EUROfusion

3D effects on transport and plasma control in the TJ-II stellarator

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Contributors & the TJ-II Stellarator

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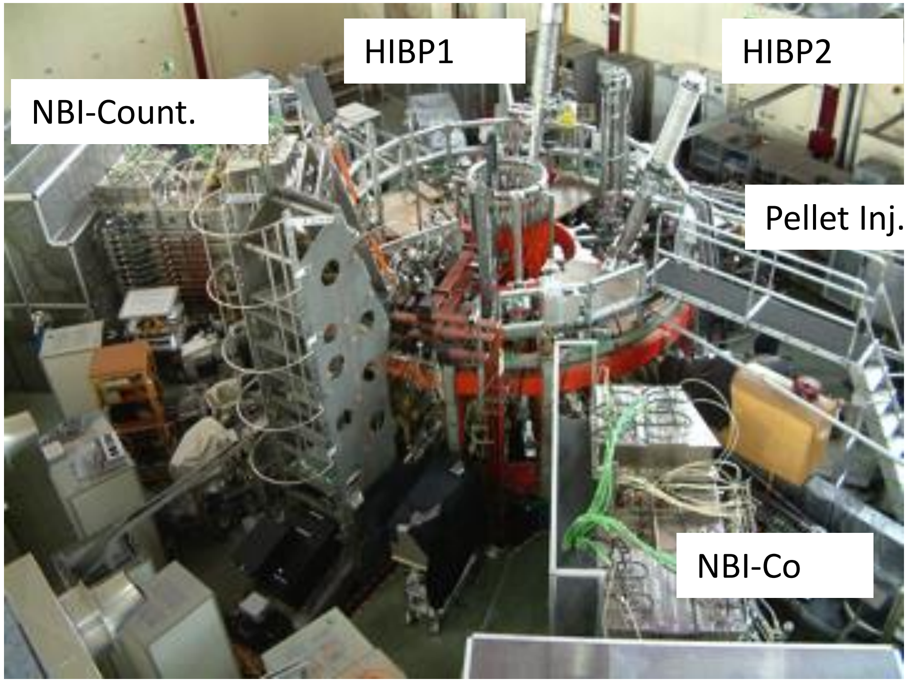

TJ-II Heliac
$B(0) < 1.2$ T; R=1.5 m, a<0.22 m
$0.9 < \iota/2\pi < 2.2$
ECRH (0.3 + 0.3 MW);
NBI (0.6 + 0.6 MW) co- and counter injection
MEASUREMENTS: rake Langmuir Probe, dual HIBP, Mirnov coils, fast bolometers and Doppler reflectometer

Outline

- Motivation
- Impurity transport
- Plasma fuelling results
- Plasma stability studies
- Flows and electromagnetic effects
- Controlling fast particle confinement: Role of ECRH and magnetic configuration
- Innovative power exhaust scenarios using liquid metals (not 3D-specific)
- Conclusions

Motivation

- **3D Geometry** relevant for Stellarators and Tokamaks (TBM, RMP, Islands,…). => Physics and simulation methods
- **NC Transport Enhanced and onset of ambipolar Er. => Impact on Fuelling and Transport:**
  - **Fuelling -> Pellets**
  - **Impurity Transport.**
- **Dispersion Relation of waves and instabilities => Changes in AEs, GAMs,…**

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Avoiding Impurity Accumulation

Impurity accumulation is an issue in stellarators (NC effect in ion root)

$$\Gamma_I = -n_I L_{11}^I \left(\frac{n'_I}{n_I} - \boxed{\frac{Z_I e E_r}{T_I}} + \delta_I \frac{T'_I}{T_I} \right)$$

Nevertheless, experiments w/o accumulation:

Mode HDH in W7-AS and K McCormick et al. PRL 2002

Impurity Hole in LHD. M Yoshinuma et al. NF 2009

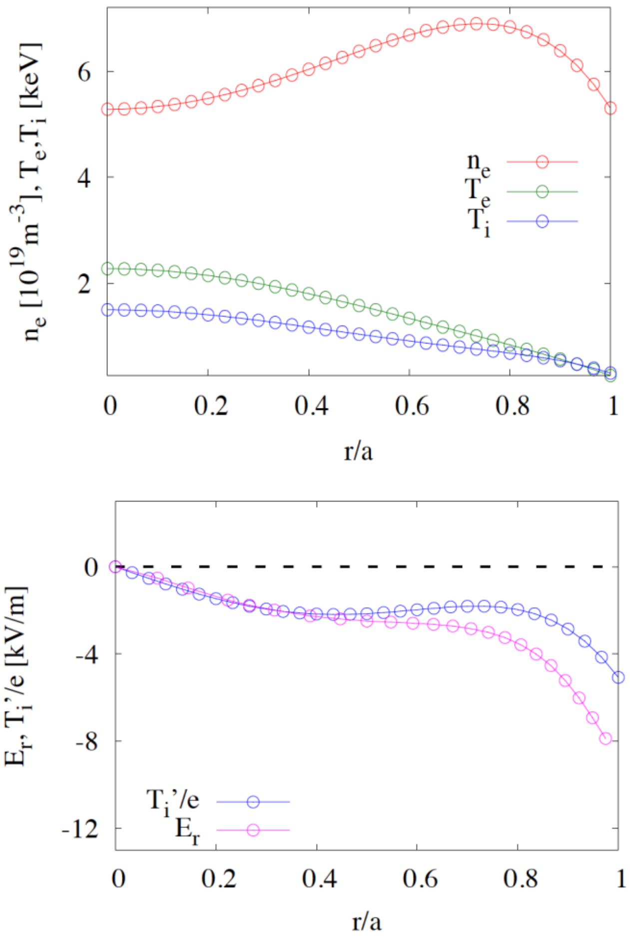
Look for regimes without impurity accumulation:

- Revisit impurity hole

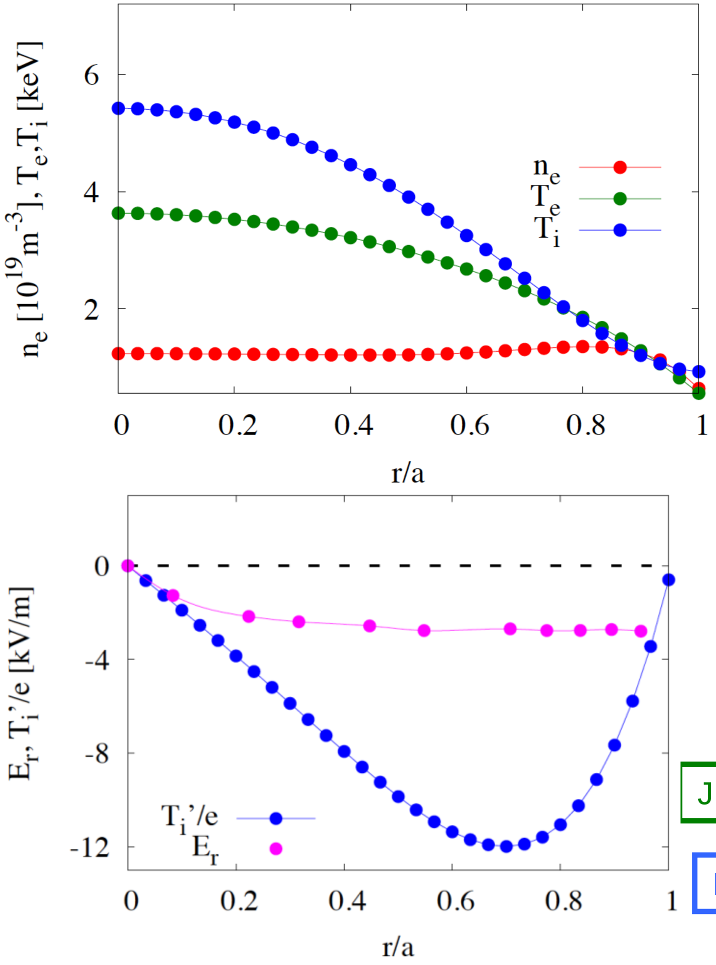
- 3D NC calculations predict that asymmetries in potential modify the impurity flux. J. M. García-Regaña et al., PPCF 2013

Moderation of impurity accumulation in impurity hole plasmas

Ion Root



Impurity Hole



Electric field is negative but small in Impurity Hole conditions,

despite the large grad(Ti).

$$\Gamma_I = -n_I L^I_{11}\left(\frac{n'_I}{n_I} - \frac{Z_I e E_r}{T_I} + \delta_I \frac{T'_I}{T_I}\right.$$

Because of this, the outward and inward pinches are almost balanced. Resulting in a small inward impurity flux.

J. L. Velasco et al., NF 2016, In press

Nunami TH/P2-3

Additional terms could play a relevant role: **turbulence, asymmetries,**…

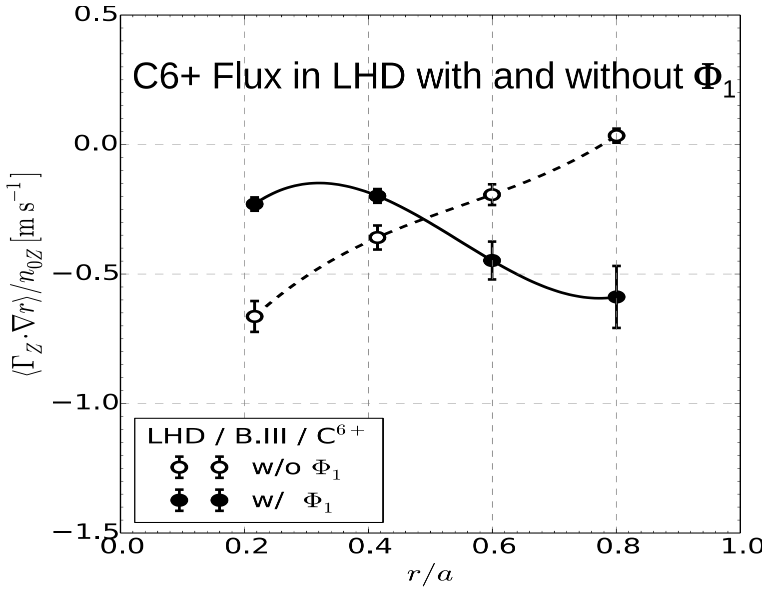
Empirical actuators to try to make Er more positive (less negative): ECRH.

