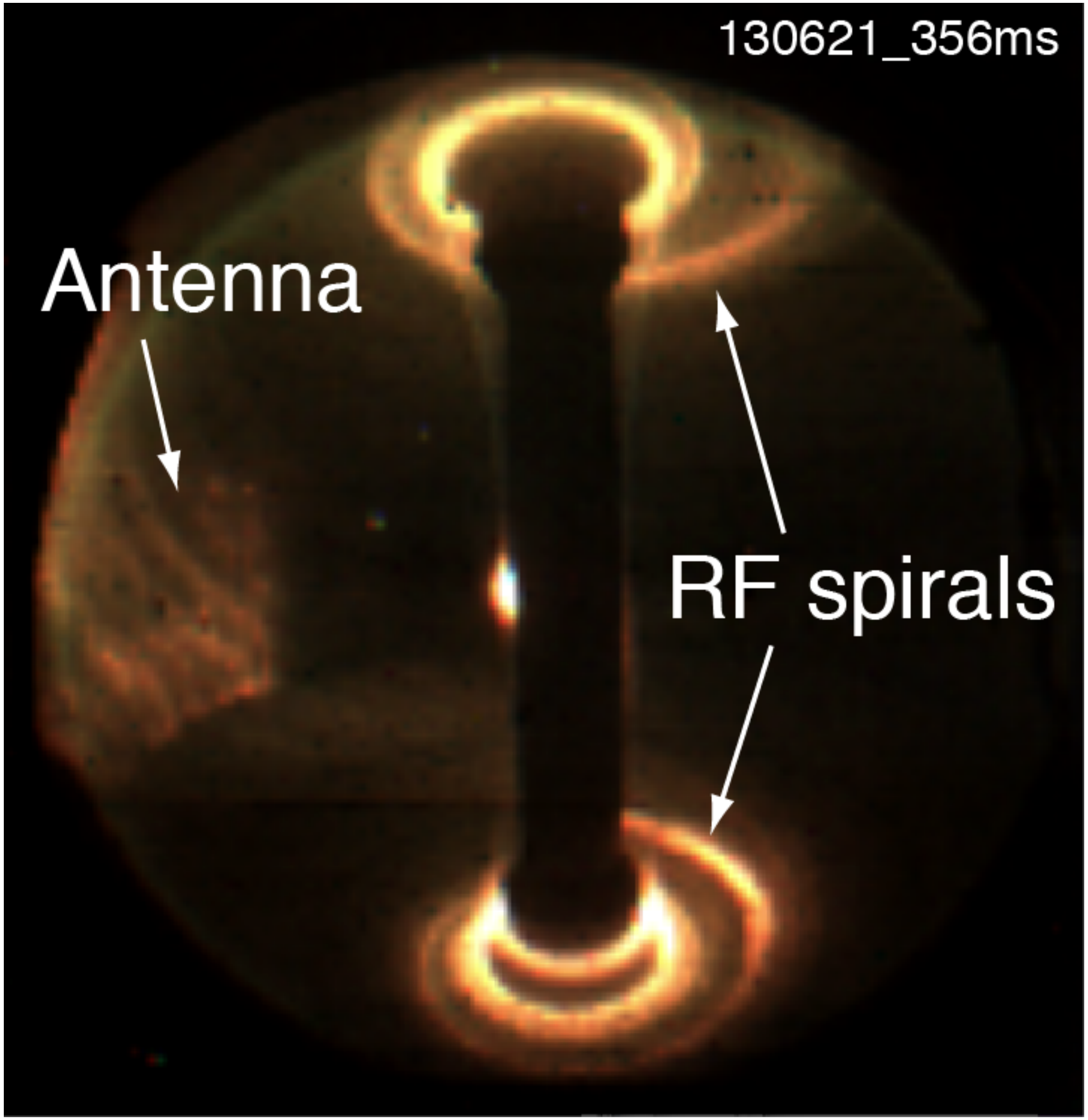
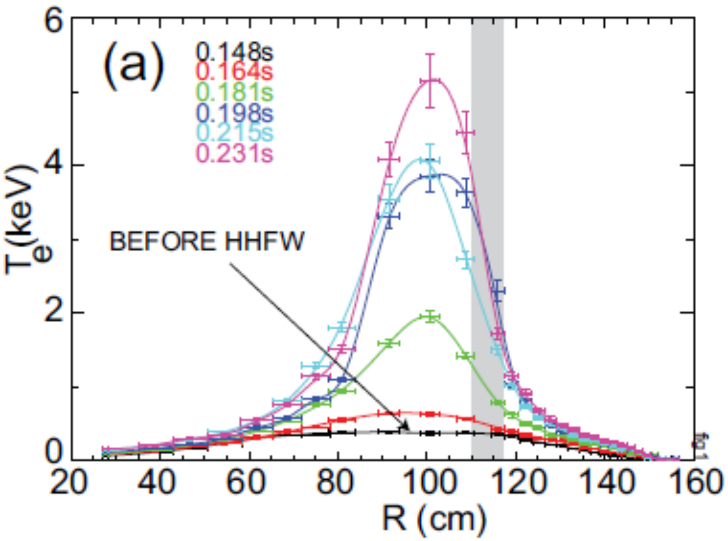
BACKGROUND: SOL losses of HHFW power are a significant operation hindrance

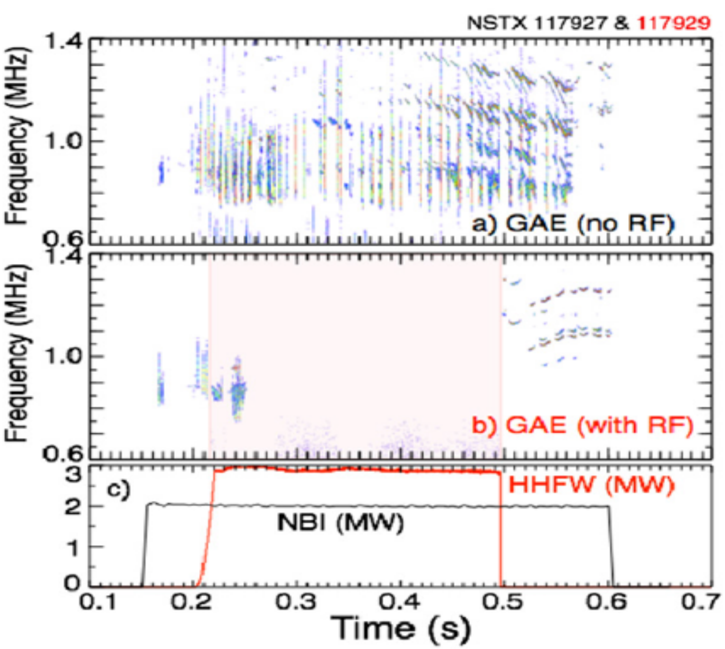


- Up to 60% of HHFW missing from core
- RF power deposited in bright spirals on divertor
    - Heat fluxes up to 2 MW/ m^2 under spirals
    - RF rectification is suspected mechanisms
- It is important to determine is this general to fast-wave systems
    - 20 MW of ICRH planned for ITER

BACKGROUND: HHFW heating on NSTX(-U) supports a broad spectrum of science research



Record-high T_e (≥ 5 keV) using HHFW (LeBlanc, 2009)

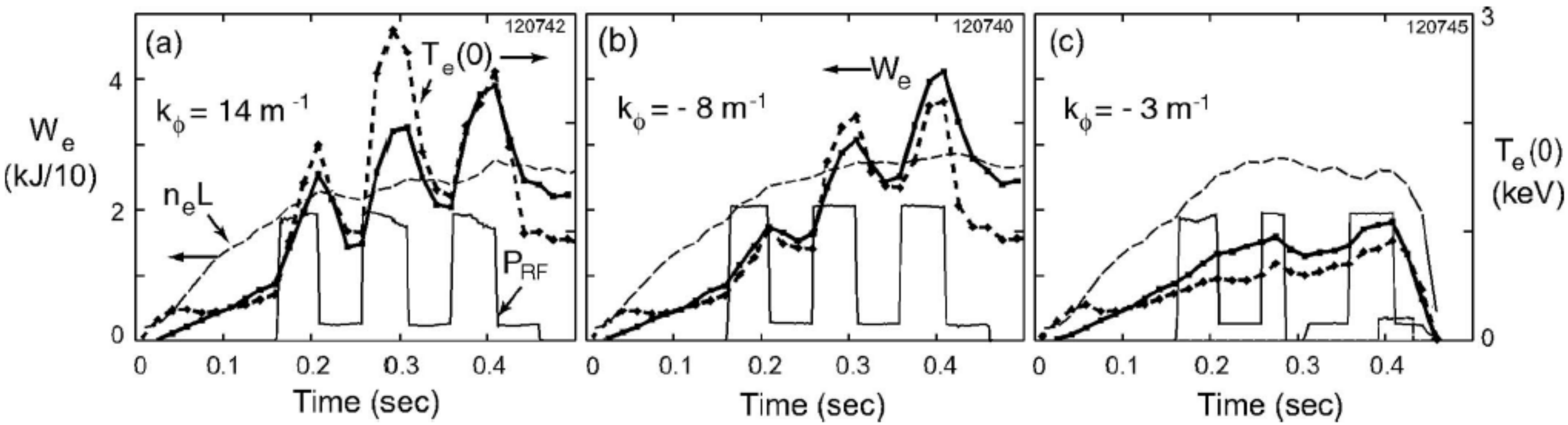


HHFW influences EP/*AE activity (Fredrickson, NF 2015)

