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Studies of Electron Temperature Characteristic Length in FTU

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Introduction.

The shape of temperature profiles in FTU ohmic discharges (R=0.935,a=0.3,BT up to 8T) changes from concave, at low density, to convex, at high density, at fixed plasma current and magnetic field. This fact is pointed out in fig 1, where the temperature characteristic length $(L_T^{-1}=|d(\ln T_e)/dr|)$ is plotted versus the density at two different radii (r/a = 0.3 and r/a = 0.6), for fixed plasma current and magnetic field. The temperature length increases with the radius and changes with the density. The trend with density is different for different radius. This behaviour seems to indicate that temperature profiles can assume any shape when plasma density and current is changed so that temperature profiles are not „stiff„. This is not surprising as the „stiffness„ of the temperature profiles has been observed in discharges with auxiliary heating, in particular with ECRH [1,2,3] where L_T^{-1} become much greater than a certain threshold valued L_C^{-1}. The experiments with ECRH on FTU [3] have shown that the threshold value in FTU was about 8-10 m^{-1}, that is lower than the typical L_T^{-1} values found in ohmic profiles. In this paper, the temperature profiles are analysed plotting the temperature gradient versus the temperature, at fixed current, magnetic field and radius. This has been done for a large number of FTU discharges, avaraging all temperature profiles in the flat-top of the current, during the saw-toothing phase over hundreds of millisecs. Discharges overall the operation space of FTU have been included. Temperature profiles are obtained from ECE Michelson scanning interferometer[4], that is absolutely calibrated.

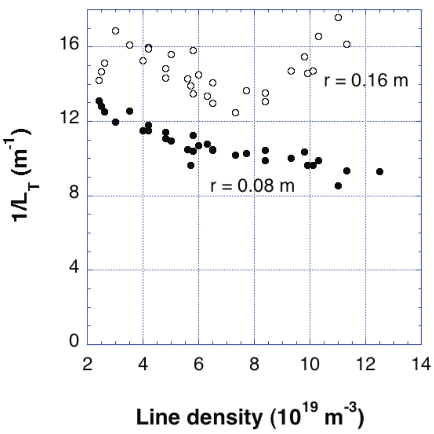

Fig 1.: Temperature characteristic length versus the density at two different radii.

The T_e- ∇T_e plot

In Fig 2, the absolute values of temperature gradients have been plotted directly versus the temperatures for the same data of fig 1, for r/a= 0.3, together with the expected critical length observed in ECRH discharges (red dashed line). Data in this plot, are now aligned along a straight line, and the temperature profiles can be described by two parameters: the slope of the straight line ($1/l_T$) and the temperature offset (T_a). This offset-linear behaviour is observed at all radii and current, with a spread that depend, obviously, on the data quality.

Dependence on the radius

When the same plot is made at all radii (in the confinement region: $r_{mix} < r < 0.8a$, where r_{mix} is the sawtooth mixing radius), the dependence of l_T and T_a from r can be obtained. How l_T changes with radius is shown in fig 3, at I_P=0.4 MA. There is a region (in this case between 8 cm and 20 cm) where the l_T does not change. This was an unexpected result as we had different behaviours with radius in fig 1. This analysis indicates that, even though L_T changes with radius, there exist a characteristic length within the „good confinement region„, that however do not correspond to the usual characteristic length, suggesting that profiles are „stiff„ also in ohmic discharges. The relation in fig 2, between the temperature and its gradient $dT_e/dr = -\alpha(r)T_e - \beta(r)$, represents a linear differential equation for the temperature profile, that in principle could be integrated, when $\alpha(r)$ and $\beta(r)$ are known, for instance, by a polynomial fit of the experimental data. The integration can however be easily done only considering the region where l_T is constant (where experimentally it is also found that the offset term changes linearly with the radius). The profile obtained is: $T_e = p_o(r_o - r) + T_n e^{-r/l_T}$ where T_n is an arbitrary integration constant, p_o=4.43 keV/m, r_o=0.23 m, l_T^{-1}=16 m^{-1}, r is in meter, and temperatures in keV. This expression do not have any general meaning, but it is only an interpolation formula of the experimental profiles where a single arbitrary parameter is present. However, the formula highlights that there is an „offset profile„(the linear term) at which profiles approaches at high density (where $T_n \approx 0$). From this expression

