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

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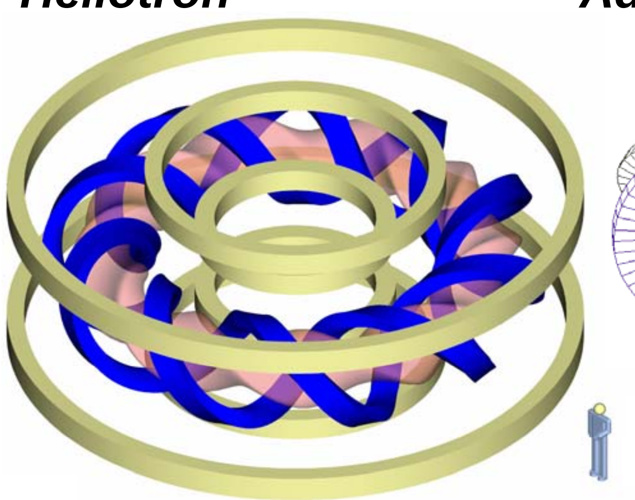
Under auspices of IEA Implementing Agreement for Cooperation in Development of the Stellarator Concept

Outline

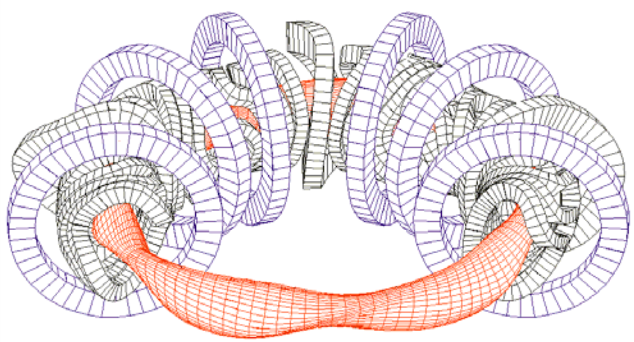
1. Motivation and background
2. Extended International Stellarator Confinement Database
3. Towards a unified scaling law of energy confinement time
4. Discussion about a configuration dependent parameter
5. Summary with future prospects

