Comparative confinement studies in large stellarators

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Defense of the Master thesis

University of Greifswald

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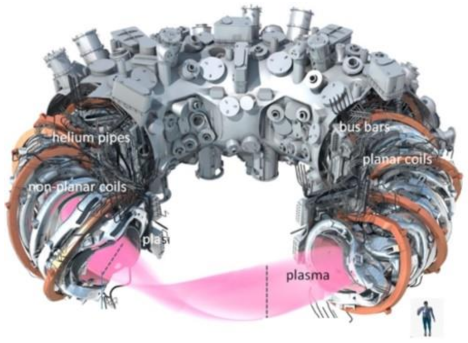
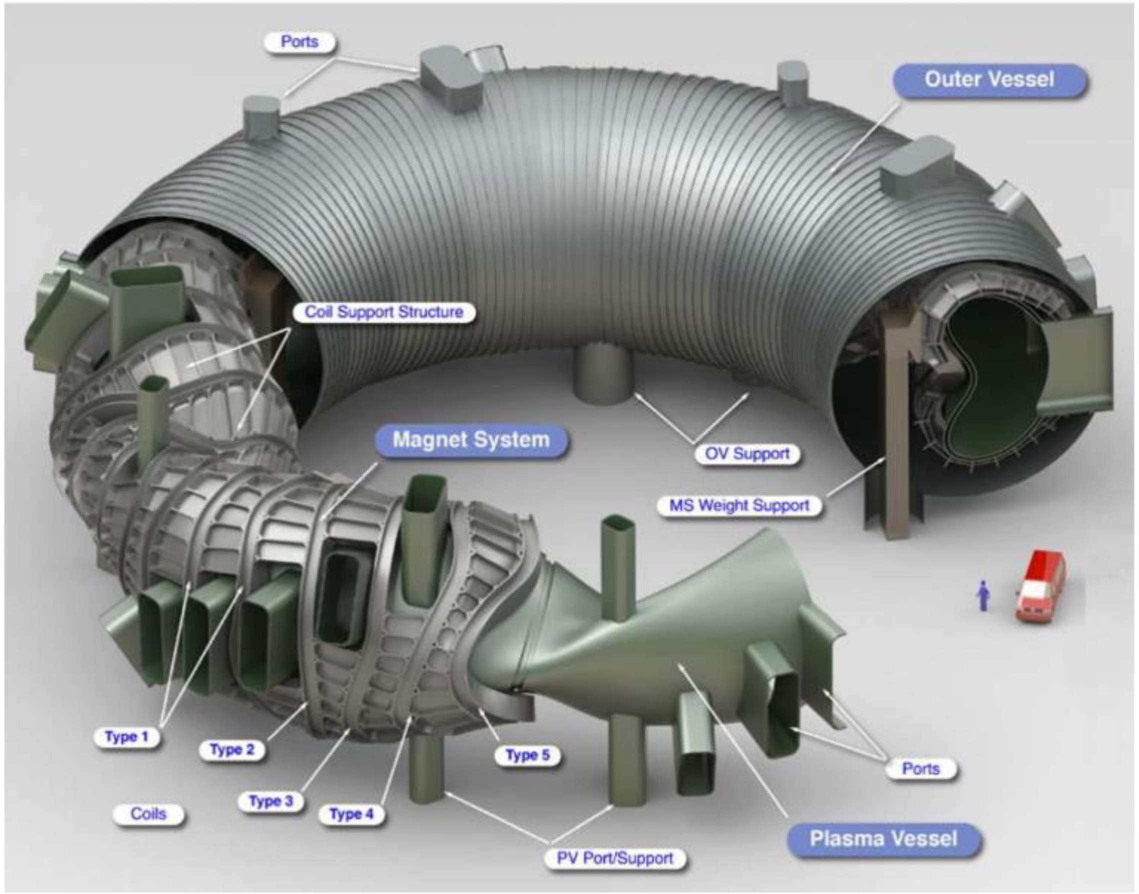
What can be learned from existing devices for future devices?



T. Klinger *et al* 2017 *Plasma Phys. Control. Fusion* **59** 014018

Extrapolating from today‘s fusion device to reactor size:



“HELIAS 5-B magnet system structure and maintenance concept“, F. Schauer et al, Fus. Eng. Des. 88 (2013)

How to extrapolate from smaller to bigger scales

Wind Tunnel Test on Model Cessna - Laboratory Report, T.J. Sheng, 2018

Scaling from model to full-sized plane →

https://commons.wikimedia.org/wiki/File:Cessna_172_%28D-EGUP%29_03.jpg

Reynolds number: $R_e = \frac{\rho v d}{\mu}$

medium density:	ρ
velocity:	v
characteristic length:	d
dynamic viscosity:	μ

Principle of similarity:
Two geometric similar bodies with equal R_e possess equal flow physics.

How to extrapolate from smaller to bigger scales

Model size ten times smaller

$$R_e = \frac{\rho v d}{\mu}$$

		full-sized plane	velocity scaling	medium: water
airfoil length	d (m)	1.6	0.16	0.16
velocity	$v \left(\frac{m}{s}\right)$	60	600	28
medium density	$\rho \left(\frac{kg}{m^3}\right)$	0.82	0.82	997.8
dynamic viscosity	μ (10^{-5} Pa s)	1.66	1.66	0.95
Reynolds number R_e		4 700 000	4 700 000	4 700 000

Wind Tunnel Tests on a Model Cessna- Laboratory Report, T.J. Sheng. London: Department of Aeronautics, Imperial College London; 2018

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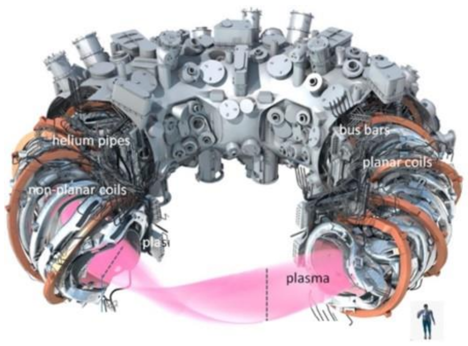

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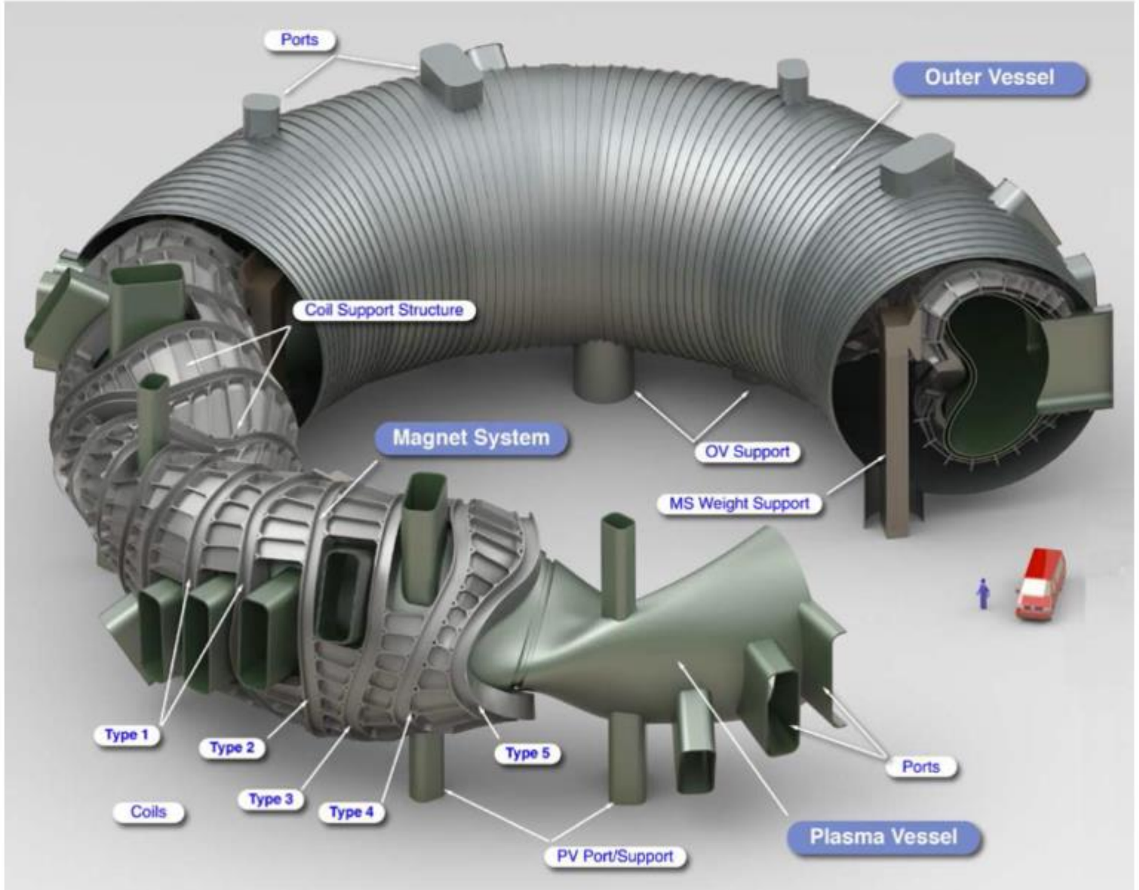

