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

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Significant progress has been made 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. 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.

The scalings of heat transport with safety factor (q), normalized collision frequency (ν), plasma beta (β), and relative gyroradius (ρ_*) have been measured on the DIII–D tokamak in order to develop a strong experimental constraints on theoretical models of turbulent transport. Gyroradius scaling experiments have shown gyroBohm-like scaling for ITER-relevant H–mode discharges both globally and locally [1], which 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. Beta scaling experiments have found confinement to have only a weak β dependence [2], which favors theories of anomalous transport for which $E\times B$ transport is dominant over magnetic flutter transport. Collisionality scaling experiments showed an increase in heat transport with increasing ν for H–mode plasmas and no ν dependence of heat transport for L–mode plasmas [2]. Thus, the measured ν scaling falls between those of the collisionless ion temperature gradient (ITG) and collisionless trapped electron modes and that of the resistive ballooning mode; the ν scaling of the dissipative trapped electron and dissipative trapped ion modes which is in the opposite direction 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. 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, and ν were kept constant. The confinement time was found to scale like $\tau_{th} \propto q^{-2.42\pm 0.31}$ 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, $\tau_{th} \propto q_{95}^{-1.43\pm0.23}$; this weaker scaling was attributed to the smaller variation in the volume-averaged q profiles.

The combined q, ρ_*, β, and ν scalings of heat transport for H–mode plasmas on DIII–D reproduce the physical parameter scalings of confinement derived from regression analysis of multi-machine databases, with the exception of weaker power degradation. Converting a confinement scaling relation from dimensionless variables to physical (dimensional) variables is

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a straightforward algebraic manipulation. Assuming a power law form for the scaling relation, the dimensionless parameter scalings for H–mode plasmas on DIII–D can be summarized as

$$\tau_{\rm th} \propto \Omega^{-1}\, \rho_*^{-3.15\pm0.2}\, \beta^{0.03\pm0.11}\, \nu^{-0.42\pm0.03}\, q_{95}^{-1.43\pm0.23}$$

$$\propto I^{0.84\pm0.16}\, B^{0.39\pm0.20}\, n^{0.18\pm0.07}\, P^{-0.41\pm0.06}\, L^{2.00\pm0.24}$$

where Ω is the cyclotron frequency and L represents the physical size scaling (i.e., a, R, etc.) needed to make the scaling relation dimensionally correct. For comparison, a thermal confinement scaling for ELM-free H–mode plasmas that is nearly dimensionally correct has been determined for the ITER project [3],

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

A comparison of these two relations finds that the B, n, and size scalings agree to within 1 σ, while the difference in the I scalings is a little larger. The main discrepancy is in the power scaling, where the DIII–D experiments find a weaker power degradation than ITER-93H, leading to a more optimistic projection for H--mode confinement on larger machines.

To further differentiate between various theory-based transport models, the scaling of transport with T_e/T_i is also being studied. In addition, the T_e/T_i dependence of transport is being studied to test an important predicted scaling of theory-based transport models. Experiments in L–mode plasmas on DIII–D have shown that intense electron heating, using either fast wave or electron cyclotron heating, in a beam heated plasma with $T_i \gg T_e$ increases the electron and ion thermal diffusivities and slows the plasma rotation. Further experiments on DIII–D will study the T_e/T_i dependence of heat transport in H–mode plasmas in three ways: (1) T_e/T_i scans at fixed beta, (2) T_e scans at fixed T_i, and (3) T_i scans at fixed T_e. The combined results of these experiments will test an important dependence of theory-based transport models that affects both the critical gradients and the incremental diffusivities.

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[3] KAYE, S.M., et al., Plasma Phys. and Contr. Nucl. Fusion Research 1994, Seville, (International Atomic Energy Agency, Vienna, 1995) Vol. 2, p. 525.

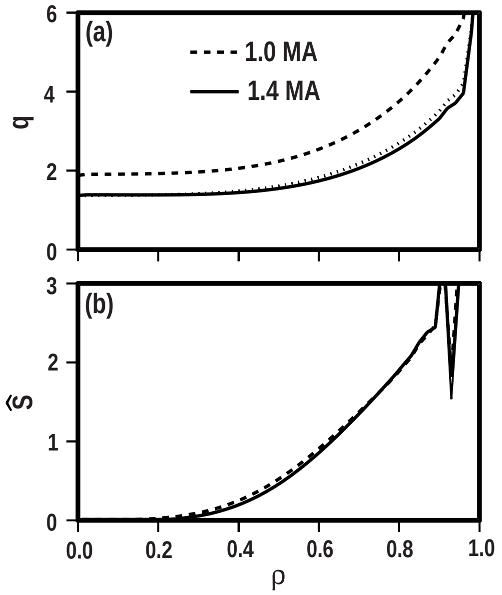

Fig. 1. Radial profiles of (a) safety factor, and (b) magnetic shear for H–mode discharges. The dotted line in (a) represents the 1.0 MA profile scaled to 1.4 MA.

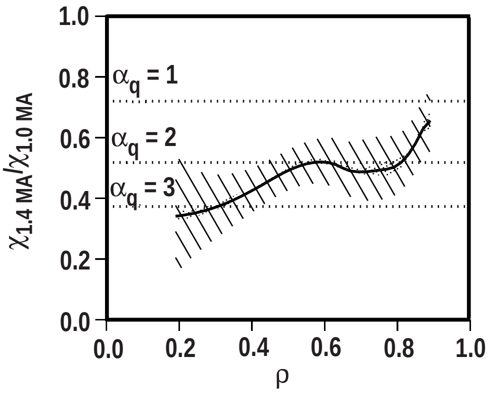

Fig. 2. Ratio of effective thermal diffusivities for H–mode discharges with fixed magnetic shear. The lined shading indicates the standard deviation of the random error.