

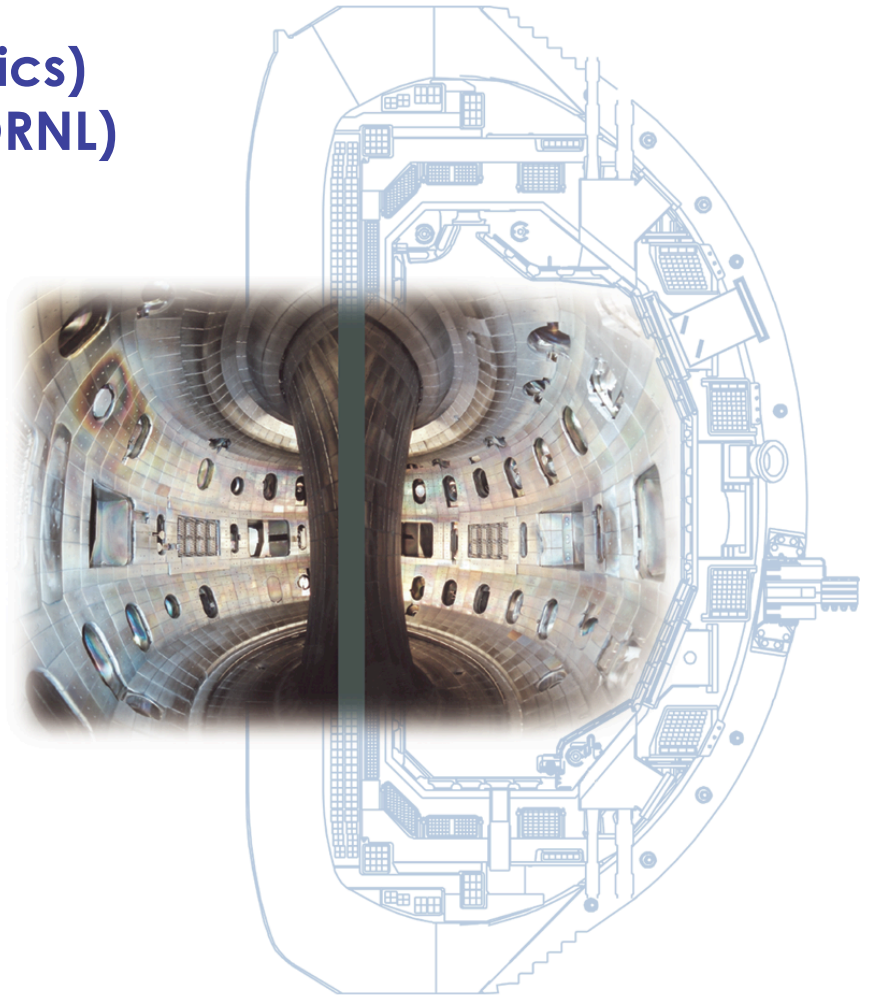
# Ion Finite Drift Orbit Effect on Quasi Linear ICRH Modeling Using Monte Carlo Particle Solver

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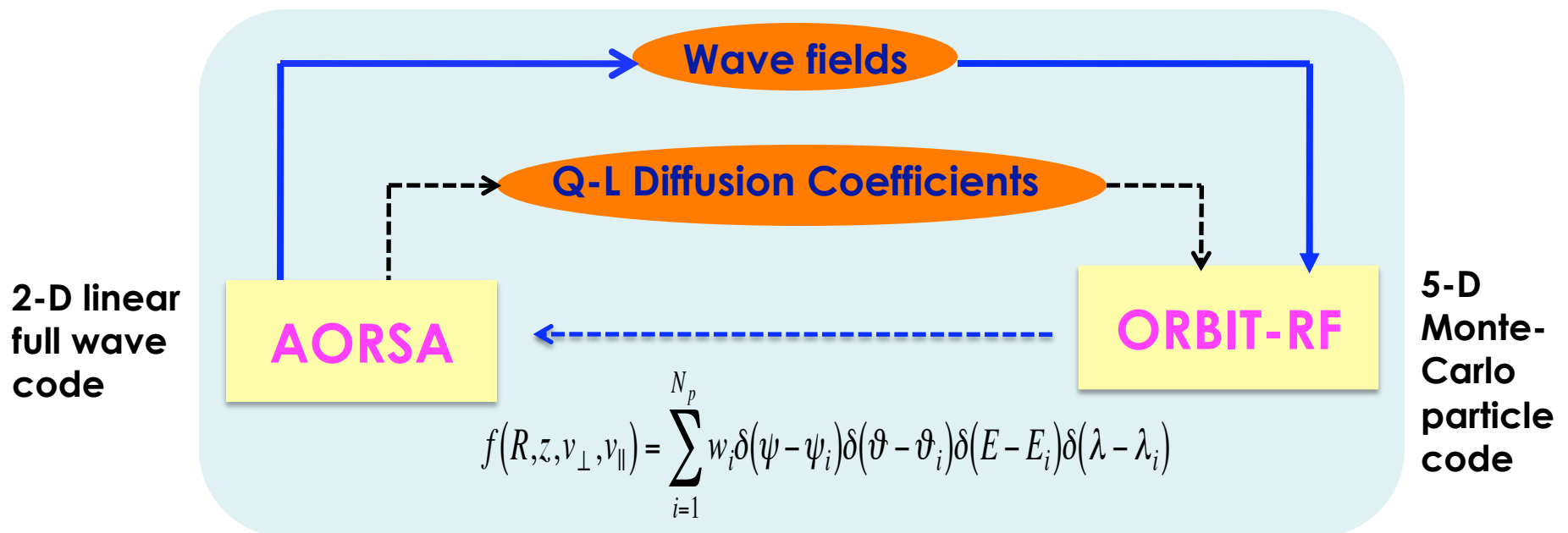
Dallas, TX, USA

November 17-21, 2008



# Self-Consistent Calculation Between Wave and Plasma Distribution Solver Is Required in ICRH Modeling

- Previous work on the coupling of **AORSA** and **CQL3D**
  - no finite orbit effect (Jaeger, Berry and Harvey)
- New attempt to couple **ORBIT-RF** and **AORSA**
  - Finite orbit effect



Need to create a differentiable (smooth), bounce-averaged distribution function from Monte-Carlo particle list (D. Green in ORNL)

