NSTX-U

Supported by U.S. Department of Energy Office of Science

TH/P4-14

Full wave simulations for fast wave heating and power losses in the scrape off layer of tokamak plasmas

N. Bertelli[1], E.F. Jaeger[2], J.C. Hosea[1], C.K. Phillips[1], L. Berry[3], P.T. Bonoli[4], G.-Y. Fu[1], S.P. Gerhardt[1], D.L. Green[3], B. LeBlanc[1],
R. J. Perkins[1], C.M. Quin[5], R.I. Pinsker[6], R. Prater[6], P. Ryan[3], G. Taylor[1], E.J. Valeo[1], J.R. Wilson[1], J.C. Wright[4], and X.J. Zhang[5]

1 - Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA 2 – XCEL Engineering Inc. Oak Ridge, TN 37830, USA 3 – Oak Ridge National Laboratory, Oak Ridge, TN 3781-6169, USA 4 – MIT Plasma Science and Fusion Center, Cambridge, MA 021139, USA 5 - Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, Peoples Republic of China 6 - General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA

Introduction

Experimental:

- In NSTX, up to ~ 60% of the power possibly lost to SOL
  - Larger SOL losses for high density in front of the antenna
- Field-line mapping models flow of lost HHFW power from the antenna region to the divertor [Perkins *et al*, PRL 2012]
  - Computed strike points form a spiral that matches the observed RF spiral
- In DIII-D, observed increase in edge losses as the SOL density increases in ELMy H-mode plasmas [Petty *et al*, NF **39**, 1421 (1999)]

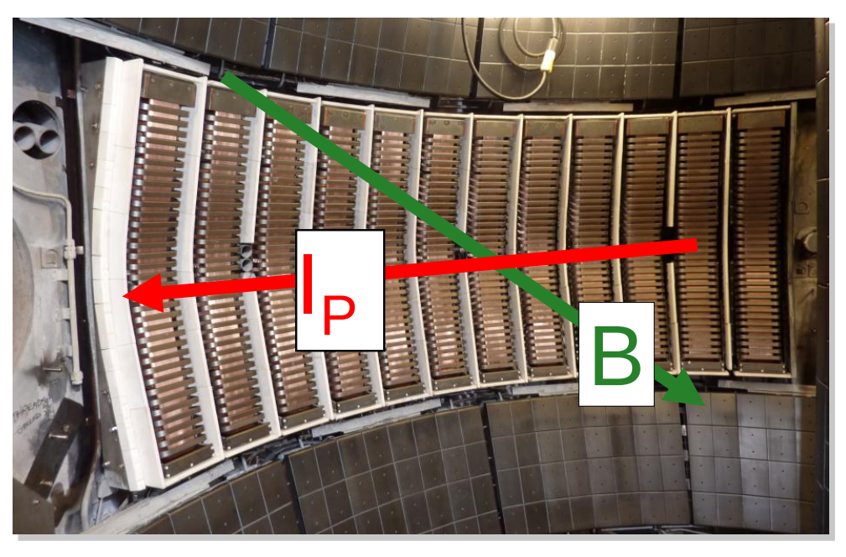
Modelling:

- SOL region now included in full wave code AORSA [Green et al, PRL 2011]
- Simulation results show:
  - Indication of cavity mode in AORSA simulations on NSTX
  - Negligible power absorbed in the SOL with only standard kinetic model

Need to understand and minimize these RF power losses for improving FW performance and compare different devices with different geometry and heating regime

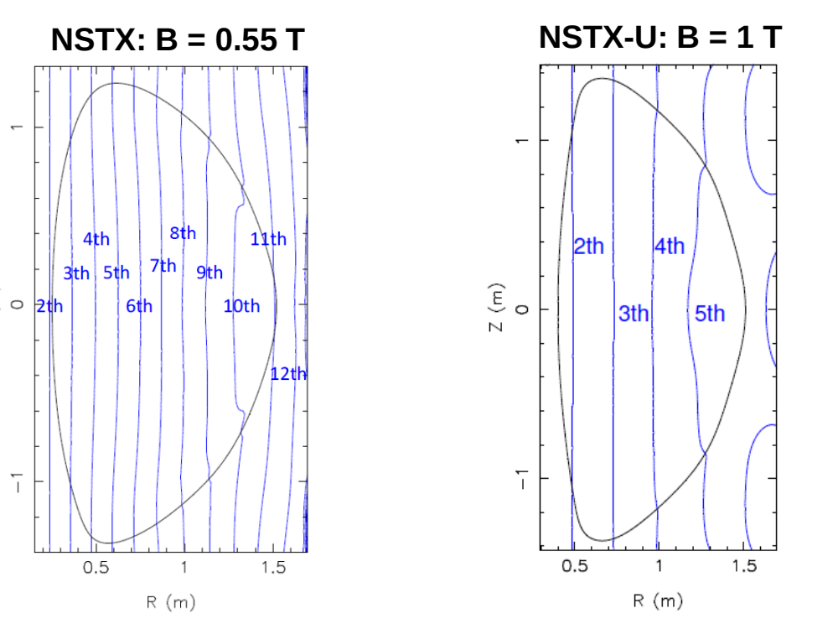
1

Same 30 MHz FW system in NSTX & NSTX-U



- 12-strap antenna on the outboard midplane, extends 90º toroidally
- Well-defined spectrum
- $|k_\phi| = \pm 3, \pm 8$, and ± 13 m-1 when $\Delta\phi = \pm 30^o, \pm 90^o$, and $\pm 150^o$

for Deuterium main ion



B_T → $2 \times B_T$

ω/ω_D → $0.5 \times \omega/\omega_D$

High harmonic regime in NSTX → **Mid harmonic regime in NSTX-U**

2

Full wave code AORSA

Wave fields modeled with linear wave equation (inhomogeneous plasma):

$$\nabla\times\nabla\times\mathbf{E} - \underbrace{\frac{\omega^2}{c^2}\left(\mathbf{E} + \frac{4\pi i}{\omega}\mathbf{J}_\mathrm{p}\right)}_{=\boldsymbol{\varepsilon}\cdot\mathbf{E}} = \frac{4\pi i}{\omega}\mathbf{J}_\mathrm{A}$$

where

ε is the dielectric tensor, $\mathbf{J}_\mathrm{A}$ is the antenna current

$$\mathbf{J}_\mathrm{p}(\mathbf{r}) = \int \mathrm{d}r'\boldsymbol{\sigma}(\mathbf{r},\mathbf{r}')\cdot\mathbf{E}(\mathbf{r}')$$

- AORSA includes the complete non-local, integral operator for ε that is valid for “all orders” ($k_\perp \rho_s > 1$) [E. F. Jaeger *et al*, *Phys. Plasmas* **9,** 1873 (2002)]
- AORSA utilizes a local Cartesian grid in the poloidal plane and a Fourier decomposition in the toroidal direction of symmetry:

$$\mathbf{E}(x,y,\phi) = \sum_{n_\phi}\sum_{n,m}\mathbf{E}_{n_\phi,n,m}e^{in_\phi\phi}e^{i(k_n x + k_m y)}$$

