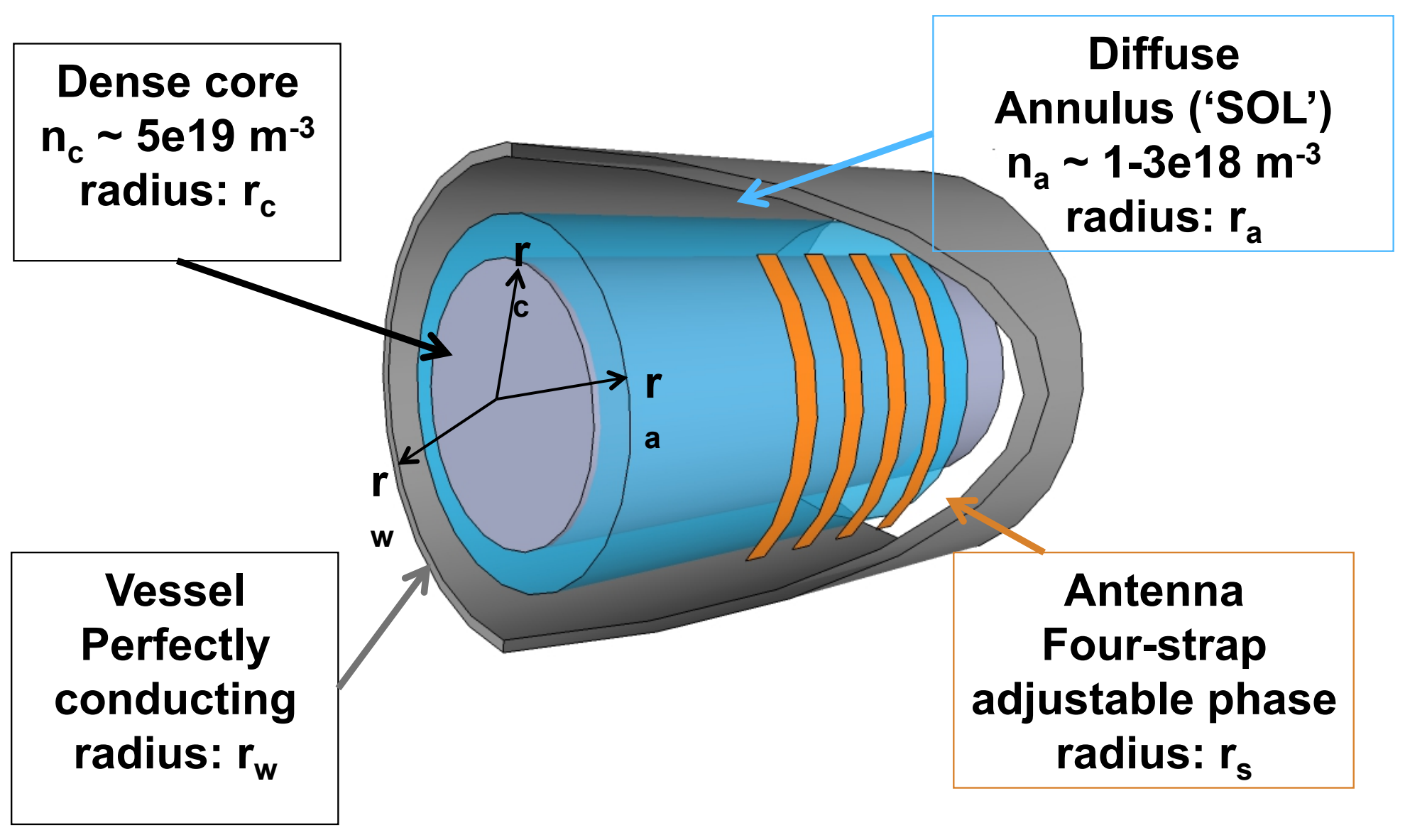
RF field amplitudes in the SOL and far-field RF sheaths: a proposed mechanism for the anomalous loss of RF power to the SOL of NSTX

R. J. Perkins[1], J. C. Hosea[1], N. Bertelli[1], J.-W. Ahn[2], R. E. Bell[1], A. Diallo[1], S. Gerhardt[1], T. K. Gray[2], J. C. Hosea[1], M. A. Jaworski[1], B. P. LeBlanc[1], G. J. Kramer[1], A. McLean[3], R. Maingi[1], L. Roquemore[1], S. Sabbagh[4], G. Taylor[1], and J. R. Wilson[1] [1]Princeton Plasma Physics Laboratory, [2]Oak Ridge National Laboratory, [3]Lawrence Livermore National Laboratory, [4]Columbia University

Summary

- Direct loss of HHFW power to the SOL prevents efficient fast-wave heating on NSTX
- We propose a two-step mechanism to explain these losses:
  - Large RF electric fields are drive in SOL due to cavity-like modes
  - The large RF fields drive RF rectification in the divertor sheaths, which dissipate signifcant power
- Cavity-like modes are explored using a cylindrical cold-plasma model
  - Annulus resonant modes are shown, which have large field-amplitudes in the edge and large loading resistances
- Data in support of RF rectification in the divertor is presented
  - First-principle calculations suggest that the observed level of rectification greatly increases the heat flux within the spirals

