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Turbulent transport in fusion magnetised plasmas/Transport turbulent dans les plasmas magnétisés de fusion

The dimensionless scaling of ELMy H-mode confinement

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Abstract

This article describes the use of dimensionless analysis in the study of energy confinement in ELMy H-mode tokamak plasmas, with a focus on the use of dedicated dimensionless parameter experiments. This work has involved a strong collaboration between many machines and countries. The experiments have demonstrated that such analysis is indeed valid, and have given important information on the scaling of the characteristic turbulent length, the separation of electrostatic and electromagnetic transport regimes, and the effects of collisionality on plasma transport. They have also provided a method for scaling existing experiments to next step machines, such as ITER, and have suggested the possibility of enhanced performance at high normalised pressure. ***To cite this article: D.C. McDonald, C. R. Physique 7 (2006).***

Résumé

Principe de similitude en mode H. Cet article décrit l'utilisation de lois d'échelles adimensionnelles pour l'étude du confinement de l'énergie dans les plasmas de tokamak en Mode-H et en présence de modes localisés de bord. Cette revue est centrée sur les expériences dédiées au principe de similitude, et représente le résultat d'une collaboration internationale très active sur le sujet. Les expériences sur tokamak ont montré la validité d'un principe de similitude appliquée aux plasmas magnétisés. Elles ont aussi fourni des réponses aux questions portant sur les lois d'échelle de longueur de corrélation de la turbulence, la nature électrostatique ou électromagnétique des fluctuations, et les effets des collisions sur le transport. Ces études ont abouti à une loi d'échelle qui a permis de dimensionner la prochaine génération de machines, dont ITER, et suggèrent la possibilité d'atteindre des régimes de plasmas à forte pression avec un bon confinement. ***Pour citer cet article : D.C. McDonald, C. R. Physique 7 (2006).***

Keywords: Tokamak plasmas; ELMy H-mode

Mots-clés : Plasmas de tokamak ; Mode-H

1. Introduction

By normalising the physical parameters of fluid mechanics to the scale lengths of a given physical system, it can be shown that, for matched geometry, sources and sinks, the system can be described by a small number of dimensionless parameters. This principle underlies wind tunnel experiments, where the dimensionless physics parameters are matched between systems of different physical sizes. In a similar way, it can be shown that, for matched geometry, sources and sinks, the transport physics of a given isotope tokamak plasma can be described by three dimensionless

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parameters [1]. The increased complexity of plasma physics transport means that sinks and sources include applied currents and fields and velocity space sources, such as the heating of the plasma. As current diffusion is usually on a slower time scale than thermal transport, matched sources and sinks of current and field can usually be replaced by the condition that the applied field and the profile of the safety factor, the number of toroidal rotations of a field line required for it to make one poloidal rotation, are matched. The matching of velocity space sources is simplified by assuming that high order moments of the velocity distribution are negligible, so the condition becomes simply that heating profiles are matched. A complication to this is that ions and electrons must be treated as separate channels for heating and transport.

The choice of the three dimensionless parameters has some freedom, but the standard set chosen are the normalised ion Larmor radius, $\rho^* = \rho_{\mathrm{Ti}}/a \propto T^{1/2}/aB$, the normalised plasma pressure, $\beta = 2\mu_0 p/B^2 \propto nT/B^2$, and the normalised collision frequency, $\nu^* = (\nu_{\mathrm{ie}} R/a)/\omega_{\mathrm{Tbi}} \propto na/T^2$, where ρ_{Ti} is the thermal ion Larmor radius, $a(R)$ is the machine minor (major) radius, T is the temperature, B is the magnetic field, μ_0 is the permeability of the vacuum, p is the plasma thermal pressure, n is the plasma density, ν_{ie} is the ion–electron collision rate, and ω_{Tbi} is the thermal ion bounce frequency. This particular choice has been shown to be convenient for separating classes of physics models [2]. A direct consequence of this dimensionless analysis is that the energy confinement time, τ_{E}, may be expressed in terms of the non-dimensional parameters as,

$$\omega_{\mathrm{ci}} \cdot \tau_{\mathrm{E}} = F(\rho^*, \beta, \nu^*; q, shape, M, Z) \tag{1}$$

where ω_{ci} is the ion Larmor gyro-frequency, $q \propto aB/I$ is the safety factor, $M(Z)$ is the mass (charge) of the ions normalised to that of a proton, and I is the plasma current. The method can be applied to confinement in any plasma scenario, but this paper concentrates on ELMy H-modes which are robust, high confinement modes seen on most modern tokamaks.

