QP1.00024: Full Wave Modeling of Wave - Plasma Interactions in NSTX*

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In collaboration with the RF SciDAC Group

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Overview

- Introduction
- Part I: HHFW applications
- Part II: “fast ion” driven mode applications

Introduction: *Wave plasma interactions play an important role in the dynamics of NSTX plasmas*

I. High harmonic fast waves (HHFW), with $f_{RF} > 6\ f_{CD}$, are used to heat and drive noninductive currents in NSTX plasmas.

II. Fast ions from neutral beam injection can excite compressional and/or global Alfven eigenmodes (CAE/GAE) with $f \leq f_{CD}$.

III. The full wave code, TORIC, will be used to simulate:

- » recent HHFW experiments that show that the wave propagation and absorption depend strongly on the antenna phasing and plasma conditions [see J.C. Hosea NO1.00002 this meeting]. The issue of mode conversion from the HHFW to shorter wavelength modes will be revisited.
- » the possibility of driven modes in the CAE / GAE frequency range, using the HHFW system.

The TORIC full-wave code can simulate wave-plasma interactions in axisymmetric toroidal magnetic equilibria

- **TORIC solves Maxwell's Equations for a fixed wave frequency with a linear plasma response in a mixed spectral-finite element basis:**

$$\nabla \times \nabla \times \vec{E} - \frac{\omega^2}{c}\vec{\vec{\varepsilon}} \cdot \vec{E} = \frac{4\pi i\omega}{c^2}\vec{J}_A$$

$$E(\vec{r}) = \sum_m E_m(\psi)e^{i(m\theta + n\phi)}$$

- **Antenna is modeled as a sheet current:** $J_A(\psi_A, \theta, n)$

- **(ψ,θ,ϕ) are "radial", "poloidal", and "toroidal" coordinates**

TORIC is used to model RF heating and current drive in plasmas with nonthermal ions and / or electrons

NSTX

"Finite Larmor Radius" version used for:

» fast wave heating and mode conversion current drive in tokamaks

- energetic ions from NBI, rf-heating, fusion products
- Maxwellian electrons

» lower hybrid current drive:

- nonthermal electrons and cold ions
  - will have to include energetic fusion alphas n ITER

"Quasi-local" version for the high harmonic fast wave regime in tokamaks and ST's that retains large $k_{\perp}\rho$ effects

- energetic ions primarily from NBI

TORIC has been extended to the High Harmonic Fast Wave Regime

Kinetic model for plasma dielectric response derived using:

- » **Eikonal ansatz for wave fields:**
  - resulting differential wave equation is same order as in vacuum
- » **Quasi-local evaluation:**
  - assumes range of spatial dispersion (~ ρ_i, thermal Doppler width) is small compared to equilibrium magnetic field scale lengths
  - resulting dielectric tensor similar in form to uniform plasma model, but with slowly varying $k_{//} = (n+m/q)/R$
    - evaluated using local parameters and local hot plasma dispersion relation for propagating HHFW
    - *assumes no mode conversion*

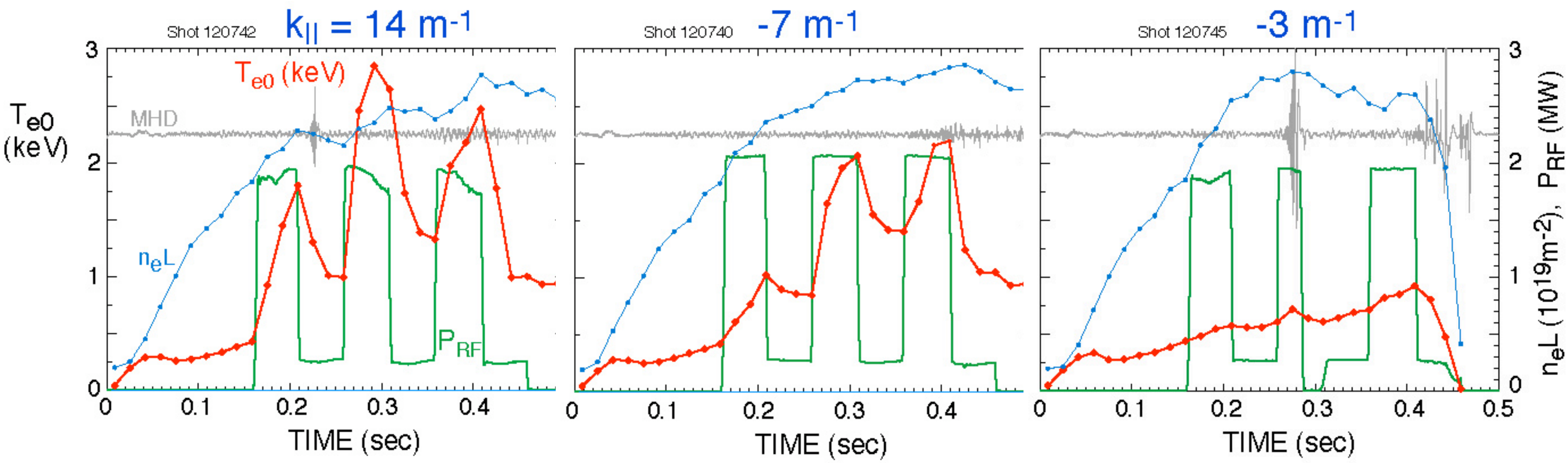
No FLR-approximation required: valid to all orders in $k_\perp \rho_i$:

⇨ ***Valid for HHFW's in NSTX***

See *M. Brambilla, Plas. Phys. and Controlled Fus. Res. 44(2002)2423*

Part I: *Recent NSTX experiments show that HHFW heating improves with higher $k_{//}$ and B*

Electron heating for B_T = 5.5 kG, I_P = 720 kA



⇒ **Strong dependence on $k_{//}$: almost no heating at 3 m^{-1}**

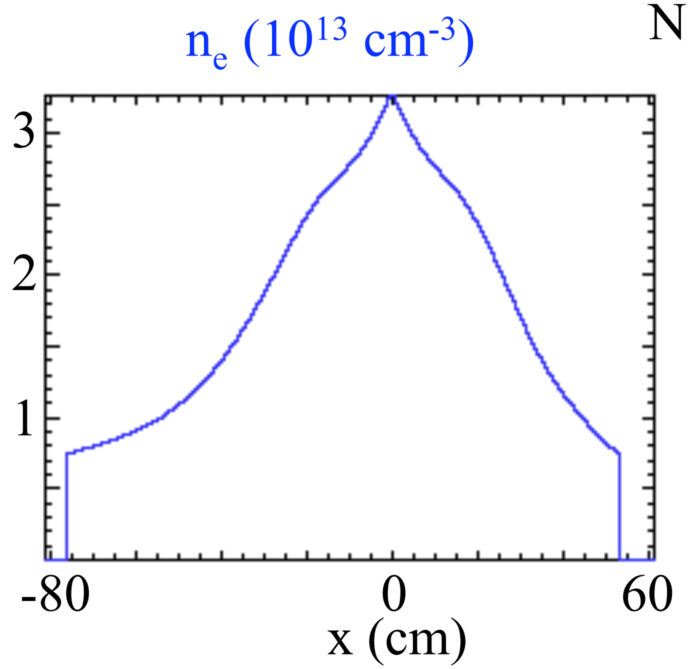
⇒ **Heating at 7 m^{-1} for B_T = 5.5 kG higher than observed previously at 4.5 kG**

