DENSITY LIMIT IN ASDEX DISCHARGES WITH PEAKED DENSITY PROFILES

A. Stäbler, H. Niedermeyer, R. Loch, V. Mertens, E. R. Müller, F. X. Söldner,
F. Wagner and the ASDEX-, NI- and Pellet-Teams

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

1. INTRODUCTION

Results concerning the density limit in OH and NI-heated ASDEX discharges with the usually observed broad density profiles have been reported earlier /1,2/: In ohmic discharges with high q_a (q-cylindrical is used throughout this paper) the Murakami parameter ($\overline{n}_eR/B_t$) is a good scaling parameter. At the high densities edge cooling is observed causing the plasma to shrink until an m=2-instability terminates the discharge. When approaching q_a=2 the density limit is no longer proportional to I_p; a minimum exists in $\overline{n}_{e,max}(q_a)$ at $q_a \approx 2.15$. With NI-heating the density limit increases less than proportional to the heating power; the behaviour during the pre-disruptive phase is rather similar to the one of OH discharges.

There are specific operating regimes on ASDEX leading to discharges with strongly peaked density profiles: the improved ohmic confinement regime /3/, counter neutral injection /4/, and multipellet injection /5/. These regimes are characterized by enhanced energy and particle confinement. The operational limit in density for these discharges is, therefore, of great interest having furthermore in mind that high central densities are favourable in achieving high fusion yields. In addition, further insight into the mechanisms of the density limit observed in tokamaks may be obtained by comparing plasmas with rather different density profiles at their maximum attainable densities.

2. CO AND COUNTER NEUTRAL INJECTION INTO GAS FUELLED DISCHARGES

A series of experiments to compare the density limits of co- and ctr-NI heated plasmas have been performed on the same day ($H^0 \rightarrow D^+$, P_{NI}=1.3 MW, B_t=1.86 T, I_p=320-460 kA). By feedback controlled gas puffing the density was steeply ramped up to values slightly below the density limit followed by a slow rise until the plasma disrupted. In all co- and some of the ctr-heated discharges the slow rise required a slowly increasing gas puff rate. For the remaining ctr-heated discharges (preferably those at higher I_p) the gas puff rate continuously dropped to zero during the slow density rise. These discharges show all the signs of an improved confinement with ctr-NI which usually is triggered by a reduction in gas puffing /6/: β increases considerably, the density profile continuously peaks ($Q_n = n_e(o)/\langle n_e\rangle$ rises from 1.15 to above 1.8), the central SX radiation increases with initially large sawtooth amplitudes; in the later phase sawteeth completely disappear which leads to a further steep rise of the SX signal. In contrast, those discharges requiring an increasing gas puffing show normal L-mode behaviour up to the disruptive limit with the density profiles staying broad ($Q_n \leq 1.15$).

The maximum line averaged densities obtained prior to the disruption are shown in a Hugill diagram in Fig. 1a (□: peaked ctr-NI, O: broad ctr-NI, ●: co-NI). The $\overline{n}_e$-values obtained with peaked profiles exceed the ones with broad profiles (either co- or ctr-NI) by up to about 20%. They do not show the minimum in $\overline{n}_{e,max}(q_a)$ at $q_a \approx 2.15$.

The plasma behaviour close to the disruption is quite different for the two types of discharges. The density limit shots with broad n_e-profiles are characterized by the development of a cold dense divertor plasma as shown by a decreasing C III radiation from the divertor and increasing H_α light measured close to the divertor plate. This is not observed for the discharges with peaked profiles. As already indicated by the SX signal the bolometrically measured radiation profiles develop quite differently. With co-NI the central radiation stays at a low level for the whole of the discharge, in contrast to the peaked ctr-NI case (Fig. 2) where the central radiation steeply increases, as soon as the sawteeth disappear, to values above 1 W/cm^3 exceeding the local power input of about 0.6 W/cm^3. This rise is due to central accumulation of heavy impurities /6/. Consistently, in this final phase a hollow T_e-profile develops. The discharges with peaked density profiles, therefore, are terminated by a thermal collapse in the plasma centre, not by edge cooling. This is supported also by electron temperature measurements (laser scattering) close to the plasma edge: $T_e(r=0.88{\cdot}a)$ drops during the last few 10 ms for broad profiles and stays roughly constant for the peaked profiles.

The density development close to the plasma edge is also different for the two types of discharges: for broad profiles $n_e(r=0.88{\cdot}a)$, measured by laser scattering, slowly rises in parallel to $\bar{n}_e$ whereas with peaked profiles it remains constant or even slightly decreases during the density peaking, in all cases staying below the corresponding broad profile values. Data taken just before the plasmas disrupts are shown in Fig. 1b, again in a Hugill-type presentation. The edge densities of those discharges terminated by a normal density disruption are higher by roughly 20% compared to the discharges terminated by a central thermal collapse. Fig. 1c shows the results for the maximum $n_e(o)$ values and clearly demonstrates the advantage of peaked profiles in attaining high central density values: $n_e(o)$ is enhanced by 35-65% for the peaked ctr-NI plasmas compared to the corresponding co-NI plasmas. The increase in volume-averaged density, however, is rather small; it amounts to about 5% for the low q_a-values.