The aims of dedicated dimensionless analysis experiments are two-fold. Firstly, through identity experiments, one can demonstrate that the chosen parameters are the correct ones to describe the underlying physics. Secondly, through single parameter scans, one can identify the dependence of the physics on each of the dimensionless parameters. Identity experiments must be performed between machines of different sizes, whereas single parameter scans can be performed on a single machine at different fields. By setting the required subset of parameters ρ^*, β, ν^*, and q fixed, and using the relations above, the required scaling for the dimensional variables B, I, n, T and a for a given dimensionless transport experiment can be determined. These scalings are summarised in Table 1. Central to the experimental design is the matching of the profiles of the fixed dimensionless parameters, which includes those relating to sinks and sources (Section 2.5). This is performed by tuning of the plasma fuelling, careful selection and tuning of the plasma heating method, and control of the plasma impurity level. Once matches have been achieved, analysis concentrates on determining the global energy confinement time and the more detailed study of the local transport properties. These analyses involve modelling of the absorption of the applied heating, the non-thermal particles generated in the plasma, and the interchange of energy between the ions and electrons. This is usually performed by an interpretative transport code, such as TRANSP [3,4].

The article is structured as follows. Section 2 discusses the dedicated experiments that have been performed to study the role of dimensionless parameters on confinement. Section 3 reviews the attempts to understand the international database of multi-machine plasma confinement experiments in terms of dimensionless parameters. In Section 4, the results are brought together and conclusions drawn.

Table 1
Scaling of variables in dimensionless parameter scans

Scan	Fixed parameters	Scalings
Multi-machine identity	ρ^*, β, ν^*, q	$B \propto a^{-5/4}, I \propto a^{-1/4}, n \propto a^{-2}, T \propto a^{-1/2}$
Single machine ρ^*	β, ν^*, q, a	$I \propto B, n \propto B^{4/3}, T \propto B^{2/3}$
Single machine β	ρ^*, ν^*, q, a	$I \propto B, n \propto B^4, T \propto B^2$
Single machine ν^*	ρ^*, β, q, a	$I \propto B, n \propto B^0, T \propto B^2$

2. Energy confinement studies

2.1. Identity studies

Identity experiments test the validity of the Kadomtsev constraint, the underlying assumption of the studies discussed in this paper. Shape, q-profile and ρ^*, β and ν^* are matched on machines of different size. If the Kadomtsev constraint is valid, the normalised confinement time on machines should agree within the experimental errors. This demonstrates that confinement physics is dominated by the physics of fully ionised plasmas.

Such an identity experiment was performed for ELMy H-mode plasmas matched between JET and DIII-D [5]. The normalised global confinement was found to agree to within 10%. A similar results was found for local transport, with the normalised thermal diffusivity, $\chi/(\omega_c a^2)$, agreeing within errors [6]. Further experiments on JET and ASDEX-Upgrade [7] and JET and C-Mod [8] have also found similar results. Thus, the available experiments all demonstrate that the Kadomtsev constraint is indeed valid.

More recently, this question has been revisited in the light of observations that confinement may be affect by proximity to the Greenwald density limit, n_{GDL}, an empirically derived maximum plasma density above which density limit disruptions occur [9]. n_{GDL} is at least partially related to atomic physics and so plasma density scaled to it, $F_{\mathrm{GDL}} = n/n_{\mathrm{GDL}}$, is not a dimensionless parameter of a fully ionised plasma. Studies performed between JET and DIII-D [10] and JET and C-Mod [11] have, however, shown no evidence of a dependence on normalised confinement on F_{GDL}, outside of the experimental errors.

