Iterated Finite Orbit Monte-Carlo Simulations with Full-Wave Fields for ICRF Wave Heating Experiments

by

M. Choi

In collaboration with
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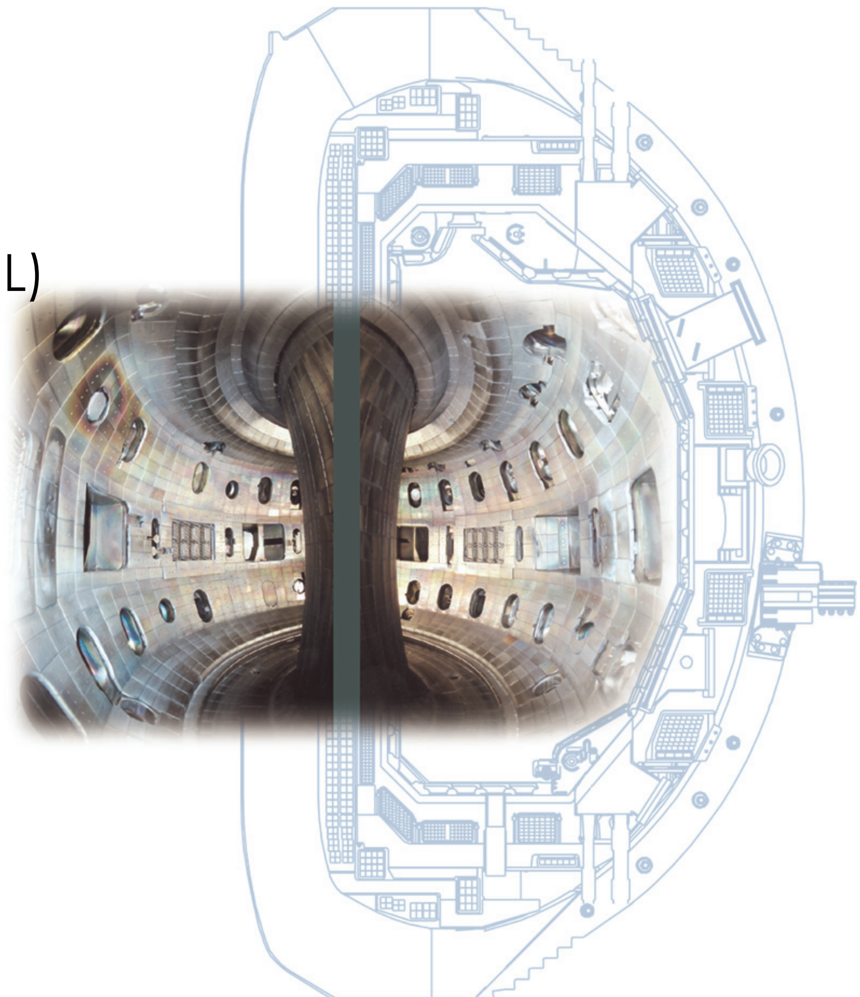
D.N. Smithe (Tech-X)
RF SciDAC and SWIM Team



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Fifty First APS Meeting of
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Atlanta, Georgia

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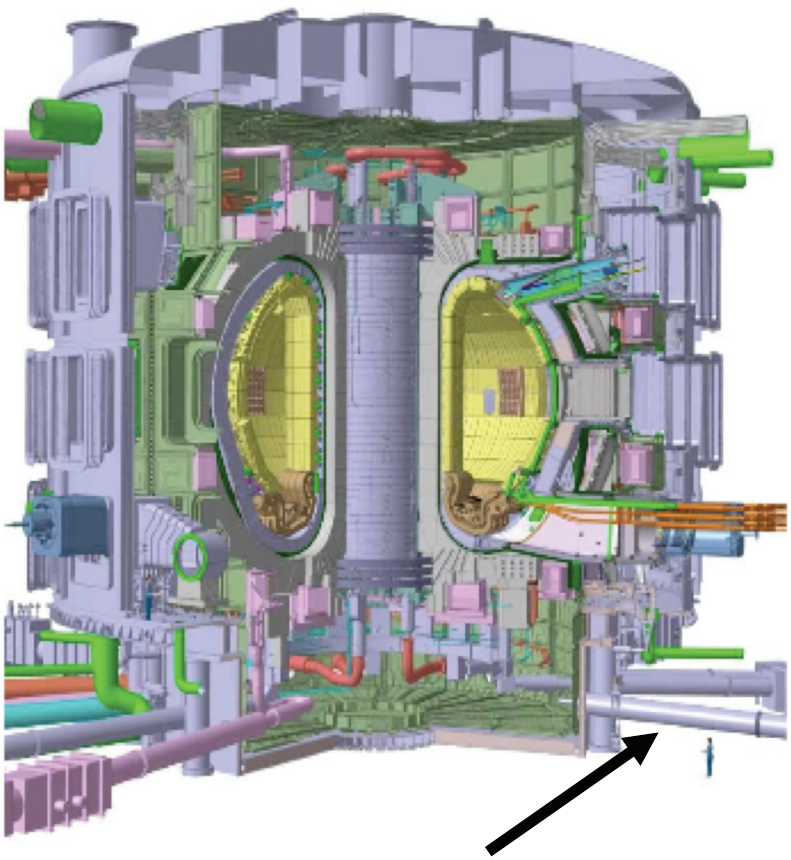
Motivation

ITER



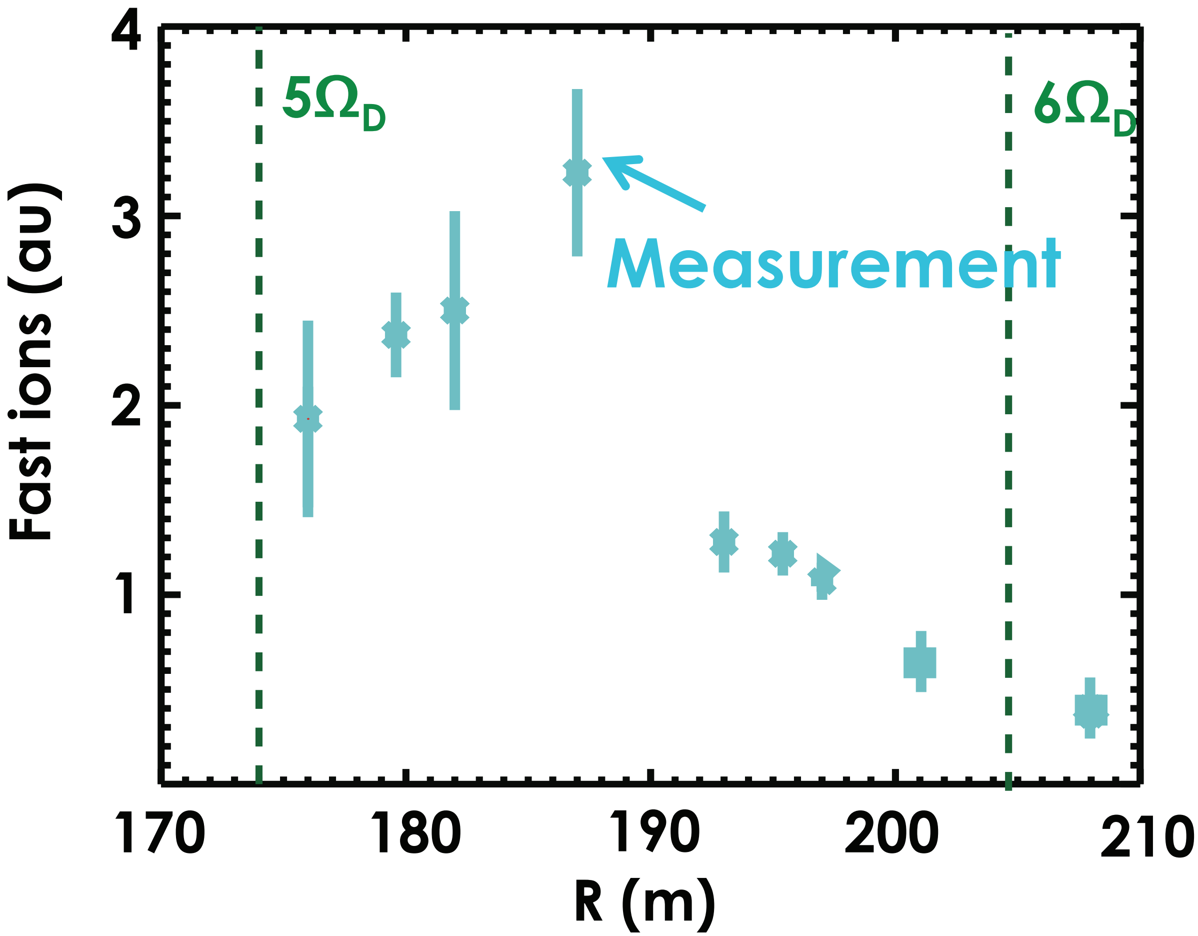
ICRF Antenna

- **ICRF wave is a main heating scheme in future ITER**
  - A predictive understanding of ICRF wave-fast ion interaction in present tokamaks is important

- **Zero-orbit study does not fully explain DIII-D and NSTX ICRF heating experiments**

Previous Comparison Indicates Fast-Ion Non-Zero Orbit Width Effect May Be Important

- DIII-D FW heating experiment



- Measurement indicates outward spatial shift

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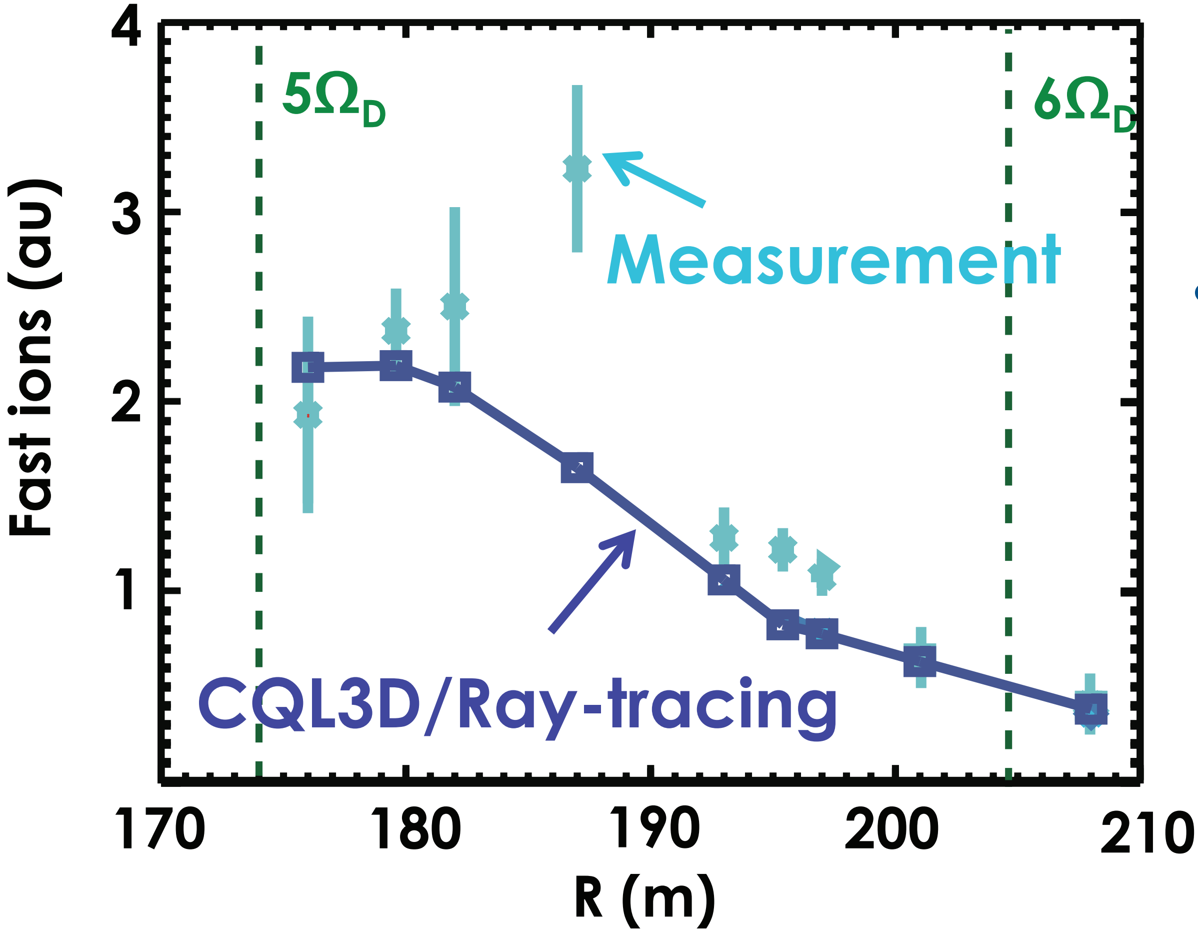

- Measurement indicates outward spatial shift
- CQL3D indicates peak near axis
  - zero drift orbit

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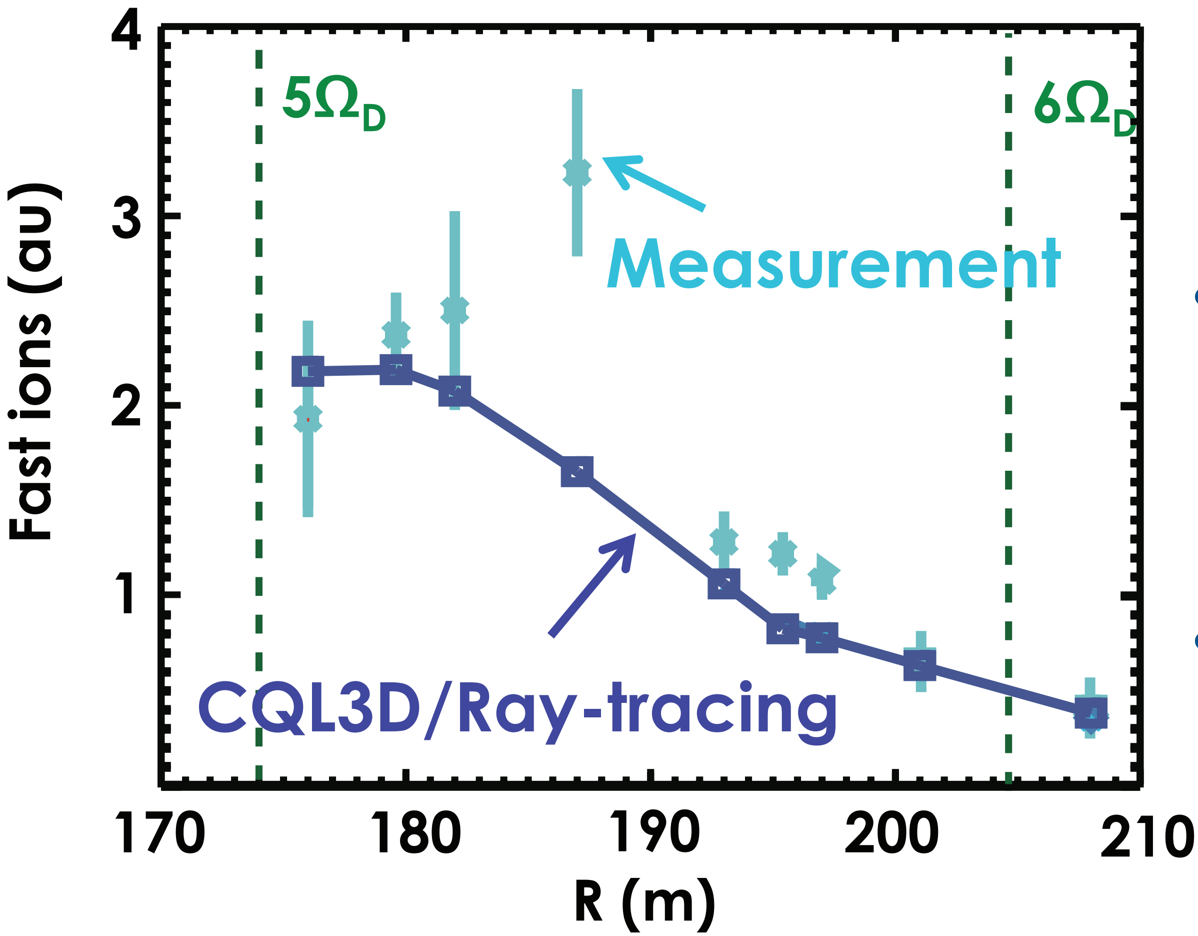

- Measurement indicates outward spatial shift
- CQL3D indicates peak near axis
  - zero drift orbit
- This study is aimed at resolving the discrepancy with non-zero orbit width effect

Outline

- **Fast-ion non-zero orbit width effect is important in modeling HHFW heating experiments**

- Iterations between ion distribution and ICRF wave field are necessary to allow accurate modeling

- Fast-Ion D-Alpha (FIDA) spectroscopy provides a comprehensive tool to validate the theory

- ORBIT-RF coupled with AORSA reproduces spectra and outward spatial shift of ICRF heated fast ions, qualitatively consistent with measurements

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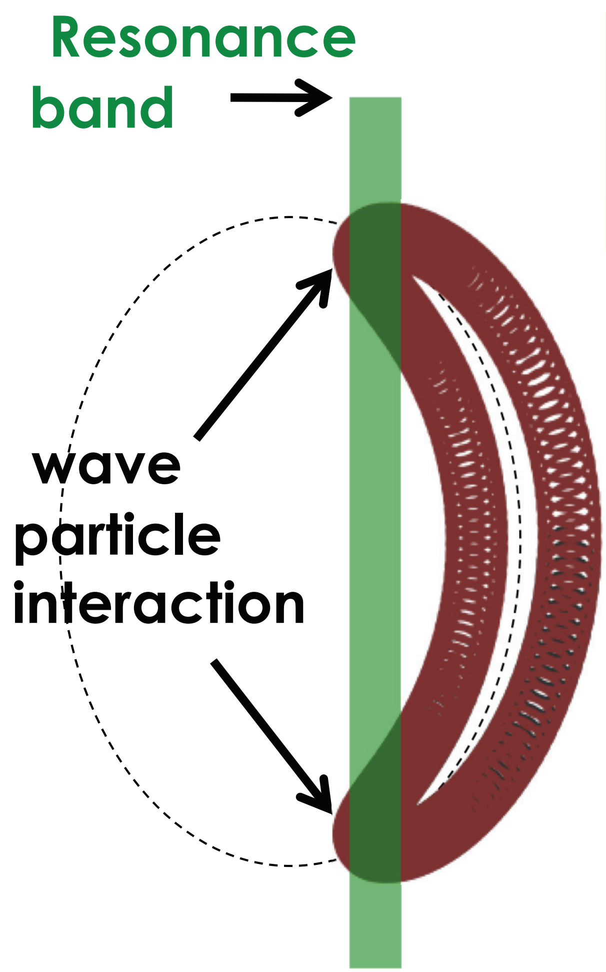
ICRF Wave Resonant Interaction with Fast Ion is Modeled Using Stochastic Quasi-Linear Diffusion Theory



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

Magnetic moment undergoes random walk in interaction region

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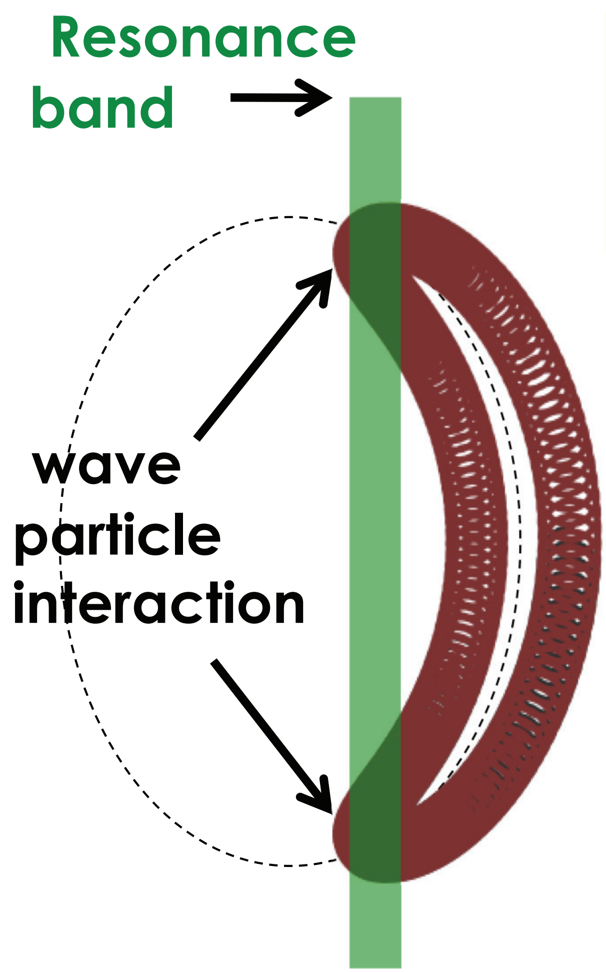

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$$\overline{\Delta\mu_{rf}} = \frac{\pi q^2 l^2 \Omega^2}{m\omega^2 B}\left|E_+\right|^2 \left[\left|J_{l-1} + e^{2i\vartheta_k}\frac{E_-}{E_+}J_{l+1}\right|^2 + \mu\left\{2\left(J_{l-1}+e^{2i\vartheta_k}\frac{E_-}{E_+}J_{l+1}\right)\left(\frac{\partial J_{l-1}}{\partial\mu} + e^{2i\vartheta_k}\frac{E_-}{E_+}\frac{\partial J_{l+1}}{\partial\mu}\right)\right\}\right]\frac{K}{\left|\dot{w}_l\right|}$$

S.C. Chiu, Phys. Plasma 7 (2000)

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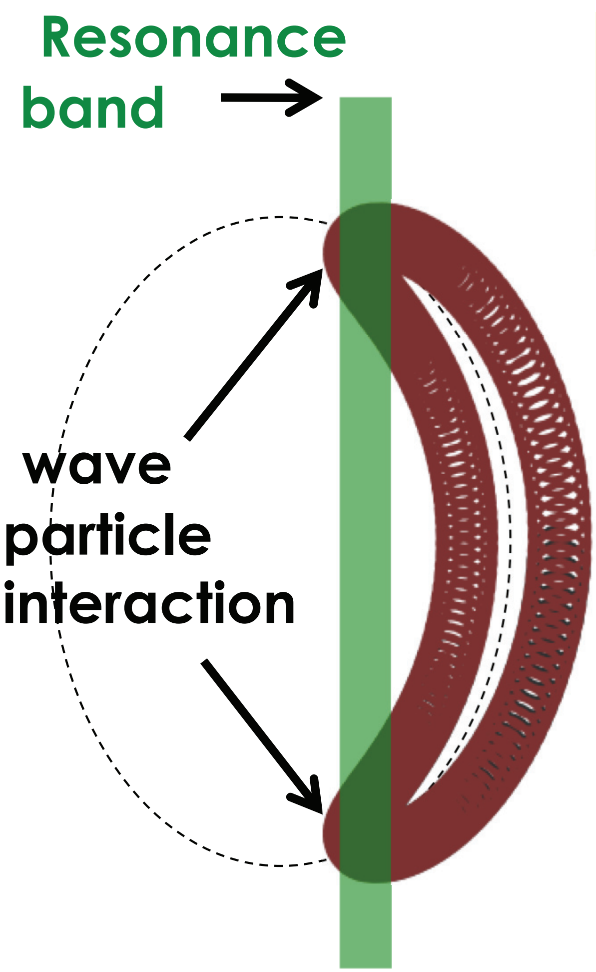

