EUROfusion

OVERVIEW OF THE TJ-II STELLARATOR RESEARCH PROGRAMME TOWARDS MODEL VALIDATION IN FUSION PLASMAS

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on behalf of the TJ-II team and collaborators

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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Outline: TJ-II supporting W7-X

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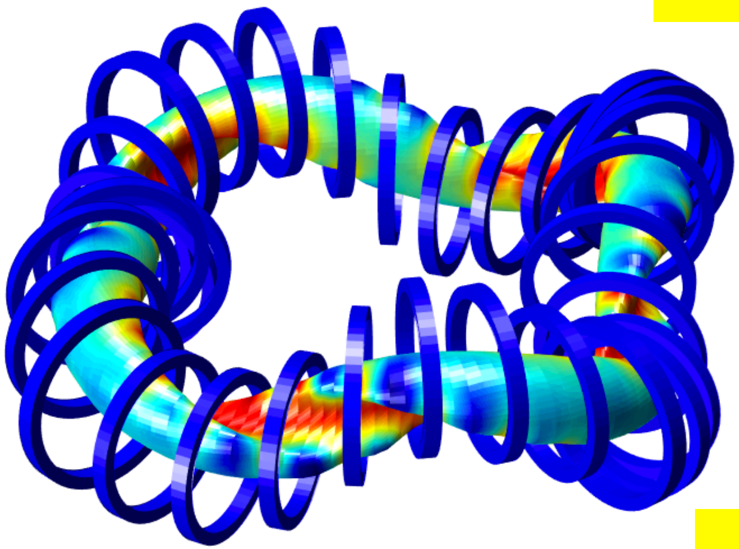
Transport and asymmetries

Physics of plasma fuelling



Fast particles: actuators and stability

Turbulence control: Zonal Flows

Edge – SOL coupling physics

Power exhaust

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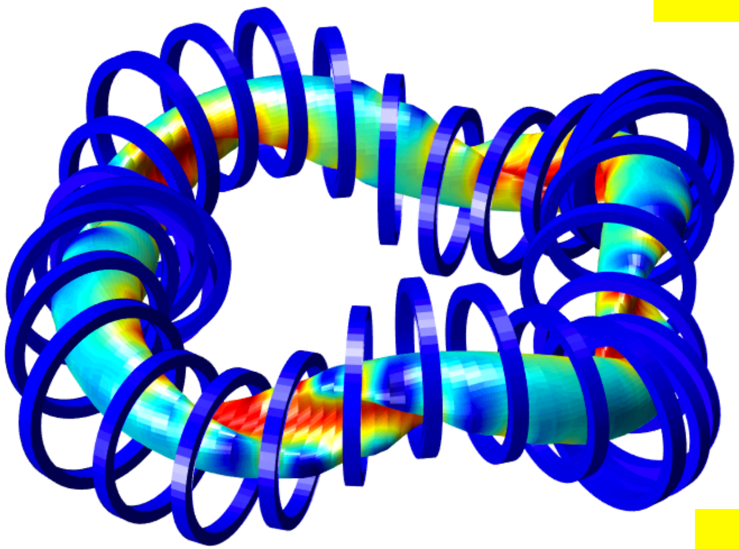
Transport and asymmetries



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CHALLENGE:
Transport and impurity control

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Configuration optimization requires reduction of neoclassical transport and understanding and controlling turbulent transport.

Effective impurity control seems possible in some regimes

TJ-II strategy:

characterization of flux surface plasma POTENTIAL ASYMMETRIES and NC model validation

characterization of TURBULENCE ASYMMETRIES and GK model validation

Asymmetries in radial electric fields:

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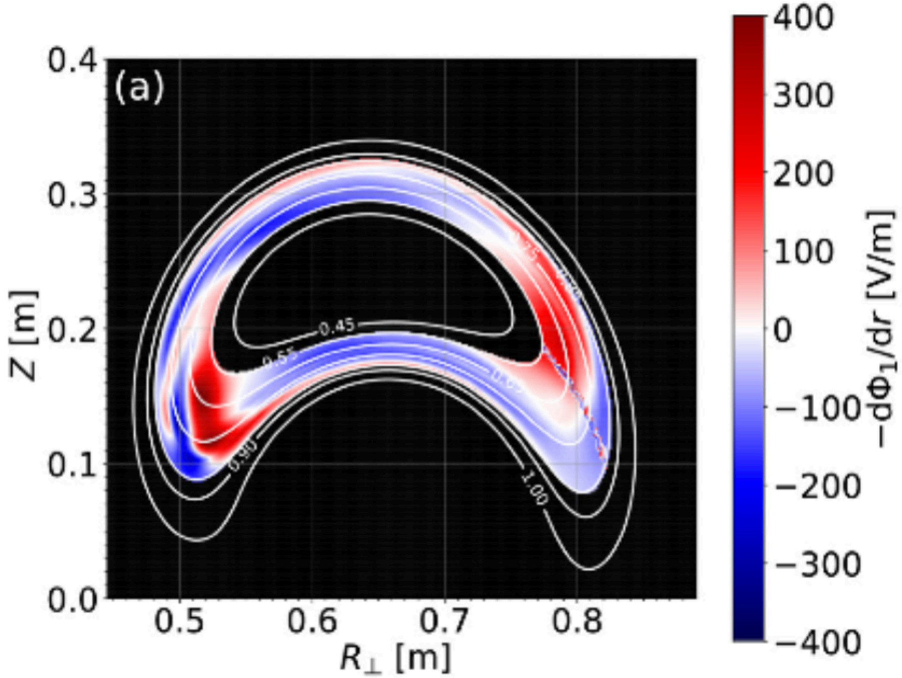
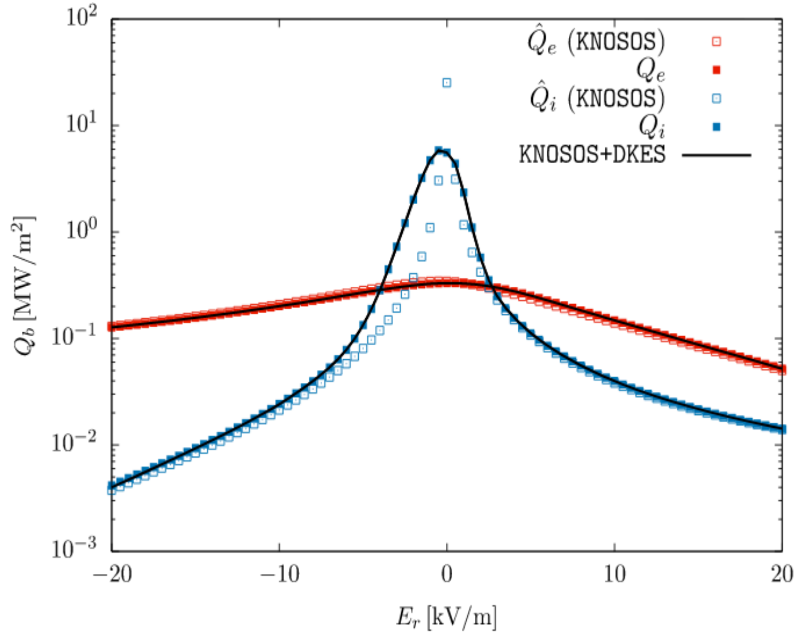
TOWARDS VALIDATION OF NEOCLASSICAL SIMULATIONS





Predicted poloidal asymmetries in radial electric field (E_r) are comparable to those found in the experiments [Doppler reflectometry]

T. Estrada et al., NF-2019
E. Sanchez et al., NF-2019

KNOSOS produces more accurate calculations of the neoclassical energy flux for small values of the radial electric field.