Thus, identity experiments have indicated that the Kadomtsev constraint is satisfied, for all plasmas studied, and that dimensionless analysis in terms of ρ^*, β and ν^* is valid. It remains, then, to derive the individual dependence of confinement upon each parameter.

2.2. ρ^* studies

Treating transport in a turbulent plasma as a random walk process, the thermal diffusivity should scale as $\chi \approx \Delta r^2/\Delta t$, where Δr is the radial correlation length of the turbulence and Δt is the decorrelation time scale. Radial transport is dominated by drift wave turbulence, for which $\Delta t \approx \Delta r/v_{\mathrm{drift}} \propto \Delta r/(\rho^* c_s)$, where v_{drift} is the diamagnetic drift velocity and c_s is the ion sound speed. This implies that transport scales as $\chi \approx \rho^* c_s \Delta r$. For macro-turbulence, where the turbulent scale length is related to the machine size, $\Delta r \propto a$, the normalised thermal diffusivity scales as $\chi/(\omega_c a^2) \approx \rho^{*2}$. Such scaling is termed Bohm-like. For micro-turbulence, where the turbulent scale length is related to the ion gyroradius, $\Delta r \propto \rho$, $\chi/(\omega_c a^2) \approx \rho^{*3}$. Such scaling is termed gyroBohm-like. Fluid simulations of turbulence [12,13] and more sophisticated gyrokinetic modelling [14,15], both suggest that turbulence is gyroBohm below a critical ρ^* (Fig. 1) and Bohm-like above it. However, there is no consensus on the value of this critical ρ^*.

Early L-mode experiments on DIII-D [16], JET [17] and TFTR [18] all demonstrated confinement that was Bohm-like, or worse, in contrast to stellarator L-modes, observed on ATF [19], LHD and CHD [20], that were essentially gyroBohm-like. Studies on DIII-D [21] found gyroBohm-like behaviour for low density plasmas with predominantly electron heating, but Bohm-like behaviour for discharges with mixed electron and ion heat fluxes. This led to the conclusion that, in L-mode, transport in the electron channel is always gyroBohm, whereas in the ion channel it is Bohm.

Dedicated ρ^* scans in ELMy H-modes have been performed on DIII-D [22], JET [23], ASDEX-Upgrade [24], Alcator C-Mod [25], and JT-60U [26]. DIII-D results for the ion and electron thermal diffusivities were broadly consistent with gyroBohm-like scaling, but showed significant variation across the plasma profile, possibly due to the mismatch in the toroidal rotation Mach number. JET, ASDEX-Upgrade and Alcator C-Mod experiments all showed gyroBohm-like scaling for the effective thermal diffusivity, but were unable to separate the ion and electron channels in the analysis. As for DIII-D, Alcator C-Mod found a variation of the ρ^* scaling across the plasma profile. These experiments used ICRH, which has a very low momentum input, and so mismatches in Mach number are unlikely to account for the observed variation of ρ^* scaling. A JT-60U experiment with $q_{95} = 3.7$ found gyroBohm-like scaling for ion and electron thermal diffusivity. A further experiment at $q_{95} = 3.0$ found a weaker, Bohm-like, scaling, but this was associated with transitions in the ELM behaviour, indicating that the results were polluted by proximity to a confinement regime threshold. Thus it would appear that, for the ELMy H-modes studied, the local transport is broadly described by a gyroBohm-like scaling, but that significant profile variations are observed, which may be due

