Effect of rotational transform and magnetic shear on confinement of stellarators

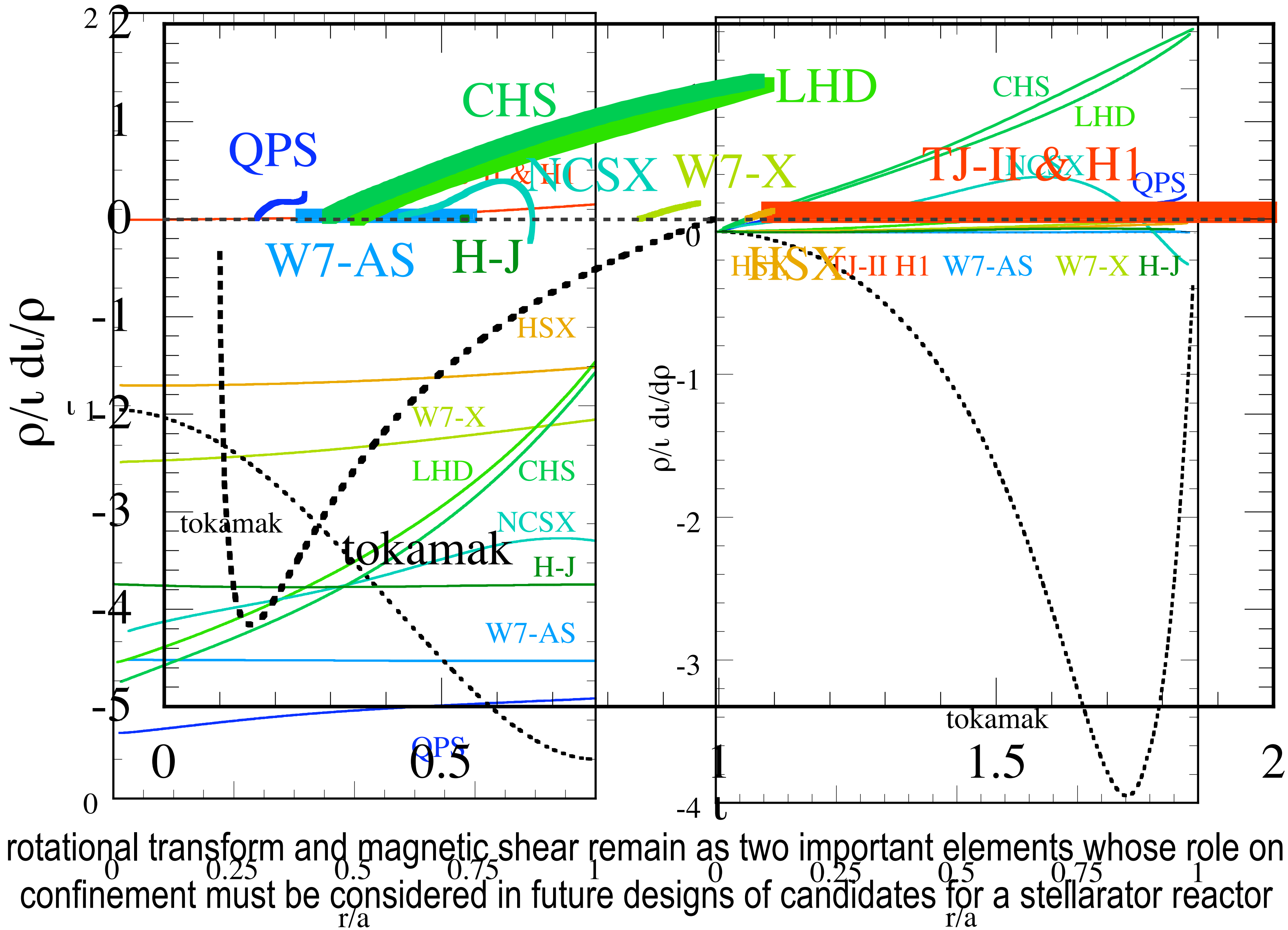
E. Ascasíbar(1), D. López-Bruna(1), F. Castejón(1), V.I. Vargas(1), V. Tribaldos(1), H. Maassberg(2), C.D. Beidler(2) R. Brakel(2), A. Dinklage(2) J. Geiger(2), J.H. Harris(3,4), A. Kus(2) T. Mizuuchi(5), S. Murakami(5), S. Okamura(6), R. Preuss(2), F. Sano(5), U. Stroth(7), Y. Suzuki(6), J. Talmadge(8), K.Y. Watanabe(6), H. Yamada(6), M. Yokoyama(6)

(1) CIEMAT, Madrid, Spain
(2) Max-Planck-Institut für Plasmaphysik, EURATOM Association, Greifswald, Germany
(3) Oak Ridge National Laboratory, USA
(4) Australian National University, Canberra, Australia
(5) Kyoto University, Kyoto, Japan
(6) National Institute for Fusion Science,322-6 Oroshi-cho, Toki 509-5292, Japan
(7) Institut für Plasmaforschung, Universität Stuttgart, Germany
(8) University of Wisconsin, USA

International Stellarator/Heliotron Confinement Database and Profile Database (ISHCDB & ISHPDB)

