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Comprehensive Energy Confinement Scalings Derived from Similarity Experiments

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Significant progress has been made recently towards predicting and understanding energy confinement in plasmas on the DIII–D tokamak using the related methods of dimensional analysis, similarity, and scale invariance. Up to now, predictions of the energy confinement time were derived from empirical fits to multi-machine confinement databases. Typical of these empirical scaling relations is the one derived for the ITER project for high confinement (H-mode) plasmas,

$$\tau_{98H} = 0.036\, I^{0.97}\, B^{0.08}\, n^{0.41}\, P^{-0.63}\, R^{1.70}\, a^{0.23}\, A^{0.20}\, \kappa^{0.67}$$

where I is the plasma current, B is the magnetic field strength, n is the plasma density, P is the heating power, R is the major radius, a is the minor radius, A is the hydrogen isotope mass, and κ is the plasma elongation. A major drawback of these empirical scaling relations is that they are not constrained by the underlying plasma physics principles that govern the energy transport and loss processes; this is especially a concern when extrapolating the confinement time to future, larger machines that lie outside the parameter range of existing databases.

Recent experiments on DIII–D have applied dimensional analysis to this problem by measuring the dependence of energy confinement on the dimensionless plasma physics parameters such as the gyroradius normalized to the plasma radius ρ_*, the ratio of plasma pressure to magnetic pressure β, the detrapping collision frequency normalized to the average bounce frequency in the magnetic well ν_*, and the safety factor q. Since the principle of similarity requires that confinement in a non-rotating plasma depends only upon these dimensionless parameters, the validity of this approach can be tested by comparing the normalized energy confinement time ($\Omega\tau$ or more simply $B\tau$, where Ω is the cyclotron frequency) for two plasmas with widely different physical parameters but identical values for the dimensionless parameters. In a comparison with tokamaks both 1.8 times larger (JET) and 2.6 times smaller (Alcator C–Mod) than DIII–D, the normalized energy confinement times agreed to within the experimental uncertainties, as shown in Table I.

These experiments provide a strong constraint on theoretical models of turbulent transport. For example, ρ_* scaling experiments in H-mode plasmas have shown gyroBohm-like scaling of the energy confinement time (thermal diffusivity $\chi \propto \rho_* T/B$), which agrees with the majority of transport theories that assume that the radial wavelength (or radial correlation length) of turbulence that is responsible for transport scales with the gyroradius. Other experiments found that the energy confinement time has no β dependence, which favors theories for which E×B transport (electrostatic turbulence) is dominant over magnetic flutter transport (electromagnetic turbulence). The energy confinement time is also found to increase with decreasing safety factor, in accordance with theoretical expectations, which can explain the strong current dependence and weak magnetic field dependence of confinement since $q \propto B/I$. Finally, the energy confinement time increases with decreasing ν_*, which is a surprise since these H–mode plasmas are relatively collisionless. Recent ideas in turbulent transport theory suggest that the ν_* dependence can arise from collisional damping of radial modes in the plasma.

Combining these measured dimensionless parameter scalings for H-mode confinement results in a scaling relation that is founded in the principles of plasma physics,

$$\tau \propto B^{-1}\, \rho_*^{-3.15\pm0.2}\, \beta^{0.03\pm0.11}\, \nu_*^{-0.35\pm0.04}\, q_{95}^{-1.08\pm0.23}$$

$$\propto I^{0.78\pm0.14}\, B^{0.36\pm0.18}\, n^{0.28\pm0.07}\, P^{-0.46\pm0.05}\, L^{2.12\pm0.22},$$

where L represents the physical size scaling (a combination of major and minor radius, a and R) needed to make the relation dimensionally correct. A comparison with the ITER98H scaling finds that the I, B, n, and size dependences agree to within 2σ. The main discrepancy is in the scaling with power, where the DIII–D similarity experiments have found a weaker power degradation (resulting from the weak β scaling). This leads to a more optimistic projection for H-mode confinement on larger machines.

Table I: Test of similarity between three different tokamaks

Parameter	C–Mod	DIII–D	DIII–D	JET
ρ_*	0.34	0.35	0.35	0.34
ν_*	0.52	0.40	0.41	0.43
β	0.51	0.52	1.6	1.6
q_{95}	3.6	3.7	3.5	3.5
$B\tau$	0.14	0.13	0.22	0.21

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