EXCEEDING THE GREENWALD LIMIT BY SUPPRESSION OF MARFEs IN TEXTOR-94

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1. Introduction

In order to achieve thermonuclear fusion conditions, high temperatures and densities are required in tokamak plasmas. However, the operational range of the plasma density is limited. A too high density may lead to a degradation of plasma confinement or a disruption of the tokamak discharge. In strongly heated plasmas with a low impurity concentration an empirical density limit, the so-called Greenwald limit ($\overline{n}_e^{GW}$ = 1 $\cdot 10^{14} I_p/\pi a^2$, in units of [A] and [m]), was found, which is only a function of the average plasma current density [1]. In L-mode discharges, often the appearance of MARFEs just prior to the density limit disruption is observed [2-4]. As the development of the MARFE does not depend on the plasma current alone, but also on the heating power, the Greenwald limit can be slightly exceeded by sufficient auxilary heating. It is thought that this radiative instability is the cause of the density limiting process in strongly auxiliary heated plasmas. An effect, which was neglected so far, is the influence of the poloidally asymmetric particle fluxes on the development of the MARFE, which will be discussed in this paper.

The experiments described here were carried out in circular plasmas (R_0 = 1.75 $\pm$ 0.05 m) limited by the toroidal pumped limiter ALT-II or by movable poloidal main limiters. In our investigations the minor radius was varied between 0.42 m and 0.46 m. The magnetic field was usually 2.25 T and the plasma current was changed between 180 kA and 350 kA (q_a = 6.2 - 3.3). We only consider NBI heated discharges (H$\rightarrow$D, Co and Counter) with heating powers of 0.8 - 2.2 MW.

2. Suppression of MARFEs

The underlying idea for the suppression of MARFEs is a change in the plasma wall interaction at the inner bumper limiter on the high field side (HFS). To study a possible influence of the plasma wall interaction on the MARFE development and hence the density limit (DL), experiments with different horizontal plasma positions were performed [5]. In those experiments the minor radius was reduced to a = 0.42 m by inserting the poloidal main limiters from the top and the bottom. It was found that plasmas which were shifted towards the HFS disrupted near the predicted Greenwald limit, whereas outward shifted plasmas overcome this limit easily. This phenomenon was explained by a reduction of the localized recycling at the inner bumper limiter. The conditions of the outward shifted discharges were optimized by increasing the auxiliary heating power (P_{aux} = 1.9 MW). In those discharges the line averaged density could be increased to $\overline{n}_e$ = 8 $\times 10^{19}$m^{-3} at I_p = 228 kA, which is a factor of 2 beyond the Greenwald limit (Figure 1a). During the density ramp the density profile is only slightly peaking. Finally, when the radiated power reaches the heating power, the discharge is terminated by a radiative collapse.

