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Study on energy confinement time of net-current free toroidal plasmas based on extended international stellarator database

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1. Introduction

Stellarators are widely recognized as the alternative to the tokamak as a toroidal fusion reactor. Large experiments have advanced parameters, and theoretical and design studies have developed advanced configurations for the next generation of experiments. The configuration space of possible stellarator designs is so large that comparative studies of experimental behavior are important to making choices that lead to an attractive reactor. Both experimental and theoretical confinement studies have been intensively conducted in a variety of concepts for a long time.

In 1995, a collaborative international study used available data from medium-sized stellarator experiments, i.e. W7-AS, ATF, CHS, and Heliotron-E to derive the ISS95 scaling relation [1]

$$\tau_E^{ISS95} = 0.079 a^{2.21} R^{0.65} P^{-0.59} \bar{n}_e^{0.51} B^{0.53} \iota\!\!\!-_{2/3}^{0.4} \qquad (1)$$

Here the units of τ_E, P and $\bar{n}_e$ are s, MW and 10^{19}m^{-3}, respectively, and $\iota\!\!\!-_{2/3}$ is the rotational transform at r/a = 2/3. This expression can be rephrased into an expression by important non-dimensional parameters,

$$\tau_E^{ISS95} \propto \tau_{Bohm} \rho*^{-0.71} \beta^{-0.16} \nu_b *^{-0.04},$$

where $\rho*$ and ν_b* are defined by the ion gyro radius normalized by the plasma minor radius and the collision frequency between electrons and ions normalized by the bounce frequency of particles in the toroidal ripple, respectively. β is the ratio of the plasma kinetic pressure to the magnetic field pressure. Since ISS95, new experiments, i.e., LHD [2], TJ-II [3], Heliotron J [4], and HSX [5], most with different magnetic configurations, have started. Device improvement with divertor also has been taken into operation in W7-AS which has developed an improved confinement mode [6,7]. Extension of the confinement database aims at confirmation of our previous understanding of ISS95 and examination of possible new trends in confinement performance of stellarators. We have started to revise the international stellarator database incorporating these new data to improve assessment of a stellarator reactor and deepen understanding of the underlying physics of confinement.

2. Extension of International Stellarator Confinement Database

More than 2500 data have been compiled in the database to date and 1747 data representing typical discharges have been used for this study. The largest device, LHD (*R*/*a* = 3.9 m/ 0.6 m) has extended the parameter regime to substantially lower ρ^* and ν_b^* regimes which are 3-10× closer to the reactor regimes than those of the mid-size devices (Fig .1). Data from the flexible heliac TJ-II allows us to investigate the ι dependence over a much larger variation ($1.3 < \iota < 2.2$) than is available in the other experiments.

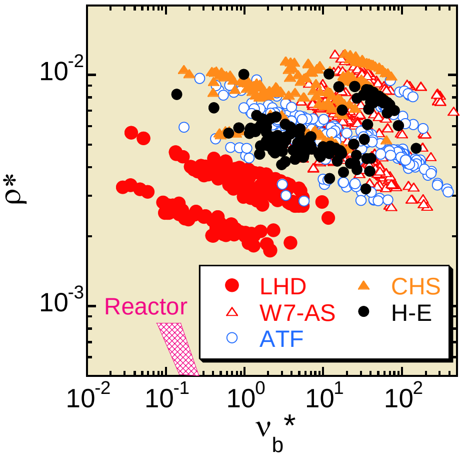

Fig.1. Parameter regime of data in the international stellarator database on the space of normalized gyro radii ρ^* and collisionality ν_b^*.

3. Towards a Unified Scaling

A simple regression analysis of the entire data set using the same parameters as in ISS95 yields

$$\tau_E^{REG} = 0.30 a^{2.07} R^{1.02} P^{-0.60} \bar{n}_e^{0.58} B^{1.08} \iota_{2/3}^{-0.16} \propto \tau_{Bohm} \rho^{*-1.95} \beta^{0.14} \nu_b^{*-0.18} \quad (2)$$

with root-mean-square error (RMSE) = 0.101. This expression is characterized by strong gyro-Bohm as a similar analysis of heliotron lines has suggested [8]. However, application of expression (1) to data from a single device leads to contradictory results. For example comparison of dimensionally-similar discharges in LHD indicates that the transport lies between Bohm and gyro-Bohm scalings [9]. Rotational transform scans in TJ-II also show that τ_E is proportional to the power of 0.35-0.6, which contradicts the weak ι dependence of Eq.2 [10].

We conclude that while Eq. 2 is useful for unified data description as a reference, its application is limited to the available data set alone and is not valid for extrapolation. Data inspection and experience from inter-machine studies suggest necessity to introduce a magnetic configuration dependent parameter in order to supplement the set of regression parameters and resolve this seemingly contradictory result. A systematic gap between W7-AS and heliotron/torsatrons was noted during the earlier studies on the ISS95 scaling. A recent example showing the pronounced effect of magnetic configuration

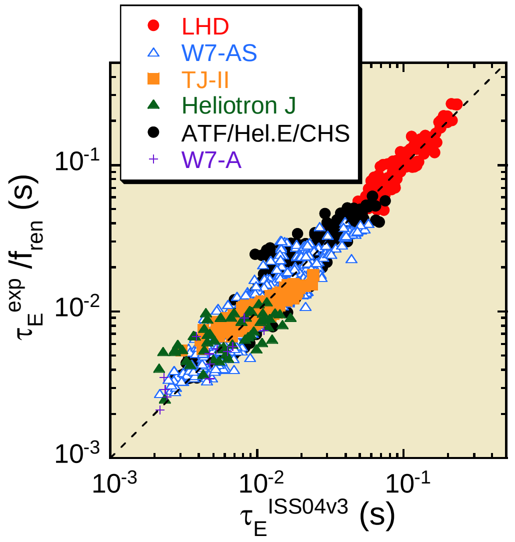

Fig.2. Comparison of energy confinement in experiments and predicted by ISS04v3. Experimental data is corrected by a renormalization factor f_{ren}..

