Fast particle confinement and interaction with Alfvén waves.

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Key Physics Uncertainties and Research Needs for Stellarator DEMO Development

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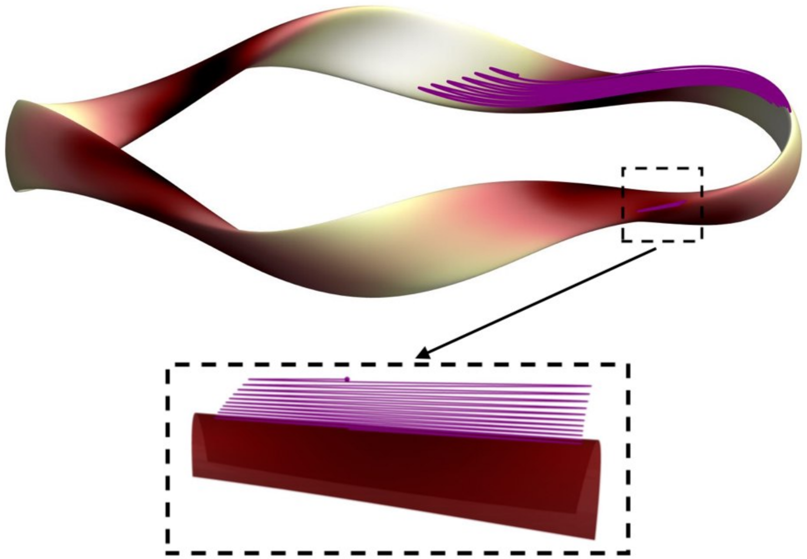
Stellarator reactor needs connected to fast ions



Specifities of fast ions in a stellarator due to 3D magnetic configuration

- Confinement is generally worse (historically, one of the main disadvantages).
- Study (theoretical / experimental) is more complicated.

General needs in a stellarator reactor:

- Fast ion losses have to be small enough to:
  - **Avoid damage to plasma facing components**.
  - Heat the bulk plasma as required by the reactor scenario.
- Impact of on bulk plasma (either postive or negative) has to be **compatible with reactor scenario.**

Gaps grouped in two areas:

(1) **Neoclassical** (i.e. orbits+collisions) transport of fast ions;

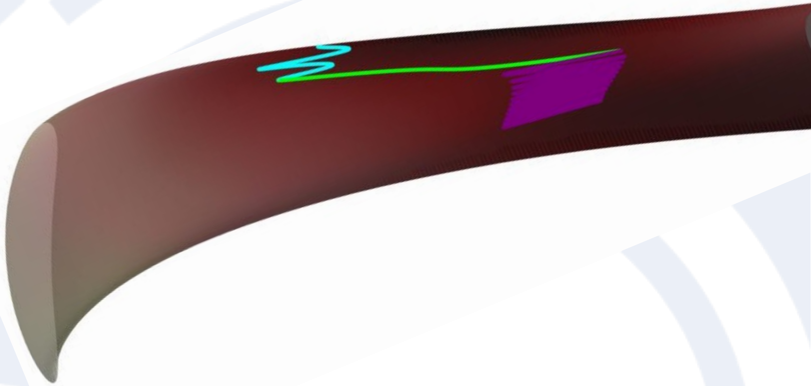
(2) Interplay between **turbulence and Alfvén waves and fast ions**;

with two overarching aspects:

(3) **Experimental validation** (and diagnostics).

(4) Stellarator **optimization** and design.

Neoclassical transport: background



- Equations are well known (full-orbit/guiding-center/bounce-averaged) e.g. [Calvo, EPS2025] and refs. therein.

- (Partially) benchmarked codes exist that solve these equations (ASCOT, BEAMS3D, SIMPLE…); CPU time is generally affordable.

- Solutions can be complicated: many different loss mechanisms due to three-dimensionality ([Paul, 2022] and refs.therein).