3 where $x = R - R_0$ and y is the distance from the midplane

Exponential decay for the SOL density to fit the exp. density data

- Extended AORSA to include SOL plasma:

density at the separatrix

$$n_\mathrm{e}(\rho) = n_\mathrm{e,ant} + [n_\mathrm{e}(\rho=1) - n_\mathrm{e,ant}]\exp\left[-\frac{\rho-1}{d_\mathrm{SOL}}\right], \quad \rho > 1$$

density in front of the antenna

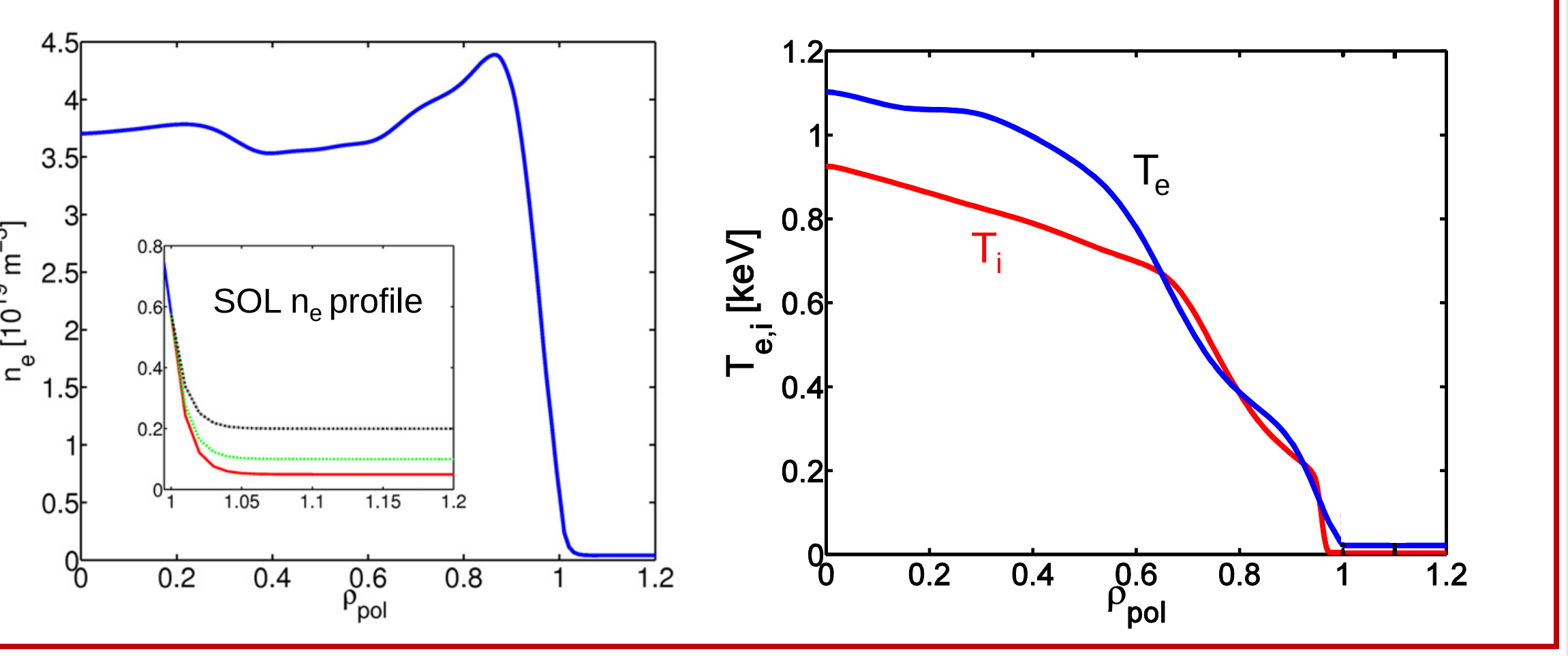
decay length

- Density at separatrix is set by experimental measurements
- T_e and T_i assumed to be constant across the SOL
- Will vary values of the density in front of the antenna
- Will vary decay length in order to cover the range of possible density profiles

4

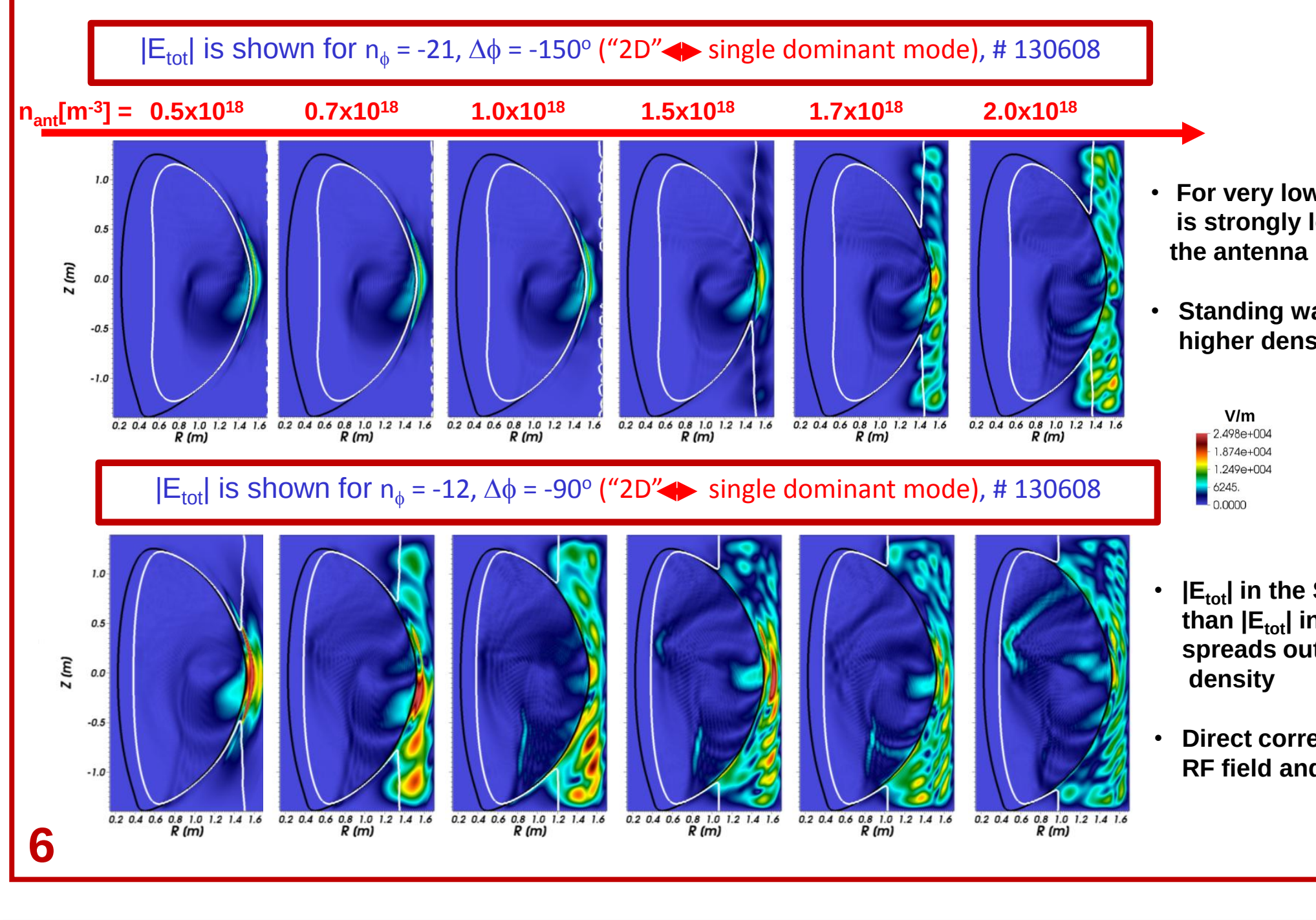
NSTX discharge 130608: temperature and density profiles

