HEATING EFFICIENCY OF HIGH-POWER PERPENDICULAR NEUTRAL-BEAM INJECTION IN PDX

BY

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Abstract

The heating efficiency of high power (up to 7.2 MW) near-perpendicular neutral beam injection in the PDX tokamak is comparable to that of tangential injection in PLT. Collisionless plasmas with central ion temperatures up to 6.5 keV and central electron temperatures greater than 2.5 keV have been obtained. The plasma pressure, including the contribution from the beam particles, increases with increasing beam power and does not appear to saturate, although the parametric dependence of the energy confinement time is different from that observed in ohmic discharges.

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Neutral beams have been used successfully for auxiliary heating in many tokamak experiments. In most, the beams have been injected essentially tangentially to the toroidal magnetic field. For future large machines, perpendicular injection is attractive for achieving good beam penetration at beam energies that are practical for positive ion sources. Up to ~ 1 MW was injected near-perpendicularly into the TFR tokamak.[1] On PDX, these results have been extended to power levels of 7.2 MW in order to examine the effectiveness of perpendicular injection. The PDX heating results have been compared with those from tangential injection on PLT under similar operating parameters and the detailed profile data has been studied using a transport analysis code to evaluate the ion and electron transport.

Experimental Facility: The PDX tokamak is described in Ref. 2. Neutral beam injection experiments have been conducted in both circular cross-section limiter discharges with water-cooled carbon limiters and in inside-Dee diverted discharges, in which titanium neutralizer plates absorb the incident power. In both configurations, titanium gettering in the upper and/or lower domes is used.

The PDX beam injection system developed by the joint PPL-ORNL Heating Project consists of four beam lines each with a 50 keV ion source.[3] The maximum power injected into the vessel is 7.2 MW with deuterium beams and 5.5 MW with hydrogen. The beams are oriented to inject along the direction of the plasma current at a tangency radius of 35 cm, giving an angle of 14° from the perpendicular at the center of the vessel.

Ion Heating: The central ion temperature is deduced from measurements of the Doppler broadening of TiXXI K_α line at 2.3 Å with a crystal spectrometer and by measurements of the charge exchange neutral spectrum. measured, both with ("active" method) and without ("passi diagnostic neutral beam to enhance the neutral density, and ion temperature measurement. During high power injection i average density less than 4 x 10^{13} cm^{-3}, all three mea agree within 10%.

Figure 1 shows the scaling of ion temperature as a for circular discharges with $\bar{n}_e$ in the range of 2 - 4 x 1 *the injected power less the power calculated to shine thro* high current (500 kA) and high field (2.2 T) discharges, up to 6.5 keV were obtained. The ion heating quality facto is somewhat variable and reaches values up to 4.5 (10^{13} In discharges with lower plasma current, η_i is smaller. circular discharges with I_p = 400 kA, the ion heating q comparable.

In the low-to-modest density (1 - 3 x 10^{13} cm^{-3}) di PLT, beam penetration was still quite good, and a direct cc heating efficiency in PLT and PDX can be made. In PLT, 4 injection, η_i was typically 4.5 in discharges with ion te keV; however, during some periods the ion heating was poor 3. The reasons for the variability in ion heating in PLT are not known, but it is nonetheless clear that the ion h perpendicular injection is comparable to that in PLT injection, for similar plasma current, toroidal field, a radii.

The similarity of the ion heating in PDX and PLT confirmed by an analysis of the ion thermal transport calculation[5,6] assumes classical electron-ion coupling (typically the main loss term in the ion energy balance in the core of PDX), a convective loss term ($5/2\ \nabla\ n_i\ T_i\ v_r$), and the neoclassical thermal conductivity[7] enhanced by some factor. The convection term is associated with a calculation of the particle balance based on the recycling neutral density profile normalized to a 40 ms recycling time and on the source rate of charged particles and thermal neutrals due to beam deposition. In the core, the neutral density is dominated by the beam sources, and thus the convective loss is relatively insensitive to variations in the recycling time. For high current (500 kA) and high field (2.2T) discharges, the ion transport model correctly predicts the central ion temperature with $\kappa_i \sim (1-2)\ \kappa_i^{NC}$. These results apply even when the ions are very deep in the banana regime of neoclassical theory ($\nu_{*i} \rightarrow 2 \times 10^{-2}$). The ion temperature in PLT is correctly predicted using a similar ion thermal transport model,[5] indicating that the ion heat loss during either perpendicular or tangential injection is comparable under similar conditions. By contrast, in lower current, lower field discharges, in PDX where decreased ion heating has been observed an enhancement of the neoclassical ion thermal conductivity by up to a factor of 5 was required to simulate the central ion temperature.