- Most relevant loss mechanism: superbananas due to large ratio
  [Nemov, 2008; Velasco, 2023] => prompt losses => PCF damage and inefficient heating)

- **Minimization imperfectly included in W7-X** at high β [Wobig, 1993].

- **Minimization successfully included in Helias/QI design** [Sánchez, 2023; Goodman, 2024; Lyon, 2024; Bader, 2025] even at low b.
  - Target (at the end of the optimization) some alpha heating efficiency (~>90-95%) and maximum wall loading (<~1-2 MW/m^2).
  - Balance between performance w.r.t. and other criteria (specially coil complexity) -> **quantitative predictive capability is key!**

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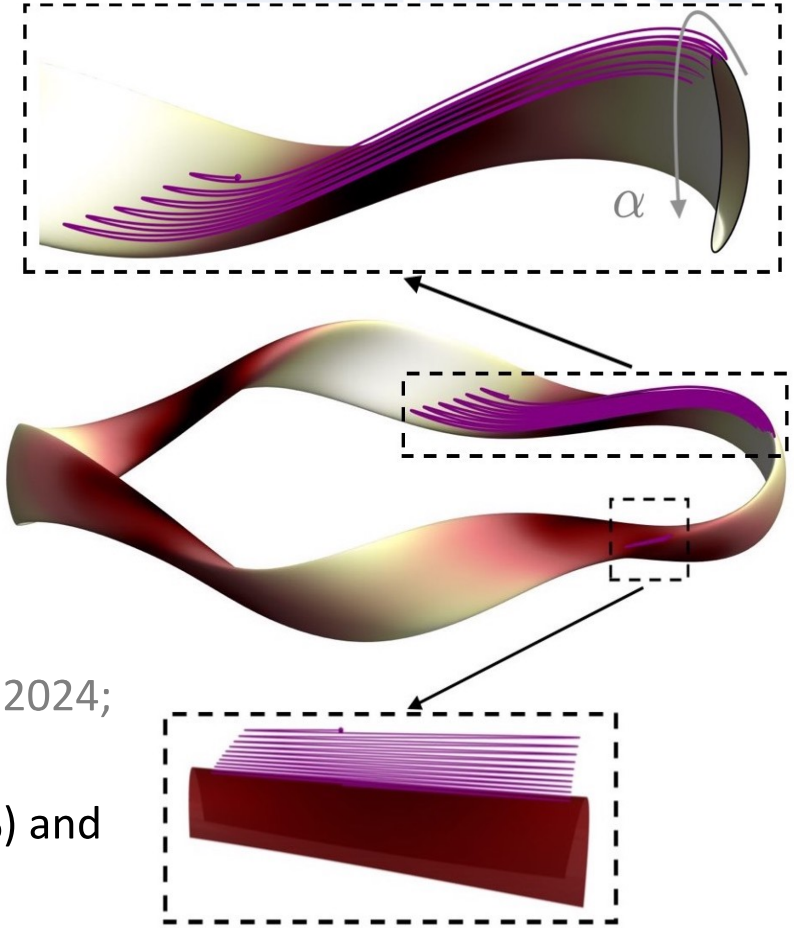

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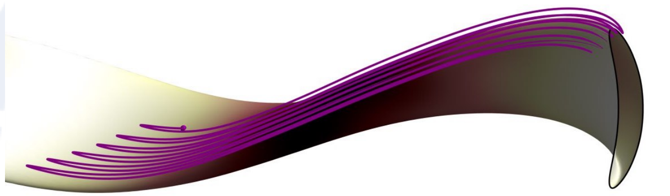