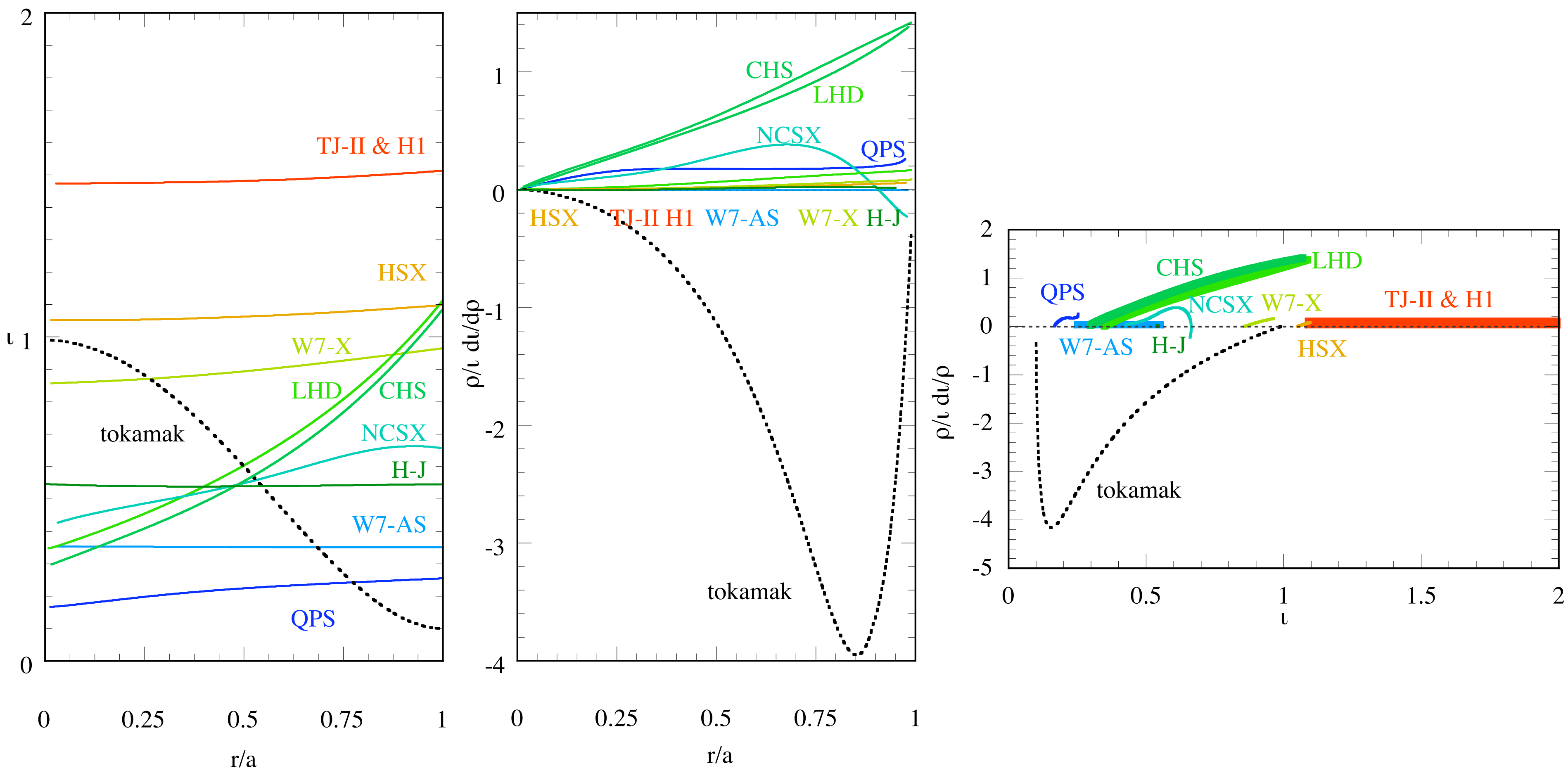
http://iscdb.nifs.ac.jp/ and http://www.ipp.mpg.de/ISS

Introduction/motivation



rotational transform and magnetic shear remain as two important elements whose role on confinement must be considered in future designs of candidates for a stellarator reactor

Introduction/motivation



rotational transform and magnetic shear remain as two important elements whose role on confinement must be considered in future designs of candidates for a stellarator reactor

Open questions

•Is there a threshold for the magnetic shear over which low order resonances lose their detrimental character? Does this threshold depend on the value of the rotational transform itself?

•What is the effect of resonances when the shear is above this threshold?

•Is the sign of the shear important, or is only its magnitude what matters?

•Impact of large shear: Is there a saturation or even degradation of confinement over a certain upper threshold?

Outline

Scope of the work restricted so far to low shear devices: W7-AS, TJ-II and Heliotron J

- Dependence of global confinement on iota
- Effect of low order resonances on confinement
  - Degraded confinement at low β with no shear
  - Improved electron transport in the vicinity of low order rationals
    - TJ-II specific: Local lowering of X_e when “moving” low order rationals through the plasma
- Role of (moderate) magnetic shear
- Summary

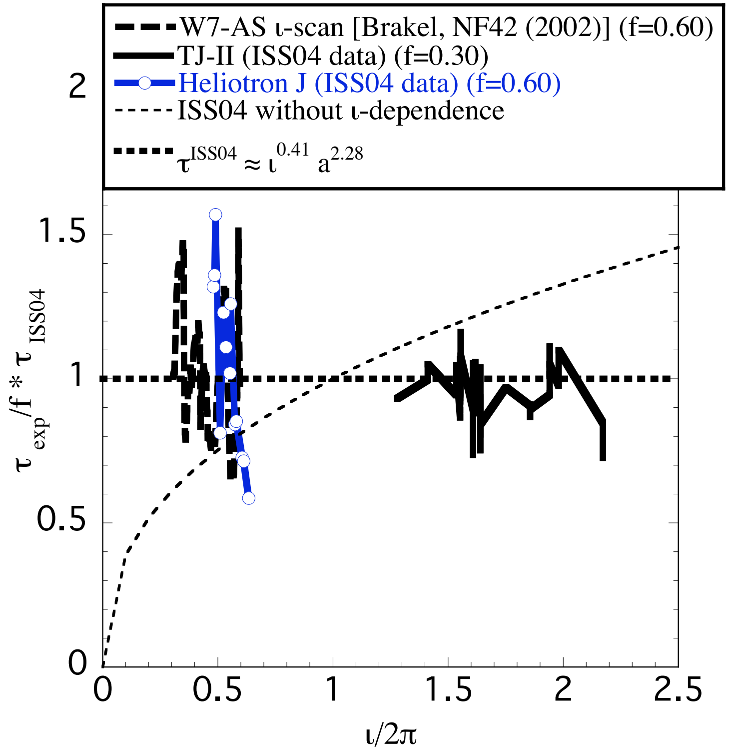
Impact of iota and shear in ISS95 and ISS04: 0-d scaling

ISS95 [1]
$\tau_E \propto \text{iota}_{2/3}^{\ 0.4}$

- –deduced from W7-AS
- –suported by intermachine analyses
- –configuration-dependent parameter needed for a unified scaling (s-parameter, related to shear)

ISS04 [2,3]
$\tau_E \propto \text{iota}_{2/3}^{\ 0.41}$

- –additionally supported by TJ-II individual results
- –old s-parameter not sufficient for unified scaling
- –configuration-dependent renormalization factor needed, related to properties of the helical field structure. i.e., effective helical ripple, plateau factor, elongation