# Can Local ICRF Wave Power Absorption From Particle Following Solver Reproduce Full Wave Prediction ?

- ICRH physics is modeled with quasi-linear diffusion theory

**AORSA** E. F. Jaeger, Phys. Plasma  
13, 056101 (2006)

$$P_{\text{abs}} = \frac{1}{2} \text{Re} \left( \frac{e_0 w}{i} \sum_{\mathbf{k}_1, \mathbf{k}_2} e^{i(\mathbf{k}_1 - \mathbf{k}_2) \cdot \mathbf{r}} \mathbf{E}_{\mathbf{k}_2}^* \cdot \mathbf{W}_l \cdot \mathbf{E}_{\mathbf{k}_1} \right)$$

$$\mathbf{W}_l = 2\pi \frac{\omega_p^2}{\omega^2} \sum_{l=-\infty}^{\infty} e^{il(\beta_1 - \beta_2)} C^{-1}(\beta_2) \cdot$$

$$\left( \int_{-\infty}^{\infty} \frac{du_{\parallel}}{1 - \frac{n_{\parallel} u_{\parallel}}{\sqrt{u}} - \frac{l\Omega}{\omega}} \int_0^{\infty} du_{\perp} US' \right) \cdot C(\beta_1)$$

- Diffusion in  $\mathbf{v}_{\perp}$  and  $\mathbf{v}_{\parallel}$

**ORBIT-RF** S.C. Chiu, Phys. Plasma  
7 (2000)

$$P_{\text{abs}} = \sum_{\text{particles}} \left[ \Delta\mu_{\text{rf}} + R_s \sqrt{\langle \overline{\Delta\mu_{\text{rf}}^2} \rangle} \right]$$

$$\Delta\mu_{\text{rf}} = \frac{1}{4} \frac{\pi q^2 l^2 \Omega^2}{m \omega^2 B_0} K |E_+|^2 \times \left[ \left| J_{l-1} + e^{2i\theta_k} \frac{E_-}{E_+} J_{l+1} \right|^2 + \right.$$

$$\left. \mu \left\{ 2 \left( J_{l-1} + e^{2i\theta_k} \frac{E_-}{E_+} J_{l+1} \right) \left( \frac{\partial J_{l-1}}{\partial \mu} + e^{2i\theta_k} \frac{E_-}{E_+} \frac{\partial J_{l+1}}{\partial \mu} \right) \right\} \right] \delta(w_l)$$

- $K$  (resonant interaction time) with orbit topology
- Diffusion in  $\mathbf{v}_{\perp}$

# Outline

“Model problems” set-up to benchmark quasi-linear ICRH modeling in existing ICRF wave heating experiments in C-Mod and DIII-D tokamaks

Local ICRF wave power absorption from particle following solver agrees qualitatively with full wave prediction in a linear regime for “model problems”

Finite drift orbit effect of energetic particles is important in high harmonic ICRH modeling

- Edge loss
- Wave damping near axis

# “Model Problem” Is Set Up To Validate Quasi Linear ICRH Modeling of ORBIT-RF Against AORSA

- **Same background plasma profile and EQDSK**
  - Analytically fitted profile
- **A single  $k_{\parallel} = N_{\phi}/R$**  (ignoring upshift of  $k_{\parallel}$ )
- **Maxwellian energy distribution** of resonant ion species

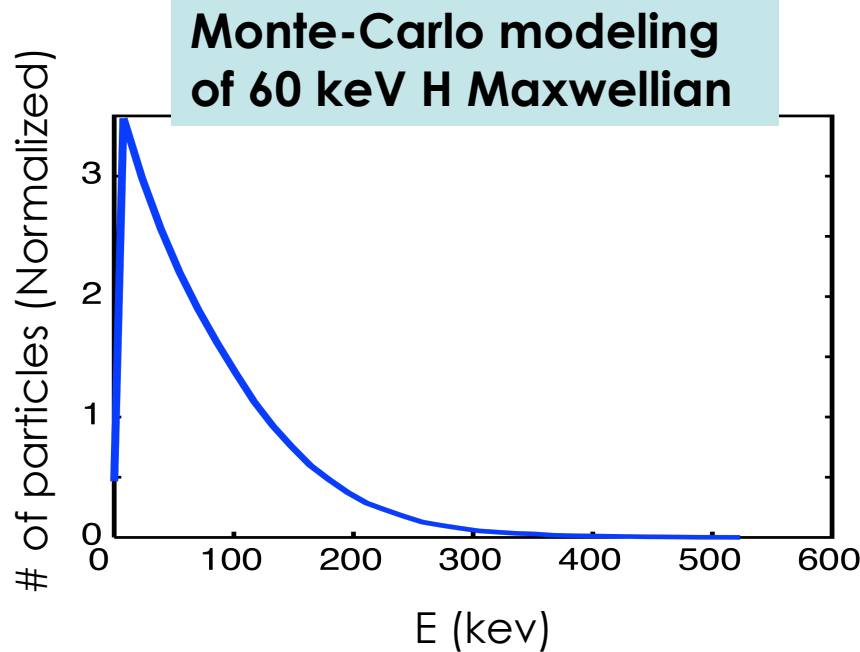
## Modeling in ORBIT-RF

- **Test particles not updated in energy and pitch**
- **Random RF diffusion off**
- **Coulomb collision off**
- **$k_{\perp}$  from cold plasma dispersion relation**

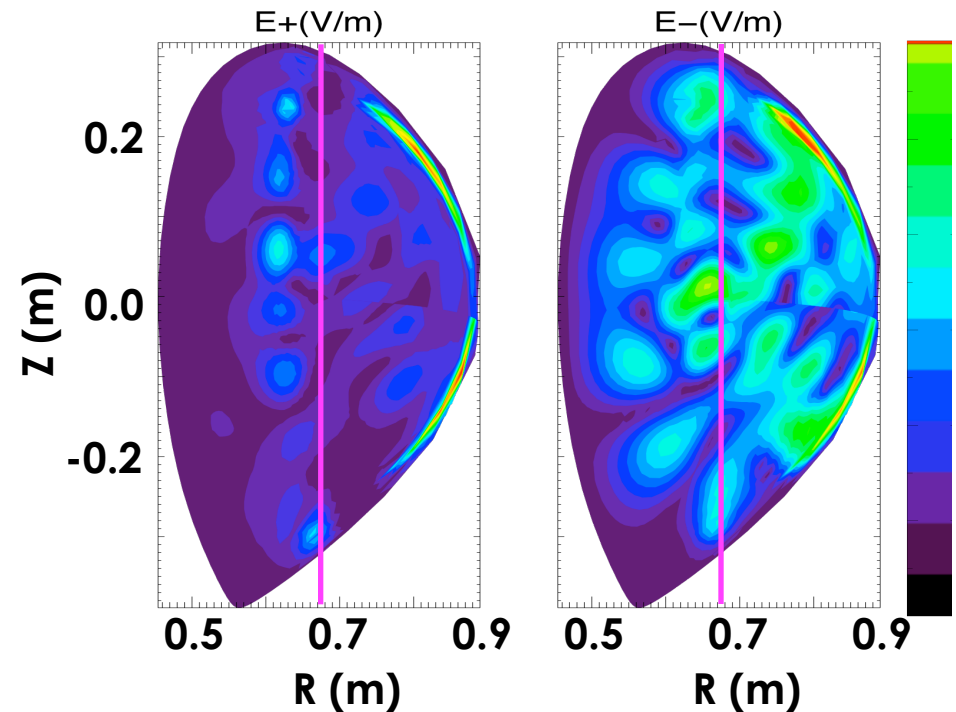
- **$k_{\perp} = k_x \rightarrow e^{2i\theta_k} = 1$  in  $\Delta u_{rf} = \dots \left[ \left| J_{l-1} + e^{2i\theta_k} \frac{E_-}{E_+} J_{l+1} \right|^2 \dots \right]$**
- **Single pass of each particle**