Electron Heating: The electron density and temperature profiles are measured with a 56-point, single-shot, horizontal Thomson scattering system. In circular discharges, the density increases during injection without additional gas puffing, and the density rise increases with neutral beam power. However, in diverted discharges additional gas is required to sustain or increase the electron density.

A summary of electron heating results is shown in Fig. 2. For P_{abs} < 2 MW and in both circular and diverted discharges, the electron temperature rise on axis is about 0.5 eV/kW which is comparable with the heating rate on PLT. The line-average electron density in the diverted discharges was $\sim 3.3 \times 10^{13}$ cm^{-3} and in the circular discharges varied from 1.7 at the lowest to 3.9×10^{13} cm^{-3} at the highest beam power. At higher powers, up to 5.5 MW absorbed, as a result of the density increase accompanying neutral beam injection in circular discharges, the total stored energy continues to increase, though the heating rate ($\Delta T_e/P_{abs}$) is reduced. Radiation losses are not significant in the electron power balance in the core of the discharge. Bolometric measurements indicate that the losses from the core by radiation and charge exchange are small ($\sim$ 10% of the input power), and measurements of the soft X-ray and ultraviolet spectrum substantiate this conclusion.

Further experiments have been conducted to clarify the scaling of electron heating with density. Preliminary experiments in diverted discharges have shown that the increase in electron temperature during beam injection is less with higher electron density. Transport analysis indicates that the total energy confinement time in these discharges is a weak function of electron density and that electron thermal conduction is the principal loss channel in the core. Consequently the favorable INTOR[10] scaling of electron heat conduction with electron density, based in large part on ohmically heated discharges, is not observed. Similar results have been obtained during tangential injection on ISX[11] and DITE,[12] suggesting that the difference in scaling for ohmic and neutral beam heated discharges is not simply a function of injection angle.

Magnetics: Magnetic measurements of $\ell_i/2 + \beta_\theta$[13] have been used to investigate the scaling of plasma β_θ with power. The quantity, $\beta_\theta I_p^2$, is a good measure of the total stored plasma energy. Typically, the calculated change in the internal inductance ($\ell_i/2$) (based on the measured electron temperature profiles) is small compared with the change in β_θ; thus the linear increase of $\Delta(\ell_i/2 + \beta_\theta)$ with beam power shown in Fig. 3 reflects mainly variations in β_θ. In 200 kA discharges, magnetic equilibrium analysis indicates that β_θ has reached 1.7, corresponding to $\beta_\theta \sim 0.5$ R/a at $q(a) = aB_T/RB_\theta = 7.5$. In 500 kA discharges at 2.2T and q(a) = 3, the total plasma pressure corresponds to $\beta(0) \simeq 4.4\%$ and $\langle\beta\rangle \simeq 0.7\%$. The major contribution to β_θ comes from the beam and thermal ions. In the PDX experiments, no indication of saturation of β_θ with power such as that seen in ISX[11] and DITE,[12] has been observed.

The ISX[11] and DITE[12] data imply that at a given power the stored plasma energy increases roughly as $I_p^{3/2}$, whereas in PDX the stored energy tends to increase approximately linearly with plasma current. Hence, according to the magnetic measurements, the global energy confinement time is found to be proportional to I_p in PDX and to $I_p^{3/2}$ in ISX[11] and DITE.[12]

In summary, ion temperatures of ~ 6 keV at electron densities in PDX of 3-4 x 10^{13} cm^{-3} have been obtained with perpendicular injection. Ion heating, defined as $\bar{n}_e \, \Delta T_i/P_{abs}$, improves with current, and at 500 kA the heating is equivalent to that seen with tangential injection in PLT. The energy confinement time is a weak function of electron density. The value of β_θ increases linearly with injected power up to 7 MW, and its dependence on plasma current shows improved global energy confinement at higher current. The parametric scaling of τ_E with plasma current and electron density, however, remains somewhat uncertain because the variables which affect the enhanced heat transport have not been identified. Just as techniques to optimize τ_E in ohmically heated discharges have been discovered, so too it is probable that new techniques will be developed to optimize τ_E in beam heated discharges and to decrease the variability in heating results.

