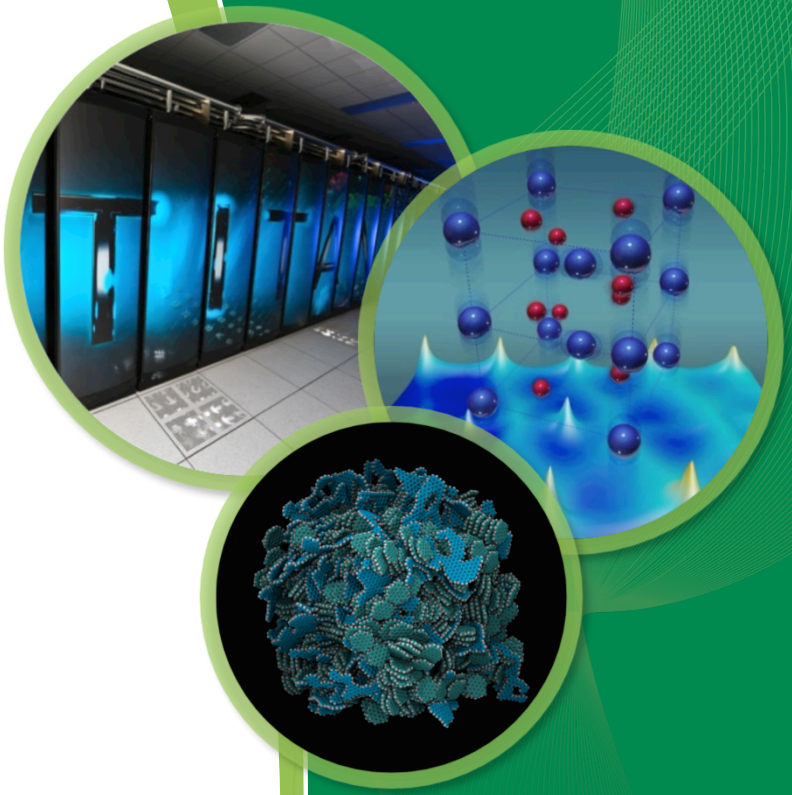
Numerical modeling and synthetic diagnostics for fusion-born ions

Leopoldo Carbajal Gomez

FMNSD, ORNL



ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE National Laboratory

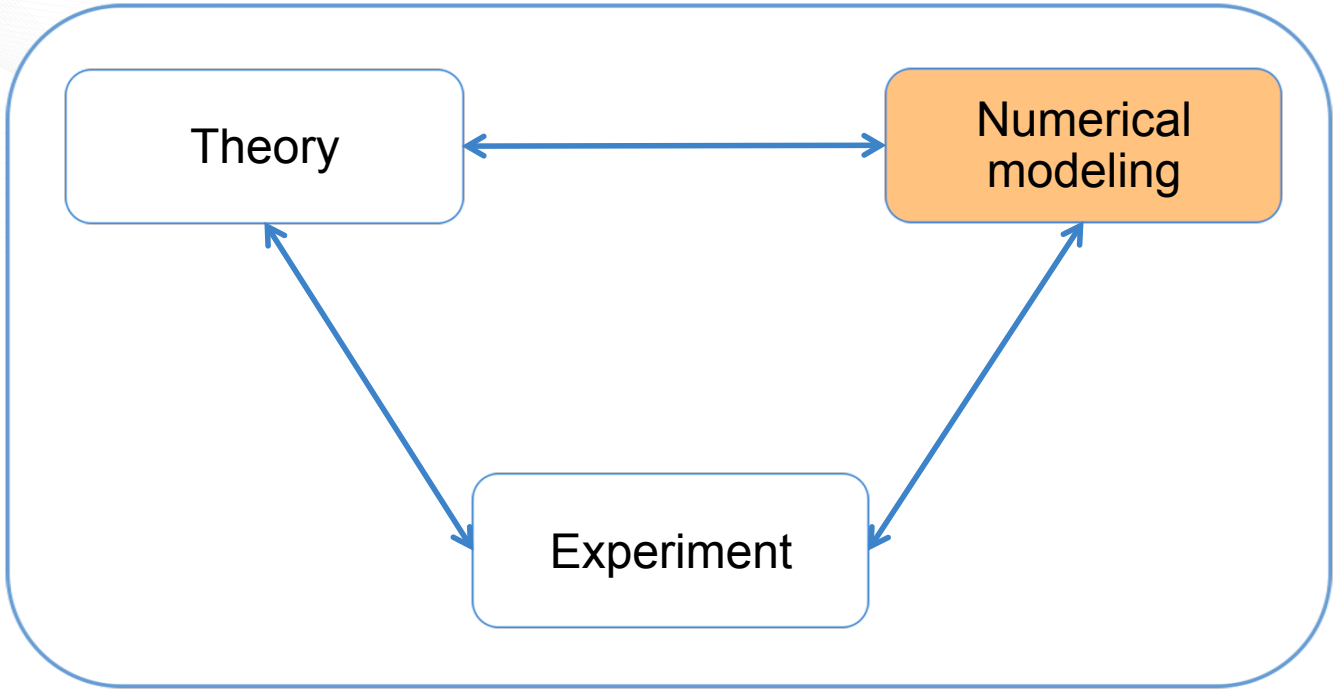
- New postdoc in the FMNSD working on runaway electrons.
- Synthetic diagnostics for SOL plasmas (Aix-Marseille, France).
- Numerical modeling of fusion-born ions (Warwick, UK).
- Numerical modeling of multiphase flows (Mexico).
- Theoretical plasmas physics (UNAM Mexico, ORNL).
- Theoretical physics (Mexico).

OAK RIDGE National Laboratory

Outline of the talk

- Fusion-born ion effects in MCF plasmas.
- The Ion Cyclotron Emission (ICE).
- Numerical modeling and synthetic diagnostics for fusion-born ions in MCF plasmas: ICE in D-T JET plasmas.
- Summary

OAK RIDGE National Laboratory



THE UNIVERSITY OF WARWICK

CCFE CULHAM CENTRE FOR FUSION ENERGY

OAK RIDGE National Laboratory

Richard O. Dendy (CCFE)

Sandra C. Chapman (CFSA)

James W. S. Cook (CFSA)

More people involved: JET,

LHD, IPP,…

THE UNIVERSITY OF WARWICK

CCFE CULHAM CENTRE FOR FUSION ENERGY

OAK RIDGE National Laboratory

Fusion-born ion effects in MCF plasmas

- **Fusion-born ions** (alpha-particles) will provide most of the **plasma heating** needed to achieve **self-sustained nuclear burning** in future thermonuclear fusion reactors: **it's important to keep an eye on these guys!**
- In some scenarios, fusion-born ions can drive instabilities, AEs for example, which in turn modify the distribution of fusion-born ions. This might result in **enhanced radial energy transport in MCF plasmas**.
- In general, these instabilities can be classified as [Sharapov et al., 2013]:
  1) **perturbative instabilities** (frequency locked)
  2) **non-perturbative instabilities** (frequency sweeping)

OAK RIDGE National Laboratory

Fusion-born ion effects in MCF plasmas

- In general, this instabilities can be classified as [Sharapov et al., 2013]:
  1) **perturbative instabilities** (frequency locked)
  2) **non-perturbative instabilities** (frequency sweeping)

