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# Density Limit Study on the W7-AS Stellarator

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**Abstract**

Data from currentless NBI discharges in W7-AS strongly indicate that the maximum density for quasi-stationary operation is limited by detachment from limiters. The threshold density at the edge scales with $P_s^{0.5}B^{0.8}$ (with $P_s$ being the net power flow across the LCMS) which is consistent with an edge based analytic estimation presuming constant threshold downstream temperatures.

**Keywords:**

stellarator, W7-AS, plasma edge, density limit, limiter

## 1. Introduction

In currentless stellarator discharges, the maximum achievable plasma density is basically limited by an impurity radiation induced thermal instability (density limit, DL) [1,2] which, however, does not lead to MHD instability with subsequent disruption as is typical for tokamak DL discharges [3-5]. The sequence of events leading to thermal instability is governed by the same basic physics as in tokamaks and should exhibit some similarity, at least in limiter machines. This paper continues previous DL studies on W7-AS [1,2] and concentrates on the starting event of the DL sequence (onset condition) which can be described in terms of edge quantities alone, and which practically determines the actual operational window for quasi-stationary limiter discharges. The aim is to give a status report rather than a comprehensive description.

## 2. Experimental

The analysis was made for net current-free NBI discharges in W7-AS ($R$ = 2 m, $a$ = 0.18 m) at $B$ = 1.25 and 2.5 T and $\iota$ = 0.34. The configuration was bounded by two tangential graphite limiters at the top and bottom of an elliptical cross section. The absorbed NBI power was varied between 0.35 and 1.2 MW. The power deposited onto the limiters (from limiter-integrated thermocouples) in discharges with flat-top density below the DL was typically about 80 % of the non-radiated power fraction. For the DL study, the density was slowly ramped up (typically for about 0.4 s) until the discharges collapsed. Particle confinement times are estimated to be less than 50 ms.

## 3. Results and Discussion

### 3.1 Core parameters, radiation

With the line-averaged density $\bar{n}_e$ ramped up, the stored energy slightly increases up to a more or less pronounced maximum and subsequently rolls over, at first along a time scale of some ten milliseconds and then much faster (see example in Fig. 1). This fast decay coincides with a rapid decrease of the density,

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even though the feedback controlled gas valves fully open in this phase. At $B$ = 2.5 T, the total radiated power $P_r$ (from bolometer cameras) is found to increase approximately as $P_r \propto \bar{n}_e^2(Z_{eff}-1)$ ($Z_{eff}$ from bremsstrahlung) up to a critical density $\bar{n}_e^{crit}$. Above this density the increase becomes much steeper indicating radiative instability. Discharges at $B$ = 1.25 T, where $Z_{eff}$ values were not available, show in general a quite similar evolution of $P_r$ with time. Abel-inverted radiation profiles (from 12-channel bolometer camera) are typically hollow below $\bar{n}_e^{crit}$, then increase first at the edge, and become strongly peaked during the collapsing phase. Data from bolometer cameras at three different toroidal positions do not indicate significant radiation asymmetries within the last closed magnetic surface (LCMS); MARFE formation was not observed. Whether the phase after having attained $\bar{n}_e^{crit}$ leads to a complete collapse following the example in Fig.1, seems to depend primarily on the external gas programme. In contrast to feedback control, with constant or slowly increasing gas feed the discharges could often be further sustained at a degraded energy level or even oscillated between low and high energy contents. Within the low energy phases, $n_e$, $T_e$ (from Thomson scattering) and $P_r$ radial profiles indicate a radial shrinking of the plasma column.

