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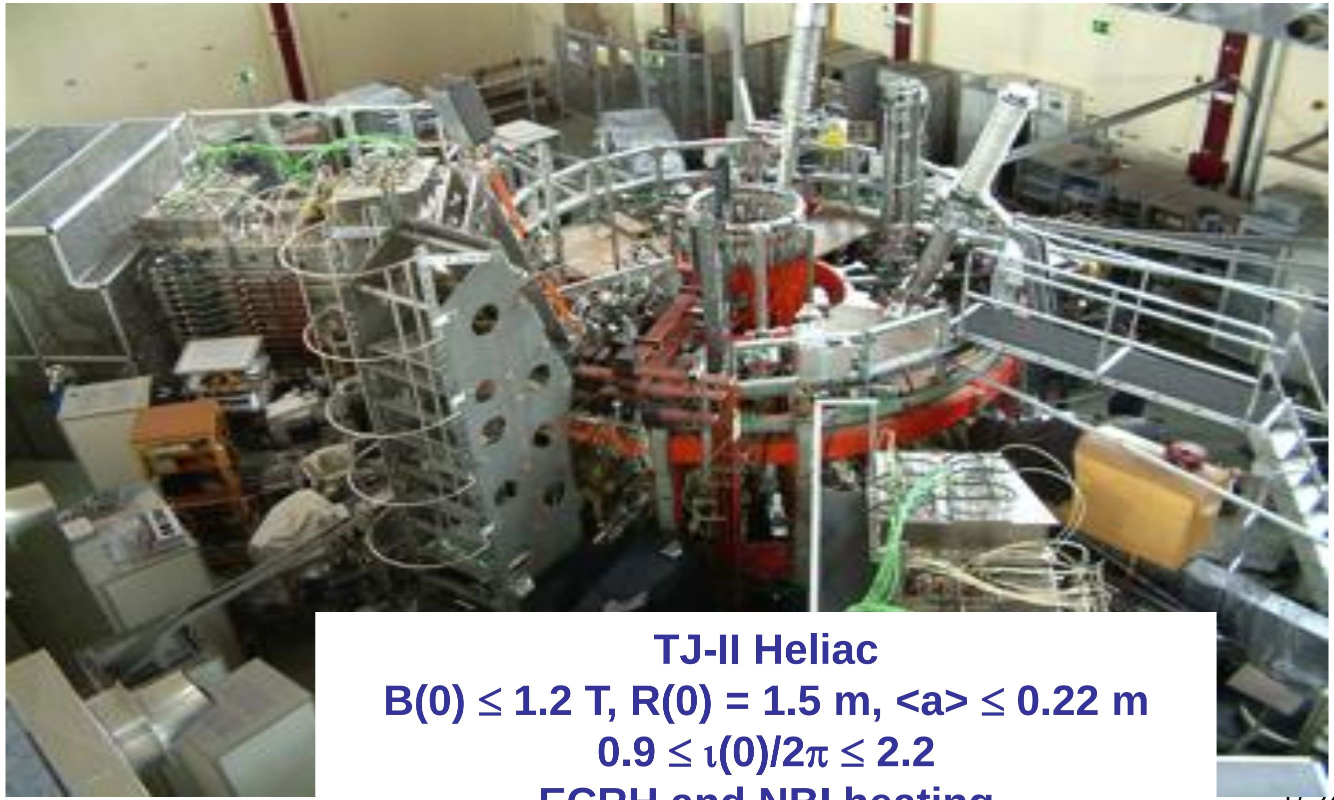
Transport, stability and plasma control studies in the TJ-II stellarator

presented by **J. Sánchez**

Laboratorio Nacional de Fusión, CIEMAT and collaborators

Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain.
Instituto de Plasmas e Fusao Nuclear, IST, Lisbon, Portugal.
Max-Planck-Institut für Plasmaphysik, Greifswald, Germany.
Institute of Plasma Physics, NSC KIPT, Kharkov, Ukraine.
Institute of Nuclear Fusion, RNC Kurchatov Institute, Russia.
Universidad Carlos III, Madrid, Spain.
Instituto Tecnológico de Costa Rica, Costa Rica.
University of California-San Diego, USA
A.F. Ioffe Physical Technical Institute, St Petersburg, Russia
General Physics Institute, Russian Academy of Sciences, Russia
National Institute for Fusion Science, Toki, Japan
Instituto Tecnológico de Costa Rica, Cartago, Costa Rica.



TJ-II Heliac
$B(0) \leq 1.2$ T, $R(0) = 1.5$ m, $\langle a \rangle \leq 0.22$ m
$0.9 \leq \iota(0)/2\pi \leq 2.2$
ECRH and NBI heating

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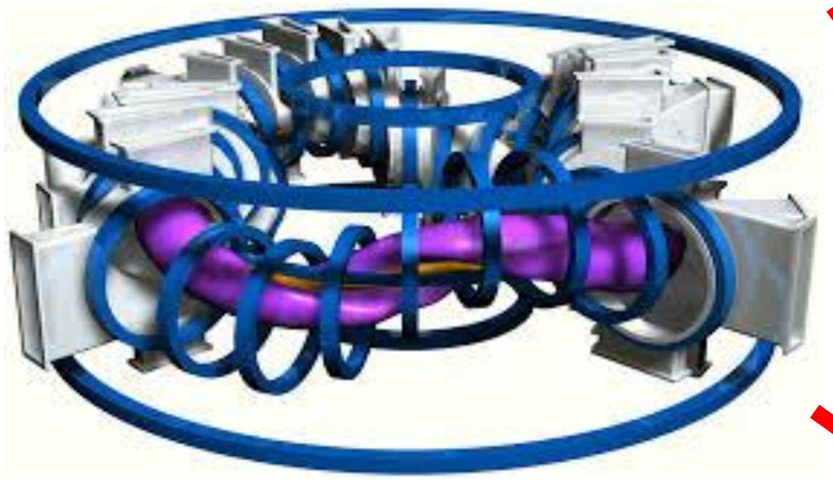
Stellarator



Development of the concept for a **steady state, disruption free, high density reactor** for the power plant

Current free controlled configuration: "laboratory" for **basic plasma physics** studies **relevant to tokamaks and ITER**

TJ-II research programme supporting stellarator and ITER physics

PARTICLE, ENERGY AND IMPURITY TRANSPORT:

NC effects, flux surface asymmetries in plasma potential, conf. vs charge and mass

MOMENTUM TRANSPORT:

Dynamics of Limit Cycle Oscillations and isotope effect

POWER EXHAUST PHYSICS:

Plasma facing components based on liquid metals (Li)

PLASMA STABILITY STUDIES:

Magnetic well scan and plasma stability

FAST PARTICLE PHYSICS:

Role of ECRH on Alfven Eigenmodes

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Asymmetries and impurity transport

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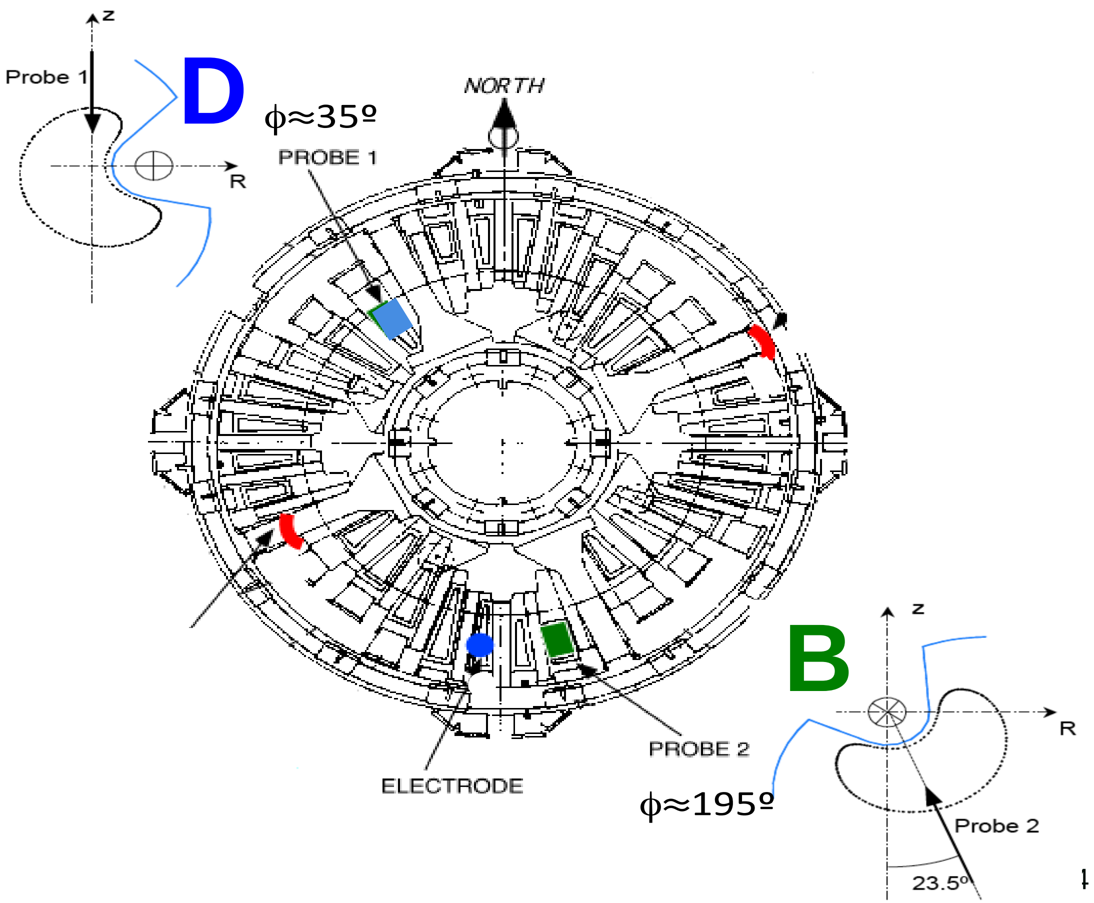
Impurity accumulation a potential problem in stellarators
Need to find “knobs” which can affect high Z transport:

- ✓ JET (2000) : asymmetries in edge radiation
- ✓ J.M. Regaña (PPCF 2013, Theory): High Z imp. transport in stellarators very sensitive to 3D asymmetries of electrostatic potential

Experimental difficulty: how to “label” exactly a whole flux surface?