Potential Asymmetries influence Impurity Transport

$$\Gamma_I = -n_I L_{11}^I \left(\frac{n'_I}{n_I} - \frac{Z_I e E_r}{T_I} + \delta_I \frac{T'_I}{T_I} \right)$$

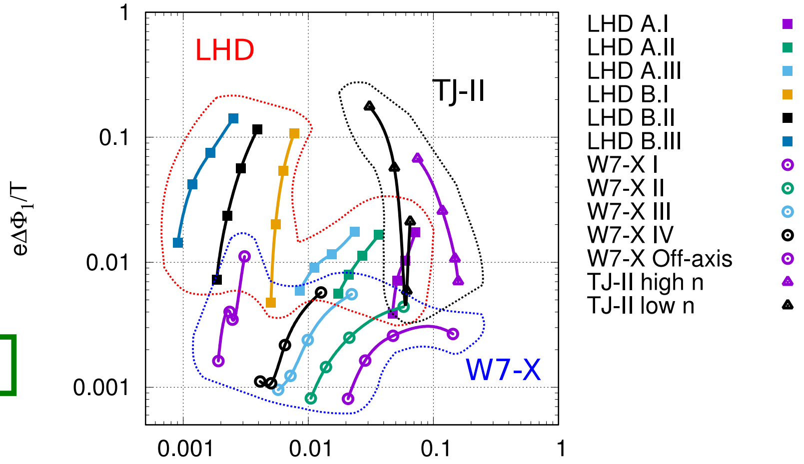
- Impurities are more sensitive to Er than bulk ions (charge state).

- An asymmetric first order potential (usually neglected in NC calculations) Φ_1 is calculated using the EUTERPE code.
- Φ_1 has effects on impurity transport: reduce impurity accumulation in LHD.

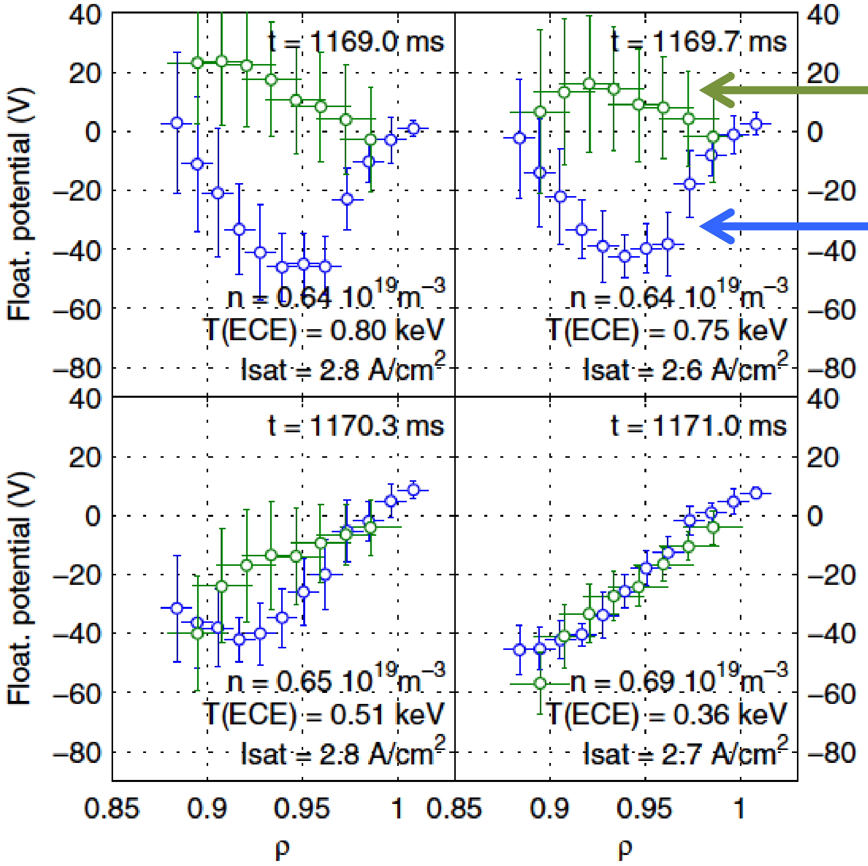


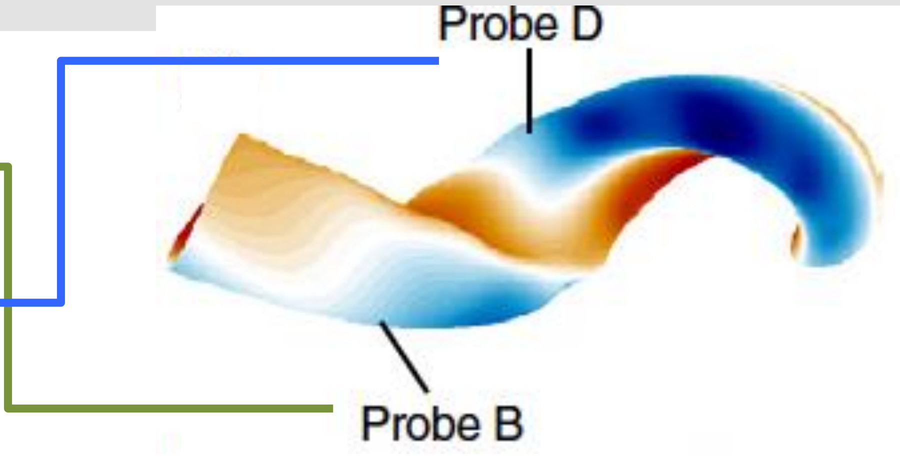
- Calculated asymmetries pronounced in TJ-II: CAN BE DETECTED

J. M. García-Regaña et al., Submitted to PPCF 2016



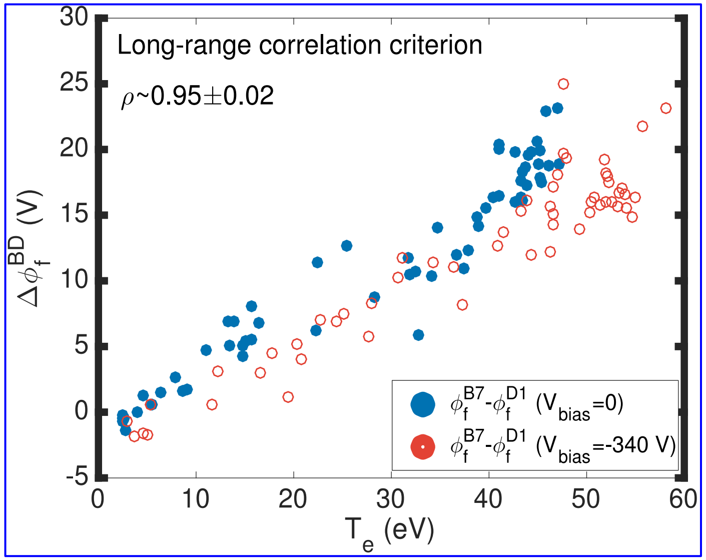
Asymmetries of potential do exist in TJ-II





Poloidal/ toroidal potential variation in the order of 10 – 40 V.

M. A. Pedrosa et al., NF 2015



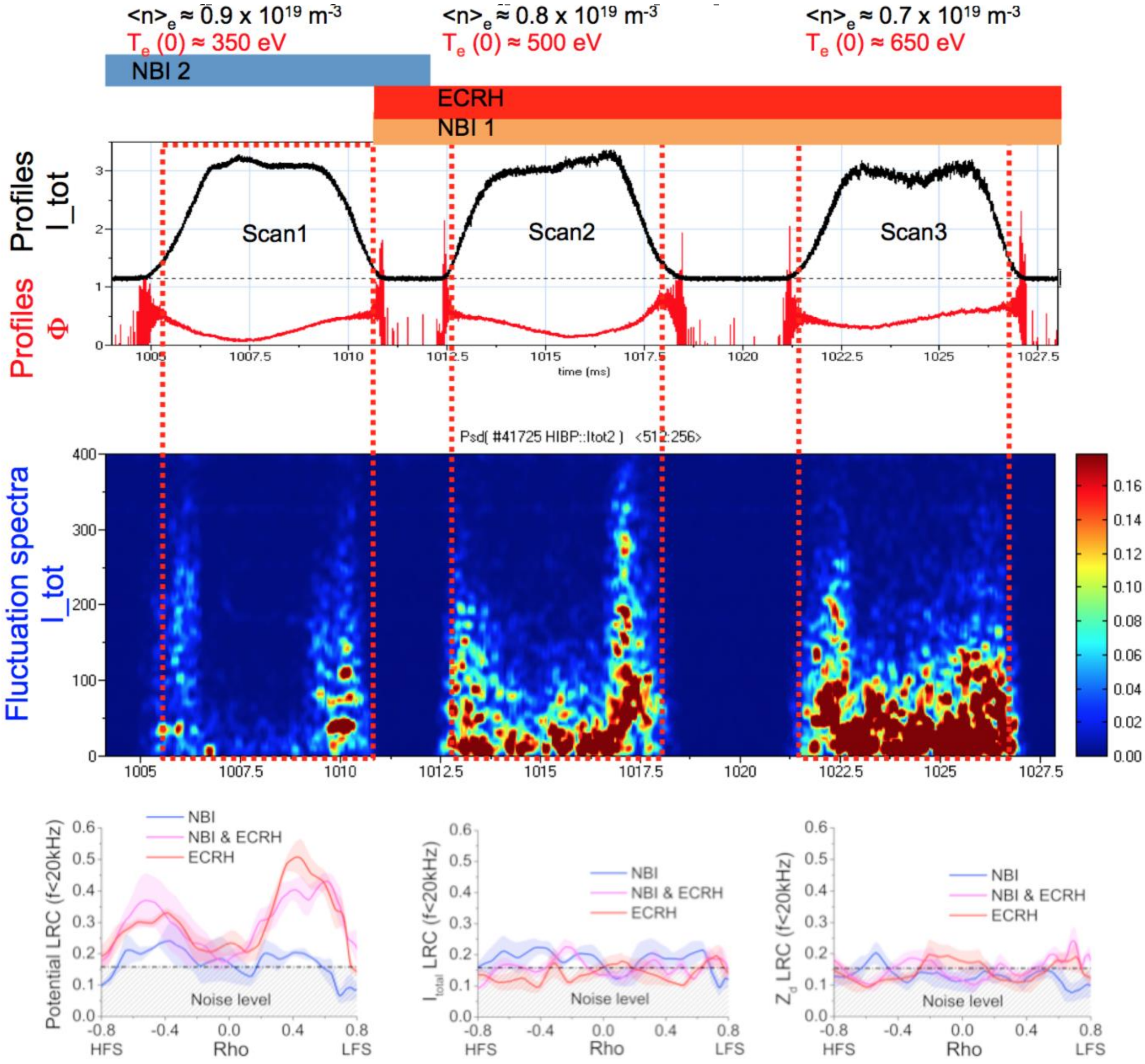
Poloidal / toroidal asymmetries decrease when temperature decreases.

Empirical actuators: ECRH makes Er less negative

- ECRH: Er less negative.
- The sign of Er depends on density and power.

- ECRH+NBI plasmas: higher turbulence level than in NBI.
- Dual HIBP: LRC found (at ρ=0.6) in potential but not in Density or Bpol fluctuations.

