THE TRANSIENT BEHAVIOUR OF THE BETA LIMIT IN ASDEX

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Introduction

In a previous paper /1/ it was shown that the ß limit in ASDEX follows a law $\beta_{max} = C \cdot I/(a \cdot B)$ (%,MA,m,T) with $C \simeq 3.5$ for β^{equ} (ß from equilibrium measurements) and $C \simeq 2.8$ for β^{dia} (ß from a diamagnetic loop), in agreement with theoretical predictions /2/. It was also pointed out that ß - at constant neutral beam power - cannot be kept at that maximum value but decreases to a lower value. It was speculated that this decay in ß corresponds to a resistive adjustment of the current density distribution to the less favourable broad H-mode temperature profiles.

In the following we discuss this transient behaviour of the ß limit and show that in ASDEX H-discharges the stationary ß limit (for β^{dia}) lies about 20 - 30 % below the maximum value.

Qualitative description of a ß limit discharge

Although important aspects of the ß limit are still not understood, we have by now at least a good qualitative picture of an H-discharge close to the ß limit. Not surprisingly, this behaviour is closely connected to the transport and profile developments characteristic of the H-phase.

We discuss the main phases of an H-mode ß limit discharge with the aid of Fig. 1, which shows $\beta_p{}^{dia}$ and D_α signals together with $\dot{B}$ data from 7 outer and one inner Mirnov coils (1a) and radial profiles of electron pressure $n_e \cdot T_e$ obtained from a recently commissioned 60 Hz Nd-YAG laser scattering diagnostic (1b):

During the L-phase, which is relatively long in this particular shot, the pressure profile peaks. The $\dot{B}$ signals first show a continuous and then a bursting mode with mode numbers $n = 1$, $m = 3$ and a frequency rising from 28 to 43 kHz /3/.

At $t = 1.27$ s the L/H-transition occurs and the MHD modes stop (probably due to q(o) becoming larger than 1). The most distinctive feature at the H-transition is an instantaneous steepening of the pressure profile at the plasma edge leading to a "pedestal" in the profile (Fig. 1b). This confirms our previous findings /5/ that the H-mode is an edge phenomenon which, as a

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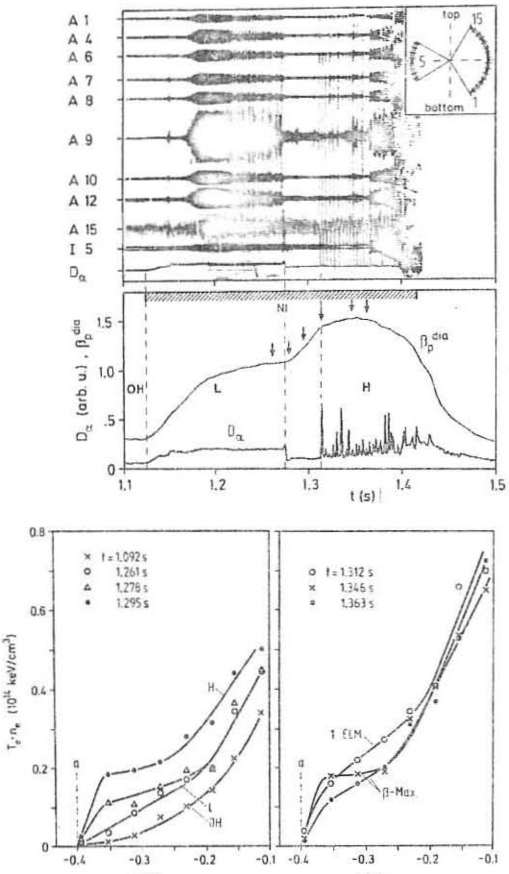

Fig. 1: $\dot{B}$ (from 7 outer and 1 inner Mirnov coils), β_p^{dia} and D_α signals (Fig. 1a) together with profiles of electron pressure $T_e \cdot n_e$ at characteristic times (Fig. 1b) of an H-mode β limit discharge (I = 310 kA, $\bar{n}_e = 3.4 \times 10^{13}\ cm^{-3}$, P_{NI} = 3.5 MW).

result of high edge T_e and strong shear in the separatrix vicinity, suppresses the anomalous transport prevailing in this region. The resulting pressure gradient, assuming $T_e = T_i$, corresponds, to a very good approximation, to the theoretical limit for ballooning modes /4/

$$-\frac{dp}{dr} \leq 0.3 \frac{B^2 r}{\mu_o R q^3} \frac{dq}{dr} \quad \text{yielding} \quad -\frac{dp}{dr}\bigg|_{r=a} \leq 0.6 \frac{B^2}{\mu_o R q_a{}^2} \quad \text{for } q = q_a \left(\frac{r}{a}\right)^2.$$

After the H-transition, with its formation of a transport barrier at the plasma edge, the plasma energy rises again by increasing the pressure in the plasma interior. As the pressure gradients there approach the ballooning limit (possibly even only locally), the outflux of energy increases. Since the pressure gradient at the plasma edge is already at its marginal stability limit, the edge layer becomes unstable, expelling particles and energy from the plasma periphery (so-called edge localized modes, ELM's

/1/). Such a situation is reached in shot 15520 at t = 1.31 s, when the first and largest ELM occurs and the rate of increase of β is substantially reduced. This picture also explains the absence of ELM's in the burst-free H-discharges described in /1/: The large radiation losses (from iron) encountered in these discharges (which were produced rather close to the SS limiters) transport enough energy out of the plasma in a non-conductive way that the ballooning limit is not exceeded.

