COMPREHENSIVE ENERGY TRANSPORT SCALINGS DERIVED FROM DIII–D SIMILARITY EXPERIMENTS*

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Abstract

The dependences of heat transport on the dimensionless plasma physics parameters has been measured for both L–mode and H–mode plasmas on the DIII–D tokamak. Heat transport in L–mode plasmas has a gyroradius scaling that is gyro-Bohm-like for electrons and worse than Bohm-like for ions, with no measurable beta or collisionality dependence; this corresponds to having an energy confinement time that scales like $\tau_{\mathrm{E}} \propto n^{0.5} P^{-0.5}$. H–mode plasmas have gyro-Bohm-like scaling of heat transport for both electrons and ions, weak beta scaling, and moderate collisionality scaling. In addition, H–mode plasmas have a strong safety factor scaling ($\chi \sim q^2$) at all radii. Combining these four dimensionless parameter scalings together gives an energy confinement time scaling for H–mode plasmas like $\tau_{\mathrm{E}} \propto B^{-1} \rho^{-3.15} \beta^{0.03} \nu^{-0.42} q_{95}^{-1.43}$ $\propto I^{0.84} B^{0.39} n^{0.18} P^{-0.41} L^{2.0}$, which is similar to empirical scalings derived from global confinement databases.

1. INTRODUCTION

Significant progress has been made recently towards predicting and understanding heat transport in L–mode and H–mode plasmas on DIII–D using the related methods of similarity and scale invariance. In these experiments, the dependences of transport on the relative gyroradius ($\rho_* \sim T^{1/2} / aB$), plasma beta ($\beta \sim nT / B^2$), normalized collision frequency ($\nu \sim na / T^2$), and safety factor ($q \sim aB_{\mathrm{T}} / RB_{\mathrm{p}}$) are measured one at a time while keeping the other dimensionless parameters fixed (including those related to plasma shape and $T_{\mathrm{e}} / T_{\mathrm{i}}$). Experimentally determining the transport scalings in this way helps to distinguish between various proposed instability mechanisms of turbulent transport and permits a comprehensive energy confinement scaling relation to be developed that is founded in the principles of plasma physics. In addition, the $T_{\mathrm{e}} / T_{\mathrm{i}}$ dependence of transport is being studied to test an important predicted scaling of theory-based transport models.

2. H–MODE PLASMAS

The scalings of heat transport with ρ_*, β, ν, and q have been measured on DIII–D for H–mode plasmas. The results provide a strong experimental constraint on theoretical models of turbulent transport. Gyroradius scaling experiments in low q discharges have shown gyro-Bohm-like scaling for both the heat [1] and particle [2] transport, $B\tau_{\mathrm{E}} \propto \rho_*^{-3.15\pm0.2}$. This scaling is consistent with the majority of anomalous transport theories that assume that the radial wavelength (or radial correlation length) of the turbulence scales with the Larmor radius. Other H–mode experiments have found energy confinement to have only a very weak beta dependence, $B\tau_{\mathrm{E}} \propto \beta^{0.03\pm0.11}$, which favors theories of anomalous transport for which $E \times B$ transport is dominant over magnetic flutter transport [3]. The measured collisionality scaling falls between

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those of the collisionless ion temperature gradient (ITG) and collisionless trapped electron modes and that of the resistive ballooning mode [4], $B\tau_\mathrm{E} \propto \nu^{-0.42\pm0.03}$. The ν scaling of the dissipative trapped electron and dissipative trapped ion modes was not observed.

Recent experiments on DIII–D have found a strong safety factor scaling of heat transport at all radii for H–mode plasmas [5]. In the first experiment, the safety factor was varied by a factor of 1.4 at fixed magnetic shear (see Fig. 1) while the other dimensionless parameters such as ρ_*, β, ν, and $T_\mathrm{e}/T_\mathrm{i}$ were kept constant. The confinement time was found to scale like $\tau_\mathrm{E} \propto q^{-2.42\pm0.31}$ for this case. A local transport analysis also found a strong safety factor dependence of the effective thermal diffusivity, as shown in Fig. 2, the magnitude of which agreed with the scaling of the global confinement time. This transport scaling is close to the expected scaling of the resistive ballooning mode and is near to the upper limit of the scalings for the toroidal ITG mode and the collisionless trapped electron mode. In the second experiment, the safety factor and magnetic shear were both varied such that q_{95} was scanned at fixed q_0. A weaker confinement scaling was measured for this case, $\tau_\mathrm{E} \propto q_{95}^{-1.43\pm0.23}$; this weaker scaling was attributed to the smaller variation in the volume-averaged q profiles rather than the change in the magnetic shear [5].

