

Density Profile Changes Induced by on- and off-axis Electron Cyclotron Heating

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Introduction. Particle transport in tokamaks is an area of active research. Generally, the observed peaked density profile can be explained by an inward pinch velocity v_p and diffusion outwards. In the scarce experiments in which both are determined [1,2], the particle diffusion coefficient D_n exceeds the neo-classical estimate by one order. Further, the necessary v_p exceeds the neo-classical Ware pinch [3-5].

The research at the Rijnhuizen Tokamak Project (RTP; $I_p \leq 150$ kA, $B_T \leq 2.5$ T, $R/a = 0.72/0.164$ m) focuses on electron transport. At RTP experiments have been performed with Electron Cyclotron Heating (ECH) at powers exceeding the Ohmic input power by a factor of ~ 5 and with a deposition width less than 10% of the minor radius a . The dominant ECH power causes strong changes of the electron density (n_e) profiles as well as the electron temperature (T_e) profiles. The comprehensive set of diagnostics enables detailed study of these reactions. In this contribution the steady state n_e profiles as well as their temporal development are investigated.

The data are obtained with multi-position Thomson scattering [6] resolving n_e and T_e profiles with a spatial resolution of $\Delta z/a = 0.02$ and errors of 3% and 5%, respectively, at $n_e = 5 \cdot 10^{19} \text{ m}^{-3}$. Further, data of a 19 channel interferometer and 20 channel ECE polychromator are used.

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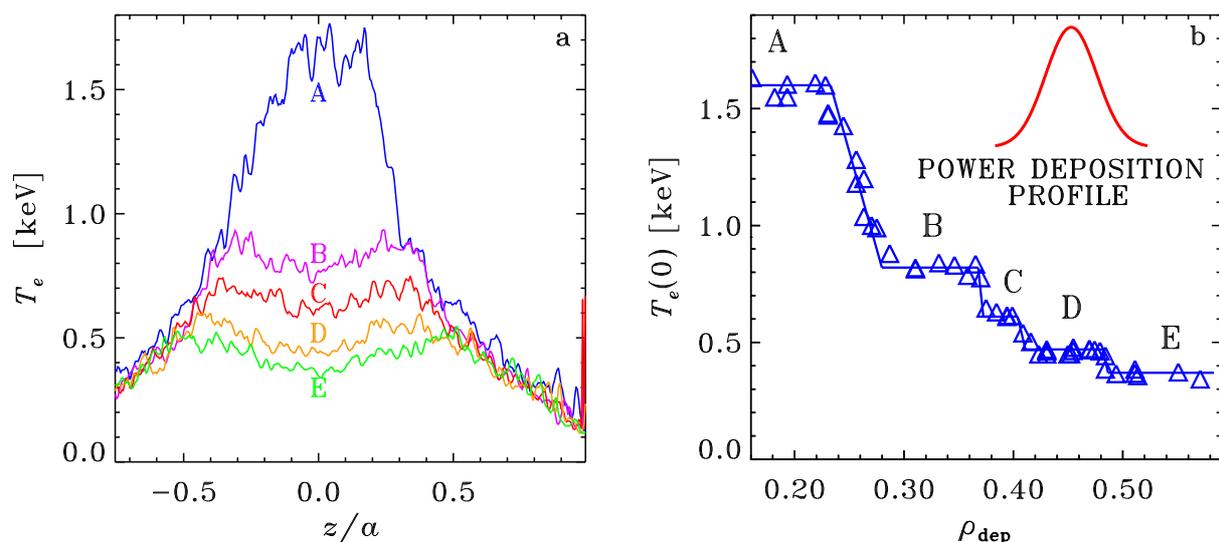


Figure 1: a) Five typical T_e profiles taken from the plateaux in b) the trace of the central T_e versus the deposition radius. These data are obtained in a series of 80 kA discharges of intermediate density in which ρ_{dep} was scanned along the horizontal axis. In b) the power deposition profile is indicated. Note that the transitions between the levels are much sharper than the profile width. The line is a guide to the eye.

