Full Wave Modeling of High Harmonic Fast Wave Heating in NSTX*

C.K. Phillips, S. Bernabei, J. Hosea, B. LeBlanc, J.R. Wilson,
***PPPL*,**

P.T. Bonoli, J.C. Wright,

***PSFC-MIT*,**

E.F. Jaeger, P. Ryan, D. Swain,

ORNL

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Overview

- **Description of the TORIC code for the high harmonic fast wave (HHFW) regime**

- **Summary of data analysis of two comparison discharges from NSTX: shot #112699 and #112705**

- **TORIC analysis of these discharges**

- **Summary and future work**

The TORIC ICRF Full-wave Code Solves the Kinetic Wave Equation in 2D Axisymmetric Equilibria

NSTX

- **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 Has Been Extended to the High Harmonic Fast Wave Regime

NSTX

- **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**
- **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*

Other Significant Enhancements of the TORIC Code Have Been Implemented

NSTX

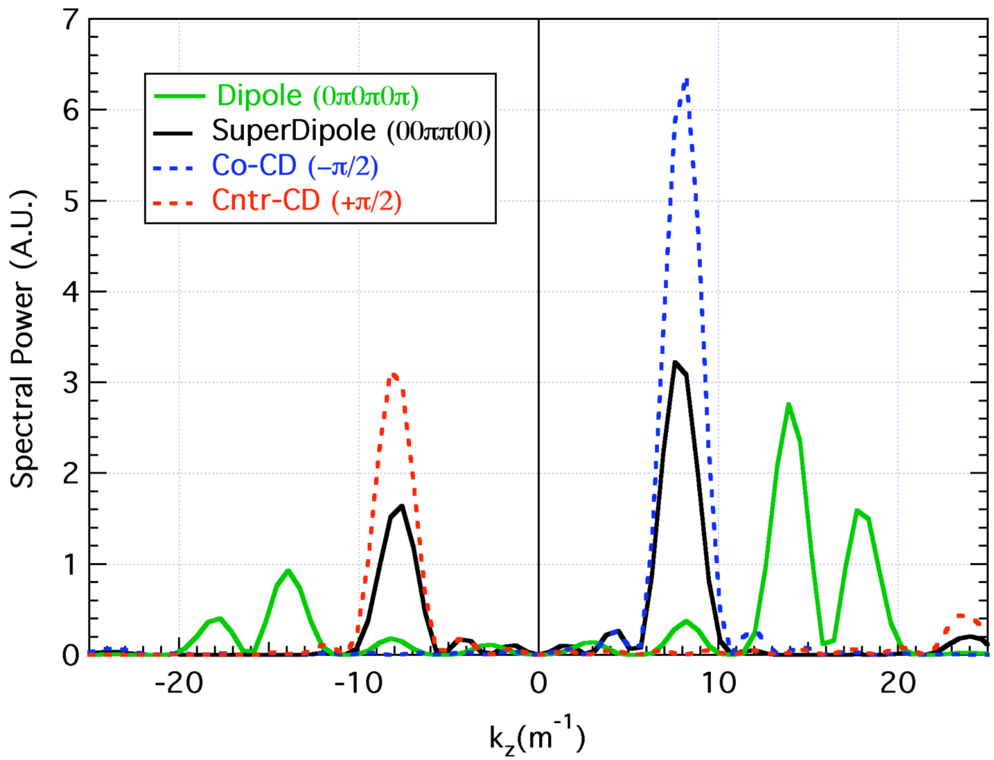
- **Work funded through many sources: RF SciDAC Initiative, NSTX Collaborative Grant, PPPL, MIT, IPP.**

- **Code now reads and uses EFIT equilibria and experimental profiles of density and temperature (IPP and PPPL).**

- **Code implemented on both serial and parallel computing architectures (MIT – Beowulf cluster).**

Power Modulation Experiments on NSTX show Phase Dependence of Absorption

- Lower k_T excitations have less power absorption
  [Bernabei JP1.011, Hosea JP1.012]
  - » differences in absorption between co- and ctr- phasing
  - » power absorbed by electrons qualitatively agrees with theory
- Significant power goes into edge ion heating
  [Diem JP01.014, Biewer RI1.001]
  - » amount increases at lower k_T
  - » consistent with parametric decay