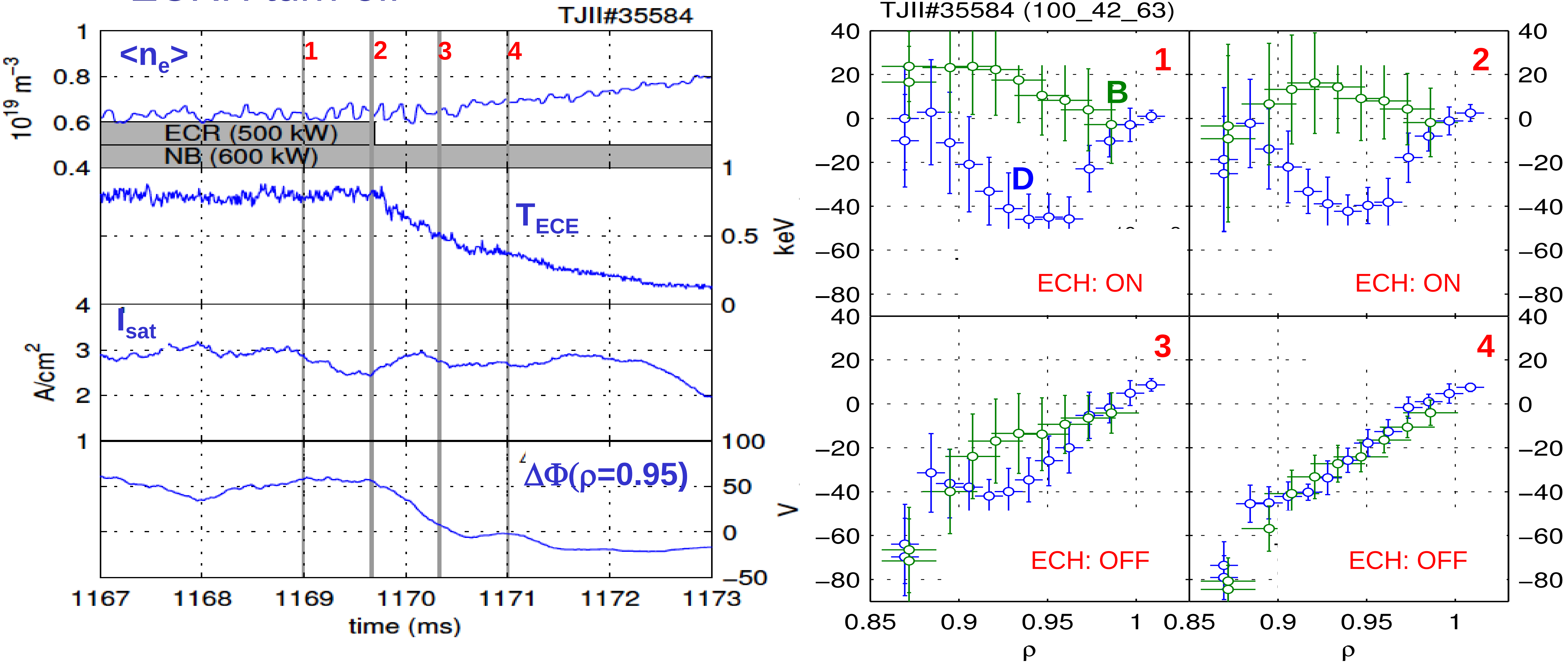
Long range correlations along flux surfaces

- ✓ Evidence of long-range correlations amplification during in the proximity of the Electron-Ion root transition
  [M. A. Pedrosa et al., PRL 2008]
- ✓ due to a reduction in neoclassical viscosity
  [J.L. Velasco et al., PRL-2012]



Electrostatic potential asymmetries observed

ECRH turn-off



Assuming T_e variations on flux surfaces are small, in-surface **floating potential** differences reflect those of **plasma potential**, affected by ECRH   A. Alonso et al., EPS-2014

Asymmetries, 3D neoclassical calculations:

Potential variation on magnetic flux surfaces in TJ-II stellarator using particle in cell (PIC) Monte Carlo code EUTERPE

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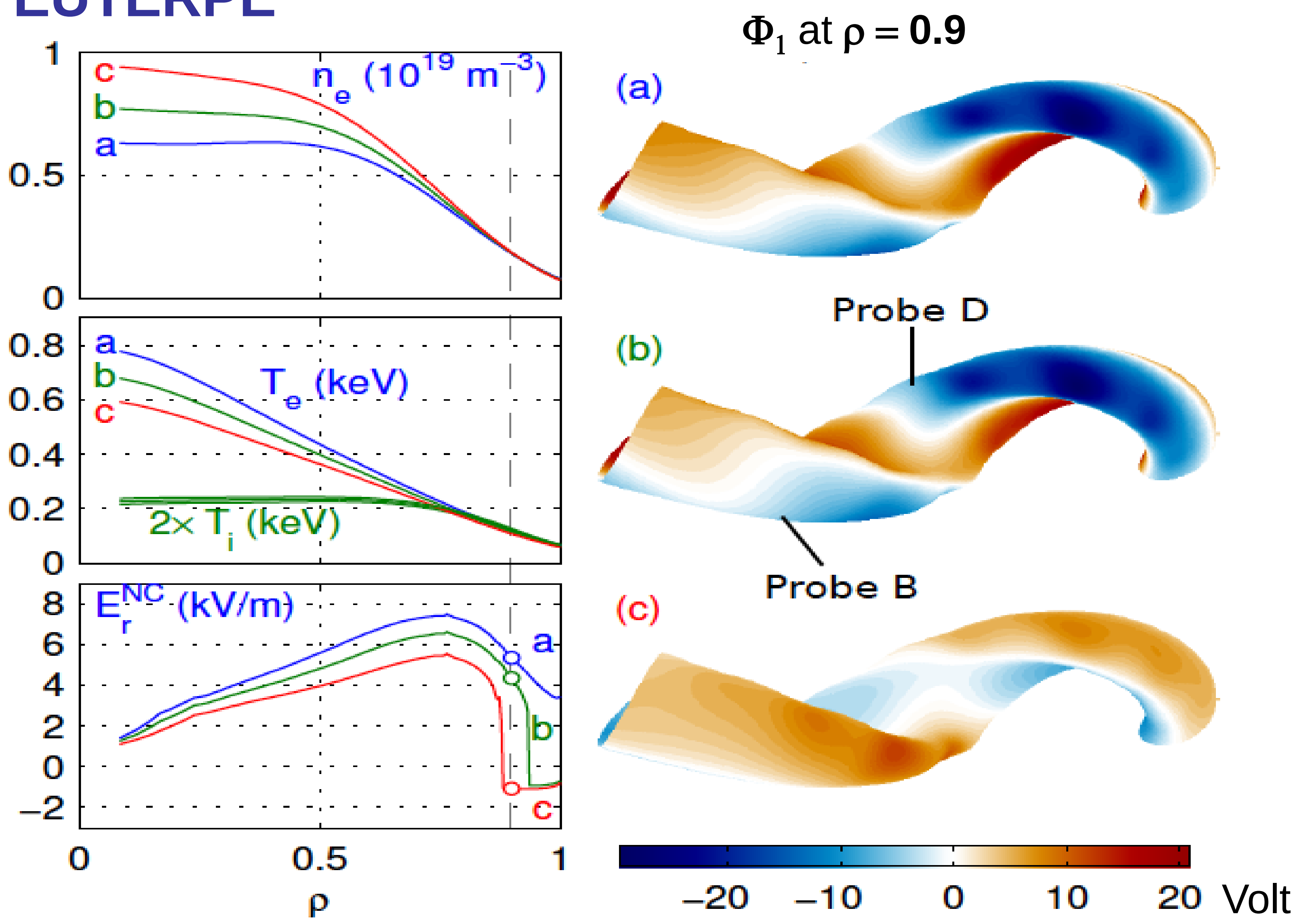

Φ=Φ₀ + Φ₁ → asymmetric part

$\Phi = \Phi_0 + \Phi_1$ → asymmetric part

Low density E_r root transition: Φ_1 computation.

✓NC electron-to-ion root transition occurs with relatively minor changes in n and T profiles→ good to test the dependence on E_r.

✓EUTERPE simulations cast large Φ_1 and clear dependence with E_r.

See also necoclassical results on Er and transport from code FORTEC 3D (poster OV4-5)

Charge dependence of Impurity Confinement (ECRH Plasmas)

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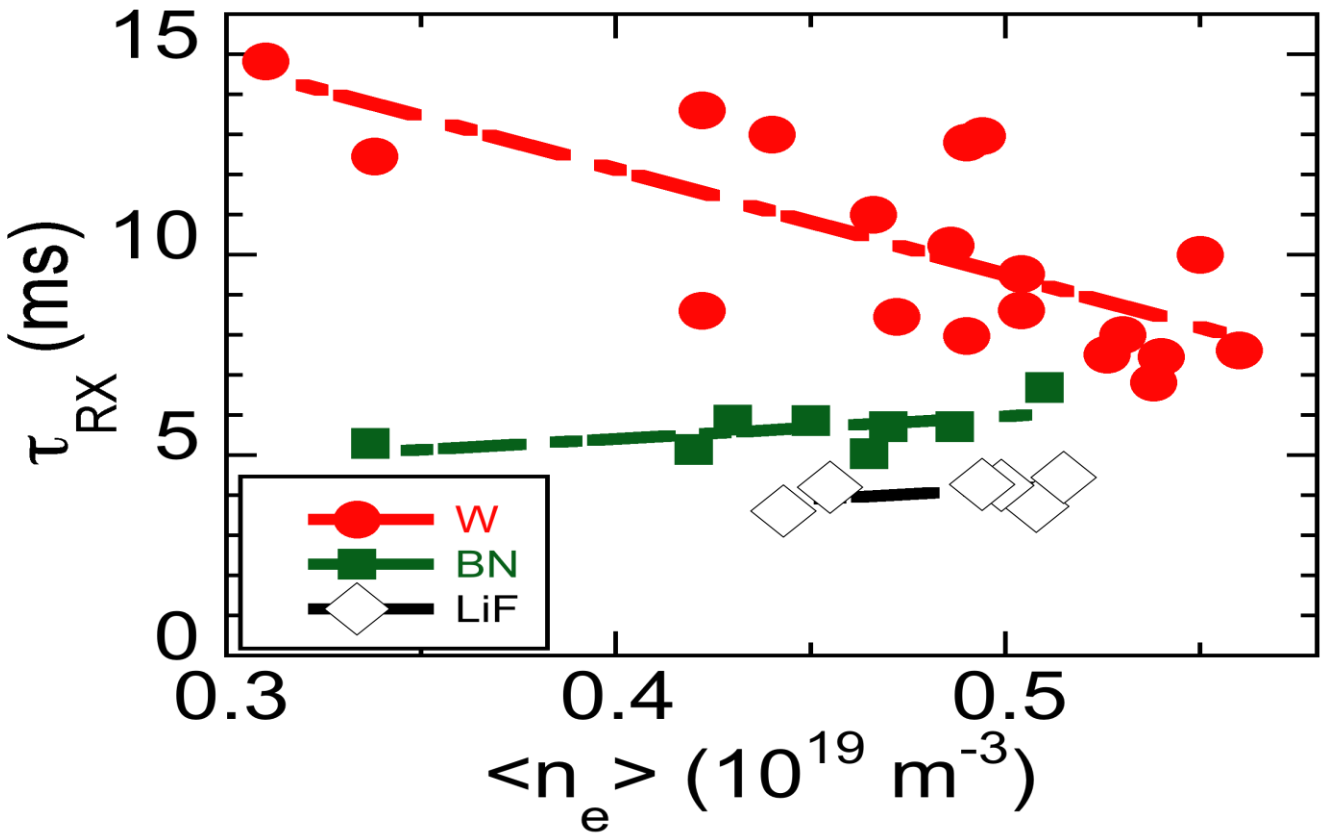

- ✓ The dependence of impurity confinement time has been also studied as a function of **charge and mass** of the impurity ions. A distinct impurity confinement of injected ions is distinguished clearly in the plasma core as revealed from soft X-ray analysis and tomographic reconstructions.