Stellarator : A wide spectrum of approaches

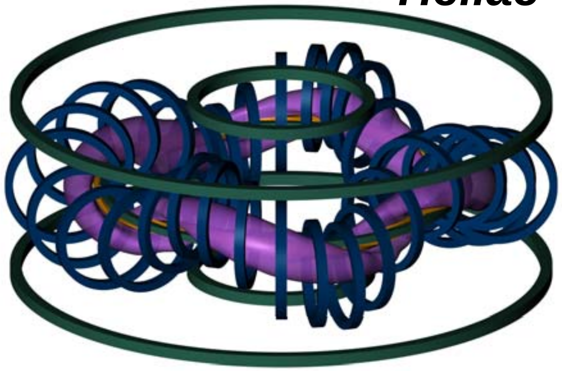
Heliotron



Advanced stellarator



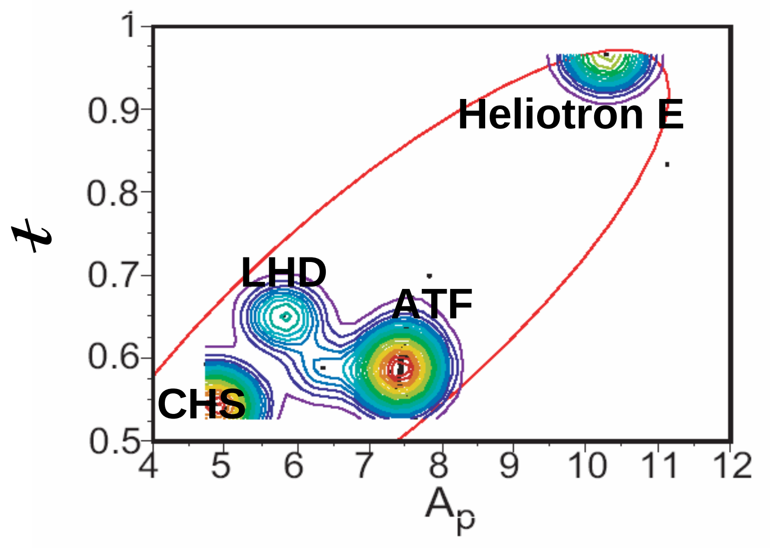
Heliac

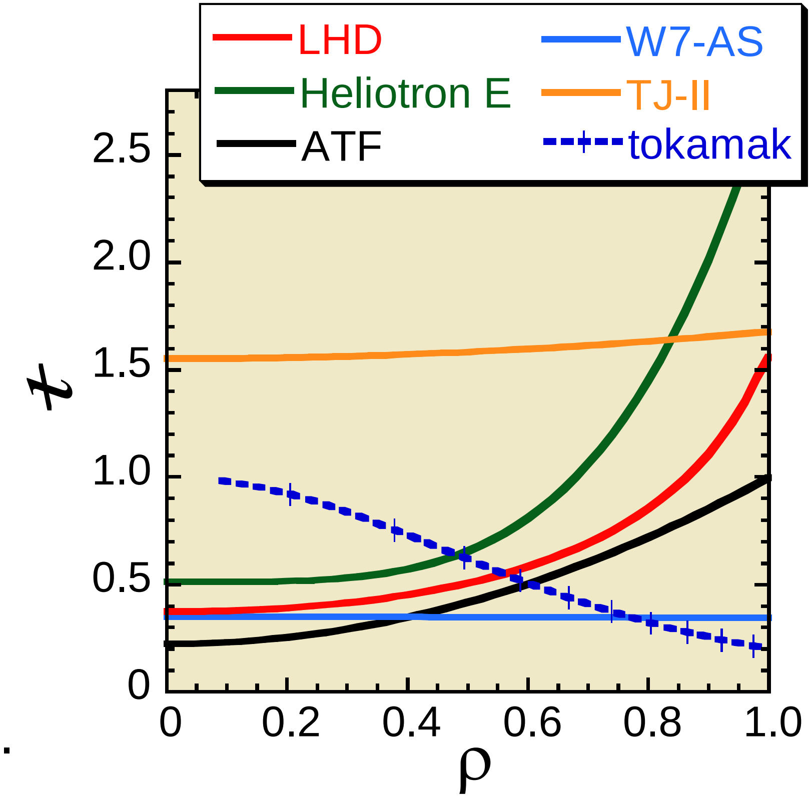


✓ Reactor assessment
✓ Physical understanding of underlying physics
➔ Effect of optimization principle on confinement

Need for inter-machine analysis

Collinearity in Heliotron line





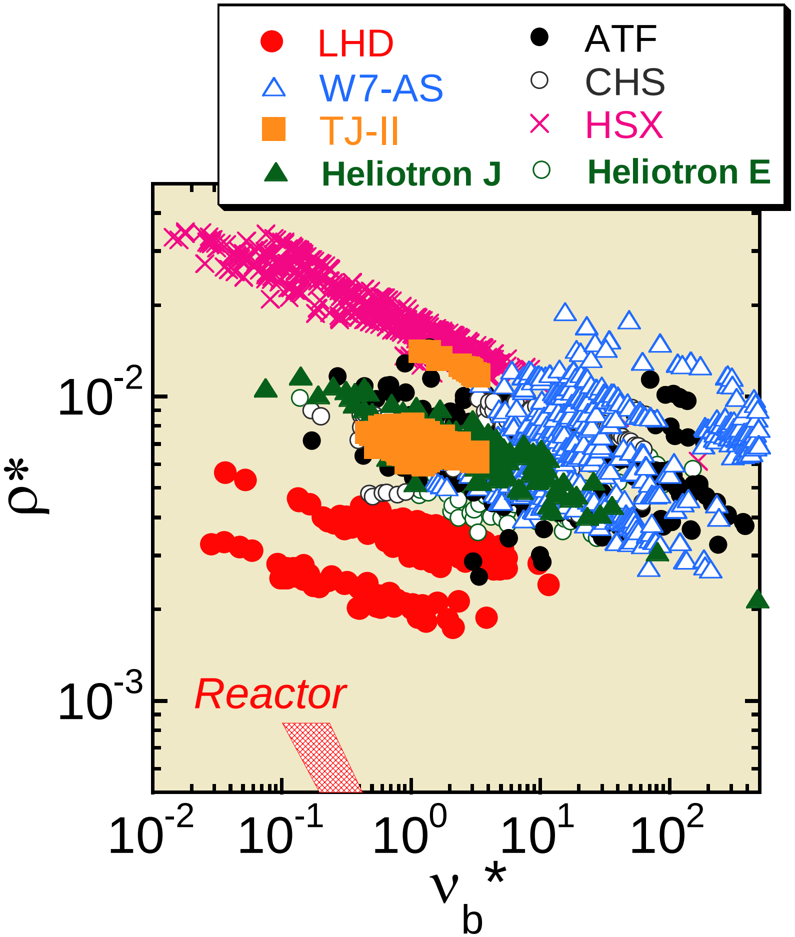
W7-AS and TJ-II can scan ι,
but cannot provide size dependence.

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

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

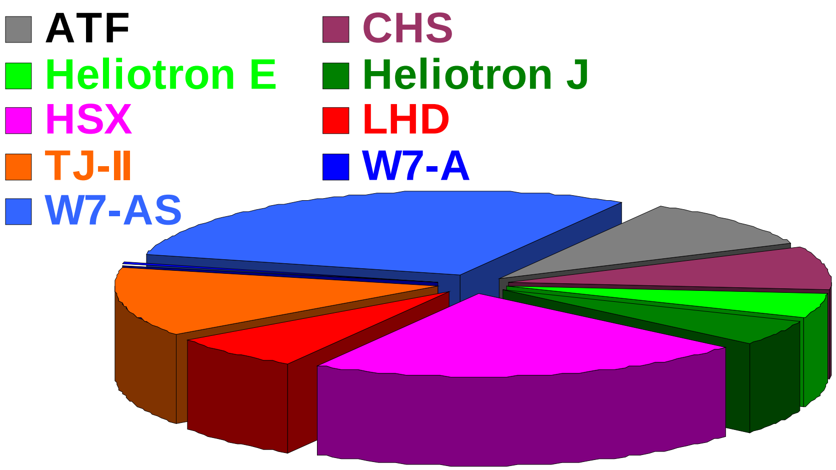
Weak gyro-Bohm, No significant dependence on β and ν*.

