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CONFINEMENT STUDIES DURING
NEUTRAL BEAM INJECTION IN PLT

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Confinement Studies During Neutral Beam Injection in PLT

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I. Introduction

Neutral beam injection experiments on PLT have furnished information on ion energy confinement at low collisionalities, on central particle confinement, and on the effects of toroidal field ripple. These experiments have also provided some "tantalizing hints" into the behaviour of electron energy transport during auxiliary heating. The ion heating observed on PLT during neutral beam injection is found to be in good agreement with the usual model for ion energy transport, which includes neoclassical thermal conduction, classical ion-electron coupling, charge-exchange, and anomalous thermal convection. The thermal convection term in the ion energy balance is large and quite uncertain at low densities, leaving considerable room for possible anomalous ion thermal conduction. At moderate densities in PLT, however, thermal neutrals originating at the walls and limiter cannot penetrate into the central region of the plasma, and the particle source rate is dominated by the injected beam. Under these circumstances, the central particle confinement time and the concomitant ion thermal convection can be evaluated with some confidence. The resulting ion power balance leaves relatively little room for further anomalous effects.

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During much of 1979 PLT was operated with ~2.5% local ripple in the toroidal field (TF) due to damage to one of the 18 toroidal field coils. During this period, ion heating at low density and high beam power showed significantly poorer results than in 1978. However titanium gettering had been reduced in 1979 to avoid coating the ICRF coils, and Taylor discharge cleaning had been largely replaced by glow discharge cleaning (GDC). Along with the continued conditioning of the carbon limiters, this resulted in $Z_{eff} < 2$ even at the lowest densities and increased central core radiation, as well as significantly broadened electron density profiles. Broad profiles have been previously shown in PLT to correlate with relatively poor confinement (Ref. 1). In 1980 four of the five damaged turns in the bad TF coil were returned to service, GDC was reduced, and titanium gettering was intensified; the heating efficiency found in 1978 was again observed. In order to determine if this was due to the reduced toroidal field ripple, a shunt was installed on the TF coil opposite to the damaged one to simulate the 1979 ripple. Experiments at the lowest collisionalities obtainable in PLT showed no significant difference between ripple and no ripple cases, in clear contradiction with a simple extension of the usual ripple theories to the PLT geometry. Monte-Carlo calculations, however, show that the analytic calculations overestimate ripple effects in the case of a single shallow well.

Electron energy confinement studies in PLT have given intriguing results. At low densities and high temperatures we find an improvement in central electron energy containment, while the gross electron energy confinement is approximately constant. At the highest power levels this regime is now inaccessible, however, due to increased central core radiation. A recent scan of electron heating as a function of plasma density using D^0 beams shows that in the moderate temperature and density range for

PLT little degradation of heating efficiency occurs as the plasma density increases and beam penetration is reduced. The electron heating, moreover, is found to be linear with respect to the input beam power, up to the presently achieved limits of $P_b(H^0) \sim 2.0$ MW and $P_b(D^0) \sim 3.0$ MW.

II. Ion Power Balance

Heating experiments using neutral beam injection on PLT are analyzed using the TRANSP transport analysis code (Ref.2). This computer code takes as input $n_e(r,t)$ from the multi-channel TV Thomson scattering system (TVTS) normalized to a single channel 2 mm microwave interferometer, $T_e(r,t)$ either from TVTS or from electron cyclotron emission (ECE), $P_{rad}(r,t)$ from a scanning or fixed array bolometer, as well as the measured $V_{loop}(t)$, $I_p(t)$ and beam powers as functions of time. It employs Monte-Carlo algorithms to calculate the thermal neutral density (Ref.3), the beam power transferred to the bulk ions and electrons (Ref. 4), and the particle source rates from the beam and thermal neutrals as functions of time and radius. Special care has been taken to properly evaluate beam deposition and neutral transport, taking into account all of the various charge-changing collisions that take place between charged and neutral, beam and bulk particles in strongly non-Maxwellian injection heated plasmas.

