Effect of Array Phasing on the HHFW Power Coupling Through the NSTX and NSTX-U Edge Plasmas

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Abstract

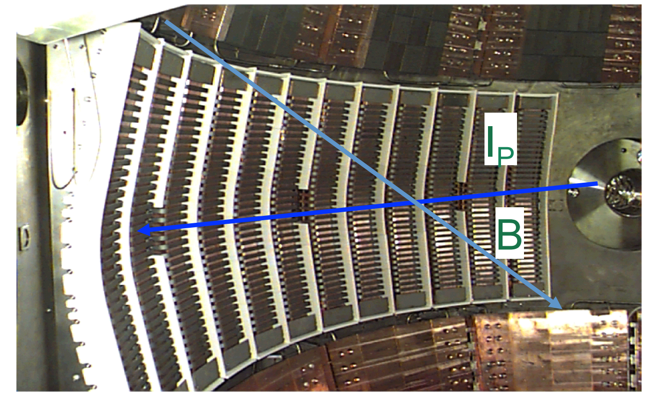
The plasma load presented to the HHFW system in the upcoming NSTX-U experiment will differ from that of NSTX due to increased operational parameters: B_T increased from 0.55 to 1.0 T, I_P from 1 MA to 2 MA, and the addition of a second neutral beam (7 MW to 14 MW). Changes in the ICH harmonics, beta, and the fast ion population are expected to change the power division between the electrons, thermal and fast D^+, and H^+ minorities; these are being calculated with the AORSA code, recently extended to include the edge plasma [1]. Power coupling through and propagation within the edge plasma are being analyzed as a function of plasma gap, edge density profile, and array phasing. The optimal launched spectrum for core power absorption may well differ from that needed for effective power transmission though the edge plasma, and is the primary focus of this study. Collisional damping is being used as a proxy dissipation mechanism to study the anomalous power loss associated with normal modes in the scrape-off layer [2]. The AORSA analysis is being guided by recent experimental measurements of HHFW power deposition in the NSTX scrape off layer [3].

[1] D. L. Green, et al., *Phys. Rev. Lett.*, **107** (2011), 145001

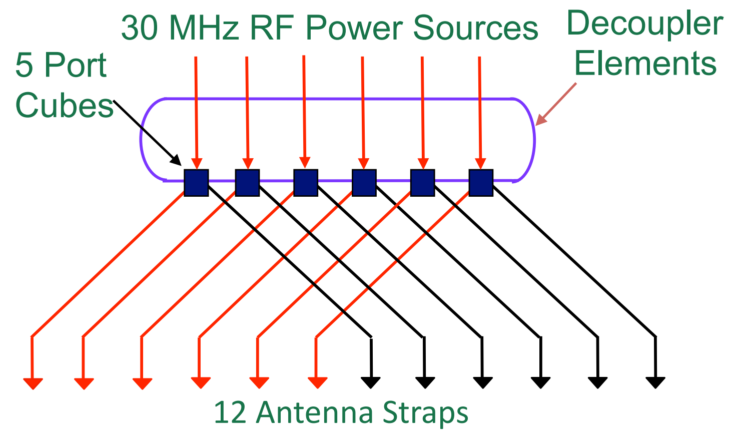
[2] N. Bertelli, invited paper, this conference

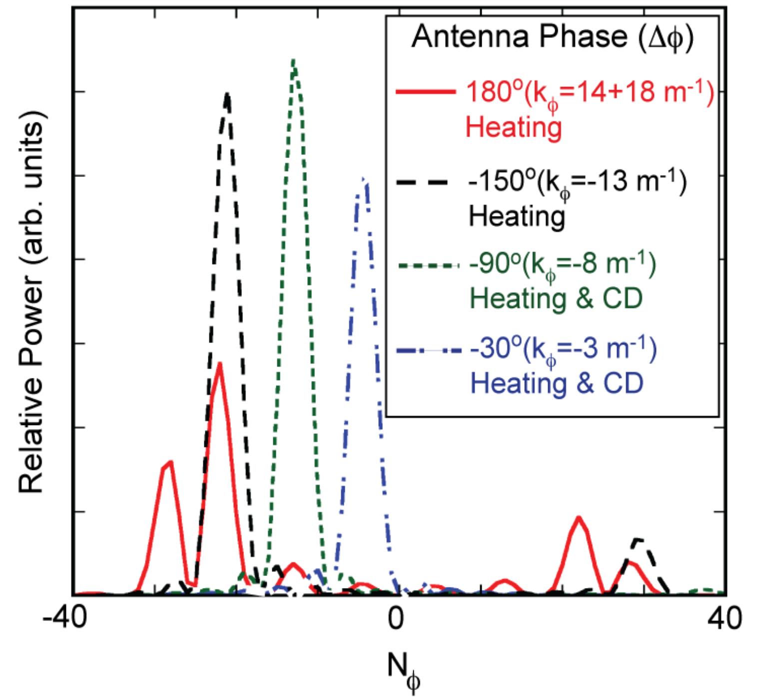
[3] R. J. Perkins et al, *Phys. Rev. Lett.*, **109** (2012), 045001