C. Hidalgo et al. EXC / P7-44



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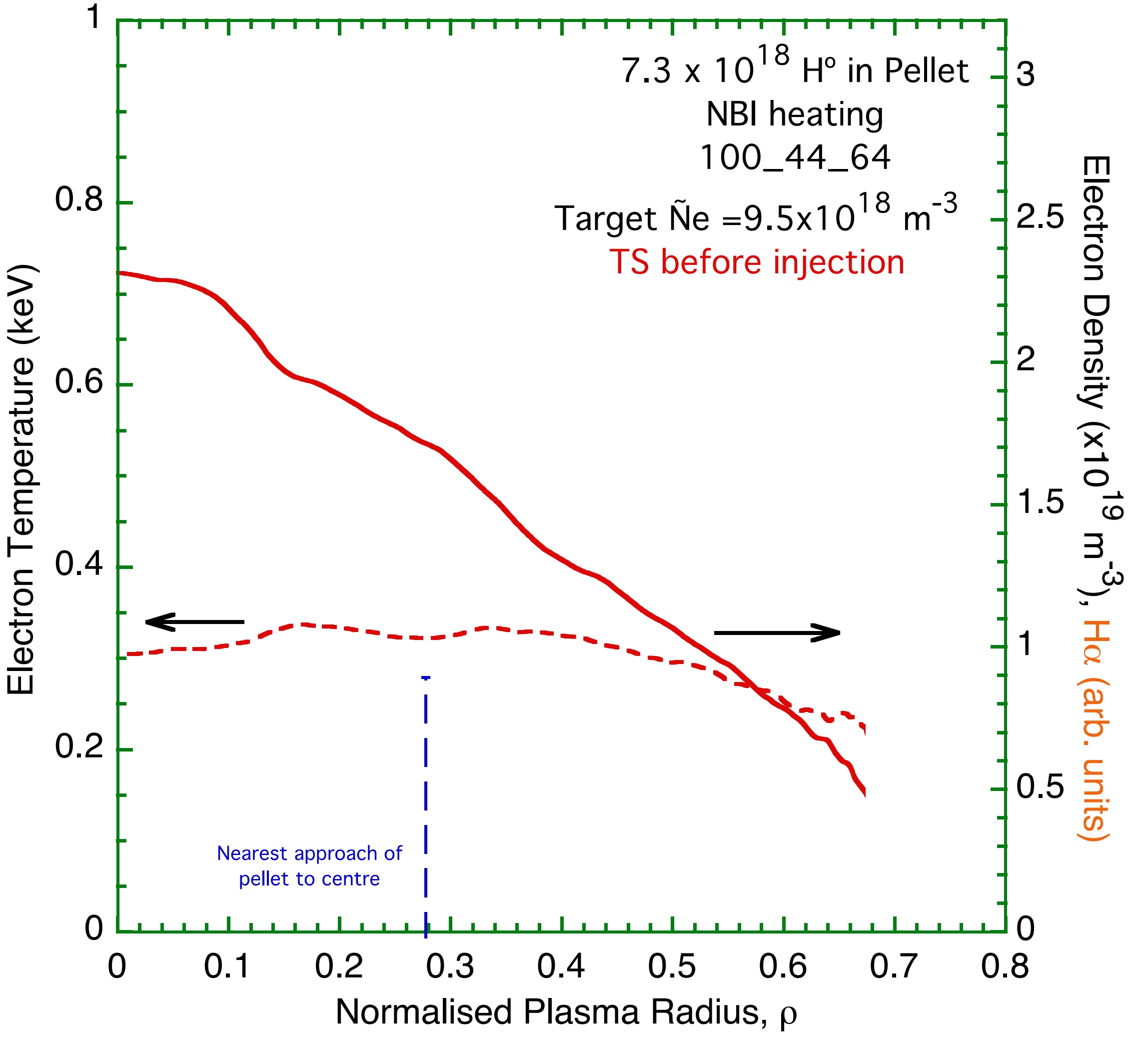
Fuelling plasma core in 3D devices



- Hollow density profiles appear in 3D devices (also in tokamaks) when Te high --> Core Fuelling Difficulties.

H. Maaßberg et al. PPCF 1999

- Injecting a pellet in TJ-II NBI plasmas.
- Follow electron density profile after injection using the Thomson Scattering system.
- Set of reproducible discharges.

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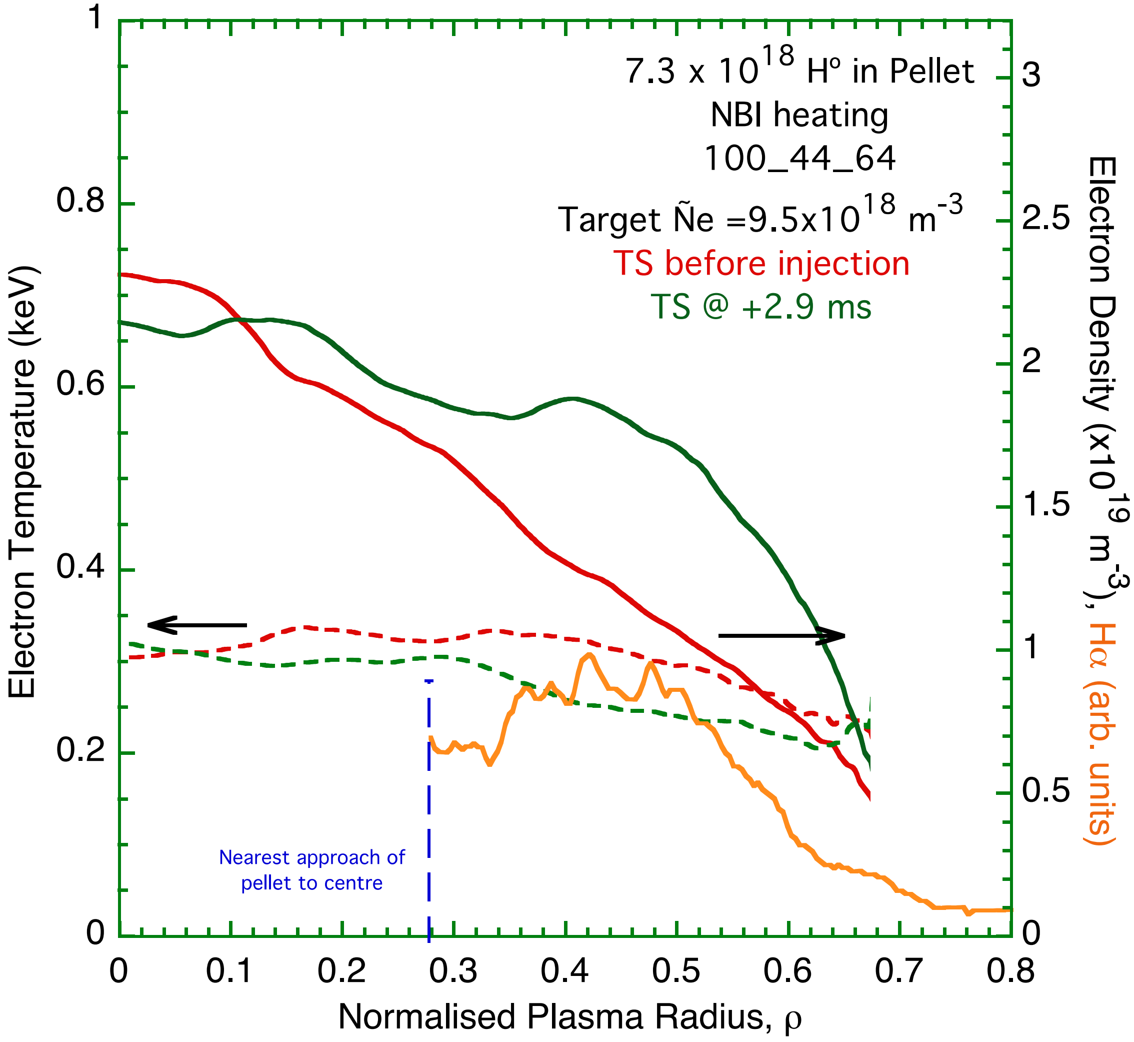
Fuelling plasma core in 3D devices



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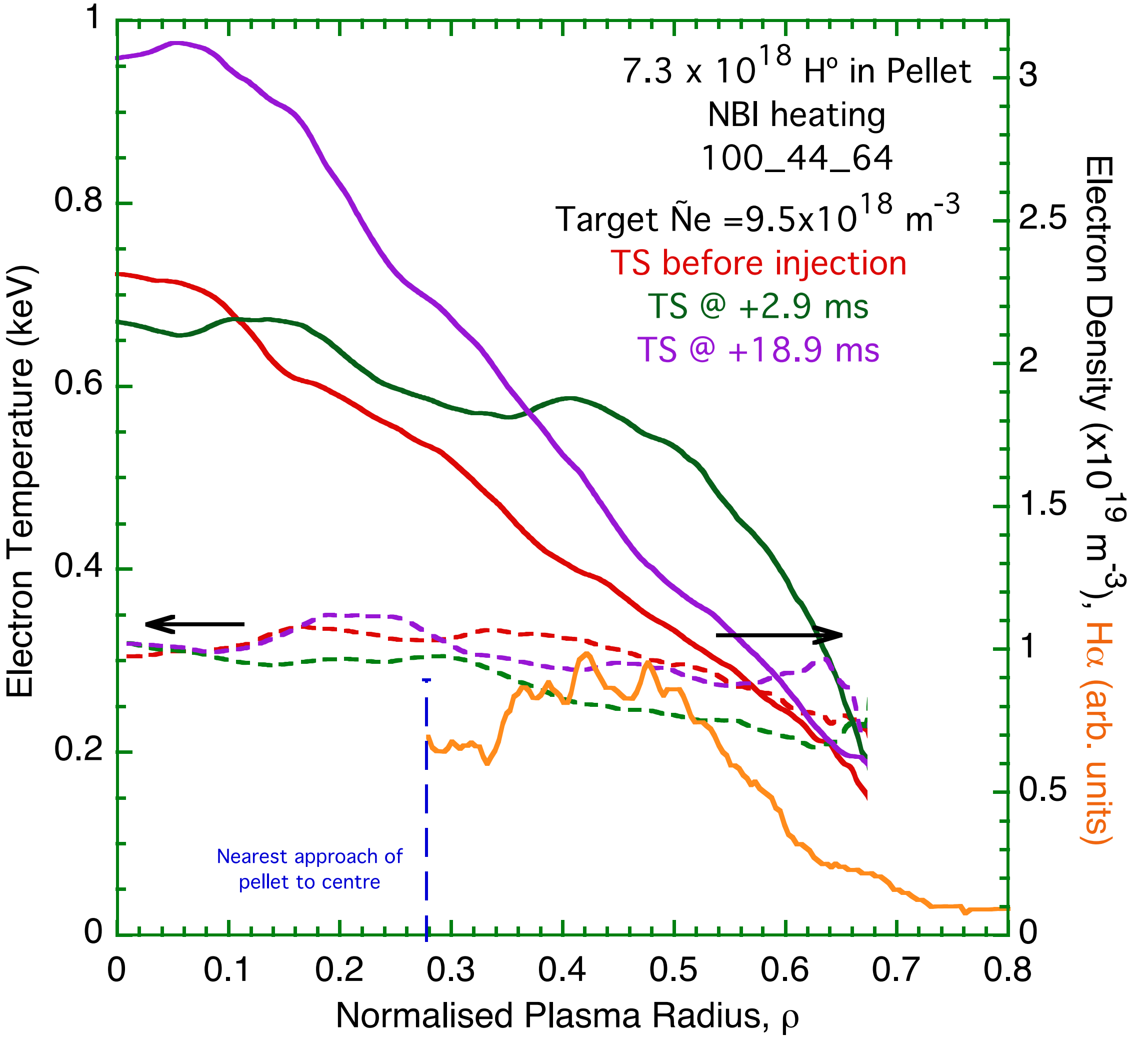
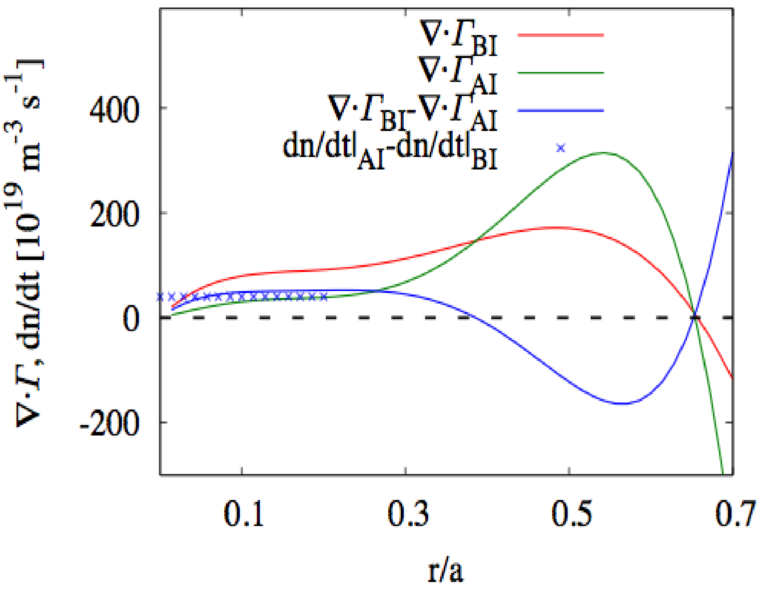
Fuelling plasma core in 3D devices



