ANALYSIS OF THE INVARIANCE PROPERTY OF THE ELECTRON TEMPERATURE DURING AUXILIARY HEATING IN ASDEX

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A crucial and still unsolved problem in tokamak physics is the understanding of anomalous heat transport across the magnetic field via heat conduction of the electrons. All efforts to establish a universal expression for the diffusivity χ_e as a function of local plasma parameters which is valid also for auxiliary heating have failed so far. The problem has become even greater since it became evident that plasma confinement deteriorates during additional heating in a parameter range that is still very close to ohmic heating conditions. The conventional way of thinking is that additional heating of plasma affects its temperature locally according to the energy deposition profile. Consequently the electrical conductivity $\sigma \propto T^{3/2}$ will rise and thus the current density profile takes a new shape determined by the power deposition profile. This statement is, however, in clear contradiction to the experimental finding: electron temperature profiles exhibit a remarkable invariance to external influences and possess a very characteristic shape. An example is given in Fig. 1 showing temperature profiles as taken with a new Thomson scattering device with relatively high spatial resolution using a 60 Hz Nd:YAG laser. The profiles are normalized to the central value and represent four different cases: Ohmic heating (OH) alone, OH with additional neutral beam injection (NI) with different power deposition. In one case 29 keV D^o-particles were injected into a relatively high density target plasma. The beam power is then deposited at radii of 25 ... 30 cm. This is compared to the case of 40 keV D^o injection in a low density plasma with peaked power deposition. Although the central T_e values rise appreciably, the relative T_e-profile shapes remain unchanged. This profile invariance has been further checked in discharges with addition of Ne impurities, which clearly documents that rather $1/T \cdot dT/dr$ and not dt/dr keeps constant. Profile consistency has also been confirmed in cases with and without sawtooth activity. Despite the lack of sawteeth the T_e profiles are found to be consistent and are still affected by q_a. The electron density profile $n_e(r)$, however, becomes steeper in this case. Another example of this disparity is a discharge with pellet refuelling during which the $n_e(r)$ profile is changed enormously while the T_e-profile shape keeps practically fixed (Fig. 2).

It is well-known, on the other hand, that T_e-profiles can easily be influenced by the choice of the safety factor q_a, i.e., the ratio of the

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toroidal magnetic field to the plasma current. Amazingly, this statement has also proved to hold for additionally heated plasma discharges: the T_e-profile shapes are influenced in the same manner by q_a as in the OH case, regardless where the heating power is deposited. This is demonstrated in Fig. 3 for two cases with identical plasma current but variable toroidal field with $q_a = 2.9$ and 4.7, respectively. Profiles are normalized to the peak value again and do not change shapes when NI-power is applied. The dependence on q_a, however, is quite evident and can be summarized impressively for a large variety of plasma conditions in a plot of $T_e(0)/\langle T_e \rangle$ versus q_a, where $\langle T_e \rangle$ is the volume averaged electron temperature (Fig. 4). $T_e(0)/\langle T_e \rangle$ represents a measure for the peakedness of a T_e profile and shows a characteristic q-dependence. The tendency is similar for $n_e(r)$ profiles but many exemptions exist which do not fit to the same characteristics, e.g. discharges with pellet injection or witout sawtooth activity /1/.

So far we concentrated on OH an NI conditions. When the plasma is additionally heated by high frequency radiation e.g. ion cyclotron resonance heating or lower hybrid heating, the profile invariance has to be restricted to a region $r > r_1$, where r_1 might be interpreted as the radius of the $q = 1$ surface. In both cases the heating effect is higher in the plasma center. Obviously this region $r \lesssim r_1$ is a confinement region of its own, and has to be treated separately in comparison to the region $r > r_1$. But if the T_e-profiles are normalized to a value at a radius where the influence of the $q = 1$ surface is negligible one observes that all profiles coincide amazingly for $r > r_1$ within the error bars of the diagnostic and yield an almost constant slope

$$(1) \qquad \frac{1}{T_{r/a\,=\,0.45}} \cdot \frac{dT}{dr} = (4 \pm 0.3)\ \mathrm{m}^{-1} \text{ for } r > r_1 \cdot \sqrt{2}$$

for all discharge conditions (see Fig. 5). If we apply the same procedure to merely OH and NI heated discharges, we note that eq. (1) is valid as well. In this case the deviation from eq. (1) for radii $r < r_1$ is only due to the different q_a values (Fig. 6). Thus, the profile steepening for large q_a values (Fig. 4) is mainly caused by phenomena within the $q = 1$ surface. Then the plasma turns into the high confinement regime during neutral injection (NI(H)) the T_e-profiles deriate slightly from the general shape due to an additional edge temperature rise.

The dominant role of q alone to constitute the T_e profile shape is quite obvious and points to the current density profile as a leading quantity to be invariant. This is also supported by the observation that the inversion radius of sawteeth is only a function of q_a and otherwise remarkably constant /2/. Via the coupling $T_e(r) \propto j(r)^{2/3}$, the temperature profile is then forced to become invariant, too. There are indeed reasons for $j(r)$ to take a "natural shape" arising from very basic principles as minimization of magnetic field energy in a plasma column with a given toroidal current I.