The combined ρ_*, β, ν, and q scalings of heat transport for H–mode plasmas on DIII–D reproduce the physical parameter dependences of empirical scalings derived from global confinement databases, with the possible exception of weaker power degradation. Converting a confinement scaling relation from dimensionless variables to physical (dimensional) variables is a straightforward algebraic manipulation. Assuming a power law form for the scaling relation, the dimensionless parameter scalings for low q H–mode plasmas on DIII–D can be summarized as

$$\begin{aligned}\tau_\mathrm{E} &\propto B^{-1}\rho_*^{-3.15\pm0.2}\beta^{0.03\pm0.11}\nu^{-0.42\pm0.03}q_{95}^{-1.43\pm0.23}\\ &\propto I^{1.43\pm0.23}B^{0.66\pm0.38}n^{-0.39\pm0.11}T^{-0.70\pm0.16}L^{1.30\pm0.31}\\ &\propto I^{0.84\pm0.16}B^{0.39\pm0.20}n^{0.18\pm0.07}P^{-0.41\pm0.06}L^{2.00\pm0.24}\ ,\end{aligned} \tag{1}$$

where L represents the physical size scaling (*i.e.*, a, R, etc.) needed to make the scaling relation dimensionally correct. Thus, it can be seen that the dimensionless parameter scaling approach

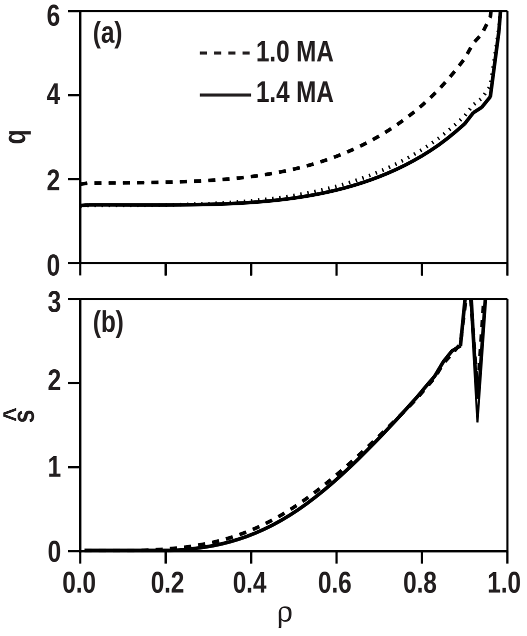

FIG. 1. Radial profiles of (a) safety factor, and (b) magnetic shear for H–mode discharges. The dotted line in (a) represents the 1.0 MA profile scaled to 1.4 MA.

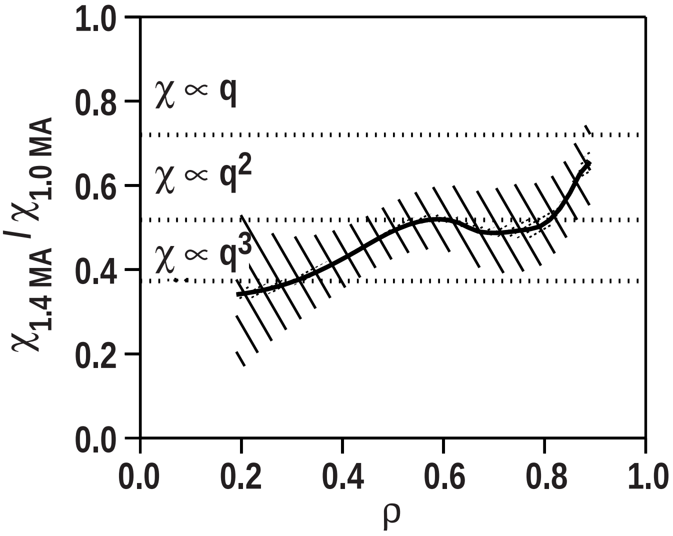

FIG. 2. Ratio of effective thermal diffusivities for H–mode discharges with fixed magnetic shear. The lined shading indicates the standard deviation of the random error.

yields a definitive prediction for the size scaling of confinement from single machine experiments. For comparison, the confinement time derived from a dataset of H–mode plasmas on DIII–D and JET is [6,7]

$$\tau \propto I^{0.9} B^{0.3} n^{0.2} P^{-0.5} L^{1.5} \quad . \tag{2}$$

Comparing Eqs. (1) and (2) finds that the physical parameter scalings derived from DIII–D similarity experiments agree with those derived from a regression analysis of multi-machine confinement databases to the 2σ level. Another interesting comparison can be made using a confinement scaling for ELM-free H–mode plasmas that is nearly dimensionally correct [8],

$$\tau_{\mathrm{ITER-93H}} = 0.036\, I^{1.06} B^{0.32} n_{19}^{0.17} P^{-0.67} R^{1.9} a^{-0.11} A^{0.41} \kappa^{0.66} \quad . \tag{3}$$

A comparison of Eqs. (1) and (3) finds that the B, n, and size scalings agree to within 1σ, while the difference in the I scalings is only a little larger. The main discrepancy is in the power scaling, where the DIII–D experiments find a weaker power degradation than ITER-93H (owing partially to the weaker beta scaling), leading to a more optimistic projection for H–mode confinement on larger machines [9].