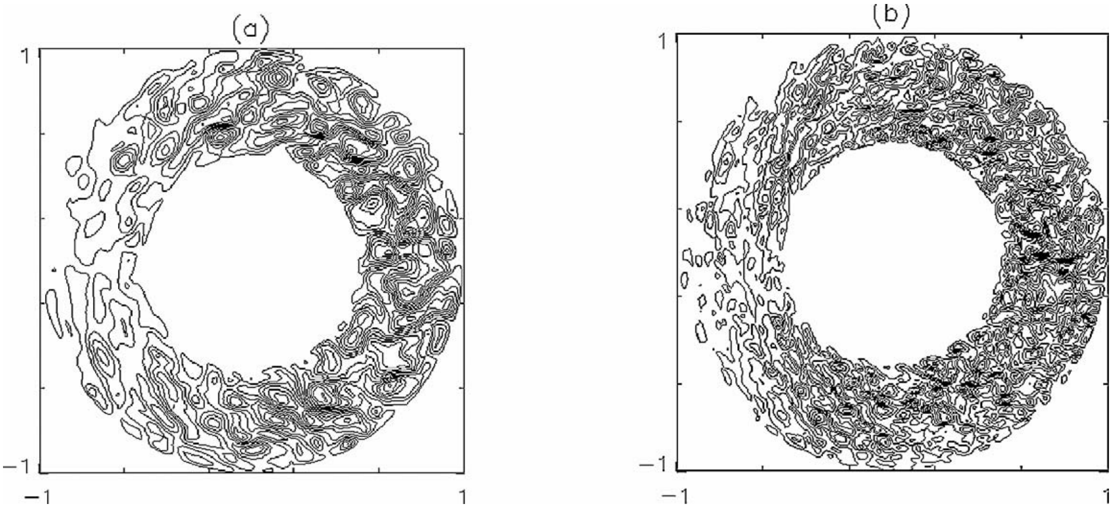

Fig. 1. 3D full torus simulations of ion turbulence for two values of the normalised gyroradius (a) $\rho_* = 1/50$ and (b) $\rho_* = 1/100$ [13]. The size of the vortices is proportional to ρ^*. This behaviour is consistent with a gyroBohm scaling law.

to other mismatched parameters. The effects of the radial scale lengths of the density and q-profiles, believed to be important in L-mode confinement, remain to be studied.

In recent years, diagnostics to directly measure turbulent fluctuations have become available. Such measurements have been made for a ρ^* scan in L-Mode on DIII-D [27]. The correlation length scale of the turbulence was found to scale as $\Delta r \propto \rho$ and the decorrelation time to scale as $\Delta t \propto a/c_s$. These are both consistent with gyroBohm-like transport, although the observed thermal diffusivity was intermediate between Bohm-like and gyroBohm-like. Studies on Tore-Supra [28], found similar gyroBohm-like scalings for Δr and Δt.

The normalised ion Larmor radius, ρ^*, is the only dimensionless physics parameter whose value on ITER, or proposed power plants, cannot be matched on existing machines [16]. It is for this reason that the understanding of the dependence of confinement upon ρ^* is crucial for extrapolating existing results to future devices. It also implies that existing experiments can be scaled to ITER in a single parameter ρ^* scan, by matching the other non-dimensional ITER parameters on two machines of different radius. Such an experiment was carried out on JET and DIII-D [29] and indicated a close to gyroBohm-like scaling, $\omega_{ci} \cdot \tau_E \propto \rho^{*-2.7}$, resulting in a prediction of the ITER confinement time very close to that derived by empirical fits to a multi-machine database, Fig. 2.

2.3. β studies

For electrostatic turbulence models, the magnetic fields produced by the turbulence are assumed to be weak. Such an assumption results in the transport being independent of the parameter β. Drift wave turbulence models are largely of this form and, consequently, tend to predict little change in transport with increasing β, until β begins to approach the ideal ballooning stability limit [30]. Electromagnetic turbulent transport models, on the other hand, are strongly β dependent, with confinement usually decreasing with β. In addition, large scale MHD physics is strongly β dependent and can also affect transport. In particular, Neoclassical Tearing Modes can be triggered above a critical β and result in localised island structures within which transport is large [31,32]. However, provided such modes are avoided, the experimentally determined β dependence of transport is a strong differentiator between electrostatic and electromagnetic turbulent transport models.

Dedicated β scans in ELMy H-modes have been performed on JET [33,34] and DIII-D [35,36]. They comprise a series of scans, all performed in plasmas without significant Neoclassical Tearing Mode activity. All of these scans show a weak dependence of energy confinement on β ($\omega_{ci}\tau_E \propto \beta^{\alpha}$; $-0.1 < \alpha < 0.1$). Analyses of the local transport, on both DIII-D and JET, have shown a similar weak dependence of the effective thermal diffusivity across the plasma. However, studies on JT-60U [37] have shown a degradation of confinement with increasing β, $\omega_{ci}\tau_E \propto \beta^{-0.6}$. Analysis of a wider multimachine database indicates a correlation between the strength of the β degradation of confinement and plasma shape [38]. The exact nature of this interdependency remains to be resolved.

