Observation of Temperature Dependent Transport in TFTR

P.C. Efthimion, D.K. Mansfield, B.C. Stratton, E. Synakowski, A. Bhattacharjee^(a),
H. Biglari, P. H. Diamond^(b), R. J. Goldston, C. C. Hegna^(a), D. McCune, G. Rewoldt,
S. Scott, W. M. Tang, G. Taylor, R. E. Waltz^(c), R. M. Wieland, M.C. Zarnstorff
Princeton Plasma Physics Laboratory, Princeton University, Princeton, N. J.

Abstract

Local particle and heat transport coefficients have been measured in a controlled temperature scan of neutral-beam-heated plasmas with n , I_p , and $B\phi$ held constant. The electron particle transport is ascertained from a general flux analysis of a small density perturbation, and the heat transport is obtained from the equilibrium power balance. The local particle and heat transport coefficients vary as T_e^α , where $\alpha = 1.5-2.5$. The observed temperature dependence for these plasmas is predicted by numerical calculations of anomalous transport due to trapped-particle drift-type microinstabilities.

Auxiliary-heated plasma transport is particularly interesting because of the variety of plasma regimes (e.g., L-mode, H-mode, supershot) that have been identified.¹⁻³ For L-mode plasmas the global confinement has been extensively characterized on many tokamaks, and empirical global scaling laws have been developed.^{1,4-6} These plasmas exhibit a degradation of global confinement with increasing heating power ($\tau \propto P^{-0.6}$). However L-mode studies have not identified the transport mechanism. Electrostatic drift-type microinstability transport theory predicts degradation of confinement with heating power due to its strong temperature dependence. Examples of approximate analytical forms of the theory⁷ for different modes include

$$D_{dte} = \epsilon^{1.5} (\rho_s C_s / L_n)^2 / \nu_{ei} \propto \epsilon^{1.5} T_e^{3.5} / (n L_n^2) \quad \text{for } \nu_{eff} / \omega_* \gg 1,$$

$$D_{cte} = 3 \epsilon^{0.5} \rho_s^2 C_s / L_n \propto \epsilon^{0.5} T_e^{1.5} / L_n \quad \text{for } \nu_{eff} / \omega_* \ll 1, \text{ and}$$

$$D_{itg} = \epsilon^{0.5} (\rho_s C_s)^2 L_s / (\nu_{eff} L_{Ti}^3) \propto \epsilon^{0.5} T_e^{3.5} L_s / L_{Ti}^3,$$

where D_{dte} , D_{cte} are estimates of the diffusivities for the dissipative⁸ and collisionless trapped-electron mode⁹; D_{itg} represents a sheared-slab model estimate of the diffusivity for the trapped-ion mode¹⁰ in the dissipative trapped-electron regime of collisionality; ρ_s is the

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25

ion Larmor radius using the electron temperature; C_s is the sound speed; L_n , L_{Ti} , and L_s are the density gradient, ion-temperature gradient, and shear scale lengths; T_e is the electron temperature; n is the electron density; ν_{ei} is the electron-ion collision frequency; $\nu_{eff} = \nu_{ei}/\epsilon$; ϵ is the inverse aspect ratio; and ω_* is the diamagnetic drift frequency. Note that D_{te} has also been expressed with $L_n L_{Te}$ replacing L_n^2 , where L_{Te} is the electron temperature scale length.⁸ These expressions are typical representations of transport coefficients using mixing length estimates. It has also been pointed out¹¹ that the analytic expressions for D_{dte} and D_{cte} given here are strictly applicable only at the two extreme limits of collisionality. However, many plasmas including those with L-mode confinement have $\nu_{eff}/\omega_* \approx 1$. A recent model for trapped-electron transport in this regime of collisionality indicated that the T_e and L_n dependences are functions of ν_{eff}/ω_* and L_n itself. The model interpolates between the two regimes based upon the ratio ν_{eff}/ω_* . All of the electrostatic drift-type microinstability theories have the temperature as a fundamental parameter through the Larmor radius, collision frequency, and sound speed. Therefore, knowledge of the temperature dependence of the transport coefficients may provide insight into the transport mechanism, and select applicable theories. In this paper the dependence of heat and particle transport on temperature for L-mode plasmas are examined.