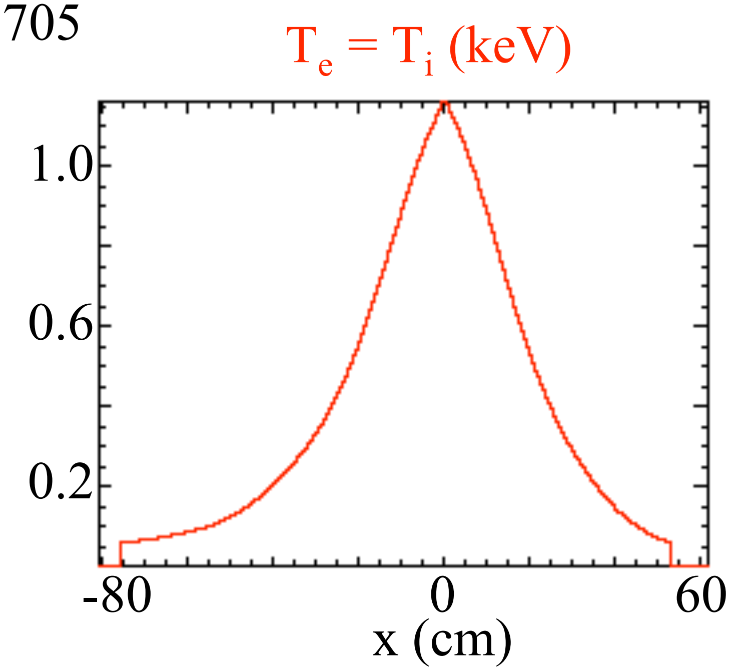
⇒ **PDI edge heating and surface wave heating appear to be contributing significantly to RF power losses**

see J.C. Hosea *et al* NO1.00002 this meeting for details

TORIC uses measured equilibrium profiles to simulate the HHFW fields in NSTX

NSTX #112705



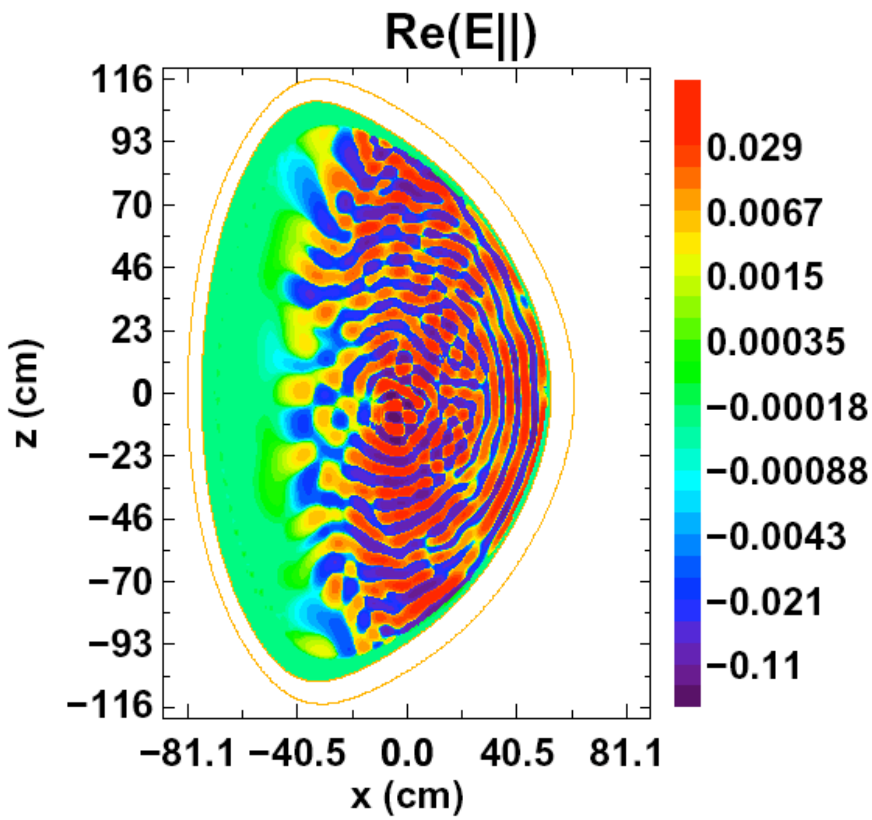


EFIT equilibrium and n_e, T_e profiles from TS used in simulations

B_T(axis) = 0.426T $\quad$ I_p= 0.6 MA $\quad$ q_a=12

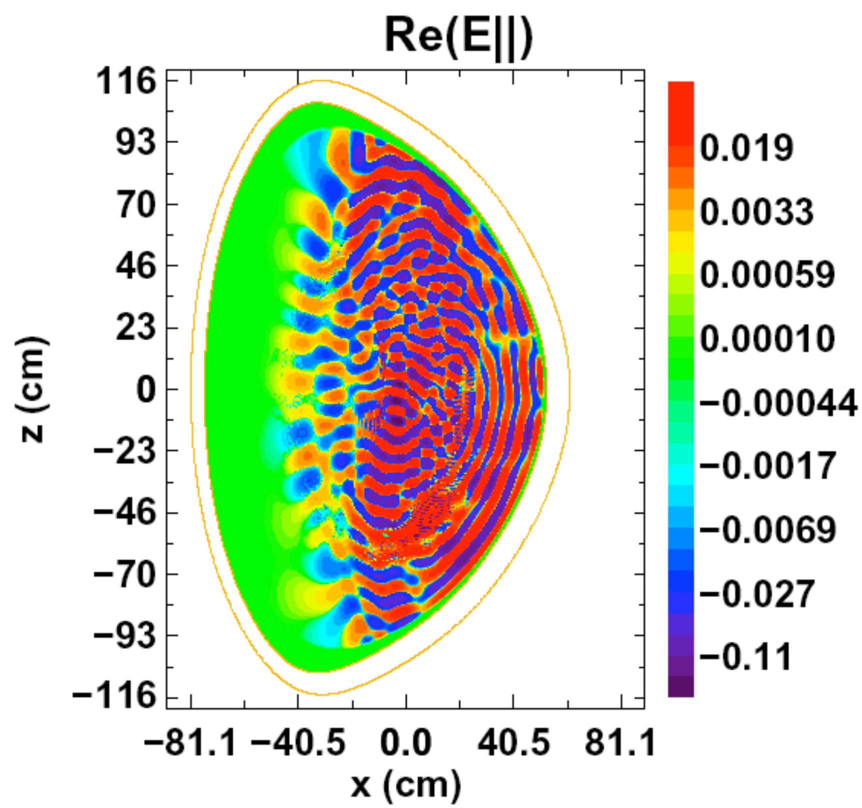
f_0 = 30 MHz for HHFW experiments

Short wavelength structure appears in TORIC simulations of HHFW experiments in NSTX……



