NSTX

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High Resolution Full Wave Modeling of Fast Waves in NSTX

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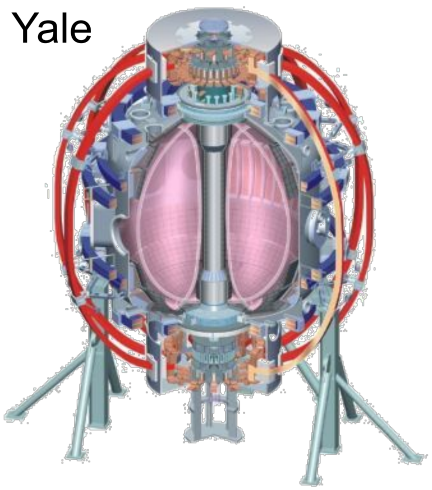

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High Resolution Full Wave Modeling of Fast Waves in NSTX*

Abstract:

High Harmonic Fast Waves (HHFW) are being used in NSTX for plasma heating and noninductive current profile control. Numerical solutions for the wave fields obtained with the full wave TORIC and AORSA codes with ultrafine spatial resolution reveal the presence of a short wavelength feature that is predominantly polarized in the direction parallel to the equilibrium magnetic field and which is predicted by the codes to damp on electrons. A similar short wavelength mode also appears in simulations of the rf fields in C-Mod in the ICRF regime. Preliminary analysis indicates that the mode may be related to a slow mode that can propagate above the fundamental ion cyclotron frequency. The predicted power deposition profiles will be compared to those inferred from experimental measurements to see if the mode has a significant effect on the wave propagation and absorption. Possibilities for detecting the mode in NSTX and C-Mod will be discussed.

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Outline of Key Ideas

Motivation:

- Efficient rf heating and current drive required in ST devices and ITER

Approach:

- Utilize ultrahigh resolution full wave simulations of the HHFW fields in NSTX to understand dynamics of HHFW heating and current drive

Conclusions:

- A short wavelength "slow mode" may be excited in addition to the HHFW's that are launched by the antenna
  - The mode propagates when the electrons are sufficiently hot so that $\omega < k_{//} v_{te}$ and it damps heavily on electrons in some regions
- The mode has also been identified in simulations of fast wave heating in the ion cyclotron range of frequencies (ICRF) in C-Mod
- Numerical simulations under a range of assumptions are consistent with a theoretical model for the fast and slow wave fields.

Wave Fields Modeled with Linear Wave Equation

Full field wave equation (inhomogeneous plasma):

$$\nabla \times \nabla \times \mathbf{E} - \frac{\omega^2}{c^2}\underbrace{\left(\mathbf{E} + \frac{i}{\omega\epsilon_0}\mathbf{J}_p\right)}_{\vec{\vec{\mathbf{K}}}\cdot\vec{\mathbf{E}}} = i\omega\mu_0\mathbf{J}_s$$

$\vec{\vec{\mathbf{K}}}\cdot\vec{\mathbf{E}}$ **, where** $\vec{\vec{\mathbf{K}}}$ **is the dielectric tensor**

and $$\mathbf{J}_p(\mathbf{r}) = \int d\mathbf{r}'\,\overline{\overline{\boldsymbol{\sigma}}}(\mathbf{r},\mathbf{r}')\cdot\mathbf{E}(r')$$

- AORSA includes the complete non-local, integral operator for $\vec{\vec{\mathbf{K}}}$ that is valid for "all orders" ($k_\perp\rho_s > 1$)

E.F. Jaeger et al, Phys. Plasmas 9 (2002) 1873

- TORIC utilizes a quasi-local differential operator for $\vec{\vec{\mathbf{K}}}$ that is valid in the HHFW regime but assumes that one dominant mode is propagating.

M. Brambilla, Pl. Phys. and Controlled Fus. Res. 44(2002)242

Numerical Codes Utilize Spectral Decomposition to Solve for the Wave Fields

AORSA utilizes a local Cartesian grid in the poloidal plane and a Fourier decomposition in the toroidal direction of symmetry:

$$\vec{E}(x,y,\phi) = \sum_{n_\phi} \sum_{n,m} \vec{E}_{n_\phi,n,m} e^{in_\phi \phi} e^{i(k_n x + k_m y)}$$

$$\text{where } x = R - R_0 \text{ and } y \text{ is distance from midplane}$$

TORIC utilizes a poloidal mode expansion and radial finite elements in the poloidal plane and a Fourier decomposition in the toroidal direction.

$$E(\vec{r}) = \sum_{n_\phi} e^{in_\phi \phi} \sum_{m=-n\,mod/2}^{n\,mod/2} E_m(\psi, n_\phi) e^{im\theta}$$

