Simulation of Fast Alfvén Wave Interactions with Fast Ions using Monte-Carlo Hamiltonian Orbit Code Coupled with Full Wave Code

by
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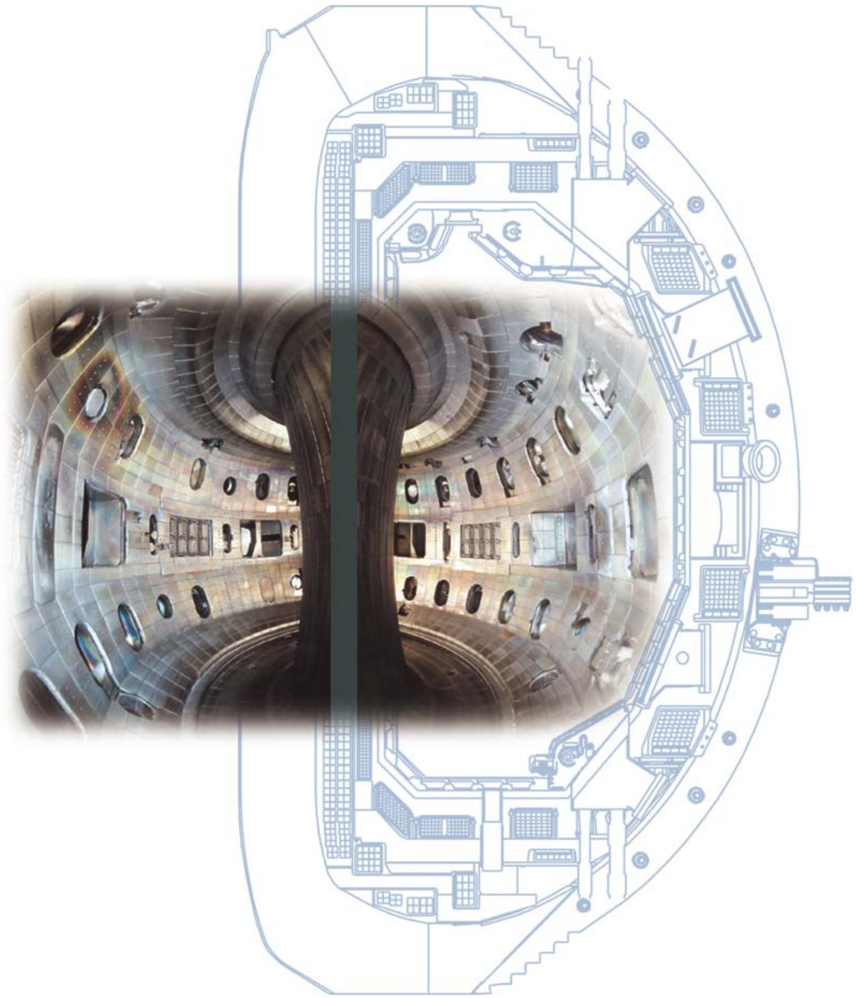

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GENERAL ATOMICS

217-05/MC/jy

Our Goal Is To Develop More Quantitative Model For RF Wave Interactions With Fast Ions In Tokamaks

- Strong damping of fast Alfvén wave (FW) on non-Maxwellian species at higher ion cyclotron harmonics may occur in neutral beam preheated tokamaks and burning plasmas.
- Linear theory is sensitive to assumed fast ion distribution particularly at high harmonics. Self-consistent determination of fast ion distribution is essential for quantitative modeling.
- ORBIT-RF/TORIC4 Includes comprehensive physics features needed for quantitative modeling
  - Finite drift orbit
  - Slowing down neutral beam distribution
  - Stochastic quasi-linear wave-particle interactions at arbitrary harmonics
  - Coulomb collisions
  - 2-D wave field structure

Key Results from Experiment and Simulation in DIII-D and C-Mod Tokamaks

EXPERIMENTS

- **Beam ion acceleration in DIII-D experiments** (Pinsker's Poster #QP1.00006)
  - **Strong damping of 60 MHz FW at $4\Omega_D$**
  - **Weak damping of 116 MHz FW at $8\Omega_D$**
- **Minority hydrogen ion acceleration in C-Mod experiments**