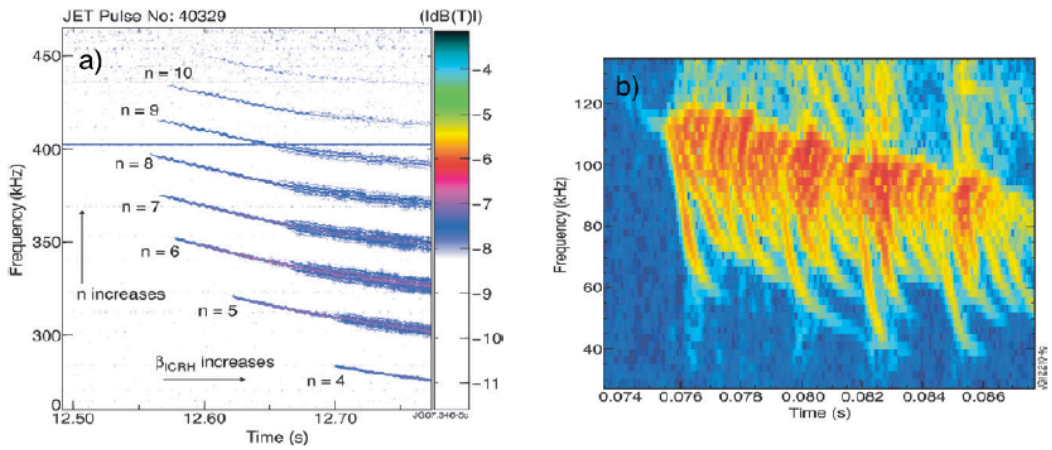


Figure 1.2: Examples of spectrograms of the magnetic field in JET and MAST. Panel a): Spectrogram of the magnetic field in JET discharge #40329 showing (perturbative) ICRH-driven TAEs. Panel b): Spectrogram of the magnetic field in MAST discharge #27177 showing (non-perturbative) chirping Alfvén modes driven by NBI energetic ions. Reproduced from Sharapov et al. [2013].

OAK RIDGE National Laboratory

Fusion-born ion effects in MCF plasmas

- A deep understanding of these instabilities will allow us to diagnose some parameters of the plasma and to monitor the confinement of fusion-born ions.

Experiment + Theory + Numerical modeling

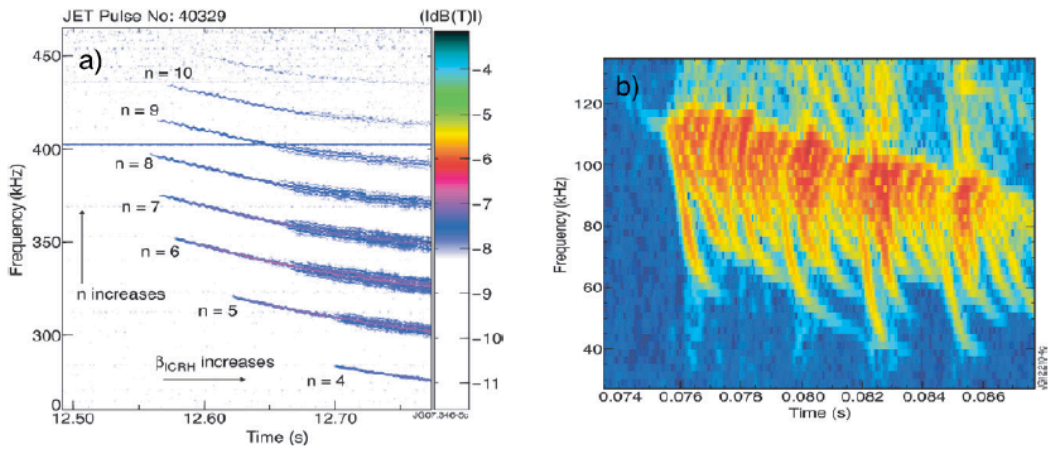
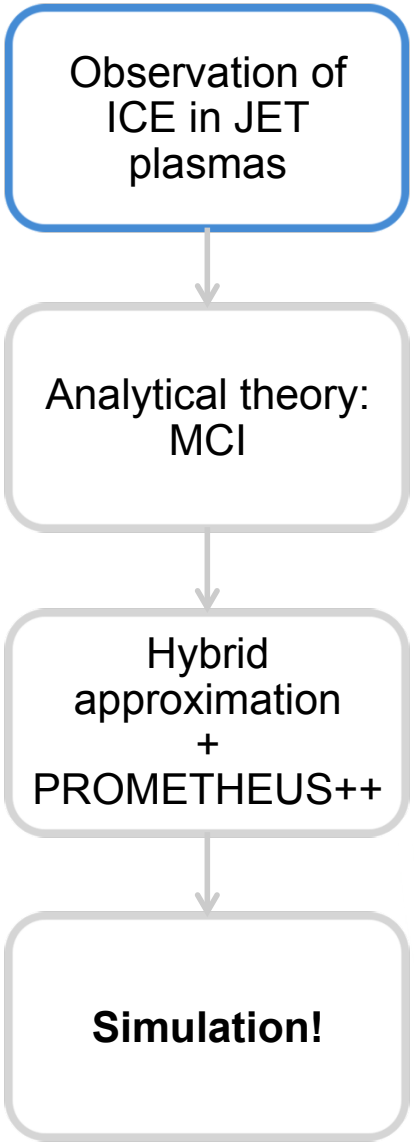


Figure 1.2: Examples of spectrograms of the magnetic field in JET and MAST. Panel a): Spectrogram of the magnetic field in JET discharge #40329 showing (perturbative) ICRH-driven TAEs. Panel b): Spectrogram of the magnetic field in MAST discharge #27177 showing (non-perturbative) chirping Alfvén modes driven by NBI energetic ions. Reproduced from Sharapov et al. [2013].

OAK RIDGE National Laboratory

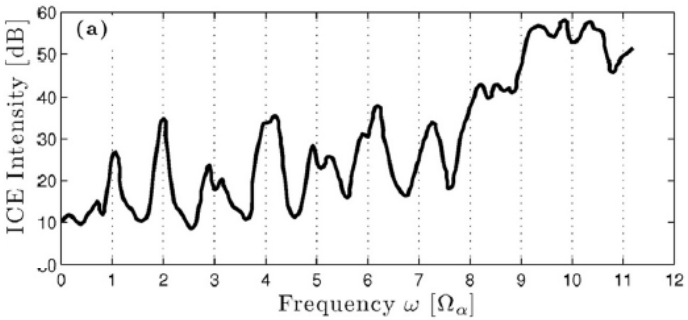
Numerical modeling of ICE in D-T JET plasmas



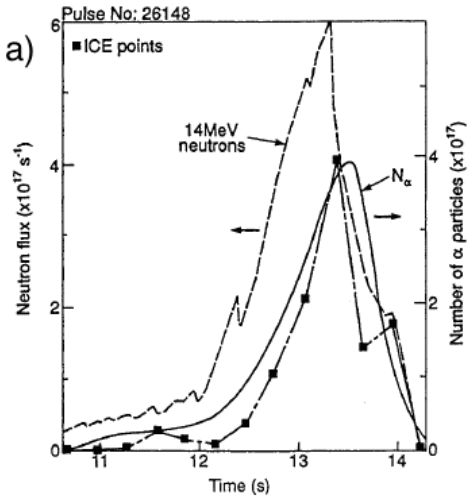
OAK RIDGE National Laboratory

The Ion Cyclotron Emission (ICE)

- ICE is a (perturbative) **radiative instability driven by fusion-born ions** in MCF plasmas**.**
- ICE was first detected in pure deuterium JET plasmas (ICE driven by energetic protons), and later in D-T JET plasmas (ICE driven by alpha-particles).
- In these plasmas, the Fourier spectrum of magnetic field perturbations showed well defined **spectral peaks at frequencies corresponding to consecutive cyclotron harmonics of alpha-particles**.
- **Measured ICE intensity (P_{ICE}) at the second cyclotron harmonic exhibited linear scaling with alpha-particle concentration.**
- Correlation with MHD activity (ELMs and sawtooth instabilities).