[**B. Zurro, IAEA FEC 2014, EX/P4-43**; B. Zurro, PPCF 2014 *in press*]

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L-H transition near the threshold:

LCOs and role of turbulence

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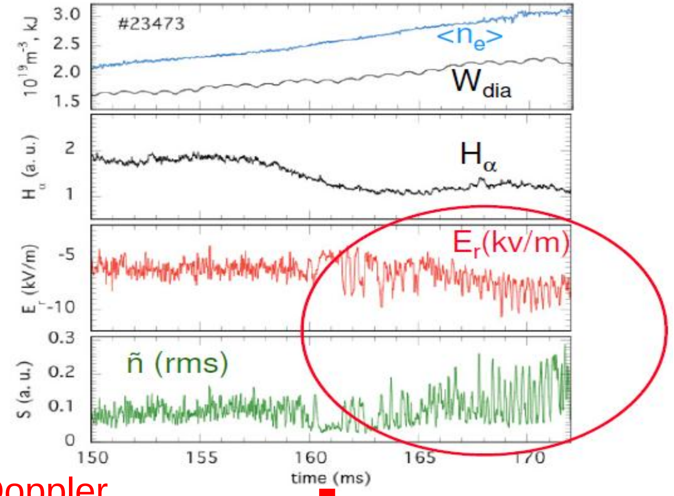
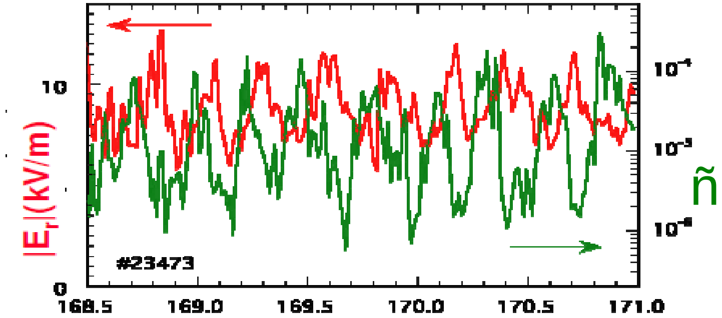


Doppler Reflectometry



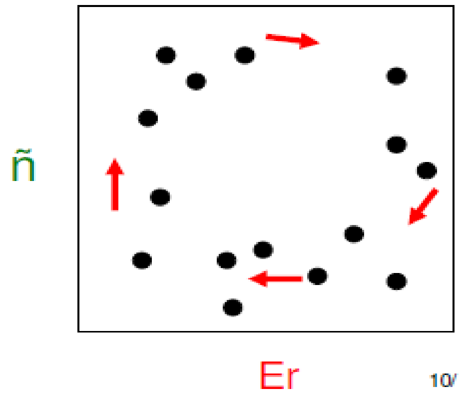
IAEA 2010 Estrada et al., EPL 2010, PRL 2011

Gradual transitions happen for P ~ $P_{treshold}$
Very useful for detailed analysis of L-H transition (LCOs)

Predator-prey oscillations observed between electric field and turbulence, Er following ñ

Similar predator prey behaviour observed in DIII D and AUG
Schmitz et al., PRL (2012), Conway et al., PRL (2011)

In 2013, HL-2A observes in addition the opposite trend (Er preceding ñ) , which leads to a different intrepretation
Cheng et al., PRL (2013)

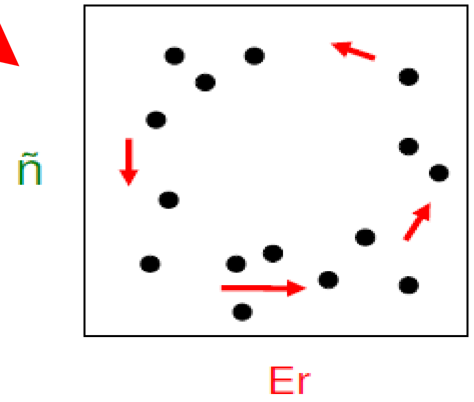


Clock-Wise

Turbulence trigger model

Counter Clock-Wise

∇p trigger model



L-H transition near the threshold:

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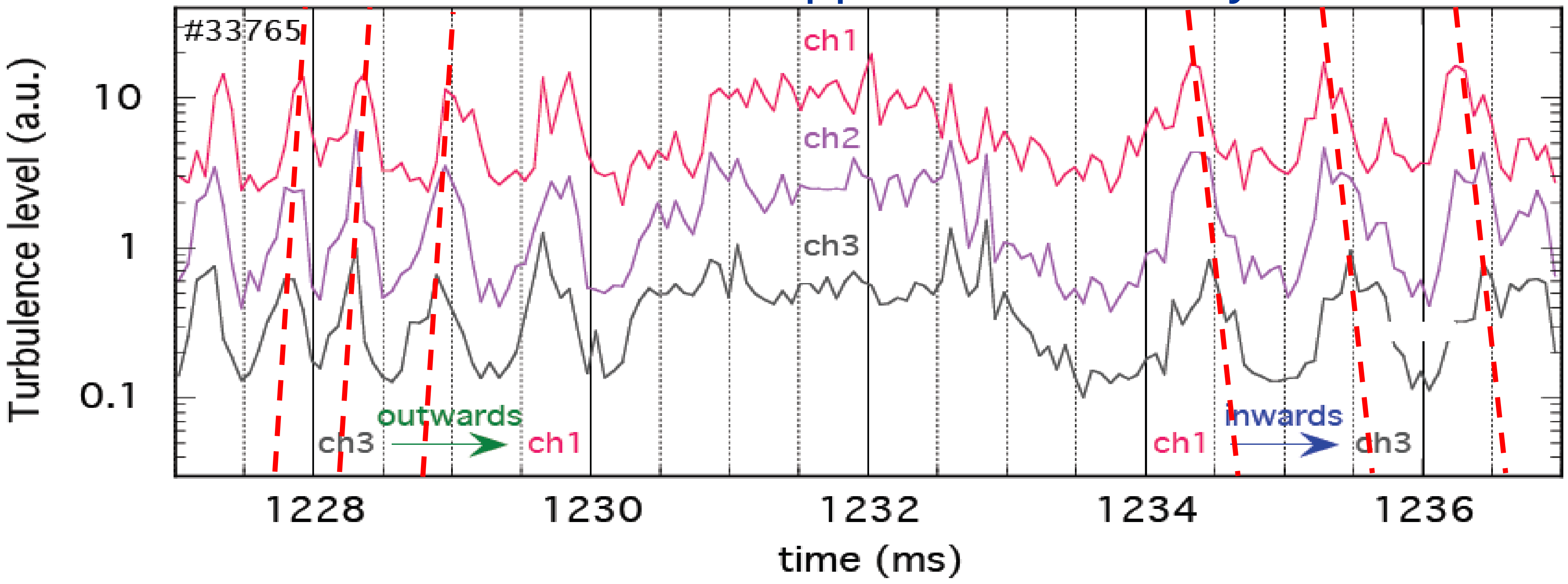
Experiments in TJ-II 2013-14: measure in three radial points simultaneously

Multichannel Doppler reflectometry



3-point measurement allow to measure:

- ✓ Propagation of the ñ and ExB flow modulation
- ✓ Measurement of the Er shear: dEr/dr (parameter actually relevant in the predator-prey model)

L-H transition near the threshold:

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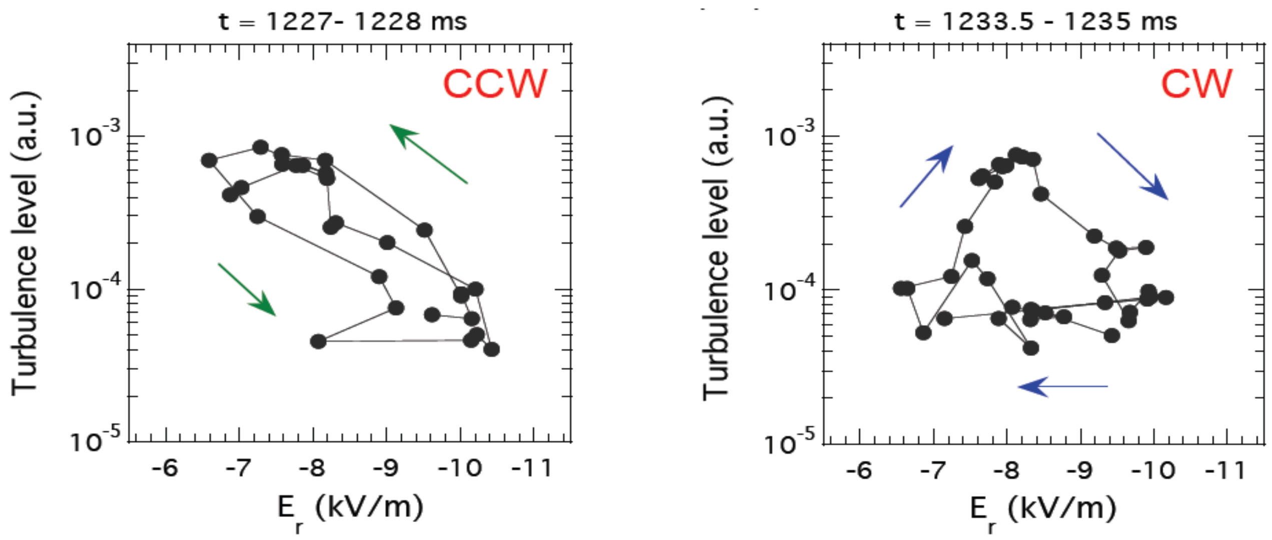
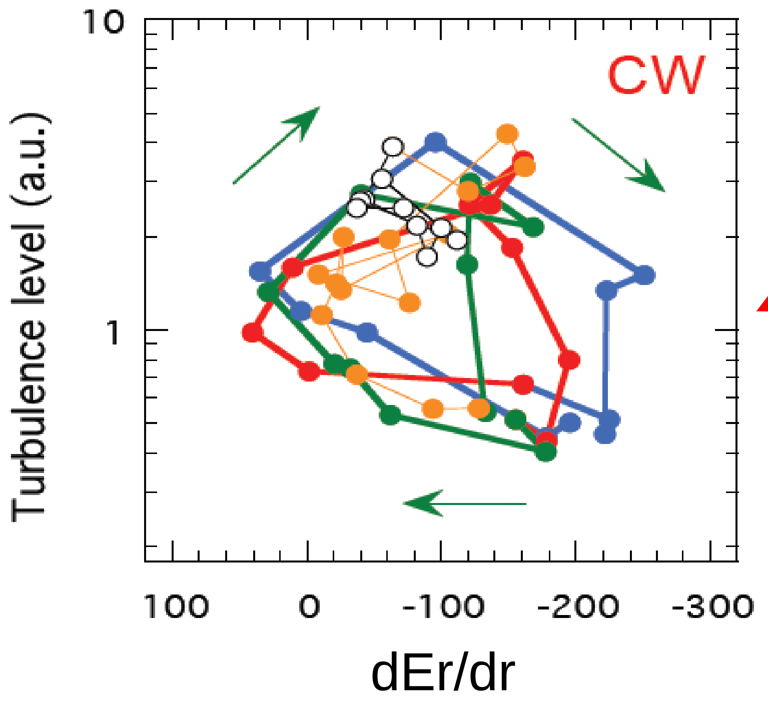


Using Er as x-axis: different rotation direction



Using Er shear (dEr/dr) as x-axis: single rotation direction: **Turbulence leads**

See Estrada et al., **IAEA 2014, EX/P4-47**

The isotope effect and multi-scale physics: a possible mechanism

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Larmor radius (ρ_s) dependence of turbulent structures
i.e. size of turbulent structures increases with ρ_s

$\rho_s \uparrow$ should have deleterious effects on transport:
The mystery of the isotope effect

Change in the k-spectra of turbulence

Zonal flow development by inverse energy cascades via ExB symmetry breaking

Beneficial effects on transport

Stronger in magnetic configurations with reduced damping of zonal flows: tokamaks vs stellarators