On the basis of the calculated source rates and the input data, the TRANSP code determines the ion and electron particle balances and the electron energy balance, and then calculates the expected evolution of the ion temperature. The ion energy loss processes taken into account are neoclassical ion thermal conduction (Ref.5), charge-exchange, empirical thermal convection (with energy flux of the form $P_{conv} = 5/2 nkTv_r$), and classical ion-electron coupling. The volume particle confinement time and the

energy of the neutrals taken to be recycled from the limiter, since they are highly uncertain, may be adjusted in the neutral transport code. This has the result of varying the neutral density profile, which simultaneously affects both the charge-exchange and the convection losses. A substantial amount of charge-exchange loss can be driven directly by the beam itself, since the deposition of a beam particle by charge-exchange results in an important energy loss from the thermal ions when $3/2 T_i$ is ~ 10 keV ($=E_{inj}/4$). In addition, a significant portion of the "empirical" convection loss can be driven by the beam, in the sense that the particle source rate on axis from high power injection reaches $\sim 4 \times 10^{14}$ cm³/sec, and if the measured electron density does not rise at this rate, a certain minimum amount of outward convection of thermal ions can be deduced. We term these beam driven loss channels "hard" losses, since they are independent of the boundary conditions used in the neutral transport calculation and are relatively well-known on the basis of the input data and beam power.

The ion heating observed at high power and low density in PLT in 1978 (Refs. 6,7) was found to be in rough agreement with the ion power balance model used in TRANSP, but the ion energy loss due to neoclassical conduction was small compared to the charge-exchange and convection losses. Figure 1 shows the calculated volume integrated ion power balance in the central 30 cm of PLT for the 5.5 keV case described in Ref. 6. While a significant fraction of the dominant charge-exchange and convection losses in this case is due to "hard" beam-driven transport, much is due to neutrals penetrating from the periphery of the plasma. As a result the ion thermal conduction is poorly determined by the data, since the neutral density due to the recycling source is not well known. Figure 2 illustrates the ion power balance for the 6.3 keV ion temperature case described in Ref. 8. In this case ion-electron coupling

is much stronger due to the lower electron temperature, and neoclassical thermal conduction is greater due to the somewhat reduced toroidal field (25 kG vs 32 kG) and the higher central q value arising from the broad electron temperature profile. Almost all of the charge-exchange and convection losses in the inner region of this case are "hard" losses. Thus, reducing the neutral density due to the recycling source has only a modest effect on the calculated ion temperature. Indeed if the ion thermal conduction is taken to be 3 x neoclassical, it appears difficult to obtain agreement with the measured ion temperature even by increasing T_e by 15% and raising the particle confinement time to extremely high values.

The ion energy balance in this 6.3 keV case does not permit a substantial recycling source neutral density on axis. Thus the central particle balance is predominantly determined by the particle source due to the beam, and by the measured evolution of the central electron density. Figure 3 shows the time evolution of $n_e(0)$ as determined from TVTS and microwave interferometry. The linear rise of the central density as a function of time is a common characteristic of PLT injection experiments starting at low density. Figure 4 shows the calculated time evolution of the particle sources on axis in this case. The beam deposition source is due to fast neutrals which are captured by impact ionization collisions with ions and electrons, and by charge-exchange and impact ionization with impurities (Ref. 9). Beam particles which are deposited by charge-exchange with thermal hydrogenic ions give rise to thermal neutrals, and when these particles eventually ionize (perhaps after further generations of charge-exchange) they contribute to the beam volume source. During injection the total particle source on axis is roughly constant at $4.1 \times 10^{14} \text{ cm}^{-3} \text{ sec}^{-1}$. If we define the central particle balance equation as

$$dn_e(0)/dt = S(0) - n_e(0)/\tau_p(0) ,$$

we can deduce $\tau_p(0) \sim 65 \times n_e(0) \text{ cm}^3/10^{13} \text{ msec}$ during this injection experiment, based on the known approximately constant values of $dn_e(0)/dt$ and $S(0)$.

This particle balance, which has been calculated for the electrons, is not directly applicable to the thermal ions due to the substantial beam ion density, but through quasi-neutrality it describes the radial flow of the thermal ions as well. In general in low and moderate density PLT neutral beam injection experiments, if we use the recycling source neutral density that is required to obtain the correct ion temperature, assuming neoclassical ion thermal conduction, we deduce a particle diffusivity in the inner $\sim 25 \text{ cm}$ of the radial profile that is a factor of 2-3 below the INTOR value of $1.25 \times 10^{17}/n_e$. Thus we conclude that the INTOR model for ion energy confinement, including both neoclassical conduction and anomalous convection, is conservative when applied to the core region of PLT.