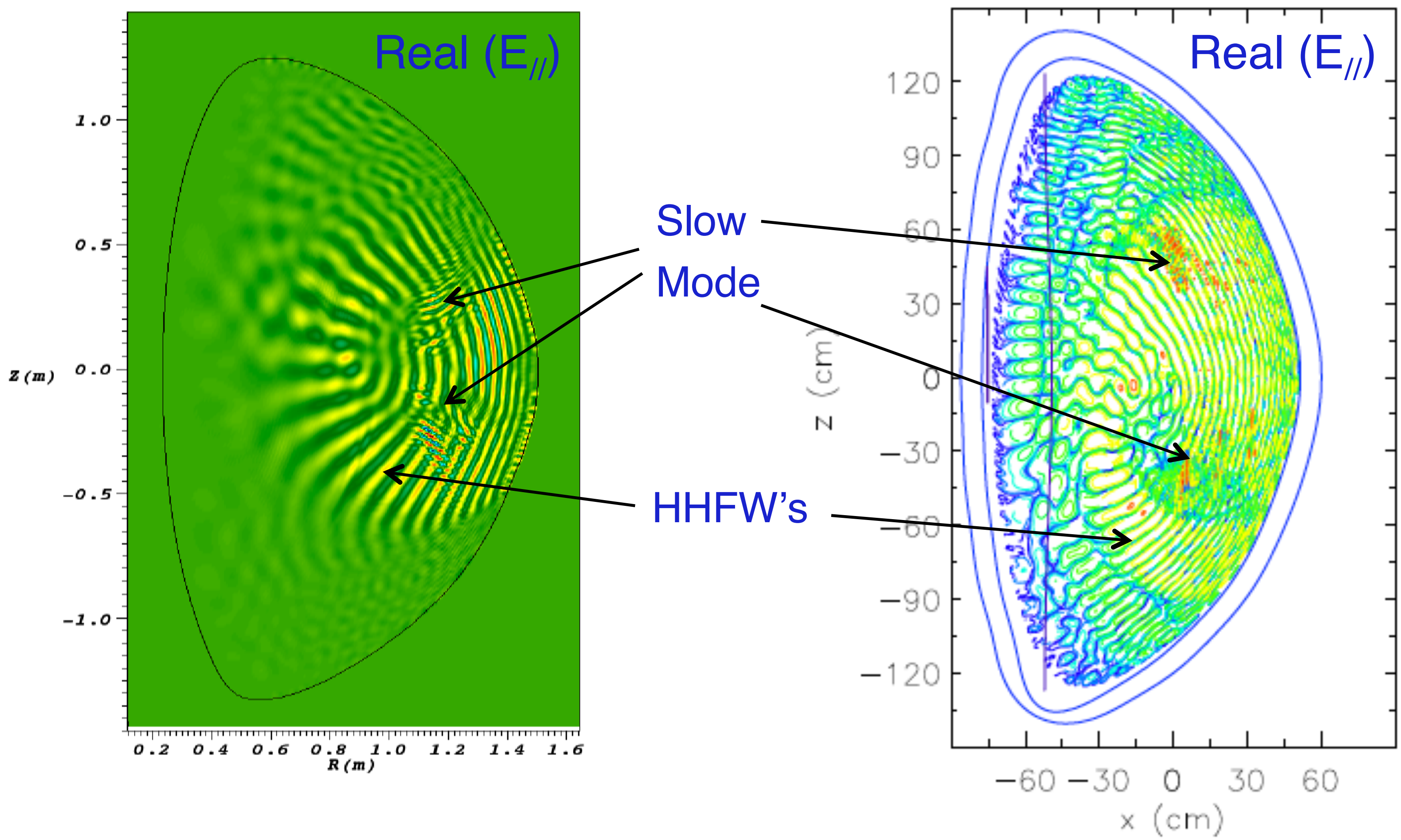
$$\text{and } E_m(\psi, n_\phi) \text{ is solved with nelm cubic Hermite polynomials}$$

Both codes must be run on multi-processor supercomputers to be able to include sufficient modes in the expansions to achieve fine spatial resolution of short wavelength modes.

Short Wavelength Mode Seen in High Resolution Simulations of HHFW in NSTX

AORSA with 256x256 modes

TORIC with nmod=255 and nelm=300



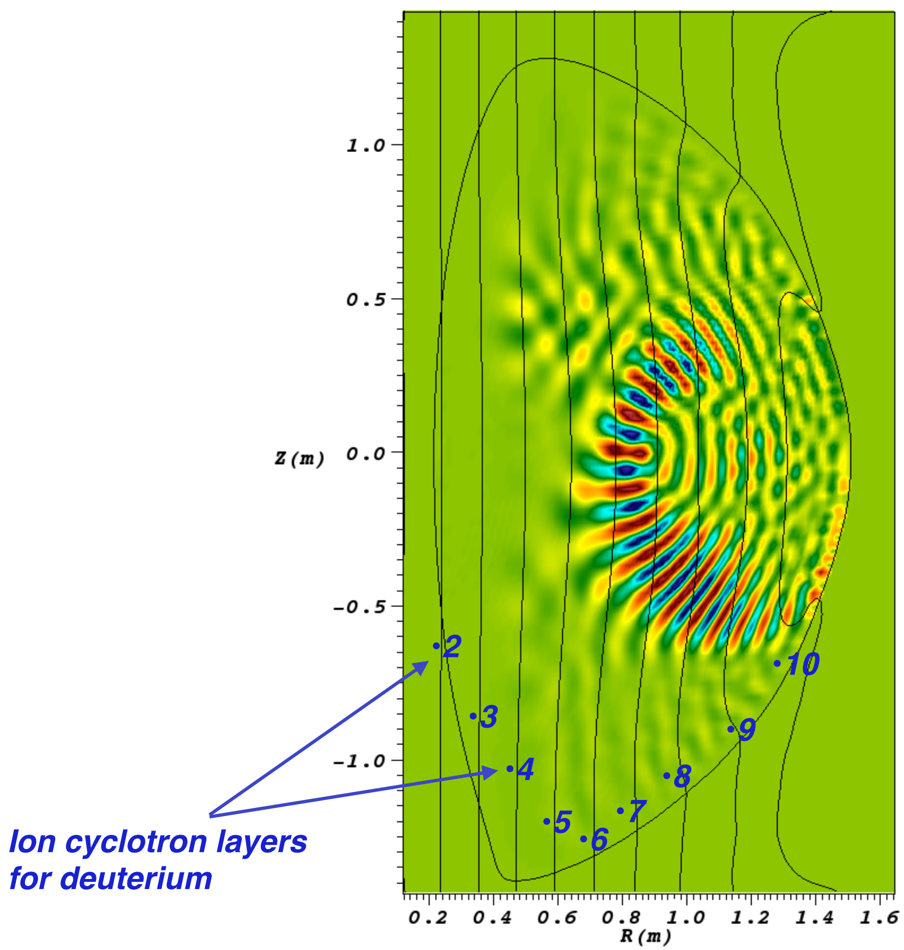
The new mode appears in solutions from 2 independent full wave codes