SIMULATIONS

- **ORBIT-RF with TORIC4 is in qualitative agreement with DIII-D and C-Mod experimental results**
  - **with measured neutron enhancements at $4\Omega_D$ and $8\Omega_D$**
  - **with measured fast ion spectrum**
- **ORBIT-RF simulations reproduce the trend in linear theory using analytical beam slowing-down distribution**

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ORBIT-RF Uses 2-D Full Wave Information from TORIC4

ORBIT-RF

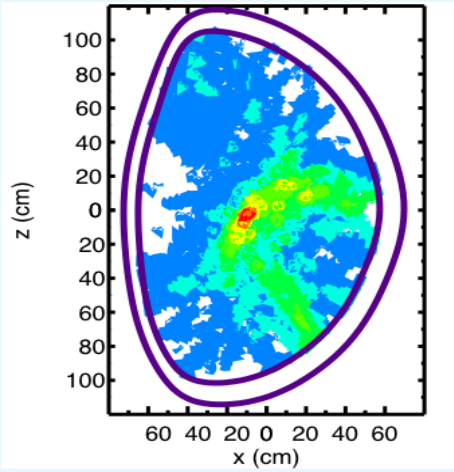
- **Stochastic quasi-linear RF diffusion operator**

$$\Delta\mu_{rf} = \overline{\Delta\mu_{rf}} + R_s \sqrt{\left\langle \overline{\overline{\Delta\mu_{rf}}}^{\,2} \right\rangle}$$

$$\overline{\Delta\mu_{rf}}\ ,\ \left\langle \overline{\overline{\Delta\mu_{rf}}}^{\,2} \right\rangle \ \propto\ \begin{matrix} |E_+|^2, & |E_-|^2 \\ k_\perp\ , & k_{//} \\ J_{l-1}\ , & J_{l+1} \end{matrix}$$

TORIC4

- |E+| per unit antenna current



- $$I(\mathrm{A}) = \sqrt{\frac{P_{\mathrm{Exp}}(\mathrm{W})}{R_{\mathrm{TORIC}}(\Omega)}}$$