Extended International Stellarator Database



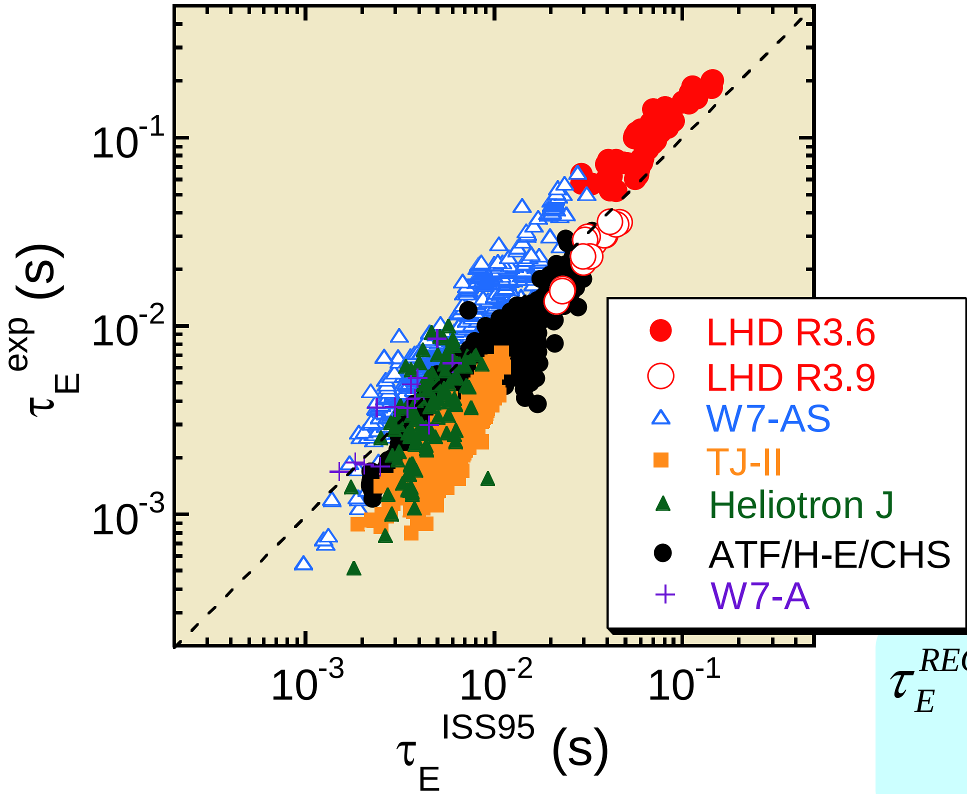
✓ New experiments
✓ New operational modes
➔ extending operational parameter range and property of magnetic configuration

✓ 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.

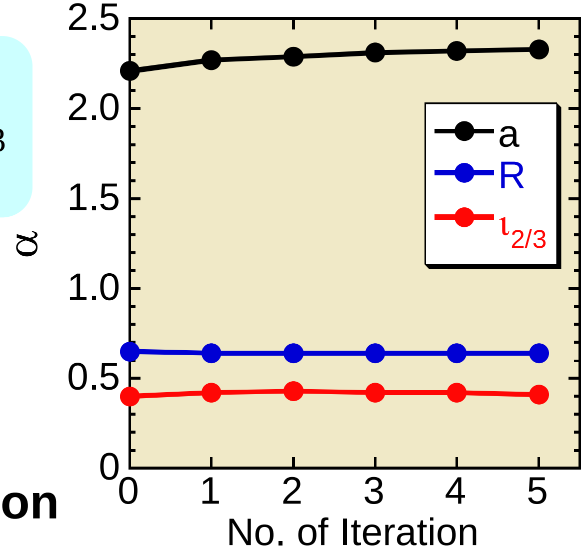
→ Averaged value of confinement enhancement factor in each sub-group is used as a configuration dependent parameter.

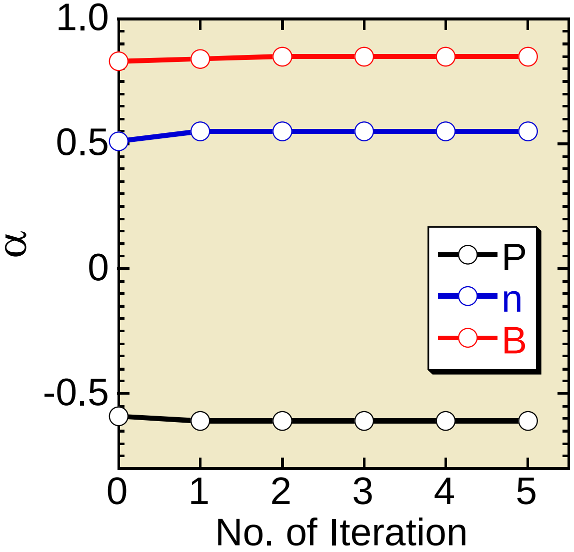
→ Iteration of regression analysis of normalized data

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

Each exponent on the operational parameter converges after 5 iterations.