- Record T_e using HHFW
- HHFW influences impurity transport
  - Important for high-Z transport
- Perturbative electron transport studies investigating non-local transport
- Modified HHFW for edge-harmonic oscillations → control particle transport and ELMs [Park, NF 2014]
- Validate ETG transport with high-k measurements, e.g. in e-ITB plasmas (Yuh, PRL 2011;
- Peterson, PoP 2012)
- Change of fast ion phase space on EP instabilities (XP proposed)
- Influences [clamps] edge rotation
- Study NTV offset velocity with HHFW (zero-torque input)

BACKGROUND: Experiments suggest poor heating efficiency when fast-wave cutoff is too close to antenna

- *In contrast to conventional ICRH, NSTX results suggest that heating efficiency degrades if the plasma density at the antenna is too high*
- The following figures demonstrates improved central T_e and stored e^- energy by increasing antenna phasing (k_φ)
  - HYPOTHESIS: increased k_φ increases cutoff density, making the plasma in front of antenna evanescent to FW



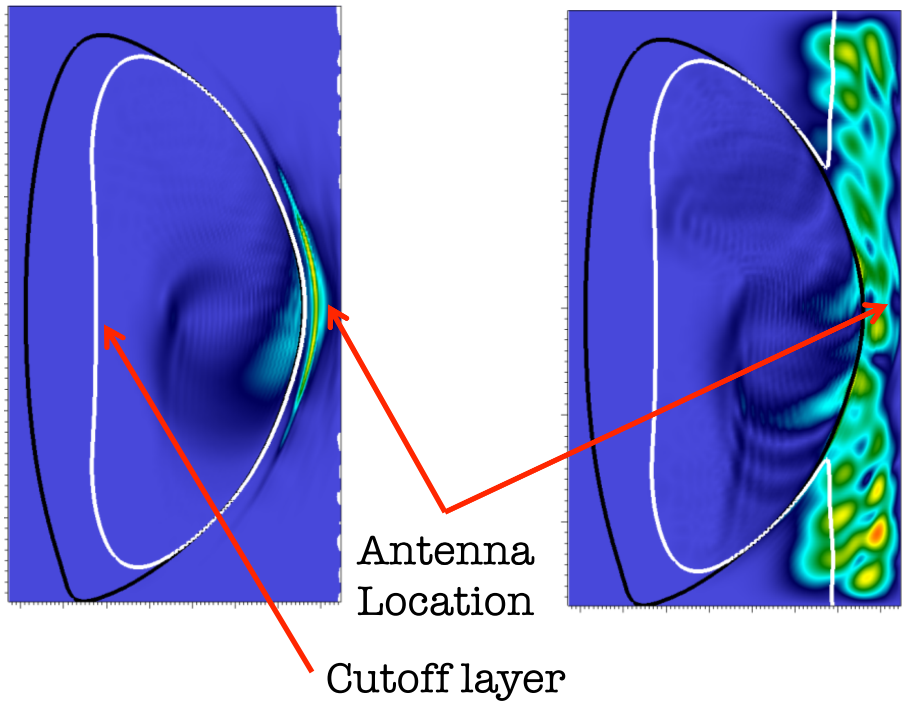
- Similar improvements in heating obtained by:
  - Increasing B_T from 0.45 to 0.55 T
  - Decreased SOL n_e

$$n_{\text{cutoff}} \approx \frac{Bk_\parallel^2}{\omega}$$

J. C. Hosea *et al.*, *Phys. Plasmas* **15** (2008) 056104, He discharges, B_T = 5.5 kG, I_p = 0.72 MA, P_{RF} = 2 MW

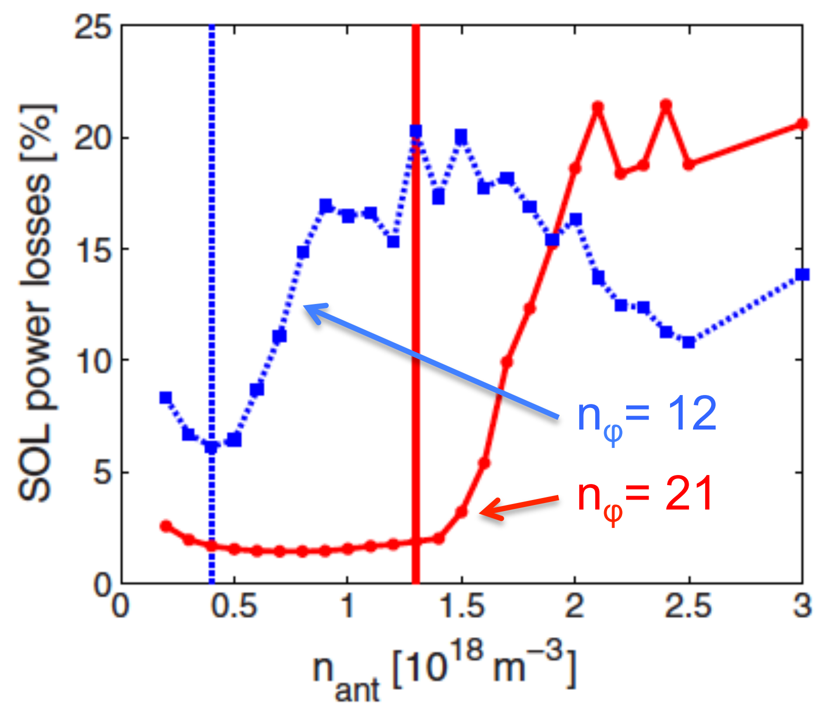
BACKGROUND: AORSA shows enhanced RF fields in SOL when cutoff layer opens in front of antenna

Lower SOL density (n_{ant} = 1e12 cm^{-3}) | Higher SOL density (n_{ant} = 2e12 cm^{-3})



When SOL is raised so that the region in front of antenna supports FW propagation, large fields are computed in SOL. k_φ = 13 m^{-1}.

When collisional damping is made artificially high to mimic the actual (but unknown) loss mechanism, an abrupt increase in SOL absorption (loss) is seen as density at antenna exceeds RH cutoff (vertical lines).



N. Bertelli *et al.*, *Nucl. Fusion* **54** (2014) 083004

A Cylindrical Cold-Plasma Model: motivation for a simplified picture

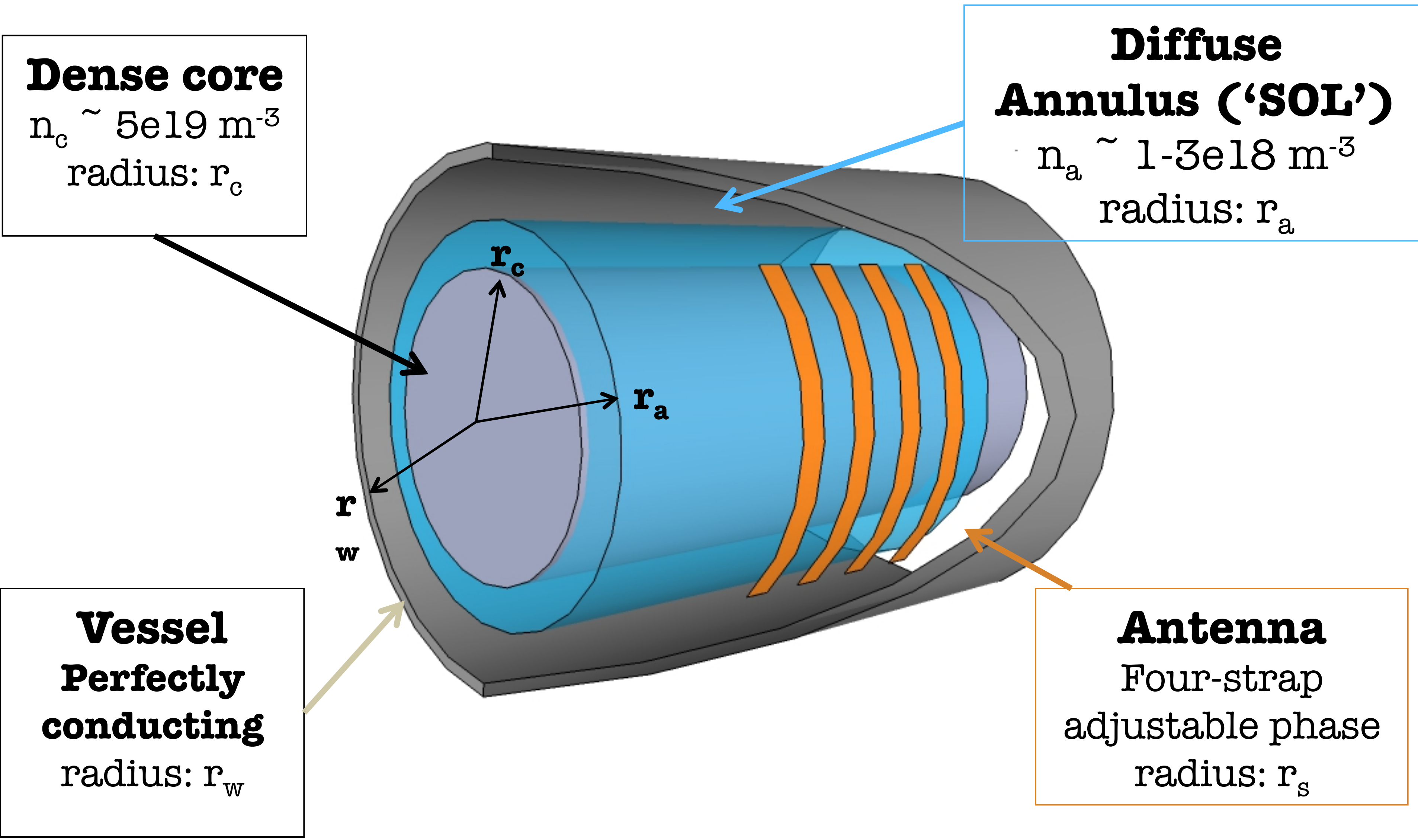
- AORSA (full-wave code) results are difficult to interpret
  - Role of toroidal geometry and vessel geometry is being studied but is currently unclear [N. Bertelli et al., *Nucl. Fusion* 2016]

