NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

High-fidelity 3D HHFW full wave simulations in NSTX-U

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Princeton Plasma Physics Laboratory

ISTW 2022
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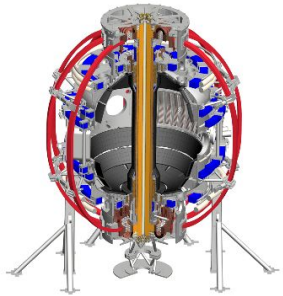
Oct. 31- Nov. 4, 2022
Virtual event



Outline

- Heating and current drive systems in NSTX-U
- Introduction and motivation
- Petra-M framework
- 3D HHFW simulations in NSTX-U
  - Phasing scan
  - B scan
  - SOL density scan
- Conclusions and future steps

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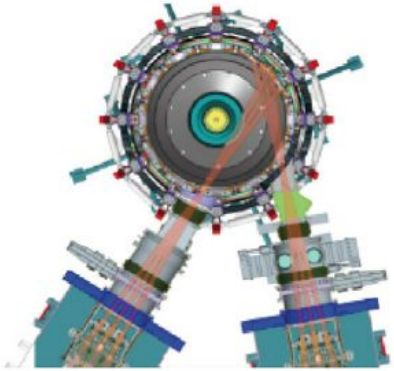
Heating and current drive systems in NSTX-U

Neutral Beam Injection

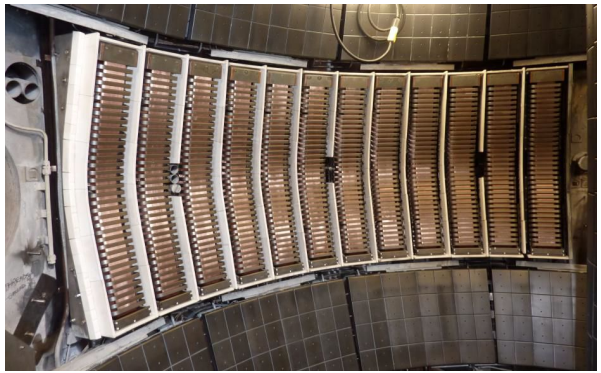
- 2 NBI (radial and tangential)
- Up to 10 MW



Present NBI New 2nd NBI

High Harmonic fast wave (HHFW)

- 12-strap antenna located on the outboard midplane and extends 90º toroidally
- Wave frequency = 30 MHz,
- Up to P_{RF} = 6 MW
- $|k_{\varphi}|$ = 3, 8, and 13 m^{-1} or n_{φ} = 5, 12, and 21 when $\Delta\varphi$ = 30º, 90º, and 150º
- $2^{nd} - 4^{th}/5^{th}$ Deuterium IC resonance for B = 1 T



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Introduction and motivation

- HHFW could play a major role in NSTX-U plasma particularly for
  - Driving current in the plasma ramping phase
  - Providing a significant core electron heating

- HHFW heating efficiency showed large amounts of HHFW power missing from core
  - Strong interactions between HHFW and SOL plasma and bright plasma "spirals" [Hosea *PoP* 2008, Perkins *PRL* 2012]
  - Larger SOL losses for high plasma density in front of the antenna
  - 2D AORSA & FW2D simulations shown cavity modes in SOL plasma [Green *PRL 2011*, Bertelli *NF* 2014 & 2016, Kim E.-H. *PoP* 2019]
- Significant interaction between HHFW and NBI (not discussed here)
- Evaluation of the HHFW coupling resistance was done assuming a planar antenna geometry and a slab model for the plasma [Swain et al, FST 2003]

Introduction and motivation

- HHFW could play a major role in NSTX-U plasma particularly for
  - Driving current in the plasma ramping phase
  -
- HH
  -
  -
  -
- Significant interaction between HHFW and NBI (not discussed here)
- Evaluation of the HHFW coupling resistance was done assuming a planar antenna geometry and a slab model for the plasma [Swain et al, FST 2003]

Need to consider a 3D HHFW high fidelity antenna geometry and 3D SOL plasma to improve HHFW modeling and support future HHFW experiments

