How MeV-Range Ions and High β Will Shape the Core Plasma Dynamics of Fusion Power Plants

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[a] see C.F. Maggi et al., Nucl. Fusion 64, 112012 (2024)
[b] see E. Joffrin et al., Nucl. Fusion 64, 112019 (2024)

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Motivations & Background

Fast-Ion-Driven Alfvén Eigenmodes Shaping Core Performances

- Fast Ions ubiquitous in tokamaks: externally generated and fusion-born α particles
- Fast Ions may destabilize Alfvén Eigenmodes (AEs) → Potentially leading to fast-ion losses
- AEs expected unstable in ITER [Pinches2015]

What impact on confinement properties and performance?

Fast Ions (fusion-born α) → Alfvén Eigenmodes → High β (Electromagnetic fluctuations) → Turbulence → …

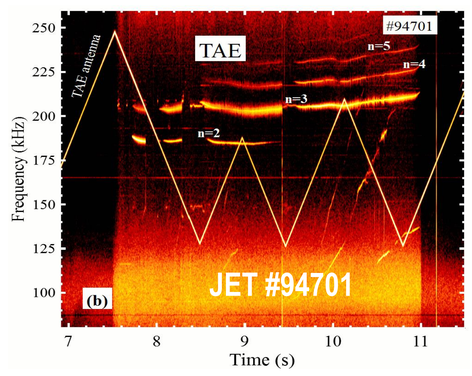
High β Conditions Shaping Turbulence Properties & Electron Distribution Function

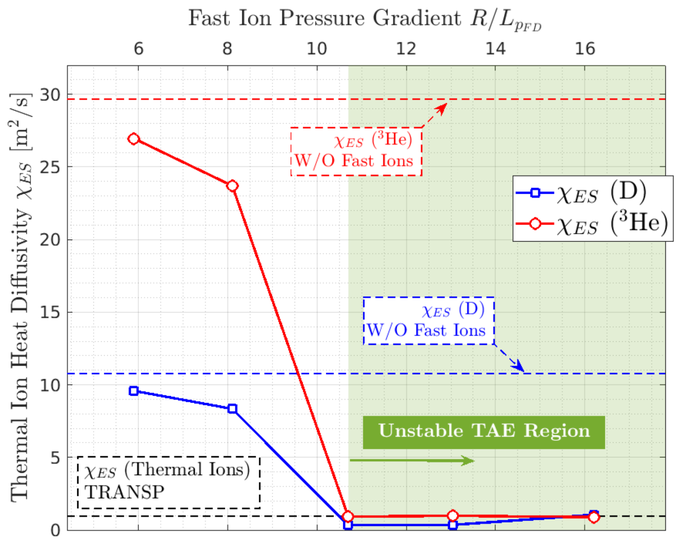
- High β (high temperature and density) conditions in reactor-relevant plasma scenario → Destabilization of core Kinetic Ballooning Modes (KBMs) [Moradi2014,Kumar2021,Mazzi2025]

What impact on confinement properties and performance?

Mechanisms Dissection: How Nonlinear Complex Interactions Impact on High-Performance Core Plasma Dynamics

- MeV-range fast ions (generated through 3-ion heating scheme [Kazakov2017]) destabilize Toroidal Alfvén Eigenmodes (TAEs) – and other AEs and EPMs – in JET core
- Improved thermal ion confinement observed experimentally in the presence of unstable core-TAEs [Mazzi2022a] …
- … Also reproduced in DT plasma [Garcia2024]
  - ➢ Thermal ion diffusivity strongly reduced in the plasma core!

