UC Irvine

UC Irvine Previously Published Works

Title

Fusion product measurements of the local ion temperature gradient in the plt tokamak

Permalink

<https://escholarship.org/uc/item/37t0q950>

Journal

Nuclear Fusion, 27(1)

ISSN

0029-5515

Authors

Heidbrink, WW
Lovberg, J
Strachan, JD
[et al.](#)

Publication Date

1987

DOI

10.1088/0029-5515/27/1/011

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

FUSION PRODUCT MEASUREMENTS OF THE LOCAL ION TEMPERATURE GRADIENT IN THE PLT TOKAMAK

W.W. HEIDBRINK, J. LOVBERG, J.D. STRACHAN, R.E. BELL
Plasma Physics Laboratory,
Princeton University,
Princeton, New Jersey,
United States of America

ABSTRACT. Measurements of the gradient of the d-d fusion rate profile in an Ohmic PLT plasma are used to deduce the gradient of the ion temperature and thus the local ion thermal diffusivity through an energy balance analysis. The inferred ion diffusivity is consistent with neoclassical theory.

1. INTRODUCTION

The transport of energy by ions in tokamak plasmas is usually studied through calculations of the ion energy balance. In early work, ion transport was estimated entirely from central ion temperature measurements [1]. In recent years, measurements of the ion temperature profile have permitted more accurate determination of the ion thermal diffusivity. Brusati et al. [2] measured the ion temperature profile in Ohmic PLT plasmas with charge exchange, neutrons, and Doppler broadening of impurity lines and found that, to within a factor of two, the profiles were consistent with Hinton-Hazeltine [3] neoclassical heat conduction. The TFR group [4] measured the ion temperature profile in Ohmic and beam-heated discharges by tilting a charge exchange analyser. In Ohmic deuterium plasmas, they found that the ion heat conduction seemed to exceed the Hinton-Hazeltine neoclassical prediction by a factor of two to three, but the data had large scatter. In DITE, charge exchange measurements by Gill et al. [5] indicated ion heat fluxes about five times greater than predicted by neoclassical theory in both Ohmic and beam-heated discharges. Recent measurements using charge exchange recombination spectroscopy in heavily beam-heated Doublet III discharges [6] found that the ion heat conduction was comparable to Chang-Hinton [7] neoclassical conduction at $r/a \cong 0.1$ but exceeded the value from neoclassical theory by a factor of 3–13 at $r/a = 0.5$. One source of uncertainty in these measurements is uncertainty in the local gradient of the ion temperature, which was inferred from measurements of the ion temperature at a few points.

This paper discusses a recently developed technique to measure accurately the local gradient of the ion temperature profile through measurement of the fusion reaction rate profile. In a previous paper [8] the fusion profile diagnostic was described and the measured emission profile was presented. The present paper extends those results by presenting measurements of the local gradient of the ion temperature (Section 2) and by giving a discussion of the inferred ion thermal diffusivity (Section 3). The diffusivity measurement is as accurate (a factor of two) as any previously published results. The local temperature gradient measurement is the most accurate yet reported (30%). Within the uncertainty, the results are consistent with neoclassical theory [7].

2. LOCAL ION TEMPERATURE GRADIENT

The emission of 3 MeV d(d, p)t protons was measured during a series of Ohmic PLT discharges using an array of collimated silicon surface barrier detectors [8]. Each detector viewed an approximately vertical chord through the plasma, accepting unconfined protons that had descended on ∇B drift orbits. A striking feature of this measurement was the very large difference in proton signal (about a factor of 200) between adjacent detectors that were separated by about ten centimetres. The large gradient in proton emission is readily understood from the equation for the fusion emissivity S of a deuteron population of temperature T_i [9],

$$S = \frac{1}{2} n_d^2 \langle \sigma v \rangle \cong A n_d^2 T_i^{-2/3} \exp(-BT_i^{-1/3}) \quad (1)$$

FIG. 1. (a) Electron temperature measured by Thomson scattering (solid points) and by X-ray pulse height analysis (open points) versus vertical position. (b) Electron density measured by Thomson scattering versus vertical position. (c) Ion temperature measured by 3 MeV proton detectors [8] versus minor radius. The dotted lines through the data points are the measurements of the ion temperature gradient. The curve is the profile deduced by SNAP from the measured neutron yield.

where A and B are constants and n_d is the deuteron density. For parabolic ion temperature and density profiles, with central T_i around 1 keV, this expression gives a strongly peaked emission profile (roughly parabolic to the seventh power).