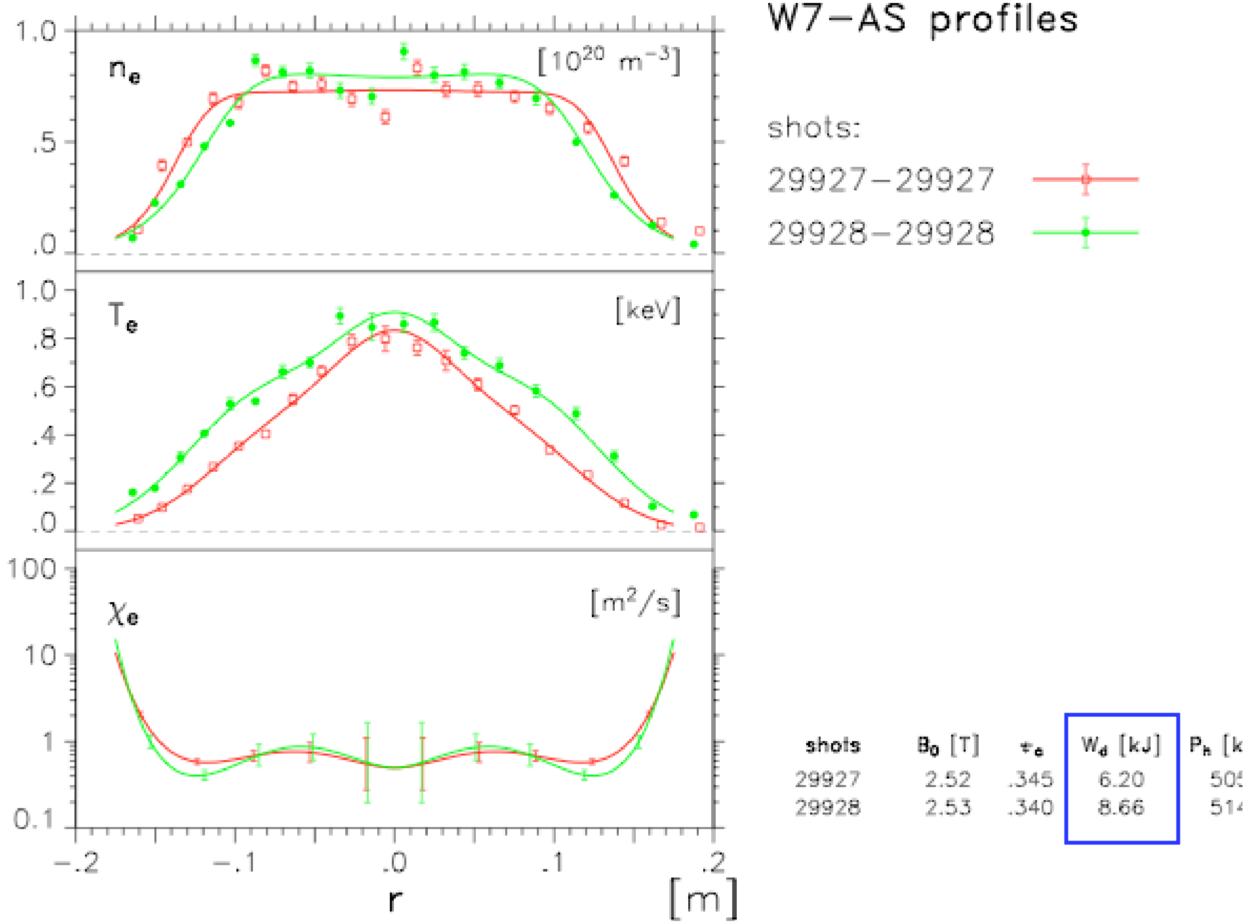
0-d scaling is not enough

[1] Stroth et al., NF 1995
[2] Yamada et al., NF 2005
[3] Dinklage et al., FST 2007, NF 2007

Local transport analysis needed

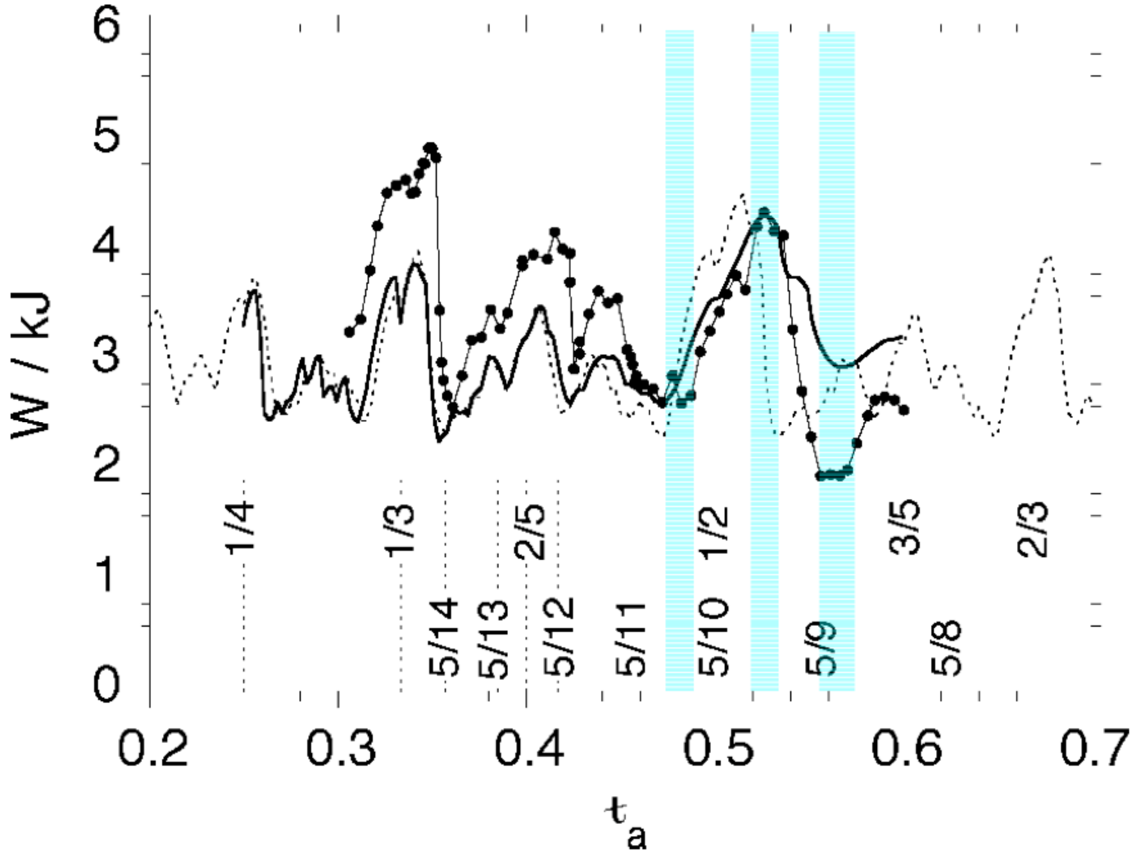
•Understanding the physics behind the configuration-dependent renormalization factor (role played by iota, rationals and shear) requires local transport analysis of density and temperature profiles.

•Warning: Particle confinement (also sources) can depend on edge iota and shear. Example from W7-AS: a degradation of global t_E, can have negligible impact on local *X*e. Important to analyze completely both density and temperature profiles.



