Dimensionally Similar Discharges in the W7-AS Stellarator

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Dimensionally similar discharges and energy confinement of the W7-AS stellarator were investigated. The results presented, as well as other confinement properties of the net-current-free stellarator, are different from what is known from tokamaks. As expected from global scaling laws for stellarator confinement, the local transport coefficients of dimensionally similar discharges show a gyro-Bohm-like parameter dependence.

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The problem of understanding the energy transport processes of plasmas in toroidal fusion devices and finding the scaling expressions needed to predict the performance of future reactors are two interrelated and intensively studied topics in plasma physics.

Energy confinement times (τ_E) of stellarators and tokamaks can be described by similar expressions in terms of global plasma parameters such as the heating power (P), plasma current ($I=a^2B/Rq_a$) or edge safety factor (q_a), magnetic field strength (B), plasma density (n), isotope mass (m), and geometrical quantities such as minor and major radii (a,R) or $\epsilon=a/R$:

$$\tau_E=P^{\alpha_P}I^{\alpha_I}n^{\alpha_n}B^{\alpha_B}a^{\alpha_a}R^{\alpha_R}m^{\alpha_m}\,. \qquad (1)$$

Although much effort has been devoted to estimating the parameters α_i from joint data bases of different tokamaks, the geometrical and B parameters, which make a major contribution to the cost of a reactor, are still not very precisely known.

The character of scaling law expressions is formed by the underlying energy transport mechanisms, which themselves are far from being uniquely identified. Since a definitive description of plasma transport seems at present to be beyond reach, there have been attempts to identify the leading term of the transport mechanism. From dimensionally similar discharges [1] it has been investigated whether transport is governed by macroscopic (Bohm-like) or microscopic (gyro-Bohm-like) plasma turbulence, a question which ultimately defines the B and size scalings of τ_E.

For this purpose, the heat diffusivity (χ) is written as a function of dimensionless parameters with a leading term composed out of the Bohm diffusion coefficient ($\chi_B\sim T/B$) and the dimensionless gyro-radius ($\rho_*\sim\sqrt{T}/Ba$) multiplied by an unknown function depending on all the other independent dimensionless parameters which could in principle contribute to transport, such as $\beta\sim nT/B^2$, the collisionality $\nu_*\sim T^2/na$ and relative density and temperature profile scale lengths ($L_n/a,L_T/a$): $\chi=\chi_B\rho_*^{\alpha_\rho}\mathcal{F}(\nu_*,\beta,q,L_n/a,L_T/a,\epsilon,\ldots)$. Dimensionally similar discharges have all the dimensionless parameters the same except ρ_*. Such discharges with reactor relevant β and ν_* can be scaled to ignition if the dependence on ρ_* is known [1].

Global scaling.— Depending on α_ρ the transport can be attributed to macroscopic ($\alpha_\rho=0$) or microscopic ($\alpha_\rho=1$) turbulence. The corresponding scaling laws under the similarity constraints are $\tau_E^B\sim a^{5/3}B^{1/3}$ and $\tau_E^{gB}\sim a^{5/2}B^1$, respectively. Only in the specific case that B scales as $a^{-5/4}$, the confinement time of similar discharges scales the same irrespective of whether the plasma transport is Bohm-like or gyro-Bohm-like. In Table I we demonstrate that it is difficult to infer α_ρ from global scaling laws for τ_E. For this purpose, we have applied the constraints for dimensionally similar discharges to the α_i in Eq. (1): From the conditions that β and ν_* be constant and the relation $\tau_E\sim a^2RnT/P$ the constraints that $n\sim a^{-1/3}B^{4/3}$ and $P\sim a^3B^2/\tau_E$ are derived. Together with $I\sim aB$ and $R\sim a$ (q,ϵ are constant) only

TABLE I. Scaling coefficients of the most common scaling laws under the constraints of dimensionally similar discharges for L- and H-mode tokamak plasmas, W7-AS, and the joint tokamak stellarator scaling LHD. Predictions from Bohm-like and gyro-Bohm-like scalings are listed for comparison. The parameters $\alpha_a^{\rm sim}$ and $\alpha_B^{\rm sim}$ are not independent if the scaling law is dimensionally correct (see text). If this is the case, the value in the last column is 1.