To measure the gradient of the fusion profile, the in-out position of the plasma column was varied shot-to-shot in 1.0 ± 0.1 cm steps. The measurements were performed in the steady state portion (300 ms) of deuterium plasmas with line averaged density of $\bar{n}_e = 2.4 \times 10^{13} \text{ cm}^{-3}$, plasma current of 470 kA, toroidal magnetic field of 31.3 kG, and major radius of 132 cm. The central electron temperature measured by Thomson scattering was 1.7 keV and the neutron ion temperature was 1.0 keV (Fig. 1). The plasmas were limited by vertical limiters (top and bottom) at $a = 40$ cm and horizontal limiters at $a = 42$ cm. No systematic dependence of plasma behaviour (I_p , T_e , T_i , V_L , $\bar{n}_e$) on position was observed for changes in plasma major radius of $< 3\%$ (± 3 cm). However, the proton signal levels varied with plasma position by an order of magnitude (Fig. 2), indicating large local gradients in fusion emission. As expected, the emission measured by four detectors at major radial locations outboard of the plasma centre showed an increase as the plasma moved outwards, while the emission measured by the one inboard detector showed a decrease.

The data in Fig. 2 can be used to infer the ion temperature and its gradient. For circular flux surfaces, differentiation of Eq. (1) gives

$$\frac{dT_i}{dr} = T_i \left[\frac{d(\ln S)}{dr} - 2 \frac{d(\ln n_d)}{dr} \right] / \left(\frac{B}{3T_i^{1/3}} - \frac{2}{3} \right) \quad (2)$$

For these PLT plasmas, Z_{eff} was low (Spitzer conductivity $Z_{\text{eff}} \approx 1.5$) so it is reasonable to use Thomson scattering measurements of electron density for n_d (Fig. 1(b)). Since the fusion emissivity decreases rapidly with increasing radius, most of the 3 MeV protons measured by a detector originate near the horizontal midplane where the emissivity is largest [8]. Ideally, one would have many proton measurements at different radii and deduce the ion temperature profile using an inversion algorithm such as the one described by Karulin and Putvinskij [10]. In the absence of sufficient information for a full inversion, we calculated the ion temperature profile (Fig. 1(c)) with a time-independent radial-profile analysis code (SNAP) [11] by matching the neutron emission and assuming Chang-Hinton neoclassical conductivity for the ions with a 'neoclassical multiplier' of 1.5 and a particle con-

FIG. 2. Proton detection efficiency ϵ (3 MeV proton counts divided by $d(d, n)$ emission) versus horizontal plasma position during steady state Ohmic heating in PLT. The plasma position was scanned by varying the vertical field. Each point is the average over the steady state portion (300 ms) of several reproducible discharges; the error bars represent the error due to counting statistics. The lines are least-squared fits to the data used in the orbit code to infer $d(\ln S)/dr$. Each line is labelled by the major radius of the detector (for instance, P138 corresponds to the proton detector mounted at $R = 138$ cm). The data from the inner detector (P118) are not included in Figs 1(c) and 3 since the radius of the protons measured by this detector depends sensitively on the spatial distribution of the plasma current [8].

finement time of 30 ms [12]. Using this profile, the radii (r) of the proton temperature measurements were found by calculating the average birth position ($\langle r \rangle$) of the detected protons with an orbit code [8]. The orbit code was also used to relate the measured fluxes and gradients to the temperature through Eqs (1) and (2). Comparison of the data with the SNAP profile (Fig. 1(c)) shows that the magnitude of the proton flux is consistent with the SNAP profile. Near the magnetic axis, the temperature gradient inferred from the emission profile is steeper than predicted by SNAP, suggesting that the true ion temperature profile may be more peaked there than shown in Fig. 1(c). At $r \approx a/2$, the gradient of the proton emission is consistent with

the SNAP calculation. These general trends do not depend sensitively on the temperature profile used to invert the proton data.