- $B(R_0) = 0.55$ T
- $n_e(0) = 3.7 \times 10^{19}$ m^{-3}, $n_e(1) \sim 5.8 \times 10^{18}$ m^{-3}, $T_e(0) \sim 1.1$ keV
- Density (and SOL density), temperature profiles used in the simulations:



5

$|E_{tot}|$ in the SOL increases when FW can propagate within the SOL



- **For very low density the RF field is strongly localized in front of the antenna**
- **Standing wave appears at higher density**
- **$|E_{tot}|$ in the SOL is much greater than $|E_{tot}|$ inside the LCFS and spreads out with increasing density**
- **Direct correlation between SOL RF field and FW cut-off location**

6

Phys. mech. behind the damping in the SOL not yet been identified

- “Collisional” damping included in AORSA as a **proxy** to represent the real SOL damping processes
- It is essentially a “Krook model”:

ε related to $\underbrace{Z\left(\frac{\omega - n\Omega_c}{k_\parallel v_{th}}\right)}_{\text{Plasma Dispersion Function}} \xrightarrow{\text{Damping}} Z\left(\frac{\omega - n\Omega_c + i\nu}{k_\parallel v_{th}}\right)$

dielectric tensor

- ν/ω “collision” parameter is input into AORSA
- absorption obtained through the anti-hermitian part of

$$\alpha = \frac{\omega}{4\pi}\frac{\mathbf{E}^*\cdot\varepsilon^a\cdot\mathbf{E}}{|\mathbf{S}|}$$

Poynting vector

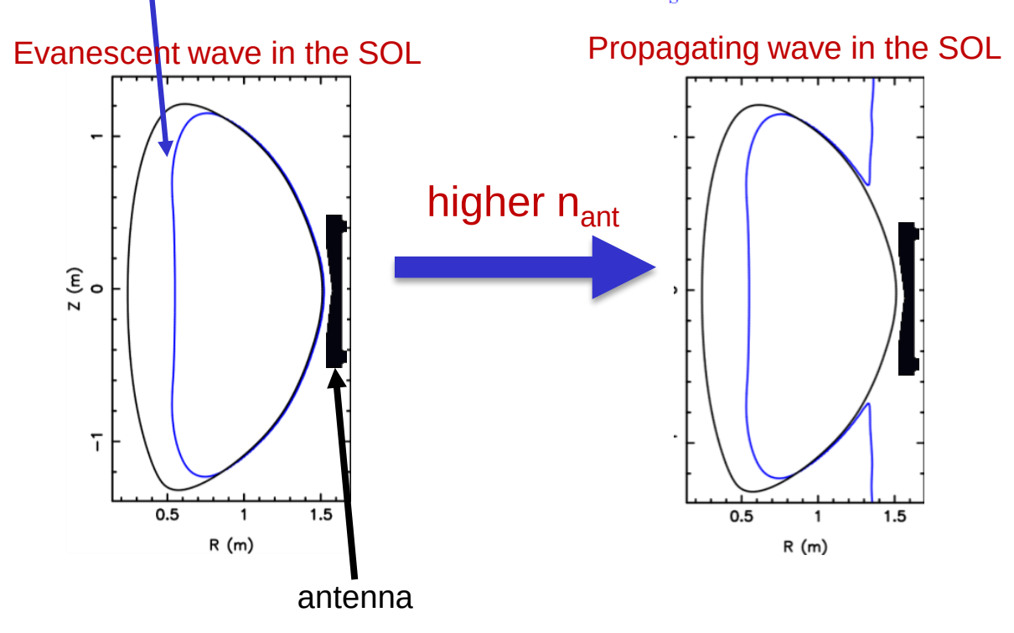
7

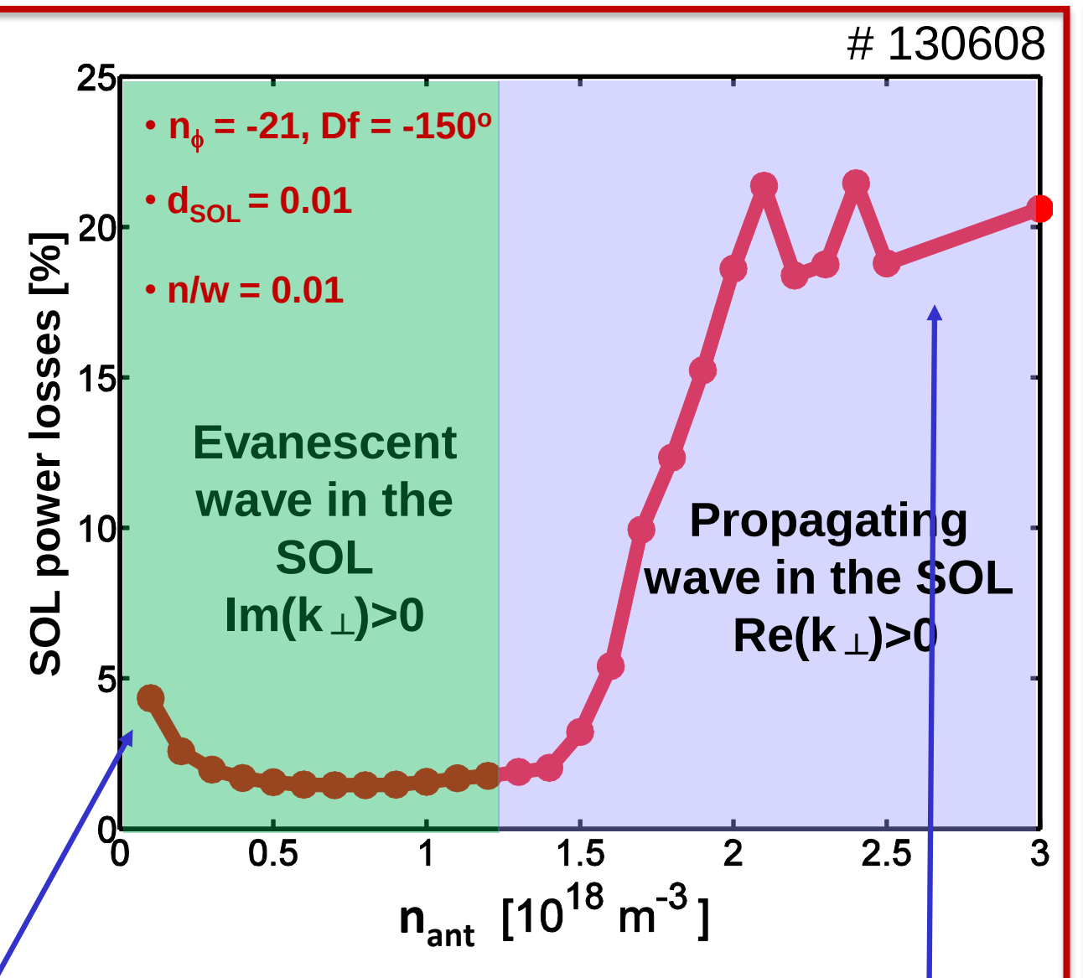
Sharp increase in SOL pow. loss. when FW propagates within SOL