Cylindrical Cold-Plasma Model for Enhanced Edge RF Fields



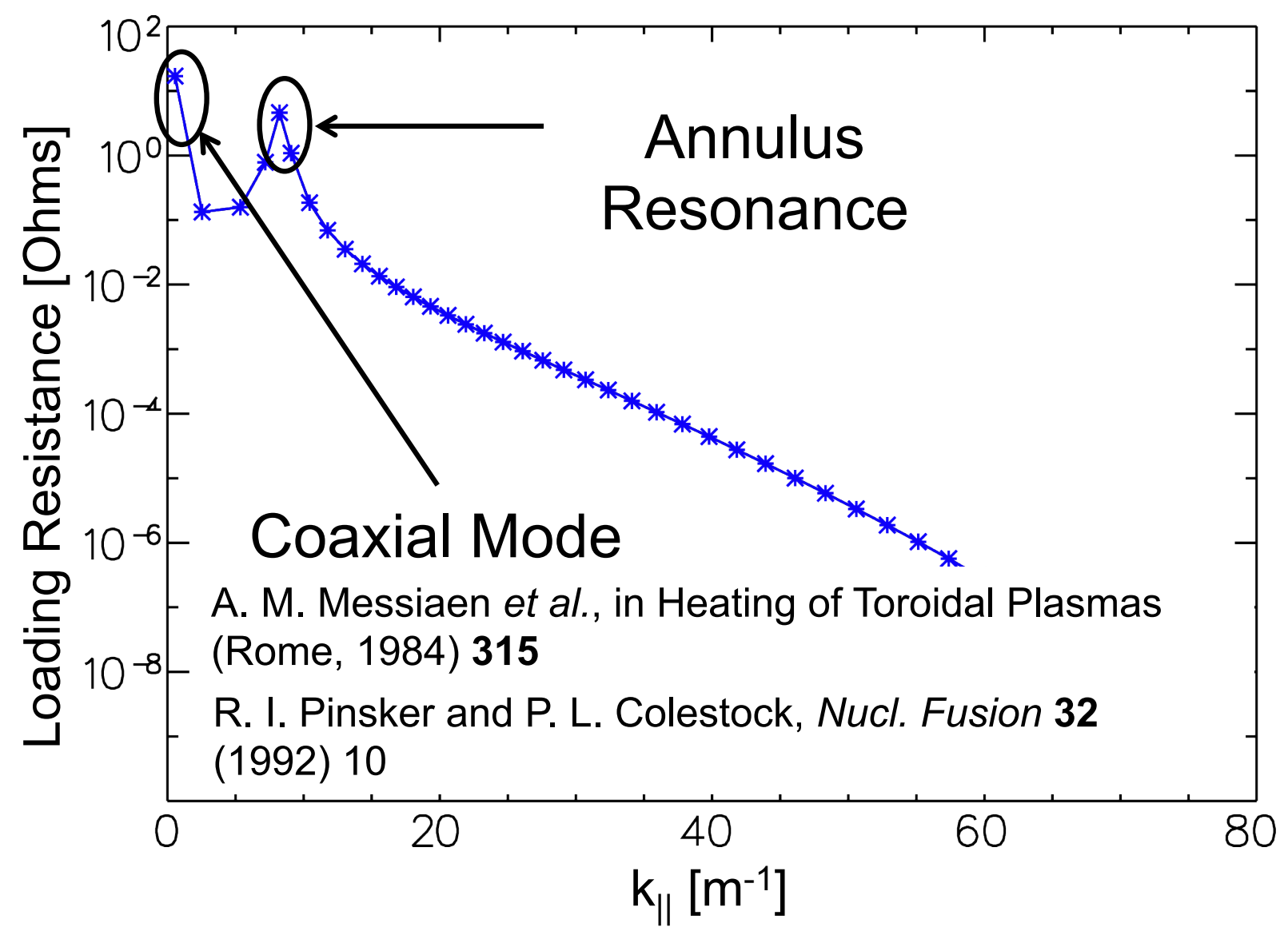
- Full-wave code results are difficult to interpret
  - Role of `toroidal geometry and vessel geometry is being studied but is currently unclear [N. Bertelli et al., Nucl. Fusion 2016]
- Cylindrical model isolates fast-wave propagation physics in simplified geometry
- Two-step density profile provides minimal complexity to study role of steep gradient
  - Partially justified by large perpendicular wavelength (~21 cm) of fast wave in SOL compared to density gradient scale length (~1-2 cm)
- Uniform magnetic field throughout

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 of a peak in loading resistance

