# Coupled full-wave / Fokker Planck simulations of lower hybrid wave propagation and absorption in the EAST tokamak

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# Abstract

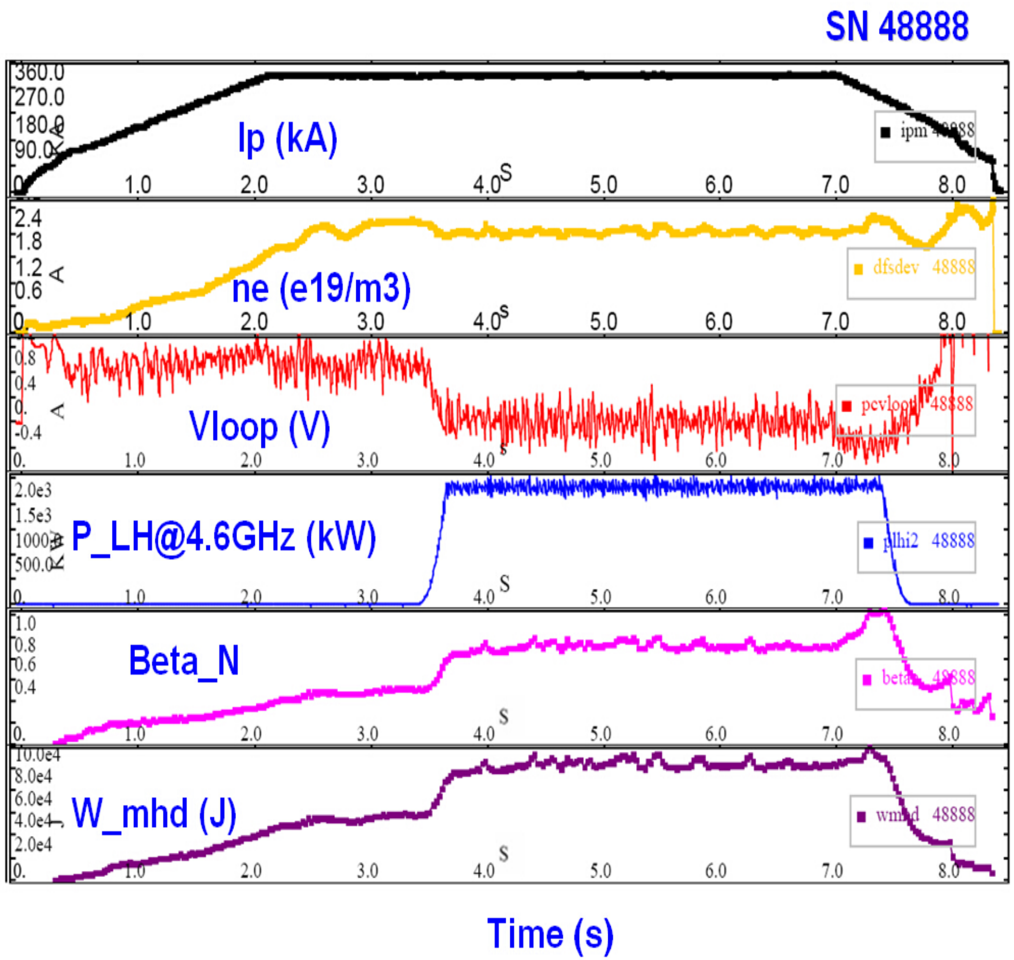
Studies of lower hybrid (LH) wave propagation have been conducted in the EAST tokamak where electron Landau damping (ELD) of the wave is typically weak, resulting in multiple passes of the wave front prior to its being absorbed. Under these conditions full-wave effects can become important at the wave cut-off at the plasma edge, as well as at caustic surfaces in the core. High fidelity LH full-wave simulations have been performed for EAST using the TorLH field solver [1]. These simulations used sufficient poloidal mode resolution to resolve the perpendicular wavelengths associated with electron Landau damping of the LH wave at the plasma periphery, thus achieving fully converged electric field solutions at all radii of the plasma. Results will be presented that demonstrate how the rate of numerical convergence depends on the strength of the local ELD where higher electron temperature resulting in numerical convergence with fewer poloidal modes. We will also discuss progress on automating the workflow for a coupling the TorLH solver with the CQL3D Fokker Planck code [2].

# This work is the subject of the 2017 Theory and Performance Target

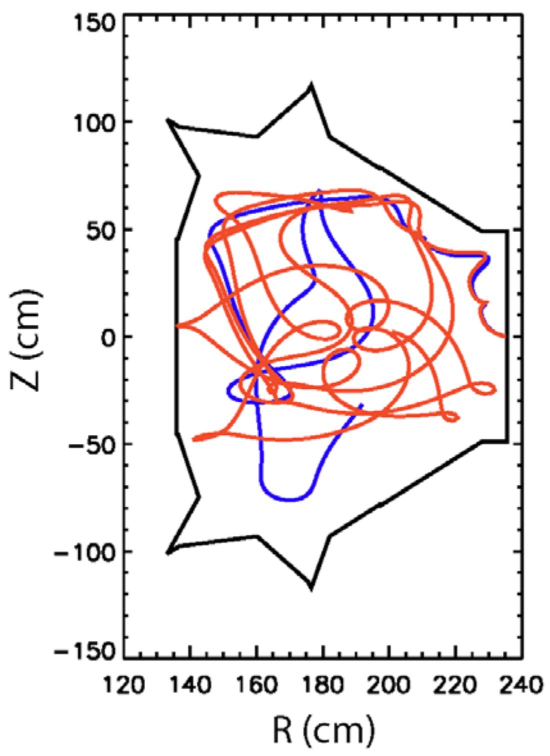
- **Lower Hybrid current drive (LHCD) will be indispensable for driving off-axis current during long-pulse operation of future burning plasma experiments including ITER, since it offers important leverage for controlling damaging transients caused by magnetohydrodynamic instabilities.**
- **However, the experimentally demonstrated high efficiency of LHCD is incompletely understood [in weak damping regimes].**
- **In FY 2017, massively parallel, high resolution simulations with 480 radial elements and up to 4095 poloidal modes are being performed using the TorLH full-wave electromagnetic field solver and the CQL3D particle Fokker-Planck code to elucidate the roles of toroidicity and full-wave effects in LHCD experiments on the EAST tokamak**
  - **Prior simulations using TorLH and CQL3D [3] were only performed for up to 2047 modes where numerical convergence on all radial flux surfaces was not complete.**
- **This work spans the research interests of the CSWPI SciDAC Center, the MIT Theory Grant, the Alcator C-Mod Project and the EAST / KSTAR Scenario Extension and Control Collaboration.**

# LHCD in the EAST Tokamak

- **LHCD experiments in EAST are in the weak damping regime where full-wave effects and interference effects can potentially be very important [3]:**




**Ray tracing / Fokker Planck simulations show multi-pass nature of absorption:**




**[3] C. Yang et al, PPCF (2014)**

# Set-up for “low temperature” simulations

- **Use experimental profiles and EFIT equilibrium reconstruction for discharge 048888.05500:**
  - **Created Fourier MHD equilibrium representation for TorLH (equigs.dat) and kinetic profiles data file (equidt.data):**
  - **$B_0$ = 2.31 T, $I_p$ = 373 kA, a = 0.42 m, $R_0$ = 1.85 m, $T_e(0)$ = 3.2 keV, $n_e(0) = 3.6 \times 10^{19}$ $m^{-3}$.**
- **RF parameters:**
  - **$P_{LH}$ = 2 MW, $f_0$ = 4.6 GHz, $n_{//}$ = -1.80**
- **Status of TorLH / CQL3D executables (05-2017):**
  - **NERSC: Edison**
  - **MIT-PSFC Engaging Cluster**
  - **IPP Shenma Cluster**

