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High harmonic fast wave propagation in the scrape-off layer (SOL) of NSTX/NSTX-U

Effect of Wall Boundary on Power Losses in the SOL

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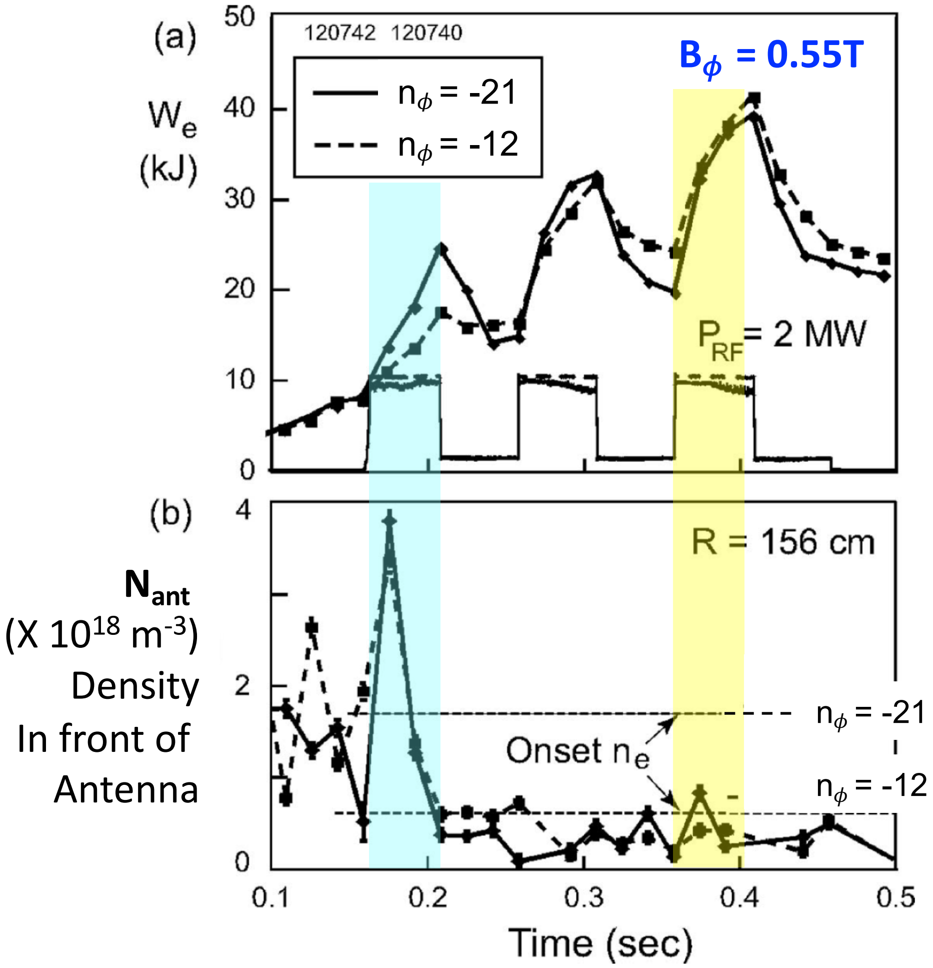
NSTX studies showed significant amounts of HHFW power missing from core

- The Interaction between the RF antennas and the scrape of layer (SOL) plasma is of crucial importance in determining the overall performance of RF in a tokamak
  - All frequencies: LH, IC, HHFW, etc …

- In NSTX
  - Strong interactions between HHFW and SOL plasm
    [*Hosea et. al* POP 2008, Phillips et al., 2009, *Perkins et. al.* PRL 2012]
  - Core Heating Effieicny (η) enhanced in stronger magnetic field
    - B_ϕ = 0.45T (n_ϕ = -12) : η ~ 44% → Power loss (P_{loss}) ~ 56%
    - B_ϕ = 0.55T (n_ϕ = -12) : η ~ 65% → Power loss (P_{loss}) ~ 35%
  - Larger power losses occur for high density in front of the antenna

Density where FW cutoff is open is critical

NSTX HHFW



[Hosea et al, POP 2008]

Critical Density (N_{ec}) (or Onset Density)

: where FW cutoff in front of the antenna is open

$$\left(n_{||}^2 - \mathcal{R}\right)_{\mathrm{LCFS}} = 0$$

$$N_{\mathrm{ec}} \propto \frac{k_{||}^2 B}{\omega}$$

$N_{ant} \leq N_{ec}$ (N_{ant} : density in front of antenna)

- FW cannot propagate in the SOL
- Higher heating
- less power losses

$N_{ant} >> N_{ec}$

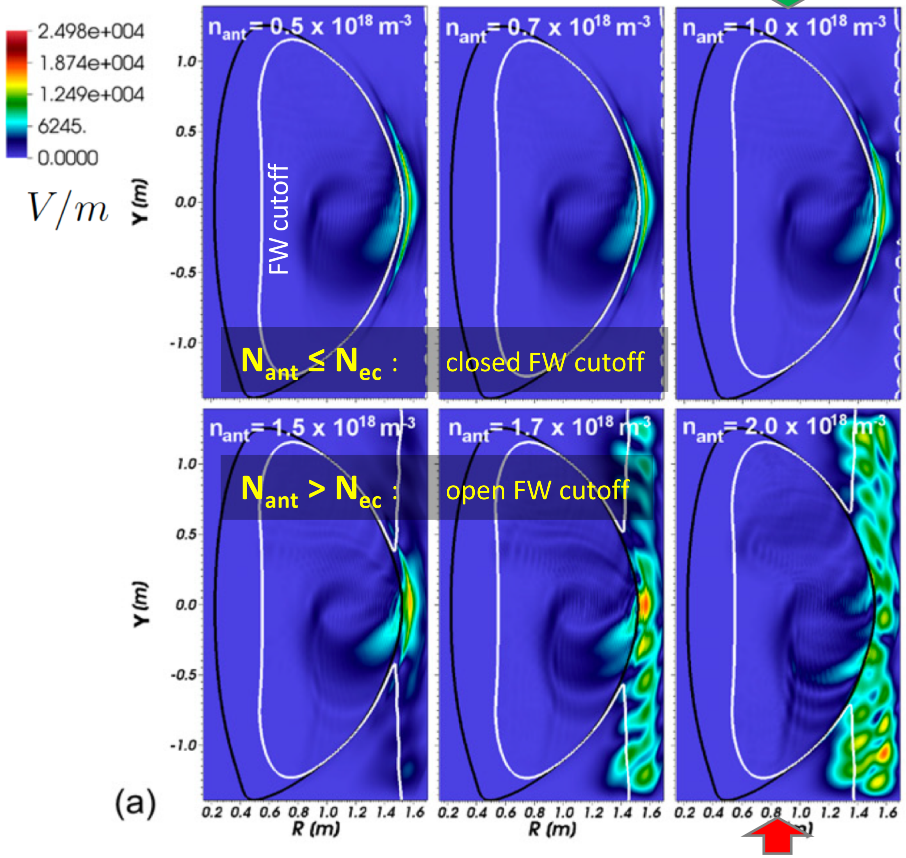
- FW propagate in the SOL
- Lower heating
- higher power losses