J. L. Velasco et al., IAEA-2021

Asymmetries in plasma fluctuations:

TOWARDS VALIDATION OF GK SIMULATIONS

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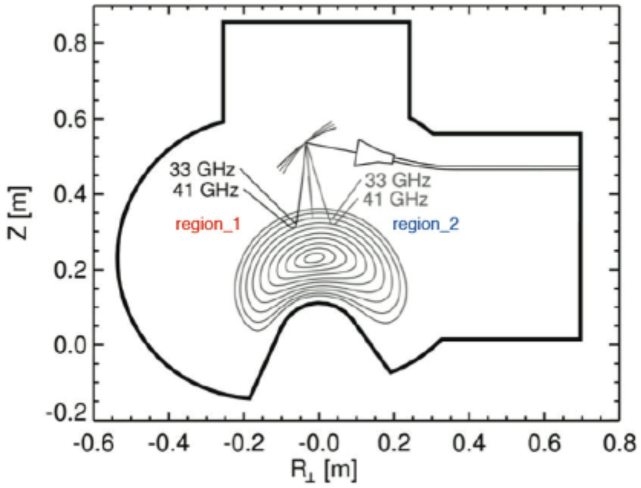
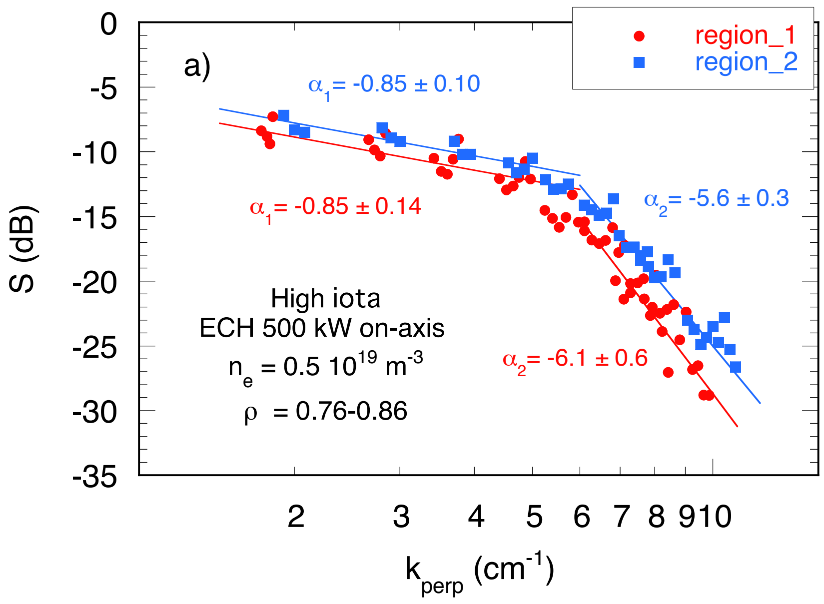
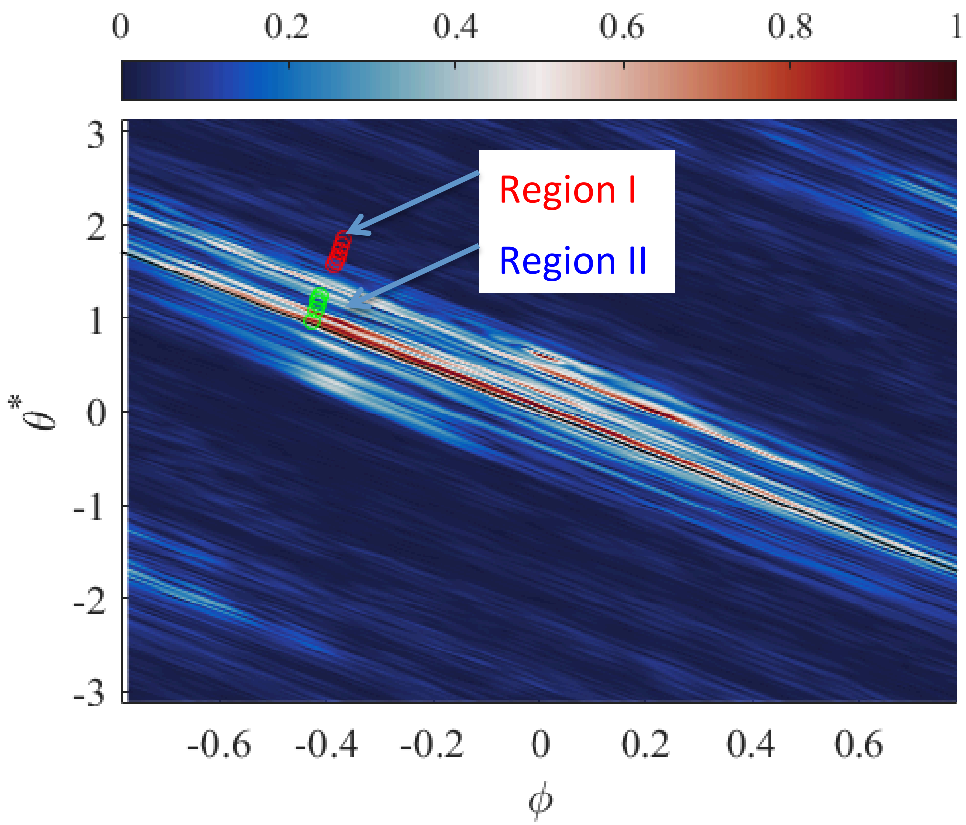




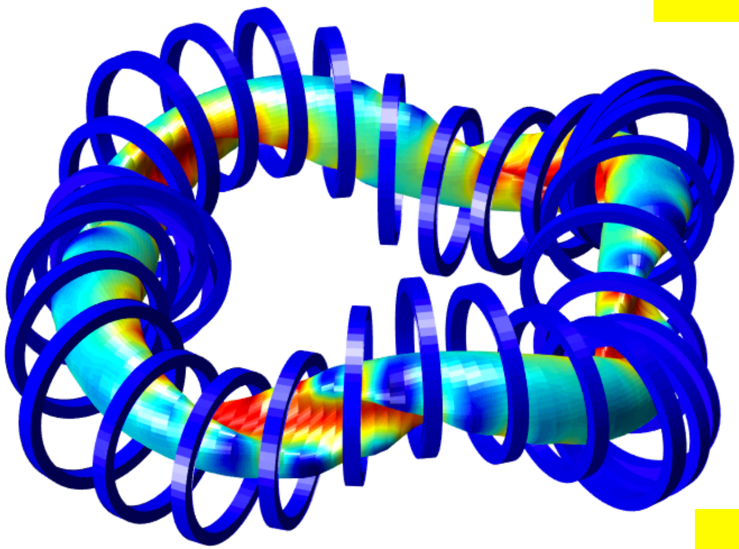


Different intensity in the density fluctuation spectra can be related to the poloidal locatlization of instabilities found in GK simulations.

T. Estada et al., NF-2019
E. Sánchez et al., NF-2019

Transport and asymmetries

Physics of plasma fuelling



Fast particles: actuators and stability

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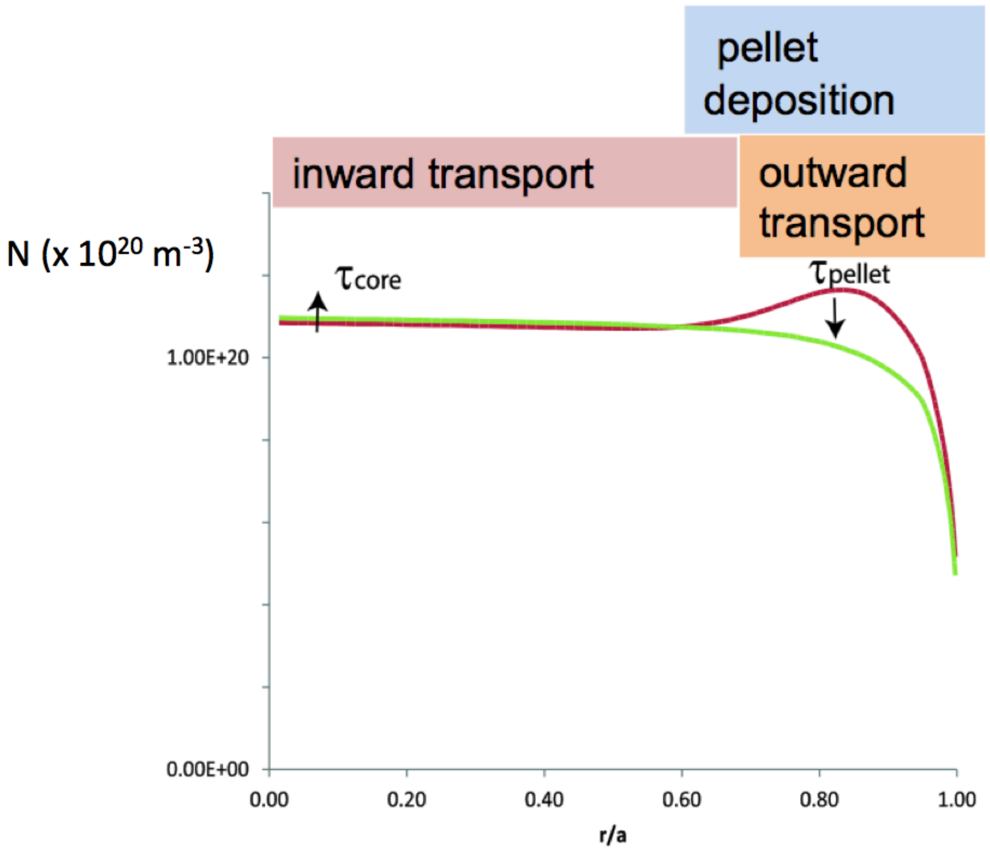
Power exhaust

