PPL-1919

PPPL-1919

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9-2-82
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J-5/63 (1)

Dr. 798

CONFINEMENT STUDIES WITH NEUTRAL-BEAM INJECTION

ON PDX AND PLT

PPPL--1919

by

DE82 020784

R. Goldston Et al.

July 1982

MASTER

PLASMA
PHYSICS
LABORATORY

UNIVERSITY OF THE STATE OF NEW YORK

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THIRD JOINT VARENNA-GRENOBLE INTERNATIONAL
SYMPOSIUM ON HEATING IN TOROIDAL PLASMAS

CONFINEMENT STUDIES WITH NEUTRAL-BEAM INJECTION
ON PDX AND PLT

Princeton Plasma Physics Laboratory
Princeton, NJ 08544

R. Goldston, S. Kaye, S. Davis, M. Bell, M. Bitter, K. Bol, D. Boyd*,
K. Brau, N. Bretz, A. Cavallo*, P. Colestock, D. Dimock, F. Dylla,
P. Efthimion, H. Eubank, M. Finkenthal, R. Fonck, B. Grek, L. Grisham,
R. Hawryluk, E. Hinnov, J. Hosea, H. Hsuan, D. Hwang, F. Jobs, D. Johnson,
R. Kaita, H. Kugel, D. Manos, K. McGuire, R. McCann, D. McCune, D. McNeill,
S. Medley, D. Mueller, E. Meservey, M. Okabayashi, K. Owens, M. Reusch,
N. Sauthoff, G. Schilling, J. Schivell, G. Schmidt, F. Stauffer*,
S. Sesnic**, L. Stewart***, S. Suckewer, G. Tait, H. Takahashi, F. Tenney,
P. Thomas****, H. Towner, S. von Goeler, R. Wilson, and G. Zankl**

ABSTRACT

Neutral beam injection experiments on PLT and PDX have been conducted over a wider range in parameter space than previously. On PLT H⁺ beams have been injected into well-confined high toroidal field, high density Ohmic plasmas, giving $n_e(0) \tau_{Ee}$ products during injection of up to 5×10^{12} sec cm⁻³. τ_{Ee} is found to rise slowly with increasing density in these experiments. Comparing these results with earlier (1979) discharges, which showed much lower heating efficiency, the importance of starting with a hot Ohmic plasma and a peaked density profile is striking. On PDX high power injection experiments over a range in plasma current have shown a significant variation with current of both ion heating and total stored plasma energy. Transport analysis of these results indicates that global confinement drops little when I_p is varied from 480 to 320 kA, but as I_p falls to 200 kA, τ_E deteriorates significantly.

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* University of Maryland, College Park, MD USA

** Max-Planck Institut für Plasmaphysik, 8046 Garching, Germany

*** Exxon Nuclear Co., Inc., Bellevue, WA USA

****JET Joint Undertaking, Abingdon, United Kingdom

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Attention has recently focused on low q operation, for the purpose of obtaining high beta plasmas. PLT and PDX have both been operated with cylindrical q in the range of 2.0 or below, with absorbed beam power of 1.8 MW (D°). Operating in this regime, the two machines have obtained, similar results, with PDX reaching a toroidal β of 1.3 - 1.4%, at $B_t = 12.6$ kG. These results suggest that parallel and perpendicular neutral beam injection are about equally well suited for low q operation. Strong sawtooth oscillations have been observed to travel to the plasma edge in PDX, but confinement is not substantially degraded relative to the higher toroidal field PDX results reported here.

I. INTRODUCTION

Initial neutral beam injection experiments on PLT focused on obtaining high temperature, collisionless tokamak plasmas. Towards this end operations concentrated on moderate density, high current, high toroidal field conditions. With these plasma parameters, global energy confinement was found to be similar in beam - heated and in Ohmically - heated plasmas. In initially high electron temperature, low density plasmas, the central electron energy confinement was found to improve during injection.^{1,2}

Since reactor plasmas will require high plasma pressure, as well as low collisionality, more recent injection experiments on PLT have concentrated on higher density discharges.^{3,4,5} In references 4 and 5 electron heating results measured with electron cyclotron emission over a range in density were reported. In Section II we show confinement analyses for a similar density scaling experiment, with full $n_e(r,t)$ and $T_e(r,t)$ data from Thomson scattering.

Initial injection experiments on PDX have concentrated on the low collisionality regime, in order to be able to make direct comparisons with PLT, and thus to assess confinement with perpendicular vs. tangential injection.⁶ When PDX was operated in conditions as similar to those of PLT as possible, similar ion heating (normalized to absorbed power) and ion energy confinement were obtained. Electron energy confinement seems to have been somewhat poorer. In the course of these experiments plasma current was found to be an important global parameter affecting both ion heating and total stored energy. Systematic power scaling experiments were therefore performed at different plasma currents and fixed toroidal field, in order to permit detailed analysis of changes in confinement with beam power, and especially with plasma current. In Section III we show the results from this study, and

discuss the implications for the variation of confinement with I_p in the PDX parameter range.