III. Ripple Effects

In order to study the effects of non-axisymmetry on highly collisionless plasmas, and in order to determine if the toroidal field ripple was a cause of the relatively inefficient heating observed in PLT in 1979, a shunt was installed on the toroidal field coil directly opposite to the originally damaged (and now largely repaired) TF coil. With 5 turns removed, the damaged

coil caused a 2.7% ripple on axis; as repaired it now causes a ripple of 0.54%. The shunted coil can be used to create an additional ripple of up to 2.5%. The form of the perturbation in the toroidal field in all cases is reasonably well approximated as

$$\begin{aligned}\delta B/B &= \delta(r,\theta) [\cos(3\phi) - 1] & 0 < \phi < 2\pi/3 \\ \delta B/B &= 0 & 2\pi/3 < \phi < 2\pi \\ \delta(r,\theta) &= 0.68 \delta_0 \exp(L/107.7) ,\end{aligned}$$

where L is the distance from the point (r,θ) to a "ripple center" on the horizontal midplane at $R = 92.7$ cm, and δ_0 is $\delta B/B$ on axis. The ripple trapping efficiency of this perturbation is modest because of the low toroidal mode number. Even at the full 2.7% ripple, particles which become ripple trapped at $r < 20$ cm rapidly drift up into the region where toroidal effects eliminate the ripple wells (Fig. 5).

We were able to perform controlled experiments on PLT in which we installed and then removed the TF coil shunt, keeping plasma conditions as constant as possible. Figure 6 shows the results from these experiments, as well as our accumulated ion heating data with and without ripple at densities of $1.5 - 3.0 \times 10^{13} \text{ cm}^{-3}$. One ripple/no ripple experiment was performed at $P_b/n_e \sim 0.75 \text{ MW}/10^{13} \text{ cm}^{-3}$, giving $T_i = 4.2 \pm 0.2 \text{ keV}$ without ripple, and $T_i = 3.7 \pm 0.3 \text{ keV}$ with ripple. A more definitive experiment was performed at $P_b/n_e \sim 1.25$, using 2 co beams and one counter beam, in an attempt to recreate the extremely low collisionality 7.1 keV plasma described in Ref. 8. The plasma density we obtained was slightly higher than before, particularly in the ripple phase of the experiment, but the heating efficiency per particle

was identical with and without the ripple, and somewhat greater than achieved previously. Interestingly, the slightly higher density ripple case ($n_e = 2.0 \times 10^{13} \text{ cm}^{-3}$) showed the enhanced fluctuations reported in Ref. 6 in about half the shots, while the no ripple case at $n_e = 1.8 \times 10^{13} \text{ cm}^{-3}$ did not. Studies of the fast ion charge-exchange spectrum showed no measurable effect ($\pm 20\%$) due to the ripple, either in the parallel or in the perpendicular direction. While direct comparisons of plasma rotation with and without ripple were not made, the 1979 central rotation results with a 2.7% perturbation on axis agreed well with measurements made before the coil damage.

The theoretically expected enhancement in the ion thermal conductivity due to a single shallow dip in the toroidal field is difficult to calculate. For the ripple trapping calculation (Refs. 10-12) we have proceeded as though the ripple were a simple $N = 3$ perturbation, and we have divided the final result we obtain by 3. To calculate the ripple plateau (Ref. 13) thermal conductivity, we Fourier-analyzed the ripple in the toroidal field, and then summed the contributions from each component. Figure 7 shows the theoretically expected effect of the enhanced thermal conductivity due to 2.5% ripple on a PLT plasma which has a central ion temperature of 6.7 keV without ripple. This calculation is in clear disagreement with the experimental results.

The analytic calculations of the ion thermal conductivity described above, however, are subject to considerable doubt. The ripple trapping calculation is called into question, for example, by the fact that a toroidal $N = 3$ ripple well subtends an arc of $\sim 100^\circ$ in the poloidal plane. This is greater than the angle from the horizontal midplane to the region where local trapping is eliminated (Fig. 5); thus the usual calculation of the reduction of the well depth due to toroidal effects is inappropriate. In addition the

particles at $\sim 5T_i$ which contribute the most to ripple trapping transport are highly collisionless, and are more likely to be expelled from the ripple wells by drifting into the region where the wells themselves are eliminated, than by gaining parallel velocity through collisions. Interestingly, both of these problems of the generally accepted ripple trapping calculation may persist even with the usual sinusoidal ripple in cases with very small ripple strength. The ripple plateau calculation for PLT geometry is called into question because it requires the two conditions $Nq \gg 1$ and $v_{*i} > 1/(Nq)^2$, neither of which is satisfied by the low N components of the ripple.