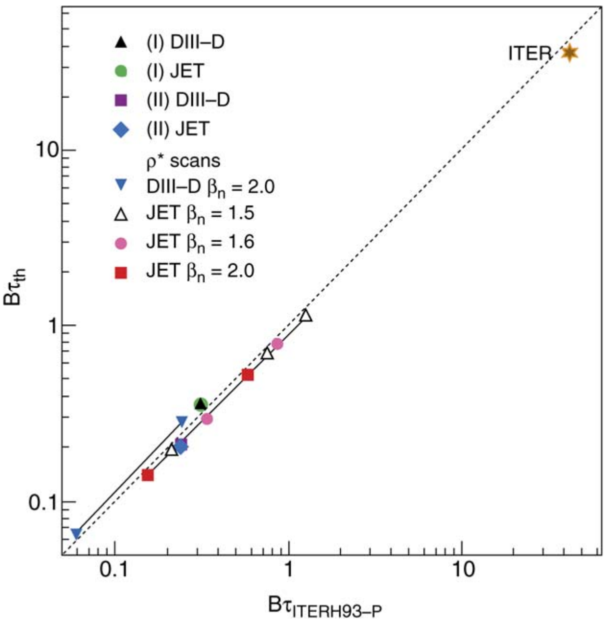

Fig. 2. Normalised energy confinement time, $B\tau_E \propto \omega_{ci}\tau_E$, against the empirically derived scaling law ITERH93DP [29]. The discharges shown are from dedicated ρ^* scans, in ITER-like conditions, performed on DIII-D and JET.

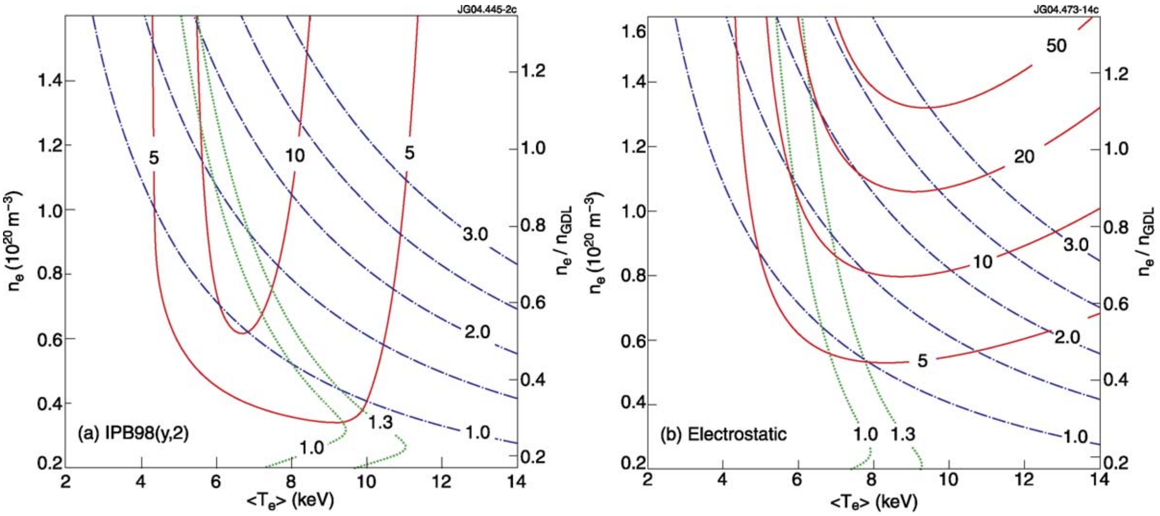

Fig. 3. POPCON plots of the ITER operation space in volume averaged density and temperature showing contours of fusion gain Q (red solid lines), normalised β (blue dashed and dotted lines), and power relative to the L–H threshold (green dotted lines). Energy confinement is assumed to vary as (a) IPB98(y,2) and (b) as for an electrostatic scaling [39].