m=2 and n_a = 3x10^{18} m^{-3}

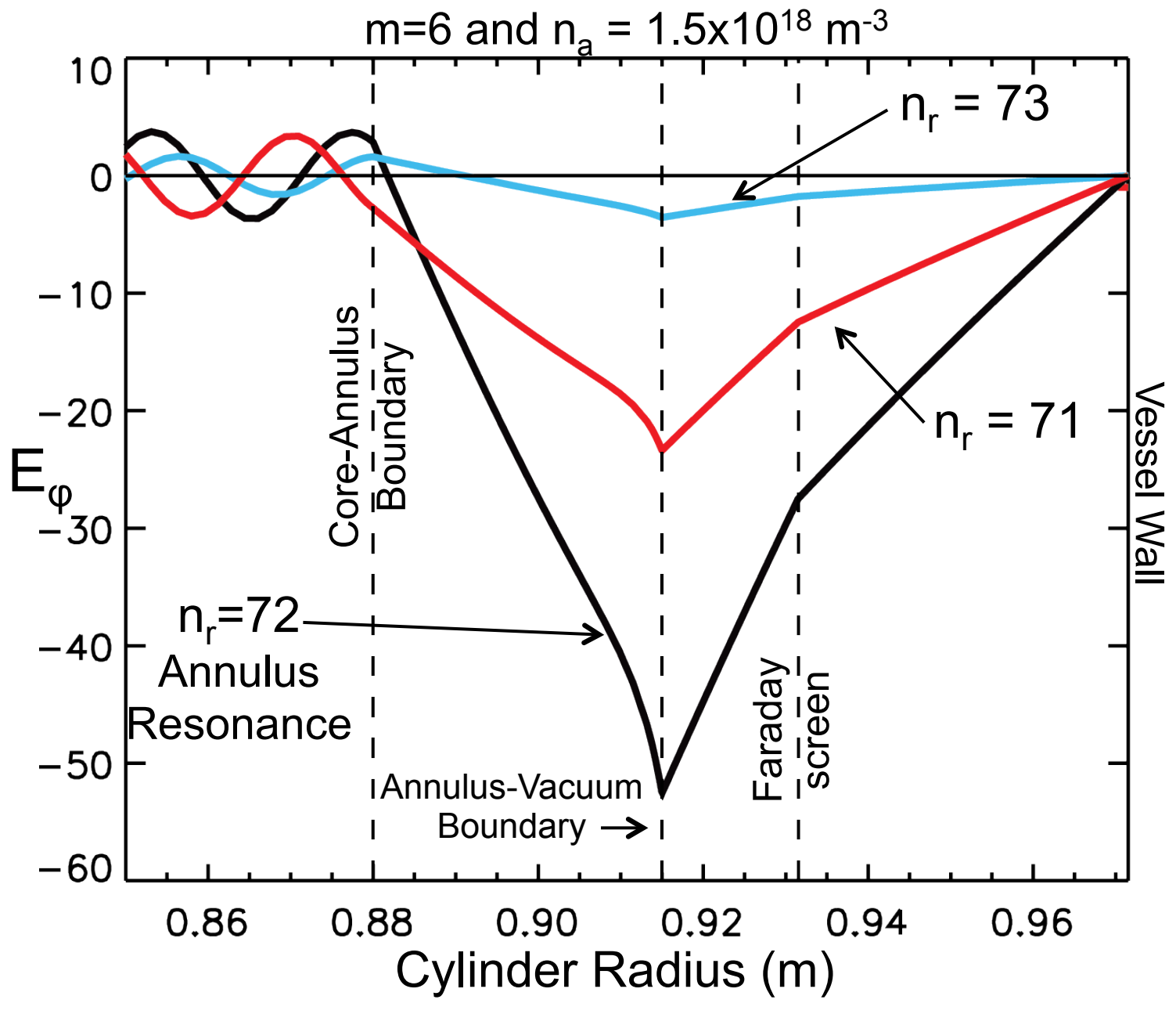


A. M. Messiaen *et al.*, in Heating of Toroidal Plasmas (Rome, 1984) **315**

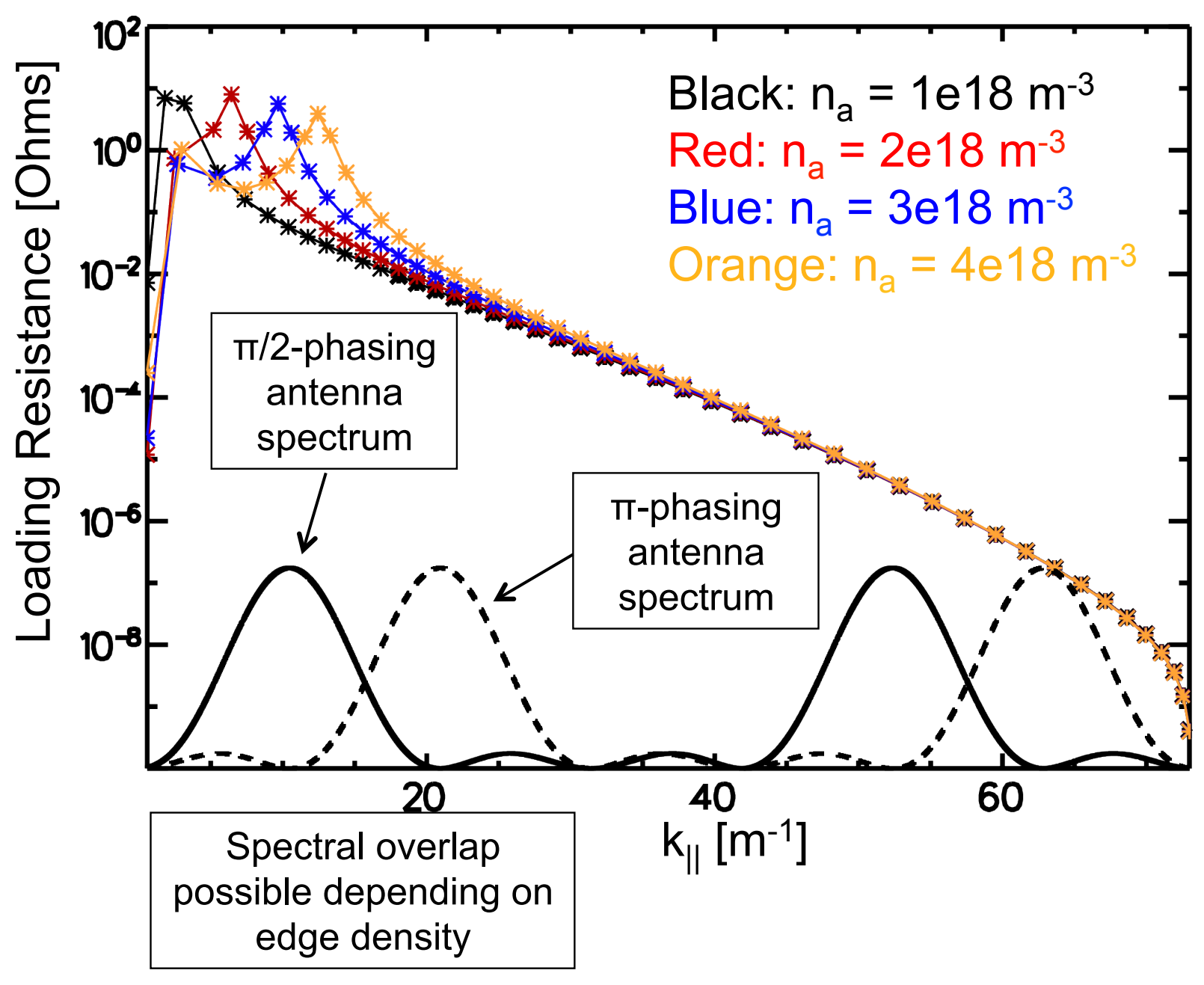
R. I. Pinsker and P. L. Colestock, *Nucl. Fusion* **32** (1992) 10

Field amplitude in SOL depends on how closely each mode has ½ a radial wavelength in edge