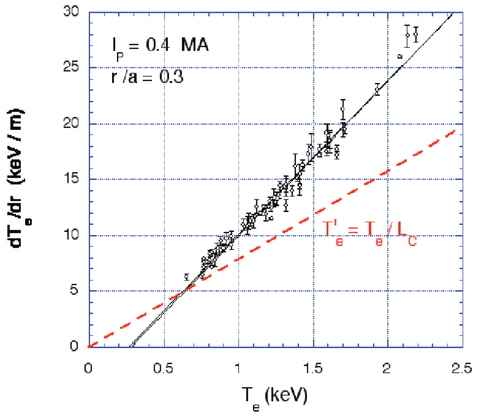

Fig 2: Temperature gradient versus temperature at fixed radius and plasma current, for different density

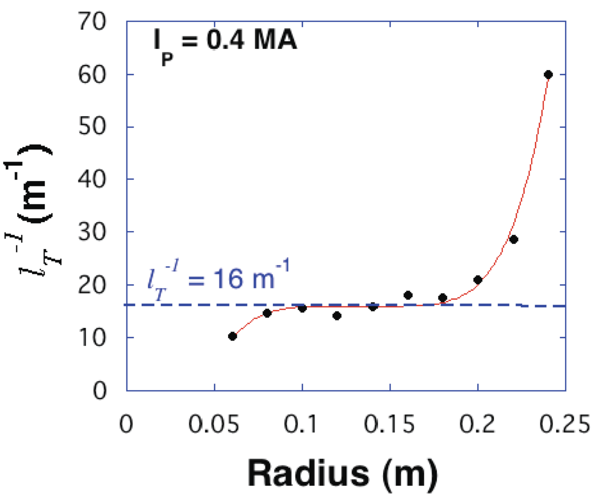

Fig 3.: L_T^{-1} versus the radius at I_P=0.4MA.

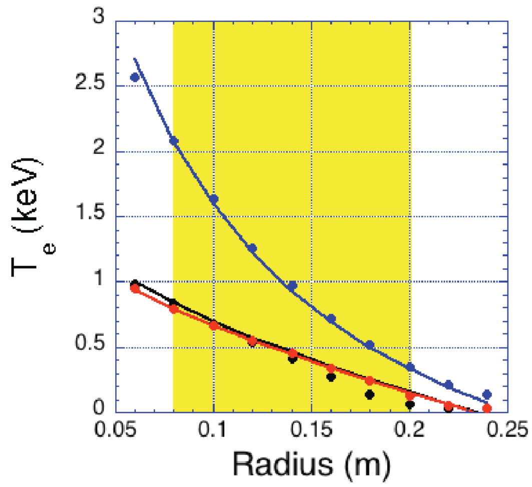

Fig 4.: Experimental profiles (dots) and interpolation formula (lines), at low density (blue) and high density (red and black). the shadow region is the range of validity of the approximations.

we can deduce that when temperature is raised, as during the ECRH, the exponential term becomes more important and a constant L_T can be observed. Three experimental profiles, at the extremes of the density range, have been plotted in fig 4, together with the interpolation formula. The arbitrary constant has been calculated to fit the temperature at r=8 cm. The shadow region represents the radial extend of the validity of the approximation made in the integration.

Behaviours with the current.

The same result has been obtained at different plasma current, but within a smaller radius interval, as the extension of mixing radius of the sawtooth increases with the current. Some differences are also observed in the way l_T rises at the plasma edge. The dependence of l_T on the current is small (at half radius a regression gives $l_T^{-1}(m^{-1})=12+7\,I_P(MA)$, I_P = 0.35÷0.7 MA, but with a large uncertainty), while the offset term changes of a good amount.

Diffusion coefficient.