Long Range Correlation and H/D isotope effect:

Experiments

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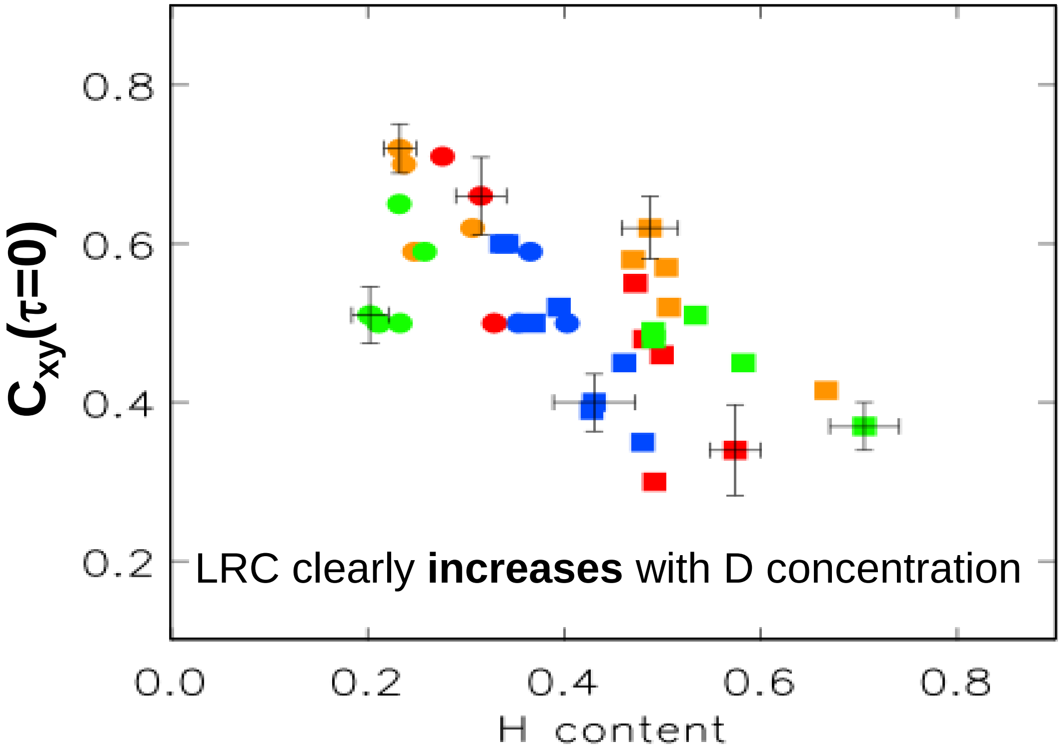
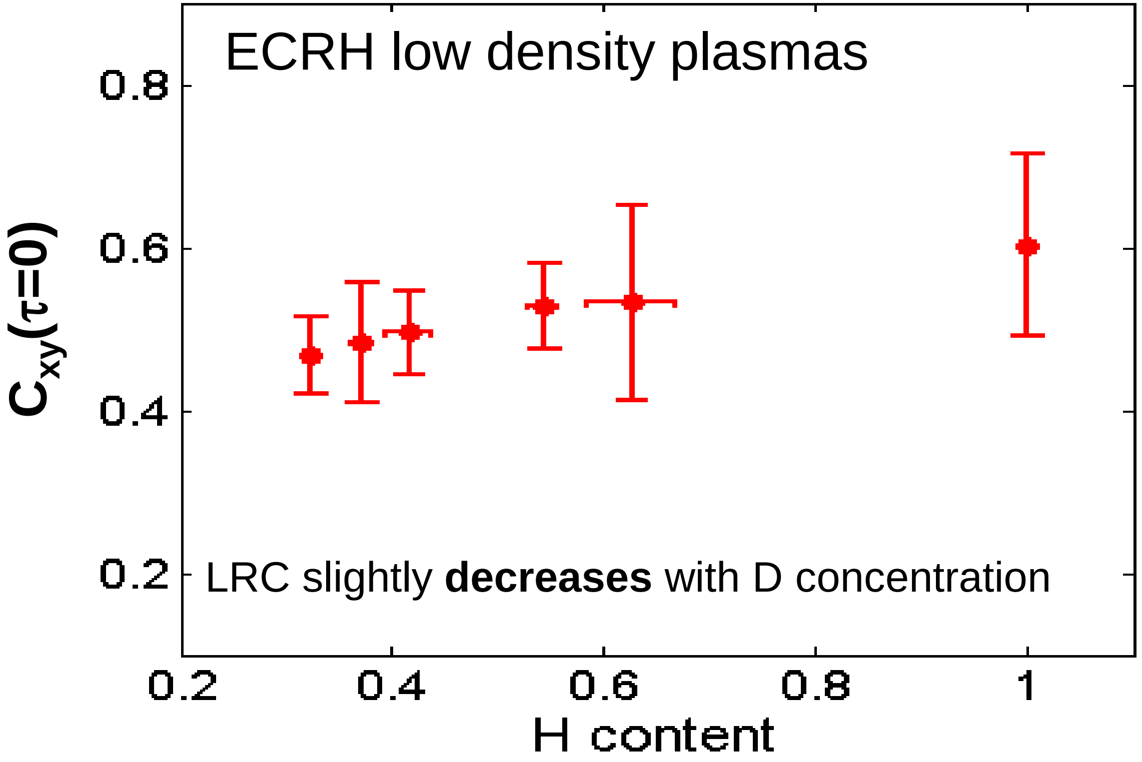
TEXTOR (Y. Xu, C. Hidalgo et al., PRL-2013)



TJ-II (B. Liu et al., EPS-2014, submitted PRL)



Experimental findings show **a systematic increasing in the amplitude of zonal flows during the transition from H to D dominated plasmas in TEXTOR tokamak but NOT in the TJ-II stellarator.**

FURTHER WORK: investigate the role of multiscale physics in the isotope effect

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Liquid Lithium Limiter: power loads and particle sources

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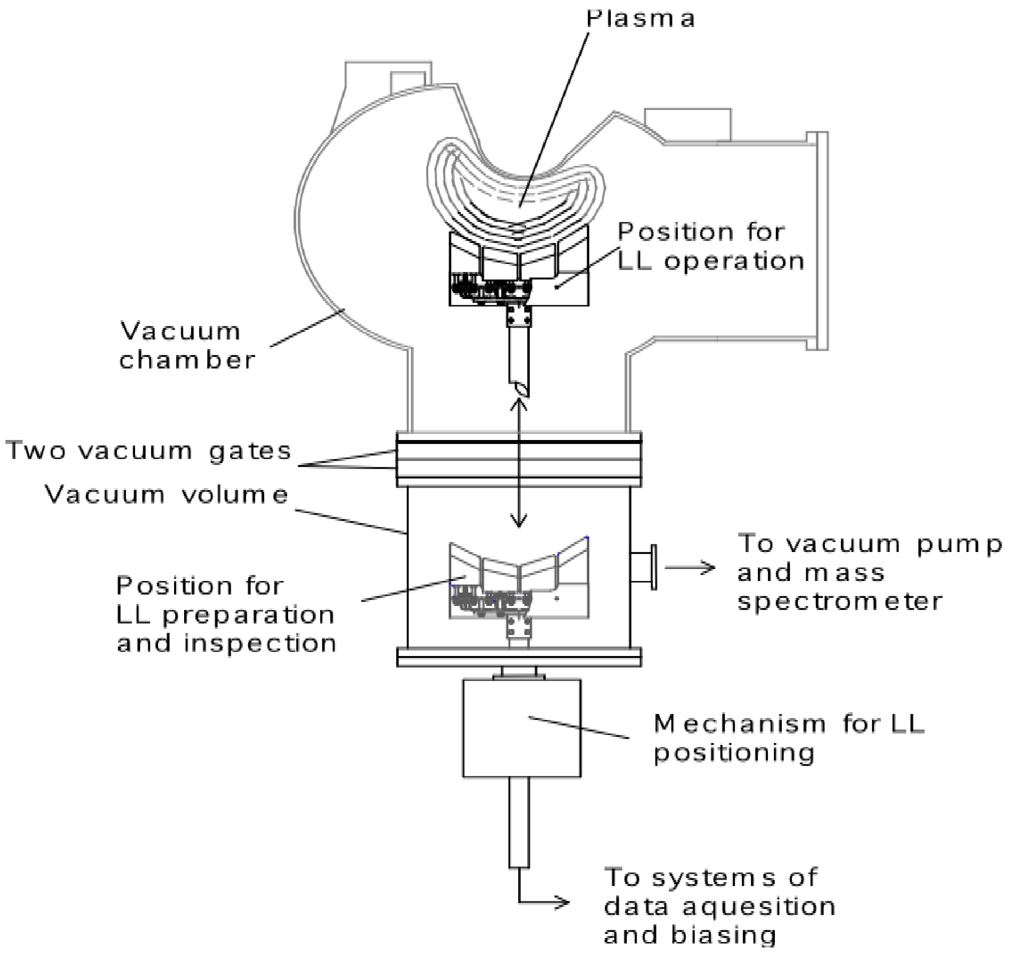
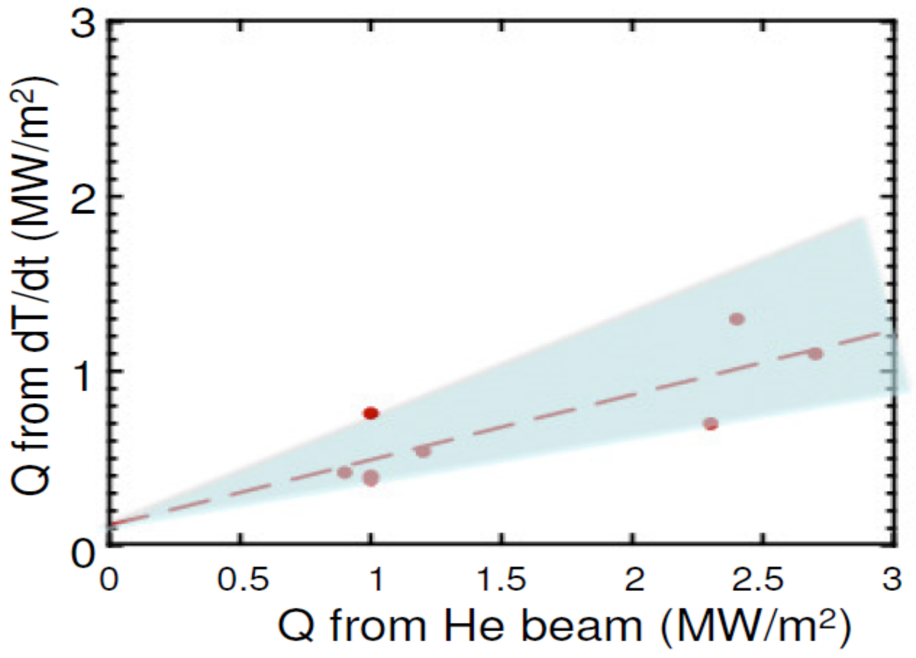
The TJ-II programme on liquid metals addresses fundamental issues like the self-screening effect of liquid lithium driven by evaporation to protect plasma-facing components against huge heat loads



Power loads to the limiters evaluated through the enhanced emission of Li atoms by evaporation.

Significantly lower power loads deduced compared to those derived from the edge parameters (He beam diagnostic.)

