INVESTIGATIONS INTO THE DENSITY LIMIT OF THE TOKAMAK WITH OHMIC AND NEUTRAL BEAM HEATING

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Introduction: In /1/ we showed that in ASDEX the disruption at the density limit in an Ohmic discharge at $q = 4.2$ ($q = 2\pi B_T a^2/\mu_0 I_p R$) is preceded by the poloidally asymmetric formation of a cold high density plasma near the boundary ("marfe" /2/) and a shrinking of the current profile. In order to get an improved data base for an empirical density limit scaling and more insight into the phenomena involved we now extended our investigations to discharges in a large parameter range including neutral beam heating. Results from discharges with continuous pellet injection are reported in /3/.

The experimental method: After non-gettered divertor discharges had reached a current plateau and quasi-stationary conditions with sawtooth activity, the line averaged electron density was slowly increased by controlled gas puffing until a disruption was detected. When desired, neutral beam injection started simultaneously with the density increase. With injection, slow density ramp up was made possible by extending the heating pulses in time at the cost of power by firing our two beamlines one after the other. The reduced maximum beam power of 1.7 MW permits only L-type discharges.

Parameter scaling: Figure 1 shows Hugill-diagrams /4/ for Ohmically and beam heated discharges in hydrogen with a toroidal magnetic field B_T of 1.9 T (left) and various B_T-values between 1.3 T and 2.5 T (right). The data points represent peak values of $\bar{n}$ (electron density averaged along a horizontal chord in the midplane). Ohmic data show the well known linear dependence $\bar{n} \sim 1/q \sim I_p$ for high q-values and the bending off at q-values below about 3. Discharges with beam heating reach an appreciably higher $\bar{n}$ for all q-values.

While at the density limit $\bar{n}/B_T$ is fairly independent of B_T and only a function of q in the Ohmic case, we see in Fig. 1, that the maximum density reached in beam heated discharges is a more complicated function of B_T. At least at this power level $\bar{n}$ is also a function of the beam power.

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$\bar{n}\,R/B_T$ obviously being no scaling parameter for beam heated discharges we plot the maximum density as a function of the variables I_p and B_T (Fig. 2). We see again that $\bar{n}$ is proportional to I_p in Ohmic discharges for $q > 3$. The maximum of all the curves corresponds to $q = 2.7$. For beam heated discharges we still have an explicit variation of the density limit with I_p. A function proportional to the square root of I_p fits well all data points from discharges with $q > 3$.
In both cases the total heating power varies with the plasma current. The heating power shortly before the disruption varies roughly with the square root of I_p in Ohmic discharges, in beam heated discharges P_{OH} is only a small fraction of the total power, so that despite of a variation of P_{OH} with I_p the total power is constant within 10 % at fixed beam power. The few data available for different beam powers are compatible with $\bar{n} \sim P^{\alpha}$, $\alpha = 0.3 \ldots 0.4$. This scaling applied to Ohmic discharges together with an assumed "intrinsic" I_p-scaling is too weak to explain the linear I_p scaling observed. If we assume a universal scaling law to be valid for all heating methods we have to postulate a more complicated power dependence.

Phenomena observed before the disruption: As one might already presume from the strong bend in the density limit curves we have to distinguish between low q and high q discharges, the boundary q value being about 2.7 in ASDEX. Typical signal traces from q=2.2 and q=4.7 discharges with Ohmic and beam heating are plotted in Fig. 3.

The Ohmic high-q discharge shows all signs of a growing marfe and shrinking current channel as described in /1/: increase of U_L and l_i, strong increase of radiation from low ionization states of low-Z impurities (CIII), reduced divertor loading (H_{α}!). The difference between the interferometer signals at half radius above and below midplane shows that the "marfe" is located below the midplane. This is also confirmed by space resolved bolometer measurements (not shown). Poloidally asymmetric radiation sources are not measured correctly by the bolometers. Nevertheless we can state that the power radiated from the marfe is substantial. Strongly growing MHD activity (probably $m = 2$, localized at the $q=2$ surface) sets in about 15 - 20 ms before the disruption.

With beam heating we observe the signs of a marfe mentioned above already at rather low densities. (See also shaded areas in Fig. 1). l_i measurements do not clearly indicate a shrinking of the current profile, but Thomson scattering measurements show a peaking of the T_e and n_e profiles well before the disruption. The power radiated from the marfe seems to be higher than in the Ohmic case but small compared to the total power. About 50 ms before the disruption the lower edge channels of the bolometer array (which see the region of the lower stagnation point) detect a strong increase of the radiation. This might indicate a stronger marfe or a dramatic change of the scrape-off plasma at the divertor entrance. We do, however, not observe a drop of the neutral gas density in the divertor chamber. The onset of MHD-activity is similar to the Ohmic case.