Because of the uncertainties in the analytic calculations, and because of the now clear disagreement with experiment, we have carried out Monte Carlo studies of beam particle confinement, and of thermal ion diffusivity in PLT. Using the guiding center equations described in Ref. 14 in our Monte Carlo beam orbit code (Ref.4), we find that the heating efficiency of the neutral beams should be reduced by only $\sim 5\%$. Furthermore, Monte Carlo calculations of the particle diffusivity of mono-energetic groups of bulk ions starting at $r = 10$ cm in PLT give results at $E_i = 5 - 10$ keV which are a factor of 2-3 less than the value calculated analytically for mono-energetic particles. These Monte Carlo calculations also fail to show the strong increase with energy that is theoretically expected (Fig.8). A much more extensive Monte-Carlo study would be required, however, to determine if the experimentally measured ion heating and plasma rotation are consistent with theory.

IV. Electron Energy Confinement

In Refs. 6 and 7 we reported electron heating experiments at high temperature, and low plasma density, in which the central electron energy confinement time increased during injection, and the volume integrated

confinement time stayed roughly constant. In Ref. 8 we reported experiments at high density, and very low electron temperature, in which the central electron energy confinement time stayed constant but the volume integrated confinement fell significantly. In both cases the radial profile of τ_{Ee} was peaked on axis, rather than approximately flat, as typically found in Ohmic heated tokamak discharges. This arises from the experimental fact that the radial profiles of the beam electron heating and of the ion-electron coupling are quite broad compared to the Ohmic heating profile, but the electron pressure profile does not change shape correspondingly during high-power injection (see Fig. 9). At high temperature and low density the plasma seems to achieve this by increasing confinement in the central region, while at very low temperature and high density the transport in the outer region of the plasma increases.

Figure 10 illustrates an intermediate case. The electron temperature, as measured by the ECE emission at $2\omega_{ce}$, in this case rose from 1 to 2 keV during injection of 1.5 MW D^0 beams, while the ion temperature rose from ~ 700 eV to 2.2 keV, as measured by the passive charge-exchange system. The active charge-exchange measurement indicated that the true central ion temperature was approximately 10% higher, reaching 2.4 keV on axis during injection. Assuming that this same correction factor held throughout the discharge, the time-dependent central ion temperature calculated by the TRANSP code is in good agreement with experiment. Figure 11 shows the calculated volume integrated electron energy confinement time before and during injection, where τ_{Ee} is defined by

$$\tau_{Ee}(r) \equiv \frac{\int \frac{3}{2} n_e k T_e d^3r}{P_{cond}(r) + P_{conv}(r) + P_{rad}(r)}$$

and the capital "P" indicates a volume integrated power. Also shown is the "net" electron energy confinement time, τ_{Ee} , for which the measured radiation is subtracted from the power flow in the definition of τ_{Ee} . Confinement on axis clearly improves in this case, but the volume integrated confinement time drops slightly.

In order to study the effect of varying beam penetration on electron heating, we injected D^0 beams into H^+ plasmas in PLT over a relatively wide range of densities. The electron temperature was measured using the University of Maryland $2\omega_{\text{ce}}$ ECE system, and the radiated power profile was measured bolometrically. We attempted to hold the line average electron density approximately constant during injection using the pulse valve feedback system (Ref. 1), but at the lowest initial densities the electron concentration increased during injection even in the absence of gas flow, with the result that the minimum line average density achieved with 4 beam injection was $2.9 \times 10^{13} \text{ cm}^{-3}$, the minimum with 2 beam injection was $2.4 \times 10^{13} \text{ cm}^{-3}$, while the minimum initial density employed was as low as $1.6 \times 10^{13} \text{ cm}^{-3}$.

Figure 12 shows the electron heating results from this density scan experiment. Surprisingly the electron heating efficiency of the D^0 beams did not fall dramatically when the density was increased. [Note that even at $\bar{n}_e = 5 \times 10^{13} \text{ cm}^{-3}$, the ohmic heating central electron temperature did not fall below 1 keV, indicating that these high density PLT plasmas were hotter, and presumably better confined, than the very low temperature ($T_e(0) \sim 600 \text{ eV}$) high density ($\bar{n}_e = 5.7 \times 10^{13} \text{ cm}^{-3}$) target plasma employed for the electron heating experiment of Ref.7.] Figure 13 shows a calculation of $H(0)$ as a function of line average density in PLT, where $H(0)$ is defined as the beam power per cm^3

deposited on axis, divided by the ratio of the total neutral beam power to the plasma volume. In this calculation the density profile was taken to be parabolic, since it was not measured experimentally. In spite of the uncertainty introduced by not knowing the true density profiles, it is clear that at the highest line average densities achieved in this scan the D^0 beam deposition on axis has fallen substantially, and the heating profile has become peaked off axis.