NSTX HHFW System: Six (1 MW each) Transmitters Drive a 12-element Phased Array at 30 MHz



HHFW antenna extends toroidally 90°



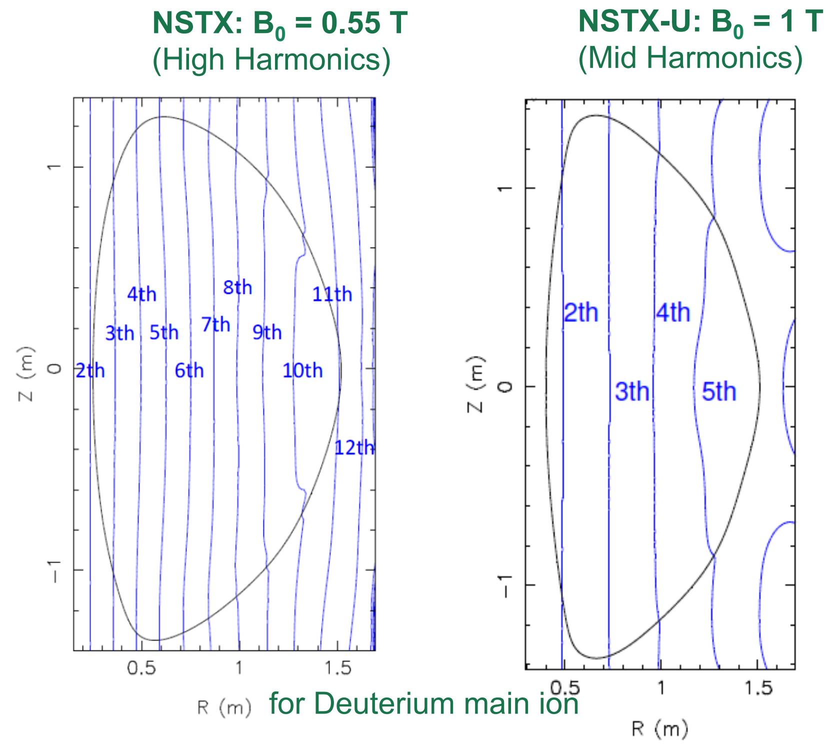


- 12 straps are connected to form two adjacent 6-element arrays, 180° out of phase with each other.
- For phase shifts of 30°, 90°, and 150°, it operates as a full 12-element array with a single highly directional peak (3, 8, 13 m^{-1}).

NSTX vs. NSTX-U

Increased B ⇒ lower IC harmonics ⇒ more wave-ion interaction

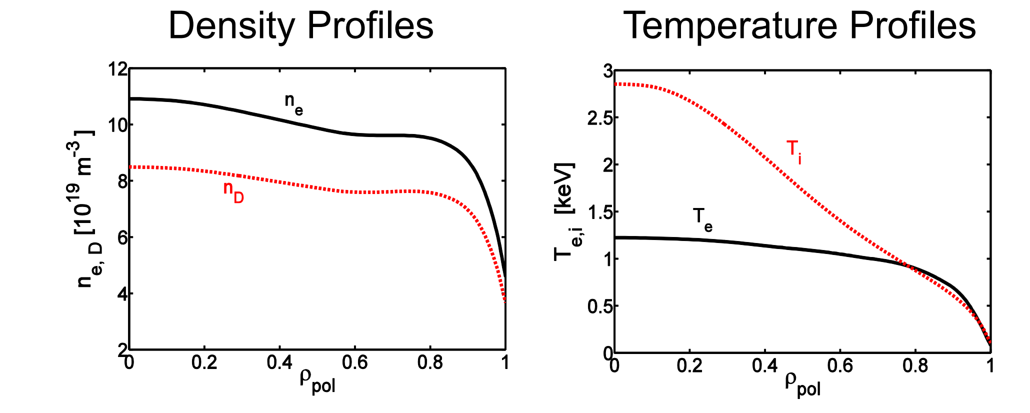
	NSTX	NSTX-U
Major Radius R_0 (m)	0.86	0.94
Aspect Ratio R_0/a	≥ 1.3	≥ 1.5
Plasma Current (MA)	1	2
Toroidal Field (T)	**0.55**	**1**
Neutral Beam Power (MW)	~7 MW	~14 MW