Phasing of Transmitters allows variable k_T excitation

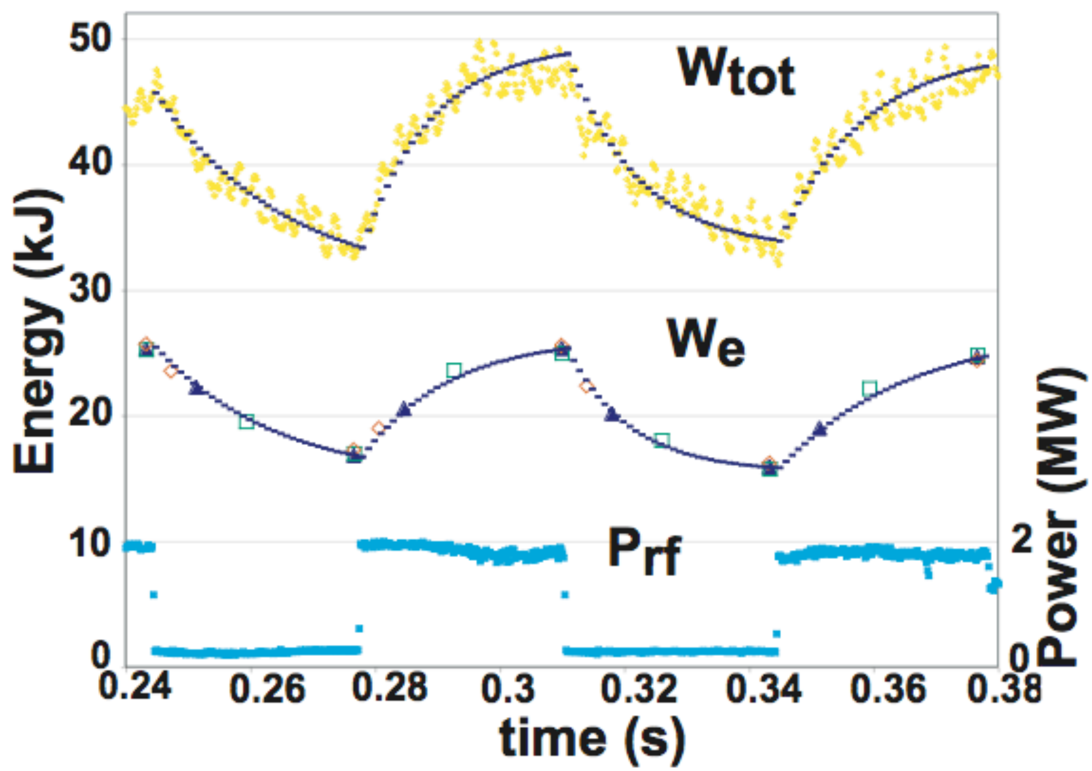
J.R. Wilson CO3.012

RF Power Absorption and Incremental Confinement Obtained from Power Modulation

Heating efficiency increases with k_T

k_T	%Power absorbed
14	80
+7	70
-7	55
+3	<20

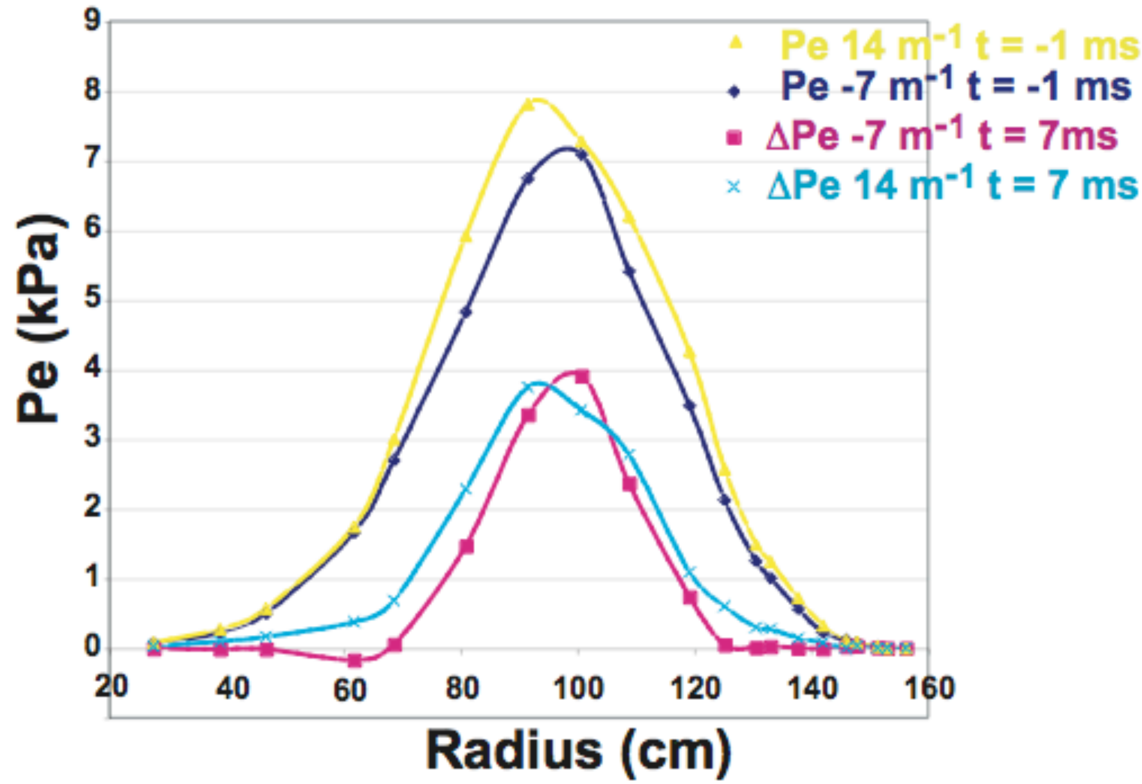
Simulate 14 m^{-1} and -7 m^{-1} with TORIC code



Hosea JP1.012
Bernabei JP1.011
Wilson CO3.012

Radial Power Deposition into Electrons Broader for Higher Toroidal Wave Numbers

- radial profiles from Thomson scattering used to get change from sudden reduction in rf power
- Inferred power deposition profile broader for -14 m^{-1} as expected from theory