Previous simulations suggest SOL wave excitation can lead to significant SOL power losses

[Bertelli et al., NF 2014]

Wave evanescent
Weaker P_{abs}

n_φ = -21

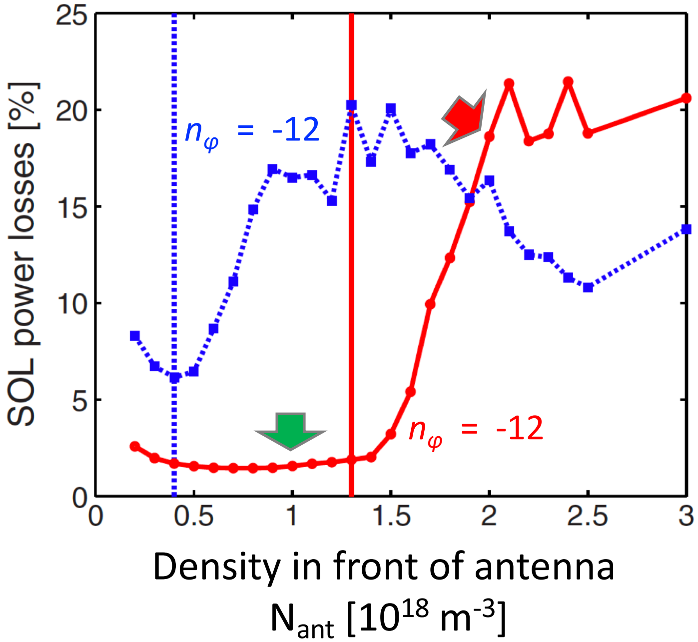


Strong |E|
Strong P_{abs}

Fraction of SOL power losses (P_{abs})

$$P_{abs} = \frac{W_{SOL}}{W_{SOL} + W_{core}}$$

$W_{SOL\,(core)}$: Power loss in the SOL (core)

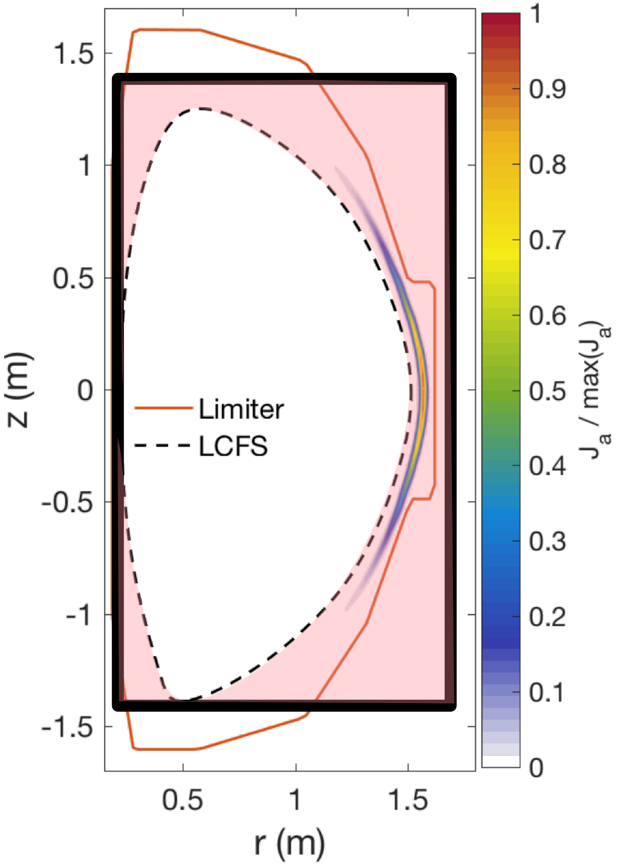


Previous simulations adopted idealized boundary for simplicity

🟥 Scrape-off Layer

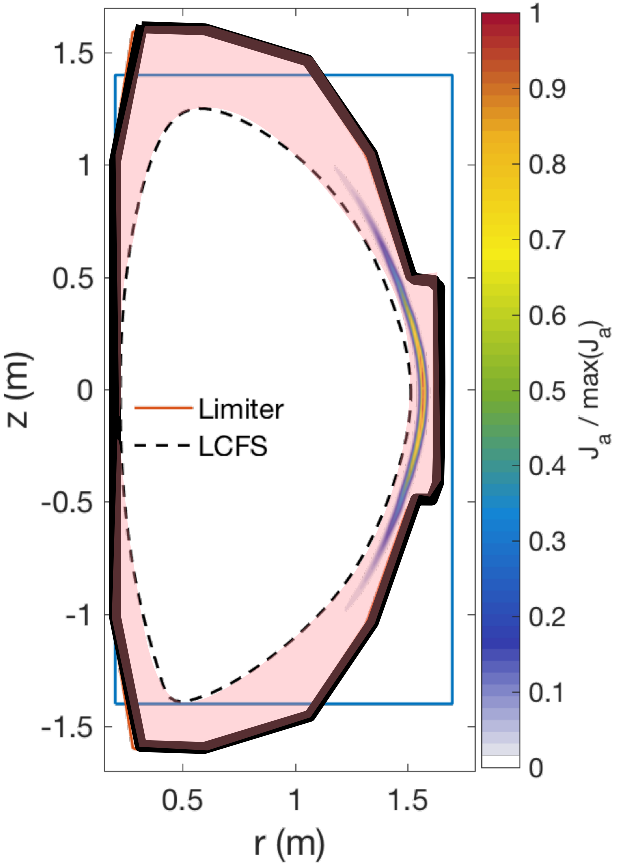
Rectangle

Wide SOL !



[Bertelli et al 2014]

Vacuum vessel



FW2D Model Description

2D Full-wave model (FW2D) has been developed to investigate SOL physics in realistic boundaries

- Wave equations : frequency domain

$$\nabla \times (\nabla \times \vec{E}) - \left(\frac{\omega}{c}\right)^2 \epsilon \, \vec{E} = 4\pi \frac{i\omega}{c^2} \vec{j}_{ext}$$

External source

output

dielectric tensor in *cold* plasma

$$\vec{E}(r,z) = (\underbrace{E_\eta, E_\mu}_{\perp}, \underbrace{E_b}_{\parallel \vec{B}_0}) \exp(im\phi)$$

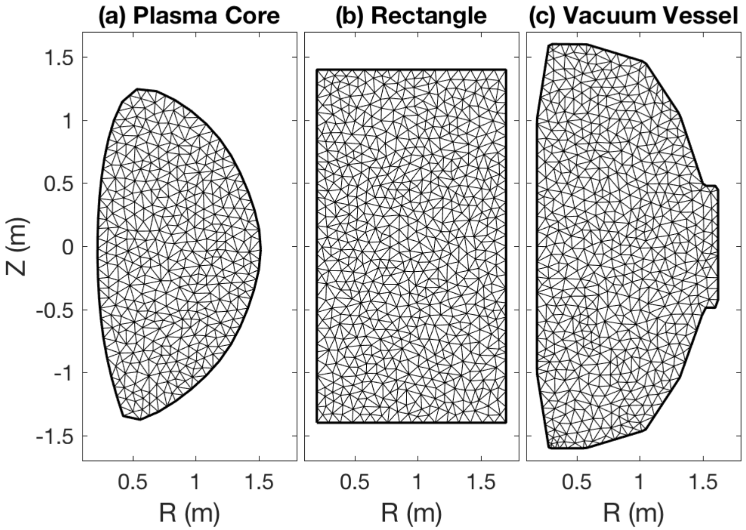
m : Azimuthal (toroidal) wave number

- Wave solution using finite element method and unstructured triangle mesh

→ Easily adopted to various geometries (e.g., dipole, tokamak…)