- B_T, I_p and P_{nbi} in NSTX-U will be up to twice as high as in NSTX
- This has implications for FW coupling & heating efficiency:
  - Higher B_T moves the FW cut off towards or inside the separatrix → reducing surface wave losses
  - Scrape off layer (SOL) width may shrink at higher I_p → also reducing surface wave losses
  - SOL density may be higher, moving FW cut off outside separatrix and closer to the wall → possibly increasing surface wave losses
  - Larmor radius (and banana width at high I_p) will be smaller → reducing fast-ion interactions with the antenna

RF Power Deposition for NBI-driven H-mode in NSTX-U

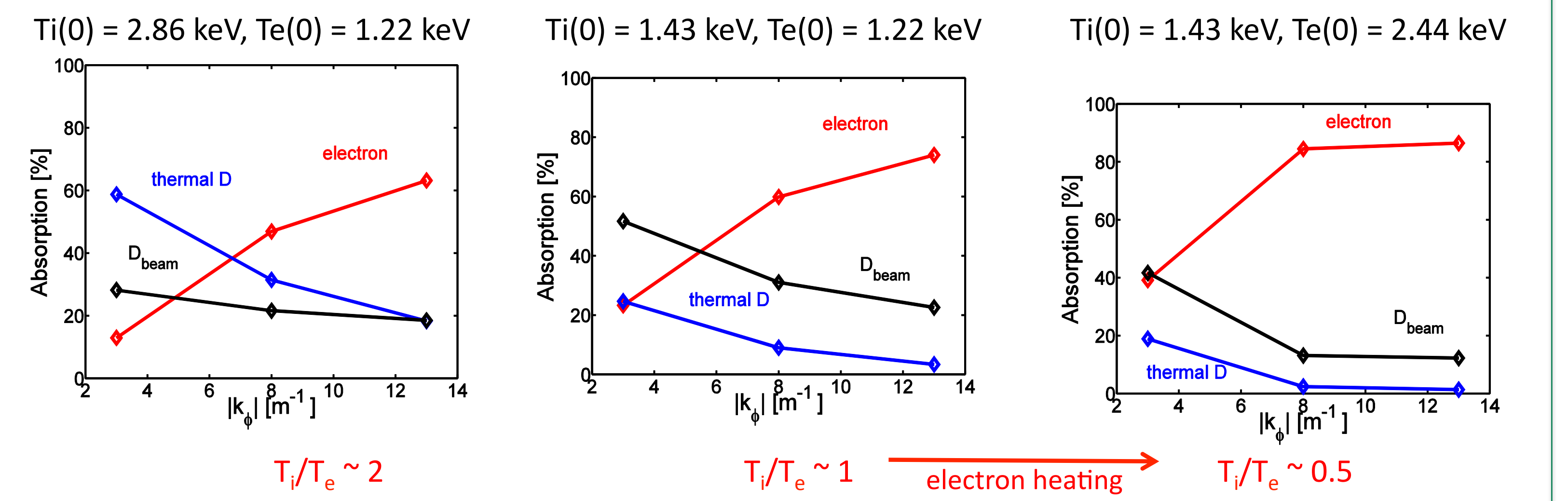
- Increased ion absorption on NSTX-U due to lower ion cyclotron harmonics and increased fast ion population from 2nd beamline.
- Competition between thermal ions (primarily 5th ICH) and electrons (Landau damping and TTMP).
- Electron heating is more effective at high k_ϕ.
- Electron heating will increase β, which in turn will increase the power damped on electrons.



