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UNDERSTANDING TRANSPORT THROUGH DIMENSIONLESS PARAMETER SCALING EXPERIMENTS*

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Introduction. The related methods of dimensional analysis, similarity, and scale invariance provide a powerful technique for analyzing physical systems. For example, the complex plasma dynamics governed by the Vlasov-Maxwell system of equations can be characterized by sets of dimensionless quantities through the application of these techniques [1,2]. Significant progress has been made recently towards predicting and understanding radial heat transport using dimensionless parameter scaling techniques. Previous experiments on the DIII–D tokamak have measured the variation of heat transport with the relative gyroradius (ρ_*) [3–6]; in this paper, the scaling of heat transport with plasma beta (β) and normalized collisionality (ν) for L–mode and H–mode plasmas on the DIII–D tokamak is reported.

Following the scale invariance approach to confinement scaling, the thermal diffusivity (χ) is assumed to depend only on local dimensionless quantities. One possible form for χ is

$$\chi = \chi_\mathrm{B} \beta^{\alpha_\beta} \nu^{\alpha_\nu} F(\rho_*, q, R/a, \kappa, T_\mathrm{e}/T_\mathrm{i}, \cdots) \ , \tag{1}$$

where $\chi_\mathrm{B} = cT/eB$. By varying either β or ν while keeping the other dimensionless quantities fixed, the scaling exponents α_β and α_ν can be determined since the unknown function F remains constant. Understanding the beta and collisionality scaling of transport helps to differentiate between various proposed mechanisms of turbulent transport and allows the origin of power degradation and density scaling of confinement to be determined.

Beta Scaling of Heat Transport. Experimental results from the beta scaling of confinement should help discern the anomalous transport mechanism. Theories for which $E \times B$ transport is dominant show little enhancement or perhaps even slight reduction in transport with increasing beta, while transport models that invoke electromagnetic effects like magnetic flutter transport are generally expected to have a strong, unfavorable beta scaling. Empirically-derived scaling relations seem to favor the latter transport mechanism; the ITER-89P L–mode scaling gives $\alpha_\beta = 0.525$, whereas the ITER-93H H–mode scaling gives $\alpha_\beta = 1.235$.

In these experiments on the DIII–D tokamak, scaling of L-mode and H-mode confinement was determined for a factor-of-2 scan in beta. In order to keep ρ_*, ν, and q constant while varying β, the plasma parameters were scaled like $n \propto B^4$, $T \propto B^2$, and $I \propto B$ at fixed plasma geometry. Fast wave heating was utilized for L–mode discharges while neutral beam injection (NBI) heating was used for H–mode discharges. The global parameters for these β scans are given in Table I, which shows that the dimensionless parameters were well matched.

The energy confinement was found to depend only weakly upon beta for both the L–mode and H–mode scans. Table I shows that the normalized confinement time scaled like

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Table I: Global dimensionless parameters for β scans

	L–mode		H–mode	
Parameter	#90118	#90108	#90117	#90108
B (T)	1.63	1.91	1.62	1.93
q_{95}	3.66	3.64	3.76	3.88
$\bar{n}/B^4$	0.25	0.28	0.53	0.53
$W_{\rm th}/B^6$	5.0	5.1	15.4	16.3
$\beta_{\rm N}^{\rm th}$	0.26	0.49	0.80	1.71
$B\tau_{\rm th}$	0.166	0.161	0.229	0.257

$B\tau_{\rm th} \propto \beta^{-0.05\pm0.10}$ for L–mode plasmas and $B\tau_{\rm th} \propto \beta^{0.15\pm0.13}$ for H–mode plasmas. This beta dependence was much weaker than the prediction of empirically-derived scaling relations, which indicates that the (apparent) beta scalings contained in these scaling relations are not due to an actual beta dependence of heat transport.

A local transport analysis verified that the beta scaling of the thermal diffusivity for the L–mode plasmas was weak or possibly non-existent. The beta scalings of the ion and electron thermal diffusivities are plotted as a function of the normalized radius in Fig. 1. The error bars indicate that the beta scalings of $\chi_{\rm e}$ and $\chi_{\rm i}$ are not statistically different from each other. For H–mode plasmas, the local transport analysis found that the beta scaling for the electron fluid was weak, but a significant beta scaling was observed in the ion fluid, as shown in Fig. 2. The nearly linear, favorable beta scaling for ion transport is not explained as yet; however, any comparison of these experimental results with theoretical models should include the effect of the outward shift of the magnetic axis with increasing beta since large Shafranov shifts can stabilize trapped particle modes and reduce anomalous transport [7].

