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High Density Operation In Auxiliary Heated ASDEX Upgrade Discharges

V Mertens, P T Lang, K Büchl, R Dux, Ch Fuchs, O Gruber, G Haas, A Kallenbach, M Kaufmann, R Lang, F Mast, H W Müller, R Neu, J Neuhauser, F Ryter, H Salzmann, J Schweinzer, W Suttrop, M Weinlich, H Zohm, ASDEX Upgrade & NBI Teams

Max-Planck-Institut für Plasmaphysik, EURATOM Association,
85748 Garching, Fed. Rep. of Germany

Introduction :

The highest achievable density in a tokamak is restricted by the normally disruptive density limit DL. This limit is quite successfully described, even on machines of different sizes, by the empirical 'Greenwald' limit $\bar{n}_e^{GW} = \kappa < j >$ (κ is the plasma elongation and $< j >$ the area averaged plasma current density) [1]. Since the ITER (EDA) concept aspires an operation density significantly beyond this limit ($\approx 1.5\ \bar{n}_e^{GW}$ [2]), one needs reliable scenarios to overcome it without deterioration of the energy confinement time τ_E. At large heating powers, however, the particle fuelling efficiency of gas injection degrades such that high densities are difficult to achieve. Furthermore, the corresponding high neutral particle densities cause normally the backtransition of the favourable H-mode to an L-mode, yielding divertor detachment and probably a 'classic' DL. Presently, the only methode to achieve long lasting phases with $\bar{n}_e > \bar{n}_e^{GW}$ seems to be the repetitive injection of pellets.

This paper deals mainly with the characteristics of the L-mode phase preceeding every density limit disruption including impurity gas injection forced L-modes. The latter is found to prevent effectively detrimental divertor heat load.

Discharge Parameters :

Our investigations concentrate on lower single null discharges (R = 1.65 m, a = 0.5 m, $\kappa \sim 1.6$) with plasma currents between 0.6 MA and 1.2 MA and NBI heating powers up to 10 MW. The corresponding safety factors q_{95} vary between 2.5 and 5. The plasma facing vessel components are boronized. The ion ∇B drift is directed towards the target plates. A centrifuge enables to inject strings of pellets with velocities up to 1.2 km/s and repetition rates up to 80 Hz (representing a maximum fuelling rate of $\Phi \sim 3 \cdot 10^{22}$ D atoms/s). The working gas is mostly deuterium but in a smaller amount of discharges also hydrogen. Highly radiative discharges are performed by injecting Ne, Ar or Nitrogen gas into the main chaimber.

Experimental Observations :

We first describe the typical sequence from reaching very high line averaged densities finally ending in a DL disruption. At the applied high heating power levels P_{heat} the discharges stay normally in the ELM'y H-mode. During this mode the Greenwald limit could so far not be surpassed only by applying excessive gas puffing ($\Phi \lesssim 3 \cdot 10^{22}$ D atoms/s) as can be seen on Fig. 1 a) summarizing the highest achieved $\bar{n}_e$ in various regimes.

If the separatrix electron temperature in the H-mode decreases below ≈ 130 eV according to the strong particle influx and radiation cooling the discharge falls back into the

L-mode [3]. Owing to the reduced particle confinement of the L-mode the line averaged density decreases transiently until the density feedback control system rises the external gas flux and $\bar{n}_e$ grows again. Thereupon the divertor detaches, visible e.g. by the strong drop of the ion saturation current measured by langmuir probes mounted in the target plates. After the divertor electron temperature falls to a few eV a small Marfe forms close to the active X-point observable in a slight enhancement of the bolometer signals measuring the X-point region. If $\bar{n}_e$ raises further, the divertor throats become so cold that the radiating zone shifts up to the X-point and the Marfe starts to expand smoothly into the region of closed flux surfaces. This leads to a concentration of the boundary density into the X-point region observed by Li-beam and Thomson scattering diagnostics measuring close to the midplane and near the X-point, respectively. Correspondingly, the electron temperature close to the X-point reduces strongly from values of up to 100 eV to a few eV. An analysis of the electron pressure at the outside midplane boundary and in front of the divertor plates shows a clear pressure drop as signature of detachment. The smooth Marfe expansion is an unambiguous precursor of the local instability of the Marfe and hence of the DL. There is a large density operational window found with detached plasmas between q_{95} values of ≈ 3 and 4.