Experimental observations. If the deposition radius of the ECH (ρ_{dep}) is scanned, a discrete set of steady state T_e profiles can be distinguished [7]. This scan can be done statically, by varying ρ_{dep} between discharges, and dynamically, by varying ρ_{dep} during the discharge. In Fig. 1 this discrete set of T_e profiles is shown as well as the central T_e ($T_e(0)$) as a function of ρ_{dep} . For central deposition the T_e profile has a hot core, for off-axis ECH it is flat or slightly hollow with a maximum close to ρ_{dep} . Outside ρ_{dep} the profiles are equal.

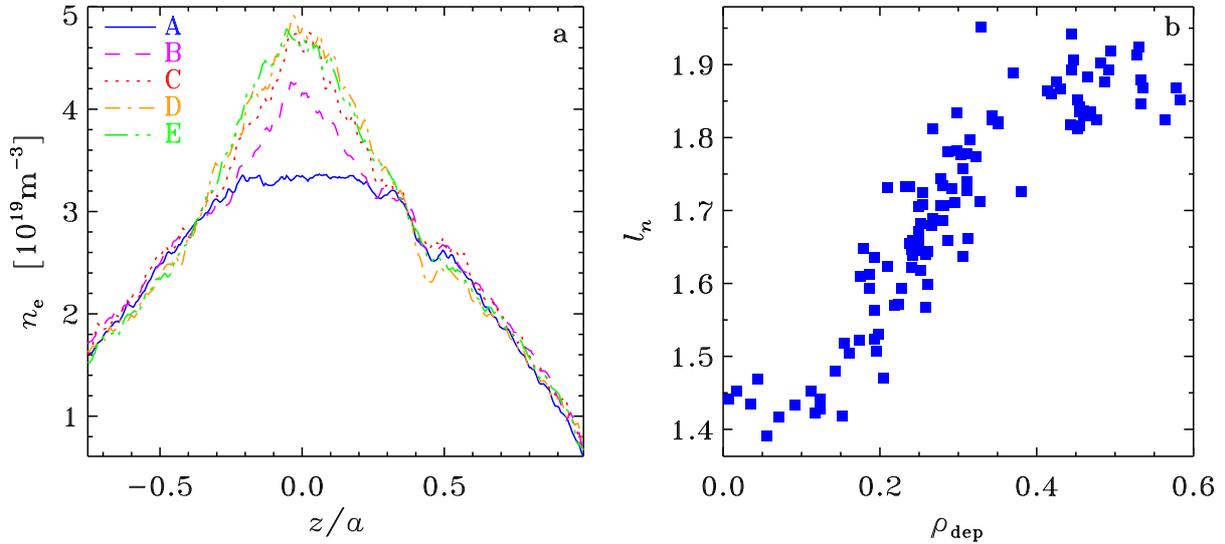


Figure 2: a) n_e profiles averaged over the levels indicated in Fig. 1. The original edge gradients are almost equal to each other. In the plot they are scaled. b) Corresponding density line peaking factor l_n vs. ECH deposition radius ρ_{dep} .

In Fig. 2 the corresponding n_e profiles are shown as well as the line peaking factor $l_n \equiv an_e(0)/\int n_e dr$ as a function of ρ_{dep} for the series of discharges of intermediate density ($n_e(0) \sim 4 - 5 \cdot 10^{19} \text{ m}^{-3}$) of Fig. 1. The profiles are averages of several discharges in the same levels.

The trend of n_e is opposite to that of T_e : The higher ρ_{dep} , the higher $n_e(0)$. For central ECH, n_e is flat in the core region. l_n is constant within level A up to $\rho_{\text{dep}} = 0.15$ where it starts a gradual increase through level B and C to its end value of level D and E. This gradual increase differs from the behaviour of $T_e(0)$ in that $T_e(0)$ has no intermediate values in between the levels. The l_n value of level D and E remains just below that of Ohmic discharges, which is typically $l_n = 2.0$.

A picture very similar to Fig. 2 was found for a series of low density discharges ($n_e(0) \sim 2.5 - 3 \cdot 10^{19} \text{ m}^{-3}$). The profile shape is almost independent of the absolute n_e value.