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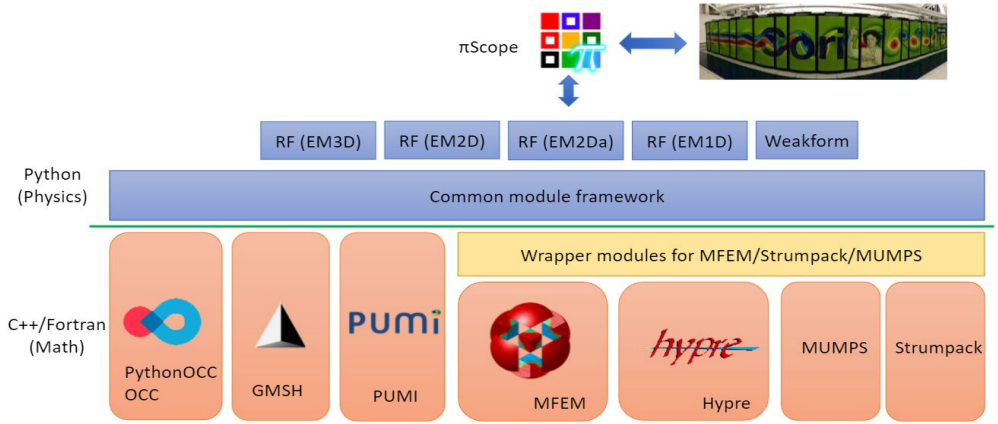
Petra-M: integrated multi-physics FEM platform

- Geometry/mesh generation
  - Utilize GMSH / Open CASCADE
- FEM assembly and solve
  - FEM interfaces from MFEM
  - Tightly integrated with πScope Python workbench
  - RF Physics module (1D/2D/3D)
  - Weakform module
    - Multiphysics coupling
- Solver/Post-processing
  - Steady State and Time dependent solver
  - MUMPS/Strumpack direct solver
  - Hypre iterative solvers
  - Visualization on πScope
- Scales from laptop to cluster

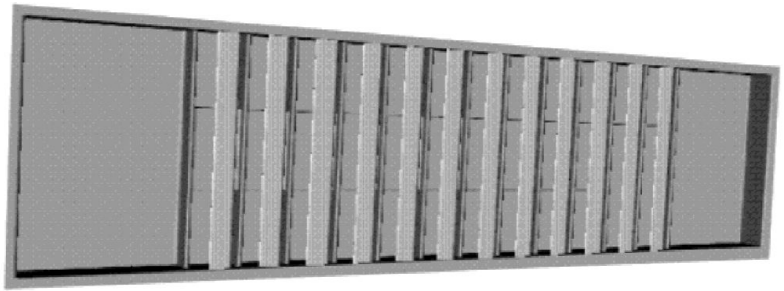


- **SHIRAIWA, S. et al, 28th IAEA-FEC (2021)**
- **SHIRAIWA, S. et al., EPJ Web of Conferences 157, 03048 (2017).**