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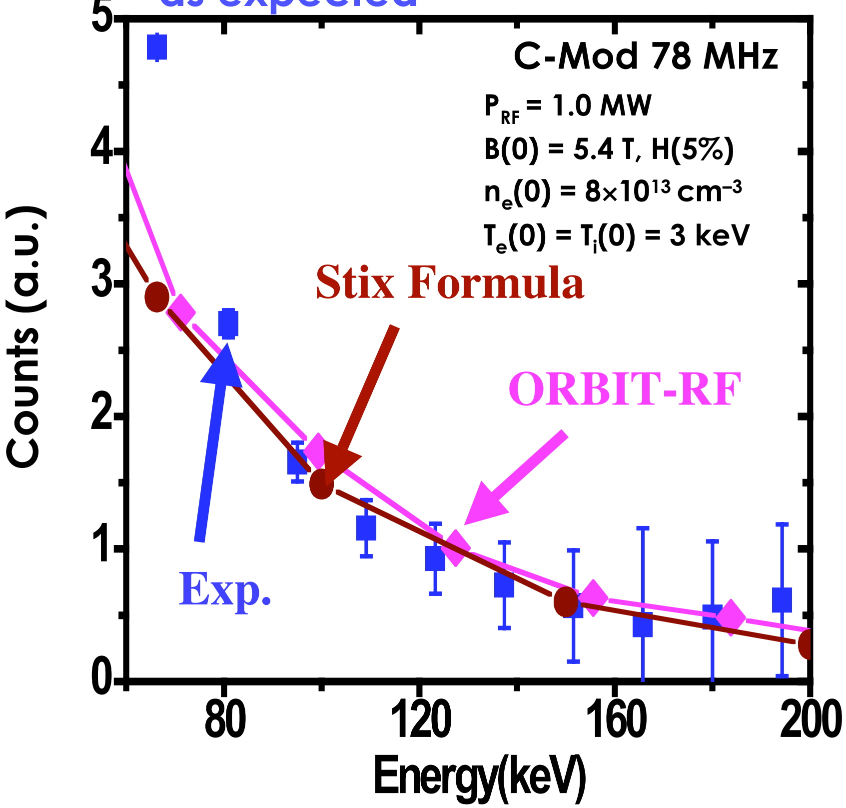
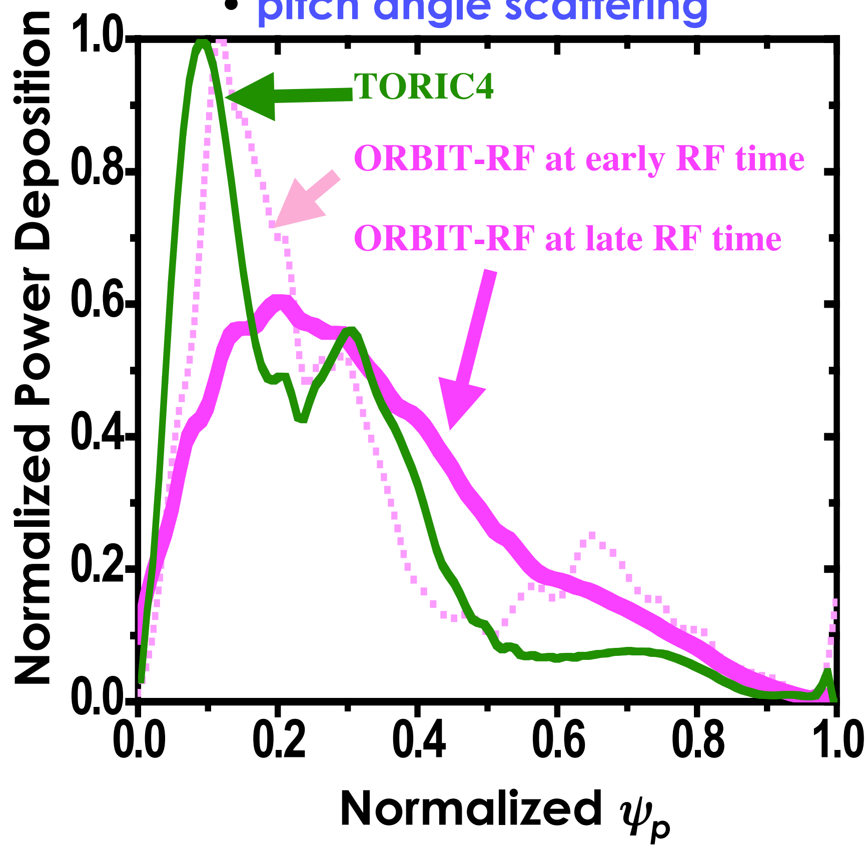
ORBIT-RF Agrees with Measured Minority Ion Spectrum from NPA for C-Mod Minority Heating Scenario