Recent results from ISX-B ⁷ increase the importance of studying confinement at high β in machines with greater plasma current capability. In order to obtain high λ plasmas, it is clearly advantageous to operate at low toroidal field, and thus low q . Both PLT and PDX have obtained high current, low toroidal field plasmas. With similar absorbed beam power, Thomson scattering and charge exchange measurements give very similar heating results. This suggests that plasma transport losses are not significantly different in this regime for tangential and perpendicular injection. Confinement analyses of these results are reported in Section IV.

In Section V we summarize the results reported here, and discuss their implications for future high β neutral beam injection experiments.

II. PLT DENSITY SCALING EXPERIMENT

In order to investigate changes in confinement as a function of plasma density, a series of experiments were performed on PLT varying the line average electron density from 2.7 to $6.5 \times 10^{13} \text{ cm}^{-2}$. The toroidal field was fixed at 32 kG, and the plasma current varied from 510 to 450 kA. The H^0 neutral beam power absorbed in the plasma was fixed at $\sim 1.2 \text{ MW}$, using 2 co-injectors and 1 counter-injector. The electron density and temperature were measured as functions of time and radius using the TVTS system, (with density normalized to the 2 mm interferometer), and the neutron detection system was used as the primary monitor of the ion temperature of the background D^+ plasma. Passive charge exchange measurements, while available, were severely cut off at the higher densities. A multi-channel bolometer array was used to measure the radiated power as a function of time and radius. At each density

measurements were made both before and during NBI. Measurements were also made during the same run sequence, but without injection, in order to determine Ohmic confinement at the same late time in the discharge that the beams were fired. The central electron temperatures measured in these experiments are shown in Fig. 1. At a line average density of $4 \times 10^{13} \text{ cm}^{-3}$, we obtained $\sim 2/3$ eV/kW electron heating efficiency, which is characteristic of previous good quality electron heating with H^0 injection in PLT.^{1,4}

Ion temperature measurements in these discharges were more problematical. In interpreting neutron measurements with H^0 injection into D^+ plasmas, one always has the problem of evaluating the effect of the dilution of deuterium by hydrogen ions, either injected as energetic particles or recycling from the walls. In particular in these experiments the hydrogen beams were conditioned continuously with their isolation valves open during the time between shots. Hydrogen flowing from the ion sources would therefore have loaded the gettered surfaces substantially. Comparing similar density Ohmic plasmas before the beam valves were opened, and well into the run day, we found that the neutron emission dropped by a factor of 2-3. This result can be explained by assuming that an initially 80% D^+ , 20% H^+ isotopic mixture plasma became a 50:50 mixture during all of the relevant part of the experimental run. In particular the high density Ohmic cases that were alternated with beam injection would have had very large $T_e - T_i$, if one assumed that 100% of the hydrogenic ions in the discharge were deuterons.

The experimental data described above were analyzed using the TRANSP transport analysis code.^{8,9,5} The code computes the ion temperature profile as a function of time, using an ion power balance which includes conduction, convection ($\propto 5/2 \text{ nTv}_y$), charge exchange, and classical ion-electron coupling. The global particle confinement time, τ_p , which controls the

recycling neutral density, was set to 30 msec, and the ion thermal conduction was taken to be neoclassical, in the form given by Rutherford et. al.¹⁰ This prescription has been previously shown to give good agreement with PLT "good" ion heating results.^{3,5} The "Rutherford" formula tends to be a factor of ~ 1.5 higher than the conduction coefficient given by Hinton and Hazeltine,¹¹ but it shows surprisingly good agreement with the results of Bolton and Ware,¹² for $Z_{\text{eff}} = 1$, over a wide range of parameters. The initial target plasma hydrogenic ions were assumed to be a 50:50 mixture of H^+ and D^+ . Thermal H^+ ions in the plasma were assumed to move with the same radial velocity as the bulk plasma, and H^+ and D^+ were assumed to recycle from the wall as neutrals with the same probability. The neutron emission predicted with this model shows good agreement with the data (Table 1), given that neutron emission scales as T_i^4 . The uncertainties in the model are considerable, however, at the lowest density, where a large fraction of the D^+ is replaced by H^+ . While this uncertainty is lower at high density, small errors in $T_i - T_e$ become important in evaluating ion-electron coupling. Thus the electron energy confinement studies described here should properly bear the caveat that they assume "Rutherford" neoclassical ion thermal conduction. The neutron emission results are consistent with this assumption, particularly in their relative increase with injection, but they do not prove its validity.

