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

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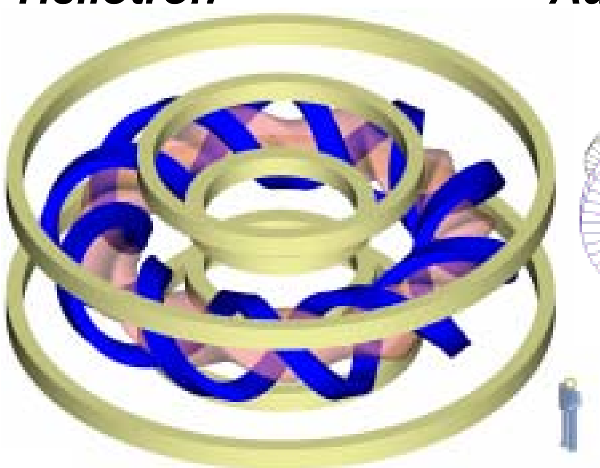
Outline

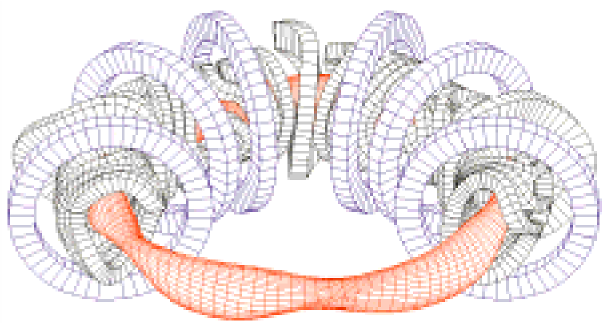
1. Motivation and background
2. Extended International Stellarator Confinement Database
3. Towards a unified scaling law of energy confinement time
4. Discussion about a configuration dependent parameter
5. Summary with future prospects

Stellarator : A wide spectrum of approaches

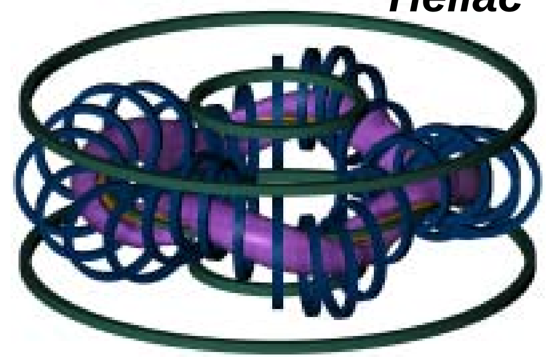
Heliotron



Advanced stellarator



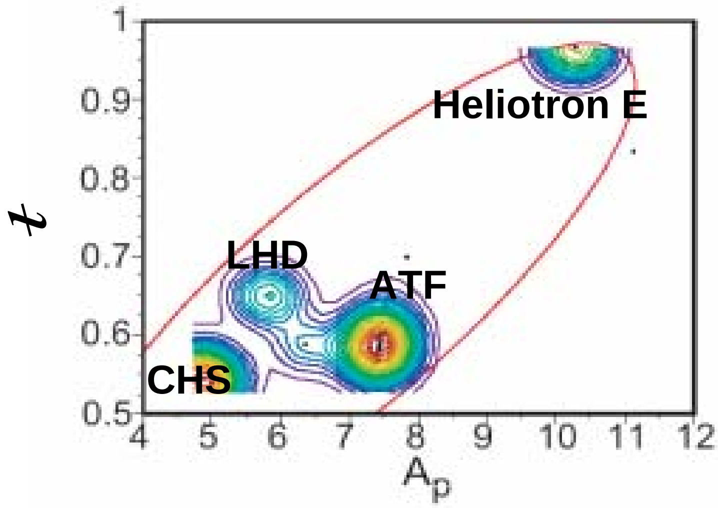
Heliac



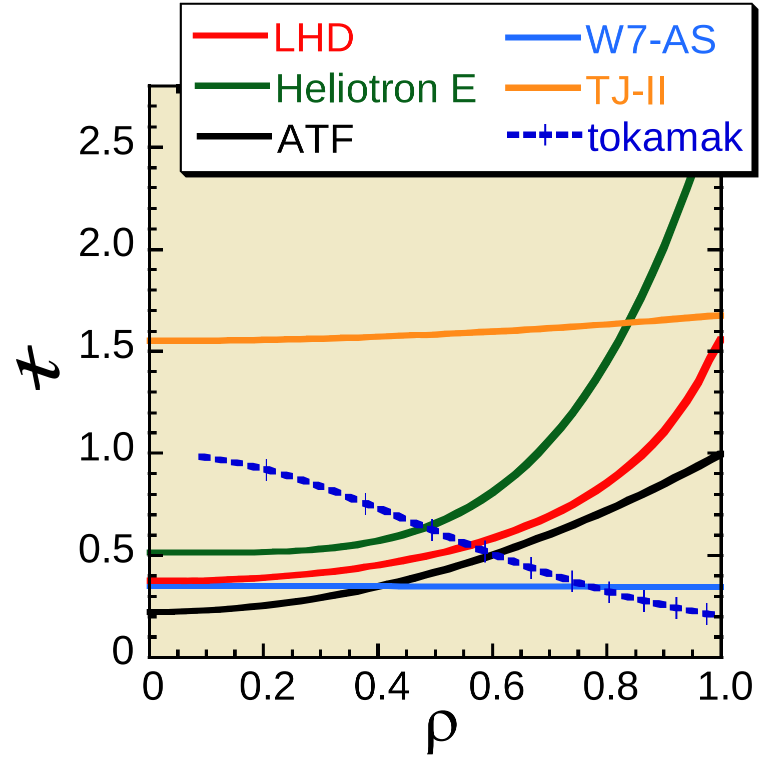
✓ Reactor assessment
✓ Physical understanding of underlying physics
➔ Effect of optimization principle on confinement

Need for inter-machine analysis

Collinearity in Heliotron line



W7-AS and TJ-II can scan ι,
but cannot provide size dependence.