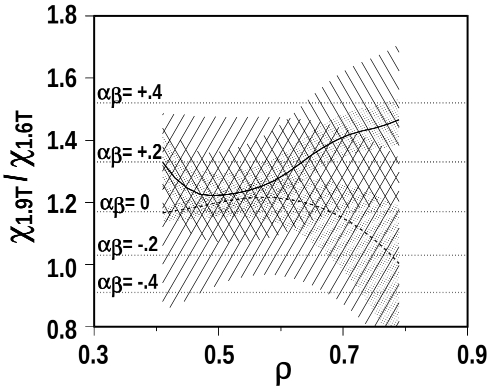

Fig. 1. Ratio of electron (solid line) and ion (dashed line) thermal diffusivities for the L–mode beta scan. The lined shading indicates the standard deviation of the random error, while the dotted shading indicates the potential effect of systematic error.

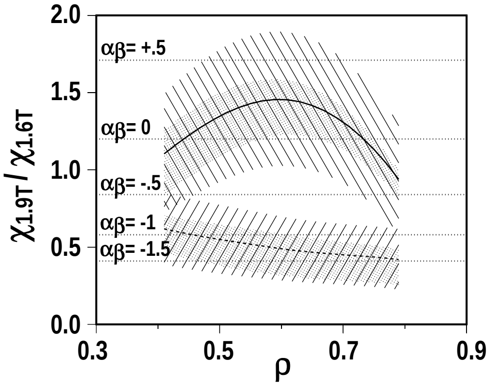

Fig. 2. Ratio of electron (solid line) and ion (dashed line) thermal diffusivities for the H–mode beta scan.

Collisionality Scaling of Heat Transport. Drift wave models of anomalous transport can generally be classified by their predicted dependence on collisionality. The thermal diffusivities for η_i and collisionless trapped electron modes are expected to have no dependence on ν, while the thermal diffusivities for the dissipative trapped particle and resistive ballooning modes are expected to have strong ν scalings [8]. In addition, neoclassical transport has a linear, unfavorable ν dependence in the banana regime. Both the ITER-89P L–mode scaling and the ITER-93H H–mode scaling have the same $\nu^{-0.28}$ dependence.

In these experiments, the scaling of L–mode and H–mode confinement was determined for a factor-of-8 scan in collisionality. In order to keep ρ_*, β, and q constant while ν varied, the plasma parameters were scaled like $n \propto B^0$, $T \propto B^2$, and $I \propto B$ at fixed plasma geometry. Combined NBI and fast wave heating was used for L–mode discharges while NBI heating was utilized for H–mode discharges. The global parameters are given in Table II, which shows that the dimensionless parameters were well matched for these ν scans.

Table II: Global dimensionless parameters for ν scans

	L–mode		H–mode	
Parameter	#90765	#90753	#90768	#90740
B (T)	1.14	1.91	1.15	1.92
q_{95}	3.60	3.56	4.04	3.98
$\bar{n}B^0$	2.4	2.6	6.6	6.1
W_th/B^2	63	63	240	230
$\nu_{*,\mathrm{min}}$	0.15	0.019	0.090	0.011
$B\tau_\mathrm{th}$	0.128	0.123	0.180	0.406

The confinement was found to be almost independent of collisionality for L–mode plasmas, whereas a moderate ν dependence was observed for H–mode plasmas. Table II shows that the normalized confinement time scaled like $B\tau_\mathrm{th} \propto \nu^{0.02\pm0.03}$ for the L–mode scan and $B\tau_\mathrm{th} \propto \nu^{-0.37\pm0.05}$ for the H–mode scan. The ν dependence for H–mode plasmas was similar to that of the ITER-93H scaling, but the ν dependence for L–mode plasmas was much weaker than in the ITER-89P scaling.

