IMPLICATIONS FROM DIMENSIONLESS PARAMETER SCALING EXPERIMENTS*

T.C. Luce, C.C. Petty, J.C. DeBoo, D.S. Schissel, and R.E. Waltz
General Atomics, P.O. Box 85608, San Diego, California 92186-9784

Scaling dimensionless parameters rather than engineering parameters has the advantage of posing the empirical extrapolation for energy transport in terms of variables which have known theoretical limits. Present-day experiments can operate at values of the standard dimensionless parameters equal to those projected for ignition, with the exception of the size normalized to the gyroradius. Furthermore, the scaling of energy transport with the inverse of this parameter, ρ_*, has a physical interpretation concerning the mechanisms causing the transport. Therefore, dimensionless parameter scaling experiments are of great importance in the challenge of understanding and predicting tokamak energy transport. Experiments to validate this scaling principle by directly comparing DIII–D to different machines with identical dimensionless parameters are in progress with JET, Alcator C-Mod, and ASDEX-Upgrade. Significant progress in determining when favorable confinement scaling is obtained has been made since the last IAEA meeting.

As previously reported, experiments on the DIII–D tokamak have measured the ρ_* scaling for electrons and ions separately in L–mode at large safety factor q [1] and in H–mode at low q [2]. The ρ_* scaling of the power balance diffusivity for both electrons and ions in the low-q H–modes was found to be linear in ρ_*, called “gyro-Bohm.” In the L–mode discharges, the electrons again had gyro-Bohm scaling while the ions had significantly different scaling – $\chi_i \propto \rho_*^{-1/2}$. This was called Goldston scaling because it is consistent with $\tau \propto I/\sqrt{P}$. The different scalings for electrons and ions points out the necessity of determining the scaling independently for both species. Other than the change in density scale length (L–mode versus H–mode) and q, the two experimental conditions were significantly different in β (H–mode is higher) and T_e/T_i ($T_i > T_e$ for the H–modes and $T_i < T_e$ for the L–modes). Therefore, these two sets of conditions alone were not sufficient to isolate the quantities responsible for the dramatic difference in ion ρ_* scaling.

Two new experiments have been performed to isolate the effects of each parameter as much as possible. First, a pair of low-q L–mode discharges were run at the maximum possible β (limited by transition to H–mode) and $T_i > T_e$. The goal was to isolate the effect of the density scale length on the ion ρ_* scaling. The electrons scale again as gyro-Bohm, while the ion scaling is independent of ρ_*, called Bohm scaling. This eliminates large magnetic shear and $T_e > T_i$ as necessary conditions for the ρ_* scaling to deviate from gyro-Bohm. The second new set of data is a pair of high-q, H–mode discharges with $T_i > T_e$. The goal is to isolate the effects of q or magnetic shear. The electrons again exhibit gyro-Bohm scaling while the ions have Bohm scaling. This result demonstrates that a short density scale length is not a necessary condition for the ion ρ_* scaling to be different from gyro-Bohm. It is notable that neither short density scale length nor high shear alone bring the ion ρ_* scaling to Goldston.

An empirical model has been constructed which is consistent with the above observations. Gyro-Bohm scaling implies the wavelength dominating the turbulent transport varies with ρ_* in such a manner that $k_\perp\rho$ is constant. This means there is a substantial penalty for raising the temperature at fixed magnetic field and size. If the size $\left(k_\perp^{-1}\right)$ to which the turbulence can grow were limited, then the temperature could be increased more easily, since the particle motion would begin to average out the fluctuations. This would lead to Bohm or Goldston scaling depending on the details of the limit and the actual temperature. Since the ion gyroradius is significantly larger than the electron gyroradius, it is logical that the effect would appear first in the ions. The model is then that the magnetic shear and the density

---

*Work supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114 .

scale length (or perhaps the gradient length of the diamagnetic drift frequency) set a limit on the maximum wavelength in the turbulent spectrum. Raising ρ_* beyond some critical value then leads to a change in scaling from gyro-Bohm to Bohm or Goldston. While the explanation above relies on a spatial decorrelation, it may be possible to find a model with a temporal decorrelation through sheared E×B flows which limit the minimum correlation time.