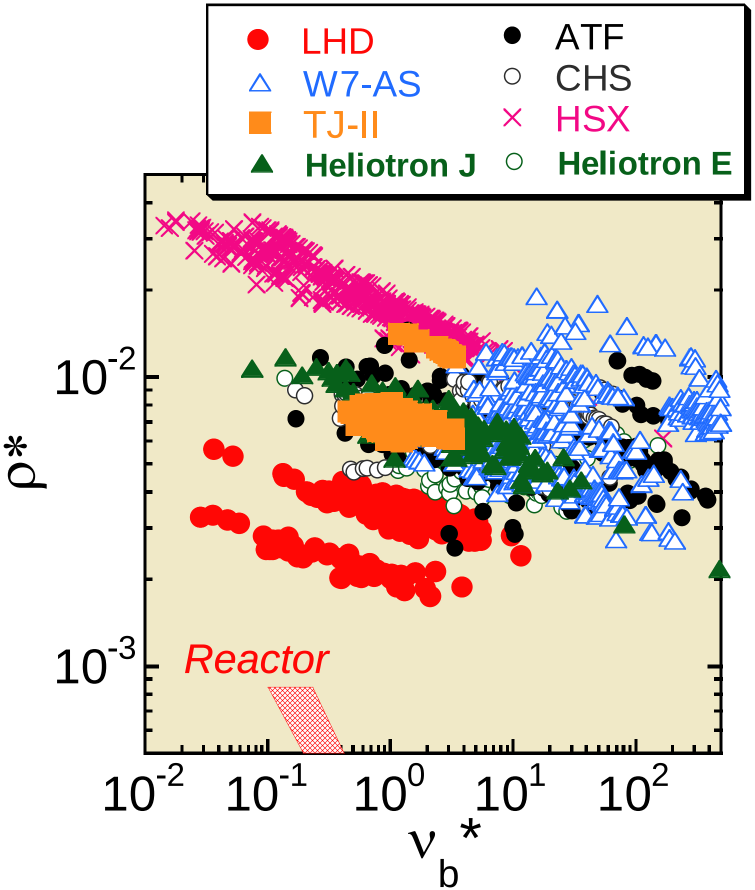


Earlier work: **ISS95** derived from the database of medium-size stellarators (W7-A, W7-AS, ATF, CHS, Heliotron E),

$$\tau_E^{ISS95} = 0.079 a^{2.21} R^{0.65} P^{-0.59} \bar{n}_e^{0.51} B^{0.83} \iota_{2/3}^{0.4} \propto \tau_B \rho_*^{-0.71} \beta^{-0.16} \nu_*^{-0.04}$$

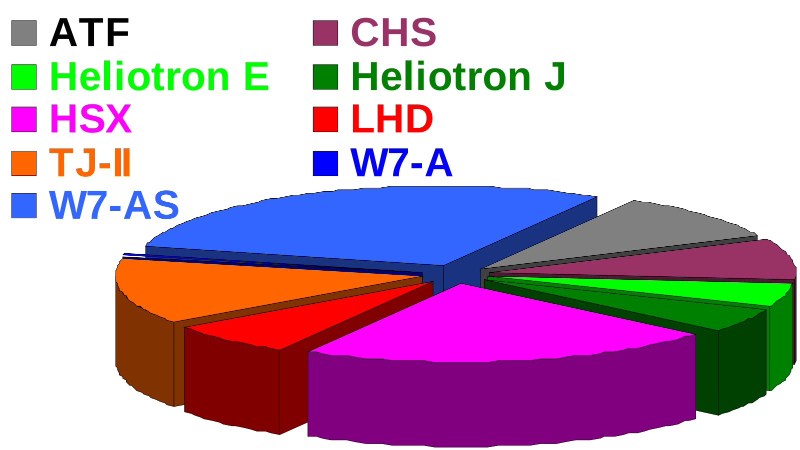
Weak gyro-Bohm, No significant dependence on β and ν∗.