To explicitly examine the temperature dependence it is necessary to vary the temperature with all other quantities held constant. In this experiment, a neutral-beam power scan was completed with the final line-integrated density held constant by adjusting the injection target electron density at each power level. Helium gas was applied to the target plasmas for the power scan to obtain broad density profiles, and insure L-mode plasma confinement. The neutral beams inject counter- and co-tangential to the plasma current and fuel the plasma with deuterium neutrals with a maximum energy near 100 keV. Four beam powers were used with the power in the co- and counter-beam sources balanced to minimize plasma rotation ($P_b = 0, 4.5, 9.0$, and 14 MW). The ohmic heating power is 1.1 MW in the plasma with no neutral beam heating, and is only 0.6 MW in the plasma with $P_b = 14$ MW. The toroidal magnetic field $B_\phi = 4.0$ T, the major radius $R = 2.58$ m, the minor radius $a = 0.93$ m, the safety factor $q = 5.1$ and the plasma current $I_p = 1.5$ MA were also held constant. The Z_{eff} increased from 2.8 to 3.6 with beam power. Figure 1 shows the four electron density and temperature profiles achieved in the scan, and measured by a 10 channel far infrared interferometer and by electron cyclotron emission radiometry, respectively. With very similar density profiles, the central electron temperature varied by a factor of two. These discharges had sawteeth, and the location of the inversion radius at $r = 0.23$ m was measured from the electron cyclotron emission. There is similar ion heating with the ratio of T_i/T_e increasing from 0.8 to 1.25 with input

power. The global energy confinement time for plasmas in increasing order of input power were 0.27, 0.127, 0.105, and 0.100 sec. The confinement times were, on the average, 1.1 times L-mode confinement scaling.¹ The duration of the neutral-beam-heating is 1.0 sec which is approximately 4 - 10 energy confinement times for the ohmic and neutral-beam-heated plasmas.

A small amount of helium gas (15 tl/sec for 0.05 sec) is puffed into these plasmas to determine the particle transport from the evolution of the density profile using perturbation analysis techniques. A 10 channel far infrared interferometer measured the density profile evolution.¹² The time-dependent profile data, the neutral-beam fueling rate, and the edge wall source are used to solve for the electron particle flux, Γ , from the particle balance equation: $\partial n / \partial t = -\nabla \cdot \Gamma + S$, where S is the total electron source as a function of time and radius. The neutral-beam fueling rate profile is calculated with a Monte Carlo beam deposition algorithm, and the wall source is calculated from the total number of particles in the plasma and an estimate of the particle confinement time of 0.1 sec. The wall source is also compared to the D_α emission. Figure 2 shows $\Gamma(t)$ at a minor radius of $r = 0.6$ m for the four power conditions. The gas puff is put in at 4.0 sec, and the outward flux decreases in each case due to the density perturbation. The amount of time for the flux to return to equilibrium from its minimum value is indicative of the transport time and the particle transport coefficients. Note that there is a reduction in this recovery time between the low temperature ohmically-heated plasma ($P_b = 0$ MW) and the highest temperature neutral-beam-heated plasma. The majority of the change in the transport time is observed between the ohmic and the 4.5 MW neutral-beam-heated plasmas. The recovery time and the electron temperature for the 9.0 and 14.0 MW cases look nearly identical. The same observations can be made in comparing the global energy confinement times for these plasmas. Thus, temperature dependence of the particle transport can be seen directly in the particle flux in Fig. 2 without additional analysis.

In previous particle transport experiments, the particle transport coefficients were determined by fitting the flux to the form $\Gamma(r,t) = -D(r) \nabla n(r,t) + V(r) n(r,t)$, where D and V are the particle transport coefficients at each radius, r . This form assumes that D and V are constant over the time of the perturbation.¹³⁻¹⁷ It is easily seen that the use of the above flux form to obtain transport coefficients leads to erroneous conclusions if the coefficients are themselves functions of ∇n or n .^{18,19} The perturbed flux, $\delta \Gamma$, is expressed as

$$\delta \Gamma = (-\langle D \rangle - \partial D / \partial \nabla n \langle \nabla n \rangle + \partial V / \partial \nabla n \langle n \rangle) \delta \nabla n + (\langle V \rangle + \partial V / \partial n \langle n \rangle - \partial D / \partial n \langle \nabla n \rangle) \delta n ,$$

