OPERATIONAL WINDOW AND PERFORMANCE AT HIGH HEATING POWER IN THE ASDEX UPGRADE TOKAMAK

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1. INTRODUCTION

Recently, a second neutral beam injector was taken into operation on the ASDEX Upgrade tokamak. This allows to investigate the plasma properties, the various operational windows and the operation of the new divertor-II with its cryopump over a wider range of parameters. This paper shortly describes the ASDEX Upgrade NBI system and gives an overview of the operational windows (density limit, β-limit, H-mode region) as well as of the plasma performance at high NBI heating power.

2. THE ASDEX UPGRADE NBI SYSTEM

The 2^{nd} neutral beam injector is essentially a copy of the first one. Each injector is equipped with four ion sources. All beams are injected in co-direction, however rather perpendicularly with radii of tangency R_T = 0.53 m for the more radial and R_T = 0.93 m for the more tangential beams (plasma: R_0 = 1.65 m, a = 0.50 m). The beams are routinely operated at 55 kV in H_2 or 60 kV in D_2. With eight beams 14 MW (H^0) and 20 MW (D^0), respectively, are injected. The only difference between the two injectors are the plasma sources: conventional arc sources are used on the 1^{st} injector whereas the 2^{nd} injector has new rf sources [1]. This later system is simpler in many respects and yields a higher proton fraction: 71% of the neutral power is in the full energy component compared to 65% in case of an arc source. The 2^{nd} injector not only increases the heating power but also improves the flexibility of NBI system. The two injectors can be operated with different voltages and/or species and for a required power less than the maximum value the power injected per beamline can be reduced to minimize duct losses.

3. OPERATIONAL WINDOWS

An important precondition for fully exploiting the available heating power on ASDEX Upgrade is the improved power handling capability of the new divertor-II. For P_{NI} = 20 MW, P/R is at least comparable to high power JET discharges and P/S exceed the values of JET and ITER by typically a factor of 2. So far no problems have been encountered at the corresponding heat fluxes: $p_{max} \approx 4$ MW/m^2 onto the divertor plates was measured for P_{NI} = 20 MW [2].

3.1 H-mode operation

Whereas 10 MW of D^0 beams from only one injector was sufficient to study H-mode plasmas in deuterium well above the L/H-threshold for nearly all parameters such investigations were restricted in hydrogen with 7 MW (H^0) to rather low n_e and B_T. With 14 MW H^0 beams this restriction is not valid anymore. Fig. 1 shows the operational diagram P_{Heat} vs. $\bar{n}_e * B_T$ as obtained during the recent experimental campaign in hydrogen (parameter range: $0.6 \leq I_P[MA] \leq 1.0$, $1.5 \leq B_T[T] \leq 2.5$, and $4.3 \leq \bar{n}_e[10^{19}\ m^{-3}] \leq 13.0$). L-mode and H-mode with type-III and type-I ELMs are distinguished. The line separating L- and H-mode discharges is given by $P_{Heat} = 4.2 * \bar{n}_e * B_T$, roughly in agreement with what has been found earlier with P_{NI} < 7 MW. There are, however, some L-mode data well above the L/H threshold. All these

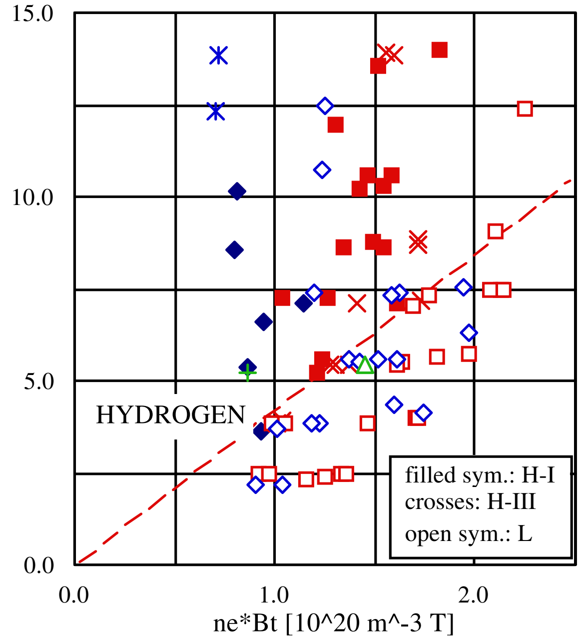

Fig.1 *Operational diagram: H-mode (type-I and type-III ELMs) and L-mode in hydrogen*