A key performance measure of a fusion power plant is the fusion gain, Q, the ratio of fusion power production to power injected. In a given machine, of fixed field and size, the fusion triple product, related to the fusion gain, may be written as $nT\tau_E \propto \beta\tau_E$. This implies that high β operation of burning plasmas is strongly advantageous if energy confinement is β independent, but less so if energy confinement falls with increasing β [36]. For these two reasons, the scaling of energy confinement with β has taken on a considerable importance. This can be seen, for ITER, in the parameter operating space contour (POPCON) plots of Fig. 3. Fig. 3(a) shows the ITER performance assuming that energy confinement scales as IPB98(y,2) (see Section 3), which scales negatively with β as $\omega_{ci}\tau_E \propto \beta^{-0.9}$. Fig. 3(b) shows the same analysis, but assuming a β independent scaling [39]. Assuming plasma density to be limited by the Greenwald density limit, the fusion gain for the case with $\omega_{ci}\tau_E \propto \beta^{-0.9}$ does not significantly exceed 10. For the β independent case, high β operation leads to fusion gains above 20.

2.4. ν^* studies

Theoretically, the effect of collisionality on turbulent transport is complicated by several competing processes. Trapped Electron Modes (TEM) are stabilised by collisions, leading to improved confinement with increasing collisionality [40]. Large scale azimuthal flows in plasmas, known as zonal flows, tend to stabilise ITG modes and thus reduce transport. Collisionality effects tend to damp these flows, resulting in reduced confinement with increasing ν^* [41]. In addition, neoclassical transport, which may play a role at the edge of modern tokamaks, scales linearly with collisionality, giving reduced confinement with increasing ν^*.

Dedicated ν^* scans in ELMy H-modes have been performed on JET [23], DIII-D [42], JT-60U [26], COMPASS [43], and C-Mod [25]. These all showed a fall in the energy confinement with increasing ν^*. The strength of the scaling tended to increase with increasing collisionality, with a scaling of $\omega_{ci}\tau_E \propto \nu^{*-0.27}$ for the JET experiment ($\nu^*/\nu^*_{ITER} \approx 1$–4) and $\omega_{ci}\tau_E \propto \nu^{*-1.0\pm0.2}$ for the C-Mod experiment ($\nu^*/\nu^*_{ITER} \approx 10$–80). Thus, the competing effects of collisionality on the underlying transport processes appear to result in different scalings in different parameter regimes. From the point of view of extrapolation to ITER, this change in scaling makes it vital to run scans at collisionalities close to the ITER value and over a wide range.

2.5. Studies of further dimensionless parameters

As discussed in Section 1, the equations of plasma physics for a given set of isotopes can be reduced to the three parameters ρ^*, β and ν^* if the geometry, q-profile, and sinks and sources are all matched. The effects of varying the geometry, sources and sinks can themselves be expressed in terms of further dimensionless parameters and their effect on confinement studied. These include the q-profile; the plasma geometry, usually represented by aspect ratio, elongation and triangularity; the ratio of ion to electron temperature; the plasma rotation, expressed as a Mach number; and the mass and charge of the isotope normalised to that of the proton.

No single parameter scan study of the inverse aspect ratio, $\varepsilon = a/R$, scaling has yet been reported. Studies of multi-machine databases have indicated that confinement increases with increasing ε—for example $\omega_{ci}\tau_E \propto \varepsilon^{0.8}$ [29]—but these have been shown to be sensitive to strong correlations between ε and β [33,44]. Scans on DIII-D, found that at fixed ν^*/q confinement decreased strongly with increasing q, $\omega_{ci}\tau_E \propto q^{-2.42\pm0.31}$, with the thermal diffusivity increasing in a consistent manner [5]. DIII-D scans of elongation, found that at fixed q local heat transport increased with increasing κ, as $\chi/(\omega_c a^2) \propto \kappa^{-1.8}$ [45]. Triangularity has been observed to affect plasma confinement on several machines [46–50]. In general, increasing triangularity is seen to be favourable for confinement, but the affect is subtle. The ratio of ion to electron temperature has been studied experimentally [51,52] and in all cases energy confinement is found to increase with increasing T_i/T_e for $T_i > T_e$, with a less clear dependency for $T_e > T_i$. Plasma rotation has also been seen to affect energy confinement experimentally, although again the effect is subtle and complicated by the coupling between momentum and energy transport [53–58]. Isotope mass studies [59,60] indicate that increasing isotope mass, M, has a weakly positive effect on confinement. Comparisons of Hydrogen, Deuterium and Helium-4 plasmas on JET [61] indicate that increasing isotopic charge, Z, has a negative impact on energy confinement scaling as $\omega_{ci} \cdot \tau_E \propto Z^{-3.5}$.