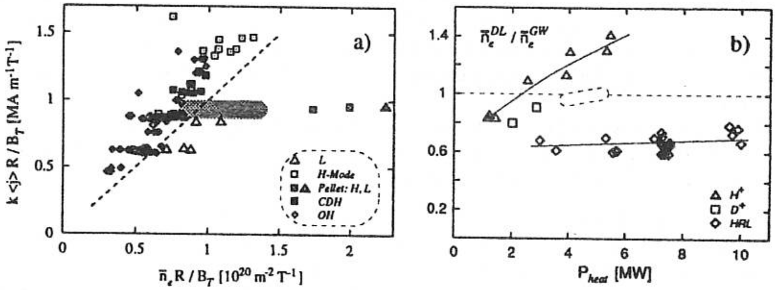

Figure 1: *a) shows the Greenwald plot indicating the typical ASDEX Upgrade density operating space. The dark area represents the region of feedback controlled pellet fuelled plasmas in H- as well as in L-mode. The white dashed surrounded area in Fig. b) corresponds to the* $\bar{n}_e$ *achieved up to now. Technical reasons prevent the further increase of* $\bar{n}_e$*. HRL denotes highly radiating L-modes.*

To obtain quickly and stationary high densities, we combined moderate gas puffing and repetitive pellet injection (with pellet injection alone $\bar{n}_e$ could not be successfully increased). Each pellet causes a quick (< 1 ms) raise in density, followed up by a slow decay of the density increment. In parallel, each pellet triggers an ELM expelling a part of the injected fuel [4]. The magnitude of the pellet induced increment is governed by the pellet fuelling efficiency ϵ_f. As during the injection sequence plasma cooling occurs (see Fig. 2 a), the pellets penetrate deeper into the plasma starting with roughly half minor radius ending up to approximately central deposition. Concomittantly, the fuelling efficiencies rise markedly. It has been shown that ϵ_f is a clear function of the penetration depth ranging between 30 % and 40 % in L-mode plasmas and dropping down to ≈ 0 %

in ELM'y H-mode phases for shallow penetration.

As a special tool to maintain long lasting high density phases we performed a control circuit using a bremsstrahlung signal as a measure of the line averaged density and inhibit the injection of pellets when the preprogrammed $\bar{n}_e$ is reached. Using this setup stationary phases ($>> \tau_E$) of up to 1.5 $\bar{n}_e^{GW}$ have been achieved as demonstrated in Fig. 2 a). In this example a smooth H → L transition occurs at about 1.9 s.

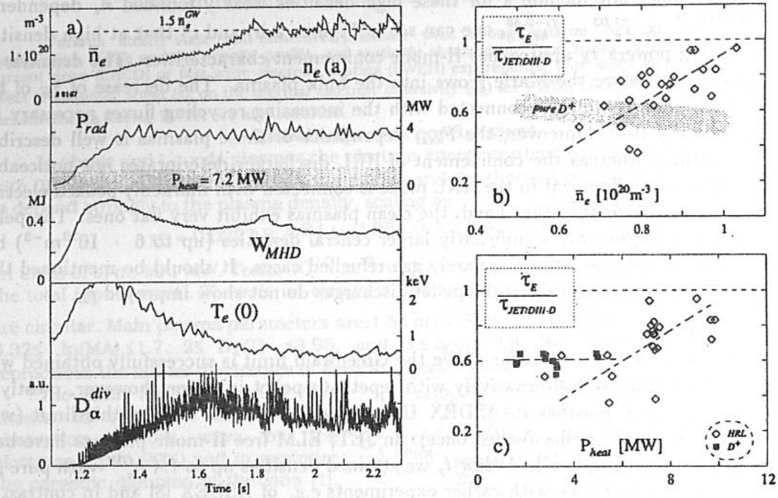

Figure 2: *a) shows a feedback controlled pellet fuelled discharge with preprogrammed $1.5\bar{n}_e^{GW}$. The shaded area in b) corresponds to the full squares of c) and represent clean deuterium L-mode plasmas.*