Q deduced from temperature rise *vs* Q from edge parameters (He beam)



F L Tabarés et al. PSI 2014

Liquid Lithium Limiter biasing experiments

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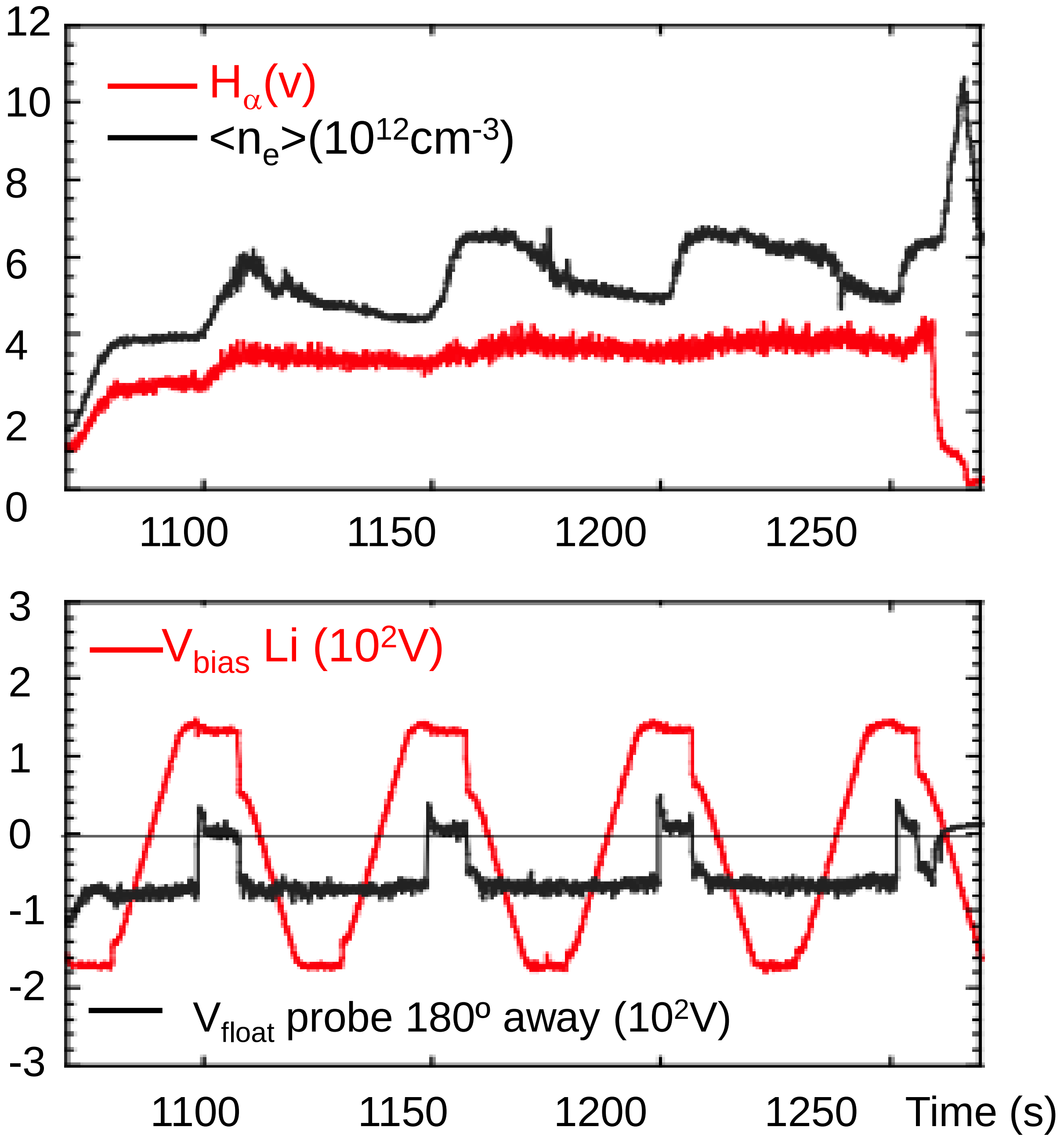

LLL biasing is more efficient in triggering plasma confinement improvement compared to carbon limiter

No deleterious effect due to the high power load induced on it was seen (deep penetration into edge plasma)

Edge voltage affected 180º toroidally away

F L Tabarés et al. PSI 2014

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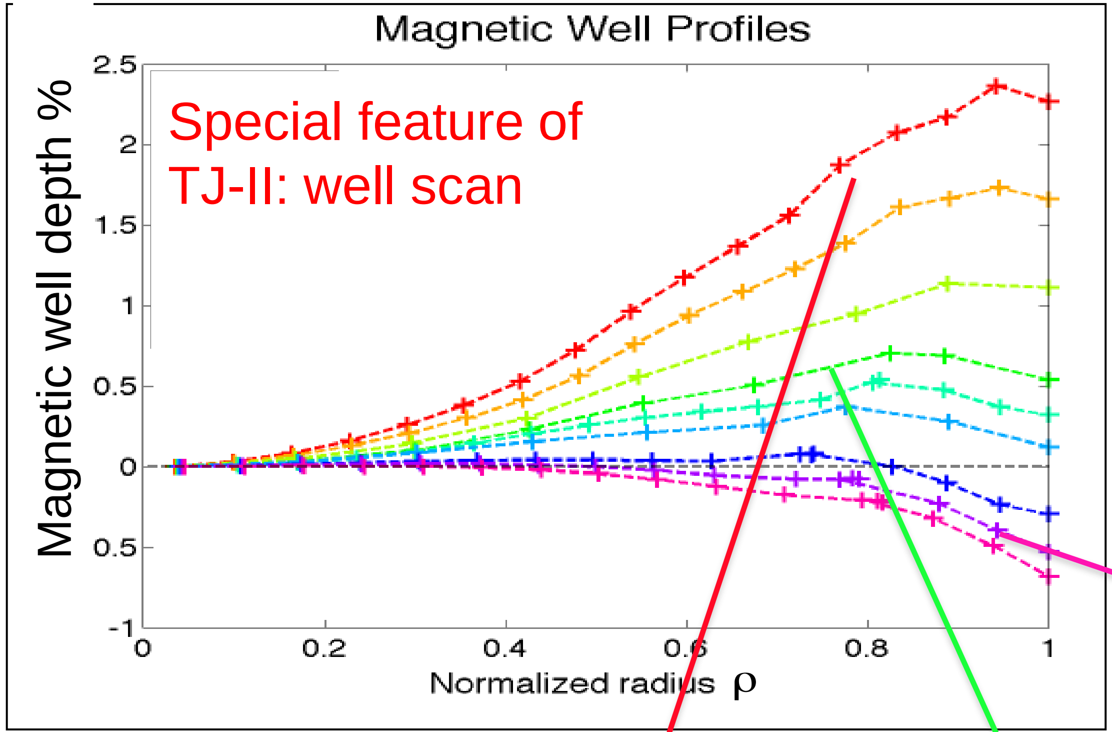
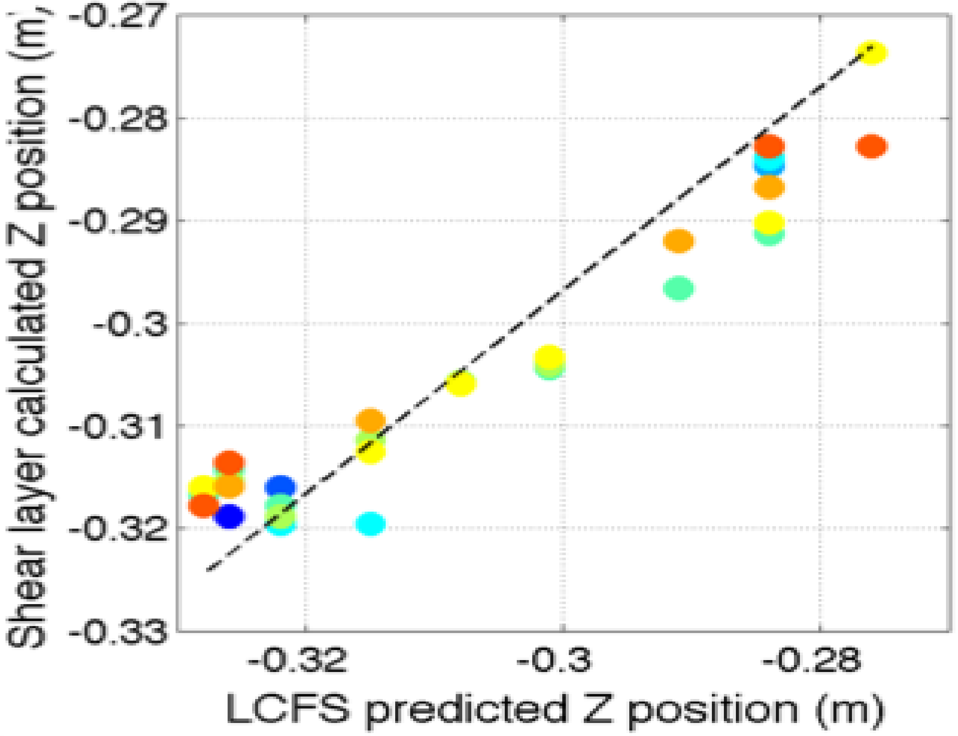
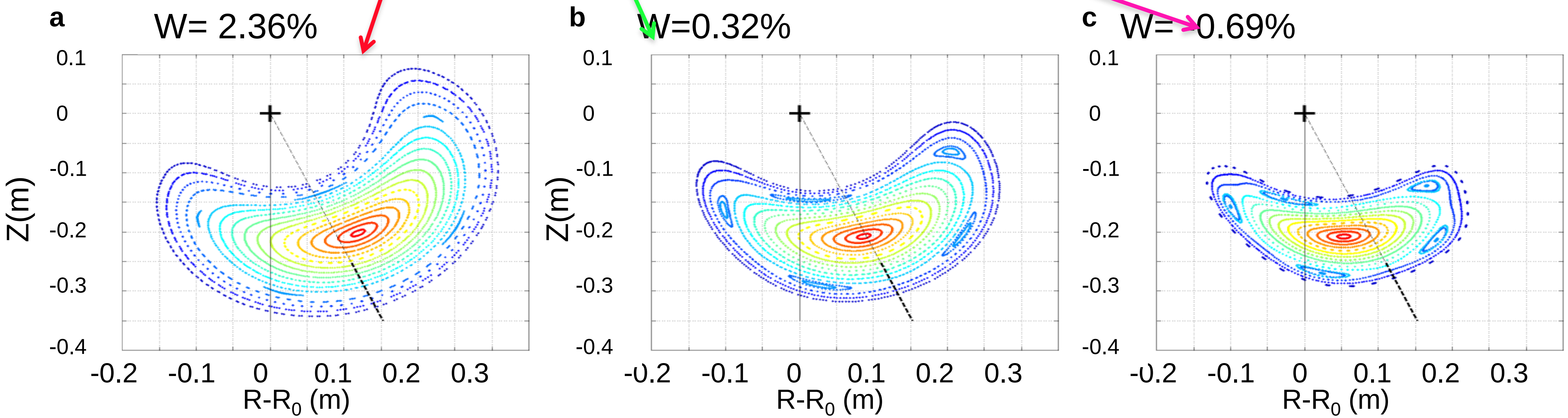
Magnetic well scan & Mercier stability