CHALLENGE:
Physics of fuelling



Is core fuelling feasible with shallow pellet penetration in reactor scenarios?

Role of turbulent / neoclassical mechanisms?

TJ-II strategy:

Influence of neoclassical and turbulence mechanisms during pellet ablation

Plasma fuelling and impurities
EXPERIMENTS AND VALIDATION

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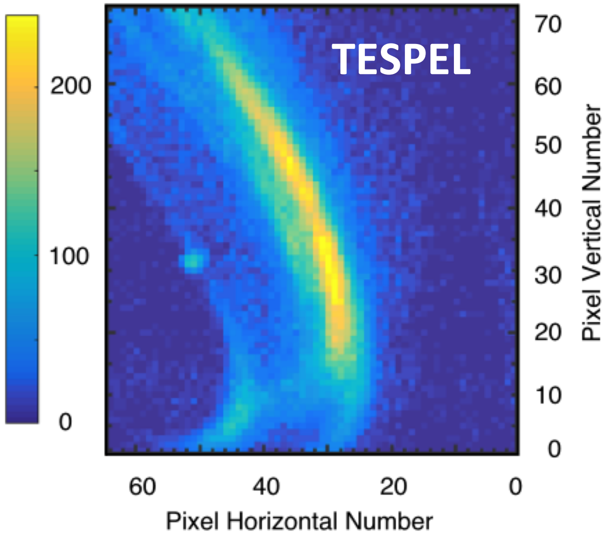

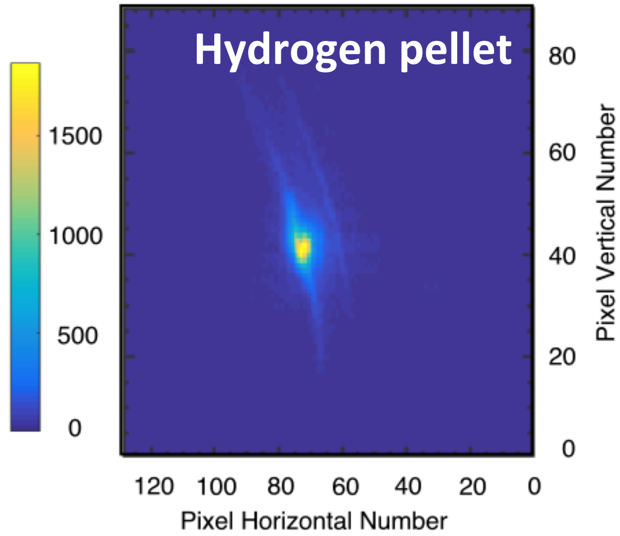

NIFS, IPP-Greifwald, Centre for Energy Research [Budapest] collaboration

- ✓ **Post-injection particle radial distributions can be understood qualitatively from neoclassical predictions. BUT pellets can also impact strongly MHD plasma stability and plasma turbulence** [N. Panadero et al., NF-2018 / K. McCarthy et al., IAEA-2021].

- ✓ **Enhanced pellet ablation due to fast-electron impacts can lead to higher fuelling efficiencies (<40%)** [K. McCarthy et al., PPCF-2019 / IAEA-2021]

- ✓ **Comparisons with HPI2 simulations have revealed that interactions between outward drifting pellet material and a resonant surface can lead to the abrupt deceleration and hence reduced pellet material loss** [K. McCarthy et al., NF-2021 / IAEA-2021].

2-D mapping of plasma profiles and fluctuations
TOWARDS THE VALIDATION OF FUELLING PHYSICS

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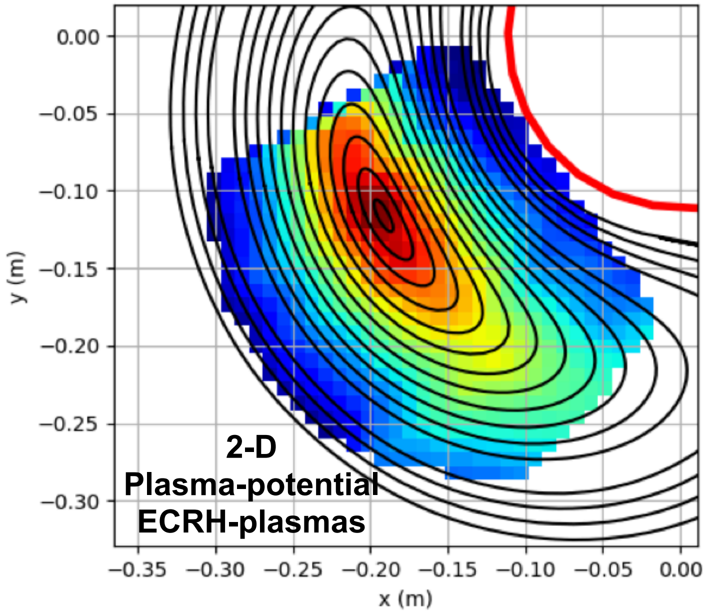
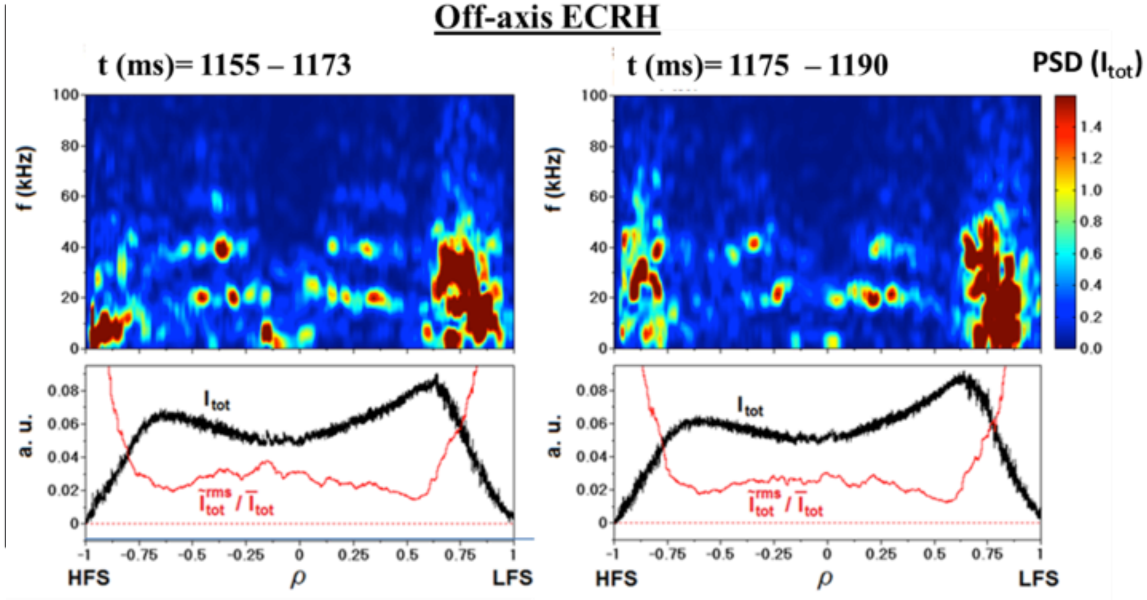




