26^{th} EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 1397 - 1400

SCALINGS OF DENSITY CHARACTERISTICS NEAR THE GREENWALD LIMIT IN ASDEX UPGRADE H-MODE DISCHARGES

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Introduction :

In order to achieve thermonuclear burn, future fusion experiments must safely operate at rather high density, while retaining sufficiently high energy confinement. This suggets probably operation in H-mode. Present experiments, however, show that the useful tokamak operation space is limited towards high density by various processes, such as exessive edge radiation cooling eventually causing a disruption, by the onset of fast MHD-instabilities (e.g. ballooning limit), detachment or simply by intolerable energy confinement degradation (e.g. loss of H-mode, called here 'H-mode density limit'). Furthermore, the type-I ELMy H-mode regime might not be suitable for a reactor since the peak power load in the divertor during ELM's exceeds clearly engineering limits. The type-III ELMy regime with its reduced power load which is accessible at high densities might denounce an alternative operation scenario.

The empirical heating power independent Greenwald line averaged density limit scaling $\overline{n}_e^{GW} \propto I_p / a^2 \propto B_t/(q_{95}R)$, which primarily has been developed for OH and L-mode discharges, has also been shown to be quite successful in describing experimental H-mode data. I_p is the plasma current, a the horizontal minor radius, B_t the toroidal magnetic field, R the major radius and q_{95} the edge safety factor. Greenwald et al. suggested a severe degradation of particle confinement when approaching this limit [1]. Its credibility for extrapolation to next step devices has still to be confirmed.

This paper presents H-mode density behaviour and scalings in the vicinity of the Greenwald limit and discusses especially the influence of increased plasma triangularity δ on the density operation space.

Discharge Parameters :

Our investigations concentrate on lower single null discharges (R = 1.65 m, a = 0.5 m, $\kappa \sim 1.6$) in deuterium with I_p of 0.4-1.2 MA and B_t of 1.5-3 T, corresponding to q_{95} between 3 and 12. NBI heating powers up to 15 MW have been applied. $\overline{n}_e$ ranges between $0.5 \cdot 10^{20} m^{-3}$ and $1.3 \cdot 10^{20} m^{-3}$.

Most experiments covering the large parameter space in I_p, B_t and P_{heat} are performed with a relatively low triangularity of $\delta \approx 0.2$. A few recent experiments, however, are carried out with an increased δ of ≈ 0.3. The actual divertor is a closed one [8].

High Density H-mode Operation :

The H-mode is generally accessible when the input heating power P_{heat} exceeds a certain limit depending on density and magnetic field $P_{heat}^{L\rightarrow H} = P_{thresh} \propto \overline{n}_e B_t$ [2]. In the validity range of the scaling the H$\rightarrow$L-mode back-transition shows hysteresis character and happens at roughly $P_{heat}^{L\rightarrow H}/2$. Closely above the threshold the H-mode is characterized by high frequency type-III ELM's but deeper in the H-mode the ELM activity changes to low frequency type-I ELMs [3].

Generally, during an increase of line averaged density in the H-mode up to the non-disruptive H-mode density limit the discharges exhibit normally a wide type-I ELM operation window. At high densities type-III ELMs reappear slightly below the H→L back-transition. Divertor detachment begins at medium line averaged densities firstly in between type-I ELMs and develops continuously further in the type-III ELM phase. This behaviour can be clearified in Figure 1 showing the carbon III radiation C_{div}^{III} and the ion saturation current I_{sat} profiles in the outer divertor at the start of detachment (solid lines) and slightly below the H-mode density limit during type-III ELMs (dashed lines). A reduction of I_{sat} by roughly an order of magnitude, as demonstrated in Fig. 1 b) at the strike point, can be interpreted as complete detachment [4]. The energy confinement,