Extended International Stellarator Database



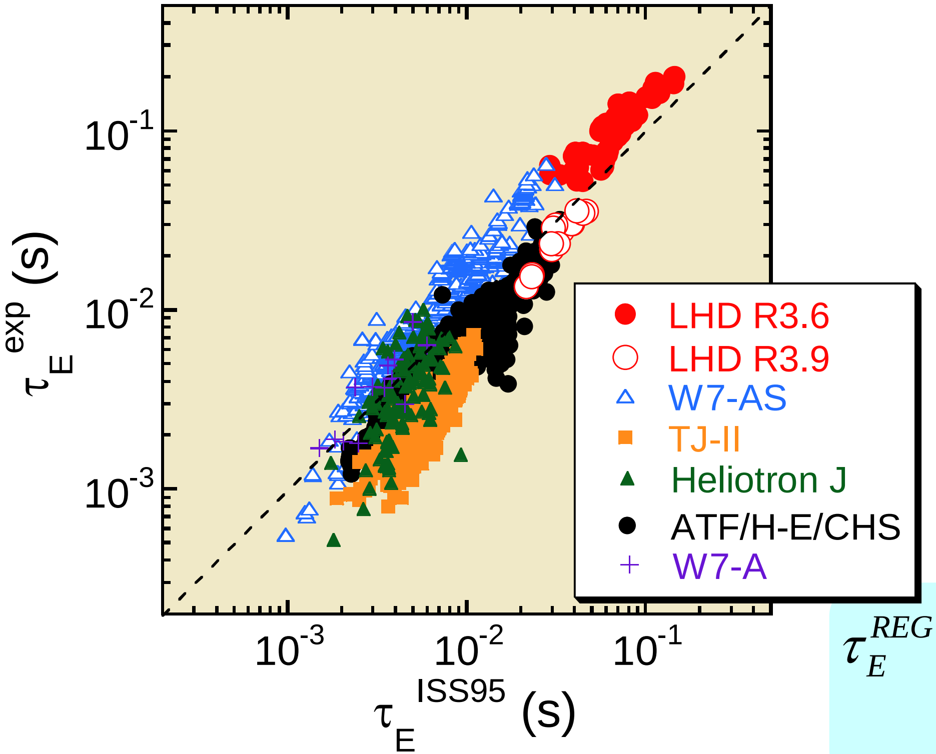
✓ New experiments
✓ New operational modes
➔ extending operational parameter range and property of magnetic configuration

✓ 9 major stellarators :
J: LHD, CHS, Heliotron E, Heliotron J
G: W7-A, W7-AS
US: ATF, HSX
S: TJ-II
➔ 2404 data points
1747 data points are used in the following analysis



Scalar data in the format similar to the ITER ELMy H-mode database.

Trend of parameter dependence is quite similar for each configuration, however, there exist offsets.



Ex.1 Offset between W7-AS and medium sized heliotrons which was recognized in the stage of ISS95.

Ex.2 Comparison of cases with R_{ax}=3.6m and 3.9m in LHD.
➔ Inward shift of the magnetic axis doubles the energy confinement.

Simple regression analysis of entire data results in an unusual expression.

$$\tau_E^{REG} = 0.30 a^{2.07} R^{1.02} P^{-0.60} \bar{n}_e^{-0.58} B^{1.08} \iota_{2/3}^{-0.16}$$

$$\propto \tau_{Bohm} \rho^{*-1.95} \beta^{0.14} \nu_b^{*-0.18} a^{-0.55}$$

➔ contradicting experimental observations, i.e, gyro-Bohm and iota dependences

Acceptance of systematic difference in different magnetic configuration is prerequisite for derivation of a useful unified scaling.
But, **what is a deterministic parameter to describe performance of magnetic configuration ?**

A posteriori approach: Converging to a unified expression successfully.

Leading parameter for magnetic configuration

⇐ involves the details of the helically corrugated magnetic field.

➔ has not been identified yet.

Alternative approach:

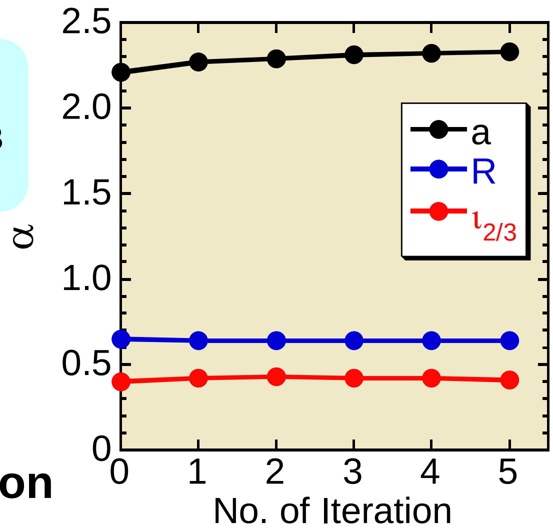
Conjecture : Nature in ISS95 is common to all experiments.

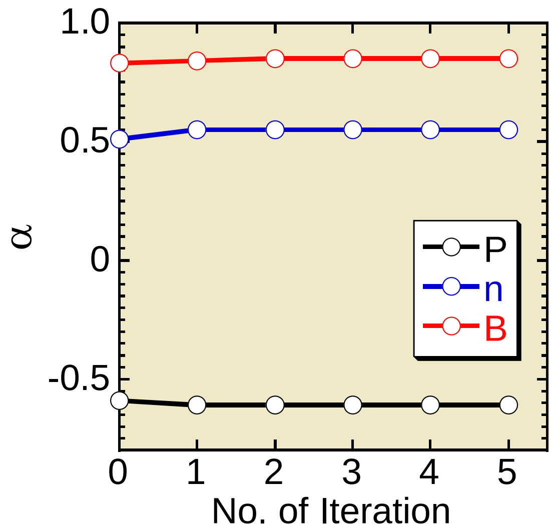
➔ Confinement enhancement factor on ISS95 includes configuration effect.

➔ Averaged value of confinement enhancement factor in each sub-group is used as a configuration dependent parameter.

➔ Iteration of regression analysis of normalized data

$$\tau_E \propto a^{\alpha_a} R^{\alpha_R} P^{\alpha_p} \bar{n}_e^{\alpha_n} B^{\alpha_B} \iota_{2/3}^{\alpha_\iota}$$





Each exponent on the operational parameter converges after 5 iterations.

