Confinement Study of Net-Current Free Toroidal Plasmas Based on Extended International Stellarator Database

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Abstract. International collaboration of a stellarator confinement database has been progressing. About 2500 data points from major 9 stellarator experiments have been compiled. Robust dependence of the energy confinement time on the density and the heating power has been confirmed. Dependences on other operational parameters, i.e., the major and minor radii, magnetic field and the rotational transform ι , have been evaluated using inter-machine analyses. In order to express the energy confinement in a unified scaling law, systematic differences in each subgroup should be quantified. An *a posteriori* approach using the confinement enhancement factor on ISS95 yields a new scaling expression ISS04v03; $\tau_E^{ISS04v3} = 0.148 a^{2.33} R^{0.64} P^{-0.61} \bar{n}_e^{0.55} B^{0.85} \iota_{2/3}^{0.41}$. Simultaneously, the configuration dependent parameters are quantified for each configuration. The effective helical ripple shows correlation with these configuration dependent parameters.

1. Introduction

Stellarators are widely recognized as the main alternative to the tokamak as a toroidal fusion reactor. A large experiment has extended 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 for the energy confinement time [1]

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

with the root mean square error (RMSE) in the logarithmic expression of 0.091. Here the units of τ_E, P and $\bar{n}_e$ are s, MW and $10^{19}\mathrm{m}^{-3}$, respectively, and $\iota_{2/3}$ is the rotational transform at r/a = 2/3. This expression is dimensionally correct and 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 ρ^* 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. ISS95 is characterized by a weak gyro-Bohm nature and no definitive dependence on β and collisionality. Since ISS95, new experiments, i.e., LHD [2], TJ-II [3], Heliotron J [4], and HSX [5], most with different magnetic configurations, have started. In LHD, parameter dependences similar to ISS95 have been found but there exists a systematic improvement on it [6]. Also, collisionality independence like that in ISS95 has been confirmed in the deep collisionless regimes ($\nu_b^* \approx 0.05$) when geometrical optimization of neoclassical transport is applied [7]. Confinement improvement with divertor operation also has been taken into account for W7-AS [8,9]. 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, so as to deepen understanding of the underlying physics of confinement and its relationship to magnetic configuration details and improve the assessment of stellarator reactors.

2. Extension of International Stellarator Confinement Database

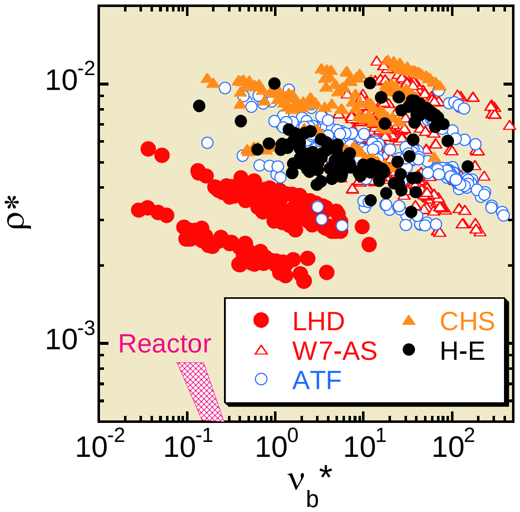

FIG.1. Parameter regime of data in the international stellarator database on the space of normalized gyro radii ρ^* and collisionality ν_b^*.

About 2500 data points have been compiled in the database to date from nine stellarators, i.e., ATF, CHS, Heliotron E, Heliotron J, HSX, LHD, TJ-II, W7-A and W7-AS. 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 [10] (Fig .1). Heliotron lines (Heliotron E, ATF, CHS and LHD) have colinearity between the aspect ratio and the rotational transform ɫ. This obtains because the transform scales as the number of toroidal field periods M, which scales as R/a. Therefore, the $\iota\!\!\!-$ dependence tends to be statistically unstable for the data from heliotrons. W7-AS alone, which has contrasting $\iota\!\!\!-$ profile to heliotrons, can not provide the size and $\iota\!\!\!-$ dependences simultaneously. In the extended database, however, data from the flexible heliac TJ-II allows us to investigate the $\iota\!\!\!-$ dependence over a much larger variation ($1.3 < \iota\!\!\!- < 2.2$) than is available in the other experiments. Data from HSX has not been employed yet in the present combined analysis since non-thermal electrons characterize plasma confinement there.

The present database contains scalar data of parameters described in ref.[1], the format of which is similar to the ITER H-mode database [11]. 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.