Equation (2) implies that the accuracy of the temperature gradient measurement is sensitive to the accuracy of the measurement of the gradient of the proton signal (about 20%) and to the accuracy of the ion temperature measurement (about ± 100 eV). When the temperature gradient is relatively flat, uncertainty in the density gradient also plays a role. In our experiments, the accuracy of the ion temperature gradient measurement was typically 30%. This accuracy is superior to that possible with existing diagnostics that use pairs of detectors of known separation Δr . For example, for $\Delta r = 6$ cm, T_i must be measured to about 5% accuracy to achieve 30% accuracy in dT_i/dr at $r/a = 0.4$.

The proton and Thomson scattering data can also be used to deduce the ratio of ion temperature gradient to density gradient, $\eta_i \equiv (d \ln T_i/dr)/(d \ln n_i/dr)$, which is an important parameter in drift wave theory. The data imply that $\eta_i = 2.6 \pm 0.8$ at $r/a \approx 0.25$ and $\eta_i = 1.5 \pm 0.5$ at $r/a \approx 0.6$. Within the errors, these values equal the critical values η_c for marginal stability to the ion mixing mode given by Antonsen et al. [13].

3. ENERGY BALANCE

Following the notation of Brusati et al. [2], the total ion energy content inside a toroidal shell changes with time as

$$\frac{dE_i}{dt} = Q_{ei} - Q_{tc} - Q_{pd} - Q_{cx} + Q_{iz} + Q_{ext} \quad (3)$$

Here the ion energy content dE_i is enhanced through energy exchange with electrons (Q_{ei}) and through ionization of neutrals (Q_{iz}), and depleted through thermal conduction (Q_{tc}), through particle diffusion to the colder edge region of the plasma (Q_{pd}) and through electron exchange reactions with cold neutrals (Q_{cx}). In cases where neutral beam or wave heating is present, the external power deposition (Q_{ext}) must be determined and included in the balance, but for our Ohmic PLT plasma, the external heating term vanishes. An additional simplification for the data points near the magnetic axis is that, in these PLT plasmas, those processes involving neutral particles (ionization, diffusion and charge exchange) are thought to be insignificant since the central neutral density is estimated to be low there ($n_0 = O(10^8 \text{ cm}^{-3})$). Near $r = a/2$, the neutral density

FIG. 3. Ion thermal diffusivity (Eq. (4)) versus minor radius. The hatched region is a conservative estimate of the neoclassical diffusivity [7], assuming that the current profiles and impurity concentrations are not well known. The line is the neoclassical prediction from SNAP assuming Spitzer conductivity.

is estimated (on the basis of previous PLT experiments [2, 12]) to be sufficiently large that convection is as important as conduction in the ion power balance.

Using Eq. (3) and the expressions of Ref. [2] for Q_{tc} and Q_{ei} , the ion thermal diffusivity χ_i at radius r is

$$\chi_i(r) = f \frac{3.6 \times 10^{-8}}{n_i(dT_i/dr)} \int_0^r \frac{n_e^2 (T_e - T_i)}{T_e^{3/2}} r dr \quad (4)$$

where T_i is in eV and n_e is in cm^{-3} , and $f \equiv Q_{tc}/(Q_{tc} + Q_{pd} + Q_{cx} - Q_{iz})$ is the fraction of the energy transported by conduction.