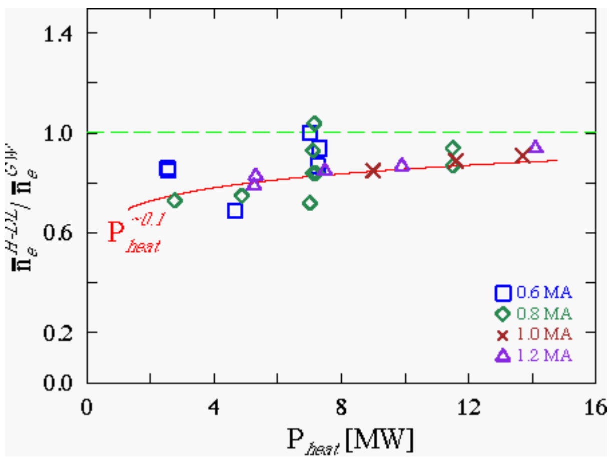

Fig.2 *Upper density limit for H-mode operation normalized to n_e-Greenwald in deuterium*

data are taken at high density: $\bar{n}_e > 0.7 * n_{GW}$ {Greenwald density: $n_{GW}[10^{20}\ m^{-3}] = I_p[MA] / (\pi a^2[m])$}. On the other hand, all H-mode data in Fig. 1 have: $\bar{n}_e < 0.7 * n_{GW}$. This upper density limit for the H-mode will be further discussed below. In deuterium, the L/H power threshold is given by $P_{Heat} = 2.1 * \bar{n}_e * B_T$ for the new divertor-II, about 20% above the value found for divertor-I. This higher threshold power is attributed to a higher edge density in Div-II [2].

3.2 Density limit

During a continuous density rise in H-mode discharges fuelled by gas puffing at constant input power two types of density limits are observed [3]: At $\bar{n}_e$ close to but below n_{GW} the discharge falls back into L-mode – as described above for hydrogen plasmas. Further rising n_e leads to the well-known disruptive (L-mode) density limit which is power-dependent. So far, only the upper density limit for H-mode discharges has been further explored with the now available higher heating power. Results for deuterium discharges are given in Fig. 2. Obviously, the limit is well defined for all plasma currents with a very weak dependence on input power ($P^{-0.1}$). Typically, the upper H-mode density limit is in the range of $0.7\text{-}0.8 * n_{GW}$ which is similar to what has given above for hydrogen plasmas.

3.3 Beta limit

The doubling of the NBI power has enabled β-limit studies to be performed over a much wider range of parameters in deuterium plasmas and, for the first time, in hydrogen. In all cases the stationary β-values achieved are limited by the occurrence of a (3/2) MHD-mode at $q \approx 1.5$ which is interpreted as neoclassical (resistive) tearing mode (NTM) [4]. During a discharge the plasma energy content first rises with increasing heating power until the growth of the (3/2)-mode causes β to drop by typically 20-30% within some 200 ms. With the mode persisting quasi-stationary conditions are usually obtained at constant input power and a further rise in P_{NI} can lead to higher β again, however, the confinement deterioration remains. NTM`s show a hysteresis type of behaviour; they disappear only after a significant reduction in heating power. For $q_{95} \approx 3.0$ or lower – cases not considered here – the β-limit can be disruptive.