- Fundamental harmonic heating result agrees with Stix formula as expected



- radial diffusion
- pitch angle scattering



Alcator C-Mod

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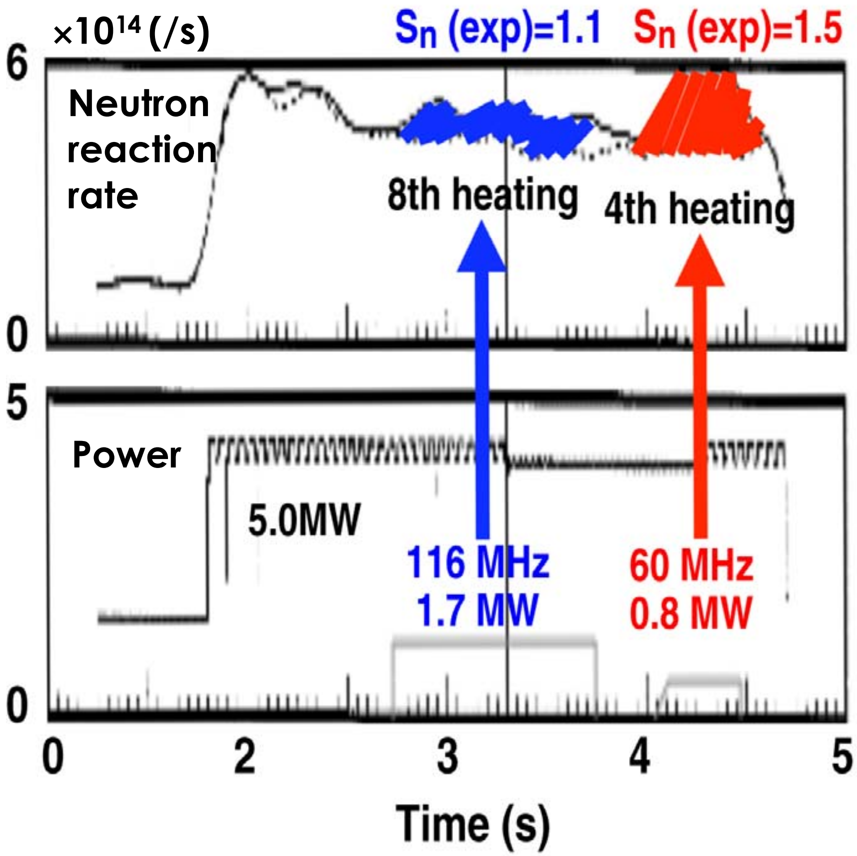
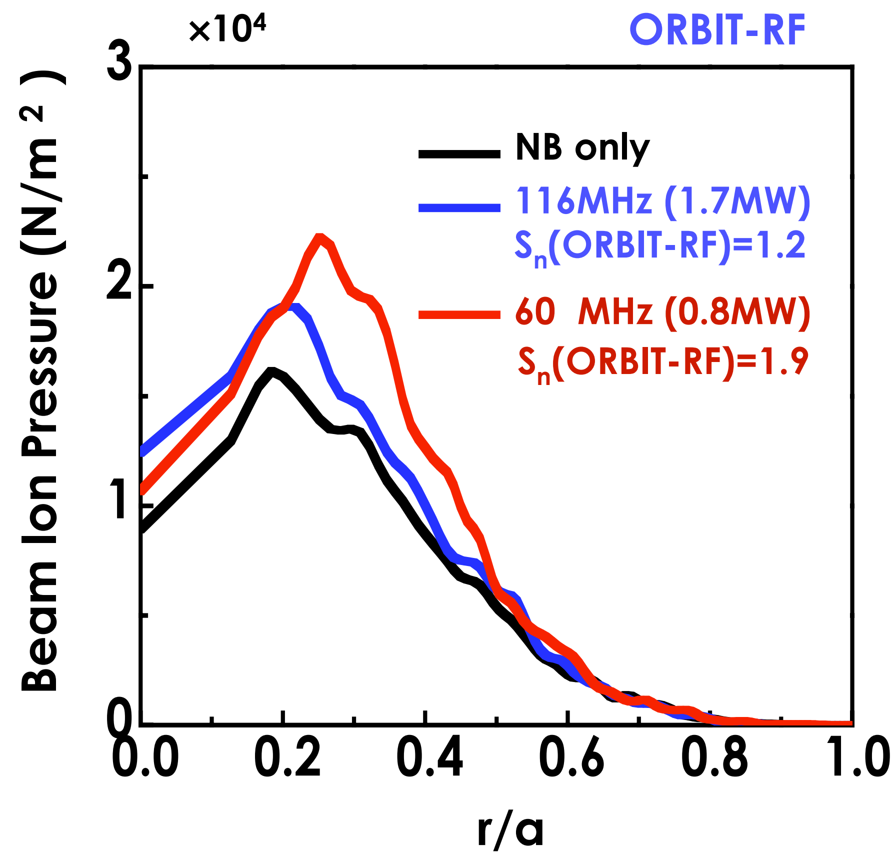
ORBIT-RF Reproduces Stronger Beam Interactions at $4\Omega_D$ (60 MHz) Than at $8\Omega_D$ (116 MHz) Observed in DIII-D