H-mode scenario planned for NSTX-U, obtained by TRANSP simulations

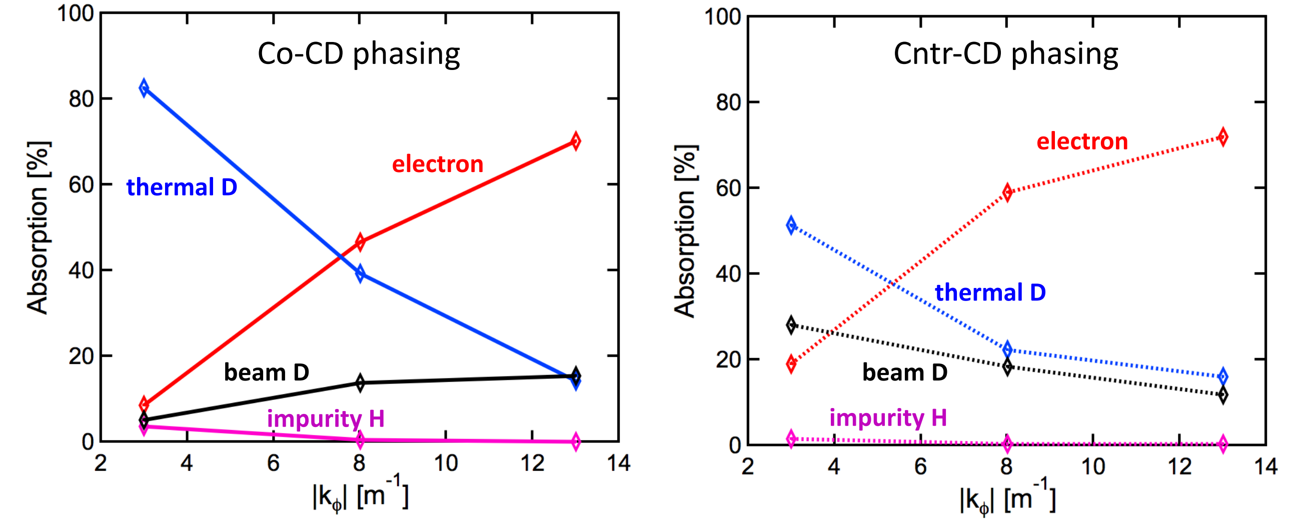
[S. P. Gerhardt, Nucl. Fusion 52, 083020 (2012)]

$B(R_0)$=1 T, I_p=1.1 MA, P_{NBI}=6.3 MW, $n_e(0)$=1.1 x 10^{20} m^{-3}, $T_e(0)$=1.22 keV, $T_D(0)$=2.86 keV



Power deposition channels are sensitive to electron β, T_i/T_e

[Bertelli et al, RF Power in Plasmas, Sorrento Italy, May 2013, to be published in AIP Conf. Proc.]



Power division between thermal ions and fast beam ions is sensitive to the direction of launched waves for low k_ϕ (long wavelengths)

Taking the edge plasma into account with AORSA

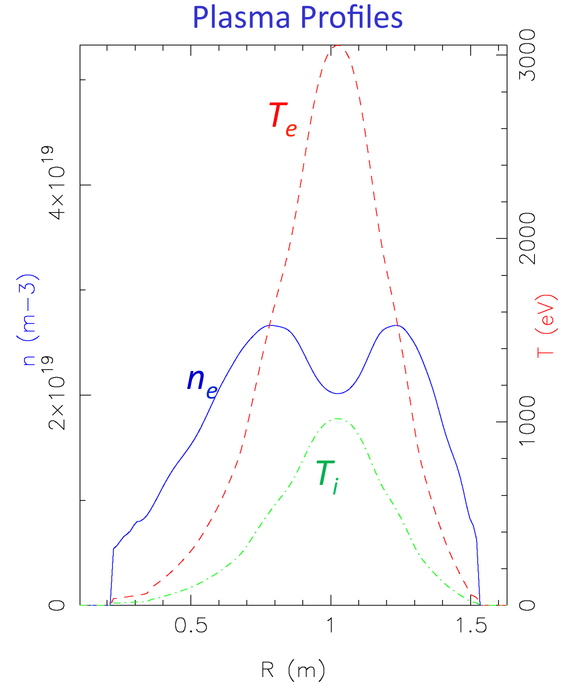
- RF power absorption on core electrons favors fairly high k_ϕ, where the wave velocity matches the electron thermal velocity.
  - Full wave codes, including AORSA, have typically focused on core absorption.
- RF power propagation through the edge plasma favors low k_ϕ and high density, where the fast wave is not cutoff.
  - $n_{cutoff} \propto B^* k_\phi^2$
  - AORSA can accurately model waves in the edge plasma
- Experiments on NSTX have shown that edge losses increase when the fast wave can propagate too close to the antenna [Hosea et al, PoP **15** (2008) 056104].
  - AORSA does not have a physical mechanism for these edge losses.
  - Using artificially high collisional damping as a proxy loss mechanism.