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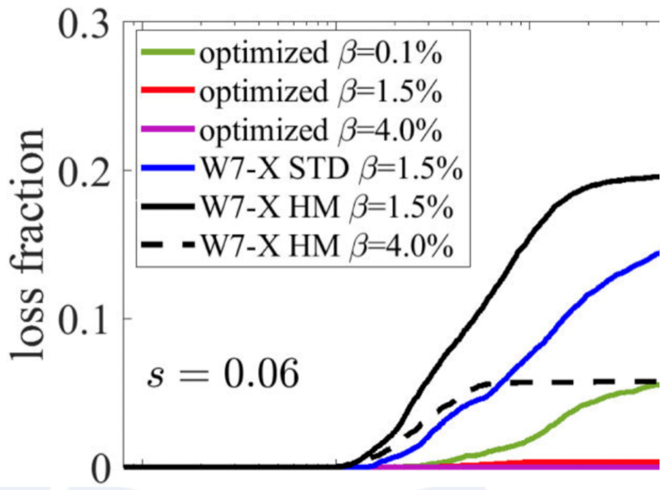


GP.FI.1: Experimental validation of improved confinement at large β

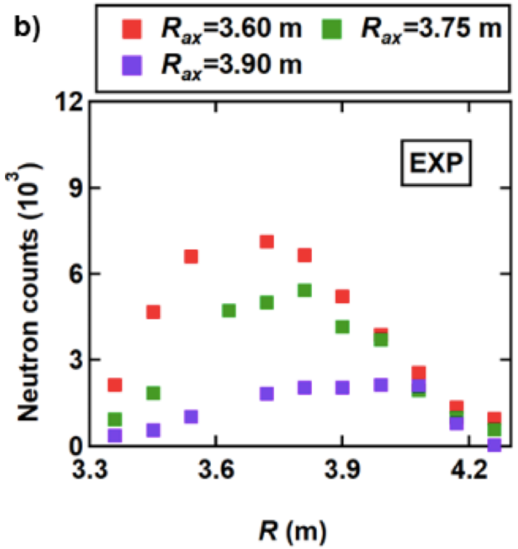
Classification of the gap: E&S.

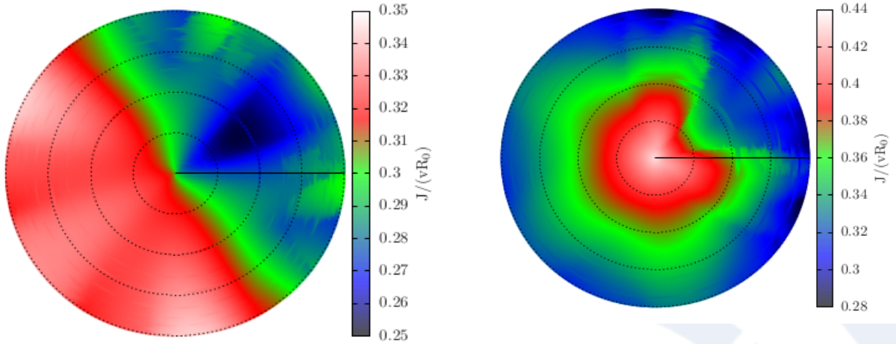
Relevance: *high*, at the basis of QI reactor design.

Urgency: *low*, particle tracing is well understood, *similar* physics has been validated for LHD (inward-shifted vs. outward shifted).

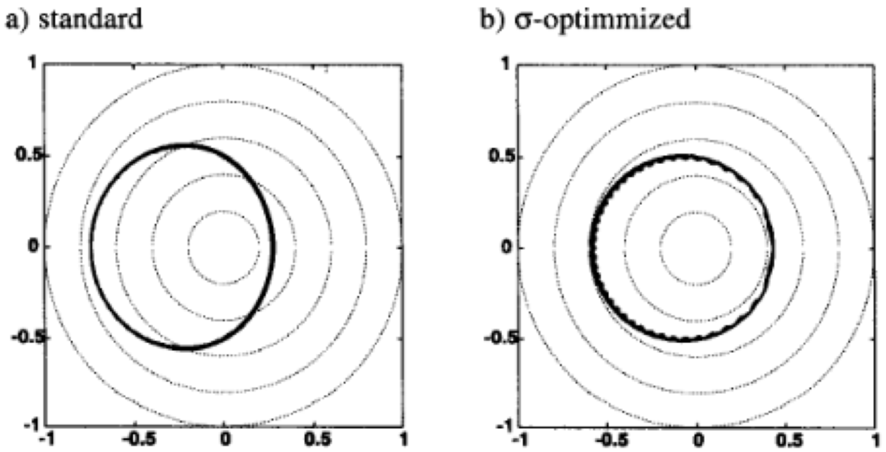
Effort required: *high*, significant experimental progress is required for W7-X conditions:

- Missing scenario (E_r effects, collisions…)
- Fast ion sources.
- Diagnostics.





[Murakami, 2002; Ogawa, 2019; Velasco, 2021]



GP.FI.2: Reliable quantitative prediction of losses to the first wall

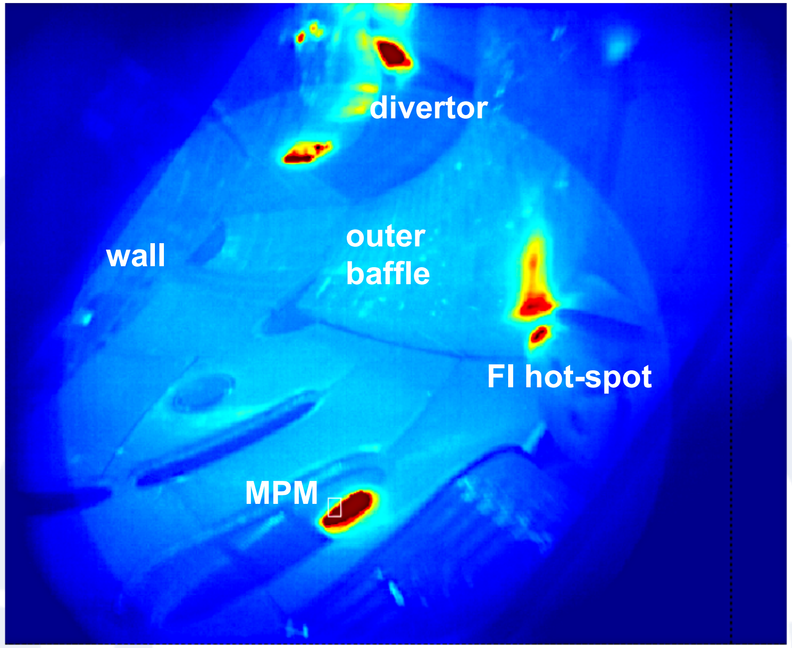
Classification of the gap: E&S.

Effort required: *high*,

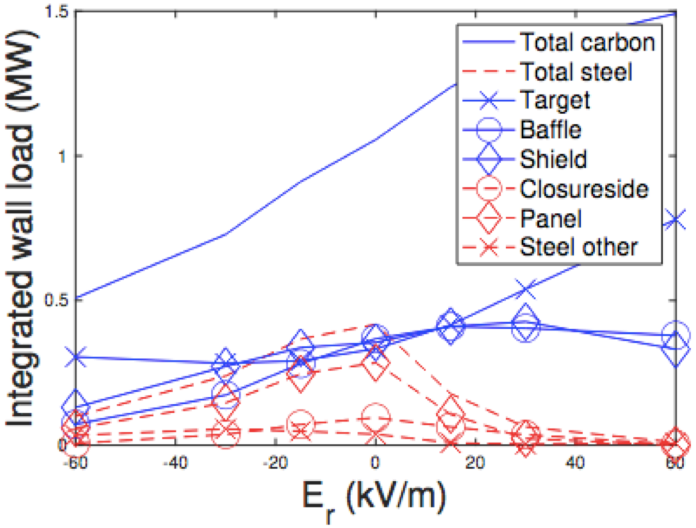
- Small fraction is lost to the areas outside of the divertor, forming hot spots.
- Local loads in the MW/m² (subject to the local geometry) are expected.
- Experimentally the loads are found to be lower.
- Codes have not been extensively benchmarked for this type of prediction.
- Effects of density [Carbajal, 2025], E_r [Kiviniemi, 2025] and neutrals [Mulas, 2023] in the SOL has to be taken into account.