-**Core Plasma Fuelling** in NBI plasmas, despite outside ablation.



J. L. Velasco *et al.*, PPCF 2016.

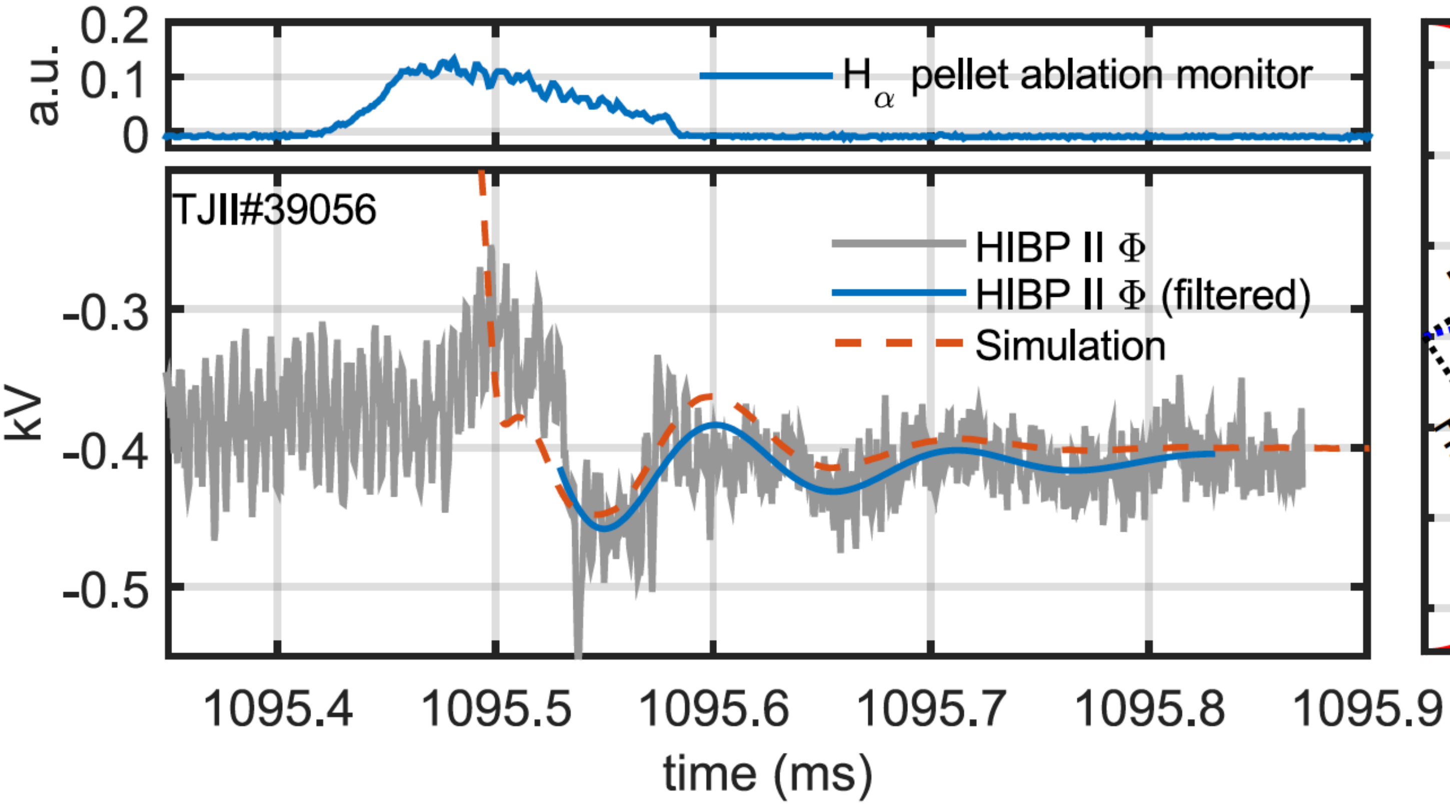
A. Dinklage. EX/P5-1

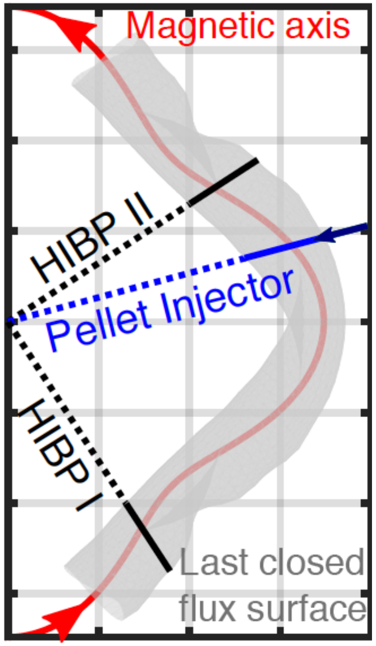
K.J. McCarhy. EX/P7-47

- Pellet Injection as a tool for core fuelling (NC transport afterwards understood in TJ-II)

Pellet Injection & Relaxation of Potential Oscillations

- Experiments beyond core fuelling: Direct observation of the Relaxation of Zonal Potential Oscillations.





- Damped oscillations of plasma potential well simulated by GK calculations of ZF relaxation in 3D systems.
- Oscillations in the freq. of ZFs.

A. Alonso et al. Submitted, 2016

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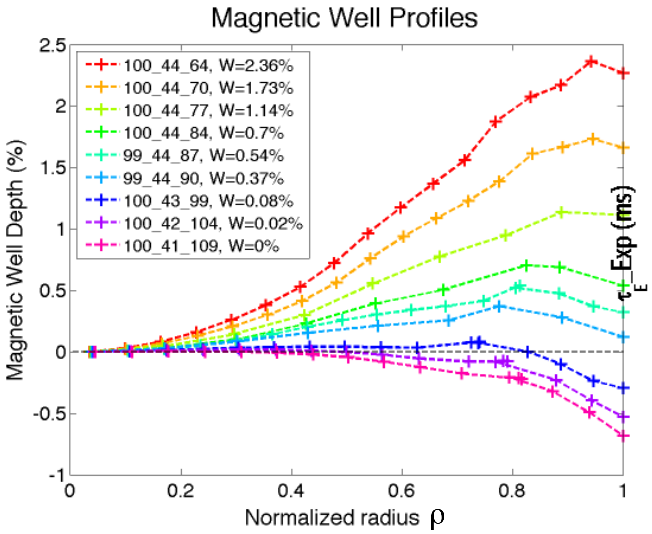
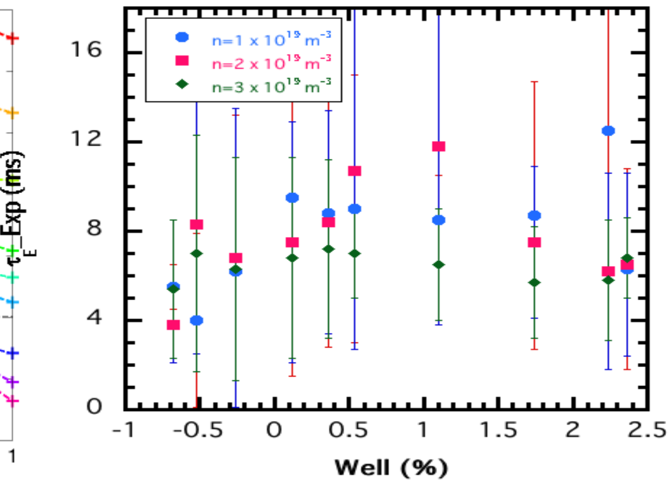
Stable plasmas in Mercier-unstable configurations

- **Mercier Criterion in TJ-II: stable plasmas need positive magnetic well.**



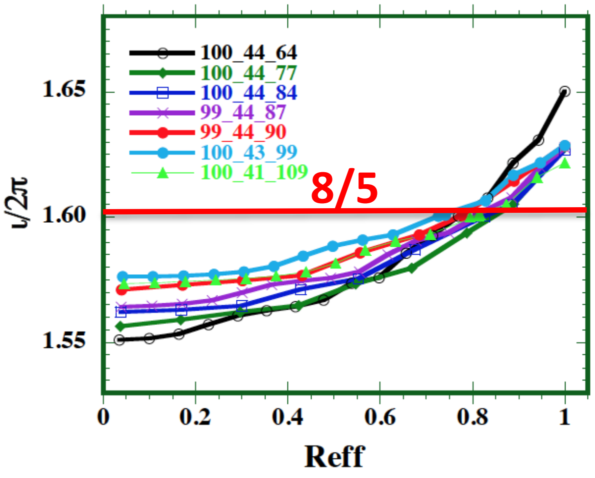


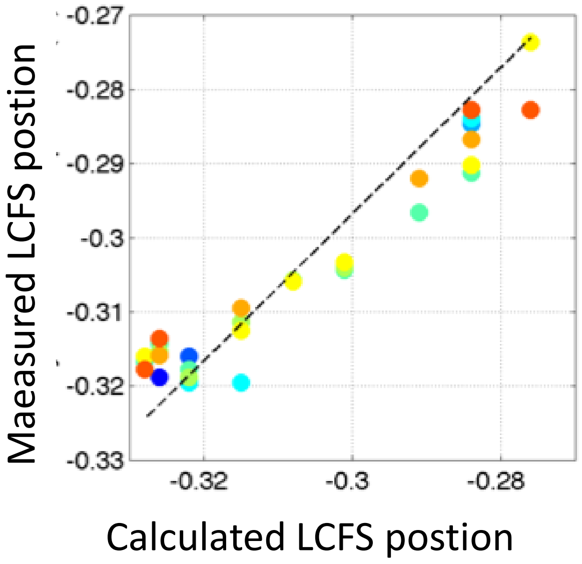
- Mercier criterion applied in 3D devices instability.