# Inputs for C-Mod ICRF Fundamental Harmonic Heating Experiment “Model Problem”

- C-Mod 11051206002 at 1120 ms
- 8% Hydrogen minority
- Hydrogen **Maxwellian** distribution
- $n_e(0) = 1.28 \times 10^{13} \text{ cm}^{-3}$   
 $T_e(0) = 2.6 \text{ keV}, T_D(0) = 2.0 \text{ keV}$
- $P_{\text{ICRF}} = 0.6 \text{ MW}$
- $N_\varphi = 10$
- $f = 80 \text{ MHz}$
- $k_\perp = 50 \text{ cm}^{-1}$

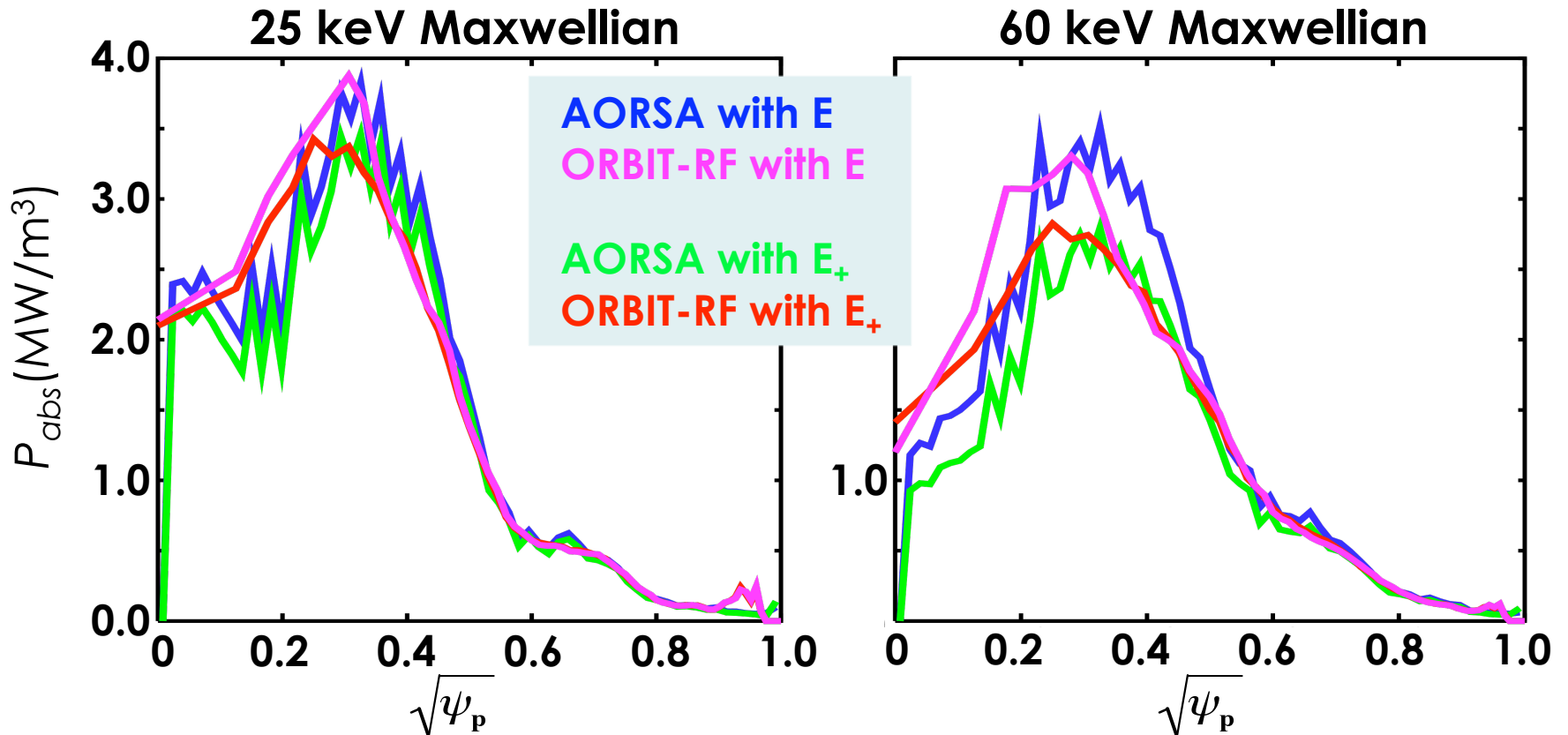


## AORSA wave fields for 60 keV



# Quantitative Agreements Are Found in ICRF Hydrogen Minority Maxwellian Heating at Fundamental Harmonic

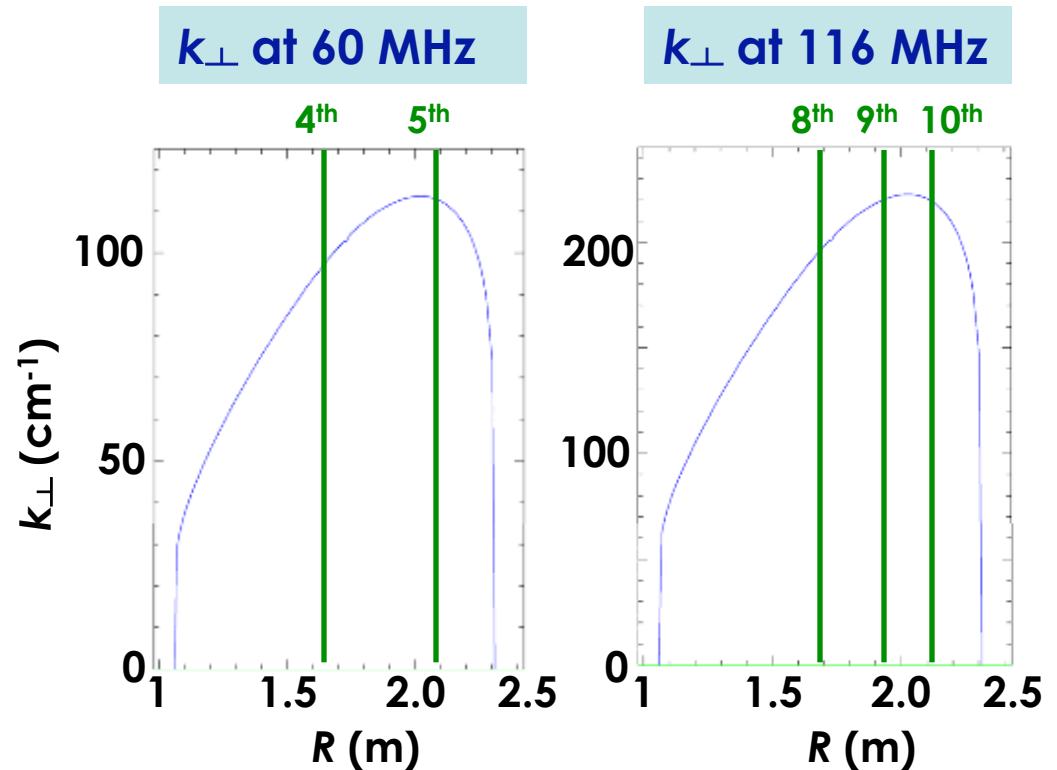
- C-Mod 11051206002



- E<sub>+</sub> effect on  $P_{abs}$  is minor at fundamental harmonic regime due to small  $J_2$