Scaling law	Type	$\alpha_a^{\rm sim}$	$\alpha_B^{\rm sim}$	$\alpha_a^{\rm sim}/\frac{5}{4}(1+\alpha_B^{\rm sim})$
Bohm	⋯	1.67	0.33	1
Gyro-Bohm	⋯	2.50	1.00	1
Kaye-all [8]	L	0.93	0.57	0.48
Kaye-Goldstone [8]	L	1.37	0.80	0.61
Goldstone [9]	L	1.76	0.00	1.41
ITER89-P [2]	L	1.63	0.37	0.96
ITER90-mhd [10]	H	2.17	1.02	0.86
ITER90-P [10]	H	2.28	0.43	1.27
ITER90-a [10]	H	2.79	1.75	0.81
Riedel-1 [11]	H	2.61	0.69	1.24
Riedel-2 [11]	H	2.67	0.21	1.76
ITER92 [12]	H	2.37	0.63	1.16
ITER92-th [12]	H	3.11	1.06	1.21
Ryther-th [13]	H	2.10	0.49	1.13
LHD [14]	S	1.86	1.43	0.61
W7-AS	S	⋯	0.85 ± 0.1	⋯

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two parameters remain free: $\tau_E^{\rm sim} \sim a^{\alpha_a^{\rm sim}} B^{\alpha_B^{\rm sim}}$ with

$$\alpha_a^{\rm sim} = (\alpha_a + \alpha_R + 3\alpha_P - \tfrac{1}{3}\alpha_n + \alpha_I)/(1+\alpha_P)\,,$$
$$\alpha_B^{\rm sim} = (\alpha_B + 2\alpha_P + \tfrac{4}{3}\alpha_n + \alpha_I)/(1+\alpha_P)\,. \tag{2}$$

If only plasma physics determines transport, the two parameters are not independent and the scaling law is called dimensionally correct: $\alpha_a^{\rm sim} = \frac{5}{4}(1+\alpha_B^{\rm sim})$. In this case both $\alpha_a^{\rm sim}$ and $\alpha_B^{\rm sim}$ are determined if α_ρ is known.

In Table I the coefficients $\alpha_i^{\rm sim}$ are listed for the most common scaling laws. $\alpha_i^{\rm sim}$ correspond to the different ways of changing ρ_*. The size scaling is different for L- and H-mode tokamak discharges, with the L mode being more Bohm-like and H-mode scaling more gyro-Bohm-like. Also the B scaling of L-mode tokamak confinement and especially the most complete and dimensionally correct (see last column) study (ITER89-P [2]) are more consistent with Bohm-like transport. For W7-AS a more gyro-Bohm-like B scaling is indicated; without further assumptions, the size scaling ($\alpha_a^{\rm sim}$) cannot be inferred from global scalings of one device alone. The scatter in the values shows that the uncertainty introduced by the choice of data selection and analyzing procedure is large. Hence, no firm conclusions (especially for the H-mode scalings) for the underlying transport mechanism can be drawn from global scaling laws.

Dimensionally similar discharges.— More instructive is the direct investigation of the local transport coefficient. In tokamaks, discharges with different $\chi_B \rho_*^{\alpha_P}$ (via B) and the other local plasma parameters being similar were analyzed, showing an undecided situation for DIII-D [3] and a more Bohm-like dependence for TFTR and JET [4,5]. But in no experiment with dimensionally similar discharges τ_E has shown to scale gyro-Bohm-like.

W7-AS is ideally suited for investigating dimensionally similar discharges. Electron cyclotron resonance (ECR) heating can be operated at $B=1.25$ and 2.5 T and provides localized central power deposition. Heating profile modifications, which are a problem for investigations in tokamaks [3], are very small. There is no residual Ohmic heating power in the net-current-free W7-AS, whereas the Ohmic heating power changes in tokamaks when B is increased at constant q_a. We performed our experiments at low density, where the ion energy transport as well as radiation losses can be neglected. Hence, we study the electron heat conductivity and not a one-fluid coefficient as in tokamaks [1,4,5].

In the W7-AS local database are two discharges which fulfill the similarity constraints with $B=1.25$ and 2.5 T and line-averaged densities ($\bar{n}_e$) of 1.2×10^{19} m^{-3} and 3.2×10^{19} m^{-3}. Centrally localized ECR heating with powers of 0.35 and 0.54 MW was applied to make T_e of the low-B, high-$\bar{n}_e$ discharge superior to that of the low-$\bar{n}_e$ one. The ECR heating cutoff density at 3×10^{19} m^{-3} and 6×10^{19} m^{-3} was not approached and both deuterium discharges were far from operational limits. The radiation losses are small compared to the heating power.