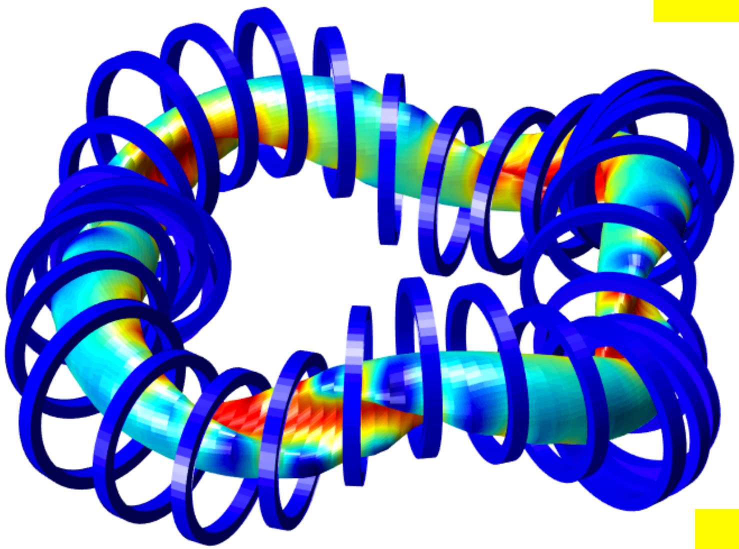
- ✓ 2-D mapping of plasma potential and density paves the way for model validation under positive and negative density gradient scenarios and asymmetries [Melnikov et al., EPS-2021].

- ✓ Density fluctuations appear both at the positive and negative density gradient regions being stronger in the negative gradient region in agreement with TEM GK simulations [Sharma et al., PoP-2020].

Kurchatov – Kharkov collaboration

Transport and asymmetries

Physics of plasma fuelling



Fast particles: actuators and stability

Turbulence control: Zonal Flows

Edge – SOL coupling physics

Power exhaust

CHALLENGE:
Fast particle dynamics

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Upcoming fusion devices will explore plasma regimes fully dominated by **FAST PARTICLE DYNAMICS** that are far from present devices in many aspects.

Extrapolations from pure empirical data can be misleading and reliable data are required to validate [fast particle] models in existing plasma scenarios.

Physics of AEs actuators?
Why fast particle EM induced stabilization?

TJ-II strategy:

Identification of AEs actuators (ECCD, ECRH, topology)
Validation of fast ion induced stabilization (Zonal Flows)

TOWARDS THE VALIDATION OF FAST ION CONTROL

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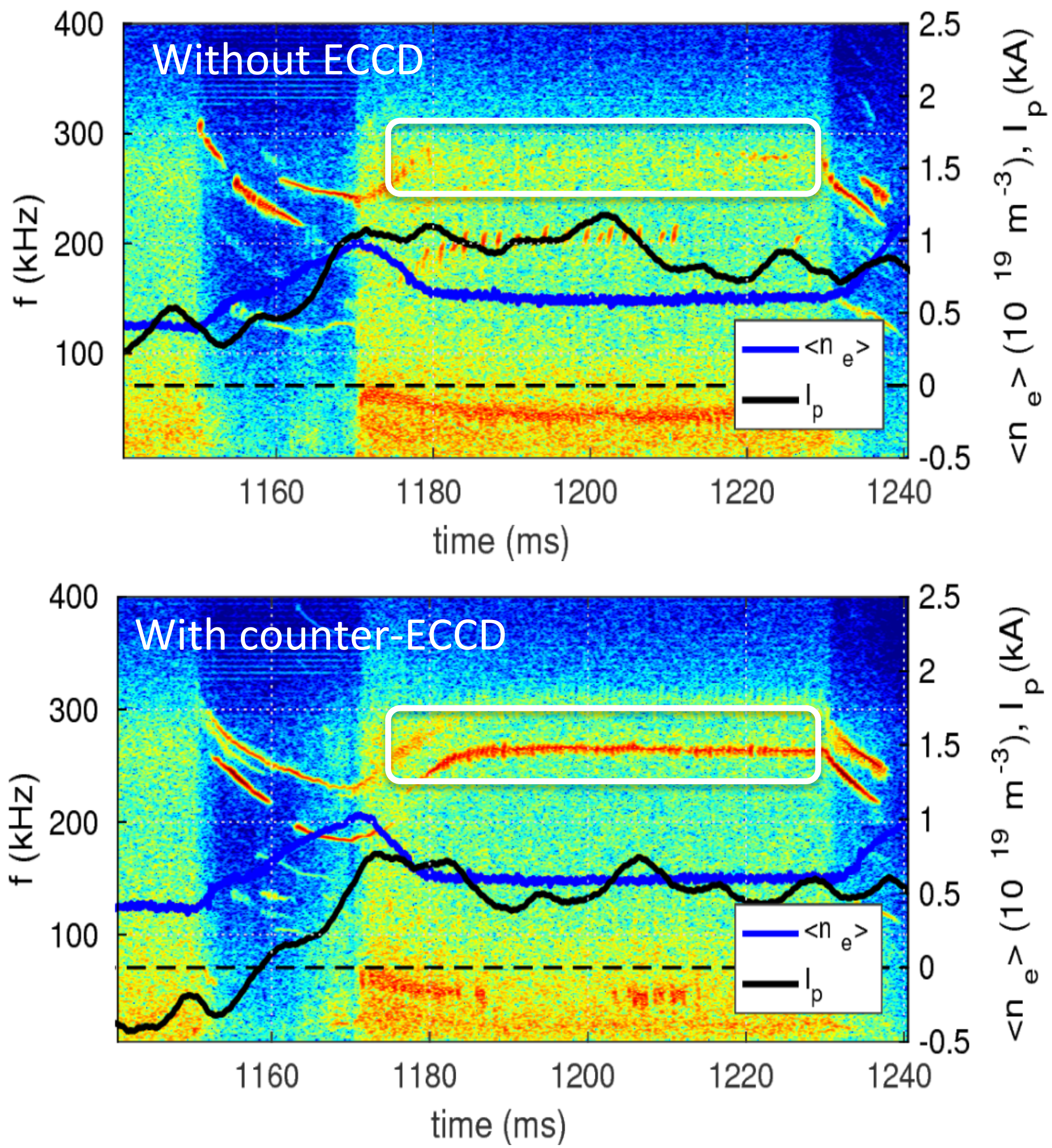
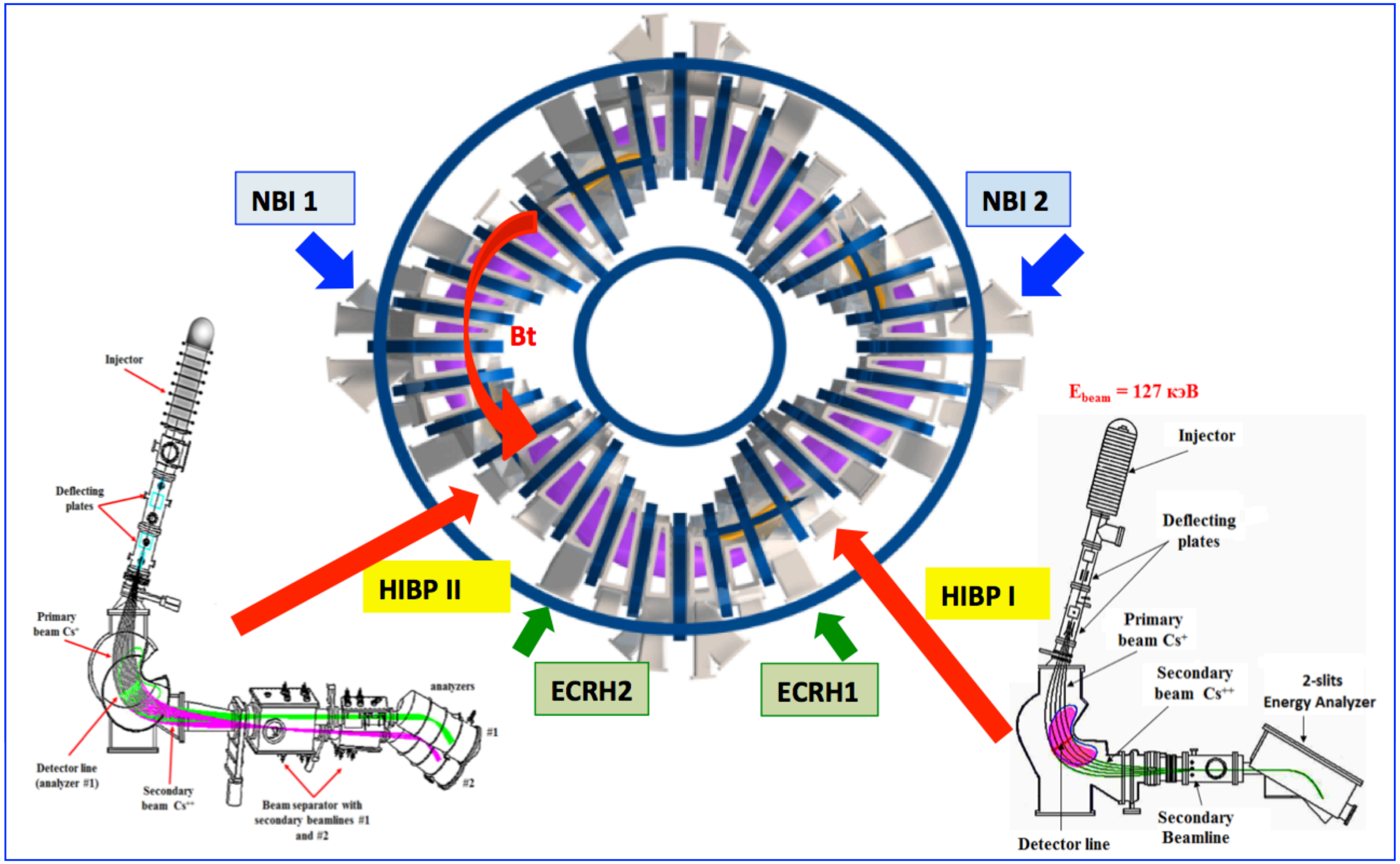


