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Particle density behavior in FTU electron heated plasmas

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Introduction

An overview is presented here on the effects of radio frequency heating on particle confinement in FTU (Frascati Tokamak Upgrade) discharges. This analysis aims to complement the study of the density profiles in electron heated plasmas conducted in other Tokamaks [1,2,3] at higher densities (n_e up to 10^{20} m^{-3}) and higher magnetic field (B_T=5.3 T). Two scenarios are considered: high collisionality L-mode non inductive discharges [4] (Lower Hybrid full current drive with central heating provided by ECRH Electron Cyclotron Heating 1.6 MW, 140 GHz), and inductive discharges with ECRH central heating alone. The analysis of the electron convective flow in the non inductive discharges has been carried out by focusing on the parametric dependence of the electron density profile on the gradients of the electron temperature T_e and safety factor q as suggested by quasi-linear drift-turbulence transport theory. The electron flux can be written as:

$$\Gamma_e = -D_{turb}\,[\,\nabla_r n_e + C_q n_e\, \nabla_r q/q - C_T\, n_e\, \nabla_r T_e/T_e + C_n\, n_e/a] + V_{Ware} n_e \qquad (1)$$

where D_{turb} is a turbulent diffusion coefficient calculated from mixing length quasi-linear models [5,6] or derived from the experimental data by transport analysis, *C's* are free parameters and V_{Ware} is the Ware pinch velocity proportional to $E\phi$. The analysis of the inductive discharges is focused on the scaling of the density peaking with ECRH power.

Non inductive current drive scenario: experimental setup and main observations

FTU magnetic field can reach values up to 8T and plasma current up to 1.6MA. The major radius is R=0.93m and minor radius a=0.3 m. FTU plasmas allow the study of central electron densities higher than other tokamaks, up to 10^{21} m^{-3}. The density is measured by a two colors scanning interferometer (CO_2 10W, λ=10.6μm; CO 1W, λ=5.4μm). Forty chords at 1cm spatial resolution cover the radial section from the internal middle radius to the external edge including the plasma core, full profile is scanned every 62 μs [7]. The T_e is measured by the Thomson Scattering system (2 cm resolution). The ion temperature profile is calculated through the JETTO transport code [8] using the ion neoclassical conductivity times an anomaly factor to match the neutron emissivity profile provided by the 6-channel neutron profile monitor; for an overview of FTU diagnostics see [9]. In non inductive plasmas V_{Ware}=0 and for negligible particle sources at steady state Γ_e = 0 so (1) becomes: $\nabla n_e/n_e = - C_q\ \nabla q/q + C_T\ \nabla T_e/T_e - C_n/a$ (2). The density profile in the stationary phase, according to (2) depends on the gradients of the T_e and of the q. The ratio between neutral and electron densities at middle radius is found to be of the order of 10^{-5}[4], so the assumption of negligible particle source is satisfied in the region $r/a \leq 0.5$. In the set of LH current driven and ECH heated L-mode discharges (I=360-500 kA, B=5.3-7 T, coupled P_{LH}=0.8-1.8 MW, coupled ECH P_{ECH}=0-1.2 Mw, q_{95}=7-9, n_{e0}=0.7-1.5 10^{20} m^{-3}, T_{e0}=3-6 keV, T_{i0}=1.5-2 keV), density profiles remain peaked and no relevant pump out is observed. The data can be split in two groups with different $\tau = \nabla T_e/\nabla T_i$ [5] in terms of radial position: $r/a \leq 0.3$ and $0.3 < r/a \leq 0.5$, the ratio τ is different in the two regions being greater than 4 in the internal region. In order to investigate the correlation of $-\nabla n_e/n_e$ with the two other variables, a subsets of the data has been selected in which one of the two variables is held constant, e.g. the correlation of $-\nabla n_e/n_e$ with $\nabla q/q$ has been studied in the gradient region ($0.3 < r/a \leq 0.5$) with separate subsets having $-\nabla T_e/T_e \approx$ 9, 10, 11, 12, 14 m^{-1} respectively. The results of the correlation analysis are reported in fig1; substituting in (2) the experimental values found of the C parameters are: $C_T \approx -0.4$, $Cq \approx 0.2$, $C_n \approx 2.4$ [4].