https://github.com/piScope/piScope
https://github.com/mfem/PyMFEM

High fidelity 3D HHFW antenna and device geometries

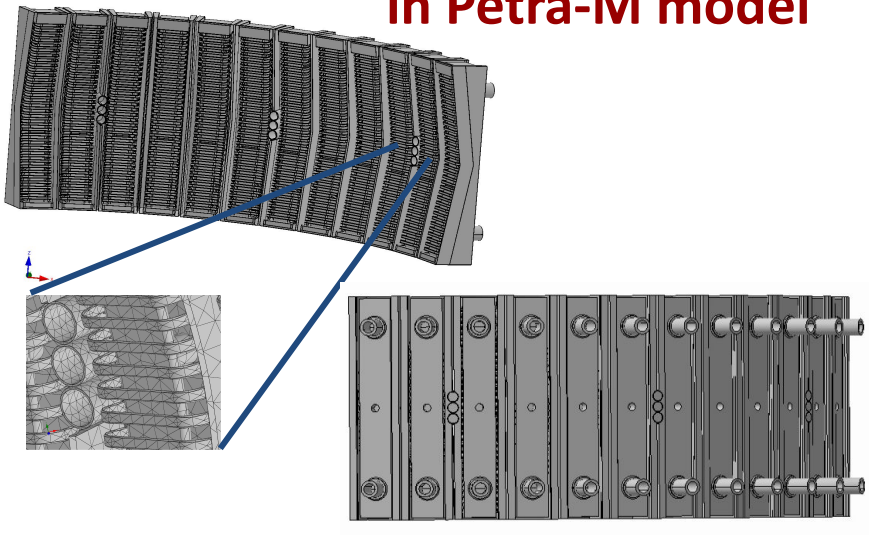
Previous work



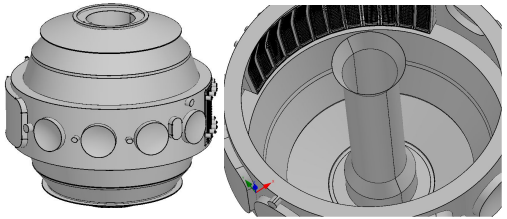
Antenna model used in Swain et al FST 2003

- Planar antenna geometry and a slab model for the plasma
- To evaluate S-matrix
- Antenna loading

in Petra-M model



Including passive plates and divertor + 3D SOL-core plasma



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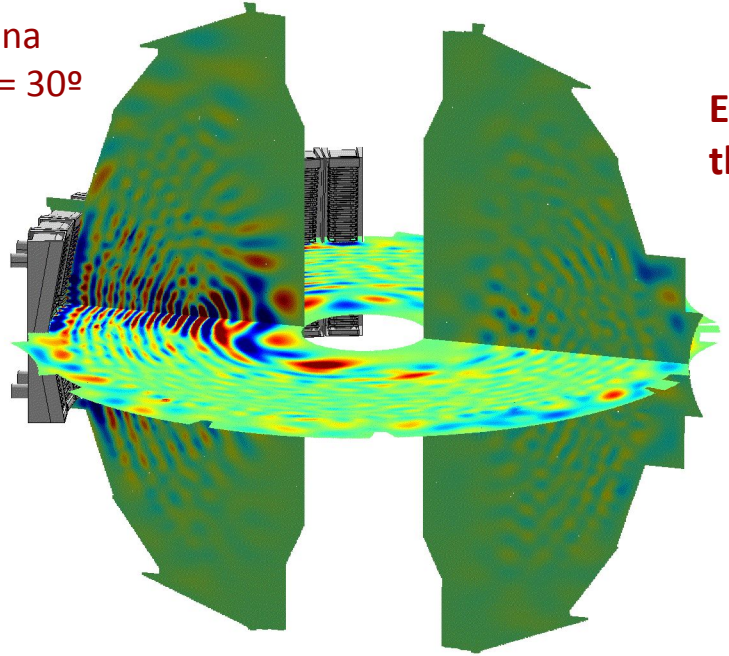
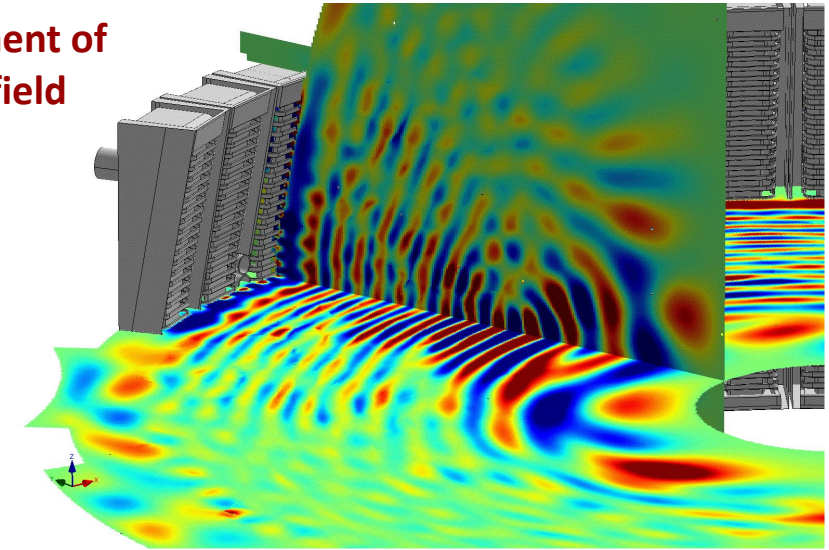
Full 3D torus simulation including realistic antenna geometry

Antenna phasing = 30º



[N. Bertelli, S. Shiraiwa, and M. Ono, Nucl. Fusion **62** 126046, 2022]

