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ABSTRACT

The dimensionless parameter scaling approach is increasingly useful for predicting future tokamak performance and guiding theoretical models of energy transport. Experiments to determine the ρ_* (gyroradius normalized to plasma size) scaling have been carried out in many regimes. The electron ρ_* scaling is always "gyro-Bohm" ($\chi \propto \chi_B \rho_*$), while the ion ρ_* scaling varies with regime. The ion variation is correlated with both density scale length (L mode, H mode) and current profile. The ion ρ_* scaling in the low-*q*, H–mode regime (where fusion power plants are expected to operate) is gyro-Bohm, which is the most favorable confinement scaling observed. New experiments in β scaling and collisionality scaling have been carried out in low-*q* discharges in both L mode and H mode. In L mode, global analysis shows that there is a slightly unfavorable β dependence ($\beta^{-0.1}$) and no ν_* dependence. In H–mode, global analysis finds a weak β dependence ($\beta^{0.1}$) and an unfavorable dependence on ν_* ($\nu_*^{-0.35}$). The lack of significant β scaling spans the range of β_N from 0.25 to 2.0. The very small β dependence in L mode and H mode is in contradiction with the standard global scaling relations (ITER–89P: $\tau \propto \beta^{-0.52}$, ITER-93H: $\tau \propto \beta^{-1.23}$). This contradiction in H mode may be indicative of the impact on the H–mode database of low-*n* tearing instabilities which are observed at slightly higher β_N in the β scaling experiments. For the low-*q*, H–mode experiments, the observed scalings can be combined to yield a global scaling law $\tau_E \propto I^{6z/11} B^{(2-z)6/11} P^{-5/11} n^{3/11} a^{(31-6z)/11}$, where z is the yet unmeasured q scaling experiment. The measured β and ν_* scalings explain the weak density dependence observed in engineering parameter scans. It also points to the power of the dimensionless parameter approach, since it is possible to obtain a definitive size scaling from experiments on a single tokamak.

1. INTRODUCTION

Significant progress has been made in the last two years on applying dimensionless parameter scaling techniques to the problem of predicting and understanding tokamak energy transport. The value of this approach with respect to prediction of future machine performance is that present-day devices can operate at ignition-relevant values of the standard dimensionless parameters with the exception of ρ_*, which is the gyroradius normalized to the plasma linear size [1]. Therefore, the performance extrapolation is reduced to knowledge of a single parameter scaling which can be validated independently on many machines.

Experiments to measure the ρ_* scaling of local transport in various operating regimes have been carried out on the DIII–D tokamak. In low-*q* H–mode, the ρ_* scaling is ''gyro-Bohm'' [2], which means the net diffusivity χ scales like $\chi_B \rho_*$ where χ_B is the Bohm diffusivity. This gyro-Bohm scaling is qualitatively consistent with the H–mode global regression scaling (ITER-93H) used by the ITER EDA for its confinement projections . For L–mode plasmas, the measured global scaling lies near Bohm scaling (consistent with $\chi \propto \chi_B \rho_*^0$). This is consistent with the standard L–mode regression scaling (ITER-89P). Two-fluid analysis showed the origin of the derivation from the expected gyro-Bohm scaling to be exclusively in the ion scaling [3,4]. Recently, high-q H–mode discharges have also been shown to exhibit Bohm scaling in the ion channel [5]. The data clearly show that the deviation from gyro-Bohm scaling in the ion channel is correlated with shorter density scale length (L–mode) or a current profile scale length (high-q). The physical mechanisms for this behavior are a topic of active research. Combining the most favorable confinement scaling regime (low-q H–mode) and the H–mode power threshold scaling, it is possible to construct a paradigm for minimizing the size of the plasma core for an ignition power balance point [6]. Extrapolating from DIII–D discharges, a plasma with 500 MW of fusion power could be sustained in the H mode against transport losses at $B = 5.7$ T, $I = 9.9$ MA, $\bar{n} = 2.0\times10^{20}\,\mathrm{m}^{-3}$, $R = 2.7$ m, and $\beta_N = 3.3$. This ignition power balance point is below the Troyon β limit and the Greenwald density limit.