An extreme example of the antagonism of the T_e and n_e profiles has been found in case of counter current drive with ECH (ECCD, [8]) in low density discharges. The resulting steady state T_e profile has an extremely high gradient at the hot centre, see Fig. 3. The high T_e gradient corresponds to a reversed gradient of the n_e profile.

The temporal behaviour of the T_e profile and the n_e profile in the intermediate density discharges of Figs. 1 and 2 is illustrated in Fig. 4. This discharge jumps spontaneously from profile A to B during ECH. The central density and $T_e(0)$ crash at the transition on a MHD time scale. $T_e(0)$ reaches its new value almost immediately. The whole n_e profile decreases on the long current diffusion time scale ($\tau_\eta \sim 30 - 50 \text{ ms}$ during ECH). The final value of $l_n = 1.7$ is in agreement with Fig. 2.

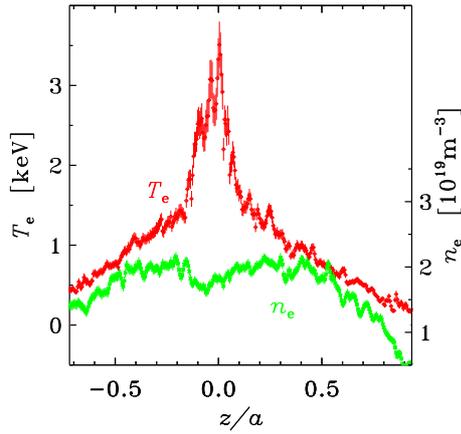


Figure 3: Typical T_e and n_e profiles obtained with Electron Cyclotron Current Drive in counter current direction. $I_p = 120$ kA, $B_T = 1.93$ T

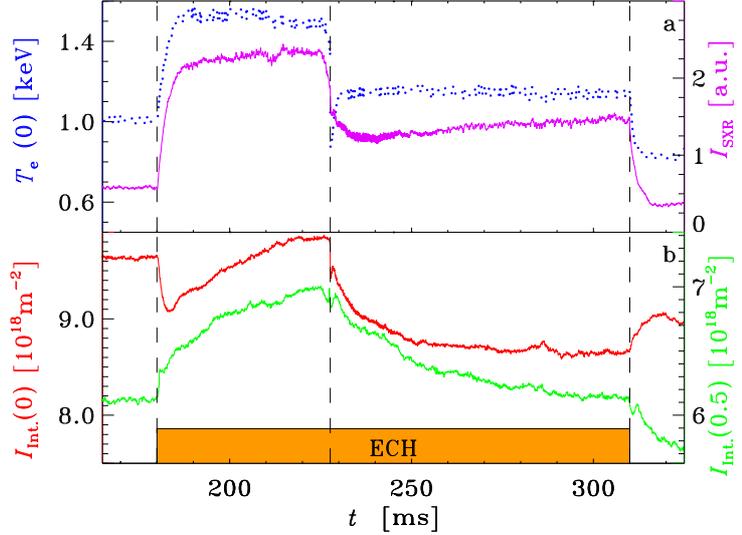


Figure 4: Time traces of central ECE (dots) and soft X-ray (a) and of interferometer channels at zero (upper curve) and half radius (b) of a discharge with ECH from 180 to 310 ms at $\rho_{\text{dep}} \sim 0.2$. At $t = 228$ ms a spontaneous transition from level A to B occurs.

Dynamic scans of ρ_{dep} show that all transitions between the profiles are clearly marked by changes of both $T_e(0)$ and $n_e(0)$. This can be either by MHD crashes or by changes on the particle diffusion time scale ($\tau_D \sim 5 - 10$ ms). In these dynamic scans the l_n values of phases A and B at the end of ECH are in agreement with Fig. 2b. For the other levels this could not be confirmed.

Interpretation. During ECH the edge density increases and this causes a reduction of the peaking factor with respect to the Ohmic phase. The n_e profiles of levels D and E resemble Ohmic profiles except for the higher edge density.