Scaling of the confinement with dimensionless parameters to extrapolate to larger machines

Extrapolating stellarators to ignition

Dimensionless parameters in fusion:

plasma beta $$\beta = \frac{2\mu_0 nT}{B^2}$$ → Set by economical targets and physical limits

normalised collisionality $$\nu^* = \frac{R}{\iota}\frac{\nu_{ei}}{\mathrm{v}_{th}} \propto \frac{n}{T^2}$$

normalised gyroradius $$\rho^* = \frac{\sqrt{m_i T}}{aBZe}$$

plasma density:	n
plasma temperature:	T
magnetic field:	B

Extrapolating stellarators to ignition

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normalised gyroradius	$\rho^* = \frac{\sqrt{m_i T}}{aBZe}$		

plasma density: n
plasma temperature: T
magnetic field: B
major plasma radius: R
electron-ion collision frequency: ν_{ei}
thermal velocity: v_{th}

Extrapolating stellarators to ignition

Dimensionless parameters in fusion:

plasma beta $\beta = \frac{2\mu_0 n T}{B^2}$ → Set by economical targets and physical limits

normalised collisionality $\nu^* = \frac{R}{\iota}\frac{\nu_{ei}}{v_{th}} \propto \frac{n}{T^2}$ → Set by limits in density and temperature

normalised gyroradius $\rho^* = \frac{\sqrt{m_i T}}{aBZe}$ → Dependency on ρ^* gives insight on turbulence

$$\Omega_i \tau_E \propto \rho^{*\alpha_\rho} F(\beta, \nu^*, \dots)$$

$\alpha_\rho = 1$ → gyro-Bohm scaling
$\alpha_\rho = 0$ → Bohm scaling
$\alpha_\rho = -1$ → $\lambda \gg a$

plasma temperature:	T
magnetic field:	B
ion mass:	m_i
ion charge:	Z
minor plasma radius:	a
electron charge:	e

Confinement

Global energy confinement time:

$$\tau_E = \frac{W_{dia}}{P_{heat} - \frac{dW_{dia}}{dt}}$$

Confinement

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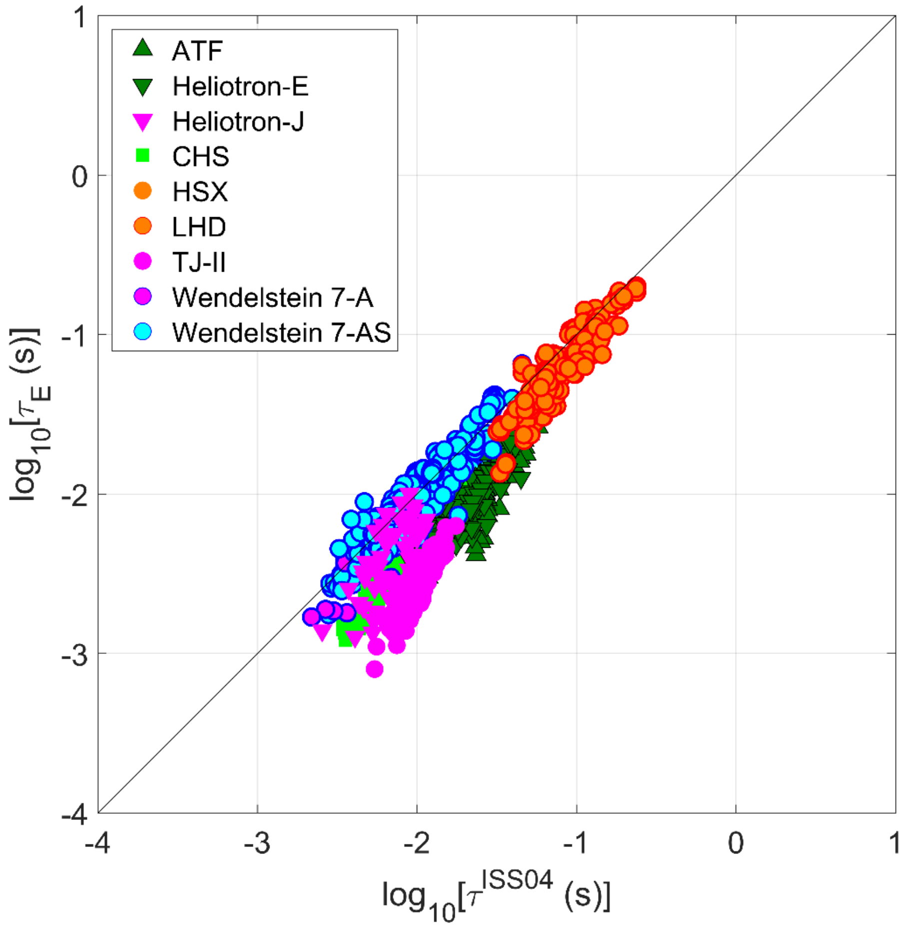
$$\tau_E = \frac{W_{dia}}{P_{heat} - \frac{dW_{dia}}{dt}}$$

Empirical scaling law ISS04: [1]

$$\tau^{\mathrm{ISS04}} = 0.134\ \mathrm{a}^{2.28}\mathrm{R}^{0.64}\mathrm{B}^{0.84}\iota_{\frac{2}{3}}^{0.41}P_{heat}^{-0.61}n_e^{0.54}$$



Recreated from *A. Dinklage et al 2007 Nucl. Fusion* ***47*** *1265*

[1] H. Yamada *et al* 2005 *Nucl. Fusion* **45** 1684

Confinement

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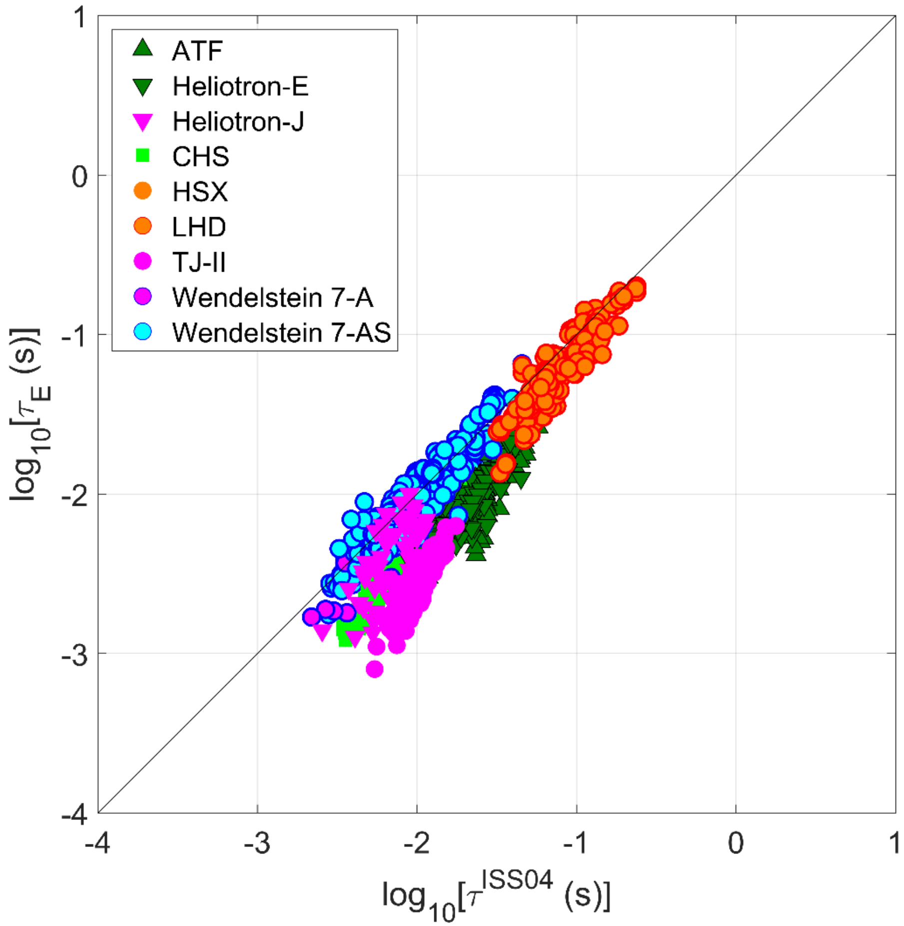
Renormalisation factor:

$$f_{ren} = \frac{\tau_E}{\tau_{scaling}}$$



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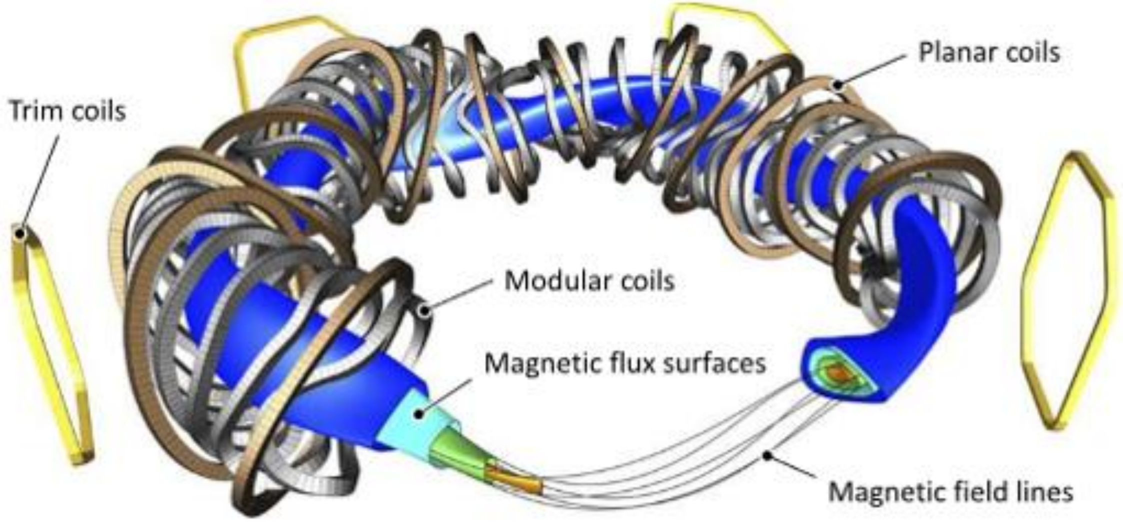
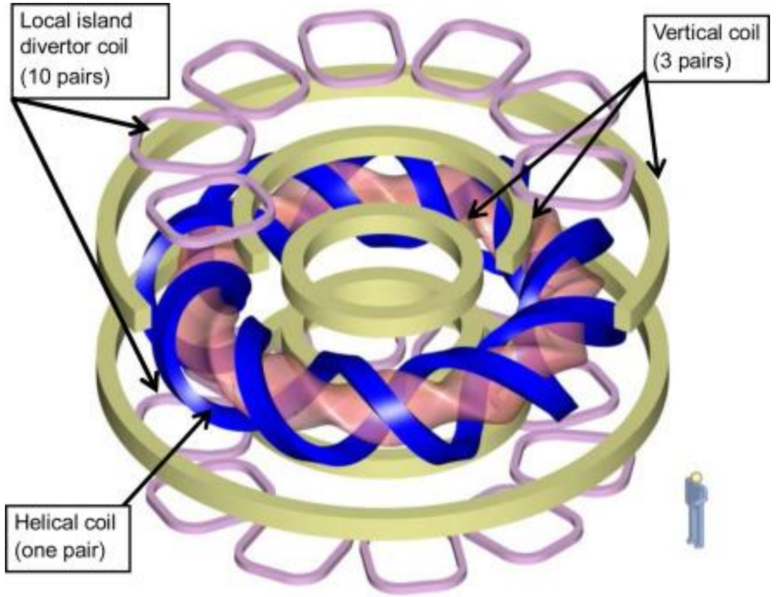
Machines

W7-X



R. C. Wolf, A. Alonso, S. Äkäslompolo, et al., "Performance of Wendelstein 7-X stellarator plasmas during the first divertor operation phase"

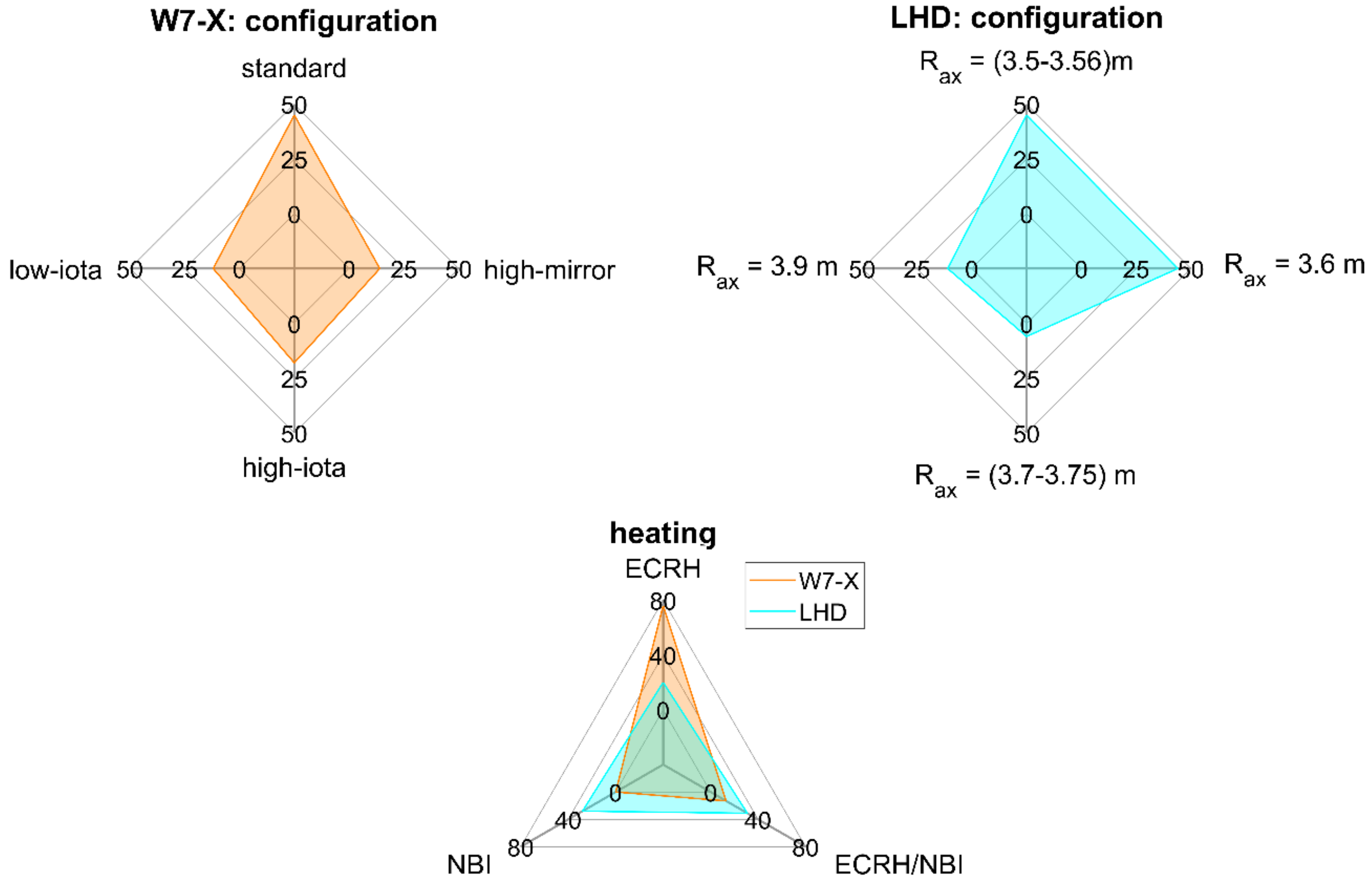
LHD



"Magnetic Fusion Energy From Experiments to Power Plants", George H. Neilson

	W7-X	LHD
major plasma radius R (m)	5.5	3.9
minor plasma radius a (m)	0.55	0.65
plasma volume V (m^3)	30	30
magnetic field B (T)	2.5	< 3