In Fig. 1 the relevant plasma parameters of the similar discharges are plotted. A high level of similarity is achieved for the radial profiles of ν_* and the toroidal electron β. The profile shapes for both the electron temperature and density are self-similar and differences in L_T and L_n are erratic rather than systematic. The poloidal magnetic field in W7-AS is defined by the external coil system, which produces a nearly shearless q profile. Therefore, it is not necessary to balance the effect on q when B is doubled by an increased plasma current. W7-AS is operated in a net-current-free mode, where the bootstrap current is compensated by a small counter Ohmic current. These two currents introduce a modification of the flat external q profile, making, unlike in a tokamak, the central q higher than q_a. In the similar discharges, the edge values were $\iota_a = 1/q_a = 0.48$ at 1.25 T and 0.52 at 2.5 T. Analyses of the global confinement time do not reveal a distinct ι_a dependence (not stronger than $\iota_a^{0.25}$) [6]. Hence, a 10% change in ι should not have a strong influence on transport. The discharge with $B=2.5$ T has a $q=2$ surface inside the plasma. If a deterioration of the confinement was introduced by this surface, it would lead to a trend towards smaller transport improvement and therefore more to Bohm-like behavior when the discharges are compared (see Fig. 1). This would support even more the finding of a gyro-Bohm-like character of the underlying transport mechanism. The shear introduced by Ohmic and bootstrap currents, which is 10 times as small as in tokamaks, differs by a factor of up to 2 (being larger at $B=1.25$ T).

As indicated in Fig. 1, the ratio of the heat conductivities of the two discharges indicates a 60% improved confinement for the high-B discharge. This is in good agreement with the prediction of gyro-Bohm scaling and is much stronger than predicted by a Bohm-like transport model.

Error analyses.—The uncertainty of the results is mainly introduced through the larger error bars on the profile measurements of the low-B discharge. To include the errors for this discharge in the analyses, we made transport calculations with T_e and n_e profiles that were $\pm10\%$ of the best fits (shaded areas in Fig. 1). The different χ_e profiles from this procedure are responsible for most of the shaded area in the lower part of Fig. 1. The profile shape was not varied. A variation of the profile shape (dotted lines) introduces a modulation of χ_e which affects the radial average much less than the local values.

The error introduced by the coupling of the electrons to the ions is small. It is included in the shaded area of Fig. 1 and contributes only in the outer 20% of the plasma cross section.

Both τ_E and χ_e of these discharges conform to scaling expressions which describe W7-AS confinement. The total confinement time improves by a factor of 2.5 when B is doubled. Partly due to the improved coupling of elec-