variation even in a single device has come from comparison of the performance of configurations with shifted magnetic axes in LHD. A discharge with an inward shift of the magnetic axis from R_{ax}=3.9 m to R_{ax}=3.6 m, results in a doubling of τ_E for similar operational parameters a, P, $\bar{n}_e$, B and $\iota\!\!-$ [9]. Therefore, acceptance of a systematic difference in different magnetic configurations is a prerequisite for derivation of a useful unified scaling law. A deterministic parameter characterizing the magnetic configuration has not been identified yet, but certainly involves the details of the helically corrugated magnetic fields, so an enhancement factor on ISS95 is used for renormalization to describe the magnetic configuration effect. One renormalization factor is defined by the averaged value of experimental enhancement factors for each configuration (subset). Iteration of a regression analysis of data normalized by these factors specific to configurations tends to converge into the following expression :

$$\tau_E^{ISS04v3} = 0.148 a^{2.33} R^{0.64} P^{-0.61} \bar{n}_e^{-0.55} B^{0.85} \iota\!\!-_{2/3}^{0.41} \quad \propto \tau_{Bohm} \rho^{*-0.90} \beta^{-0.14} \nu_b^{*-0.01} \qquad (3)$$

with RMSE =0.026 (see Fig.2). In this process, weighting of the square root of the number of each subset is applied. This expression appears more comprehensive than Eq. 2. The leading coefficient is determined so as to give an renormalization factor of 1 for the case with $\iota\!\!-$<0.48 in W7-AS, and Fig. 3 shows the resultant renormalization factor for subsets f_{ren} with different configuration.

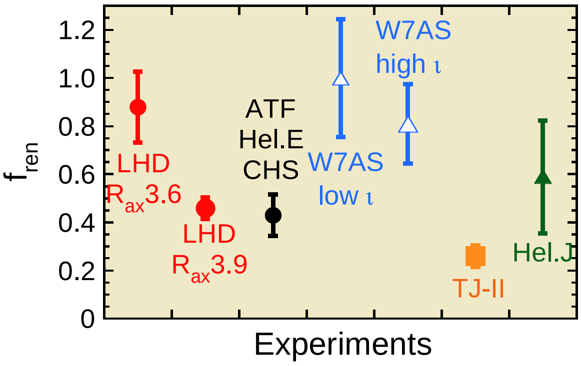

Fig.3. Renormalization factors for devices considered. Data of W7-AS are divided into two groups with low $\iota\!\!-$ (<0.48) and high $\iota\!\!-$ (≥0.48).

3. Discussions and Conclusions

The above mentioned results lead to a task for the immediate future of these studies. The first step is clarification of the hidden physical parameters to interpret the renormalization factor shown in Fig.3. It is reasonable to suppose that this renormalization factor is attributed to specific properties of the helical field structure of the devices. One possible leading parameter is an effective helical ripple, ε_{eff} [11] although there exist other potential configuration factors such as fractions of direct-loss orbits and trapped particles and the plateau factor, etc. The values of ε_{eff} have been calculated accurately by the numerical codes, DCOM [12], DKES[13] and MOCA[14]. Validation of results from the codes has been proven for several configurations. Figure 4 shows the correlation of ε_{eff} with the enhancement of confinement times with respect to the unified scaling law ISS04v3. The upper envelope resembles an $\varepsilon_{eff}^{-0.4}$ dependence, however, detailed studies on ε_{eff} behaviour are required as the data indicate, e.g. large scattering of W7-AS data. Also the expression of a power law of ε_{eff} diverges to infinity when it approaches zero. Hence, a simple power law is expected to fail. Although all data in the database are not located in the collisionless regime where the neoclassical transport is enhanced, $\varepsilon_{\mathrm{eff}}$ can be related to effective heating efficiency through the neoclassical-like losses of high energetic particles and anomalous transport through flow dumping due to neoclassical viscosity. Due to the aforementioned reasons, an incorporation of that factor to a unified scaling is premature at present. Nonetheless, the correlation encourages a more systematic study of other potential configuration -dependent factors to project a path to the optimal configuration.

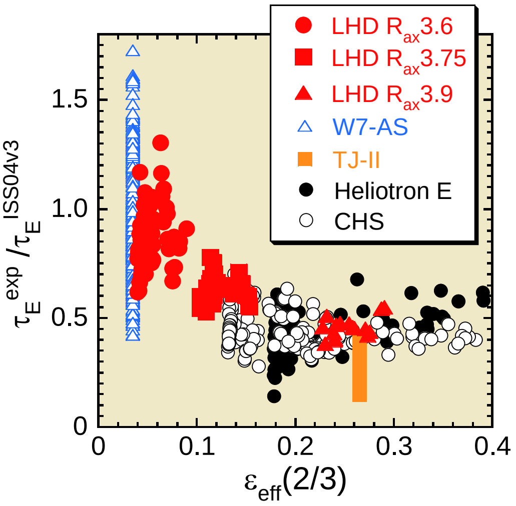

Fig.4 Confinement enhancement factor as a function of ε_{eff} at r/a=2/3.

The web page of the international stellarator confinement database is jointly hosted by National Institute for Fusion Science and Max-Planck-Institut für Plasmaphysik, EURATOM Association, and available at http://iscdb.nifs.ac.jp/ and http://www.ipp.mpg.de/ISS.

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