ELECTRON TEMPERATURE PROFILES IN DISCHARGES WITH PELLET INJECTION AND IN OTHER MODE DISCHARGES

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1. Introduction. Pellet injection in ASDEX can result in a plasma regime with substantially improved plasma performance. This regime is characterised by strongly peaked electron density profiles, while the electron temperature profile shows little change. The energy confinement is significantly enhanced [1]. At least part of the reduced transport can be attributed to an improved ion energy confinement [2, 3]. When the density peaks during ohmic discharges, the ion transport becomes neoclassical over a large part of the plasma cross-section. It is interesting to note that this holds for deuterium as well as for hydrogen discharges. As in discharges without pellets, however, one still observes the global energy confinement to be worse for hydrogen than for deuterium. An enhanced electron transport compensates the better ion confinement which leads to a nearly unchanged temperature profile compared to the deuterium discharge. Another observation seems to support the picture of a very "stiff" electron temperature profile: after pellet injection the relative electron temperature profile recovers within a few milliseconds, although the pellet mass is very inhomogeneously deposited around half the plasma radius.

Earlier investigations on ASDEX [4] found already the high insensitivity of the relative electron temperature profile, especially in the outer part. An independent recent analysis of ohmic discharges [5] confirmed this result. The investigation reported here broadens the experimental basis by a larger number of discharges with different confinement modes, includes an analysis of the absolute value of the temperature, and discusses the energy confinement time.

The electron temperature profile was statistically investigated by applying the SAS-code [6]. About 5000 data points of 70 discharges measured by the ASDEX YAG-system [7] covered the following parameter range:

$$
\begin{array}{lll}
5 \cdot 10^{18}\ m^{-3} & \le n_{35} & \le 6 \cdot 10^{19}\ m^{-3} \\
2 \cdot 10^{19}\ m^{-3} & \le n_o & \le 2.3 \cdot 10^{20}\ m^{-3} \\
0.2\ MW & \le P & \le 3.5\ MW \\
1 & \le Z_{eff} & \le 2.7 \\
0.24\ MA & \le I_p & \le 0.47\ MA \\
1.7\ T & \le B_t & \le 2.6\ T.
\end{array}
$$

(n_{35}: density at r=35 cm, n_o: central density, P: power flowing through the boundary determined as heating minus radiation power, I_p: plasma current, B_t: toroidal field). The analysis included pellet and non-pellet discharges in different modes of confinement (OH-SOC, -IOC, L-mode) and with different heating methods (OH, NI-co, -counter, ICRH). The working gas was deuterium or hydrogen. All discharges were carried out in divertor configuration (old and new design) with a plasma radius of a=40 cm. The data set excludes H-mode data and does not cover the low density range ($\bar{n} \lesssim 2 \cdot 10^{19}\ m^{-3}$).

2. The boundary temperature. If the electron temperature profile is "stiff" in its relative shape, the absolute overall temperature is proportional to the boundary temperature. Precisely speaking it is the temperature at that location in the boundary where "stiffness" stops. For practical reasons the boundary temperature was taken at r=35 cm, which means 5 cm inward from the separatrix. At this location reliable electron temperatures can be obtained from the YAG system. Meanwhile, the system has been improved and temperature at locations, closer to the separatrix will be analysed in the future.

The electron temperature T_{35} at r=35 cm shows significant variations with the density n_{35} at the same location, the heating power P_{tot}, the toroidal current I_p and the toroidal magnetic field B_t. The boundary temperature increases weakly from hydrogen to deuterium. The influence of pellet injection is small. On average T_{35} is about 10 % smaller immediately after injection while 10 ms after injection and later no significant difference can be found. This holds even for the extended periods of improved confinement after injection. No significant dependence on the confinement mode, the heating scenario or Z_{eff} was observed.

In summary, the boundary temperature can be described by

$$T_{35} = 600 \cdot n_{35}^{-0.4} \cdot P^{0.2} \cdot I_p^{1.4} \cdot B_t^{-0.4} \cdot A^{0.2}\ [eV, 10^{20} m^{-3}, MW, MA, T] \quad \text{A : atomic weight}$$

For simplicity, we used ordinary least squares after a logarithmic transformation. The uncertainty of the exponents is typically $\pm$ 0.1 and the rootmean squared error (rmse) of the fit is 17 %. In the investigated data set, T_{35} ranges from 140 eV to 330 eV where the lower limit seems to correspond to the density limit. It should be noted that the I_p and B_t-dependencies can not be expressed as a pure q_a-dependence.