m=6 and n_a = 1.5x10^{18} m^{-3}

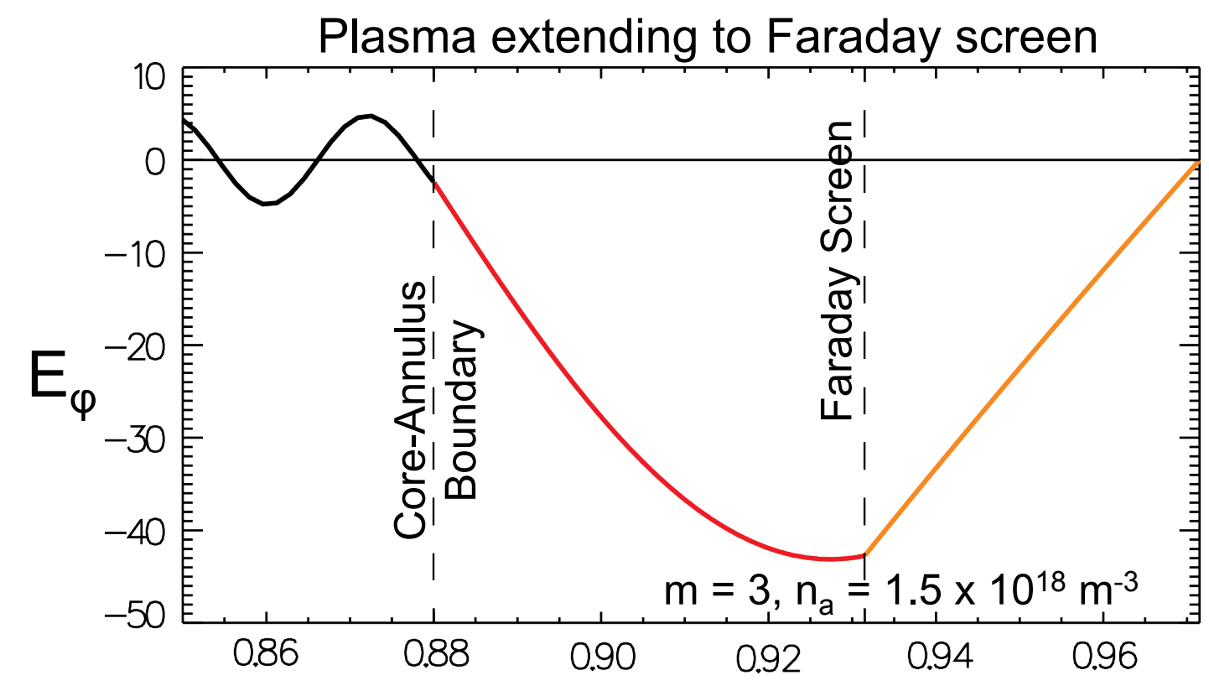


Increasing the annulus density increases the $k_{||}$-location of peak loading

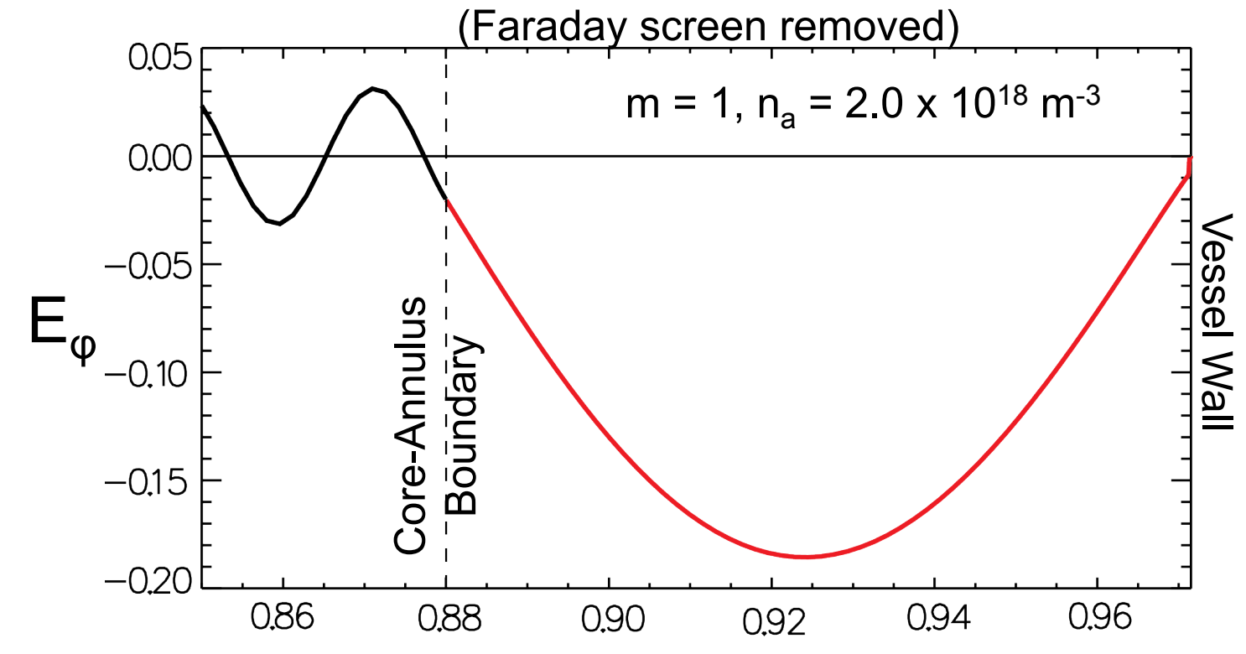


½ radial wavelength condition is robust: holds in various configurations

Plasma extending to Faraday screen

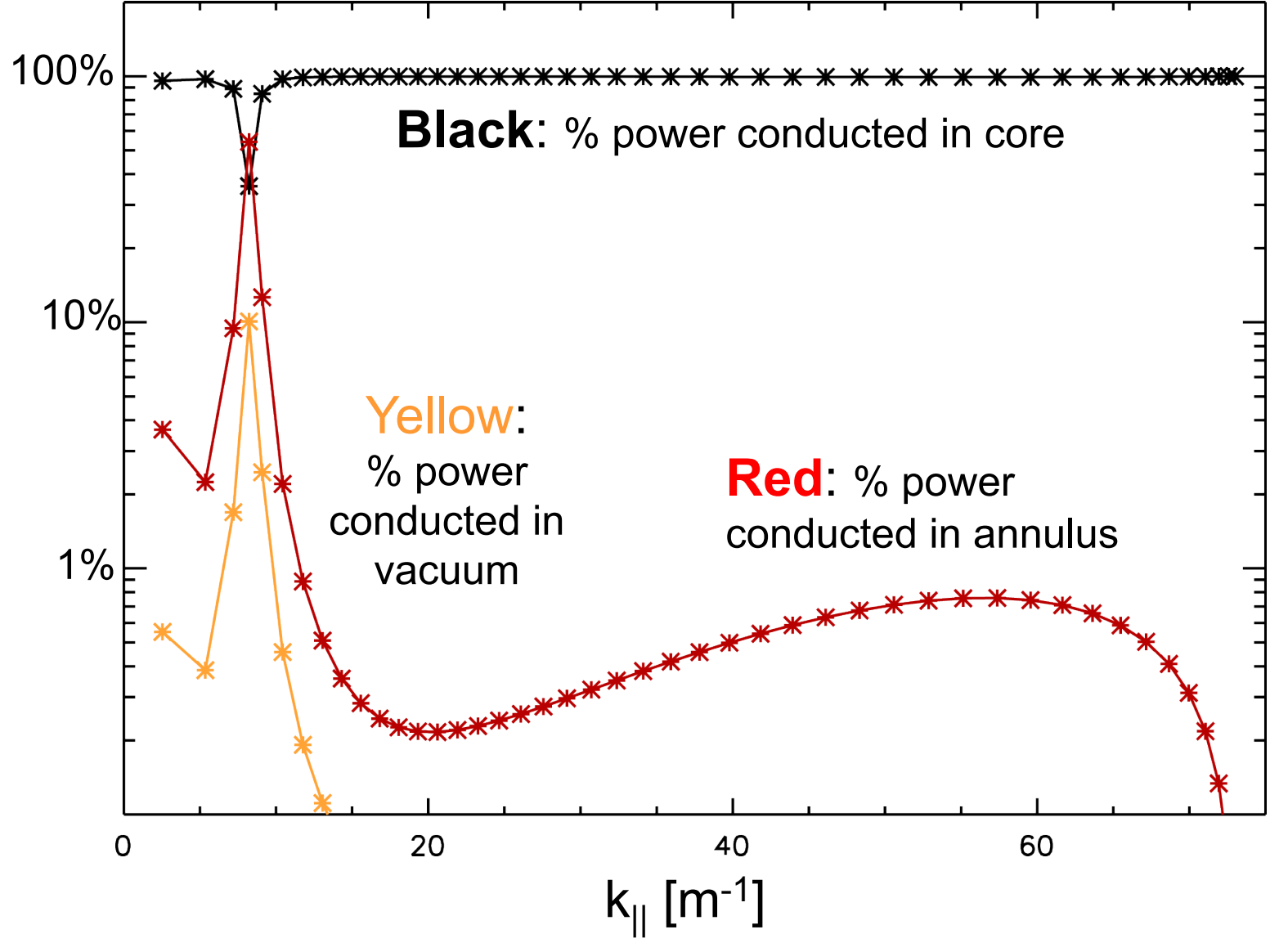


Plasma extending to Vessel Wall;
(Faraday screen removed)



Annulus Resonance conducts a large fraction of power in the annulus

Percentage of Wave Power Conducted in Core/Annulus/Vacuum Regions
m = 2, n_a = 2.0 x 10^{18} m^{-3}



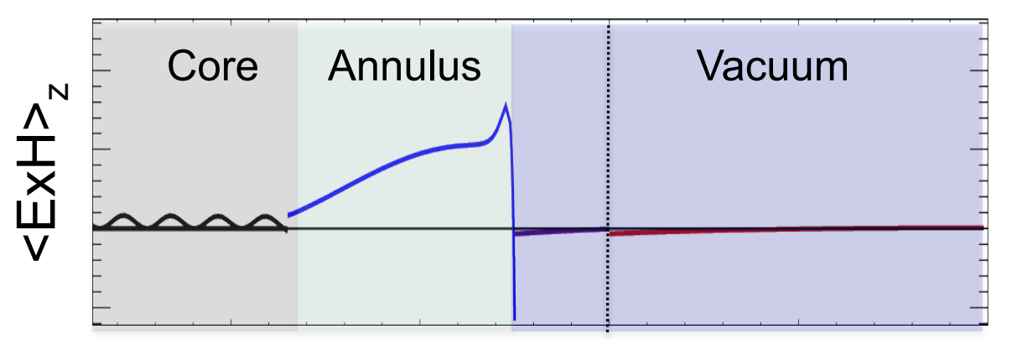
Wave power distribution for annulus resonance:

- 36% in core
- 54% in annulus
- 10% in vacuum

Annulus resonant modes are distinct from coaxial modes

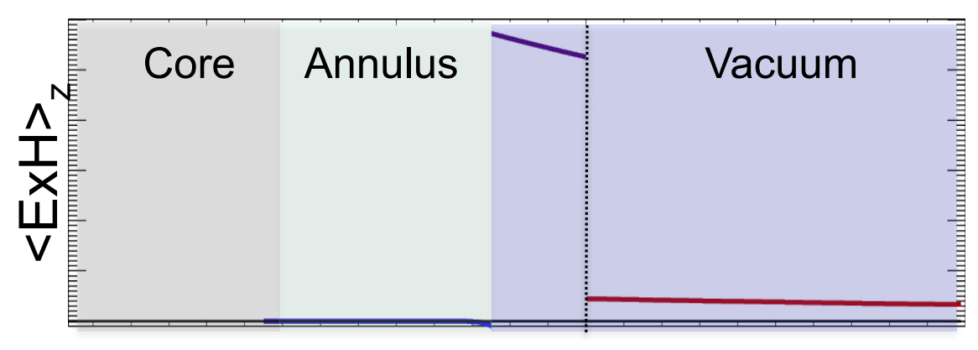
- Coaxial modes: low-$k_{||}$ modes resembling TEM modes in coaxial cables
  - Very large loading resistance
  - Often considered spurious and removed from analysis
- Annulus resonance are distinct from coaxial modes
  - Not TEM modes; have substantial H_z component.
  - Wave fields propagate in core
  - $k_{||}$ sensitive to the annulus density.