- Cylindrical model isolates fast-wave propagation physics in simplified geometry

- Step-density profile provides minimal complexity to investigate role of steep density gradient
  - Justification: Perpendicular FW wavelengths in SOL are generally larger (21 cm for current-drive phasing) than density gradient scales lengths (1-2 cm)

- Model ignores: core absorption, warm-plasma phenomena, non-linear phenomenon (PDI), toroidal effects, magnetic field gradient

Cylindrical cold-plasma model: higher-density core plasma surrounded by lower density annulus [SOL]



Full solution given a sum of modes

- Fourier transforms in the azimuthal and axial directions

$$E_\phi(r,\phi,z) = \sum_{m,k_{||}} e^{ik_{||}z+im\phi-i\omega t}\,\tilde{E}_\phi(r,m,k_{||})$$

- Radial boundary conditions can only be satisfied for a finite set of $k_{||}$
  - Cold-plasma dispersion gives k_{perp} in each region given $k_{||}$
  - Each solution corresponds to a half-integral number of radial wavelengths

Solutions found via Fourier decomposition in axial and azimuthal directions

- Full solution determined by inverse Fourier transform; leading to convolution with antenna spectrum

$$E_\phi(r,\phi,z) = \sum_{m,k_\parallel} e^{ik_\parallel z + im\phi - i\omega t}\tilde{E}_\phi(r,m,k_\parallel)\tilde{J}^*_{\mathrm{ant}}(m,k_\parallel)$$

- In simply geometry, antenna spectra factors into z- and phi-parts $J_{ant}(m,k_{||}) = J_{ant,z}(k_{||}) * J_{ant,\varphi}(m)$
  - For a model antenna of four infinitely-thin phased straps, the axial component is

$$J_{\mathrm{ant},z}(k_\parallel) = \frac{1}{2\pi}\left[2\cos\left(\frac{1}{2}dk_\parallel + \phi_0\right) + 2\cos\left(\frac{3}{2}dk_\parallel + 3\phi_0\right)\right]$$

  - For uniform current density along strap (justified at these frequencies), a strap of angular span alpha has

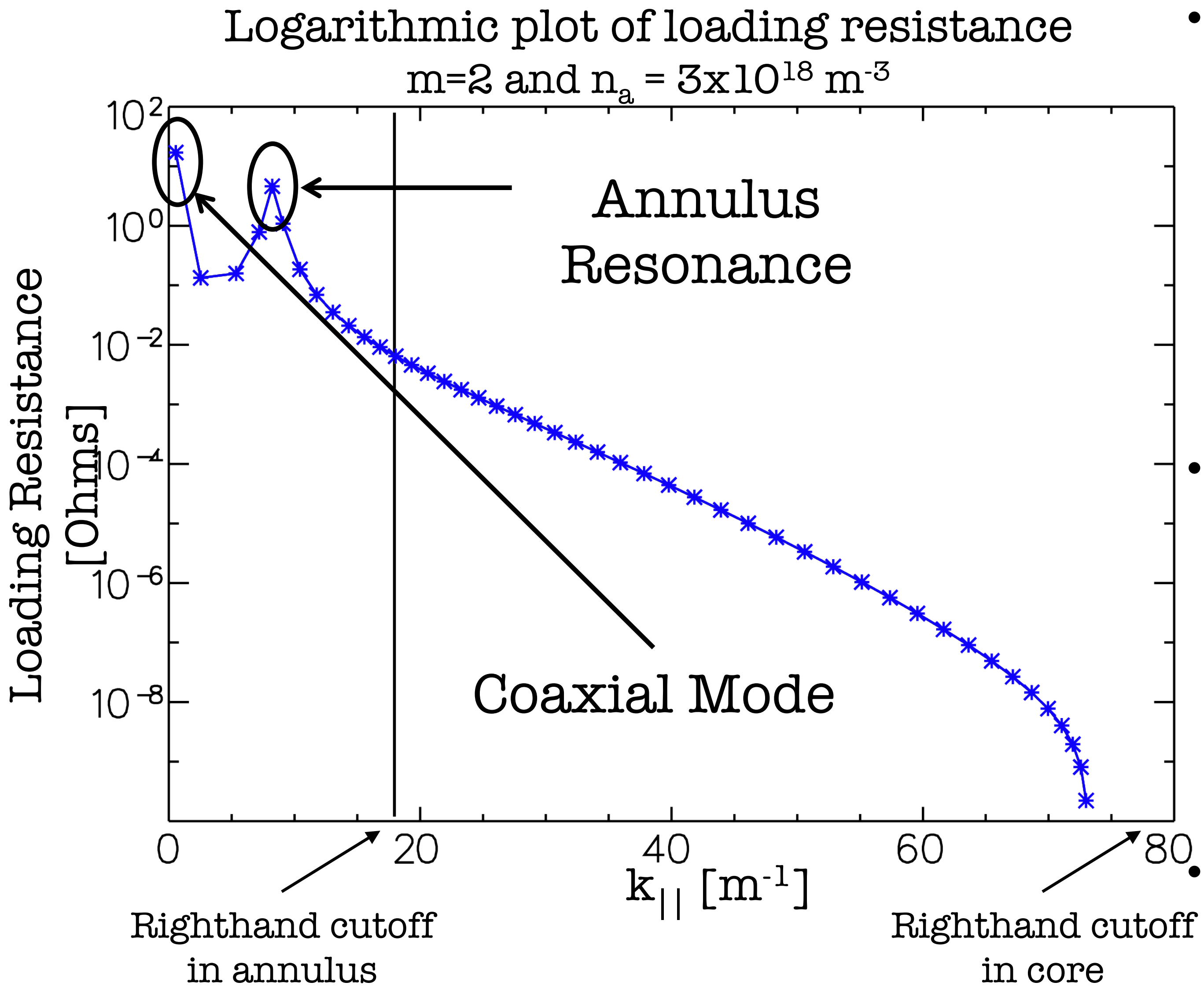
$$J_{\mathrm{ant},\phi} = \sum_m e^{im\phi}\frac{\sin(m\alpha/2)}{m\pi}$$

- Half of this poster focuses on single-m results for clarity
  - However, the full solution requires summing over all m and is approached in the last several slides.