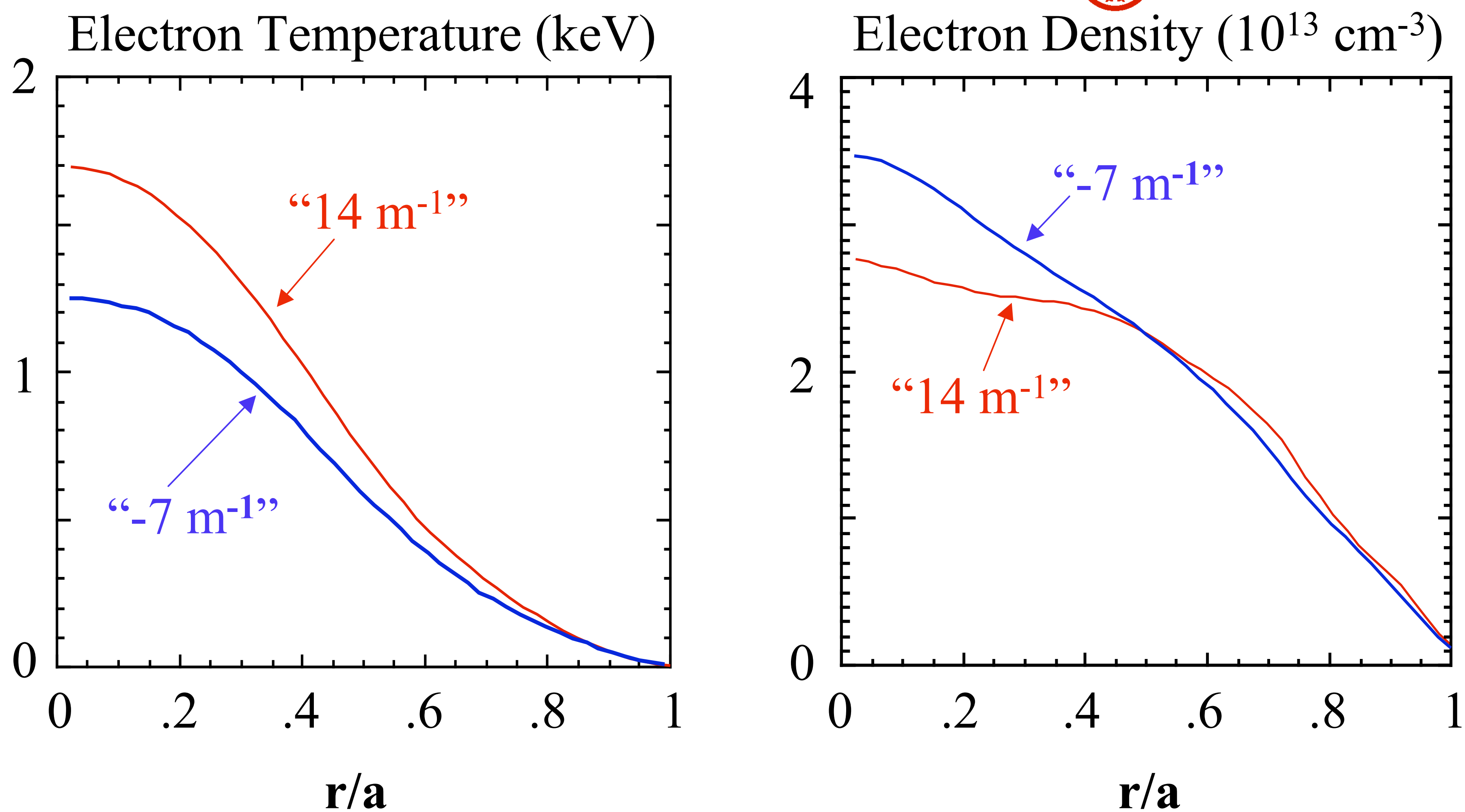


For power in electrons : see ***Hosea JP1.012, Bernabei JP1.011, or Wilson CO3.012***

Look for missing power in ions - see ***Diem JP01.014, Biewer RI1.001***

Equilibrium Electron Density and Temperature Profiles Similar for the Two Discharges

NSTX

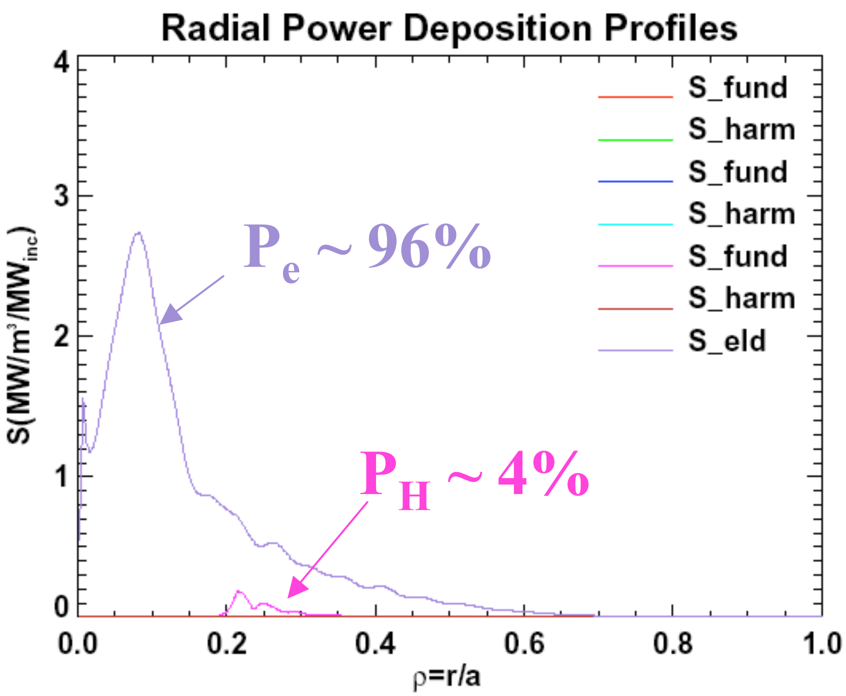


assumed $T_i(r) \sim 0.7 \times T_e(r)$ for these simulations

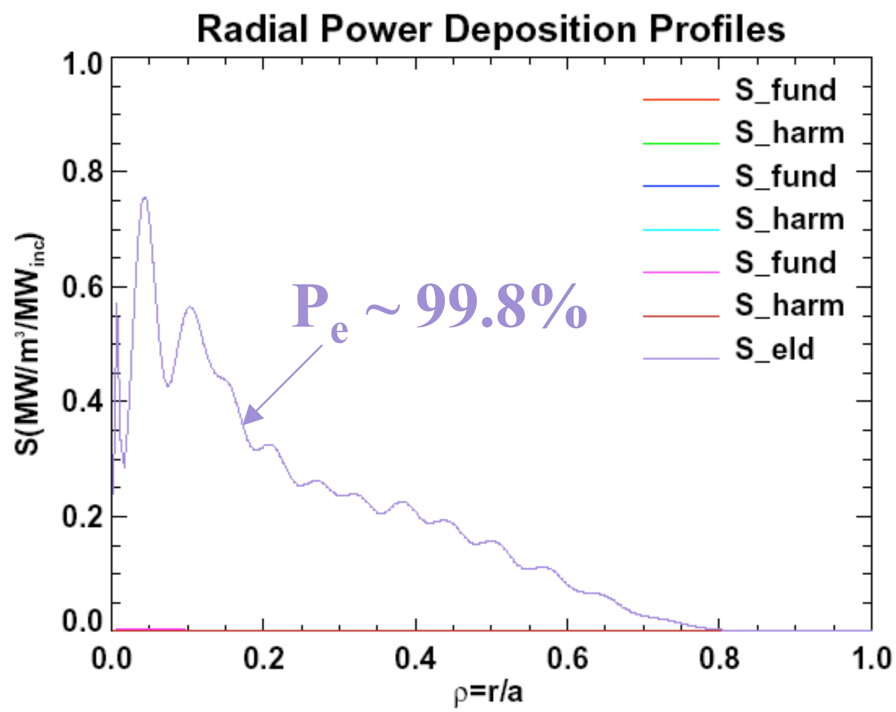
assumed 35% He-4, 20% D, and 10% H in plasma