Annulus Resonance: Axial Poynting Flux



Large Poynting flux in annulus

Coaxial Mode: Axial Poynting Flux

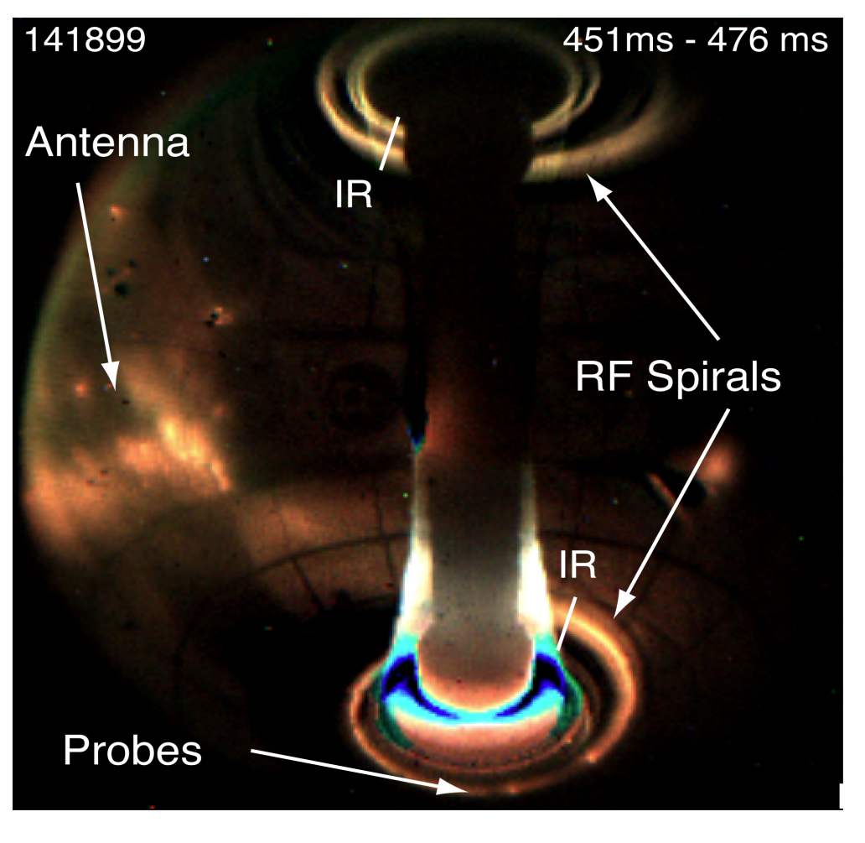


Poynting flux confined between plasma and Faraday screen

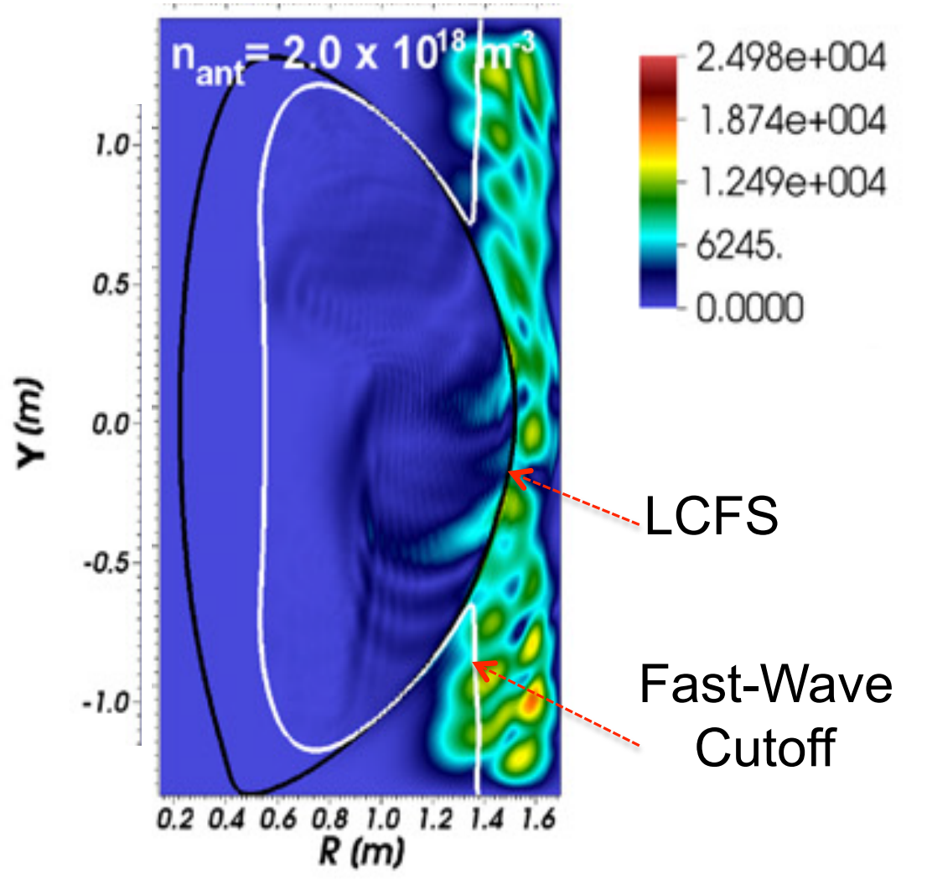
R. J. Perkins *et al.*, *Nucl. Fusion* **53**, 8 (2013)

BACKGROUND: anomalous SOL loss of RF power on NSTX

- SOL losses of HHFW power account for up to 60% of coupled power [Hosea 2008 & 2009]
  - Losses form bright and hot spirals in divertors
  - Heat flux up to 2 MW/m^2 (via IR thermography, 1.8 MW applied HHFW)
- Losses believed to driven by enhanced fast-wave amplitude in SOL
  - Experiments show losses are tied to location of righthand cutoff layer relative to antenna
  - Full-wave modeling predicts cavity-like behavior in SOL when density at antenna exceeds fast-wave cutoff density [Bertelli 20014 & 2016]
- These losses are *prompt* losses
  - Not multi-pass damping
  - NSTX core plasma is high beat and highly absorbative



Fast-camera image showing the HHFW antenna, the spirals on upper and lower divertor, the radial Langmuir probe array, and the views of IR cameras.