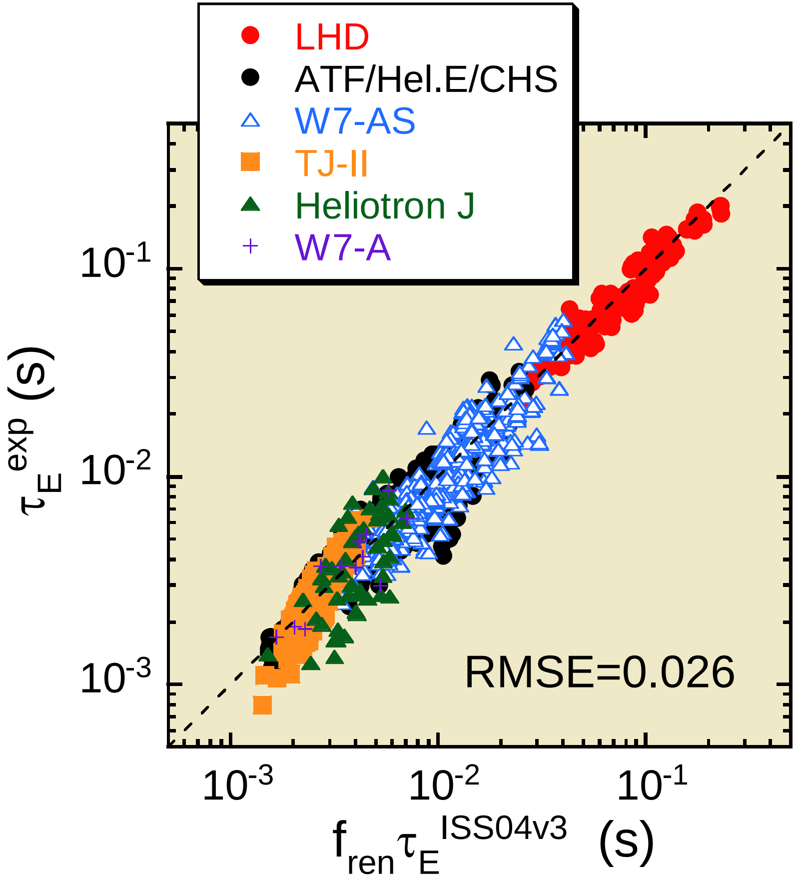
➔ **Unified scaling expression**

Configuration dependent factor is quantified simultaneously.

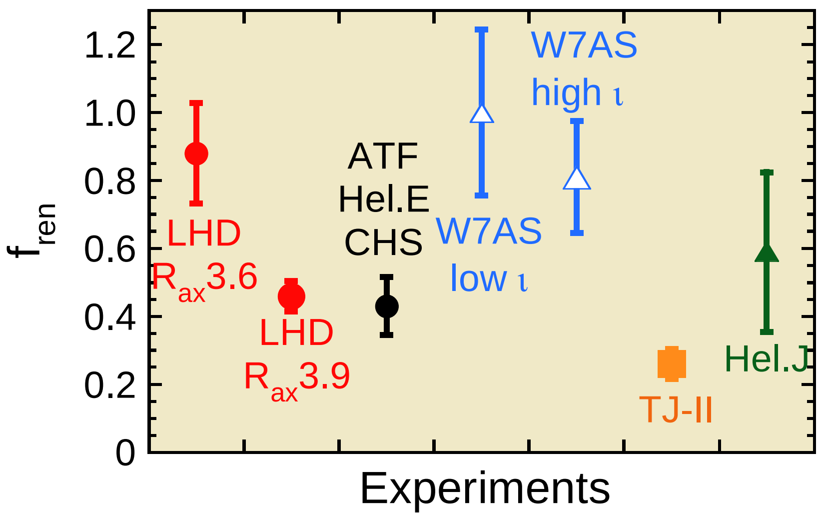
$$\tau_E^{ISS04v3} = 0.148 a^{2.33} R^{0.64} P^{-0.61} \bar{n}_e^{0.55} B^{0.85} \iota_{2/3}^{0.41}$$
$$\propto \tau_{Bohm} \rho^{*-0.90} \beta^{-0.14} \nu_b^{*-0.01} a^{0.04}$$

✓ Gyro-Bohm, ✓ no definitive dependences on collisionality and beta.

✓ Dimensionally correct.



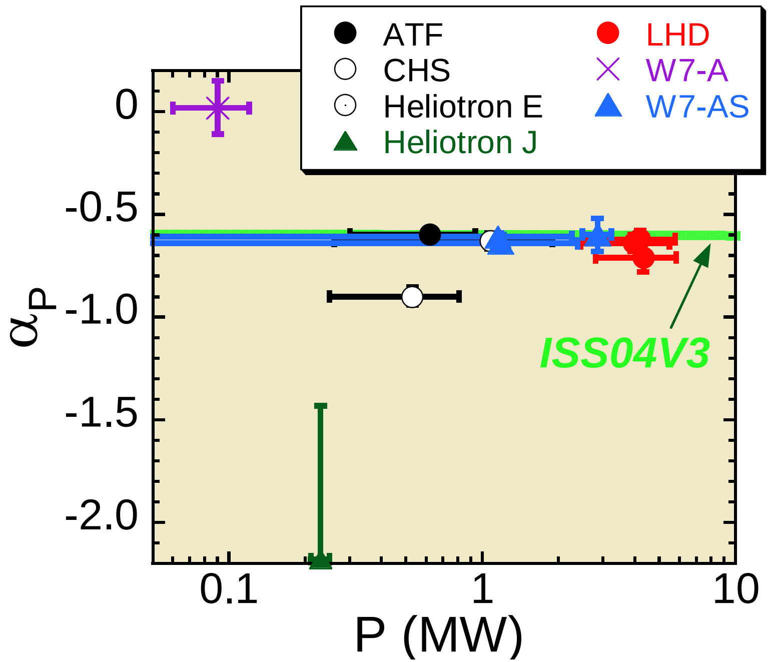
Configuration dependent parameter has been simultaneously obtained as a normalization factor.