- ✓ The impact of ECRH and ECCD has been investigated demonstrating a clear effect of ECCD [due to rotational transform profile] on the observed mode spectrum
- ✓ Moreover, linear stability analysis, using STELLGAP [MHD] and FAR3d [gyrofluid] codes, has allowed AEs identification in different heating scenarios.

A. Cappa et al., NF 2021 / IAEA-2021
S. Mulas et al., IAEA-2021

TOWARDS THE VALIDATION OF FAST ION DYNAMICS



Why fast particle EM induced stabilization?

Alfvén Eigenmodes and Zonal Flows

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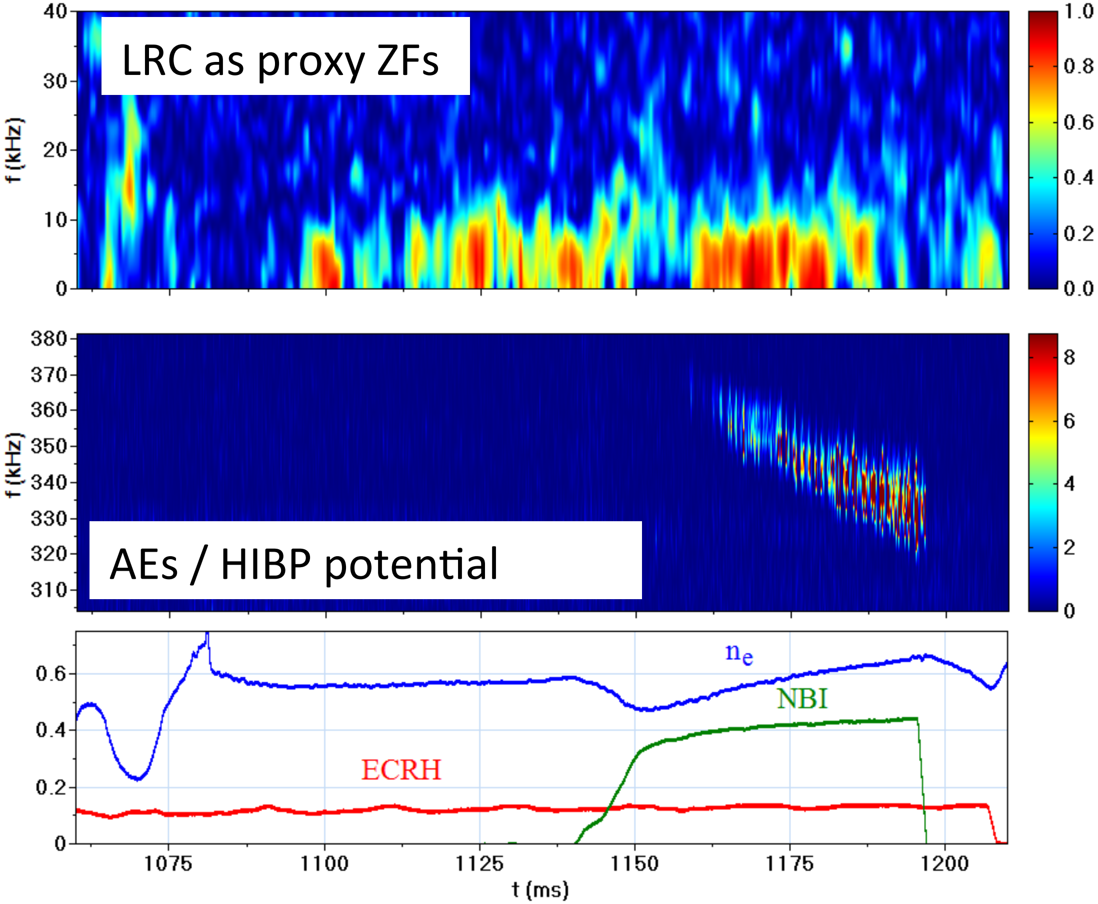
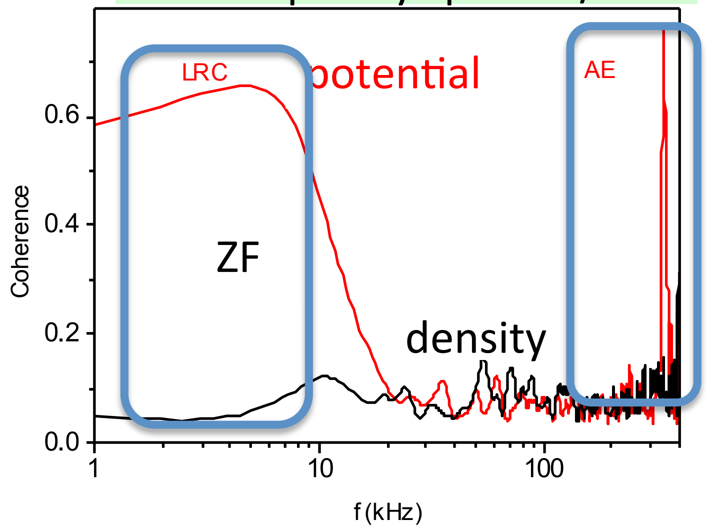


HIBP-1 & HIBP2 rho ≈ 0.3

LRC frequency spectra / NBI

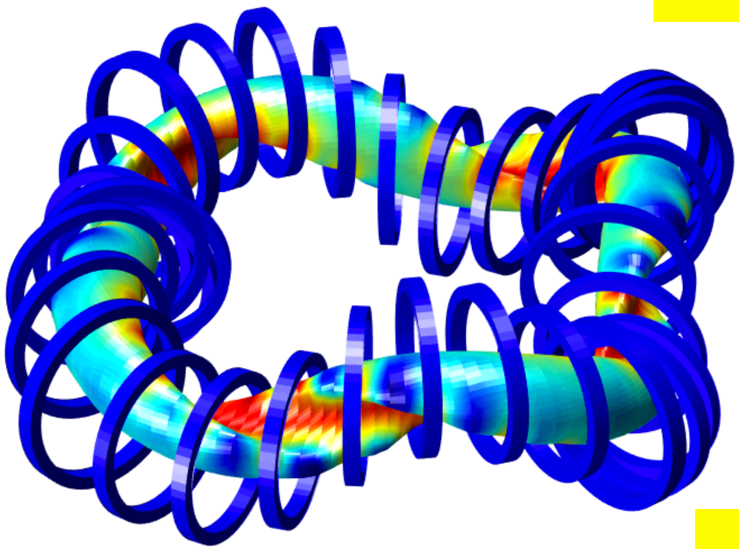


- ✓ **LRC correlations are detected both at the AEs frequencies and low frequencies (1 – 10 kHz).**
- ✓ **LRC are observed in potential fluctuations but not in density fluctuations [i.e. ZF-like structures]**

It is an open question whether those ZFs can be directly driven by fast particle effects

Transport an asymmetries

Physics of plasma fuelling



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Power exhaust

CHALLENGE:
PHYSICS OF SELF-ORGANIZATION

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Historically, transport simulations have first predicted the development of inverse cascade of turbulent energy spectra to form Zonal Flows structures.