Fig. 3 shows the β_N-values $\{\beta_N = \beta_{tot}[\%] / (I_P[MA] / (a[m] * B_T[T]))\}$ vs. P_{Heat} as achieved in NBI heated (D^0), gas puff (D_2) fuelled H-mode plasmas with type-I ELMs during the recent experimental campaign (parameter range: $0.6 \le I_P[MA] \le 1.4$, $1.5 \le B_T[T] \le 3.0$, $3.0 \le q_{95} \le 6.9$ and $3.7 \le \bar{n}_e[10^{19} m^{-3}] \le 10.8$). The saturation of β_N with increasing input power is obvious from the data. The open symbols refer to the stationary phases in the presence of NTM`s. Even under these conditions $\beta_N \approx 3$ is found, however, at a significantly higher heating power as com-pared to the cases where those values are achieved transiently before the confinement is deteriorated by the occurrence of the mode. NTM`s have also been observed in hydrogen plasmas at $\beta_N > 2.2$.

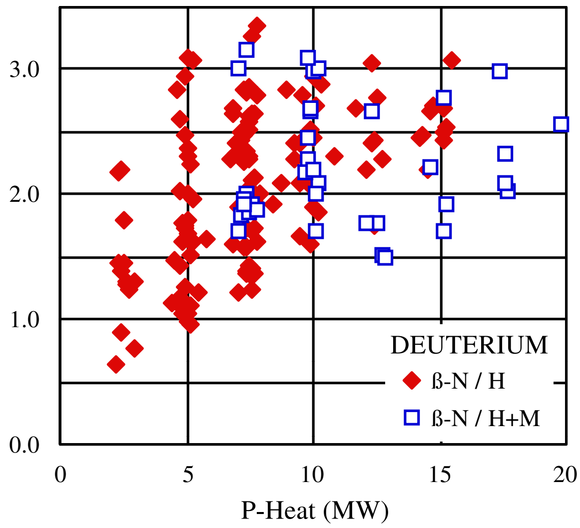

Fig.3 *β_N-values in deuterium. Open symbols: β_N during quasi-stationary phases with NT mode.*

The onset of a NTM, however, is not only determined by exceeding a β_N threshold value. At higher densities (i.e.: lower temperature, higher collisionality at q = 1.5) higher plasma pressures can be maintained stationary, unperturbed by the (3/2)-mode. On the other hand, at low enough collisionalities on the q = 2 surface additional (2/1)-neoclassical tearing modes occur. Sawteeth and/or fishbones have been found to trigger the (3/2)-modes. Obviously, both instabilities can create the seed island necessary for the growth of a NTM [4]. However, spontaneous growth of the mode is also observed. Control of sawteeth or fishbones is therefore not sufficient to suppress this mode. Attempts to stabilize NTM`s by local EC current drive inside the island have been started [5].

The significantly widened data base of high-β discharges as obtained due to the now available enhanced heating power has triggered more detailed theoretical investigations on NTM`s [6]. The ASDEX Upgrade results were shown to agree well with the analytical theory based on a generalized Rutherford equation and the mechanisms responsible for destabil-ization of the mode could be clearly identified. The observed dependence of the onset of the mode on the collisionality as well as the above mentioned hysteresis are predicted correctly.

4. PLASMA PERFORMANCE

Within the operational windows described above, the 2nd neutral beam injector on ASDEX Upgrade allows to study the performance of high power heated plasmas over a larger range of parameters. The deterioration of confinement observed at high β-values, as discussed in the previous section, however, significantly restricts this performance in deuterium discharges. Maximum values of the plasma energy content exceeding 1.2 MJ are achieved only transiently.