→ **Unified scaling expression**

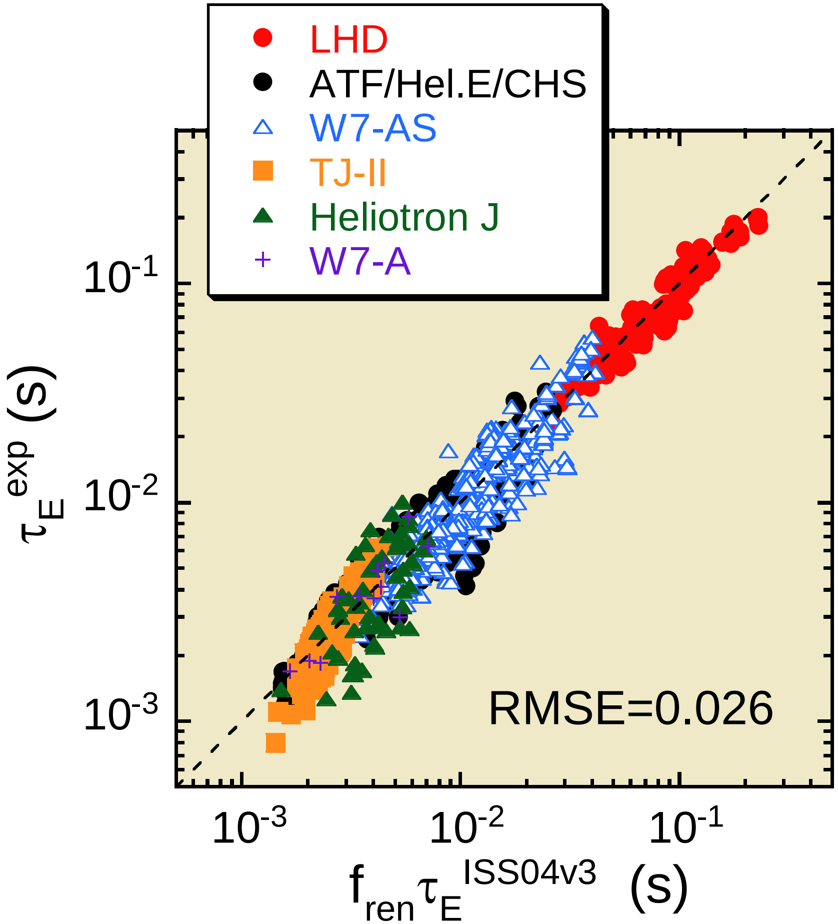




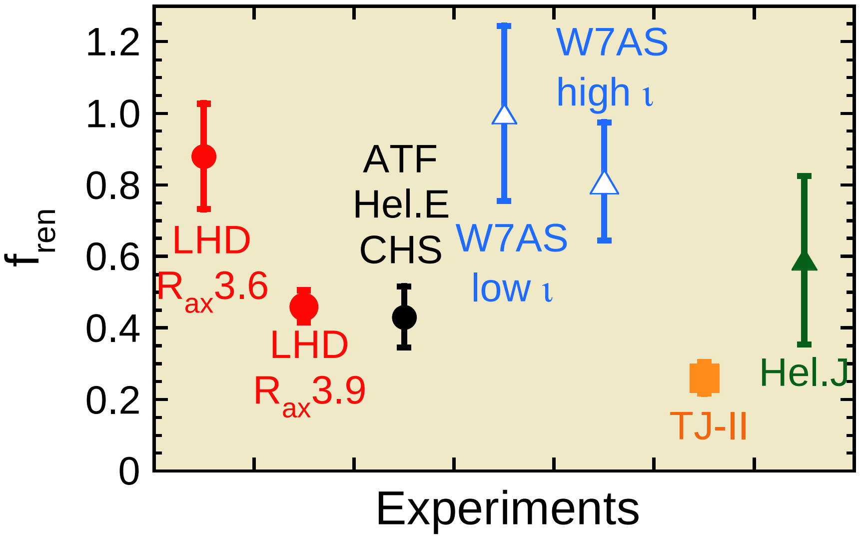
Configuration dependent factor is quantified simultaneously.

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

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



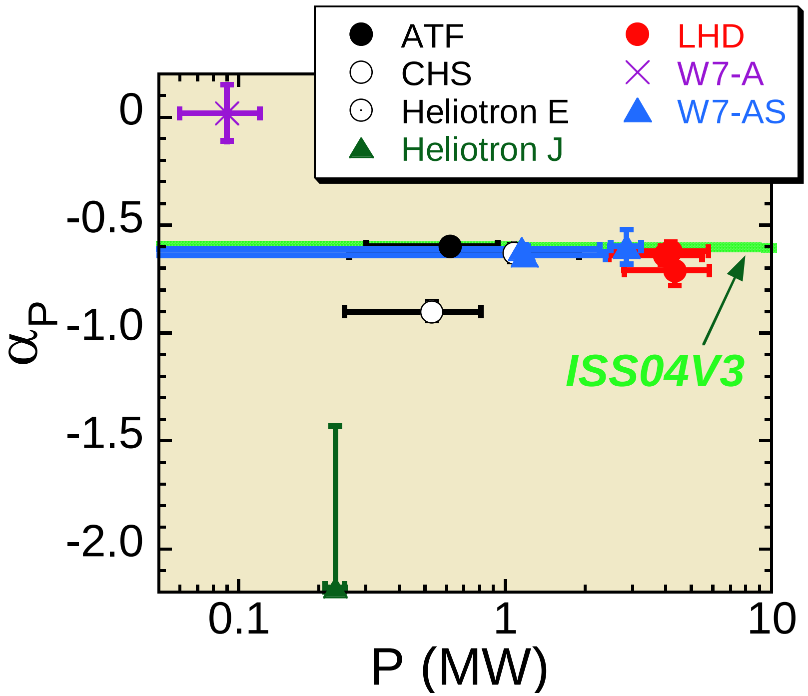
Configuration dependent parameter has been simultaneously obtained as a normalization factor.