Dataset used

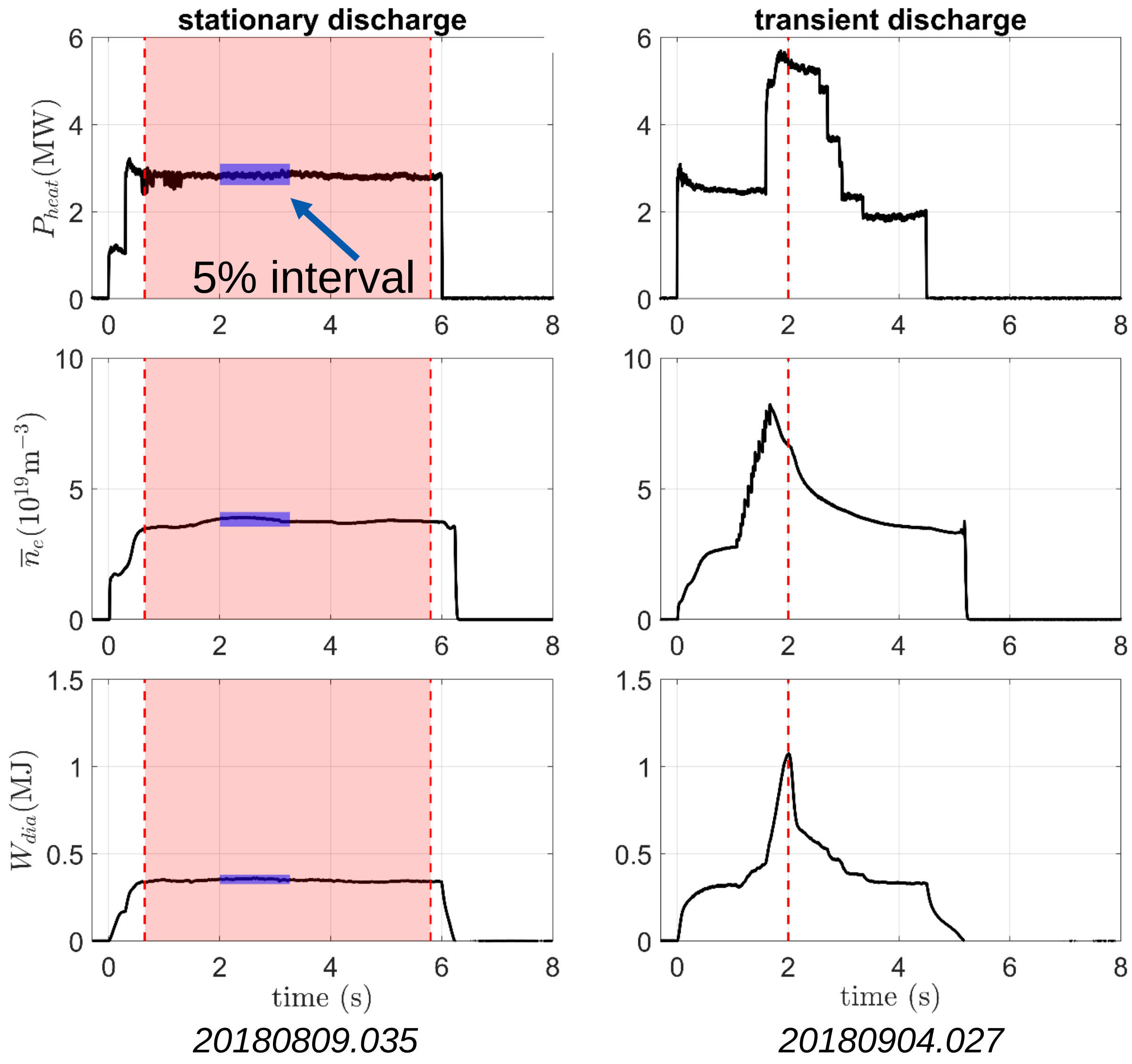


- **Across both machines:**
  168 discharges

- **W7-X dataset**:
  89 discharges from OP1.2b (2018)

- **LHD dataset**:
  79 discharges from three different OP (2017-2022)

Calculation of τ_E and τ^{ISS04}



$$\tau_E = \frac{W_{dia}(t)}{P_{heat}(t) - \frac{dW_{dia}}{dt}}$$

$$\tau^{\mathrm{ISS04}} = 0.134\ \mathrm{a}^{2.28}\mathrm{R}^{0.64}\mathrm{B}^{0.84}\iota_{\frac{2}{3}}^{0.41} P_{heat}(t)^{-0.61} n_e(t)^{0.54}$$

“Stationary“ discharges:

Employing average values of P_{heat}, n_e and W_{dia} during the stationary phase (red shaded region)

“Transient“ discharges:

Employing values of P_{heat}, n_e and W_{dia} at instance when W_{dia} is maximal (red dashed line)

Calculation of the renormalisation factor for temporal analysis

$$\tau_E = \frac{W_{dia}}{P_{heat} - \frac{dW_{dia}}{dt}} \quad \& \quad \tau^{\mathrm{ISS04}} = 0.134\ \mathrm{a}^{2.28}\mathrm{R}^{0.64}\mathrm{B}^{0.84}\iota_{\frac{2}{3}}^{0.41}P_{heat}^{-0.61}n_e^{0.54}$$

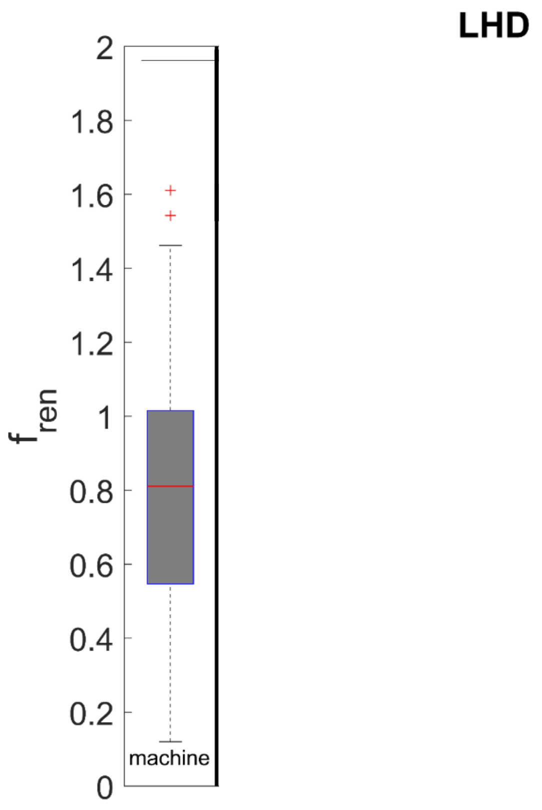
$$\frac{dW^{ISS04}(t)}{dt} + \frac{W^{ISS04}(t)}{\tau^{ISS04}(t)} = P_{heat}(t)$$

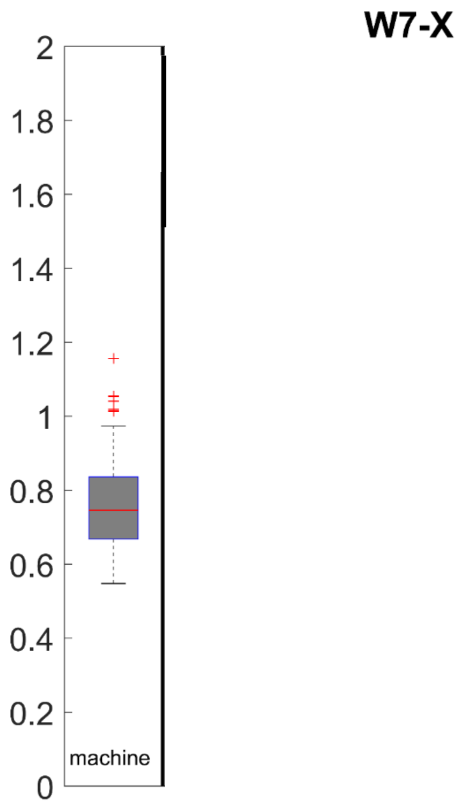
Using integrating factors:

$$I(t) = \exp\left(\int_{t0}^{t} \frac{dt'}{\tau^{\mathrm{ISS04}}(t')}\right)$$

$$W^{ISS04}(t') = \frac{\int_{t0}^{t} dt'\, I(t') P_{heat}(t')}{I(t')}$$

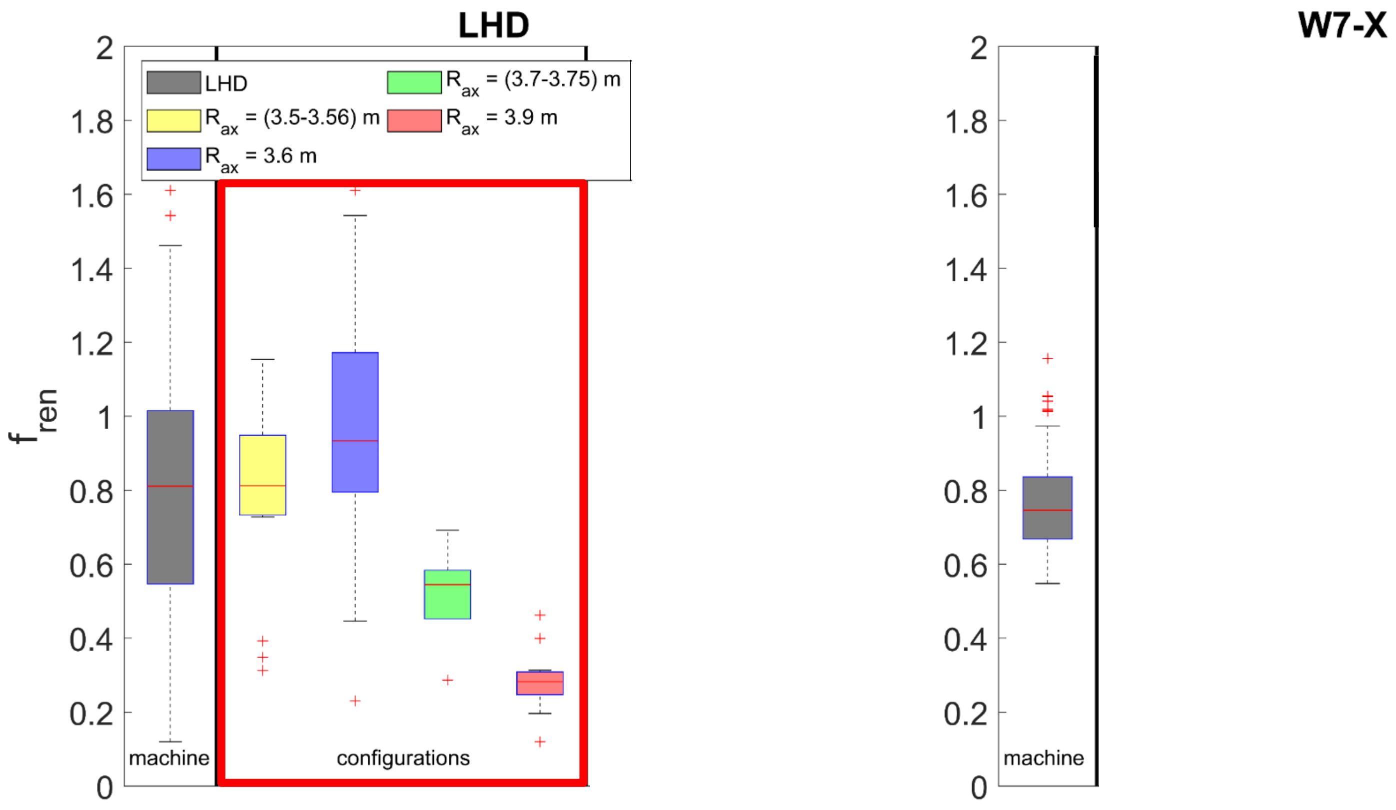
Existence of dependencies in τ_E





LHD and W7-X datasets show similar confinement quality

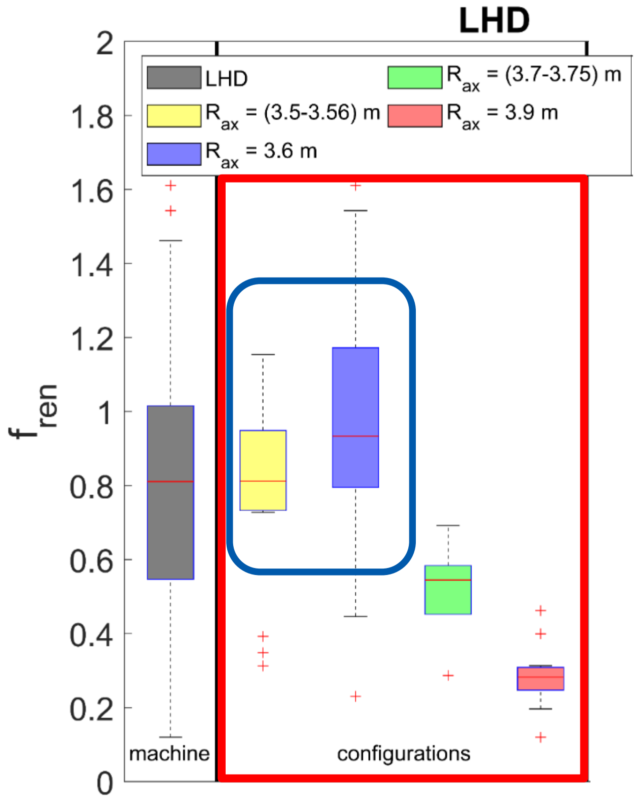
Existence of dependencies in τ_E

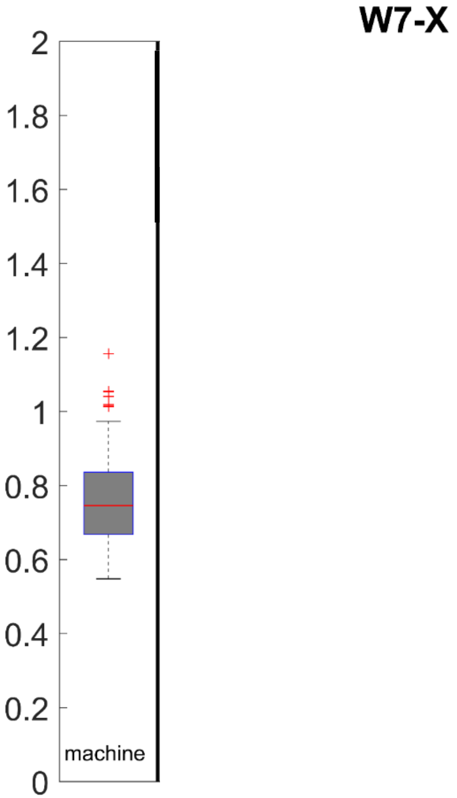


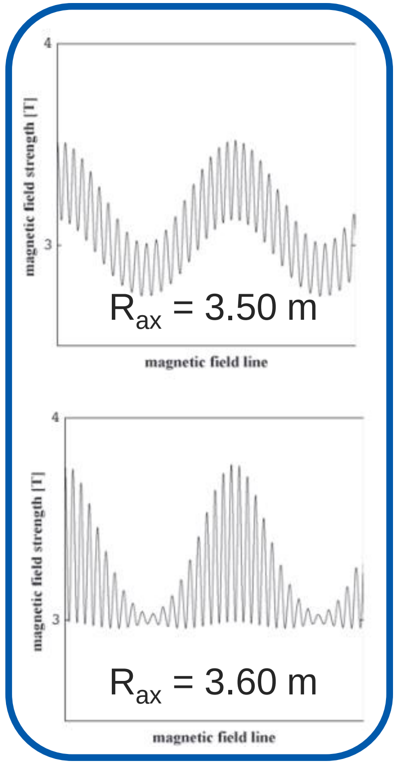
Dependency of the confinement on magnetic configuration in LHD dataset: optimal at R_{ax} = 3.60 m [1]