3. The relative temperature profile. The relative electron temperature profile was analysed in terms of the two ratios T_{20}/T_{35} and T_0/T_{20} (T_0: central temperature, T_{20}: temperature at $r = a/2 = 20$ cm). The reference value at r=20 cm was chosen as a radius value always outside the q=1-radius.

The analysis revealed the following dependencies:

$$T_{20}/T_{35} = 3 \cdot \left(\frac{n_{20}}{n_{35}}\right)^{-0.2} \cdot A^{0.2} \qquad T_0/T_{20} = 0.19 \cdot I_p^{-1.2} \cdot B_t^{1.2} \cdot \left(\frac{n_o}{n_{20}}\right)^{-0.2}$$

The uncertainty in the exponents is again $\pm$ 0.1 and the rmse is 17 % and 10 % respectively. The relative temperature gradient in the outer part is invariant to a high degree. It decreases somewhat at a higher density gradient and gets somewhat larger if one switches from hydrogen to deuterium. If we take deuterium, and the average

n_{20}/n_{35}-value the ratio T_{20}/T_{35} corresponds to a critical temperature decay length of $L_T \equiv T_{20}/\partial T/\partial r = 0.23$ m ($L_T = 0.25$ m was found in [4]).

In the inner part, a strong dependence on q_a is found: $T_0/T_{20} \propto q_a^{1.2}$ which can be attributed to the shrinking of the q=1-radius. Besides this effect, no other strong influence on the temperature profile was observed.

4. Consequences for the energy confinement scaling. If we fix I_p and B_t and neglect the small other causes for a change, we can assume $T(r)$ to be self-similar. Together with the assumption $T_e \approx T_i$ we can rewrite the energy confinement τ_E:

$$\tau_E = \frac{E}{P} = c\frac{\int rdrn_eT_e}{P} = c\frac{T_e(a)\int rdrn_e(r)\Theta(r)}{P}$$

canonical profile of the relative temperature: $\Theta(r) \equiv T(r)/T(a)$,

with: $\langle n\rangle_T \equiv \int rdrn(r)\Theta(r)/\int rdr\Theta(r)$,

we get: $\tau_E \propto T_e(a)\cdot\langle n\rangle_T\cdot P^{-1}$,

with the scaling-law (see above): $T_e(a) \approx T_{35} \propto n_{35}^{-0.4}\cdot P^{0.2}\cdot A^{0.2}$,

one gets finally: $\tau_E \propto \langle n\rangle_T\cdot n_{35}^{-0.4}\cdot P^{-0.8}\cdot A^{0.2}$.

If we allow I_p and B_t to change we have to include two effects:

1. The temperature averaged density has to include the different $\Theta(r)$ profiles for different q;
2. The I_p and B_t influence of T_{35} has to be taken into account.

Hence we get: $\tau_E \propto \langle n\rangle_T\cdot n_{35}^{-0.4}\cdot P^{-0.8}\cdot A^{0.2}\cdot I_p^{1.4}\cdot B_t^{0.4}$.

A direct regression analysis of τ_E ($T_i = 0.9\ T_e$) with these parameters yields

$$\tau_E \propto \langle n\rangle_T^{0.5}\cdot n_{35}^{-0.2}\cdot P^{-0.7}\cdot A^{0.2}\cdot I_p^{0.7}\cdot B_t^{-0.1}.$$

The τ_E-values for all the investigated conditions are relatively well described by this scaling law with a rmse of 14 % (see figure). Phases of discharges with pellet injection, IOC periods, and L-mode periods do not show a significant deviation from the fit to the complete data set. The improvement of energy confinement in pellet and IOC discharges enters the τ_E expression via the increased $\langle n\rangle_T/n_{35}$-value, that means through the density peaking.

In assessing the differences between these two expressions for τ_E it has to be noted that n_{35} and $\langle n\rangle_T$ are of course highly correlated in our data base, and that the shape factor represented by the ratio $\langle n\rangle_T/n_{35}$ will itself depend on I_p/B_t in a form leading to a partial cancellation of the discrepancies. The very unfavourable power dependence of τ_E is at least partly a consequence of the assumption $T_i = 0.9\ T_e$, which will systematically tend to underestimate the increase in energy content with heating power.

References.

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