The confinement times (τ_{mhd}) related to the ITER-89P scaling [7] as function of the total heating power (for deuterium and hydrogen) and of the plasma density (for deuterium) are shown in Fig. 4 for the parameter ranges given in sections 3.1 (H^+) and 3.3 (D^+). The open symbols refer to quasi-stationary H-mode (D^+) discharges in the presence of the neoclassical tearing mode and illustrate the reduced confinement of these discharges. In deuterium, H-mode multipliers above 2.0 are measured in many cases. However, there is a clear trend of confinement degradation with increasing density as described earlier [3]. The strong gas puffing necessary to rise n_e is always associated with a decrease in plasma energy in contrast to $n_e^{0.1}$-dependence of the scaling. The few data around $\bar{n}_e = 8*10^{19}$ m^{-3} with $f_{ITER89P} > 2$ are from discharges with low ELM frequency (≈50 Hz) where the density rises with no or little gas puffing and the divertor neutral density remains low. The reason for this (transient) behaviour

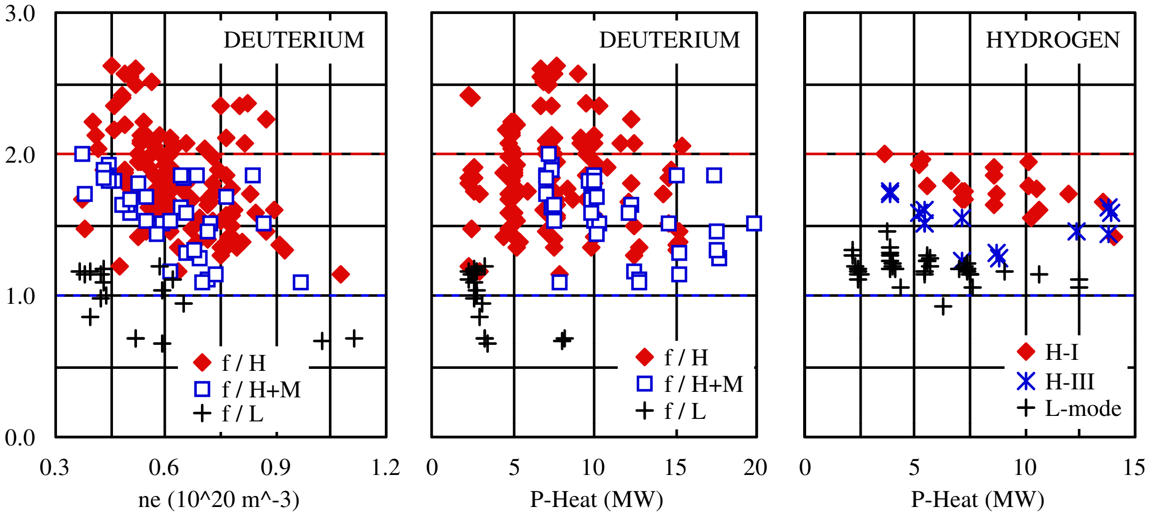

Fig.4 *Confinement time (τ_{mhd}) normalized to ITER-89P scaling vs. density (deuterium) and P_{Heat} (hydrogen and deuterium) in L- and H-mode*

is not yet clear. Deuterium discharges not affected by the NTM roughly follow the power dependence ($P^{-0.5}$) of the scaling law up to the highest heating power. The best confinement ($f_{ITER89P} \geq 2.5$ at ≈8 MW) is found for discharges where the new divertor cryopump is active and NBI starts at a relatively low density, sometimes even during the current ramp. The density rises during NBI again without gas puffing. These discharges are characterized by rather high temperatures: $T_i(0) \approx 10$ keV and $T_e(0) \approx 6$ keV have been measured.

In hydrogen, H-mode discharges with type-I ELMs have f_{ITER89}-values of 1.5 - 2.0, indicating that for ASDEX Upgrade H-modes the isotope dependence is slightly stronger than assumed in the scaling ($A^{0.5}$); see also ref. [8]. The confinement of L-mode (H^+) plasmas is higher by 10-20% than predicted by ITER-89P; H-mode plasmas with type-III ELMs observed close to the L/H threshold or at high densities lie in between L-mode and H-mode with type-I ELMs.

In summary, the 2nd neutral beam injector has proved to be a very useful tool to enhance the operational range of ASDEX Upgrade plasmas. The power handling capability of the new divertor-II allows discharges to be investigated up to the available 20 MW of NBI power. The plasma performance is however limited by the occurrence of neoclassical tearing modes.

References

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