In addition to ρ_* scaling experiments, scaling studies for the dimensionless parameters β and collisionality have also been carried out in both L–mode and H–mode. These experiments help clarify what physical processes are involved in the energy transport. In principle, a complete set of scaling experiments would define an empirical local scaling relation for transport. The experiments reported here represent a significant step in that direction, including the first reported β and collisionality scaling experiments in H–mode.

2. PROOF-OF-PRINCIPLE EXPERIMENTS

A critical test of the dimensionless parameter scaling approach to transport studies is the realization of ‘‘identity’’ discharges — discharges on two tokamaks with widely different physical parameters, but exact matches of the dimensionless parameters. The first steps in this direction have been successfully carried out by comparing ELMing H–mode discharges on DIII–D and JET. The magnetic geometry of both machines was identical to 1% in aspect ratio, elongation, and q. The fluid dimensionless parameters ρ_*, β, and collisionality ν_* will be constant if na^2, $Wa^{-1/2}$, and $Ba^{5/4}$ are constant. The experimental match is 2%, 5%, and 3%, respectively. The proof of principle for the global confinement is whether the thermal confinement normalized to the cyclotron frequency is constant. This figure of merit agrees to within 2% for these discharges [5]. The next step is to show that the diffusivities scale appropriately ($\chi a^{-3/4}$ constant) across the plasma for both electrons and ions. Unfortunately, T_i is unavailable for the JET discharge, so it is assumed that $T_i = T_e$ and a one-fluid diffusivity $\chi \equiv (\kappa_e + \kappa_i)/(n_e + n_i)$ is used. The comparison is shown in Fig. 1. The scaled diffusivities agree to within 20% everywhere from $\rho = 0.2$–0.8. Recent JET discharges with ion temperatures will be analyzed in the near future. The present degree of agreement between the scaled JET and DIII–D plasmas provides confidence in the dimensionless scaling approach.

3. β SCALING

Experimental results from the scaling of energy transport with β should differentiate between various proposed instability mechanisms. Most drift wave models show little enhancement or perhaps even slight reduction in transport with increasing β. On the other hand, transport models which invoke resistive MHD or magnetic fluctuations are generally expected to have strong β degradation. Standard regression analysis of global confinement databases would favor the latter. The ITER-89P L–mode scaling gives $\beta^{-0.52}$, while the ITER–93H H–mode scaling gives a very strong $\beta^{-1.2}$ dependence. In order to keep ρ_* and ν_* fixed while β varies, the