References

/1/ Gehre, O., et al., this conference
/2/ Wagner, F., Phys. Rev. Letters, to be published

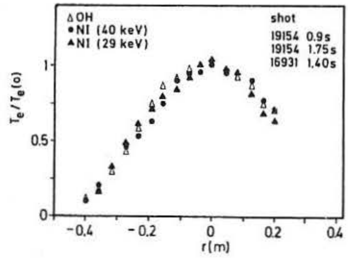
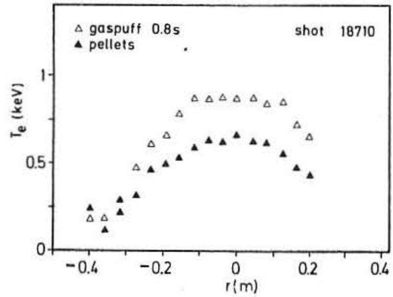


Fig. 1:
Variation of the deposition profile
△ ohmic heating (OH)
$q = 2.9$; $T_e(0) = 0.65$ keV
● 2 MW neutral injection (NI) D^o (40 keV) $\rightarrow H^+$ $\bar{n} = 2.9 \cdot 10^{13} cm^{-3}$; $T_e(0) = 1.68$ keV; $q = 2.9$
▲ 1.3 MW NI, D^o(29 keV) $\rightarrow D^+$; $q = 2.6$ $\bar{n} = 5.6 \cdot 10^{13} cm^{-3}$; $T_e(0) = 1.1$ keV



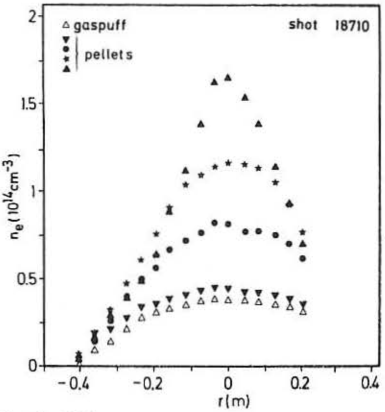


Fig. 2: Comparison: gasfuelling - pelletfuelling
left: $T_e(r)$ with gasfuelling (△) and after a series of 20 pellets (▲)
right: $n_e(r)$ during gasfuelling (△) and pellet fuelling (dark symbols) showing the time evolution of $n_e(r)$; (t = 1,3-1,5-1,7-2,1 s).

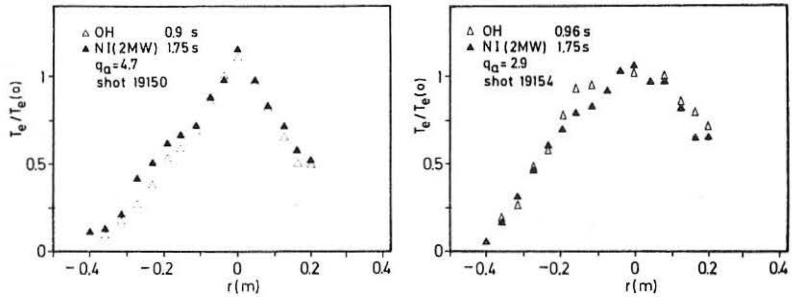


Fig. 3: Comparison of T_e profile shapes during ohmic heating (△) and 2 MW neutral injection (▲) at $q_a = 2.9$ and $q_a = 4.7$

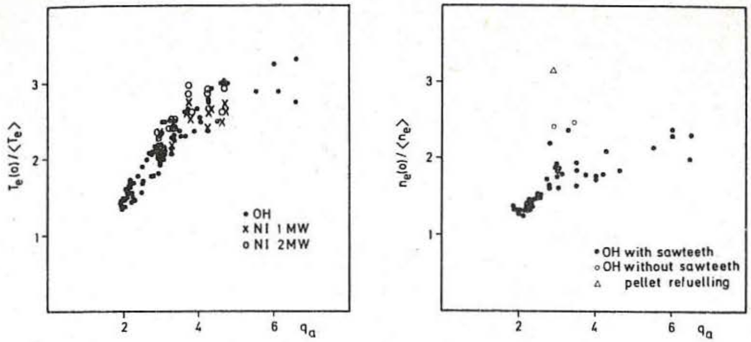


Fig. 4: left: peakedness $T_e(0)/\langle T_e \rangle$ of temperature profiles vs. q_a at different heating powers
● OH, x 1 MW(NI), o 2 MW(NI)
right: $n_e(0)/\langle n_e \rangle$ vs. q_a

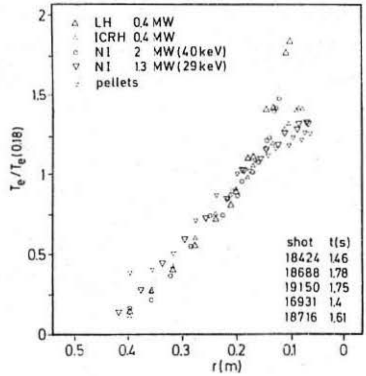


Fig. 5: different cases of additional heating

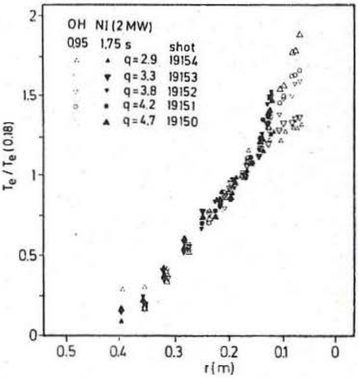


Fig. 6: OH and NI heated discharges with $2.9 \leq q_a \leq 4.7$

Fig. 5 and 6: Temperature profiles normalized to the T_e value at r = 0.18 m vs. radius r of the flux surface at which T_e is measured. The β-shift of the flux tubes is taken into account. A small area around the magnetic axis is not covered by the laser beam of the scattering diagnostic.