Table 2 shows results from the transport analysis of these discharges. The first two columns show the measured line average, and central electron densities. $n_e(0)/\bar{n}_e$ is close to 1.7 for all cases, except the lowest density injection case, where $n_e(0)/\bar{n}_e = 2$. This strong central peaking has been found to be characteristic of beam injected discharges with optimal confinement. The third column shows the effective Z deduced from the plasma

resistance, assuming Spitzer resistivity in the solution of the magnetic diffusion equation. There was evidently little change in Z_{eff} during injection. The low density discharges, however, were somewhat different from the others. In the injection case $\bar{n}_e$ was $1.2 \times 10^{13} \text{ cm}^{-3}$ at 300 msec, the beam turn-on time, and then rose to $2.7 \times 10^{13} \text{ cm}^{-3}$ by the end of injection at 600 msec, with no additional gas feed. In the Ohmic case the density was raised by means of programmed deuterium gas feed to give nearly the same $\bar{n}_e(t)$. In all other cases the density was ramped from near the beginning of the discharge, and the neutral beams were injected for 150 msec during a density flat top period near the end. In the injection cases the gas feed was shut off at the beginning of the beam pulse, and the density remained approximately level. In the Ohmic cases continuous gas feed was required in order to hold $\bar{n}_e$ constant.

The fourth column shows the electron energy stored in the region of the plasma from $r = 0$ to $a/2$. Columns 5 - 7 show the terms that go into heating the electrons. Despite the decreased beam penetration at high density, the power transferred directly from the beam ions to the electrons (P_{be}) is approximately constant. This is because the fractional power delivered to the electrons increases as T_e falls. The ion - electron coupling term (Q_{ie}) is nearly constant as well. This is because a larger fraction of the power delivered to the ions is transferred to the electrons in the higher density cases. These two effects, then, serve to counteract the reduced beam penetration at high density, and thus maintain the total electron heating power nearly constant. In the highest density NBI case the ion energy loss through thermal conduction at $a/2$ is 80 kW. If this loss term were changed by $\pm 50\%$, with the difference then appearing in ion-electron coupling, the net effect on the calculated τ_{pe} at $a/2$ would be $\pm 7\%$.

Columns 8 - 11 show the deduced confinement times for these discharges. Confinement times are defined in terms of stored energy, integrated from $r = 0$ to the given radius, divided by loss power across the radius. For example τ_{Ee} at $a/2$ is defined by

$$\tau_{Ee}(a/2) = \frac{3}{2} \int_0^{a/2} n T_e dV / (P_{cond} + P_{conv} + P_{rad})$$

where P_{cond} , P_{conv} , and P_{rad} are the conduction, convection, and radiation power losses, respectively. A "*" indicates that radiation has been excluded from the sum of loss powers. In order to take some account of the neutral charge - exchange power intercepted by the bolometer system, the radial profile $P_{rad}(r,t)$ is scaled by a factor $[P_{rad}(t) - 1/2 P_{esc}(t)]/P_{rad}(t)$, where $P_{rad}(t)$ is the total measured bolometer power, and $P_{esc}(t)$ is the total calculated power efflux in thermal charge exchange neutrals.¹ In the lowest density Ohmic and beam injection cases this scale factor is ~ 0.7 . In the other cases it is ~ 0.9 . The overall importance of radiation in the electron power balance can be assessed by comparing τ_{Ee} and τ_{Ee}^* . In the two middle density cases there was a long enough density flat top period (~ 100 msec) prior to the time of injection to obtain a confinement time. The evolution of the confinement times in the Ohmic plasmas is shown by giving two values; one for early in the flat top of the density, and one for late. Clearly these discharges were improving during this period. T_e was rising, and the loop voltage was falling, while $\bar{n}_e$ was held constant. In general it is clear that these Ohmic targets were good high density PLT plasmas, attaining $n_e(0)\tau_E = 8 \times 10^{12} \text{ sec cm}^{-3}$.¹³ Secondly they do not show a strong scaling of τ_E with density; the low density cases are especially good. Even τ_{Ee}^* at $a/2$ only varies by a factor of 1.5 over the full density range.

The beam heated cases all show significantly lower electron energy confinement times than the equivalent Ohmic cases. The middle density injection cases show more nearly constant confinement times, however, when compared to the Ohmic plasmas prior to injection. There appears to be a weak positive scaling of electron energy confinement with density, although certainly not as strong as "INTOR" scaling.¹⁴ $\tau_E(a)/(\bar{n}_e a^2) = 5 \times 10^{-19}$ sec cm for the injection case at $\bar{n}_e = 5 \times 10^{13}$ cm⁻³.

Table 3 shows electron temperatures and confinement times from a number of previous PLT injection experiments performed at moderate to high densities, where P_{rad} was small. It would appear that τ_{Ee} at $a/2$ even for "good" D⁰ injection into nominally H⁺ plasmas is lower than for H⁰ injection. In the poor heating cases of H⁰ injection into initially cold D⁺ target plasmas, or plasmas with broad density profiles, τ_{Ee} at $a/2$ can be a factor of 1.5 lower than the results analyzed here.