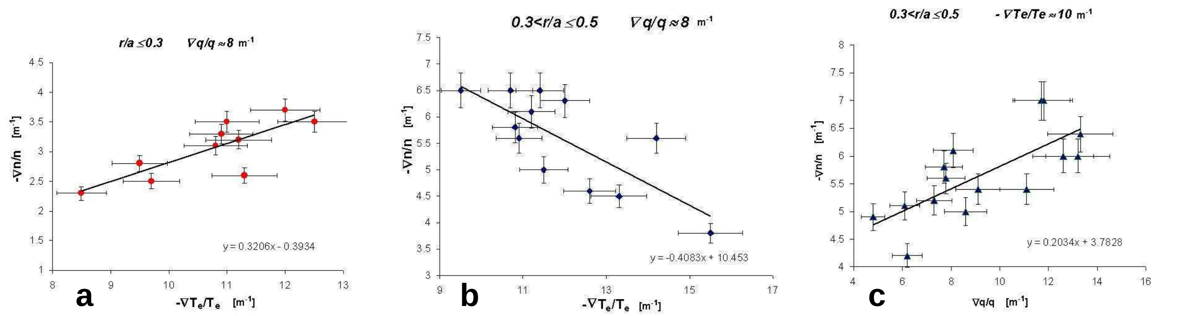

***Figure1 1.a**) Inverse scale-length of the electron density-gradient vs inverse scale-length of the temperature-gradient during the LHCD phase taken at constant $\nabla q/q \approx 8\ m^{-1}$ in the internal region ($r/a \leq 0$, $\nabla Te/\nabla Ti > 4$). **1.b**) The same as before at the gradient region ($0.3 < r/a \leq 0.5$, $\nabla Te/\nabla Ti < 4$). **1.c**) Inverse scale-length of the density-gradient vs inverse scale-length of the safety-factor in the gradient region at constant $-\nabla Te/Te \approx 10\ m^{-1}$.*

The thermo-diffusion flux is directed outward if the electron temperature gradient is large, because of a change of direction of the averaged phase velocity in the presence of TEM (trapped electrons modes). In this case the change in sign of the thermo-diffusivity in the gradient region is consistent with convection driven by TEM [7]. The results are in general agreement with ref [2]. Regarding the scaling of the density peaking with collisionality we have studied the dependence of the density gradient at mid radius versus the effective collisionality $\nu_{eff} = \nu_{ei}/\omega_{de}$ [10], where ν_{ei} is the electron–ion collision frequency and ω_{de} is the electron curvature drift frequency. The trend here is different from that found in other FTU plasma scenarios and indeed in other Tokamaks [4]. Laser blow off injection of molybdenum has been carried out in the above discharges while varying heating power deposition profile from central to off axis. Both pump-out and long lasting central retention of the impurity has been observed [11].

Density profile with ECH heating alone

The analysis presented here is conducted taking into account the density profiles evolution during the ECRH heating, in particular considering a Δt of 40ms (20ms before the ECRH switch on and 20ms after). The aim is to investigate the scaling of the density gradient with increasing ECRH power as done in other experiments [1]. It is found that in most high density discharges the switch on of the ECRH does not produce a significant effect on the density profile. Where the effect is more evident, it is observed a more rapid increase of the edge density (fig 2) and a slower one on the central chord producing a global effect of a profile flattening (fig 4a). This behavior suggests that the change of profile is an edge effect, as an increase of the particle recycling or impurity influx, rather than a pump-out induced by ECRH. In most of the discharges examined the density was still evolving when the ECRH was applied, so we subtracted the variation of the density gradient before the ECRH to study the flattening effect. In fig.3 the correlation between the variation (20 ms before and after ECRH at $0.3<r/a\leq 0.5$) of the density gradient versus an average ECRH power per particle P_{ECRH}/N is shown, where N is the electron density at mid radius times the total volume. Actually the increase of P_{ECRH}/N leads to density flattening. The discharges with higher central densities at the time of the switch on of the ECRH (red cross in fig3) seem less influenced. The figure 3 includes also some discharges of the full LHCD scenario. It's interesting to note that this behavior seems not to be affected either by the position of the ECRH resonance or by T_e. Only plasmas with ~1 MW of ECRH power and low densities (for FTU of the order of $5x10^{19}$ m^{-3}) show a clear pump out effect (fig.4.a). In such discharges, during the profile evolution, an estimate of the diffusion coefficient and the