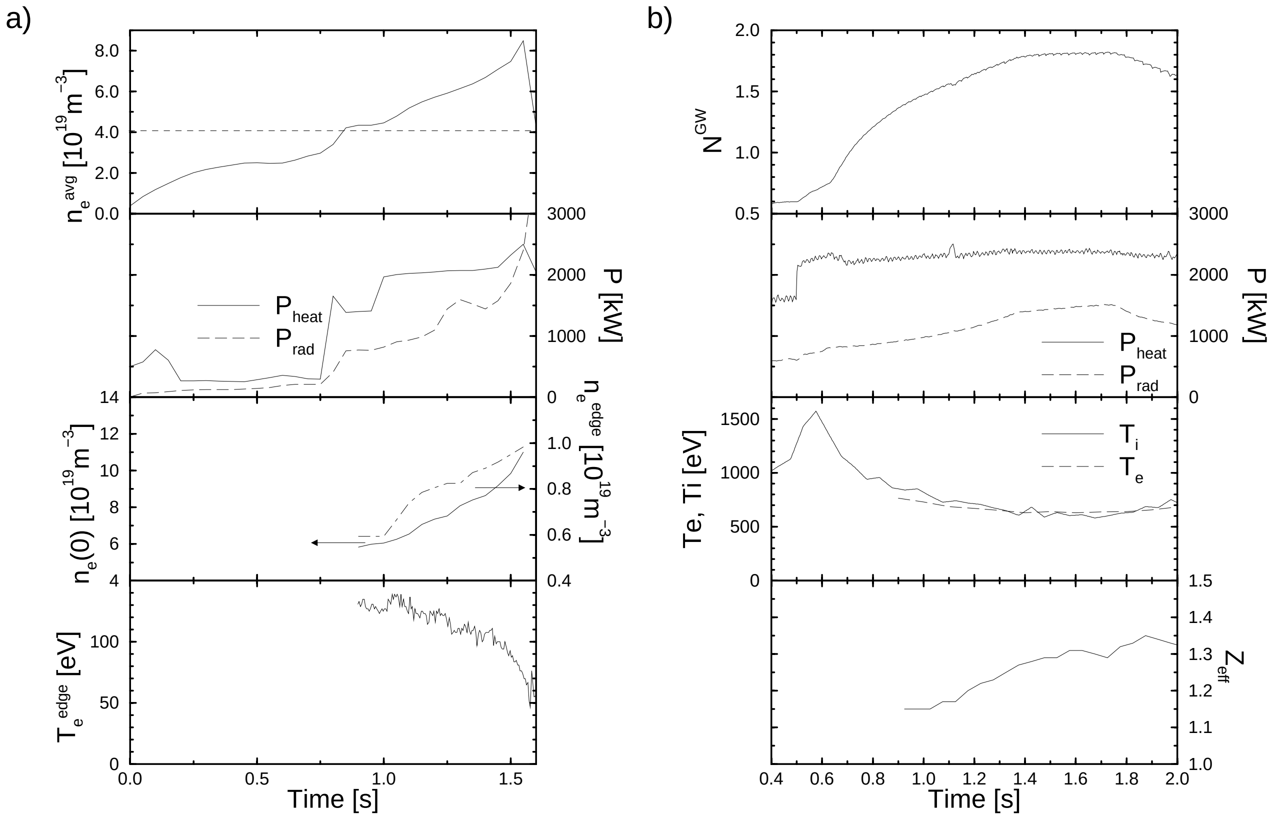

Figure 1. a) Overview of a discharge #74244 (I_p = 228 kA, P_{aux} = 1.9 MW, ΔR = 5.5 cm, a = 0.42 m, limited by poloidal main limiters, boronized) which exceeded the Greenwald limit by factor 2, line averaged density, total heating power, total radiated power, central electron density, edge electron density and temperature ($r = a + 1$cm); b) Overview of a stationary high density discharge #76330 (I_p = 308 kA, P_{aux} = 1.9 MW, ΔR = 5.5 cm, a = 0.43 m, limited by ALT-II, siliconized), Greenwald number, total heating power, total radiated power, central electron temperature, central ion temperature, central Z_{eff}.

In Figure 1b) an example of a high density discharge in shown, which reached a Greenwald number $\overline{n}_e/\overline{n}_e^{GW} = N^{GW}$ = 1.8. This high density ($\overline{n}_e$ =9.6$\times 10^{19}$m^{-3}) was maintained for about 400 ms ($\approx$ 15 $\times \tau_e$) quasi-stationary with sawtooth oscillations. However the radiated power and Z_{eff} are slightly increasing. Longer quasi-stationary phases (1.3 s) with N^{GW} = 1.5 have been obtained with stronger heating (NBI and ICRH). In all those discharges the confinement times were comparable to L-mode confinement (f_{L89} = 0.85 - 0.92).

The development and the characteristics of the MARFEs can be very different for the various plasma positions [6]. Already a small shift to the LFS (ΔR = 2 cm) can lead to a significant suppression of MARFEs. It has been found that in the case of inward shifted plasmas large MARFEs develop with radiation densities exceeding 2500 mW/cm^3. The radiated power from those large MARFEs is as high as 450 kW, which is 40% of the total radiated power (Figure 2). If the plasma is shifted outwards the radiation from the, in this case, rather thin MARFE reduces to only 10% of the total radiated power (Figure 2).

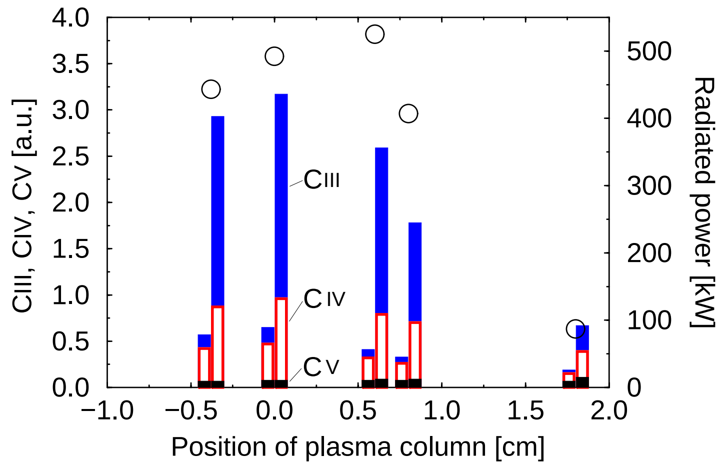

Figure 2. Contributions of carbon line emissivities CIII, CIV, CV, the short bars relate to the contributions taken prior the MARFE development at the HFS,the high bars relate to the contributions measured in the MARFE; radiated power from MARFE (○) (I_p = 350 kA, $a \approx$ 0.46 m, $P_{rad} \approx$ 1.2 MW, $P_{heat} \approx$ 1.6 MW).

For inward shifted plasmas the radiation of CIV increases only moderately (by a factor 2) during MARFE formation. Conversely, the radiation of CIII grows by factor 10-20. In the case of outward shifted discharges the radiation of both ionization stages (CIII and CIV) increase during MARFE formation, but their contribution remain comparable. These measurements confirm theoretical predictions [7,8], according to which different mechanisms are responsible for triggering the MARFE. In the former one (inward shifted plasmas) an instability of plasma recycling on the HFS develops and leads to local plasma region of high density and low temperature. The evolution of this MARFE is a consequence of this process and is further enhanced by local release of carbon at the bumper limiter. In the latter case the MARFE develops as a result of a usual radiative instability without additional plasma wall interaction. But this process becomes effective only at significantly higher plasma densities than the one due to recycling at the inner wall. Thus for outward shifted plasmas the electron density can be increased to higher values with ordinary gas fuelling.