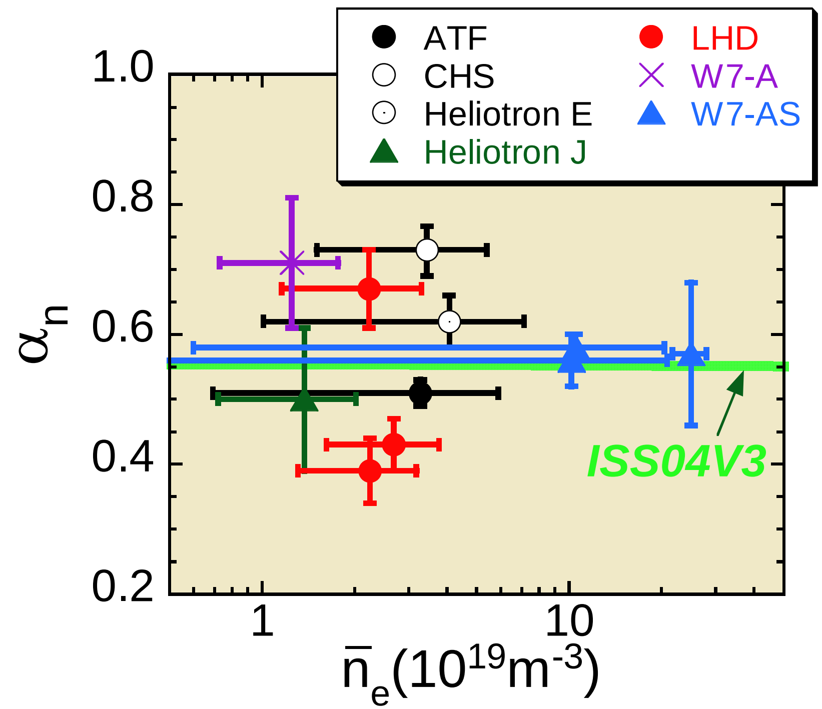


Confirmation of robustness of parameter dependence

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

Check an objective exponent with fixing other parameters at ISS04v3.