Annulus Resonances: modes that conduct significant wave power in edge

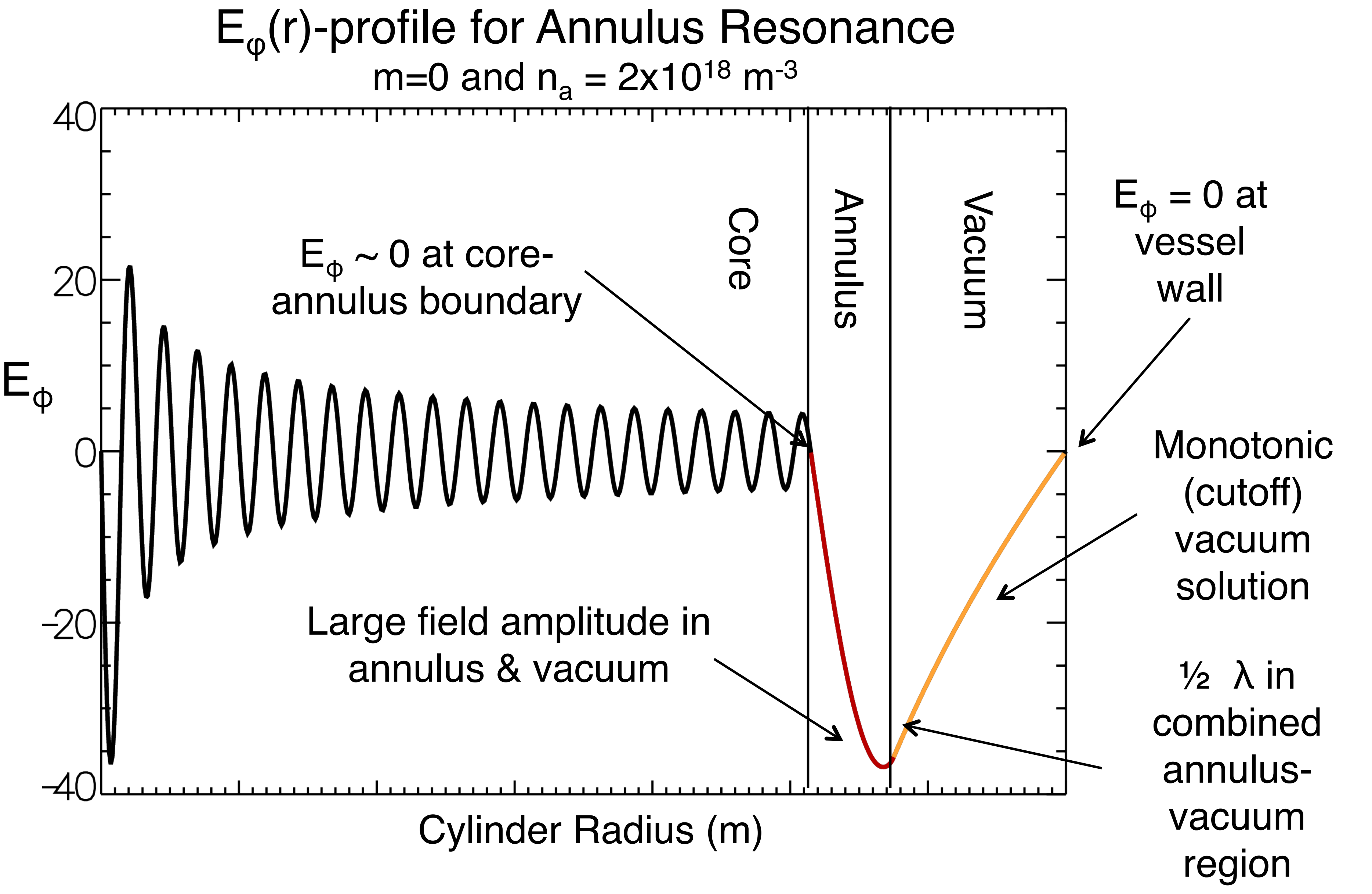
- The cylindrical model contains a peculiar class of mode named “annulus resonances”
  - Large field amplitudes in the edge
  - Large loading resistances
  - Occur when one half a radial wavelength fits into the combined annulus-vacuum region
- Annulus resonant modes are natural candidates for explaining the SOL losses on NSTX
  - Large edge amplitude could drive loss mechanisms such as RF rectification
  - Large loading resistance means they are easier to excite
  - Half-radial wavelength condition in the edge is easier to satisfy for high-harmonic fast waves.`

Annulus Resonance stands out from other modes as a peak in loading resistance



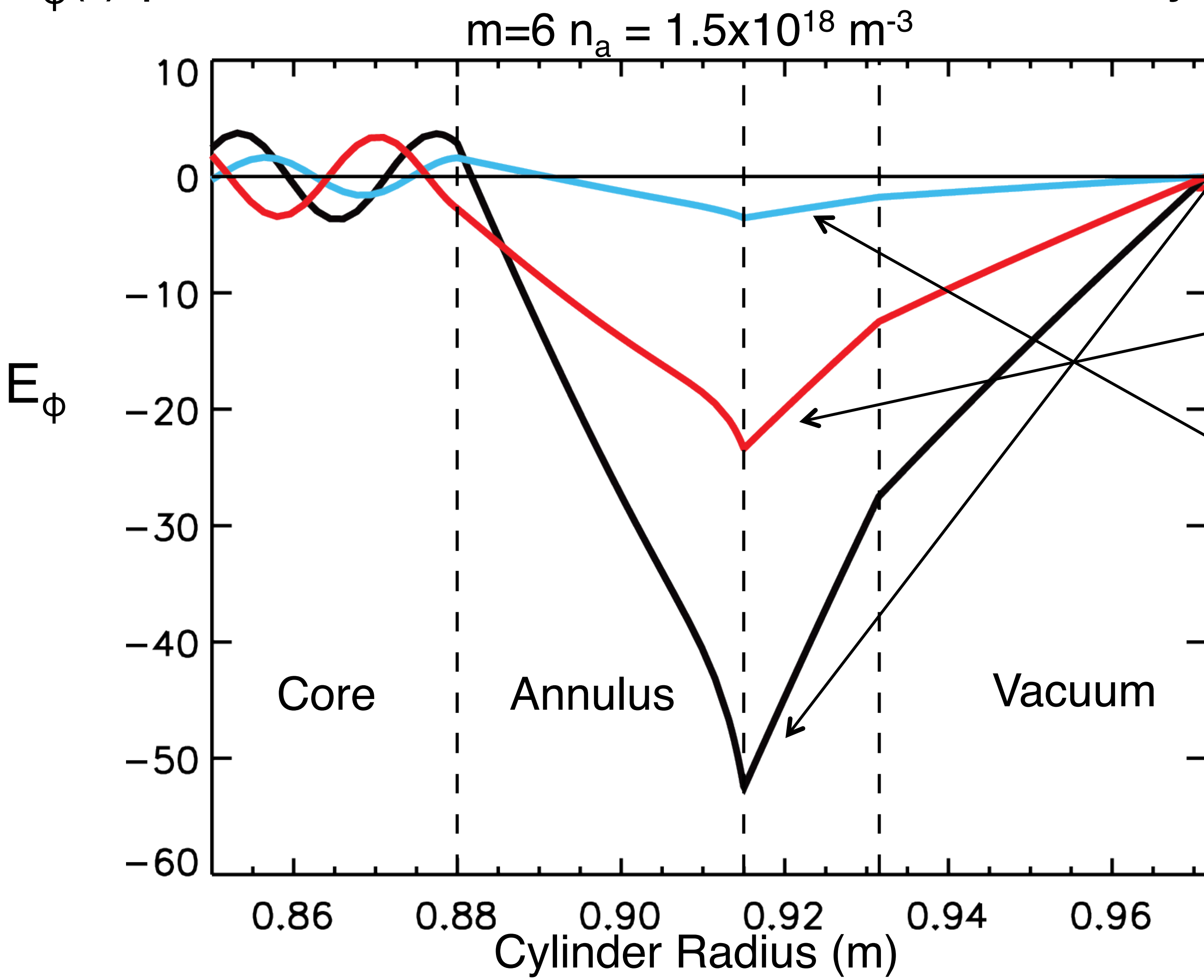
- This plot only contains m=2 modes (for clarity)
  - Typically, only one annulus resonance occurs per m
- In general, loading resistance falls off with $k_{||}$
  - Waves evanesce more in vacuum region with higher $k_{||}$
- Peak occurs at $k_{||}$ such as the half-radial wavelength condition is

Annulus Resonance: radial E_φ-profile has ½ wavelength structure in combined annulus-vacuum regions



Annulus resonances have a near half-radial wavelength structure in combined annulus-vacuum region

$E_\phi(r)$-profiles for Annulus Resonance and nearby modes



n=72 Annulus Resonance

n = 71

n = 73

Largest mode has E_ϕ ~ 0 at core annulus boundary

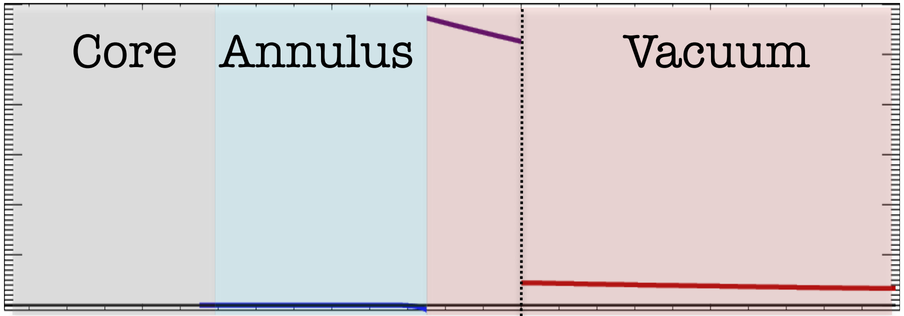
Annulus Resonances: *distinct* from "coaxial modes"

- Coaxial modes: low-$k_{||}$ modes resembling TEM modes in coaxial cables
  - Very large loading resistance
  - Often considered spurious and removed from analysis

- Annulus resonance are distinct from coaxial modes in several regards.
  - Not TEM modes; have substantial H_z component.
  - Wave fields propagate in core
  - $k_{||}$ sensitive to the annulus density.
  - Coax modes do not appear for m = 0 but the annulus resonance does.