NSTX Power absorption spectrum for no edge plasma

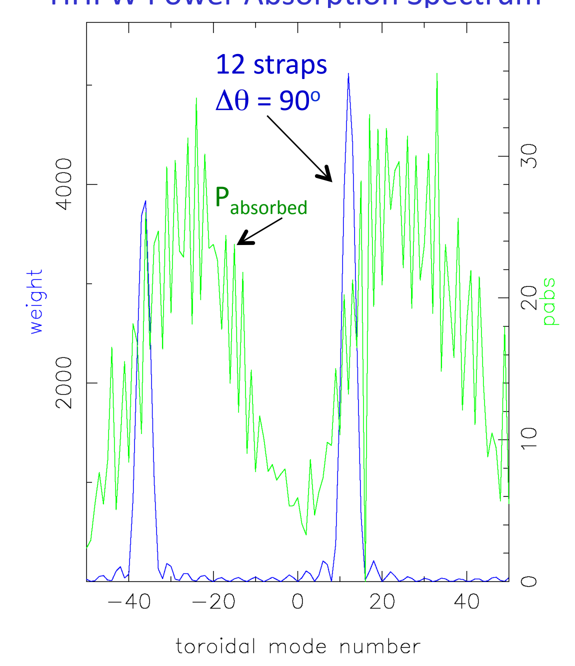
(waves are launched at last closed flux surface)

- Core power absorption, primarily Landau damping on electrons, is low for small n_ϕ when edge plasma is neglected.
- Power absorption peaked for $n_\phi \sim 25$ ($k_\phi \sim 17$ m^{-1}) for NSTX HHFW-driven plasma

Plasma Profiles



HHFW Power Absorption Spectrum



NSTX shot 123435 B_0 = 0.55 T, T_{e0} = 3 keV, No edge plasma, R_{ant} = 1.50 m, $\delta_0 = 0\times10^{-5}$

Treatment of slow waves with AORSA

A simple bi-quadratic dispersion relation can be used to understand the slow waves seen in AORSA

Cold plasma dispersion relation

$$\underbrace{[S]}_{a}n_\perp^4 + \underbrace{\left[-P(S-n_\parallel^2)-(S-n_\parallel^2)^2-n_\parallel^2(S-n_\parallel^2)+D^2\right]}_{b}n_\perp^2 + \underbrace{\left[P(S-n_\parallel^2)^2-D^2P\right]}_{c} = 0$$

where

$$\vec{n} = \frac{\vec{k}}{k_0} = \frac{\vec{k}c}{\omega} = n_\perp\hat{x} + n_\parallel\hat{y}, \quad S = K_\perp, \quad D = K_x$$

$$P = K_\parallel = 1 - \frac{\omega_{p,i}^2}{\omega^2} - \frac{\omega_{p,e}^2}{\omega^2}$$

$$\rightarrow 1 - \frac{\omega_{p,i}^2}{\omega^2} + \boxed{\frac{\omega_{p,e}^2}{\omega^2}\frac{2}{k_\parallel v_{th,e}}Z_2}$$

Warm electron term - additional terms (M. Ono) are also included

This gives a bi-quadratic dispersion solution:

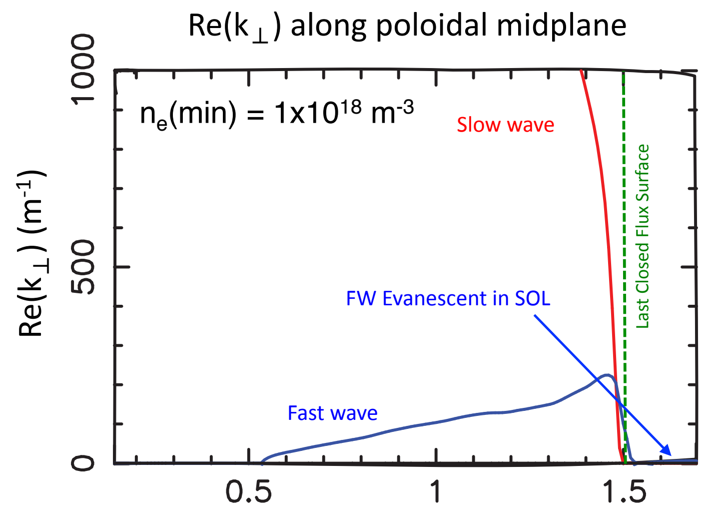
$$n_\perp^2 = \frac{-b}{2a} \pm \frac{1}{2a}\sqrt{b^2-4ac}$$