→ Easily adopt various boundaries (e.g., rectangle, vacuum vessel…)

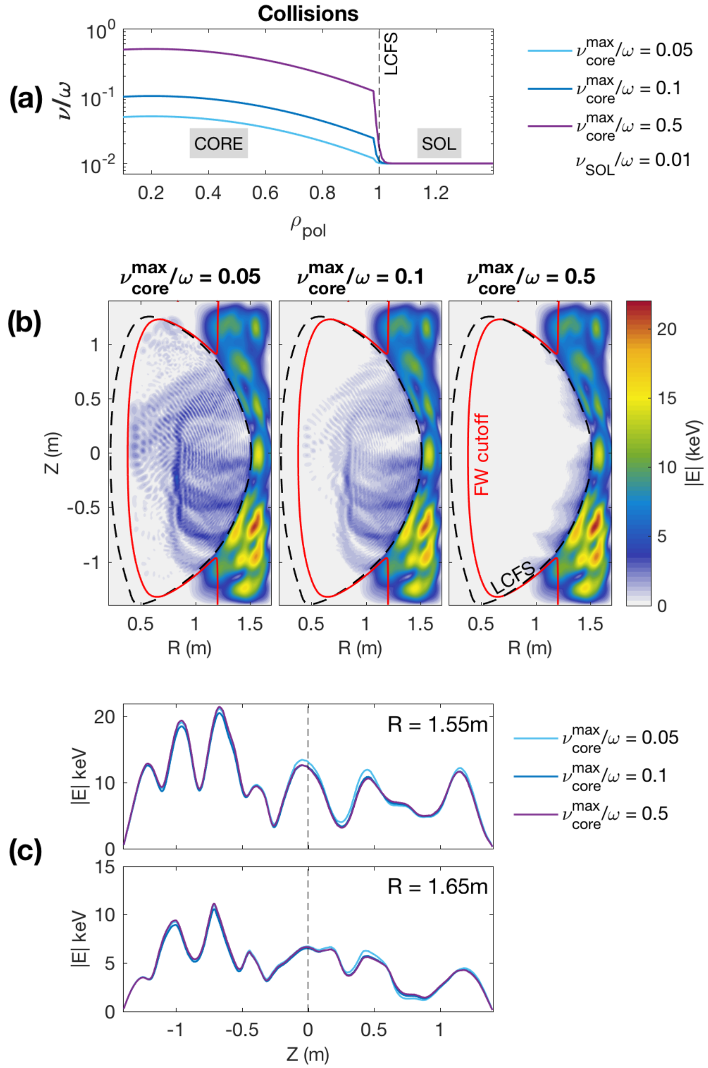
→ Fast!



- Successfully examined waves at planetary magnetospheres

Kim et al., GRL 2015; Kim and Johnson, GRL 2016; Kim et al., EPJ 2017

FW2D code provide rapid cold plasma wave field computation



- To simulate wave absorption, collisional frequency (ν) can be implemented in the momentum equation, then

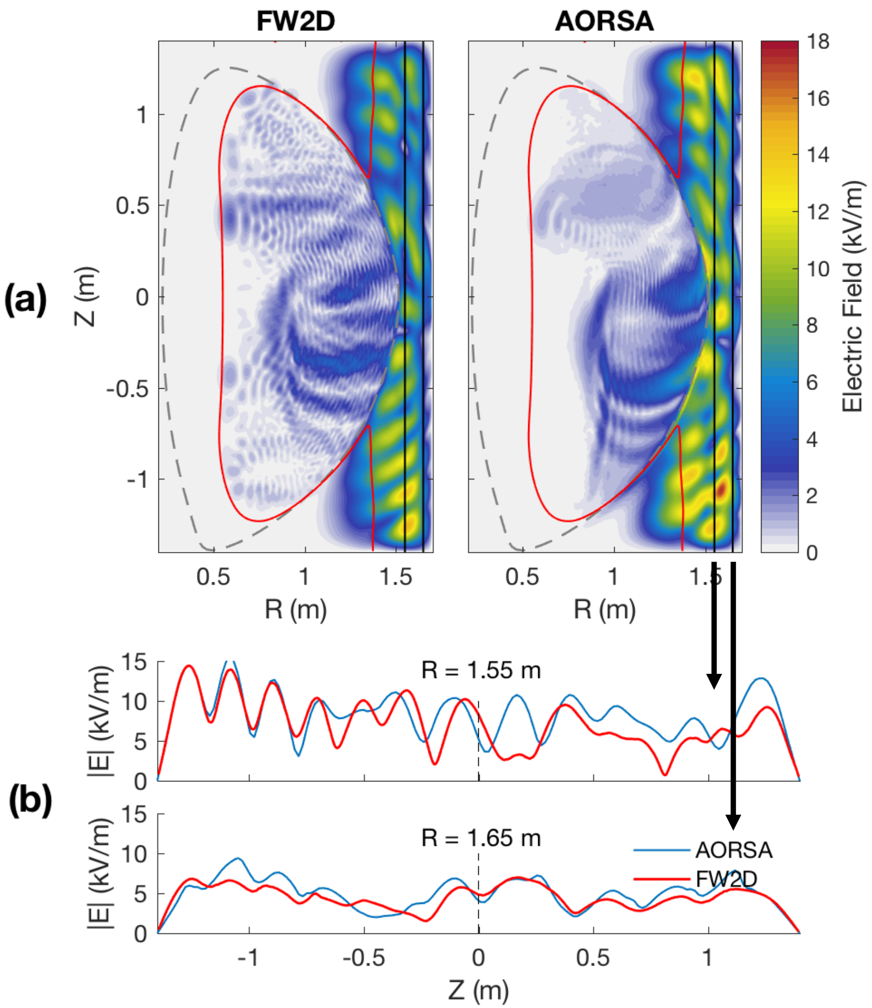
$$\omega_{p(c)} \rightarrow \frac{\omega_{p(c)}}{1+i\nu/\omega}.$$

- Wave in the plasma core : change with $\nu_{\mathrm{core}}/\omega$
- Wave in the SOL : not affected by $\nu_{\mathrm{core}}/\omega$

- Possible to estimate the SOL power losses by adopting an arbitrary collisions in the plasma core

  → 15.35± 0.5 % (almost identical)
  for $\nu_{\mathrm{SOL}}/\omega = 0.01$
  $\nu_{\mathrm{core}}^{\mathrm{max}}/\omega = \underline{0.05 - 0.5}$

FW2D and AORSA simulations show excellent agreement in SOL field structure



- FW2D → COLD approximation
  → FAST computation
- AORSA → Plasma kinetic effect
  → slow computation

- Wave transmission and reflection coefficients at the LCFS are not the same → Two wave solutions cannot be exactly same