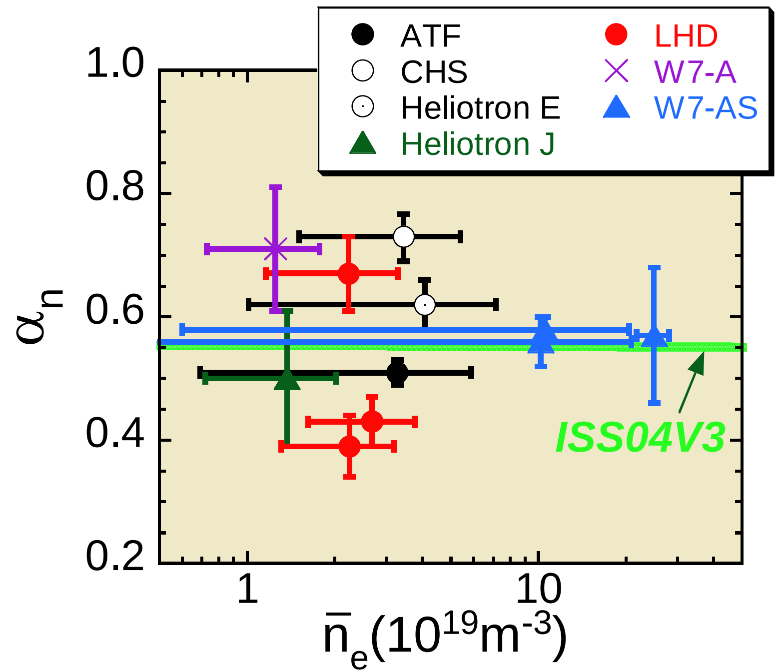


Confirmation of robustness of parameter dependence

$$\tau_E \propto P^{\alpha_p} \overline{n}_e^{\alpha_n} B^{\alpha_B} \iota_{2/3}^{\alpha_\iota}$$

Check an objective exponent with fixing other parameters at ISS04v3.