# Numerical implementation and mode resolution requirements for TorLH

- **Semi-spectral ansatz is assumed for the electric field:**

$$\vec{E}(\vec{x}) = \sum_{m,n} \vec{E}_{m,n}(\psi) e^{im\theta + in\phi}$$

  - Spectral decomposition in the poloidal (*m*) and toroidal (*n*) directions.
  - $E_{m,n}(\psi)$ are represented by finite elements in the radial direction (cubic Hermite interpolating polynomials).
- **Using the ansatz above, the wave equation can be put in a weak variational form (Galerkin method):**
  - Each toroidal mode (*n*) is solved separately assuming $N_m$ poloidal modes and $N_r$ radial elements.
  - **This results in a block tri-diagonal matrix to invert.**

# Matrix inversion is performed using a new "3D" parallel solver [4]

$$\underline{\underline{A}} = \begin{pmatrix} \mathbf{D} & \mathbf{U} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{L} & \mathbf{D} & \mathbf{U} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{L} & \mathbf{D} & \mathbf{U} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{L} & \mathbf{D} & \mathbf{U} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{L} & \mathbf{D} \end{pmatrix}$$

**L, D, U are each dense block matrices of size $(2 \times 3 \times N_m)^2$**

**Total of $N_r$ block rows**

- **Parallel decomposition of blocks is distributed over $p_2 \times p_3 \equiv$ pcblock processors.**
- **Solver distributes groups of rows over $p_1$ processors.**
- **Matrix inversion time scales like $N_r \times (N_m)^3$ using $p_1 \times p_2 \times p_3$ cores.**

# Poloidal mode resolution requirements for TorLH to simulate LH wave propagation in EAST

- **Must resolve the shortest perpendicular wavelength in the system, which is given by the LH dispersion relation:**

$$k_{\perp} \approx k_{//} \frac{\omega_{pe}}{\omega} \approx \frac{m}{r}$$

- **For an EAST discharge at r/a ~ 0.5 with $B_0$ = 2.3 T, $T_e(0)$ ~ 1 keV, $n_e(0) \sim 2.0 \times 10^{19}$ $m^{-3}$, $f_0$ = 4.6 GHz, we have:**

$$k_{\perp} = 17\ cm^{-1}\ (\text{for } n_{//} \sim \mathrm{n}_{//0} = 2) \Rightarrow m \approx r k_{\perp} \approx 372$$

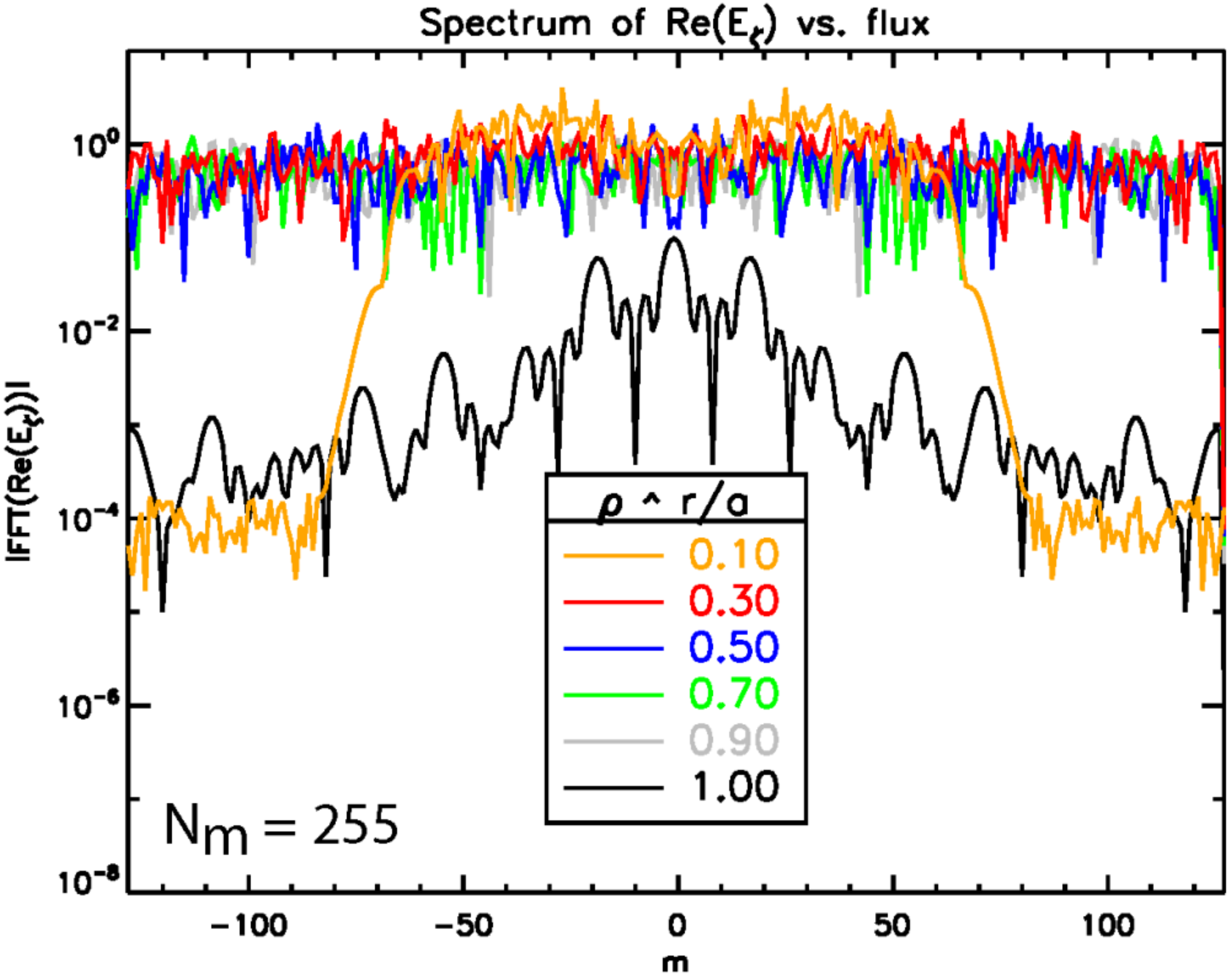
$$\text{and } N_m = 2m + 1 = 745$$

$$k_{\perp} = 46\ cm^{-1}\ (\text{for } n_{//} \sim \mathrm{n}_{//ELD} \sim 5.5) \Rightarrow m \approx r k_{\perp} \approx 1019$$

