

Scaling of density limits with respect to global and edge parameters in TEXTOR-94

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1. Introduction

In a tokamak plasma the maximum achievable density is limited. A too high density will result in a violent end of the discharge. On TEXTOR-94, a limiter tokamak with circular cross-section, it has been found that two density limits can be distinguished, which differ by the kind of instability in the plasma boundary preceding the disruption.

1. In ordinary auxiliary heated discharges the density is limited by the onset of MARFEs.
2. However, if those MARFEs are successfully suppressed by changing plasma boundary conditions (by increasing the distance from the last closed flux surface to the inner bumper limiter), the Greenwald limit can be exceeded by more than a factor of two [1]. In this case the plasma terminates due to a radiative collapse.

2. Scaling of the MARFE onset

The maximum line-averaged density \bar{n}_e^{cr} scales linearly with the plasma current and agrees well with the predicted Greenwald limit [2], as a broad parameter scan (I_p was varied by a factor 3) did show [3]. A deviation from the Greenwald scaling is observed, if the plasma boundary conditions are modified by fresh siliconization. If the wall and the carbon limiters are covered with silicon the critical density for the MARFE onset can be increased to $N^{GW} \approx 1.7$. This is mainly due to the lower impurity release of silicon with respect to carbon at high densities. The temporal evolution of such a discharge is shown in fig. 1. First the discharge evolves like an usual RI-mode discharge, the confinement increases with increasing density. But at $t = 1.26$ s a sudden confinement loss accompanied by $m/n = 3/2$ mode activity is observed. Just before $t = 1.26$ s the β_p was 1.05. Although the radiated power from the plasma core was as high as $P = 0.2$ MW/m³, it was still below the local heating power. The confinement loss leads to an increased gas fueling

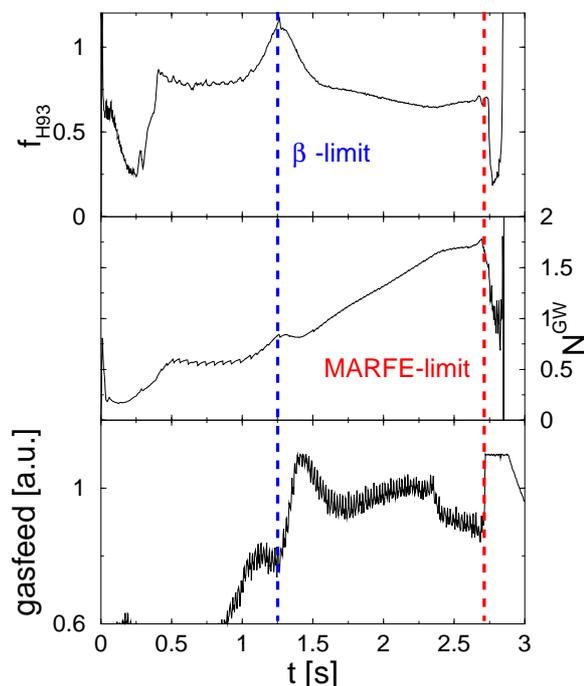


Figure 1: Density limit discharge with freshly siliconized walls: β -limit and MARFE density limit