Fast wave cut-off (cold plasma)

$$R - N_\parallel^2 = 0$$

$$R \equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega + \Omega_s)}$$

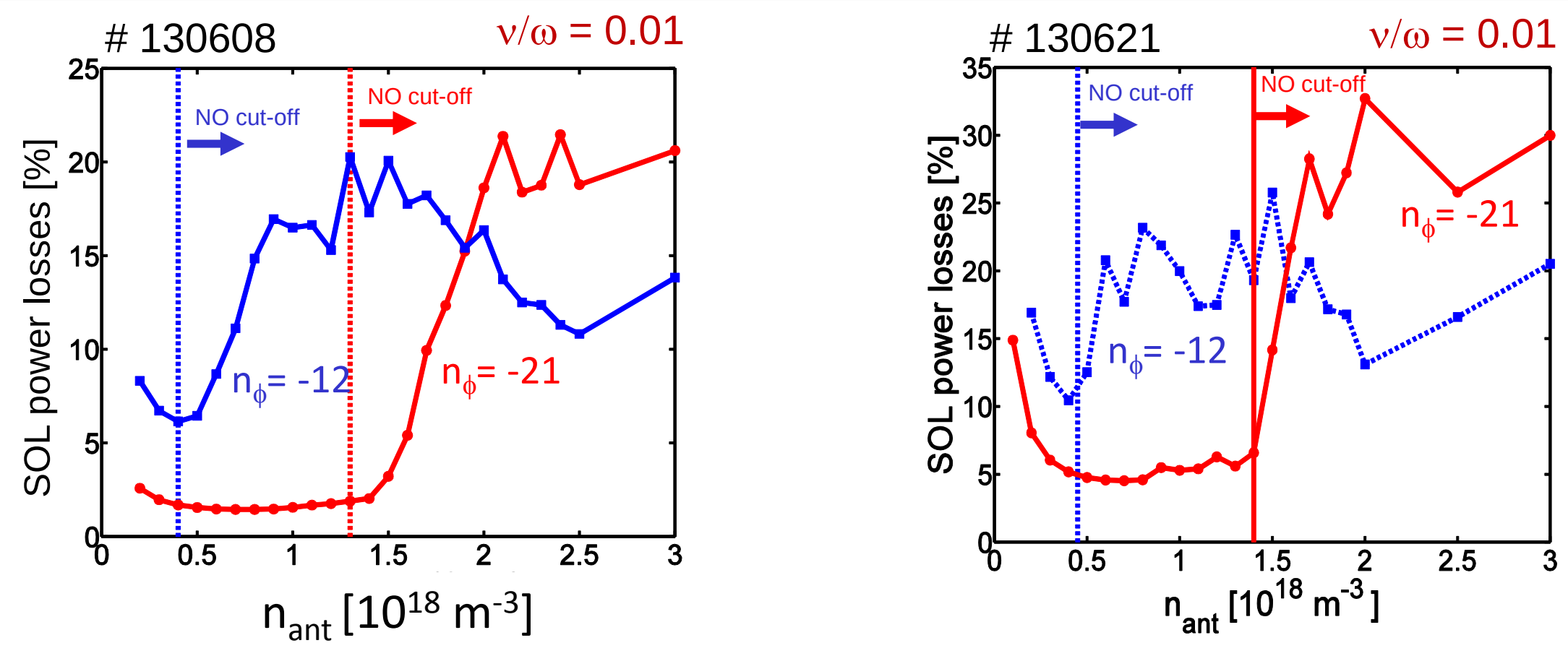




- at low n_{ant}: electric field peaked in front of the antenna
- at high n_{ant}: oscillations due to different reflections of the standing wave (different RF field amplitude)

8

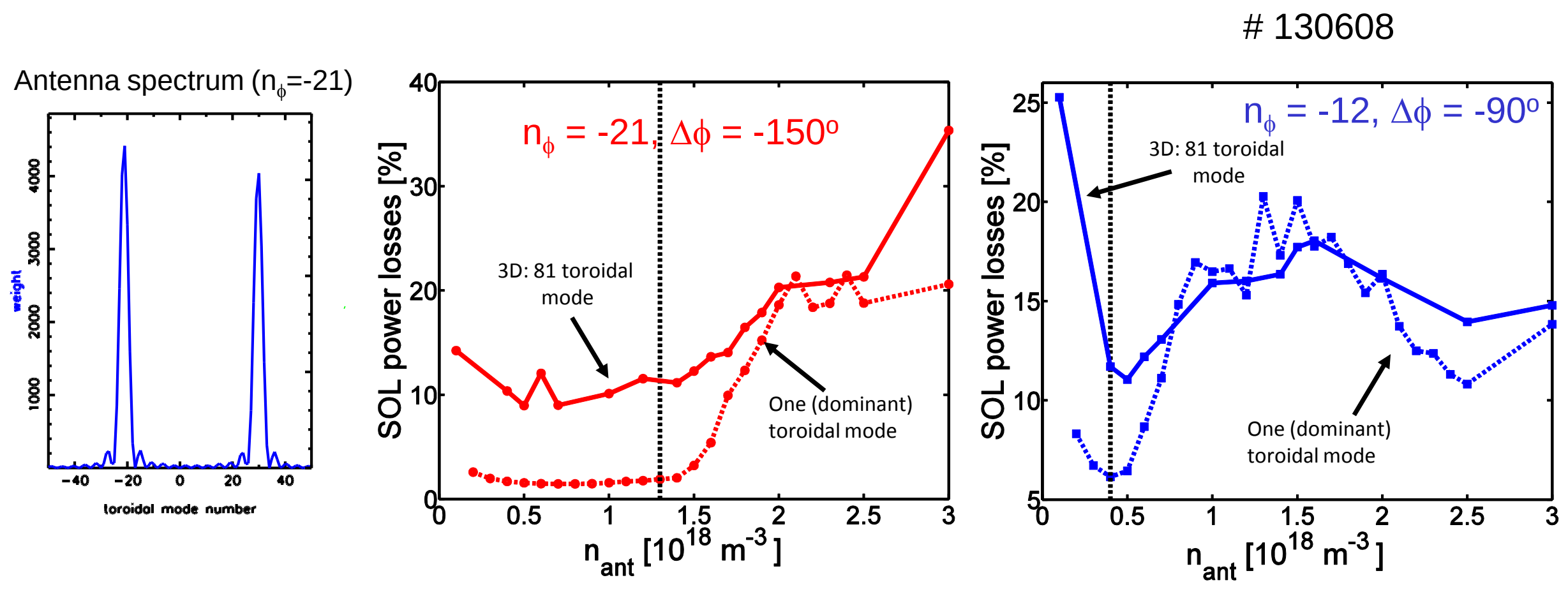
Same transition is found for lower antenna phases



- FW cut-off condition: $n_\mathrm{e,FWcut-off} \propto \frac{k_\parallel^2 B}{\omega}$
- lower n_ϕ ($n_\phi/R = k_\phi \approx k_{||}$) → transition at lower n_{ant}
- For given n_ϕ, SOL power losses increase if $n_{ant} > n_{e,\text{ FW cut-off}}$
- Same relative behavior for # 130621

9

3D results show SOL losses enhancement similar to 2D single n_ϕ



- 3D runs: 81 toroidal modes to reconstruct the full antenna spectrum
- SOL losses in 3D modeling are comparable or larger than those in 2D modeling