E_z component of the wave field



- Equilibrium B field from EFIT as well as the diverted geometry
- Vacuum in the antenna box and anisotropic cold plasma in the torus with articifial collisions

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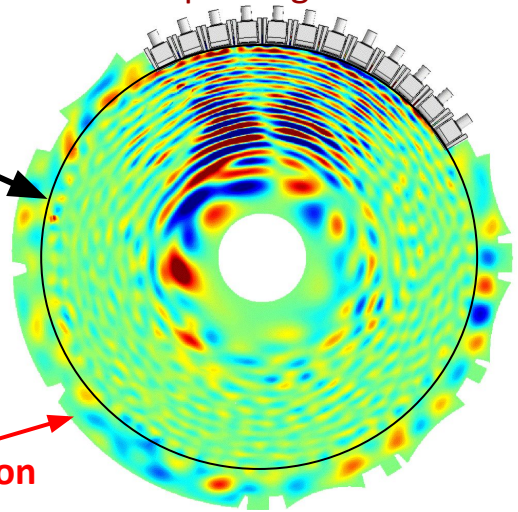
Lower antenna phasing has stronger interaction with SOL plasma

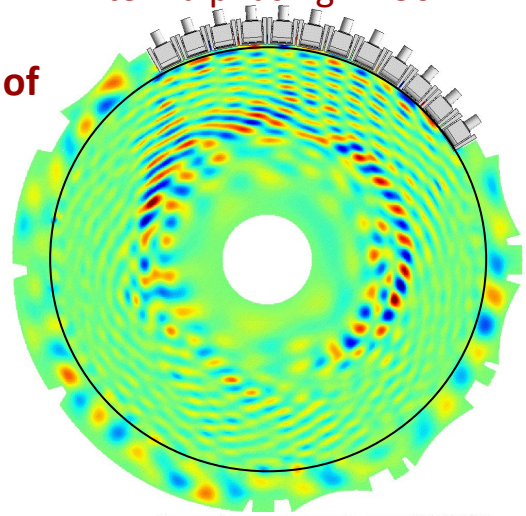
Antenna phasing = 30º

Antenna phasing = 150º

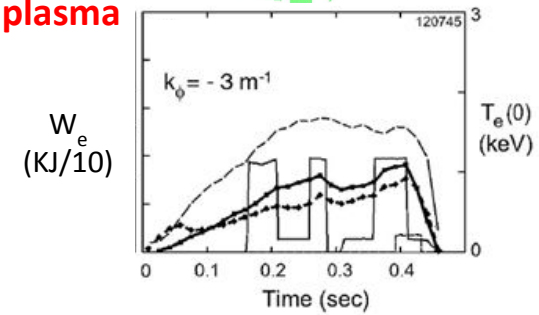
LCFS

E_z component of the wave field

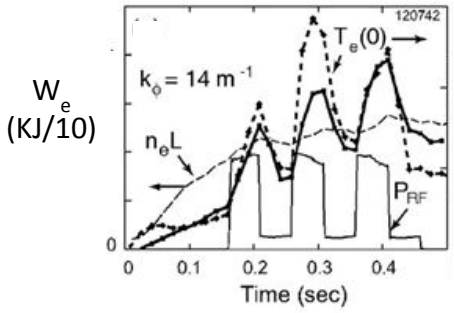




Strong interaction with the SOL plasma



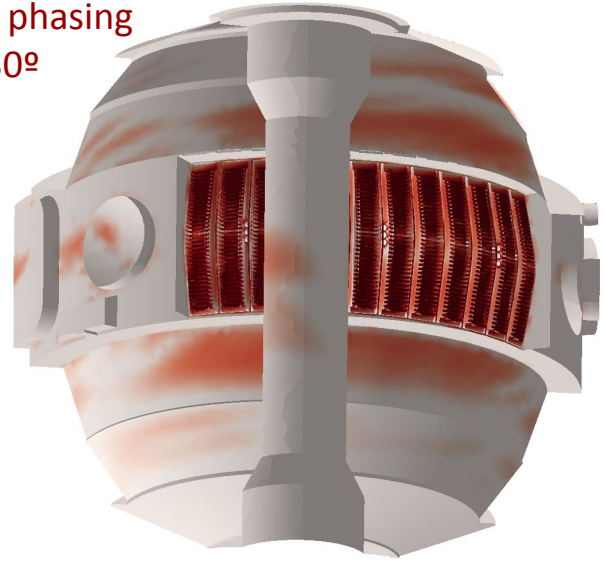
Reductions in We and Te for low k_φ (i.e, low antenna phasing)