In steady state the particle flux Γ is zero:

$$\Gamma = D_n \nabla_r n_e + n_e D_T \frac{\nabla_r T_e}{T_e} + v_p n_e = 0, \quad (1)$$

where the first and second term represent the particle diffusion driven by $\nabla_r n_e$ and $\nabla_r T_e$ respectively, and the the last term is the particle pinch [9]. Now we try to establish which role these terms play in the particle balance.

First, we consider the third term of Eq. 1, and see if the neo-classical Ware pinch can explain the observations. In steady state the expected local Ware pinch (v_{Ware}) can be determined from the loop voltage V_1 and the poloidal magnetic field B_θ profile [3] as resulting from neo-classical resistivity corrected for bootstrap current. Both in RTP [10] and in large tokamaks [11,12] it has been shown that a good match with measurements is obtained when neo-classical resistivity is used to compute the current density from T_e . In Fig. 5 the v_{Ware} profiles corresponding to the profiles of Fig. 1 and 2 are shown. Note that these are upper limits, because the profiles the spatial localisation of the trapped particles is not accounted for. The difference between these profiles is very large, since, with increasing ρ_{dep} , both V_1 and $1/B_\theta$ increase.

An enhanced Ware pinch could lead to peaking of the n_e profile. However, the v_{Ware} profile changes most strongly from level C to E, where we saw only minor effects on the n_e profile. v_{Ware} barely changes for level A and B, whereas the flat central density of

level A suggests a reduction of v_p within $z/a = 0.25$. The same holds for profile B within $z/a = 0.35$. Further, v_{Ware} changes not only inside but also outside ρ_{dep} , where we saw no effect on the n_e profile shape. This excludes the Ware pinch as the dominant mechanism.

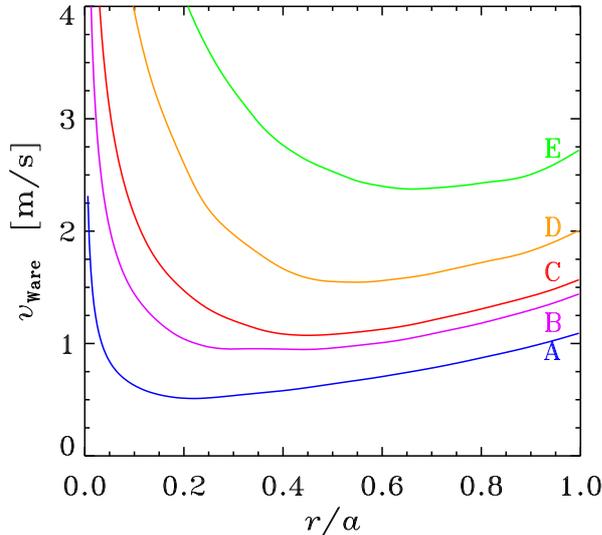


Figure 5: Estimate of the Ware pinch, calculated with neo-classical resistivity corrected for bootstrap current from the T_e profiles in Fig. 1. Note the increase from level A to E as a consequence of the redistribution of the current density.

the particle transport equation explains the opposite behaviour of ∇T_e and ∇n_e . The long time scale of the relaxation of the electron density profile puts forward the current density as a parameter, but the mechanism remains unclear.

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Second, we consider the $\nabla_r T_e$ driven term. The antagonism between the n_e and T_e profiles (see Figs. 2 and 3) suggests a significant role of this term. The hollow n_e profile during ECCD is possibly caused by an outward particle diffusion driven by the T_e gradient. If we take a steady state and neglect convection, a rough estimate from the profiles in Fig. 3 gives $D_T/D_n = -0.3 \pm 0.1$. Though it would be higher if convection were to be introduced, this value is consistent with earlier results [9]. This non-vanishing thermodiffusion can explain the low n_e gradients in high T_e gradient areas. However, it does not explain the zero and reduced n_e gradients in the centre for level A and B, respectively.

Conclusion. From experiments with high power, small deposition width ECH, it has become clear that the Ware pinch can not account for the observed effects on the electron density profile. The thermodiffusion term in