Degraded confinement due to low order resonances at low β, small shear: W7-AS

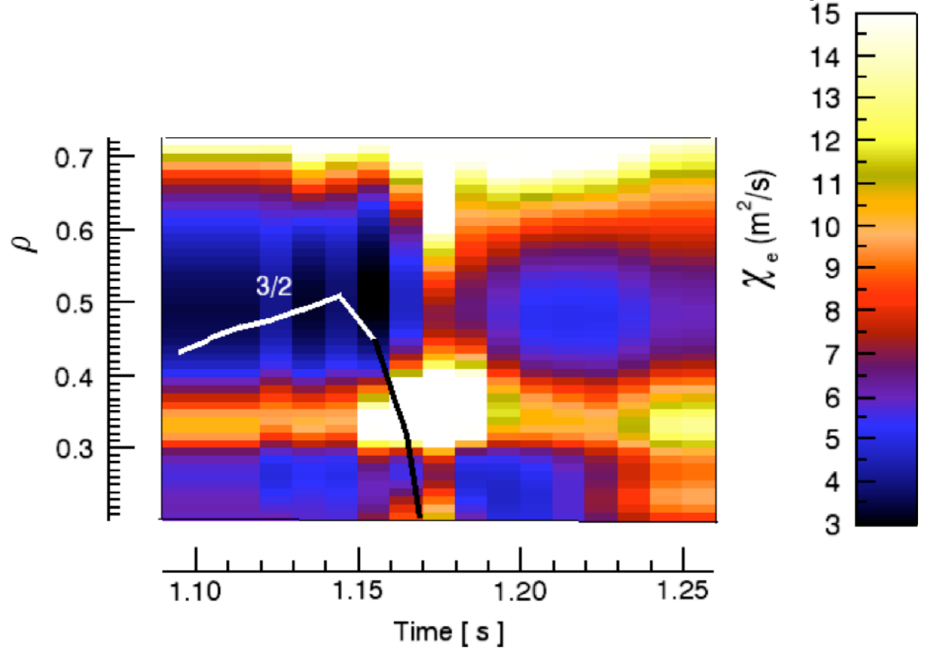
in the absence of magnetic shear, global confinement depends strongly on edge iota.
The variations correlate with changes in local electron energy transport (Brakel NF 02)

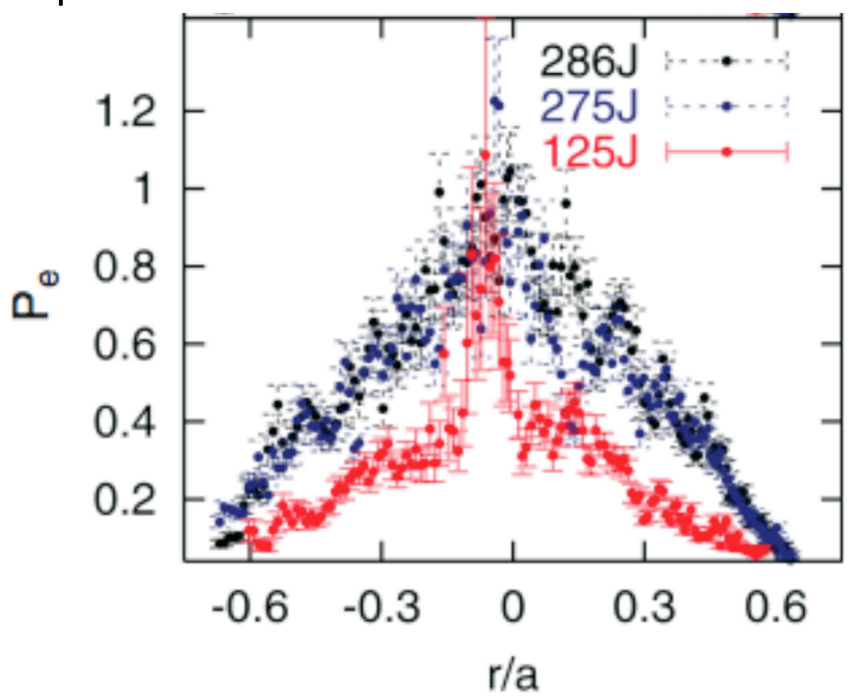


Degraded confinement due to low order resonances at low β, no shear: TJ-II

ECH discharge with induced OH current

- time evolution of effective *Xe* (obtained from power balance calculations). Te profiles from ECE diagnostic
- estimated time evolution of iota (assuming total current due to OH transformer): it is forced to flatten so that 3/2 occupies part of the plasma with no shear.





3/2 does not deteriorate transport until 1160-80 ms

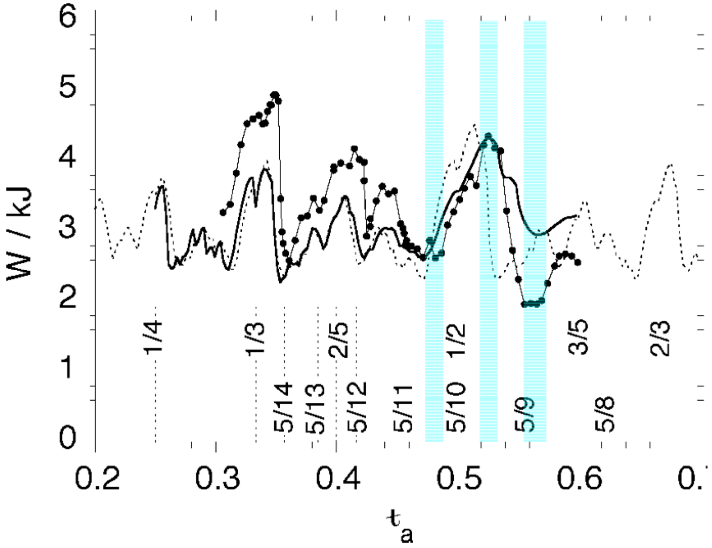
Transient flattening of the pressure profile

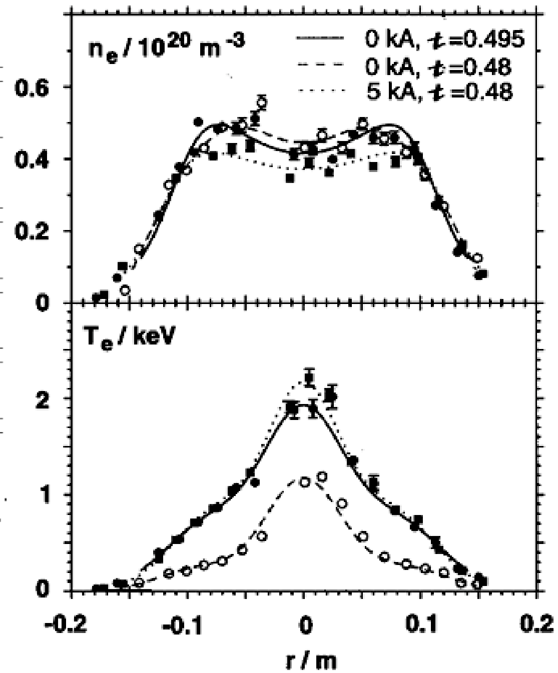
Improved electron transport in the vicinity of low order resonances: W7-AS