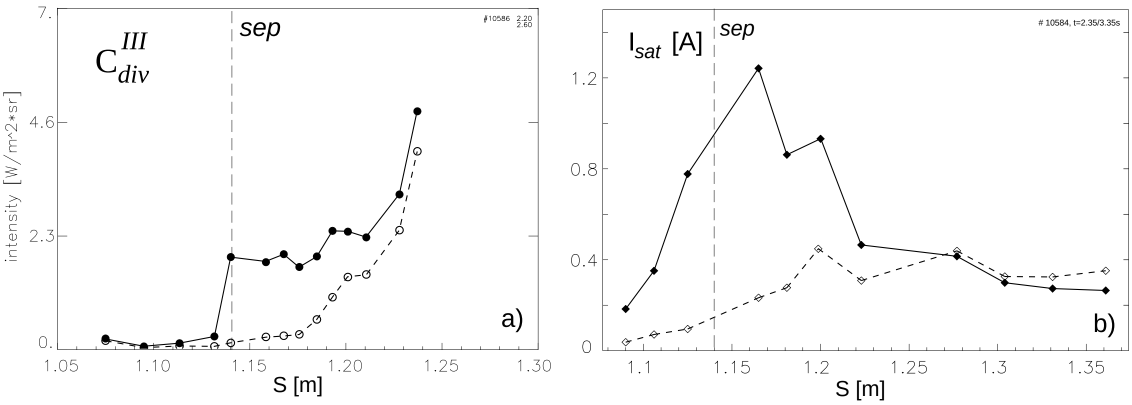

Figure 1: *Figure a) and b) show C_{div}^{III} and I_{sat} profiles, respectively, in the outer divertor during type-I ELMy phases at the start of detachment (solid lines) and close to the H-mode density limit with type-III ELMs (dashed lines). The private flux region is left of the separatrix. The suppression of I_{sat} at the strike point close to the density limit is clearly seen.*

however, degrades with increasing recycling monotonically down to L-mode levels [7,8]. No distinct confinement transition is observed from type-I to type-III ELM phases.

Earlier experiments with the low triangularity $\delta \approx 0.2$ have shown that the power necessary to sustain H-modes increases dramatically when one approaches Greenwald densities [5]. This means that the H-mode density limit becomes nearly independent of P_{heat} and, hence, deviates strongly from the conventional $\overline{n}_e \ B_t$ threshold power scaling mentioned above. Moreover, the threshold hysteresis is vanished. To show this behaviour in a demonstrative picture and to draw a common L→H-mode threshold for discharges with different plasma parameters, we replace in the conventional $P_{thresh} \propto \overline{n}_e \ B_t$ expression the line averaged densities by normalized densities $\overline{n}_e/\overline{n}_e^{GW}$, yielding $P_{heat} \ / \ (I_p \ B_t) \propto \overline{n}_e \ / \ \overline{n}_e^{GW}$.

Figure 2 exhibits the new results achieved with the increased triangularity of $\delta \approx 0.3$. The corresponding densities achieved with the low triangularity are sketched by the shaded area for comparison. It is obvious that the increase of triangularity leads to a clear gain in density operation space of about 15 %. This tendency is also observed on other machines [6]. Attributes like the weak threshold power dependence and, e.g., the flat density profile shape represented by $n_e^{sep}/\overline{n}_e \approx 0.7$ [5] seem to be preserved. There are some indications that the gain in density might be lower at high q_{95}, but additional experiments have to clearify this.

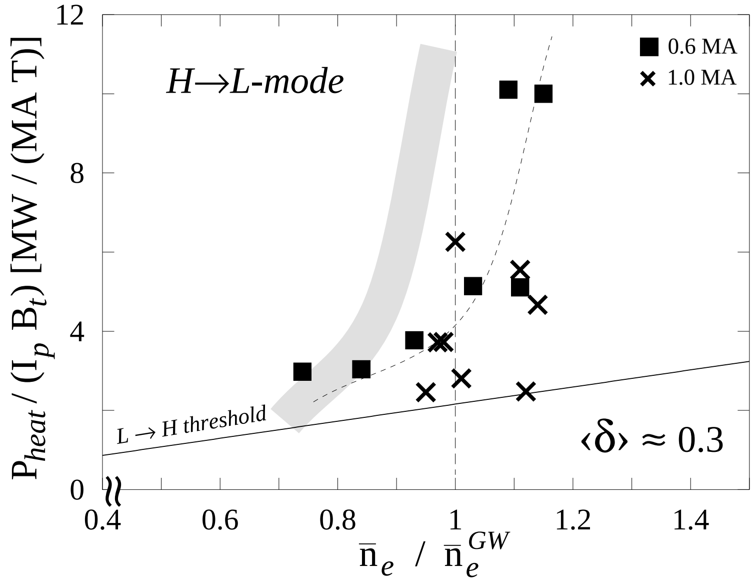

Figure 2: *The density operation diagram shows the strong deviation of the power needed to achieve and sustain H-mode close to $\overline{n}_e^{GW}$ from the usual $P_{thresh} \propto \overline{n}_e\ B_t$ scaling (inclined line). The data points are gained at $\delta \approx 0.3$. The shaded area represents the corresponding densities for $\delta \approx 0.2$.*

The large parameter variation in the low triangularity data base offers a refined fit of the parameter dependencies of the H-mode density limit. This might help to confirm density scalings for extrapolation and allow for the discrimination between different density limit models. The experiments are well described by the empirical regression fit :