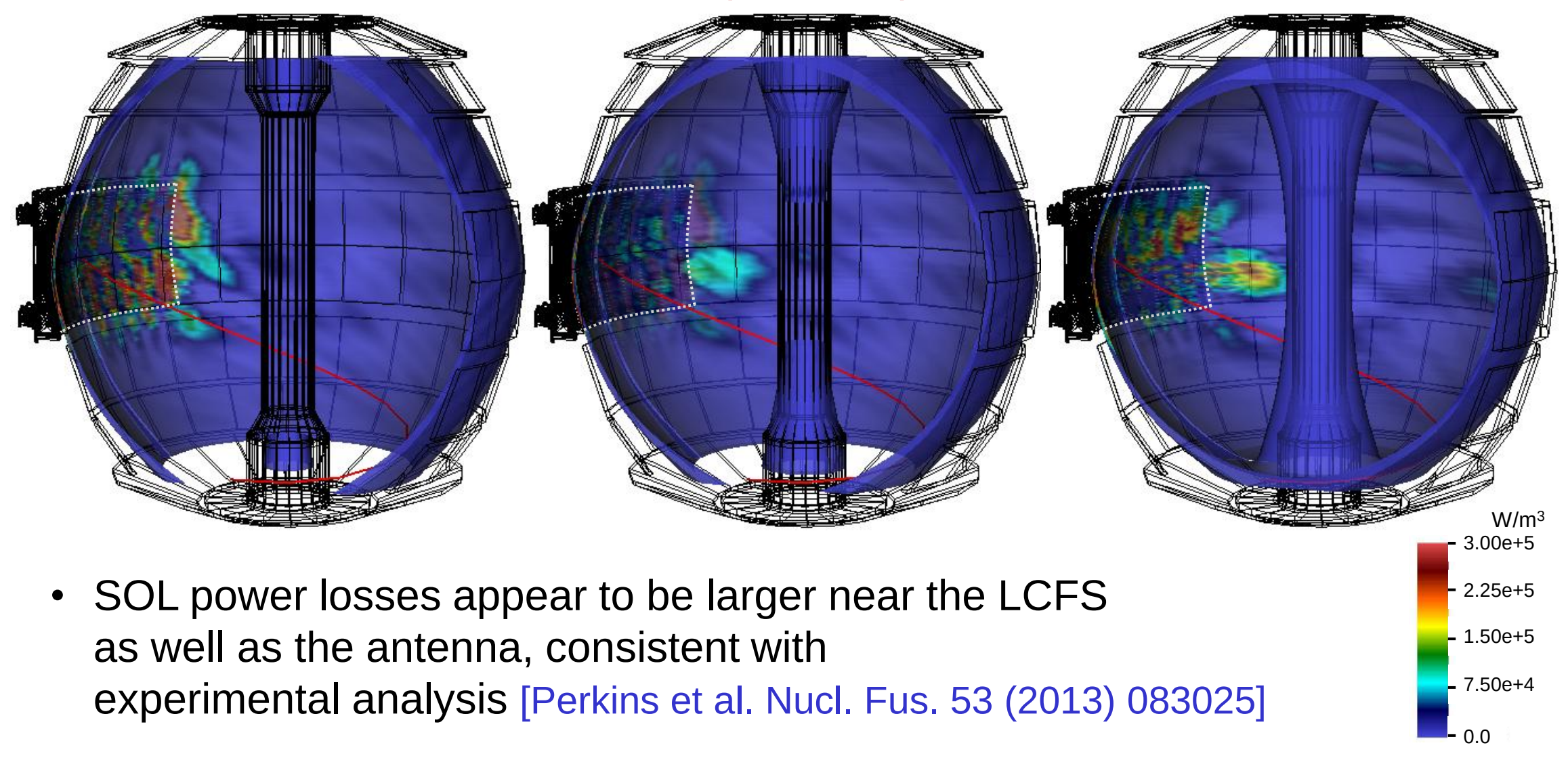
10

RF power is deposited near the antenna and near the LCFS

Low n_{ant}

130608, (n_ϕ = -21), ν/ω = 0.01, ρ_{ant} = 1.15, n_{ant} = 1.0 x 10^{18} m^{-3}

ρ= 1.1 to 1.15 (near antenna) ρ= 1.05 to 1.1 (mid SOL) ρ= 1.0 to 1.05 (near LCFS)

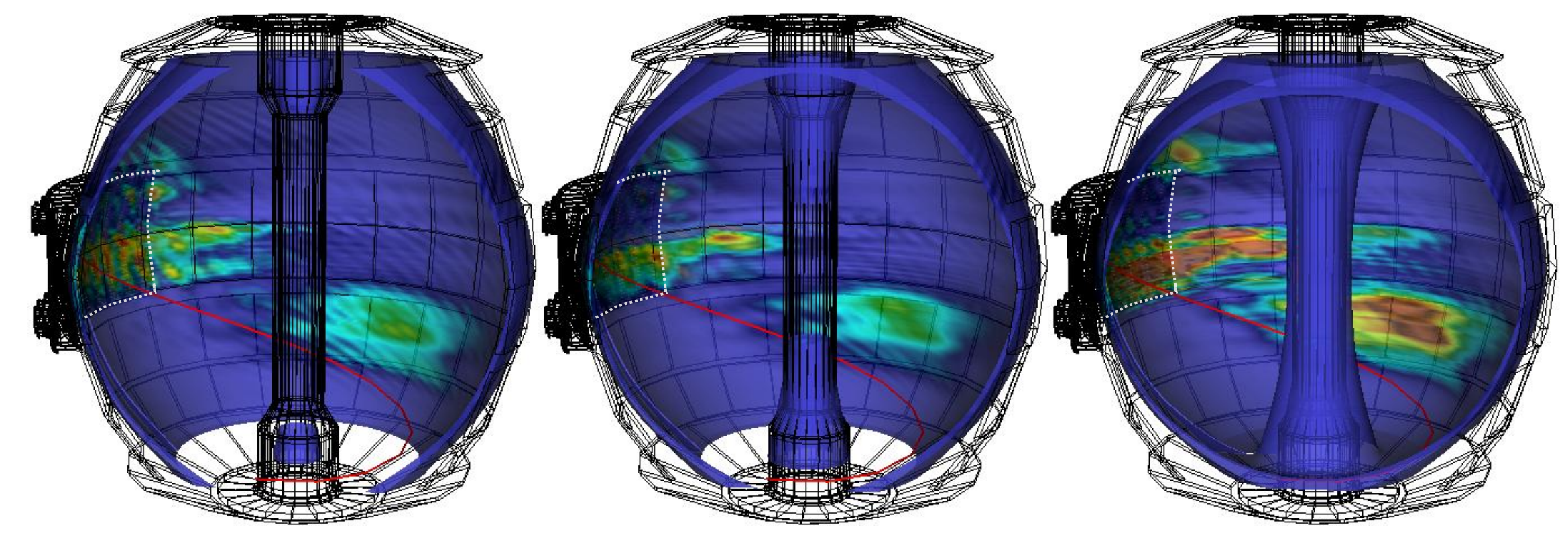


- SOL power losses appear to be larger near the LCFS as well as the antenna, consistent with experimental analysis [Perkins et al. Nucl. Fus. 53 (2013) 083025]