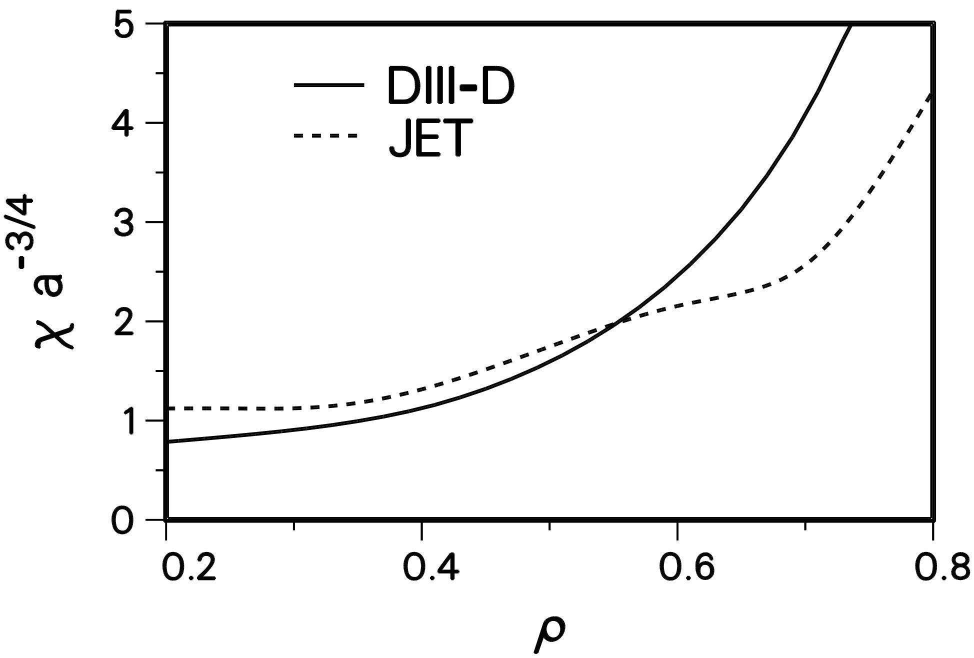

Fig. 1. The normalized one-fluid diffusivity for JET and DIII–D is shown vs. normalized radius.

following relations must be held for fixed plasma geometry: $n \propto B^4$, $T \propto B^2$, and $I \propto B$. This results in $\Delta\beta \propto (\Delta B)^4$. In the experiments reported here, a factor of 2 scan in β is made.

For the L–mode experiment, the normalized confinement scales like $\beta^{-0.1}$. The global engineering parameters and the appropriate combinations proportional to the dimensionless parameters are shown in Table I. The density and stored energy matches are better than 10%. The normalized confinement time varies only slightly as β_N goes from 0.25 to 0.5. This is significantly weaker than the ITER–89P scaling. Preliminary two-fluid analysis shows that both fluids scale similarly.

In H–mode, the normalized confinement time scales like $\beta^{0.1}$ as β_N is scanned from 1.0 to 2.0. Table I also shows the engineering and dimensionless variables for the H–mode scan. The parameters were chosen to be in a regime where gyro-Bohm ρ_* scaling would be expected. The density and stored energy matches are better than 10%. This is significantly different from the β scaling in the ITER–93H scaling relation.

One speculation on the source of this difference for H–mode plasmas is the effect of tearing modes at higher β_N. For the shots in the same sequence with slightly higher β_N, a $m = 3/n = 2$ tearing mode is destabilized and the confinement can drop by up to 30%. This destabilization is attributed to neoclassical effects rather than classical $\Delta' > 0$ destabilization [7]. Since this effect depends on collisionality and aspect ratio, it would not be discriminated in the ITER regression database by windowing on β_N. A similar effect is unlikely in the L–mode database. The source of the apparent β scaling there may be fast ion losses due to beam-driven instabilities (*e.g.*, fishbones) in the highest β_N shots.

Table I: Comparison of global plasma parameters (β)

	L–mode		H–mode	
Parameter	Low-β	High-β	Low-β	High-β
B (T)	1.63	1.91	1.62	1.93
I_p (MA)	1.13	1.35	1.13	1.35
$\bar{n}$ (10^{19} m^{-3})	1.8	3.7	3.4	7.2
W_{th} (kJ)	93	246	260	830
P_{tot} (MW)	0.91	2.91	1.75	6.2
τ (s)	0.102	0.084	0.150	0.134
R/a	2.68	2.67	2.76	2.77
κ	1.72	1.73	1.81	1.83
q_{95}	3.66	3.64	3.67	3.85
$\bar{n}/B^4$	0.25	0.28	0.49	0.52
W_{th}/B^6	5.0	5.1	14.4	16.1
β (%)	0.28	0.54	0.87	1.90
$B\tau$	0.17	0.16	0.24	0.26

4. COLLISIONALITY SCALING

The theoretical expectations for scaling with collisionality are less clear. Neoclassical theory gives normalized confinement inversely proportional to collisionality in the banana regime. Drift wave transport is expected to be roughly independent of collisionality in the banana regime. Both the ITER–89P L–mode scaling and the ITER–93H–mode scaling have a $\nu_*^{-0.28}$ dependence. In order to keep ρ_* and β fixed as collisionality varies, the following relations must hold: $n \propto B^0$, $T \propto B^2$, and $I \propto B$. This implies $\Delta\nu_* \propto (\Delta B)^{-4}$. The experiments reported here vary ν_* by a factor of 8.