Power spectrum (Fourier spectrum) of the magnetic field in a D-T JET plasma.

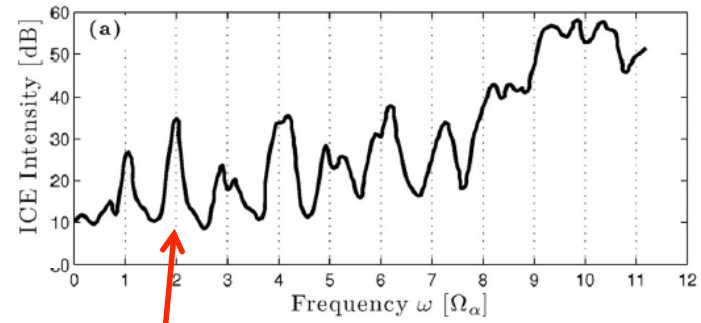


Time evolution of the neutron flux (dashed line), P_{ICE} (squares), and alpha-particle population at the outer edge plasma (solid line) in a D-T plasma in JET.

OAK RIDGE National Laboratory

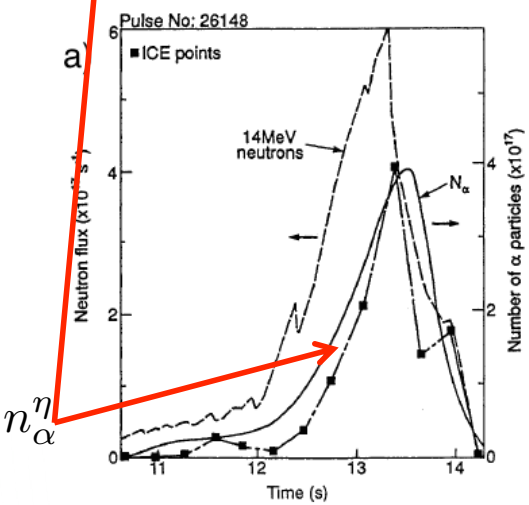
The Ion Cyclotron Emission (ICE)

- ICE is a (perturbative) **radiative instability driven by fusion-born ions** in MCF plasmas**.**
- ICE was first detected in pure deuterium JET plasmas (ICE driven by energetic protons), and later in D-T JET plasmas (ICE driven by alpha-particles).
- In these plasmas, the Fourier spectrum of magnetic field perturbations showed well defined **spectral peaks at frequencies corresponding to consecutive cyclotron harmonics of alpha-particles**.
- **Measured ICE intensity (P_{ICE}) at the second cyclotron harmonic exhibited linear scaling with alpha-particle concentration.**
- Correlation with MHD activity (ELMs and sawtooth instabilities).



Power spectrum (Fourier spectrum) of the magnetic field in a D-T JET plasma.

$$P_{\mathrm{ICE}} \propto n_\alpha^\eta$$



Time evolution of the neutron flux (dashed line), P_{ICE} (squares), and alpha-particle population at the outer edge plasma (solid line) in a D-T plasma in JET.

OAK RIDGE National Laboratory

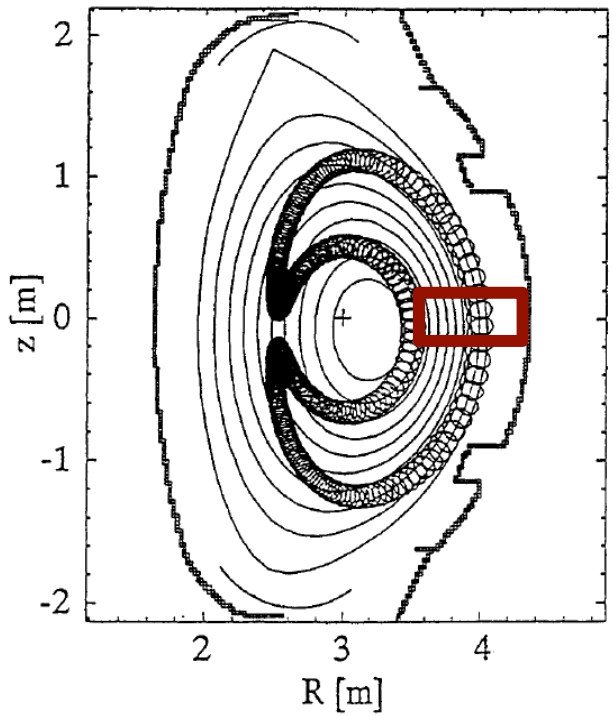
The Ion Cyclotron Emission (ICE)

- The **fusion-born alpha-particles driving ICE in JET had a ring-like distribution in velocity space** and experienced large excursions to the outer edge plasma.

- ICE has been detected in other tokamaks:
  - **ASDEX-Upgrade** (Germany)
  - TFTR (USA)
  - DIII-D (USA)
  - JT-60U (Japan)
  - LHD* (Japan)

- Notably, in ASDEX-Upgrade different types of ICE have been identified:
  - **Edge ICE**, driven by fusion-born ions and RF-accelerated ions.
  - ICE driven by **NBI-ions**.
  - **Core ICE**, which driving mechanism is still unknown.

$$\mathrm{D} + \mathrm{T} \rightarrow \boxed{\mathrm{He}^4(3.5\mathrm{MeV})} + n(14.1\mathrm{MeV})$$



Orbit of a centrally born alpha-particle driving ICE in D-T plasmas in JET.

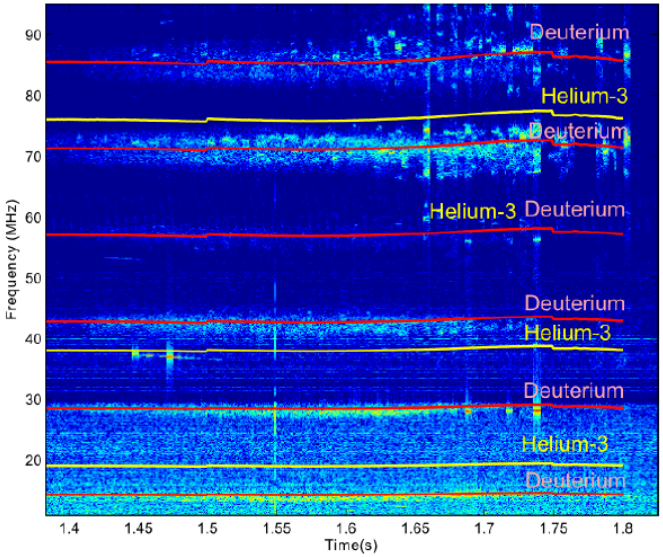
OAK RIDGE National Laboratory

The Ion Cyclotron Emission (ICE)

- The **fusion-born alpha-particles driving ICE in JET had a ring-like distribution in velocity space** and experienced large excursions to the outer edge plasma.