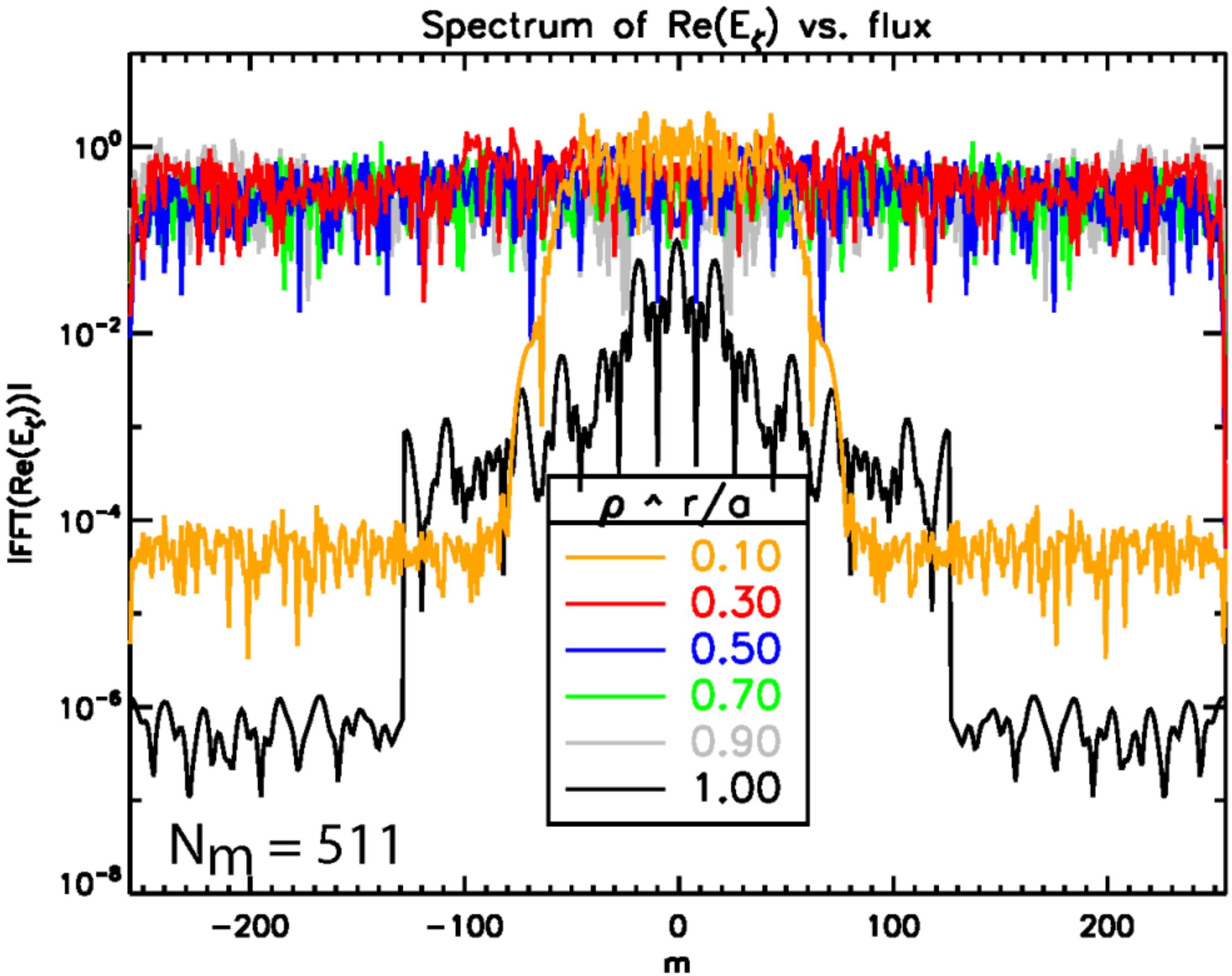
$$\text{and } N_m = 2m + 1 = 2038$$

- **May need $N_m$ ~ 4000 to resolve LH wave at edge ~ 45 cm.**

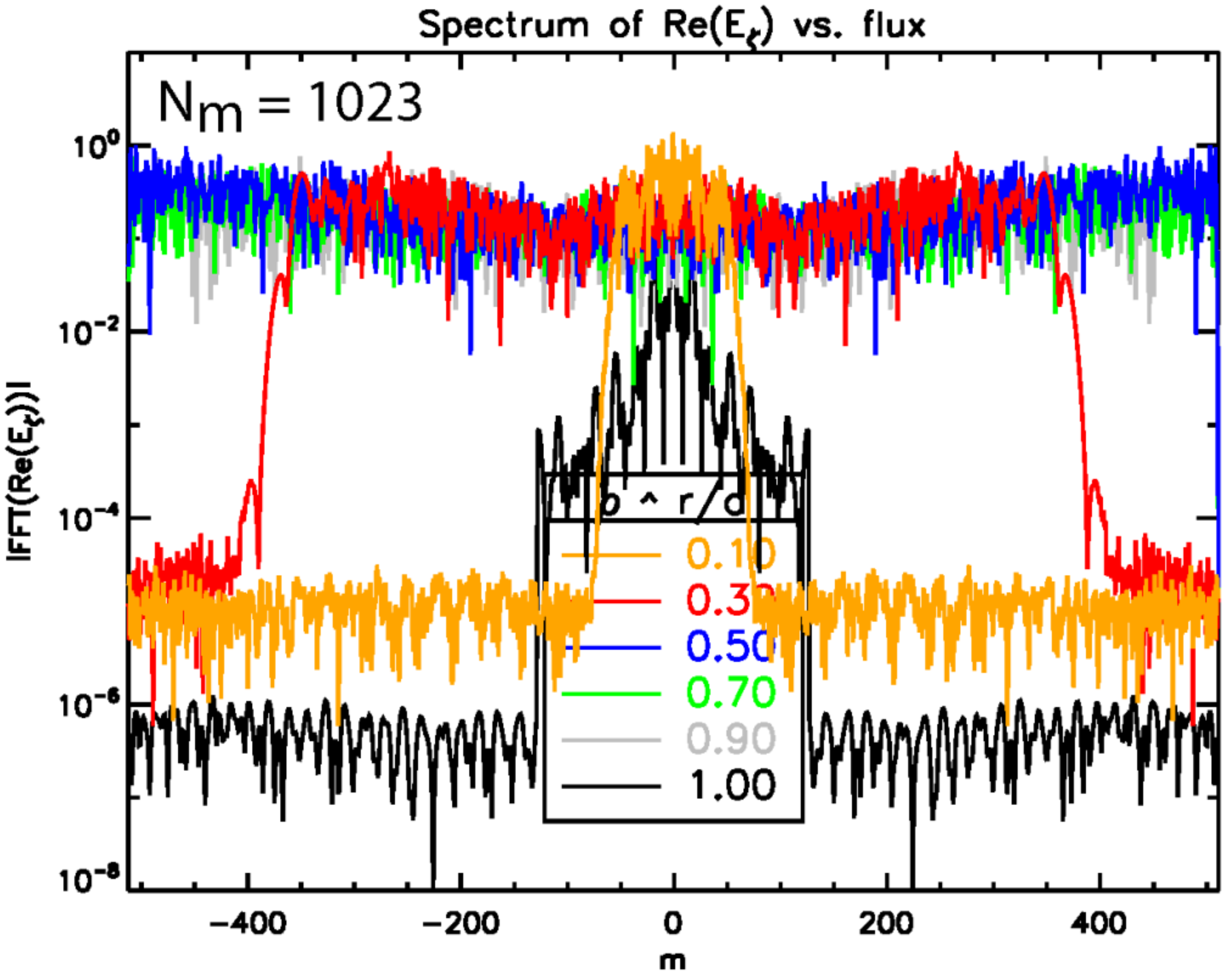
# Convergence is only achieved on innermost flux surface (r/a ≈ 0.1) at $N_m$ = 255