For the L–mode scan, the normalized confinement is almost independent of ν_*. The engineering parameters and the effective global dimensionless parameters are shown in Table II. Because of the large scan in ν_*, the effect of mismatches in ρ_* and β are minimized. The density and stored energy matches are within 10%.

For the H–mode ν_* scan, the normalized confinement time drops as the collisionality increases, consistent with a $\nu_*^{-0.35}$ scaling. The H–mode ν_* parameters are also given in Table II. The experiments were carried out in the low-q H–mode regime where gyro-Bohm ρ_* scaling would be expected. The β values are similar to the ITER demonstration discharges. It is not yet clear whether this ν_* scaling is observed in both channels. The observed scaling is close to the ρ_* scaling in the ITER–93H scaling relation.

Table II: Comparison of global plasma parameters (ν_*)

	L–mode		H–mode	
Parameter	Low-ν_*	High-ν_*	Low-ν_*	High-ν_*
B (T)	1.91	1.14	1.91	1.14
I_p (MA)	1.37	0.81	1.35	0.8
$\bar{n}$ (10^{19} m^{-3})	2.7	2.4	6.3	6.2
W_{th} (kJ)	228	82	930	340
P_{tot} (MW)	3.55	0.72	3.6	1.61
τ (s)	0.064	0.113	0.26	0.21
R/a	2.69	2.70	2.74	2.77
κ	1.73	1.73	1.7	1.7
q_{95}	3.56	3.60	3.84	4.055
$\sqrt{W_{th}/\bar{n}}/B$	4.9	5.1	6.4	6.5
β (%)	0.52	0.52	2.2	2.2
$B\tau$	0.12	0.13	0.50	0.24

5. DISCUSSION

Converting from dimensionless variables back to engineering variables for a global confinement scaling is a straightforward algebraic manipulation. Assuming a standard power law form for the scaling relation, the power degradation and density scaling are completely determined by the ρ_*, β, and ν_* scaling. [In this paper, the collisionality ν_* is defined without q; this is the collision frequency normalized to the transit time rather than the bounce time.] For the H–mode scans, the conversion to a global scaling law in engineering variables is clear because the experiments are carried out in a regime where both the electron and ion ρ_* scaling are expected to be the same. Taking the observed scalings: ρ_*^{-3} (gyro-Bohm), β^0, and $\nu_*^{-1/3}$, the following relation is obtained:

$$\tau_E \propto I^{6z/11} B^{(2-z)6/11} P^{-5/11} n^{3/11} a^{(31-6z)/11} \quad , \qquad (1)$$

where $-z$ is the q scaling in the dimensionless parameter formalism. Note that the weak density dependence observed in engineering variable scans [8] is recovered from the combination of three different scans. The rather weak power degradation is surprising. A weaker collisionality scaling than $\nu_*^{-1/3}$ would give more density scaling and more power degradation. It is important to point out that Eq. (1) also demonstrates that the dimensionless parameter scaling approach yields a definitive prediction for the size scaling from single machine experiments. By verifying the dimensionless parameter scalings independently on several machines, confidence in the size scaling can be gained while avoiding the inevitable systematic effects in multiple machine databases. If $z \equiv 11/6$ to give the standard linear current scaling, then Eq. (1) becomes

$$\tau_E \propto I^{1.0} B^{0.09} P^{-0.45} n^{0.27} a^{1.82} \quad . \qquad (2)$$

The next step is to compare these inferred engineering scaling relations with the larger set of discharges taken to find the dimensionless parameter matches to see if the experimental deviations can be described by the derived scaling relation.

The same exercise for the L–mode scans is not very straightforward, due to the variable ion ρ_* scaling. Without knowing the physical mechanism for this variation or, at least an empirical characterization of it, scaling of ion transport is uncertain. Also, various heating schemes deposit power in electrons and ions in differing proportions and the exchange term is not ‘‘dimensionally correct,’’ so the fraction of power lost in electrons and ions is uncertain.

In conclusion, great progress toward the prediction and understanding of energy transport has been made by applying the dimensionless parameter scaling approach. In the next few years, it may be possible to derive a complete scaling rule by means of this approach.

6. ACKNOWLEDGMENTS

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