- DIII–D high density L-mode





S_n: neutron enhancement factor

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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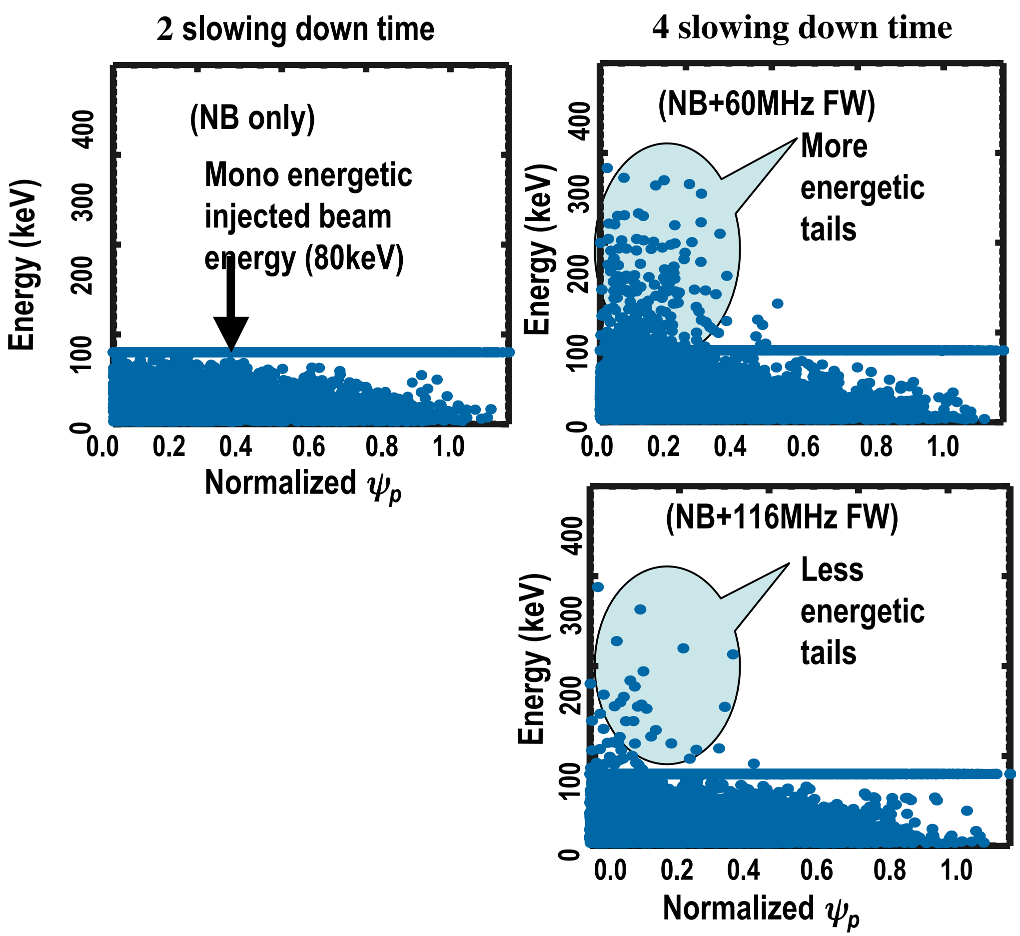
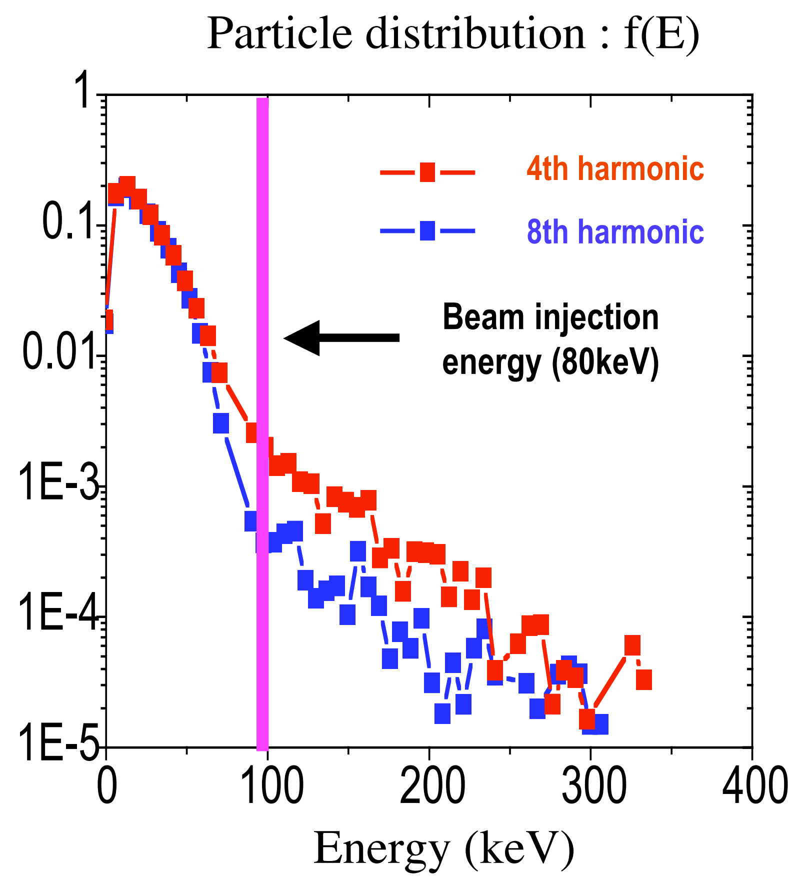
ORBIT-RF Predicts More Tails Above Beam Injection Energy at $4\Omega_D$ (60MHz) Than at $8\Omega_D$(116MHz)