III. PDX CURRENT AND POWER SCALING EXPERIMENTS

The goal of recent PDX experiments has been to determine the effectiveness of near perpendicular neutral beam injection as a function of both plasma current and injected beam power. These experiments were performed in circular H⁺ plasmas ($a=44$ cm, $R=143$ cm) with line average densities $2.0 - 3.4 \times 10^{13}$ cm⁻³ and with up to 7.2 MW of D⁰ beams injected into the plasma. The results that will be presented here are predominantly from power scalings at two different currents, 320 kA and 480 kA. A more general discussion of PDX results is given in the paper by Eubank et al.,¹⁵ also at this conference.

Central ion temperatures of the PDX discharges were measured by passive and locally doped neutral charge exchange analyzers and by Doppler broadening of Ti XXI K α line radiation. For the high power, high current

discharges ($\bar{n}_e = 2.2\text{--}3.4 \times 10^{13} \text{ cm}^{-3}$) temperatures of up to 6.0 keV were measured. At the lower current ($\bar{n}_e = 2.1 - 2.6 \times 10^{13} \text{ cm}^{-3}$) the central ion temperatures were lower; the maximum $T_i(0)$ reached was 4.8 keV. Figure 2 shows the ion heating efficiency factor, η_i , as a function of P_{abs} . Here P_{abs} , the absorbed beam power, is defined to be the injected beam power less the shine-through loss, and $\eta_i \equiv \bar{n}_e \Delta T_i / P_{\text{abs}}$. It is evident from the figure that the ion heating efficiency is reproducibly greater at the higher current; on the average $\eta_i(320 \text{ kA}) / \eta_i(480 \text{ kA}) \sim 0.6\text{--}0.7$, close to the ratio of the currents. What is also seen in the figure is that η_i tends to degrade at the highest beam power. A possible reason for this is that in the four beam 480 kA case especially, the discharges tended to have minor disruptions and sometimes showed a significant drop in $T_i(0)$ and $\beta_p + \beta_i/2$ towards the end of the beam pulse.

The variation in ion heating seen in the data has been studied using the TRANSP transport analysis code, which takes experimental input data as described in Section II, and calculates the time evolution of the ion temperature profile. The total convection loss calculated in the core of the discharge is generally due to the beam deposition and the measured evolution of n_e . Thus it is relatively insensitive to the convection due to recycling neutrals. The global particle confinement time, τ_p , is taken to be 40 msec based on estimates from the H α emission. The ion conduction loss is controlled by the ion thermal conductivity, assumed here to be the Hinton-Hazeltine neoclassical value, χ_i^{NC} , multiplied by an anomaly factor. The anomaly factor is adjusted so that the predicted and measured central ion temperatures agree. We find that for the 480 kA cases the central ion temperature can be predicted correctly using only $\chi_i = \chi_i^{\text{NC}}$ (or, within the errors, "Rutherford" neoclassical), except at the highest power where we

required $\chi_i = 3\chi_i^{NC}$. The relative reduction in η_i at 320 kA is also reflected in the transport analysis results, for to predict $T_i(0)$ correctly in these cases we need $\chi_i = 3\chi_i^{NC}$, again except at the highest power where we required $\chi_i = 5\chi_i^{NC}$. We find that in the 480 kA case the ion conduction loss is small relative to the heating power, except at the highest power. The major ion energy loss is ion-electron coupling, with convection the dominant transport loss. In the lower current cases the ion conduction loss is significant, because of the increased anomaly factor and the dependence of χ_i^{NC} on plasma current, and it is comparable to the convection loss. The ion energy confinement time at $a/2$, defined in terms of ion stored energy divided by transport and charge exchange losses, is about twice longer in the 480 kA cases than in the 320 kA ones.

Figure 3 shows the central electron temperatures and line-average densities for the various current and power cases. We see that the magnitude and behavior of $T_e(0)$ for the 320 kA and 480 kA cases are similar. At low powers (< 2.5 MW) the heating rate $\Delta T_e(0)/P_{abs}$ is ~ 0.45 eV/kW, while at the higher powers the central temperature tends to saturate, although the line-average density continues to rise. The total stored electron energy, U_e , continues to rise with beam power as shown in Fig. 4. Because of the difference in $\bar{n}_e$ the stored energies in the 480 kA cases are greater than those of the 320 kA cases at comparable P_{abs} .