- ICE has been detected in other tokamaks:
  - **ASDEX-Upgrade** (Germany)
  - TFTR (USA)
  - DIII-D (USA)
  - JT-60U (Japan)
  - LHD* (Japan)

- Notably, in ASDEX-Upgrade different types of ICE have been identified:
  - **Edge ICE**, driven by fusion-born ions and RF-accelerated ions.
  - ICE driven by **NBI-ions**.
  - **Core ICE**, which driving mechanism is still unknown.

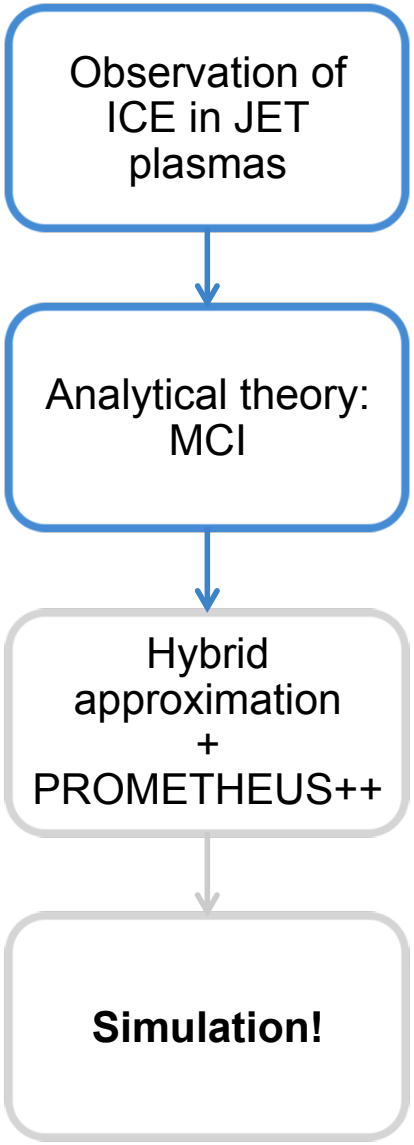


Edge-ICE as measured in ASDEX-Upgrade. Reproduced from D'Inca R. PhD Thesis [2014].

ICE is an outstanding candidate for diagnosing **fusion-born alpha-particles** in future fusion reactors (Dendy and McClements 2015; McClements et al. 2015).

OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas



OAK RIDGE National Laboratory

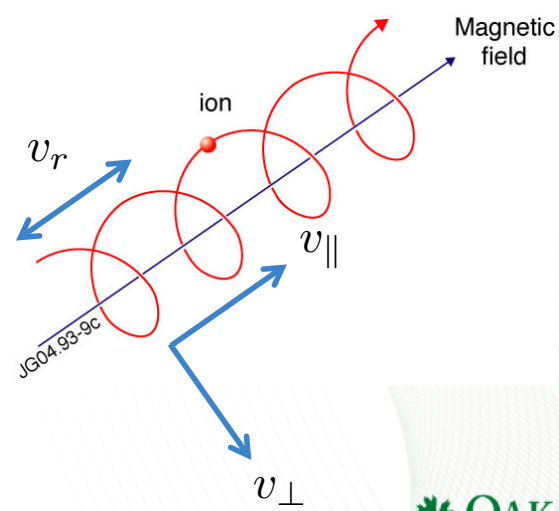
Numerical modeling of ICE in D-T JET plasmas

- We need to propose a **theoretical model** to describe the instability driven by the energetic ions.
- The **magnetoacoustic cyclotron instability (MCI)** is the leading candidate of the emission mechanism underlying ICE in JET (Dendy et al. 1995).
- The MCI assumes a **thermalized electron-deuteron background plasma**, and a minority population of **alpha-particles** with a drifting **ring-like distribution in velocity space**:

$$\mathrm{D} + \mathrm{T} \rightarrow \boxed{\mathrm{He}^4(3.5\mathrm{MeV})} + n(14.1\mathrm{MeV})$$

$$f = \frac{1}{2\pi^{3/2} u_\perp v_r} \exp\left(-\frac{\left(v_\parallel - v_d\right)^2}{v_r^2}\right)\delta(v_\perp - u_\perp)$$

$$u_\perp \sim 3.5 \text{ MeV}$$



Numerical modeling of ICE in D-T JET plasmas

- Amongst the most important predictions of the MCI in relation to JET plasmas are:

  - Simultaneous excitation of unstable electromagnetic (Alfvén) waves at consecutive cyclotron harmonics of alpha-particles.

  - Strong growth rates of waves propagating nearly perpendicular to the background magnetic field.

  - Linear scaling of growth rates (low-frequency unstable modes) with alpha-particle concentration.

OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas

- Next, we need to chose an appropriate level of description for the plasma.

Magnetohydrodynamics (MHD) ← **Hybrid approximation** → Kinetic theory

Ion dynamics

$$\frac{d\mathbf{x}_j}{dt} = \mathbf{v}_j,$$

$$m_j \frac{d\mathbf{v}_j}{dt} = eZ_j \left(\mathbf{E} + \mathbf{v}_j \times \mathbf{B}\right).$$

$$n \equiv n_e = \sum_{\alpha=1}^{N} \left(Z_\alpha n_\alpha\right)$$

$$P_e = n_e T_e \quad \text{(ideal gas)}$$

Electromagnetic fields

$$\mathbf{E} = \frac{1}{\mu_0 en}(\nabla \times \mathbf{B}) \times \mathbf{B} - \mathbf{U}_i \times \mathbf{B} - \frac{1}{en}\nabla P_e$$

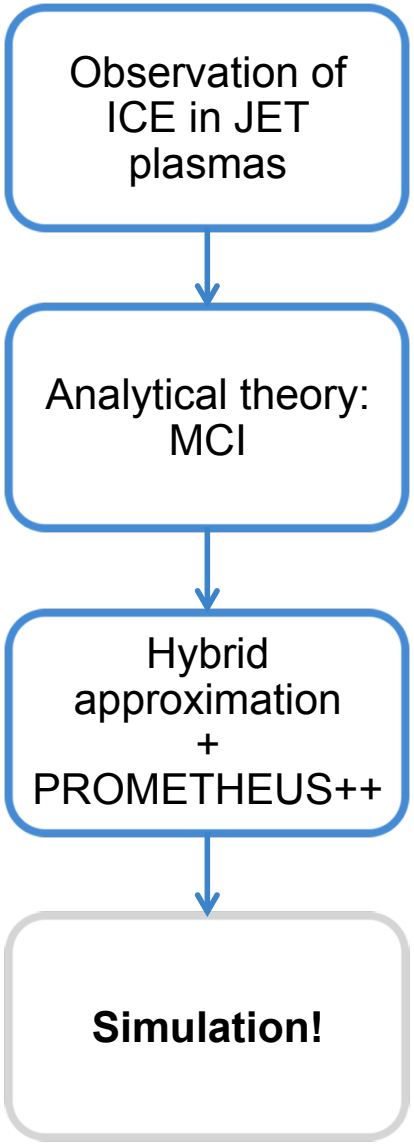
$$\mathbf{U}_i = \frac{\sum_{\alpha=1}^{N} \left(Z_\alpha n_\alpha \mathbf{u}_\alpha\right)}{\sum_{\alpha=1}^{N} \left(Z_\alpha n_\alpha\right)}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

Coupling terms

OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas



OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas

- Next, we need to chose an appropriate level of description for the plasma.