High n_{ant}

130608, (n_ϕ = -21), ν/ω = 0.01, ρ_{ant} = 1.15, n_{ant} = 2.5 x 10^{18} m^{-3}

ρ= 1.1 to 1.15 (near antenna) ρ= 1.05 to 1.1 (mid SOL) ρ= 1.0 to 1.05 (near LCFS)



- SOL power is found below the mid-plane for higher density due to large RF field in the SOL

11

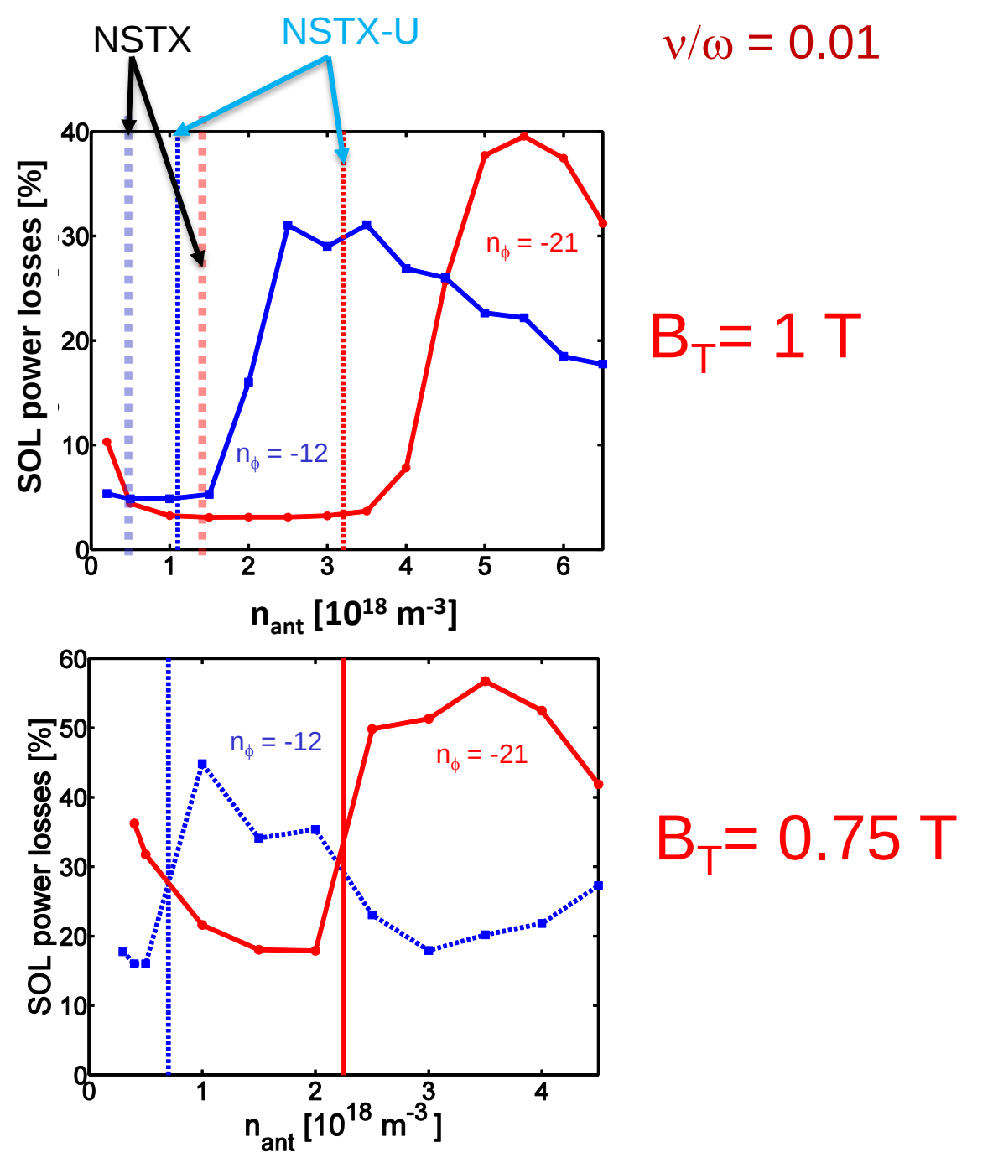
Larger evanescent region at higher B_T achievable in NSTX-U

- H-mode scenario planned for NSTX-U, obtained by TRANSP simulations [S. P. Gerhardt, Nucl. Fusion 52, 083020 (2012)]

$$n_\mathrm{e,FWcut-off} \propto \frac{k_\parallel^2 B}{\omega}$$

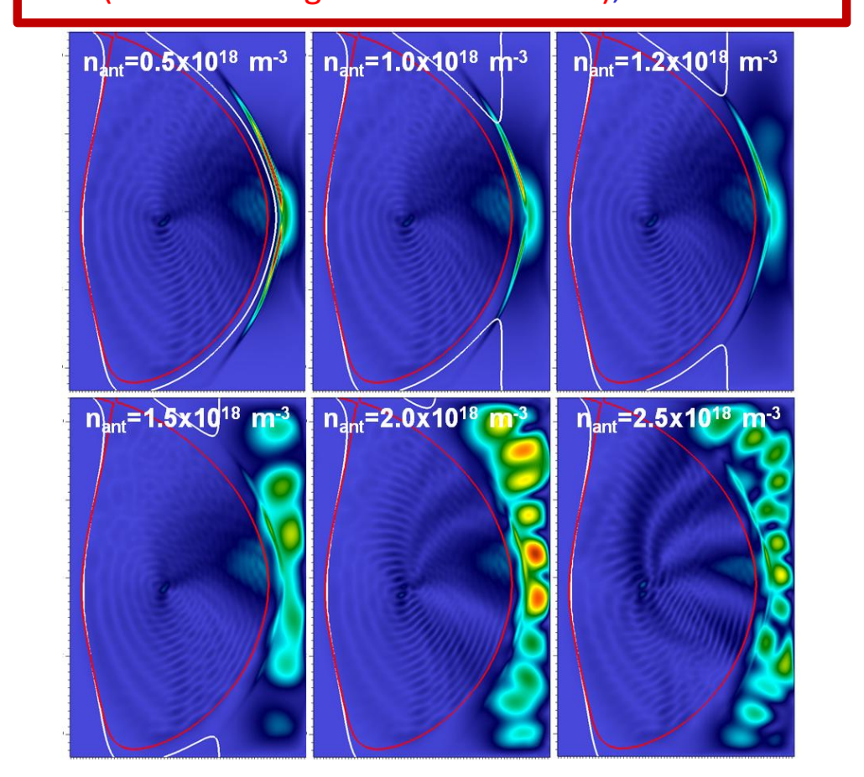
- NSTX-U (B_T = 1 T) vs. NSTX (B_T = 0.55 T): transition occurs for ~2x higher in n_{ant}
  - wider evanescent region with lower SOL power losses → **favorable for future experiments**
- NSTX-U: optimization of edge density to minimize the SOL losses and maximize the coupling to the core
- Same relative behavior found for NSXT-U case with B = 0.76 T