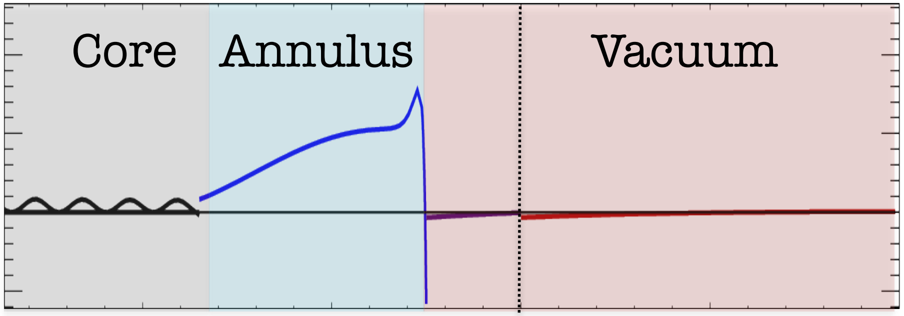
- Annulus resonances also distinct from surface modes, which decay exponentially inward radially.

<u>Coaxial Mode:</u>
Axial Poynting Flux



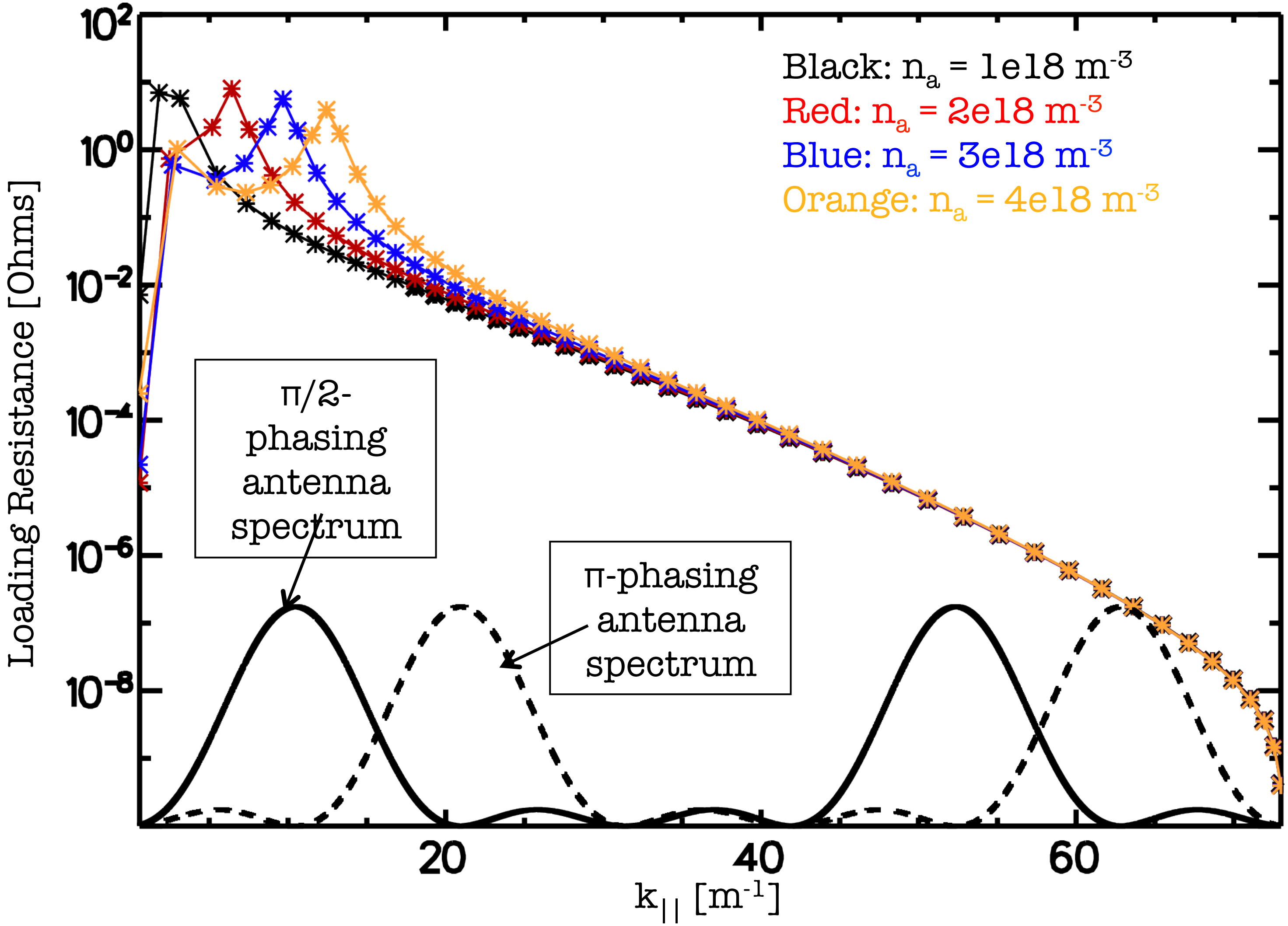
Poynting flux confined between plasma and Faraday screen