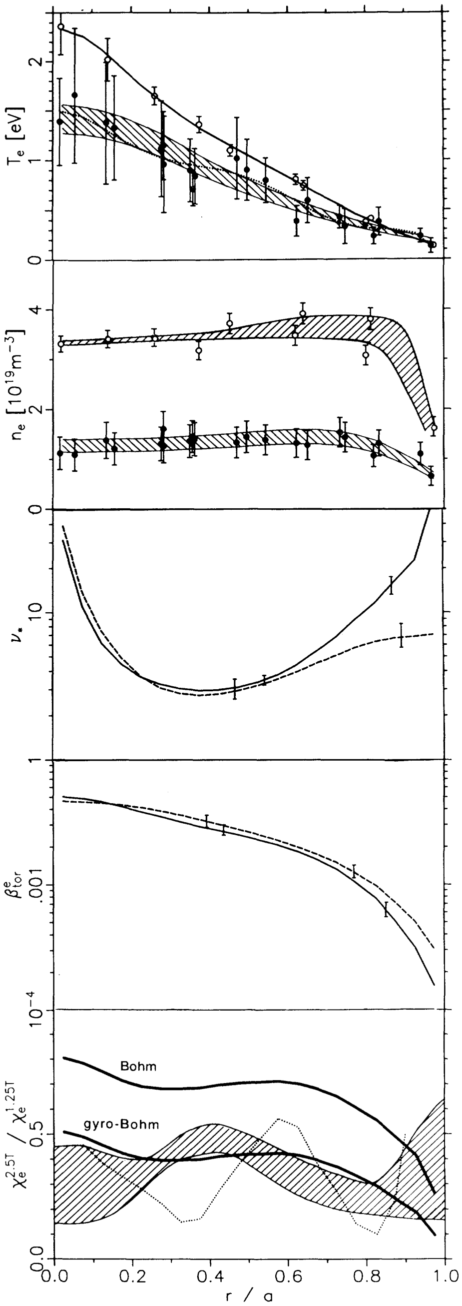

FIG. 1. Plasma parameter profiles of two similar discharges at $B=2.5$ T (high n_e, high T_e, and solid lines) and 1.25 T (low n_e, low T_e, and dashed lines). The top four panels show the measured profiles for electron temperature T_e, density n_e, collisionality ν_*, and toroidal beta β^e_{tor}. The bottom panel compares the ratio $\chi_e^{2.5\,\mathrm{T}}/\chi_e^{1.25\,\mathrm{T}}$ with the expectations from Bohm-like or gyro-Bohm-like transport coefficients. The shaded areas represent the errors, the dotted line shows the influence on the results if the T_e profile shape is modified in the case of the low-B discharge. The expectations from Bohm-like and gyro-Bohm-like transport coefficients (solid lines) were calculated using the experimental profiles. Ideally similar discharges would yield the ratios 0.794 and 0.5, respectively.

trons and ions, the factor is bigger than the value (2) expected from pure gyro-Bohm scaling. From the electron energy content alone an improvement of 2.2 is found in reasonable agreement with the prediction.

Statistical analyses.— The results from the investigation of two well suited discharges can be underpinned by regression analyses of a local database. The data set was restricted to about 100 ECR-heated discharges in $\not{\iota}_a$ ranges without configurational distortions and at densities where ions and electrons are only weakly coupled. For these discharges T_e and n_e profiles measured with Thomson scattering and power balance results were available. A complete account of the scaling expressions will be published elsewhere.

In all cases, the use of dimensional parameters such as P, n, and B as regressors yields the best results. Unconstrained fits of τ_E, the pure gyro-Bohm $\tau_E^{gB} \sim a^{2.4} \times (\bar{n}_e R/P)^{0.6} B^{0.8}$ or Bohm scaling laws fit the data with the root mean square errors (rmse) of 0.21, 0.25, and 0.27, respectively.

The main difficulty with all efforts to relate τ_E and χ_e to local plasma parameters is that none can be identified, which can effectively replace the P dependence. The T_e profile resilience in tokamak off-axis heating experiments is the most dramatic manifestation of this problem. Although stellarator plasmas do not exhibit a feature like profile resilience [7], surprisingly the same difficulty prevails: the regression fits of τ_E with ρ_*, ν_*, and β instead of P, n, and B yield much poorer results. The best scaling of τ_E can be done with a rmse of 0.35. Fits where α_ρ is constrained to 1 (gyro-Bohm) are of comparable quality (0.39) and much better than fits with $\alpha_\rho=0$ (rmse $=0.51$). Unconstrained fits yield a ρ_* dependence even stronger than gyro-Bohm-like and are of comparable quality.

Regression analyses of χ_e using the dimensionless regressors are consistent with the results for τ_E. The rmse for fits with α_ρ being unconstrained, 1, or 0 are 0.55, 0.57, and 0.64, respectively. Best fits with dimensional regressors yield a rmse of about 0.38.

In conclusion, the investigation of the transport mechanisms by means of global scaling studies is difficult because the result depends sensitively on the selection and the treatment of the data set. The L-mode tokamak scalings, however, are more conformal with Bohm-like transport while the situation remains undecided for the H-mode scalings.

More conclusive is the investigation of transport coefficients of dimensionally similar discharges. Unlike in tokamaks, where a more Bohm-like scaling of plasma energy confinement seems to be present, confinement in the W7-AS stellarator can be better described using gyro-Bohm-like parameter dependences. This has been demonstrated on two dimensionally similar discharges and has been backed by scaling studies of χ_e and τ_E, which always favor gyro-Bohm-like scaling laws to Bohm-like ones. Unlike in tokamaks, the confinement time increases by a factor of ~2 when the magnetic field strength is doubled.

Although no T_e profile resilience is present in stellarator plasmas, the difficulty prevails that the confinement can be better described when the total heating power instead of T_e is used as parameter.

In order to investigate whether the difference from tokamaks is due to the fact that we have discussed plasmas with dominant electron transport, further experiments will be devoted to find dimensionally similar discharges also at higher densities, where the ion energy transport plays a role as well. In addition, it is planned to study similar discharges with small amounts of net current to investigate the role the current has in possibly introducing nonlocal effects in plasma transport.

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