The fact that clean hydrogen/deuterium discharges normally do not detach in the H-mode at high densities, since at least the ELM's always burn through the divertor plasma, forced us to reduce the divertor power load by means of impurity gas injection. During ELM's peak power densities of up to 25 MWm^{-2} have been measured on the plates. This so achieved highly radiating and completely detached H-mode is known as CDH-mode [5]. The impurity injection can lead to radiative fractions $P_{rad}/P_{heat} > 90$ % before the plasma falls back into the L-mode. The highly radiating L-mode HRL shows qualitatively the same detachment and Marfe sequence as the clean hydrogen/deuterium discharges. No disruption has been observed without preceeding violent Marfe expansion.

The Greenwald scaling supposes the density limitation to be independent of heating power. The experiments, however, exhibit in the case of purely hydrogen/deuterium puffing a clear increase of the DL with heating power. At low plasma currents, $\bar{n}_e^{GW}$ is surpassed by up to 40 %. In contrast, the impurity dominated DL seems to be independent on P_{heat} (see Fig. 1 b). In the HRL-mode the disruption occurs normally at densities 0.6 -

$0.8\,\bar{n}_e^{GW}$. The line averaged $\bar{Z}_{eff}$ there is about 4, whereas it is ≈ 1.8 in the clean plasmas. Generally, the DL of clean hydrogen discharges is systematically about 10 % higher than those in deuterium.

If one compares the energy confinement times of the two extremes (clean deuterium $\leftrightarrow$ HRL) one gets the interesting situation that the highly radiating plasmas have significantly larger τ_E than the clean ones. Taking the JET/DIII-D H-mode scaling as reference [6] since it does not include a for these high densities weakly founded $\bar{n}_e$ dependence $\tau_E^{JET/DIII-D} \propto I_p^{1.03} \cdot P_{heat}^{-0.46}$, one can see in Figures 2 b) and c) that at high densities and heating powers τ_E approaches H-mode confinement characteritics. The densities $\bar{n}_e$ are taken just before the Marfe grows into the bulk plasma. The decrease of τ_E of the clean deuterium plasmas is connected with the increasing recycling fluxes necessary for strong density rise. Moreover, the P_{heat} dependence of these plasmas is well described by the scaling, whereas the confinement of HRL discharges deteriorates not noticeably. The improved confinement in the HRL mode is connected with markedly peaked electron density profiles. On the other hand, the clean plasmas exhibit very flat ones. The pellet refuelled discharges have significantly larger central densities (up to $6 \cdot 10^{20} m^{-3}$) but the boundary behaves as in the purely gas refuelled cases. It should be mentioned that despite strong density peaking the pellet discharges do not show improved τ_E.

Summary :

The aim to achieve densities far above the Greenwald limit is successfully obtained with strong gas puffing and alternatively with repetitive pellet injection, however, mostly in L-mode. H-mode plasmas in ASDEX Upgrade so far do not surpass this limit (with the exception of the pellet fuelled ones). In JET, ELM free H-mode plasmas have been observed exceeding $\bar{n}_e^{GW}$ [7]. At low I_p we attained densities up to $1.4\,\bar{n}_e^{GW}$ with pure gas refuelling. In accordance with earlier experiments e.g. of ASDEX [8] and in contrast to the Greenwald scaling, $\bar{n}_e^{DL}$ has been shown to increase clearly with P_{heat}. In the extreme case of strong impurity puffing the DL is markedly reduced, the heating power dependence on the DL evanesces, but τ_E can reach H-mode quality. With pellet injection we achieved controlled long lasting phases up to $1.5\,\bar{n}_e^{GW}$ and transiently maximum densities of about $2\,\bar{n}_e^{GW}$ in type-I ELM'y H-modes and $\approx 2.5\,\bar{n}_e^{GW}$ in L-modes. The related confinement in the H-mode is, however, degraded.

With respect to ITER one can conclude that operation at the projected density seems to be possible, but there are serious difficulties to maintain H-mode confinement. The injection of impurities unburdens the divertor and improves the L-mode confinement but reduces noticeably the achievable densities.

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