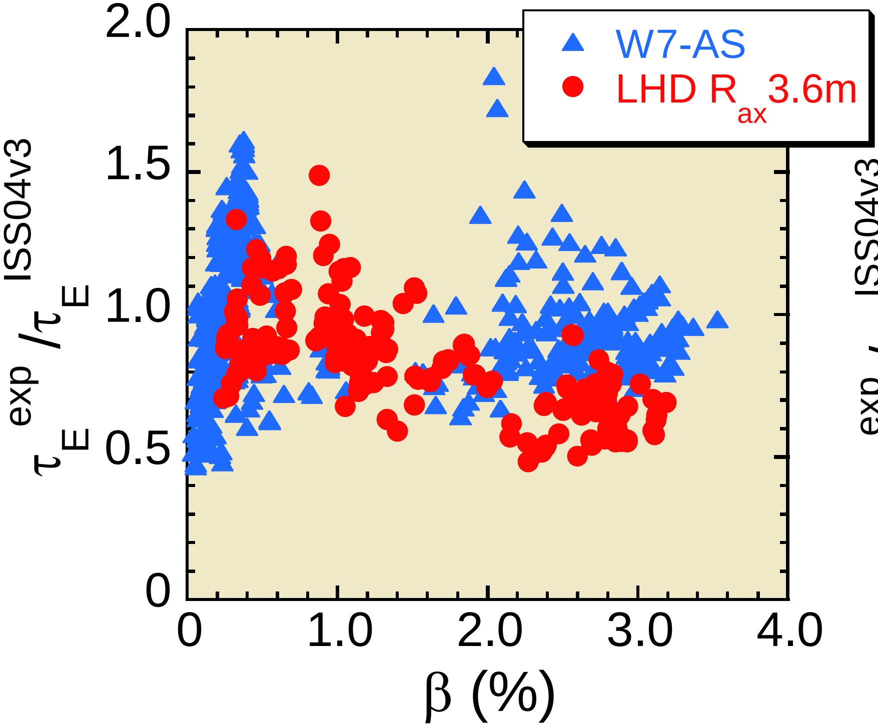


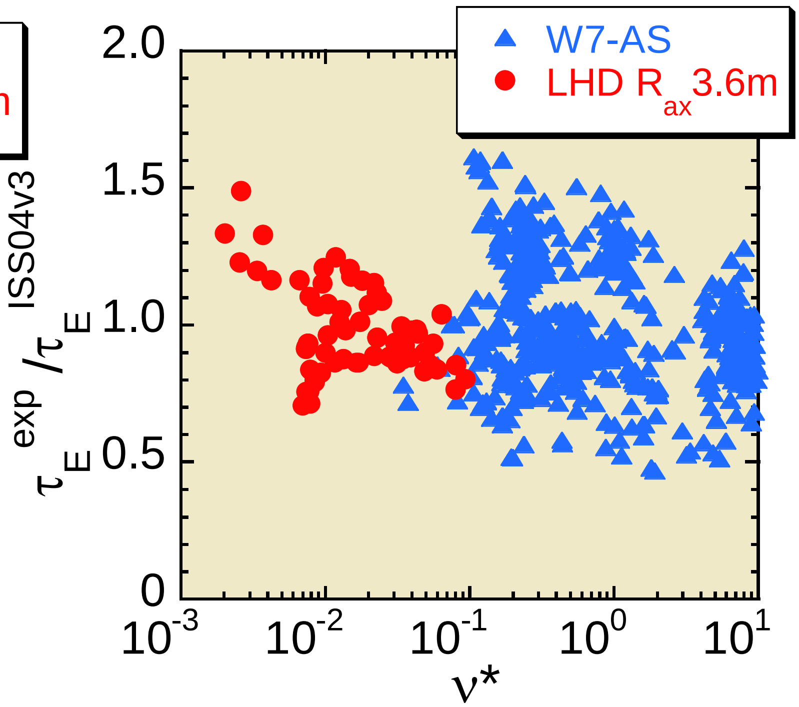
✓ Some deviation from the scaling, but it occurs at low parameter values.

➔ Power and density dependences are robust.

✓ Other parameter (R, a, B, ι) dependences result from the inter-machine regression analysis.

Moderate dependences on β and collisionality exists or not ?





✓ LHD (R_{ax}=3.6m) shows moderate degradation with β and collisionality.

➔ effects of violation of MHD instability, performance density limit ?

✓ No significant degradation in the deep collisionless regime.

⬄

✓ W7-AS does not show a trend along with β and ν*.

What reflects normalization factors ?
1. Effective helical ripple

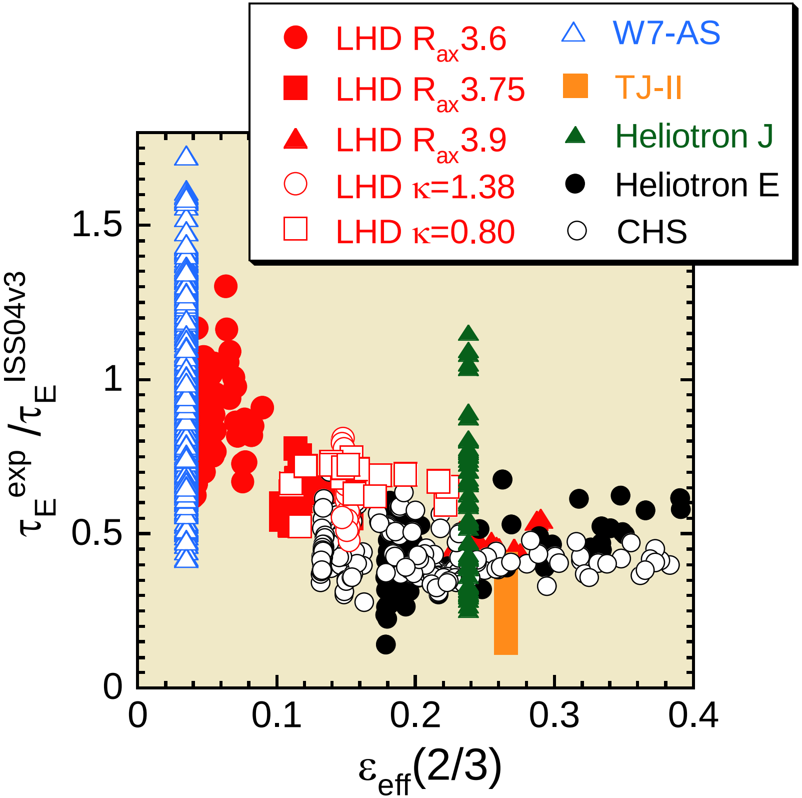
Defined in 1/ν regime due to neoclassical helical ripple transport

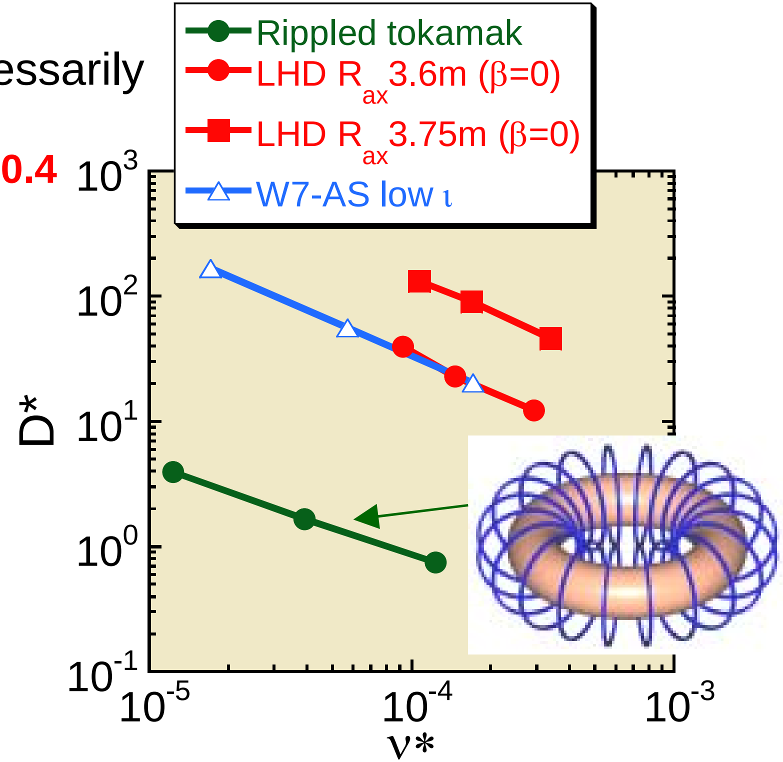
$$D \propto \varepsilon_{eff}^{1.5} \frac{v_d^2}{\nu}$$

There could be commonality with tokamaks.