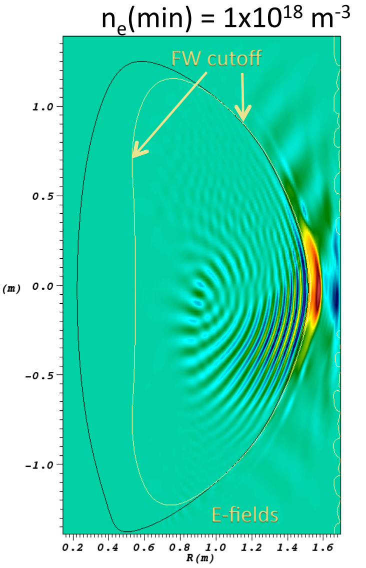
(fast and slow roots)

Ono, Phys. Plasmas 2 (1995) 4075

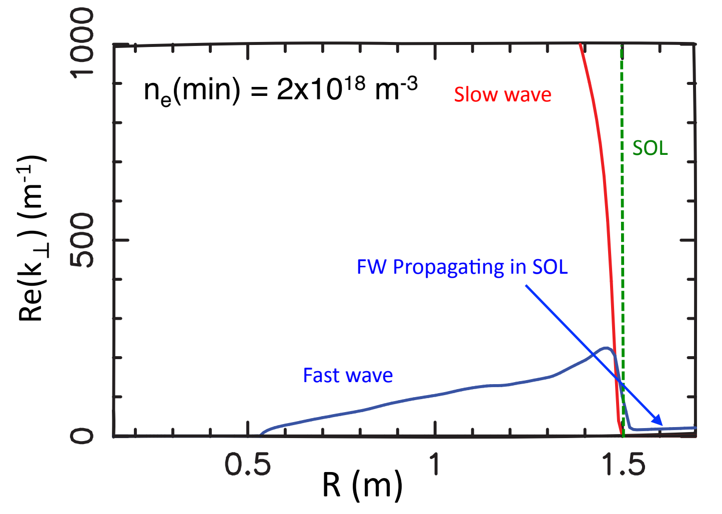
For NSTX (B_0 = 0.55 T, k_ϕ = -13 m^{-1}), the SW is evanescent in SOL, the FW may be either evanescent or propagating

