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By

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MARCH 1986

PLASMA
PHYSICS
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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CED-3073.

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FUSION PRODUCT MEASUREMENTS OF THE LOCAL ION THERMAL DIFFUSIVITY IN THE PLT TOKAMAK

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PPPL--2315

DE86 009747

ABSTRACT. Measurement of the gradient of the d-d fusion rate profile in an ohmic PLT plasma is 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.

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1. INTRODUCTION

The transport of energy by ions in tokamak plasmas is usually studied through calculations of the ion energy balance. Previously, ion transport was estimated entirely from central ion temperature measurements [1]. In recent years, measurements of the profile of the ion temperature 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 analyzer. 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 $r/a \approx 0.1$ but exceeded neoclassical theory by a factor of 2.5-6 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 reports a recently developed technique in which fusion reaction rate profiles are measured [8] and used to determine both the ion temperature profile and its local gradient in an ohmic PLT plasma. These, in conjunction with electron temperature and density profiles from Thomson scattering, give the ion energy content in the central half of the plasma and the electron-ion energy exchange rate. The power flow to the ions and the gradient of the ion temperature give the local ion thermal diffusivity. The accuracy of the diffusivity measurement is about a factor of two. Within the uncertainty, the results are consistent with neoclassical theory [7].

2. EXPERIMENT

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. The steady-state deuterium plasma had a 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, minor radius of 40 cm, 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 ion collisionality ν_{ii} was about 0.25 for $r/a = 0.2-0.5$. The measured fusion emission profile was in rough agreement with neoclassical predictions [8].

One 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 cm. 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],

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

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 about 1 cm steps. No systematic dependence of plasma behavior (I_p , T_e , T_i , V_L) 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 in four detectors at major radial locations outboard of the plasma center showed an increase as the plasma moved outward, while the one inboard detector showed a decrease.

The data in Fig. 2 can be used to infer the ion temperature and its gradient. Assuming 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 $Z_{eff} \simeq 1.5$) so it is reasonable to use Thomson scattering measurements of electron density for n_d (Fig. 1b). 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 several 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 have calculated the ion temperature profile (Fig. 1c) 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 confinement time of 30 ms. Using this profile, the radii $\langle r \rangle$ 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. 1c) 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. 1c. At $r \simeq a/2$, 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 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%.

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 $r/a \simeq 0.25$ and $\eta_i = 1.5 \pm 0.5$ at $r/a \simeq 0.6$. Within the errors, these values equal the critical values η_c for marginal stability to the ion mixing mode given by Antonsen *et al.* [12].

3. ENERGY BALANCE

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

$$\frac{dE_i}{dt} = Q_{ei} - Q_{tc} - Q_{pd} - Q_{cx} + Q_{iz} + Q_{ext}. \quad (4)$$

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 $r = a/2$, calculations with SNAP indicate that convection probably is as important as conduction in the ion power balance.

The ion thermal conduction through a toroidal shell of radius r is

$$Q_{ic} = \int_{\text{shell}} \chi_i n_i \frac{dT_i}{ds} \cdot dA = -4\pi^2 R_0 \left[r \chi_i n_i \frac{dT_i}{dr} \right]_r, \quad (5)$$

while electron-ion coupling is given by

$$Q_{ei} = \int \frac{3m_e n_e (T_e - T_i)}{m_i \tau_{ei}} dV = 2.85 \times 10^{-7} \pi^2 R \int_0^r [Z] \frac{n_e^2 T_e - T_i}{T_e^{3/2}} r dr. \quad (6)$$

Thus, the ion thermal diffusivity χ_i can be determined locally as

$$\chi_i(r) = f \frac{3.6 \times 10^{-8}}{r n_i (dT_i/dr)} \int_0^r \frac{n_e^2 (T_e - T_i)}{T_e^{3/2}} r dr, \quad (7)$$

where T_i is in eV and n_e is in cm^{-3} , and f is the fraction of the energy transported by conduction.

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

Besides the experimental uncertainties, the precision of our model rests upon various assumptions with limited regions of validity. In addition to the assumption of classical electron-ion coupling and the assumptions of the convection model these include:

a) *The deuterium density profile follows the shape of the measured electron density profile.* This assumption is necessary so that n_e profiles from Thomson scattering may be

substituted 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 to our counting time, so our model attributes the integrated effect of many oscillations to the ion thermal conduction. The sawtooth inversion radius was 8 ± 1.5 cm in our PLT discharges.

c) *The deuteron population is Maxwellian.* Measurements of the spectrum and yield of fusion products indicate that the deuteron distribution function is close to Maxwellian in the center of the plasma in ohmic [2], $H^0 - D^+$ beam-heated [14], and ^3He -minority ICRF-wave-heated [15] 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 center, the distribution function may be distorted by energy-dependent radial transport [16]. Ware [17] has predicted that the larger drift orbits of faster ions should cause them to diffuse outward more rapidly than colder ions, resulting in a bi-Maxwellian energy distribution away from the plasma center. With the strong energy dependence of the fusion cross section, this effect could distort the emission profile dramatically, with a much weaker effect on the total ion energy balance. No distortion should be seen when the energetic ion transport time τ_p is significantly longer than the ion-ion equilibration time τ_{hi} , where τ_{hi} is the time for the hot ions ($E \simeq 6T_i$) that produce most of the fusion emission to equilibrate with the bulk distribution. For PLT, the criterion for negligible distortion is $\tau_p \gtrsim 10$ msec, which is probably satisfied since typical gross confinement times are 30 — 100 msec [18]. While it is possible that local transport may be energy dependent and considerably faster than implied by gross confinement [18], 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 thermal diffusivity in the PLT tokamak have been performed using passive fusion-product detection techniques. The results are in general

agreement with Chang-Hinton neoclassical values. The values of η_i deduced from the data are equal (within 33% uncertainty) to the critical values for drift wave instability.

ACKNOWLEDGMENTS

We 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 sawtooth inversion radius. This project was supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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FIGURE CAPTIONS

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.

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 statistical error for $\epsilon = 10^{-8}$ is typically $\pm 3\%$. The curves are guides for the eye and are labeled by the major radius of the detector (e.g., P138 corresponds to the proton detector mounted at $R = 138$ cm). The data from the inner detector (P118) are not included in Figs. 1c and 3 since the radius of the protons measured by this detector depends sensitively on the spatial distribution of the plasma current [8].

Fig. 3 Ion thermal diffusivity [Eq. (7)] versus minor radius. The hatched region is the neoclassical prediction [7] for current profiles of $j \propto [1 - (r/a)^2]^{2.5-4.5}$ and impurity concentrations of $Z_{eff} = 1.2-1.9$. Following Stott [19], impurities are assumed to enhance the neoclassical conductivity by a factor of Z_{ion} .

Fig. 1

Fig. 2

Fig. 3

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