THE INFLUENCE OF THE CURRENT DISTRIBUTION ON THE ACHIEVABLE β-VALUES IN ASDEX

G. v. Gierke and G. Becker, H. S. Bosch, H. Brocken, K. Büchl, A. Eberhagen, D. Eckhartt, G. Fussmann, O. Gehre, J. Gernhardt, E. Glock, O. Gruber, G. Haas, J. Hofmann, A. Izvozchikov[1], G. Janeschitz, F. Karger, M. Kaufmann, M. Keilhacker[2], O. Klüber, M. Kornherr, K. Lackner, R.S. Lang, M. Lenoci, F. Leuterer, G. Lisitano, F. Mast, H. M. Mayer, K. McCormick, D. Meisel, V. Mertens, E. R. Müller[2], H. Murmann, H. Niedermeyer, J.-M. Noterdaeme, A. Pietrzyk[3], W. Poschenrieder, H. Rapp, H. Riedler, H. Röhr, J. Roth, F. Ryter[4], W. Sandmann, F.Schneider, C. Setzensack, G.Siller, P.Smeulders[2], F.X. Söldner, E. Speth, K.Steinmetz, K.-H. Steuer, F. Wagner, F. Wesner, G. Vlases[3], O. Vollmer, D. Zasche

Max-Planck-Institut für Plasmaphysik
EURATOM Association, D-8046 Garching

Introduction:

In the divertor tokamak ASDEX we get in the H-regime a clear β-limit /1/ at

$$\beta_{cr} = 2.8 \frac{I}{a\ B} \ \% \ [\mathrm{MA,m,T}] \qquad (1)$$

if we use for the volume averaged β the β-value measured by the diamagnetic loop. Below the β-limit the highest β-value during a shot, β_{max}, is proportional to the normalized power

$$P_N = \frac{P}{0.33 \cdot b \cdot R \cdot B} \qquad (2)$$

where P[MW] is the total heating power, 2b the vertical diameter and B the magnetic field on axis. The confinement time at β_{max} is proportional to the plasma current I. The proportionality factor depends mainly on the isotope composition and slightly on current, impurity and other parameters not yet unraveled. The confinement time at β_{max} is $I_p/4 > \tau_E > I_p/7$, where the limits are for deuterium and hydrogen respectively. After β_{max} β always decays to values about or even below $0.7 - 0.8\ \beta_{cr}$. At this level nearly time independent β-values could be observed. The β-decay is usually the faster, the closer β_{max} is to β_{cr}. There is no qualitative difference in any signal between discharges with $\beta_{max} = \beta_{cr}$ or $\beta_{max} < \beta_{cr}$.

After excluding all trivial reasons, like wall contact, radiation due to impurity accumulation etc, the only thinkable parameter which could change with time and would cause the observed β decay is the current distribution. But only the longest observed decay times are in agreement with resistive current diffusion (calculated with classical resistivity throughout this paper). We hesitated for a long time to assume faster current redistributions then those.

In the numerical calculations, which result in a similar β-limit as observed experimentally the limit seems to be caused by a combination of ballooning modes and surface kinks /2/. In a divertor tokamak the behaviour of surface kinks are unclear due to the unknown influence of the strong shear near the separatrix. In ASDEX the influence of the separatrix is very concentrated and therefore the influence should be restricted to higher n-modes. As we

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[1] Academy of Sciences, Leningrad, USSR; [2] Present address: JET Joint Undertaking, England; [3] Univ. of Washington, Seattle, USA; [4] CEN Grenoble, France

observe no pronounced changes with varying q-values we assume tentatively that the ballooning mode is responsible mainly for the observed limit.