A second feature of these measurements is that at the higher densities the electron heating seems to be at least proportional to the input beam power. This is also shown in Figure 9, which is composed of radial profiles from this same density scan experiment. At the lowest density, the discharges heated with 4 beams do not appear to have a correspondingly larger electron temperature increase than the 2 beam cases however, but this may be due in some part to the large $\frac{dn_e}{dt}$ during the injection pulse. The observed central core radiation undoubtedly also contributes to the reduced heating efficiency at high power and low density. This radiation may in addition help to explain the fact that the electron heating efficiency does not seem to vary strongly with plasma density. Figure 14 shows the bolometrically measured radiated power averaged over the central 11.5 cm in the density scan experiment. For comparison in the case shown in Fig. 10 the calculated central input power to the electrons from the beam particles and from the thermal ions totals only 270 mW/cm³. At the lowest density the central radiated power must therefore be a substantial fraction of the input power to the electrons on axis. Surprisingly the total radiated power does not vary significantly with plasma density in these beam heated cases, being ~0.6 MW for the 2 beam cases, and 0.9 MW for the 4 beam cases. In the Ohmic heated discharges, the input power was ~ 0.6 mw, and the radiated power was ~0.25 MW

at line average densities below $4 \times 10^{13} \text{ cm}^{-3}$. From 4 to $5 \times 10^{13} \text{ cm}^{-3}$ the radiated power rose to 0.5 MW , and the density we could achieve was limited at this point by major disruptions.

From the density scan results it would be tempting to conclude that electron heating efficiency is insensitive to beam penetration. However, the large dn_e/dt and central core radiation certainly mask a potentially stronger heating efficiency at low density. From the linear dependence of the electron temperature rise on beam power (also reported in Ref. 15) it is a temptation to conclude that electron energy confinement is independent of T_e . However, the fact that ion-electron coupling and beam electron heating decrease rapidly as T_e increases makes the dependence of τ_{Ee} on T_e both possibly more optimistic and certainly not directly derivable from this limited data set. We can conclude, however, that effective electron heating is possible in plasmas with $F(0)$ as low as ~ 1 , and that the continued application of higher beam powers in future tokamaks can be expected to produce corresponding increases in electron temperature, so long as impurity radiation and plasma density can be controlled.

V. Conclusions

Neutral beam injection experiments on PLT have provided definitive information on ion energy confinement in highly collisionless plasmas. We find that ion thermal conduction is consistent, within a factor of ~ 3 , with neoclassical theory, and that anomalous thermal convection of ion energy is a factor of $2-3$ less than would be calculated from the INTOR P_e with a convection loss term of the form $5/2nkT_e$. From our experiments with a shunted TF coil we have found that a single shallow ripple level of 2.5% has a negligible effect on ion energy confinement, even at the lowest collisionality

obtainable on PLT. Scrutiny of the analytic theories of ripple induced transport motivated by these experiments, suggests that more theoretical (and perhaps numerical) work is needed in this area.

Definitive conclusions on the variation of electron energy confinement during injection heating in PLT have remained elusive. Generally the results we find are encouraging for scaling to machines such as TFTR, but the attempt to form simple confinement laws based on the PLT injection experiments has been frustrated by the strong dependence of electron heating on initial plasma conditions and impurity content.

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Fig. 1. Volume integrated ion power balance for 5.5 keV T_i case of Ref. 6.

Fig. 2. Volume integrated ion power balance for 6.3 keV T_i case of Ref. 8.

Fig. 3. Central electron density vs. time in 6.3 keV T_i case.

Fig. 4. Central particle source rates on axis in 6.3 keV T_i case.

Fig. 5. Ripple profile from damaged TF coil with 5 turns removed.

Fig. 6. Ion heating results with and without ripple for $1.5 \times 10^{13} \text{ cm}^{-3}$
 $\bar{n}_e < 3 \times 10^{13} \text{ cm}^{-3}$.

Fig. 7. Calculated effect of 2.5% ripple on a 6.7 keV T_i low density plasma.

Fig. 9. $T_e(r)$ before injection, during injection with 2 and 4 D^0 beams, and after injection.

Fig. 8. Monte Carlo calculation of diffusivity for mono-energetic groups of particles.

Fig. 10. Time evolution of $T_e(0)$ and $T_i(0)$ in 1.5 MW D^0 injection case.

Fig. 11. Volume integrated electron energy confinement times before and during injection in 1.5 MW D^0 case.

Fig. 13. Approximate $H(0)$ vs. $\bar{n}_e$ for parabolic $n_e(r)$ in PLT.

Fig. 12. Electron temperature before, during, and after injection for D^0 beam density scan.

Fig. 14. Bolometrically measured average radiated power in central 11.5 cm of PLT radius during D^0 beam density scan.