The same type of behaviour was observed during another series of experiments (D^o-> D^+-plasma, 1.97 T, 420 kA) with only 300 kW (< P_{OH}) of ctr-injected beam power. By tailoring the gas puff program it was possible to switch between discharges showing the development of peaked n_e-profiles (Q_n=1.9) or staying broad ($Q_n \approx 1.3$) up to the density limit. The results of the various density values obtained are also shown in Figs. 1a, 1b and 1c (+: peaked n_e, x: broad n_e). Peaked density profiles lead to an improvement in $\bar{n}_e$ of about 25% and in $n_e(o)$ of more than 40%, whereas the edge densities (at $r=0.88{\cdot}a$) do not exceed those of the broad density profiles.

3. THE IMPROVED OHMIC CONFINEMENT REGIME

In the improved ohmic confinement regime (IOC), recently discovered on ASDEX /3/, the linear increase of confinement time with $\bar{n}_e$ is maintained up to the highest densities. It gradually develops upon reduction of the external gas puffing. Steady state discharges with sawteeth have been run at densities close to the density limit of the saturated ohmic confinement regime. By slightly increasing the gas feed under IOC conditions (at I_p=380 kA, B_t=2.2 T) $\bar{n}_e$ non-linearly increases to values above the ones obtained in a normal density limit (DL) discharge two shots later. These non-stationary IOC discharges show exactly the same type of behaviour as the peaked ctr-NI ones: the density profile further peaks to Q_n=2.1 whereas the normal density limit shot stays at $Q_n \approx 1.4$, the SX level rises, sawteeth are finally lost, and the behaviour of T_e at $r=0.88{\cdot}a$ as well as of the divertor signals prior to the disruption is as described above for the peaked ctr-NI discharges indicating that the discharges are terminated again by a central thermal collapse and not by edge cooling.

The values of $\bar{n}_e$, $n_e(r=0.88{\cdot}a)$, and $n_e(o)$ for the IOC and the corresponding density limit shots prior to the disruptions are included in Figs. 1a, b, and c (Δ: IOC, ▲: DL). The situation is equivalent to peaked ctr-NI and co-NI shots, respectively: $\bar{n}_e$ in the IOC regime increases by up to 15%, $n_e(o)$ by up to 60%, and $n_e(r=0.88{\cdot}a)$ is lower by about 20% compared to the corresponding DL shot under saturated conditions.

There exists one discharge showing all the signs of IOC behaviour but a slightly smaller increase in profile peaking ($Q_n \approx 1.95$) where the density at $r=0.88{\cdot}a$ reaches the value of the normal density limit shot. In this case T_e at the edge and all the divertor signals behave as they do in a normal density limit shot indicating that the discharge is terminated by edge cooling. This observation supports the picture that peaked n_e-profiles may be operated at higher $\bar{n}_e$-values than broad n_e-profiles as long as the density close to the edge does not exceed the one of the corresponding broad profile discharges.

4. PELLET INJECTION

Injection of pellets into a tokamak plasma is another way of obtaining improved confinement correlated with the development of peaked n_e-profiles, not only on ASDEX /5/ but also in other experiments (see references in /5/). A successful density build-up could only be obtained by providing a substantial gas flow onto the plasma boundary (e.g. by external gas puffing) leading to densities well above the normal gas puff density limit, as reported earlier /7/. In the context of this paper it is of interest how the results fit into those given for IOC and peaked ctr-NI discharges.

Compared are pairs of OH and co-NI (1.3 and 2.5 MW) shots (I_p=350-380 kA, B_t=2.2 T) running into the density limit either with gas puff only or with multipellet injection assisted by gas puffing. Corresponding shots are from the same experimental campaign. All discharges with gas puff only remain broad (Q_n=1.2-1.45) whereas in the pellet fuelled shots the density strongly peaks ($Q_n \approx 2.7$, 2.0 and 1.7; decreasing for increasing heating power). Contrary to the peaked ctr-NI and IOC discharges described above, however, the pellet discharges discussed here keep sawtoothing up to the maximum $\bar{n}_e$. They do not show any signs of significant impurity accumulation and their radiation profiles remain hollow. They, therefore, do not suffer a central thermal collapse.

The densities obtained are shown in Fig. 1a, b, and c. The strong enhancement in the Murakami parameter as well as in $n_e(o)$ for pellet fuelled discharges is obvious. Concerning the edge densities ($r=0.88 \cdot a$) there may be a tendency of a slight increase for the pellet discharges compared to their corresponding gas puff discharges but this increase is small compared to the overall gain in $\bar{n}_e$ and $n_e(o)$ and probably disappears when comparing values closer to the separatrix /5/. For these discharges the volume averaged density increases significantly as well.