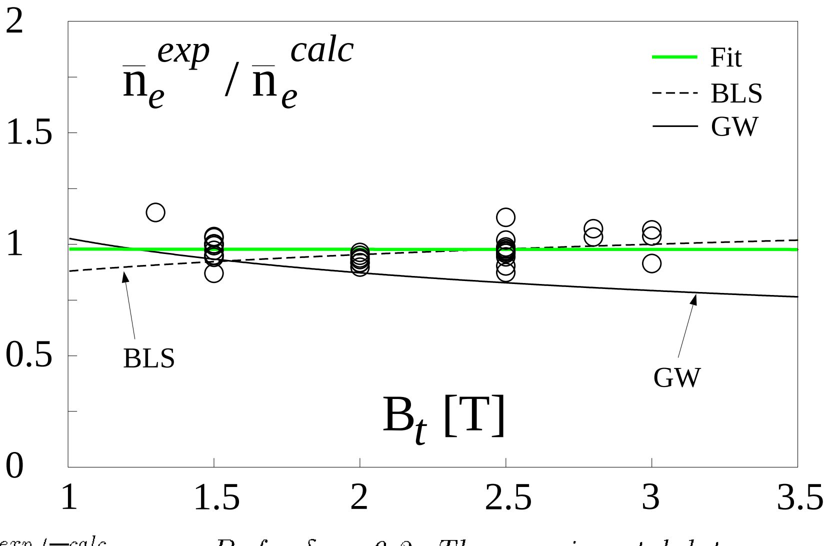

Figure 3: $\overline{n}_e^{exp}/\overline{n}_e^{calc}$ *versus* B_t *for* $\delta \approx 0.2$*. The experimental data are normalized by three different scalings (see text) and the fit through each data set is plotted. A clear difference is seen between the empirical fit* $\overline{n}_e \propto B_t^{0.6}$ *and the Greenwald scaling* $\overline{n}_e \propto B_t$.

$$\overline{n}_e^{exp} = 5.0\ \frac{q_\perp^{0.15}\ B_t^{0.61}}{(q_{95}\ R)^{0.95}}$$

$[10^{20}\mathrm{m}^{-3},\ \mathrm{MWm}^{-2},\ \mathrm{m},\ \mathrm{T}]$, where $q_\perp$ is P_{sep}/S with the plasma surface S and

$P_{sep} = P_{heat} - P_{rad}^{bulk}$ the power flowing across the separatrix into the scrape-off layer. It is remarkably close to the following scaling proposed in [9]

$$\overline{n}_e^{BLS} = 4.14 \; \frac{q_\perp^{0.09} \; B_t^{0.53}}{(q_{95} \; R)^{0.88}}$$

which relates the H-mode density limit to divertor detachment. We also compared our findings with the Greenwald scaling

$$\overline{n}_e^{GW} = \frac{I_p}{\pi a^2} \equiv 1.59 \; g \; \frac{B_t}{q_{95} \; R}$$

where g is determined by the plasma shape and held constant in our experiments. While the first two scalings virtually coincide on the existing database, the deviations from the Greenwald scaling can be reliably assessed. This is particularly true of the B_t dependence which is clearly weaker $\propto B_t^{0.6}$ than in the Greenwald scaling $\propto B_t$, as illustrated in Fig. 3.
In edge based models the B_t dependence is directly related to the B_t-dependence of the underlying transverse scrape-off layer transport (BLS scaling). The wide B_t variation in the present database offers for the first time the possibility to discriminate between various alternative transport models.

Summary :

Systematic H-mode density limit investigations are performed on ASDEX Upgrade at low (0.2) and, recently, at medium (0.3) triangularity δ. Generally, the power necessary to sustain the H-mode increases dramatically if one approaches the Greenwald limit, which means that the accepted H-mode power threshold scaling $P_{thresh} \propto \overline{n}_e \; B_t$ not longer valid is at these high densities. The H→L-mode back-transition is correlated to clear divertor detachment. A regression fit of the data set covering a large variation of the plasma parameters I_p, B_t and P_{heat} (at fixed $\delta \approx 0.2$) reveals in contrast to the Greenwald scaling a moderate but distinct B_t dependence of the H-mode density limit.
Additionally, the recent experiments with increased triangularity show that the achievable density operation space enlarges noticeably with rising δ. Nevertheless, with gas-puffing alone it is still difficult to overcome the Greenwald limit and maintain good energy confinement. Pellet injection from the magnetic high field side [5,10] may support these efforts. Future experiments tend to increase the trinagularity further.

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