- Stable plasmas in Mercier-unstable configurations in TJ-II.

A. M. de Aguilera et al. NF 2015

LHD: S. Sakakibara et al. PPCF 2008

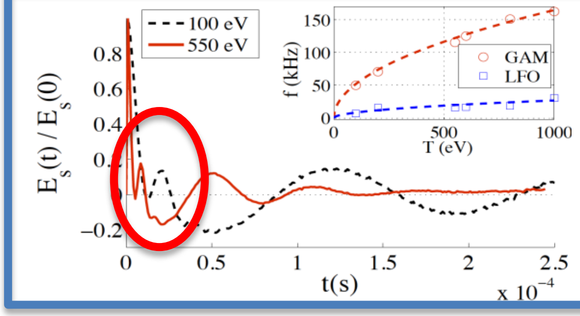




- No change in the plasma size (no effect of the rational).

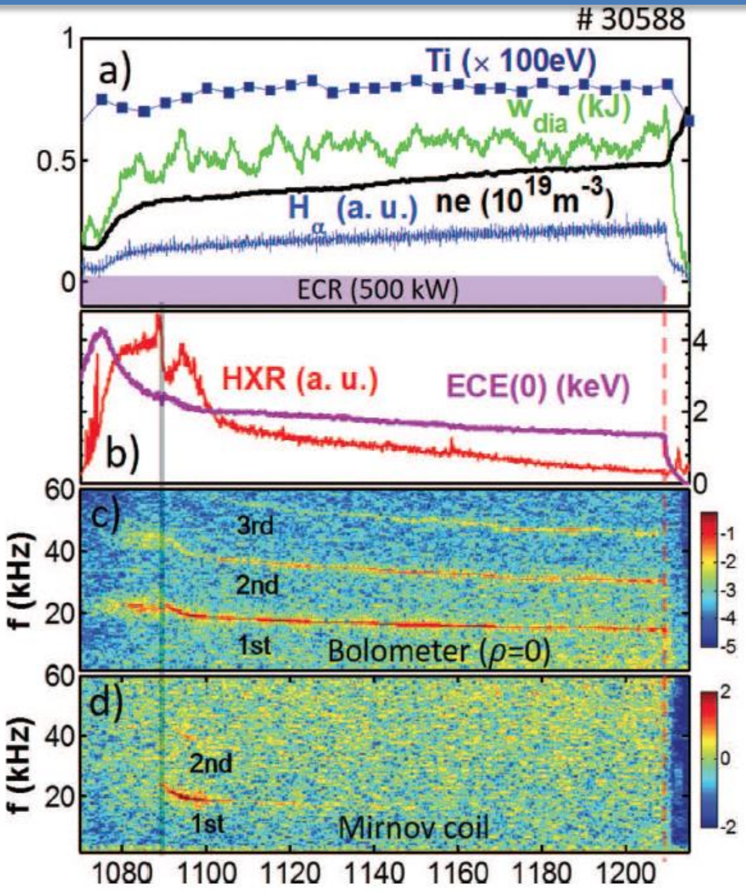
- A stabilization mechanism must exist (self-organization process).

Candidate to GAMs destabilised in TJ-II: driven by fast electrons or fast ions



- GAMs can couple with turbulence.
- Simulations: GAMs strongly damped at different temps. in TJ-II.
- Need an external drive to exist.

E. Sánchez et al., PPCF, 2013



Acoustic Mode (Possible GAM) destabilised by fast electrons.

Close to rational surfaces. Non-linear interaction with islands.

Toroidal structure (n=1), different from tokamaks.

Sun Baojun et al. EPL, 2016

Also observed: GAM destabilised by fast ions

F. Castejón et al. PPCF, 2016

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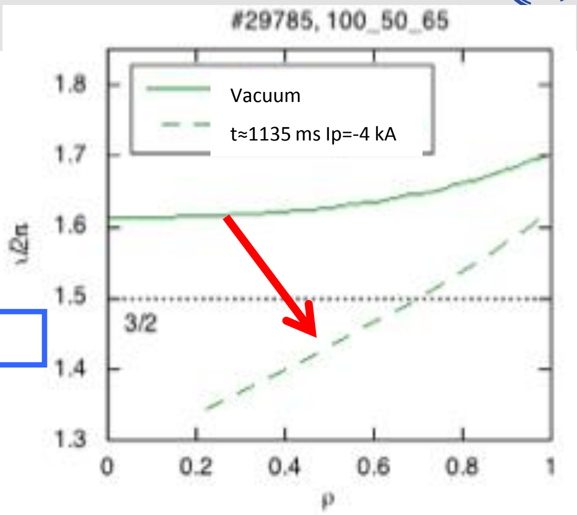
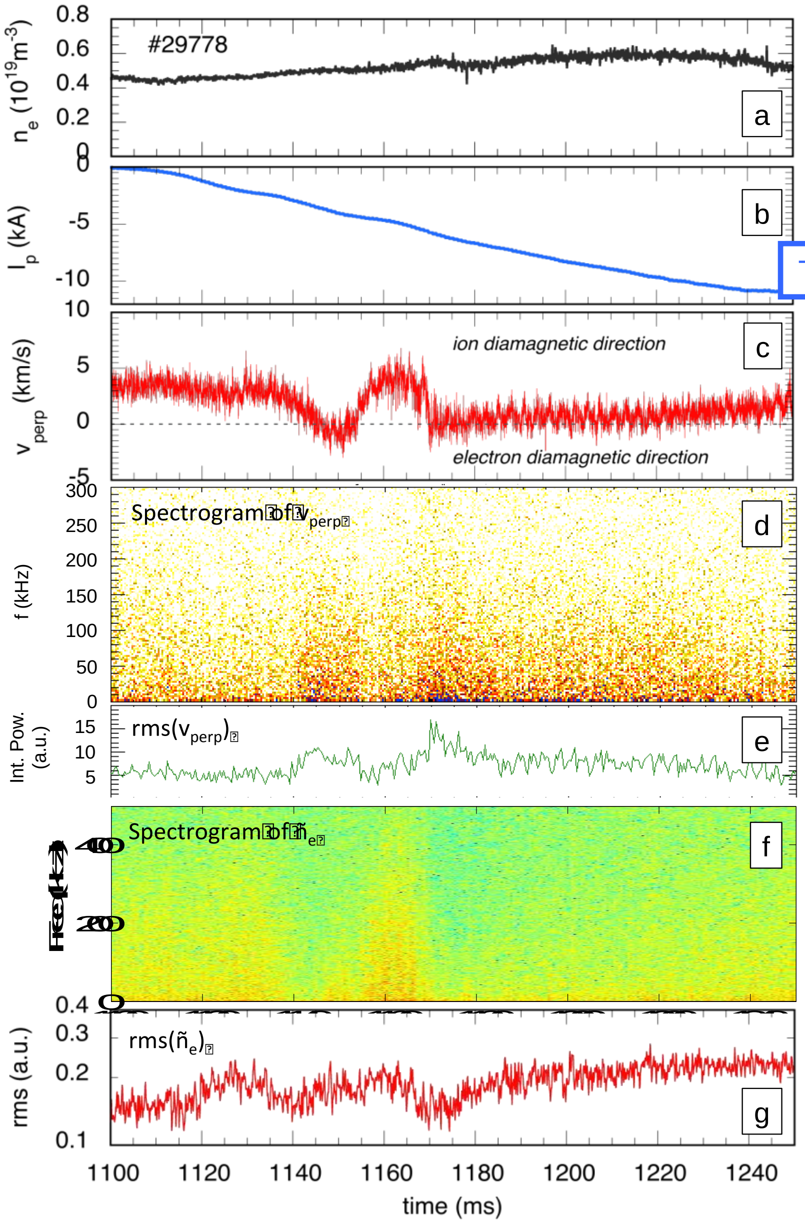
3/2 rational influences plasma flow and $\tilde{n}_e$



T. Estrada et al, EXC/P7-45



- OH driven current. Configuration scan: introduce the 3/2 rational in the plasma core in a single shot.
- Doppler reflectometer measurements: the flow changes twice direction when crosses the rational.
- Increase in the perpendicular flow fluctuations (f< 50 kHz).
- Synchronous: reduction in the density fluctuation level.
- Relation of Transport Barriers and rationals.
- L-H Transition fostered by rationals.