[Hosea, PoP 2008]

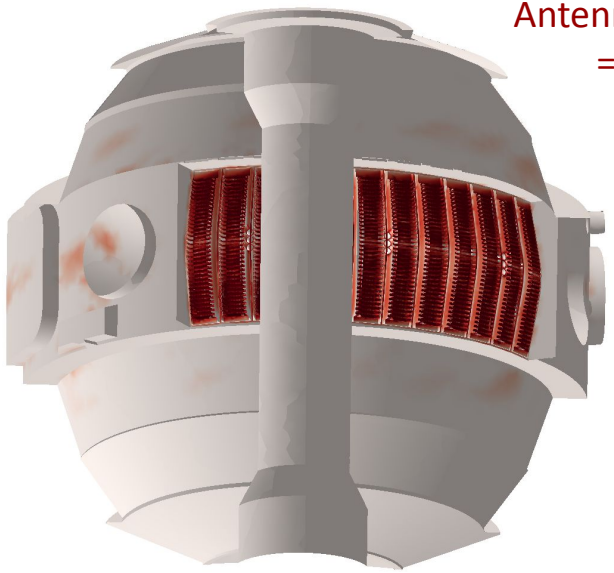
Strong E field on the wall observed on passive plates

Antenna phasing = 30º



|E| on the surface

Antenna phasing = 150º



- |E| field stronger for lower antenna phasing
- |E| field on the surface in 3D will be important for studying the antenna impurity generation and RF sheath effects

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Magnetic field (B) scan

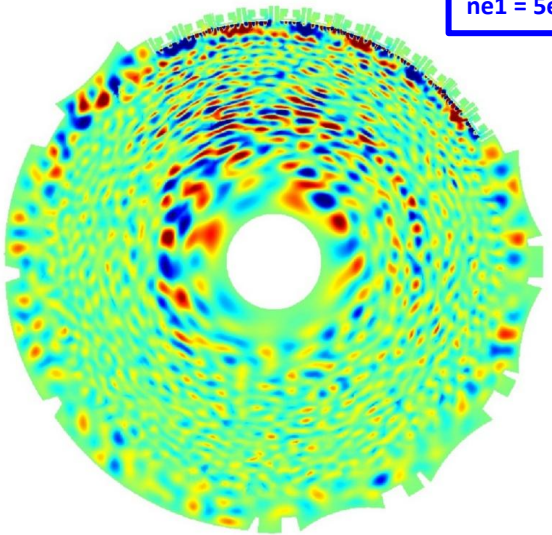
B = 0.6 T

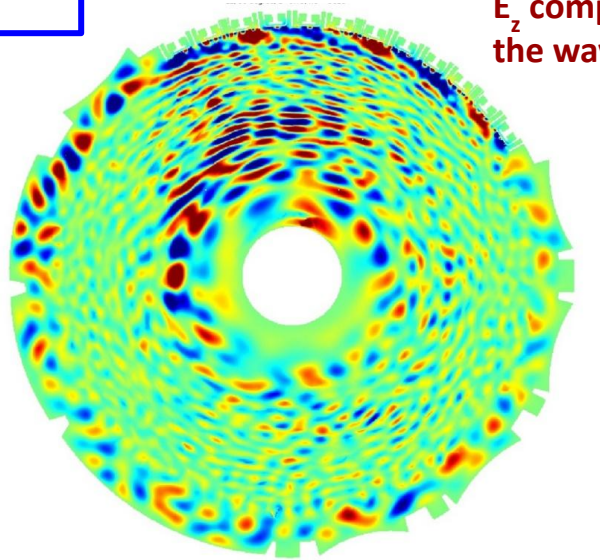
90 degree antenna phasing
ne0 = 5e19,
ne1 = 5e18