This prediction has been confirmed by experiments, providing the basis for the development of predicting capability of transport in future fusion devices

BUT,

Full validation of the plasma parameters affecting the amplitude and radial width of ZFs is still missing

TJ-II strategy:

Interplay between neoclassical E_r and zonal flows
Role of isotope effect
Influence of operational limits
Role of fast particles

Edge Zonal Flows:

INFLUENCE OF PLASMA HEATING ON RADIAL SCALE

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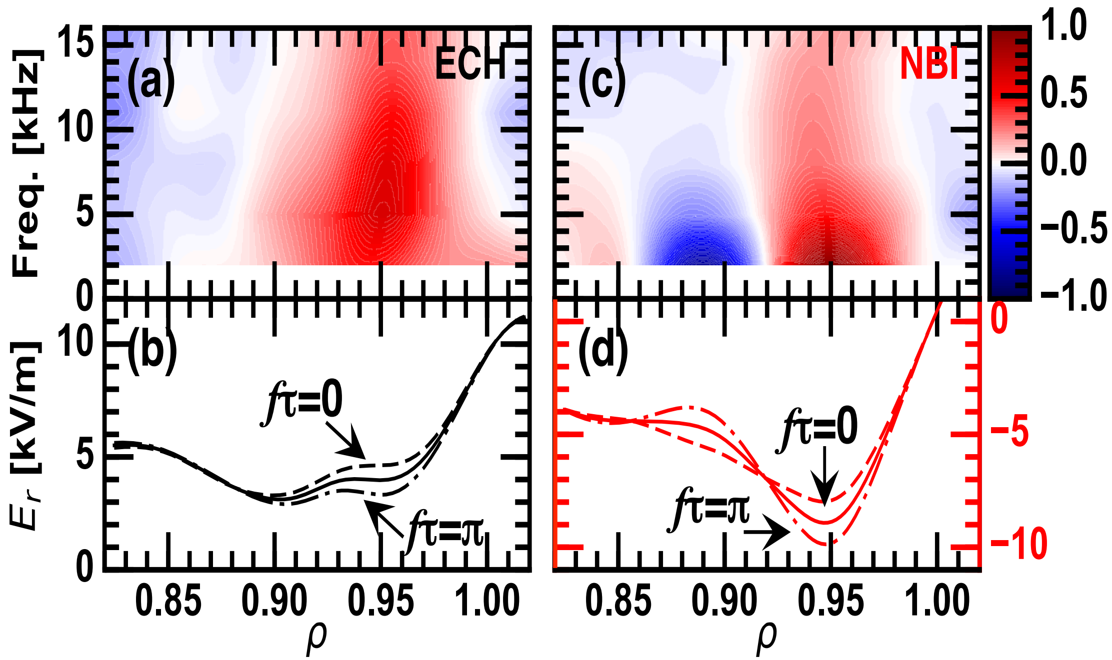

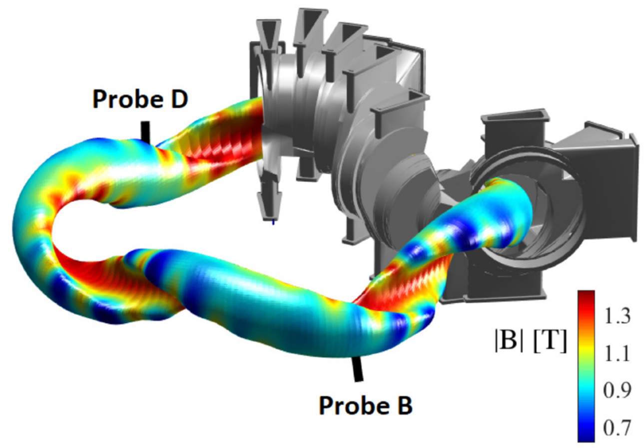

NIFS collaboration

- ✓ **The radial width of LRC is strongly affected by plasma heating**.
- ✓ **The radial scale of LRC structures** (as proxy of ZFs) is in the range of 20 ion Larmor radius in NBI plasmas, which **is comparable to the radial scale length of neoclassical radial electric fields**.

T. Kobayashi et al., NF-2019

Edge Zonal Flows:

INFLUENCE OF ION MASS AND OPERATIONAL LIMITS

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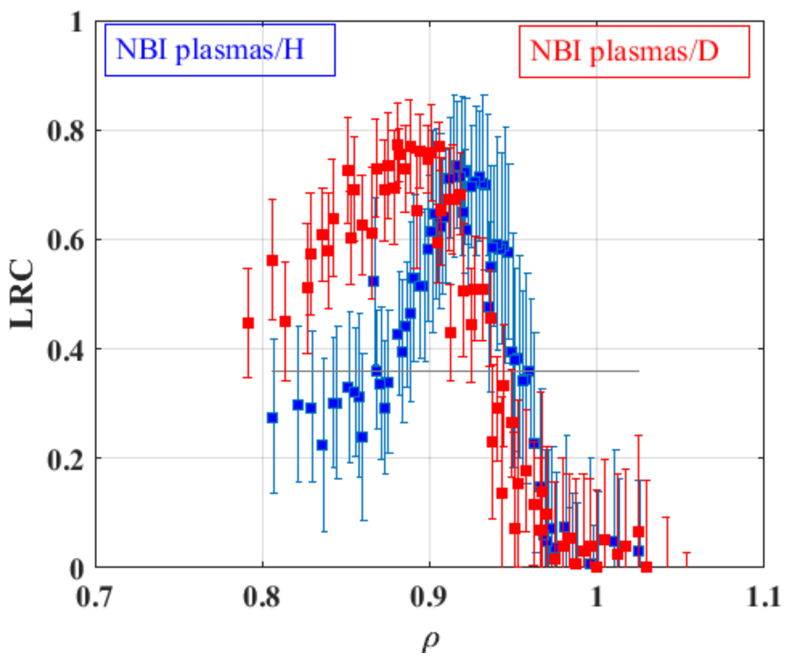
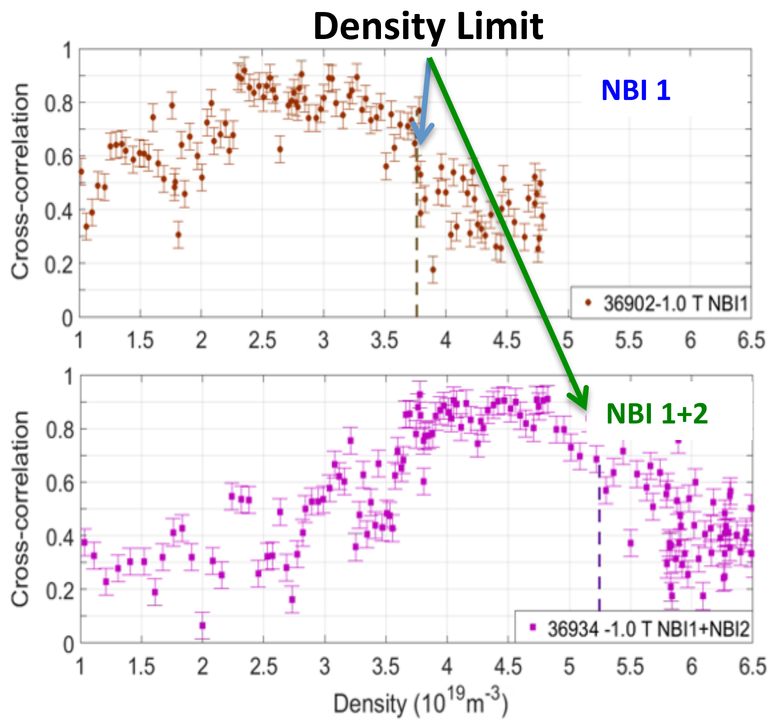
NIFS / Kyoto University collaboration