Power Deposition Dominated by Electron Absorption

112705 :-7 m^{-1}



112699 :-14 m^{-1}



Note that hydrogen can begin to absorb power at the lower k_{tor}

No edge power deposition predicted with linear absorption mechanisms

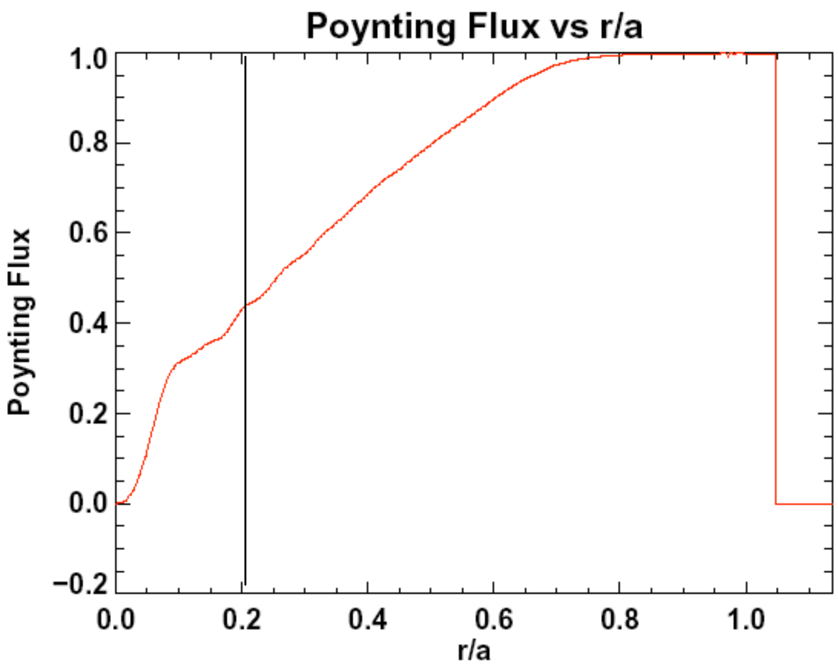
TORIC solves for single value of k_{tor} per run: for ease just consider -14 m^{-1}

(see justification slide later on)