[1] S. Murakami *et al* 2002, *Nucl. Fusion* **42** L19

Existence of dependencies in τ_E



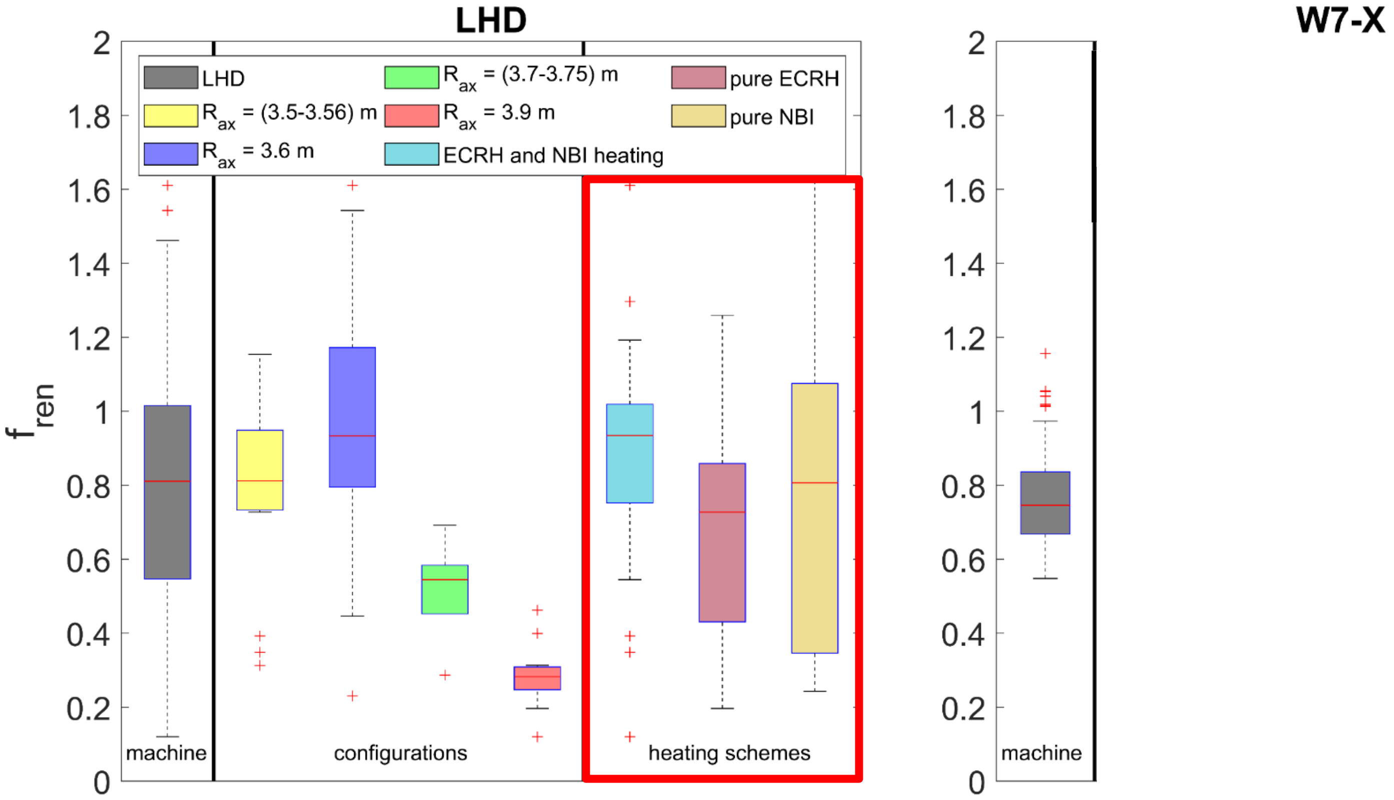




Dependency of the confinement on magnetic configuration in LHD dataset: optimal at R_{ax} = 3.60 m [1] due to improved neoclassical confinement

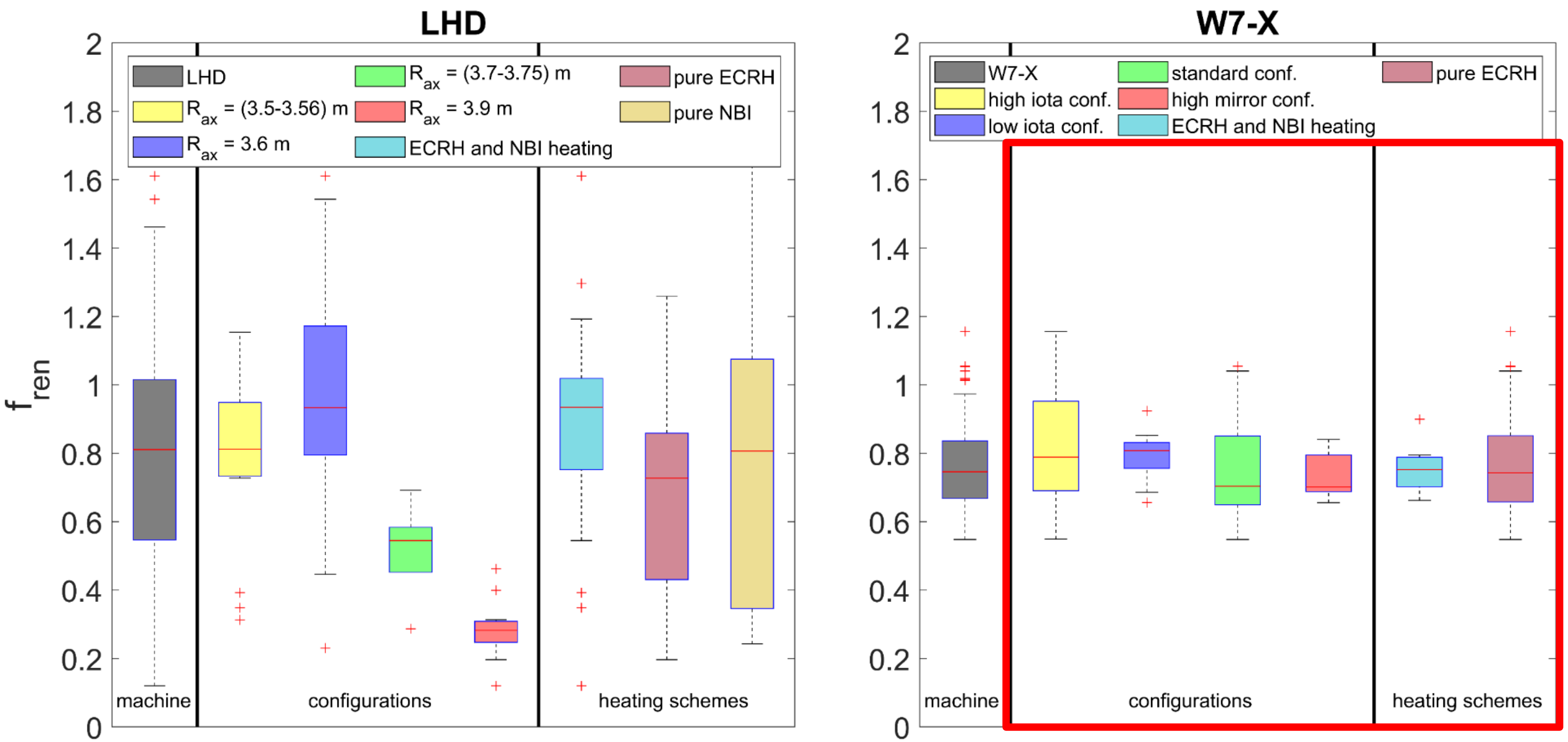
[1] S. Murakami *et al* 2002, *Nucl. Fusion* **42** L19

Existence of dependencies in τ_E



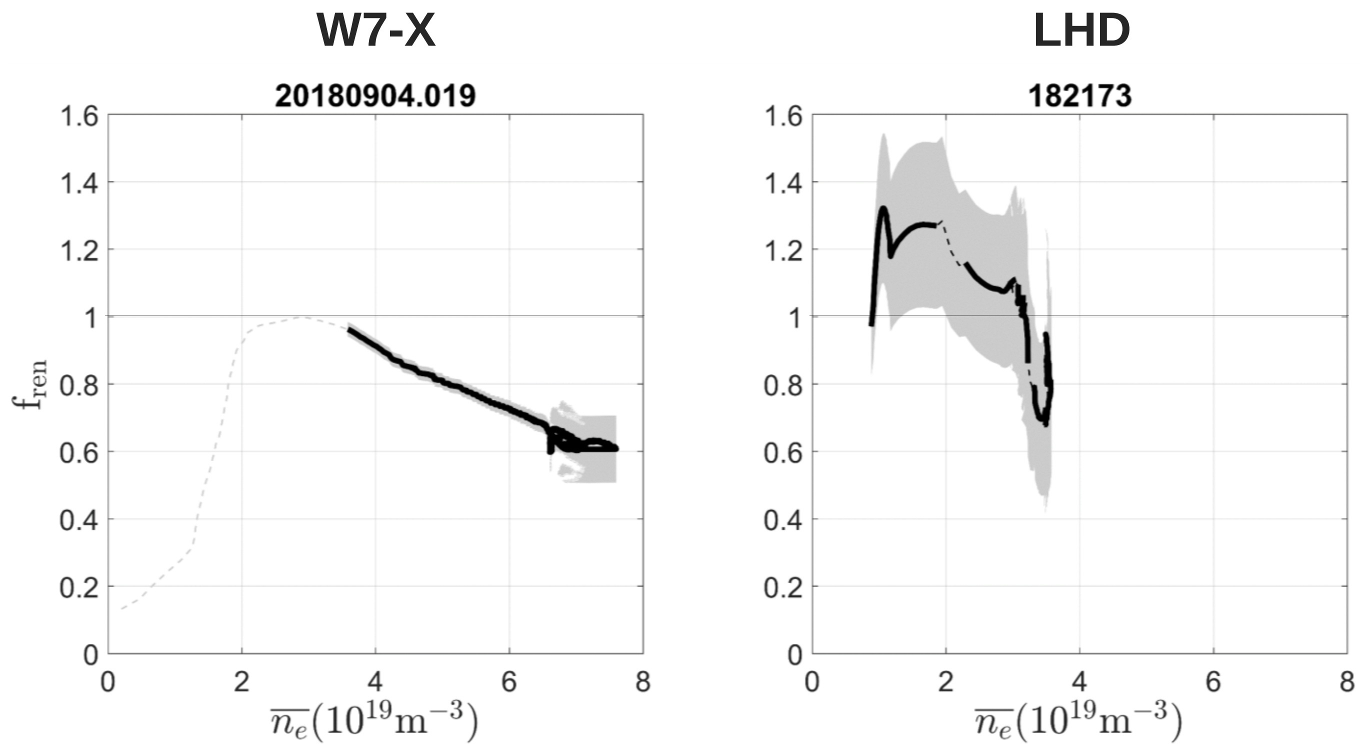
No dependency of the confinement on the heating method in LHD dataset