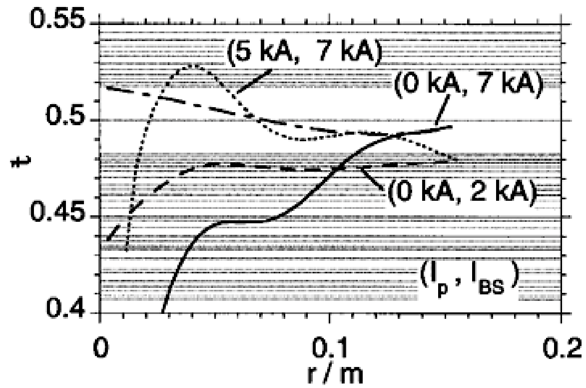
•Empirical model assuming that transport is enhanced at rational surfaces (MHD or turbulence). This enhancement is reduced by magnetic shear (Brakel NF 02)

•The favourable confinement close to rationals is due to the rarefaction of higher order rationals in their vicinity

•The model reproduces the iota-dependence of global confinement measured in W7-AS

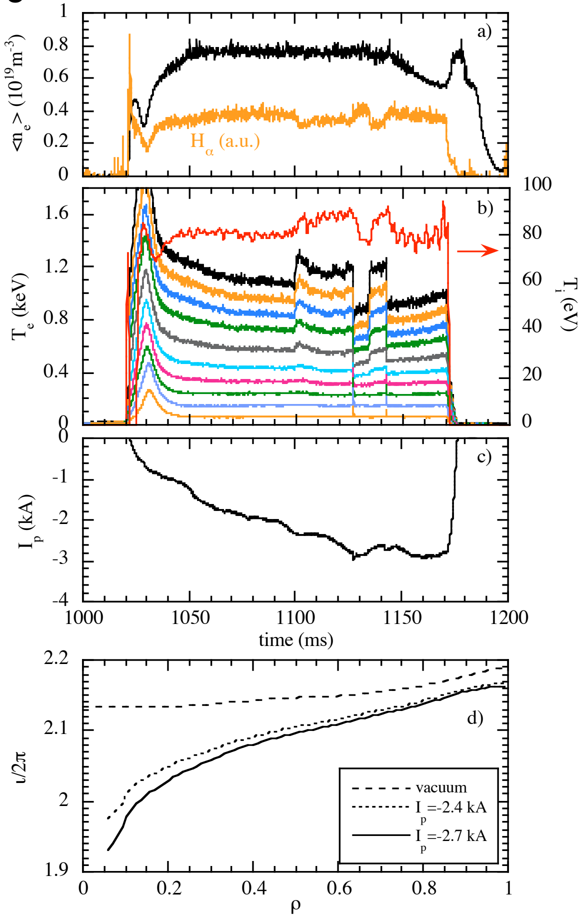


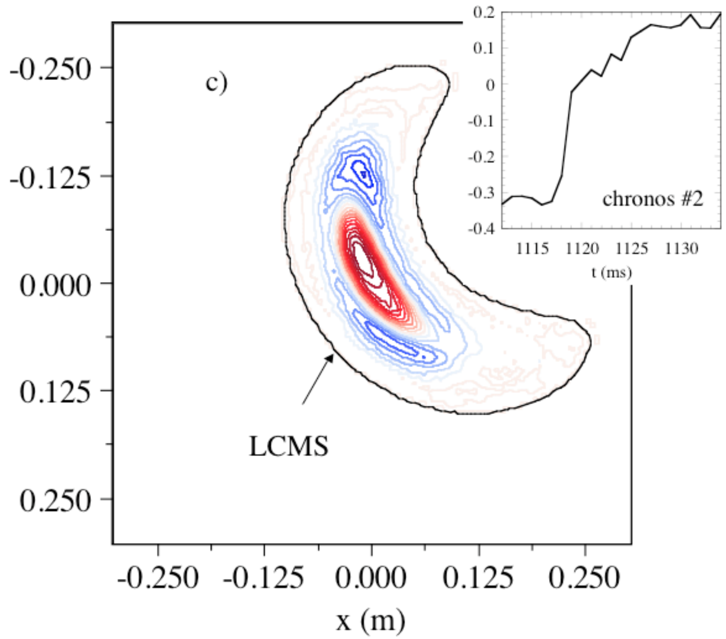




Improved electron transport in the vicinity of low order resonances: TJ-II

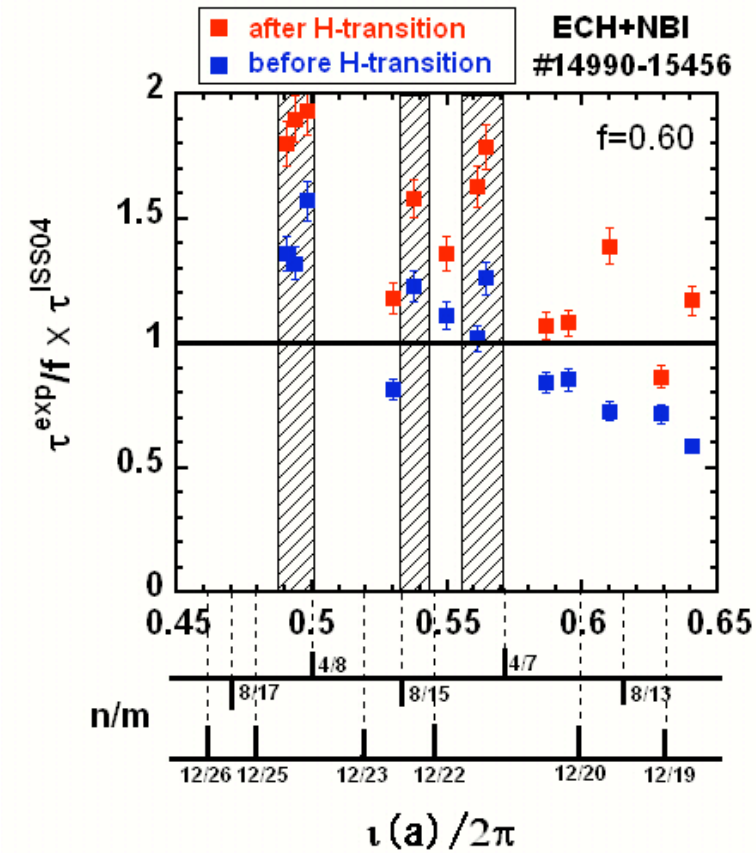
- Significant experimental evidence in TJ-II of the role of low order resonances as triggers for different improved transport events.
- Recent example of CERC in TJ-II: rational surface 4/2 with moderate shear (OH induced current) triggers a transition with increase also in the ion temperature