Relevance: *high*, in optimization, area beyond the LCFS and island divertor is ignored (no wall loading criteria) or treated with crude approximations.

Urgency: *medium*, provided predicted losses + coil complexity are small enough.



[Bozhenkov, OP2.2/OP2.3]

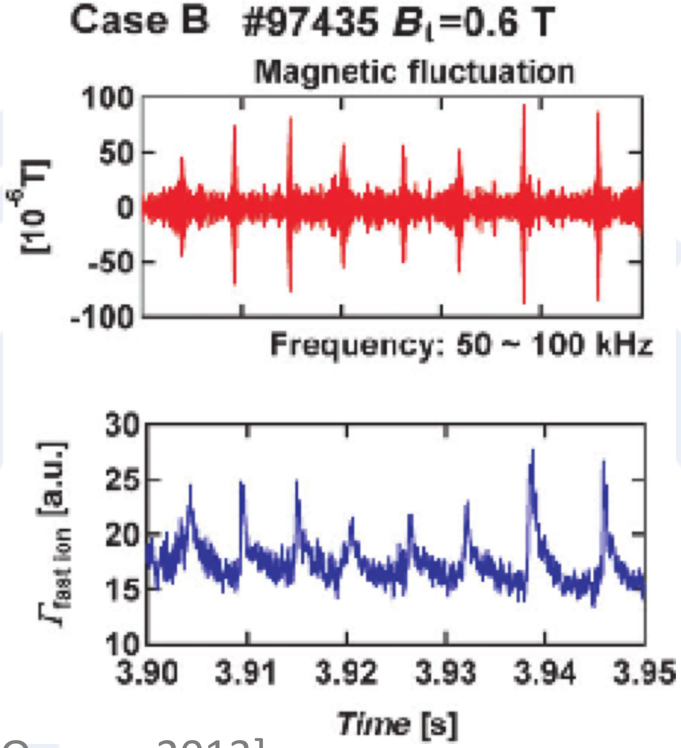


Fast ions and instabilities: background

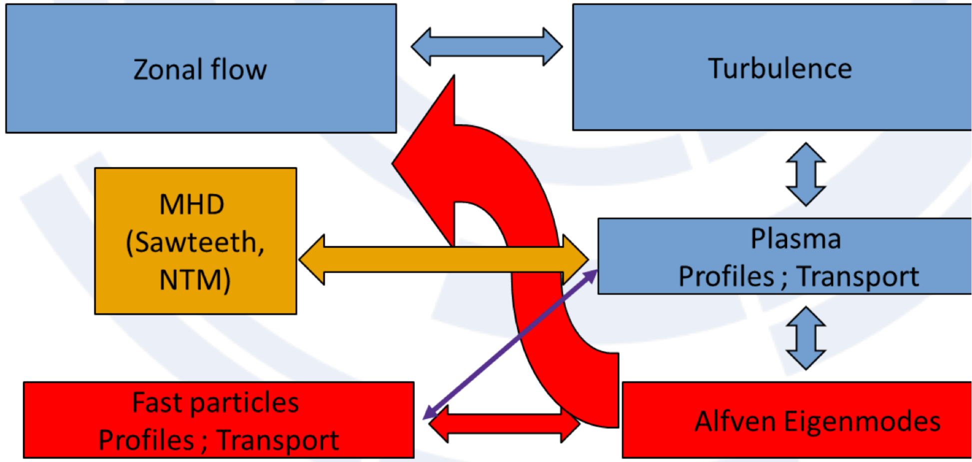
- Alfven waves are excited if the fast ion pressure is sufficiently high (e.g. in burning plasmas) -> increased FI losses and FI redistribution -> generally higher wall loads and different alpha-particle heating profile.