# Inputs for DIII-D ICRF Moderate To High Harmonic Heating Experiment “Model Problem”

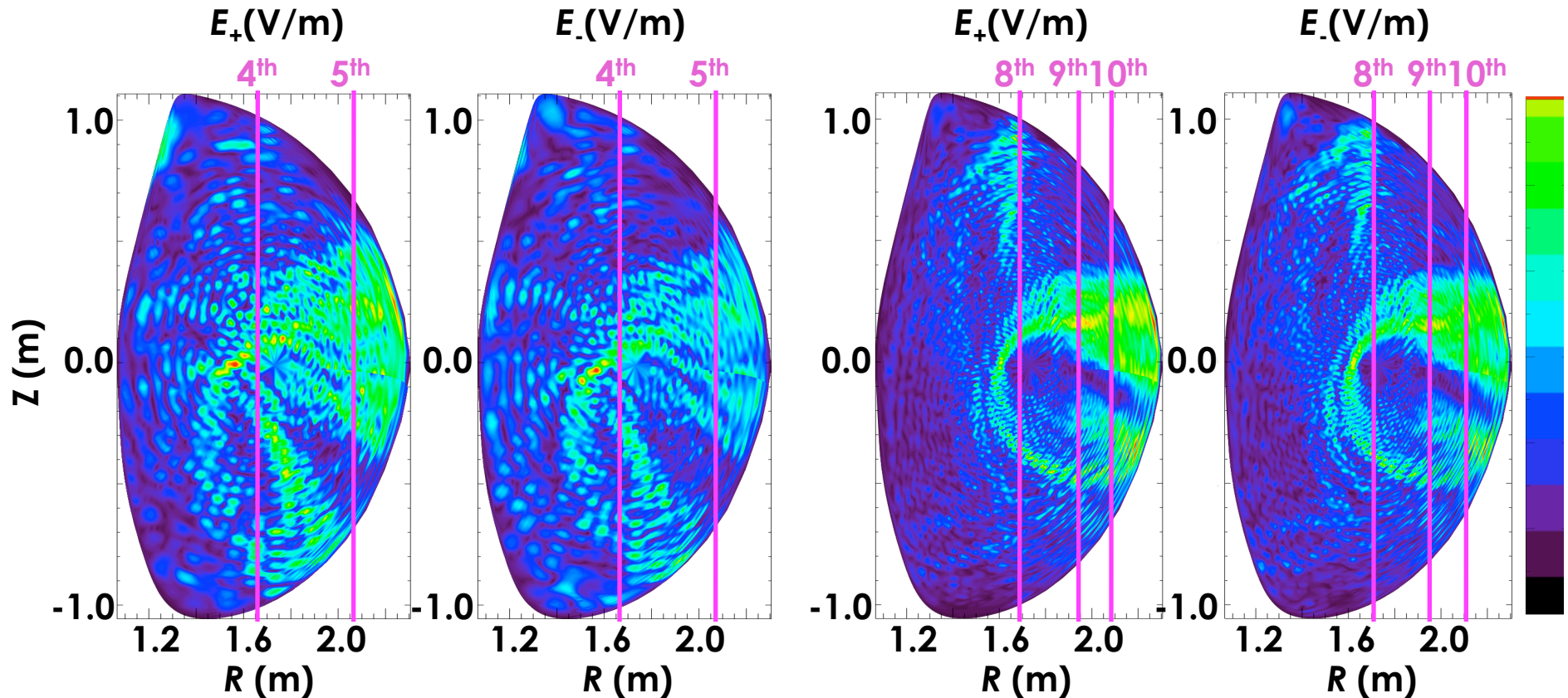
- **DIII-D 122080 at 3100 ms**
- $n_e(0) = 6.7 \times 10^{13} \text{ cm}^{-3}$ ,  $T_e(0) = 1.9 \text{ keV}$ ,  $T_D(0) = 2.2 \text{ keV}$
- $n_{\text{Beam}}(0) = 0.28 \times 10^{13} \text{ cm}^{-3}$
- **Maxwellian** Deuterium beam distribution (25 keV and 60 keV)
  - No spatial profile
  - Spatial profile
- $P_{\text{ICRF}} = 1.1 \text{ MW}$
- $N_\varphi = 13$
- $f = 60 \text{ MHz}$ 
  - **4<sup>th</sup>** at  $R = 164 \text{ cm}$
  - **5<sup>th</sup>** at  $R = 204 \text{ cm}$
- $f = 116 \text{ MHz}$ 
  - **8<sup>th</sup>** at  $R = 170 \text{ cm}$
  - **9<sup>th</sup>** at  $R = 191 \text{ cm}$
  - **10<sup>th</sup>** at  $R = 210 \text{ cm}$