Simulations Indicate More HHFW Power Penetrates to the Core with Lower k_{TOR}

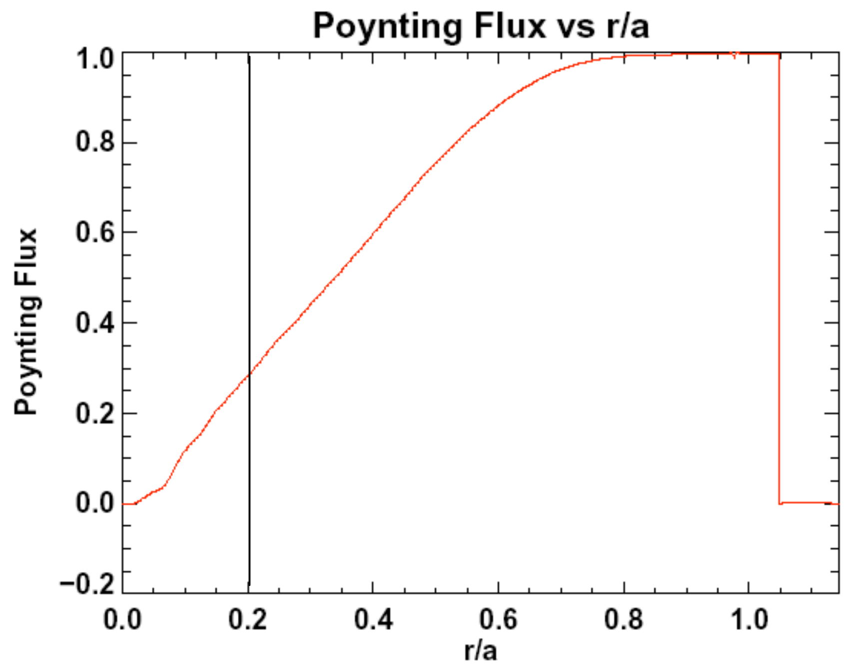
NSTX

112705 : -7 m^{-1}



~ 45% power absorbed within r/a~ 0.2 for -7 m^{-1}

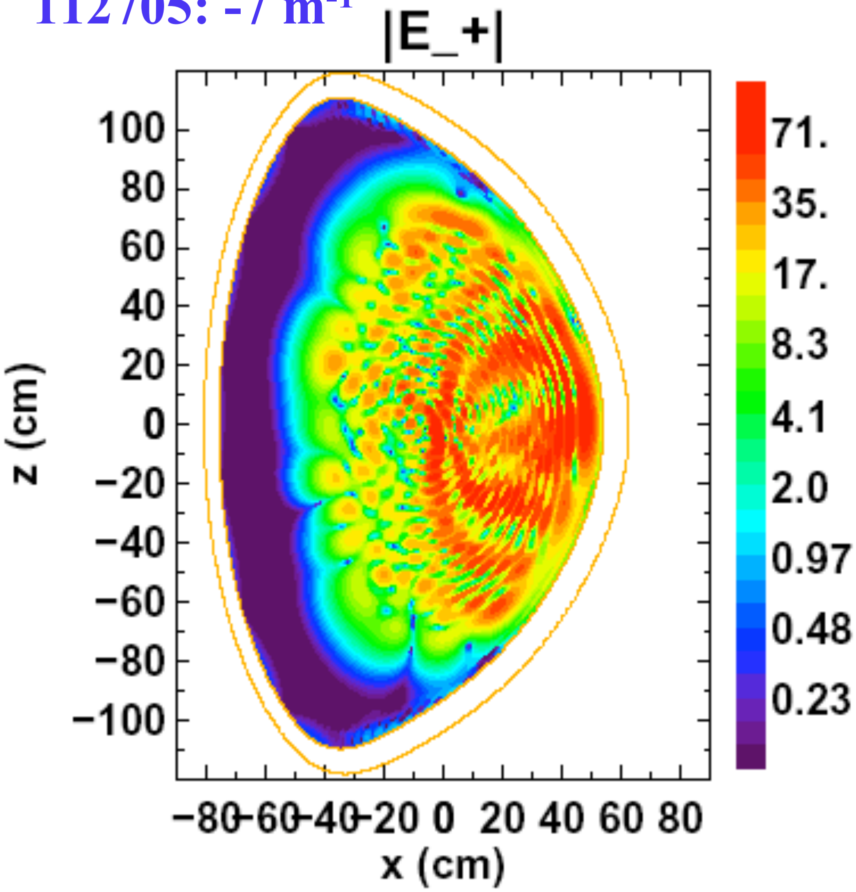
112699 : -14 m^{-1}



~ 30% power absorbed within r/a~ 0.2 for -14 m^{-1}

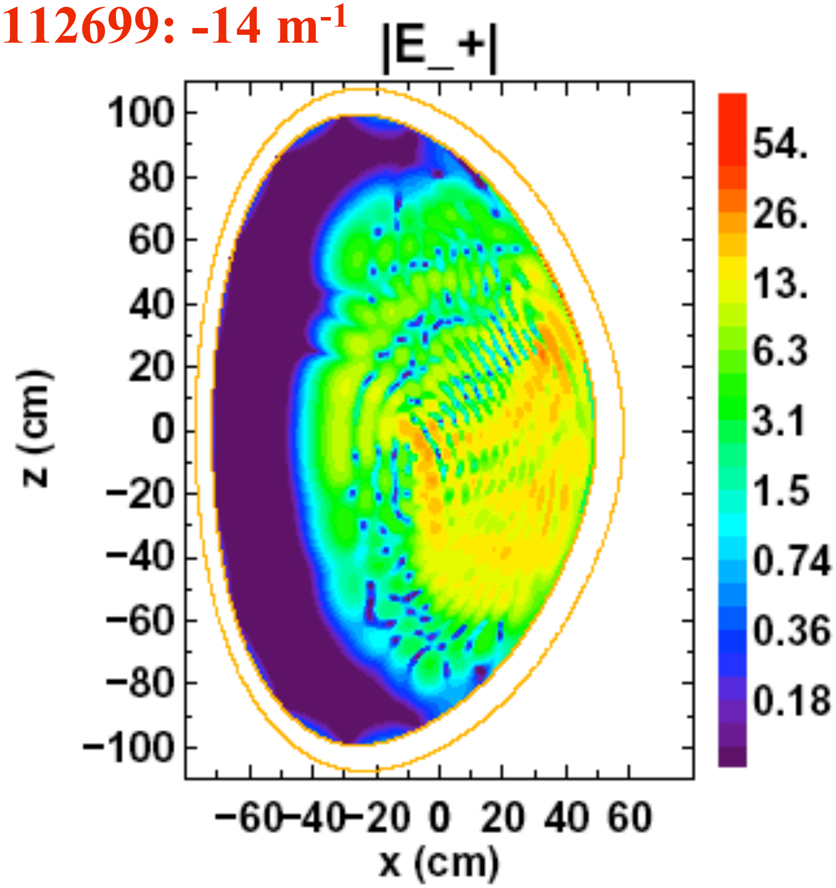
Some Differences in Wave Propagation Evident in Wave Field Structure