The influence of the current distribution

We therefore have calculated the influence of the current distribution on the ballooning mode stability limit using the inner inductivity l_i as a measure. We used the ballooning mode criterium

$$\frac{dp}{dr} = - \frac{B^2}{2\ R\ q^2} \cdot \alpha(s) \qquad s = (\frac{r}{q}) \frac{dq}{dr}$$

and the approximation $\alpha(s) = s/1.67$ /3/, but we neglected the usual condition $q_o = 1$. We assume that the ballooning mode criterium is marginal all over the cross-section.
Figure 1 shows the resulting dependence of $\beta/\varepsilon\ q^2$ on l_i for several families of current distributions as shown by the inserts ($\varepsilon = a/R$). We see the expected strong dependence of β on l_i, but the surprising result is that β depends nearly completely on the global l_i value and only marginally on the actual shape of the current distribution. We conclude that l_i is a very sensitive parameter for the description of the volume averaged β resp. the global confinement time.
The dependence found in fig. 1 can be described by the approximation:

$$\frac{\beta}{\varepsilon} = \frac{1}{q^2} (19\ l_i^{\ 2} + 44.5\ l_i - 27). \tag{3}$$

Comparing this formula with experimental l_i-values, evaluated as described later, we find that the general behaviour of the β-decay can be described, but that the calculated β-values are larger by 20 - 100 % depending on the q-value. Inserting the empirical law (1), found experimentally and numerically, for the β limit, transformed to $\beta_{cr}/\varepsilon = 14/q$ one finds that unreasonably small l_i-values belong to this β-limit especially at higher q-values. This is not surprising, because all the theoretical calculations have been done in the cylindrical large aspect ratio approximation. We therefore assume as a correction that the q in eq. (3) is not the cylindrical q but q_ψ . Figure 2 shows now the β/ε dependence on l_i with different q_ψ as parameter. The β-limit $\beta/\varepsilon = 14/q$ and q_{cyl}-curves are also shown. They have been calculated assuming a purely thermal β_p in the calculation of q_ψ, neglecting contributions by the beam or rotation.

By the measured $\beta(\beta_p^{dia})$ and the measured q_ψ a point in fig. 2 is defined and with it the corresponding l_i. q_ψ is evaluated from β_p^{equ} by

$$q \ = q_c\ [1 + \varepsilon^2 (1 + 0.5\ (\beta_p^{equ})^2]\ \text{with}\ q_c = \frac{5 a \cdot b \cdot B}{R \cdot I}$$

taking into account the empirically found dependence of a on β_p^{equ}:
$a = 0.375\ (1 + 0.07\ \beta_p^{equ})$ but limited to $a \leq 0.44$ m, due to our vessel dimensions, which was found roughly in agreement with equilibrium calculations, (quoted q_c values are always with $a = 0.4$ m).

In fig. 2 data points are shown measured in the described way of a power scan at 379 kA and $q_c = 2.79$, H^o injection (1.8-3.5 MW), where the crosses are values at β_{max} and the points intermediate β values during the β decay or the β values on the end of the heating pulses. Supplemented is this scan by shots at 311 kA, at q-values of 2.805, 2.71, and 2.85. The slightly stronger bent of the experimental curves compared with the calculated q_c = const. curves is due to the nonthermal contributions of the beam and the rotation to β_p^{equ} and by it to q_ψ and by the increasing diameter. As we shall see later the resulting l_i values agree quite well with l_i values evaluated

in quite another way beside the lowest point shown, an L-shot, where we, however, do not expect that the ballooning criterium is fulfilled all over the radius.
In fig. 3 we show q-scans at otherwise constant parameters (311 kA, 3.5 MW H_o-injection). The achieved l_i values (and consequently the β values) are limited to values <1.5. With D_o injection (4.05 MW) otherwise the same parameters very high l_i values result and the β-limit can be reached also at larger q_c values.

To compare the found l_i values we evaluate l_i out of the difference signal

$$\beta_p^{equ} - \beta_p^{dia} = \frac{l_i}{2} + \frac{\beta}{2}_{\parallel nontherm.}$$

neglecting $\beta_{\perp nonth.}$ $\beta_{\parallel nonth.}$ is estimated from the injected beam, the slowing down time and an expression for the rotation, which is proportional to the energy confinement time. The absolute value of $\beta_{\parallel nonth.}$ is adjusted so that for long lasting shots where the difference signals approach a constant value, the so evaluated l_i value approaches the l_i value calculated out of the electron temperature profile. Time dependence of l_i, evaluated in this manner are shown in fig. 4. The crosses are the l_i values according to our modified ballooning criterum. The agreement is nearly in all cases satisfying in spite of the many inaccuracies involved and the difficulty of the absolute calibration. With deuterium injection the agreement can't be reached with constant proportionality factors in every case as the nonthermal contributions (probably the rotation) seems to depend nonlinearily on the beam parameters and the confinement. But the very large l_i-values and their decay are found.

