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PROFILE CONSISTENCY AS A RESULT OF COUPLING BETWEEN THE RADIAL PROFILE FUNCTIONS OF PRESSURE AND CURRENT DENSITY

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1. Introduction.

It has been noticed since a long time [1] that in ohmic tokamak discharges a remarkable near-identity exists between the profile functions of the pressure p(r)/p(o) and of the toroidal current density j(r)/j(o). Kadomtsev [2] came to an explanation of this based on the principle of minimal free energy of the sum of plasma kinetic energy and the energy of the poloidal magnetic field and found:

$$\frac{p(r)}{p_o} = \frac{j(r)}{j_o} = \left\{1 + \frac{r^2}{a^2}\left(\frac{q_a}{q_o} - 1\right)\right\}^{-2} . \tag{1}$$

Recently, Taylor [3] came to the same expression based on the hypothesis that the current is filamented on a fine scale. In this paper we will call this form of profile consistency the K-T model.

In order to test the K-T model, the consequences for the T_e-, n_e-, $p_e(r)$-profiles are compared with the experimental ones obtained from the RTP-tokamak during steady state and transient periods, caused by applying ECRH and ramping of the plasma current. For a general description of the RTP-results, see [4].

2. Steady state ohmic discharges.

In Eq. (1) the value q_o appears, which cannot yet be measured in RTP. However, the q=1 radius is in agreement with the empirical scaling found in nearly every tokamak (Arunasalam [5]):

$$r(q=1) \simeq a/q_a \ . \tag{2}$$

Combining this with the K-T model, one finds:

$$q_o \simeq \frac{q_a}{q_a + 1} . \tag{3}$$

This simplifies the expression (1) even further for stationary states:

$$j(r)/j_o = (1 + q_a\, r^2/a^2)^{-2} . \tag{4}$$

Expression (4) is compared to experimental j-profiles found by Soltwisch [6]. The agreement is good (see Fig. 1), except for deviations caused by magnetic islands.

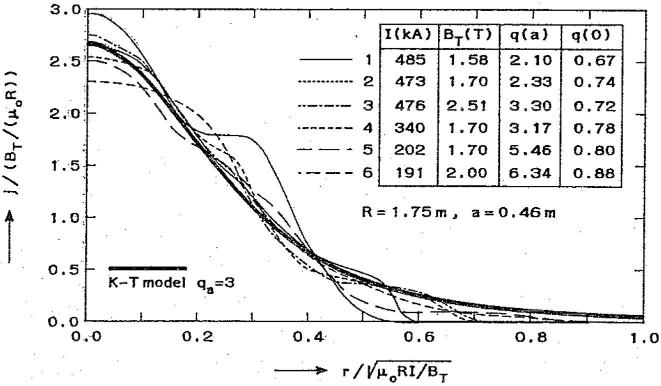

Fig. 1. Soltwisch experimental j-profiles [6], compared to the K-T model prediction.

Under the additional assumptions that corrections to Spitzer-resistivity are constant over the cross-section and that $p_i(r) \propto p_e(r)$, it is easy to predict the n_e-, T_e-, and p_e-profiles and their halfvalue radii

$$n_e(r) = n_{eo}\,(1+q_a\,r^2/a^2)^{-2/3} \qquad r(n_{eo}/2) = 1.828\;a\,q_a^{-1/2} \tag{5a}$$

$$T_e(r) = T_{eo}\,(1+q_a\,r^2/a^2)^{-4/3} \qquad r(T_{eo}/2) = 0.825\;a\,q_a^{-1/2} \tag{5b}$$

$$p_e(r) = p_{eo}\,(1+q_a\,r^2/a^2)^{-2} \qquad r(p_{eo}/2) = 0.643\;a\,q_a^{-1/2}\;. \tag{5c}$$

The experimental halfvalue radii for stationary RTP-plasmas are compared with these predictions (Fig. 2). The agreement is satisfactory.

3. ECRH-heated plasmas at constant current.

RTP-plasmas heated with 180 kW ECRH show a very high and strongly peaked T_e-profile ($T_{eo} = 650 \rightarrow 2600$ eV; $r(T_e/2) = 0.05 \rightarrow 0.02$ m). Simulation with magnetic diffusion codes indicate that the full re-adaptation of the j-profile to the new resistivity profile takes typically 200 ms i.e. longer than the applied ECRH pulse of 90 ms. Therefore, the stationary relations (4) and (5) are broken since $j(r) \neq T_e^{3/2}$. One has to go back to Eq. (1) and assume $j_{EC}(r) \simeq j_\Omega(r)$. Since, according to the K-T model $n(r) \propto j(r)/T(r)$, one expects a hollow n_{EC}-profile inside r = 3 cm radius and a broadened n_{EC}-profile outside with halfvalue radius increased by 2.5 cm. This is in excellent agreement with experimental $n_e(R)$-profile (Fig. 3).

4. Ohmic discharges with a ramped current.

Experiments were done with ohmic plasmas during which the plasma current was ramped up from 60 kA ($q_a = 6.67$) to 100 kA ($q_a = 4.0$) in 50 ms or ramped down from 100 kA to 60 kA (Fig. 4) and compared to a stationary plasma with I = 80 kA ($q_a = 5.0$). The density halfvalue radius follows the changing q_a-value as predicted by Eq. (5a), but delayed with about 10 ms, due to the finite skin current penetration.