- DIII–D high density L-mode (10000 test particles)





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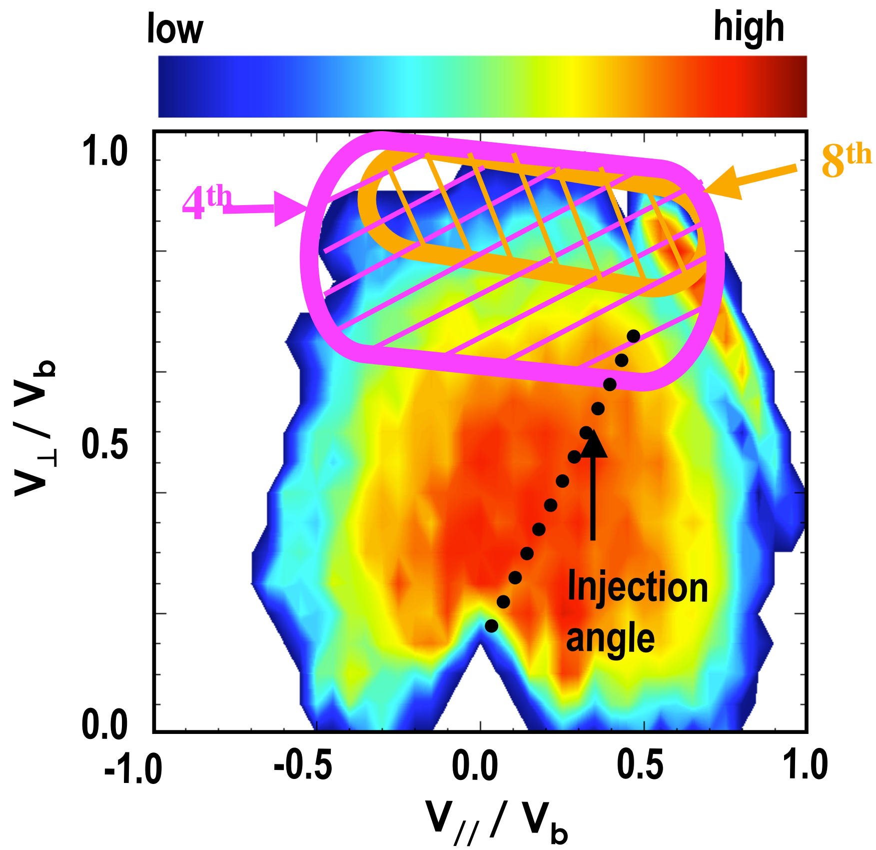
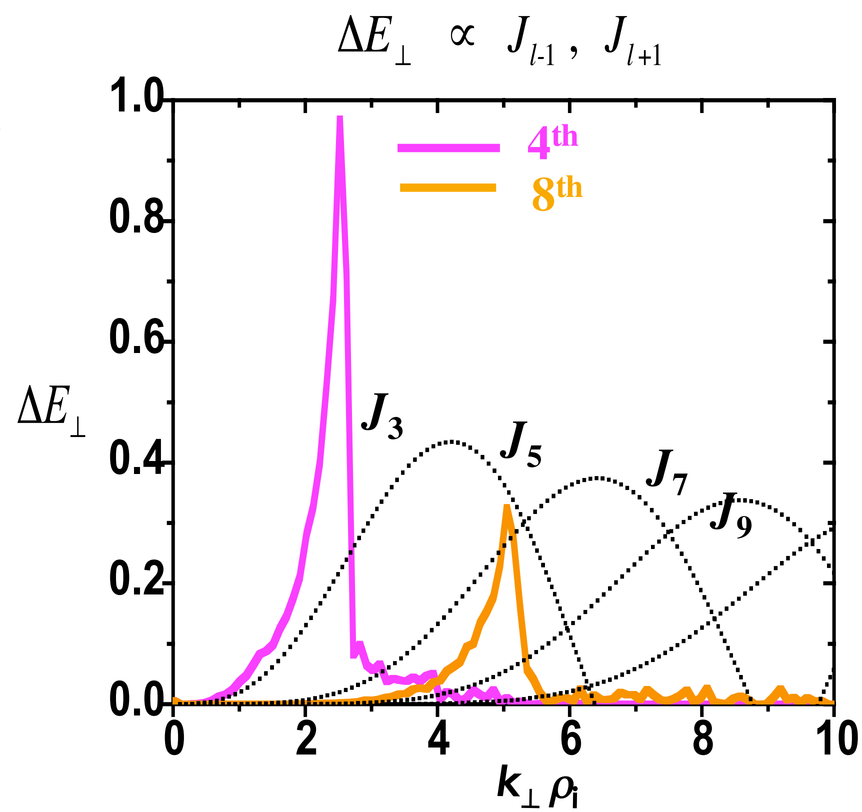
Wave Absorption Critically Depends on The Energy and Density of Resonant Fast Ions