From the temperature profiles we can calculate the diffusion coefficient if sources are known. Profiles have been extended to the plasma centre using a constant value, and the source has been assumed to be purely ohmic, having neglected the radiation (that are mainly at the plasma edge) and the energy transfer to ions. This last assumption is surely not correct, for its amount and for the strong dependence on the density, that is the parameter under investigation. Let's start from the thermal diffusion equation in a steady state, in cylindrical approximation

$$\frac{1}{r}\frac{d}{dr}r\Gamma=S$$

where $\Gamma=-\kappa\, d\,T_e/dr$ is the energy flux through a surface of radius r, and $S=\sigma T^{3/2}$ is the energy source and κ the diffusion coefficient. Integrating over r, and using the experimental profiles extrapolated to the mixing radius ($r > r_{mix}$), we get

$$\kappa=\frac{\sigma}{r\left|dT_e/d\,r\right|}\left[T_o^{3/2}\frac{r_{mix}^2}{2}+\int_{r_{mix}}^{r}\left(p_o(r_o-r)+T_n e^{-r/l_T}\right)^{3/2} r\,dr\right]$$

where r_{mix} = 0.08 m, and T_o is the temperature inside r_{mix}, and $T_n=(T_o-0.66)/0.28$. Integrating this equation numerically we get the diffusion coefficient, at different values of T_o, corresponding to different values of density. In fig 5, the calculated diffusion coefficient normalised to σ is reported for different T_o versus the inverse L_T^{-1}. A typical curve of the diffusivity in Figure 5, have a fast rise at low L_T^{-1}, reaching a high value and remains constant or decreases slightly, as L_T^{-1} increases further. This behaviour can be easily understood, considering the two components of the experimental temperature profile: the linear and the exponential part. In the region with large L_T^{-1} (say, L_T^{-1}>30 m^{-1}) that is the outer part of the profile, the linear term of the temperature profile is dominant, so that the gradient changes very little (and so does the diffusivity), while the temperature go to zero, with a consequent large change of L_T^{-1}, at constant diffusivity. For the inner part of the profile (L_T^{-1}<15 m^{-1}), the situation is inverted, and L_T^{-1} does not change much for the presence of the exponential term (temperature and gradient increase proportionally), while the diffusivity is lower for the higher gradient and lower flux.

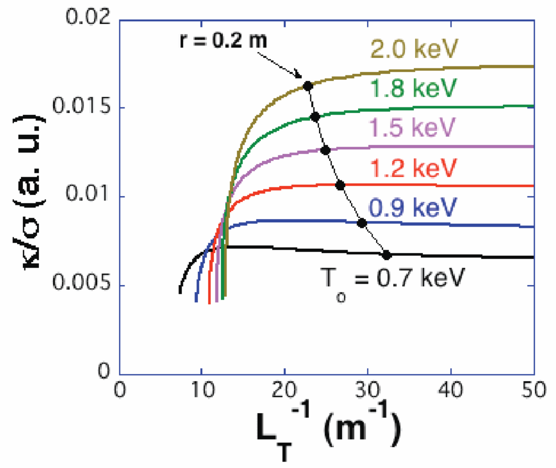

Fig 5.: Normalized diffusion coefficient versus the characteristic length at different values of To. Dots indicate the position of r=0.2 m (r/a>0.7). Points with r<0.2 m are at left of the dots.

Comparing this behaviour of the diffusivity with the simplified critical length model for the diffusion ($\chi \propto T^{3/2}(\nabla T_e/T_e - 1/L_C)^{1/2}$), we can assume that the critical length occurs at the value where the diffusivity fall down at low L_T^{-1}. The first consideration is that it should change with density. Large part of the profile lies beyond the threshold critical length and has an enhanced diffusivity. The diffusivity in this region decreases with the density, qualitatively in agreement with the $T^{3/2}$ factor present in model. Low L_T^{-1} can only be obtained when temperature is high enough, that the linear term is negligible, and characteristic length approaches the critical values. It must be remarked that the absolute value of the diffusivity at high density (low T_o) remains lower than the one at low density for any radii, in agreement with the usual better global confinement observed at high density.

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[4] P.Buratti and M. Zerbini, Rev. Sci. Instrum., 66,(1985),4208