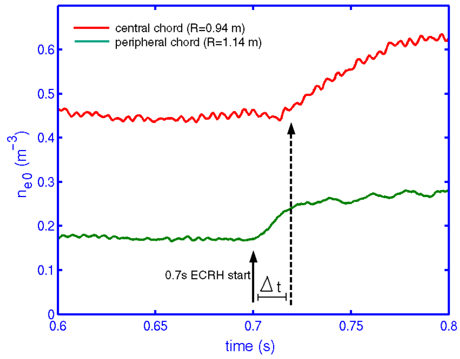

Figure 2 . *shot #29541 line integrated density, the peripheral chord reacts immediately, the central has a 20 ms delay*

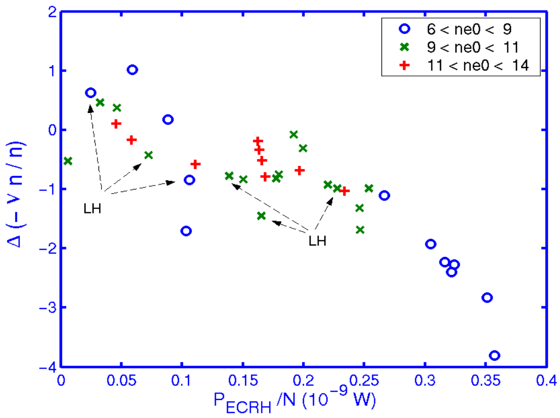

Figure 3*. Density gradient variation at mid radius vs P_{ECRH} /N. Different colors are various n_e ranges, red indicates the highest density.*

pinch velocity has been done [12,13], in the plasma core where the neutral source is negligible. For this purpose the particle flux has been written as $\Gamma/n_e = U - D/n_e \, \partial n_e/\partial r$, where U is the inward pinch and D the diffusion coefficient. Plotting the flux versus $d(\log n_e)/dr$, for a fixed radius and fitting the data, the two coefficients D and U can be obtained (fig4.c). The diffusion coefficient and pinch velocity calculated during the first 40ms of the ECRH phase are shown in fig 4.b.

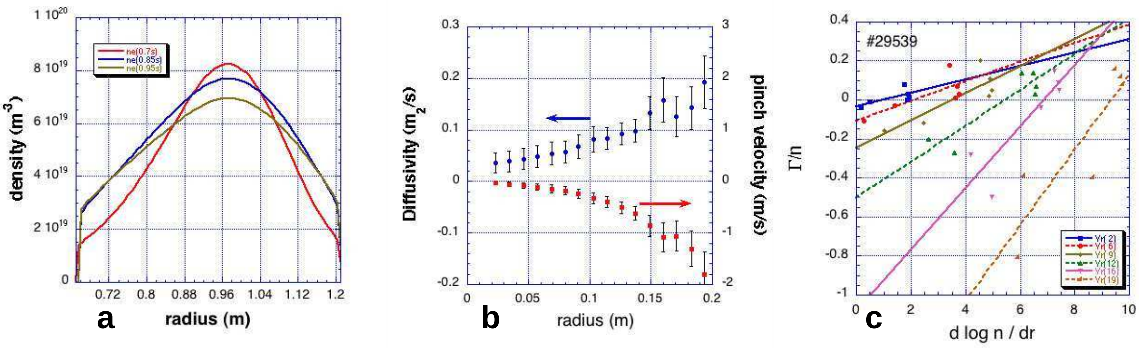

***Figure 4 4.a**) Density profiles for #29539: red profile before the ECRH heating phase. **4.b**) Particle pinch velocity. **4.c**) The straight lines determine the transport coefficients for different radius.*

Conclusions

In full LHCD discharges we observe an inward pinch sustaining peaked electron density profiles. The addition of ECRH power on non inductive discharges does not affect appreciably the shape. In the inductive discharges with ECRH heating alone, an increase of the edge density is clearly observed at the beginning of the heating phase. In high density discharges the effect of ECRH on the density profile is negligible. A clear pump out is observed only with high power ECRH at low densities where the power per particle is the highest. In both cases a different ECRH deposition radius (central up to 10cm off-axis) does not modify the experimental observation.

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