NSTX shot 130608: f = 30 MHz, B_0 = 0.511 T, n_φ = 12, T_i = 4 x Chers

High Spatial Resolution is Needed to Resolve the "Slow Mode" Structure

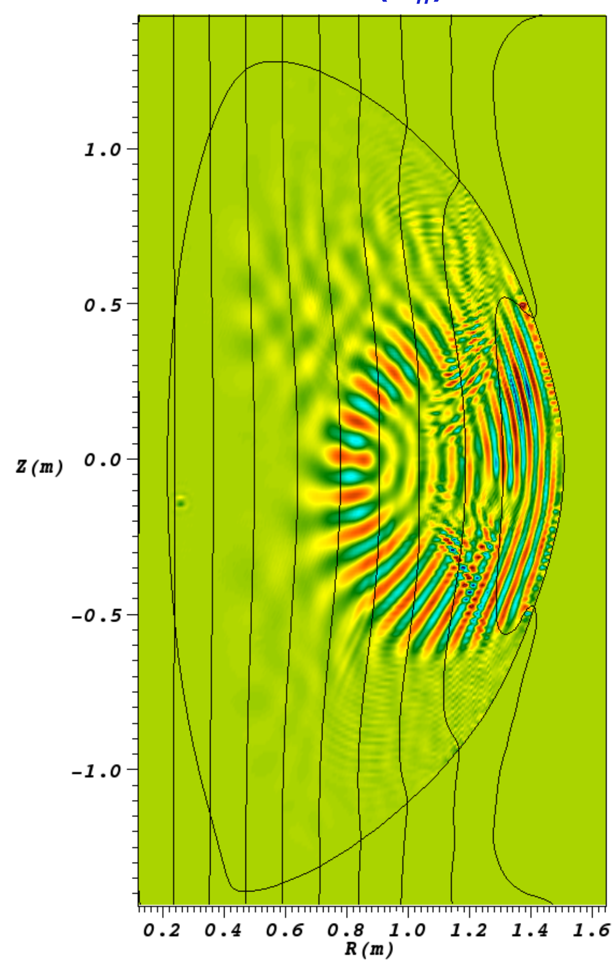
AORSA: NSTX #130608 4xTi

Real ($E_{//}$)



128x128 modes

Real ($E_{//}$)

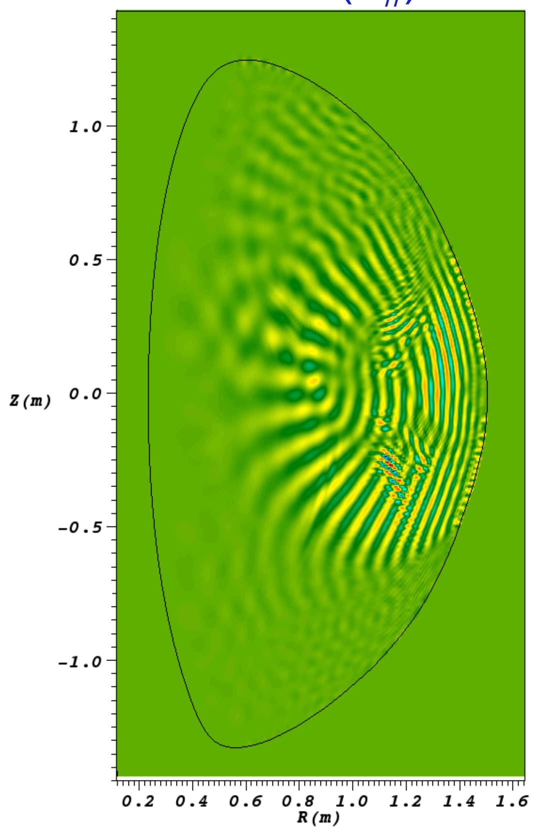


256x256 modes

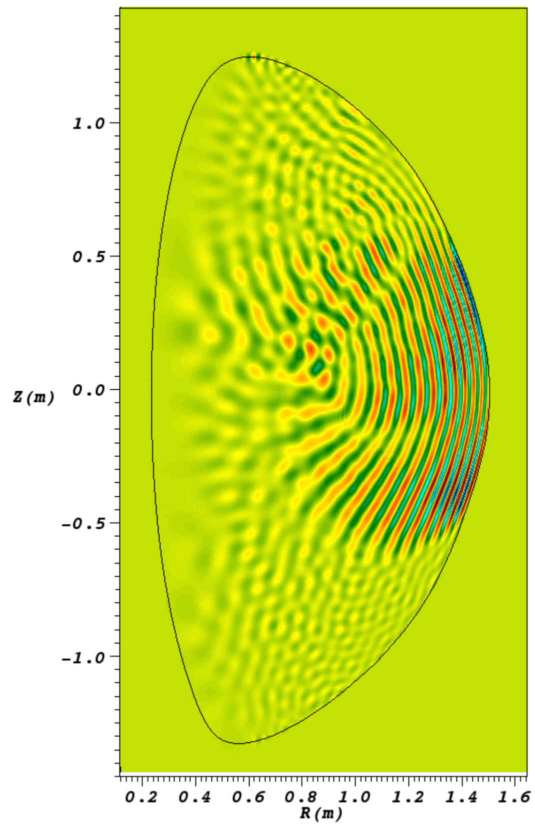
Note that the slow mode is not centered on the ion cyclotron harmonic layers

“Slow Wave” is Evident Primarily in $E_{//}$

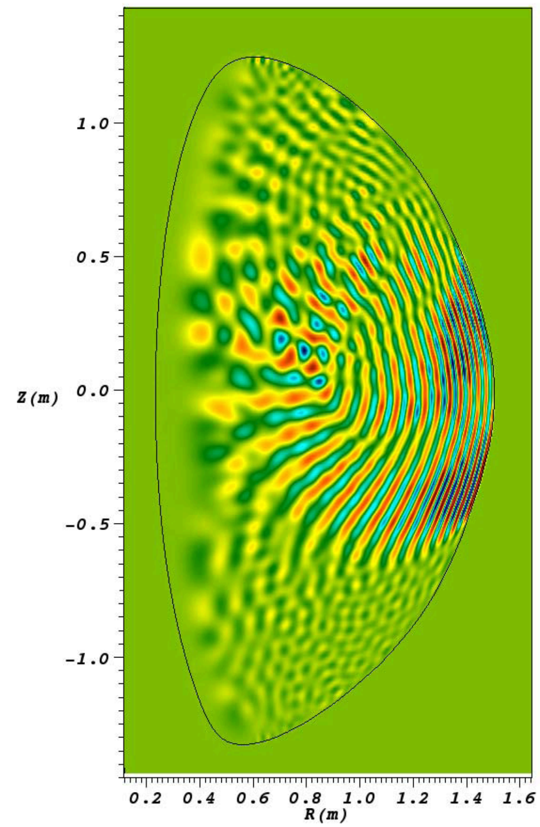
Real ($E_{//}$)



