NEUTRAL BEAM DEPOSITION EXPERIMENTS AT ELEVATED DENSITIES IN ASDEX

E. Speth, O. Gruber, G. Janeschitz, H. Murmann, H. Niedermeyer, F. Wagner, O. Vollmer, G. Becker, H.S. Bosch, H. Brocken, A. Eberhagen, G. Fussmann, O. Gehre, J. Gernhardt, G. v.Gierke, E. Glock, G. Haas, J. Hofmann, A. Jzvozchikov[1], F. Karger, M. Keilhacker[2], O. Klüber, M. Kornherr, K. Lackner, M. Lenoci[3], G. Lisitano, F. Mast, H.M. Mayer, K. McCormick, D. Meisel, V. Mertens, E.R. Müller, A. Pietrzyk[4], W. Poschenrieder, H. Rapp, H. Riedler[5], H. Röhr, J. Roth, F. Ryter[6], J. Schneider, C. Setzensack, G. Siller, P. Smeulders, F. Söldner, K.H. Steuer, D. Zasche.

Max-Planck-Institut für Plasmaphysik,
EURATOM-Association, D-8046 Garching, FRG

INTRODUCTION

In the past the penetration requirements for neutral beams have been derived from the postulate that the beam power should be deposited near the plasma axis. It has been demonstrated theoretically that the shape of the deposition profile is governed by the parameter a/λ (a = minor plasma radius, λ = mean free path of the injected neutrals at line-averaged density). Assuming constant electron thermal conductivity, it can be shown theoretically, that decreasing penetration (i.e. increasing a/λ)of the beam results in decreasing global energy confinement time and decreasing attainable central electron temperature, values of a/λ in excess of 2 being considered as critical /1/. Consequently the beam energies necessary to penetrate large plasmas in order to heat the plasma centre lie in the range of several 100 keV /2/, which leads to serious difficulties for positive-ion-based neutral beams due to the decreasing neutralisation efficiency. As a solution negative-ion-based systems have been proposed, which would offer reasonable efficiency, but require the development of a new technology.

In order to make an experimental assessment of the required beam penetration a series of experiments were started in 1984 in ASDEX, in which neutral beam deposition was varied systematically. The first results reported at Budapest /3/ showed (in agreement with other experiments /4/) no degradation of heating and confinement within the parameter range accessible, but suffered from following drawbacks: the plasma density was too low ($\bar{n}_e = 6 \times 10^{13}$ cm^{-3}) for extremely hollow deposition profiles to be produced and the power level was only moderate (1.3 MW). This paper describes the continuation of the experiments at almost twice the density and three times higher power.

EXPERIMENTAL PARAMETERS AND RESULTS

The experiments were carried out under the following conditions: I_{pl} = 420 kA, B_T = 2.2 T, $\bar{n}_e = 1.15 \times 10^{14}$ cm^{-3}, D_2-plasma, double-null, diverted. The density was built up with D_2 gas-puffing before and during the injection pulse (τ = 400 msec), and reached a stationary state towards the end of the pulse. Comparison was made between shots of different beam

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[1] Academy of Sciences, Leningrad, USSR; [2] Assigned to JET Joint Undertaking, England; [3] ENEA Frascati, Italy; [4] University of Washington, Seattle, USA; [5] Fellow of the Schiedel-Stiftung, Austria; [6] CEN Grenoble, France

energy per nucleon, i.e. 40 kV acceleration voltage, H^o-injection, $<E> =$ 25 keV/AMU (P_N = 3.6 MW) and 44 kV acceleration voltage, D^o-injection, $< E> =$ 13 KeV/AMU (P_N = 4.1 MW), keeping everything else identical. All the shots were L-type discharges.

The global energy confinement time, evaluated from the diagmagnetic β_{pol} during the stationary phase, does not show a significant difference (see Fig. 1). The value of τ_E = 35 msec is consistent with ASDEX L-scaling. The electron temperature profiles during the stationary phase (taken from YAG-laser scattering and β-shift corrected) are shown in Fig. 2. As can be seen, there is a reduction of about 10 % in $T_e(0)$ for the low-energy case (44 kV D^o) inspite of the somewhat higher power. The corresponding power deposition profiles are shown in Fig. 3.

DISCUSSION

If one interprets this reduction of $T_e(0)$ for the 44 kV D^o-case as the onset of degradation of heating, one may identify the corresponding profile parameter $a/\lambda = 6$ with the limit for off-axis deposition in tokamaks ($\lambda = (\bar{n}_e \sigma_{TOT})^{-1}$; $\bar{n}_e$ = line-averaged density, σ_{TOT} = total trapping cross-section).

In calculating $a/\lambda = 6$ a correction for steeper injection angles (15 - 20° on large machines instead of 45° on ASDEX) has been applied. Applying this scaling law to larger plasmas yields the curve shown in Fig. 4. It can be seen that e.g. 70 keV D^o in JET or 120 keV D^o in NET would be sufficient to produce deposition profiles of the same relative shape as in Fig. 3b and would hence result in non-degraded heating.

At low energy ($E < 20$ keV/AMU) the deposition limit may not be determined by heating but by impurity radiation due to enhanced charge-exchange wall erosion. Enhanced impurity (iron) influx was e.g. observed in the 44 kV D^o-case at the end of a 400 msec-pulse, but was absent in the 40 kV H^o-case. Low energy injection at $a/\lambda = 6$ may therefore be limited by an additional constraint, namely to $E > 20$ keV/AMU independently of plasma size and calls for a high proton ratio from the ion sources. From the present data it cannot be entirely excluded that this limit may even be higher ($\sim$ 30 keV/AMU).