n_{elm}=240 n_{mod}=127

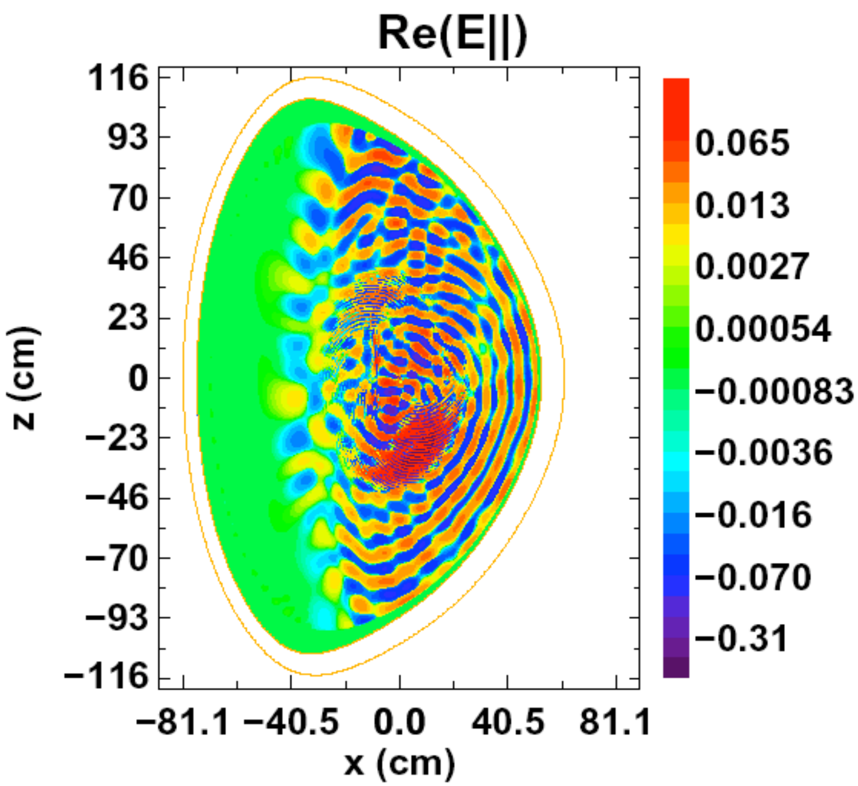
$P_{abs} = 2.71 / P_{rad} = 2.42$



n_{elm}=483 n_{mod}=255

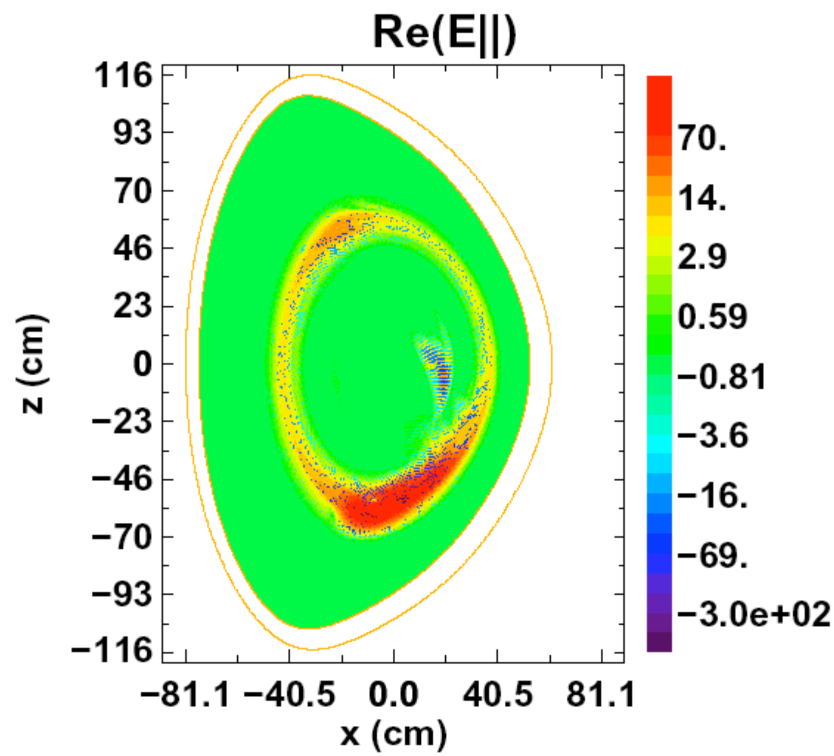
$P_{abs} = 1.83 / P_{rad} = 1.82$

More structure appears as resolution is increased….
but power balance eventually degrades



n_{elm}=720 n_{mod}=127

P_{abs} = 2.08 / P_{rad} = 1.67



n_{elm}=720 n_{mod}=255

P_{abs} = 1.15e5 / P_{rad} = 1.68

Are high k modes excited as the HHFW propagate?

Can TORIC adequately simulate these modes? (assumes no mode conversion)

Usual assumption: only the "fast wave" propagates in the HHFW regime

NSTX

No significant mode conversion to ion Bernstein waves seen in previous simulations (AORSA-2D with lower resolution, METS-1D on midplane)

Assuming cold ions (neglects IBW) and warm electrons, the simplest dispersion relation can be written as:

$$a \; n_\perp^4 - b \; n_\perp^2 + c = 0$$

where $a \sim S$, $b \sim -K_{zz} (n_{//}^2 - S)$, and $c \sim K_{zz} (n_{//}^2 - R)(n_{//}^2 - L)$

"fast root": $n_\perp^2 \sim c/b \sim (n_{//}^2 - R)(n_{//}^2 - L)/ (S - n_{//}^2)$

"slow root": $n_\perp^2 \sim b/a \sim -K_{zz} (n_{//}^2 - S)/S$

>>> slow wave ***usually assumed to be evanescent, but may propagate under certain conditions***

Simple dispersion relations indicate 'slow wave" may propagate for sufficiently "hot" electrons

In the HHFW regime, S is usually negative:

$$S \sim \frac{-\omega_{pd}^2}{\omega^2 - \Omega_D^2}$$

Therefore: $$n_\perp^2 = \frac{-K_{zz}}{S}\left(n_{//}^2 - S\right) \Rightarrow \frac{K_{zz}}{|S|}\left(n_{//}^2 + |S|\right)$$

$$K_{zz} = \frac{-\omega_{pe}^2}{k_{//}^2 v_{Te}^2} Z'(\zeta_{0,e}) \quad \text{where} \quad \zeta_{0,e} = \frac{\omega}{k_{//} v_{Te}}$$

$$\Rightarrow \frac{-\omega_{pe}^2}{\omega^2} \qquad (\text{for } \zeta_{0,e} >> 1)$$

$$\Rightarrow \frac{2\omega_{pe}^2}{k_{//}^2 v_{Te}^2}\left[1 + i\sqrt{\pi}\frac{\omega}{k_{//} v_{Te}} \exp(-\zeta_{0,e}^2)\right] \qquad (\text{for } \zeta_{0,e} << 1)$$

In NSTX, ζ_{0e} can be less than 1 for observed electron temperatures and higher $k_{//}$'s, so real(K_{zz}) can be positive $\Rightarrow$ the slow wave can propagate!

What "slow modes" might propagate in NSTX?

$$n_\perp^2 = \frac{K_{zz}}{|S|}\left(n_{//}^2 + |S|\right) \quad \Rightarrow$$

$$n_\perp^2 = \frac{K_{zz}}{|S|} n_{//}^2 \quad \text{or} \quad \omega^2 = \Omega_D^2 + k_\perp^2 c_s^2 \quad \text{if} \quad n_{//}^2 >> |S| \qquad \text{(ESICW)}$$

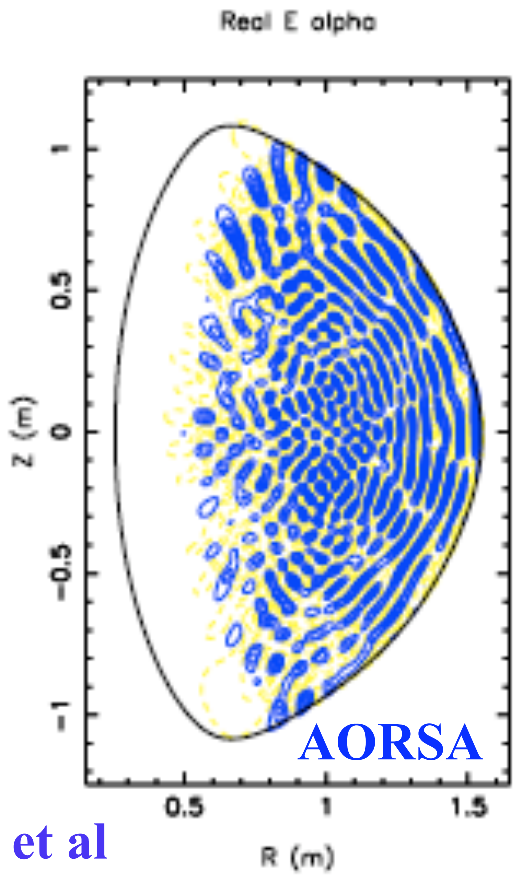
(electrostatic ion cyclotron mode)

$$n_\perp^2 = K_{zz} \qquad \text{if} \quad n_{//}^2 << |S| \qquad \text{(KAW)}$$

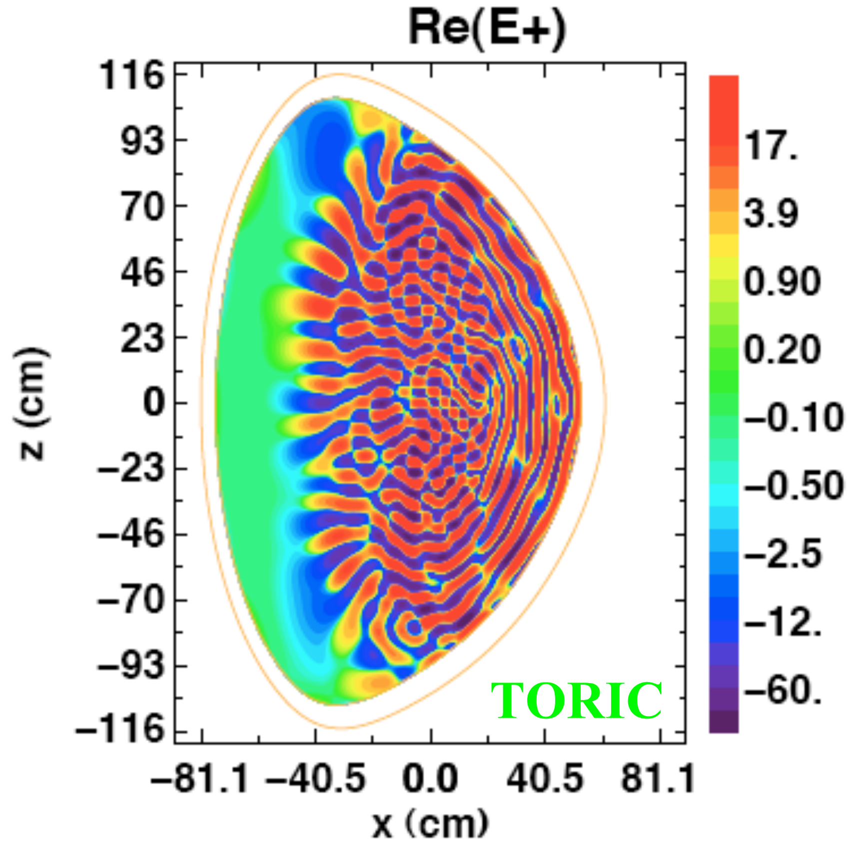
(kinetic Alfven mode)