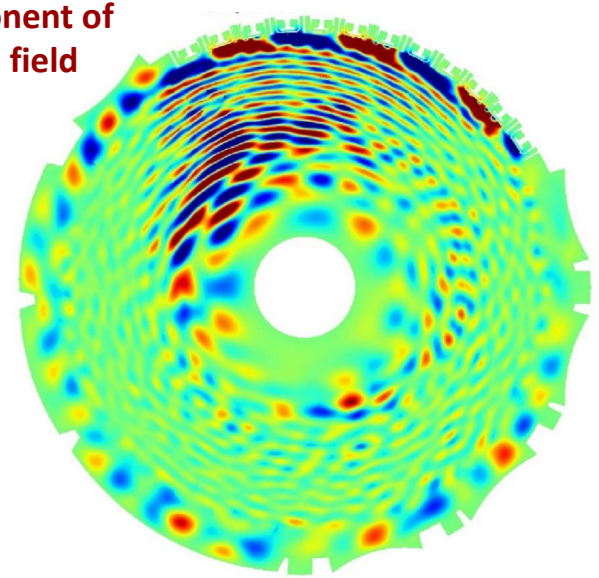
B = 0.75 T

B = 1.0 T

E_z component of the wave field







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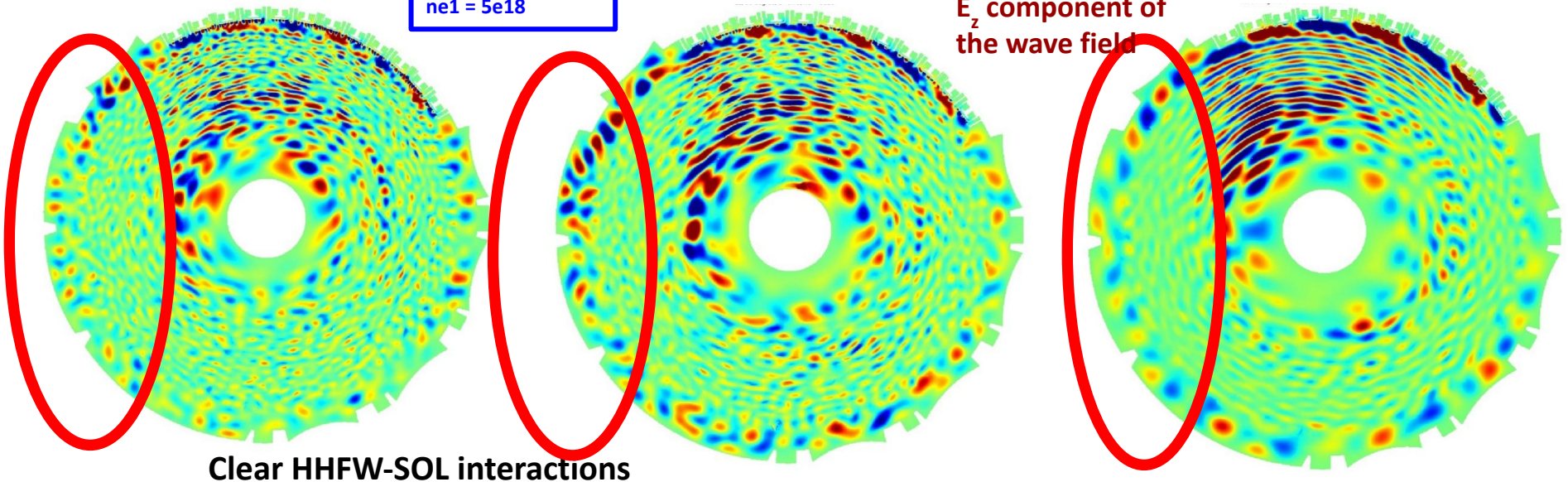
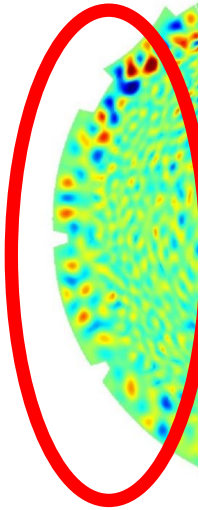


Clear HHFW-SOL interactions

- "Cavity modes" travelling toroidally in SOL
- Tend to "increase" with lower B
- Consistent with previous 2D AORSA and FW2D simulations