- The wave structure shows very good agreement between FW2D and AORSA

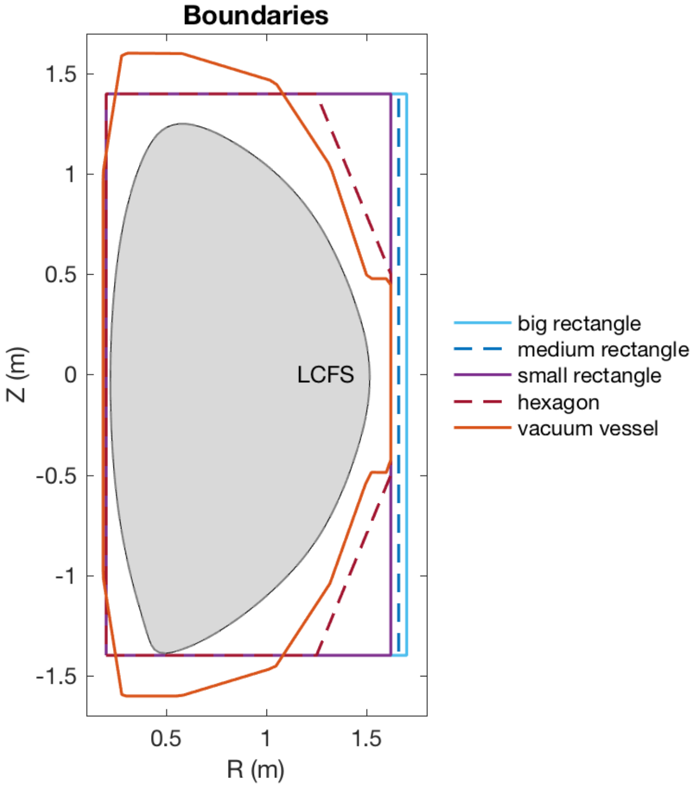
→ FW2D code can be used to (efficiently) examine waves in the cold SOL

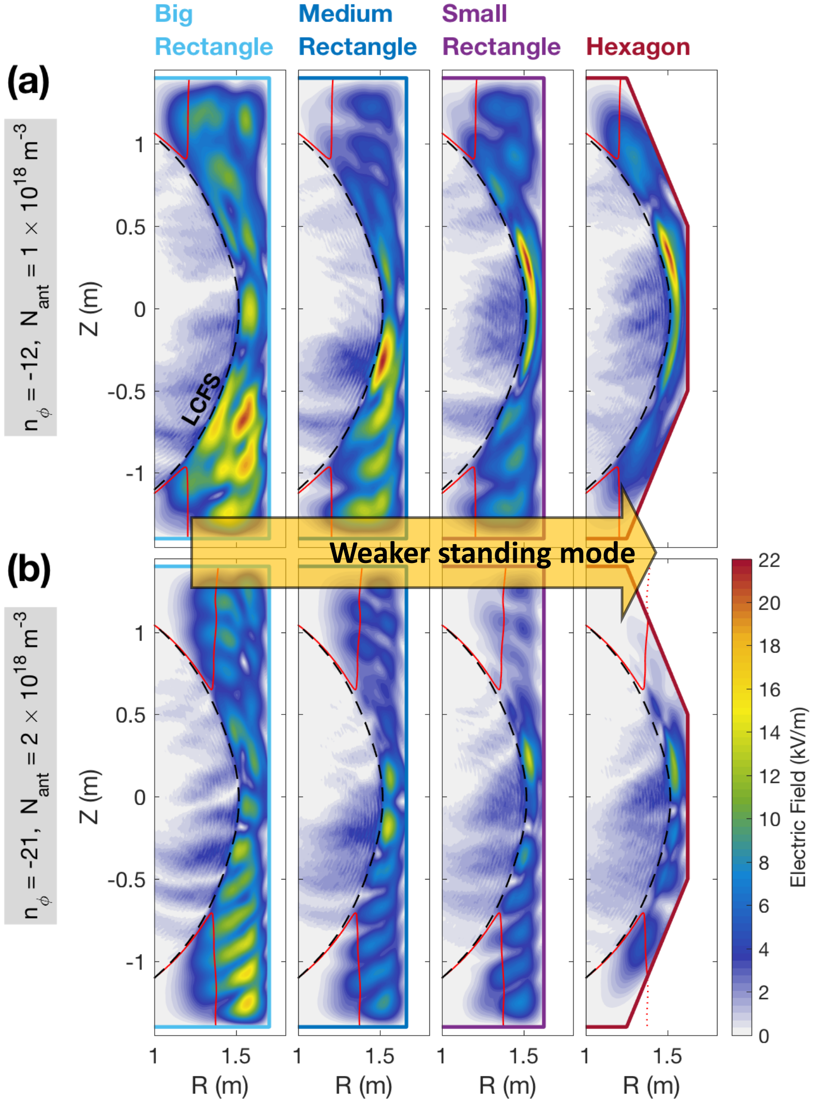
HHFW in various boundaries
: Effects of SOL size variation

HHFW standing mode in the SOL becomes weaker as SOL size is reduced

Adopted vessel boundaries

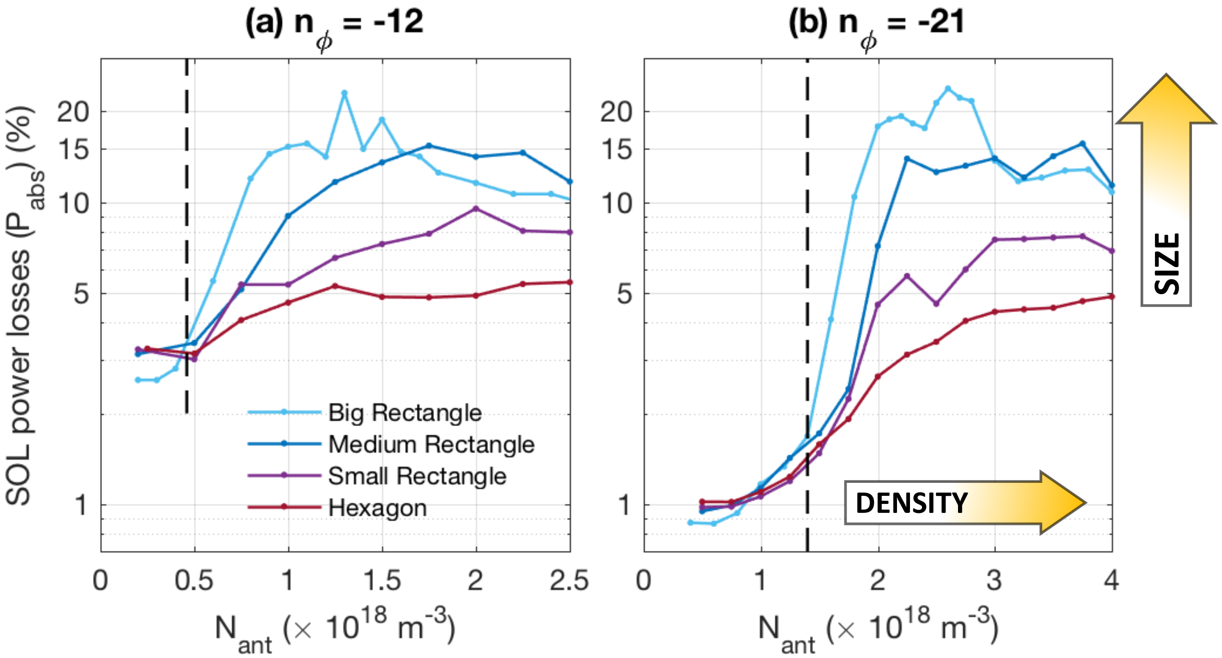
- Artificial – rectangle, hexagon
- Realistic – vacuum vessel





Weaker standing mode

SOL Power losses in the SOL size decreases as SOL size is reduced



Big Rect.