Note: ***these modes would most likely damp heavily on electrons***

Perpendicular electric fields from AORSA and TORIC look similar

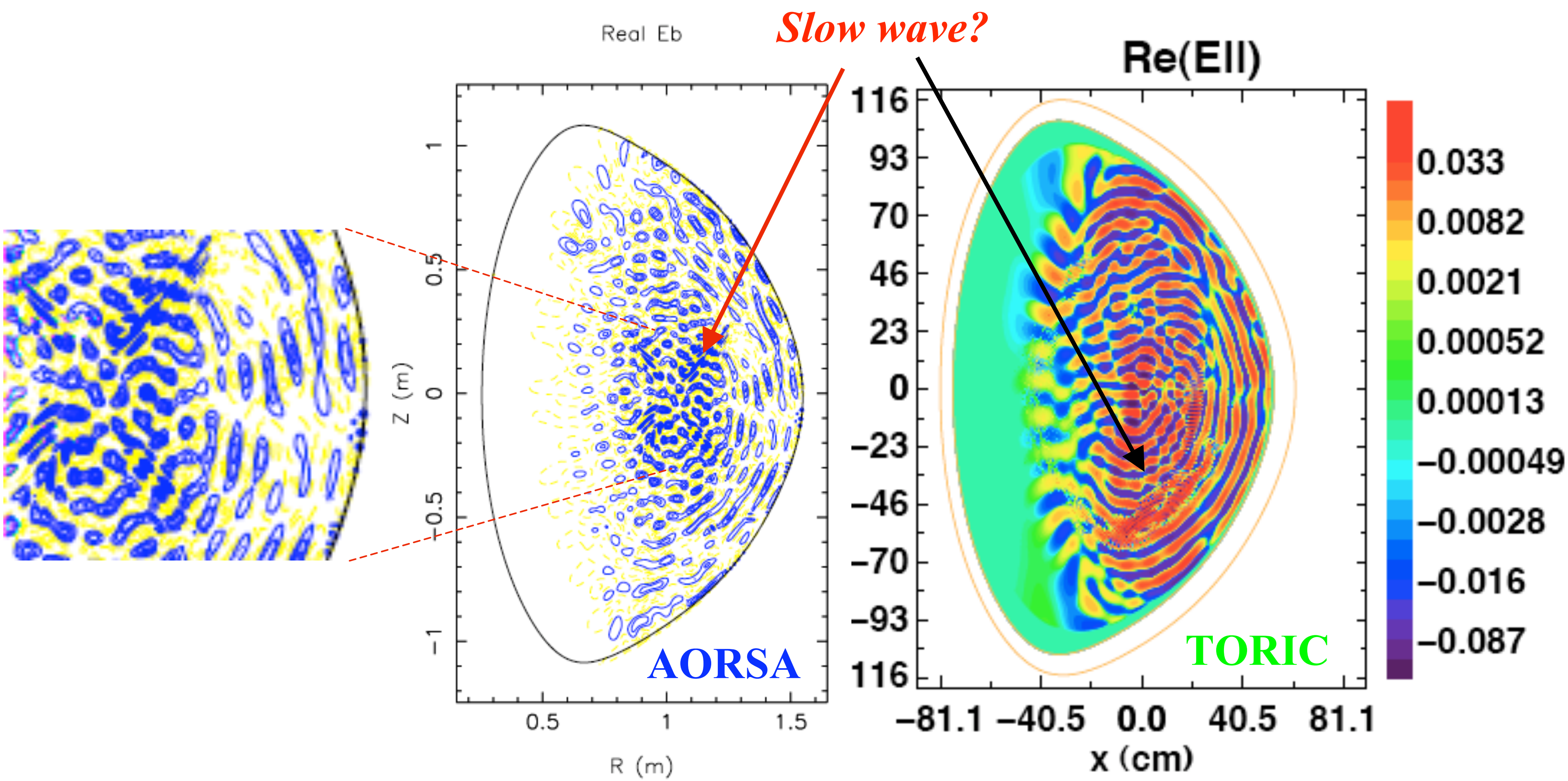


Jaeger et al



AORSA utilizes the "all-orders" approach that retains mode conversion processes

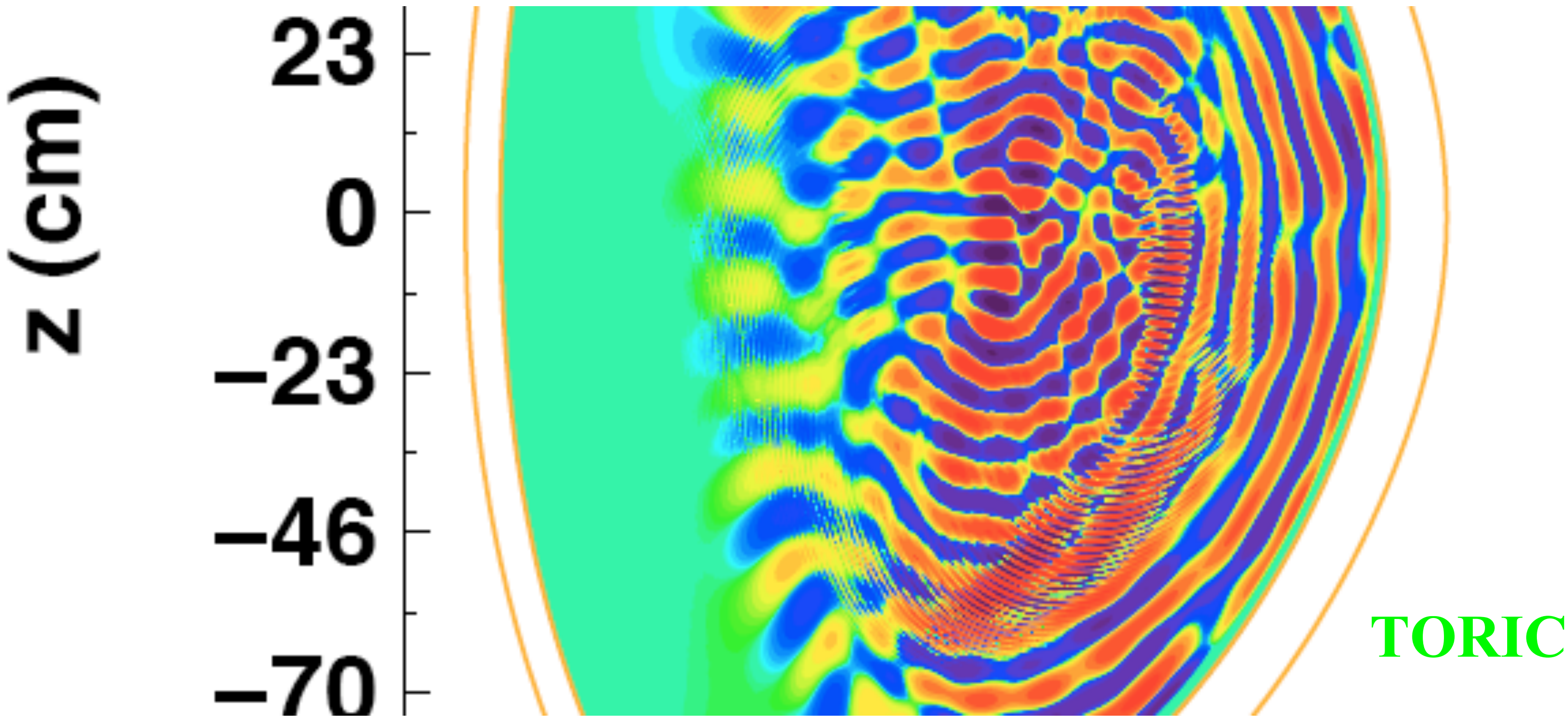
The short wavelength structure appears mostly in $E_{//}$