112705: -7 m^{-1}



"Up-down symmetric" structure of E_+ indicative of some multi-pass propagation

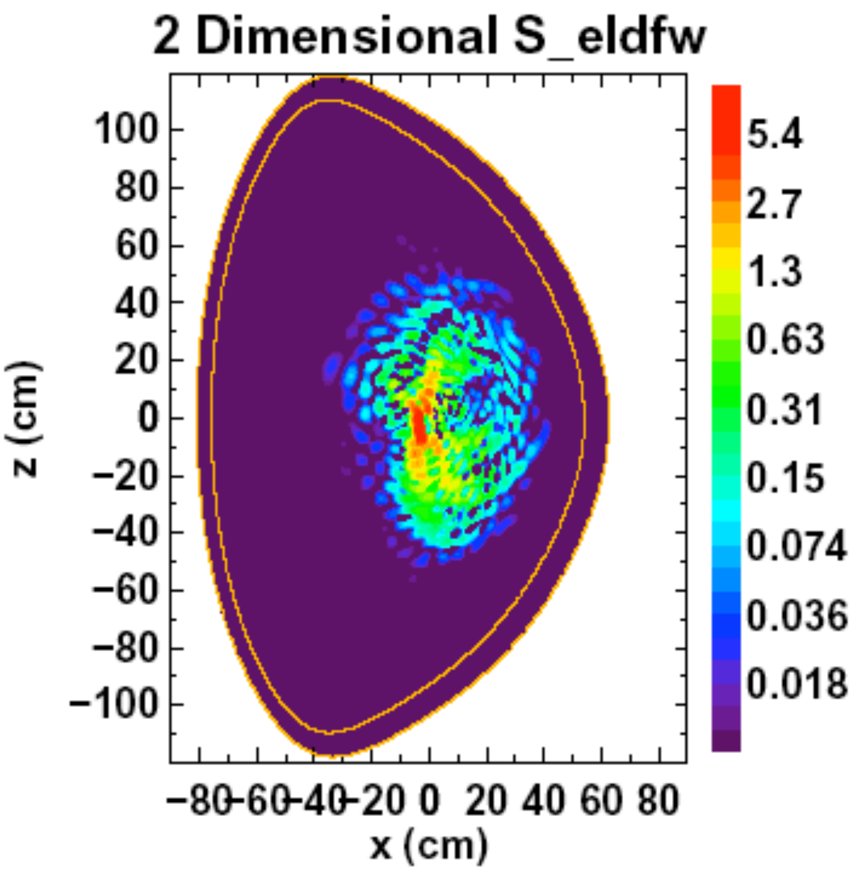
112699: -14 m^{-1}



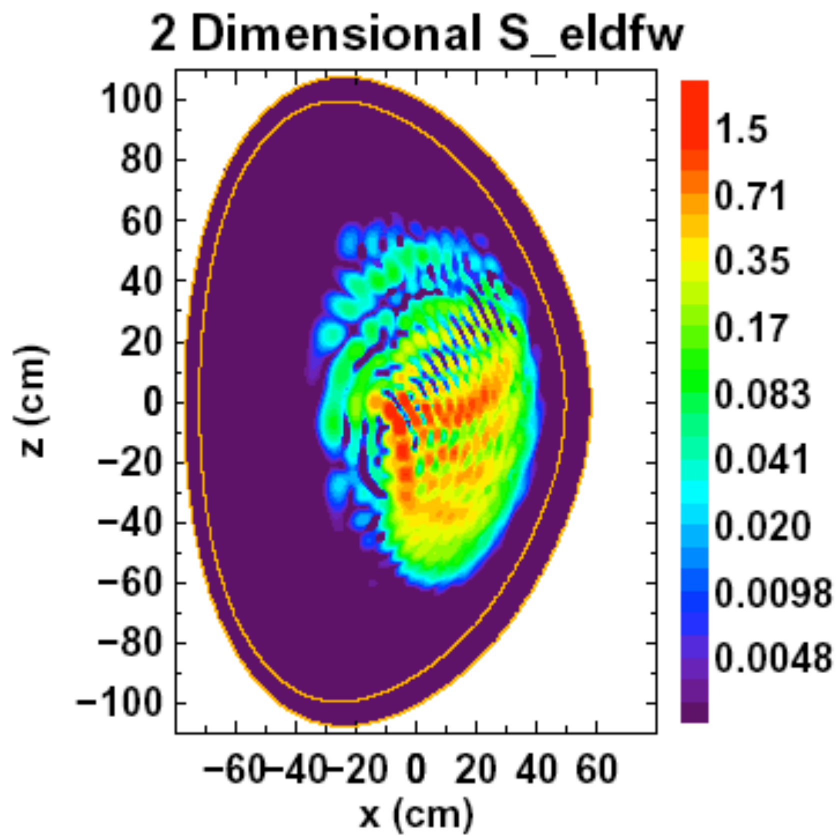
Stronger single pass absorption evident in "spiral" structure of E_+

Stronger Central Electron Absorption for Lower k_{TOR} Evident in 2D Power Deposition Contours