### 3.2 Scrape-off layer (SOL) parameters

The upstream densities $n_{es}$ at the LCMS (from Li-beam) increase $\propto \bar{n}_e^{1.1\pm0.1}$ at $B$ = 1.25 T and $\propto \bar{n}_e^{1.5\pm0.1}$ at $B$ = 2.5 T up to a maximum which coincides with the stored energy maximum, and then decrease at higher $\bar{n}_e$ (see example in Fig. 2). LCMS upstream temperatures $T_{es}$ are typically above 60 eV up to $n_{es}^{max}$ and then drop rapidly. The high $T_{es}$ values are consistent with the small wetted limiter areas, short power flux decay lengths $\lambda_q$ ($\leq$1 cm), and long field line connection lengths $L_c$ ($\approx$ 30 m) in W7-AS. Downstream strike-point temperatures $T_{ed}$ (from limiter-integrated Langmuir probes) decrease from slightly below $T_{es}$ at low density to a more or less pronounced pedestal of about 20–25 eV at about $n_{es}^{max}$ and then drop further. The downstream ion saturation currents $I_{sat}$ and densities $n_{ed}$ derived from it increase with $n_{es}$ up to a certain density $n_{es}^{det} < n_{es}^{max}$ and then fall typically by factors of about 1.5 to 5. This indicates reductions of the thermal plasma pressure along field lines by more than a factor of eight and detachment from limiters. Detached phases with high stored energy as shown in Fig.1 do not exhibit $n_e$, $T_e$ and $P_r$ radial profile shrinking. This is in contrast to limiter tokamak DL scenarios

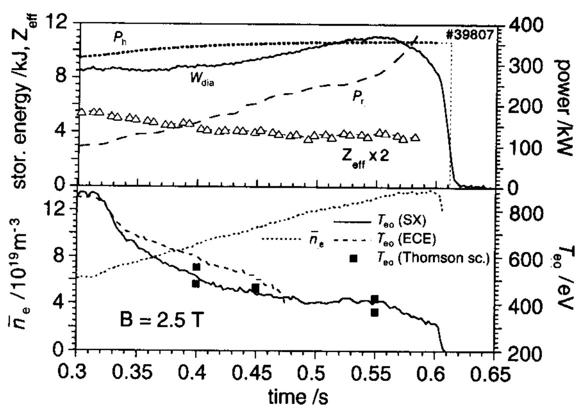


Fig. 1 Typical evolution of core parameters for the line-averged density $\bar{n}_e$ ramped up until collapse. $W_{dia}$ is the stored energy, $T_{eo}$ the electron temperature at the centre; for other symbols see text.

which alternatively show detachment by radial shrinking or MARFE formation. The difference could be due to the radial flux expansion by about a factor of two at the limiter positions in W7-AS.

The consistency of the measured SOL parameters with basic SOL physics is checked by a simple two-point estimation including the power balance along field lines, momentum balance and the sheath boundary condition [5, 6]:

$$T_{es} = \left(T_{ed}^{7/2} + \frac{7}{4\kappa_o} q_{\parallel s} L_c\right)^{2/7} \text{ with } q_{\parallel s} = \frac{P_s}{\lambda_q w} \quad (1)$$

$$2n_{ed}T_{ed} = (1-f_m)n_{es}T_{es} \quad (2)$$

$$n_{ed}\sqrt{\frac{2k}{m_i}}\, T_{ed}^{1/2}k(\xi + \gamma_s T_{ed}) = (1-f_r)q_{\parallel s}. \quad (3)$$

$P_s$, $q_{\parallel s}$, $w$, $f_r$, $f_m$ and $\xi$ are the net power crossing the LCMS, the upstream parallel power flux density, the wetted limiter width, the SOL energy and momentum loss fractions and the potential energy transferred per electron-ion pair ($\approx$ 25 eV), respectively. Further symbols have the usual meaning [5].

To visualize the role of momentum losses, the measured $P_s$ and $T_{ed}$ values (beside geometrical parameters and $\lambda_q$) and $f_r = f_m = 0$ are used as input in a first step. Then a high recycling scenario with $n_{ed} > n_{es}$ is predicted which clearly was not observed (see the discrepancy between calculated and measured $n_{ed}$ values in Fig. 2). Taking $P_s$, $n_{es}$ and $I_{sat} = en_{ed}c_sA_p$ (with $A_p$ being the probe area) as input and varying the remaining free parameter $f_r$ for $f_m$ to match the $f_m(T_{ed})$

values for CX momentum losses from Fig. 24 in Ref. [7] results in a detached scenario consistent with the measured data with the exception of $T_{ed}$. The latter should be $< 5$ eV near the $I_{sat}$ minimum, see Fig. 3. The example further indicates that both strong momentum and volumetric energy losses from the SOL are required for consistency within this estimate. Though $f_r$ in the SOL could not yet be measured, this explanation seems to be somewhat realistic because the measured $n_{es}$ and $I_{sat}$ values are much less prone to error than the $T_{ed}$ probe values. In the presence of strong $T_e$ parallel gradients, the latter are very likely overestimated due to contributions from fast tail electrons from regions further upstream [8]. On the other hand, we cannot exclude that momentum losses due to radial transport [9] contribute to detachment in this geometry. The further analysis is not affected by this uncertainty.