3. Multi-machine scalings

In contrast to the dedicated scans, which determine parametric dependencies in isolation, global multi-machine scalings attempt to describe data from a wide database of experiments on many machines. This is commonly expressed as an empirically derived power law fit, which should express the broad trends of the confinement scaling in a way that can be easily extrapolated to next step machines. A standard fit is known as IPB98(y,2) [29],

$$\tau_{IPB98(y,2)} \propto I^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78} \quad (2)$$

where I is the plasma current, P is the power, and κ_a is a measure of elongation [29]. IPB98(y,2) can be expressed in dimensionless parameters as

$$\omega_{ci} \cdot \tau_{IPB98(y,2)} \propto \rho^{*-2.70} \beta^{-0.90} \nu^{*-0.01} M^{0.96} q^{-3.0} \varepsilon^{0.73} \kappa_a^{3.3} \quad (3)$$

In common with all ELMy H-mode scalings derived in this way, the ρ^* scaling is close to a, ρ^{*-3}, gyroBohm-like scaling. The almost negligible negative ν^* dependence of confinement seen in IPB98(y,2) contrasts with the stronger negative dependencies seen in the dedicated experiments although, of course, the observed scalings vary between the experiments themselves. More problematical is the negative dependence of energy confinement with β, which clearly contradicts the dedicated scan experiments on JET and DIII-D. One explanation of this is the biasing of the regressions caused by a combination of correlations in the database and finite errors in the variables used in the fit. This can be at least partially resolved by using so called Errors in Variables fitting methods, which treat the errors on all the parameters in the fit explicitly. Such fits have been recently applied to a multi-machine ELMy H-mode database [62]. A typical such fit, applied to the same multi-machine database, gives a power law scaling of

$$\omega_{\mathrm{ci}} \cdot \tau_{\mathrm{EIV,Std}} \propto \rho^{*-2.78} \beta^{-0.20} \nu^{*-0.20} \tag{4}$$

This scaling has a close to gyroBohm-like ρ^* scaling, in common with IPB98(y,2), but a much weaker β scaling, which lies in between those found in the dedicated scans. The ν^* dependence is closer to that in the dedicated scans than IPB98(y,2), although still somewhat weak in comparison. Given the simplified nature of power law scalings, it appears that they are broadly consistent with the dimensionless scans provided an appropriate fitting method is used.

4. Conclusion

Dimensional analysis provides a useful method for relating ELMy H-mode tokamak physics experiments to the underlying turbulent transport models and for extrapolating results to future tokamak experiments and power plants. Identity experiments have demonstrated the consistency of such methods. ρ^* scan experiments have shown that confinement is largely gyroBohm-like, and have provided an independent method for estimating ITER performance. β scan experiments, on machines with ITER-like shape, have demonstrated electrostatic-like confinement scalings which would be favourable for ITER and power plant operation. ν^* scan experiments have shown that, to varying degrees, confinement falls with increasing collisionality. Global scaling laws broadly describe these dependencies, provided the errors in all of the variables are included in the analysis.

Key areas of outstanding work remain, however. Local turbulence measurements should be extended and linked to the transport and global confinement scalings. The impact of shape on the effect of β on transport needs to be confirmed and understood. The precise nature of the effect of collisionality on transport needs to be understood. In conjunction with further theoretical and modelling advances, this work will continue to improve the knowledge base of turbulent plasma transport.

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