B. Van Milligen et al, Submitted,
López- Bruna et al. PPCF,2013,

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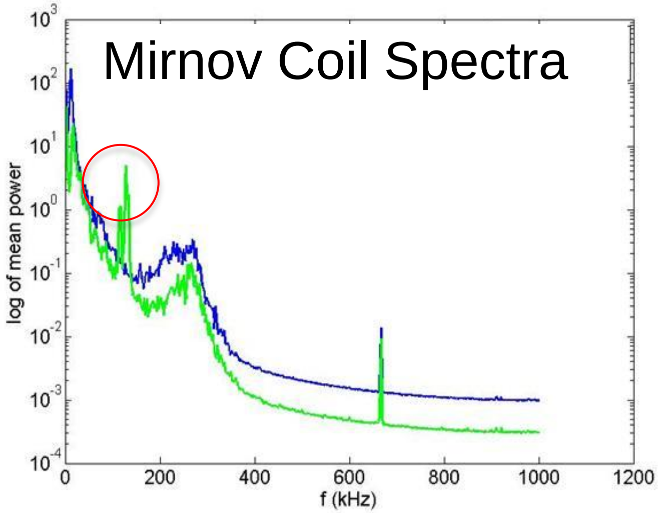
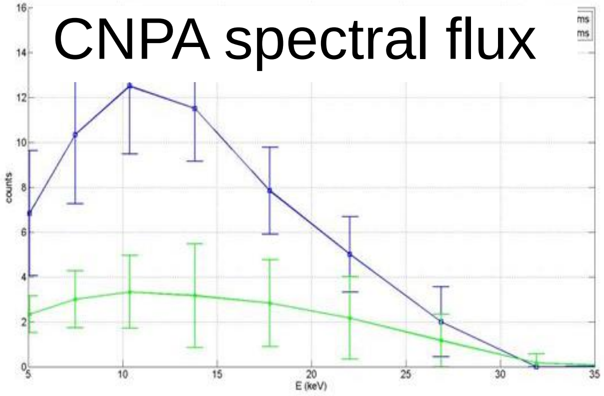
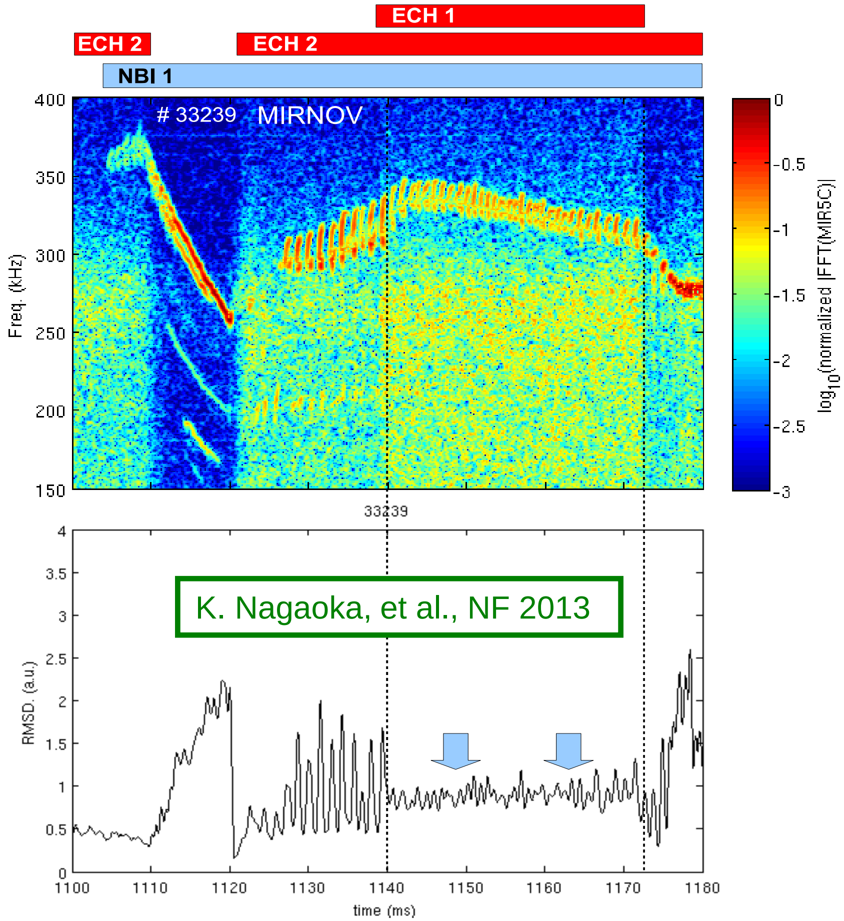
Alfvén Eigenmodes degrade Fast Ion Confinement. Mitigated by ECRH



J. Fontdecaba et al, In preparation





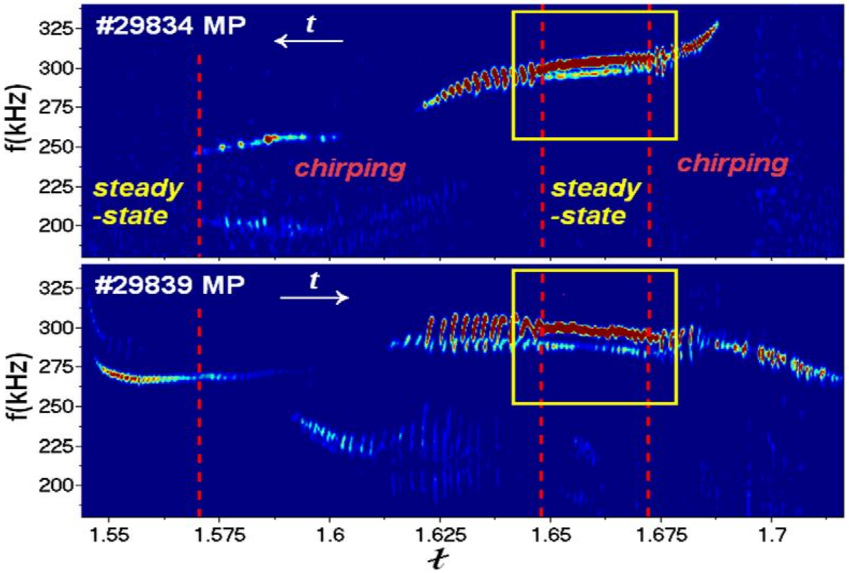
K. Nagaoka, et al., NF 2013

- CNPA flux proportional to fast ion density.
- AEs degrade fast ion confinement.

- AE Mitigation by ECRH
- Depending on ECRH power
  - ➢ Plasma profiles or
  - ➢ Modifying the damping by electron trapping

Controlling AEs by Modifying magnetic configuration

Chirping w/o ECRH in given rotational transform windows

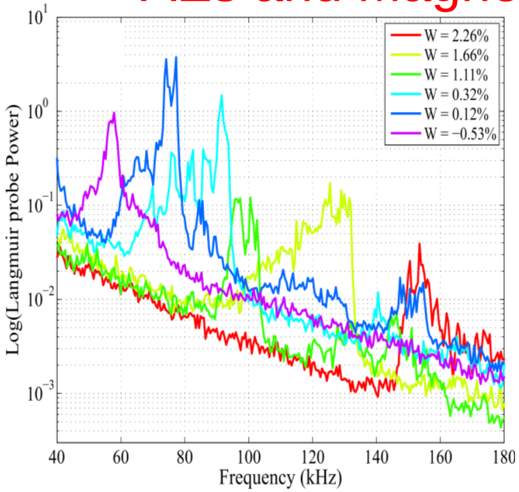


Configuration dynamic scan (increasing rotational transform and reverse:

We get chirping modes w/o ECRH at given values of the rotational transform.

A. Melnikov, et al., Nucl. Fusion 2016

AEs and Magnetic Well

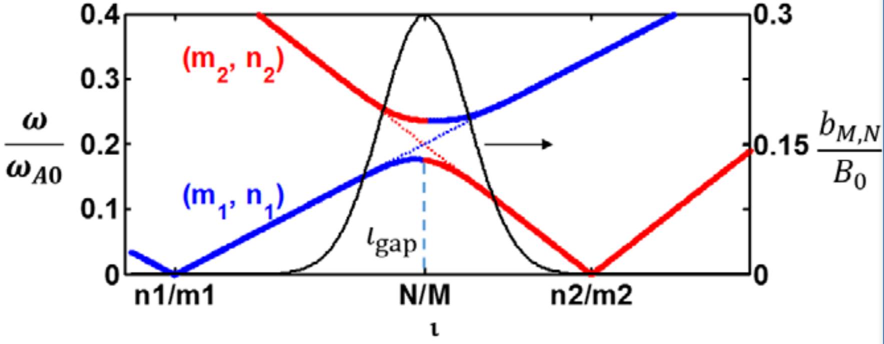


F. Castejón et al., PPCF, 2016

- **The mode frequency decreases with Magnetic Well (Understood by STELLGAP calculations)**
- **AE appears at inner radii.**

Magnetic Islands Change the Spectrum Gap: MIAEs

S. Baojun et al. NF, 2015



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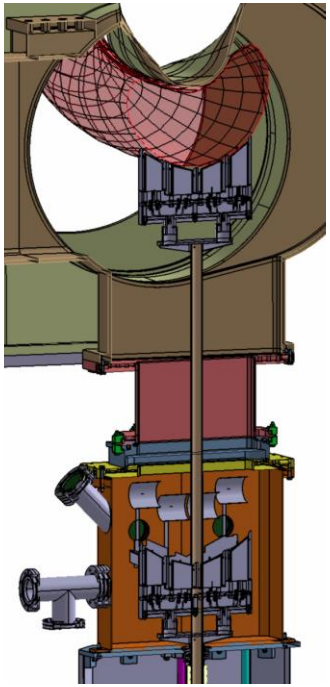
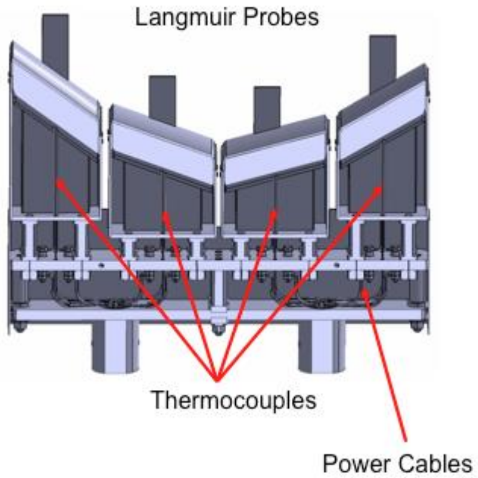
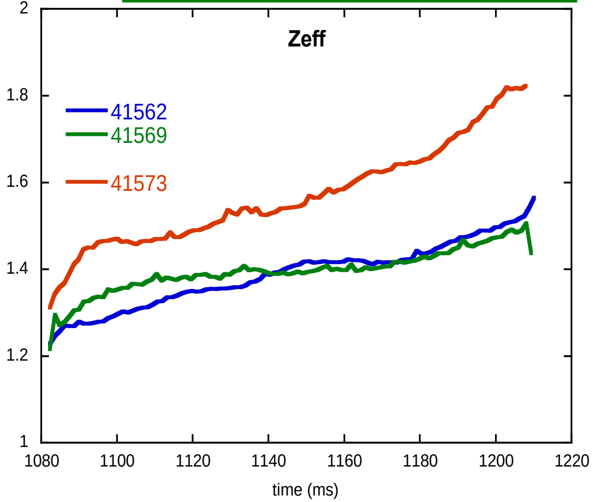
Innovative PFC and power exhaust: Liquid metal alloys (LiSn)



- Strong PWI in TJ-II.
- Experiments on TJ-II using liquid metals with a CPS.
- LiSn alloys tested: liquid limiter.
- Results:
  - Insertion of a LiSn sample w/o significant perturbation of the plasma parameters.
  - Clean plasmas: relevant in 3D devices to avoid impurity accumulation.
  - Small H retention (~ 0.01% H/(Sn+Li) at T< 450º C),
- These results provide good perspectives for the use of liquid LiSn alloys as a PFC in a Reactor (also stellarator reactor).