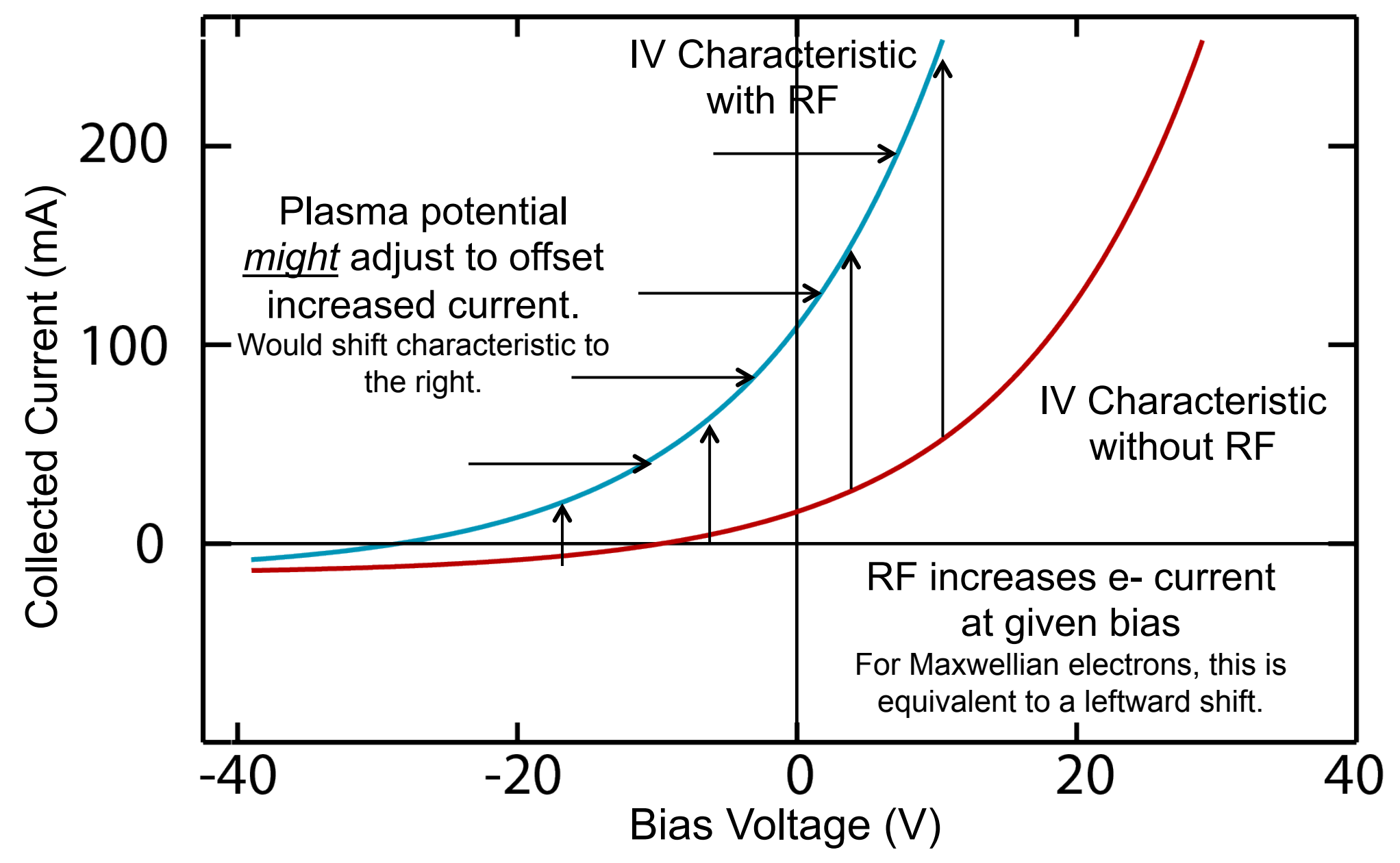
Full-wave simulation of NSTX using the AORSA code show that the fast-wave amplitude is quite large in the SOL when the density at the antenna exceeds the righthand cutoff density

J. C Hosea *et al.*, *Phys. Plasmas* **15**, 056104 (2008).
N. Bertelli *et al.*, *Nucl. Fusion*, **54**, 083004, (2014).
C. K. Phillips, *et* al., *Nucl. Fusion* **49**, 075015 (2009).

J. C. Hosea *et al.*, *AIP Conf. Proc*. **1187**, 105 (2009).
N. Bertelli, *et* al., *Nucl. Fusion*, **56**, 016019, (2016).

A review of RF rectification

- An RF voltage V_{RF} across sheath *increases* average (rectified) electron current
  - For Maxwellian electrons: this appears as a downward shift in floating potential
- Plasma potential *might* adjust positively to offset increased electron current
  - Commonly assumed near antenna
  - … but *does not* apply to NSTX divertor
- Does the RF sheath rectify voltage or current? Or both?
  - Exact response probably cannot be predicted from local considerations
  - Probably depends on details such as where the other end of the flux tube connects to, cross-field diffusion, temperature differentials, ect.



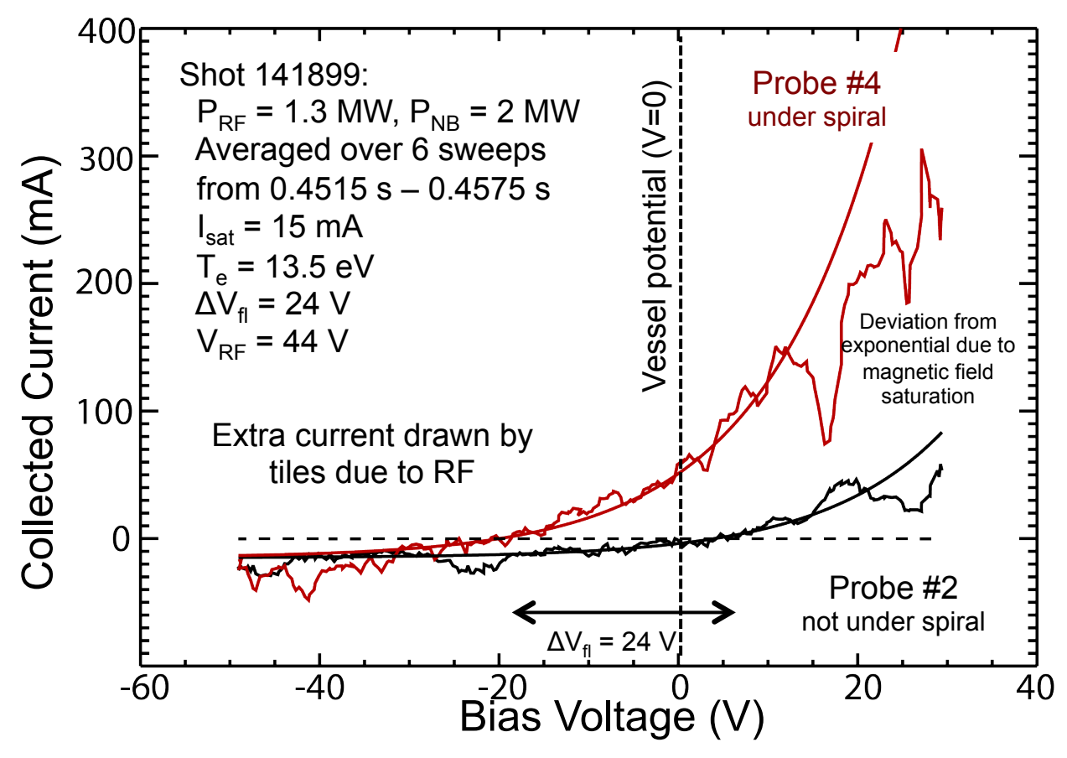
RF rectification causes an exponential IV characteristic (red) to increase its e- current, which appears as a downward shift in floating potential (blue). If drawing this extra current is not possible, the plasma potential will increase, decreasing the drawn current at V=0