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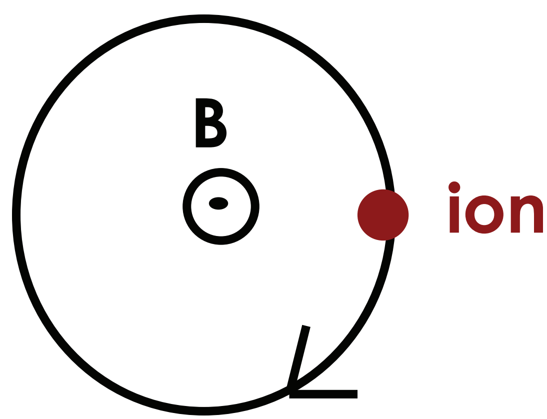

E- is important in HHFW heating due to large $k\rho_i$

ORBIT-RF Guiding Center Equations Include Non-Zero Orbit Width Effect due to Fast Ions

- **Hamiltonian guiding center equations with Coulomb collision and Q-L heating operators**

$$\dot{\zeta} = \frac{\rho_{//} B^2}{D}(q + \rho_{//} I) - (\mu + \rho_{//}^2 B)\frac{I}{D}\frac{\partial B}{\partial \psi_p}$$

$$\dot{\rho}_{//} = -\frac{(1-\rho_{//} g)(\mu + \rho_{//}^2 B)}{D}\frac{\partial B}{\partial \theta} - \frac{(q+\rho_{//} I)(\mu + \rho_{//}^2 B)}{D}\frac{\partial B}{\partial \zeta}$$

$$\dot{\theta} = \frac{\rho_{//} B^2}{D}(1 - \rho_{//} g) + (\mu + \rho_{//}^2 B)\frac{q}{D}\frac{\partial B}{\partial \psi_p}$$

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$$D = gq + I + \rho_{//}\left[gI' - Ig'\right]$$

R.White, Phys. Plasma 2 (1995)

- **Coulomb collision operators**

$$\Delta l = -l\eta_\perp \Delta t + R_s\sqrt{(1-\lambda^2)\eta_\perp \Delta t}$$

$$\Delta v_{col} = -v\eta_{//}\Delta t$$

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$$\dot{\zeta} = \frac{\rho_{//} B^2}{D}\left(q + \rho_{//} I\right) - \left(\mu + \rho_{//}^2 B\right)\frac{I}{D}\frac{\partial B}{\partial \psi_p}$$

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Drift orbit terms

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ORBIT-RF Guiding Center Equations Include Non-Zero Orbit Width Effect due to Fast Ions

- Without drift terms, fast ion stays in same flux surface

$$\dot{\zeta} = \frac{\rho_{\parallel} B^2}{D}\left(q + \rho_{\parallel} I\right) - \left(\mu + \rho_{\parallel}^2 B\right)\frac{I}{D}\frac{\partial B}{\partial \psi_p}$$

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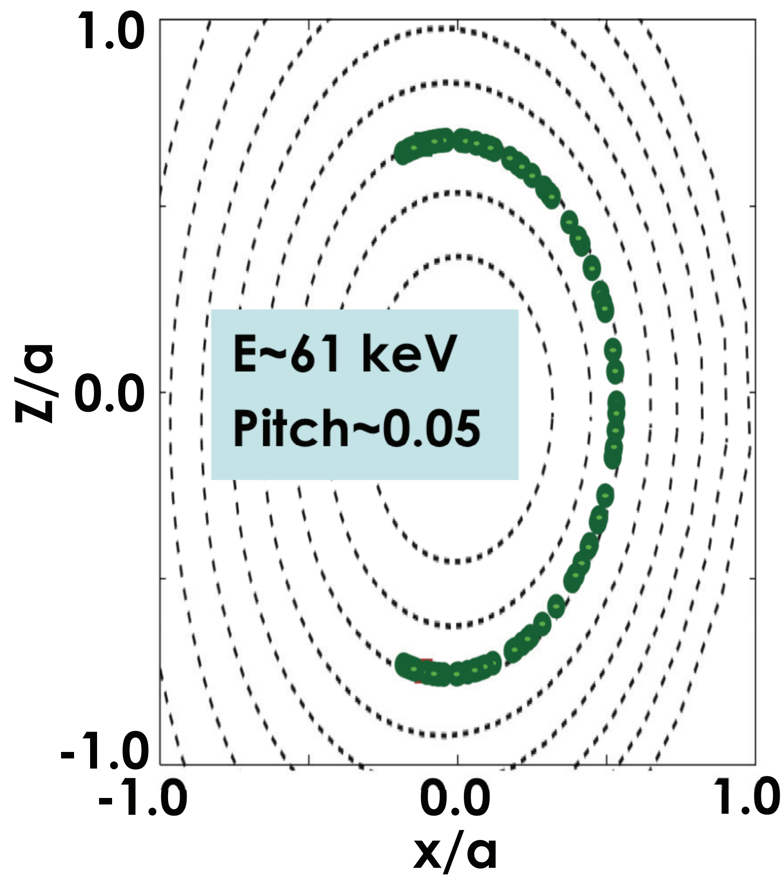

ORBIT-RF Guiding Center Equations Include Non-Zero Orbit Width Effect due to Fast Ions

- **With drift terms, fast ion moves across flux surfaces**

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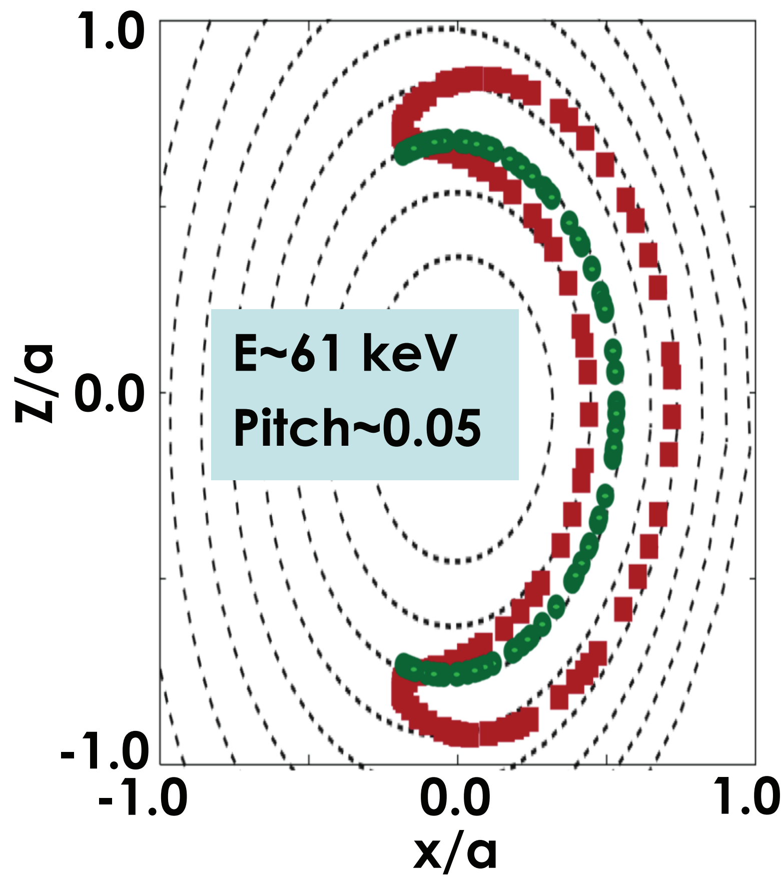

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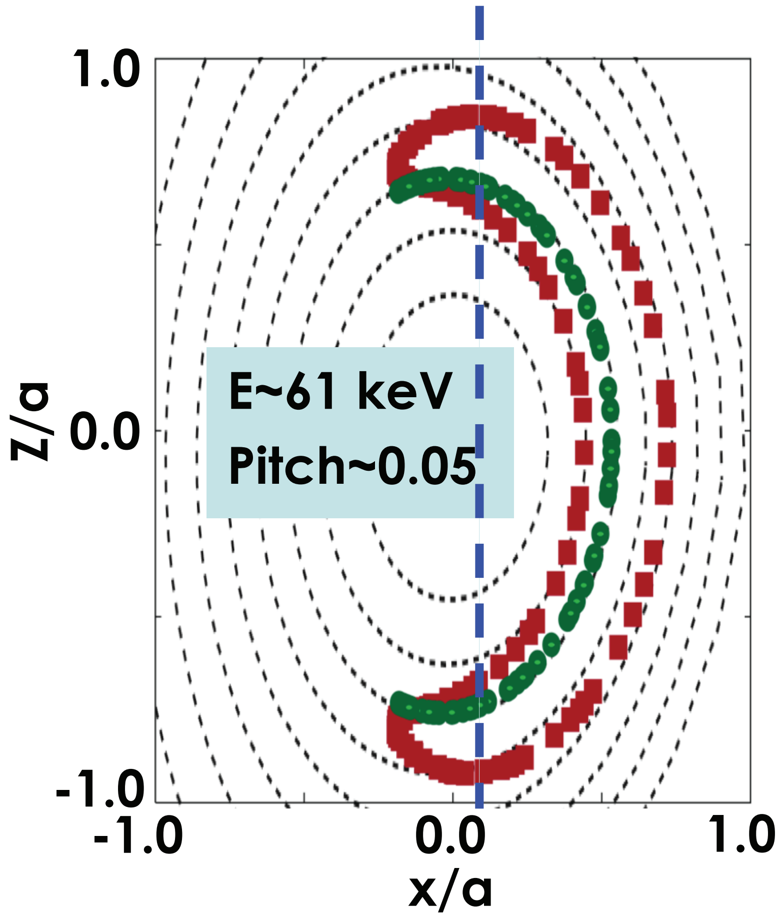
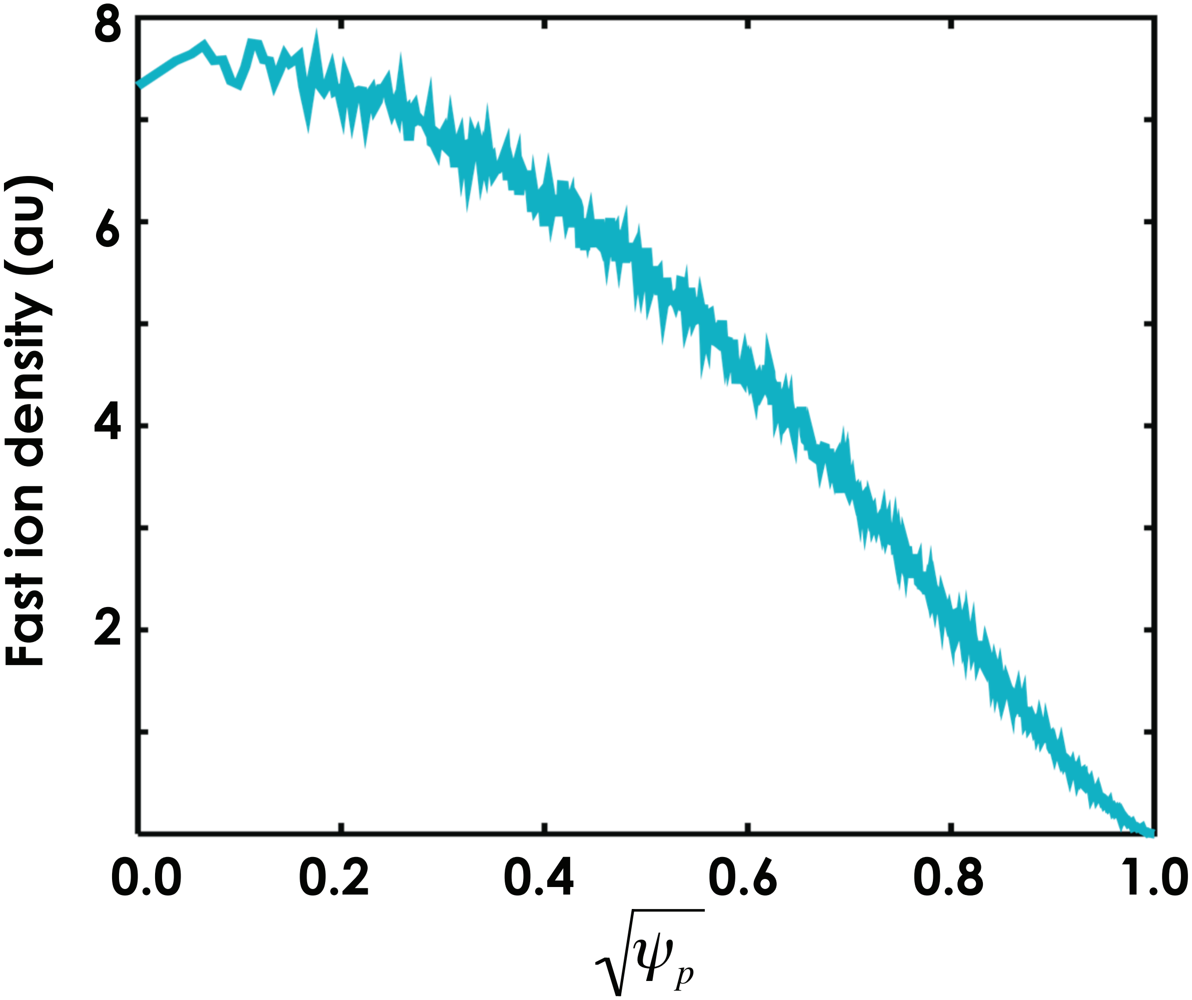


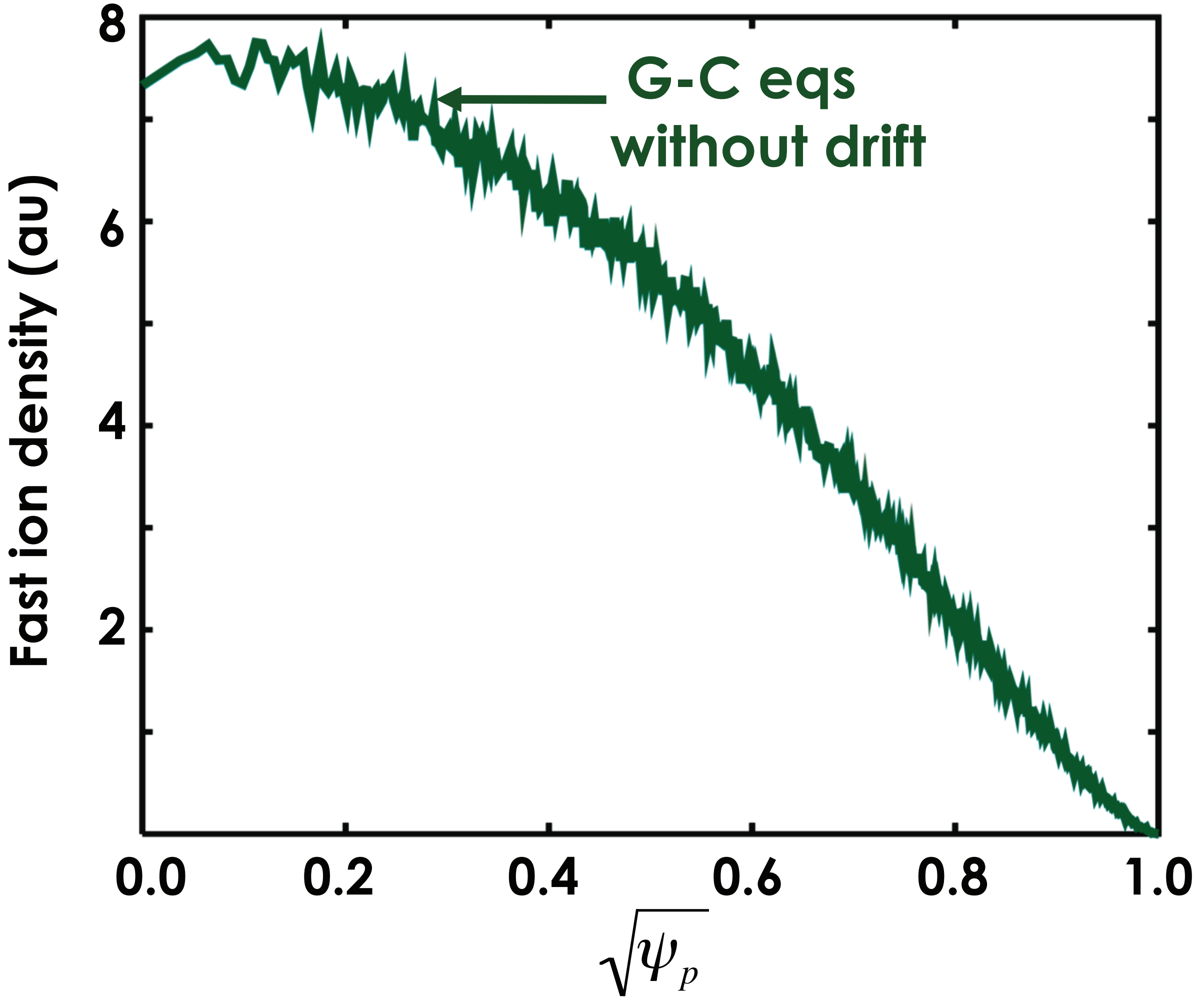
Non-Zero Orbit Width Redistributes Fast Ions

- **80 keV Deuterium ions**



Non-Zero Orbit Width Redistributes Fast Ions

- **20 toroidal turns with ICRF wave**



- **Without drift terms, no change of fast ion density**

Non-Zero Orbit Width Redistributes Fast Ions

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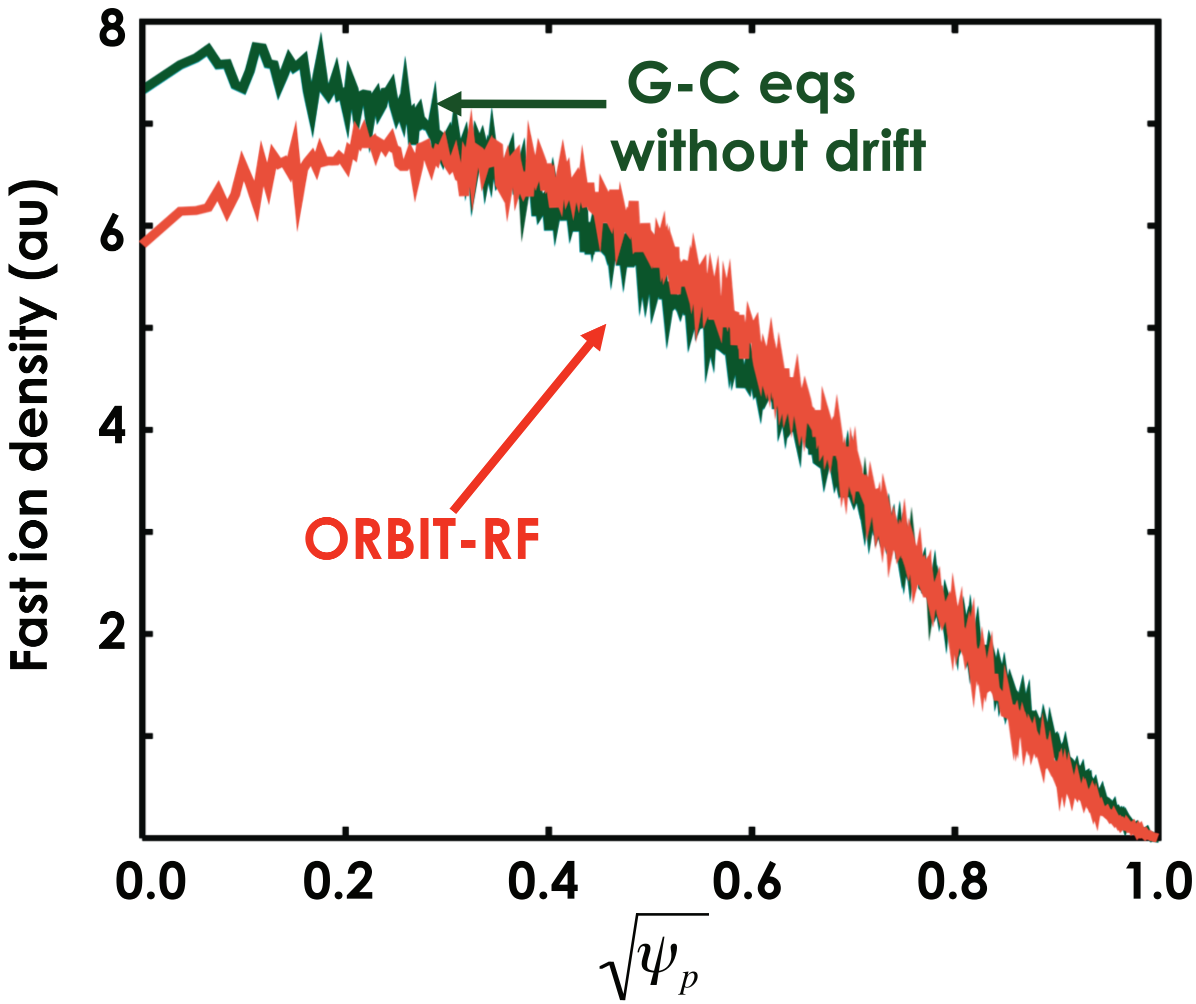

- **Without drift terms, no change of fast ion density**
- **With drift terms, "kicked" fast ions are diffused outward**

Self-Consistent Modeling of Fast Ion-ICRF Wave Interaction is Completed Under RF SciDAC Project

2-D linear full wave solver

AORSA

ORBIT-RF

5-D Monte-Carlo fast ion distribution solver

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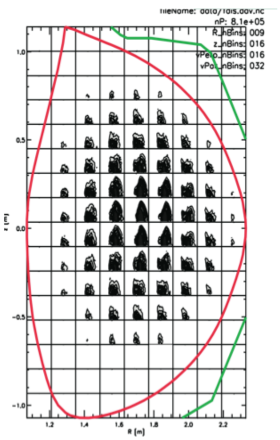

D. Green at ORNL

P2f

particle distribution

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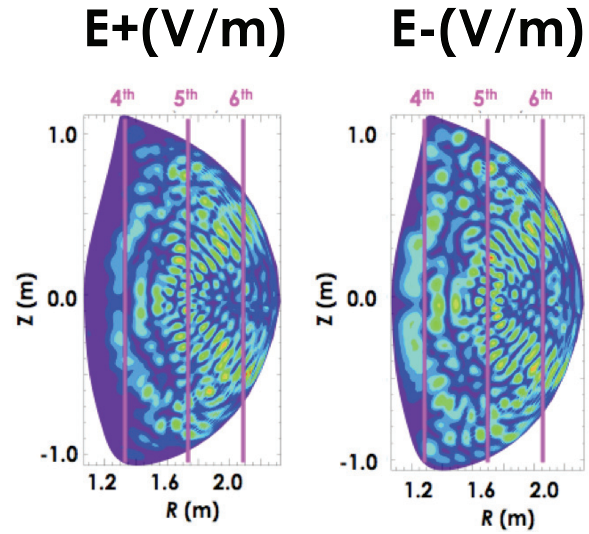
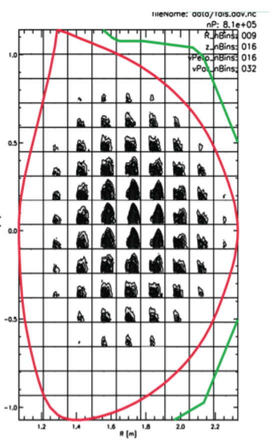