350 X 350 modes in k_x,k_y

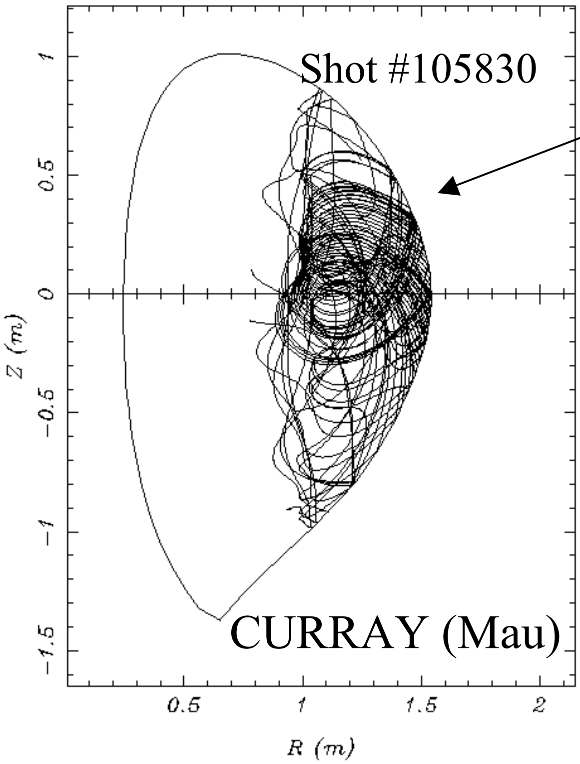
483 radial X 255 poloidal modes

“Slow wave” appears to propagate along B_0



Mode conversion to a short wavelength mode has also been seen in the $E_{//}$ generated with the 1D METS all-orders code in off-midplane regions

Simulations must include enough poloidal harmonics to resolve the high harmonic fast wave



Note that the HHFW rays spiral in towards the core

To resolve HHFW in poloidal direction,

with $\omega \sim k_\perp V_A \Rightarrow k_\perp \sim 125\ m^{-1}$ ($\lambda \sim 5$ cm)

require $\frac{m}{r} \sim \frac{m}{0.3} \sim k_\perp \sim 125 \Rightarrow m \geq 40$

TORIC uses $-M_{max}$ to $+M_{max}$ poloidal modes, so require at least nmod ~ 81

>> **must use n_{mod} = 127, 255, or higher in simulations**

(nmod ~ $2^N/2 + 1$ for FFT efficiency)

These higher poloidal modes correspond to higher $k_{//}$'s ,which may give rise to propagating "slow waves"

Further studies are needed to determine if slow wave excitation is occurring and affecting power absorption

NSTX

Are 'slow waves' excited by the HHFW or are the predicted fields caused by numerical artifacts?

➞ Is the mode an electrostatic ion cyclotron mode or a kinetic Alfven wave? or a new mode?

➞ Is the mode detectable with existing diagnostics?

➞ Is the mode adequately resolved in the AORSA and TORIC simulations?

➞ Is the mode treated correctly in the high harmonic version of TORIC?

➞ Is the mode reproducible in 1D kinetic full wave codes? (e.g. METS)

➞preliminary results show conversion from HHFW to short wavelength mode in $E_{//}$

➞***How is power absorption modified if this mode is real and present?***

Part II: Fast ions excite a variety of modes in fusion plasmas: *Can full-wave TORIC code offer any insights?*

TORIC retains effects neglected in the linear and nonlinear MHD / hybrid codes, including:

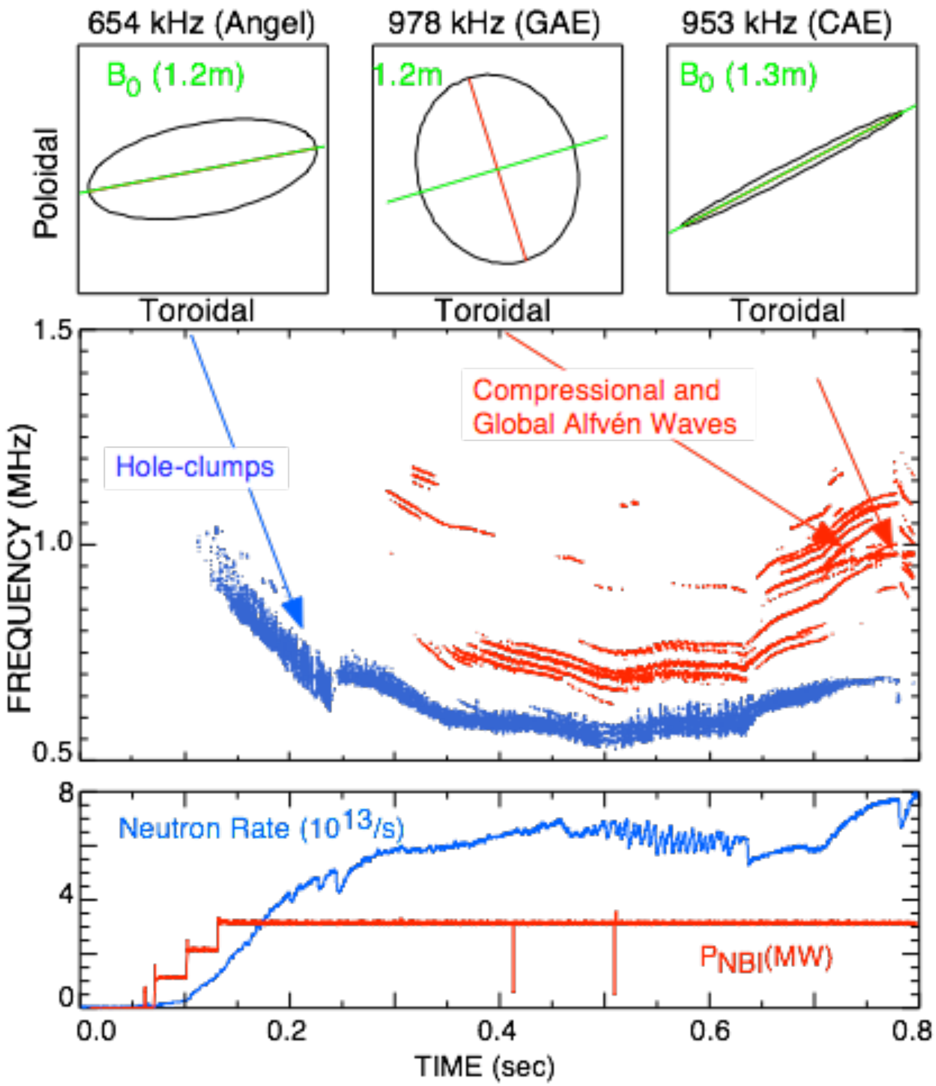
- **FLR effects, finite ω/ω_c effects, cyclotron resonances**
- **full toroidal geometry, fast ion distributions**

In addition, TORIC can attain much higher spatial resolution of modes, but in a linear (or eventually) quasilinear treatment

Approach >>> *Utilize TORIC(FLR) to study dynamics of driven modes in the linear regime*

- **begin in the $\omega \sim \omega_c$ regime (CAE, GAE modes)**
- **modify code/formalism as needed for $\omega << \omega_c$ regime (TAE,EPM, etc)**
- **validate code with results from driven mode experiments (time and resources permitting)**