- Consistent with Bertelli et al. 2014
- P_{abs} tends to be steepened near the critical density where the FW cutoff is open

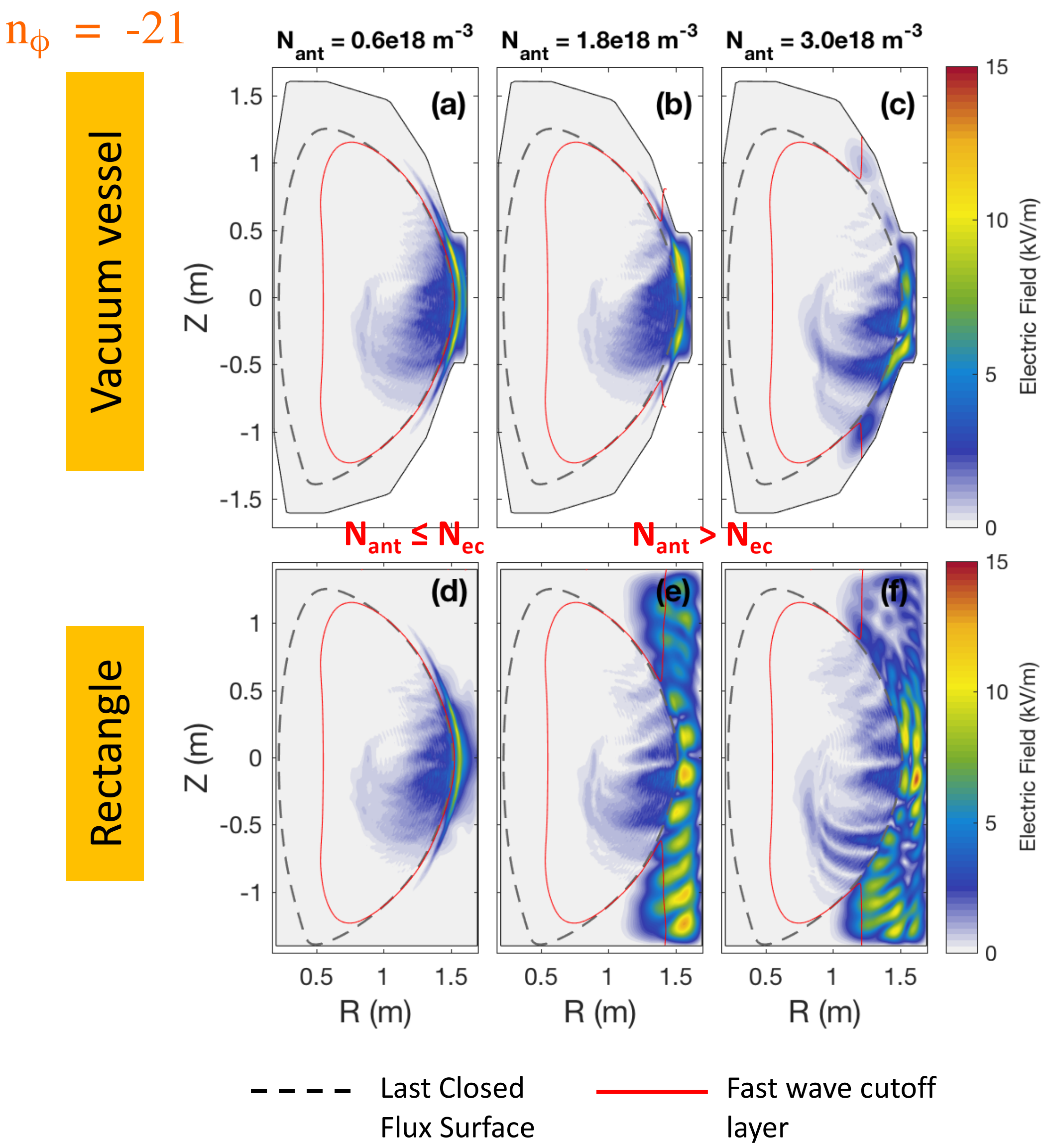
Hexagon

- P_{abs} gradually increases

- Density with maximum P_{abs} increases as SOL size increases

HHFW in vacuum vessel boundary

HHFW are examined by adopting a realistic vacuum vessel boundary



Narrow FW SOL cavity (among LCFS, FW cutoff layer and outer boundary)