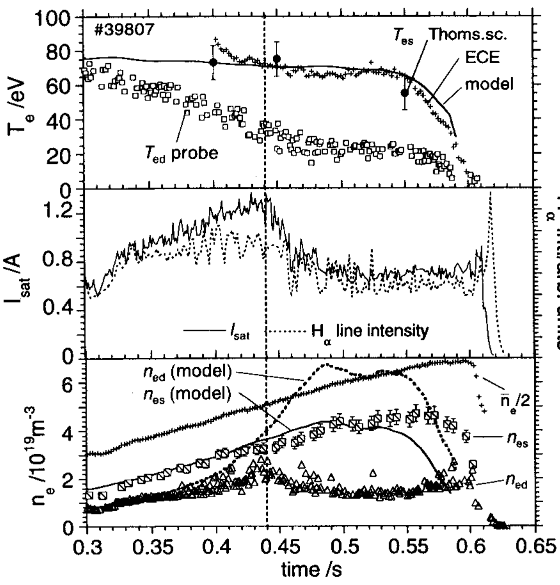


Fig. 2 Temporal evolution of LCMS upstream and downstream parameters. The $I_{sat}$ and $H_\alpha$ line intensity drops at 0.44 s indicate detachment from limiters. A two-point estimation (see text) based on the less reliable probe $T_{ed}$ and neglecting momentum losses predicts high recycling with $n_{ed} > n_{es}$ (lines in the bottom figure) which was not observed.

### 3.3 Operational limit scaling

Detached scenarios could not yet be quasi-stationarily sustained in W7-AS. We therefore focus on the upstream limit density $n_{es}^{det}$ for attached discharges which presently determines the practical operational limit for quasi-stationary limiter discharges. From equations (1)–(3) we get

$$n_{es} = \left(\frac{4\kappa_o}{7}\right)^{2/7} \frac{(1-f_r)}{(1-f_m)} \frac{q_{\parallel s}^{5/7}}{L_c^{2/7}} F(T_{ed});$$

$$F(T_{ed}) = \frac{2T_{ed}^{1/2}}{\sqrt{\dfrac{2k}{m_i}}\, k(\xi + \gamma_s T_{ed})} \tag{4}$$

Considering carbon (from limiters) as dominating SOL impurity, it can be assumed that detachment starts at a threshold $T_{ed}$ value between about five and ten eV where both radiative and momentum losses from the SOL become efficient. The exact value is not critical because $F(T_{ed})$ is only a weak function of $T_{ed}$ in this range and can be taken as constant. The above described calculation to reproduce the measured $n_{es}$ and $I_{sat}$ values for a detached state yields $f_r, f_m \ll 1$ and $(1 - f_r)/(1 - f_m) \approx$ const. when applied to the attached phases. With this approach we get the onset condition

$$n_{es}^{det} \propto \frac{q_{\parallel s}^{5/7}}{L_c^{2/7}} = \frac{P_s^{5/7}}{(\lambda_q w)^{5/7} L_c^{2/7}} \tag{5}$$

or, with $(\lambda_q w) \propto P_s^x/(n_{es}{}^y B^z)$ (see below),

$$n_{es}^{det} \propto \frac{P_s^\alpha B^\beta}{L_c^\delta},\ \alpha = \frac{5/7(1-x)}{1-5/7y},$$

$$\beta = \frac{5/7y}{1-5/7y},\ \delta = \frac{2/7}{1-5/7y} \tag{6}$$

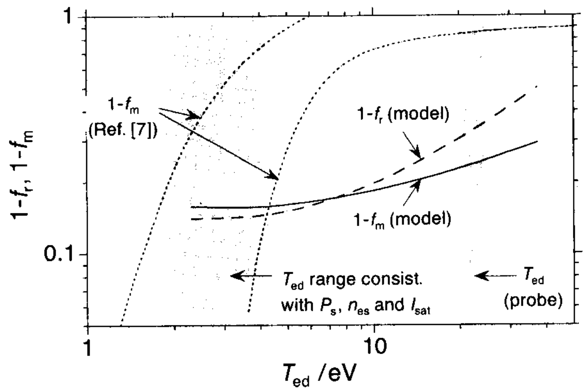


Fig. 3 SOL momentum and energy loss fractions $f_m$ and $f_r$, respectively, required to explain the observed reduction of the downstream/upstream plasma pressure at 0.53 s in Fig. 2 by friction with neutrals. The free parameter $f_r$ was varied for $f_m$ to match the $f_m(T_{ed})$ data for CX momentum losses in Ref. [7]. The dotted lines indicate the scatter range of data in Ref. [7].