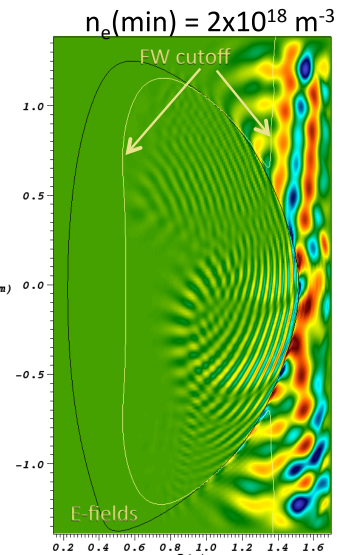
Re($k_\perp$) along poloidal midplane





evanescent





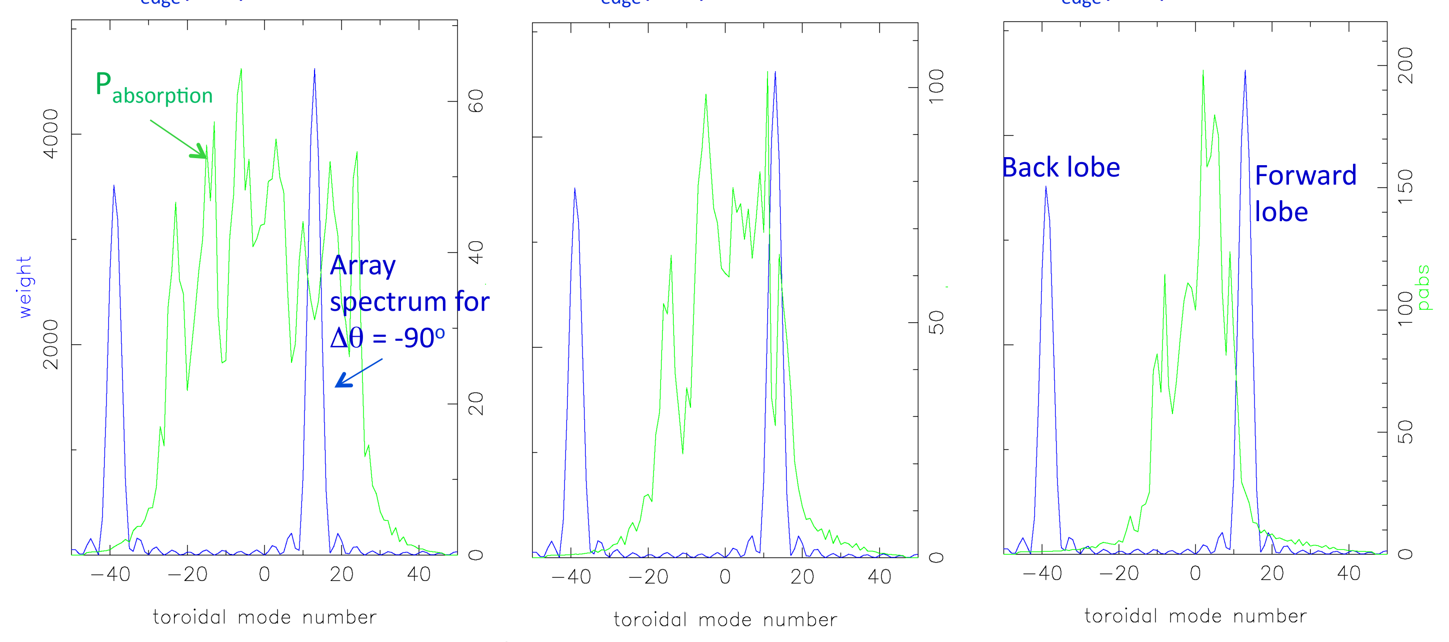
propagating

- At low edge density, FW is completely cutoff in SOL
- As edge density increases, FW begins to propagate in SOL.
- Propagating waves can form standing waves/cavity modes in edge due to reflections at cutoff boundaries

NSTX core power absorption spectrum with edge plasma

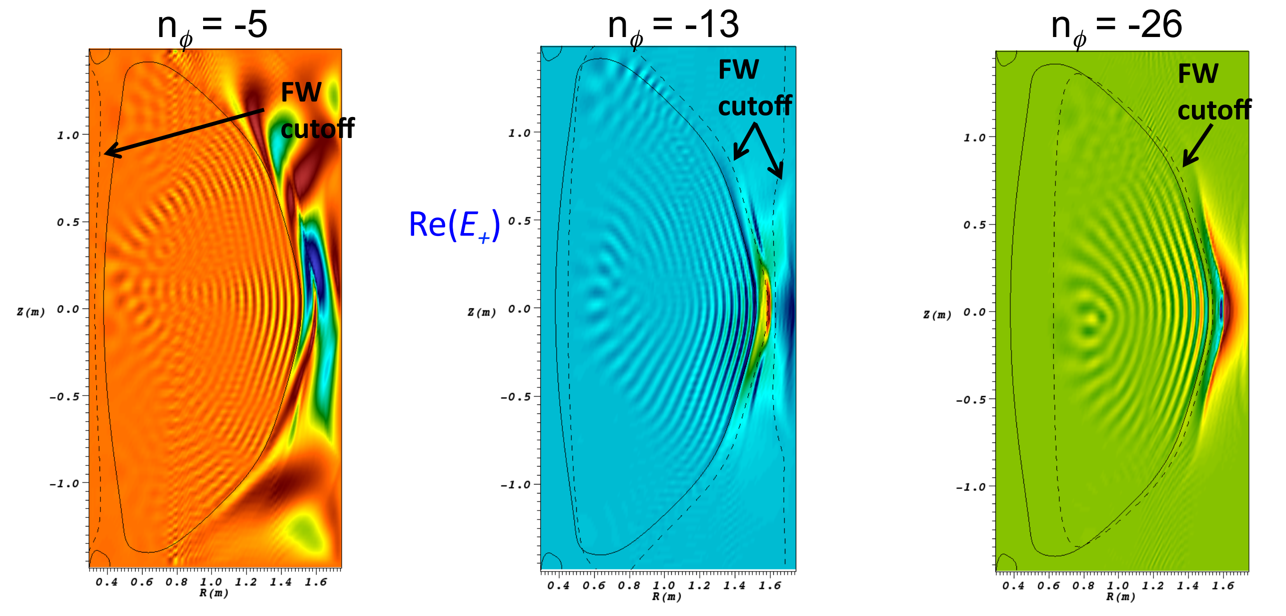
(higher k_ϕ spectral components are cutoff in the edge)

Exponentially decaying edge density profile is clamped at n_{edge}(min) in SOL



NSTX shot 123435.00390, f = 30 MHz, B_0 = 0.55 T, T_{e0} = 3 keV, R_{ant} = 1.60 m, ν/Ω = 0.01