# AORSA Calculates Comparable Wave Field Magnitudes Between $E_+$ and $E_-$ Components

60 MHz, 60keV Beam

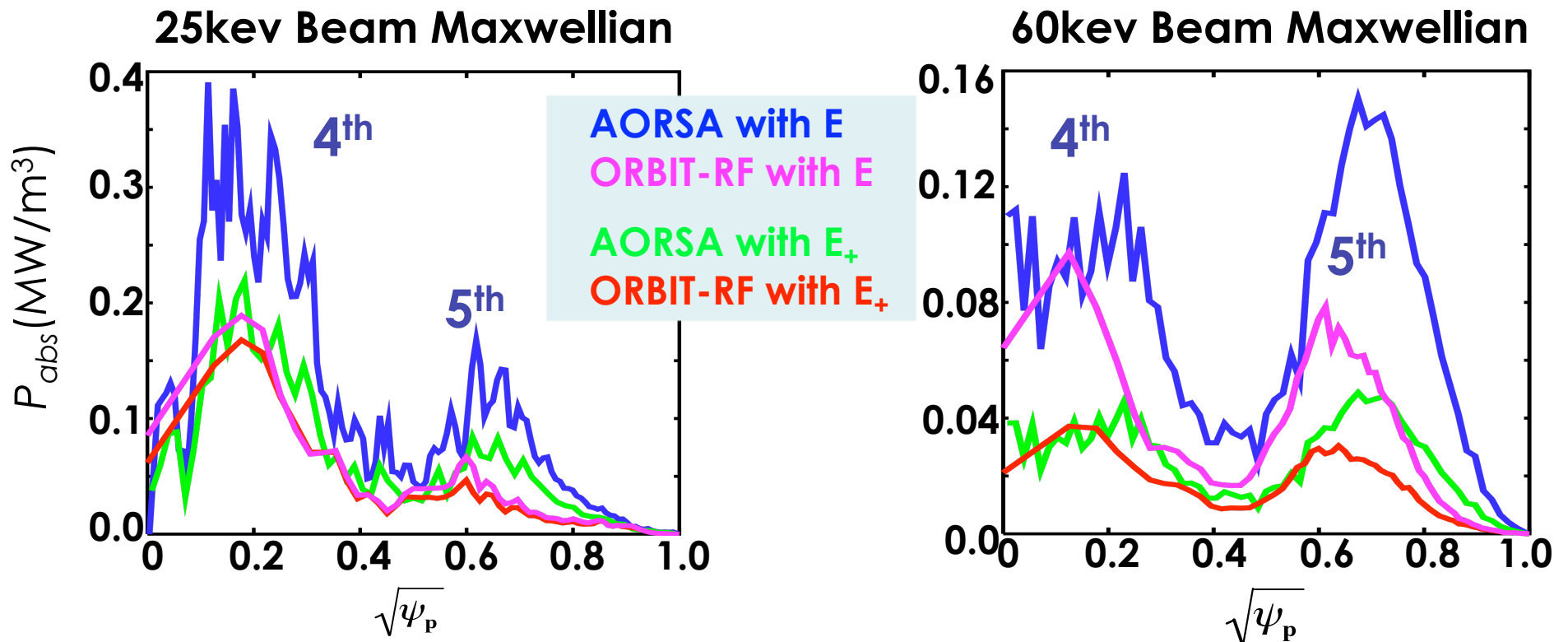
116 MHz, 60keV Beam



- $E_-$  effect on  $P_{\text{abs}}$  becomes significant at high  $n$  due to large  $J_{\text{high } n}$

# Better Agreements Are Found With $E_+$ Wave Fields

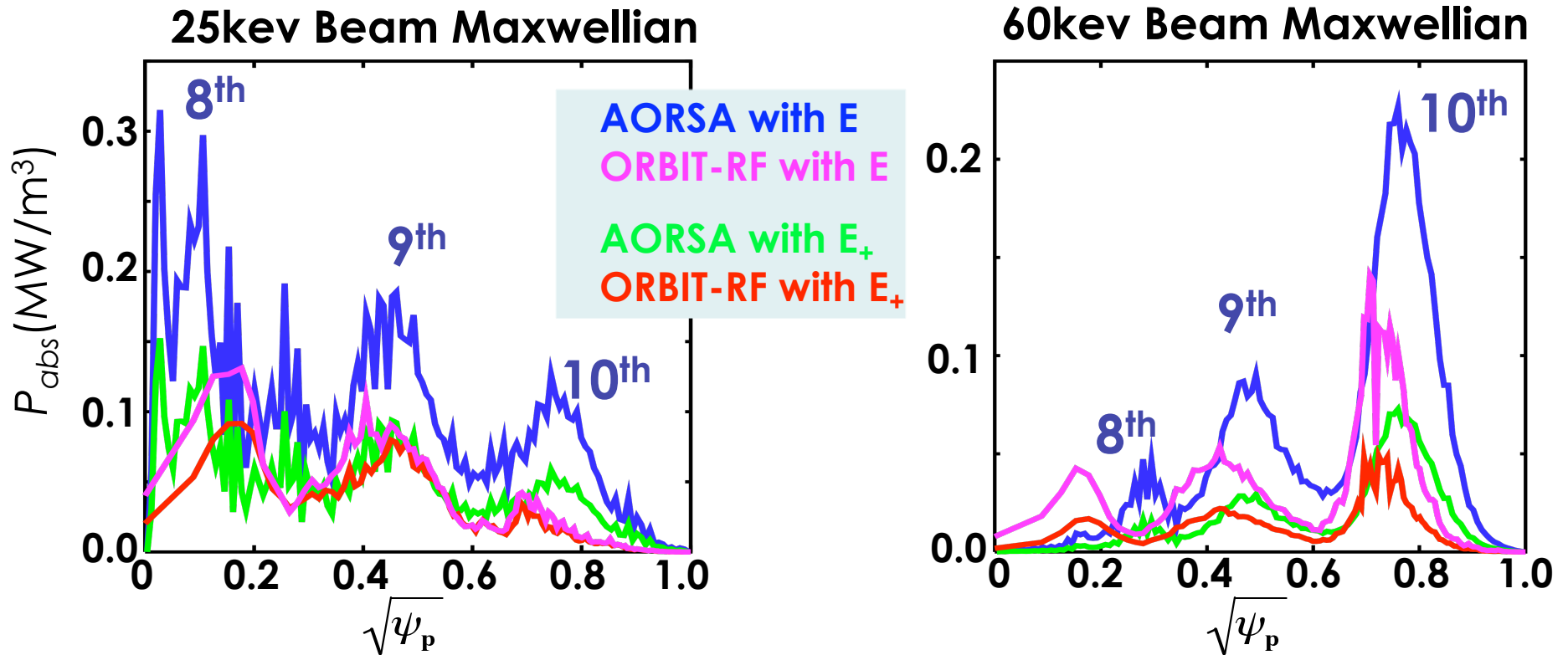
- No spatial beam profile



- Cold plasma approximation in  $k_{\perp}$  with  $k_{\perp}=k_x$  in ORBIT-RF
- No finite orbit effect in AORSA