T. Estrada
P1-28 Tuesday

Improved electron transport in the vicinity of low order resonances: Heliotron J

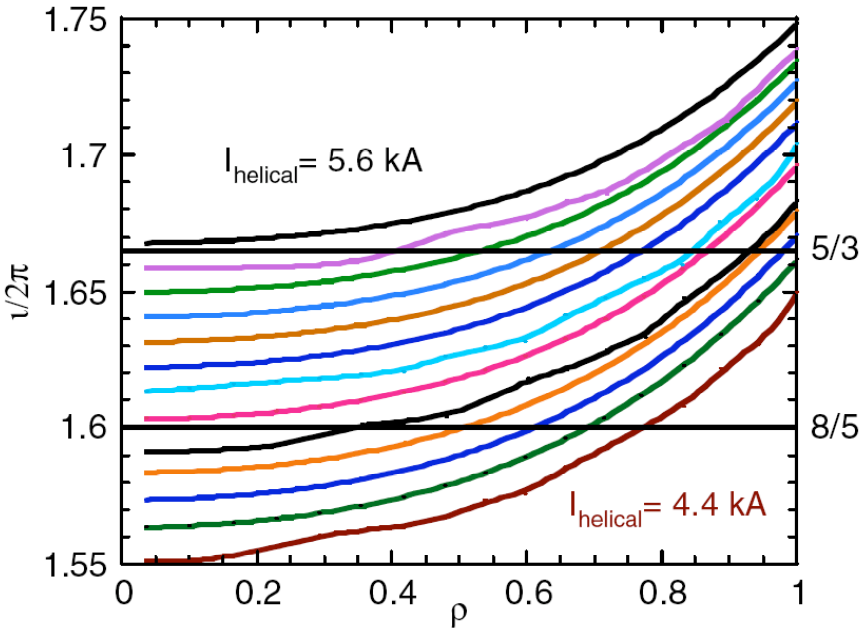


iota windows for the high quality H-mode ($\tau^{exp}/ f \times \tau^{ISS04} > 1.5$) close to low order rationals

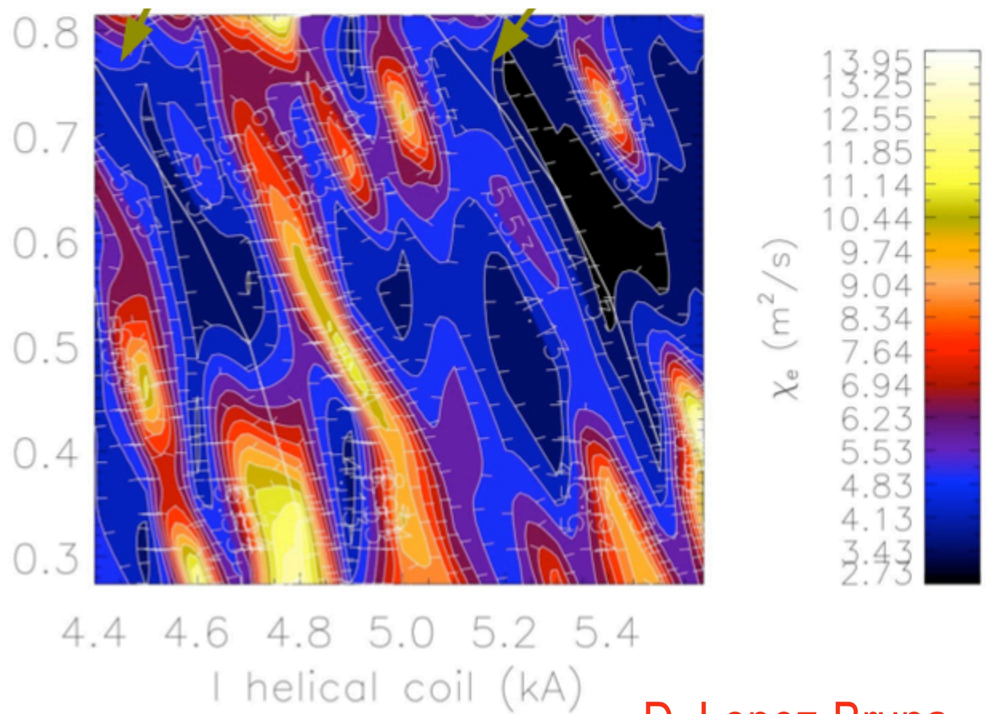
Tracking the local lowering of X_e due to low order rationals in TJ-II plasmas

Moving low order rationals shot by shot: fixed shear (Vargas NF 07)

- local power balance analysis: X_e Interpolated: pattern of grooves and ridges
- small value of net plasma currents: iota estimation more reliable for $\rho > 0.5$
- low order rationals retain fluxes at their radial location



13 configurations: sweeping the rationals inwards through the confined plasma as I_h increases

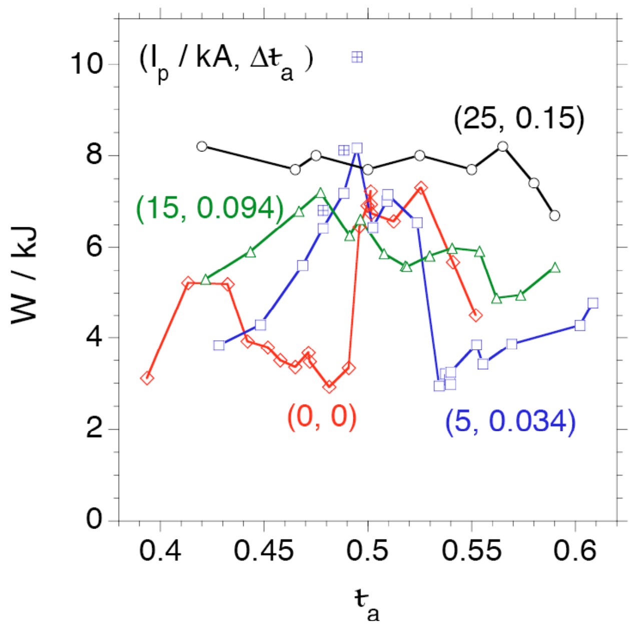


Xe contour plot
pattern of "ridges" and "grooves"

