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Temperature Dependence of the Electron Thermal Conductivity Coefficient Inferred from Neutral-Beam Injection

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ABSTRACT

It is shown that the radial variation of the electron-to-ion temperature ratio induced by neutral beam injection in PLT could account for the observed spatial dependence of the electron thermal conductivity coefficient. Quantitative evaluations using the experimental temperature and electron thermal conductivity (χ_e) profiles show consistency of the measured data with a finite beta drift wave turbulence model and also demonstrate the failure of a simple electron temperature power law scaling for χ_e.

Recent numerical calculations of tokamak reactor energy requirements indicate a strong dependence of the minimum power required to heat a plasma to ignition on the magnitude of the electron thermal conductivity coefficient χ_e [1]. This sensitivity emphasizes the importance of ascertaining the functional dependence of χ_e on discharge parameters. In spite of this, there does not seem to be any universally accepted scaling law for χ_e other than the Alcator scaling [2], $\chi_e \sim n_e^{-1}$. This inverse density dependence of χ_e is independent of other macroscopic parameters such as B, T_e, q, R/r, etc., that may exhibit significant variations both over the discharge cross section (possibly affecting local thermal conduction rates) and upon extrapolation from present tokamaks to fusion reactors. In this note, the Alcator scaling law is generalized to include the temperature dependence of χ_e implied by neutral beam heating experiments.

It is well known that the temperature dependence of the electron confinement time in tokamaks is difficult to ascertain from data of ohmically heated discharges alone [3]. This is intrinsically due to the fact that the electron temperature in an ohmically heated discharge is not an independent variable but is constrained by the energy balance between thermal conduction losses and ohmic heating [4].

The Princeton Large Torus (PLT) neutral beam injection results [5] represent an experimental basis for isolating the radially resolved temperature dependence of the electron thermal conductivity coefficient, χ_e, independently of its inverse density scaling. With injection of a 2.1 MW deuterium neutral beam into a low density hydrogen plasma ($\bar{n}_e = 2.0 \times 10^{13}\ cm^{-3}$), the PLT experiment achieved significant ion temperature increases, $\Delta T_i/T_i \leq 4$, with only a modest increase in electron temperature, $\Delta T_e/T_e \leq 1.0$. At somewhat higher densities, $\bar{n}_e > 2.5 \times 10^{13}$ cm^{-3}, the density profile and its absolute magnitude remained almost constant during injection. In these latter cases, in particular, the change in χ_e during injection can be attributed to changes in the magnitudes and profiles of the temperatures alone, without obscuring effects due to changes in shear or in density and temperature gradient scale lengths, which all remained approximately constant. In this respect, neutral beam heating performs as a selective probe of the temperature dependence of χ_e, with all other macroscopic variables kept essentially fixed. The PLT measurements provide a direct local observation of the variation of χ_e with temperature, using experimental data (rather than complex and sometimes dubious numerical simulations) to eliminate contributions to the electron energy balance arising from physical processes other than thermal conduction.

Although the volume-integrated electron energy confinement time τ_{Ee} was reported in Ref. [5] to have remained unaltered during injection, the energy confinement time in the central region of the plasma was substantially enhanced. Indeed, at low densities there was a radius r_0 (= 20 cm in PLT) inside which χ_e was reduced during injection heating and outside which it was slightly enhanced (or at least unchanged) during injection. Since both the inner and outer regions of the plasma were heated, it is unlikely that a simple scaling of $n_e\chi_e$ with T_e alone could account for the observed spatial variation of the thermal conductivity. The experimental data indicate, rather, that χ_e depends on <u>both</u> T_e and T_i. In particular, for $r < r_0$, there was substantial ion heating and the temperature ratio, T_i/T_e, changed from less than unity before injection ($T_i/T_e \sim 0.5$) to greater than unity after injection ($T_i/T_e \sim 2$). In contrast, the temperature ratio remained almost unchanged during injection for $r > r_0$.