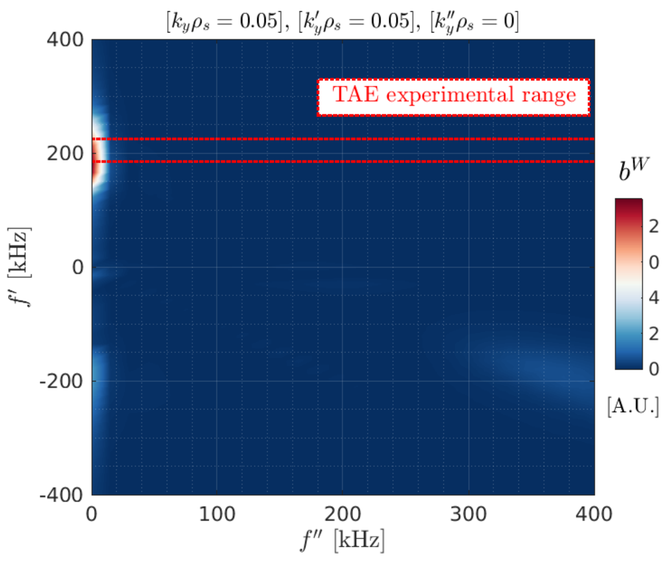


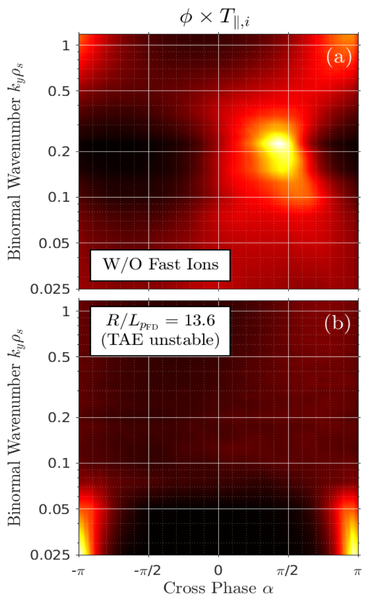


Validated multi-code (GENE and CGYRO) gyrokinetic simulations unveiling:

Fast Ions → *Destabilizing* → **TAEs** → *Coupling* → **Zonal Structures** → *Suppressing* → **Ion-scale Turbulence**

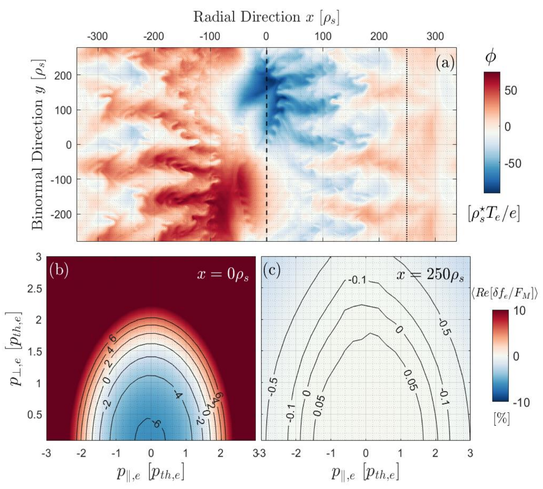
- ➢ Bicoherence analysis on DBS measures → Coupling between TAEs and zero-frequency perturbations [RuizRuiz2025]
- ➢ Reflectometry measurements confirm turbulence reduction [Mazzi2022,Heidbrink2024]
- ➢ In-phase evolution of turbulent sources (δT_i & Φ) observed in gyrokinetic simulations [Mazzi2022b,DiSiena2025] → Consistent with reduced heat fluxes





❖ Under Review in *Rev. Mod. Plasma Phys.*: S. Mazzi *et al.*, *Fast Ion Interaction with Turbulence Mediated by Zonal Flows in Tokamak Plasmas: Overview of the Recent Insights*

- Gyrokinetic simulations with GENE [Jenko2000] of selected JET plasma core [Garcia2022]
  - ➢ KBMs destabilized by a combination of high β and low magnetic shear in the deep core
  - ➢ Strong stiffness of nonlinear turbulent fluxes → Clamping the temperature profiles



- Analyzing the electron distribution function (EDF) in correlation with presence of KBM structures:

Where KBM perturbation (panel b)	Where no KBM (panel c)
Bipolar signature	Absence of structures

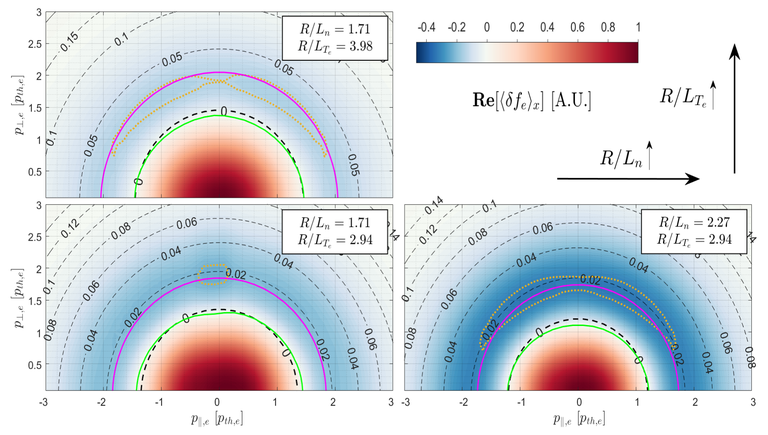
- Structure depends on electron diamagnetic frequency:

$$\omega_e^\star = \left[R/L_{n_e} + R/L_{T_e} \left(p_\parallel^2 + p_\perp^2 - \frac{3}{2} \right) \right]$$