Real (E_{+})



Real (E_{-})



The magnitude of E_{+} is larger than the magnitude of $E_{//}$ for the fast wave, as expected

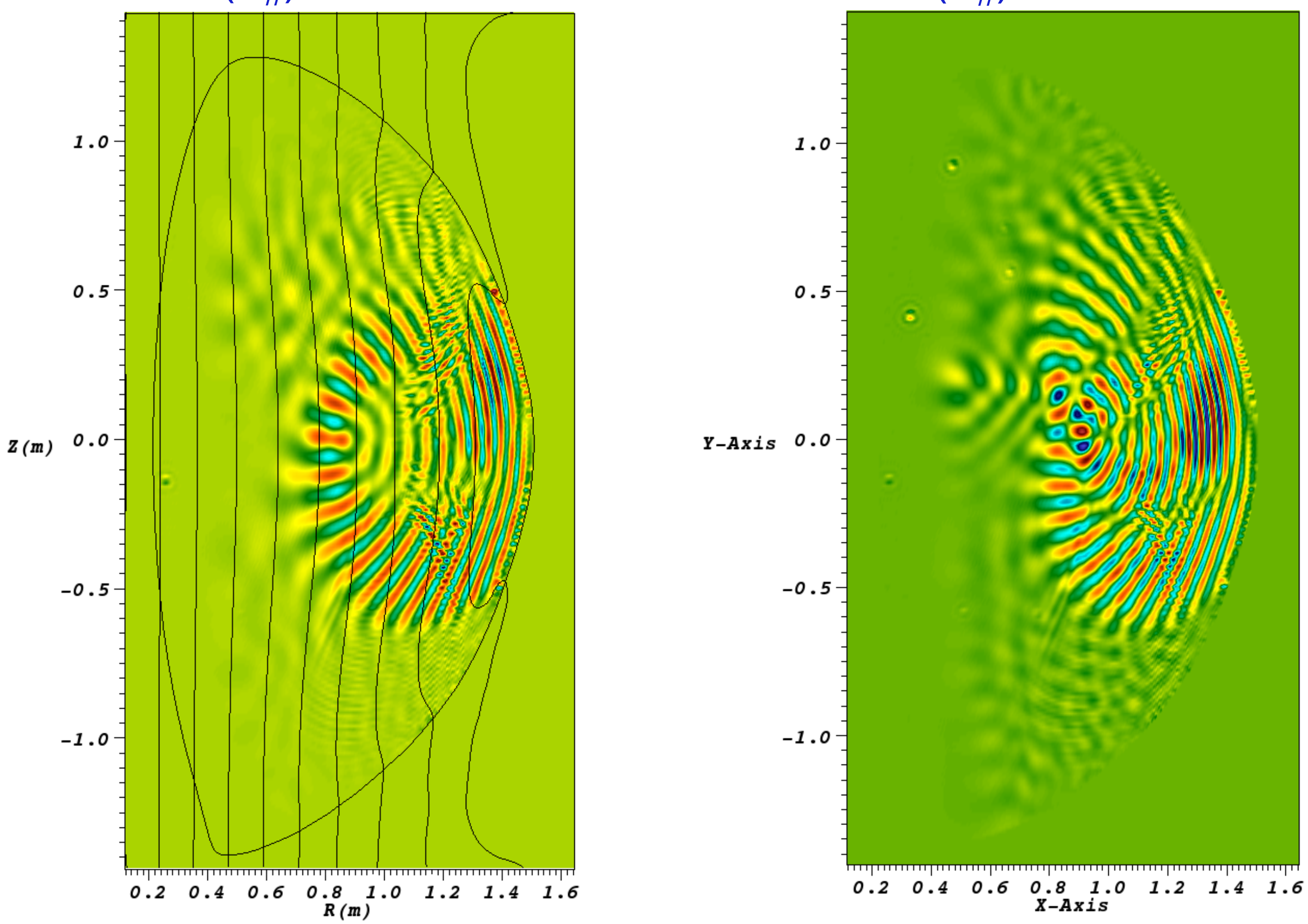
AORSA: NSTX #130608 4xTi

“Slow Mode” Excitation Disappears When the Electrons Are Assumed To Be Cold

The “Slow Mode” Persists Even if the Ions are “Cold”

Real($E_{//}$) with Hot ions

Real($E_{//}$) with Cold ions



AORSA: NSTX #130608 4xTi 256x256 modes n_{ϕ}=12

In the HHFW Regime, the Usual Assumption is That Only the "Fast Wave" Propagates

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

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

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

where

$$a = K_{xx,cold} = S = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2 - \Omega_{cs}^2}, \quad b = -K_{zz}(n_{//}^2 - S),$$

$$c = K_{zz}(n_{//}^2 - R)(n_{//}^2 - L) \quad \text{where} \quad S = \frac{1}{2}(R + L)$$

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

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

>> The slow wave is usually assumed to be evanescent, with $K_{zz} \sim -\omega_{pe}^2/\omega^2$ and $S<0$ for $\Omega_i<\omega$ in the ICRF and HHFW regimes with low field side launch.

The Slow Mode May Propagate and Damp in NSTX if "Warm Electrons" are Present

In the HHFW regime: $K_{xx} \approx S = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2 - \Omega_{ci}^2} \sim -\frac{\omega_{pi}^2}{\omega_{ci}^2}$ for $\Omega_{ci} < \omega << |\Omega_{ce}|$

$$K_{zz} = \frac{-\omega_{pe}^2}{k_{//}^2 v_{te}^2} Z'\left(\frac{\omega}{k_{//} v_{te}}\right) \quad \rightarrow -\frac{\omega_{pe}^2}{\omega^2} \quad \text{for cold electrons}$$

$$\text{but, for warm electrons, } K_{zz} \rightarrow \frac{2\omega_{pe}^2}{k_{//}^2 v_{te}^2} + 2i\sqrt{\pi}\frac{\omega}{k_{//} v_{Te}} e^{-\zeta_{0,e}^2}$$

$$\text{when } \zeta_e = \frac{\omega}{k_{//} v_{te}} < 1$$

So, for the slow wave:

$$\left[n_{\perp,slow}^2\right]_{real} \approx \left[-\frac{K_{zz}}{S}(n_{//}^2 - S)\right]_{real} > 0 \text{ for } S < 0 \text{ and } K_{zz,real} > 0$$