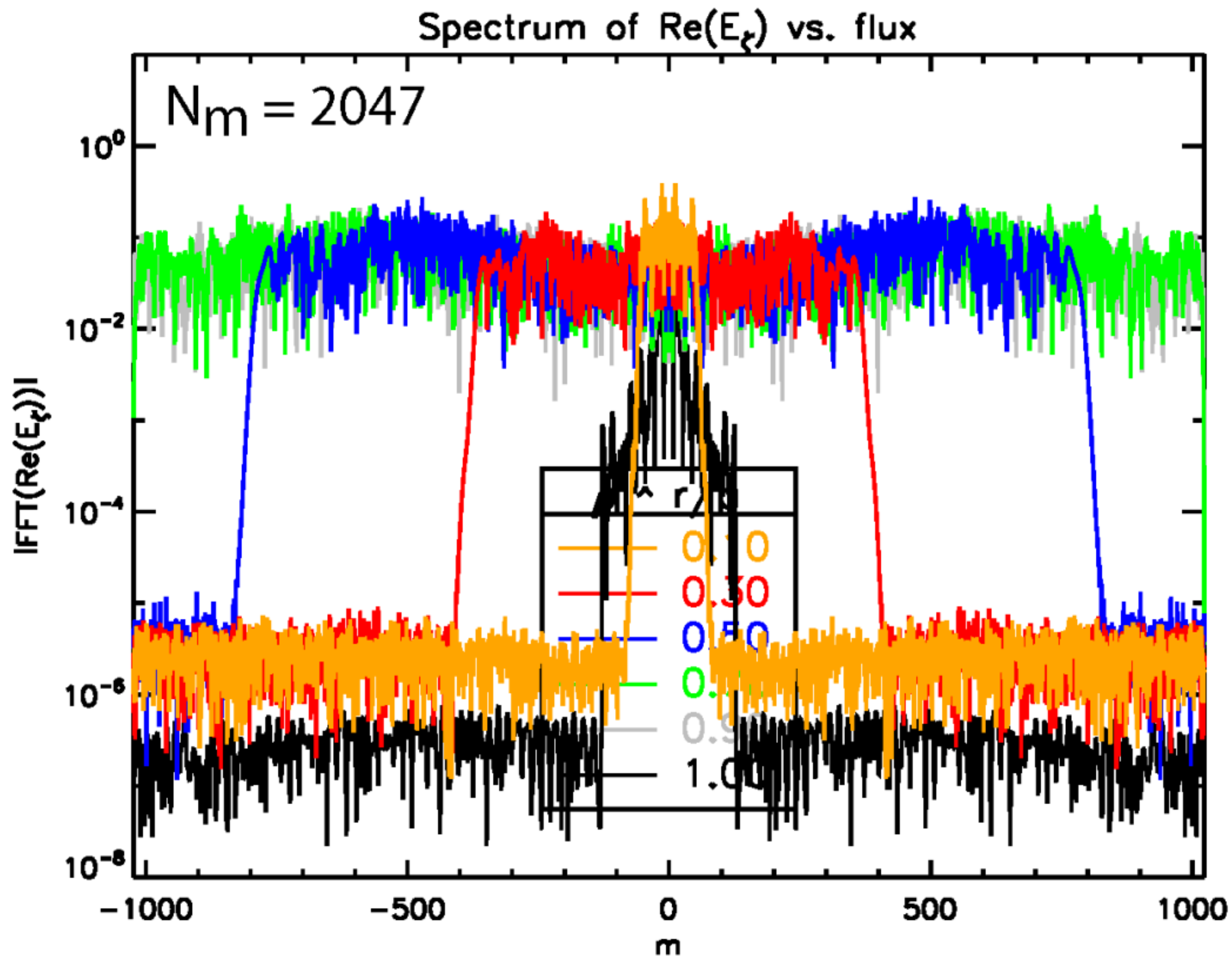
# Convergence still limited to flux surfaces at r/a < 0.3 as $N_m$ is increased from 255 → 511



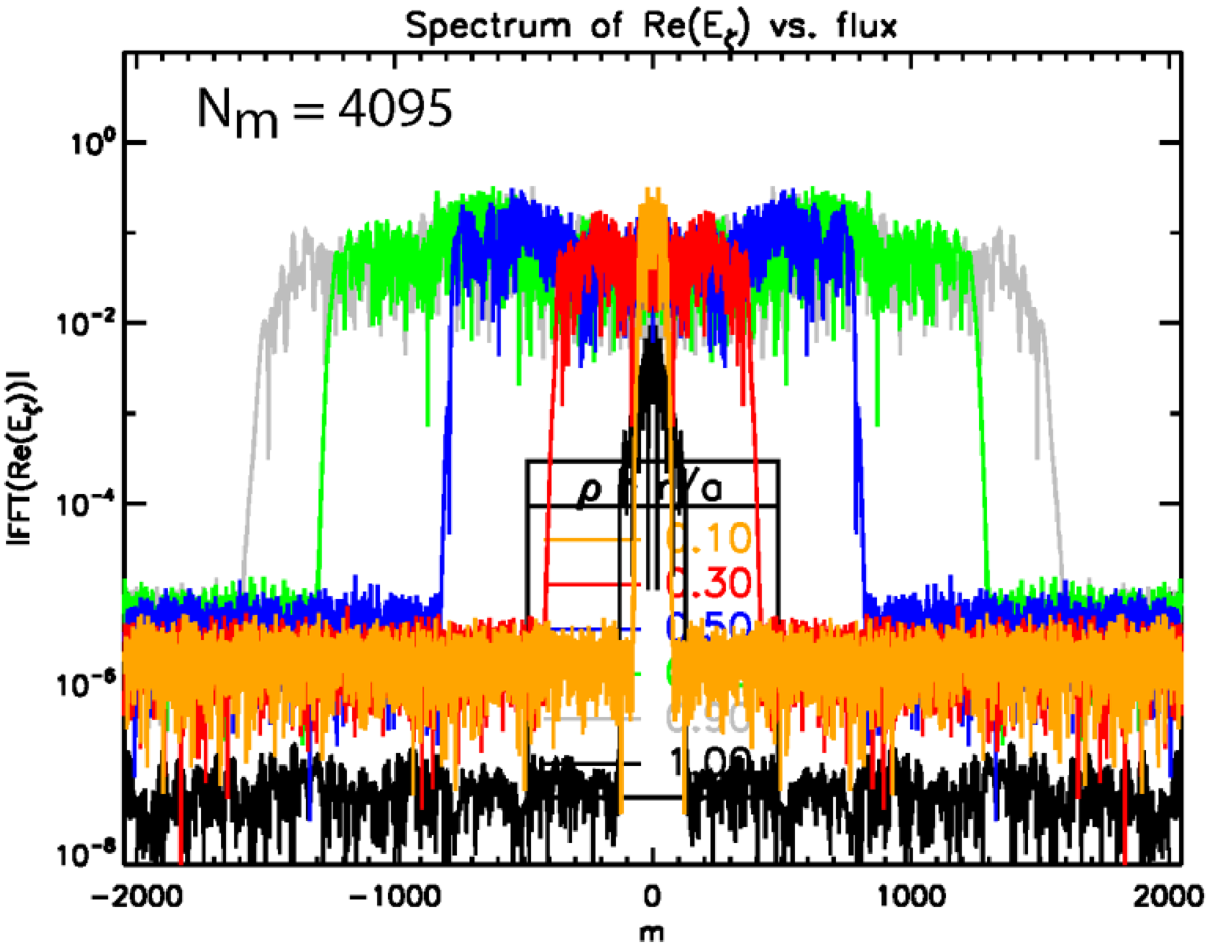
# Convergence is finally achieved out to r/a ≈ 0.3 as $N_m$ is increased to 1023