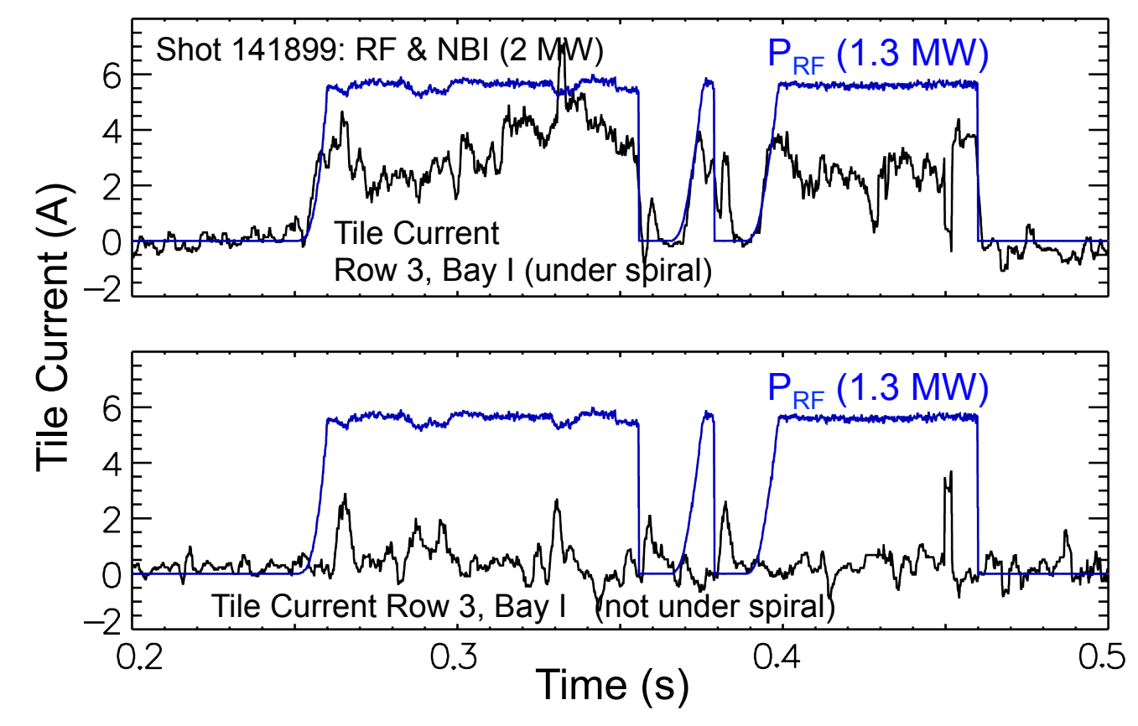
$$J^-(V) = J^{sat}\exp\left[\frac{V-V_{fl}}{T_e}\right] \longrightarrow J^-_{RF}(V) = J^{sat}\underbrace{I_0\left(\frac{V_{RF}}{T_e}\right)}_{\text{Moidfied Bessel function}}\exp\left(\frac{V-V_{fl}}{T_e}\right)$$

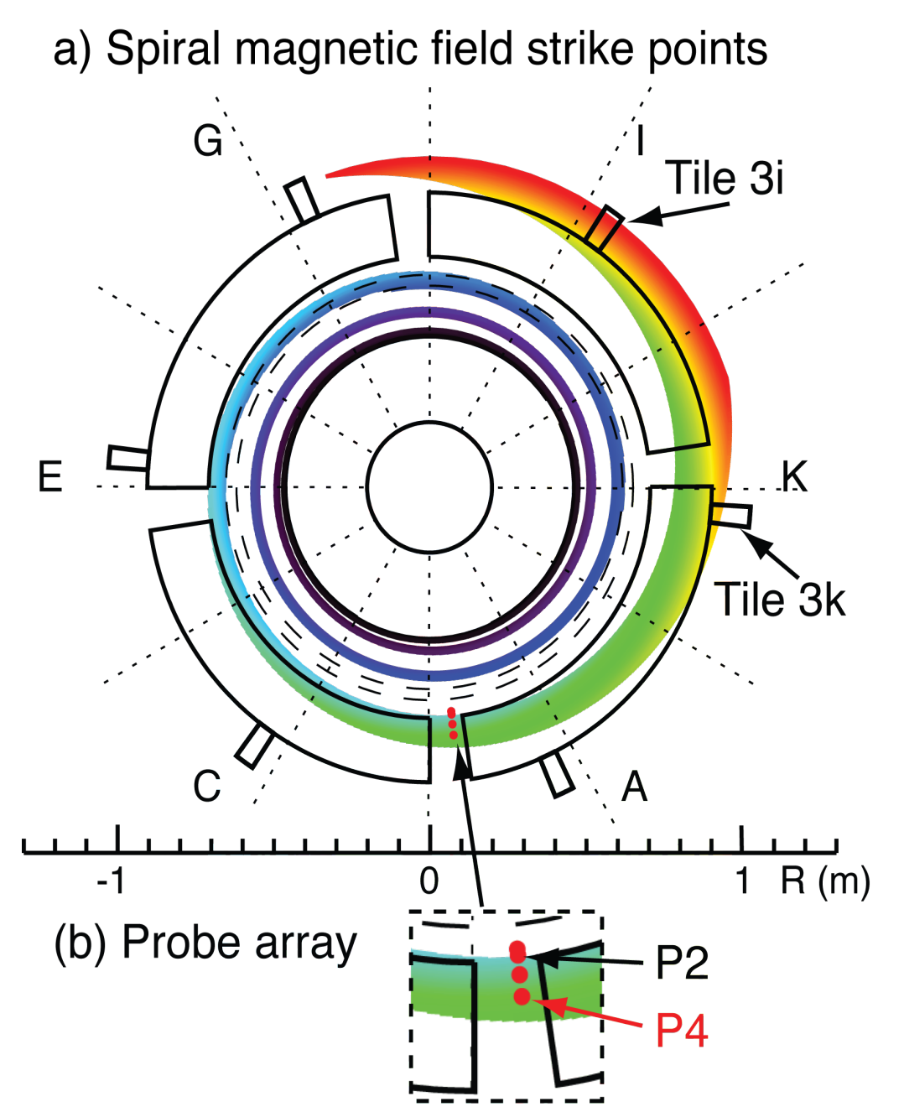
H. S. Butler and G. S. Kino, Phys. Fluids 6, 1346 (1963).