The “Slow Mode” is Related to Other Waves Studied Previously

$$n^2_{\perp,slow} \approx -\frac{K_{zz}}{S}(n^2_{//} - S) \quad \text{propagates when} \quad \zeta_e = \frac{\omega}{k_{//} v_{te}} = \frac{c}{n_{//} v_{te}} << 1$$

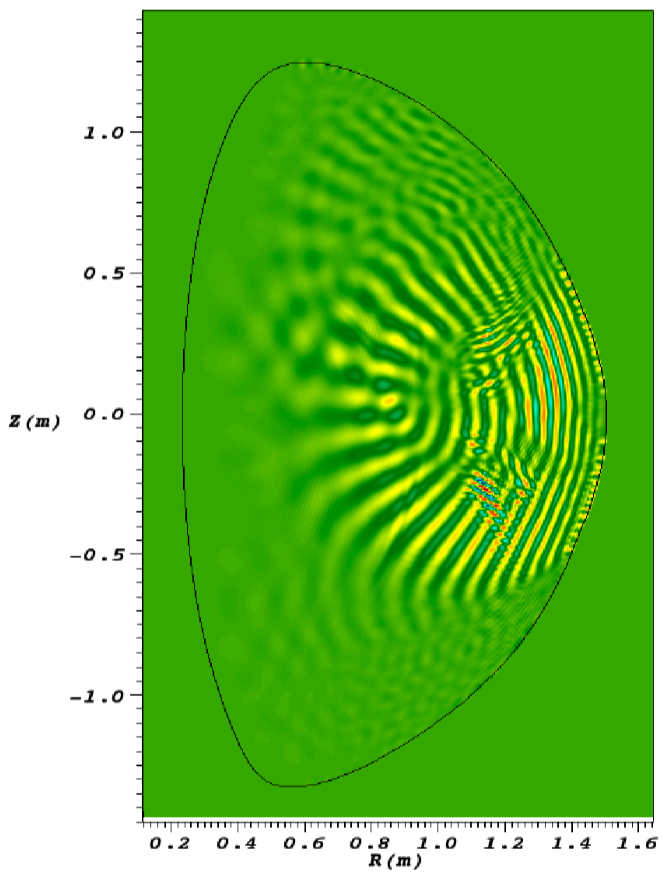
$$\Rightarrow \frac{K_{zz}}{|S|} n^2_{//} \qquad \text{or} \quad \omega^2 = \Omega^2_D + k^2_\perp c^2_s \quad \text{if} \quad n^2_{//} >> |S|$$

*This is the warm electrostatic ion cyclotron wave, observed by D’Angelo and Motley [Phys. Fluids **5** (1962) 633] in a linear device*

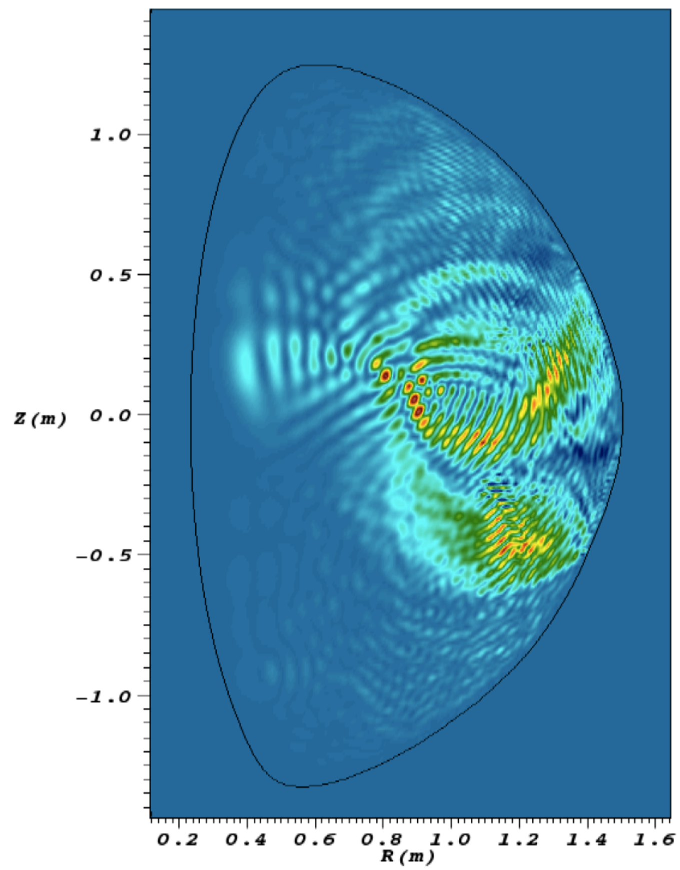
$$\Rightarrow K_{zz} \qquad \text{if} \quad n^2_{//} << |S|$$

For $\omega < \Omega_{ci}$ and cold ions, this is the kinetic Alfvén wave, discussed in Stix, “Waves in Plasma”, (AIP,1992) pg. 356-358.

Electron Power Absorption is Associated with the Slow Wave Excitation Regions



Real ($E_{//}$)



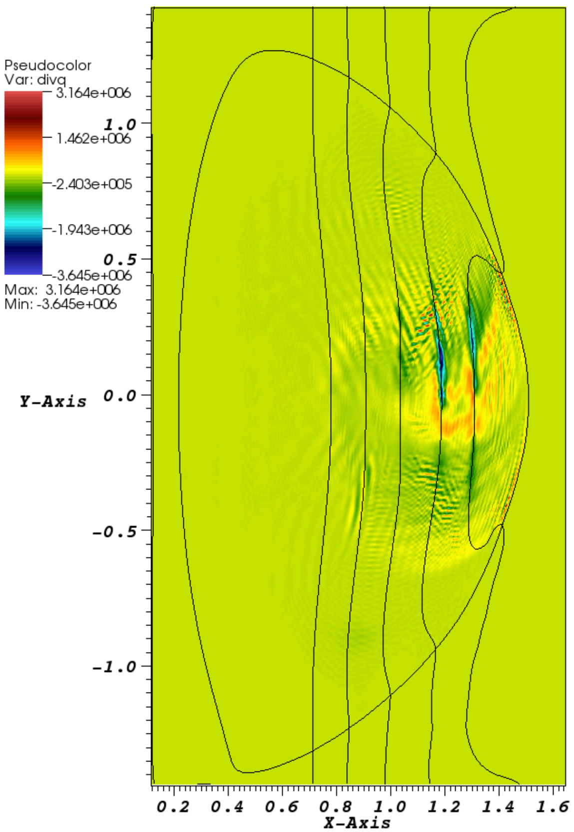
electron absorption

Electron damping is seen on both the launched HHFW's and the mode-converted "slow wave"