<u>Annulus Resonance:</u>
Axial Poynting Flux



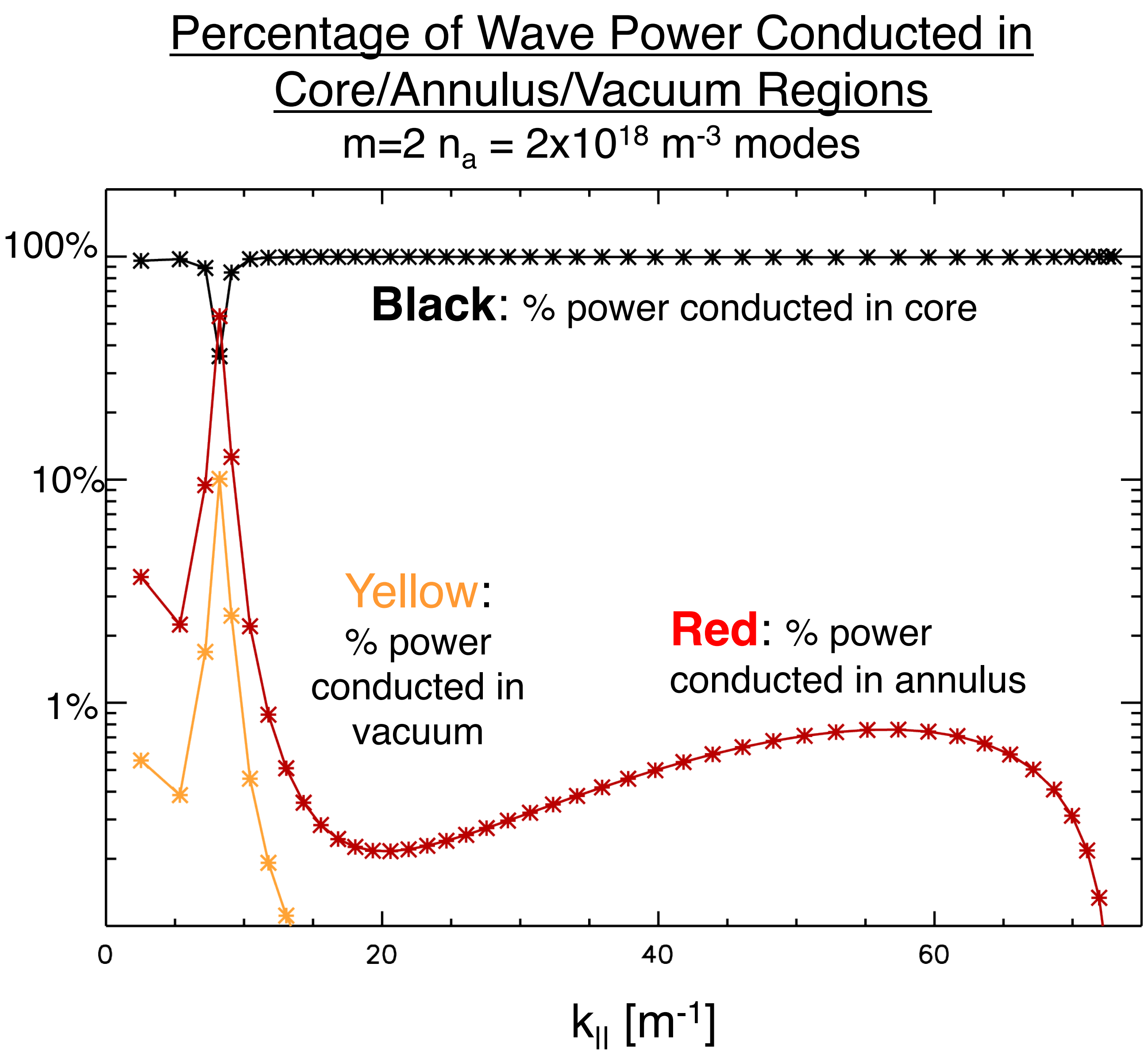
Large Poynting flux in annulus

Annulus Resonance: $k_{||}$ increases as the annulus density is raised



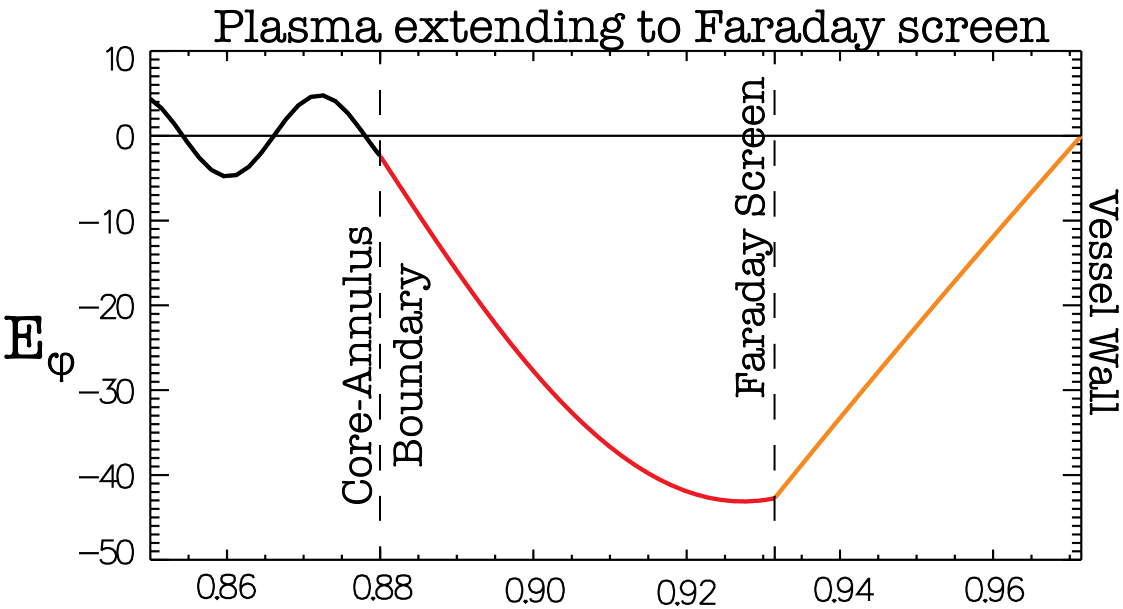
Increasing annulus density increases k_{perp}, so maintaining ½ radial wavelength in edge requires lowering $k_{||}$, which decreases k_{perp}

Annulus Resonance: unique in that significant wave power is conducted in edge region



- Wave power measured by integrated axial Poynting flux over cross-sectional regions
- Most modes conduct power in core region
- For annulus resonance, ~ 54% of power is in annulus
- Annulus resonance accounts for ~ 66% of m=2 wave power

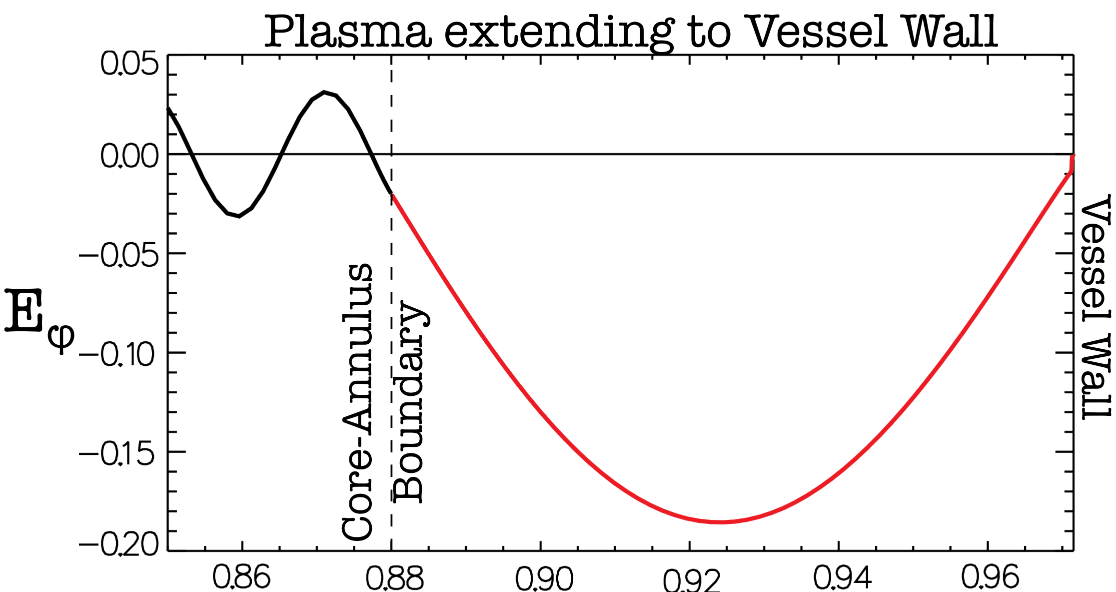
½ radial wavelength condition is robust: holds in various configurations