Note: Most data show anomaly and do not necessarily lie in the 1/ν regime. **Nonetheless !,**

Upper envelope shows a trend like $\varepsilon_{eff}^{-0.4}$





ε_{eff} is related to anomalous transport ?

Indirect effect : viscous damping of flow

Neoclassical effect : high energetic particles

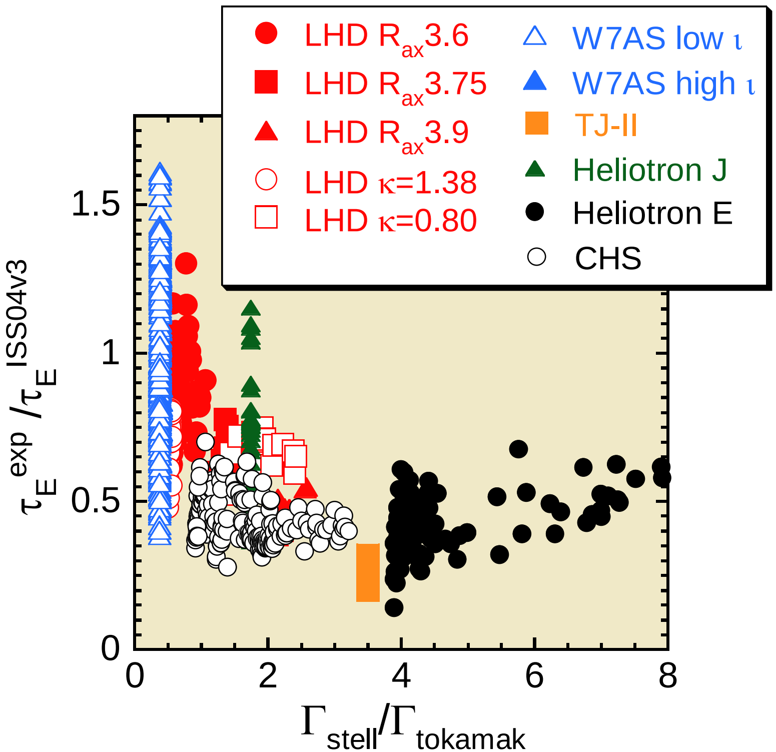
ion heat flux

What reflects normalization factors ? 2. Plateau factor

Plateau regime: neoclassical ion diffusivity driven by parallel viscosity yields

Lackner-Gottardi scaling : $\tau_E^{L-G} = 0.063 a^2 R P^{-0.6} \overline{n}_e^{0.6} B^{0.8} \iota_{2/3}^{0.4}$

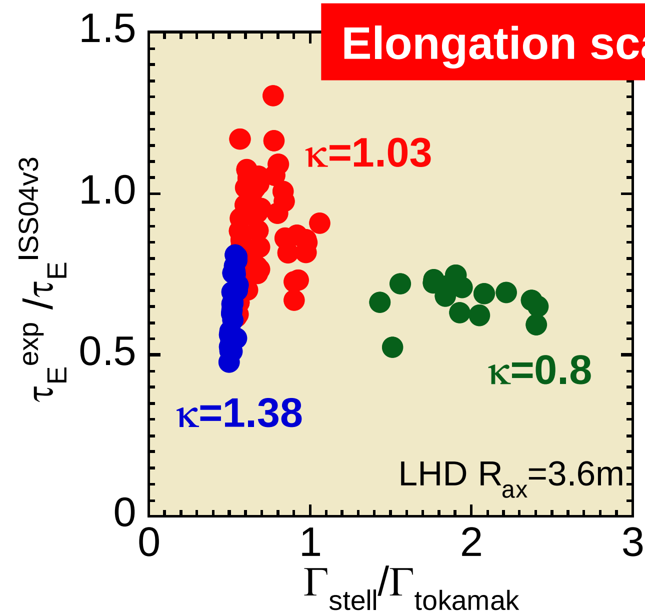
Again, this trial is **not** motivated by observation of neoclassical transport.

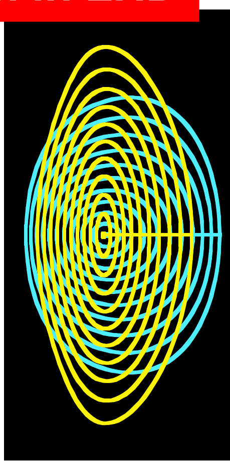


$$\Gamma_{stell} = \sum_i \frac{\varepsilon_i^2 (\iota l_i^2 - \iota \gamma l_i m_i)}{|m - \iota l|}, \quad \Gamma_{tok} = \varepsilon_t^2$$

Key geometrical factor is closely related to elongation.

Elongation scan in LHD





Plateau factor is remarkably like ε_{eff}, but ε_{eff} is more likely to be the essential configuration factor.

Both factors are a measure of the difference between drift surfaces and flux surfaces.