DIII-D #122993

60 MHz

P_{RF}=1MW

N_{φ}=13



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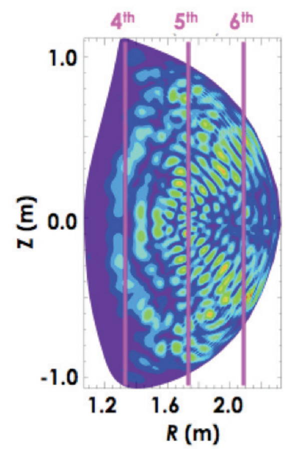

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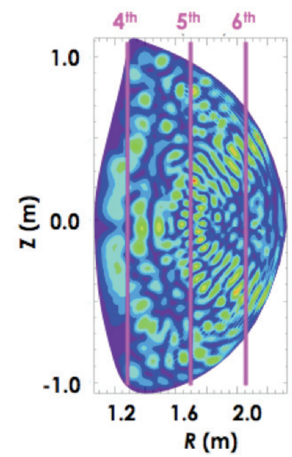

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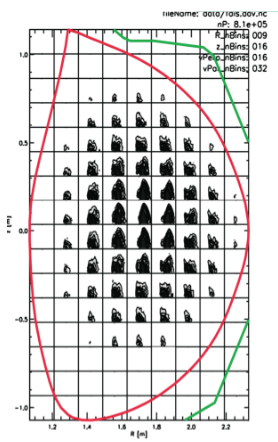

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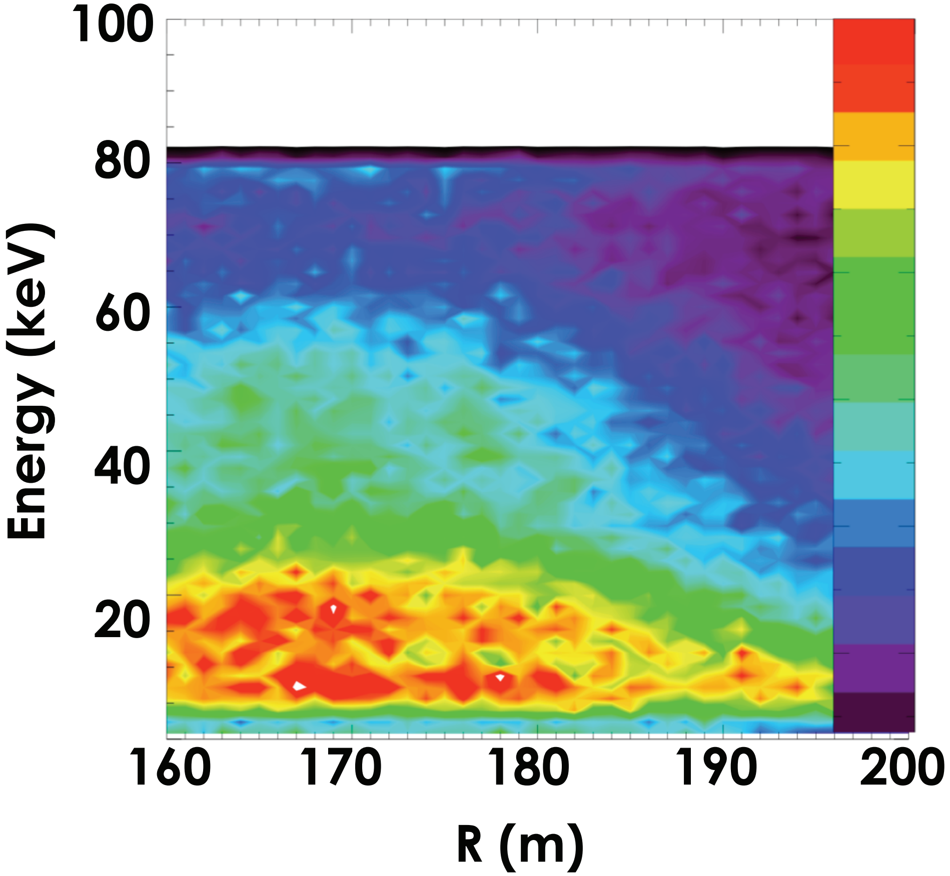
Iteration Between Fast Ion and ICRF Wave is Necessary to Allow Accurate Modeling

Fast ion distribution



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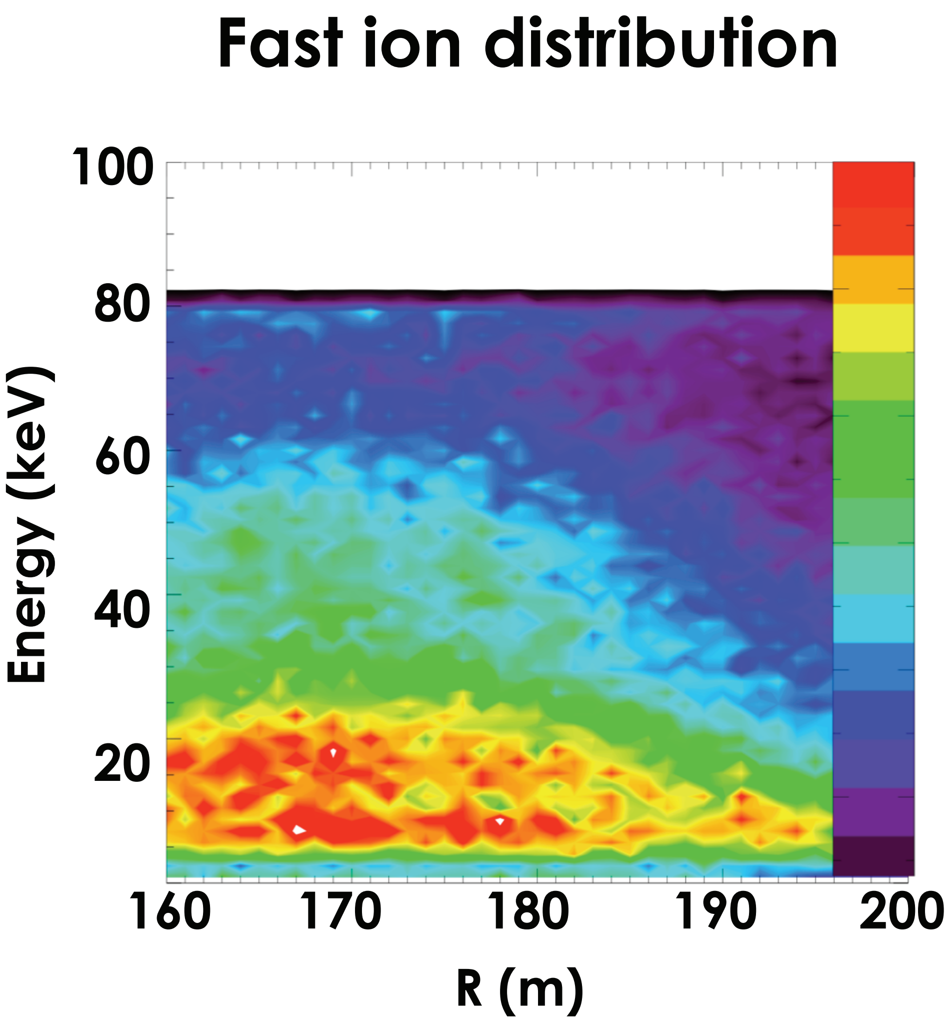
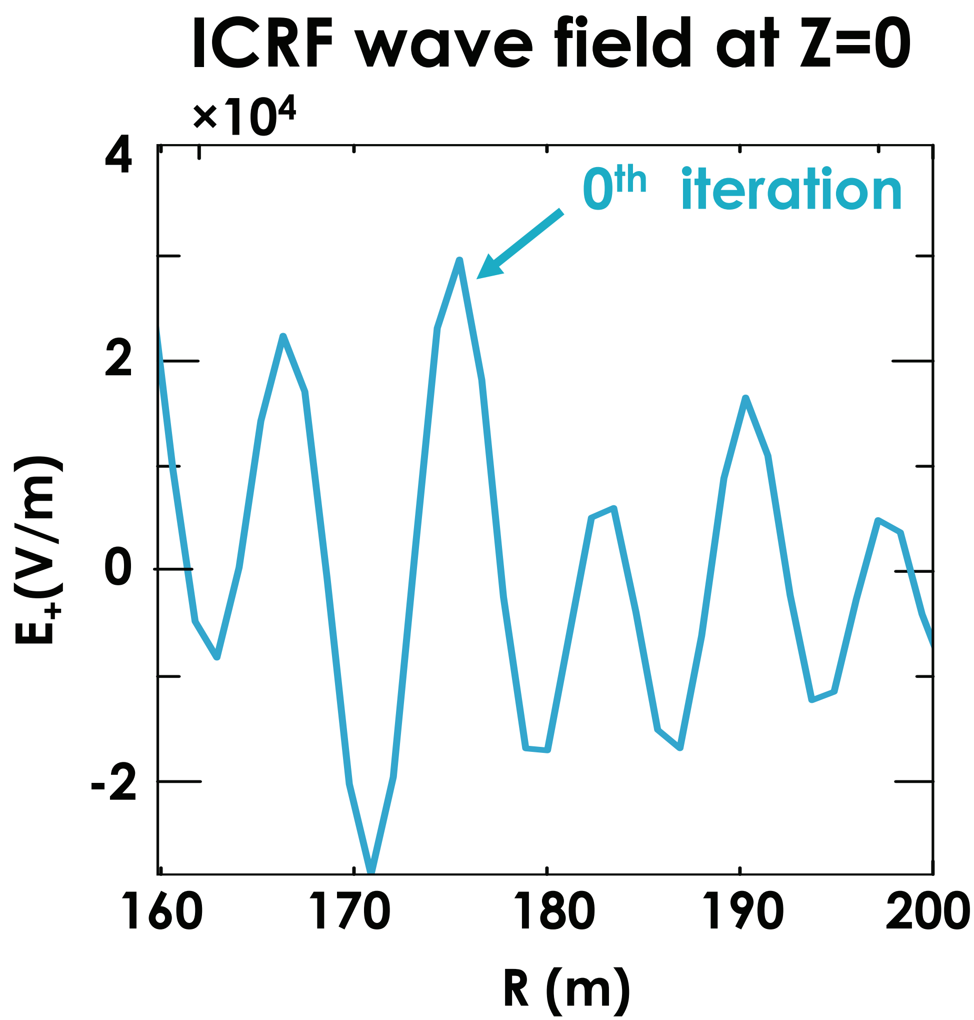
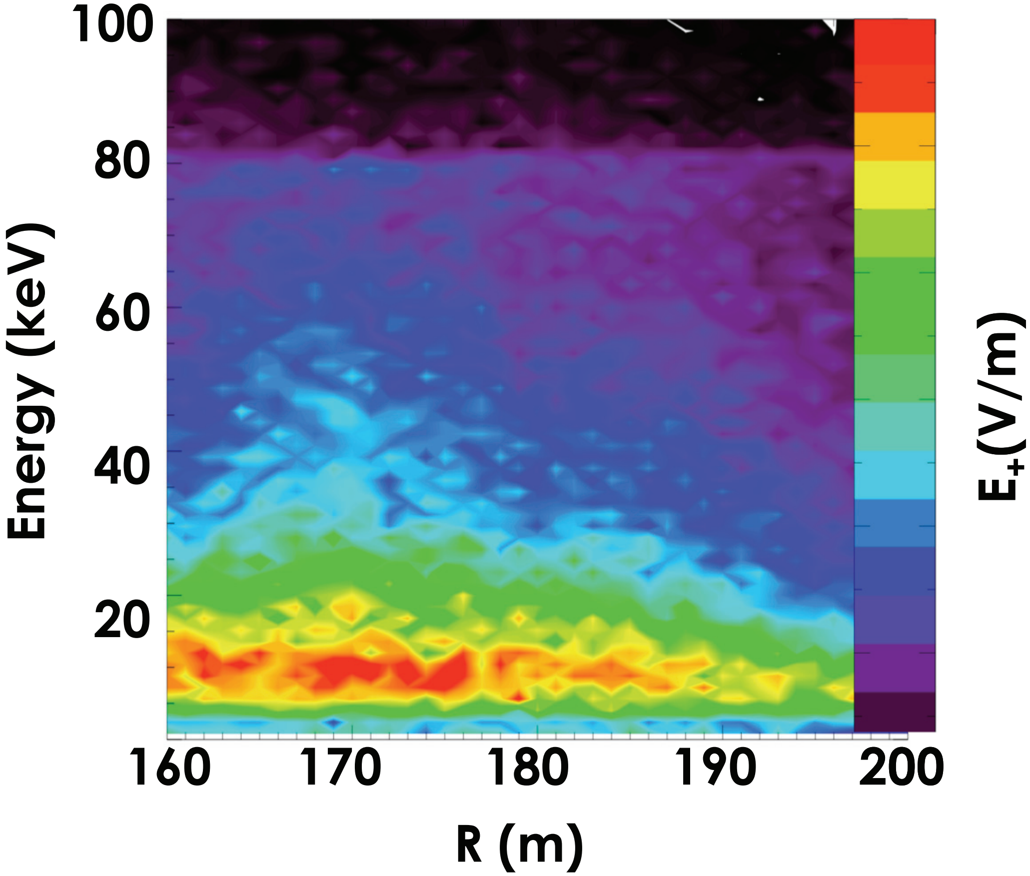




Iteration Between Fast Ion and ICRF Wave is Necessary to Allow Accurate Modeling

- Fast ion tail reduces wave amplitude due to stronger damping of FW on beam tail



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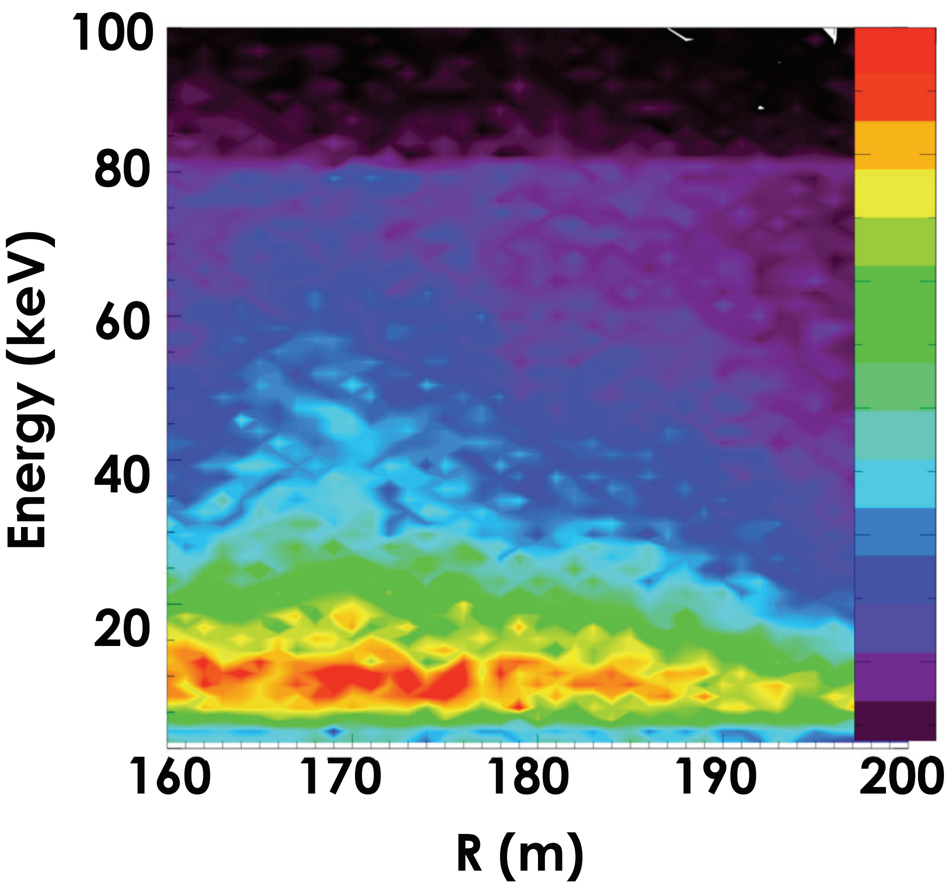
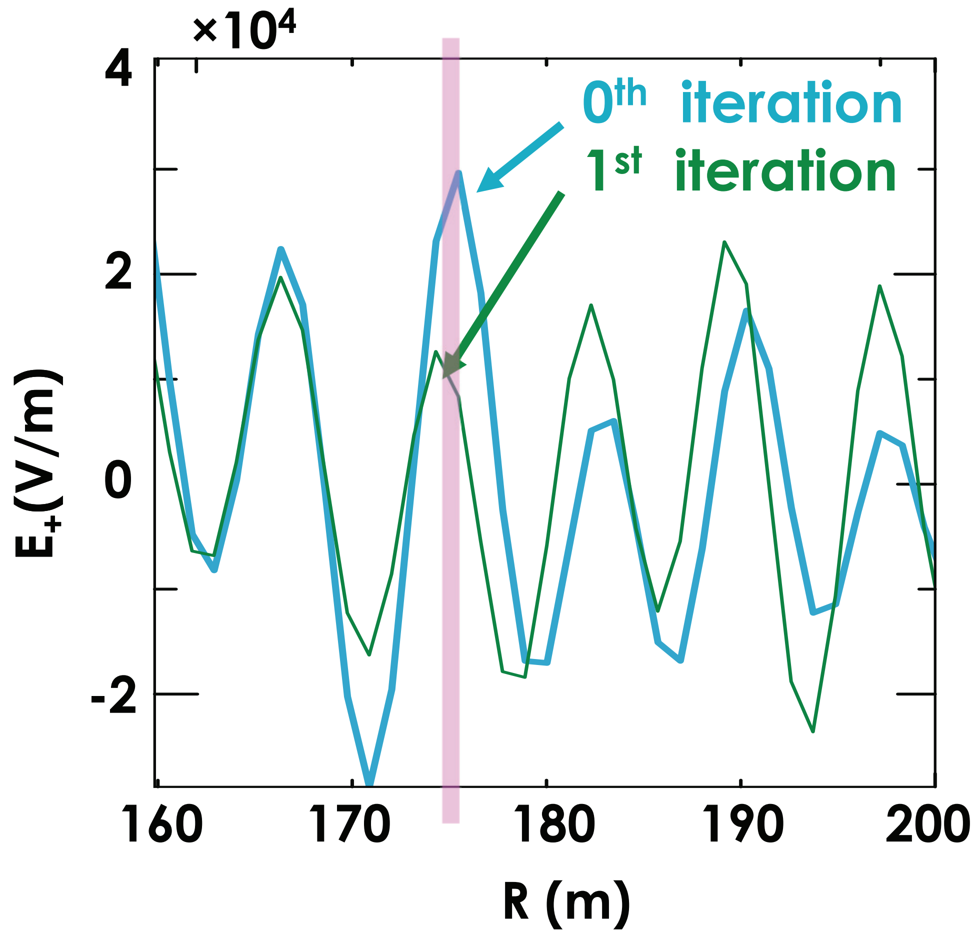
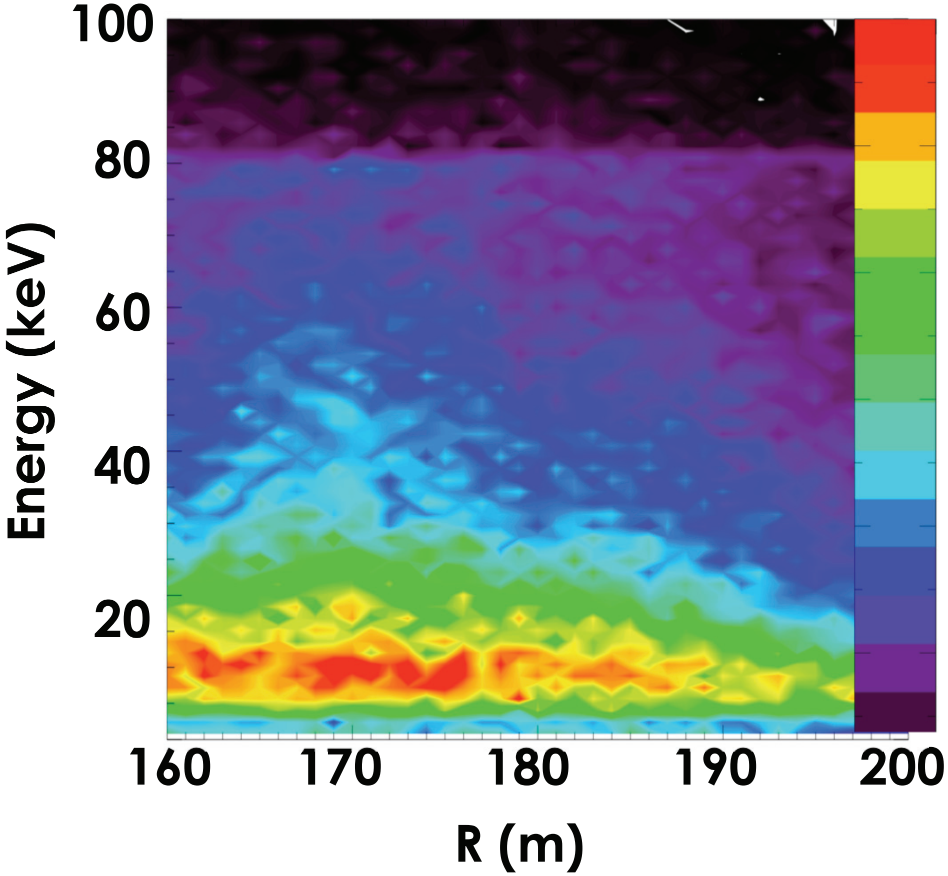
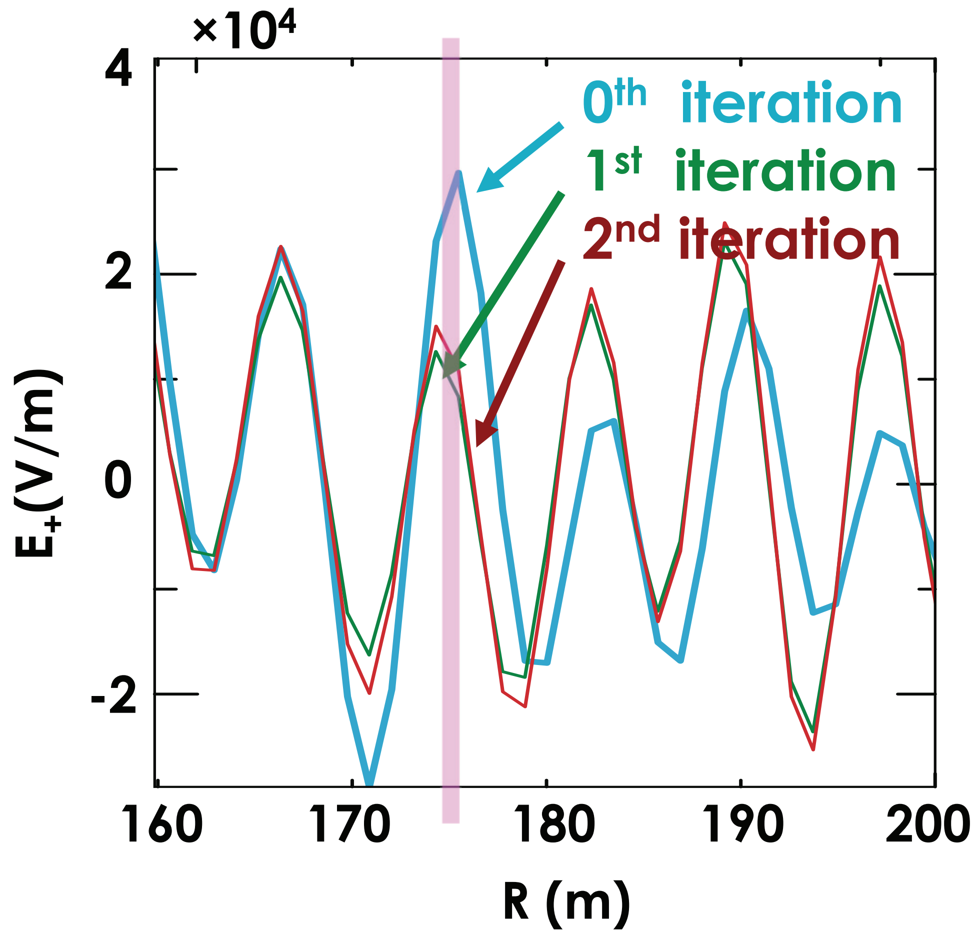




