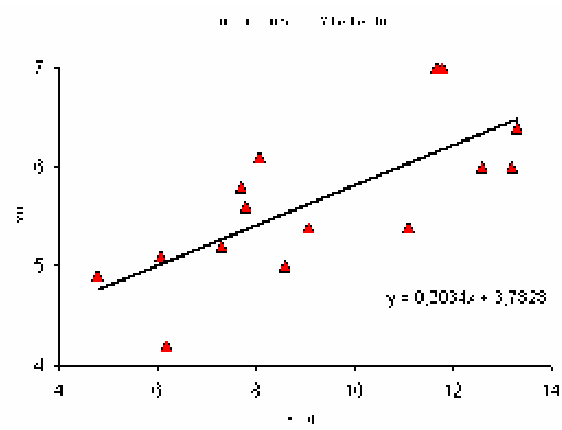

Fig. 3a: *Density gradient scale length versus safety factor scale length in the gradient region*

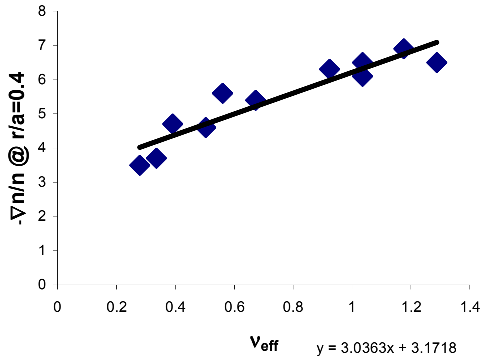

Fig. 3b: *Normalized density gradient versus effective collisionality*

While the scaling of density peaking versus collisionality found in other Tokamaks is confirmed in FTU ohmic discharges, an opposite scaling is found in LH heated discharges. The latter observation can not be explained by gyrokinetic simulations done so far [16] and could be linked to the result that the curvature pinch, driven by unstable TEM, is not a leading transport mechanism on FTU whereas it is found to be dominant in other Tokamaks. Other transport mechanisms recently investigated [17] such as LH driven particle flux could also play a role.

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