We want to express our particular appreciation to H. Haselton and his group at ORNL for the development of the neutral beam sources, to M. Williams, T. Kozub, A. Von Halle, and the Neutral Beams technicians for their assistance in operating and maintaining the beam system, and to the PDX crew of engineers and technicians whose devoted efforts have made these experiments possible. Finally, we wish to thank Drs. H.P. Furth, P.H. Rutherford, and, especially, D.M. Meade for their continuing support of our efforts. This work was supported by the U.S. Department of Energy, Contract No. DE-AC02-76-CHO-3073.

Figure Captions

Fig. 1 The central ion temperature in circular hydrogen discharges increases with P_{abs}/n_e during deuterium injection as determined by passive charge exchange measurements.

Fig. 2 Thomson scattering measurements of central electron temperature (closed circles and triangles) and stored electron energy (open circles and triangles) in both circular and diverted discharges.

Fig. 3 $\ell_i/2 + \beta_\theta$ as determined by magnetic measurements in circular discharges increases linearly with injected power. Each point is the average of 5 - 25 shots.

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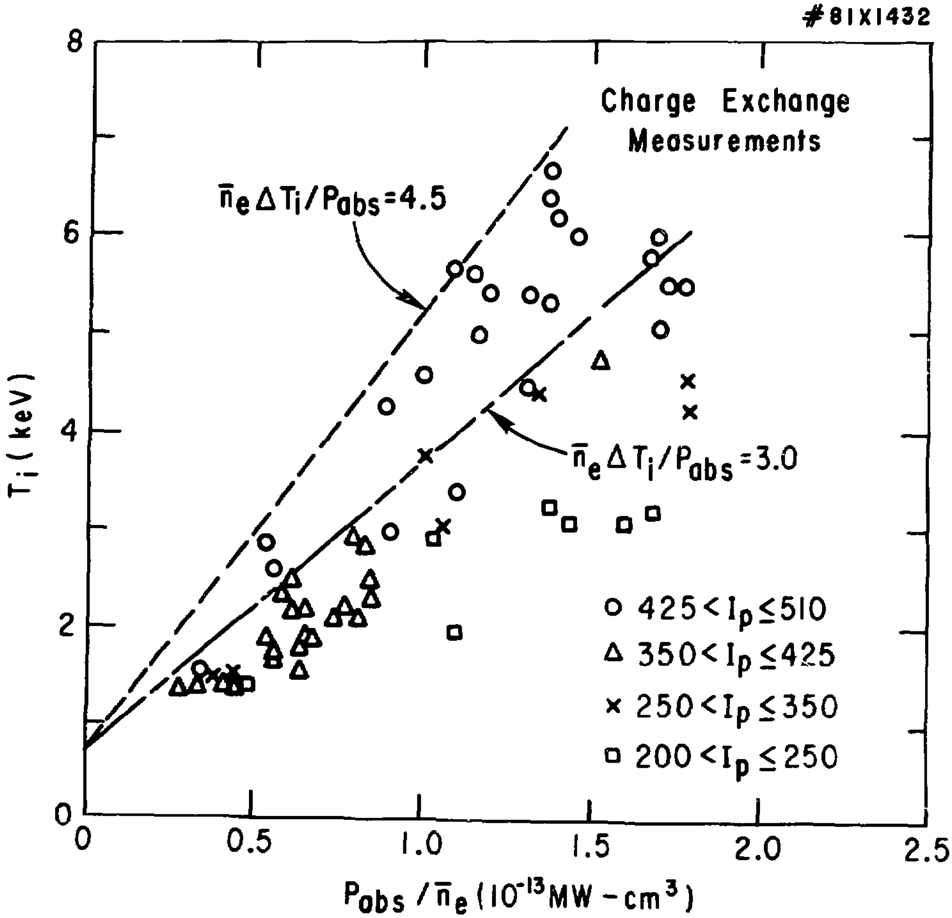
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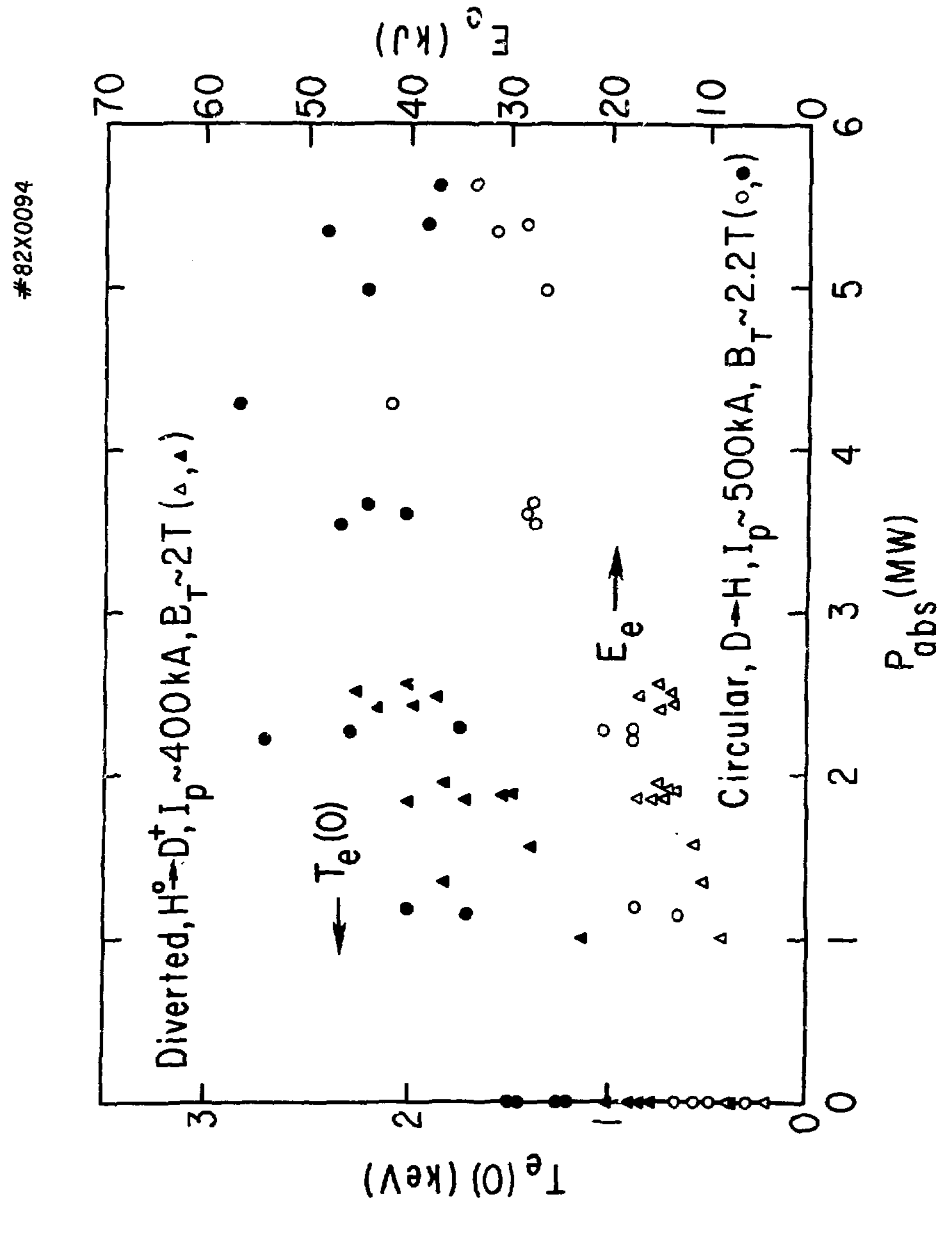
Charge Exchange Measurements
$\bar{n}_e \Delta T_i / P_{abs} = 4.5$
$\bar{n}_e \Delta T_i / P_{abs} = 3.0$
T_i (keV)
$P_{abs} / \bar{n}_e$ (10^{-13} MW - cm^3)
0
2
4
6
8
0
0.5
1.0
1.5
2.0
2.5
○ $425 < I_p \leq 510$
△ $350 < I_p \leq 425$
× $250 < I_p \leq 350$
□ $200 < I_p \leq 250$