Annulus plasma extends to Faraday screen

m = 3

$n_a = 1.5 \times 10^{18}\ m^{-3}$



Annulus plasma extends to vessel wall; Faraday screen removed

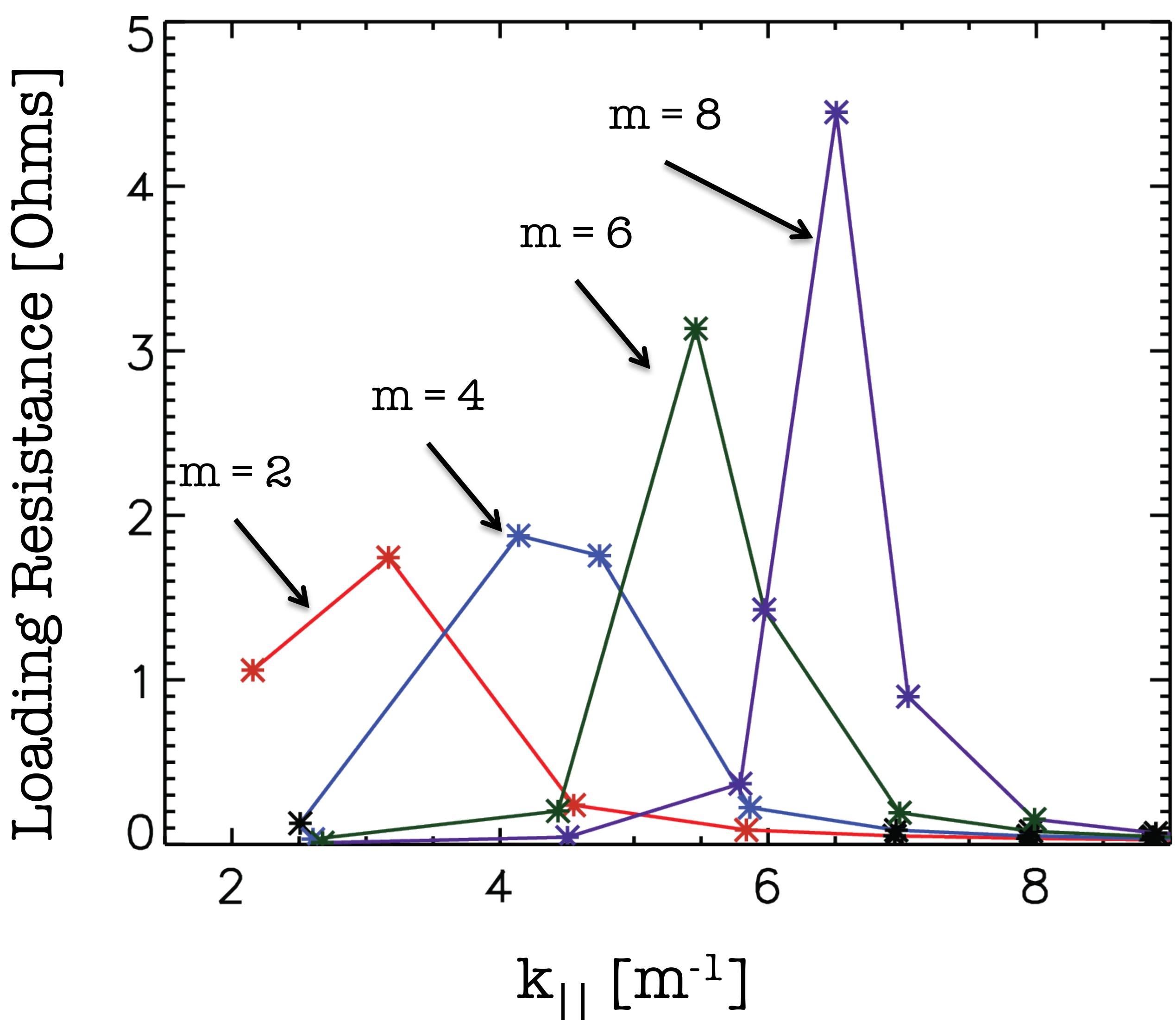
m = 1

$n_a = 2.0 \times 10^{18}\ m^{-3}$

Summing Over Azimuthal Wavenumber

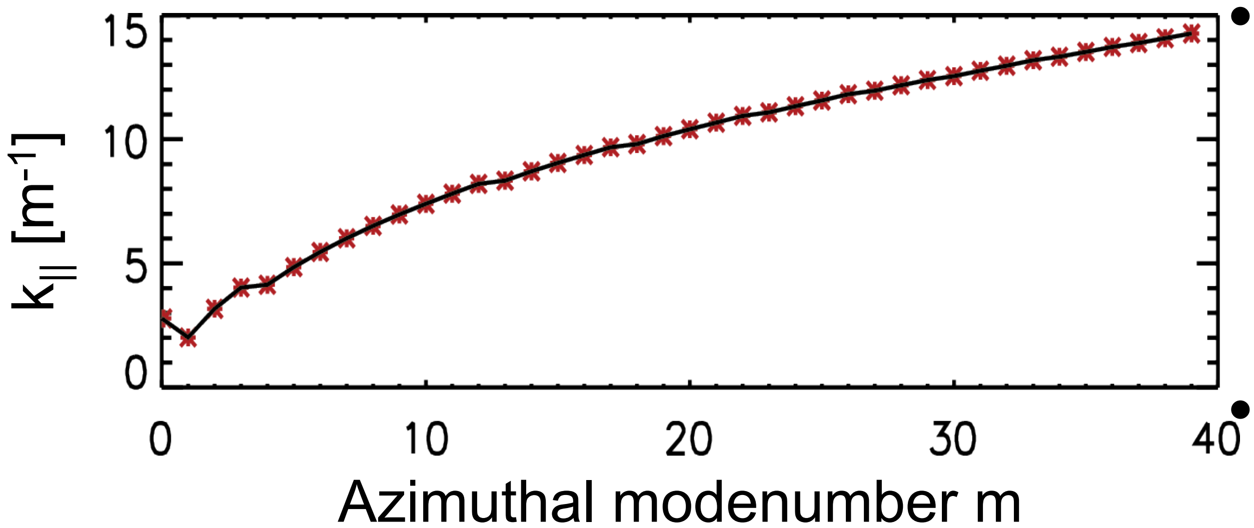
- Annulus resonances are strong candidates for explaining SOL losses on NSTX
  - Large field amplitudes in edge
  - Large loading resistances and can easily be excited if the exist for given parameters
  - Exist when ½ a radial wavelength fits into the edge
    - a condition that varies with $k_{||}$, magnetic field, and edge density, as observed experimentally
- However…
  - Modes still propagate significant (~ 50%) power in core
  - Since core damping is large for spherical tokamaks, annulus resonances, considered individually, would damp out quickly
    - Unlikely to reach divertor
  - However, summing annulus resonances may produce new phenomena such as phase coherence

Axial wavenumber $k_{||}$ of annulus resonance increases with azimuthal wavenumber m

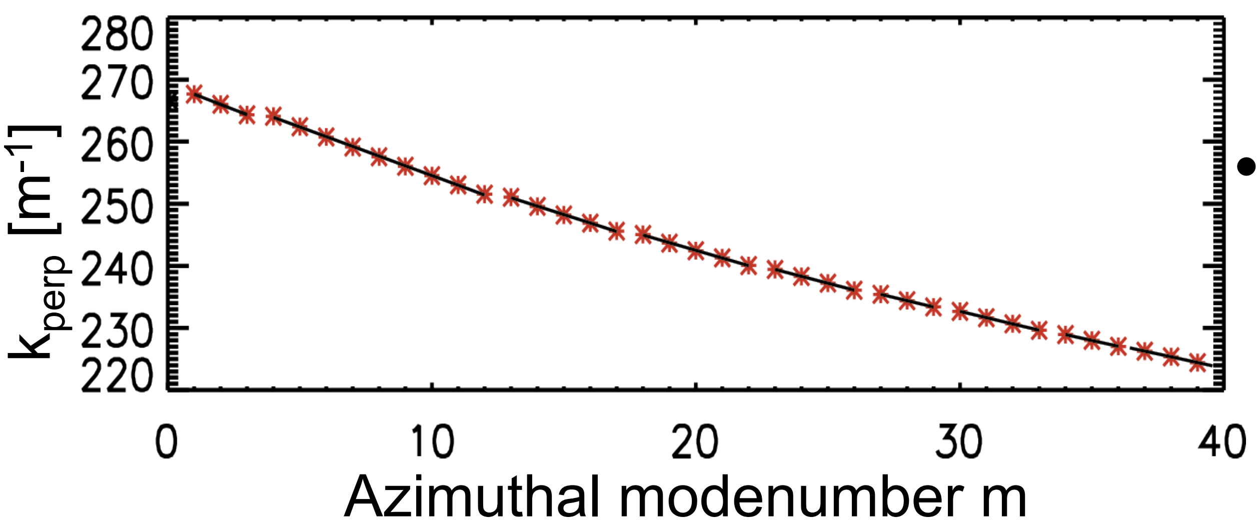


- Azimuthal antenna spectral density not included
  - Would weight modes roughly as m^{-2}
- Coaxial modes suppressed
- For lower m, annulus resonance disappears into vacuum cutoff

m-dependence of annulus resonance $k_{||}$ and k_{perp} is smooth with "breaks"

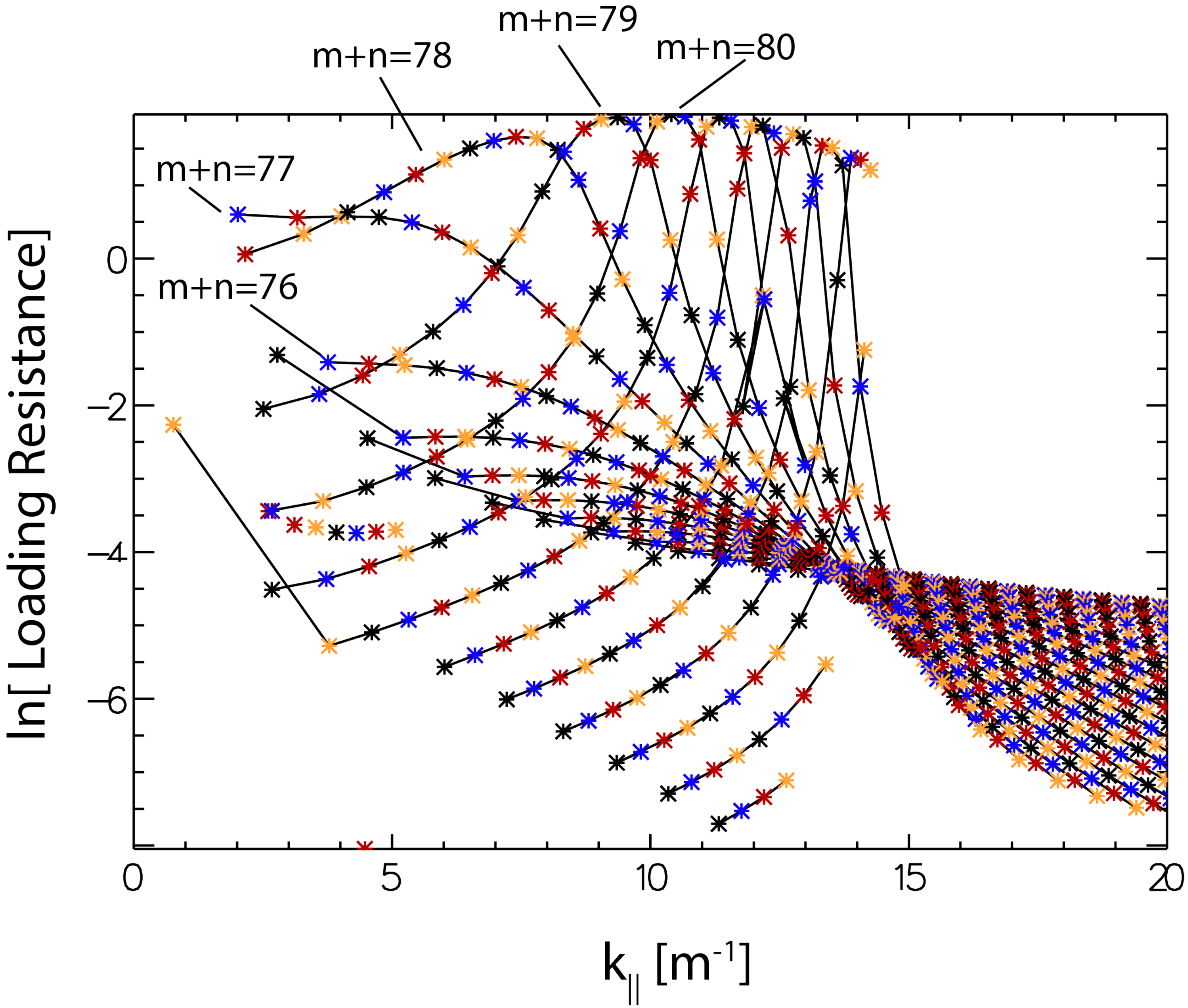


- Only plotting annulus resonant mode for each m
- $k_{||}$ is a smooth curve with "breaks"