3. L–MODE PLASMAS

The dependences of heat transport with ρ_*, β, and ν also have been measured for L–mode plasmas on DIII–D. The ρ_* scalings of the electron and ion heat transport were measured separately [10], with the electron diffusivity scaling gyro-Bohm-like, $\chi_e \propto \chi_B \rho_*^{1.1\pm0.3}$, and the ion diffusivity scaling worse than Bohm-like, $\chi_i \propto \chi_B \rho_*^{-0.5\pm0.3}$. Here, $\chi_B = T / eB$ is the Bohm diffusion coefficient. The scaling of the global confinement time could vary from gyro-Bohm-like to Bohm-like depending upon whether the electrons or ions dominated the heat transport. The beta scaling of energy confinement was close to zero, $B\tau_E \propto \beta^{-0.05\pm0.10}$, with the electron and ion thermal diffusivities having the same scaling to within the experimental errors [3]. The scaling of energy confinement with collisionality in the banana regime was also close to zero, $B\tau_E \propto \nu^{0.02\pm0.03}$, with the electron and ion heat transport again having the same scaling to within the experimental uncertainties [4].

By combining the ρ_*, β, and ν scalings, the power degradation and density scaling of energy confinement can be uniquely determined for L–mode plasmas. However, this calculation is complicated by the fact that the ρ_* scalings of the electron and ion thermal diffusivities are not the same. If we limit ourselves to the typical case of approximately equal electron and ion heat conduction, then the global confinement exhibits Bohm-like scaling, and the scaling of the energy confinement time in physical parameters is

$$\begin{aligned} \tau_{\mathrm{E}} &\propto B^{-1}\rho_*^{-2}\beta^{-0.05\pm0.10}\nu^{0.02\pm0.03} \\ &\propto n^{0}T^{-1.1} \\ &\propto n^{0.5}P^{-0.5} \quad . \end{aligned} \tag{4}$$

The B and I dependences of τ_{E} cannot be determined until the safety factor scaling of transport is measured for L–mode plasmas. Comparing Eq. (4) with the commonly used ITER-89P L–mode scaling relation [11],

$$\tau_{\mathrm{ITER-89P}} = 0.048\, I^{0.85}R^{1.2}a^{0.3}n_{20}^{0.1}B^{0.2}A^{0.5}\kappa^{0.5}P^{-0.5} \quad , \tag{5}$$

one sees that the power degradation factors are the same but Eq. (5) has a weaker density scaling than what was measured on DIII–D.

4. $T_{\mathrm{e}}\,/\,T_{\mathrm{i}}$ DEPENDENCE OF TRANSPORT

In order to further differentiate between various theory-based transport models, the scaling of transport with $T_{\mathrm{e}}\,/\,T_{\mathrm{i}}$ is also being studied. Experiments in L–mode plasmas with internal transport barriers (ITB) on DIII–D have shown that intense electron heating, using either fast waves or electron cyclotron heating, in a beam heated plasma with $T_{\mathrm{i}} \gg T_{\mathrm{e}}$ increases the electron and ion thermal diffusivities and slows the plasma rotation [12]. Further experiments on DIII–D have studied the $T_{\mathrm{e}}\,/\,T_{\mathrm{i}}$ dependence of heat transport in ELMing H–mode plasmas without ITBs and with $T_{\mathrm{e}} \sim T_{\mathrm{i}}$. In these experiments, increasing the ratio of $T_{\mathrm{e}}\,/\,T_{\mathrm{i}}$ at fixed beta resulted in an increase in both the electron and ion heat transport as well as the particle transport. This result, combined with related H–mode experiments that varied T_{e} at fixed T_{i}, and *vice versa,* can be summarized as $\tau_{\mathrm{E}} \propto \langle T_{\mathrm{i}}\rangle^2\,/\,\langle T_{\mathrm{e}}\rangle^2$. This strong scaling may be limited to the conditions near those measured. In addition, since the toroidal rotation also decreased with increasing $T_{\mathrm{e}}\,/\,T_{\mathrm{i}}$, some of the transport change may be only indirectly related to $T_{\mathrm{e}}\,/\,T_{\mathrm{i}}$ owing to the small decrease in $\omega_{E\times B}$ with electron heating.

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