It is important to note, that hollow deposition profiles as shown in Fig. 3b are sensitive to central impurity radiation leading to radiation collapse. The viability of hollow deposition profils must therefore be confirmed in long pulse experiments.

If the principle of "profile consistency", i.e. the invariance of the temperature profile with respect to power deposition /3,5,6/ will persist in larger tokamaks, it may even not be required to obey a/λ = const. in order to produce heating and confinement without degradation. Other scaling laws may have to be considered, e.g. relating λ to the width of the toroidal shell outside $q = 2$ /6/, or possibly λ = const., suggesting that it may be sufficient to deposit the power independently of plasma size at constant depth measured from the plasma edge and λ chosen just large enough to avoid enhanced charge exchange wall sputtering (see above).

It should be noted, that the conclusions contained in this paper are valid for injection into tokamaks and do not necessarily apply to stellarators.

Finally it may be appropriate to reconsider the development of power recovery and plasma sources with high atomic ion yield in comparison with negative ions.

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FIGURE CAPTIONS

Fig. 1: Global energy confinement time τ_E vs. species-averaged beam energy <E> and full beam energy E_0 respectively

Fig. 2: Electron temperature profiles

Fig. 3: Power deposition profiles for ohmic power (p_Ω), electrons (p_e), ions (p_i) and total power (Σ).
a) for 40 KV H^0, 3.6 MW
b) for 44 kV D^0, 4.1 MW

Fig. 4: Opacity $\bar{n}_e \cdot a$ vs. species-averaged beam energy <E> ;
injection angle < 20°,
σ_{TOT} = total trapping cross section,
$\bar{T}$ = average plasma temperature

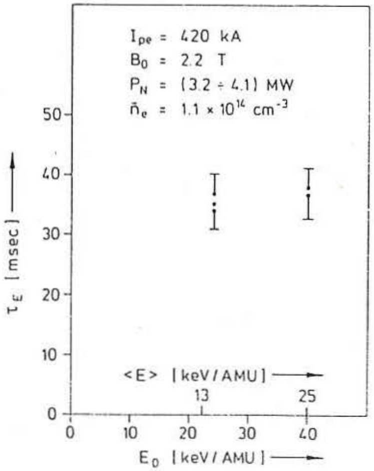

Fig. 1

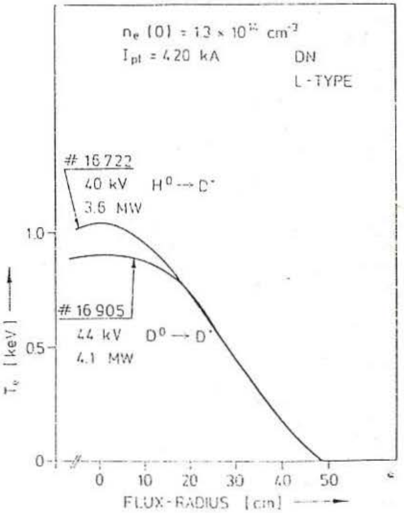

Fig. 2

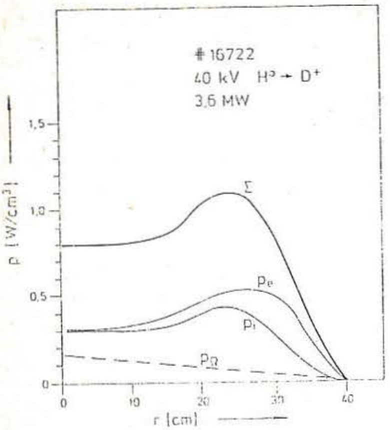

Fig. 3a

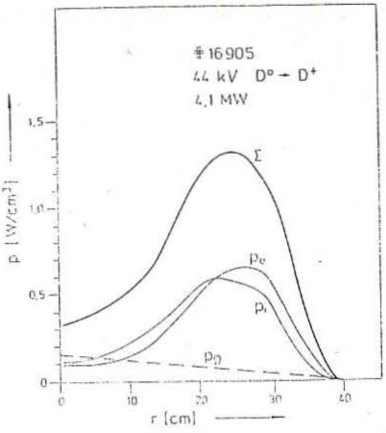

Fig. 3b

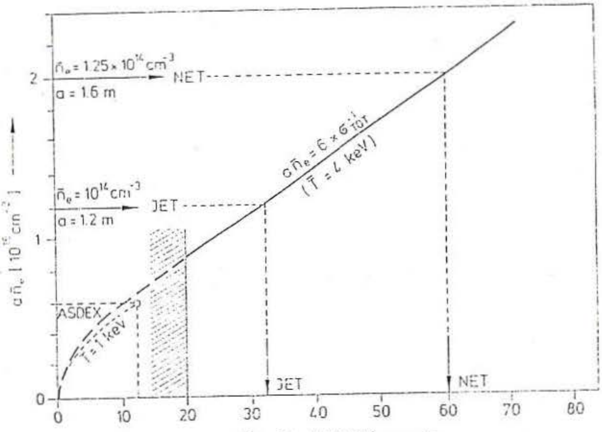

Fig. 4