How the variation of stored energy with absorbed power translates into energy confinement times is depicted in Fig. 5. In this figure the electron energy confinement times at $r=a/2$, as defined in Section II, are plotted versus beam power. For the electrons within $a/2$ the calculated electron power balance indicates that the convection and radiation losses are negligible. It is clear from the figure that for the neutral beam heated

discharges in this current range τ_{Ee} is a weak function of both current and beam power. This may be surprising in light of Fig. 4, where we saw that $U_e(320 \text{ kA})/U_e(480 \text{ kA}) \sim 0.6-0.7$ for comparable P_{abs} . However, we note that the relevant parameter for determining τ_{Ee} is not P_{abs} but rather $P_{cond} + P_{conv} + P_{rad}$ ($= P_{heat,e}$ in equilibrium, where $P_{heat,e}$ is the total electron heating power). $P_{heat,e}$ includes beam-electron collisional heating, P_{be} , Ohmic heating, P_{OH} , and ion-electron coupling, Q_{ie} . While P_{be} is not a strong function of plasma current in the core of the discharge, P_{OH} and Q_{ie} are, both being greater for the 480 kA cases. The increase in P_{OH} is due to an increase in current, as well as surface voltage, and the increase in Q_{ie} with current is due to an increased density as well as an increased ion-electron temperature difference, owing to higher ion temperatures. Summing these effects we find that $P_{heat,e}(320 \text{ kA})/P_{heat,e}(480 \text{ kA})$ is also $\sim 0.6-0.7$, yielding values of τ_{Ee} that are essentially independent of I_p . We observe also that τ_{Ee} is flat with P_{abs} except at the highest powers where there is a suggestion that τ_{Ee} decreases slightly. Since $\bar{n}_e$ rose with P_{abs} in these experiments we conclude that the observed τ_{Ee} scaling with P_{abs} is not consistent with simple INTOR type scaling where $\tau_{Ee} \propto \bar{n}_e$ and is independent of P_{abs} . This inconsistency with INTOR scaling was observed in PDX over a wider range of $\bar{n}_e$ in diverted discharges.⁶

The variation of the global energy confinement time, τ_E , with current and power is similar to that of τ_{Ee} at $r=a/2$. The results are shown in Fig. 6, and it is evident that the current dependence of the global confinement time is weak, with $\tau_E(480 \text{ kA})$ perhaps 5-10% greater than $\tau_E(320 \text{ kA})$. As was the case for the electrons, we find here that the ratio P_{heat}/P_{abs} is greater in the higher current case. The difference is because P_{abs} does not take into account either beam losses through charge exchange and bad orbits or Ohmic

heating power. It turns out that the differences in charge exchange and bad orbit losses between the two currents account for $\sim 1/3$ of the variation of $P_{\text{heat}}/P_{\text{abs}}$ with current, while the Ohmic input accounts for the remainder of the variation. In fact, the code calculation indicates $P_{\text{heat}}(320 \text{ kA})/P_{\text{heat}}(480 \text{ kA}) = 0.69$, comparable to the scaling of the total stored energy, indicating again little current scaling of the global confinement for this current range. In the core of the discharge ($r < a/2$), the total electron and ion confinement does improve with current. This difference in the radial profiles of the confinement times correlates with the more peaked power deposition profiles in the 320 kA cases, due to the lower densities.

Preliminary analysis of ~ 200 kA discharges suggests that both $\tau_E(a)$ and $\tau_{EE}(a/2)$ degrade at this lower current. $\tau_{EE}(a/2)$ drops moderately to 7-9 ms with 2 and 3 beam heating while τ_E falls to ~ 12 msec.

An independent means of estimating the current scaling of changes in stored energy within the discharge has been to assume that the magnetically measured $I_p^2 \Delta\Lambda$ [$\Delta\Lambda = \Lambda$ (during beam) - Λ (Ohmic), where $\Lambda = \beta_p + l_i/2$] reflects changes in only the plasma and beam stored energy. A simple "incremental" confinement time is then given by " τ_E " $\propto I_p^2 \Delta\Lambda/P_{\text{abs}}$. This technique, though, becomes especially problematical when there are significant changes in current or in electron temperature profile during injection. Using the above method for PDX discharges it was found that " τ_E " scaled as $I_p^{3/4}$.¹⁵ For ISX-B discharges, where the current range was below ~ 200 kA, the scaling of " τ_E " was found to be $I_p^{3/2}$.⁷ It is clear that the τ_E 's computed in TRANSP and the " τ_E "'s from the magnetic analysis both show a much weaker current scaling in PDX for I_p in the range 320 to 480 kA, relative to the ISX-B result.