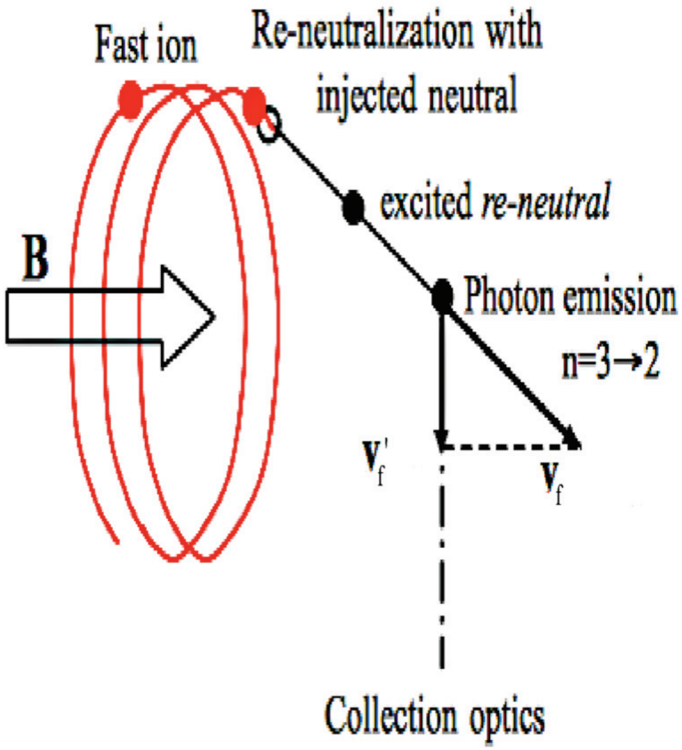
Iteration Between Fast Ion and ICRF Wave is Necessary to Allow Accurate Modeling

- **Wave fields converge after two iterations**





FIDA Spectroscopy Provides A Comprehensive Tool to Measure Fast Ion Distribution



W.W. Heidbrink, PPCF **46** (2004)
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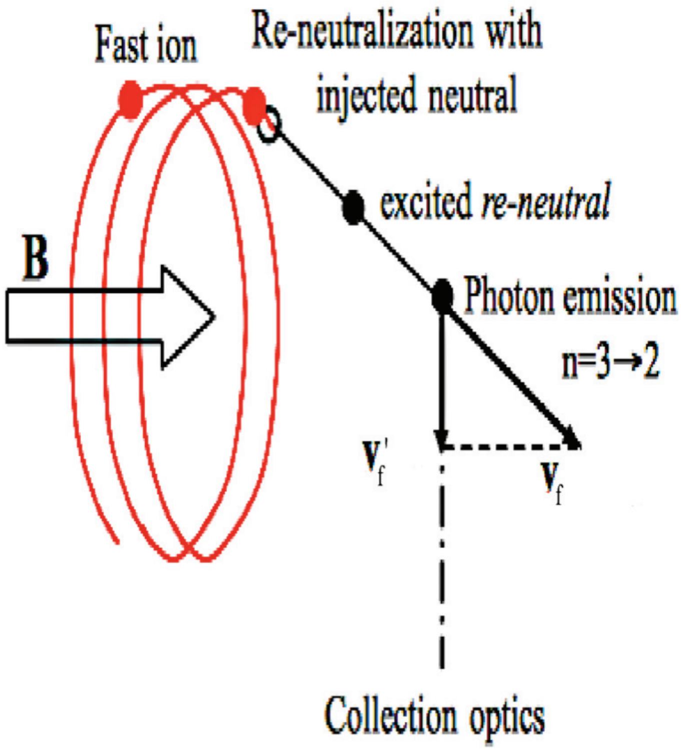

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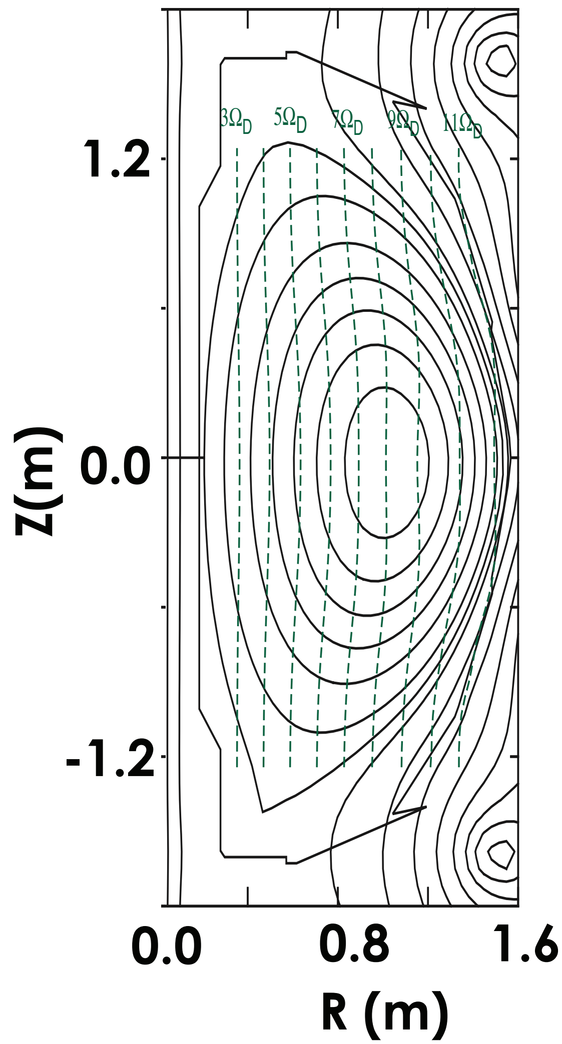
NSTX : 16 channels



DIII-D :

9 channels

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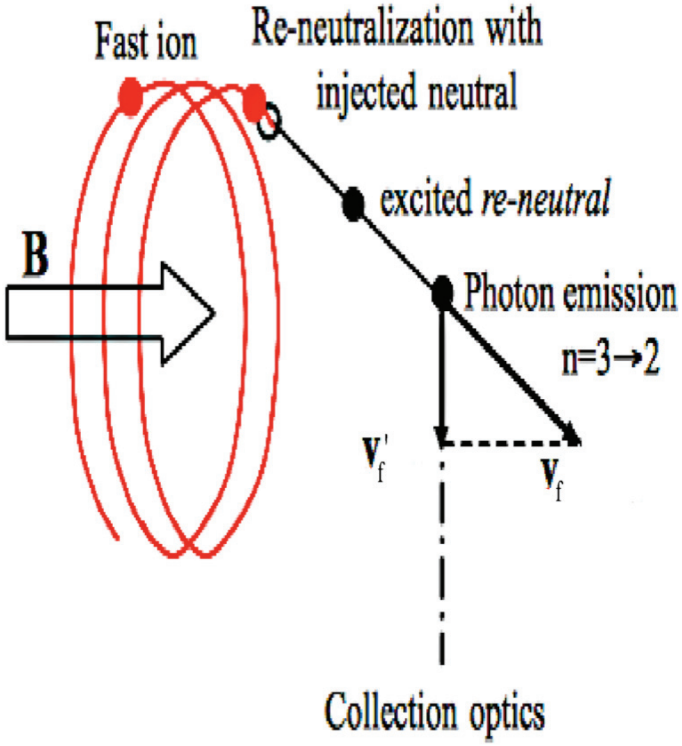

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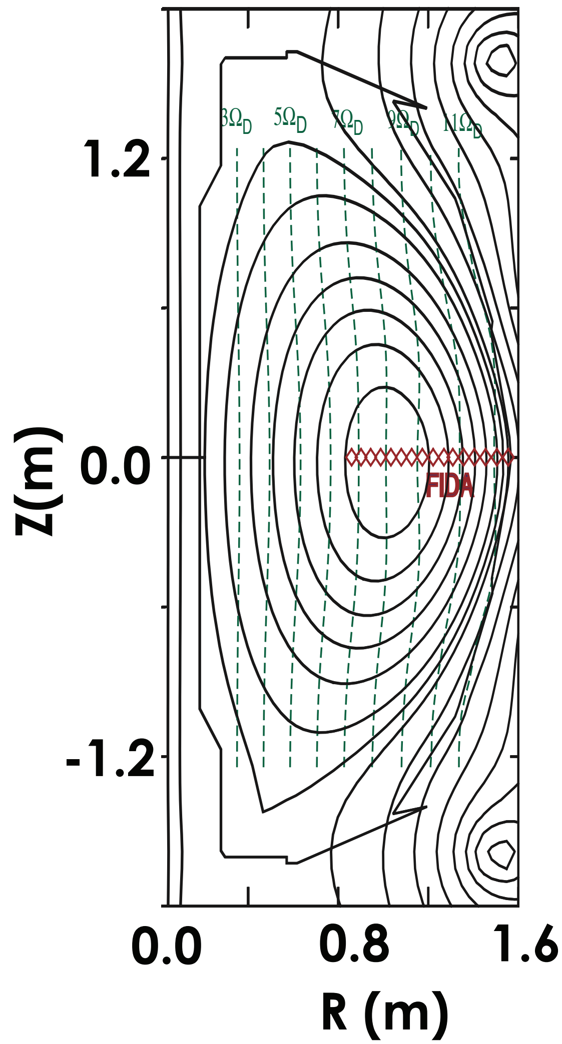

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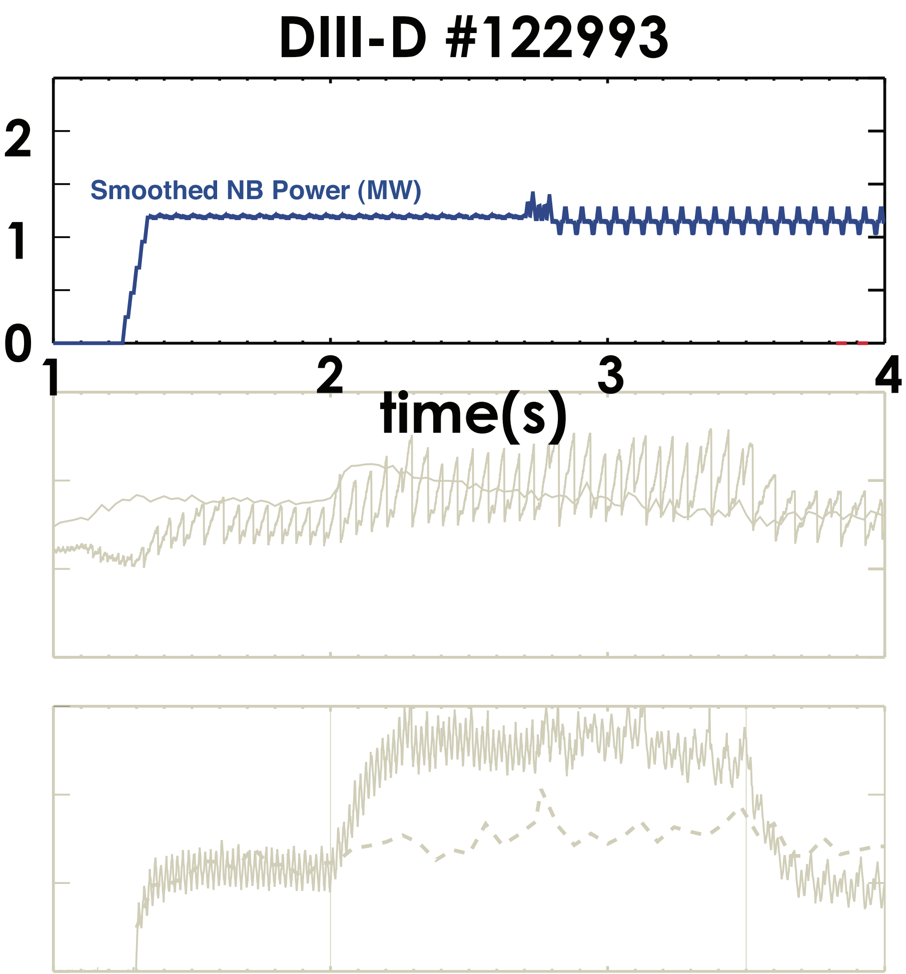
Increase of Neutron Rate During ICRF Heating Indicates Fast Ion Acceleration



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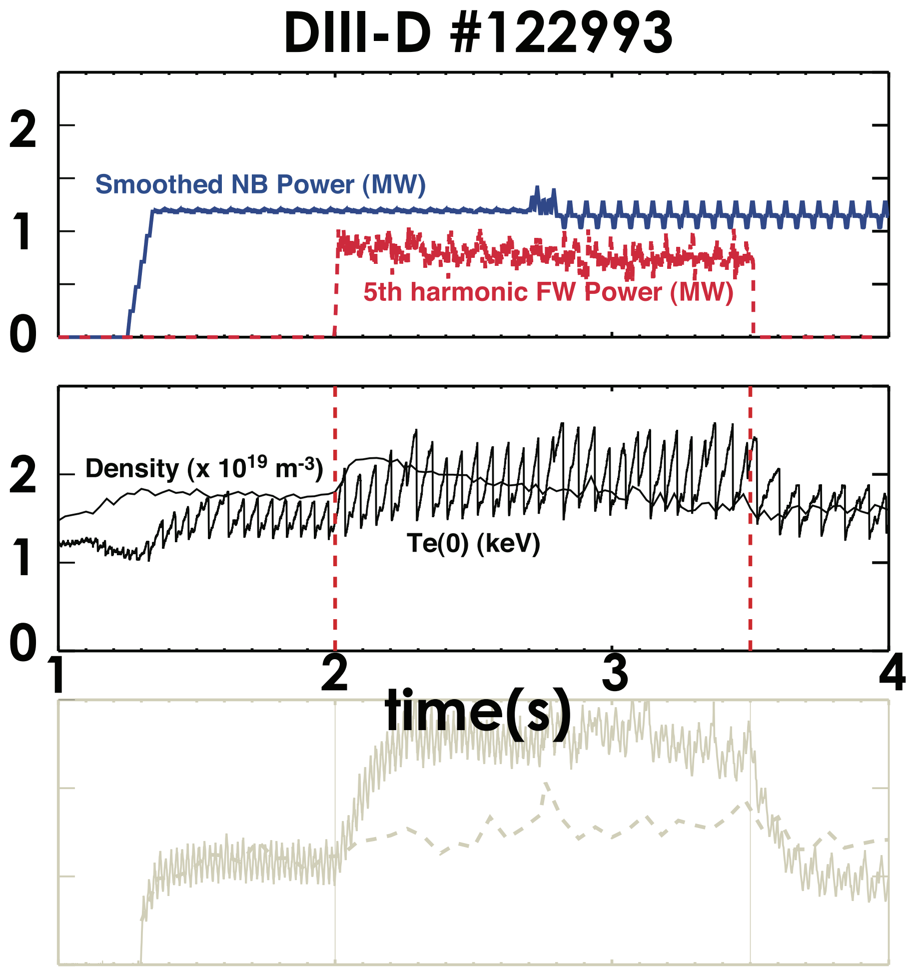

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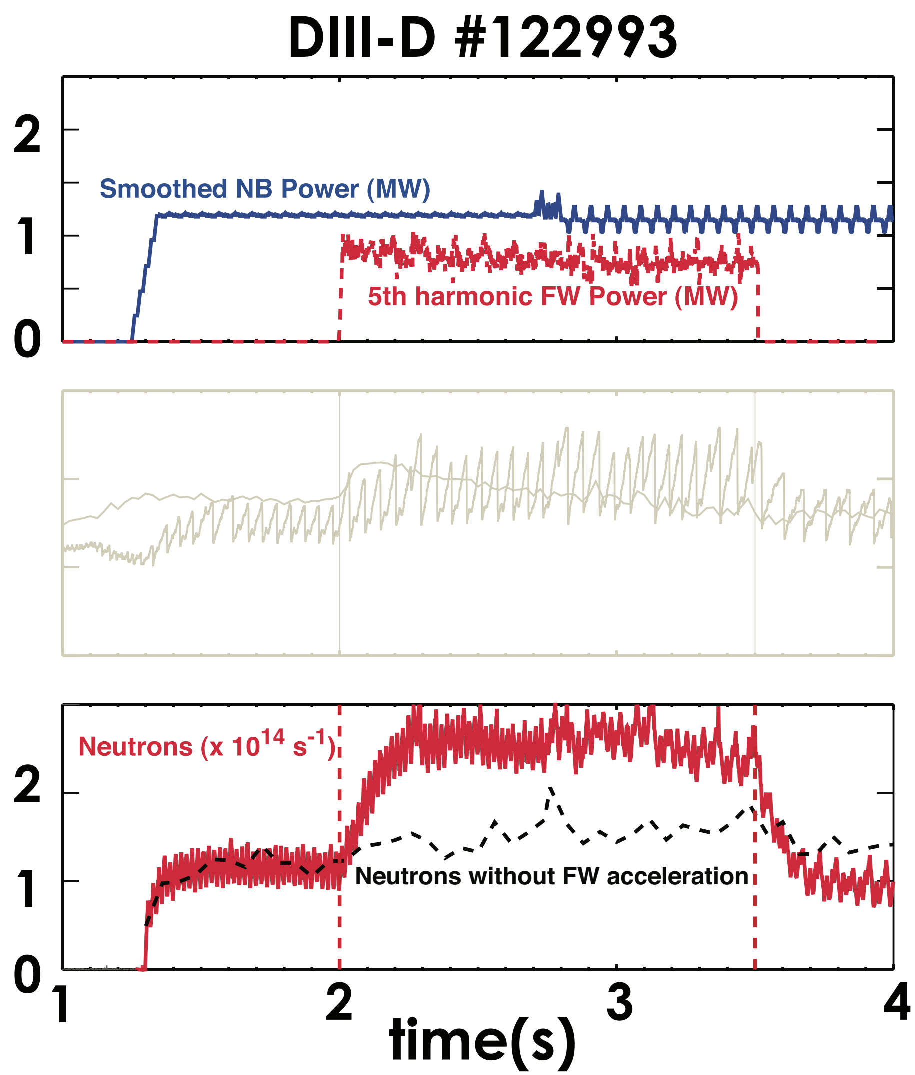
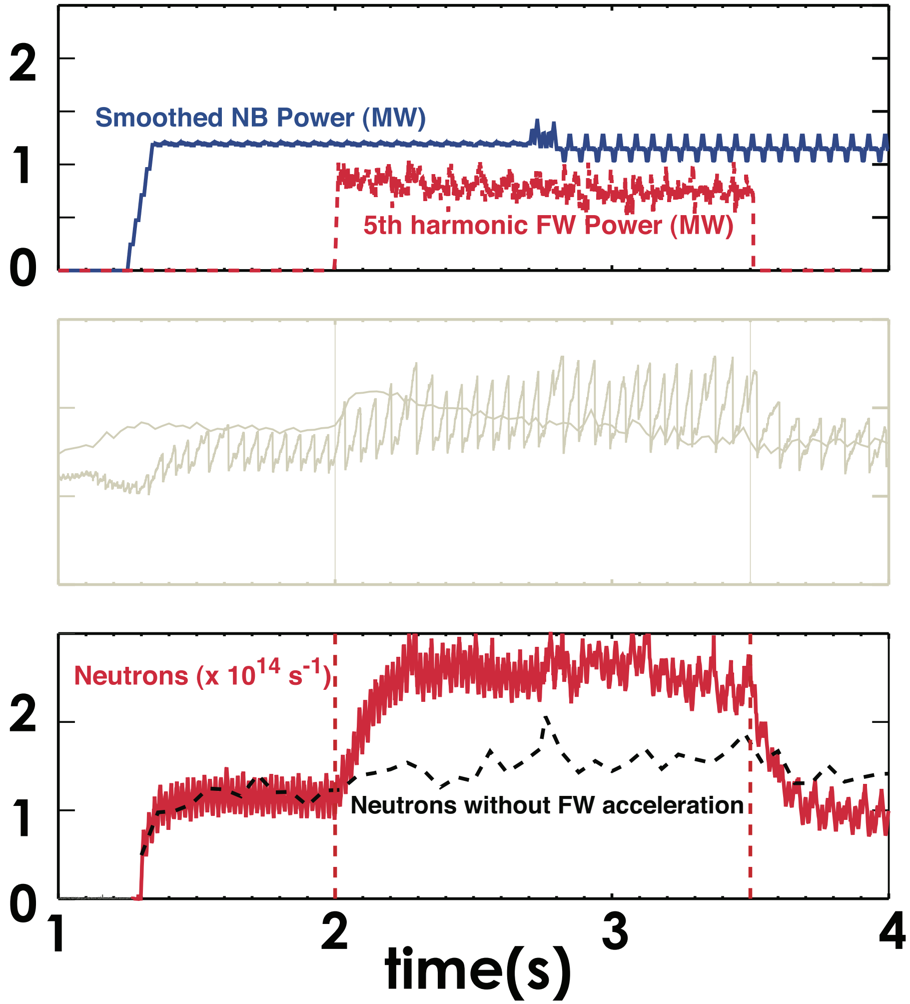
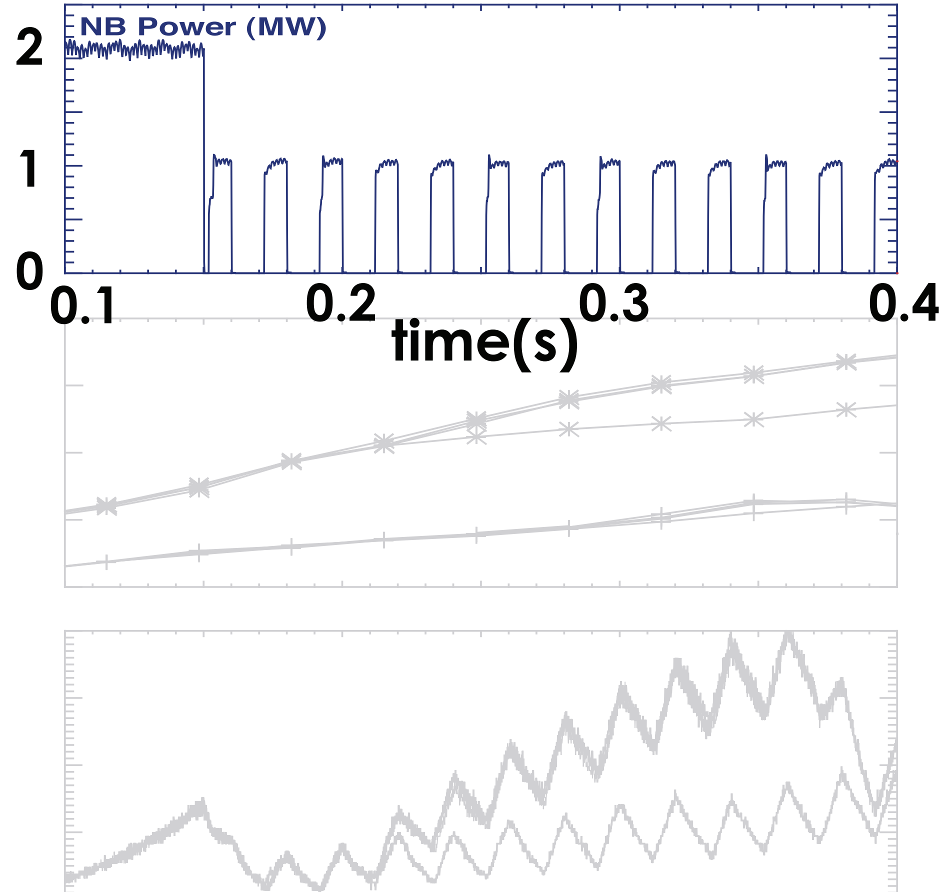


