THE POWER DEPENDENCE OF τ_E IN THE H-MODE OF ASDEX

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INTRODUCTION: The global energy confinement time τ_E of H-mode plasmas is found in ASDEX to be power independent for hydrogen injection into deuterium plasmas / 1 /. DIII-D reports the same behaviour for deuterium injection into deuterium plasmas / 2 /. These findings are contrary to those from JET / 3 / and JFT-2M / 4 /, where degradation of τ_E in the H-mode is observed as in the L-mode. This causes great uncertainty in predicting H-mode confinement of next - generation tokamak experiments. In this paper we try to analyze the power dependence of τ_E in the quiescent H-mode, H*, in comparison with regular H-mode results. The H*-mode may display the intrinsic H-mode confinement properties because ELMs do not additionally contribute to the energy losses. The power scaling studies of JET were done without ELMs, but the published results of ASDEX and DIII-D were obtained with ELMs.

POWER SCALING OF τ_E IN THE H*-MODE: Under the conditions I_p=0.32MA, B_t=2.2T power scans in the quiescent H-mode were possible in ASDEX both for H^o- and D^o- injection into deuterium plasmas in the restricted power range of $1.75 \leq P_{NI} \leq 3.5$ MW. Without ELMs an additional difficulty in the τ_E analysis arises because the H*-phase does not reach the steady state. During the beam pulse the H*-phase is terminated by a thermal quench caused by large impurity radiation which finally matches the power input (globally as well as locally in the plasma centre) and which initiates an intermediate L-phase / 5 /. The duration of the H*-phase depends on the heating power and increases from 95ms at 1.75MW to 125ms at 3.5MW. During the H*-phase the particle content increases linearly at a rate corresponding to 2-3 times the beam fuelling. The impurity radiation increases nearly exponentially. After the H*-transition, β_p increases once more owing to the improved confinement; when the impurity radiation starts to affect the energy balance, β_p rolls over and decreases already during the H*-phase.
Because of the non-steady-state conditions and the central radiation issue, the τ_E analysis was done in three steps: τ_E is evaluated according to $\tau_E^{(1)} = E / (P_{tot} - dE/dt)$ to correct for the lack of stationarity. These values allow the comparison with those from other experiments. In a second step the following relation is used:

$$\tau_E^{(2)} = \tau_E^{(1)} \bullet \left[1 - \frac{\int r \int p^{rad}(\rho)\, \rho d\rho dr}{\int r \int p^{heat}(\rho)\, \rho d\rho dr} \right]^{-1} \qquad (1)$$

Equ. (1) corrects for the radiation power emitted in the radial zone where the radiation - and heating power densities overlap. Mere edge radiation does not lead to a correction. The $\tau_E^{(2)}$ values should represent the actual transport properties of the quiescent H*-mode. There is a certain arbitrariness in the choice of $\tau_E^{(2)}$ as it is strongly varying with time. In a final step, full transport analysis (using TRANSP) is done for two H*-discharges, the one with the lowest and the one with the highest heating power, to have a further check on the data and the analysis.

Figure 1 shows the power dependence of the global confinement times $\tau_E^{(1)}$ and $\tau_E^{(2)}$ in the H*-mode, evaluated as described above in comparison with τ_E values of the regular H-mode with ELMs. As H-phases with ELMs reach steady state, τ_E is calculated in this case simply from $\tau_E = E / P_{tot}$. While the H-mode does not show any distinct power dependence (τ_E (ms) = 52.2•P (MW)$^{-0.05}$) with H^o into D^+, the quiescent H-mode does. The following power dependence is obtained for the H*- phase (based, however, on 4 data points only !): $\tau_E^{(1)}$=86•P$^{-0.45}$ for H^o into D^+ and $\tau_E^{(1)}$= 132 •P$^{-0.75}$ for D^o into D^+. The curve in Fig. 1 is the power fit to the D^o into D^+ cases; the horizontal line guides the eye to the results obtained with ELMs.

Figure 2 shows the time dependence of τ_E as obtained from the full transport analysis and of $\tau_E^{(1)}$. The confinement times are plotted from the OH-phase into the L- and finally into the H*-phase. The results are shown for the extreme power cases. The τ_E values in Fig. 2 are obtained taking into account the radiation losses and correspond to $\tau_E^{(2)}$ as obtained from equ.(1) / 5 /.

In summary we also find in ASDEX a power dependence of τ_E in the quiescent H*-mode as in JET. As such a dependence is not observed in the regular H-mode, it can be speculated that τ_E in this case is predominantly determined by the energy losses caused by ELMs superimposed on the heat transport losses so that the overall confinement time is power-independent. We shall try to analyze this possibility in the following.

THE EFFECT OF ELMs ON THE GLOBAL CONFINEMENT: As ELMs are an external mode, the global confinement is affected. Figure 3 shows a discharge where quiescent phases follow those with ELMs. As soon as ELMs set in, the particle and energy contents decrease. It is difficult to assess the energy losses per ELM. From the changes in slope of the βp trace in Fig. 3 we conclude that τ_E^{ELM} (representing the ELM losses) is about 110 ms.