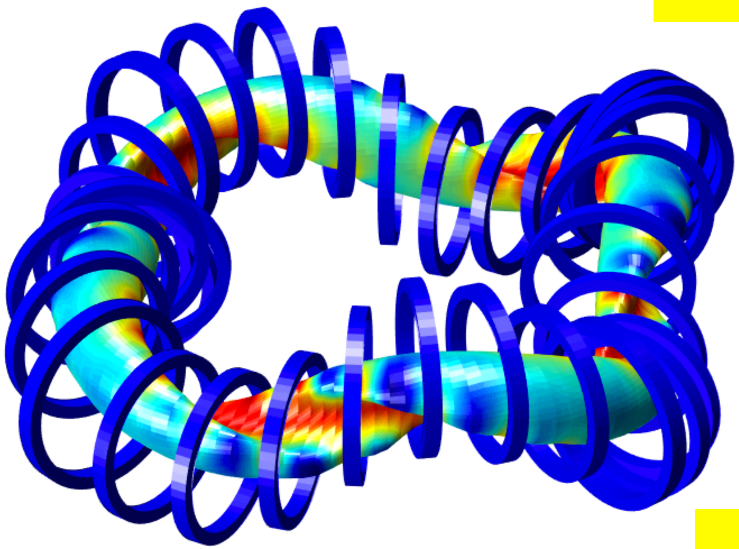




- ✓ The radial radial of LRC is strongly affected by isotope mass [Losada et al., PPCF- 2021 / IAEA-2021]
- ✓ Amplification of ZFs in the vicinity of the density limit [Fernández-Ruiz et al., NF-2021]

Transport and asymmetries

Physics of plasma fuelling



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Power exhaust

CHALLENGE: EDGE – SOL coupling

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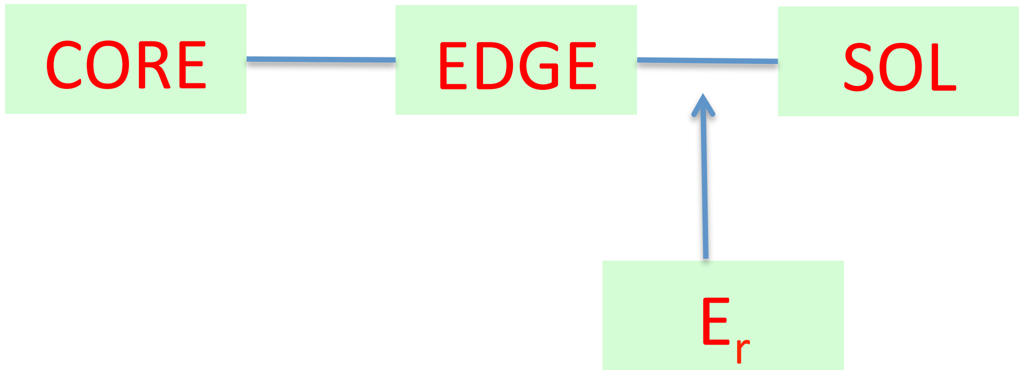
Plasma regimes of operation:
Development of integrated scenarios with controllers



TJ-II strategy:

Characterization of plasma Edge-SOL coupling and role of Radial Electric Fields on turbulence spreading

Role of radial electric fields on EDGE–SOL coupling

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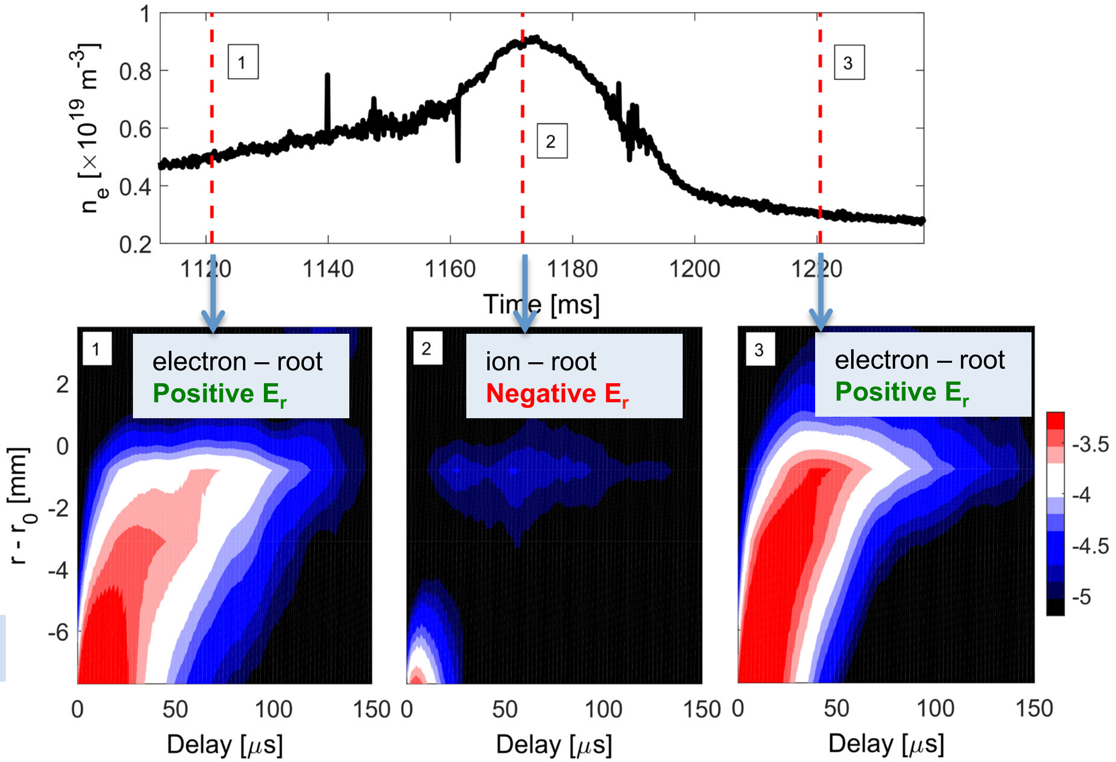
TOWARDS THE VALIDATION OF SOL WIDTH PHYSICS



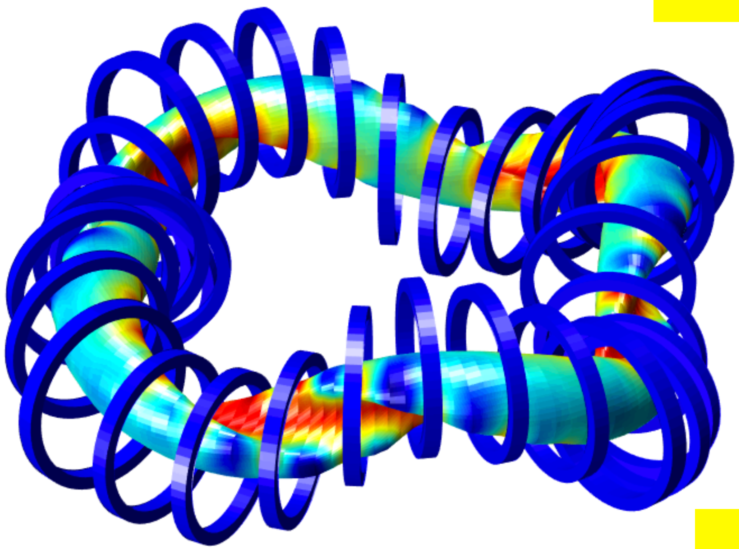
RFX collaboration

- ✓ **Turbulence radial spreading controlled by edge (sheared) radial electric fields** has been experimentally identified during the electron-ion root transition and edge biasing [Grenfell NF-2019 / NF-2020].