5. SUMMARY AND CONCLUSIONS

Peaked density profiles in ASDEX obtained by three different operating scenarios have been shown to allow higher Murakami parameters and a significant increase in central density compared to corresponding discharges with broad density profiles. The measured densities close to the plasma edge (at $r=0.88 \cdot a$) for peaked profiles, however, are either slightly below (for some ctr-NI and IOC shots) or very similar to the ones with broad profiles. The maximum edge density obtained is depending on heating power (see Fig. 1b) but increases less than proportional with power as observed for the density limit. The termination of those discharges with a lower edge density was shown to be due to a central thermal collapse contrary to the effects of edge cooling in the other cases where substantial gas puffing is required to obtain the high densities. These results suggest that the local density close to or at the plasma edge and the rather high edge losses seen at high edge densities are the determining factors in the density limit observed in tokamaks. Discharges with peaked densities which, in ASDEX, are also correlated with an improved energy and particle confinement are, therefore, very attractive for fusion application.

REFERENCES

/1/ H. Niedermeyer et al., Proc. 12th Europ. Conf. on Contr. Fus. and Plasma Phys. (Budapest 1985), Vol. I, p. 159

/2/ H. Niedermeyer, F. Wagner et al., Proc. 11th Intern. Conf. on Plasma Phys. and Contr. Nucl. Fus. Research (Kyoto 1986), IAEA, Vienna, Vol. I (1987), p. 125

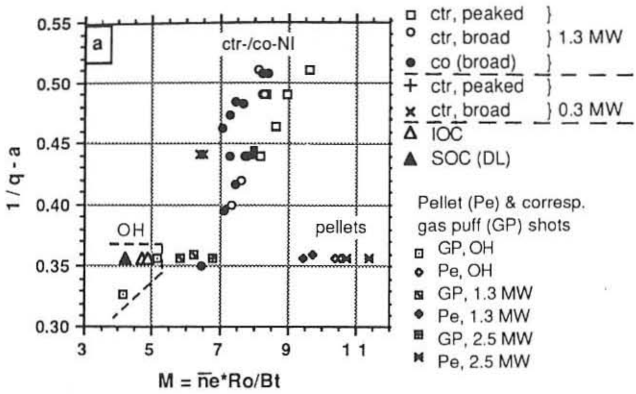
/3/ F. X. Söldner et al., Phys. Rev. Lett. 61 (1988) 1105

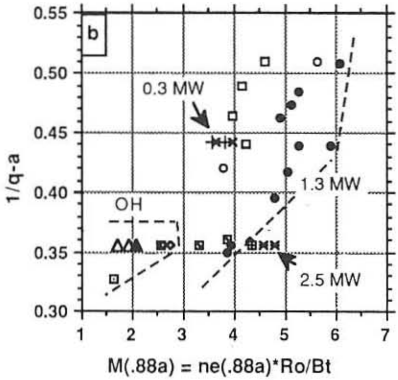
/4/ O. Gehre et al., Phys. Rev. Lett. 60 (1988) 1502

/5/ M. Kaufmann et al., Nucl. Fus. 28 (1988) 827

/6/ G. Fussmann et al., Proc. 12th Intern. Conf. on Plasma Phys. and Contr. Nucl. Fus. Research (Nice 1988), IAEA, Vienna, to be published

/7/ O. Gruber et al., Plasma Phys. and Contr. Fus. 30 (1988) 1611





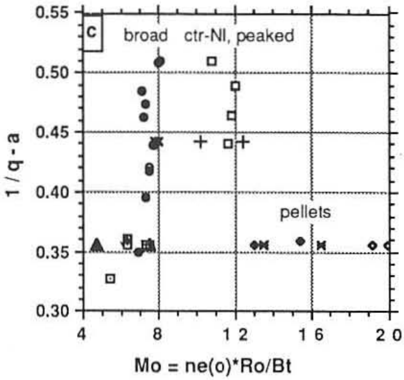


Fig. 1

Densities prior to the disruption for peaked and broad density profiles, presented in a Hugill-diagram:

a. line-averaged $\overline{n_e}$
b. n_e at r=0.88xa
c. central density

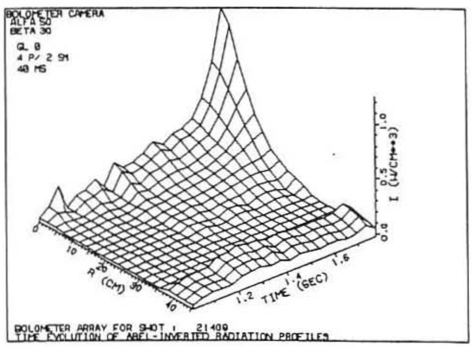


Fig. 2

Time evolution of Abel-inverted radiation profiles for ctr-NI (1.3 MW) with peaked density profiles (Ip=440 kA, Bt=1.86T), indicating the strong increase of central radiation towards the end of the discharge