The behaviour of low q-discharges with Ohmic or NB-heating is completely different before the disruption compared to the high-q case: Nothing indicates a thermal instability at the plasma edge. Thomson scattering shows also in this case that T_e decreases all over the cross section when $\bar{n}$ is being increased, but there is no sign of a slow current shrinking. It seems that in low q-discharges an MHD instability not being triggered by a thermal instability leads to the disruption. Discharges at very low q-values do not even show the strongly increasing oscillations indicating rotating modes: the plasma simply disrupts.

Spurious density limits: In a few discharges, especially in deuterium one observes completely different phenomena leading to a density limit at lower values than given by the scaling described above.

Ohmic discharges in D_2 at low I_p showed an increase of the radiation from the plasma centre with increasing $\bar{n}$, then a stop of the sawtooth activity and finally a disruption at a rather low $\bar{n}$ value. Thomson scattering confirmed the radiational collapse from the centre: T_e-profiles flattened at the plasma centre or became even indented the outer part of the profiles staying unperturbed. The flat area expanded until it reached about half the plasma radius, then the discharge disrupted. This effect results from the higher content of metal impurities in D_2-discharges.

Other (beam-heated) discharges showed some kind of "density clamping" obviously caused by an increased mode activity. By strongly increased gas puffing it was possible to further increase $\bar{n}$, but we cannot exclude that the density limit would be higher, if we were able to avoid these modes.

We believe that limits of this kind can be overcome by improved discharge scenarios, wall conditioning or other choice of wall materials and excluded them from further discussions.

Conclusion: The increase of $\bar{n}$ beyond the density limit is finally prevented by MHD phenomena, probably an instability arising at the q=2 surface. But all our observations indicate that this is related to the power balance.

In high q-discharges the q=2 surface considered to be most sensitive is so distant to the boundary that it is not directly affected by the power losses at the edge. With increasing losses edge cooling does not simply flatten gradients at the edge, but leads to a thermal instability which causes a shrinking of the current channel and finally an MHD unstable situation.

In low-q discharges the q=2 surface is very close to the boundary. The zone of strong volume losses (ionization, charge exchange losses, low-Z radiation) overlaps with it. The discharge becomes MHD unstable before the boundary becomes thermally unstable.

A theoretical treatment of the problem suffers from the poor knowledge of particle transport. A simple model leads to the conclusion that the power lost only by refuelling is proportional to $D \cdot n^2$, D being the particle diffusion coefficient. Assuming a proper functional dependence of D on n, I_p, B_T and P we can explain any empirical density limit scaling by thermal effects. An increase of D with power would explain the weak increase of the density limit with power. Vice versa we might deduce the functional dependence of D from empirical density limit scaling laws.

References

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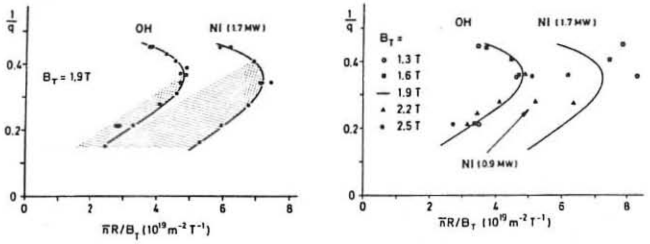

Fig. 1: Hugill diagrams for B_T = 1.9 T (left) and various B_T-values. Shaded area: appearance of marfes.

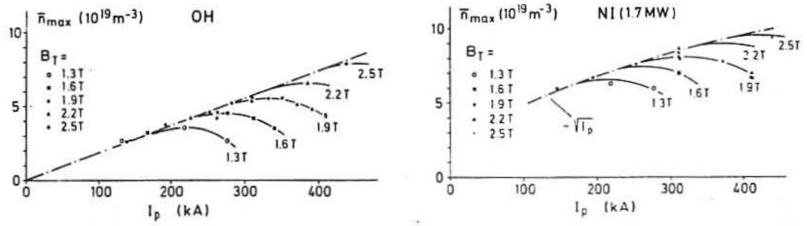

Fig. 2: Density limit as a function of I_p and B_T for Ohmic (left) and neutral beam heated discharges (right)

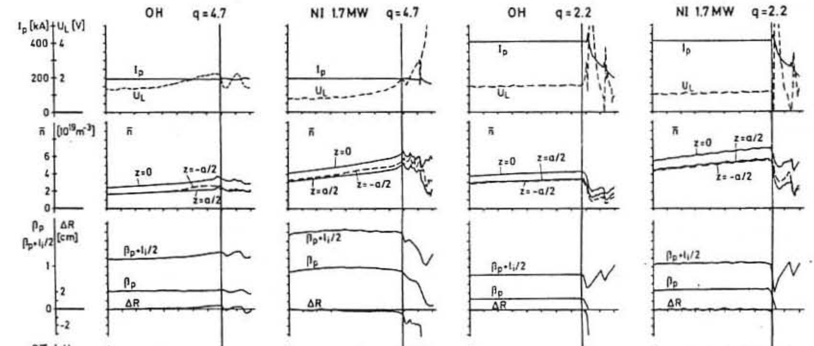

Fig. 3: Characteristic behaviour of different types of discharges in a short period before the density limit disruption (marked by vertical lines)