Ion distributions as kinetic particles
(Lorentz force)

+

Electrons as a charge-neutralising massless fluid
(isotropic and isothermal ideal gas)

Ion dynamics

$$\frac{d\mathbf{x}_j}{dt} = \mathbf{v}_j,$$

$$m_j \frac{d\mathbf{v}_j}{dt} = eZ_j \left(\mathbf{E} + \mathbf{v}_j \times \mathbf{B}\right).$$

$$n \equiv n_e = \sum_{\alpha=1}^{N} \left(Z_\alpha n_\alpha\right)$$

$$P_e = n_e T_e \quad \text{(ideal gas)}$$

Electromagnetic fields

$$\mathbf{E} = \frac{1}{\mu_0 en}(\nabla \times \mathbf{B}) \times \mathbf{B} - \mathbf{U}_i \times \mathbf{B} - \frac{1}{en}\nabla P_e$$

$$\mathbf{U}_i = \frac{\sum_{\alpha=1}^{N} \left(Z_\alpha n_\alpha \mathbf{u}_\alpha\right)}{\sum_{\alpha=1}^{N} \left(Z_\alpha n_\alpha\right)}$$

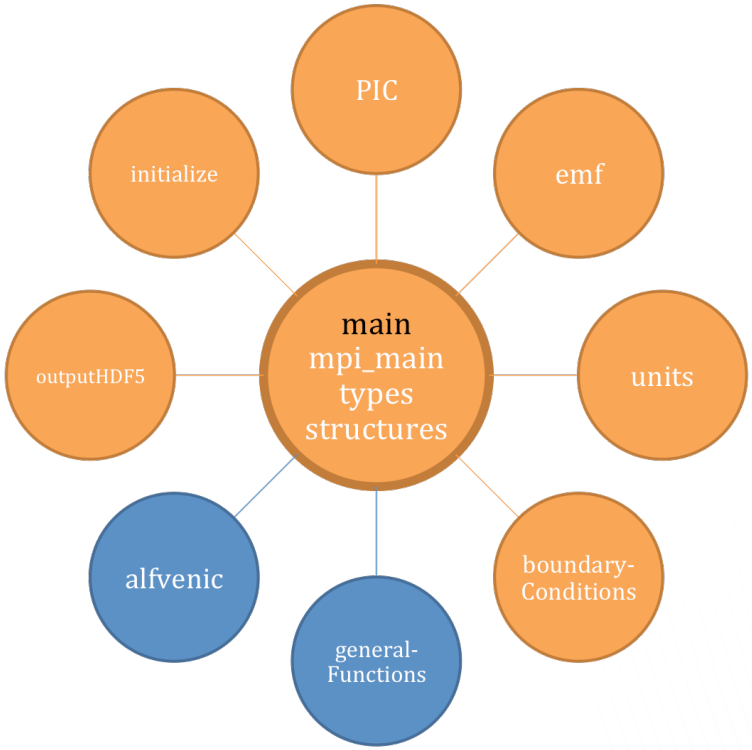
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

Coupling terms

OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas

- Finally, we need a numerical tool for solving the plasma equations.
- **PROMETHEUS++:** A hybrid code (open MP + MPI) written in C++ for solving the equations of the plasma.

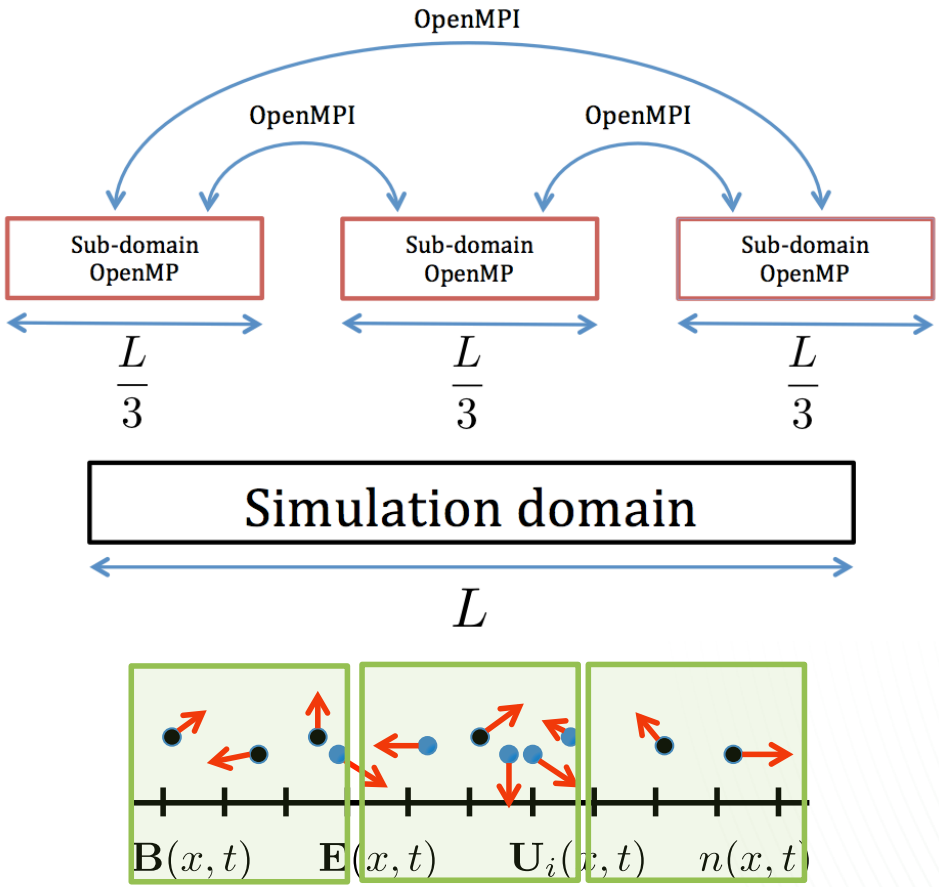


OAK RIDGE
National Laboratory

Numerical modeling of ICE in D-T JET plasmas

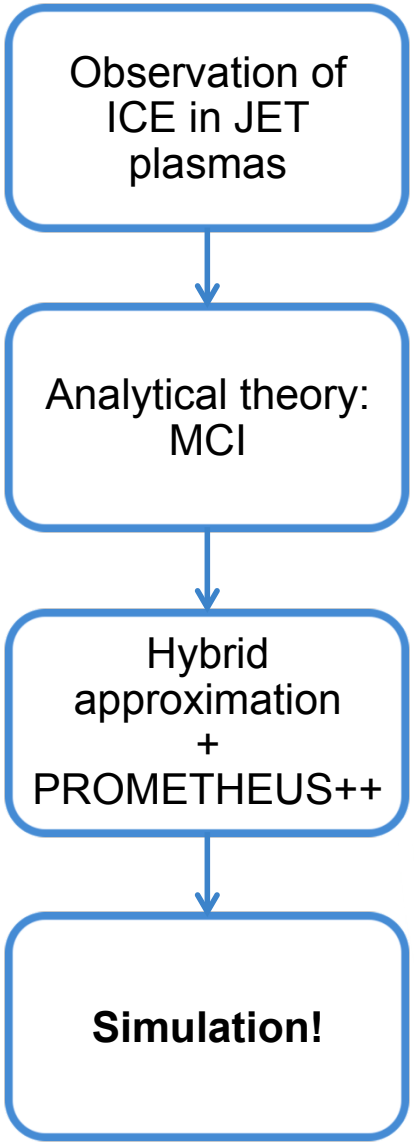
- **PROMETHEUS++:** A hybrid code (open MP + MPI) written in C++ for solving the equations of the plasma.