# Finite Orbit Effect Becomes More Significant Near Magnetic Axis and Edge In 60 KeV Beam Heating Case

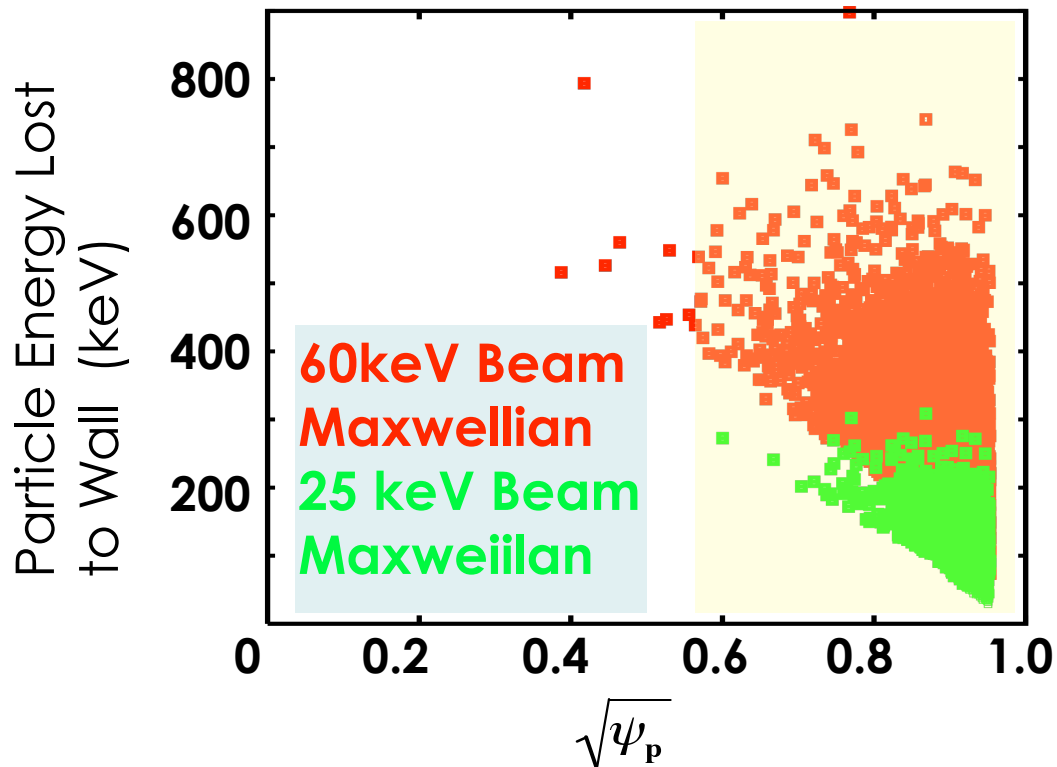
- No spatial beam profile



- Losses of energetic ions near edge are significant
- Banana orbits of highly energetic ions in 60 keV Maxwellian broaden resonance

# Loss of Energetic Particles Near Edge Due to Finite Orbit Is Significant In 60 keV Case

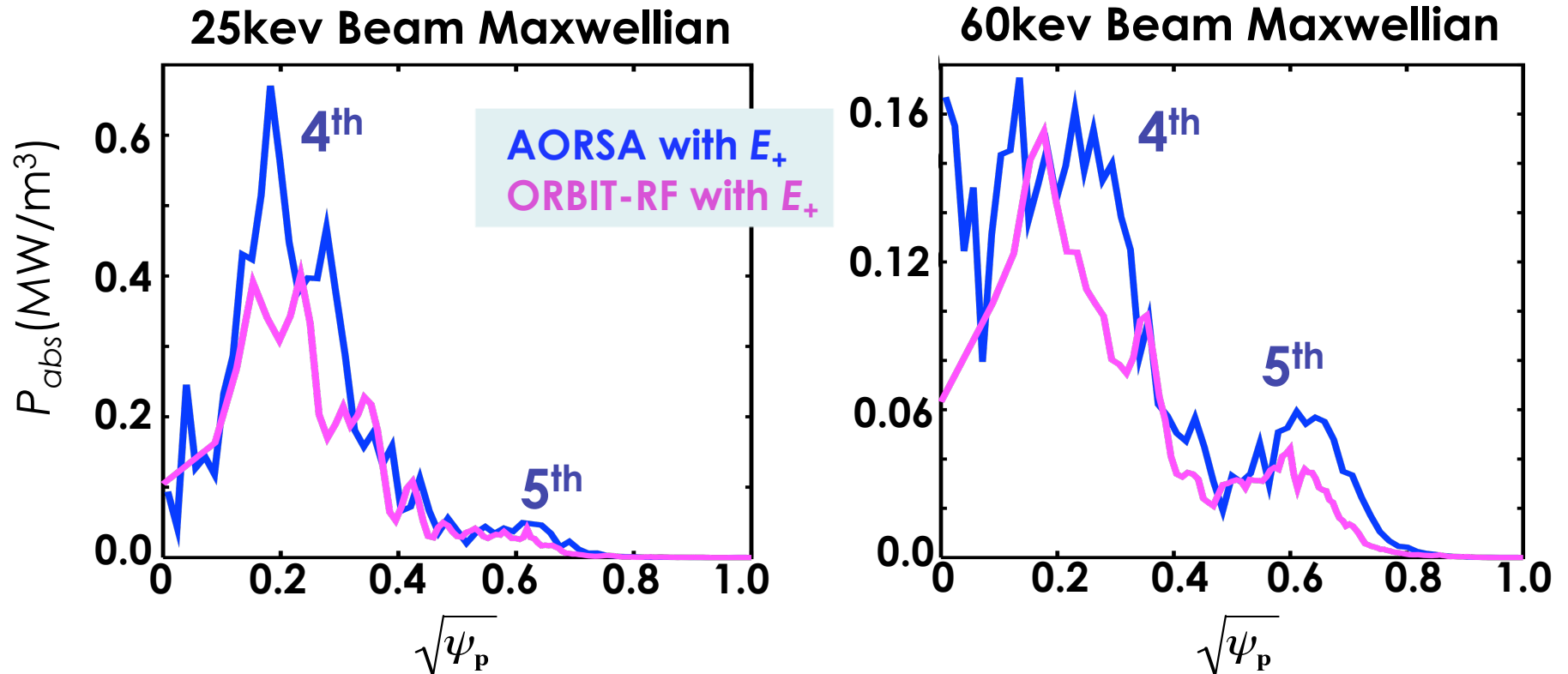
- No spatial beam temperature profile



- Edge particle loss is important in ORBIT-RF
- AORSA assumes Maxwellian without loss cone