Temperature, density, and temperature gradient data (Fig. 1) were substituted into Eq. (4) to obtain the ion thermal diffusivity profile (Fig. 3). At $r \approx 8$ cm, the measured diffusivity is $960 \pm_{310}^{410} \text{cm}^2 \cdot \text{s}^{-1}$. The largest uncertainty (about 50%) is associated with uncertainty in the minor radius of the local proton measurement (typically ± 3 cm). Uncertainties in electron and ion temperature (± 100 eV), in density ($\pm 2 \times 10^{12} \text{cm}^{-3}$) and in f ($= 0.8$ – 1.0) make smaller contributions ($< 20\%$) to the total error at this radius. At $r \approx 20$ cm, the measured diffusivity is $2500 \pm_{1200}^{2500} \text{cm}^2 \cdot \text{s}^{-1}$ with the error being primarily associated with uncertainty in the relative importance of convection ($f = 0.3$ – 0.8). Neoclassical theory [7] predicts $\chi_i = 2250 \pm_{1040}^{1390} \text{cm}^2 \cdot \text{s}^{-1}$ at $r \approx 8$ cm and $\chi_i = 1200 \pm_{350}^{540} \text{cm}^2 \cdot \text{s}^{-1}$ at $r \approx 20$ cm, with the uncertainty being

associated with uncertainties in poloidal field and Z_{eff} . The measured ion diffusivity in these PLT plasmas is a factor of one to four less than that predicted by neo-classical theory at $r \approx 8$ cm, but it exceeds theory by a factor of one to four at $r \approx 20$ cm.

Besides the experimental uncertainties, various assumptions with limited regions of validity determine the precision of our model. In addition to the assumption of classical electron-ion coupling and the assumptions of the convection model the following assumptions are made:

(a) *The deuterium density profile follows the shape of the measured electron density profile.* This assumption is necessary for the substitution of the n_e profiles from Thomson scattering for n_i in our calculations, as $n_i(r)$ is not directly measured. This assumption is reasonable for a plasma with low Z_{eff} . Since the fusion emissivity depends more strongly on temperature than on density, modest errors in n_i result in smaller errors in the deduced ion temperature profile and gradient.

(b) *Sawteeth are unimportant in the power balance.* Ion energy transport associated with the gross readjustment of plasma in the unstable region of a sawtooth discharge occurs on a time-scale short compared with our counting time, so our model attributes the integrated effect of many oscillations to the ion thermal conduction. Measurements with a grating polychromator indicated that the sawtooth inversion radius was 8 ± 1.5 cm and $\Delta T_e/T_e$ was 9% in these PLT discharges. Since the fusion reactivity is a strong function of temperature (Eq. (1)), time averaged fusion measurements weight the temperature before the sawtooth crash more heavily than the temperature after the crash.

(c) *The deuteron population is Maxwellian.* Measurements of the spectrum and yield of fusion products indicate that the deuterium distribution function is close to Maxwellian in the centre of the plasma in Ohmic [2], $\text{H}^0 \rightarrow \text{D}^+$ beam-heated [15], and ^3He minority ICRF wave-heated [16] plasmas. In cases where a fast-ion component is observed, the fusion emission is dominated by reactions with the fast ions, so the proton diagnostic cannot measure the ion temperature. But even in plasmas where the central deuteron distribution is Maxwellian, there is some evidence that, away from the plasma centre, the distribution function may be distorted by energy dependent radial transport [17]. Ware [18] has predicted that the larger drift orbits of faster ions should cause them to diffuse outwards more rapidly than colder ions, resulting in a bi-Maxwellian energy distribution away from the plasma centre. With the strong energy dependence of the fusion cross-

section, this effect could distort the emission profile dramatically, but the effect on the total ion energy balance would be much weaker. No distortion should be seen when the energetic ion transport time τ_p is significantly longer than the ion-ion equilibration τ_{hi} , where τ_{hi} is the time for the hot ions ($E \approx 3T_i$) producing most of the fusion emission to equilibrate with the bulk distribution. For PLT, the criterion for negligible distortion is $\tau_p \gtrsim 10$ ms, which is probably satisfied since typical gross confinement times are 30–100 ms [12]. While it is possible that local transport is energy dependent and considerably faster than implied by gross confinement [12], the total effect on χ_i of the outward energetic motion predicted by Ware is less than 1% for our PLT Ohmic plasma. In plasmas with hotter central ions or lower plasma currents (larger poloidal gyroradius), however, this effect could become important in the interpretation of the fusion emission profile.