Parallel programming paradigm: Geometry decomposition



OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas



OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas

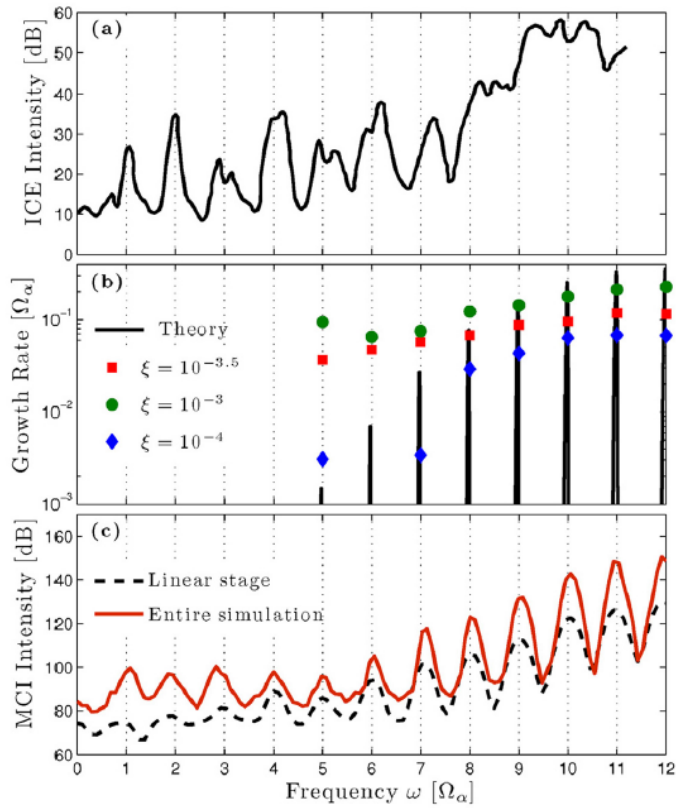
We simulate the MCI with characteristic plasma parameters of JET plasmas where ICE was detected.

The **linear stage** of our hybrid simulations of the MCI recovered:

- **Simultaneous excitation of electromagnetic (Alfvén) waves at consecutive cyclotron harmonics of alpha-particles.**
- Strong growth rates of waves propagating nearly perpendicular to the background magnetic field.

By going deep into the **nonlinear stage** of the MCI (Carbajal et al. 2013) we recovered:

- Full power spectrum of ICE as measured in JET. Modes at **lower cyclotron harmonics** recovered!.



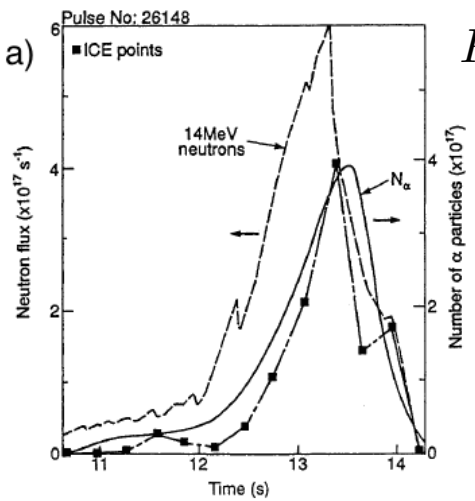
OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas

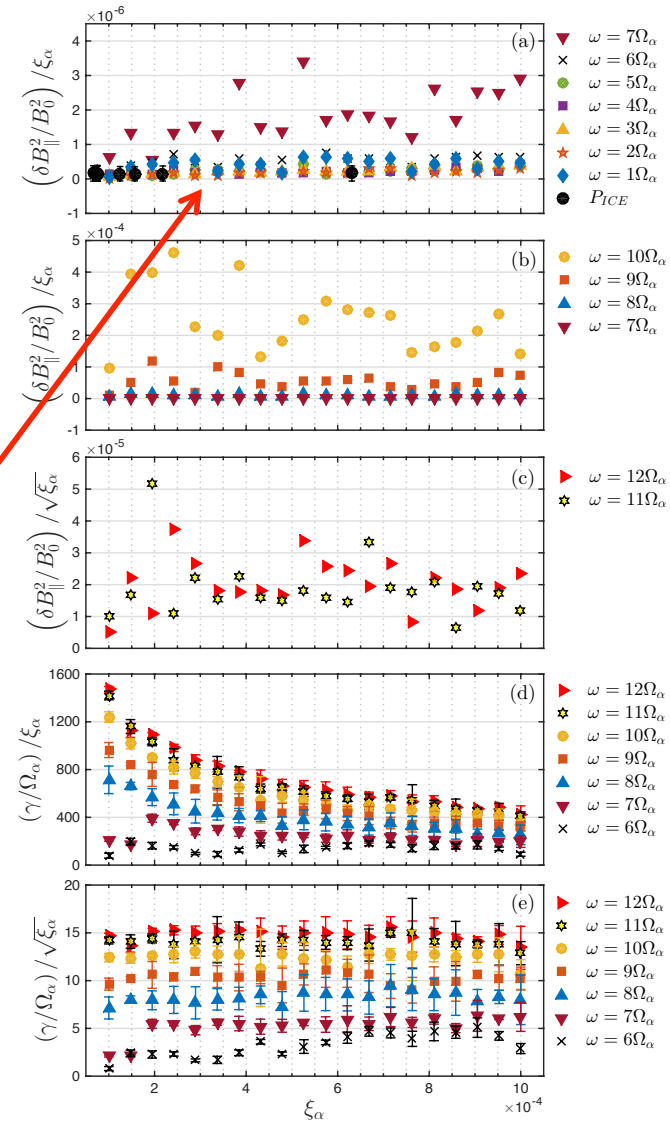
We simulate the MCI with characteristic plasma parameters of JET plasmas where ICE was detected.

In the **linear stage** of our hybrid simulations of the MCI we also observe:

- **Linear scaling of the MCI intensity with alpha-particle concentration ($\xi_\alpha = n_\alpha/n_D$) at low cyclotron harmonics of the fusion-born alpha-particles.**