# Convergence continues to improve on flux surfaces out to r/a ≈ 0.5 as $N_m$ is increased to 2047

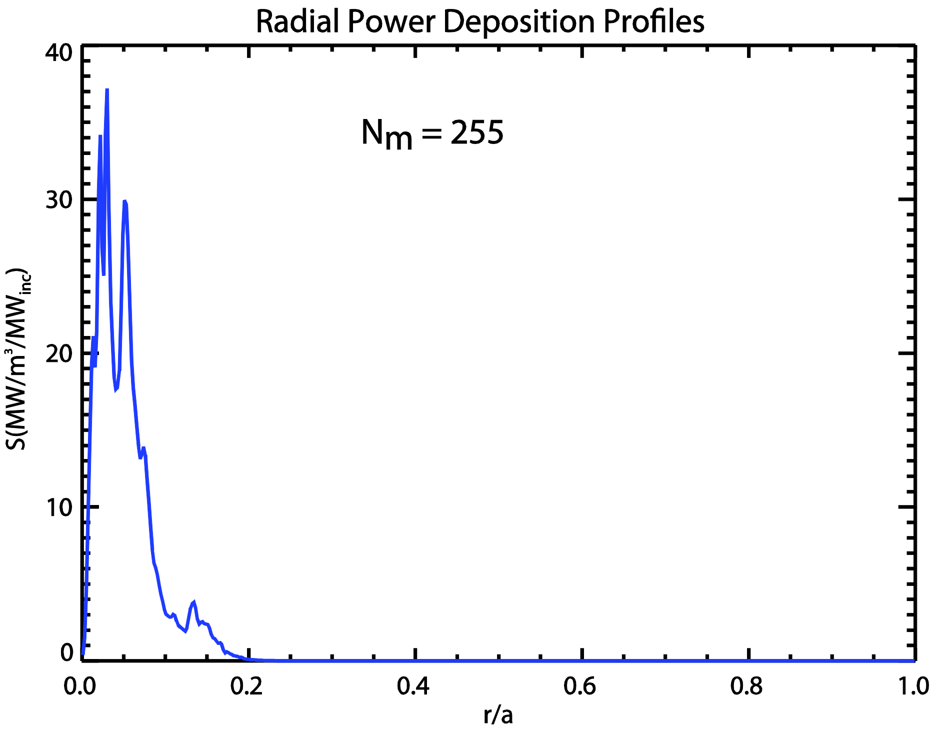


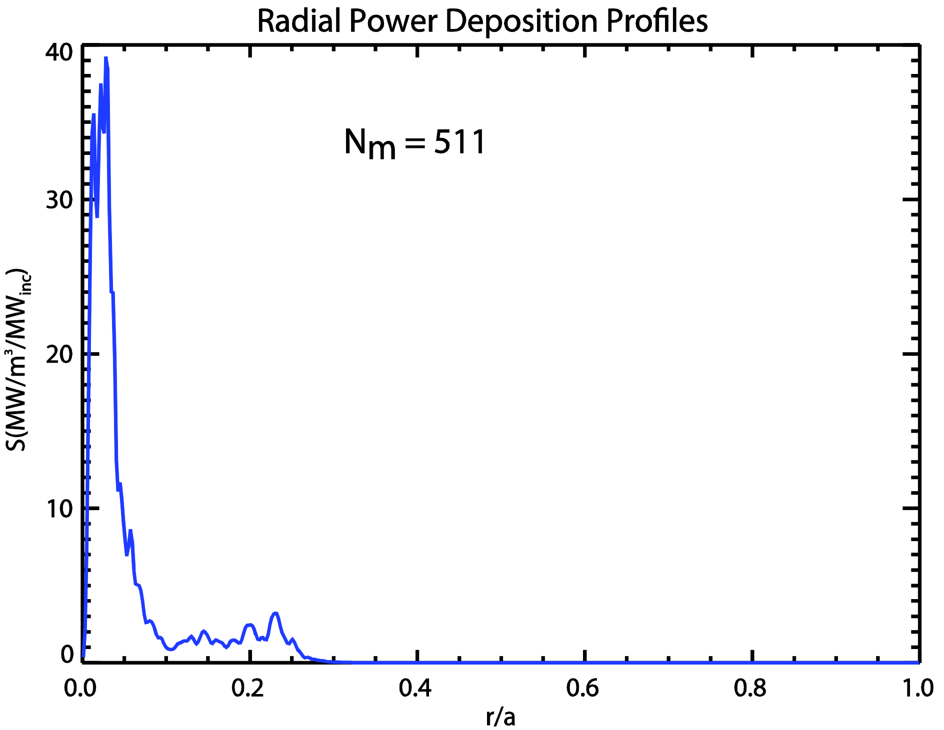
# Find that convergence is achieved on all flux surfaces as $N_m$ is increased to 4095




- **Simulation required 0.57 hours of wall clock time on Edison platform at NERSC using 32,256 cores**

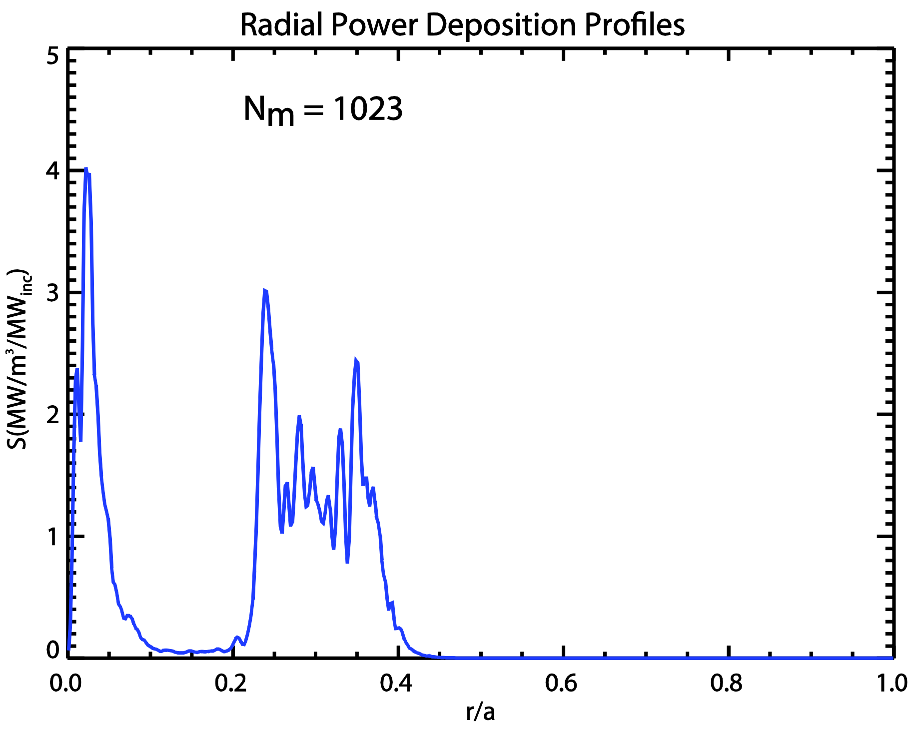
# LH power deposition profile is peaked on-axis at $N_m$ = 255, but starts to broaden as $N_m$ is increased to 511

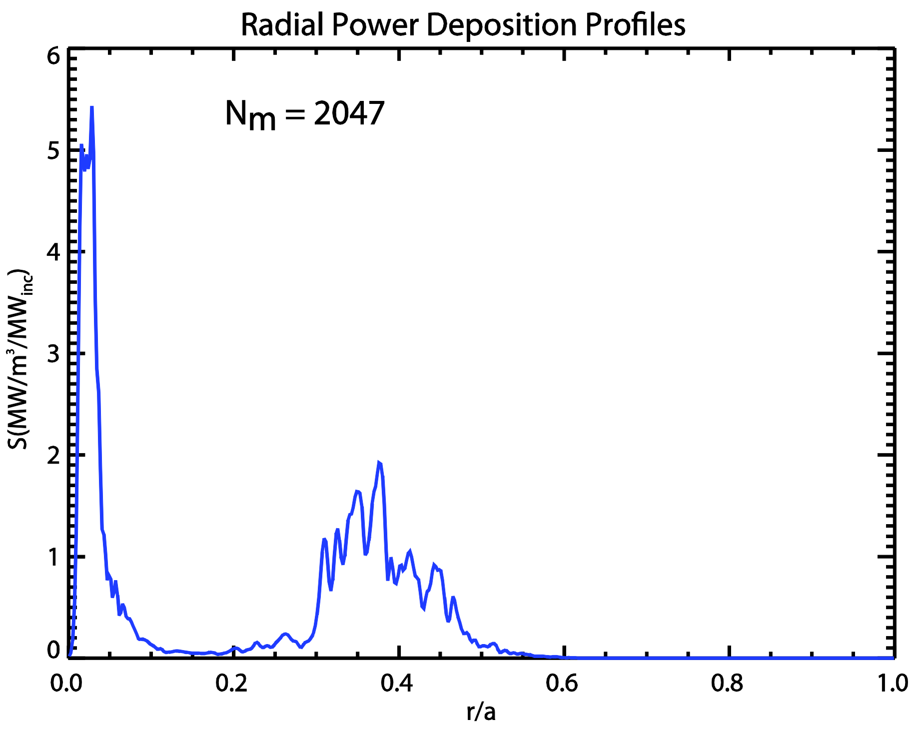



- **Broadening of the LH power deposition profile is consistent with adding higher $k_{//}$ components to the spectral solution in TorLH that correspond to higher m.**