→ Weaker wave power

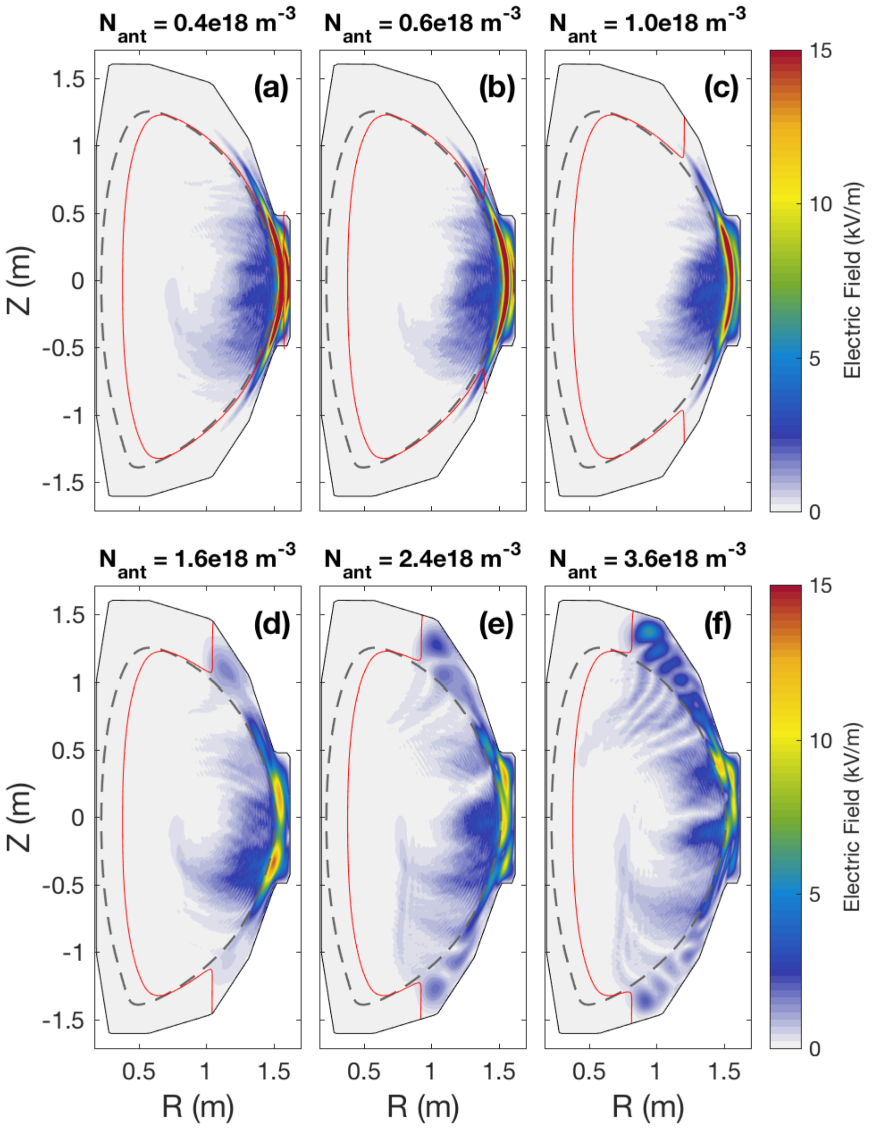
Large FW SOL cavity

→ FW standing mode

→ Large P_{abs}

HHFW *gradually* propagate into the SOL as N_{ant} increases

$n_\phi = -12$



N_{ant} ~ N_{ec}

Waves are localized near the antenna even though the FW cutoff layer is *open*

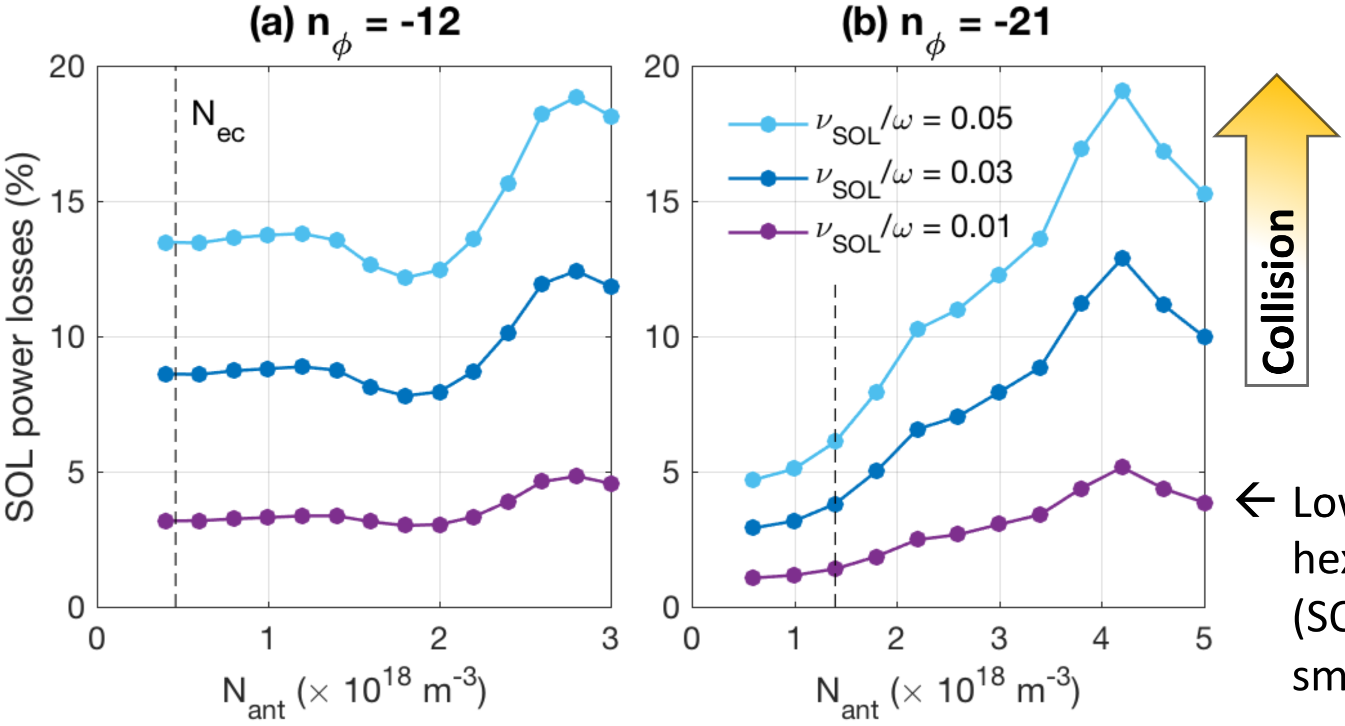
N_{ant} > N_{ec}

Standing mode structure appears

- - - - Last Closed Flux Surface

— Fast wave cutoff layer

Power losses increases linearly with collision in SOL

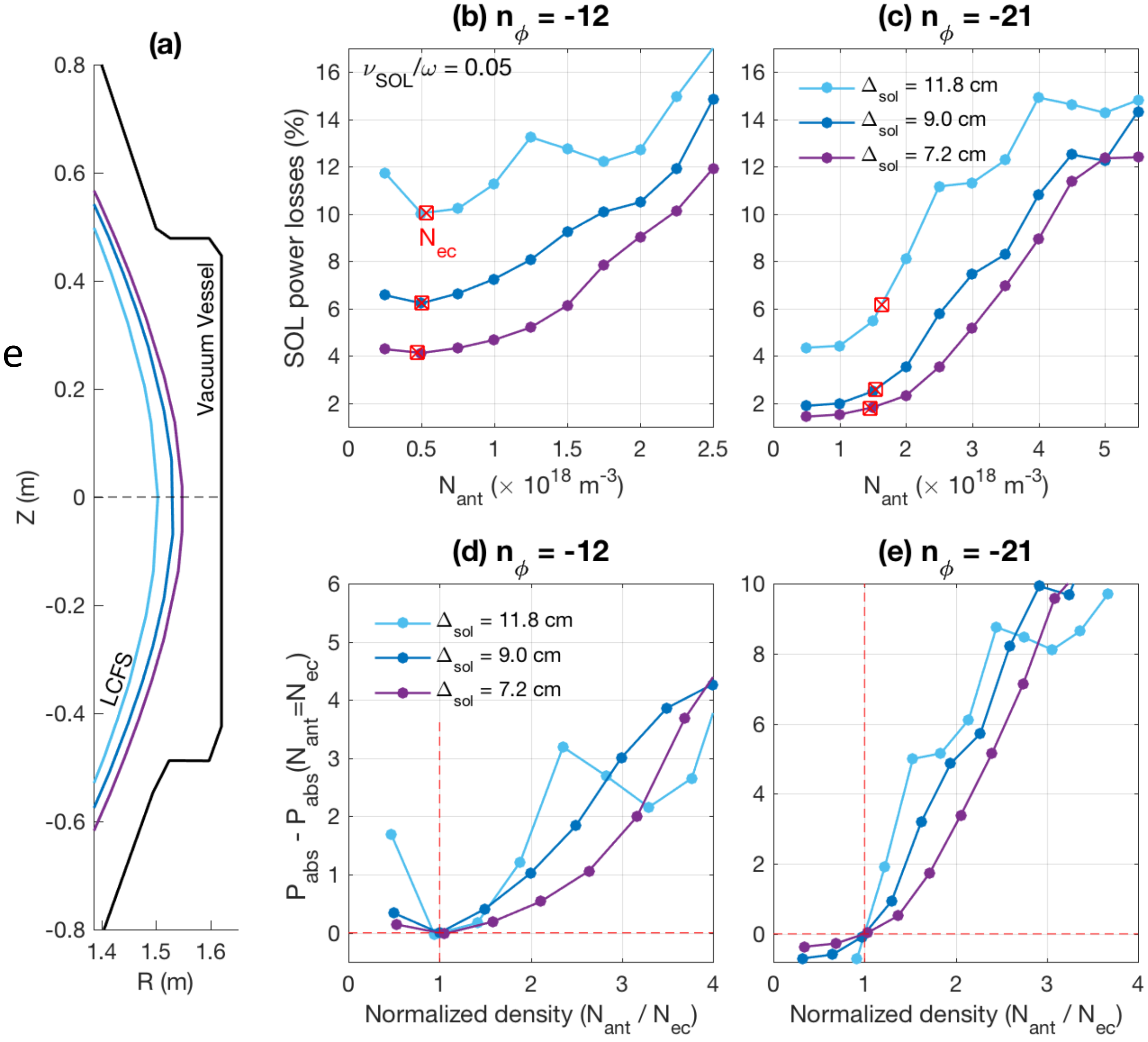


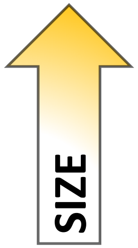
← Lower than one in a hexagonal boundary (SOL in this boundary is smaller)

- SOL $\nu_{\mathrm{SOL}}/\omega$ could be collisional losses but also represent other loss mechanisms such as convective losses to walls