- FI dynamics introduces couplings across scales -> predictive analyses based on first principles computations is challenging -> TSVV10 [Mishchenko]: "develop a self-consistent description and simulation tools (high-fidelity and reduced models) for interaction of FI with MHD modes, turbulence, and kinetic plasma profiles".

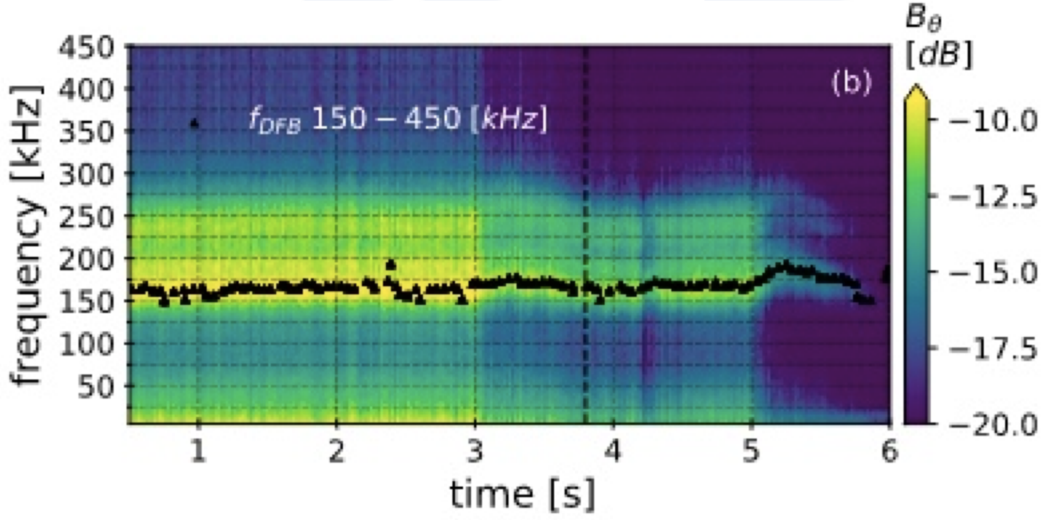
- Seldom included in stellarator reactor optimization and design:
  - Smaller FI drive for Alfvén modes (higher n_e / lower T than tokamak).
  - A posteriori analisis of Alfvén continuum (e.g. STELLGAP) and stability analysis of AE in these Alfvén gaps (e.g. FAR3D) [Carbajal, 2025].
  - Recently, optimization of Shear Alfven Continuum (QS stellarators).



[Ogawa, 2013]



GP.FI.3: Experimental measurements of AE induced FI losses and verification of model prediction



Classification of the gap: E&S.

Relevance: *high* (increased wall loads and lower heating).

Urgency: *high* (hot-spot identification pending).

Effort required: *high*, significant experimental progress is required

- Results exist for LHD [Ogawa, 2013].
- In W7-X, the FI pressure is usually too low to excite AEs. Alfvénic fluctuations driven by ITG turbulence [Riemann and Mendes, 2025].
- Models of various complexity available (but most stop at LCFS).
  - Fully gyrokinetic approaches are numerically expensive
  - Reduced models need to be validated.