# Less Energetic Particles Due To Spatial Beam Profile Produce Better Agreements Near The Edge

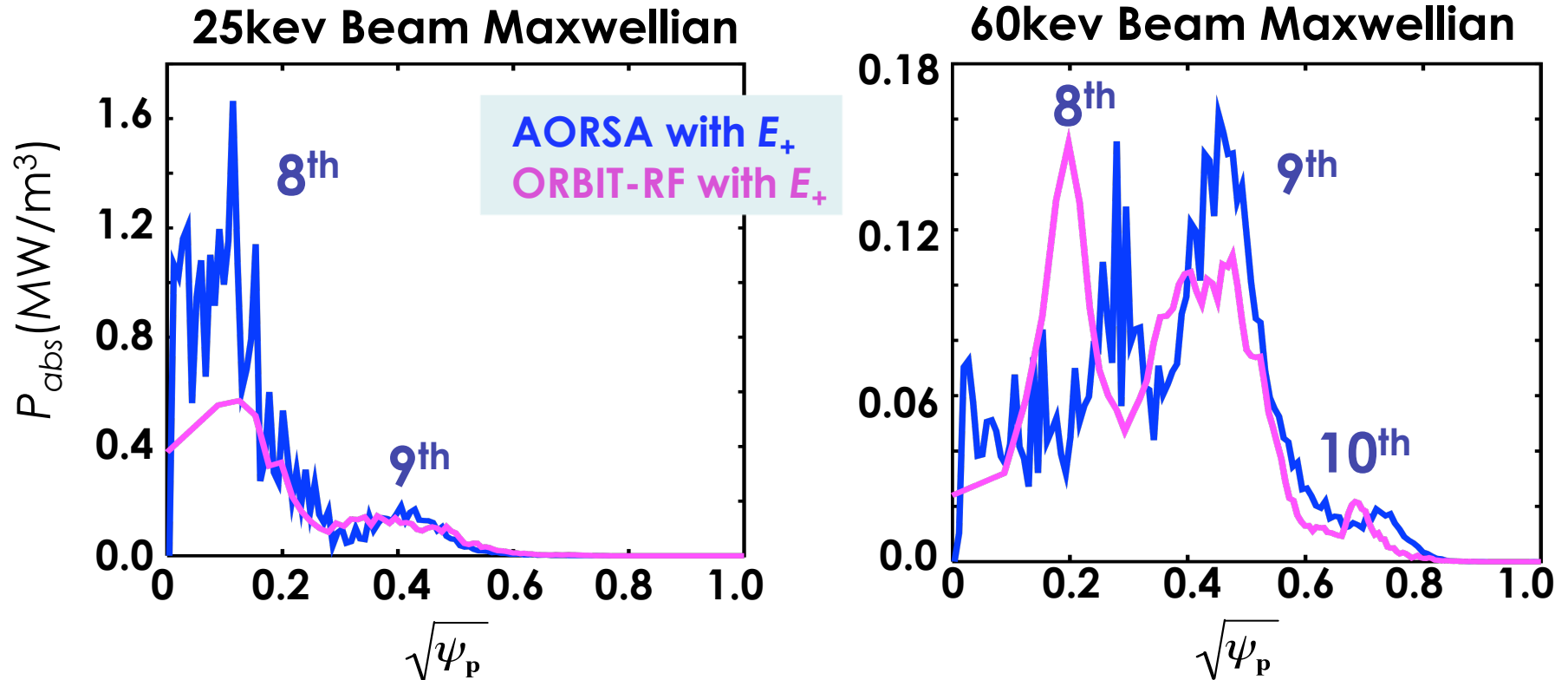
- Spatial beam temperature profile



- Cold plasma approximation in  $k_{\perp}$  in ORBIT-RF
- No finite orbit effect in AORSA

# Finite Orbit Effect Is More Significant Near At Magnetic Axis In 60 KeV Beam Heating Case

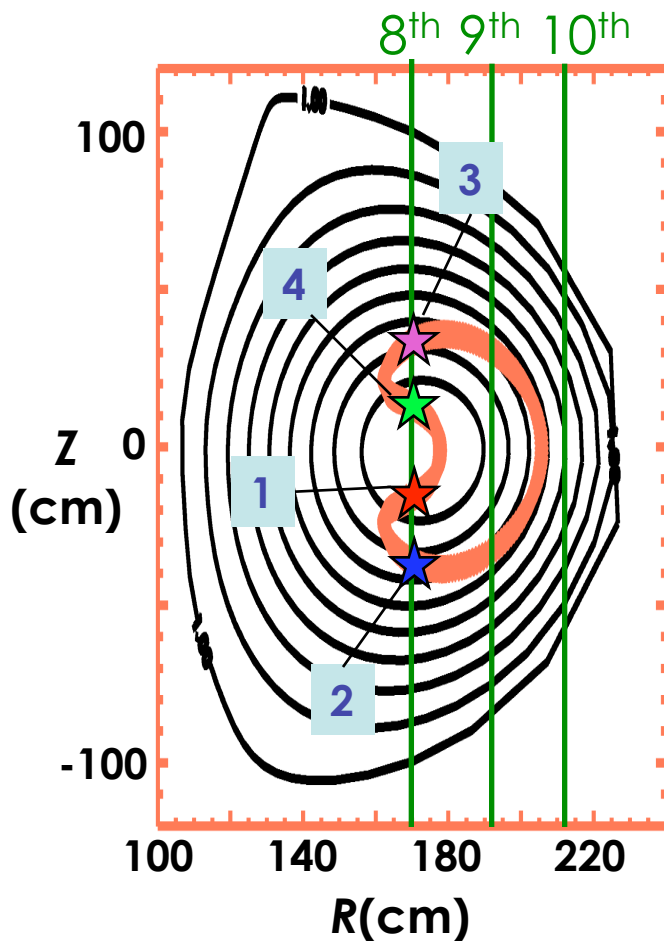
- Spatial beam temperature profile



- Peak of resonance surface at 8<sup>th</sup> is shifted to on-axis in 60 KeV case