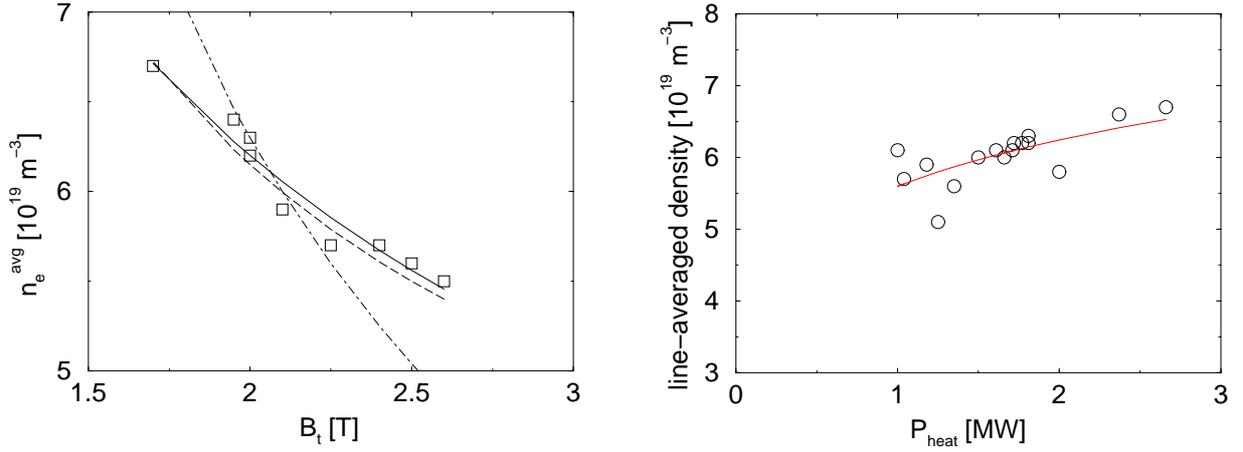


Figure 2: Scaling with global parameters; a: with toroidal magnetic field ($I_p = 350\text{kA}$, $P_{NBI} = 1.4\text{MW}$), $\bar{n}_e^{cr} \propto B_t^{-0.5}$ solid line, $\bar{n}_e^{cr} \propto a + b \times B_t^{-1}$ dashed line, $\bar{n}_e^{cr} \propto B_t^{-1}$ dash-dot line; b: with heating power, $\bar{n}_e^{cr} \propto P_{heat}^{0.16}$

and hence a further confinement degradation. Fresh siliconization and pure hydrogen operation led even to a density limit of $N^{GW} \approx 2$. Nevertheless the onset of the MARFE scales with the plasma current. A difference in the wall conditions itself was not observed. After a few days of operation, when the carbon limiter surface appears again, no difference is seen between the density limit in boronized and siliconized machines. The dependence on the toroidal magnetic field is not that clear, since B_t could only be varied by a factor of 1.5. In figure 2a the scaling $\bar{n}_e^{cr} \propto B_t^{-0.5}$ yields a good agreement. But also a linearization (with respect to q_a) around a bias point would lead to a satisfying result ($\bar{n}_e^{cr} \propto a + b/B_t$). Since the development of the MARFE is a cooling instability in the plasma edge one might expect to increase the critical density for the MARFE onset by application of strong auxiliary heating. To check predicting dependencies the heating power was varied by almost a factor of 3. As figure 2b shows the critical density is only moderately influenced by the applied heating power ($\bar{n}_e^{cr} \propto P_{heat}^{0.16}$). But a global scaling might not be the correct description for an instability in the edge. Therefore, the variation of the local edge parameters was studied too. The dependence of the electron density and the electron temperature at the last closed flux surface (LCFS) is plotted against the power flux crossing the LCFS (fig. 3). The resulting scalings are as weak as the global one. The gradients of the density profile in the edge change only very moderately, but the decay length of the temperature at the LCFS decreases from 4cm to almost 1.5cm for the highest heating power. Summarized the found global scaling for the MARFE onset is

$$\bar{n}_e^{cr} \propto I_p \times P_{heat}^{0.16} / B_t^{0.5} \quad (1)$$

and the scaling of the edge parameters is

$$n_e^{cr}(a) \propto Q_{\perp}^{0.22}, T_e^{cr}(a) \propto Q_{\perp}^{0.15} \quad (2)$$

where the power flux is $Q_{\perp} = P_{heat} - \int_0^a P_{rad}(r) / 4\pi^2 a R$. The fluxes (H-flux, C-flux) at the bumper limiter and at the toroidal ALT limiter scale linearly with P_{heat} and double in the investigated range of heating power. This usual flux dependence in L-mode plasmas

could be a reason for the weak power dependence.

The experimentally derived scalings for the MARFE onset are compared with predictions of existing models. A good agreement is found, if one takes the criterion for the critical density of the model from Tokar [4], which describes the MARFE onset by localized recycling effects at the inner bumper limiter, and assumes gyro-Bohm scaling for the diffusion coefficient. Indeed, measurements of χ_{eff} in the TEXTOR boundary plasma [5] favor the gyro-Bohm scaling rather than the Bohm scaling, which is taken in many other models. The diffusion coefficient is taken according to [6] as $D_{\perp} \approx T_e(a)^{3/2} B_t^{-2} L_n^{-1} \times q_a^2$. Furthermore it is assumed that $P \approx D_{\perp} T_e(a) n_e(a) / L_n$ and $\kappa_{\parallel} \approx T_e^{5/2}$. This leads then finally to the scaling $\bar{n}_e^{cr} \propto I_p^{1.14} \times P_{heat}^{0.1} / B_t^{0.48}$, which is close to the experimental one. But it should be mentioned that 2D-modeling of the MARFE with B2-Eirene and DORIS showed quite the opposite behavior of the MARFE onset with respect to the diffusion coefficient, presumably due to a strong impact on carbon impurities [7]. A good agreement with the weak power scaling was also found in 2D-modeling with TECXY [7]. No agreement was found with other predictions of the MARFE onset [8,9], which rely on Bohm-like transport. Additionally one has to note that in most models for the onset of the MARFE the radial heat flux in the SOL is taken to be constant poloidally, but realistically the flux is more asymmetric. With increasing auxiliary heating power the asymmetries become larger [10], which could explain the weak dependence on the heating power too.