12

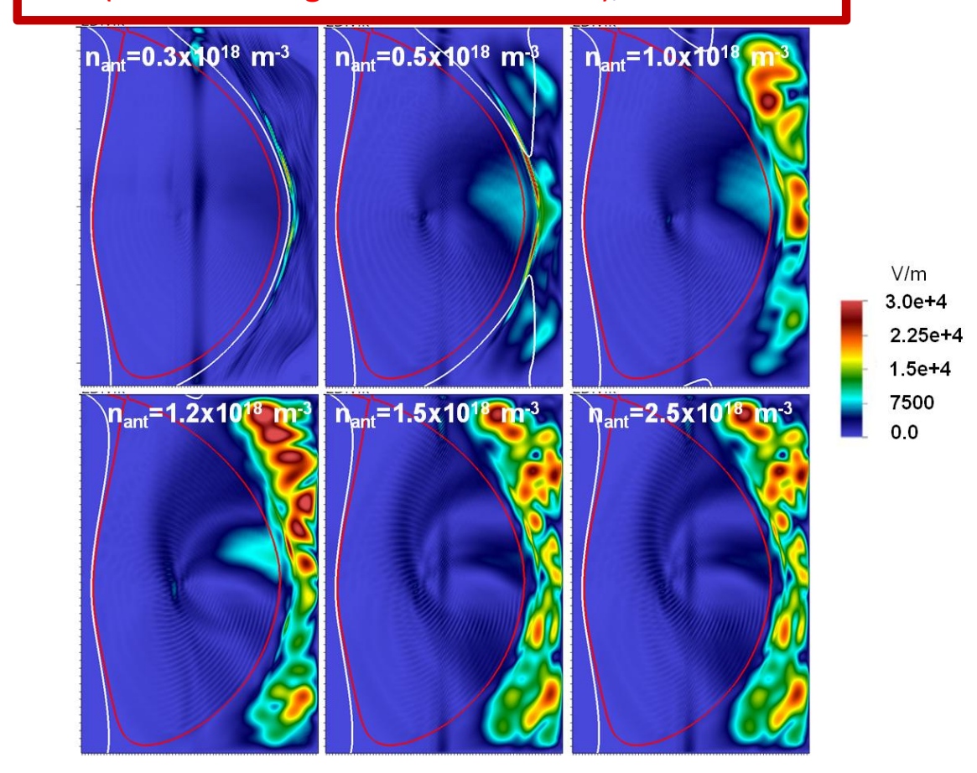


DIII-D: $|E_{tot}|$ in the SOL increases when FW propagates within SOL

$|E_{tot}|$ is shown for n_ϕ = 15, **ω/2π = 60 MHz** (“2D” ↔ single dominant mode), # 111221



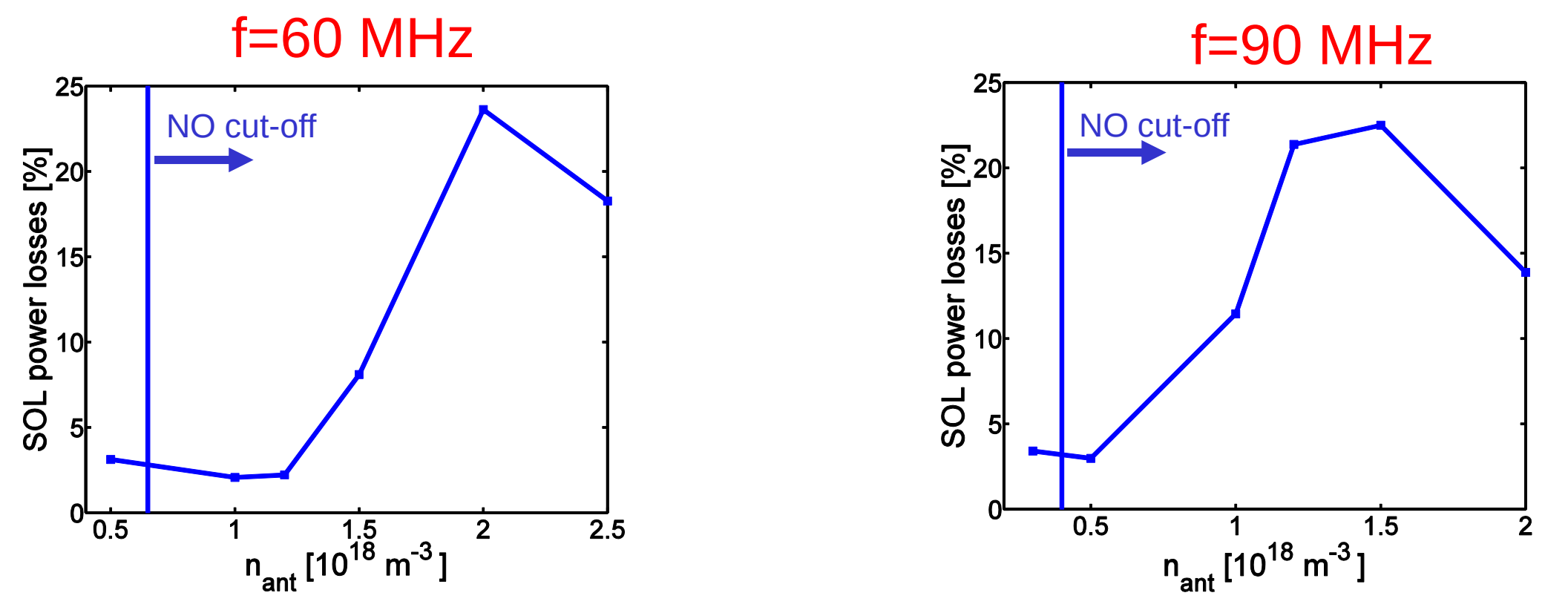
$|E_{tot}|$ is shown for n_ϕ = 15, **ω/2π = 90 MHz** (“2D” ↔ single dominant mode), # 111221



The increasing of the electric field amplitude occurs when the wave can propagate outside of the LCFS as found in NSTX and NSTX-U numerical analysis

13

Sharp increase in SOL pow. loss. in DIII-D as found in NSTX/NSTX-U



- for higher ω/2π the transition occurs at lower n_{ant} as expected by

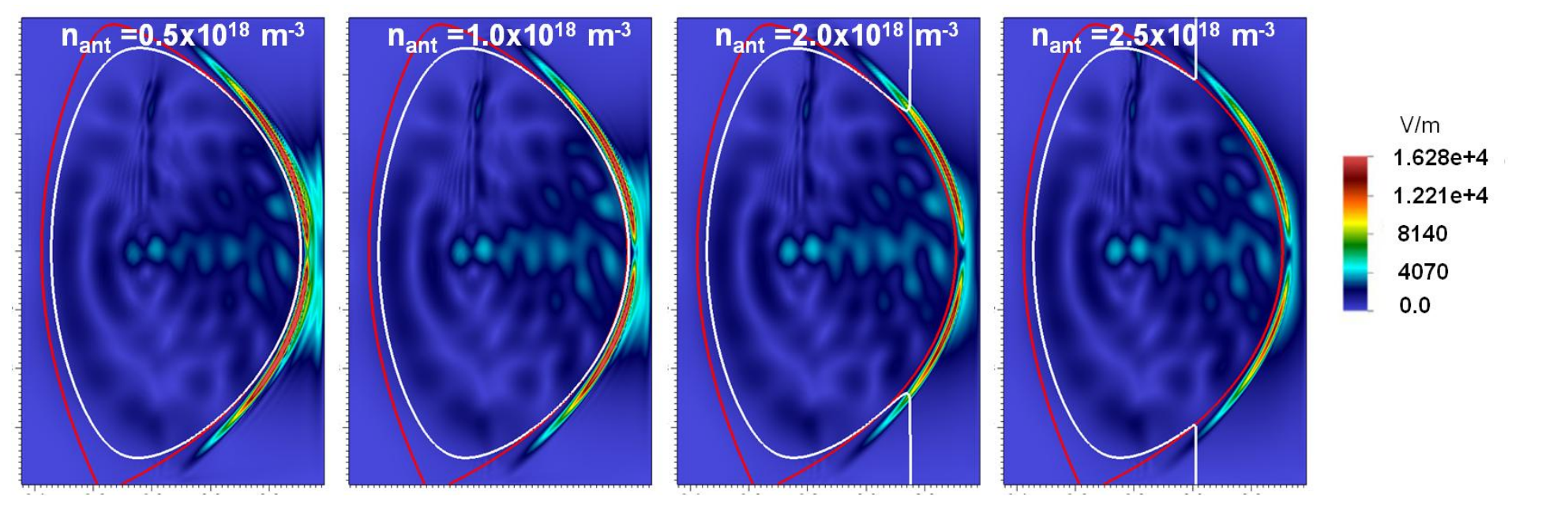
$$n_\mathrm{e,FWcut-off} \propto \frac{k_\parallel^2 B}{\omega}$$