- ✓ The radial electric field was also found to have a profound impact on turbulence intermittence. This discovery opens up a new window for the study of the complex interactions between E_r and turbulence [Milligen et al., NF-2020]

Transport and asymmetries

Physics of plasma fuelling



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CHALLENGE:
POWER EXHAUST AND LIQUID METALS

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Whether ITER baseline exhaust strategy can be extrapolated to DEMO is an open question.

Therefore the development of alternative power exhaust solutions is necessary

TJ-II strategy:

LIQUID METALS USING CPS HIGH FLUX FACILITY

Solid and liquid samples of Li/LiSn/Sn in a CPS

The kinetic energy of ejected atomic species is well correlated to the different relative contributions **of sputtered/evaporated** atoms given by the thermal sputtering model

F. Tabarés et al., JNM-2018 / IAEA-2021

D retention

The retention of evaporated or plasma injected lithium on W was investigated to assess its impact on a fusion reactor operating with hot first wall (FW).

It was concluded that an **exponentially decaying retention as the FW temperature is increased** takes place, with negligible D/Li ratios at T>350ºC.

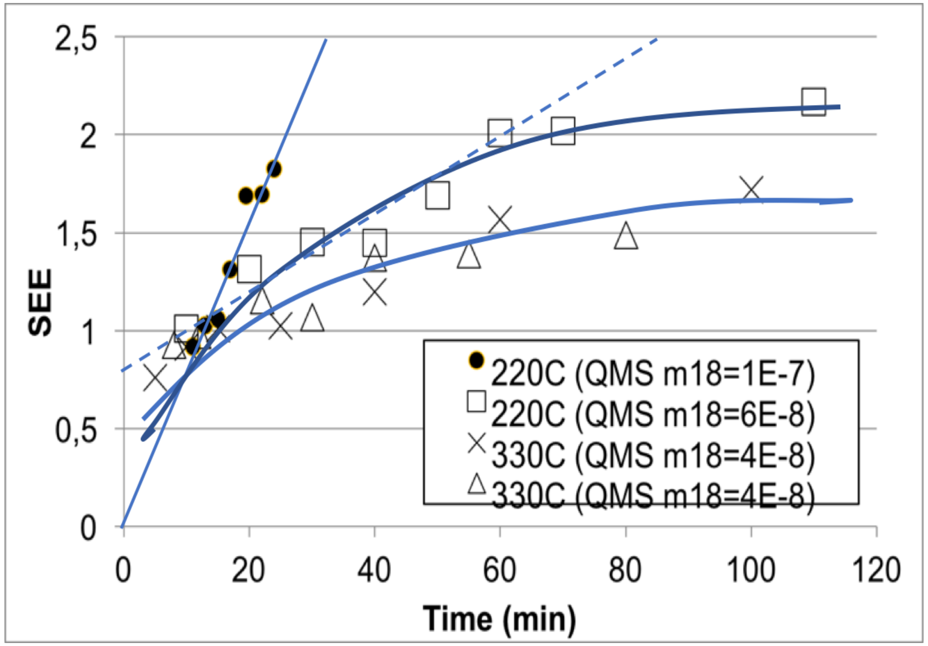
A. de Castro et al., NF-2018 / E. Oyarzabal et al., NF-2021

LIQUID METALS AND POWER EXHAUST
Secondary electron emission in Liquid surfaces

Laboratorio Nacional de Fusión Ciemat

SEE of liquid Li surfaces in a CPS arrangement was investigated for the first time

- ✓ Oxidation of Li leads to an increase in the SEE yield.
- ✓ Annealing of the Li sample at 500 ^{0}C was enough to revert the values to those corresponding to clean surfaces.
- ✓ These results have a direct impact on the development of LM-based divertor targets in fusion.



E. Oyarzabal et al., Nucl. Mater. and Energy 2021

POWER EXHAUST
OLMAT: High heat flux facility

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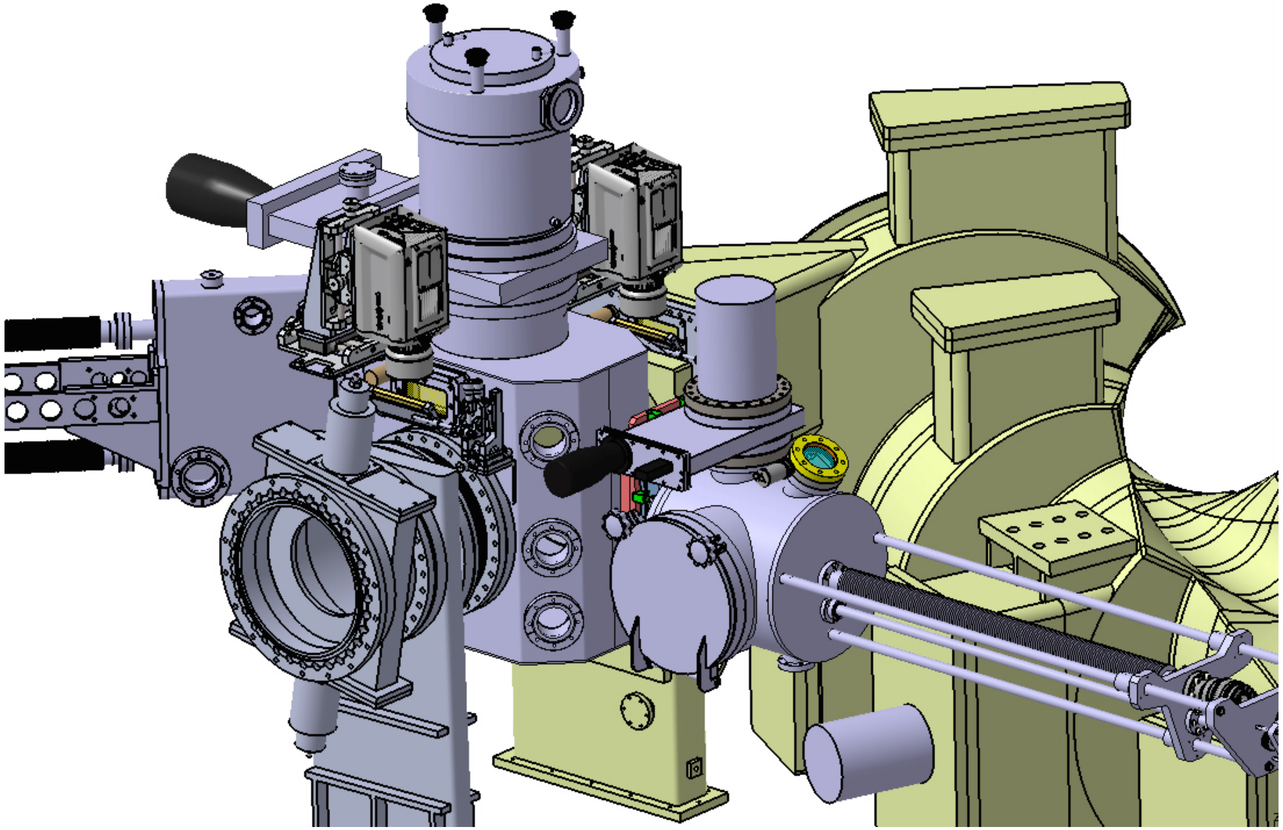

The OLMAT facility, aimed at testing prototypes under DEMO-relevant heat loads was constructed and installed.

TJ-II programme:
towards model validation in fusion plasmas

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Using its unique flexibility and advanced plasma diagnostics,
the TJ-II stellarator is contributing to
the understanding of critical challenges in fusion plasmas.

- Transport [asymmetries]
- Fast particle physics [AEs control]
- Edge-SOL coupling and SOL width
- Turbulent & neoclassical Entanglement & self-organization
- Physics particle fuelling
- Power exhausts

TJ-II collaborators

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