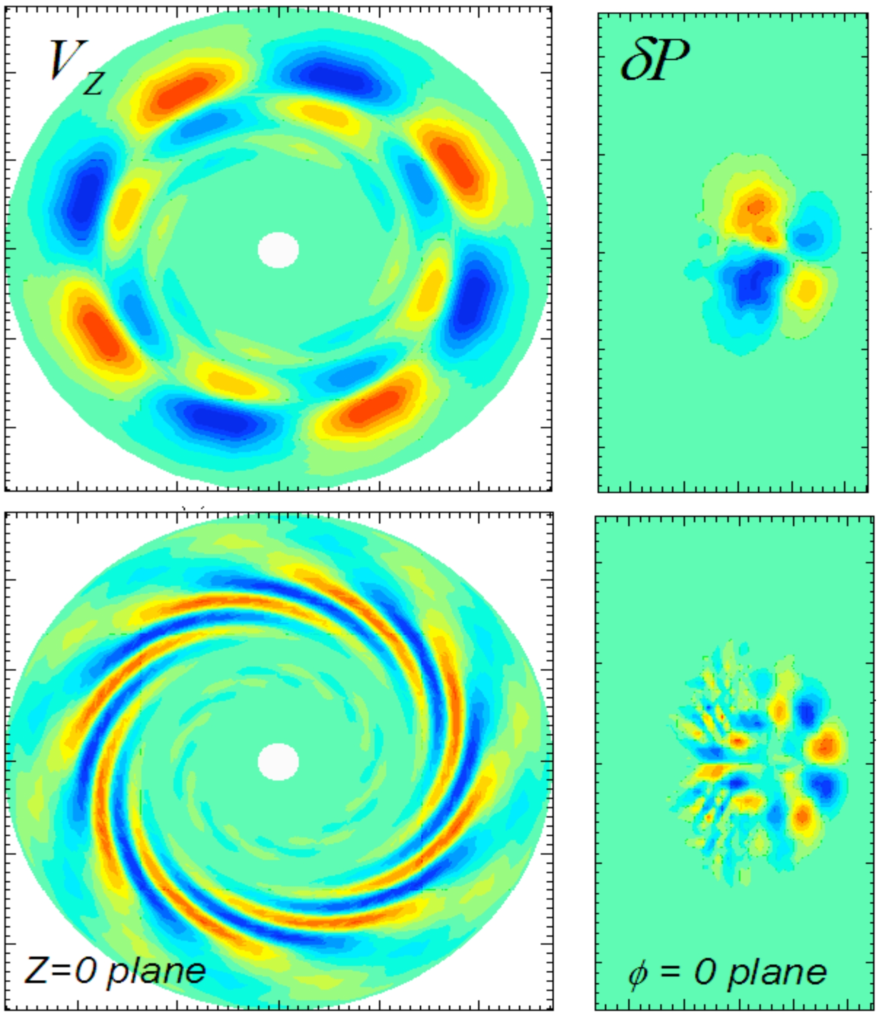
Fast ion modes dominate NSTX MHD



- **Higher frequency modes are GAE and CAE, excited through Doppler-shifted ion cyclotron resonance.**
- **Modes commonly exhibit chirping behavior.**
- **Modes have mixed polarization; CAE *or* GAE**

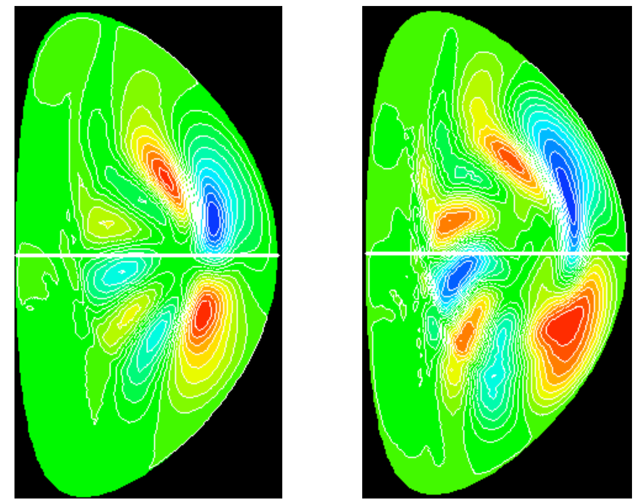
Fredrickson et al

Predicted structure of fast particle modes is commensurate with TORIC resolution capabilities



GAE

CAE



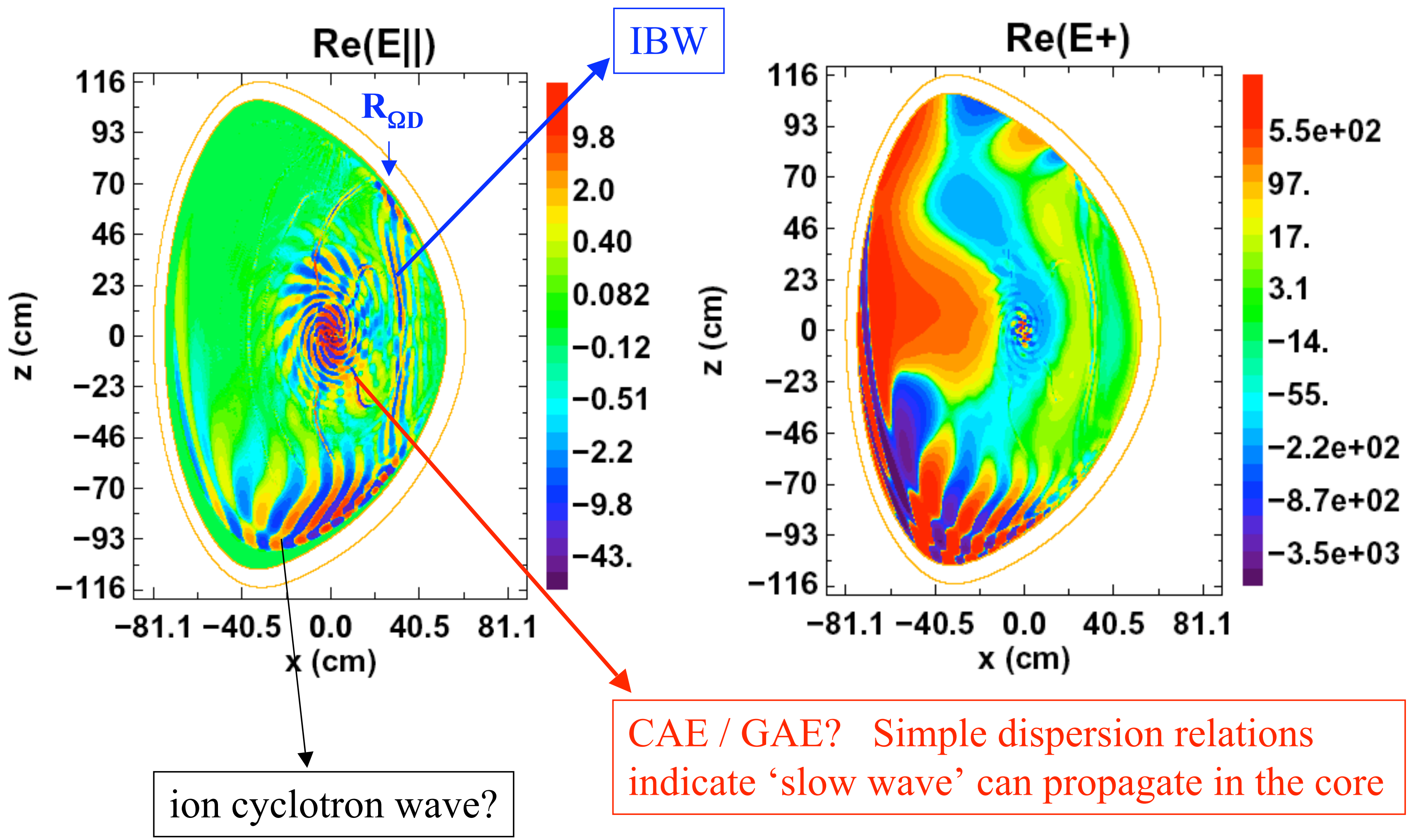
M3D nonlinear hybrid simulations of beam-driven TAE modes in NSTX (Fu)

[M3D has ≤ 200 radial nodes]

HYM code simulations of GAE and CAE in NSTX (Belova) [100 X 100 grid]

CAE's were first predicted by the HYM code and then observed in NSTX

TORIC finds three rf-driven modes in addition to the fast wave in NSTX with $f_0 \sim f_{CD}$



Simple wavelength estimates indicate "slow waves" propagate but are strongly damped in the core region