Increase of Neutron Rate During ICRF Heating Indicates Fast Ion Acceleration

DIII-D #122993



NSTX #128739-128742



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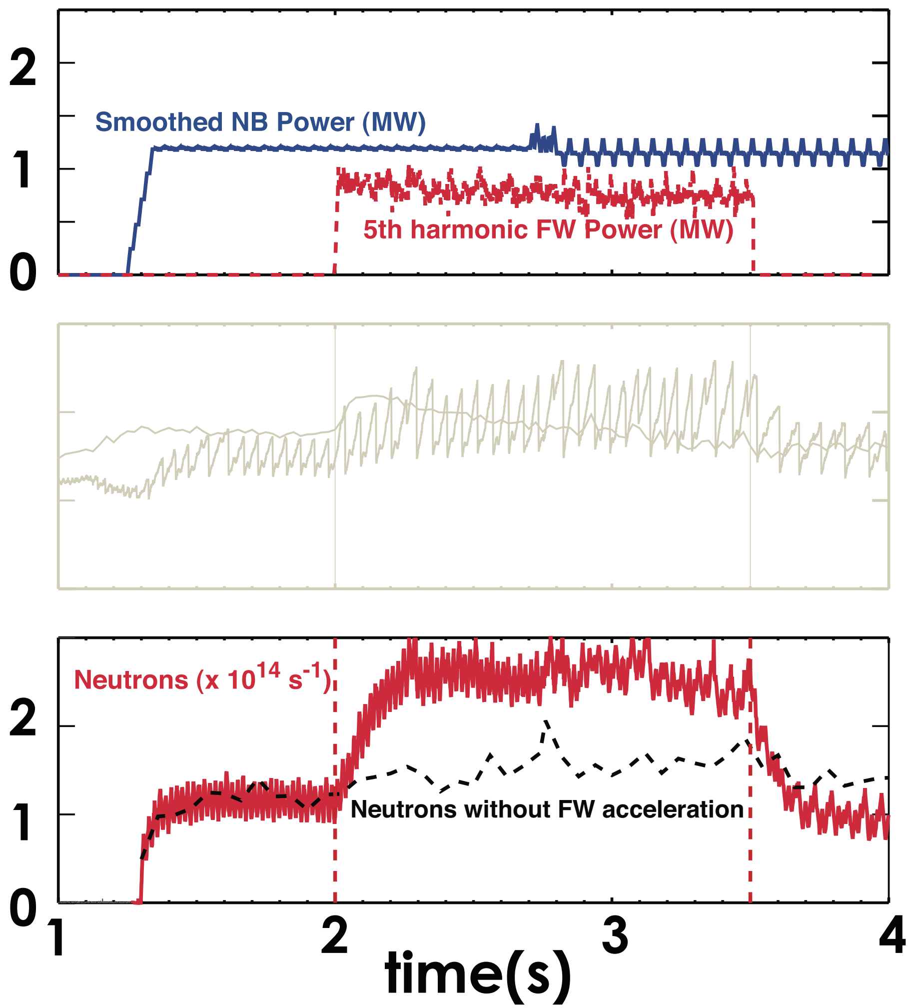
DIII-D #122993



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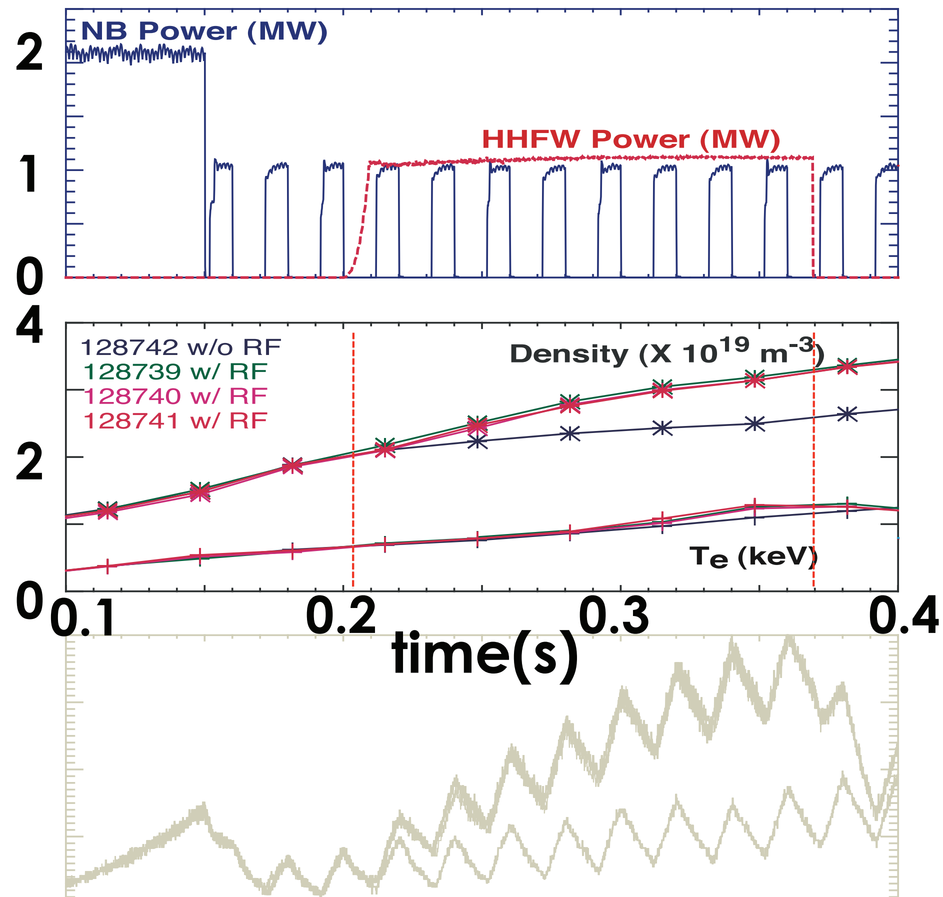

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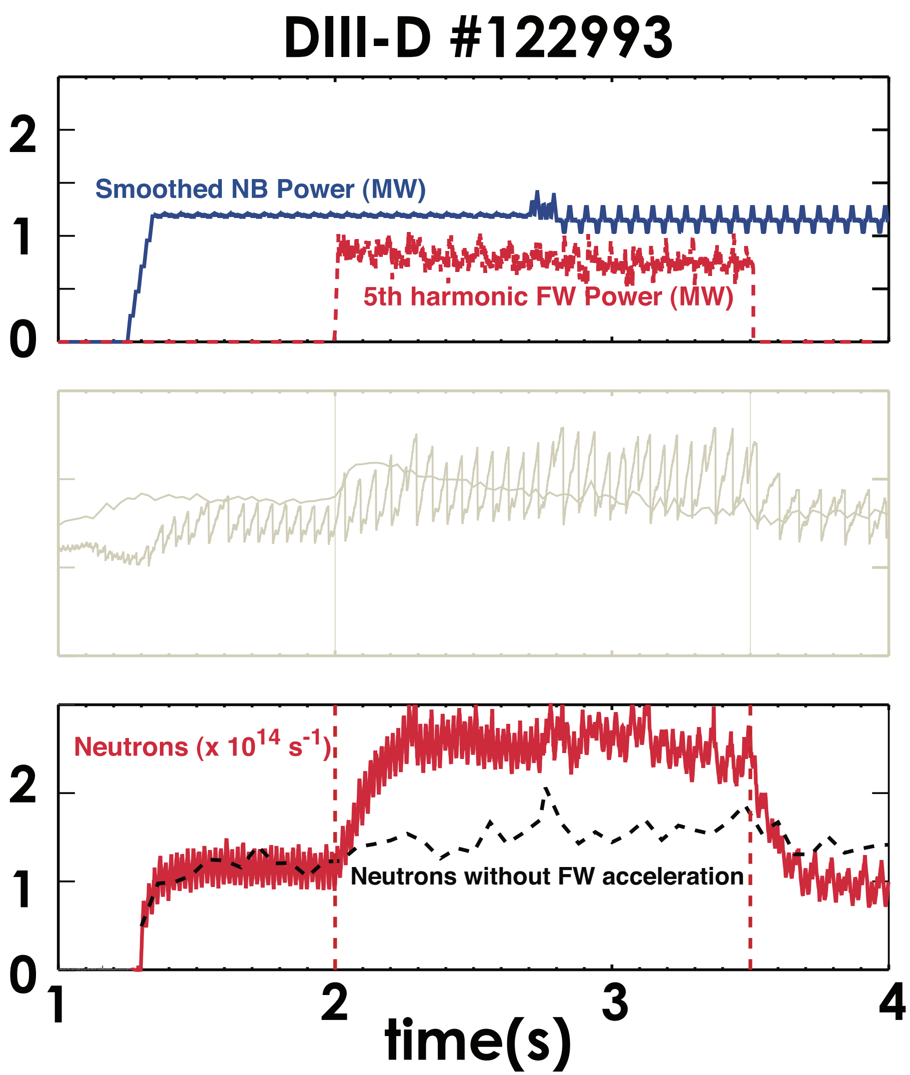
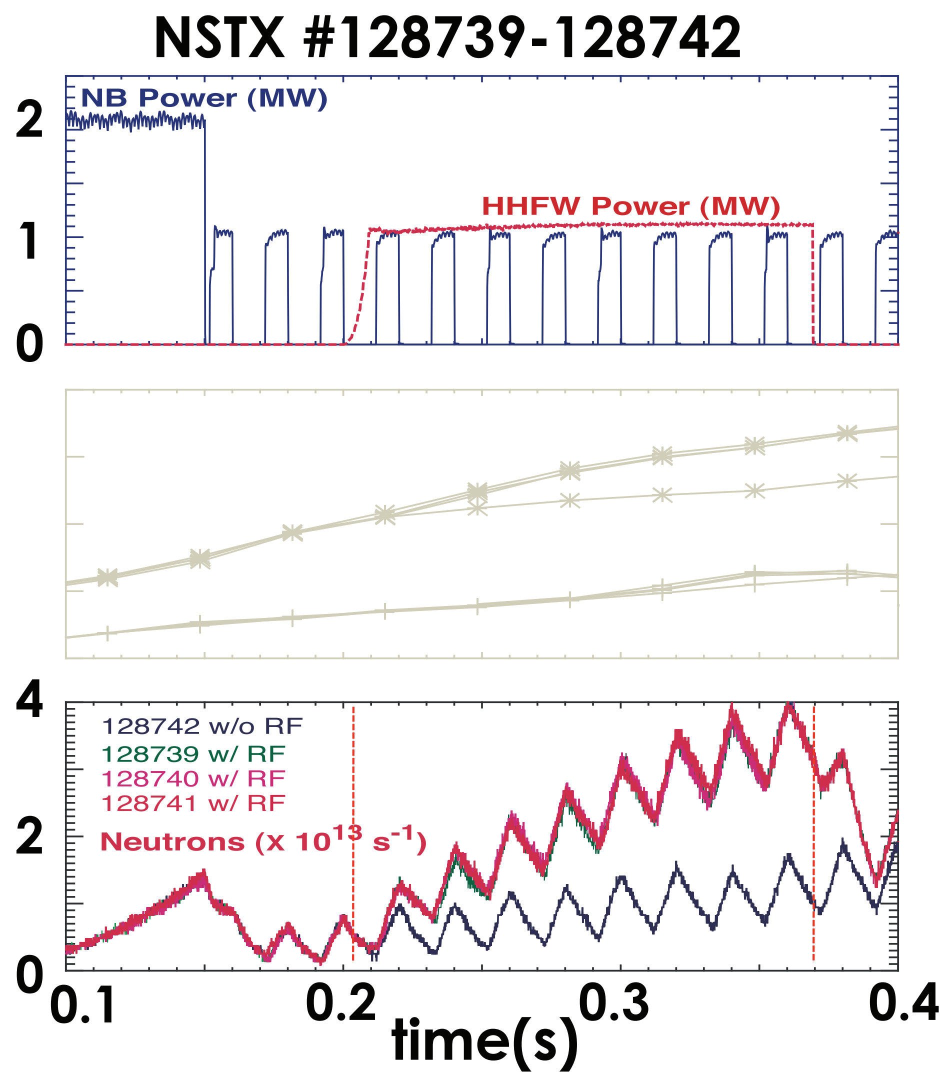
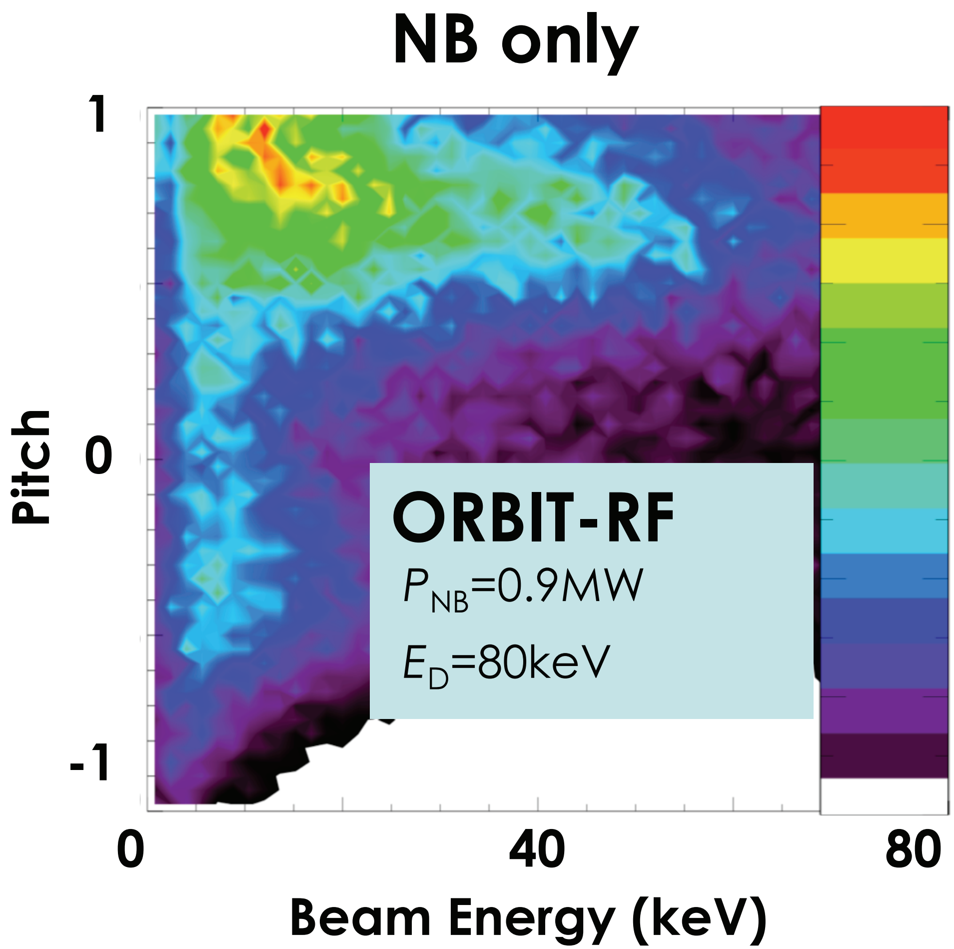




Beam Distribution Simulated by ORBIT-RF is in Reasonable Agreement with NUBEAM



- In qualitative agreement with FIDA measurement

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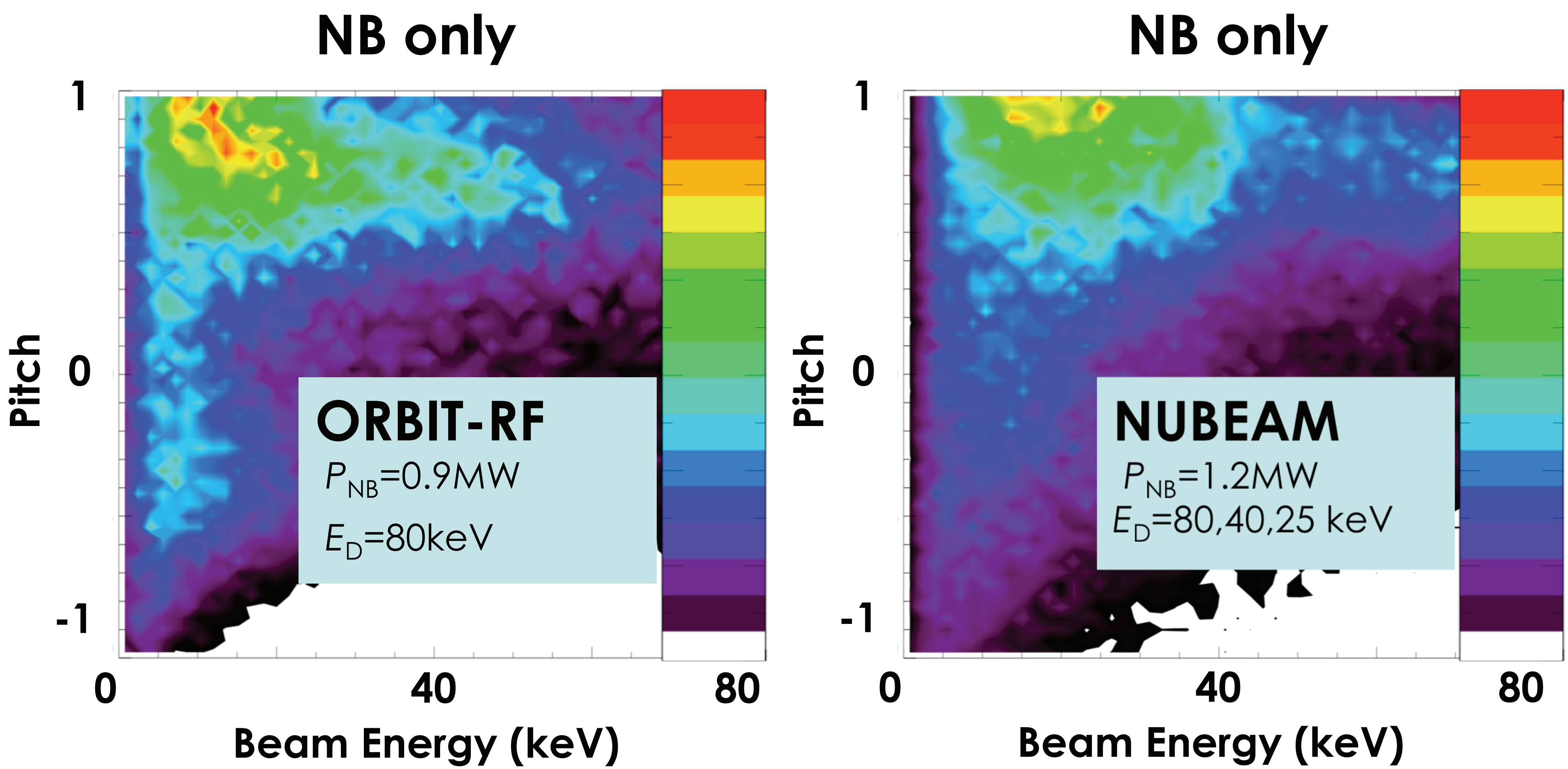
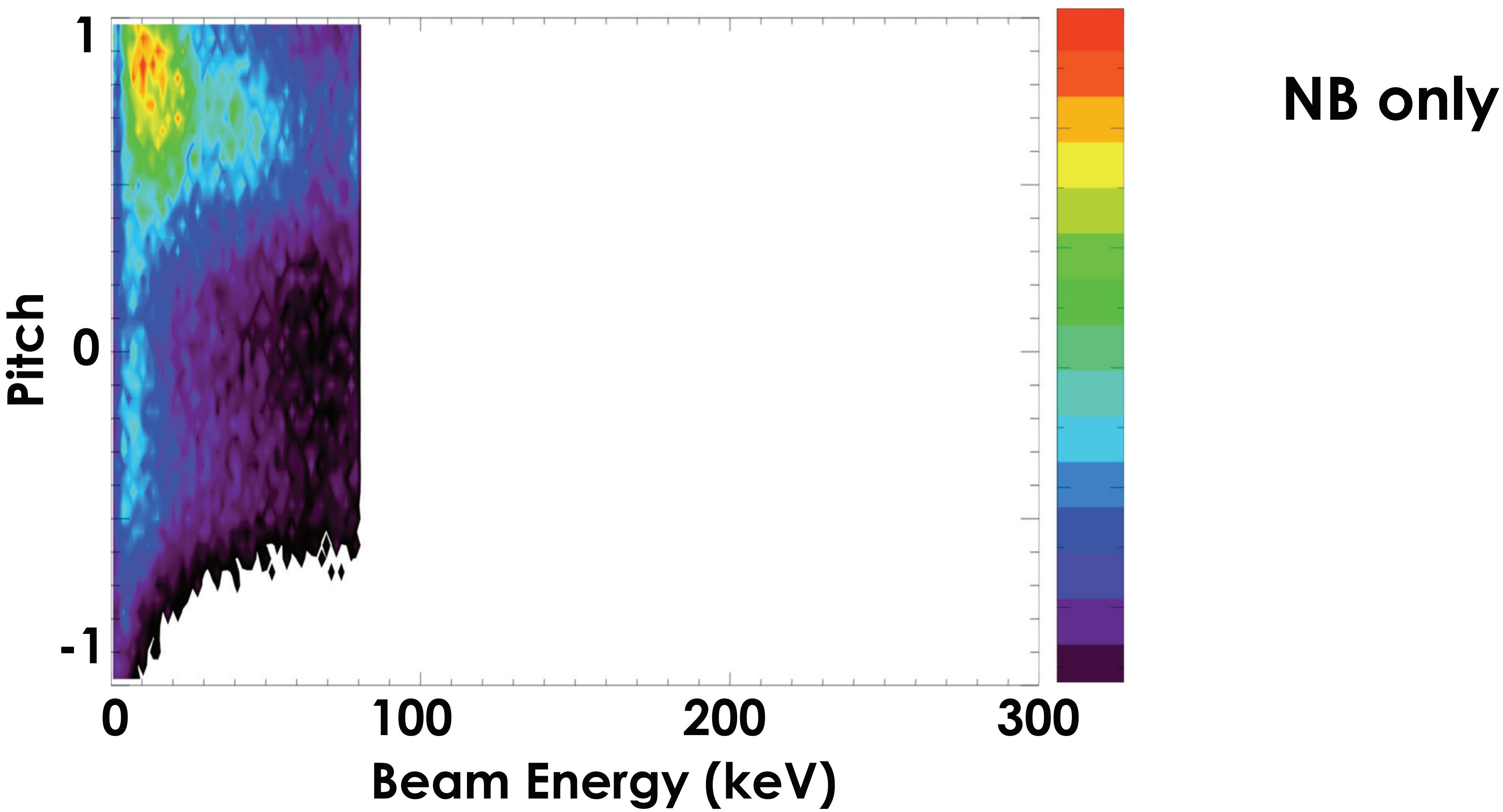