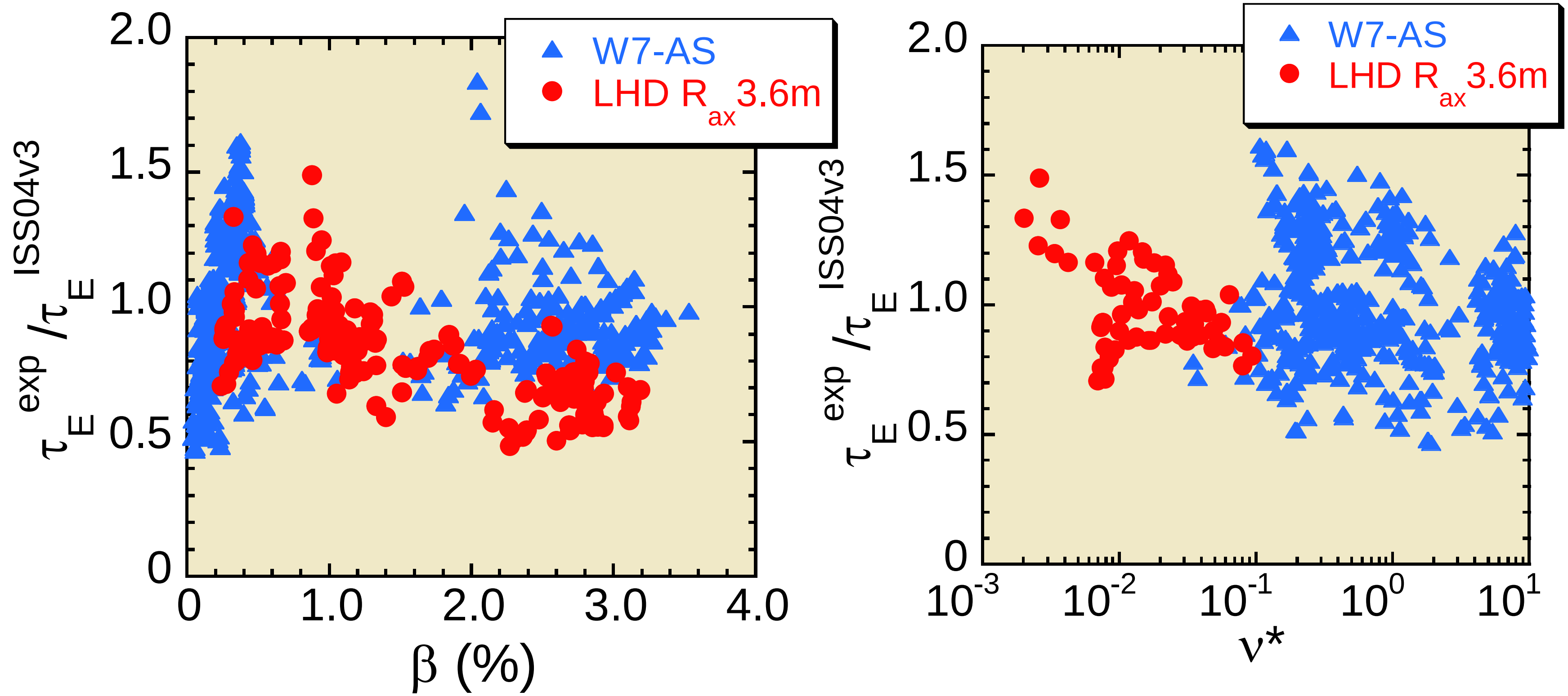


✓ Some deviation from the scaling, but it occurs at low parameter values.

➔ 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*.

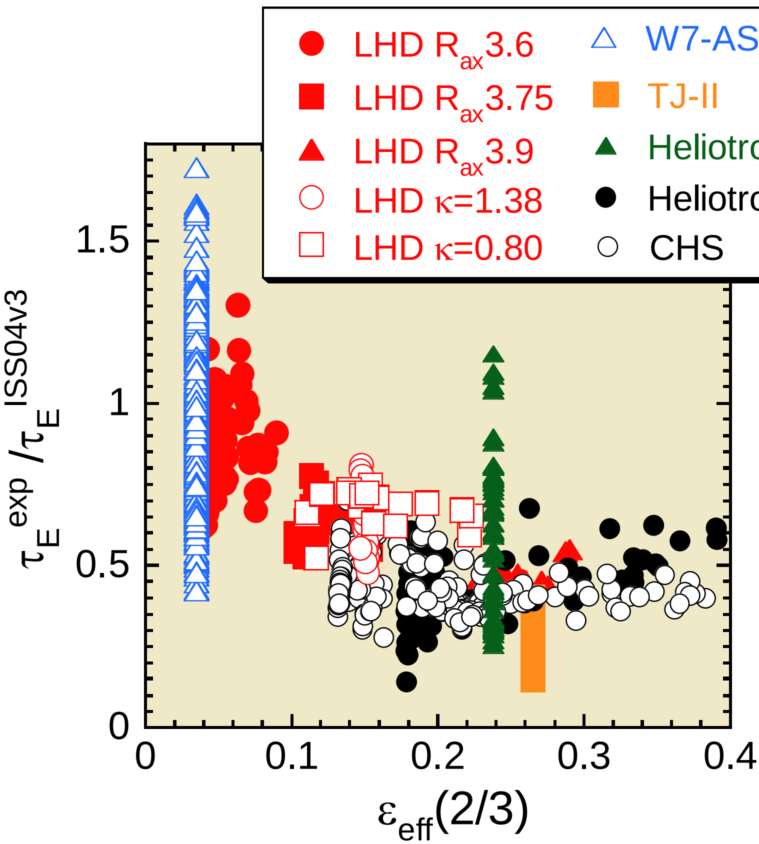
What reflects normalization factors ?
1. Effective helical ripple

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

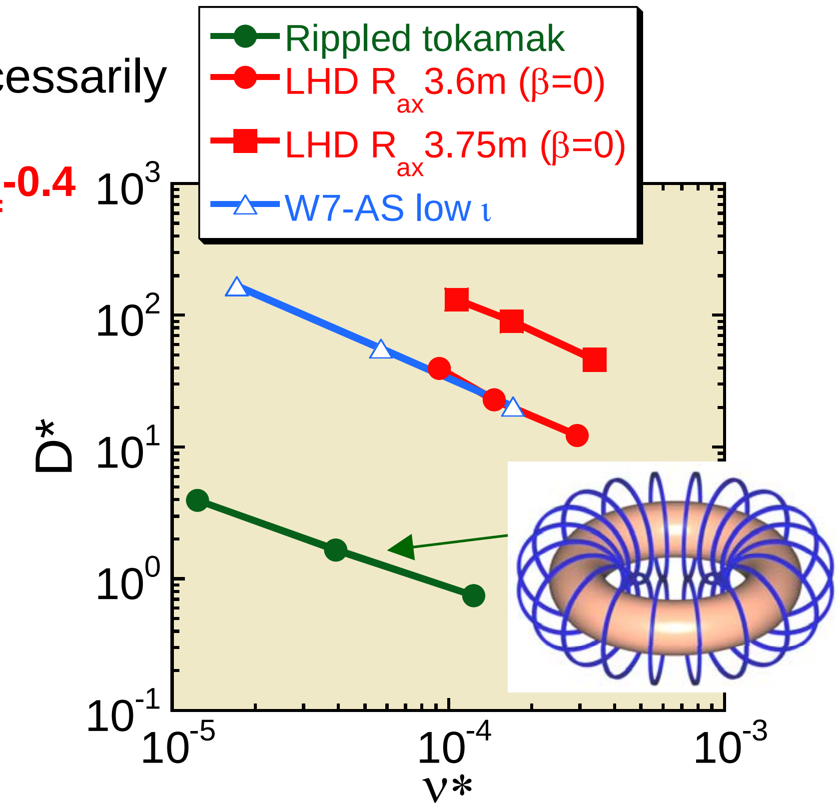
$$D \propto \varepsilon_{eff}^{1.5} \frac{v_d^2}{\nu}$$

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

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



There could be commonality with tokamaks.