# Banana Orbit of Highly Energetic Ion Passing Through Resonance Produces Wave Damping Near At Axis

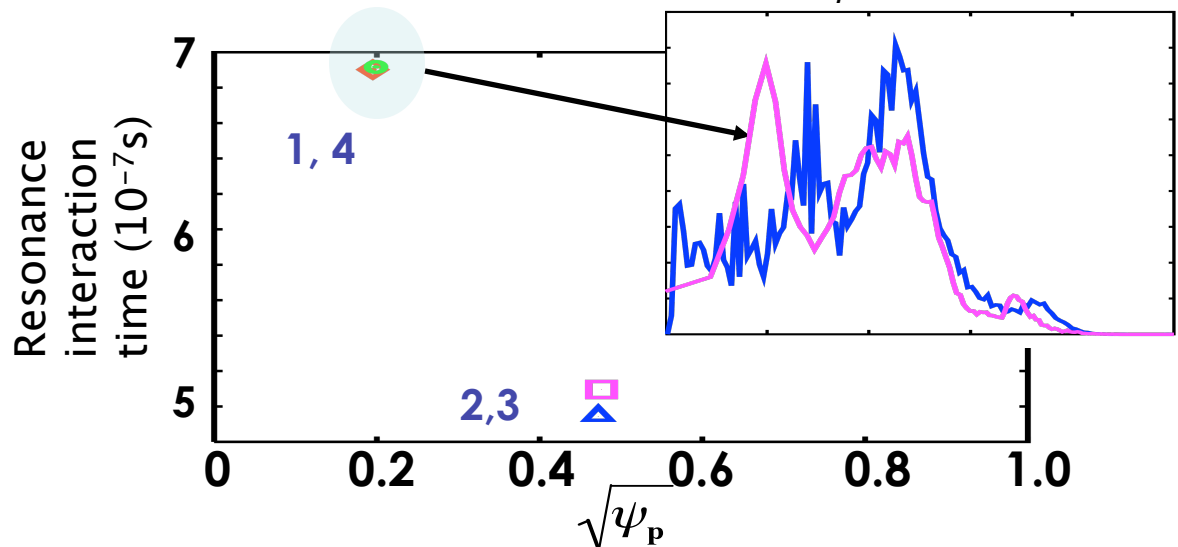
## Orbit of 206 keV ion



- Resonant interaction time

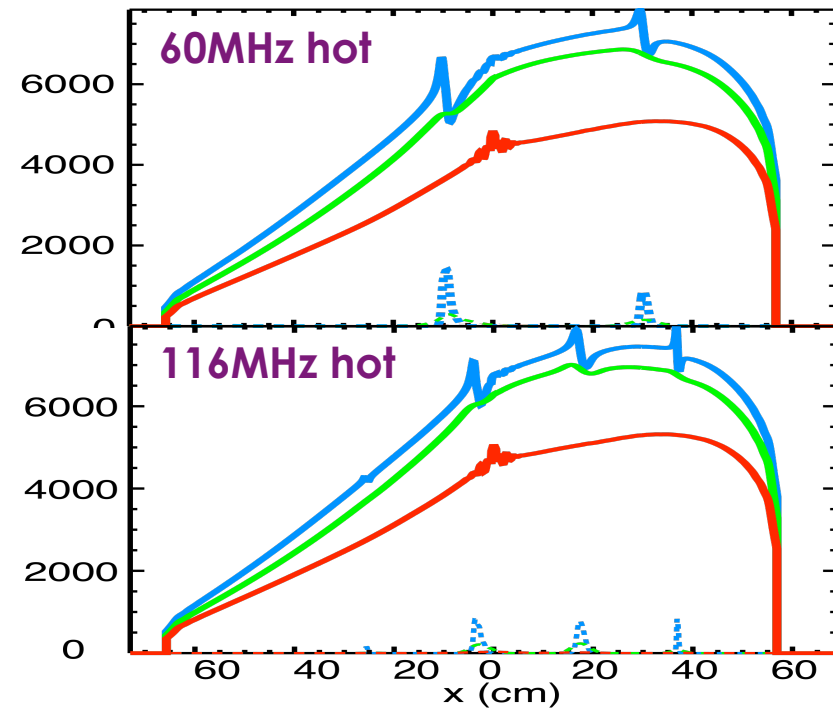
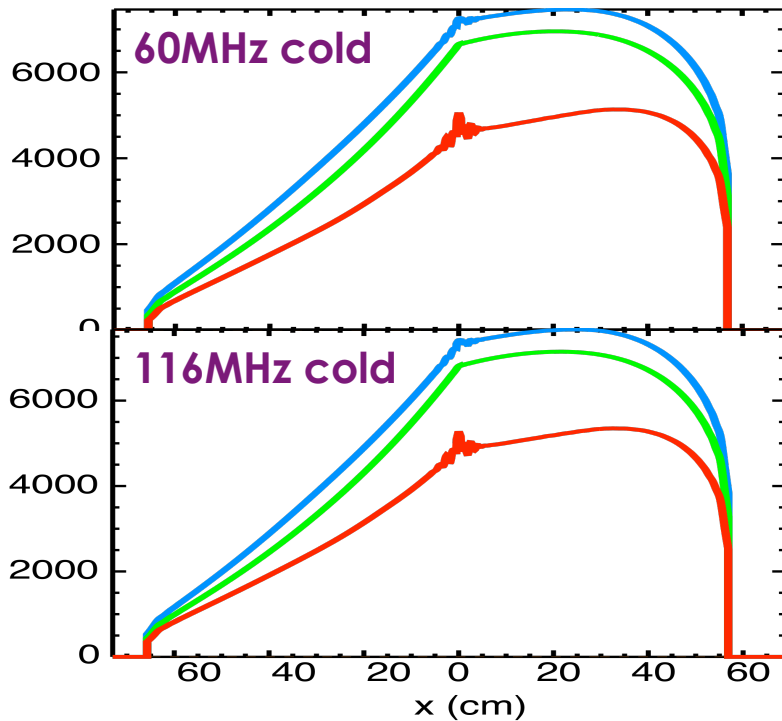
$$\tau_{rf} = \begin{cases} \frac{2\pi A_i}{|l\ddot{\Omega}|_{res} + k_{||}\ddot{v}_{G,||}^{(0)}|_{res}}^{1/3} & \text{if } l\dot{\Omega}|_{res} + k_{||}\dot{v}_{G,||}^{(0)}|_{res} \sim \frac{1}{3} \left( l\ddot{\Omega}|_{res} + k_{||}\ddot{v}_{G,||}^{(0)}|_{res} \right) \tau \\ \sqrt{\frac{2\pi}{|l\dot{\Omega}|_{res} + k_{||}\dot{v}_{G,||}^{(0)}|_{res}}} & \text{if } l\dot{\Omega}|_{res} + k_{||}\dot{v}_{G,||}^{(0)}|_{res} > \frac{1}{3} \left( l\ddot{\Omega}|_{res} + k_{||}\ddot{v}_{G,||}^{(0)}|_{res} \right) \tau \end{cases}$$

- Resonant interaction time at inner  $\psi_p$  is longer than that at outer  $\psi_p$



# $K_{\perp}$ From Hot Plasma Dispersion Relation Is Slightly Different From Cold Plasma Approximation

- TORIC for 25 keV Maxwellian, 31 poloidal modes
- Red:  $m=-15$ , green:  $m=0$ , blue:  $m=+15$



# Summary and Future Work

- Qualitative agreements are found in quasi-linear ICRH modeling in a linear regime for “model problems”
- Finite drift orbit effect of energetic particles is important in high harmonic ICRH modeling
  - Edge loss
  - Wave damping near axis
- Self-consistent coupling of ORBIT-RF with AORSA using wave fields requires improved modeling in phase information between  $E_-$  and  $E_+$  wave fields
- Alternative way to couple AORSA Q-L diffusion coefficients to ORBIT-RF is under progress (D. Green)