- consistent with DIII-D experimental observations [Petty *et al*, Nucl. Fusion **39**, 1421 (1999)]

14

NO large electric field amplitude in SOL for EAST case

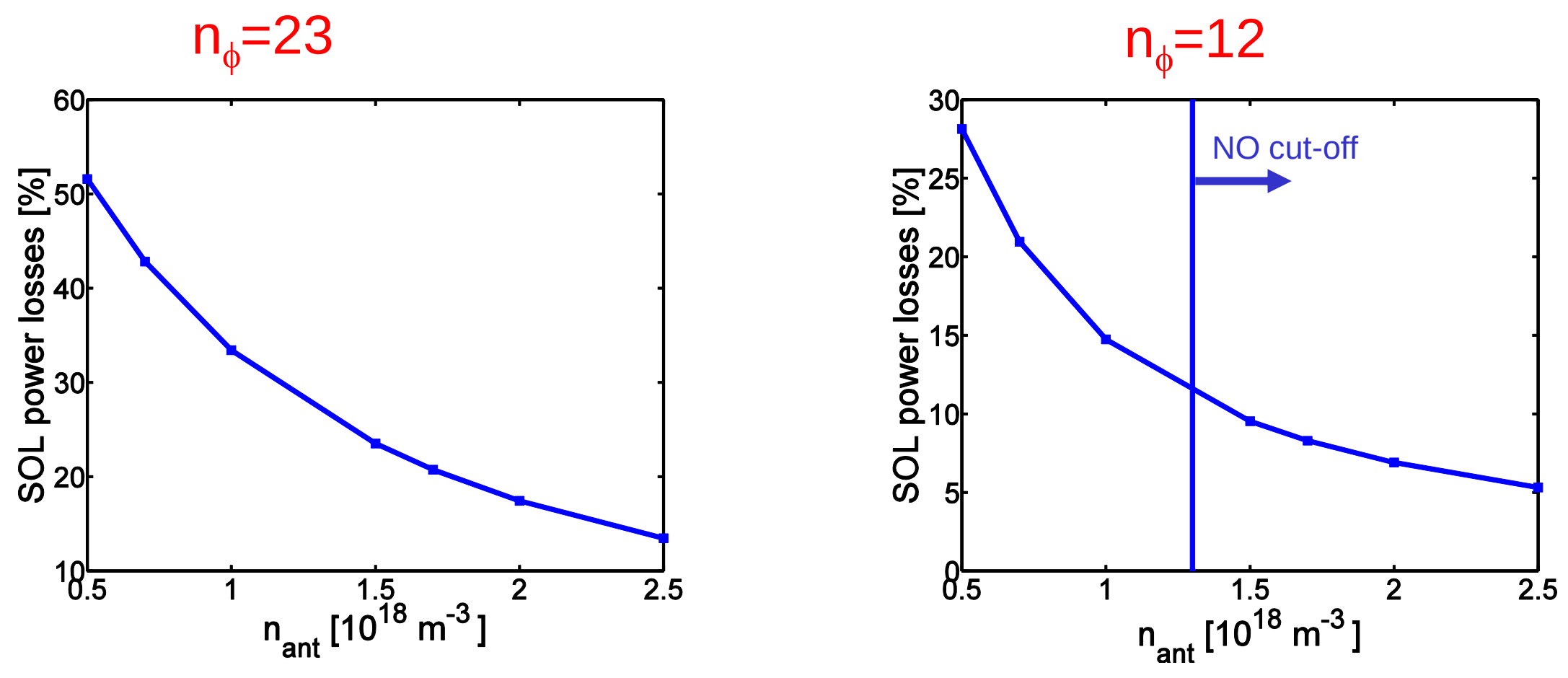
$|E_{tot}|$ is shown for **n_ϕ = 12, ω/2π = 27 MHz**(“2D” ↔ single dominant mode), # 36217



- FW experiments in EAST operates in the minority heating regime, which differs from the mid/high harmonic regime adopted in DIII-D and NSTX
- Unlike NSTX/NSTX-U and DIII-D, the electric field amplitude does NOT increase outside of LCFS with increasing n_{ant}, even when the wave propagate in the SOL
- Only a significant parallel component of the electric field is found in the SOL and is apparently larger than NSTX cases.

15

NO increasing SOL power losses for higher n_{ant} for EAST case



- Note that for n_ϕ = 23, the wave is always evanescent in the SOL for the given density range
- For n_ϕ = 12, the behavior of the SOL power losses disagrees with the behavior found in NSTX/NSTX-U and DIII-D: the transition to higher SOL power losses does not appear

16

Conclusions

- Full wave simulations for NSTX/NSTX-U and DIII-D show a direct correlation between the large SOL RF field, the location of the FW cut-off, and the SOL losses (in 2D and 3D)
  - ✓ SOL losses increase significantly as the wave transitions from evanescent to propagating as the density in the SOL increases
  - ✓ higher SOL losses with lower antenna phase, consistent with experiment
- 3D simulations show larger SOL losses near the antenna and the LCFS
  - ✓ consistent with the NSTX experiment
- NSTX-U simulations predict a wider evanescent region with lower SOL losses relative to NSTX
  - ✓ Optimization of the edge density in order to minimize the RF SOL losses
- The behavior of SOL power losses in NSTX/NSTX-U and DIII-D is really similar and is consistent with the experimental observations for both devices
- EAST (with minority heating regime) results strongly differ from NSTX/NSTX-U and DIII-D results: under investigation
- Future direction:
  - ✓ Further studies in order to identify the physical mechanism(s) behind the SOL losses [Sheath effects, PDI, non-linear processes, etc.]
  - ✓ Implementation of a more realistic boundary condition (limiter boundary) in the full wave code AORSA is underway
  - ✓ new experimental observations/measurments in the upcoming NSTX-U experimental campaign

17

See for NSTX/NSTX-U also Bertelli *et al*, *Nucl. Fusion* **54** (2014) 083004

25th IAEA Fusion Energy Conference, 13-18 October 2014, Saint Petersburg, Russia Federation