GP.FI.4: Assessment of the interplay between fast ions, zonal flows, and turbulence

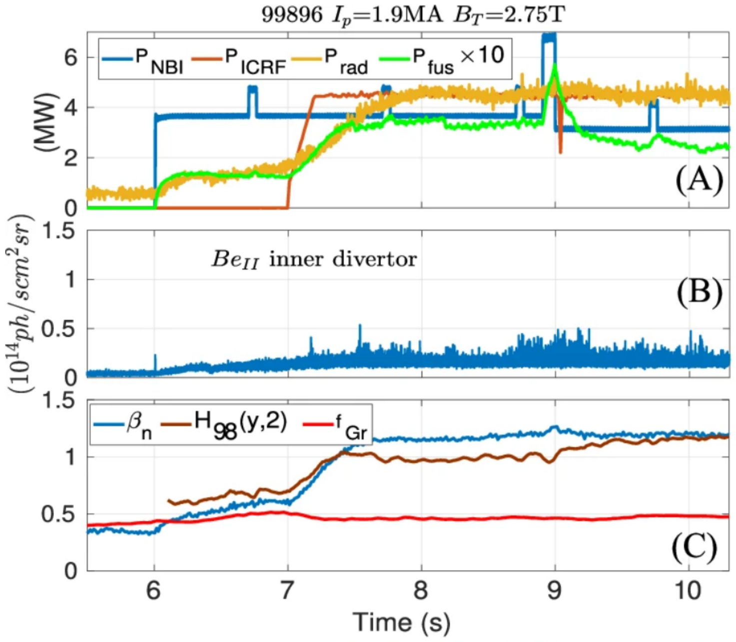
Classification of the gap: T&S&E

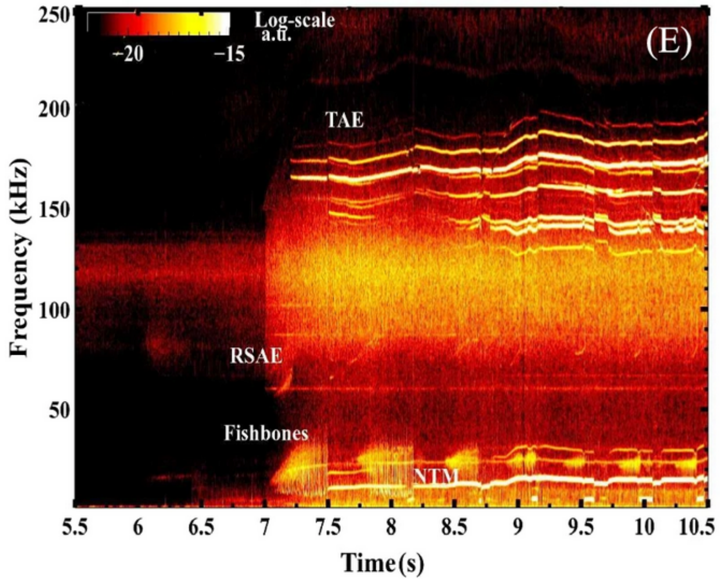
Relevance: *high* (impact on reactor scenario).

Urgency: *medium* (provided effect is not negative, unclear if it applies to a reactor scenario).