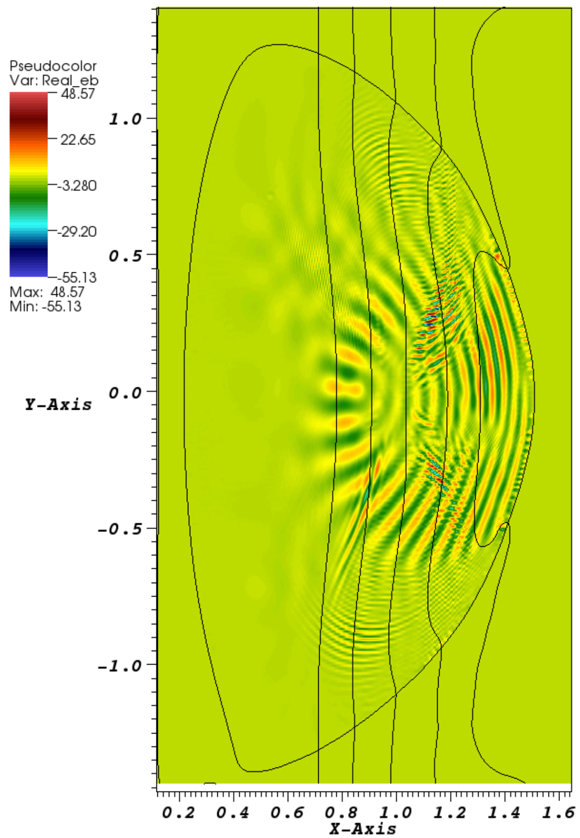
AORSA: NSTX #130608 4xTi 256x256 modes n_{ϕ}=12

Kinetic Flux is Associated with the Slow Mode and the HHFW

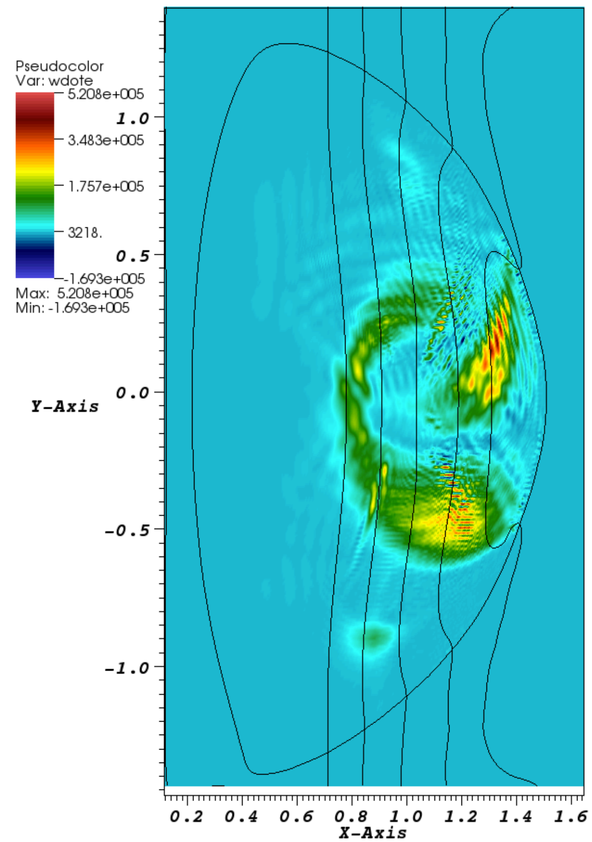
Divergence of Kinetic Flux



Real ($E_{//}$)



Electron Absorption (dWe/dt)