LCFS is linearly coupled to the edge shear location





Magnetic well scan: fluctuation levels and confinement

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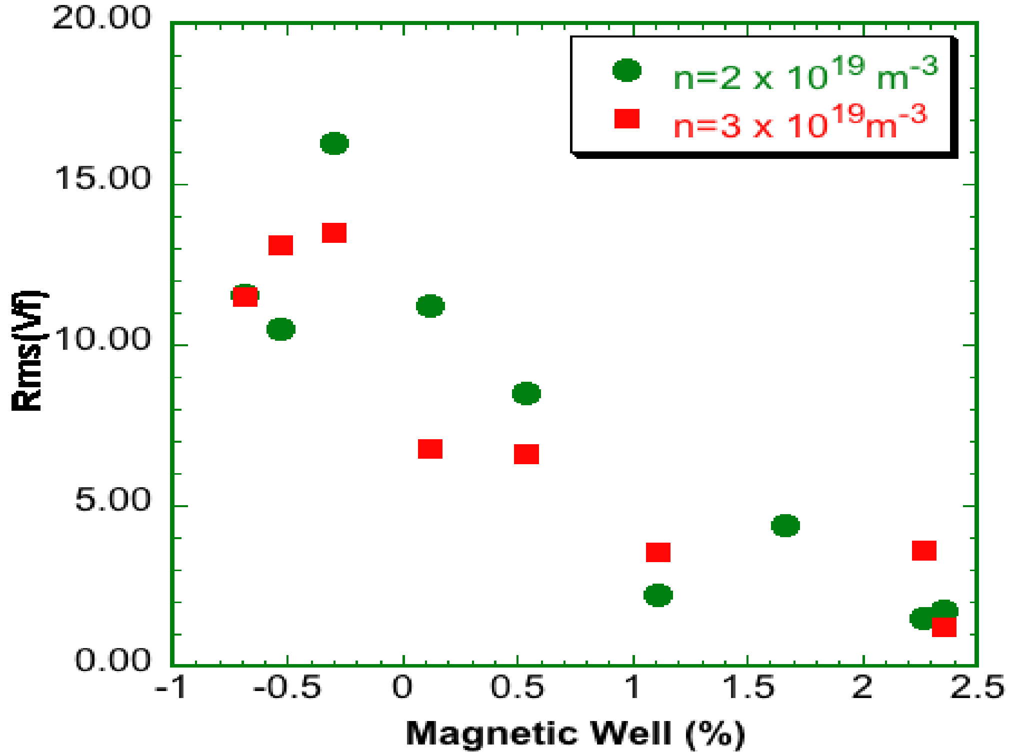
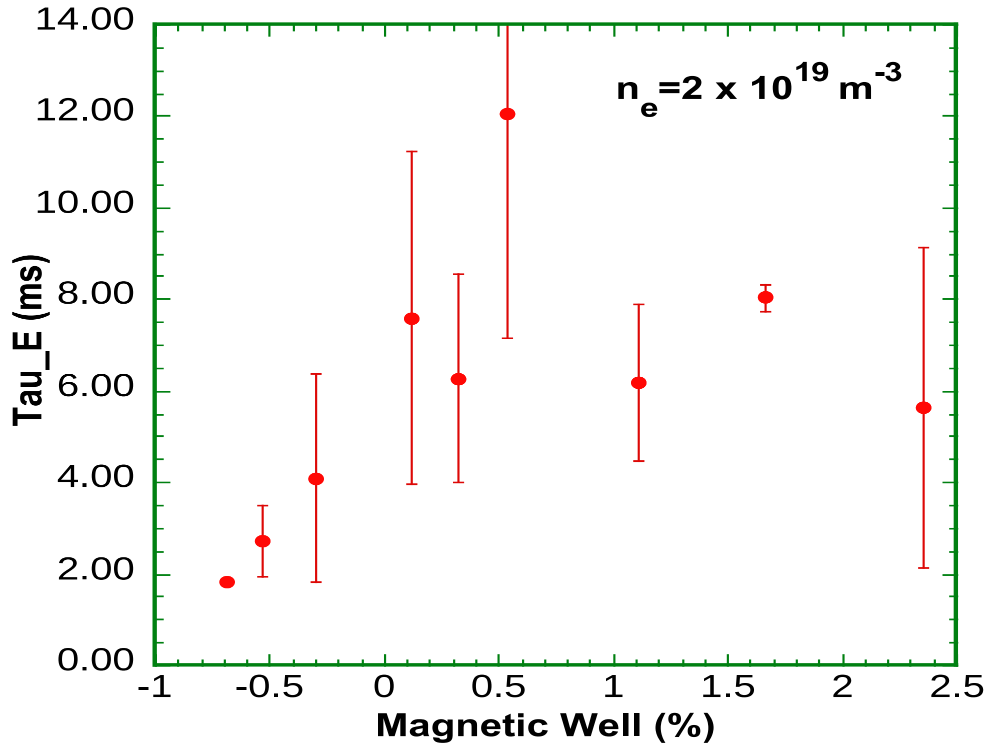


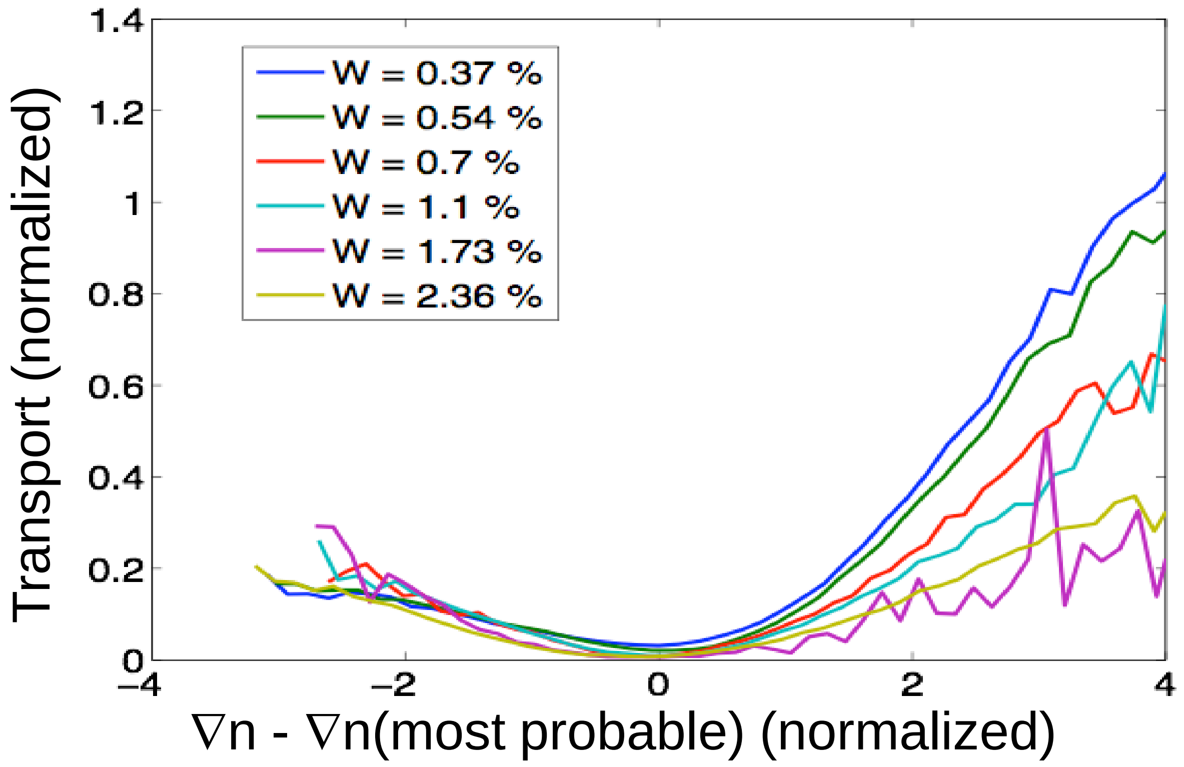


Experimental results have shown that TJ-II stellarator stability is better than standard stability analysis predictions. In particular plasma confinement is not strongly affected by magnetic well although the level of fluctuations increases in configurations without edge magnetic well.

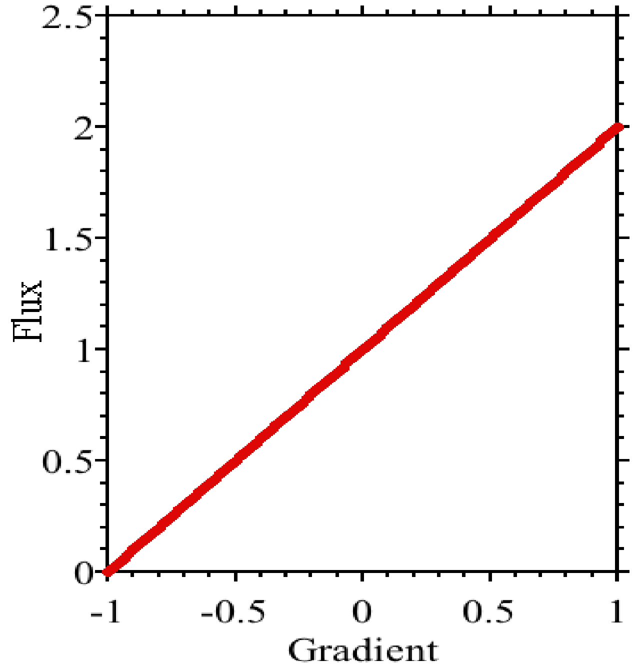
This result suggests that stability calculations, as those presently used in the optimization criteria of 3-D devices, might miss some stabilization mechanisms.

[**F. Castejón et al., IAEA-2014 EX/P4-45** / A. Martin de Aguilera et al., EPS-2014]

Dynamical coupling between gradients and transport vs magnetic well: role of non smooth profiles



FLUX GRADIENT RELATION FOR A LOCAL DIFFUSIVE PROCESS



Observations suggest that fluctuations are self-regulated in such a way that **the most probable density gradient minimizes the size of the radial turbulent transport events**

Stability calculations based on smooth profiles migth miss some stabilization mechanisms, which could be explained by self-organization mechanisms between transport and gradients

[B. Van Milligen et al., ICPP 2014, Hidalgo et al, PRL 2012]

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Fast particle control: Flexible ECRH heating and unique plasma diagnostic capabilities in TJ-II