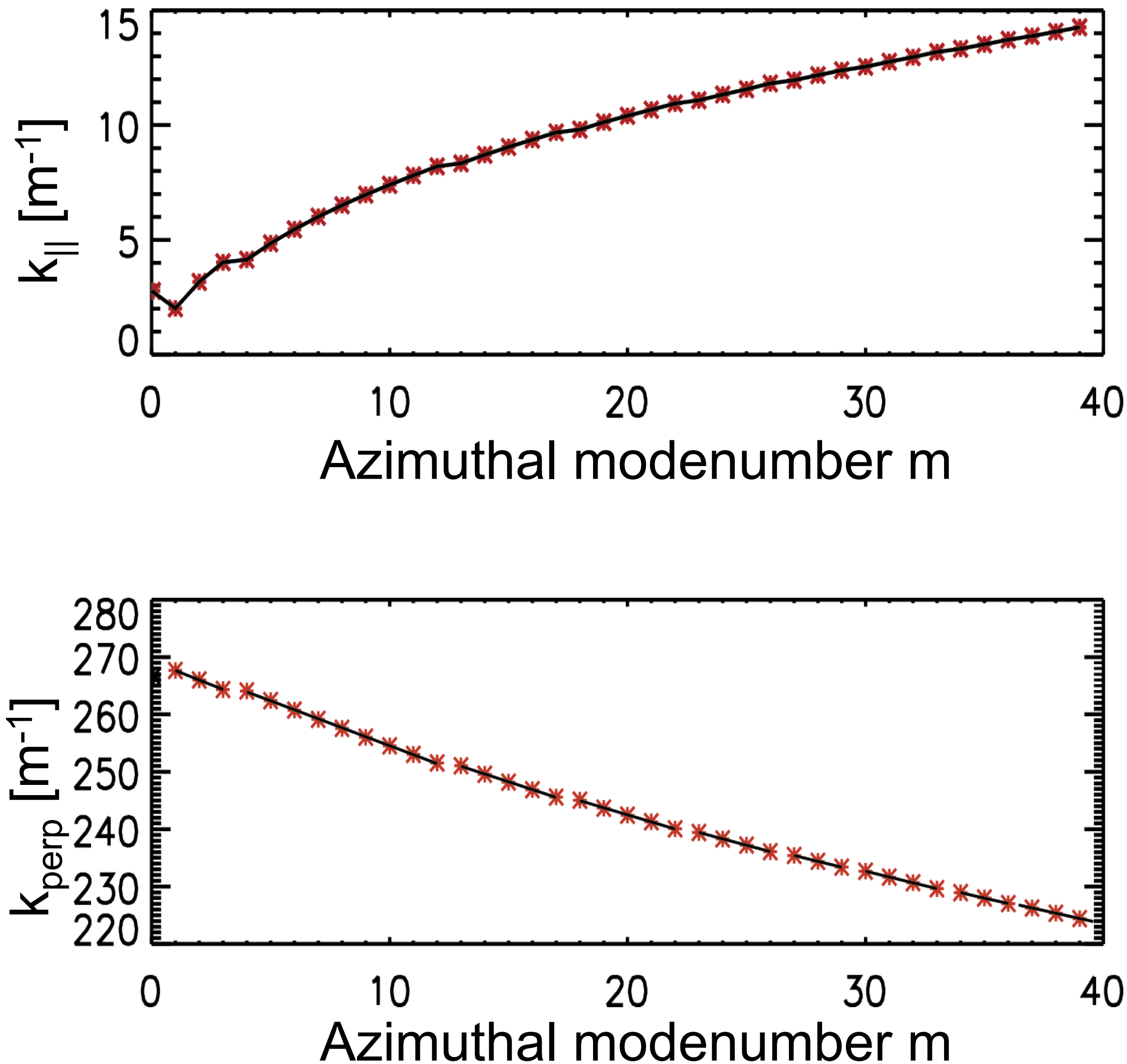
- k_{perp} is piece-wise linear

Logarithmic scatter plot of loading resistance reveals smooth curves connecting different m-values



- Scatter plot of all modes
- Smooth curves exists
  - Modes within curve are related by m + n = const
- Explanation: for modes with m+n = const, the number of wavelengths in edge varies very slowly
  - Modes within a curve satisfy ½-wavelength conditions for a while
- Set of annulus resonances is the *envelope* of this plot
  - Advances between m+n curves

Smooth curves explain piece-wise linear dependence of k_{perp} on m



- Using asymptotic forms of Bessel functions, the fast-wave phase at core-annulus boundary is:

$$\phi_{m,n} \approx k_{\perp,m,n} r_c - m\frac{\pi}{2} - \frac{\pi}{4}$$

- For an m+n = const curve, we thus have

$$k_{\perp,m+1,n-1} = k_{\perp,m,n} - \frac{1}{r_c}\frac{\pi}{2}$$

- As the dominant smooth curve changes with $k_{||}$, this causes the "breaks" in the linear dependence

Possible phase coherence could confine wave power to edge for longer distances

- $k_{||}$ of annulus resonance varies nearly linearly with m: $k_{||} \sim \beta m$
  - Especially if we are restricted to certain region of k||-space, such as by phased antenna
- Mode phase varies as: $k_{||} z + m/r\, \varphi$
  - Along the helix $d(r\varphi)/dz = - r\, k_{||} / m$, the phase ***of a single mode*** does not change
- In full reconstruction, modes are in phase close to antenna but acquire different phases away from antenna and destructively interfere
- However, along a particular helix, phase decorrelation of annulus resonance occurs much slower
  - Along the helix $d(r\varphi)/dz = - r\, k_{||} / m \sim - r\, \beta$, phase change ***of all annulus resonances*** is minimal

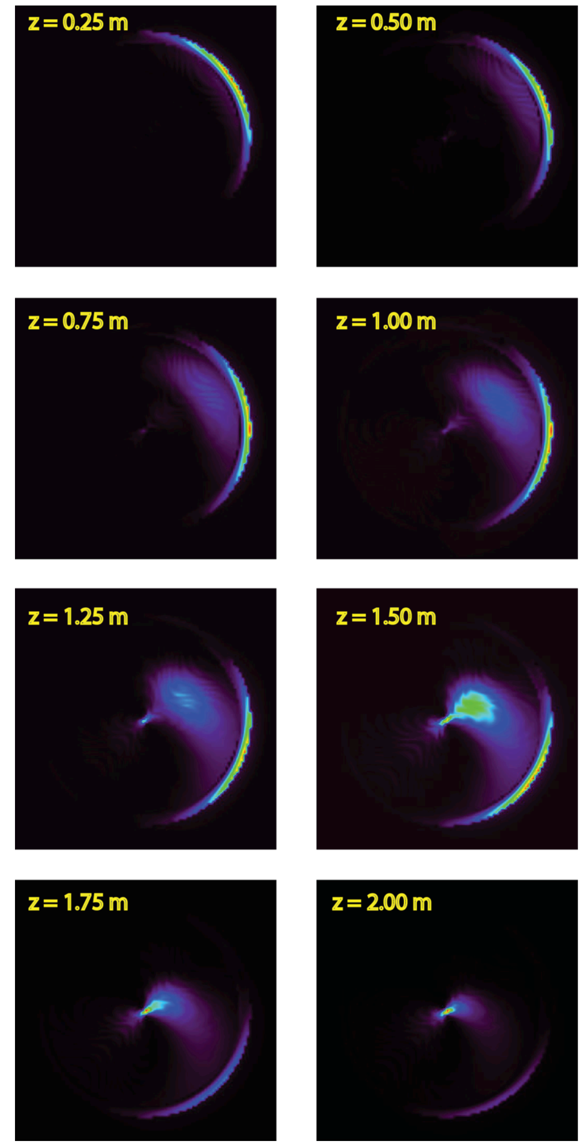
Initial 3D reconstructions suggest that wave power might remained confined in annulus for some distance

- The following are cross-section slices of the axial Poynting flux at different distances from the antenna
  - No paritcular axial antenna weighting used

- Close to antenna, wave fields are only found close to antenna itself (not surprising)

- Further from antenna, power gradually penetrates core

- However, a somewhat coherent structure persists in the annulus up to two meters from antenna



Conclusions

- SOL losses were a significant operational hindrance on NSTX
  - Understand what causes these losses will help optimize coupling on NSTX-U and facilitate a host of new experiments
- Annulus resonant modes from a cylindrical model are promising candidates to explain losses
  - Large RF field amplitudes in the edge
  - Large loading resistances
  - Exist when ½ a radial wavelength fits in edge
- Need to study how annulus resonances "sum" over multiple aimuthal modenumbers
  - Initial results suggest possible phase coherence in edge; could confine power to edge for longer distance than expected.