- In qualitative agreement with FIDA measurement

ORBIT-RF/AORSA Indicates Beam Tails are Created Above Injection Energy Due to ICRF Heating

- **DIII-D #122993: P_{RF}=1.0MW, 60MHz**



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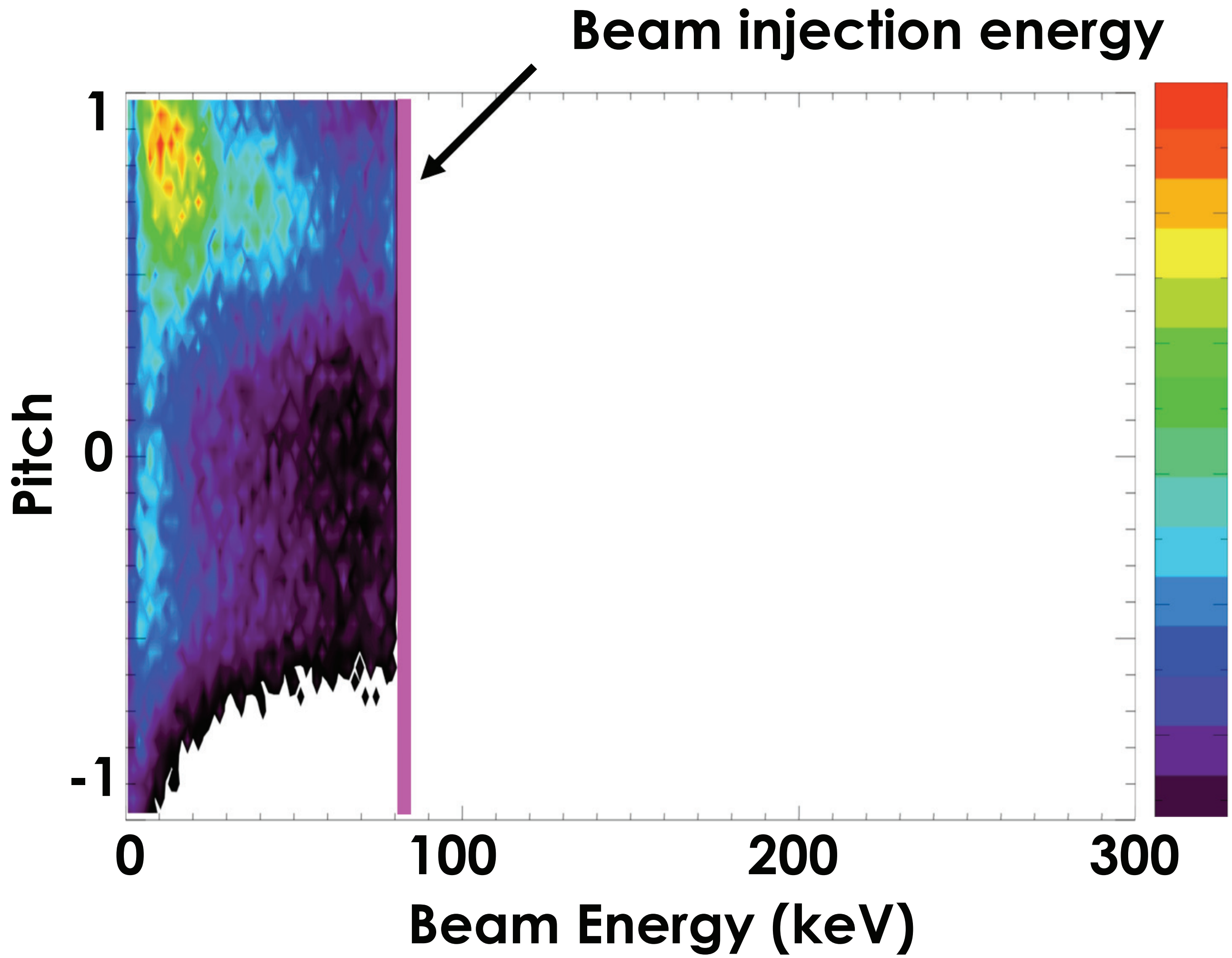
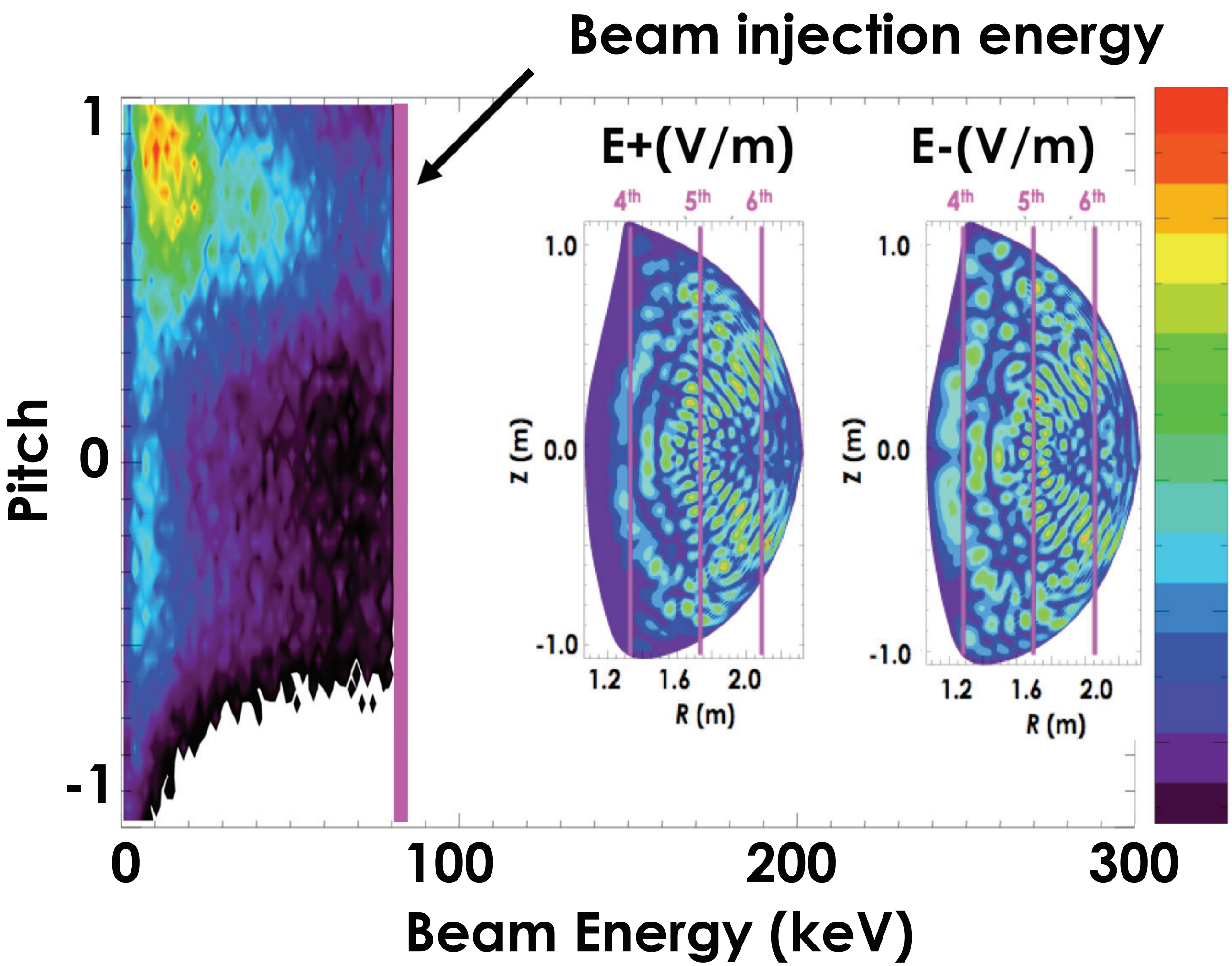


NB only

ORBIT-RF/AORSA Indicates Beam Tails are Created Above Injection Energy Due to ICRF Heating

- **Simulation for 160ms with two iterations**



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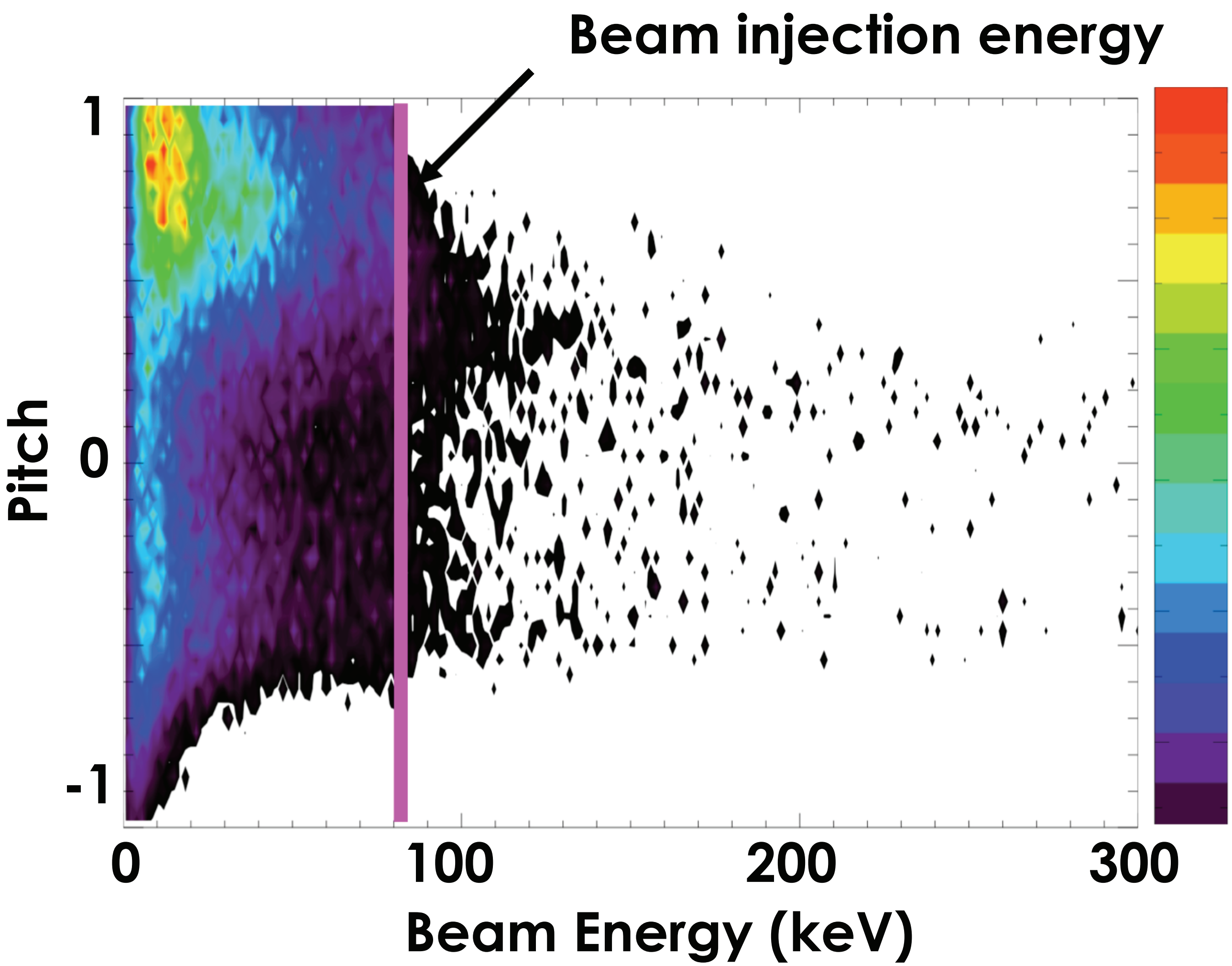

20 ms with ICRF

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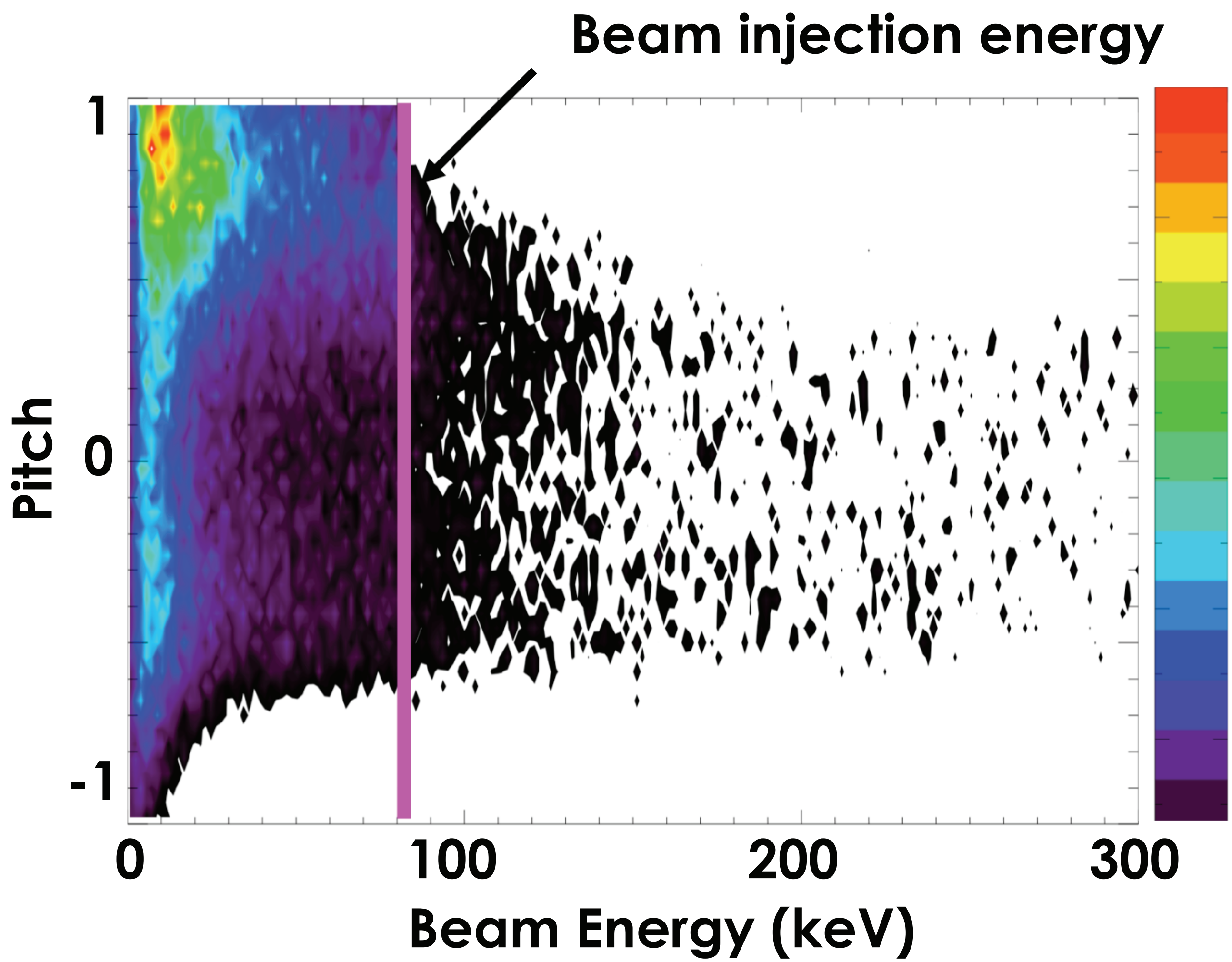

70 ms with ICRF

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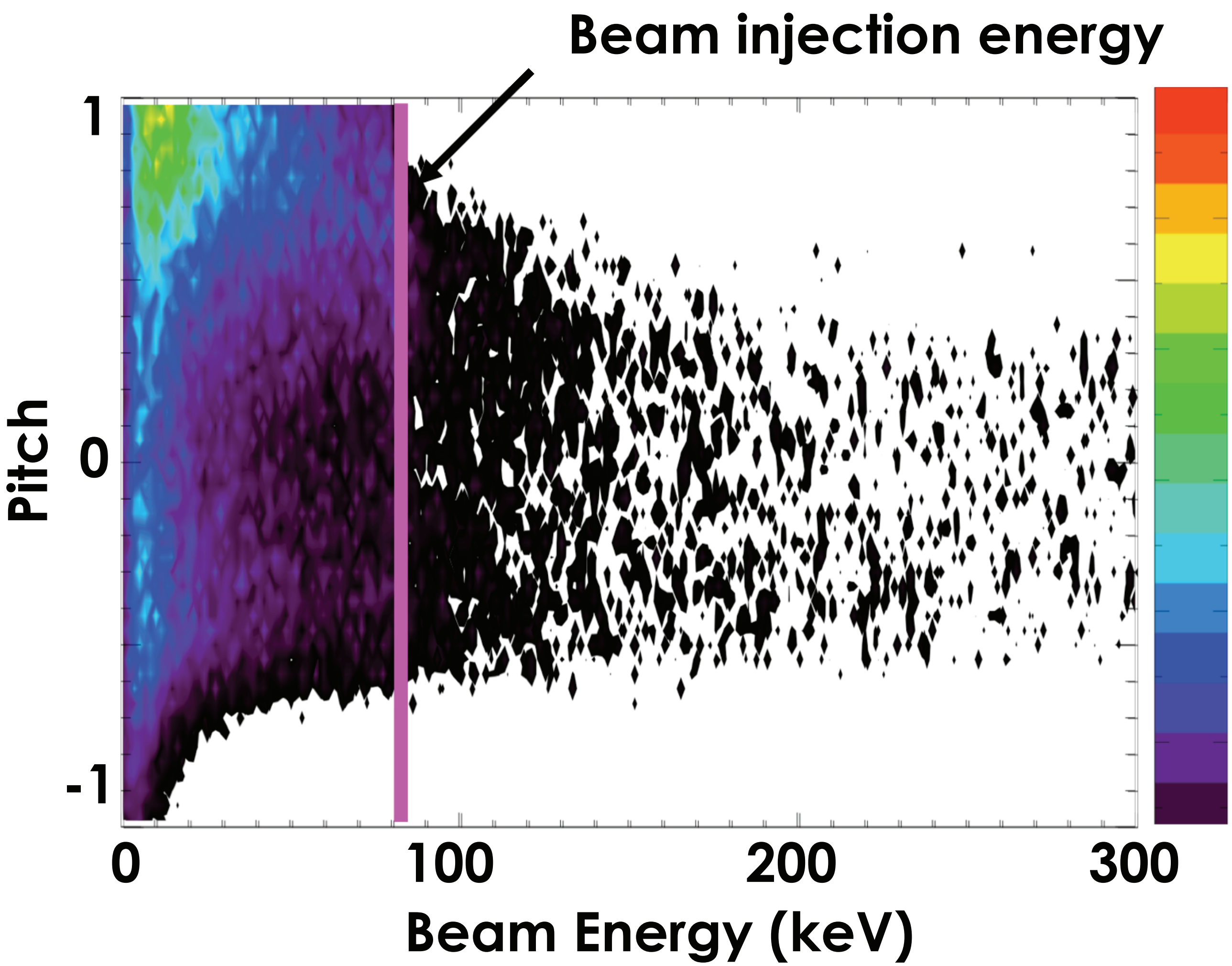
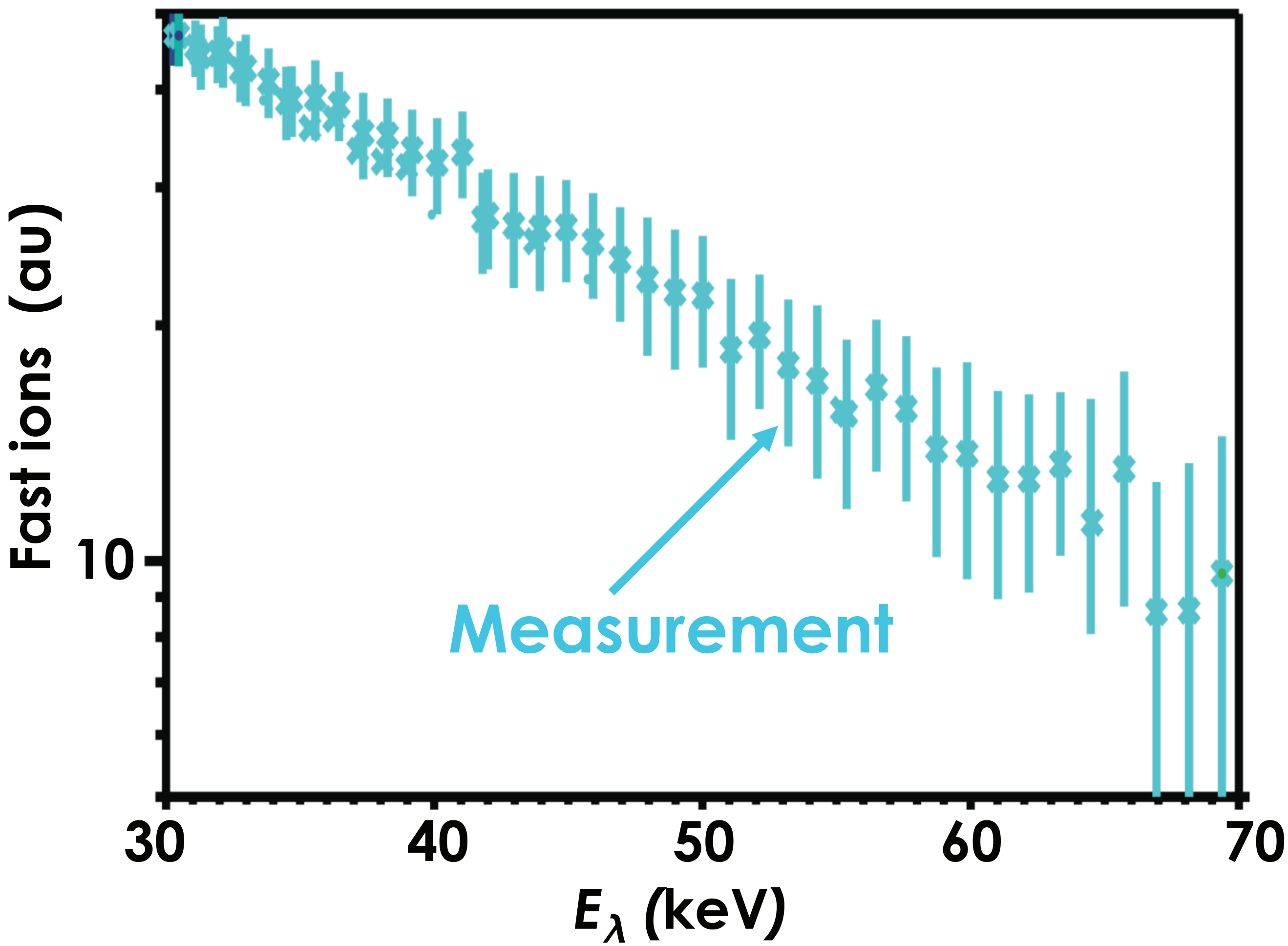
- Simulation for 160ms with two iterations