E-fields in SOL as the spectral peak is varied



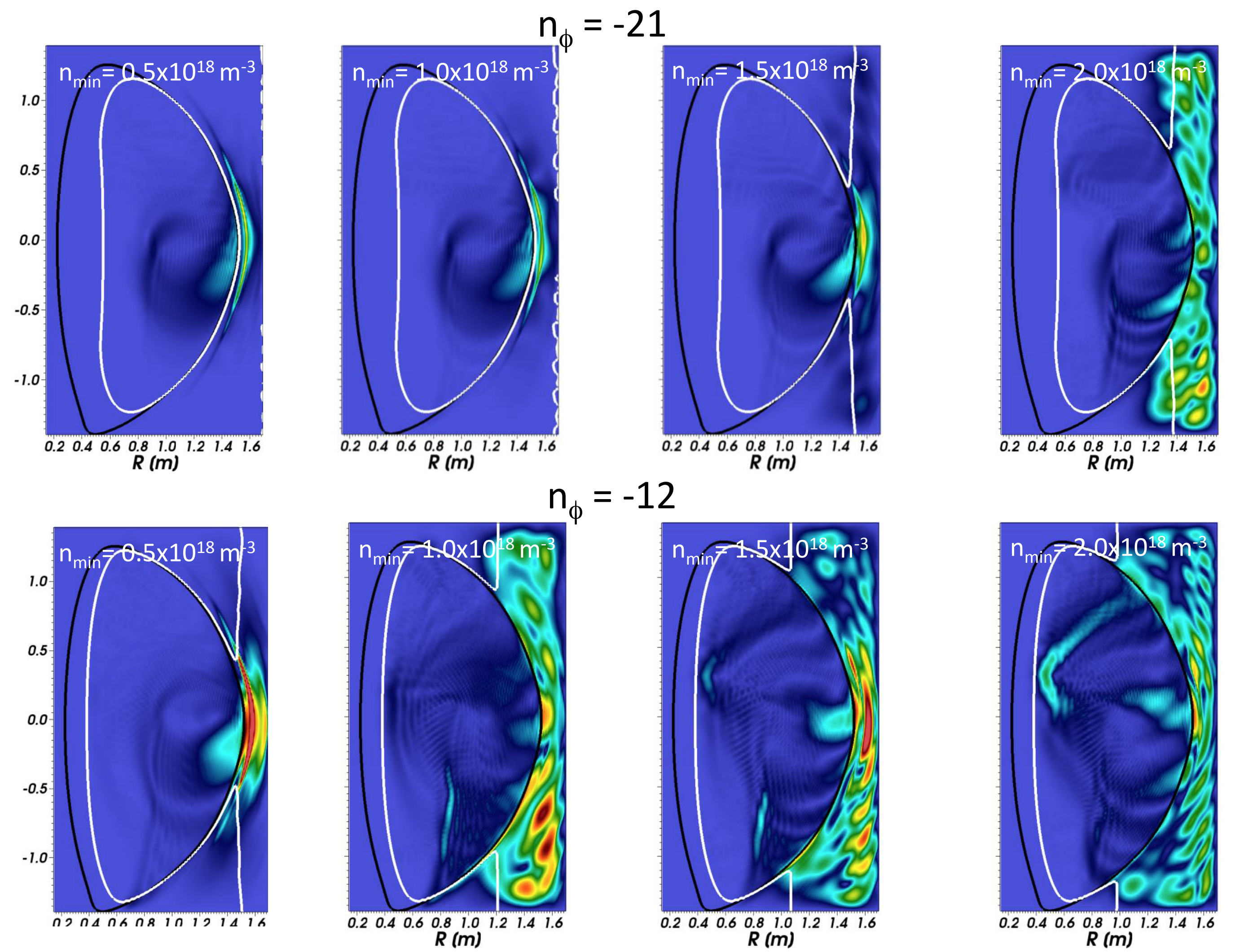
NSTX-U, B_0 = 1 T, T_e = 1.2 keV, n_e (min) = 2x10^{18} m^{-3}

Long wavelength completely propagating in the edge plasma

Medium wavelength cutoff, short evanescent length for tunneling

Short wavelength completely cutoff in the edge

E-fields in SOL as the minimum density is varied



RF power losses in the edge plasma

- see **N. Bertelli's** invited talk this afternoon **(Weds, 2:00 pm, Plaza E)** for details of introducing an artificial collisional damping term as a proxy mechanism for edge losses.
- This proxy mechanism, coupled with AORSA treatment of waves in the SOL, shows the same power loss dependence on edge density, magnetic field strength, and wave number as seen in experiments