4. CONCLUSION

Measurements of the local ion temperature gradient in the PLT tokamak have been performed using passive fusion-product detection techniques. The values of η_i deduced from the data are equal (within 33% uncertainty) to the critical values for drift wave instability. The inferred ion thermal diffusivity is in general agreement with Chang–Hinton neoclassical values for these ohmically heated PLT plasmas and is consistent with earlier PLT results for Ohmic heating [2]. In neutral beam-heated Doublet III discharges [6] the diffusivity was about a factor of three larger relative to the neoclassical value than in our experiments, but the shapes of the PLT and Doublet III profiles are similar. The large errors in both experiments preclude a definite conclusion, but it seems likely that the difference in χ_i is due to enhanced ion transport during neutral beam injection.

ACKNOWLEDGEMENTS

The authors wish to thank J. Hosea and the PLT staff for their support of this experiment, G. Estep for technical assistance, and R. Goldston for helpful

discussions. S. Von Goeler made the PHA electron temperature measurements and A. Cavallo measured the sawteeth.

This project was supported by the United States Department of Energy under Contract No. DE-AC02-76-CHO-3073.

REFERENCES

- [1] HUGILL, J., Nucl. Fusion 23 (1983) 331.
- [2] BRUSATI, M., DAVIS, S.L., HOSEA, J.C., STRACHAN, J.D., SUCKEWER, S., Nucl. Fusion 18 (1978) 1205.
- [3] HINTON, F.L., HAZELTINE, R.D., Rev. Mod. Phys. 48 (1976) 239.
- [4] EQUIPE TFR, Nucl. Fusion 18 (1978) 1271.
- [5] GILL, R.D., AXON, K.B., BAXTER, G.A., CLARK, W.H.M., HEMSWORTH, R.S., et al., in Controlled Fusion and Plasma Physics (Proc. 9th Europ. Conf. Oxford, 1979), Vol. 1, Culham Laboratory, Abingdon (1979) 150.
- [6] GROEBNER, R.J., PFEIFFER, W., BLAU, F.P., BURRELL, K.H., FAIRBANKS, E.S., et al., Nucl. Fusion 26 (1986) 543.
- [7] CHANG, C.S., HINTON, F.L., Phys. Fluids 25 (1982) 1493.
- [8] HEIDBRINK, W.W., STRACHAN, J.D., Rev. Sci. Instrum. 56 (1985) 501.
- [9] POST, R.F., Rev. Mod. Phys. 28 (1956) 341.
- [10] KARULIN, N.E., PUTVINSKIJ, S.V., Nucl. Fusion 25 (1985) 961.
- [11] TOWNER, H.H., GOLDSTON, R.J., Bull. Am. Phys. Soc. 29 (1984) 1305.
- [12] STRACHAN, J.D., BRETZ, N., MAZZUCATO, E., BARNES, C.W., BOYD, D., et al., Nucl. Fusion 22 (1982) 1145.
- [13] ANTONSEN, T., COPPI, B., ENGLADE, R., Nucl. Fusion 19 (1979) 641.
- [14] STRACHAN, J.D., COLESTOCK, P.L., DAVIS, S.L., EAMES, D., EFTHIMION, P.C., et al., Nucl. Fusion 21 (1981) 67.
- [15] STRACHAN, J.D., COLESTOCK, P.L., EUBANK, H., GRISHAM, L., HOVEY, J., et al., Nature (London) 279 (1979) 626.
- [16] CHRIEN, R.E., KAITA, R., STRACHAN, J.D., Nucl. Fusion 23 (1983) 1399.
- [17] GOLDSTON, R.J., Nucl. Fusion 18 (1978) 1611.
- [18] WARE, A.A., Phys. Rev. Lett. 51 (1983) 400; WARE, A.A., Phys. Fluids 27 (1984) 1215.

(Manuscript received 30 January 1986

Final manuscript received 23 September 1986)