Existence of dependencies in τ_E



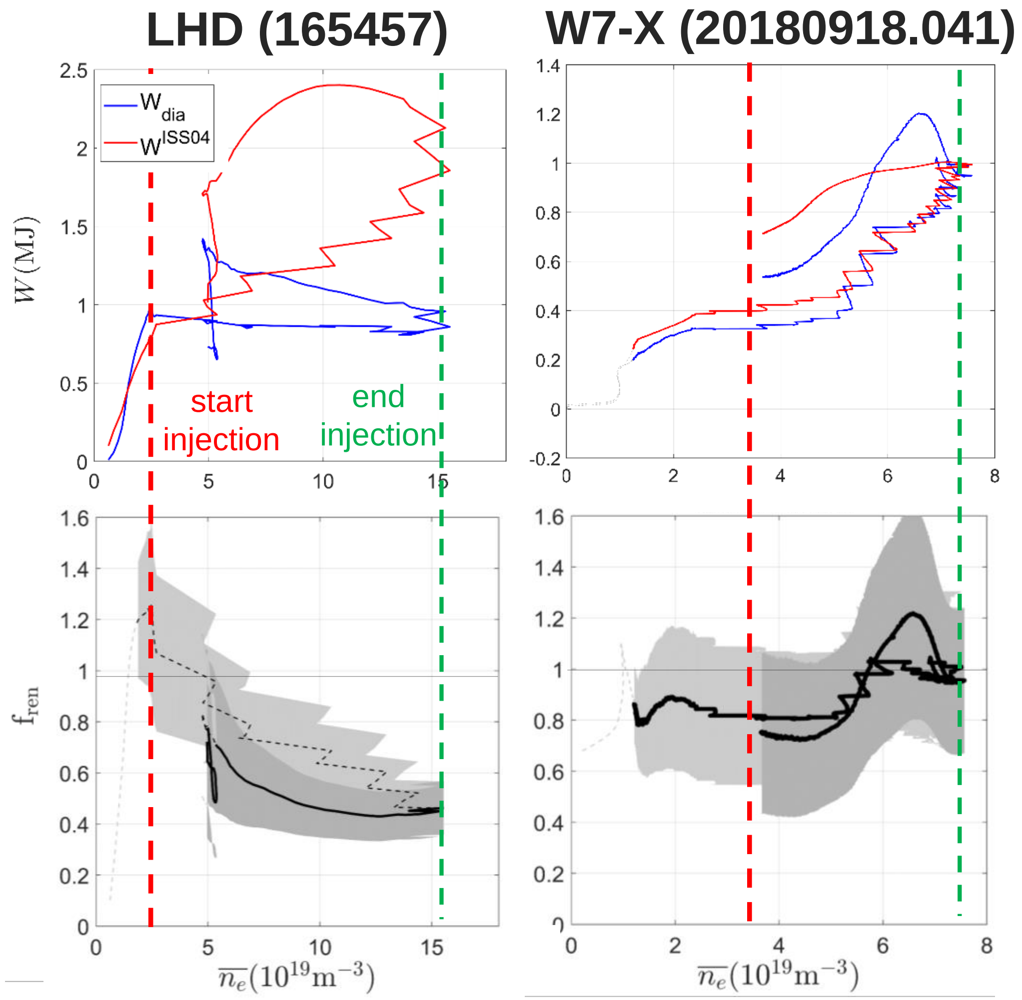
No dependency on magnetic configuration or heating method in W7-X dataset

Density dependency of confinement in typical ECR heated discharges



Linear decrease of f_{ren} for increasing density in purely ECR heated stationary discharges

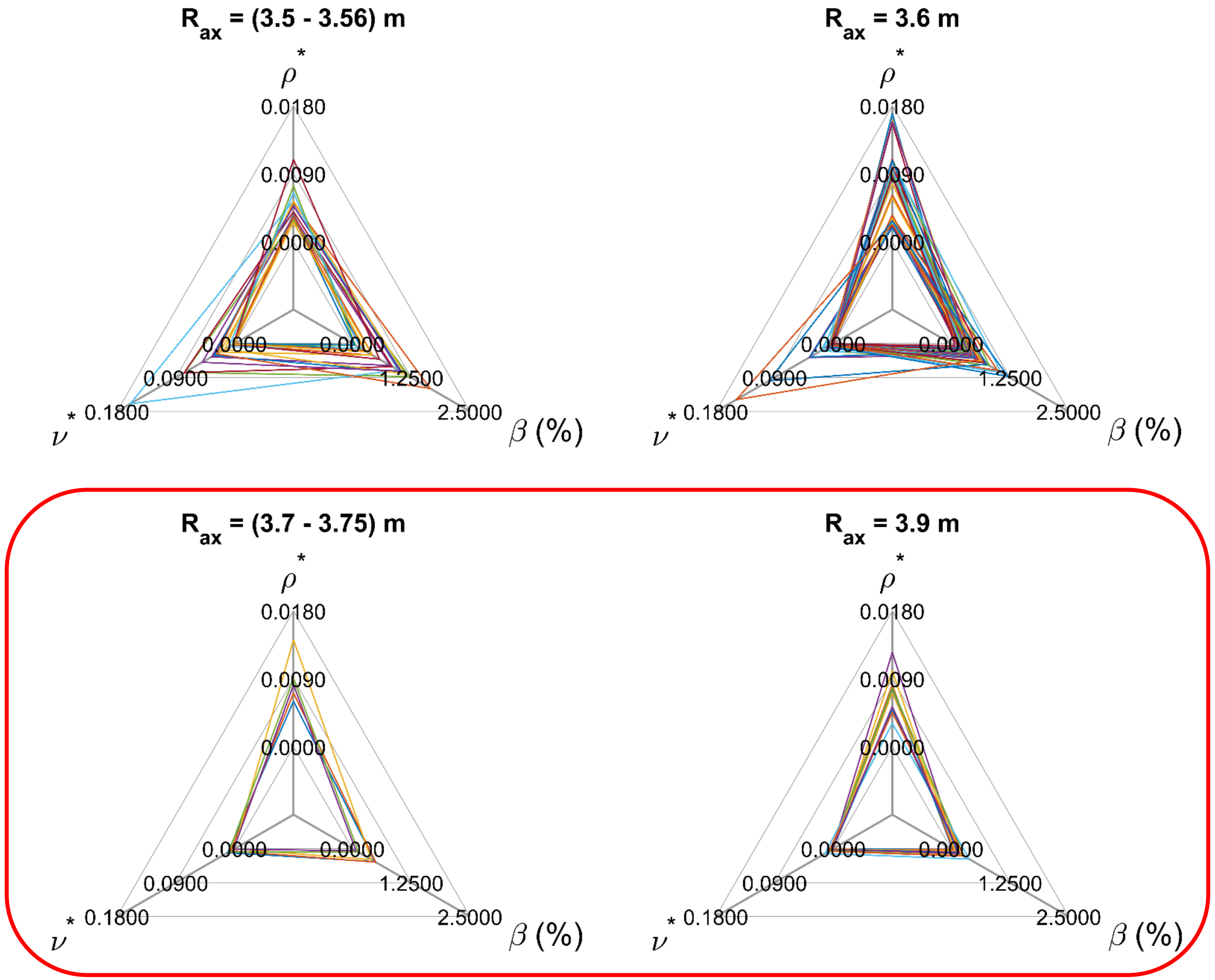
Machine dependency on confinement improvement by pellet-injection