For the simulations of the NSTX core, $\omega \sim 2\pi$ (2.5 MHz)~0.67 $k_{//} v_{Te}$

$$K_{zz} = \frac{-\omega_{pe}^2}{k_{//}^2 v_{Te}^2} Z'(\zeta_{0,e}) \quad \text{where} \quad \zeta_{0,e} = \frac{\omega}{k_{//} v_{Te}}$$

$$\Rightarrow \frac{-\omega_{pe}^2}{\omega^2} \qquad (\text{for } \zeta_{0,e} >> 1)$$

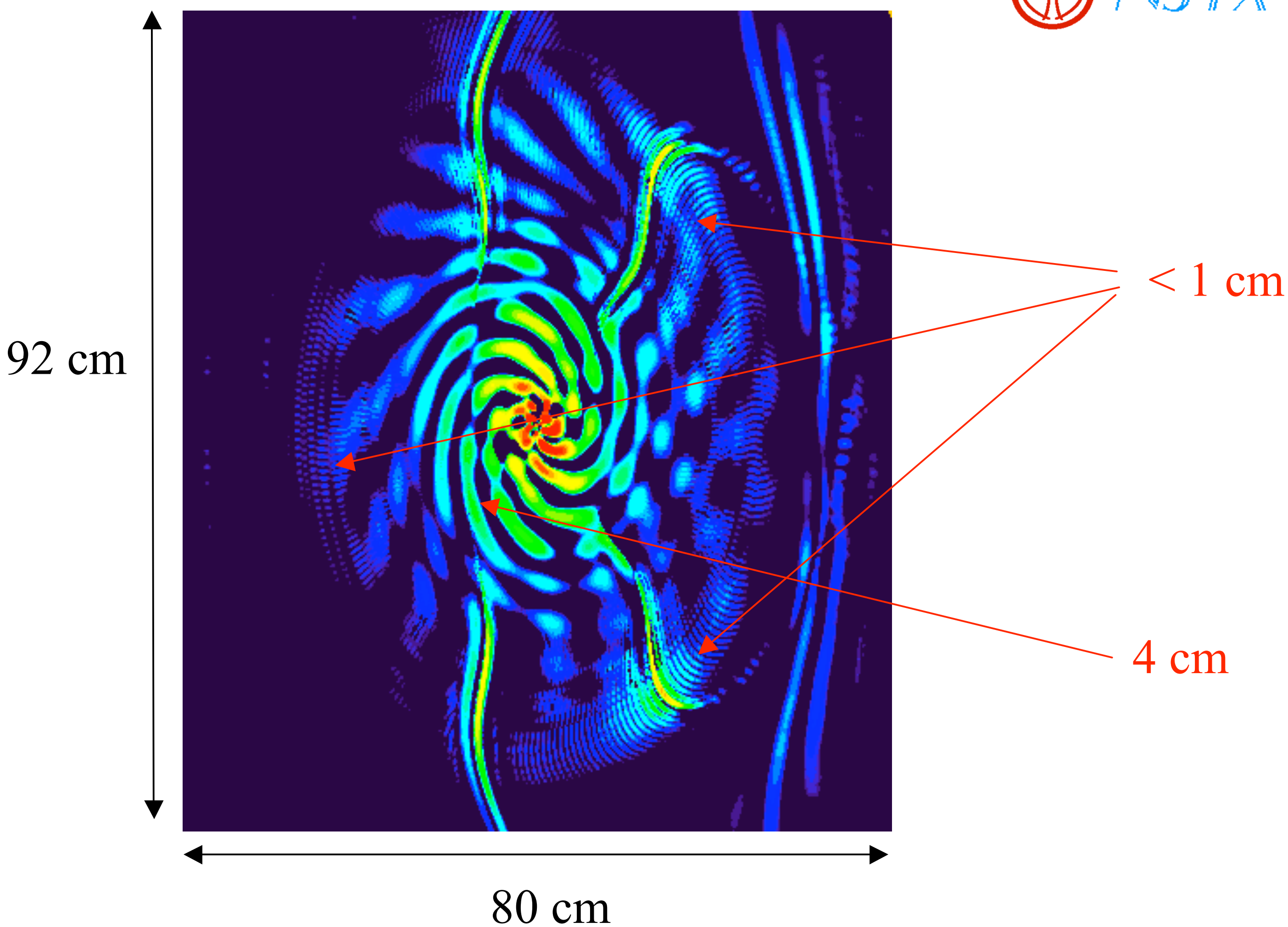
$$\Rightarrow \frac{2\omega_{pe}^2}{k_{//}^2 v_{Te}^2} + 2i\sqrt{\pi}\frac{\omega}{k_{//} v_{Te}} \exp(-\zeta_{0,e}^2) \qquad (\text{for } \zeta_{0,e} << 1)$$

$$\Rightarrow 3.6 \times 10^8 + 2.7 \times 10^8 i$$

With $S \sim 1.7 \times 10^5$ and $n_{//}^2 \sim 400 >>$ $\lambda_{\perp,SW} \leq 1$ cm while $\lambda_{\perp,FW} \sim 50$ cm

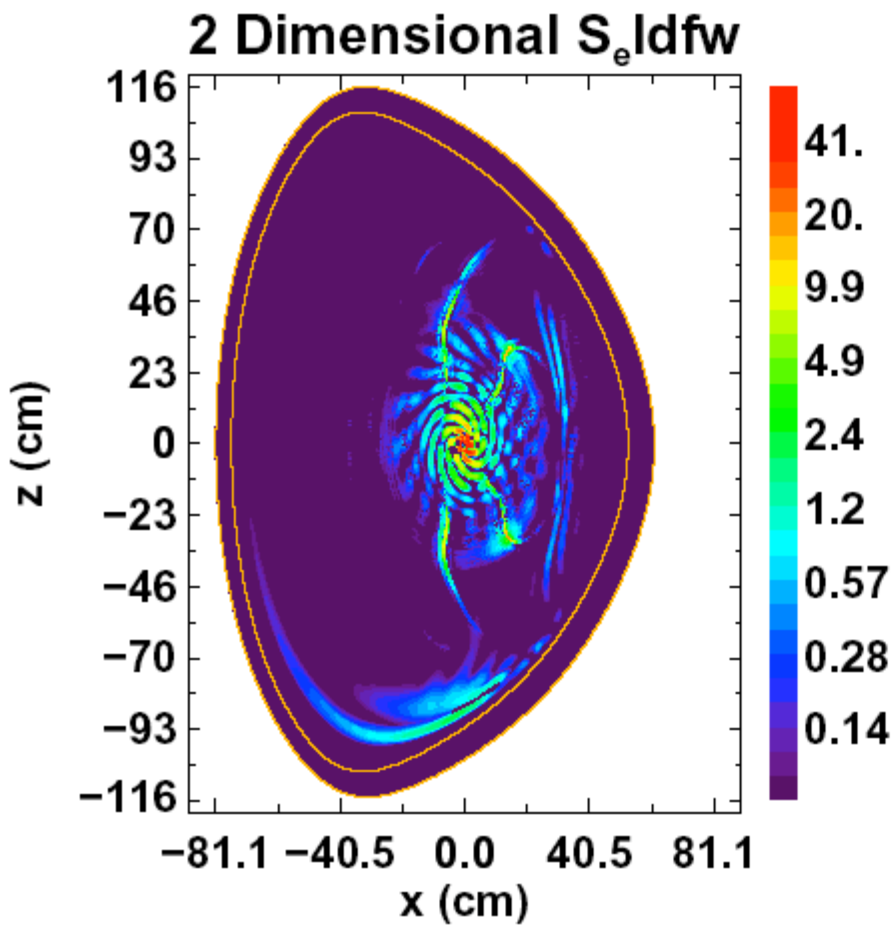
but $k_{\perp,SW,imag} / k_{\perp,SW,real} \sim 0.33$