where $\langle \rangle$ refers to equilibrium values, and δ designates perturbed terms. Small gas puffs in this experiment produce $\delta n/n \approx 0.07$, $\delta \nabla n / \nabla n \approx 0.2$, $\delta T_e / T_e \approx 0.02$, and $\delta \Gamma / \Gamma \approx 0.3-2.0$. The terms multiplying $\delta \nabla n$ are frequently referred to as the equilibrium diffusivity. If D is proportional $1/L_n^\alpha$ where $\alpha \neq 0$, then the term multiplying $\delta \nabla n$ is not just a function of the equilibrium diffusivity, $\langle D \rangle$, but also has a contribution from the perturbed diffusivity, $\partial D / \partial \nabla n \langle \nabla n \rangle \approx \langle D \rangle$. Thus, the assumption that D is constant over the time of the perturbation leads to an error in estimating the magnitude of D , and it should not be compared with the equilibrium value. Similarly, the term multiplying δn is frequently referred to as the equilibrium pinch term, but it has a contribution from the diffusivity, $\partial D / \partial n \langle \nabla n \rangle$, as well as the equilibrium pinch term, $\langle V \rangle$. If D is proportional to $1/L_n^\alpha$ where $\alpha > 0$, then failing to account for the term $\partial D / \partial n \langle \nabla n \rangle$ leads to the conclusion that the equilibrium pinch is highly anomalous, and the pinch flux $\approx$ diffusive flux. Then the magnitude of the pinch has to be reconciled from the equilibrium particle balance, or some alternate analysis technique. These complications arise for any perturbation magnitude. If the diffusivity is indeed a function of n or ∇n , as is the case in drift-type microinstability transport theories and as observed in previous experiments,^{16,17} then the simple flux analysis assuming a time independent D and V is not correct. Here we have adopted a general flux expression that allows for nonlinear transport coefficients: $\delta \Gamma = (\partial \Gamma / \partial \nabla n) \delta \nabla n + (\partial \Gamma / \partial n) \delta n$, where the partial derivatives $\partial \Gamma / \partial \nabla n$, and $\partial \Gamma / \partial n$ are determined from the fit to the perturbed flux in the experiment, and are hereafter referred to as the particle transport coefficients.¹⁹ The values of $\partial \Gamma / \partial \nabla n$ and $\partial \Gamma / \partial n$ are numerically the same as the values of D and V , respectively, obtained with the old perturbative analysis technique. However, integration of the partial derivatives, $\partial \Gamma / \partial \nabla n$ and $\partial \Gamma / \partial n$, with respect to n and ∇n is not necessary to observe the temperature dependence in the particle transport. Other dependencies in addition to temperature can be extracted from the local transport coefficients, and will be the topic of another paper.²⁰ Specifically the functional form of the partial derivatives, $\partial \Gamma / \partial \nabla n$ and $\partial \Gamma / \partial n$, can be integrated to obtain the functional dependence of the total flux, and the magnitude of the particle pinch.

The general flux analysis outlined in the previous paragraph is applied to the particle flux from the temperature scan. The analysis is applied outside the $q=1$ surface to avoid density sawtooth effects, but not within 0.23 m of the last closed flux surface of the tokamak, in order to minimize the influence of the edge electron source term in the particle balance equation and the radiative power in the heat balance. Figure 3a and 3b show the particle transport coefficients, $\partial \Gamma / \partial \nabla n$ and $\partial \Gamma / \partial n$, derived from the flux analysis as a function of radius for the four plasma cases described in Fig. 1. At each radius there is an increase in the particle transport coefficients with increasing electron temperature. In

addition there is a radial dependence in the coefficients with smaller values toward the center of the plasma. Previous studies of particle transport using gas puffs on other tokamaks have obtained limited information concerning the radial dependence of the particle transport coefficients.¹³⁻¹⁶ The electron and ion thermal conductivities, χ_e and χ_i (Fig. 3c), are obtained from equilibrium power balance analysis, and exhibit similar temperature and spatial behavior to $\partial\Gamma/\partial\nabla n$ (Fig. 3a). The thermal diffusivities are calculated for the neutral-beam-heated plasmas which have accurate measurements of the ion temperature profiles using charge-exchange recombination spectroscopy. For these L-mode plasmas $\chi_i > \chi_e$. The error bars for the thermal diffusivities represent the standard deviation of 100 power balance analyses with the plasma parameters varied within their uncertainties using a gaussian probability distribution. The particle transport coefficient error bars represent the uncertainties in the wall source, and the standard deviation of the regression fits. The particle confinement time was varied $\pm$ a factor of 4 and the uncertainty in the wall source created a 5% uncertainty in the transport coefficient at $r = 0.7$ m. Therefore, both the electron and ion thermal diffusivities, and the electron particle transport coefficients are observed to be strongly temperature dependent at a fixed density.