160 ms with ICRF

Both ORBIT-RF/AORSA and CQL3D/Ray-Tracing Predict Similar Tail Spectra to Measurement

- **DIII-D 122993: P_{RF}=1.0MW, f=60MHz**



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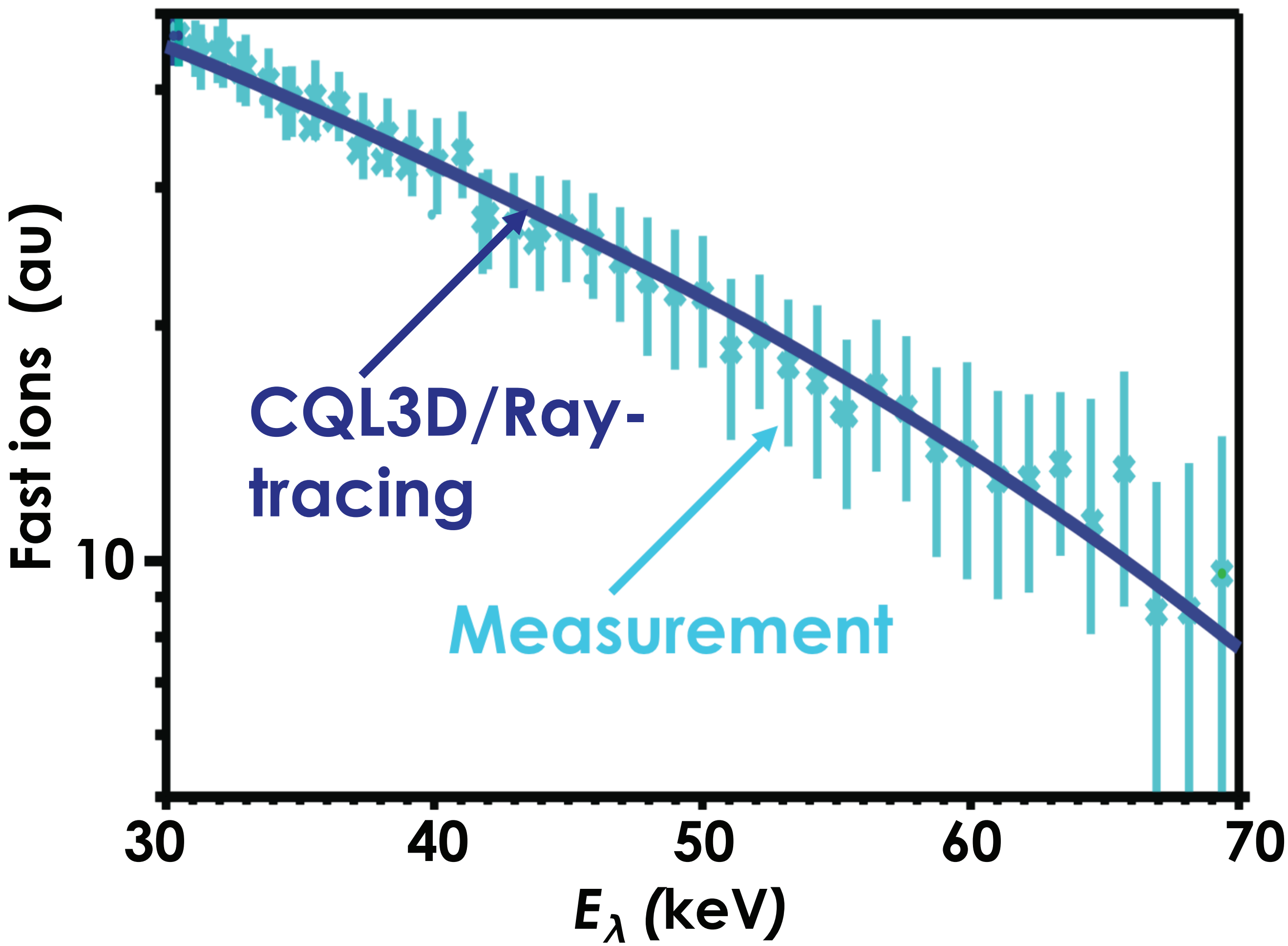

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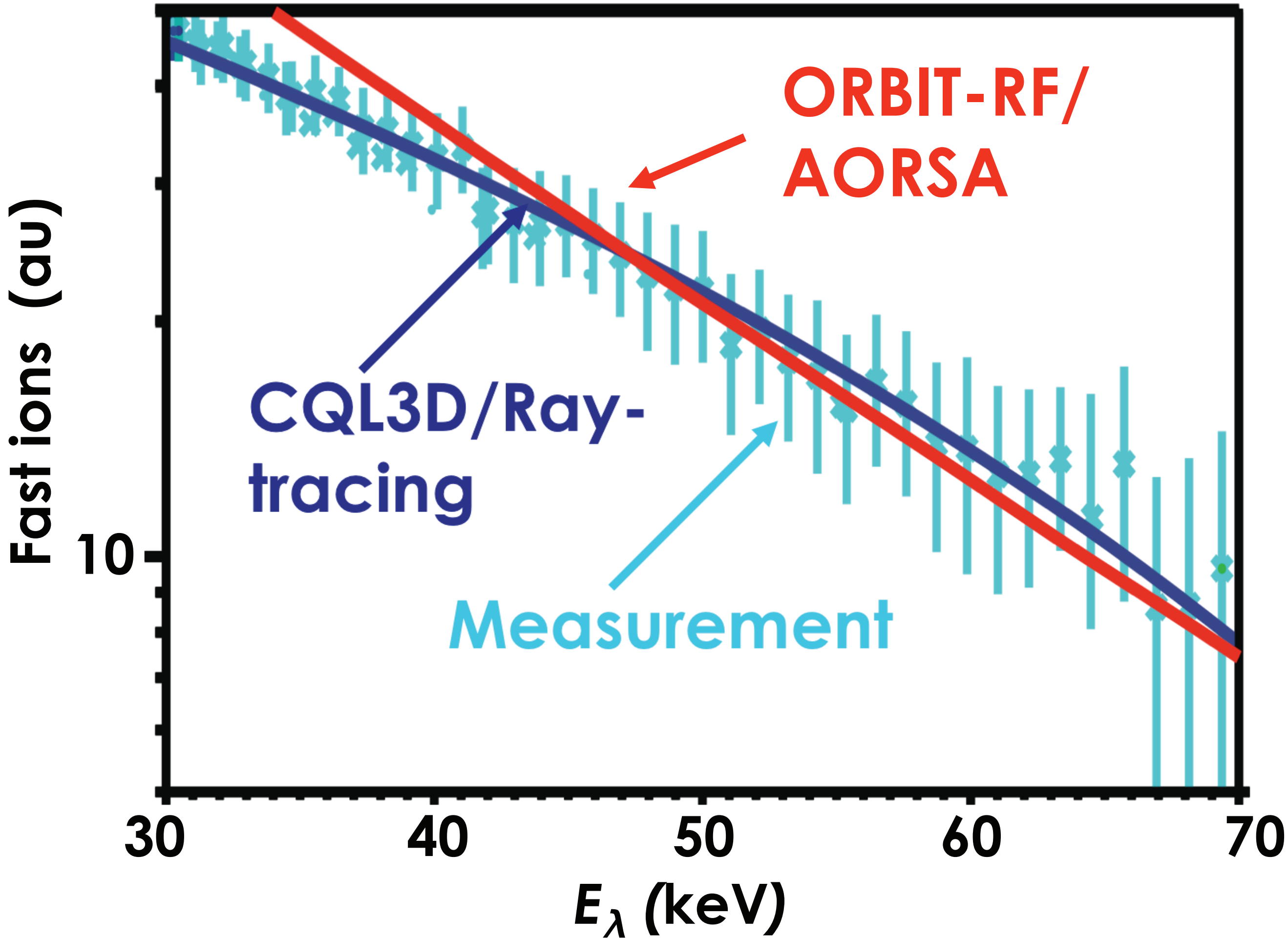

- **Neutron enhancement**

$$S_n = \frac{\left(\sum_{i=1}^{n} \langle \sigma v \rangle_i w_i\right)^{NB+RF}}{\left(\sum_{i=1}^{n} \langle \sigma v \rangle_i w_i\right)^{NB}}$$

$\langle \sigma v \rangle$ reaction rate for beam-plasma

ORBIT-RF ~2.1

Exp. ~2.4

ORBIT-RF/AORSA Predicts Outward Spatial Shift of Fast Ions, Qualitatively Consistent with FIDA

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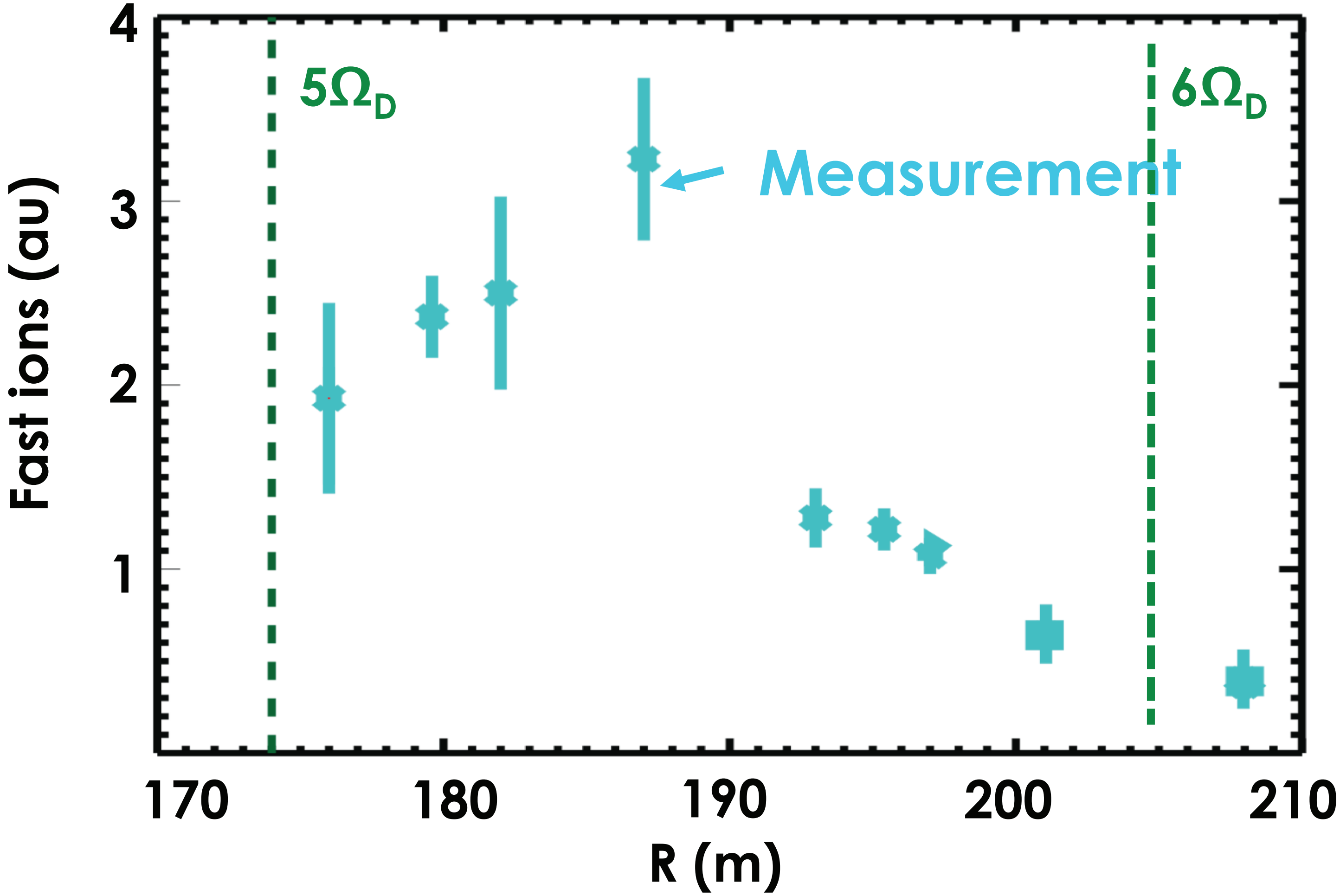

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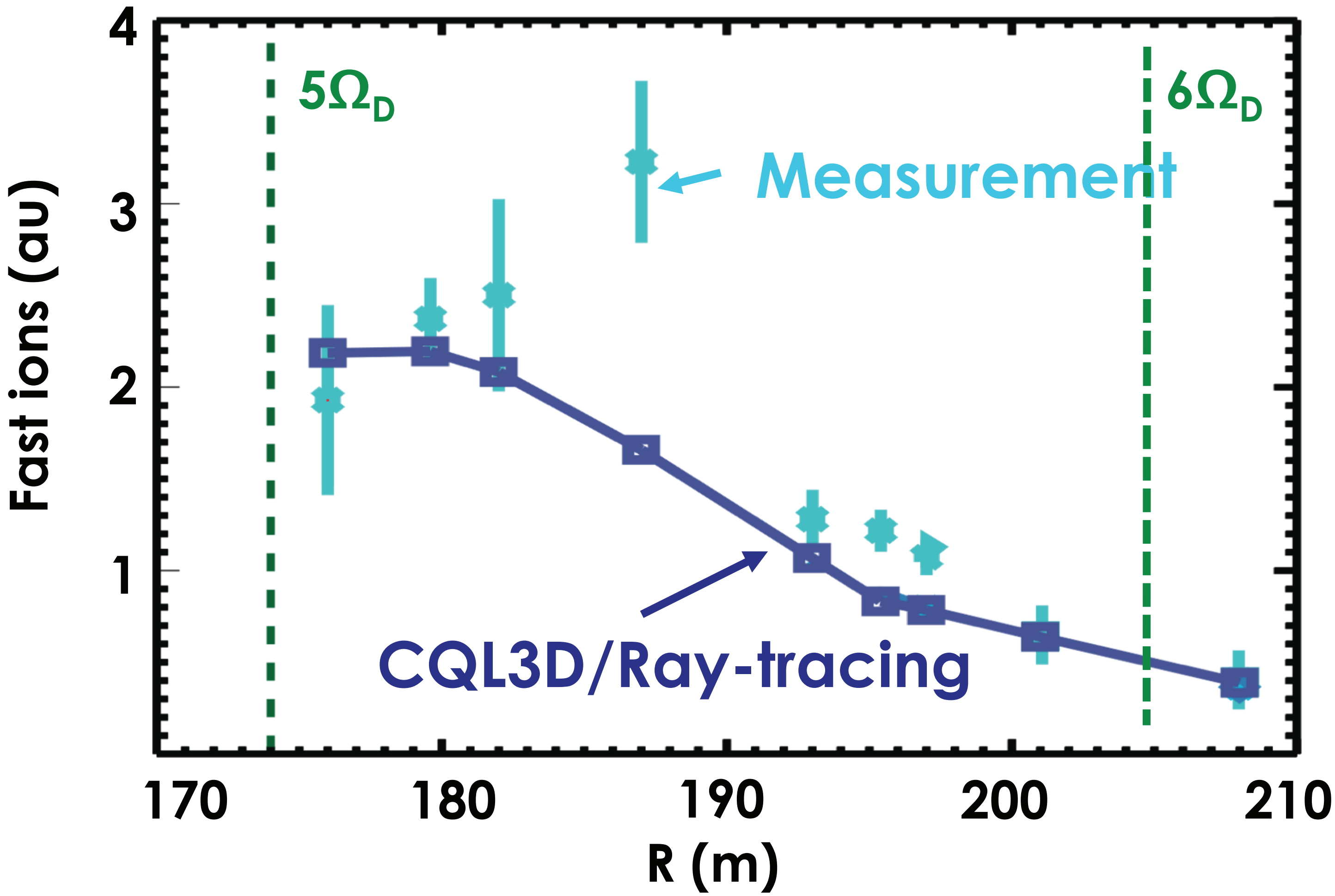

- CQL3D predicts peak near magnetic axis

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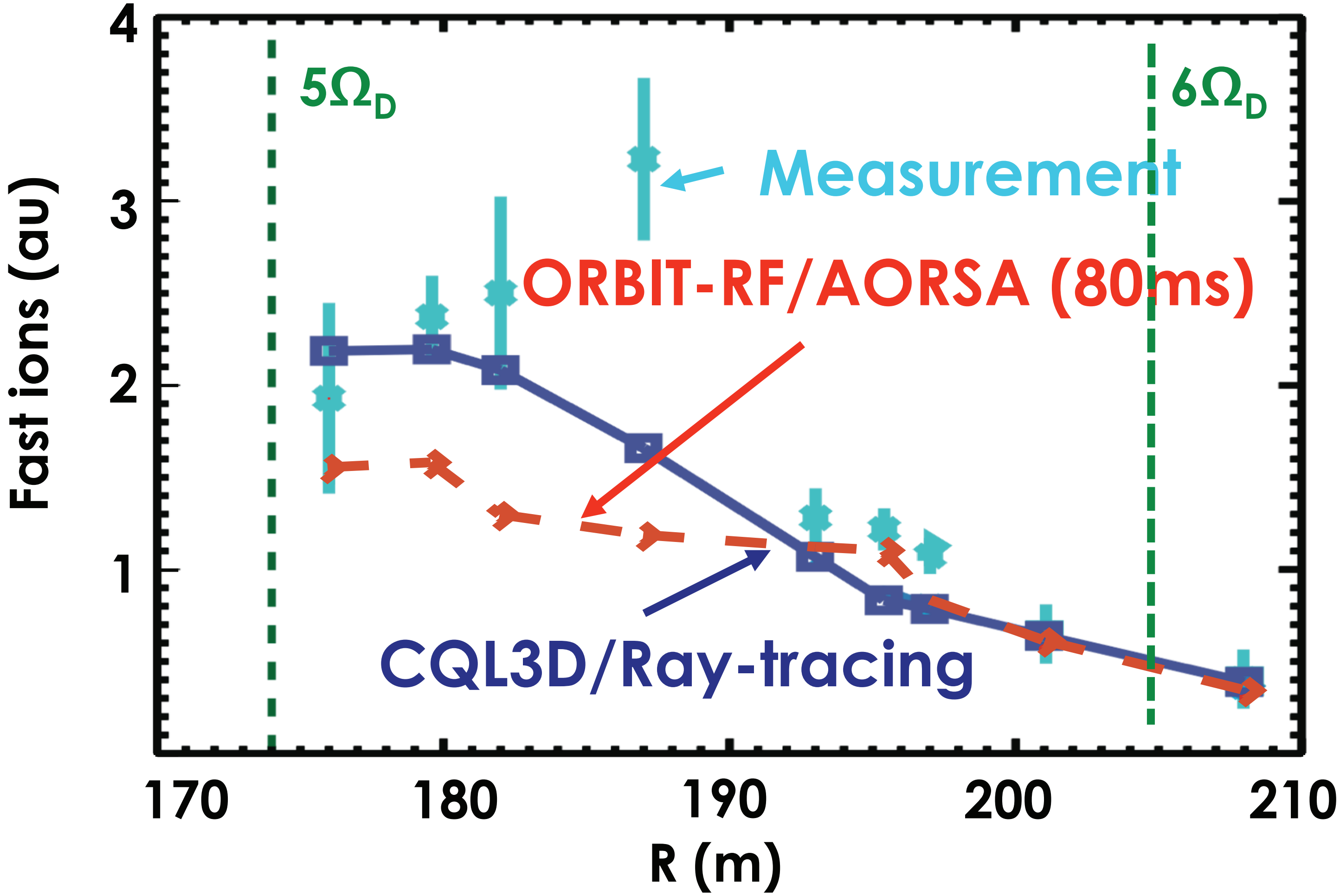

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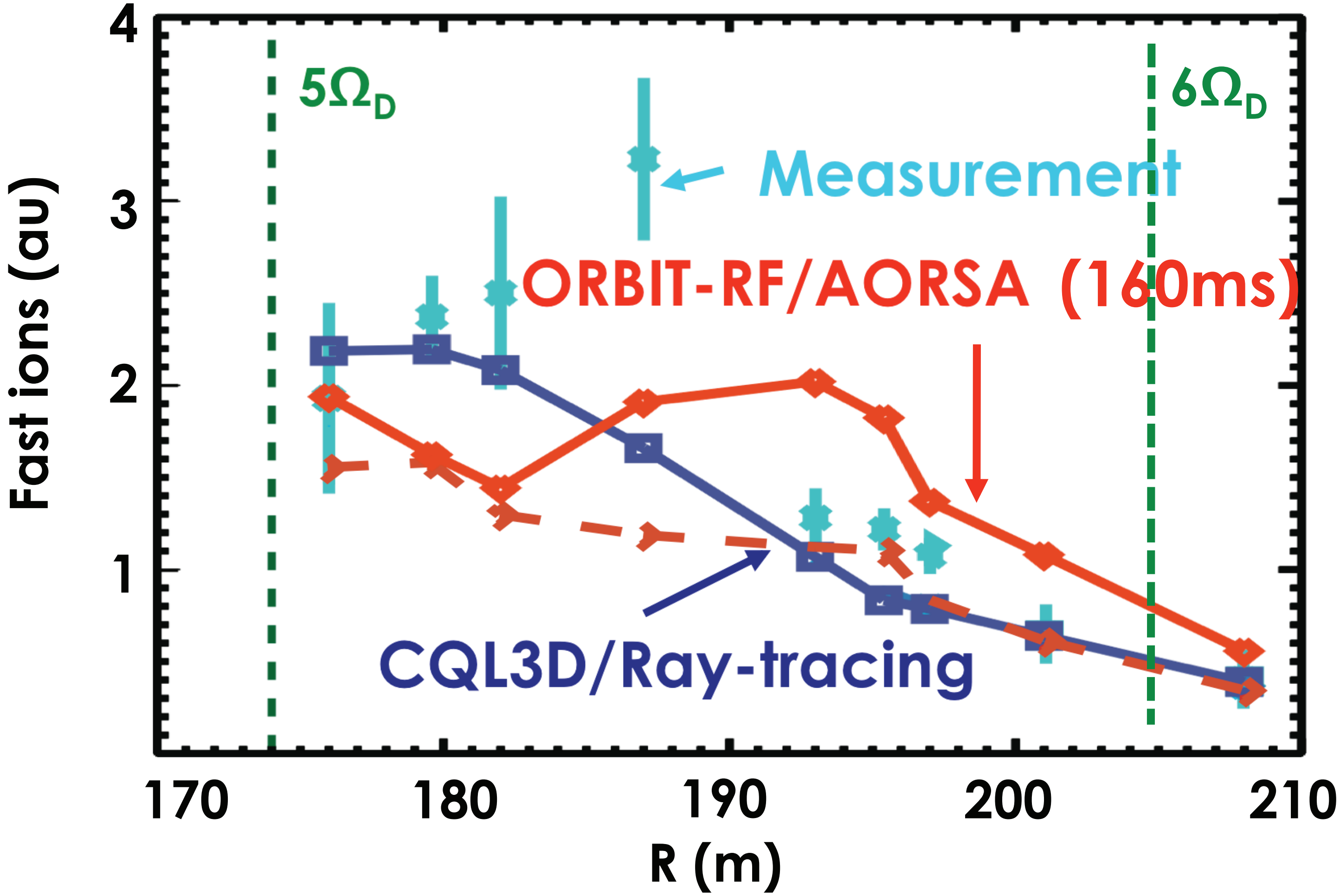
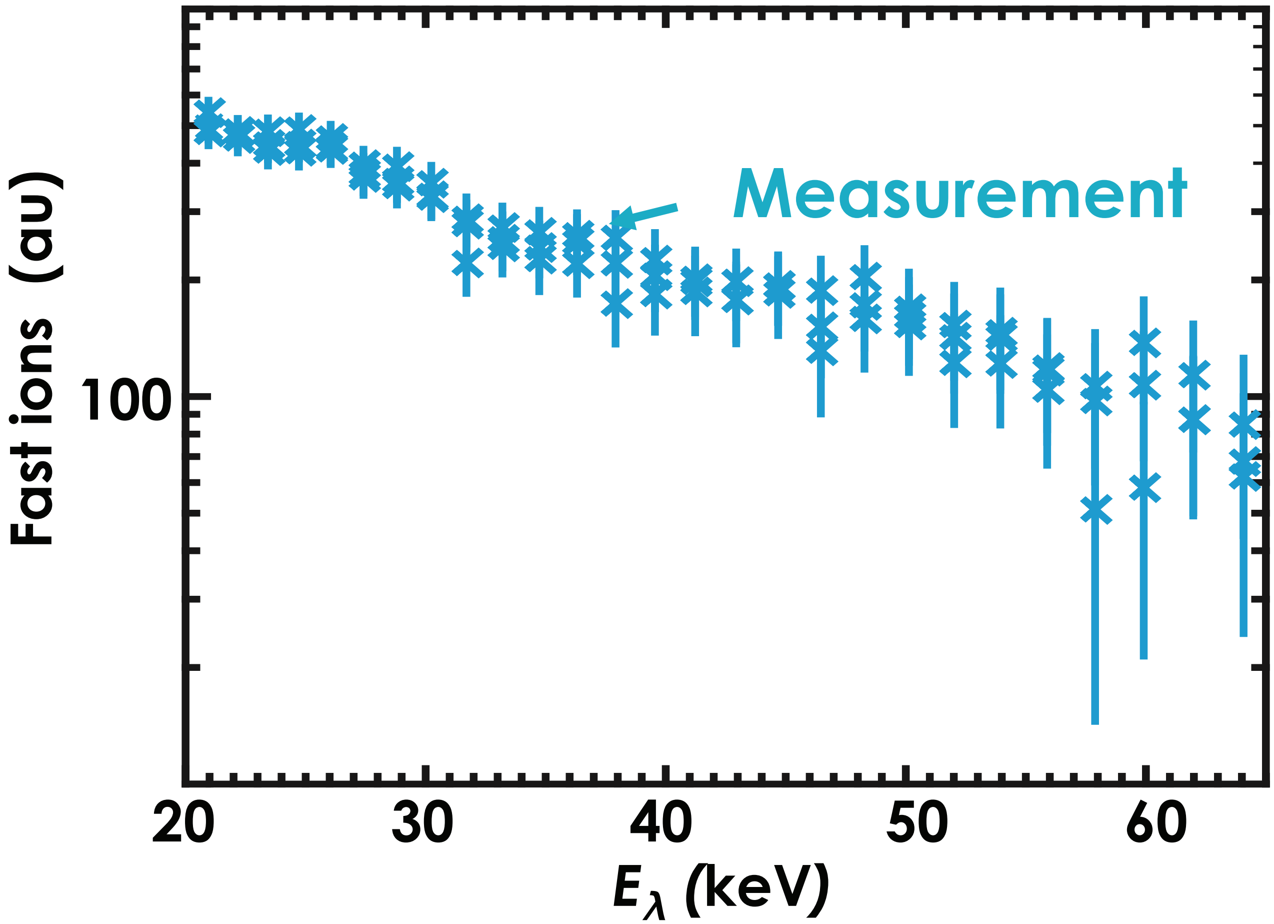