F. L. Tabarés et al. PSI, 2016





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Conclusions

- 3D Physics Relevant for tokamaks and Stellarators: NC transport and Er (Bulk Plasma & Impurities); Waves and Instabilities.
- Avoiding Impurity Accumulation: Understanding Impurity Hole.
- Potential Asymmetries have influence on impurity transport: Potential Asymmetries detected in TJ-II.
- Fuelling: Pellet injection as a tool for core fuelling, despite outside ablation (NC-effect in TJ-II).
- Stability:
  - Stable plasmas found in Mercier unstable configurations.
  - Candidates to GAMs found in TJ-II despite the expected large damping. Drivers: Fast ions and fast electrons.
- Effect of 3/2 rational on plasma flow and reduction of $\tilde{n}_e$.
- Fast Particle Physics: Controlling AEs using ECRH and magnetic configuration (rotational transform, magnetic well and magnetic islands).
- Innovative PFC power exhaust: LiSn alloys relevant for a reactor. (Not 3D-specific)

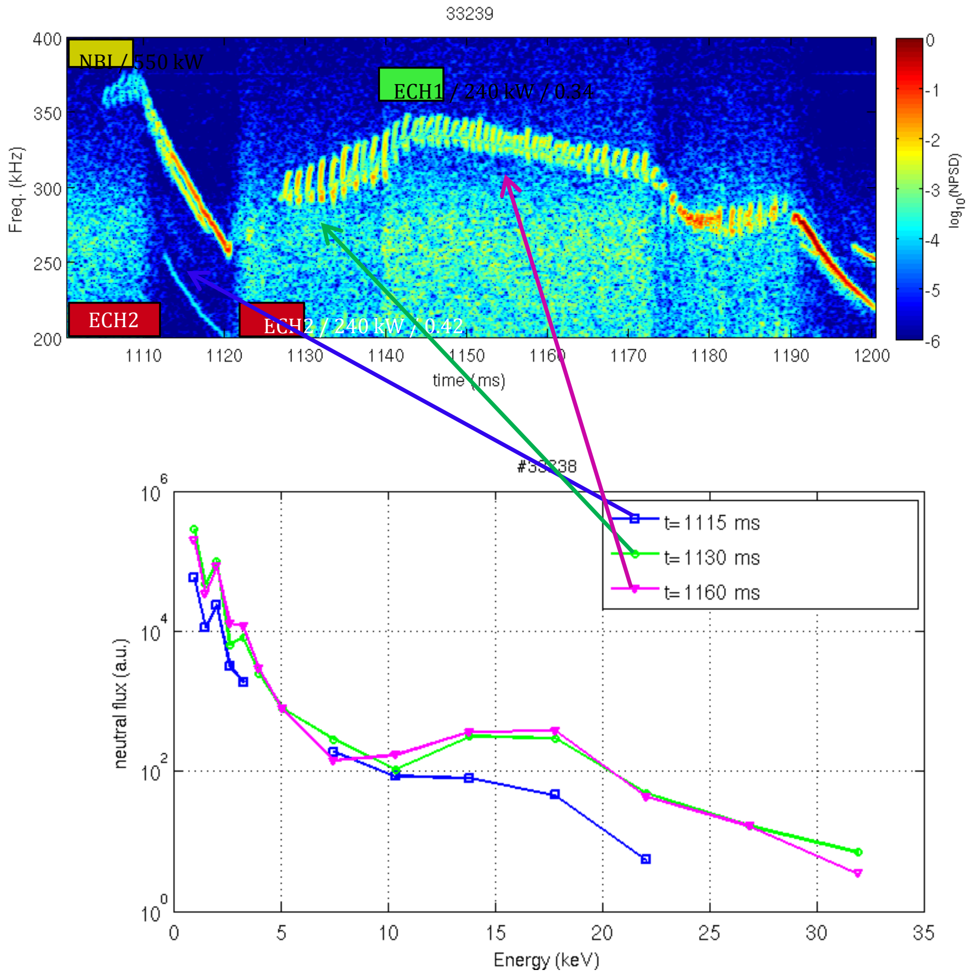
CIEMAT Contributions to IAEA-FEC 2016

- F. Castejón et al. OV/5-1. “3D effects on transport and plasma control in the TJ-II stellarator”
- T. Estrada et al. EXC/P7-45. “Plasma Flow, Turbulence and Magnetic Islands in TJ-II”
- C. Hidalgo et al. EXC / P7-44. “On the influence of ECRH on neoclassical and anomalous mechanisms using a dual Heavy Ion Beam Probe diagnostic in the TJ-II stellarator”
- D. López-Bruna et al. EX/P7-48. “Confinement modes and magnetic-island driven modes in the TJ-II stellarator”
- K.J. McCarhy et al. EX/P7-47. “Plasma Core Fuelling by Cryogenic Pellet Injection in the TJ-II Stellarator”
- E. de la Luna et al. EX/P6-11. “Recent results of High-Triangularity H-mode studies in JET-ILW”
- I. Palermo et al. FNS/P5-1. “Optimization process for the design of the DCLL blanket for the European DEMOnstration fusion reactor according to its nuclear performances”
- H. Cabal et al. SEE/P7-4. “Exploration of of Fusion Power penetration under different Scenarios using EFDA Times Energy Optimization model”

Back – up Slides

Chirping & Fast Ion Confinement

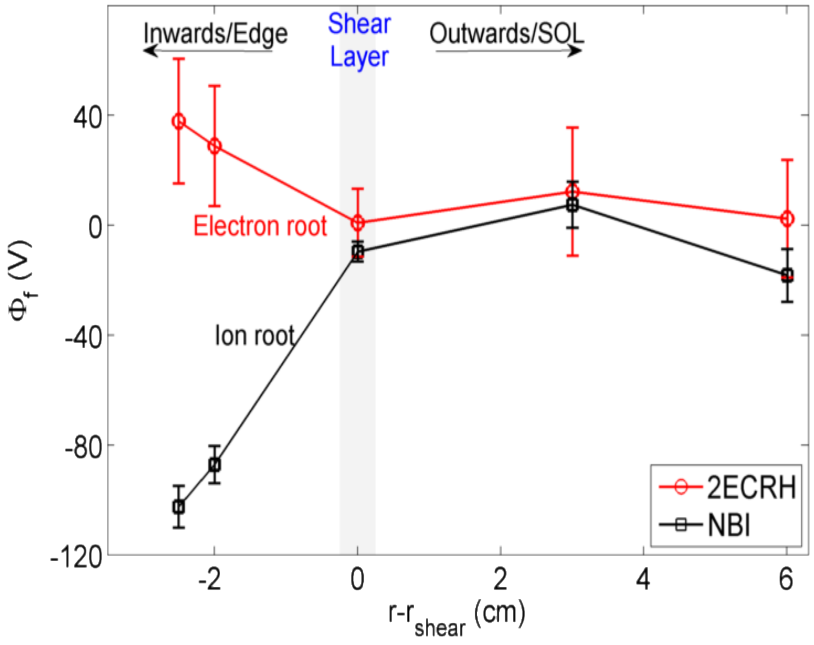
- Fast Ion confinement is not degraded in the presence of chirping.
- A key point is to understand chirping.

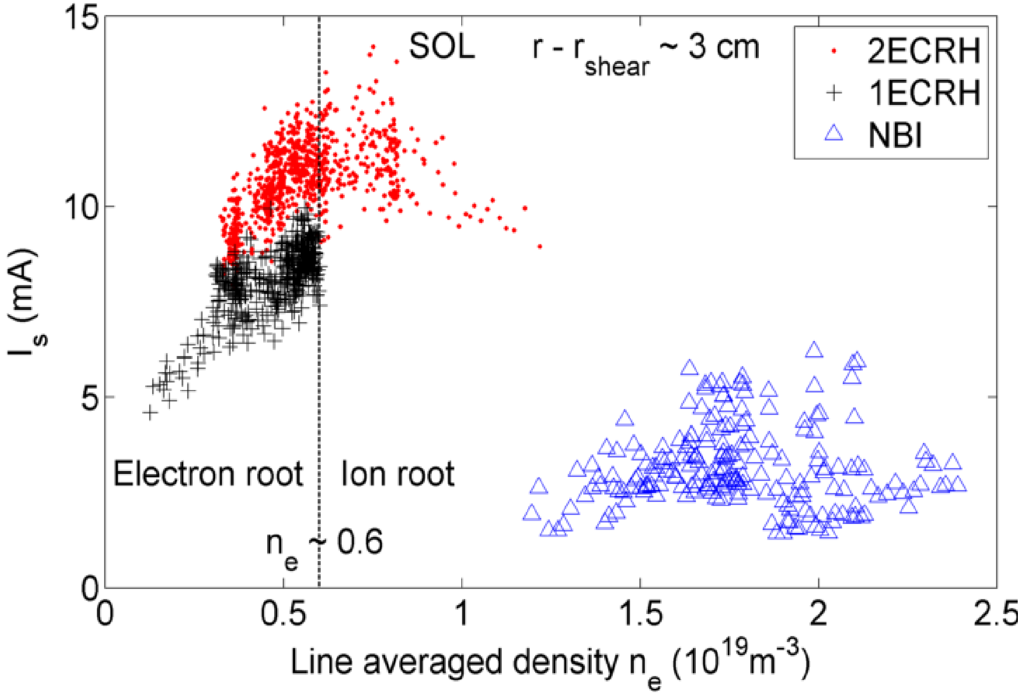


J. Fontdecaba et al, In preparation

SOL affected by plasma edge conditions

- SOL properties and, hence, fuelling are not local.
- Experiments show that they are affected by edge conditions.





- Potential in the SOL depends on plasma potential.

- SOLdensity depends on plasma characteristisl.

Wu Ting et al. Submitted to Nuclear Fusion.