3. Towards a Unified Scaling

A simple regression analysis of the entire data set (except for HSX) using the same parameters as in ISS95 yields

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

with RMSE = 0.101. This expression is characterized by very strong gyro-Bohm as a similar analysis of heliotron lines has suggested [12], and a weak negative dependence on the rotational transform. The former trend is attributed to the fact that the energy confinement time in LHD with smaller ρ* (in other words, larger dimension) is better than the gyro-Bohm prediction in comparison with other heliotrons. However, application of expression Eq.2 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 [6]. Rotational transform scans in TJ-II also show that τ_E is proportional to the power of 0.35-0.6 [13], which contradicts the weak $\iota\!\!\!-$ dependence of Eq.2. It is also pointed out that Eq.2 is not dimensionally correct.

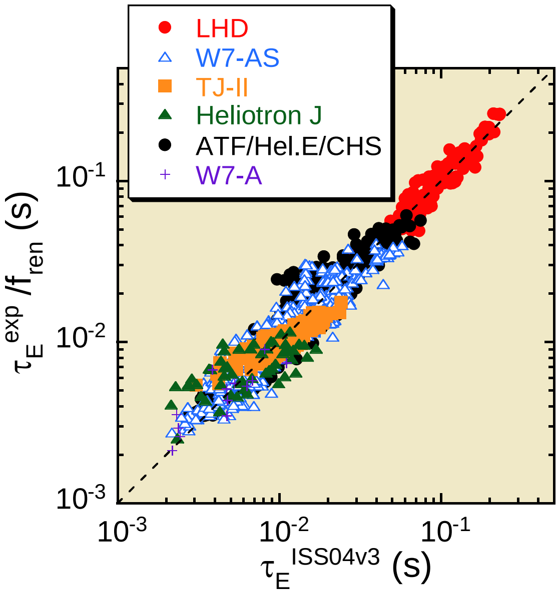

FIG.2. Comparison of energy confinement in experiments and predicted by ISS04v3. Experimental data is corrected by a renormalization factor f_{ren}..

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 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 ι [6]. 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. Since the configuration dependent parameter is not available now, an enhancement factor on ISS95 is first used expediently for renormalization to describe the magnetic configuration effect. This process is based on the conjecture that parametric dependence expressed by ISS95 is robust for stellarators and the enhancement factor on ISS95 reflects some configuration effects. 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 this factor specific to configurations tends to converge into the following expression :

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

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 ι<0.48 in W7-AS, and Fig. 3 shows the resultant renormalization factor for subsets f_{ren} with different configuration. The confinement improvement by a factor of 2 when the magnetic axis is shifted from R_{ax}=3.9 m to R_{ax}=3.6m in LHD can be seen clearly. The systematic difference for the cases with high rotational transform (ι>0.48) and low one (ι<0.48) in W7-AS has been also found in this analysis.

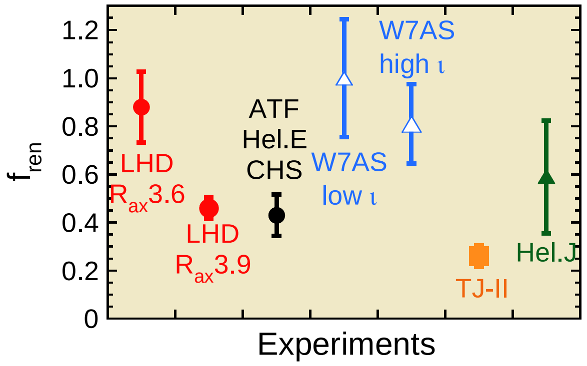

FIG.3. Renormalization factors for devices considered. Data of W7-AS are divided into two groups with low ι (<0.48) and high ι (≥0.48).

The robustness of the unified expression can be checked by examining its dependence on individual parameters. Figure 4 (a) and (b) show the exponent of density and heating