The source of the discrepancy between the TRANSP τ_E 's and magnetic " τ_E "'s is not clear. A problem in making the comparison is that the $\Delta\lambda$'s calculated in TRANSP often exceed the experimentally measured values by $\sim 20\%$. Interestingly, however, the scaling of $I_p^2 \Delta\lambda/P_{abs}$ for these cases does go as $I_p^{3/4}$ in the TRANSP runs, due to changes in $\lambda_i/2$, which are calculated from solving the magnetic diffusion equation. The uncertainties in the magnetic calculation of changes in stored energy come primarily from the uncertainty in $\Delta\lambda_i/2$, and from changes in $I_p(t)$ between beam-heated and Ohmic "baseline" discharges. Possible sources of error in TRANSP are in the ion temperature profile shape, which is not measured in these discharges, in n_i/n_e (Z_{eff} was assumed to be 2-3 for these cases), and in non-classical effects that might result in premature loss of fast ion energy.

To summarize this section, then, on the basis of the data shown here, we conclude that in the PDX parameter range studied ($I_p = 320$ to 480 kA, P_{abs} up to 5.3 MW),

- (a) Ion energy confinement scales favorably with plasma current,
- (b) Electron energy confinement varies only weakly or not at all with plasma current, and
- (c) gross energy confinement of the thermal plasma shows little variation with either current or injected power.

At lower currents, however, ($I_p \sim 200$ kA, significant degradation of τ_E and τ_{Ee} is observed.

IV. PLT AND PDX HIGH BETA EXPERIMENTS

The energy confinement times measured on PLT and PDX are too short for these machines to reach reactor - relevant values of β toroidal, at full field conditions, with their installed heating power. Since it has generally

been found that confinement scaling with toroidal field in tokamaks is weak,^{7,16} it becomes attractive to operate these machines at reduced field, in order to study confinement scaling at high β . Monte Carlo beam orbit calculations⁹ indicate that plasma currents of at least 250 kA are required in PDX in order to minimize orbit losses. Higher currents are probably also required in order to support the plasma density needed for absorption of the perpendicularly injected neutral beams.¹⁷ Since in PDX ion energy confinement has been found to scale favorably with plasma current, it is especially desirable to investigate the extreme low q , low toroidal field regime.

Towards this end PLT has recently attempted operations with neutral beam injection at toroidal fields as low as 10 kG. Disruptions at these low fields are not limited to the very low q phase of the discharge, but often occur at $q > 2.5$. At 14.5 kG, however, this problem is much less severe. Under optimal conditions, after tuning, a disruption rate of 30% has been achieved in discharges which reach $q_{cyl} < 1.7$ ($I_p \sim 500$ kA) at peak current. Indeed disruptions still typically occur during the early, higher q phase of the discharge. Rapid disruptions have also been observed in the vicinity of $q_{cyl} \sim 1.6$, however they have not yet been studied in detail. Although the details of the early gas programming are important, there is no evidence that it is necessary to employ strong gas puffing during the current ramp in order to obtain stable low q discharges in PLT. Simple toroidal corrections¹⁸ give $q_{\psi} = 1.8$ for the lowest value of $q_{cyl} = 1.6$ achieved on PLT, but full MHD code runs have not been made for the PLT poloidal field geometry.

At $B_t = 17.4$ kG, $q_{cyl} = 2.1$, $\bar{n}_e = 2.6 \times 10^{13} \text{ cm}^{-3}$, and $P_{be} = 1.8$ MW (D^0), $T_i(0) = 3.3$ keV was measured by passive charge exchange, $T_e(0) = 1.5$ keV, by Thomson scattering. Transport analysis of this discharge gives $\beta_{te} = 0.19\%$, $\beta_{ti} = 0.35\%$. The calculated β_{tb} is 0.27%, giving a total $\beta_t = 0.8\%$.

The global energy confinement time is approximately 20 msec. At $B_t = 14.5$ kG, $q_{cyl} = 1.7$, $\bar{n}_e = 2.4 \times 10^{13} \text{ cm}^{-3}$, and $P_D = 1.8$ MW (D°), $T_i(0)$ was 2.5 keV, $T_e(0) = 1.2$ keV. $\beta_{te} = 0.25\%$, $\beta_{ti} = 0.41\%$, and $\beta_{tb} = 0.41\%$. The total β_t from this energy analysis is thus about 1.1%. The global confinement time is approximately 18 msec. This represents a modest degradation from confinement times typically observed at this density (25 - 30 msec) with D° beam injection at 25 - 32 kG.