The energy lost at an ELM can be determined in three ways: $\Delta\beta_p$ can be measured direct by using the equilibrium coils, which are placed within the vacuum vessel and which have sufficient time response. Typically 5 % of the energy content is lost by an ELM. Another possibility is to determine the energy loss via the effect of an ELM on the plasma profiles. For n_e and T_e continuous measurement is possible. An ELM affects both n_e and T_e from the plasma edge to about r = 15 cm. The relative amplitude increases with radius for n_e and T_e in about the same way with $\Delta n_e / n_e \approx \Delta T_e / T_e \approx 10\%$ at r=30cm. On the assumption that the T_i profile is affected in the same way by an ELM, we can integrate the energy loss and conclude that about 8 % of the energy is lost. A final possibility to evaluate the energy loss of an ELM is by measuring the power flux into the divertor chamber onto the target plate. This measurement is rather inaccurate and can only serve as a consistency check. Typically an ELM leads to power deposition at the target plate with a peak power density of about 1 kW/cm^2 and a width of about 4 cm. The duration of increased energy loss during an ELM is approximately 0.4 ms; the energy loss is assessed to

about 10 kJ in rough agreement with the other estimates. The particle loss per ELM is typically $1 \cdot 10^{19}$ corresponding to $\Delta N_e / N_e \approx 5\%$.
The repetition time of ELMs depends somewhat on the heating power. At low power ELMs appear erratically and the ELM period fluctuates. At high power, ELMs appear in a more regular form and the repetition time becomes constant at about 6 ms. It was not possible to determine the amplitude distribution of the ELMs. The low-power, high-frequency ELMs are clearly smaller in amplitude. Assuming a constant ELM amplitude of $\Delta E / E$ of 6% and a repetition time t_{ELM} = 6 ms and superimposing these losses onto the transport losses (see Fig.1) we can calculate the power dependence of the global confinement time: $\tau_E^{-1} = \tau_E^{(2)-1} + \Delta E / E \cdot t_{ELM}^{-1}$. The results calculated in this way are also plotted in Fig. 1. They roughly agree with the measured τ_E data obtained with ELMs.

SUMMARY: First the global energy confinement time is shown to decrease with power when the H-mode is operated in the quiescent H-phase as in JET . This conclusion is drawn, however, from a rather weak experimental basis because of our limitations in operating the H-mode without ELMs . It is shown that the lack of power dependence in the regular H-mode with ELMs could be due to the power-dependent microscopic transport losses being superimposed on those caused by ELMs.
The ratio between τ_E in the quiescent H-mode of ASDEX and JET (both with D^o -> D^+) is about 20, which is a factor of 2 more than the ratio of the currents, indicating an additional size scaling given approximately by the major radius.

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FIGURE CAPTIONS:

FIG.1 Global energy confinement time in the quiescent (H*) and the regular (H) H-mode with ELMs versus heating power. The curve is a power fit to the D^o -> D^+ case, the horizontal line guides the eye to the H-cases with H^o -> D^+. The circles are calculated from the H^o -> D^+ τ_E values with the radiation correction.

FIG.2 Energy confinement time (τ_E) and replacement time ($\tau_E^{(2)}$) of two H* discharges with different heating powers, as obtained from TRANSP.

FIG.3 Line - density n_e, divertor H_α radiation and β_{pol} for a discharge with intermittent quiescent and ELM - active phases.

Fig. 1

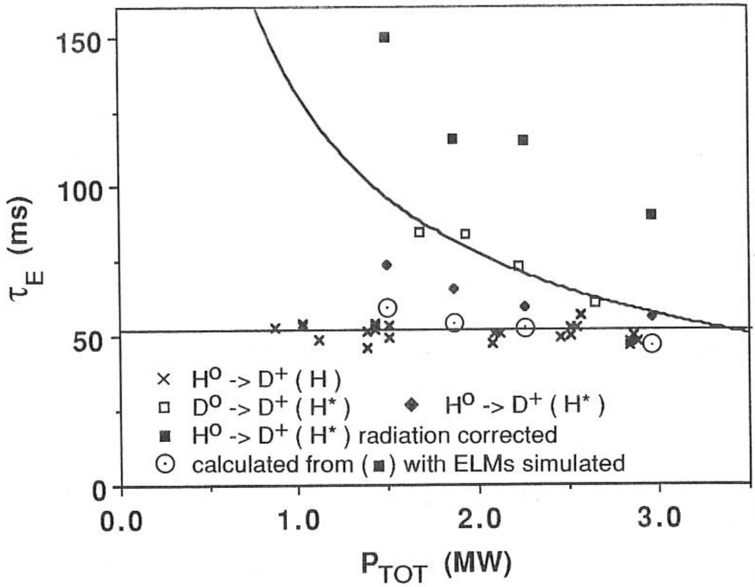
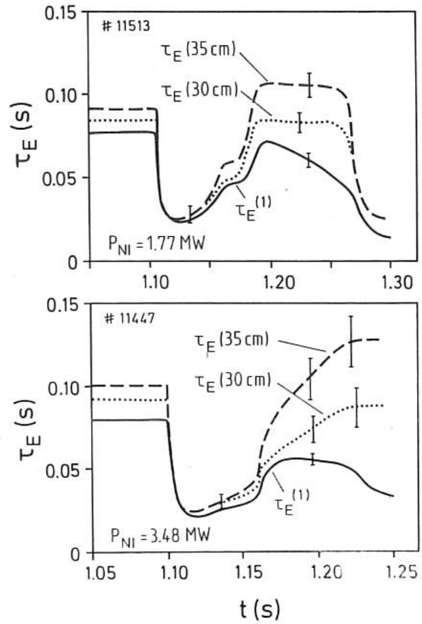


Fig. 2



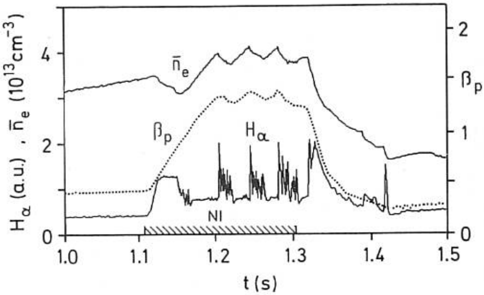


Fig. 3