- DIII-D high density L-mode





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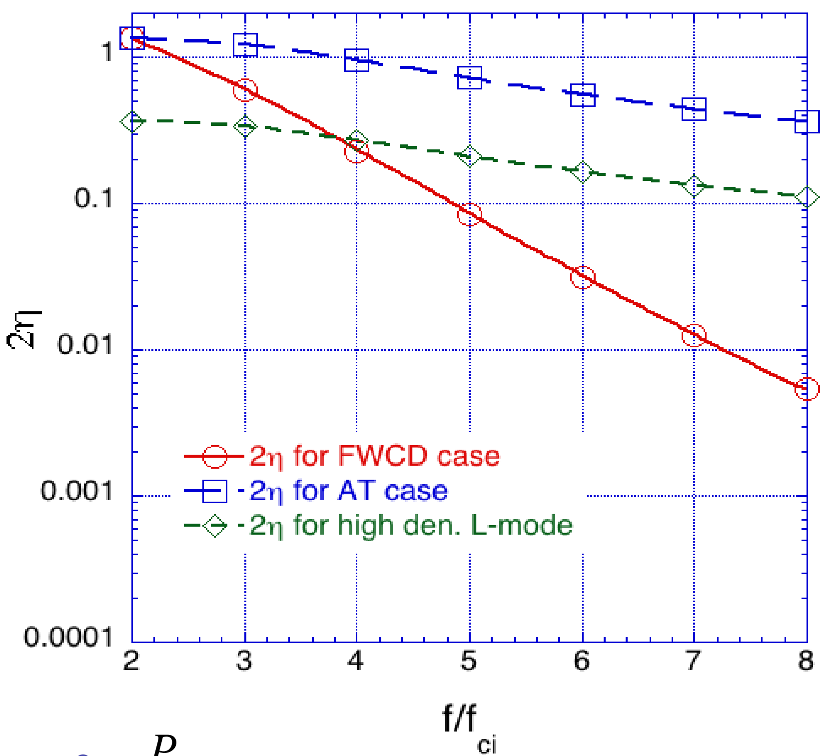
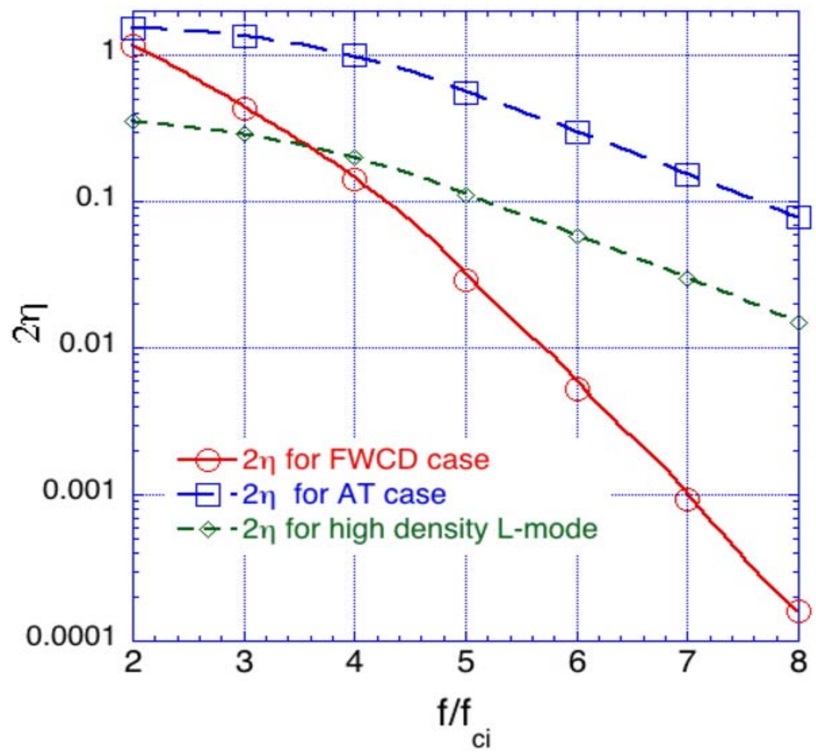
Wave Damping Estimate in Linear Theory Is Sensitive to Assumed Ion Distribution

Isotropic Maxwellian model



Slowing down model



- $\frac{P_{abs}}{P_{in}} = 1 - e^{-2\eta}$

Summary

- **ORBIT-RF with TORIC4 qualitatively reproduces DIII-D and C-Mod experimental results**

  DIII-D

  – **Reasonable agreement with measured neutron enhancements at $4\Omega_D$ and $8\Omega_D$**

  C-Mod

  – **Good agreement with measured fast ion spectrum**

- **The details of beam distribution modified by RF and collisions are important to quantitatively evaluate beam-wave interactions**

- **ORBIT-RF prediction of wave absorption at $4\Omega_D$ and $8\Omega_D$ follows the trend of linear theory using analytical slowing down distribution function**

  – Weak absorption at $8\Omega_D$ differs from AORSA-CQL3D result (Jaeger's Invited talk #QI1.00002)

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