# Off-axis peak in LH power deposition profile appears as $N_m$ is increased from 511 → 1023 → 2047

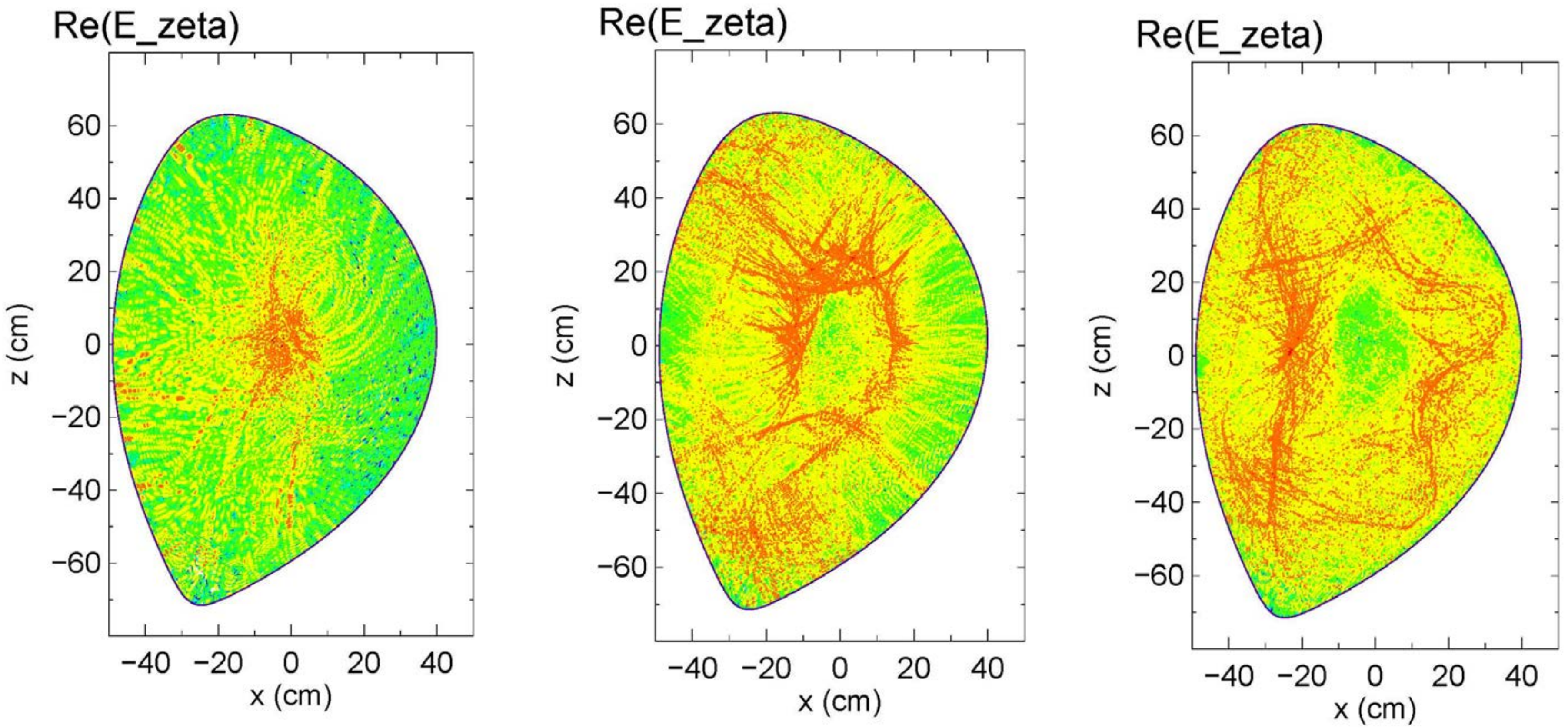


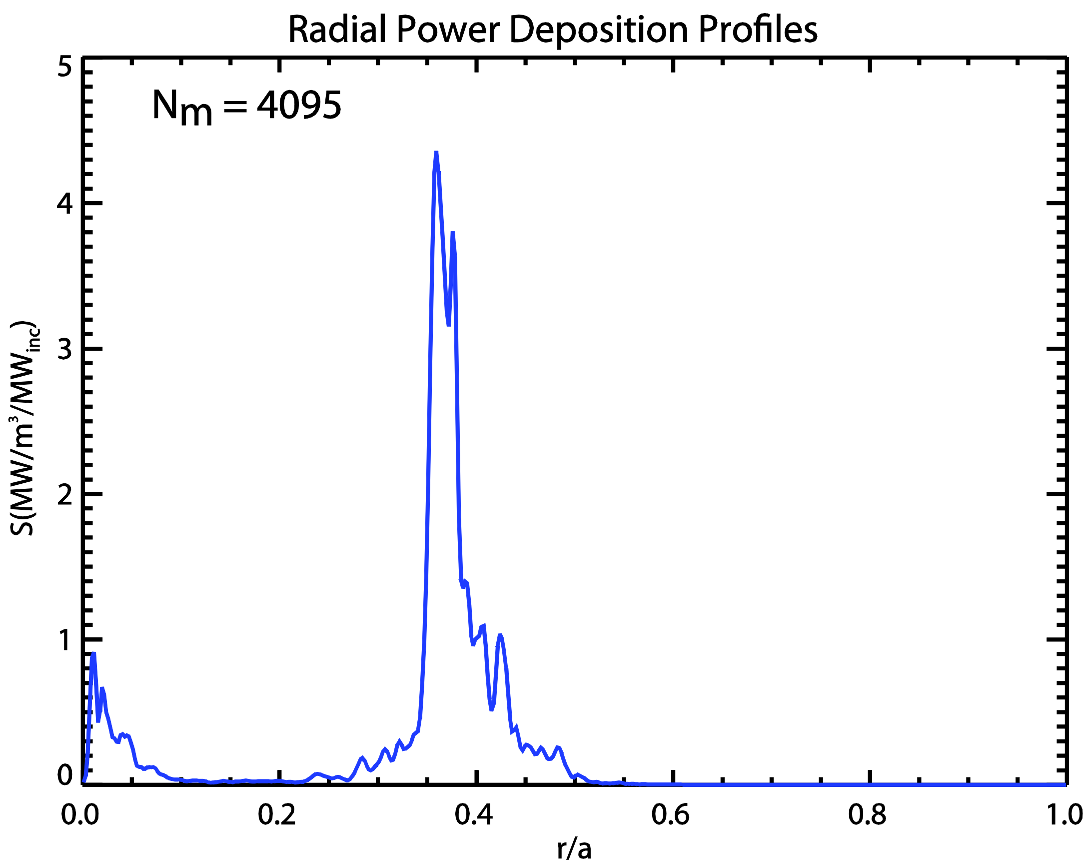

- **Broadening of the LH power deposition profile is consistent with adding higher $k_{//}$ components to the spectral solution in TorLH that correspond to higher m.**

# Parallel electric field of LH wave starts to exhibit features of multiple reflections and weak single pass absorption as $N_m$ is increased

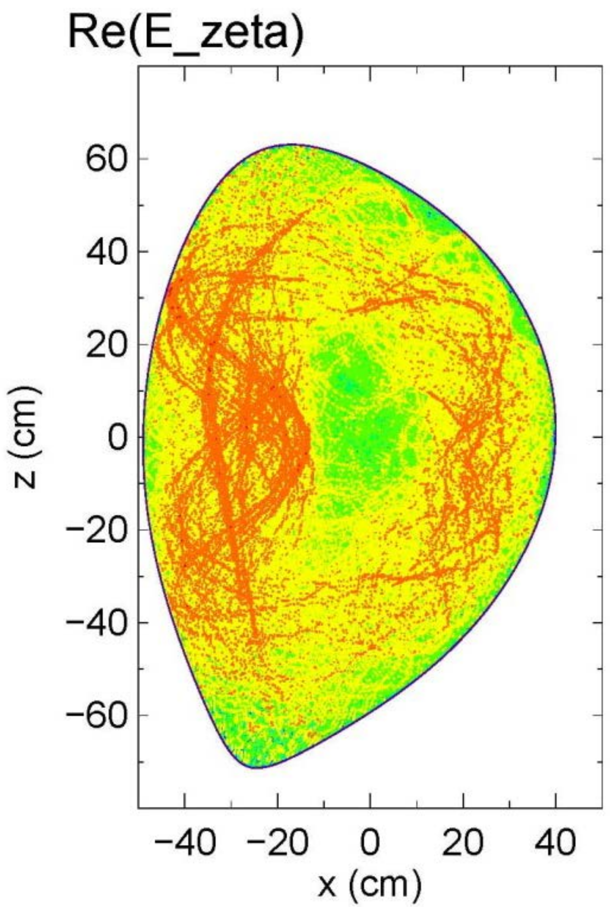
**$N_m$ = 255** **$N_m$ = 1023** **$N_m$ = 2047**