$$P_{\mathrm{ICE}} \propto n_\alpha^\eta$$



OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas

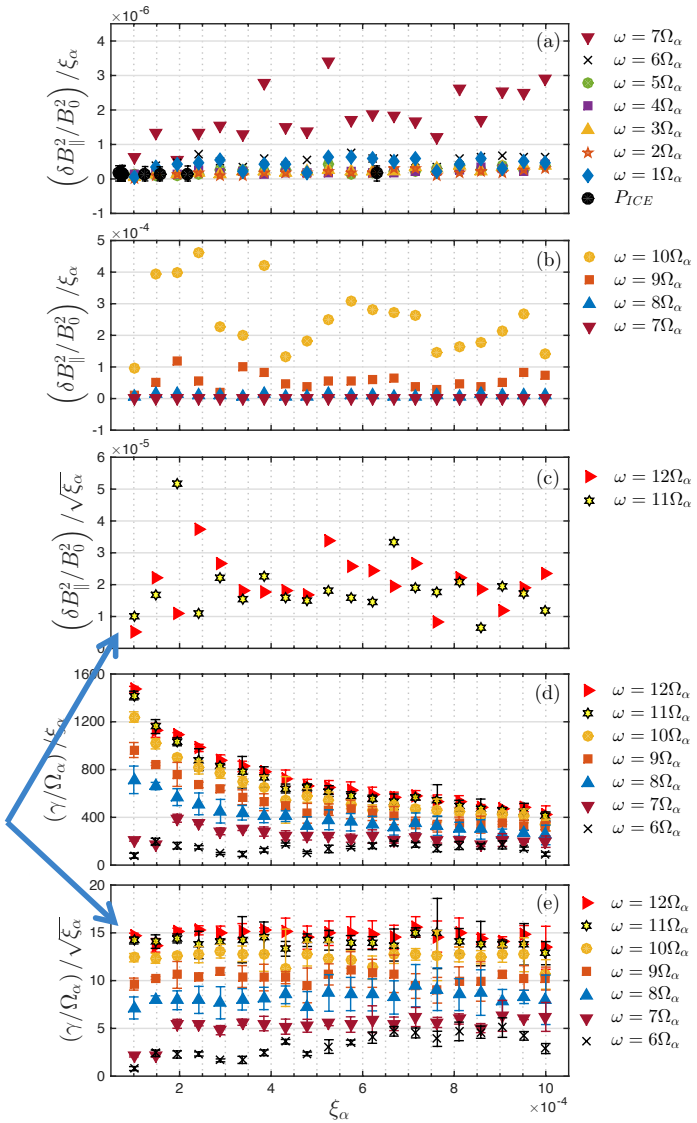
We simulate the MCI with characteristic plasma parameters of JET plasmas where ICE was detected.

In the **linear stage** of our hybrid simulations of the MCI we also observe:

- **Linear scaling of the MCI intensity with alpha-particle concentration ($\xi_\alpha = n_\alpha/n_D$) at low cyclotron harmonics of the fusion-born alpha-particles.**

The numerical simulations of the MCI show:

- Square-root scaling of the MCI intensity and linear growth rates of unstable modes at higher cyclotron harmonics.
- This is predicted by the MCI in its high-frequency limit (Carbajal et al. 2016, in preparation).

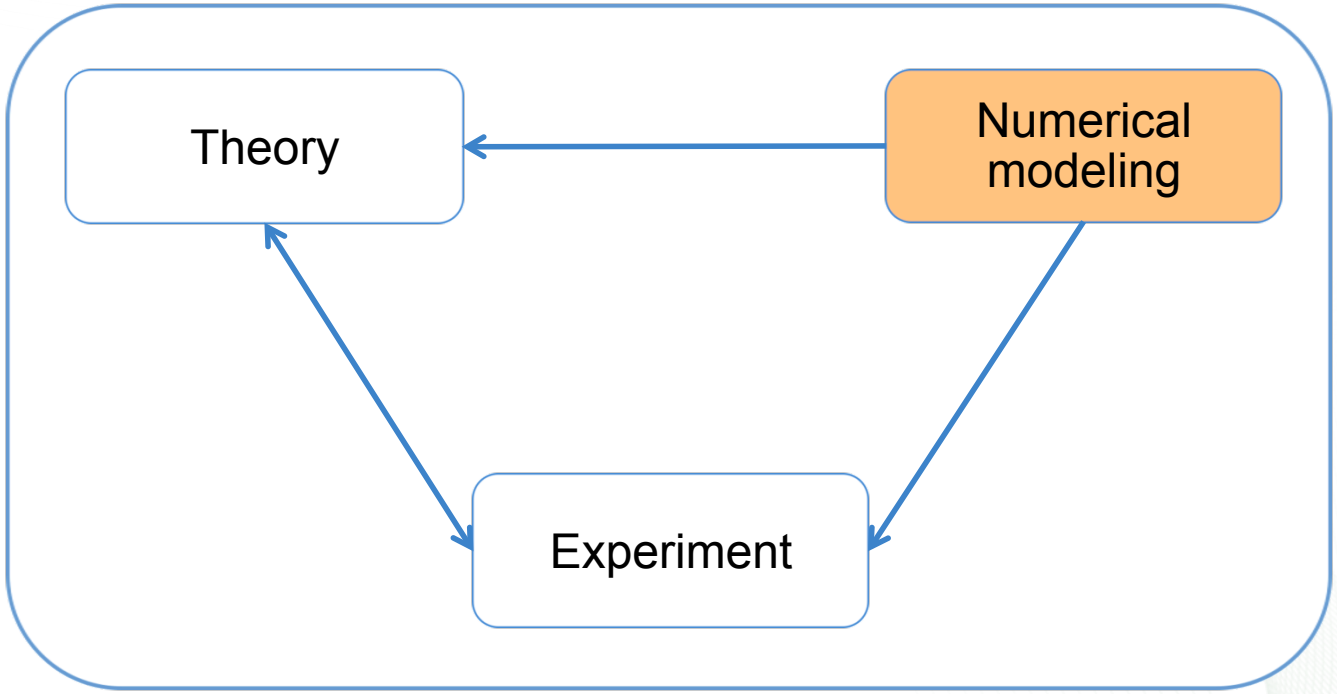


OAK RIDGE National Laboratory

Numerical modeling of ICE in D-T JET plasmas

It is time to revisit the theory and the experimental measurements!!

- Further work on numerical modeling of ICE in JET and LHD plasmas.
- Set-up of diagnostics in JET for measuring ICE.

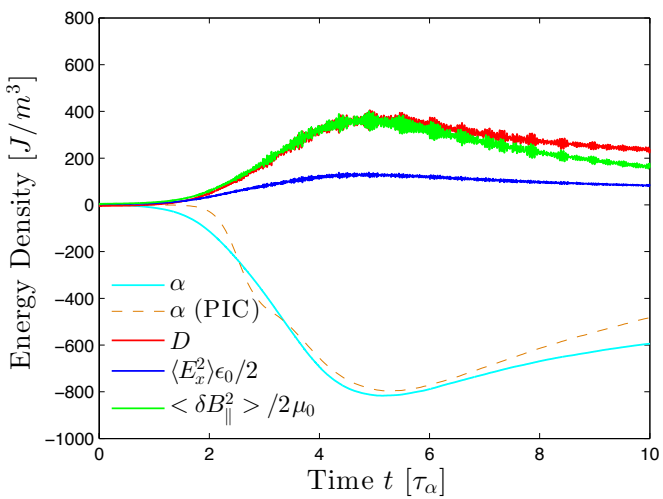


OAK RIDGE National Laboratory

First synthetic diagnostics

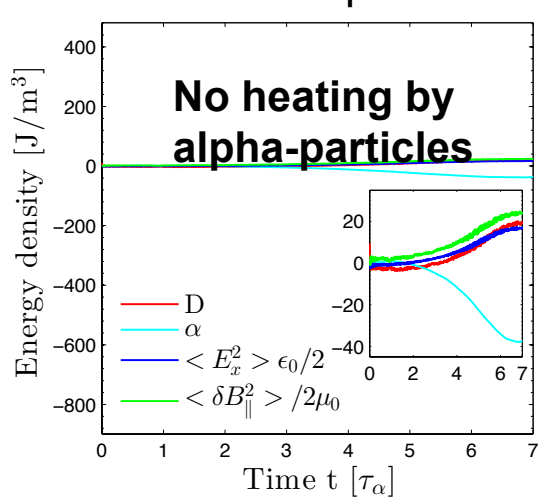
- During the **DTE1 campaign of JET in 1997** plasma heating by alpha-particles was studied**.** Anomalous ion heating by alpha-particles, larger than theoretical predictions, was observed (Thomas et al. 1998, 2001).
- No MHD instabilities driven by alpha-particles were present during this experiment.
- **No diagnostics for alpha-particles or ICE monitors were available during this experiment.**
- This anomalous heating **remains unexplained**.
- **Is ICE occurring at the core of these plasmas in JET?**