112705: -7 m^{-1}



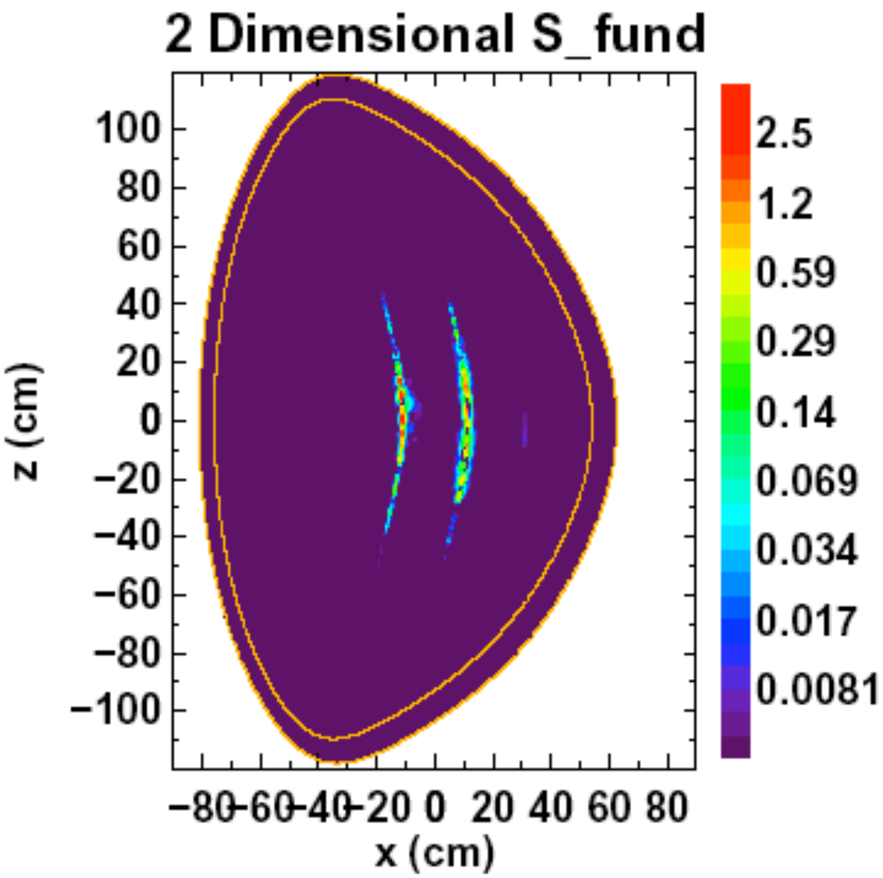
112699: -14 m^{-1}



Residual Ion Absorption is Localized Around Cyclotron Harmonic Layers

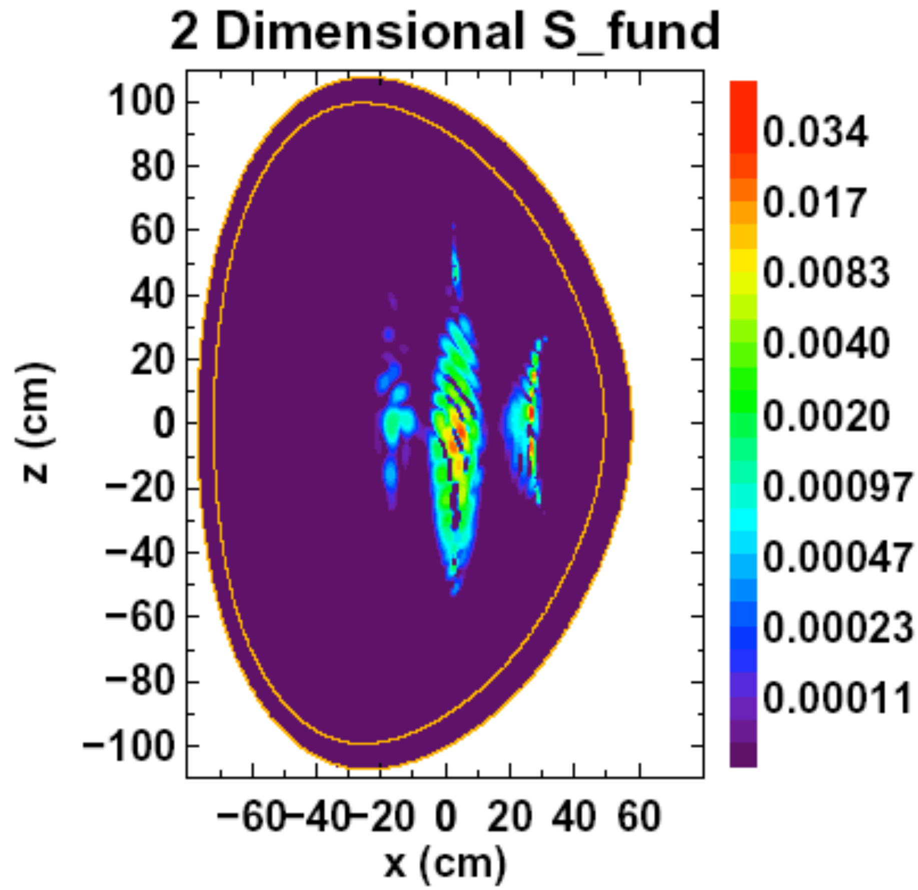
NSTX

112705: -7 m^{-1}



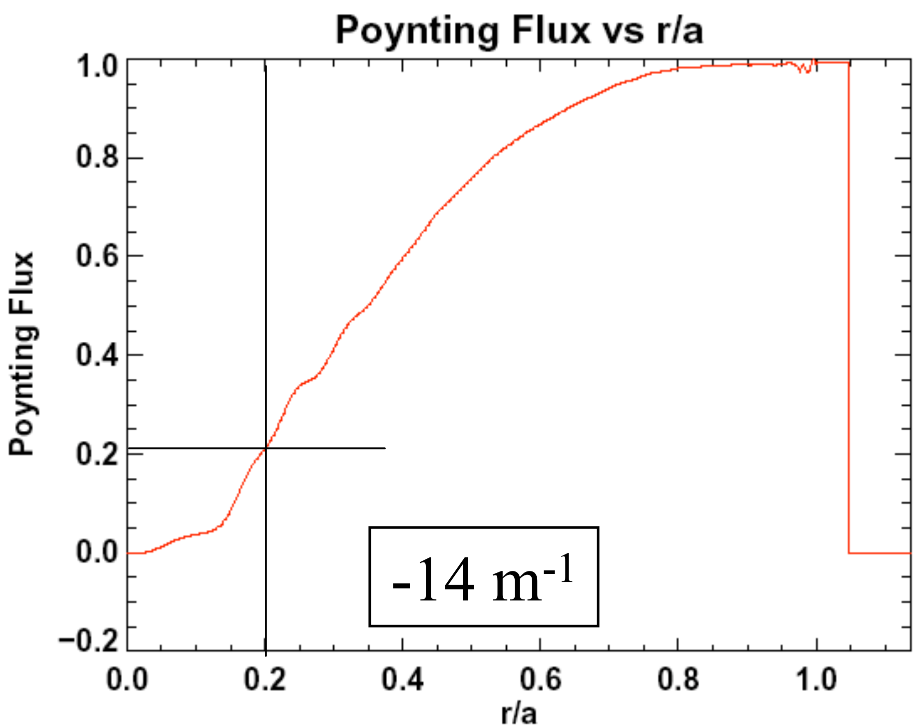
$P_H \sim 4\%$

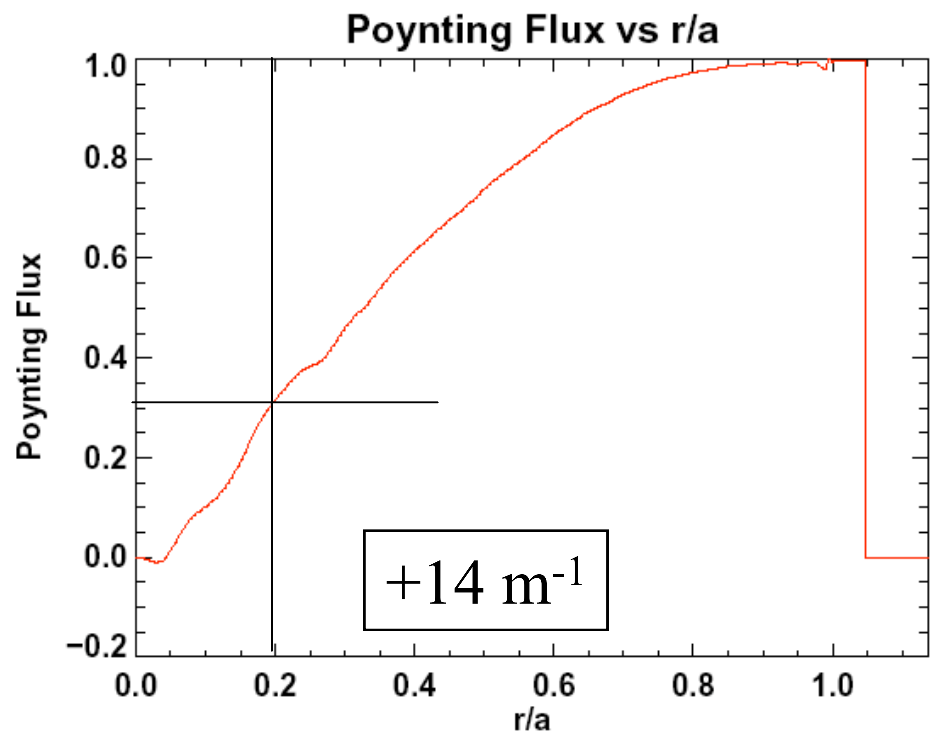
112699: -14 m^{-1}



$P_H < 1\%$

For Fixed Parameters, -14 m^{-1} has Somewhat Broader Absorption than +14 m^{-1}



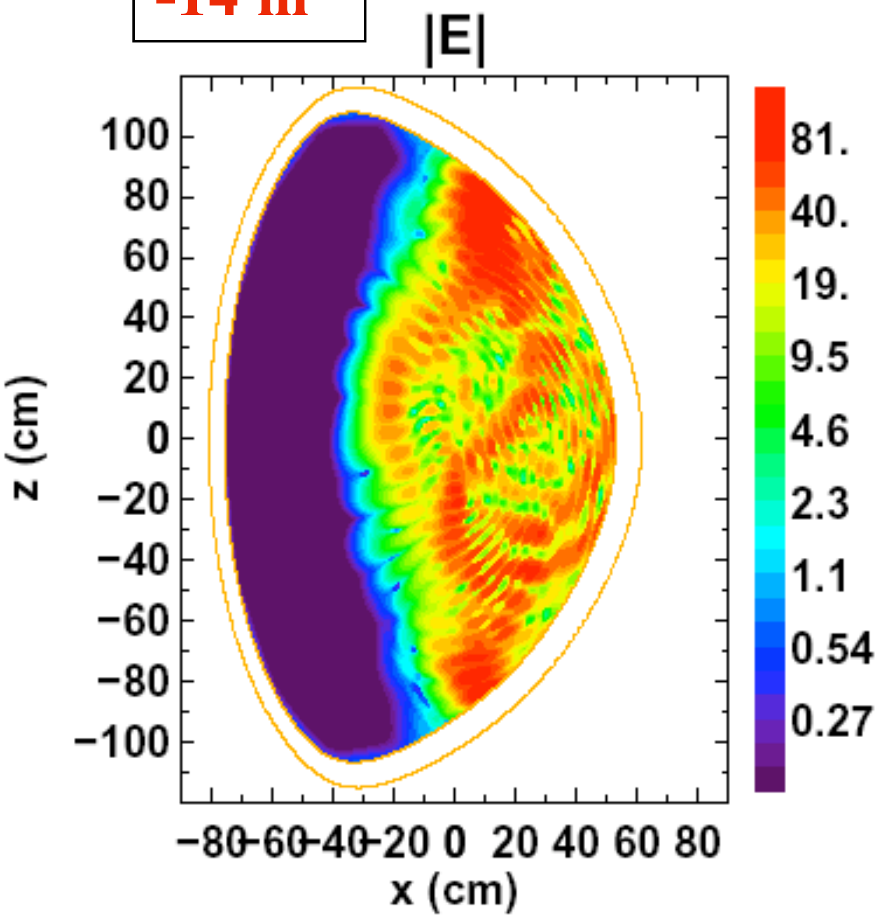


For 0-π-0-π phasing, the spectral amplitude at -14 m^{-1} is about 3X the value at +14 m^{-1} (see earlier slide), so TORIC runs used -14 m^{-1}

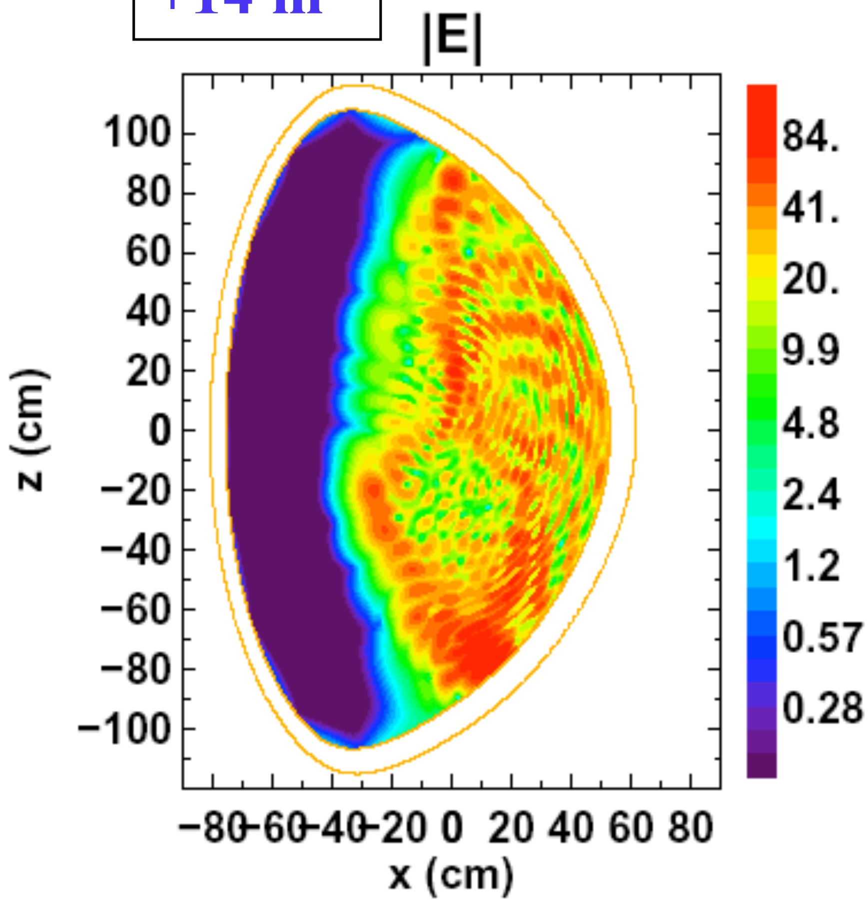
[the simulations above done with parameters typical of 112705 & 112699)

Direction of Wave Propagation Depends on the Sign of k_{tor}

-14 m^{-1}



+14 m^{-1}



Wave initially spirals in clockwise

Wave initially spirals in counterclockwise

Conclusions

- **Simulated power deposition profiles for different k_{tor} consistent with observations**

  (see Bernabei JP1.011, Hosea JP1.012 for details on observations)

  » **calculated electron absorption profiles broader at higher k_{tor}, as inferred from data**

  » **simulations do not explain the observed poorer net power absorption at lower k_{tor} -**

  - ***may be due to nonlinear edge processes***

    -(see Diem JP01.014, Biewer RI1.001)

- **TORIC code can now simulate HHFW heating in NSTX**

  » **code has been extended to include high cyclotron harmonics using a quasi-local approximation**

Future Work

- **Further development of TORIC code for NSTX applications:**
  - » **benchmark against AORSA-2D, an "all-orders" code, to check limits of validity of "quasi-local" approximation for HHFW regime**
  - » **install on the PPPL parallel cluster for more efficient modeling of NSTX experiments**
  - » **include non-Maxwellian species (e.g., beam ions) in plasma dielectric response and couple to CQL3D bounce-averaged Fokker-Planck code**
  - » **upgrade version installed in TRANSP code**