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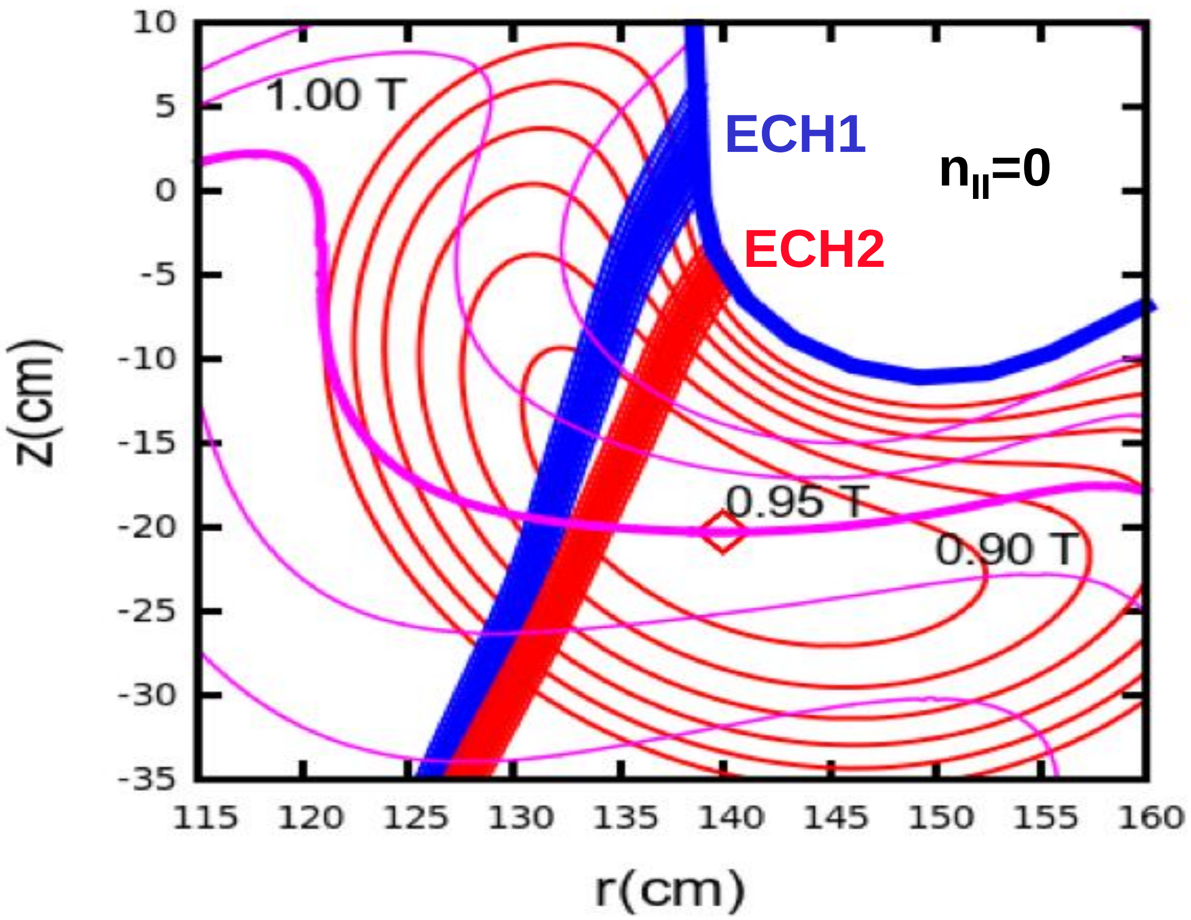
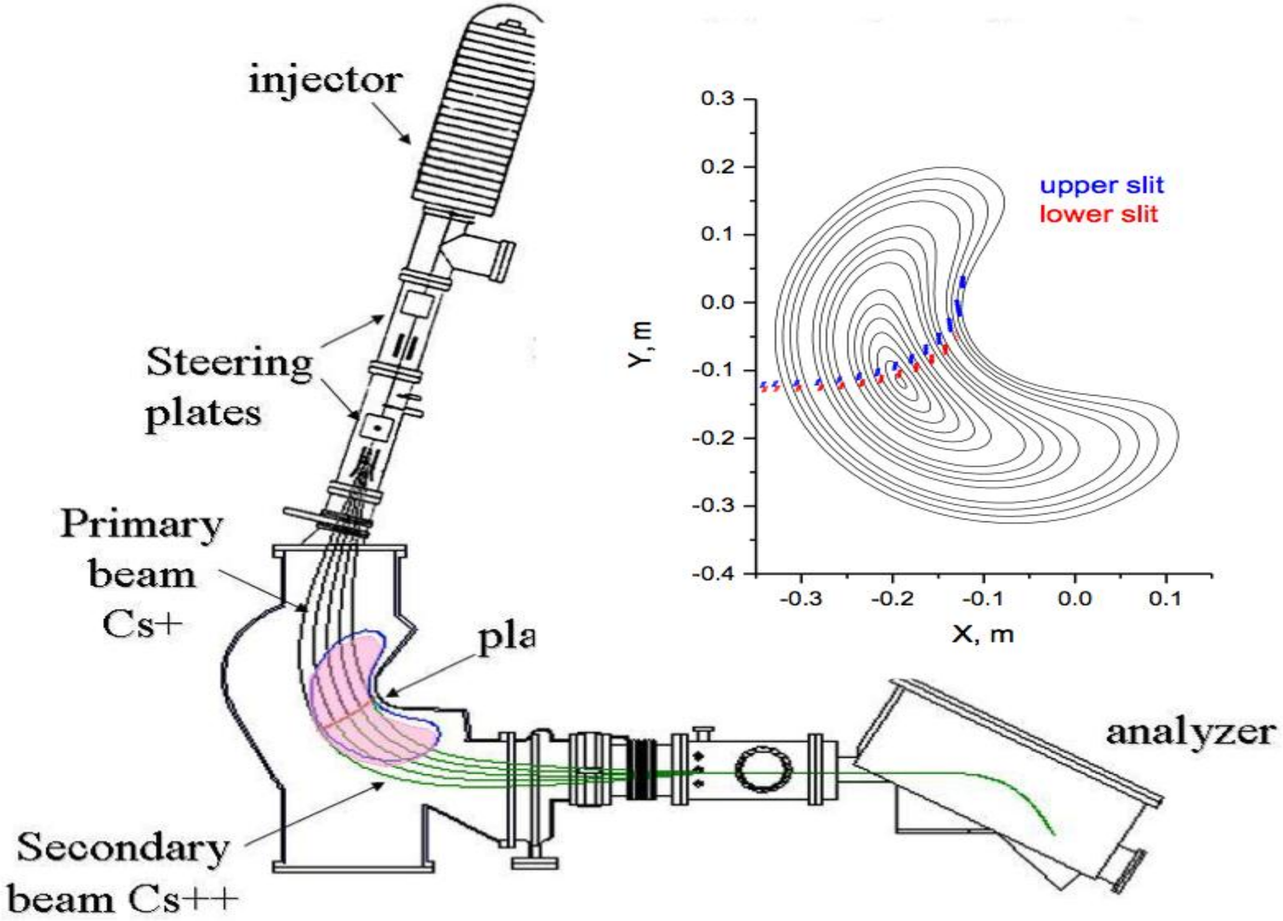


- ✓ Two 300 kW gyrotrons 2nd harmonic X mode
- ✓ Steerable system
- ✓ Beam size on-axis w_0 = 1 cm (strongly focused)

- ✓ Heavy Ion Beam Probe (potential, density and magnetic field fluctuations and profiles):
- ✓ HIBP in full operation (second HIBP in commissioning)



Alfven Eigenmodes: role of NBI / ECRH

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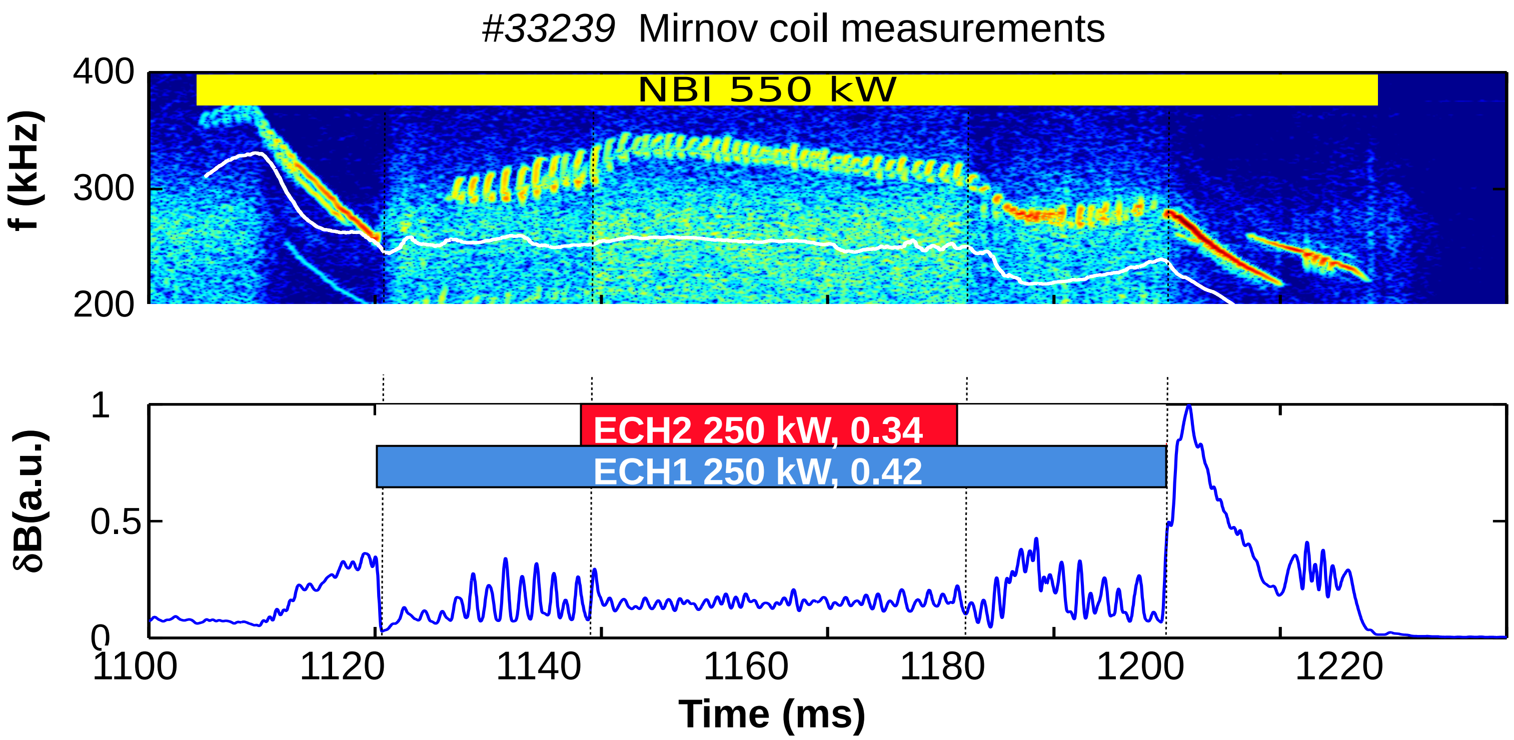

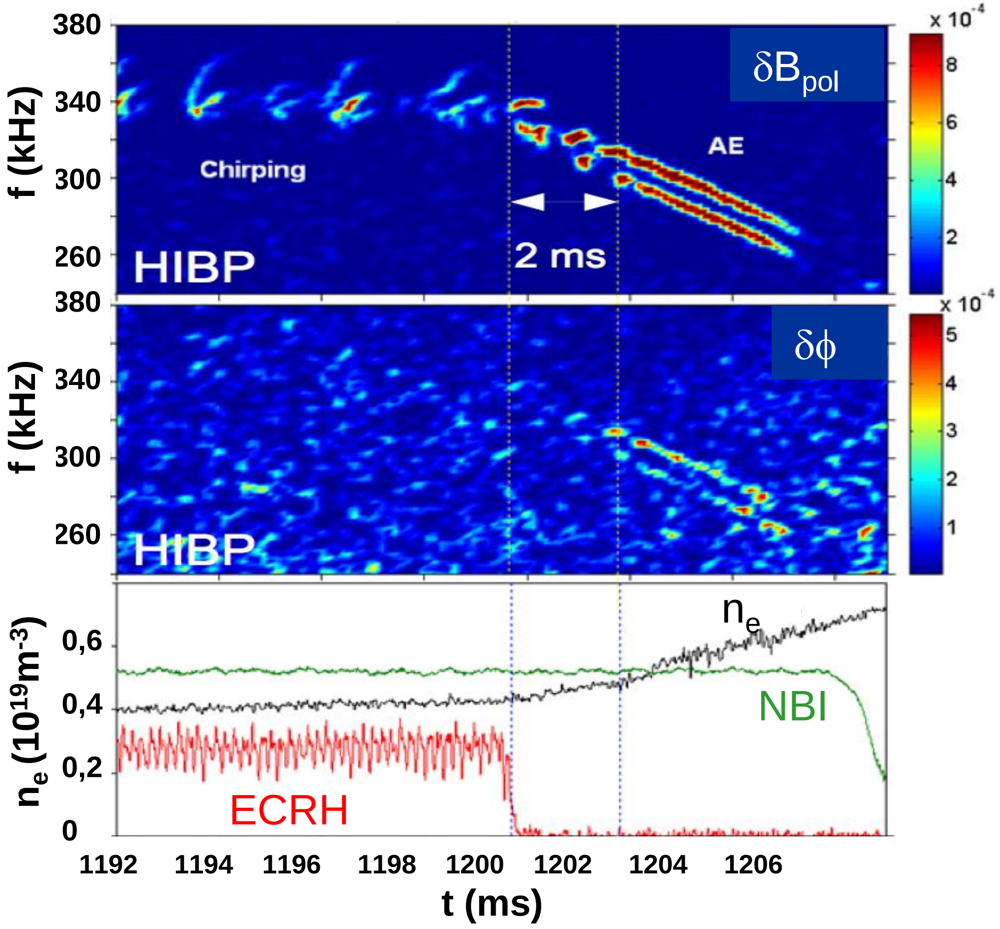

The mitigation effect of ECRH on NBI beam-driven Alfvén eigenmodes (AE's) reported in TJ-II suggests an attractive avenue for a possible control of the AE's.