Power losses decreases as the SOL size is reduced

Adopt three magnetic equilibria of NSTX
: different location of the plasma core

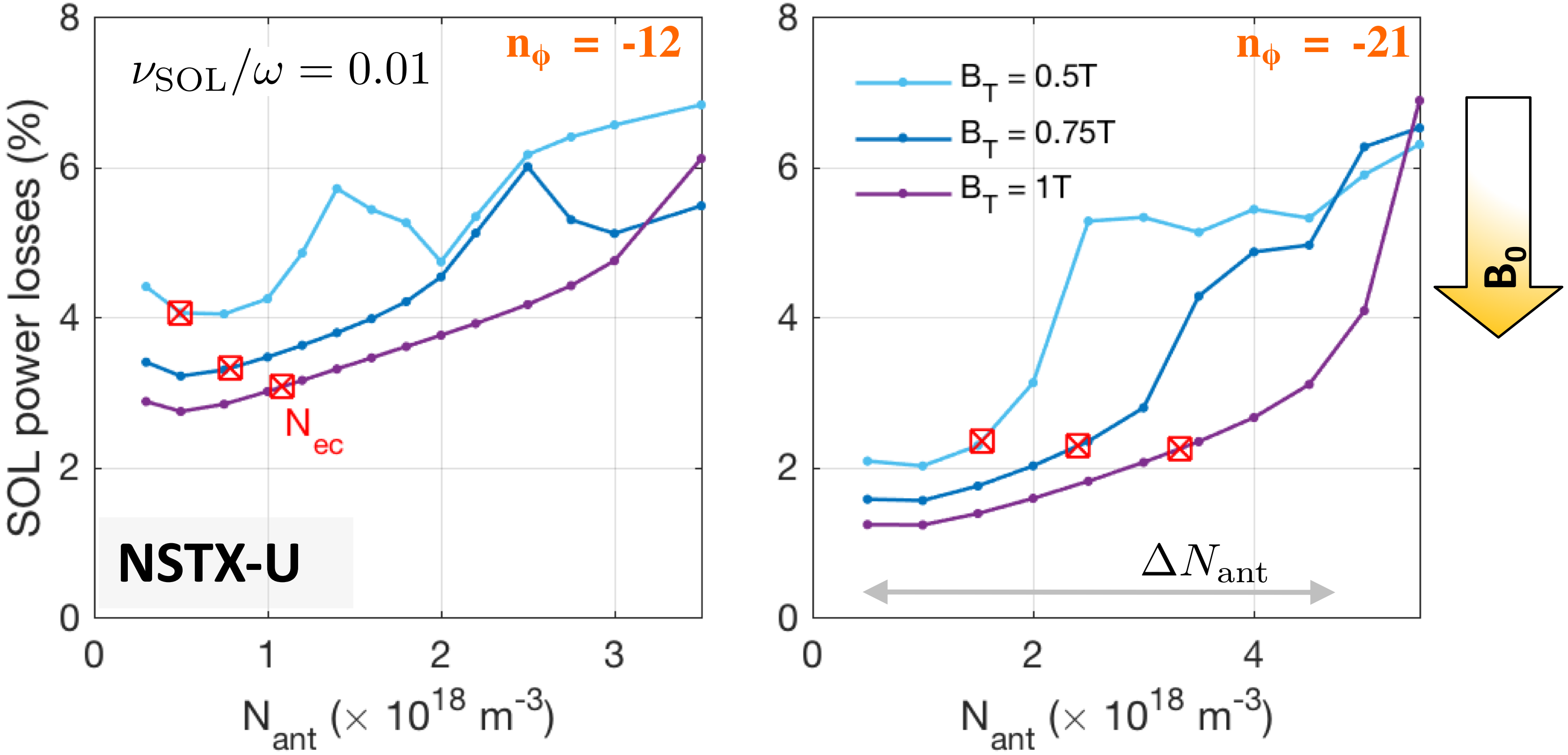




P_{abs} gradient decreases as SOL size decreases

HHFW in various magnetic field strength plasma

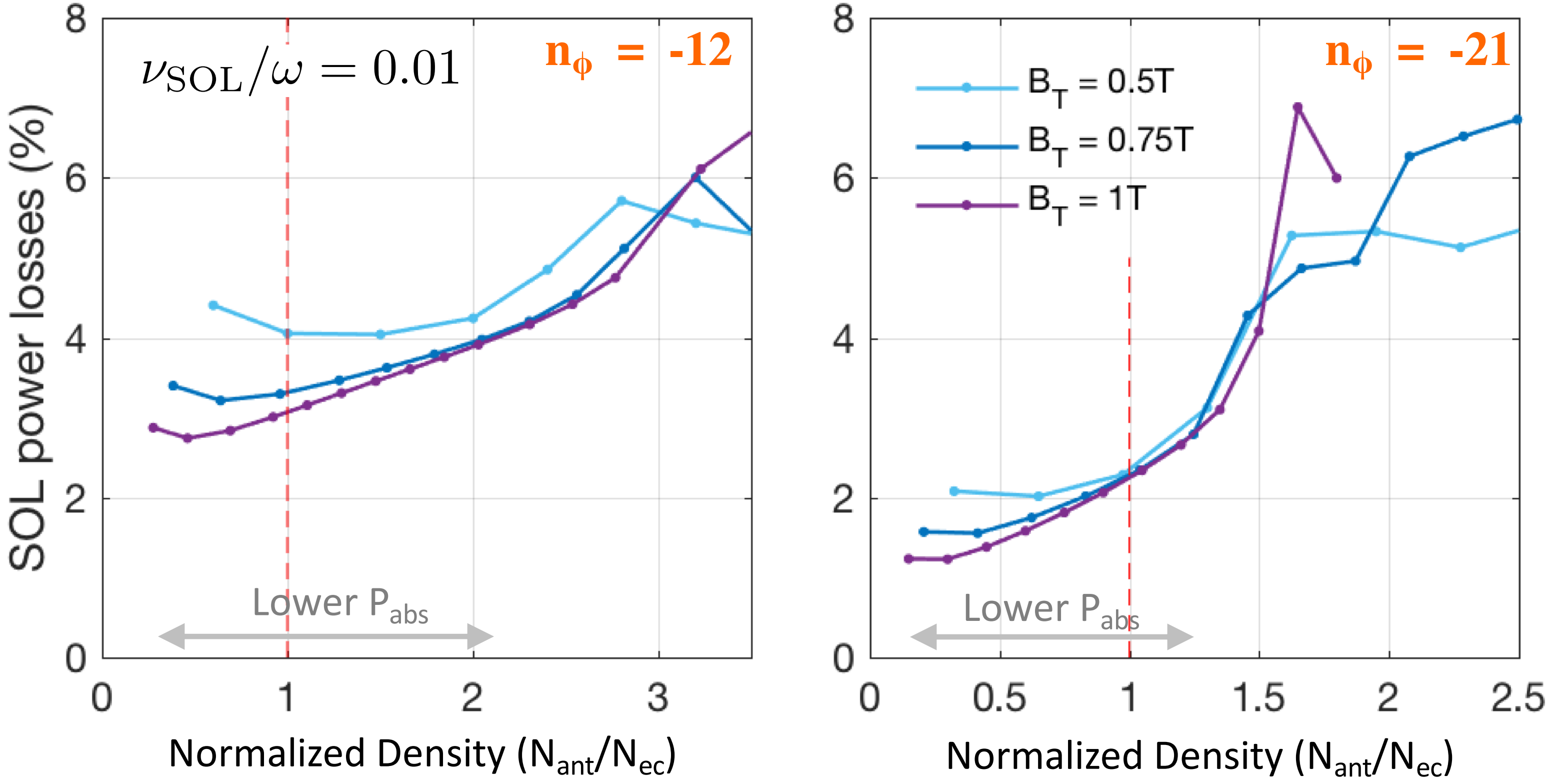
Power losses decreases as B_T increases



- Power losses increases as B_0 increases → Consistent with experiments [e.g., Hosea et al 2008]
- ΔN_{ant} (for *lower* P_{abs}) increases as B_T increases

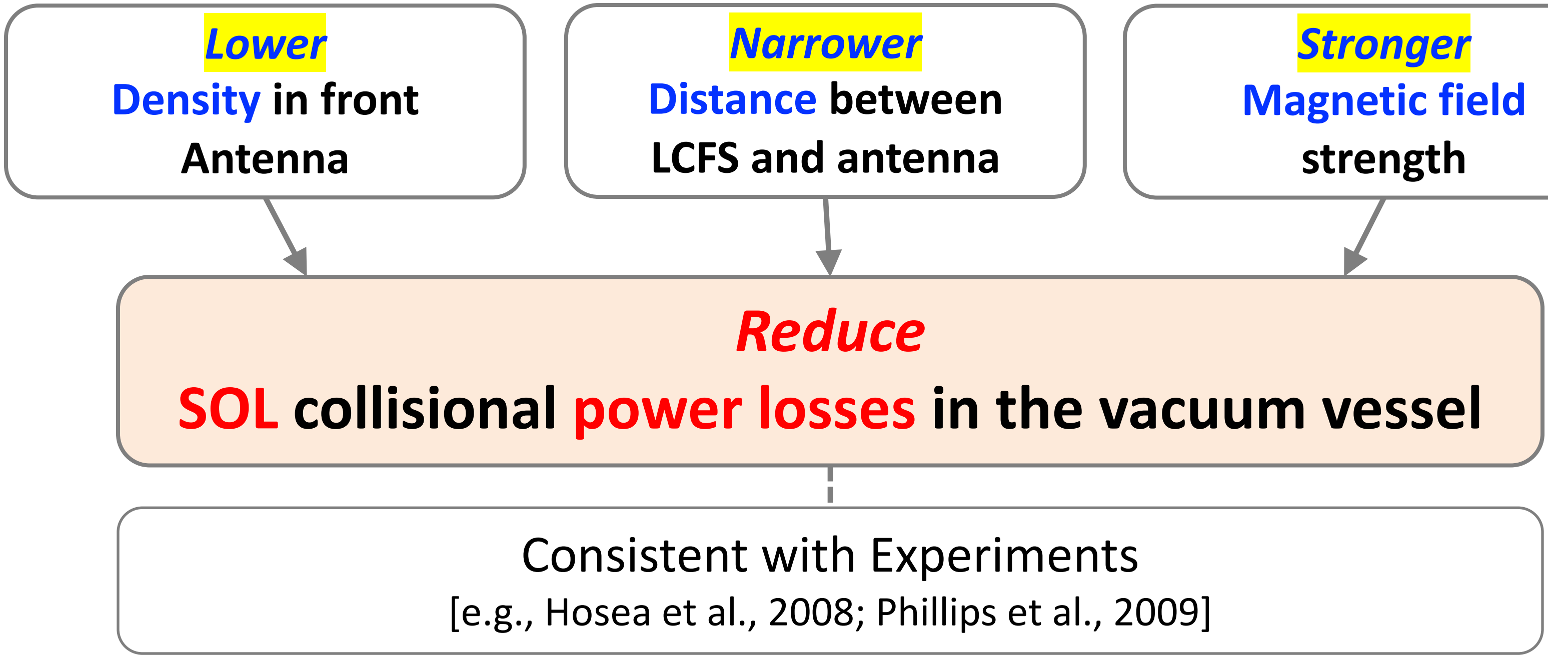
  → HHFW can propagate to the plasma core in wide range of density in front of antenna for strong magnetic field case

Power losses decreases as B_T increases



- Lower P_{abs} occurs
  $n_\phi = -12$ $N_{ant}/N_{ec} < 1.25$
  $n_\phi = -21$ $N_{ant}/N_{ec} < 2$

Summary



Lower
Density in front Antenna

Narrower
Distance between LCFS and antenna

Stronger
Magnetic field strength

Reduce
SOL collisional power losses in the vacuum vessel

Consistent with Experiments
[e.g., Hosea et al., 2008; Phillips et al., 2009]

- **Minimum** SOL collisional losses occur (all magnetic field strength) → **near the critical density** where FW cutoff is open
- Minimum SOL collisional losses occur **(strongly magnetized plamsa) → with wide range of the density in front of antenna**

Future Work

We will examine the HHFW in the NSTX/NSTX-U using recently developed Petra-M code and compare the results from FW2D

(e.g., BP11.00082 : Shiraiwa et al., Development of Petra-M Framework: toward OS integrated FEM analysis)