- CQL3D predicts peak near magnetic axis
- Neutron rate reaches stationary ~200 ms
- Iterations important

Preliminary NSTX Simulations Predict Similar Tail Spectra to Measurement

- **NSTX 128739 : P_{RF}=1.0MW, f=30MHz**



See Liu
PP8.00076
Wednesday

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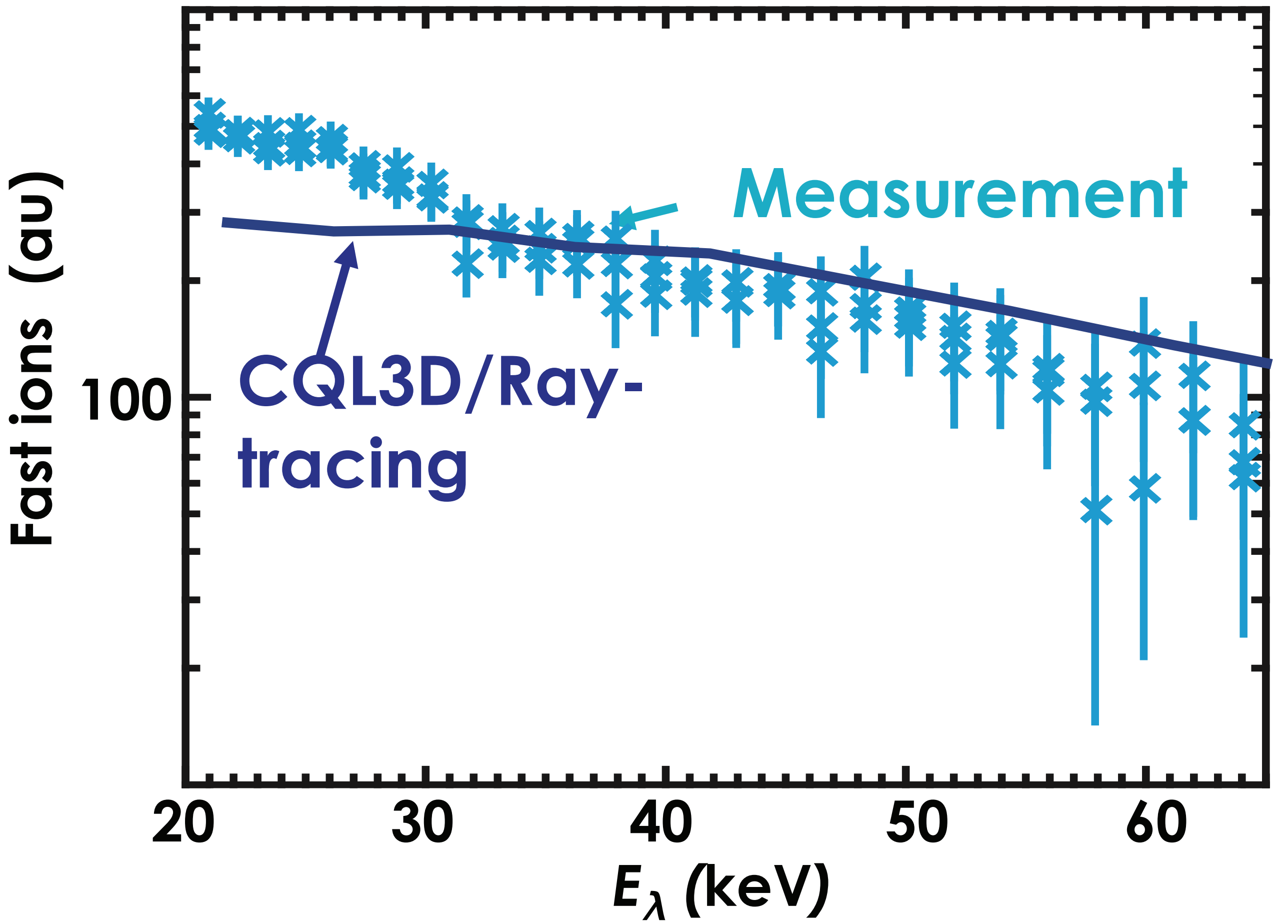

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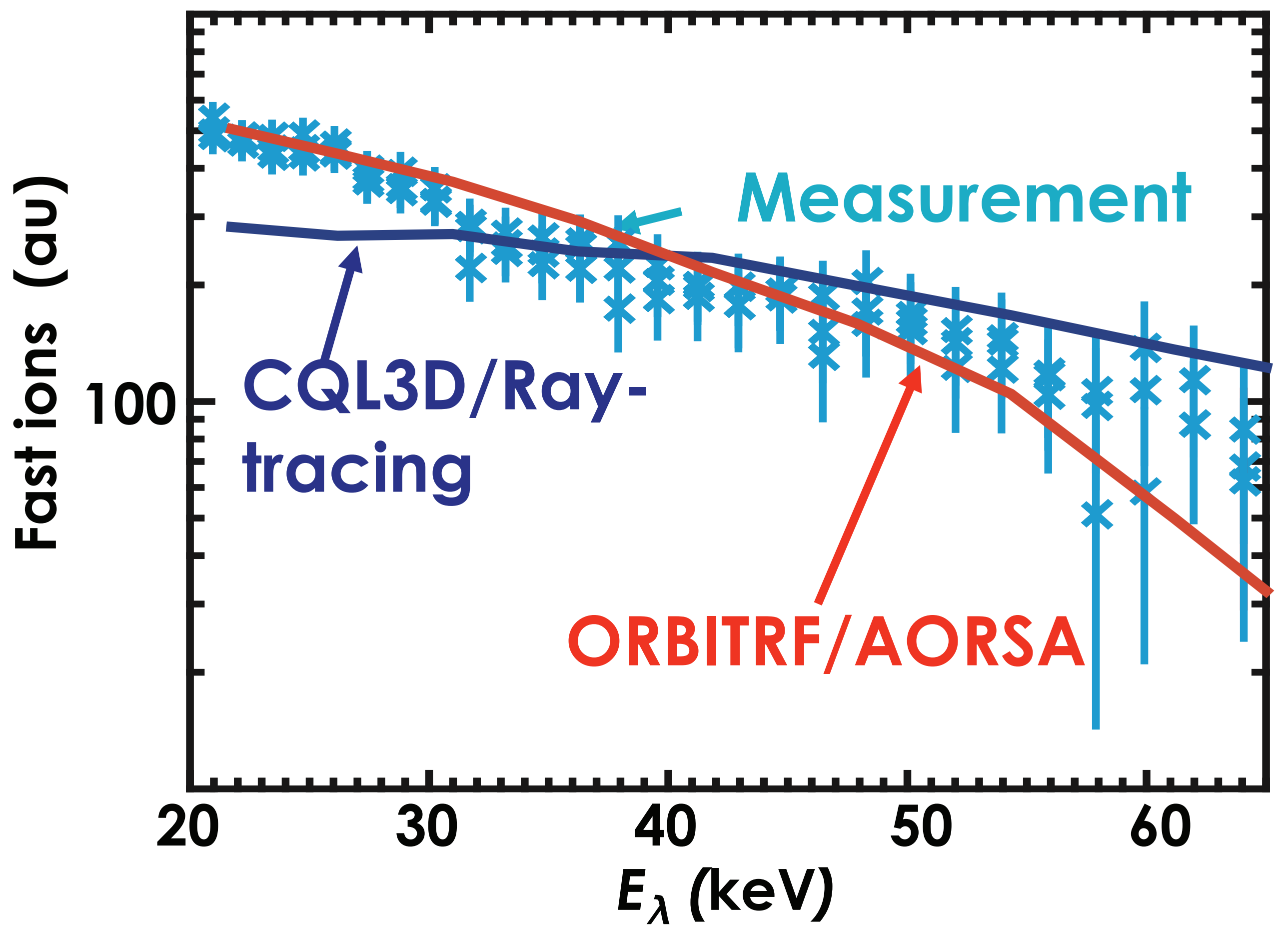

- ORBIT-RF/ AORSA 0th iteration
- Neutron enhancement

ORBIT-RF ~1.8
Exp. ~2.5

See Liu PP8.00076 Wednesday

Preliminary NSTX ORBIT-RF/AORSA Simulations Predict Outward Spatial Shift of Fast Ions

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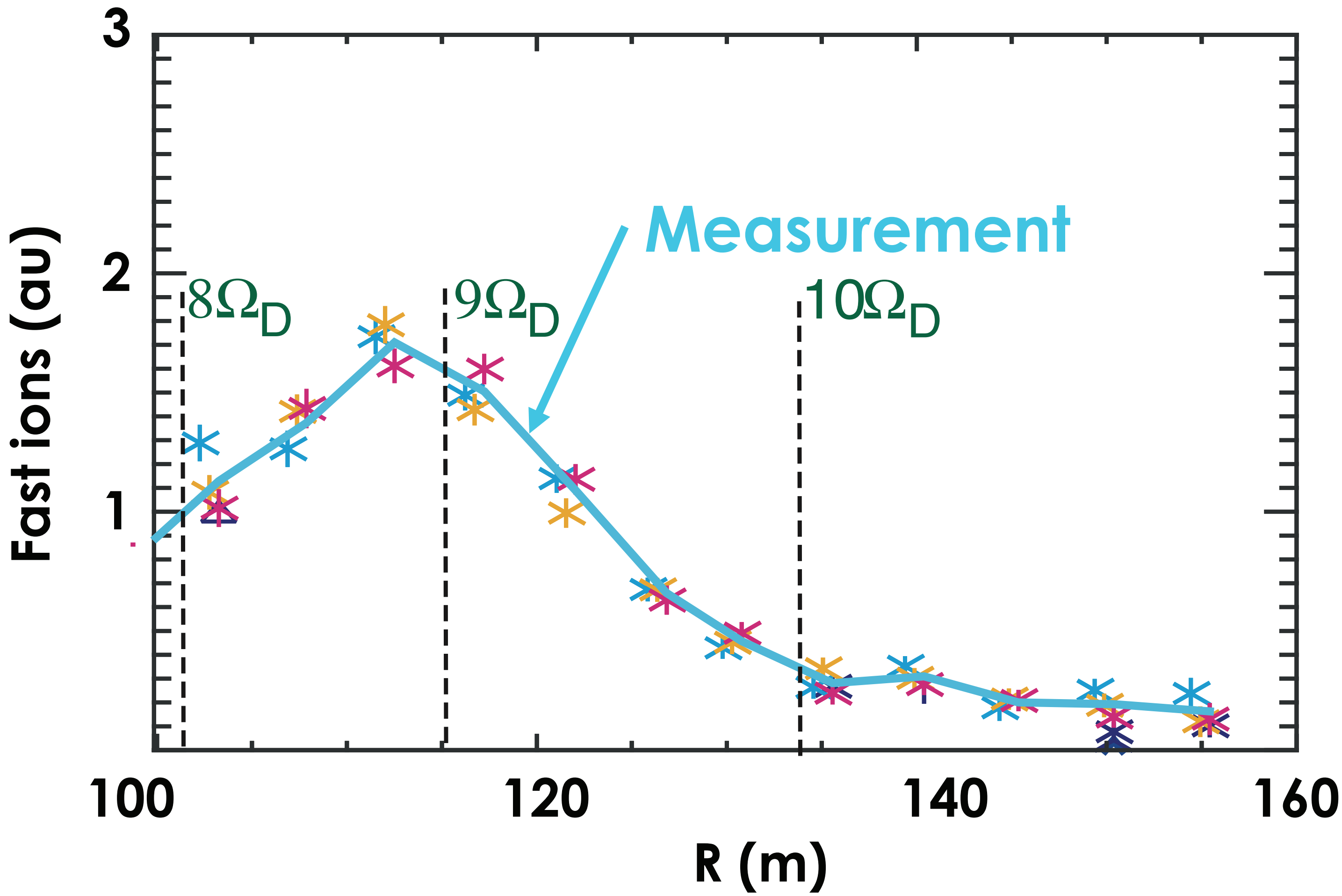

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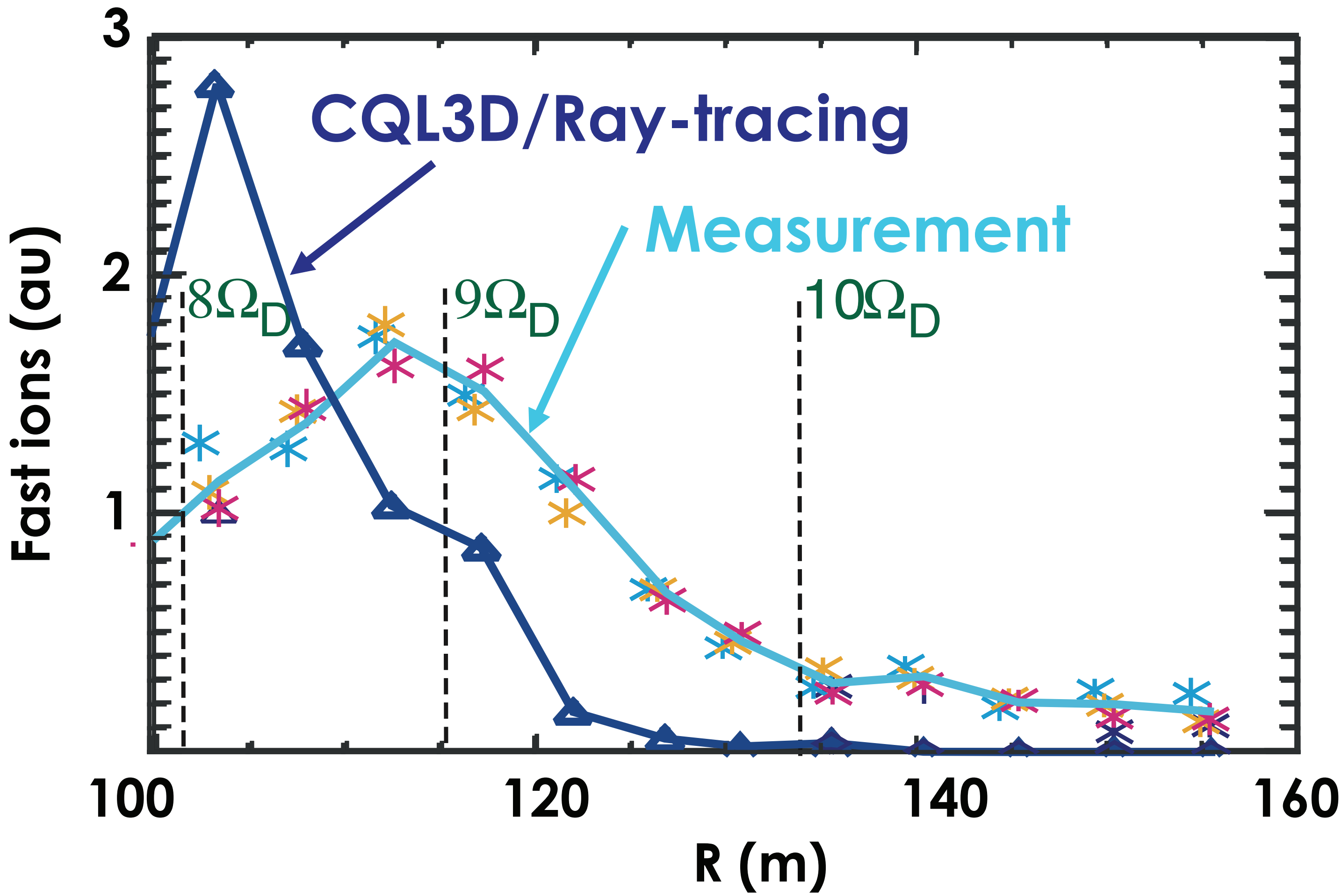

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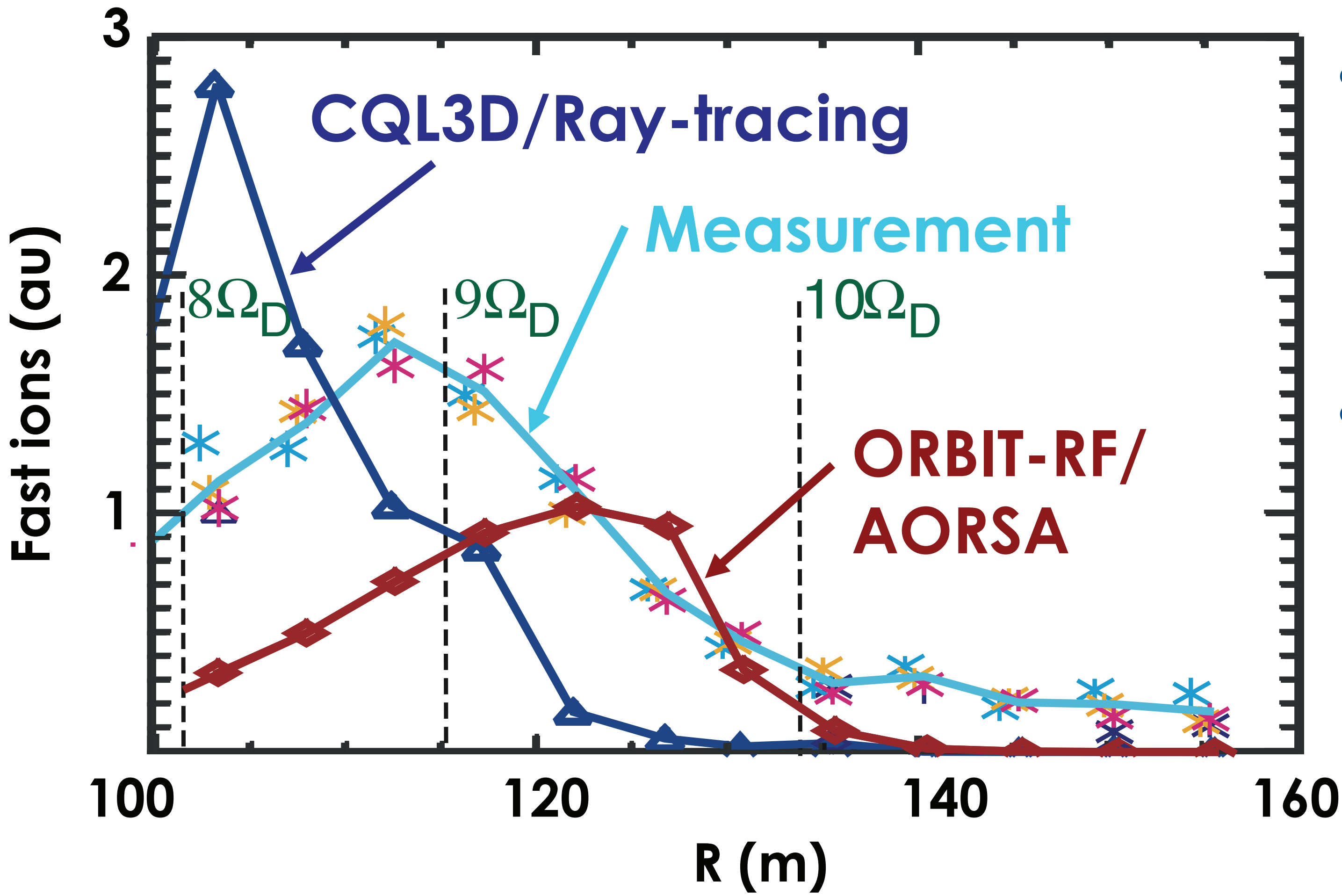

- ORBIT-RF/ AORSA 0th iteration
- More iteration required

Summary and Future Direction

- **Non-zero drift orbit effect and iteration between fast-ion distribution and wave field are important**
- **ORBIT-RF/AORSA qualitatively reproduces fast ion measurements**
  - neutron enhancement compatible with neutron detector
  - Spectra consistent with FIDA
  - Outward radial shifts with FIDA
- **Near future plan**
  - Sensitivity and convergence study
  - Comparison of CQL3D with finite orbit correction
  - Further development of synthetic diagnostics to facilitate theory-experiment comparison