The series of experiments described above clearly indicate low-q H–mode is the operational regime in which one obtains the most favorable transport scaling. Along a path in parameter space where only ρ_* is varied, the fusion triple product (which is proportional to fusion gain) varies like $B^{(7+2\alpha)/3}\, a^{(10+5\alpha)/6}$, where α is the exponent of ρ_* in the formula for the power balance diffusivity. Therefore, gyro-Bohm scaling is more favorable then Bohm or Goldston, in that an increment in B or a results in a greater increase in fusion gain. Gyro-Bohm scaling has only been observed in low-*q*, H–mode discharges. From the point of view of the working model, these discharges have long density and magnetic shear scale length, i.e., they make the machine appear much larger to the local turbulence.

The low-*q* H–mode discharges discussed above were designed explicitly to lie on a ρ_* scaling path to the ITER outline design. The projection of these discharges to the anticipated ρ_* values for ITER results in more than the desired 1.5 GW of fusion power for a 50% D-T mixture, indicating that the experimental values of β and collisionality are well chosen [2]. The surprising result was that the measured scaling indicates only 41 MW of loss power is necessary to sustain the profiles — much less than the 210 MW of loss power expected from α-particle slowing down minus the bremsstrahlung. However, recent comparisons between DIII–D and JET indicate that these values of ρ_* are inaccessible due to the intervention of the H–mode transition threshold [3]. The most favorable H–mode threshold scaling is found to have a ρ_* scaling which is Goldston. Discharges which lie along a ρ_* scaling path scale as gyro-Bohm up to the H–mode threshold at which point the power required then follows the Goldston scaling of the threshold. Therefore, the result that only 41 MW of loss power would be needed at the ITER ρ_* is numerically correct, but is not realizable unless the H–mode can be obtained with even less power.

Given the present empirical understanding of transport and the H–mode threshold, it seems reasonable to see what an ignition machine would look like which takes advantage of gyro-Bohm scaling by staying above the H–mode threshold. Since the present H–mode threshold scalings are independent of temperature, it is possible to move away from the threshold by increasing the β at fixed density. Maintaining the profiles and plasma shape from the discharges similar to the ITER outline design and scaling the confinement according to $\tau_E \propto P^{-1/2}$, the lowest β ignition solution at the H–mode threshold is at R = 3.56 m and $\beta_N = 4.2$. It does not seem likely that this β_N is feasible without active profile control. In order to lower β_N, a more triangular and elongated plasma is proposed. With a modest amount of shaping ($\kappa = 2.1$, $\delta = 0.8$), a solution is found with R = 2.74 m and $\beta_N = 3.3$. This solution has the added benefit that the similarity density lies below the Greenwald limit. The fusion output is approximately 490 MW for this case. Surprisingly, it is actually beneficial if the power degradation is stronger than $P^{-1/2}$, since this lowers the β_N at the minimum machine size machine, although the machine is physically larger. The effects of helium ash accumulation have not been accounted for in the projections, which would make the size slightly larger to correct for the reduced reactivity. The high wall loading would certainly provide a engineering challenge to protect the magnets. Clearly, this simple exercise is not an optimization or even a practical design, but it does provide an attractive starting point for designing a low-cost burn experiment with modest pulse length should such a device become interesting to the fusion community.

[1] PETTY, C.C., LUCE, T.C., PINSKER, R.I., et al., Phys. Rev. Lett. **74**, 1763 (1995).
[2] PETTY, C.C., LUCE, T.C., et al., Phys. Plasmas **2**, 2342 (1995).
[3] BALET, B., et al., in Proc. 22nd European Conf. on Contr. Fusion and Plasma Phys., Bournemouth, United Kingdom (European Physical Society, Petit-Lancy, Switzerland, 1995) Part I, p. 9; LUCE, T.C., PETTY, C.C., *ibid*, Part III, p. 25.