$\lambda_q$ values derived from SOL $n_e$ and $T_e$ radial profiles (from fast recipro-cating Langmuir probes) are found to scale as $P_s^{0.4\pm0.05} n_{es}^{-0.4\pm0.05} B^{-0.5}$ (with the $B$ depend-

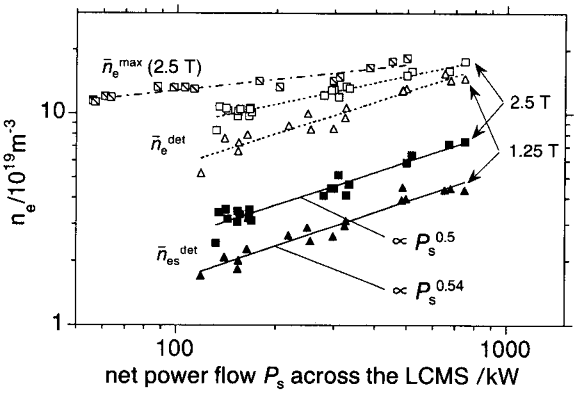


Fig. 4 Threshold densities for the onset of detachment from limiters indicated by the $I_{sat}$ drop. Errors are estimated to be about $\pm 10\%$ for the densities and $\pm 30$ kW for the power. $\bar{n}_e^{max}$ indicates maximum densities which were transiently achieved during detachment.

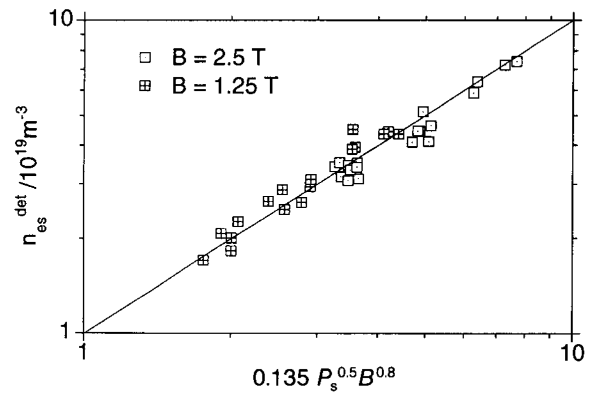


Fig. 5 Summary of the edge threshold densities in Fig. 4. The scaling pre-factor is valid for $P_s$ in MW and $B$ in T.

ence inferred from profiles at only two different $B$ values, 1.25 and 2.5 T). With tangential limiters, the wetted limiter width slightly increases with $\lambda_q$, $w \propto \lambda_q^{0.4}$. Inserting these values into eq. (6) yields $\alpha = 0.53 \pm 0.12$, $\beta \approx 0.83$ and $\delta = 0.48 \pm 0.05$ which is consistent with the experimental findings shown in Figs. 4 and 5 ($L_c$ was not varied). Nevertheless, the scaling with $B$ needs further confirmation as high power discharges at low magnetic field in general were less close to quasi- stationarity (deteriorated density control) than those at high field. With respect to the dependence of the limit density on the absorbed NBI heating power we found $n_{es}^{det} \propto P_h^{0.6}B^{0.8}$. This, together with the similar scaling with $P_s$, indicates that the limit should occur at an approximately constant core radiated power fraction which was actually observed ($f_r^{core} = 0.55 \pm 0.1$). It has to be noted that any long-term effects, for example possible impurity accumulation, are not considered in this study.

## 4. Summary and Conclusion

Data from currentless NBI discharges in W7-AS show that the maximum achievable density in quasi-stationary discharges is actually limited by detachment from limiters indicated by a drop of the downstream $I_{sat}$. Corresponding threshold densities at the edge scale as $n_{es}^{det} \propto P_s^{0.5}B^{0.8}$ which is consistent with an edge based, analytical estimation presuming constant threshold downstream temperatures. Model improvement (B2/EIRENE code) and further experiments with respect to the detached phase and possible long-term effects are planned.

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