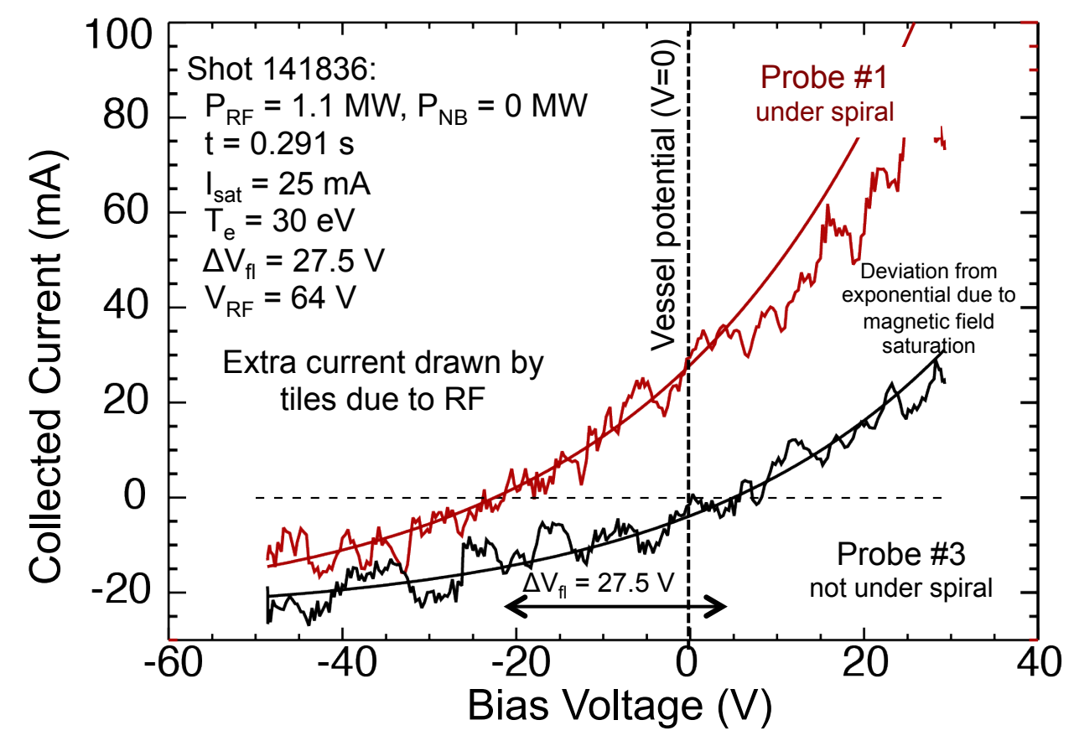
Data from the NSTX Divertor:

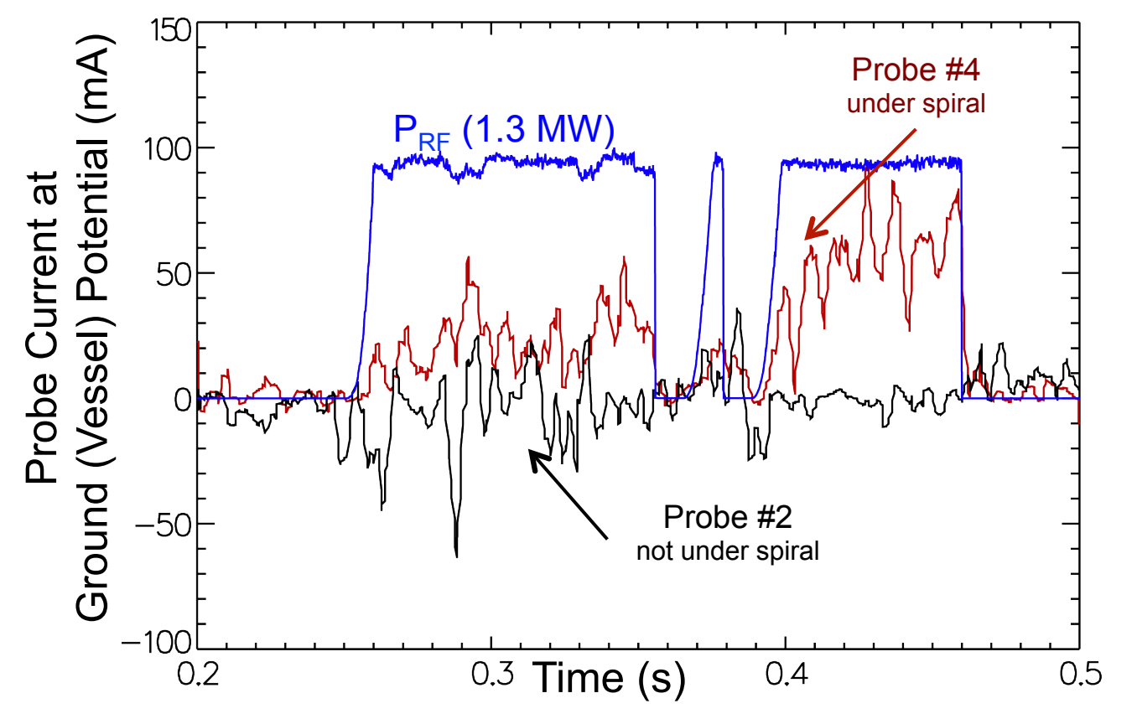
Swept Langmuir probes and tile currents show signs of RF rectification when underneath the RF spiral. The computed heat flux is larger than what would have been obtained assuming voltage rectification











Langmuir probes under spiral experience RF rectification

- Characteristics shifted negative
  - Due more RF rectification rather than an increased T_e [Perkins 2015]
  - Above fits hold I_{sat} and T_e fixed between probes
- Probes draw more current at vessel potential (V=0)
- Deviation from exponential likely due to saturation observed in magnetic field.

Divertor tiles also see increased e^- current with RF

- Rogowski coils under tiles measure (DC) current
- Tile e- currents increases with RF when tile lies under spiral
- Very similar to response of probe current when probe bias to vessel potential (V=0) [Hosea 2014]

RF rectification localized to spiral

- Diagnostics not affected when not under spiral
- Spirals are the footprint of all lines passing in front of the antenna across entire width of SOL
  - Not just lines tied to antenna!!
  - Demonstrated with field-line mapping

Heat flux to a surface in the presence of an RF potential

$$Q_{RF}(V) = \underbrace{-J^{sat}V}_{\text{Ion energy gained by falling through sheath potential}} + \underbrace{2.5T_iJ^{sat}}_{\text{Ion thermal flux; not effected by RF}} + \underbrace{\frac{2T_e}{1-\delta_e}J^{sat}I_0\left(\frac{V_{RF}}{T_e}\right)e^{(V-V_{fl})/T_e}}_{\text{e}^-\text{ thermal flux; increased by RF in proportion to J}^-}$$

- Obtained from [Stangeby 2000] by adding V_{RF} sin(wt) to V and averaging over an RF cycle.
- V = bias voltage relative to vessel, J_{sat} = ion saturation current, δ_e = secondary electron emission coefficient, V_{fl} = floating potential

Divertor Probe Data Show that Rectified Currents Can Significantly Enhance Sheath Heat Flux

	P_{RF} (MW)	T_e (eV)	V_{fl} (V)	$V_{fl,rf}$ (V)	q_{RF} (MW/m^2)	q_{noRF} (MW/m^2)	$q_{RF,fl}$ (MW/m^2)
141899 (2 MW NBI)	1.3	13.5	4	-20	0.21	0.10	0.13
141836	1.1	30	5	-23	0.49	0.35	0.50
141830	0.55	22.5	1	-10	0.44	0.37	0.38