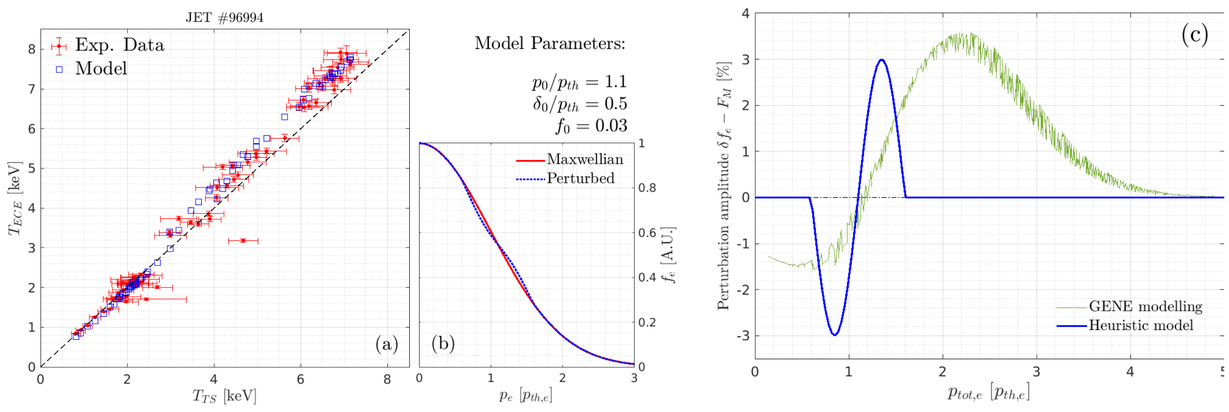
- ➢ Possible experimental validation

$$p_0[p_{th}] = \sqrt{\frac{3}{2} - \frac{R/L_{n_e}}{R/L_{T_e}}}$$

- ➢ **Persistent** KBM-induced perturbation **localized** and dependent on the **KBM amplitude**



- Long-standing issue → Systematic multi-device observation of discrepancy between Electron Cyclotron Emission (ECE) and Thomson Scattering (TS) measurements at high T_e
- Heuristic model developed [Giruzzi2023,Fontana2023] → Small perturbation on the electron distribution function (EDF) reconciling the discrepancy



- ➢ KBM-induced perturbation on EDF comparable with heuristic model → Deep-core KBMs may explain the ECE-TS measurement discrepancy
- ➢ Powerful ECE diagnostic → Possibility of tracking high β instabilities in deep core plasma

(Partial) Conclusions

- Observed beneficial multi-scale nonlinear electromagnetic mechanism triggered by MeV externally-generated ions @ JET [Mazzi2022a,Mazzi2023,Garcia2024,DiSiena2025]
  - ✓ Multi-device mechanism (JET, TCV, DIII-D, ASDEX-U) [Mazzi2023,Heidbrink2024,DiSiena2024]
  - ✓ Experimental measurements evidencing beneficial impact of AEs [Mazzi2022a,RuizRuiz2024,Heidbrink2024]
- Advanced global gradient-driven gyrokinetic simulations confirm the earlier findings and explore the mechanism [DiSiena2025]
- ➢ Need for: ✓ Better experimental diagnosing and coverage of different turbulence regimes
  - ✓ First-principle models including self-consistent sources and other EPMs [Brochard2024]
  - ✓ Reliable reduced models

- KBMs destabilized in high β core plasmas → Identified in multiple JET scenarios [Moradi2014,Kumar2021,Mazzi2025]
- Clear wave-particle interaction leading to bipolar structures in EDF momentum space:
  - ✓ Amplitude dependent on KBM-induced turbulence intensity
  - ✓ Strongly localized in deep core
  - ✓ Position in momentum space dependent on electron diamagnetic frequency
- Affecting ECE measurements → Possible explanation of long-standing ECE-TS discrepancy (other possible explanations: collisional relaxations of fast ions and α [Dumont2025] and/or radially localize MHD instabilities [Orsitto2025])
- ➢ Need for: ✓ Detailing underlying physical mechanism of wave-particle interaction mediated by $\omega_e^\star$
  - ✓ Experimental validation → Building large database [Senni2025]

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