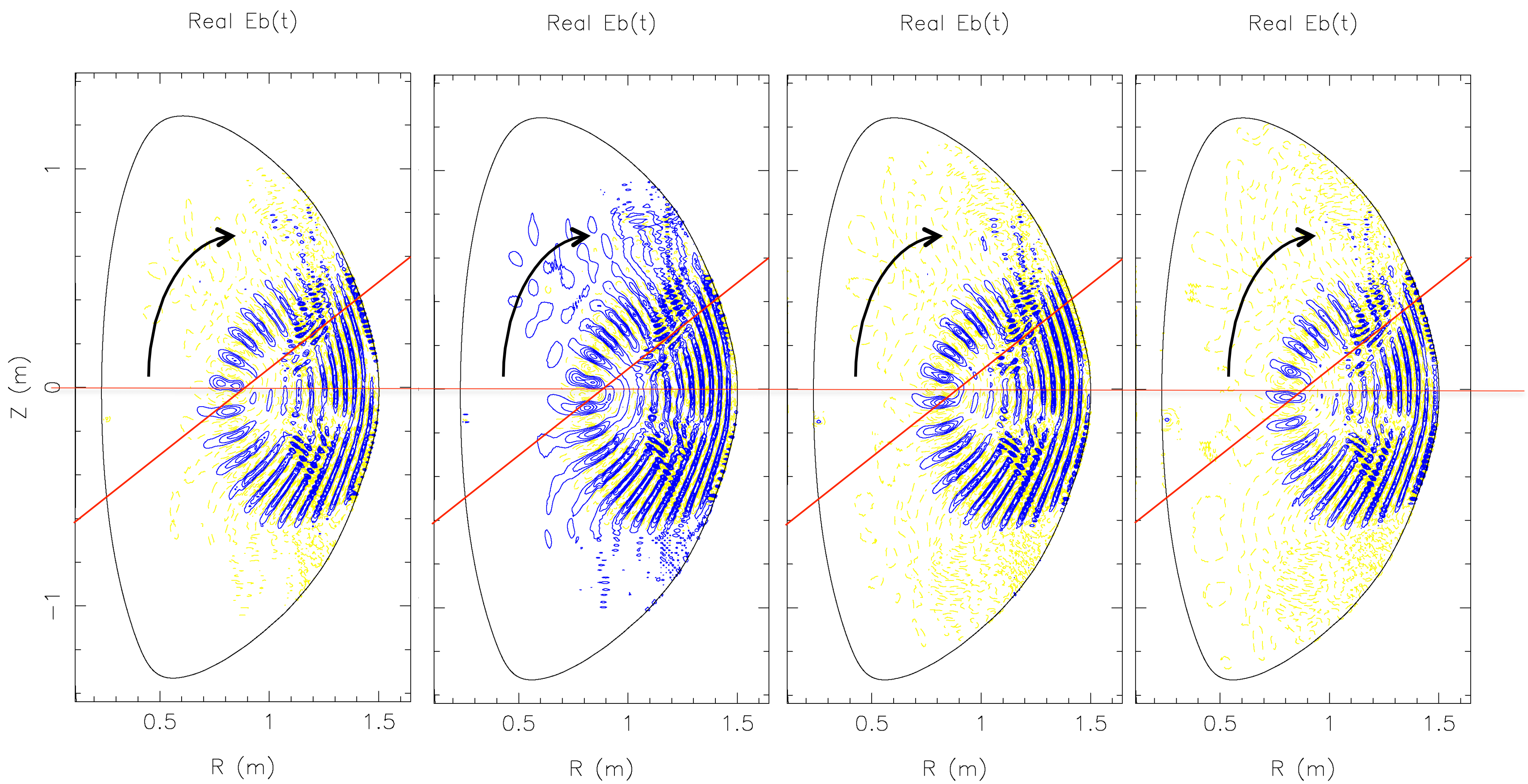
300 X 300 modes used in simulation

AORSA: NSTX #130608 4xTi 256x256 modes n_{ϕ}=12

See E. F. Jaeger et al, this meeting JP9.00089

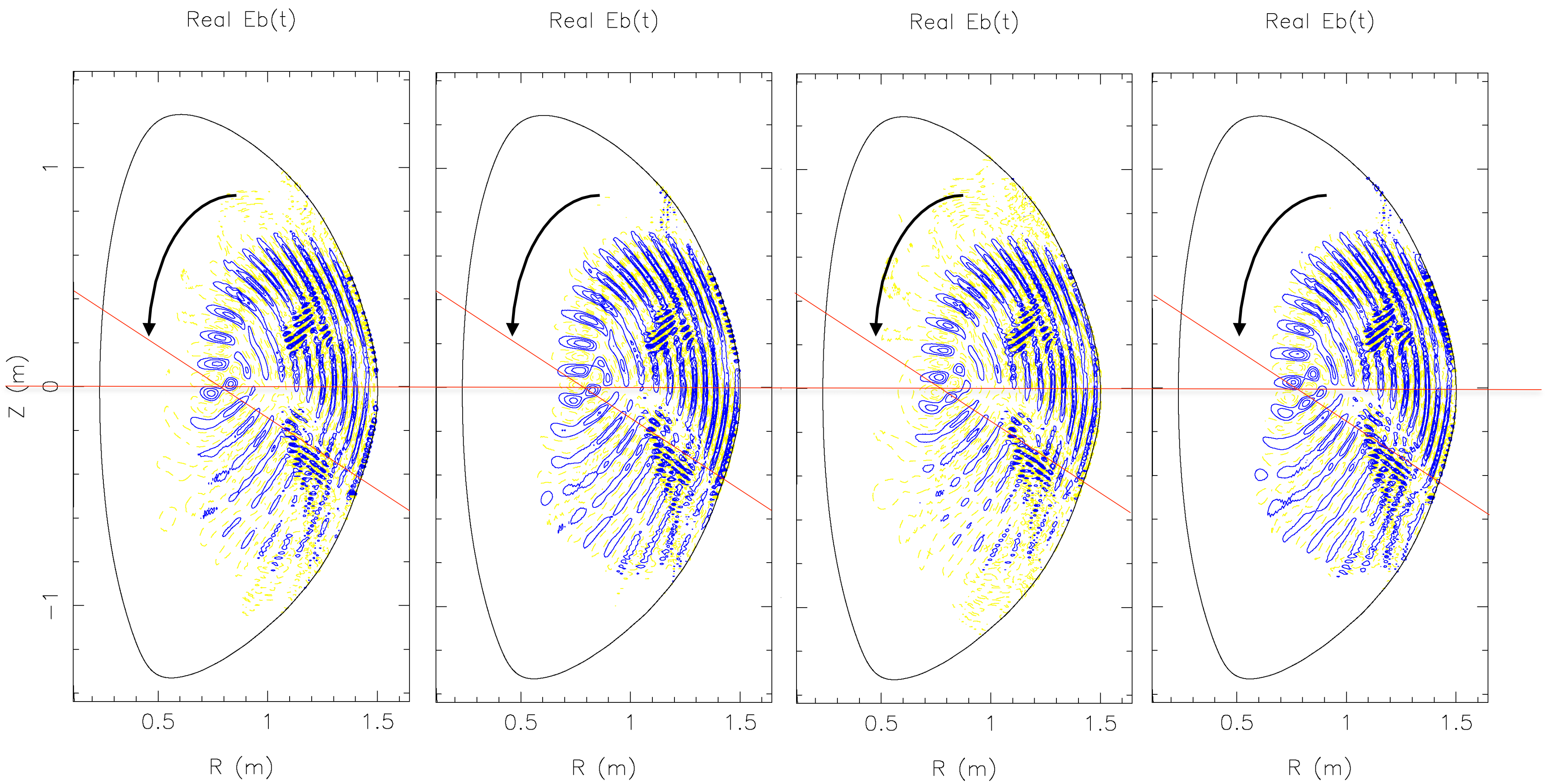
Fast and Slow Waves Propagate Clockwise Along *B* for N_ϕ = +12 (-90° phasing)