Summary

http://iscdb.nifs.ac.jp/
http://www.ipp.mpg.de/ISS

1. International collaboration of Stellarator Confinement Data Base is progressing to resolve diversity of stellarators towards a unified scaling.
2. Dependences on heating power and density are found as a generic trend in sub-groups.
3. A unified scaling expression has been proposed, which is of gyro-Bohm type and has no definitive dependences on β an $\nu*$.
4. Configuration dependent difference is required for a unified expression.
5. Configuration dependent difference has been investigated and shows a correlation with the effective helical ripple. Reason has not been clarified yet. This suggests importance of particle drifts in determining confinement due to anomalous transport as well as neoclassical transport.

➔ Profile database activity is required to clarify uncertainties in global confinement, in particular, cause of the configuration dependent parameter.

Potential effects of helical ripple transport

Comparison of cases with R_{ax}=3.6m and 3.75m in LHD.

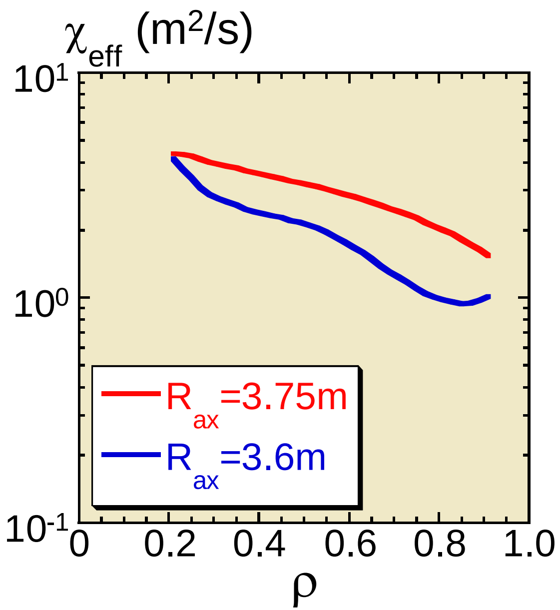
Almost equivalent T_e and n_e profiles.

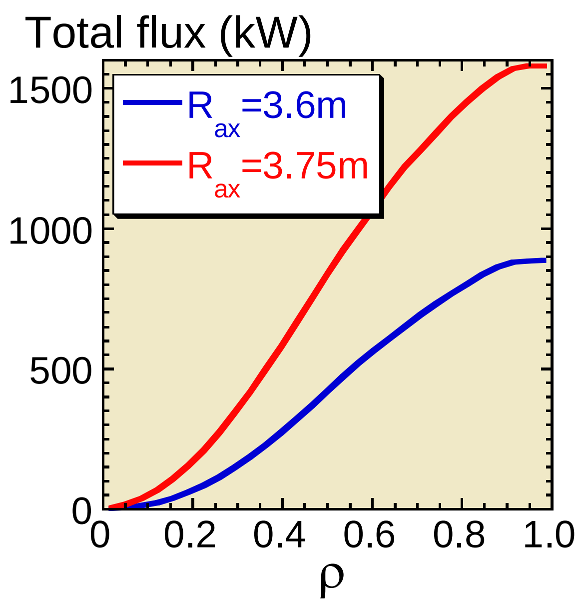
← 65% larger power for R_{ax}=3.75m

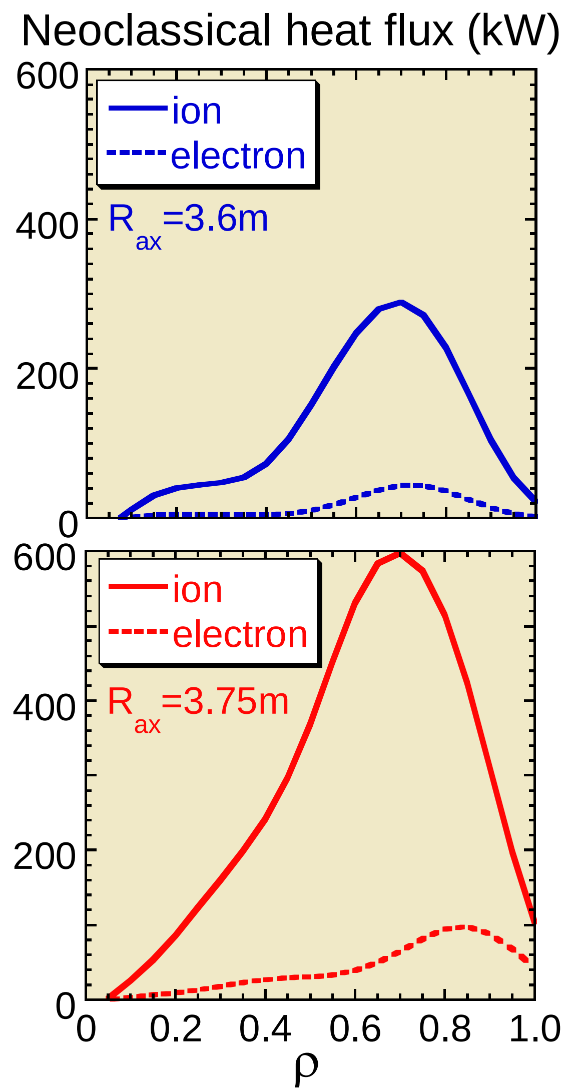
1. Loss of high energetic particle in the slowing down process is almost the same.

   11.0% in 3.6m ⇔ 10.4% in 3.75m

2. A large difference with a factor of 2 exists in neoclassical ion heat conduction loss.







Other mechanisms? flow damping, etc.