Fig. 1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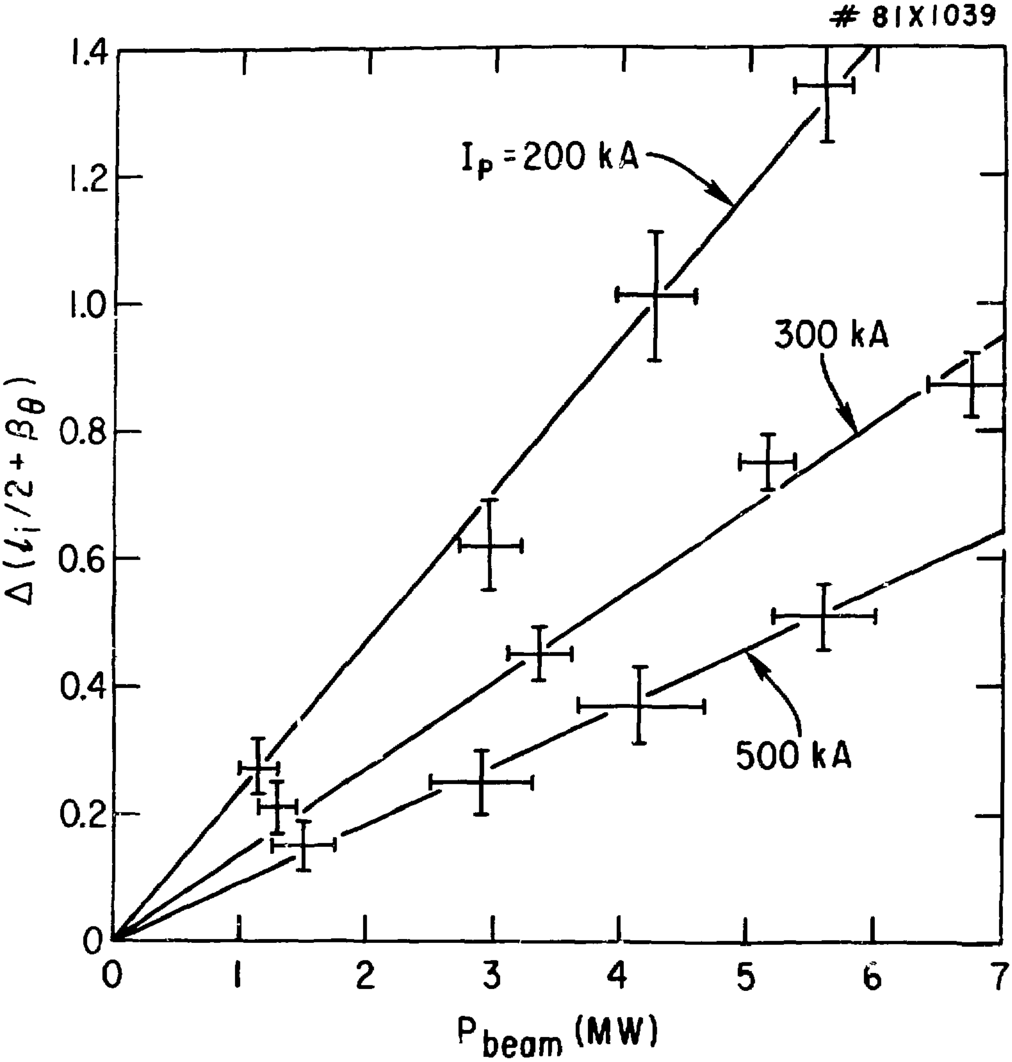
Diverted, H°→D+, Ip~400kA, BT~2T (△,▲)
Circular, D→H, Ip~500kA, BT~2.2T (○,●)
Te(0)
Ee
Pabs (MW)
Te (0) (keV)
Ee (kJ)

Fig. 2



81X1039
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
$\Delta(\ell_i/2+\beta_\theta)$
I_p = 200 kA
300 kA
500 kA
0
1
2
3
4
5
6
7
P_{beam} (MW)

Fig. 3