The analytic temperature dependence of χ_e can be estimated by assuming the electron transport results from microinstabilities that are described [4] by either (i) the "collisionless, high-beta" Vlasov equation model, which seems adequate for the high temperature regions in PLT, or (ii) the "collisional, low-beta" Vlasov Fokker-Planck equation model. Charge neutrality is assumed for the low frequency drift wave turbulence thought to be responsible for anomalous electron transport in tokamaks. Then, in the plasma interior where the transport can be expected to be dominated by Vlasov-Maxwell dynamics rather than plasma-wall interactions and atomic physics, χ_e must have the following functional form for model (i):

$$\chi_e = Ba^2 F(n_e a^2, a^2 B^2/T_e, T_i/T_e) \qquad (1)$$

where F is arbitrary and a is a characteristic density or temperature gradient scale length. Since the temperature ratio variation in PLT was substantial during injection, it has been explicitly retained in Eq. (1), whereas the nearly uniform rise in the electron temperature over the discharge cross section implies fixed current, and hence q(r), profiles. The ion temperature profile became relatively peaked during injection, so that an explicit dependence on $\eta_i \equiv \partial \ln T_i/\partial \ln n_e$

should in principle be retained in Eq. (1). In the central portion of the beam-heated discharge where $\eta_i > 1$, enhanced fluctuations, and hence increased electron thermal conduction, might be expected in a toroidal plasma due to the ion temperature gradient mode [6]. However, since just the opposite behavior of χ_e is observed experimentally, it is reasonable to suppress the η_i dependence in Eq. (1).

The function F in Eq. (1) is constrained by the experimental observations [2] that χ_e scales inversely with the density and independently of the toroidal magnetic field. Then, Eq. (1) becomes:

$$\chi_e = \frac{T_e^{1/2}}{n_e a} G\left(\frac{T_i}{T_e}\right) \quad (2)$$

where $G(T_i/T_e)$ remains to be determined. The density and electron temperature dependence in Eq. (2) agrees with the experimental scaling law obtained on T-11 [7].

In a similar way, the collisional low-beta Fokker-Planck model (which describes trapped particle modes in a tokamak, for example) predicts the scaling:

$$\chi_e = \frac{T_e^{5/2}}{n_e} H\left(\frac{T_i}{T_e}\right) \quad (3)$$

For fixed T_i/T_e, it appears that the T_e dependence of χ_e in Eqs (2) and (3) does not agree with the PLT core results or some thermal conductivity scalings previously proposed for anomalous electron transport in ohmically heated [3,8,9] and beam-heated tokamaks [10]. However, the strong ion heating for $r < r_0$ in PLT competes with the electron heating and can actually reduce χ_e through the $G(T_i/T_e)$ or $H(T_i/T_e)$ factors in Eqs (2) and (3), provided G and H decrease sufficiently rapidly for $T_i/T_e \gg 1$.

A particular case for which an explicit form for G has been previously computed is that of electromagnetic drift wave turbulence in a cylindrical tokamak [11]. The model in Ref. [11] yields an expression for χ_e that is consistent with Eq. (2), where to within an overall dimensional factor independent of the temperature:

$$G(x) = \frac{x^{3/2}}{(1 + x)^4} \tag{4}$$

Note that G has a maximum value for $x = T_i/T_e = 0.6$. Using this model form for G, the PLT observations may be qualitatively understood as follows: for $r < r_0$, G decreased rapidly during beam injection due to the relatively stronger ion heating, $G \sim (T_i/T_e)^{-2.5}$, which dominated the tendency of χ_e to increase with T_e. For $r > r_0$, χ_e increased slowly as both electrons and ions were heated at about the same rate, so that G was nearly constant during injection. A simple dependence of χ_e on T_e alone could not reproduce the observed behavior. Thus, for example, even though the Coppi-Mazzucato scaling law [9] $n_e\chi_e \sim T_e^{-1}Z_{eff}^{2/5}$ predicts a decrease in thermal conductivity for increasing electron temperature in qualitative agreement with the data inside r_0, it fails to correctly account for the lack of change (or possible small increase) in χ_e outside r_0, where there still is an increase in the electron temperature after injection. (There is no evidence of a substantial change in Z_{eff} that might account for the observations.)