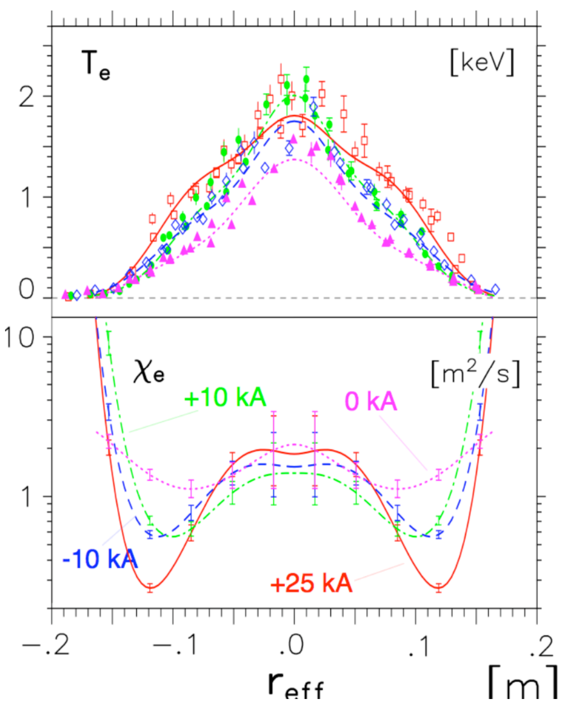
D. Lopez-Bruna
P1-16 Tuesday

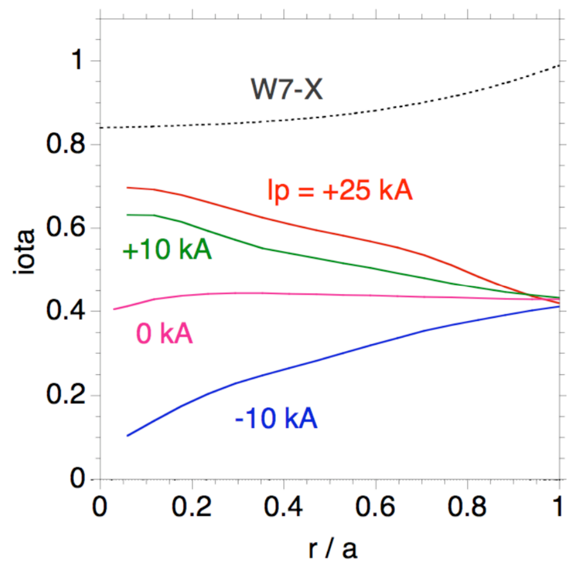
The role of (moderate) magnetic shear: W7-AS

- The strong dependence of the energy content on configuration at zero shear is smoothed as the current is raised and disappears at the highest current value. Confinement reaches its maximum with high currents (Brakel PPCF 97).
- Local power balance analysis shows restoration of degraded confinement through a strong reduction of X_e in the gradient region. The 1/2 surface can stay inside the plasma with no significant degradation of confinement
- Confinement increases independently of shear sign



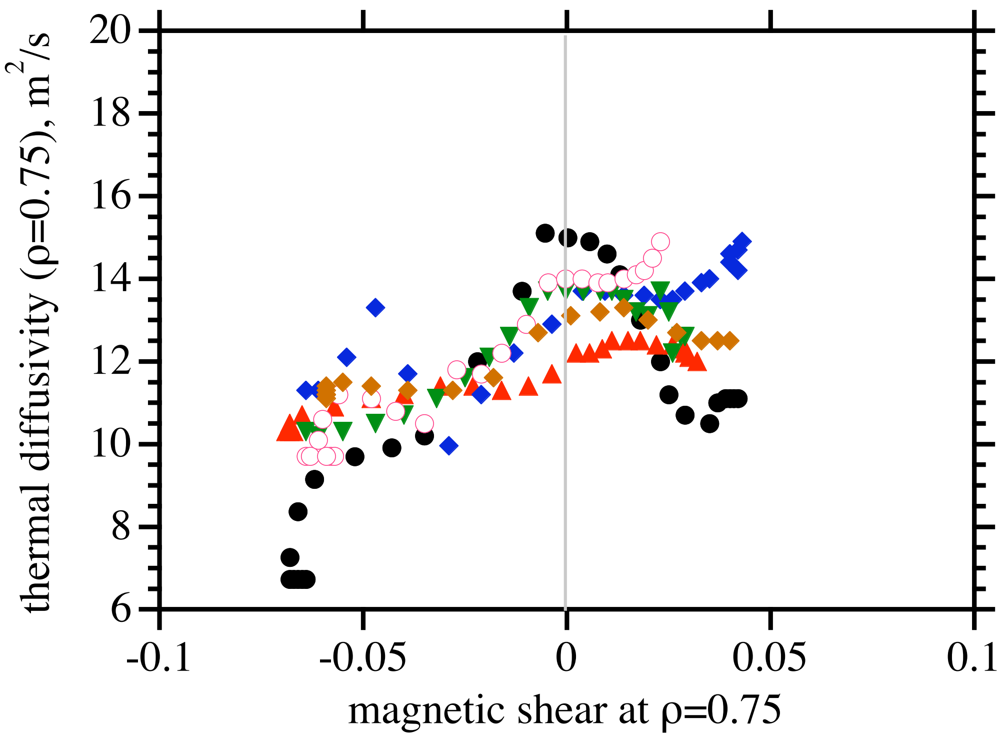
discharges with identical limiter aperture and densities





The role of (moderate) magnetic shear: TJ-II

- X_e at ρ = 0.75 for six ECRH discharges with similar density, in plasmas with induced OH current.
- largest Xe found around zero shear
- confinement improved for both shear signs. Less clear for the positive case due to the smaller accesible range



Summary

- In the absence of magnetic shear, global confinement is deteriorated by the islands caused by low order rationals
- Narrow optimum confinement windows are found in W7-AS and Heliotron-J close to low order rational values. In TJ-II, provided a small amount of magnetic shear, low order resonances trigger a variety of improved transport events. Fine configuration scans in this machine show that low order rationals retain heat fluxes at their radial location.
- Certain amount of shear allows the presence of even the lowest order rationals within the confinement region. It is still unknown whether the amount of shear needed depends on the iota value.
- The beneficial effect of shear on confinement does not depend on the sign.
- (this work is just a sterting point!)

Looking to the future

•Documentation: Continuing effort in data quality improvement (validated profiles, errors, uncertainties, ...)

•comparisons between W7-AS and TJ-II: lower threshold for the shear?, does it depend on the iota-value?