Pellet injections lead to enhancement of plasma energy

Confinement improvement different for LHD and W7-X

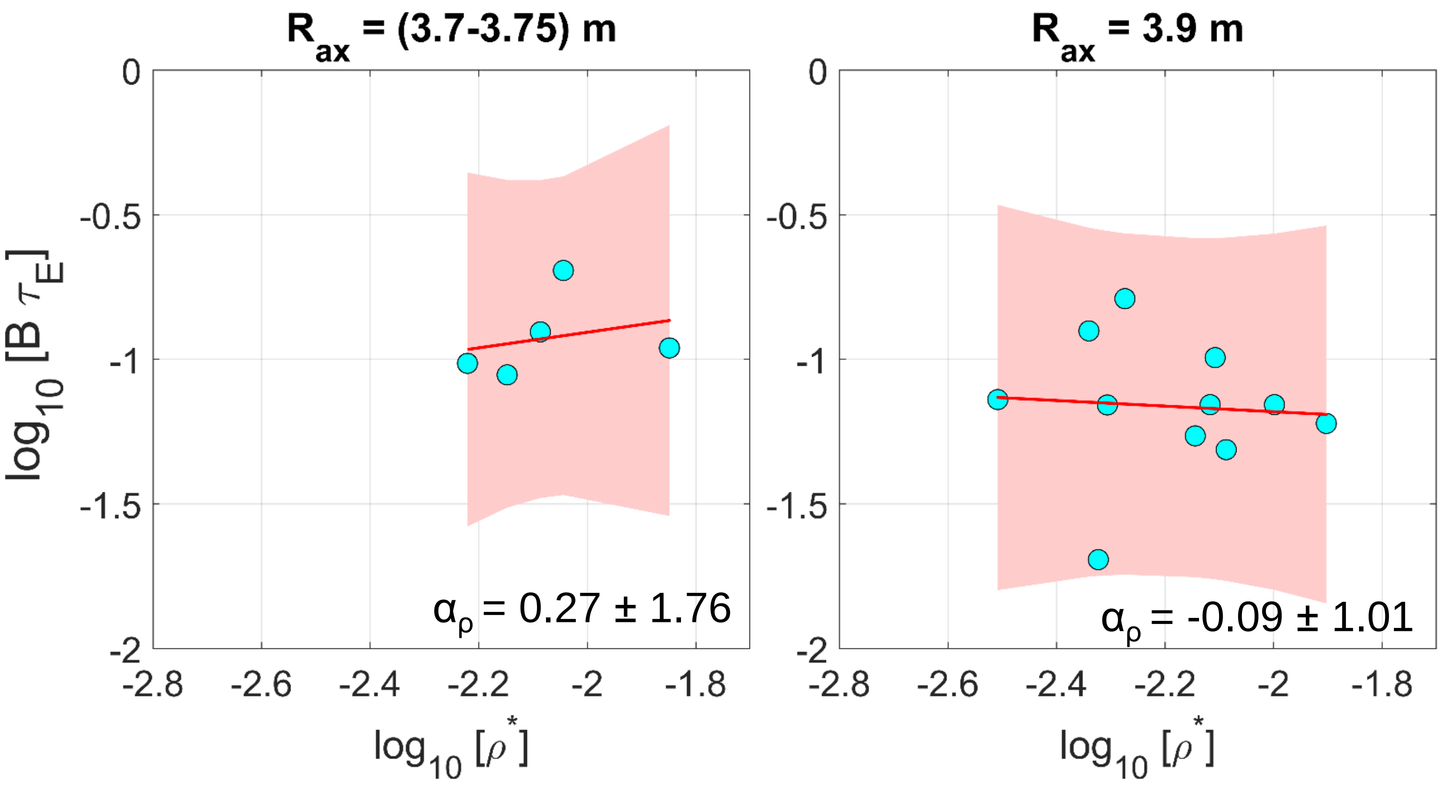
Scaling with dimensionless parameters of the LHD dataset



Possible scaling with one dimensionless parameter:

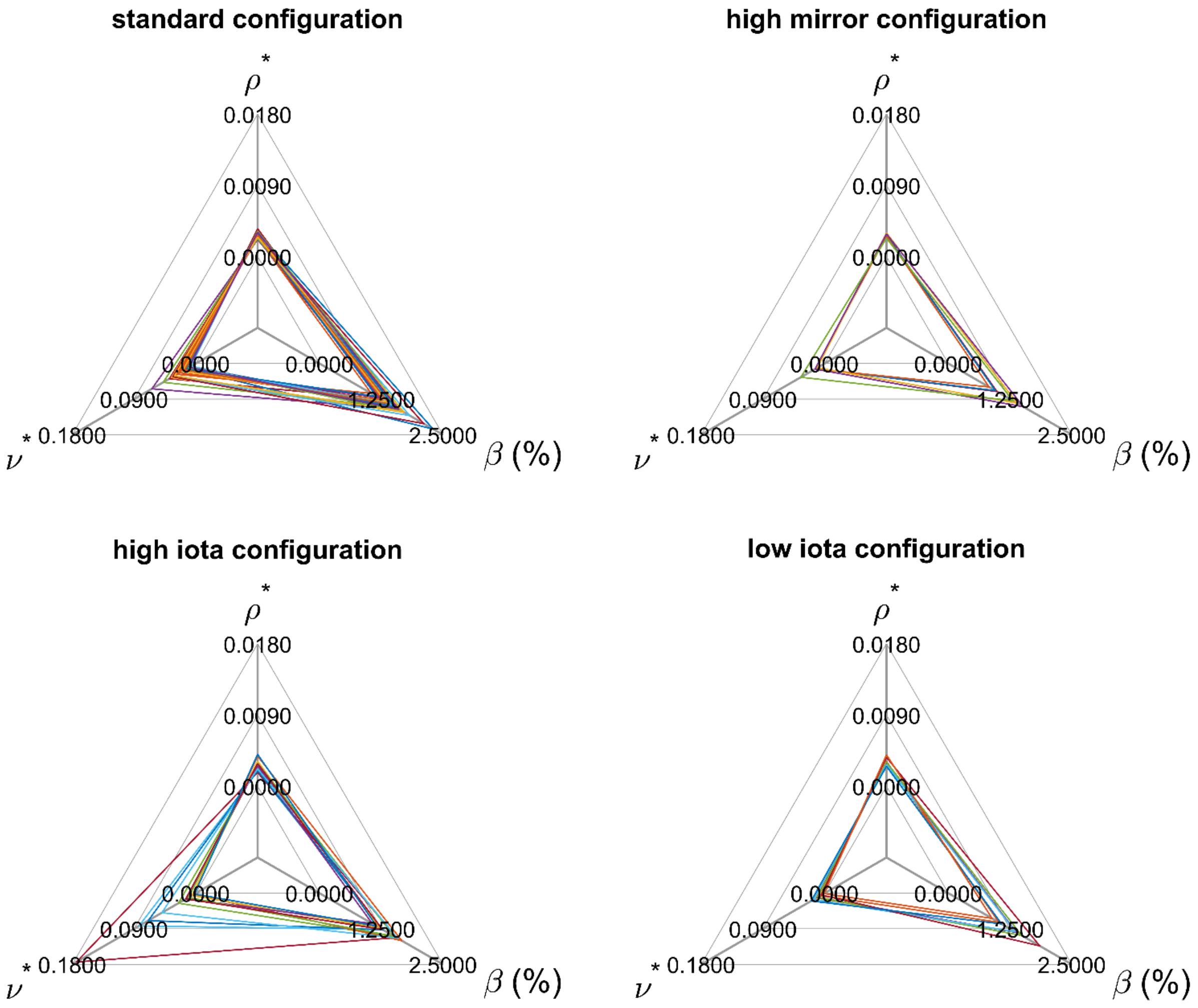
Configuration	β	ρ*	ν*
R_{ax} = (3.5 – 3.56) m			
R_{ax} = 3.6 m			
R_{ax} = (3.7 – 3.75) m		✖	
R_{ax} = 3.9 m		✖	

Confinement scaling with ρ^* of the LHD dataset



No reliable scaling of the confinement time with ρ^* in the LHD dataset due to the large error and small dataset

Scaling with dimensionless parameters of the W7-X dataset



Possible scaling with one dimensionless parameter:

Configuration	β	ρ*	ν*
standard	✖		
high-mirror	✖		
high-iota			✖
low-iota	✖		

No ρ^* scaling possible:

further ρ^* scan experiments in W7-X needed

Proposal: Variation of magnetic field for ρ^*- scans in W7-X

High- and low magnetic field for operation with O2 at high fields and X3 at low fields for similar deposition profiles:

$$B_H = 2.5\ \mathrm{T} \qquad B_L = \frac{2}{3} B_H = 1.67\ \mathrm{T}$$

Keeping β and ν^* constant over both operation scenarios by matching high and low field density n and temperature T using the magnetic field:

$$\left.\begin{aligned} \beta &\propto \frac{nT}{B^2} = \mathrm{const} \\ \nu^* &\propto \frac{na}{T^2} = \mathrm{const} \end{aligned}\right\} \quad \begin{aligned} \frac{n_L}{n_H} &= \left(\frac{B_L}{B_H}\right)^{\frac{4}{3}} = 0.58 \\ \frac{T_L}{T_H} &= \left(\frac{B_L}{B_H}\right)^{\frac{2}{3}} = 0.76 \end{aligned}$$

$$\rho^* \propto \frac{\sqrt{T}}{aB}$$

possible ρ^* variation:

$$\frac{\rho_H^*}{\rho_L^*} = \left(\frac{B_H}{B_L}\right)^{-\frac{2}{3}} = 0.76$$

Comparison of low and high field discharges provides insight in ρ^*- scaling

Summary

- Investigation of confinement quality for selected datasets from LHD and W7-X with respect to magnetic configuration, heating method and discharge scenario

- Unified approach for the assessment of LHD and W7-X confinement data
- Use of integrating factors for a temporal analysis of transient confinement

	LHD dataset	W7-X dataset
Magnetic configuration	Improved τ_E at R_{ax} = 3.6m (reduced neoclassic transport)	No dependency found
Heating methods	No apparent dependency found	No dependency found
Pellet injection	Enhanced W_{dia} with $f_{ren} < 1$	Enhanced W_{dia} with $f_{ren} > 1$

Outlook: ρ^* - scan experiment in W7-X (achievable by magnetic field variation)