Low q operations with neutral beam injection have just now begun on PDX. At a toroidal field of 12.5 kG, $q_{cyl} = 2$ has been achieved, with $R/a = 125\text{cm}/40\text{cm}$. MHD code calculations indicate $q_\psi = 2.3$, in agreement with the simple toroidal correction formula.¹⁸ The toroidally continuous inner wall armor has been used successfully as the limiter for these discharges. Diagnostic data from PDX show large sawtooth oscillations on $\beta + \ell_i/2$, and on the diamagnetic signal, as well as on the X-ray flux and line average density. Oscillations are observed on the plasma current and position as well. X-ray and charge exchange measurements indicate that the sawtooth oscillations reach to the plasma edge.¹⁵ With 1.9 MW (D°) absorbed, at $\bar{n}_e = 3 \times 10^{13} \text{ cm}^{-3}$, $T_i(0) \sim 2$ keV was measured by passive charge exchange, $T_e(0) = 1.4$ keV by Thomson scattering, triggered at a time close to the peak of the sawtooth (Fig. 7). Transport analysis based on these measurements gives $\beta_{te} = 0.4\%$, $\beta_{ti} = 0.5\%$, and a calculated $\beta_{tb} = 0.5\%$. The calculated global confinement time for this discharge is 17 msec, which does not constitute a significant deterioration from the higher field PDX results presented in Section III. The total β_t measured earlier, in the Ohmic phase of this discharge was 0.25%, at $\bar{n}_e = 2.5 \times 10^{13} \text{ cm}^{-3}$, and $q_{cyl} = 3.4$.

This discharge has also been analyzed using a 2-D MHD code fitting procedure (Fig. 8a). The current profile is adjusted in the code to give the

$q = 1$ surface at the measured sawtooth inversion radius of 18 cm. The pressure profile shape is taken from the Thomson scattering $P_e(R)$, and adjusted in magnitude to give agreement with external magnetic measurements (Fig. 8b). The result of this analysis gives β_t during injection = 1.3%, again at a time near the top of a sawtooth. Diamagnetic measurements on PDX are not yet reliable during the Ohmic phase, but should be accurate for measuring $\Delta\beta_t$ due to injection. In this case the diamagnetic measurement yields $\Delta\beta_t = 1\%$, consistent with the other measurements.

Clearly low q neutral beam injection work has just begun at PPPL. Sufficient data is not yet available to make detailed comparisons between tangential and perpendicular injection in these conditions. However the parameters obtained with similar beam powers on PLT and PDX are comparable, and thus there is as yet no evidence that confinement depends significantly on injection geometry in these low q plasmas.

V. CONCLUSIONS

We have presented here confinement studies with neutral beam injection on both PLT and PDX. On PLT a density scaling experiment was performed, using 1.2 MW of H^0 beams, injecting into nominally D^+ plasmas. Within the context of "Rutherford" neoclassical ion thermal conduction, electron energy confinement during injection was found to have a weak positive scaling with plasma density. This observation, however, held for the Ohmic discharges studied as well. The electron energy confinement at $r = a/2$ was found to be significantly lower in the beam-heated discharges than at equivalent times in the Ohmic plasmas. At a line average density of $6.5 \times 10^{13} \text{ cm}^{-3}$, however, $n_e(0) \tau_E = 5 \times 10^{12} \text{ sec cm}^{-3}$ was obtained in discharges with $P_{\text{abs}}/P_{\text{OH}} = 5$.

Current and power scaling experiments on PDX were presented as well. Transport analysis of these data indicated that global energy confinement in the beam-heated did not vary strongly with either beam power or plasma current. Ion energy confinement in the core of the discharge was found to rise as I_p was increased from 320 to 480 kA, but electron energy confinement did not change significantly. At lower currents ($I_p = 200$ kA) initial analysis results do indicate deterioration in both $\tau_{Ee}(a/2)$ and $\tau_E(a)$.

Neutral beam injection experiments at low toroidal field and low q on both PLT and PDX were described. Similar heating results have been obtained on the two devices, using absorbed beam powers of about 1.8 MW. This suggests that tangential and perpendicular injection are about equally well suited for low q / high β experiments, but more data is required in order to document this observation.

The results on PDX are particularly promising because of the 7.2 MW of 50 keV D⁺ beam power which can be injected into this device. Clearly power scaling experiments in the low q regime are of primary importance, in order to shed light on the saturation of β_p/I_p versus beam power observed on ISX-B⁷ and on DITE.¹⁷ In addition the low D⁺ beam velocity (25 keV/nucleon) allows operation with adequate absorption at reduced minor radius or moderate density. Coupled with the large horizontal limiter to limiter aperture (110 cm) available in PDX, this permits significant minor and major radius scaling experiments. With low q operation, currents in excess of 300 kA can be obtained for these experiments. The scaling experiments reported in Section III suggest that this level of plasma current is desirable.

We note that the sawtooth oscillations observed in our low q , beam injected plasmas limited on the inner wall armor extend from the plasma center to its edge. They do not appear at present to dominate the time - averaged

transport, but their evolution with increasing beam power may be critical. Thus it could prove to be important to investigate high β , low collisionality plasmas, which should be accessible to PDX at moderate density and full aperture. The PLT scaling experiments reported in Section II (and PDX results reported in Ref. 6) suggest that operation at moderate density for this purpose will entail relatively little sacrifice in confinement.

ACKNOWLEDGMENTS

The authors would like to thank the PLT, PDX and Neutral Beam technical groups for their unflagging support in this work. We would like to thank Dr. J. Strachan for providing neutron data, and insight into their analysis. Finally we would like to thank Dr. Dale Meade for his persistent encouragement.