5. EC-heated discharges with a ramped current.

The same current evolution waveforms have been used in these experiments as mentioned under Section 4, but now at elevated electron temperature because of 180 kW ECRH ($T_{eo} = 700 \rightarrow 1800$ eV). The averaged skin penetration time increases with about a factor 4. The skin current penetration time at the edge becomes equal to the current ramp time and therefore the j-profile in the centre is nearly unchanged by the current ramps. Accordingly, $r(n_{eo}/2)$

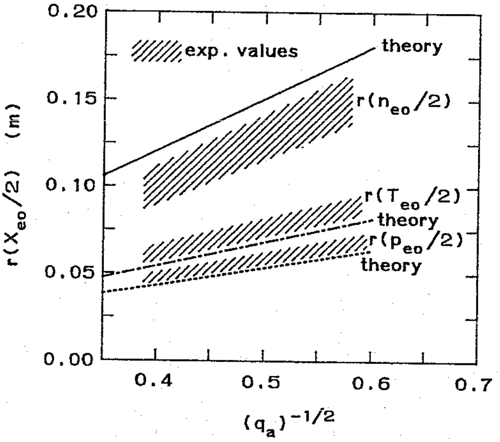

Fig. 2.
Experimental halfvalue radii for n_e-, T_e-, and p_e-profiles compared to the K-T model for a range: $3.0 < q_a < 7.0$ and $2 < n_{eo}$ $(10^{19}\ m^{-3}) < 8$.

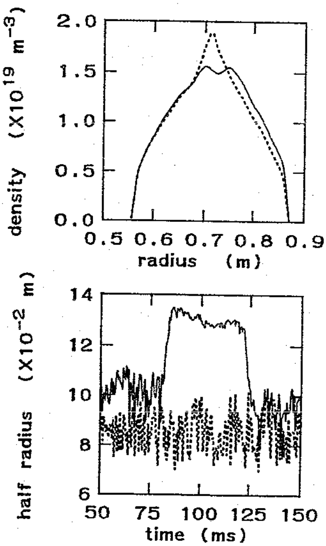

Fig. 3.
a. The density profile with ECRH (full time) and without (dotted line).
b. The density halfvalue radius as a function of time.

does not change very much. In Fig. 4c one can notice that the density halfvalue radius is increased immediately after switch-on of the ECRH, as explained in Section 3, but does not change very much during current ramp.

For these discharges the $T_e(R)$-evolution measured by superheterodyne e.c.e. was available. In Fig. 5, the $p_e(R)$-profiles calculated from measured $n_e(R)$ and $T_e(R)$ are shown for the case of a ramped-up current. The central 2 cm part is omitted since this falls into the EC-deposition profile, which presumably breaks the K-T model validity. Outside this radius the $p_e(r)$ follows the j(r)-profile: immediately after switch-on of the ECRH the pressure increases dramatically (curve 2) over the ohmic case (curve 1). After the current ramp-up (curve 3) the whole $p_e(r)$-profile appears to be lifted with a constant amount. The latter means a larger relative increase at the edge than in the centre as expected from the K-T model.

6. Conclusions.

All experimental observations made in RTP so far are in agreement with the K-T model even in transient situations where skin effects break the proportionality of $j \propto T^{3/2}$. The observed profile consistency, therefore, seems to be related to j- and p-profiles more than to a particular dependence of the transport coefficients on n and T. The density profile appears to be the quantity which adjust to maintain $p \propto j$.

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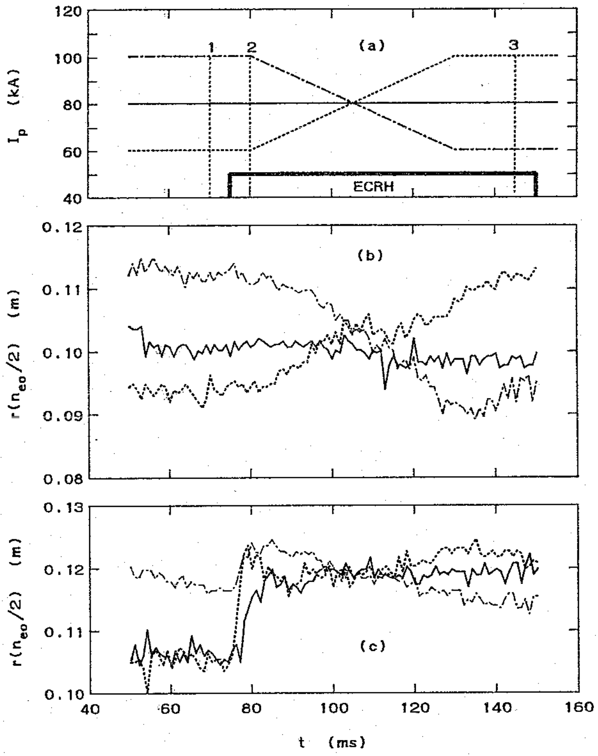

Fig. 4.
a. The plasma current ramps used with and without ECRH;
the vertical lines are referring to the pressure profiles of Fig. 5.
b. The resulting n_e halfvalue radii for ohmic discharges as a function of time. Line indicators are the same as in 4a.
c. As 4b with 180 kW ECRH.

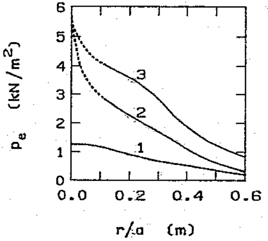

Fig. 5.
The electron pressure profiles obtained from multichannel e.c.e. and interferometry for the 3 time-points indicated in Fig. 4a.

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