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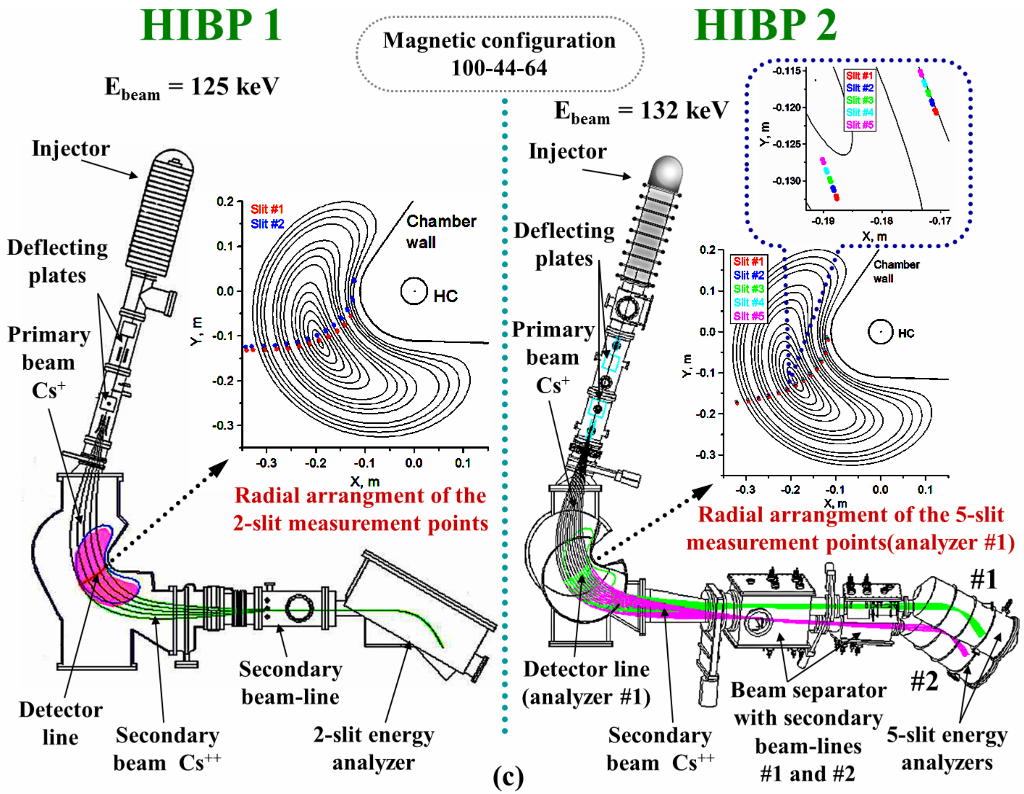
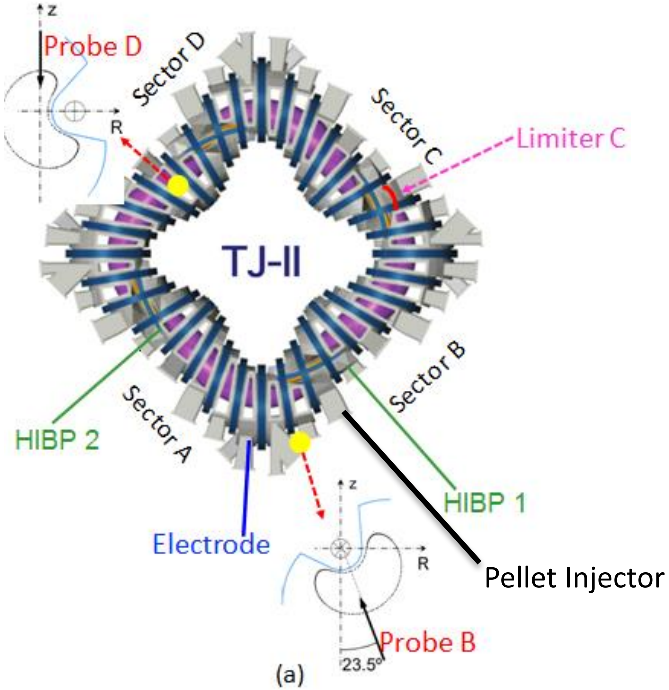
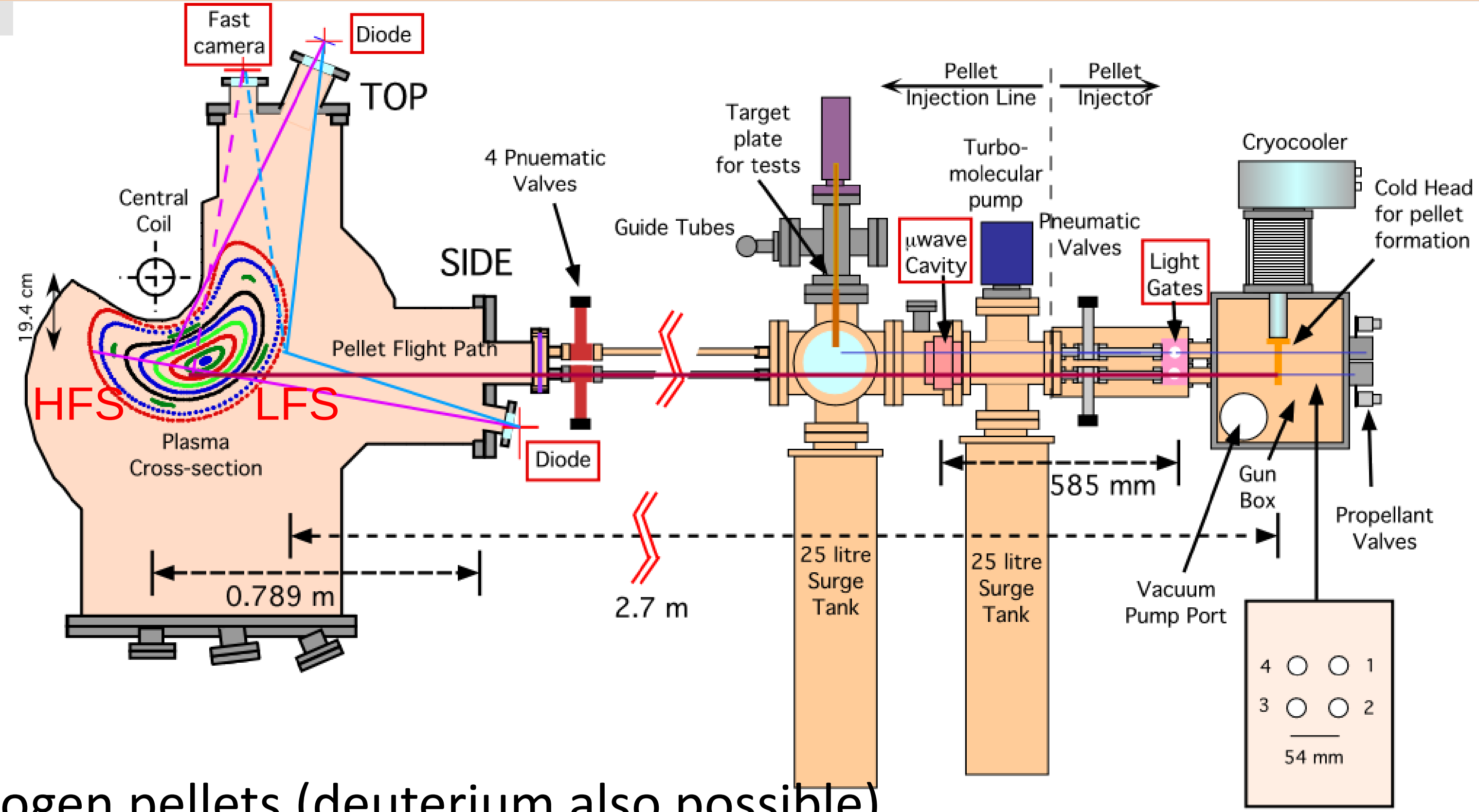
Advanced Diagnostics: Dual HIBP





- Duplicated diagnostics: new physics.
- Dual HIBP: Collaboration with KHFTI & Kurchatov.
- Duplicated probes.
- Pellet Injector and Liquid Metal Limiter.
- Future: duplicate Doppler reflectometry in W7-X.

TJ-II Pellet Injector



- Hydrogen pellets (deuterium also possible).
- Four lines-of-flight separated by 54 mm.
- 4 pellet sizes available [$3\text{x}10^{18}$ H^{o} (1), $8\text{x}10^{18}$ H^{o} (2), $1.5\text{x}10^{19}$ H^{o} (3) & $3\ \text{x}10^{19}$ H^{o} (4)] with +/- 30% variation in mass.
- Lightgate and Microwave Cavity provide timing (-> velocity) and mass signals.
- Injection velocities (800 to 1200 m/s) - propellant gas system.

K.J. McCarthy et al, Proc. Sci. (ECPD2015) 134

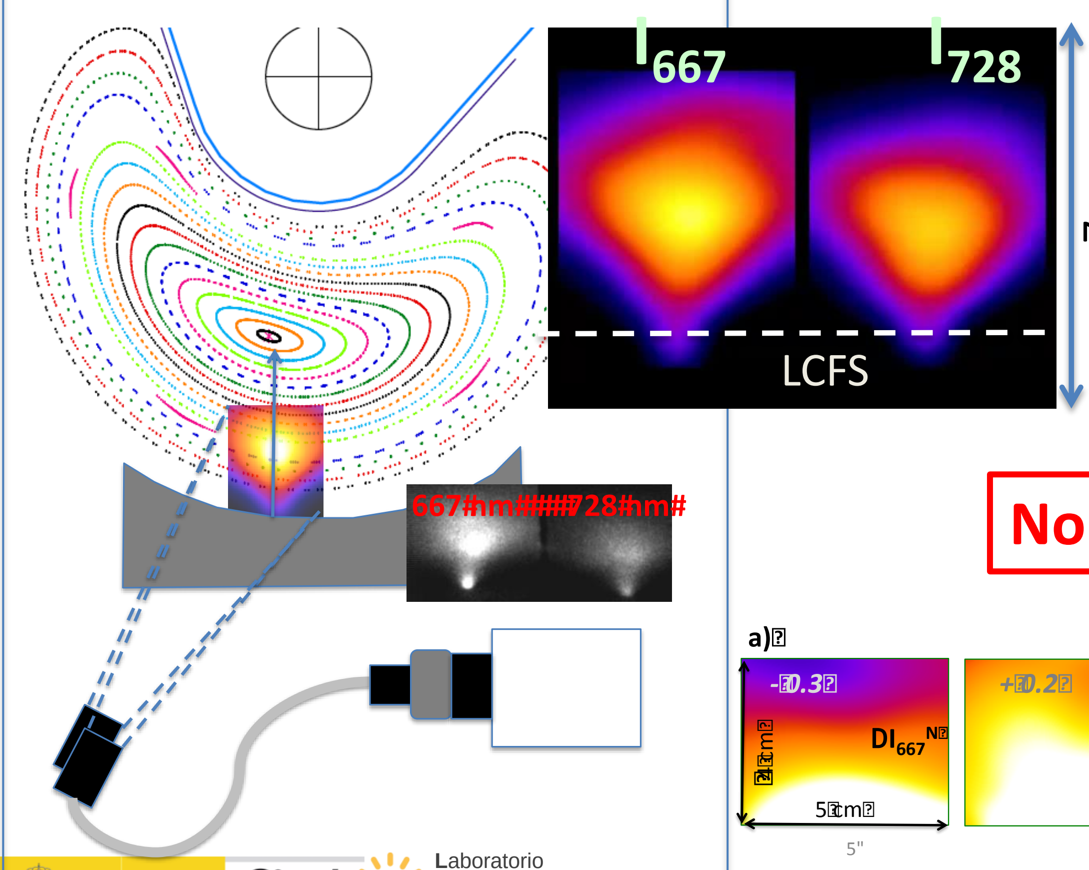
Effect of turbulence on neutrals: neutrals blobs

$$\boxed{I_\lambda = c\; n_e\; n_0\; k_\lambda(n_e, T_e)}$$

$$\Delta I = \Delta n_e\; n_0\; k_\lambda + \Delta k_\lambda\; n_e\; n_0 + \overset{?}{\xcancel{\Delta n_0\; n_e\; k_\lambda}}$$

≈ 0 for 40 < Te < 120 eV

Two-dimensional imaging of edge n_e with the He-ratio technique, t = 15 µs



Non-negligible