Edge ICE

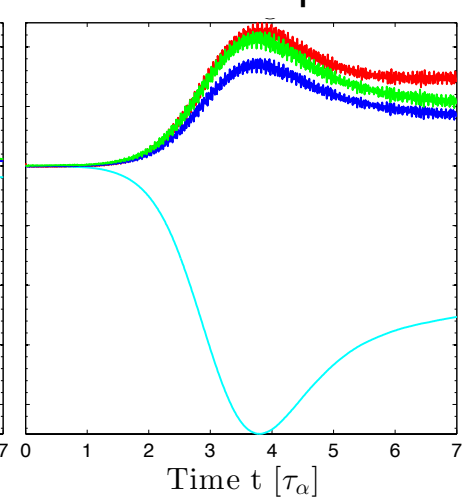


Core ICE

Isotropic



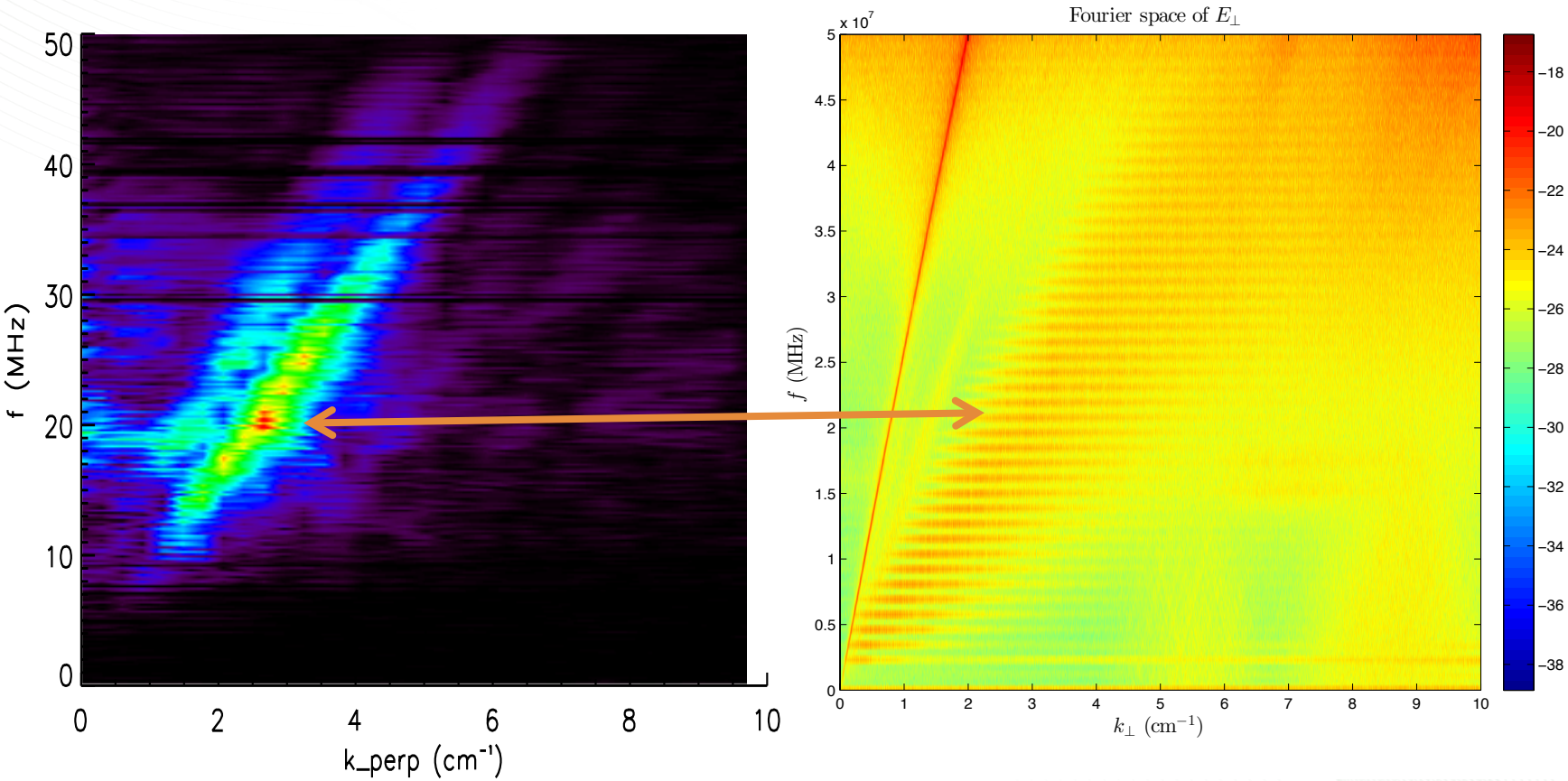
Anisotropic



OAK RIDGE National Laboratory

First synthetic diagnostics

- Instabilities driven by energetic ions in linear devices (LAPD, USA).



OAK RIDGE National Laboratory

Summary

- ✓We have studied in detail one type of perturbative instability driven by fusion-born ions in MCF plasmas: ICE in D-T JET plasmas.
- ✓Using a simple (but robust) numerical modeling we **confirmed the predictions of the MCI about ICE in JET**.
- ✓In our simulations we **recovered key fingerprints of ICE** as observed in JET plasmas.
- ✓We have started to use PROMETHEUS++ for diagnosing MCF plasmas where ICE occurs.
- ✓**This is not limited to fusion plasmas!**

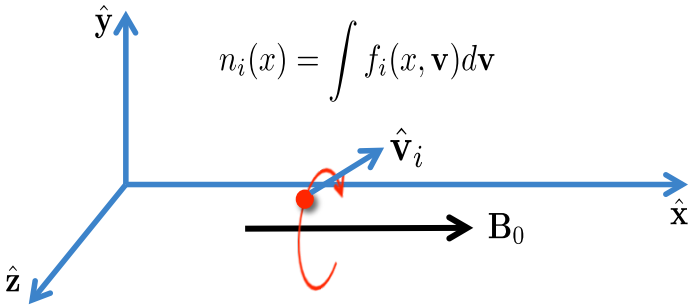
OAK RIDGE National Laboratory

1D3V Hybrid simulations

Ion dynamics

$$\frac{d\mathbf{x}_j}{dt} = \mathbf{v}_j,$$

$$m_j \frac{d\mathbf{v}_j}{dt} = eZ_j \left(\mathbf{E} + \mathbf{v}_j \times \mathbf{B}\right).$$



Electromagnetic fields

$$\mathbf{E} = \frac{1}{\mu_0 en}(\nabla \times \mathbf{B}) \times \mathbf{B} - \mathbf{U}_i \times \mathbf{B} - \frac{1}{en}\nabla P_e$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

OAK RIDGE National Laboratory