Summary and discussion

We conclude that in the H-regime the ballooning mode is limiting the energy content of the discharge at β_{max} and afterwards always and already at very low β-values. The β-limit $\beta/\varepsilon = 14/q$ can only be reached by favorable combinations of l_i and q_ψ. At large q values l_i must be larger than in the ohmic cases, which can only be reached transiently by inductive currents, for which we have some experimental hints. These currents are due to the injected beam, the plasma rotation and the β_p-changes. The β-decay after β_{max} is due to the disappearance of these inductive currents and the approach to the stationary current profile defined by the conductivity profile. As a change of β_p and the rotation induce changes of the confinement by altering the ballooning limitation, an increase as well as a decrease has a self-inforcing effect. Therefore high β values decay faster and to values well below limits achieved with smaller power.

The β-limit itself, but also the ballooning limited profiles below of it, are influenced by rational q_ψ-values (fig.5). This coupling of the ballooning mode with surface kinks seems to favour the current redistribution. But much finer scans are necessary to prove this convincingly as higher rational values are involved, too, and the self-inforcing effect mask the rationals.

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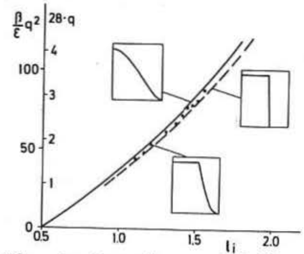


Fig. 1: Dependence of ballooning mode limited $\langle \beta_T \rangle$ on the internal inductance li for different current distributions. The second scale gives the $q_o > 1$ limit for different q.

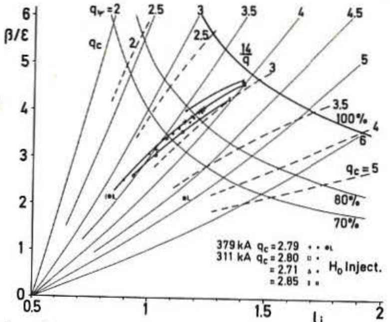
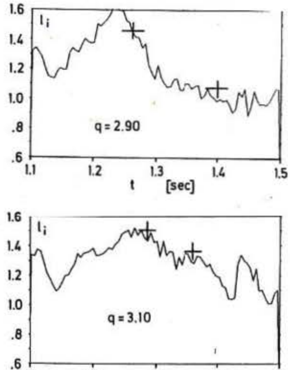
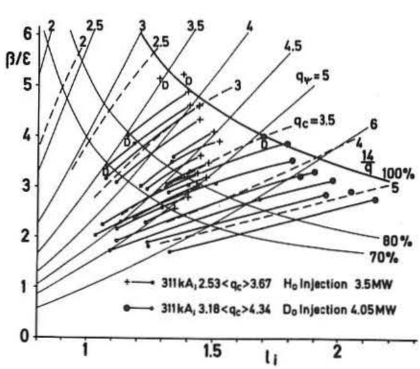


Fig. 2:
β_T dependence on li, if q_ψ instead of q_c is the important parameter in the formula derived in Fig. 1. Shown are experimental points of a power scan (q_c = const) and shots with neighbouring q_c ($+\beta_{max}$, $\cdot\beta$ at the end of the heating pulse).



Figs. 4: Time dependence of li evaluated from the difference of $\beta_p^{equ} - \beta_p^{dia}$ and an estimated beam contribution. The crosses are li-values calculated with the modified ballooning criterion.

Fig. 3: The same as Fig. 2 but q_c-scans at constant current.



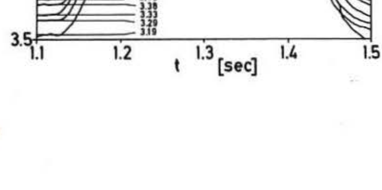


Fig. 5:
q_ψ-values calculated with β_p^{equ} showing the influence of rational q_ψ-values.