ε_{eff} is related to anomalous transport ?

Indirect effect : viscous damping of flow

Neoclassical effect : high energetic particles
ion heat flux

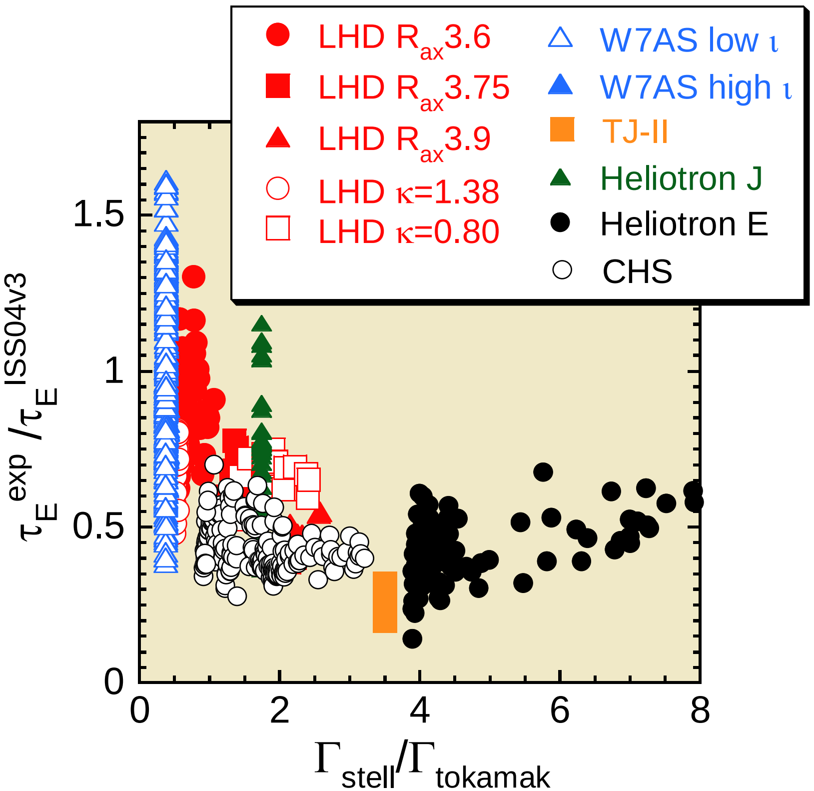
What reflects normalization factors ? 2. Plateau factor

Plateau regime: neoclassical ion diffusivity driven by parallel viscosity yields

Lackner-Gottardi scaling :

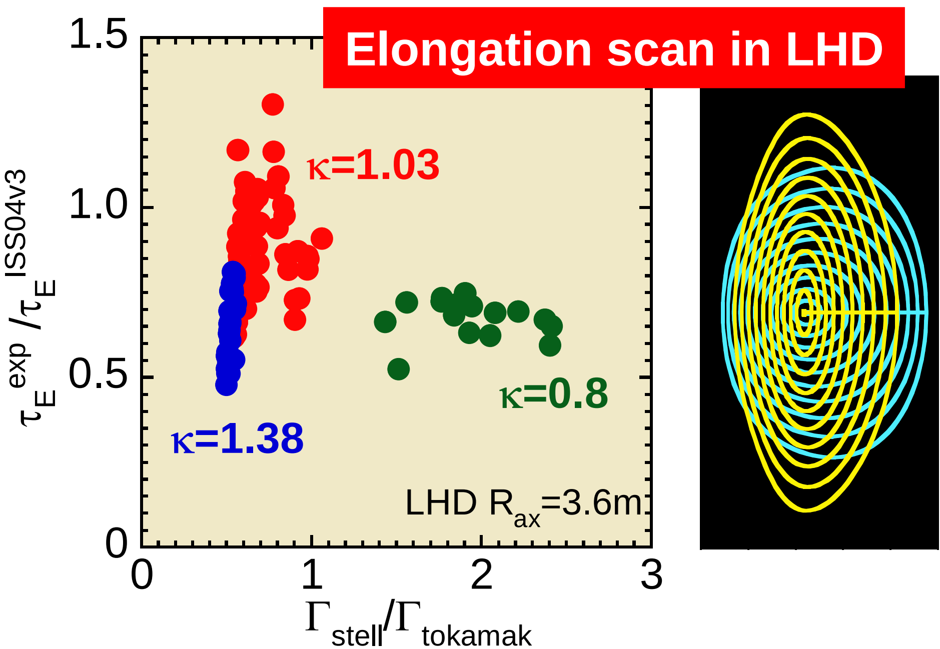
$$\tau_E^{L-G} = 0.063 a^2 R P^{-0.6} \bar{n}_e^{0.6} B^{0.8} \bar{\iota}_{2/3}^{0.4}$$

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



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

Key geometrical factor is closely related to elongation.