At each radius the transport coefficients in Fig. 3 are assumed to be proportional to T_e^α , and the temperature exponent, α is plotted in Fig. 4 as a function of radius. $\partial\Gamma/\partial\nabla n$ and $\partial\Gamma/\partial n$ exhibit the same temperature scaling at each radius, with values of α ranging from 1.5-2.5. Similar values of the temperature exponent are obtained for χ_e and χ_i . The uncertainties in determining the temperature dependence of χ_e and χ_i can be reduced by examining a single heat diffusivity for the plasma defined²¹ as $\chi_{flux} \equiv - (Q_e + Q_i) / (n_i \nabla T_i + n_e \nabla T_e)$. This avoids the large uncertainties in decoupling the electron and ion heat flows. The temperature dependence of the thermal diffusivity χ_{flux} at each radius for the neutral-beam-heated plasmas is also shown in Fig. 4, and is similar to the values obtained for the particle transport coefficients $\partial\Gamma/\partial\nabla n$ and $\partial\Gamma/\partial n$.

The temperature exponents observed for the heat and particle transport coefficients are between the values of 1.5 and 3.5 predicted by the analytical forms of trapped-particle drift-type microinstability transport theory for the two extremes of collisionality in the banana regime. Furthermore, with $v_{eff}/\omega_* \approx 1$ for the neutral-beam-heated plasmas and ≈ 4 for the ohmic case, ref. 11 indicates that the temperature exponent should lie between 1.5 and 3.5. To better estimate these values, two numerical codes were used to predict the temperature exponent from microinstability theory for these plasmas. The first involved comprehensive kinetic microinstability calculations in toroidal geometry for trapped-particle modes driven by trapped-electron and $\eta_i (\nabla T_i)$ dynamics.²² For $r < 0.65$ m, $\eta_i > 2$ for all of the plasmas, and this calculation indicates that η_i mode behavior should be dominant

in this region. The temperature exponents of the transport coefficients expressed in terms of the mode growth rate and the mode wave vector, γ/k_{θ}^2 is calculated, and the average temperature exponent for the four plasma cases at $r = 0.5$ m is shown in Fig. 4 (referred to as Toroidal QL Model). The average of the calculated values is very close to the experimental temperature exponents for heat and particle transport coefficients at the same radius. The calculation also includes examination of the separate fluxes, and indicates that the electron and ion heat diffusivities have the same electron temperature dependence as γ/k_{θ}^2 . This justifies examination of the single flux, χ_{flux} , for the temperature dependence. In addition, the average temperature exponent for the four discharges is calculated over the radius $r=0.35-0.6$ m with a slab-like quasilinear model of trapped-particle transport (referred to as Slab-like QL Model) assuming that the η_i mode behavior is dominant.¹¹ The numerical values are shown as a dotted line in Fig. 4, and are also close to the experimental results.

In summary, a strong temperature dependence has been observed in particle and heat transport coefficients for standard L-mode plasmas. The observed temperature dependence is predicted by numerical calculations of anomalous transport due to drift-type microinstabilities. The temperature dependence is consistent with, and strongly supports electrostatic drift-type microinstability transport theory.

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- (b) Permanent address: University of California at San Diego, La Jolla Ca.
- (c) Permanent address: General Atomics, Inc. , San Diego, Ca.
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Figures

Fig. 1. Electron density, and temperature profiles at four neutral-beam heating powers (0, 4.5, 9, 14 MW).

Fig. 2. The time evolution of the electron particle flux, Γ , at plasma radius, $r=0.6$ m at the four neutral-beam-heating powers ($P_b = 0, 4.5, 9.0, 14.0$ MW). A gas puff applied at 4.0s reduces the flux in all cases.

Fig. 3a. Particle transport coefficient $\partial\Gamma/\partial\nabla n$ versus plasma radius.

Fig. 3b. Particle transport coefficient $\partial\Gamma/\partial n$ versus plasma radius.

Fig. 3c. Electron and ion thermal diffusivities (χ_e, χ_i) versus plasma radius. The points with dashed lines are χ_i and those with the solid lines are χ_e . For L-mode discharges, $\chi_i > \chi_e$.

Fig. 4. The electron temperature exponent of the transport coefficients $\partial\Gamma/\partial\nabla n$, $\partial\Gamma/\partial n$, and χ_{eff} , and a comparison with numerical calculations of the temperature exponents from two drift-like microinstability theories (slab-like QL Model, and toroidal QL Model).

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FIG. 1

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FIG. 2

FIG. 3

FIG. 4

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