3. Scaling of the density limit by discharge parameters

In order to investigate the behaviour of those shifted plasmas several density limit discharges with different plasma currents were performed. The plasma was shifted outward by about ΔR = 0.05 m and the minor radius was 0.42 m$\leq a \leq$ 0.43 m. Figure 3a) shows the linear dependence of the DL on the plasma current as qualitatively shown by Greenwald. But in our case for this particular heating power (P_{aux} = 1.9 MW) the density is twice as high as the ordinary Greenwald limit. A maximum density of $\overline{n}_e^{DL} = 1.1 \times 10^{20}\mathrm{m}^{-3}$ was reached at a plasma current of I_p = 350 kA, which refers to an edge safety factor of $q(a)$ = 3.3. This linear dependence on the plasma current indicates that the density is most likely not limited by a symmetric radiative collapse, as it occurs usually at high values of Z_{eff} and low heating power. It should be mentioned that a variation of the toroidal magnetic field (1.78T$\leq B_t \leq$2.6T) did not show any significant change in the density limit (5%). Furthermore, the achieved densities of non-disrupted discharges are plotted in Figure 3a). In Figure 3b), the impact of the heating power (auxilary heated with NBI) on the density limit is shown at a plasma current of I_p = 228 kA. The exponent was found to be between 0.4 and 0.5. The same exponent is valid for a scaling of the density in the SOL ($n_e(a + 1\text{cm})$) with P_{heat}. This dependence for L-mode plasmas is similar to other machines, where the exponent is found to vary between $\overline{n}_e^{DL} \propto P_{heat}^{0.4...0.7}$.

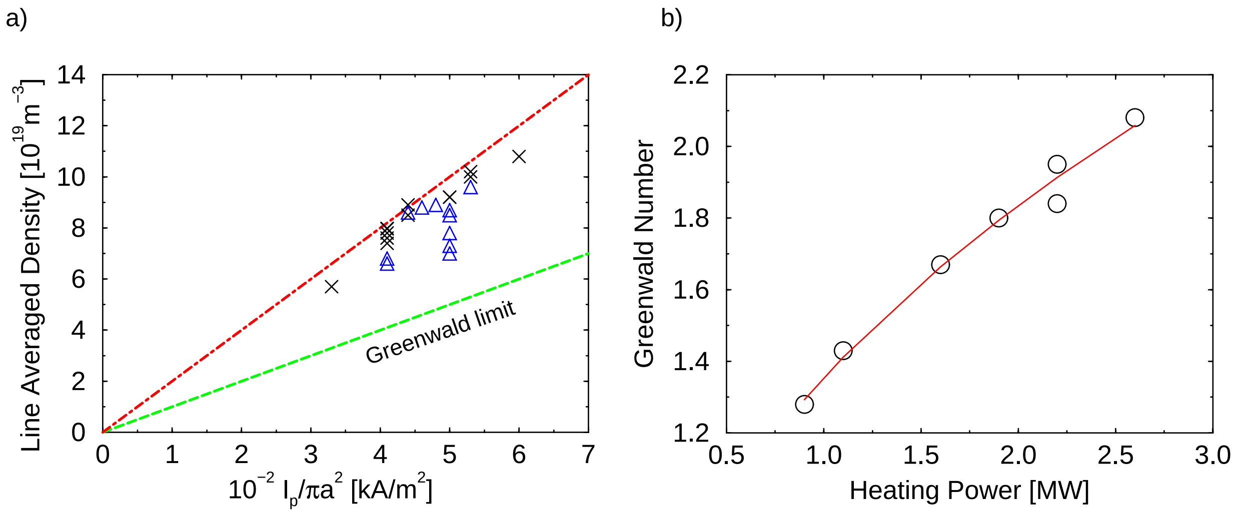

Figure 3. a) Dependence of density limit on the averaged plasma current density, disruptive density limit with P_{aux} = 1.9 MW(×), nondisruptive high density discharges (△); b) Dependence of Greenwald number on the auxiliary heating power (I_p = 228 kA).

4. Summary

As observed in other tokamaks it was found in TEXTOR-94 that a relation between the Greenwald limit and the occurrence of MARFEs exists. We have shown that the onset of MARFEs is strongly influenced by the localized recycling on the HFS of the torus. Thus by modification of these recycling properties the MARFEs could be successfully suppressed and the density limit was increased up to 2× the Greenwald limit. Although no clear indication of MARFE formation just prior the density limit disruption was found, the density limit scales linearily with the plasma current. Furthermore a clear dependence of the density limit on the applied heating power was found. Stationary discharges, with flat top phases of 0.2 - 1.3 s i.e. 10 to 50×τ_e, have been obtained leading to Greenwald numbers of N^{GW} = 1.5 - 1.9.

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