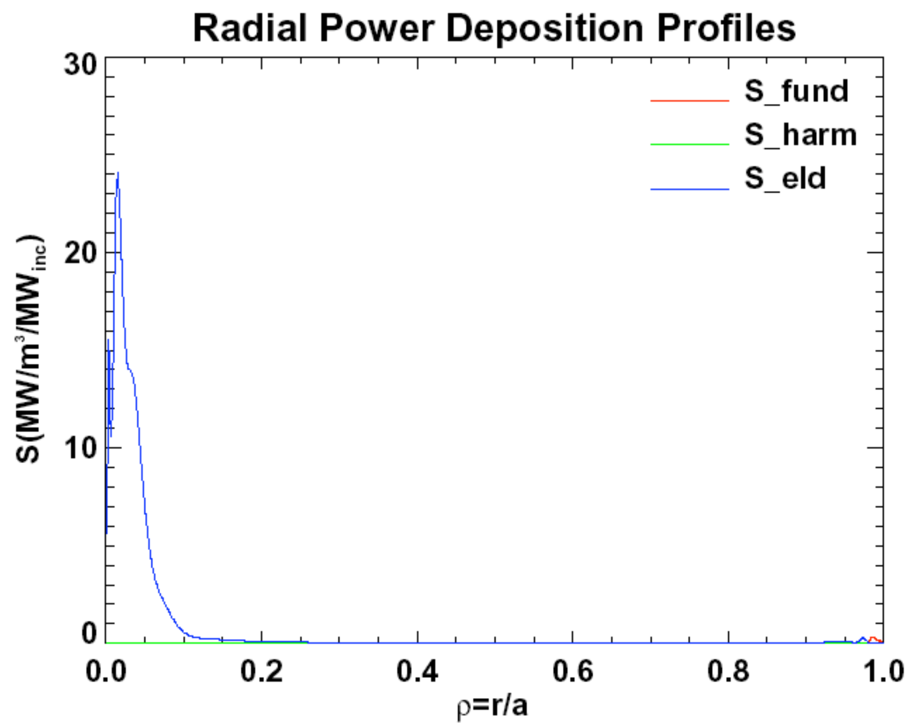
Dominant wavelength in the core mode is somewhat larger than simple "slab model" estimates



Probably need to include effects of "shear" in the simple model

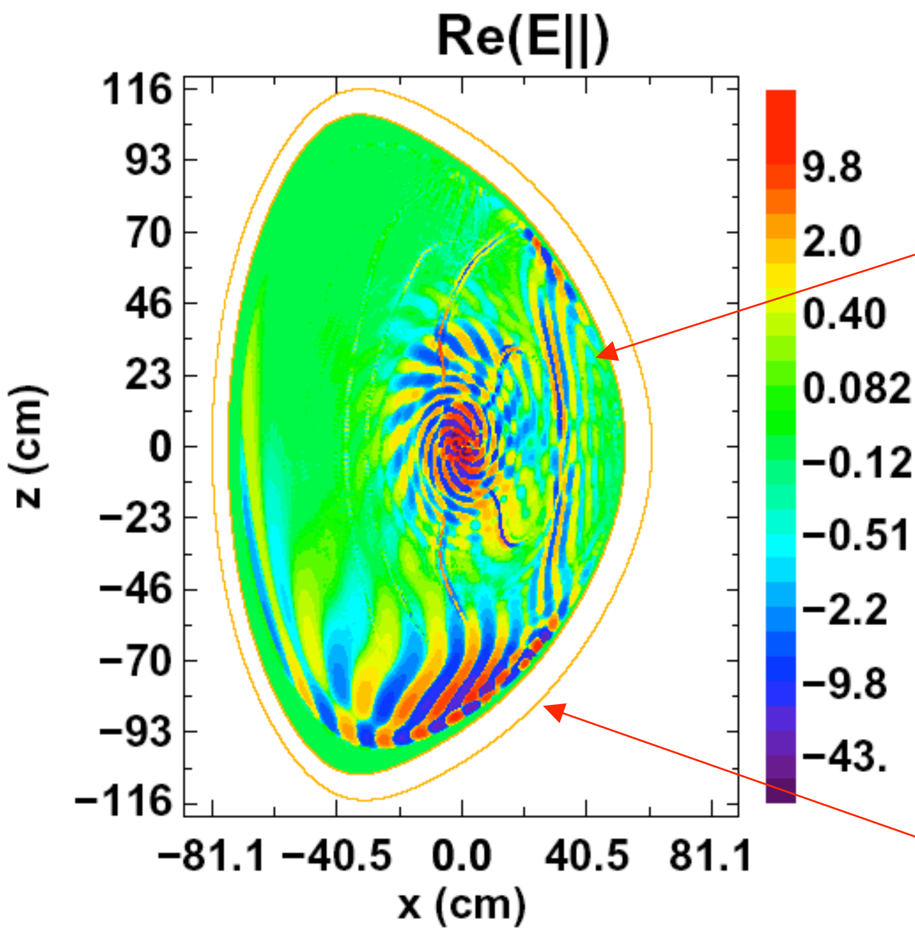
Power is damped mostly on electrons by the core mode





>> not surprising since $\omega \sim k_{//}\, v_{Te}$ over the core region

What about the other 2 modes?



IBW: $K_{xx} = 0 \quad \Rightarrow \quad \lambda_\perp \leq 7$ cm
from simple estimate

maybe an ICW?

- mainly off of midplane where Bp $\neq 0$
  (so shear may be important)
- in cold plasma region
- moves to upper half plane if sign of N_{tor} is changed
- "looks like an ICW"

Further work is needed to simulate driven eigenmodes in NSTX with TORIC

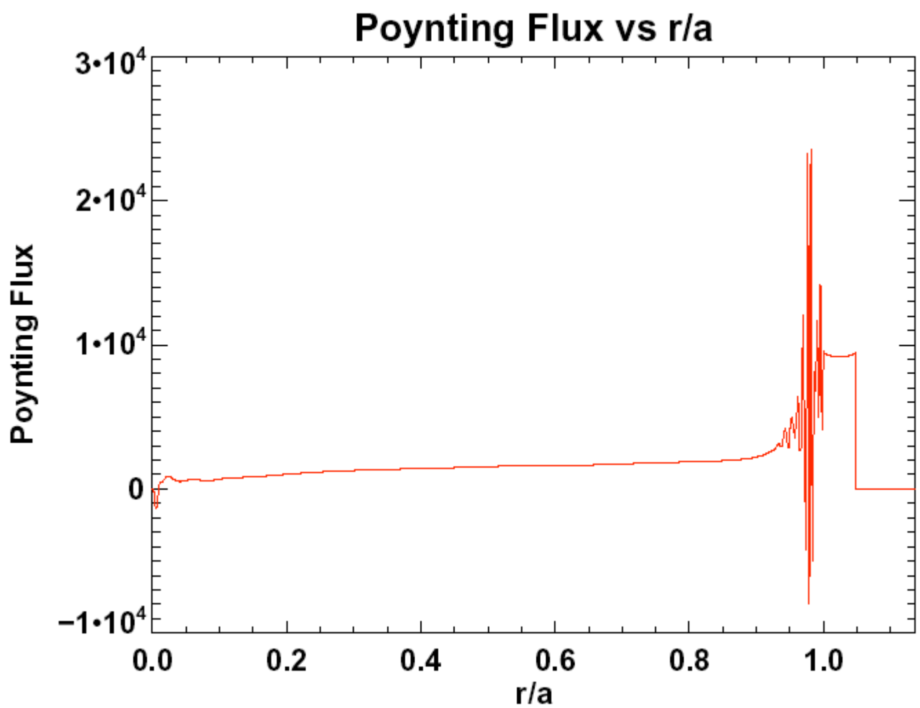
Power balance needs improvement:

code has difficulty with Poynting flux in the edge regions

⇒ due to neglect of kinetic flux?

Benchmark against other codes and NSTX data

new scattering diagnostic can see structures ~ 1 cm for f ~ 1 MHz (Smith, Mazzucatto, Park)



Brambilla notes that numerical algorithm may have trouble for $\omega << \Omega_{ci}$

initial runs with fundamental Ω_{ci} layer out of plasma had poor power balance

⇒may need new numerical algorithm

may need to extend formalism to include "drift wave" effects

Summary and Future Work

The possibility of "slow wave" excitation during HHFW experiments in NSTX is being explored

- further simulations with AORSA-2D, TORIC, and 1D kinetic codes will be compared and checked for consistency
- possible detection of "slow mode" with existing diagnostics will be considered

The use of TORIC to study the structure and damping of driven eigenmodes is promising

- approach includes physics missing from other models (FLR, full kinetic effects, ultrahigh resolution, eventually self-consistency with fast particle distributions)
- improvements to algorithm are needed
- benchmarking against other codes and validation with data will be used to evaluate simulations