A quantitative analysis of the PLT data for the 2.1 MW $D^0 \rightarrow H^+$ injection case is presented in Fig. 1, where the radially resolved ratio of $n_e\chi_e$ during injection to $n_e\chi_e$ before injection is graphed. This ratio, rather than the magnitude of $n_e\chi_e$ itself, is selected as the relevant parameter for quantitative comparison since it is relatively independent of spatially varying quantities such as n_e, B, and q, which, however, remained nearly unchanged during injection. In this way, the information about the temperature ratio scaling of χ_e is emphasized, and the effects of uncertainties in the current and temperature profiles are minimized. The open circles in Fig. 1 were obtained from the experimental values of $n_e\chi_e$ given in Ref. [5]. The density profiles were assumed to be linear with a scale length of 40 cm (as suggested by the published data), with peak densities $n_e(0) = 3.6 \times 10^{13}$ cm^{-3} and 4.5×10^{13} cm^{-3} before and after injection, respectively. The solid circles in Fig. 1 were obtained using experimental temperature profiles to evaluate the ratio $T_e^{1/2}G(T_i/T_e)$ during and before injection. Although the cross-over points in radius where $(n_e\chi_e)^{beam} = (n_e\chi_e)^{ohmic}$ are displaced for the two curves, there is approximate agreement between the radial variation of both the shapes and the magnitudes of the experimental and theoretical $n_e\chi_e$ ratios. The uncertainties in the data preclude any better quantitative comparison. The solid triangles in Fig. 1 represent the Coppi-Mazzucato [9] prediction, which consists of a uniform decrease of

$n_e\chi_e$ over the entire radial extent of the discharge inside r = 30 cm. This is clearly inconsistent with the observations.

Thus, it is possible to interpret the temperature dependence of χ_e observed in PLT by accounting for its scaling with both the electron and ion temperatures. Although a particular model for the determination of the function $G(T_i/T_e)$ was considered here, the form of χ_e in Eq. (2) is generic to microscopic finite beta turbulence. Furthermore, the asymptotic features of G or H at small and large values of the temperature ratio, which may be inferred from the neutral beam heating data over a limited parameter range, must be preserved by <u>any</u> drift wave theory of turbulence that gives $\chi_e \propto n_e^{-1}B^0$. Extrapolation of Eqs (2) and (4) to higher temperatures indicates that increasing the ion temperature at a faster rate than the electron temperature would have a favorable influence on the electron energy confinement, provided $T_i > 0.6T_e$ initially. In a tokamak reactor, the heating of ions by various proposed rf heating schemes may be beneficial in this respect.

Neutral beam heating has proven to be a means of probing the temperature dependence of the electron thermal conductivity coefficient, independent of the well-known inverse density variation $\chi_e \sim n_e^{-1}$. The present analysis suggests the use of electron cyclotron resonance heating (ECRH) in future experiments to selectively heat electrons and thus to further diagnose the variation of χ_e with electron temperature.

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FIGURE CAPTION

FIG. 1. Radial variation of the ratio of $n_e\chi_e$ during injection to $n_e\chi_e$ before injection of 2.1 MW $D^0 \rightarrow H^+$ in PLT [5]. Open circles are obtained from experimental data for $n_e\chi_e$. Solid circles are the result of using experimental temperature profiles in the formula $T_e^{1/2}G(T_i/T_e)$, where G is defined in Eq. (4). The solid triangles represent the scaling law in Ref. [9]. From Ref. [5], the beam-electron power deposition profile peaks at about r = 20 cm and is approximately equal to the ohmic and beam-ion power input at that point.