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

Under auspices of
IEA Implementing Agreement for Cooperation in Development of the Stellarator Concept (2.10.1992)
Jointly hosted by the National Institute for Fusion Science
and the Max-Planck-Institut für Plasmaphysik, EURATOM Association

- International Stellarator Scaling (ISS) Collaborators
  LHD, W7-AS, TJ-II, CHS, Heliotron J, HSX, and H-1
- Working Files
- Reports
- Publications&Talks
- Fusion Device Database

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.

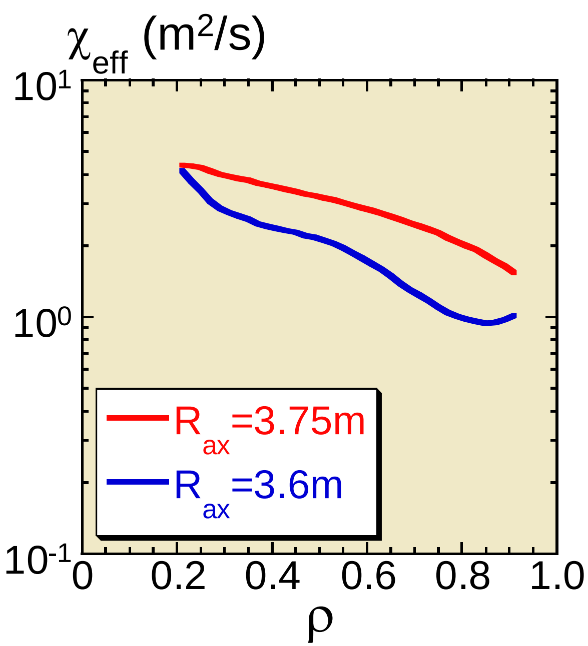
Almost equivalent T_e and n_e profiles.

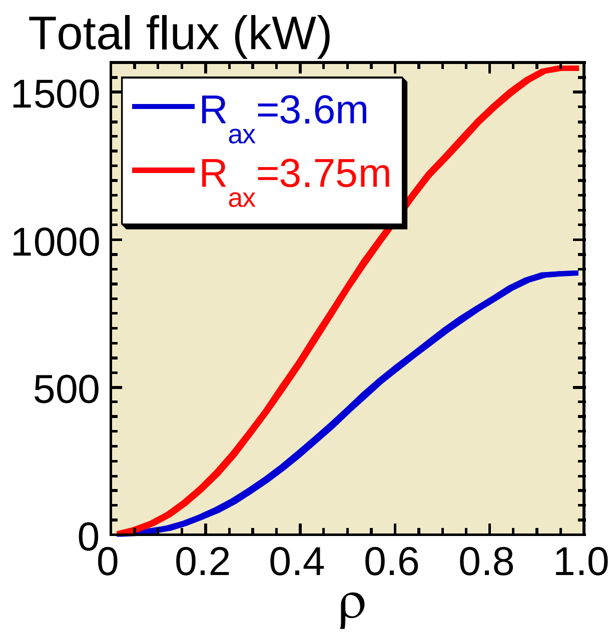
🡐 65% larger power for R_{ax}=3.75m

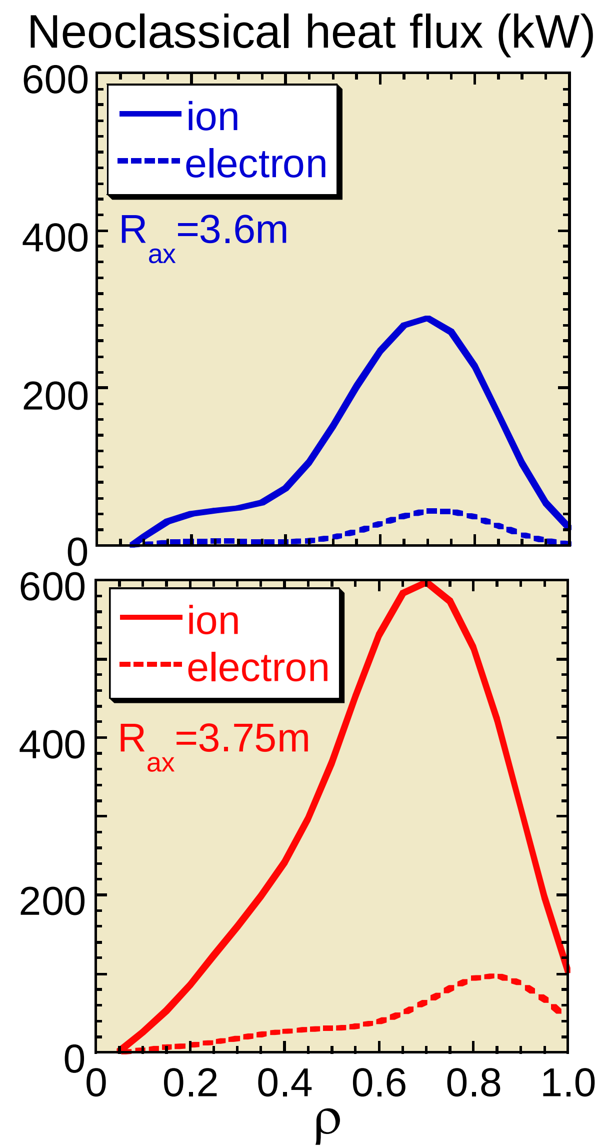
1. Loss of high energetic particle in the slowing down process is almost the same.

   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.