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Table 1

$\bar{n}_e (10^{13} \text{cm}^{-3})$	Neutron Production Rate	
OH	Exp't (sec ⁻¹)	TRANSP
3	2.5×10^{10}	1.7×10^{10}
4	1.1×10^{10}	8×10^9
5	1.5×10^{10}	1.4×10^{10}
6.5	1.4×10^{10}	2.2×10^{10}
NBI		
2.7	2×10^{10}	1.8×10^{10}
4	1.7×10^{10}	1.7×10^{10}
5	10^{10}	1.4×10^{10}
6.5	10^{10}	1.5×10^{10}

Fig. 1 Central electron temperature vs $\bar{n}_e$ for ohmic and beam injected plasmas.

Table 2

	$\bar{n}_e$ ($\times 10^{13} \text{cm}^{-3}$)	$n_e(0)$ ($\times 10^{13} \text{cm}^{-3}$)	$v_e(a/2)$ (kJ)	$Z_{\text{eff}}(\text{Sp})$	$P_{\text{be}}(a/2)$ (kW)	$\eta_{ie}(a/2)$ (kW)	$P_{\text{OH}}(a/2)$ (kW)	$\tau_{\text{Te}}(a/2)$ (msec)	$\tau_{\text{Te}}^*(a/2)$ (msec)	$\tau_{\text{E}}(a/2)$ (msec)	$\tau_{\text{E}}(a)$ (msec)
OH cases											
	1 $\rightarrow$ 3	5	11.7	2.4	—	- 70	370	38	42	58	60
	4	6.7	11	1.25	—	- 70	280	32 $\rightarrow$ 50	33 $\rightarrow$ 57	53 $\rightarrow$ 75	47 $\rightarrow$ 72
	5	9	14.5	1.4	—	- 80	350	37 $\rightarrow$ 52	48 $\rightarrow$ 67	60 $\rightarrow$ 68	62 $\rightarrow$ 77
	6.5	11	16.7	1.65	—	- 80	450	47	63	74	73
NBI cases											
	1 $\rightarrow$ 2.7	5.5	14.5	2.4	300	190	230	22	27	38	36
	4	7.3	18	1.3	330	200	170	27	29	45	40
	5	8.3	19	1.3	300	200	180	29	31	52	39
	6.5	11	23	1.55	270	150	220	36	38	54	44

Table 3

$\bar{n}_e$ ($\times 10^{13} \text{cm}^{-3}$)	$n_e(0)$ ($\times 10^{13} \text{cm}^{-3}$)	P_{inj} (MW)	Species	$T_e(0)$ (keV) before NBI	$T_e(0)$ (keV) during NBI	$\tau_{\text{Fe}}(a/2)$	$\tau_{\text{Fe}}^*(a/2)$	$\tau_{\text{E}}(a/2)$	$\tau_{\text{E}}(a)$	Comments
3.2	5.2	1.5	D ⁺ $\rightarrow$ H ⁺	1.1	2.0	21	23	35	30	"good" D ⁺ heating(ref.5)
3.1	6.8	3	D ⁺ $\rightarrow$ H ⁺	1.1	2.5	18	20	32	27	"good" D heating
3.2	4.3	1.3	H ⁺ $\rightarrow$ O ⁺	1.0	1.45	14	16	27	26	"poor" H heating
5.7	8.1	1.7	H ⁺ $\rightarrow$ D ⁺	0.6	1.2	20	(?)	37	27	"poor" H heating(ref.3)

FIGURE CAPTIONS

Fig. 1 Central electron temperature vs $\bar{n}_e$ for ohmic and beam injected plasmas in PLT density scaling experiment.

Fig. 2 Ion heating efficiency factor, η_i , as a function of P_{abs} .

Fig. 3 Thomson scattering and microwave interferometer measurements of central electron temperature, $T_e(0)$, and line-average density, $\bar{n}_e$, respectively as a function of P_{abs} .

Fig. 4 Total stored electron energy versus P_{abs} .

Fig. 5 Electron energy confinement time at $r = a/2$ versus P_{abs} .

Fig. 6 Global energy confinement time at $r = a$ versus P_{abs} .

Fig. 7 TV Thomson scattering measurements of $T_e(R)$ and $n_e(R)$. $R_0 = 125$, $a = 40$, low q operation.

Fig. 8 (a) Flux surface plot for low q plasma with inner wall armor as limiter.

(b) Pressure profile (P) from MHD fitting code, compared to $2.5 \times P_e$ from Thomson scattering (data points). Transport analysis indicates $\langle P \rangle \sim 3.5 \langle P_e \rangle$.

Fig. 1

Fig. 2

Fig. 3

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Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8a

Fig. 8b