The local transport analysis found that the ν scaling of the thermal diffusivity was weak for L–mode plasmas, in agreement with the global confinement scaling. This is shown in Fig. 3, where the ν scaling of the ion and electron thermal diffusivities is plotted as a function of the normalized radius. For H–mode plasmas, the local transport analysis found that the one-fluid thermal diffusivity had a moderate, unfavorable ν scaling similar to the global confinement scaling, as shown in Fig. 4. It is not yet clear if this ν scaling is present in both the electron and ion fluids. Since the anomalous transport is only 2–3 times the neoclassical level for these H–mode plasmas, the measured ν dependence may be a manifestation of the linear collisionality scaling of neoclassical transport.

Conclusions. Experiments in the DIII–D tokamak found weak beta scaling of heat transport for both L–mode and H–mode plasmas. For L–mode plasmas, the electron and ion thermal diffusivities had no measurable beta dependence and the normalized confinement time scaled like $B\tau_\mathrm{th} \propto \beta^{-0.05\pm0.10}$. The confinement time for H–mode plasmas scaled like

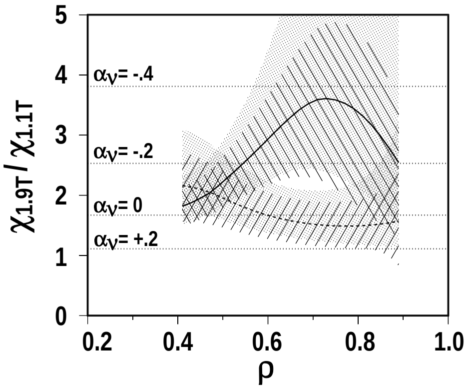

Fig. 3. Ratio of electron (solid line) and ion (dashed line) thermal diffusivities for the L–mode collisionality scan.

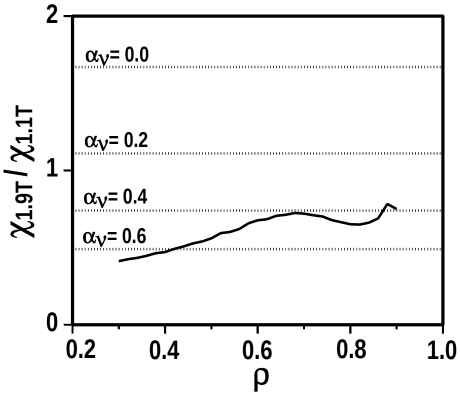

Fig. 4. Ratio of one-fluid thermal diffusivities for the H–mode collisionality scan.

$B\tau_{\text{th}} \propto \beta^{0.15\pm0.13}$; the ions had a favorable beta scaling whereas the electrons had no measurable beta dependence. Since a strong, unfavorable beta scaling of transport was not observed, these experiments indicate that electromagnetic effects like magnetic flutter transport are not a significant part of the turbulent transport process.

The collisionality scaling for L–mode plasmas was also close to zero, $B\tau_{\text{th}} \propto \nu^{0.02\pm0.03}$. The ν scalings of the ion and electron thermal diffusivities were the same to within the experimental error. The lack of ν scaling, even in the plasma edge, indicates that the dissipative trapped particle and resistive ballooning modes are not significant at any radii for these L-mode plasmas [8]. For H–mode plasmas, a moderate, unfavorable ν scaling was observed in the local heat transport, with the confinement time scaling like $B\tau_{\text{th}} \propto \nu^{-0.37\pm0.05}$. This ν dependence may be a manifestation of neoclassical transport.

The parameter scalings found in these experiments are more optimistic than the present ITER scaling relations. Assuming a power law form for the scaling relation, the power degradation and density scaling of confinement are completely determined by the ρ_*, β and ν scalings. Combining the measured β and ν scalings of confinement for L–mode plasmas with Bohm-like ρ_* scaling [3], a global confinement scaling of $\tau \propto n^{0.5}P^{-0.5}$ is obtained. For H–mode plasmas, taking the measured scalings for β and ν along with gyro-Bohm-like ρ_* scaling [5,6] results in a global confinement scaling of $r \propto n^{0.3}P^{-0.4}$. These scaling expressions lead to a more favorable prediction of the confinement time for future ignition devices than the present ITER scaling relations such as ITER-93H.

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