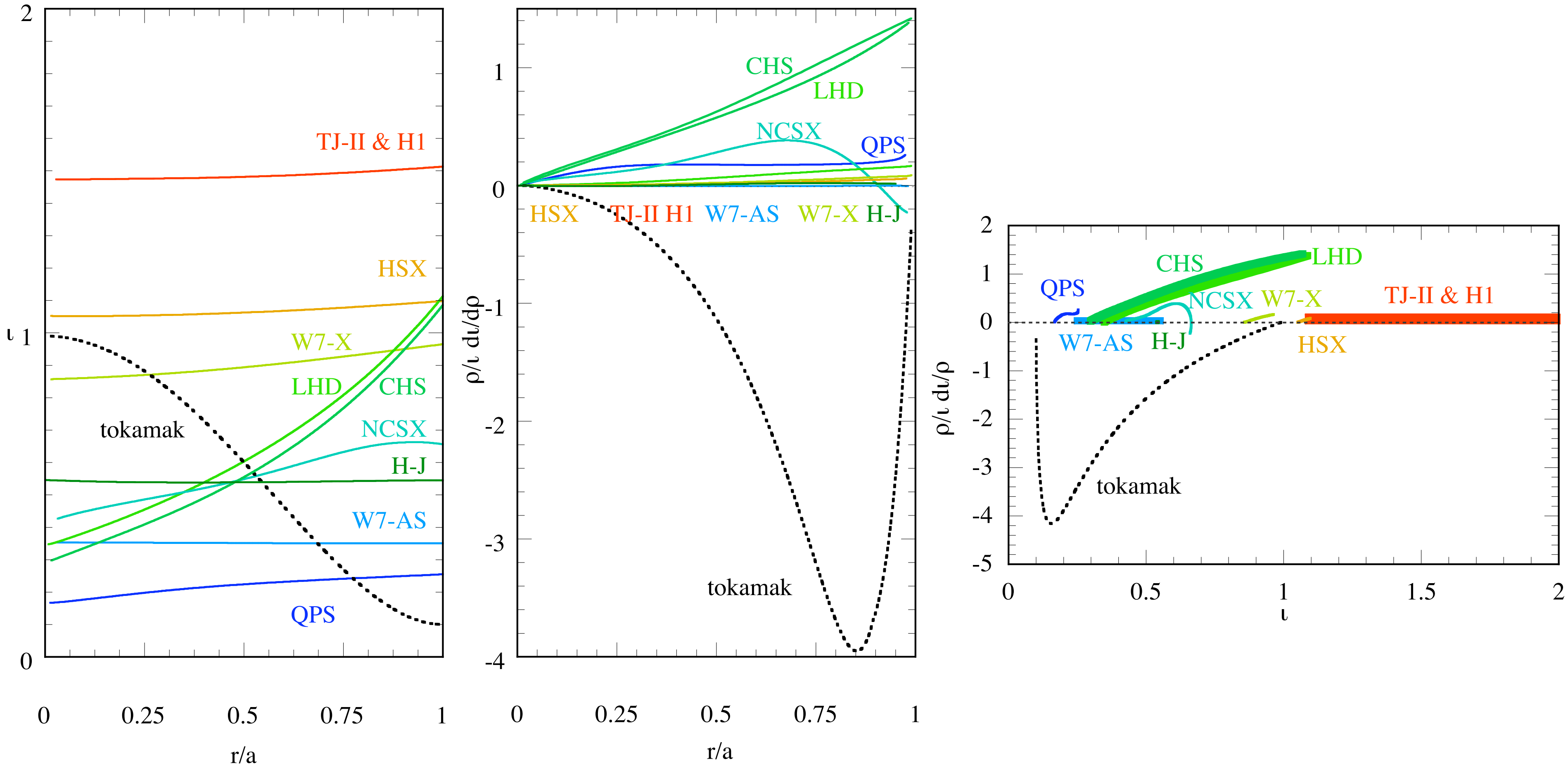
•Tracking low order rationals experiments in TJ-II:

- –issue: X_e contour plot needs further confirmation and careful estimation of internal currents
- –new experiments in the pipeline : slow increase in the flat top value of helical coil current (≈ 5 kA/s) -> dynamic change of configuration with fixed shear
- –will the effect survive in higher density NBI discharges?

•Impact of large shear: Comparison with CHS, LHD needed. Is there a saturation or even degradation of confinement over a certain upper threshold?

•W7-X is the first device able to face the challenge of keeping the configuration free of low order rationals. ECRH provides an additional tool to compensate internal currents

Introduction/motivation



rotational transform and magnetic shear remain as two important elements whose role on confinement must be considered in future designs of candidates for a stellarator reactor

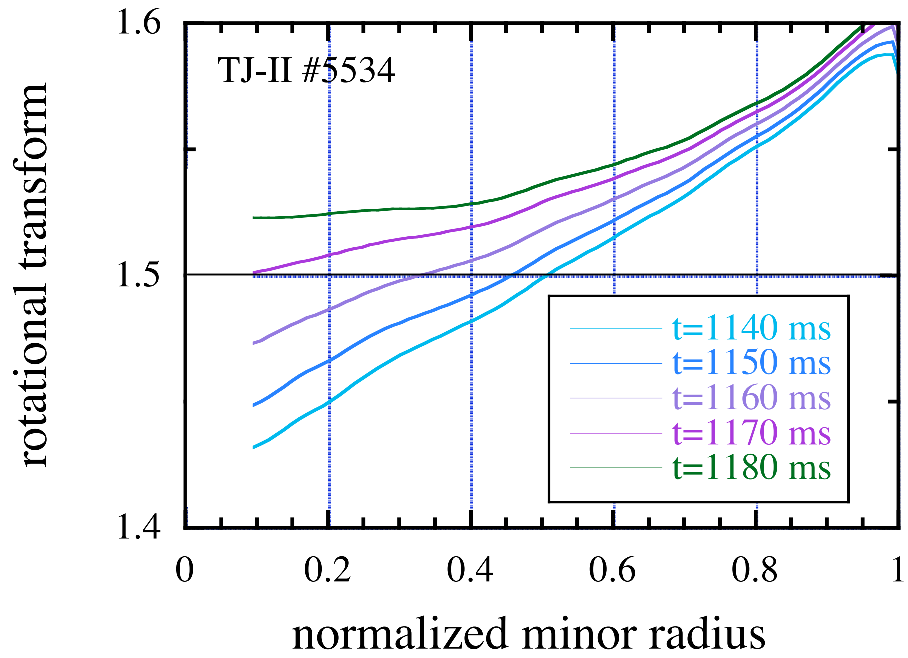
Back up

- The logic behind this type of questions is clear: Provided that low order resonances do not deteriorate confinement anymore in the presence of enough (perhaps very low) magnetic shear then the design constraints of future stellarators might be relieved: a strict control of the magnetic shear (i.e. internal currents) would no longer be necessary and the available configuration space to optimize other physics aspects would expand.

Degraded confinement due to low order resonances at low β, no shear: Heliotron J

- Transient degradation for $\text{iota}_a \approx 0.59\text{-}0.62$
- No degradation for $\text{iota}_a \approx 0.49\text{-}0.51$

Degraded confinement due to low order resonances at low β, no shear: TJ-II



estimated time evolution of iota (assuming total current due to OH transformer)