K. Nagaoka et al., Nucl. Fusion 53 (2013) 072004/A

A. Cappa et al., IAEA-2014 EX/P4-46

CONCLUSIONS

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PARTICLE, ENERGY, IMPURITY TRANSPORT:

✓Direct **experimental evidence of potential flux surface asymmetries.**

✓**Impurity confinement depends on mass/charge.**

MOMENTUM TRANSPORT:

✓The temporal **ordering of the limit cycle oscillations** at the L-I-H transition **linked to the radial propagation direction** show **leading role of turbulence**.

✓Evidence of the importance of **multi-scale physics on isotope effect**

POWER EXHAUST PHYSICS:

✓**Self-screening effect of liquid lithium** driven by evaporation **to protect plasma-facing components** against huge heat loads. LLL biasing is more efficient in plasma confinement improvement compared to carbon limiter.

PLASMA STABILITY STUDIES:

✓**Stability calculations based on smooth profiles migth miss some stabilization mechanisms**, which could be explained by **self-organization mechanisms between transport and gradients**

FAST PARTICLE PHYSICS:

✓Upon moderate off-axis ECH power application, the continuous character of the AEs changes significantly and starts displaying frequency chirping modifying the mode amplitude. This result shows that **ECH can be a tool for AE control**.

Back-up

Measurements and modelling of impurity flows

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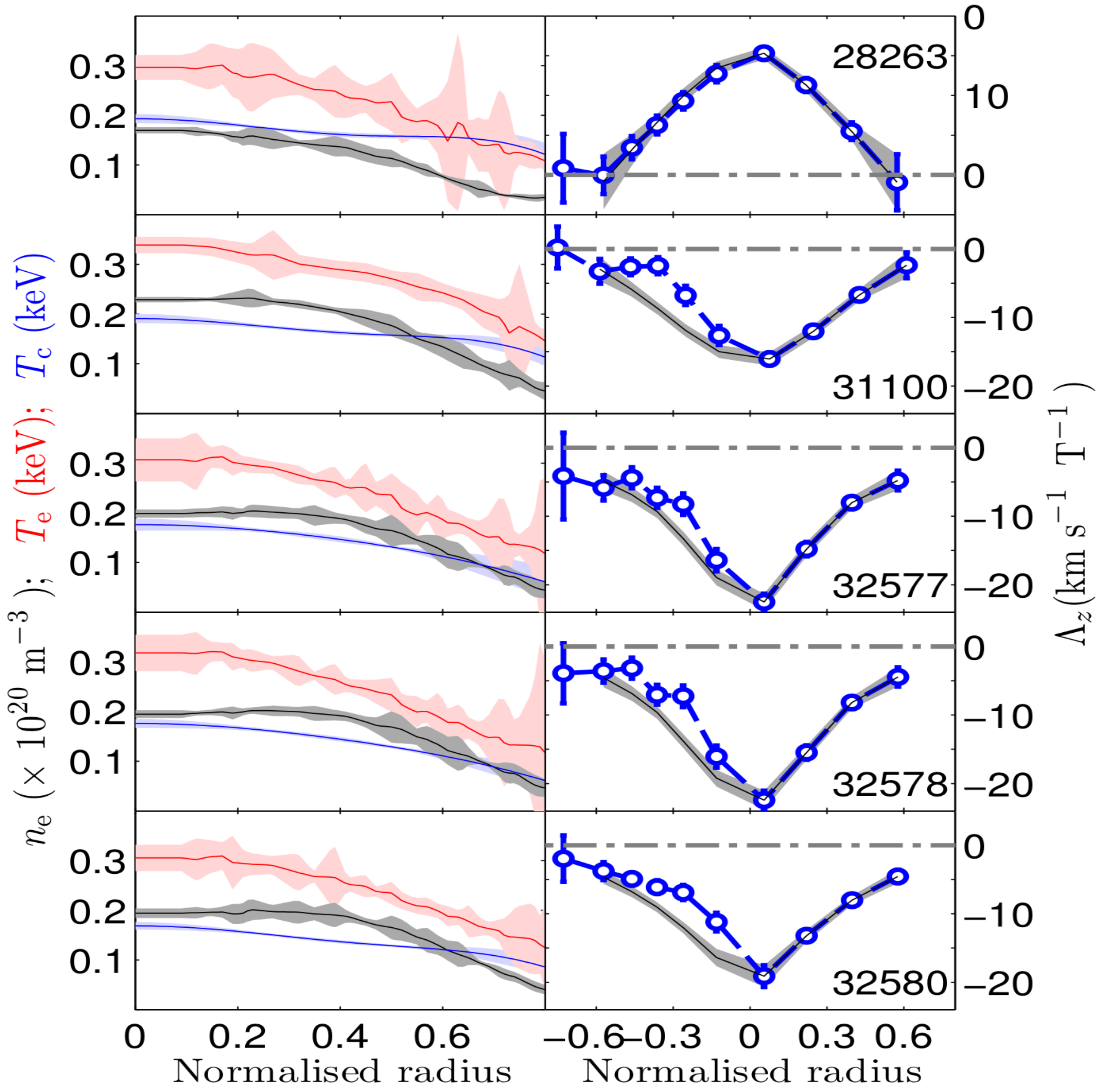
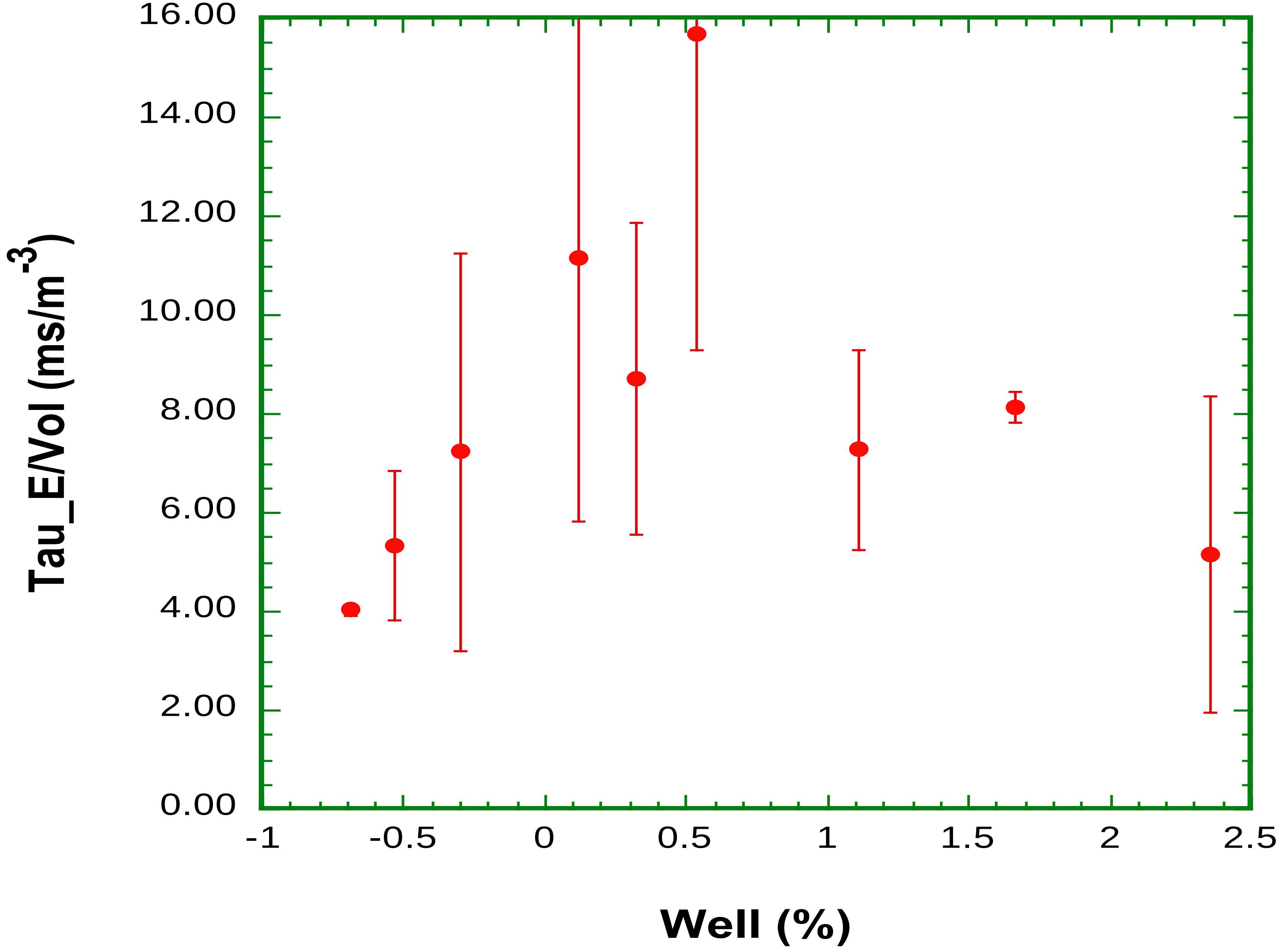


Flow measurements (C6+) showed an **incompressible parallel flow pattern in ECRH and low-density NBI** conditions (Fig. top). At **higher densities systematic flow deviations are observed** (Figs bottom).

Modelling resulted in density variations of 20-30 % for these higher density NBI plasmas and return parallel flows of the correct size (~ 5 km/s). However, flow correction was predicted to be of opposite sign to that observed in experiments.

J. Arévalo , J., et al., Nucl. Fusion **53** (2013) 023003 / Nuclear Fusion 54 (2014) 013008.

Confinement time: Magnetic well and volume



Scaling laws predict a linear dependence of confinement time with volume.

$\tau_E \;\alpha\; a^2 \;\alpha$ Volume

To distinguish the effects of magnetic well and volume, we estimate τ_E / Vol. The same behaviour as before.