AORSA for shot 130608

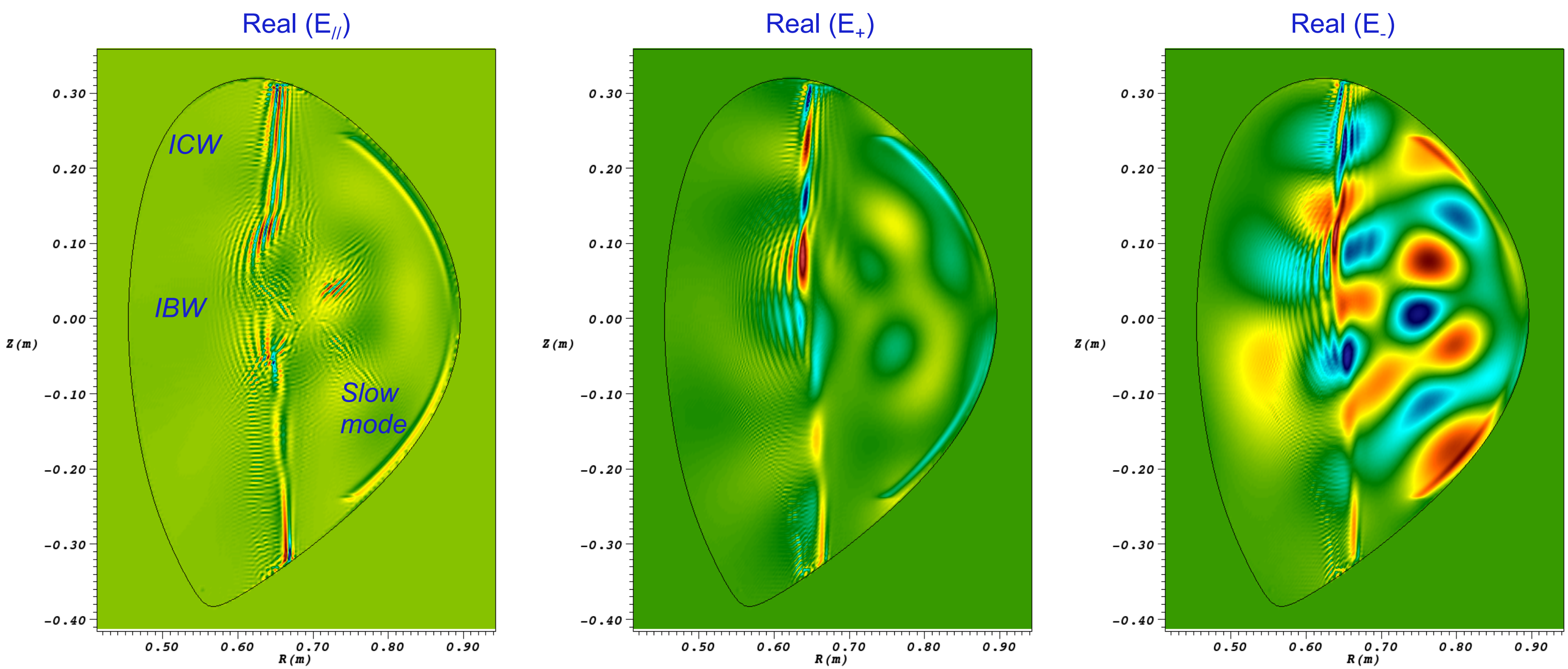


Fast and Slow Waves Propagate Counterclockwise Along *B* for N_ϕ = -12 (+90° phasing)

AORSA for shot 130608



Short Wavelength "Slow Mode" Excitation is also seen in C-Mod ICRF Wave Fields



AORSA simulation with 256X256 modes

91% D / 9% H minority heating in C-Mod with B_{T0}=5.29T, f_{RF}=80 MHz, n_ϕ=10

Slow mode also seen in TORIC simulations of this C-Mod discharge

Slow Mode Behavior in Simulations is Consistent with Theory

- Slow mode vanishes from simulation results if the electrons are "cold".
  - In AORSA, the mode vanishes if the "l=0" component of $K_{zz,e}$ is omitted
- Slow mode remains if the ions are "cold".
- Slow mode is polarized primarily in the $E_{//}$ direction
- Slow mode appears off-midplane, as expected if $k_{//}$ - upshift due to B_p is required
  - Slow mode disappears if $k_{//}$ is held constant or very high values of $k_{//}$ are omitted
  - Movies show that the slow waves propagate along the direction of ***B*** with the direction determined by the sign of n_ϕ
- Slow mode appears in regions where $K_{xxc} = S$ is negative, where $\omega > \Omega_{ci}$ [in NSTX in the HHFW regime and in C-Mod on the low field side of the ion cyclotron layers]
- Slow mode appears to damp quickly in the simulations

Enhancements of Existing Diagnostics are Needed to Detect This Slow Mode in Experiments

NSTX: The upper frequency range of the High-k scattering or the BES diagnostics would need to be extended to the 30 MHz range [D.R. Smith]

- both can resolve structures of a few cm in extent
- may be detectable by beat-wave excitation of modes in the 1-2 MHz range with the HHFW sources

C-Mod: The PCI diagnostic has the appropriate frequency range and spatial resolution but the sight lines would need to be adjusted. [P.T. Bonoli]

- the existing sightline is sensitive to wave electric fields in the major radial direction

DIII-D: The digitizers for the ECEI diagnostic would need to be increased to the 60 MHz range [B. Tobias; G. Taylor]

- As in NSTX, may be detectable by beat-wave excitation of modes in the 1-2 MHz range with the HHFW sources

Summary of Results

- High resolution numerical solutions for the high harmonic fast wave (HHFW) fields in NSTX *obtained with two independent full wave codes* predict the excitation of a new short wavelength mode, in addition to the launched HHFW's, that damps on electrons.

- Theoretical models indicate that the new mode may be an electrostatic 'slow mode' that requires hot electrons ($\omega < k_{//} v_{the}$) and $k_{//}$-upshift to propagate.
  – *More detailed comparisons against models for the dispersion relation for these modes are ongoing*
  – *Analysis is ongoing to rule out numerical origins for the mode*

- The same mode has been identified in simulations of the fast wave fields in C-Mod in the ion cyclotron range of frequencies (ICRF).

- Numerical simulations under different plasma conditions are consistent with the theoretical model.

- Prospects for detecting the mode experimentally require modifications of existing diagnostics on NSTX, C-Mod and DIII-D for frequency response and/or diagnostic sightlines.