Since the critical β for ballooning modes is highest for peaked current density distributions, whereas the H-mode is characterized by flat T_e and conductivity profiles, it is reasonable to assume that the <u>maximum β-value</u> during a β limit discharge corresponds to relatively peaked profiles frozen in from the OH and L-phases and that the observed slow <u>decay in β</u> (20 % in 200 ms, c.f. Fig. 2) reflects the resistive adjustment to the H-mode profiles. There are, however, strong indications (changes in the plasma inductance, loop voltage) that during the high-β phase additional currents in the plasma centre (which are compensated by induced currents) lead to an enhanced peaking of the current density distribution capable of relaxing on a much shorter time scale, thus explaining the first, much faster β-decay (in 20-50 ms) observed at high power input (c.f. Fig. 2d,e). These transient currents seem to be connected with neutral injection (positive effect only with co-injection, larger effect for D^o than for H^o-injection), and could be produced partly by the circulating fast ions, but to a larger extent by the beam induced plasma rotation. The increasing β might also lead to such currents. The decrease in β is accompanied by increased MHD activity and later by a growing m = 2, n = 1 tearing mode with f = 16.3 $\rightarrow$ 10 kHz /3/ (Fig. 1a).

Transient and stationary beta limit

To compare discharges with different parameters we normalize with $\beta_{max} = 2.8 \cdot I/(a \cdot B)$ (Troyon limit). This also defines the maximum energy content for a tokamak plasma (with elongation b/a) $W_{max} = 0.33\, b \cdot R \cdot B \cdot I$.

Figure 2 shows maximum normalized β-values β/β_{max} and corresponding plasma energies W obtained in a B-scan at constant beam power P_{NI} = 3.5 MW and for two plasma currents I = 311 and 370 kA. The observed linear increase of β/β_{max} with P/B for $\beta/\beta_{max} < 1$ reflects the fact that for a given heating power $P = P_{OH} + P_{NI,abs}$ (and assuming $\tau_E = f \cdot I$)

$$\beta/\beta_{max} \sim \frac{f\ P}{b\ R\ B}$$

holds /1/ (independent of I, as also found experimentally). At large enough heating power P/B the β-limit can clearly be seen.

As shown by the β_p^{dia} and D_α signals of Fig. 2a-f there is a clear correlation between the maximum normalized β values β/β_{max}, the time behaviour of the β-decay (accompanied by a characteristic feature of the D_α spikes) and the level to which β decays: Starting at low power input P/B (Fig. 2a), we have $\beta/\beta_{max} \simeq 0.7$ resulting in an <u>H-phase with no ELM's</u>. With increasing relative power (Fig. 2b), the maximum β is almost constant yielding a <u>stationary β limit $\beta_{stat} = 0.8 \cdot \beta_{max}$</u>. Increasing P/B still further (Figs. 2c-f) leads to $\beta/\beta_{max} \simeq 1.0$, followed by first a continuous and then, for higher P/B, a two-phase β-decay resulting in lower stationary β values than case 2b. At high power a disruption sets in, at first during the β decay (Fig.2 e), but then moving forward in time with increasing P/B (Fig. 2f), until it finally occurs already during the β rise (disruptive β limit; not shown here). Thus it seems that in ASDEX H-discharges, the stationary ß limit depends on an exact tailoring of the power input to the diffusive and resistive time scales.

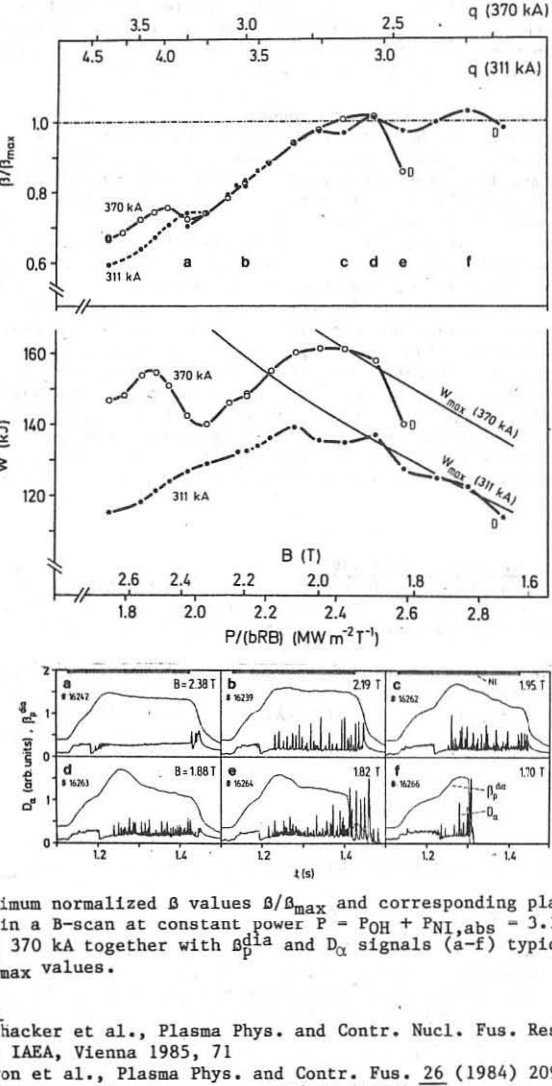

Fig. 2: Maximum normalized ß values β/β_{max} and corresponding plasma energies W obtained in a B-scan at constant power $P = P_{OH} + P_{NI,abs} = 3.15$ MW for I = 311 and 370 kA together with β_p^{dia} and D_α signals (a-f) typical of certain β/β_{max} values.

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