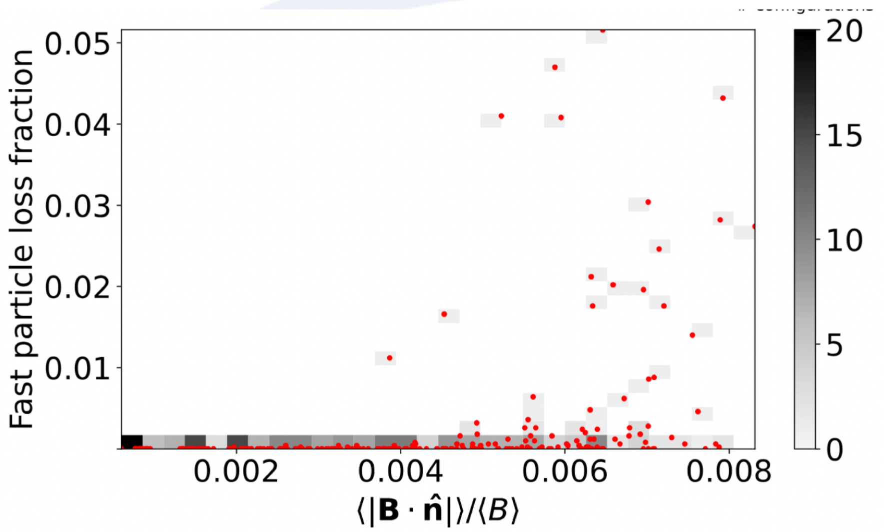
Effort required: *high*

- Scenarios as in [García, 2024] (in JET) not be available in W7-X.
- Fully accurate simulations are very expensive.
    - Predicted stabilization of electrostatic turbulence by *Maxwellian* fast ions [Di Siena, 2020].





GP.FI.5: Sensitivity of reactor scenario to error fields, β_{FI} and β_{bulk} effects, currents



[Wiedman, 2024]

Example: fast ion transport may be very sensitive to the rotational transform:

- A $B(\theta,\phi)$ is exactly QI for a given ι.
- Changes in the ι profile effect on AEs, continuum.
- Can a significant FI pressure (~20%) affect ι profile?

Classification of the gap: T&S

Relevance: *high.*

Urgency: *medium* or *high*, depending on sensitivity.

Effort required: *medium*

- For some aspects tools are available, datasets probably exist or can be created.

GP.FI.6: Development of measurement techniques for FI in a reactor

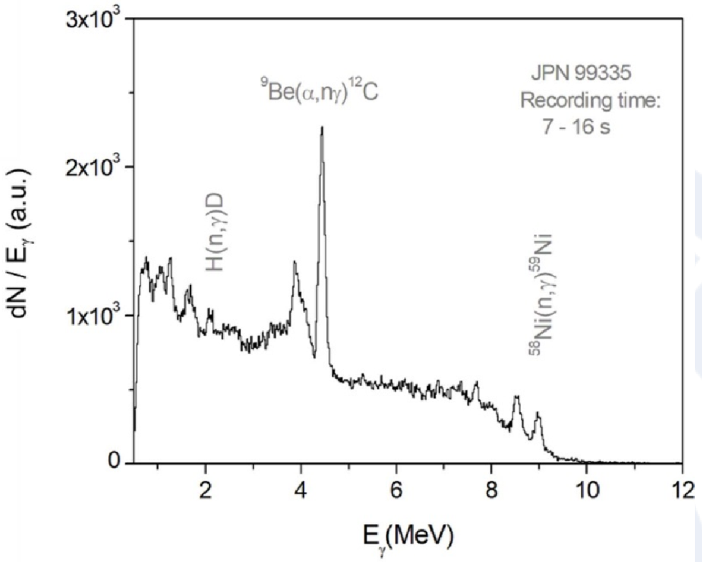
Classification of the gap: E.

Relevance: *medium, k*nowledge of FI distribution will be required in a reactor, e.g. for modelling or control purposes.

Effort required: *medium*,

- In common with tokamaks.
- Well known techniques: CTS, gamma ray spectrum, and neutron measurements. Hot-spot monitoring?
- Feasibility for a reactor should be further verified.

Urgency: *low*, not critical for the design.



Gamma ray spectrum from JET DT experiment [Kiptily, NF 2024]

Summary

Gap ID	Description	Relevance	Urgency	Effort required					
GP.FI.1	Experimental validation of improved confinement at large β	High	Low	High					
GPFI.2	Reliable quantitative prediction of losses to the first wall	High	High	Medium					
GPFI.3	Experimental measurements of AE induced FI losses and verification of model prediction	High	High	High					
GPFI.4	Assessment of the interplay between fast ions, zonal flows, and turbulence	High	Medium	High					
GPFI.5	Sensitivity of reactor scenario to error fields, β_{FI} and β_{bulk} effects, currents	High	Medium/high	Medium					
GPFI.6	Development of measurement techniques for FI in a reactor	Medium	Low	Medium					