3. Scaling of radiative collapse

In the following only discharges which were shifted outward to the LFS are considered, where MARFEs were successfully suppressed. In contrast to the discharges with plasma wall contact at the bumper limiter, the density can be increased until the plasma detaches from the ALT-II limiter and subsequent MHD-activity leads to the final disruption [11]. Scalings with respect to global parameters were already performed [3] and led to the following critical density:

$$\bar{n}_e^{cr} \propto I_p \times P_{heat}^{0.44} / B_t^{0.17} \quad (3)$$

The dependence on the plasma current is linear as for the MARFE onset, but the density limit ($P_{heat} = 2.2\text{MW}$) is twice the Greenwald limit. A significant difference is found in

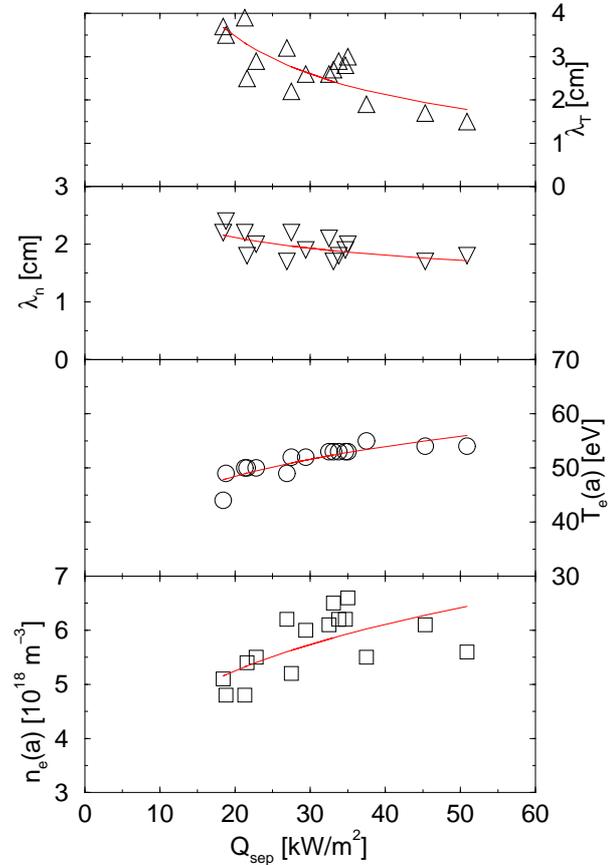


Figure 3: Scaling with local edge parameters: edge density and temperature and their decay lengths with power flux crossing LCFS.

the scaling with the heating power. For the radiative collapse it is roughly $\bar{n}_e^{cr} \propto P_{heat}^{0.5}$, which is in agreement with simple models [12]. The edge density shows qualitatively the same dependence as the line-averaged density. Also the weak dependence on the magnetic field could be explained [12]. The influence of the plasma position with respect to the bumper limiter on the development of the MARFE was satisfactorily modeled by B2-Eirene and DORIS [7], meaning that without any plasma wall contact at the HFS the density limit can be significantly increased. In figure 4 an updated Hugill-diagram of TEXTOR [13] is shown, which includes recent results from fresh siliconization and plasmas which were strongly shifted to the LFS.

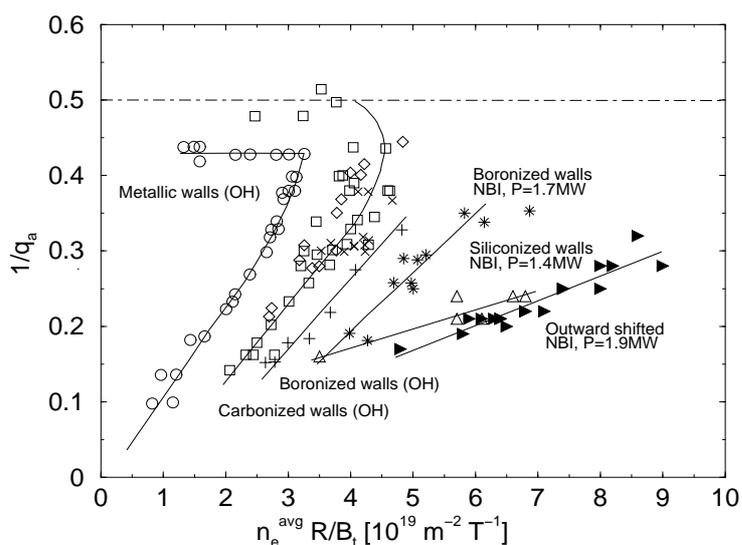


Figure 4: Hugill-diagram of TEXTOR.

4. Summary

In this paper the critical values for the onset of the MARFE and the radiative collapse were analyzed. A comparison of both instabilities showed significant differences in the scaling with respect to B_t and P_{heat} . The linear dependence on the plasma current is for both discharge types the same and resembles the Greenwald limit scaling. The derived scalings were compared with other theoretical predictions. Good agreement was found with models, which include localized recycling effects on the HFS.

The influence of the wall conditions on the development of the MARFE was demonstrated.

5. References

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