# At $N_m$ = 4095 the full-wave absorption profile is clearly off-axis (for Maxwellian electron damping).



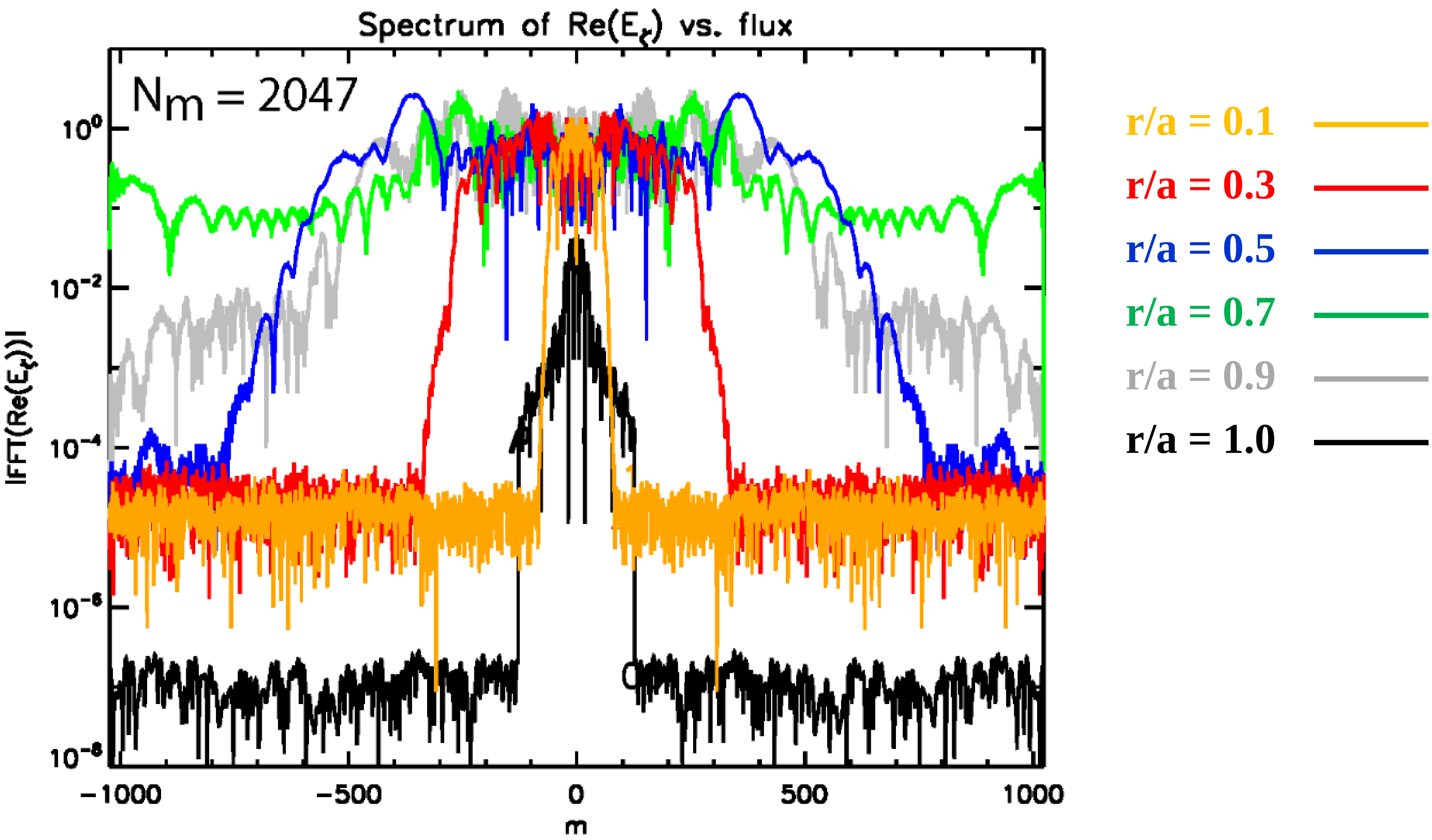

**$N_m$ = 4095**



# Set-up for "high temperature" simulations

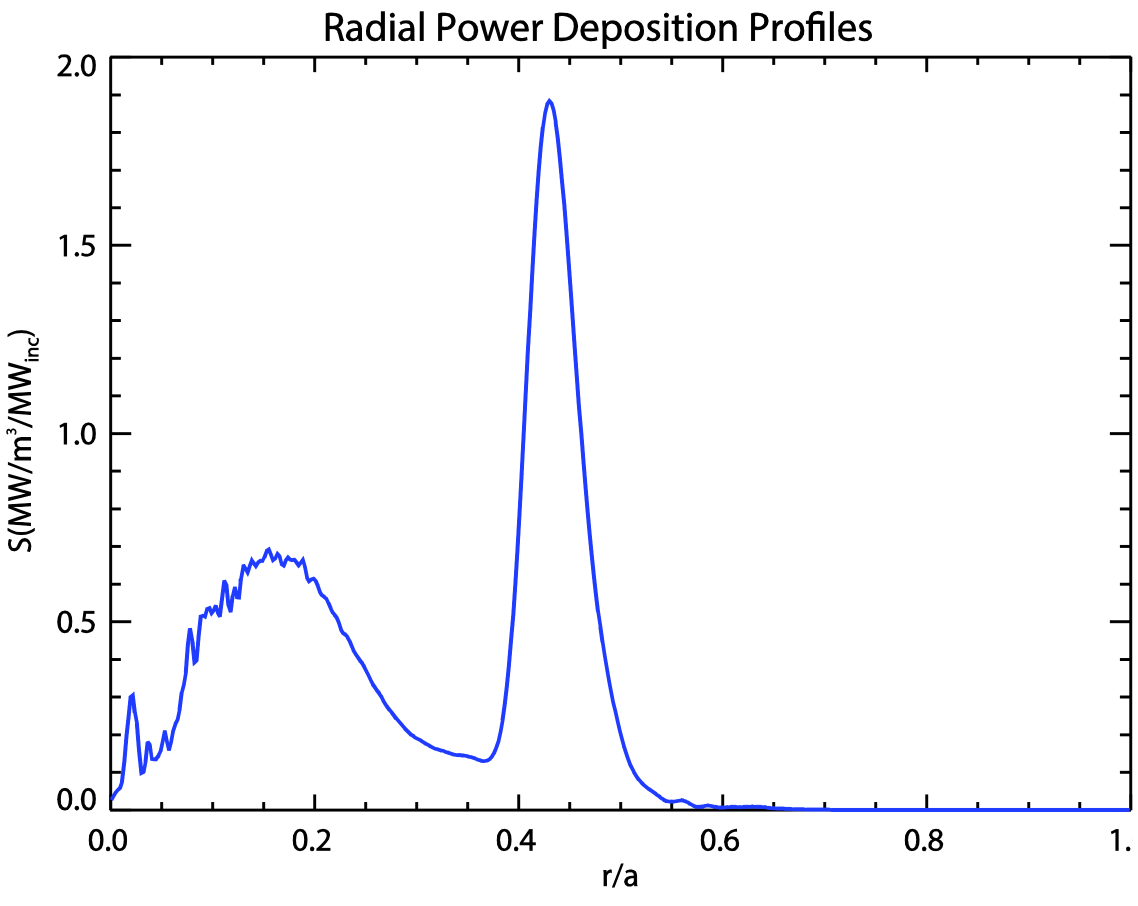
- **Use experimental profiles and EFIT equilibrium reconstruction for discharge 048888.05500:**
  - **Created Fourier MHD equilibrium representation for TorLH (equigs.dat) and kinetic profiles data file (equidt.data):**
  - **$B_0$ = 2.31 T, $I_p$ = 373 kA, a = 0.42 m, $R_0$ = 1.85 m, $T_e(0)$ = 9.5 keV, $n_e(0) = 3.6 \times 10^{19}$ $m^{-3}$.**
- **RF parameters:**
  - **$P_{LH}$ = 2 MW, $f_0$ = 4.6 GHz, $n_{//}$ = -1.80**
- **Expect to achieve convergence at lower $N_m$ because higher $T_e$ will result in wave absorption via ELD at lower $n_{//}$ (and therefore lower $k_\perp$).**