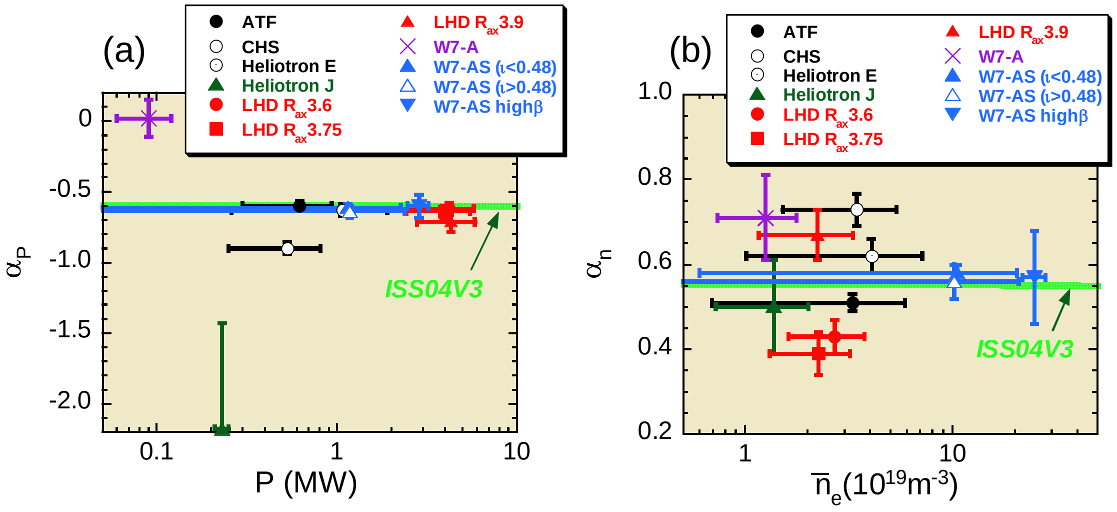

FIG.4. Exponents of (a) heating power and (b) density dependences in each subgroup with their parameter ranges.

power dependences, i.e., $\tau_E \propto P^{\alpha_p}\bar{n}_e^{\alpha_n}$ in a single experiment (configuration) with their parameter ranges, respectively. In these analyses, parameter dependences other than the density and the heating power are fixed as described by ISS04v03. Although some subgroups show significant deviation from the scaling, this discrepancy occurs mainly at low parameter values. Therefore, density and power dependences like $\tau_E \propto P^{-0.61}\bar{n}_e^{0.55}$ can be found as general trends in subgroups. On the contrary, the magnetic field dependence in subgroups appears not to be consistent with ISS04v03. Therefore the magnetic field scaling is a result of inter machine regressions, which means that its statistical nature is different from variable quantities like power and density.

4. Discussion

These results motivate future directions for stellarator confinement 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 related to specific properties of the helical field structure of the devices. A leading candidate is the effective helical ripple, ε_{eff} [14], which is defined from the neoclassical flux in the 1/ν regime,

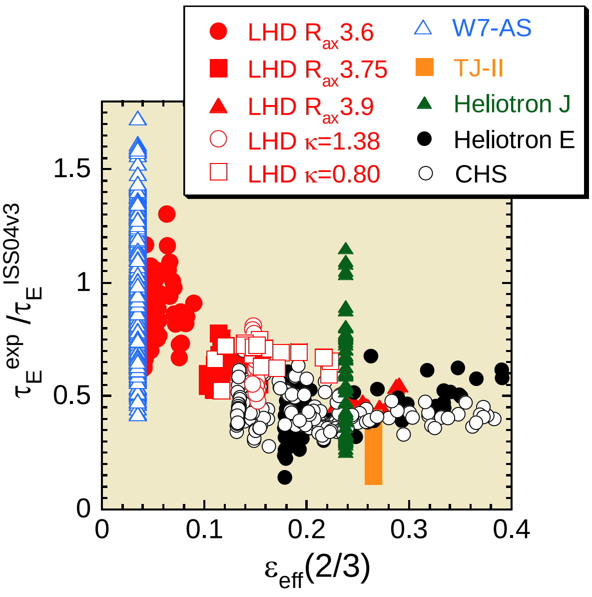

FIG.5. Confinement enhancement factor as a function of ε_{eff} at r/a=2/3.

which is proportional to $\varepsilon_{eff}^{3/2}$. The values of $\varepsilon_{\mathrm{eff}}$ have been calculated rigorously by the numerical codes, DCOM [15], DKES[16] and MOCA[17]. These codes have been successfully benchmarked for several configurations [18]. Figure 5 shows the correlation of $\varepsilon_{\mathrm{eff}}$ with the enhancement of confinement times with respect to the unified scaling law ISS04v3. The upper envelope resembles an $\varepsilon_{\mathrm{eff}}^{-0.4}$ dependence, however, detailed studies on $\varepsilon_{\mathrm{eff}}$ behaviour are required as the data indicate, e.g. large scattering of W7-AS and Heliotron J data. Also the expression of a power law of $\varepsilon_{\mathrm{eff}}$ diverges to infinity when it approaches zero (ideal tokamak case). 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 damping due to neoclassical viscosity. Also neoclassical conduction loss of ions should be carefully looked into although the anomalous transport is generally predominant in electron heat transport. Due to the aforementioned reasons, an incorporation of that factor to a unified scaling is premature at present.

The second potential geometrical parameter is that given for the neoclassical flux in the plateau regime. This factor corresponds to the effect of elongation in tokamaks. The formulation is available in ref.[19] and here the geometrical factor that is the ratio of dimensionless fluxes in the cases of stellarator with many harmonics and tokamaks with only toroidal ripple, i.e., $\Gamma_{stell}/\Gamma_{tok}$ is considered. Figure 6 shows the correlation of this plateau factor $\Gamma_{stell}/\Gamma_{tok}$ with the enhancement of confinement times with respect to the unified scaling law ISS04v3. The envelope of the data shows the trend that a smaller factor of $\Gamma_{stell}/\Gamma_{tok}$ leads to good confinement although the scattering of data is larger than in the case of $\varepsilon_{\mathrm{eff}}$. It should be note that there is colinearity between $\varepsilon_{\mathrm{eff}}$ and $\Gamma_{stell}/\Gamma_{tok}$ generally. However, an elongation scan in LHD (κ=0.8-1.38) has excluded this colinearity, which has not indicated significance of $\Gamma_{stell}/\Gamma_{tok}$ dependence (compare open squares and open circles in Fig.6). Therefore, $\varepsilon_{\mathrm{eff}}$ is more likely to be the essential configuration factor than is the plateau factor $\Gamma_{stell}/\Gamma_{tok}$.

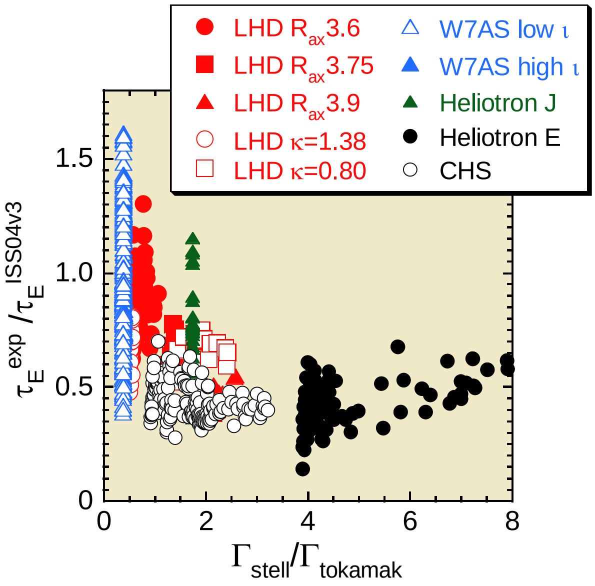

FIG.6. Confinement enhancement factor as a function of the plateau factor at r/a=2/3.

5. Conclusions

International collaboration on the stellarator confinement database has progressed significantly. About 2500 data points from 9 major stellarator experiments have been compiled. Robust dependence of the energy confinement time on the density and the heating power have been confirmed, and dependences on other operational parameters, i.e., the major and minor radii, magnetic field and the rotational transform $\iota\!\!\!-$, have been evaluated using inter-machine analyses. In order to express the energy confinement in a unified scaling law, a systematic offset between each configuration data subgroup must be admitted. This factor is correlated with the magnetic geometry. A confinement enhancement factor on ISS95 is used for a posteriori approach. This procedure converges into the ISS04v03 expression;
$\tau_E^{ISS04v3} = 0.148 a^{2.33} R^{0.64} P^{-0.61} \overline{n}_e^{0.55} B^{0.85} \iota\!\!\!-_{2/3}^{0.41}$.

The configuration dependence of confinement can usefully be expressed as a renormalization factor for ISS04v03. There are many potential candidates for this configuration factor: the effective helical ripple, the neoclassical flux in the plateau regime, fractions of direct-loss orbits and trapped particles, etc. In studies to date, the effective helical ripple shows correlation with the confinement enhancement factor.

While the explicit incorporation of this factor in a unified scaling is still premature, the correlation encourages a systematic comparative study of other potential configuration -dependent effects on stellarator confinement. The results of such studies will provide important guidance for the optimization of stellarator configurations and operational techniques.

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