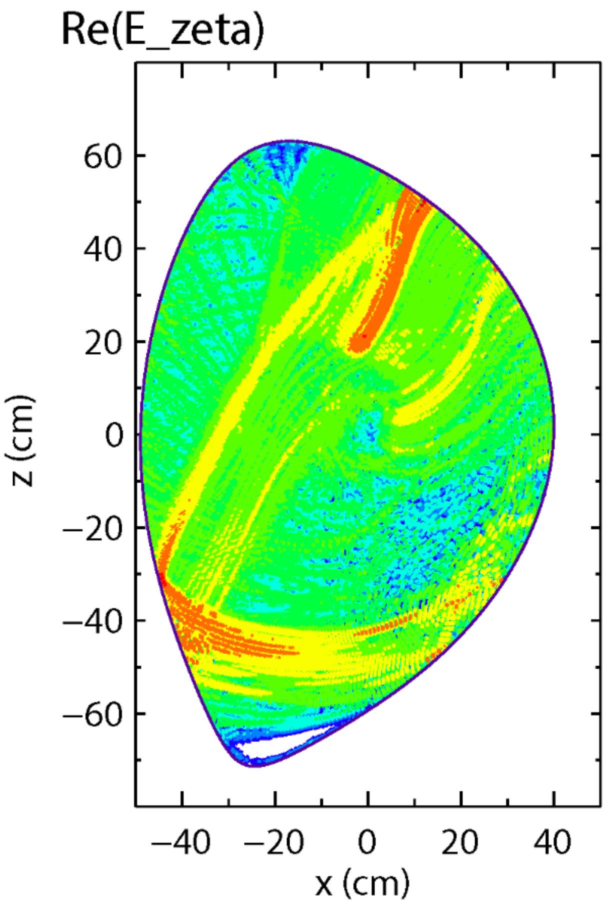
# Convergence is achieved at $N_m$=2047 on all flux surfaces at high $T_e(0)$ = 9.5 keV



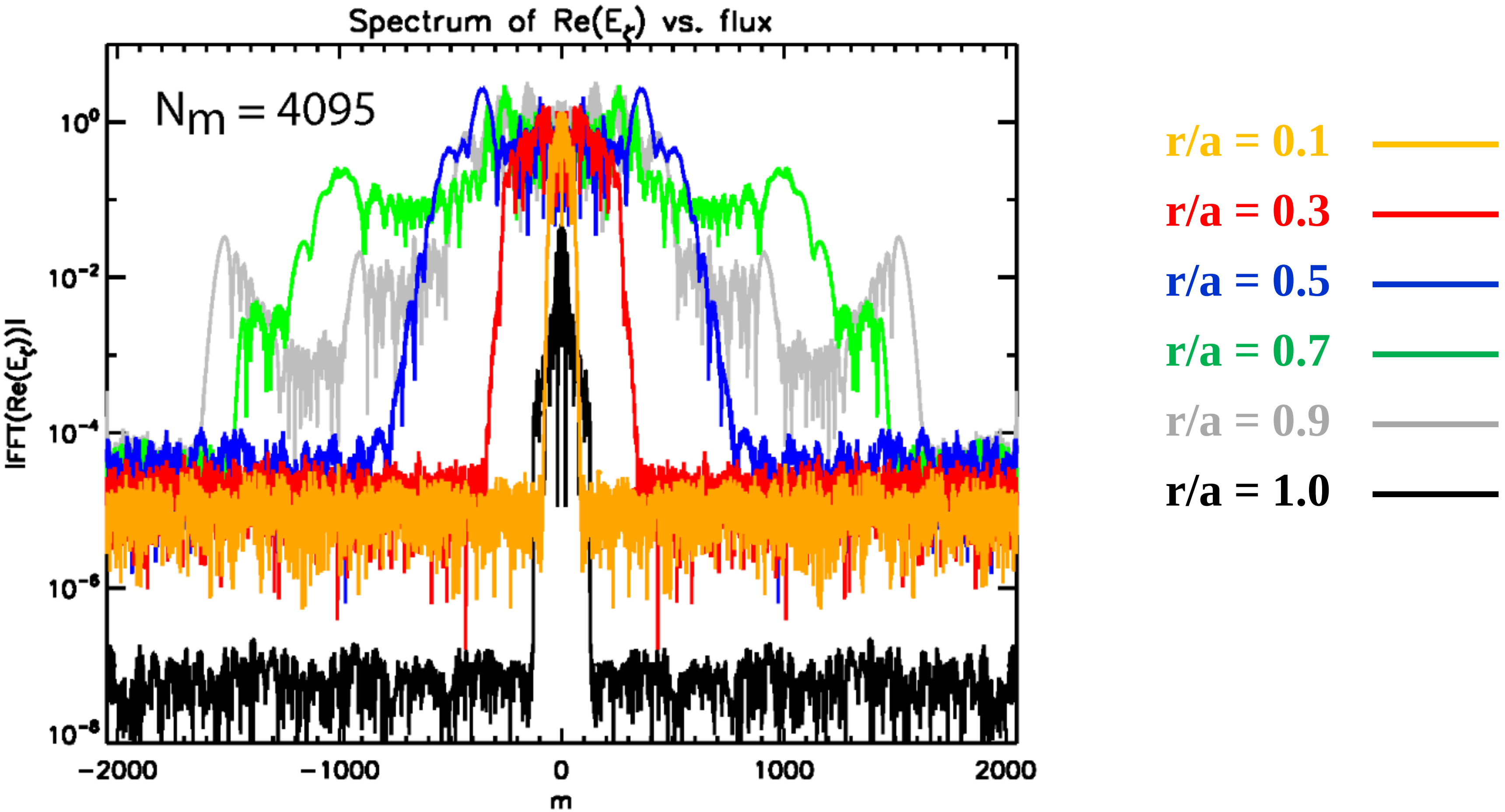
# At high $T_e(0)$ = 9.5 keV the converged LHRF absorption profile shows peaks in core and at r/a ~ 0.45

**$N_m$ = 2047**



# Simulation at $N_m$= 4095 continues to show convergence on all flux surfaces at $T_e(0)$ = 9.5 keV




- LHRF power density profile and electric field patterns remain unchanged from simulation at $N_m$=2047

# Workflow for TorLH-CQL3D simulation is being automated using the Integrated Plasma Simulator

a) Execute TorLH in "toric" mode using Maxwellian electron Landau damping (ELD):
   i. Perform a resolution scan to determine how many poloidal modes are needed to resolve the LH wave in EAST.

b) Re-run TorLH in "qldce" mode to compute the RF diffusion coefficients (D_ql) from the electric field solutions computed in Step (a):
   i. Remap D_ql from the TorLH (radial, velocity) space mesh to the CQL3D (radial / velocity) space mesh.

c) Run CQL3D to obtain first iterate for the quasilinear electron distribution $f_e(v_\perp, v_{//}, r)$:
   i. Create look-up table for $Im\{\chi_{zz}\}$ due to ELD.

d) Repeat steps (a) – (c) until $f_e(v_\perp, v_{//}, r)$ and D_ql ($f_e$) are self-consistent.

# References and Acknowledgements

**[1] J. C. Wright et al, Physics of Plasmas 16, 072502 (2009).**

**[2] R. W. Harvey and M. G. McCoy, "The CQL3D Fokker-Planck Code", in Proceedings of the IAEA Technical Committee Meeting on Advances in Simulation and Modeling of Thermonuclear Plasmas, Montreal, 1992, p. 527, IAEA, Vienna (1993).**

**[3] C. Yang et al, Plasma Physics and Controlled Fusion 56 125003 (2014).**

**[4] J. P. Lee and J. C. Wright, Computer Physics Communications 185, 2598 (2014).**

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