Magnetic field (B) scan



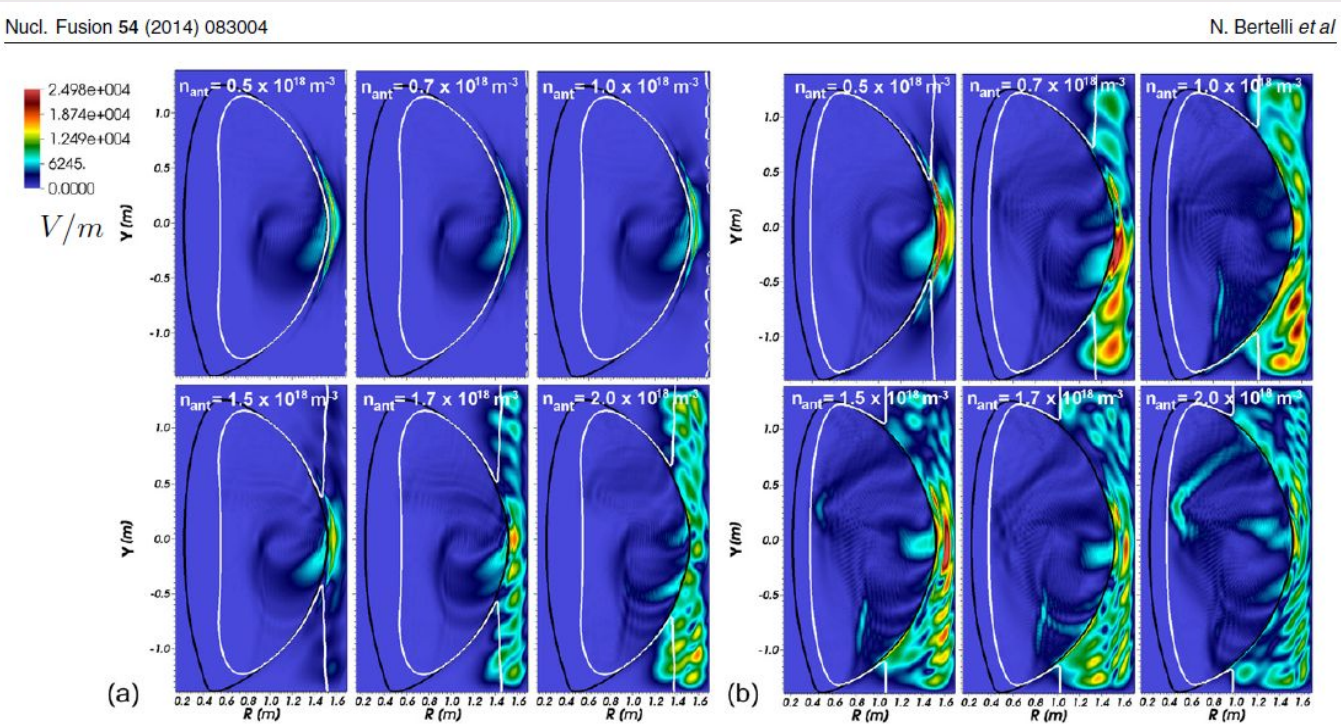
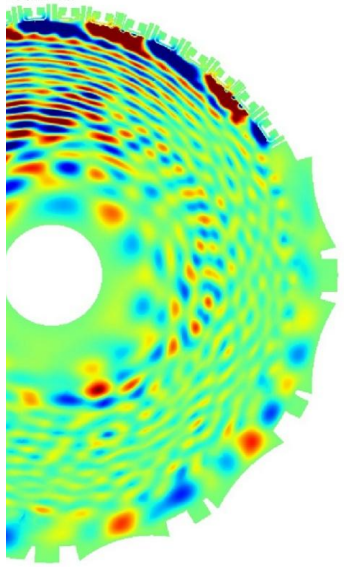


Figure 2. Electric field amplitude for different density values in front of the antenna (n_{ant}) (shown in the plots) with toroidal mode numbers $n_\phi = -21$ (a) and $n_\phi = -12$ (b). The white and black curves indicate the FW cut-off layer and the LCFS, respectively.

1.0 T



- tend to "increase with lower B and higher density
- **Consistent with previous 2D AORSA and FW2D simulations**

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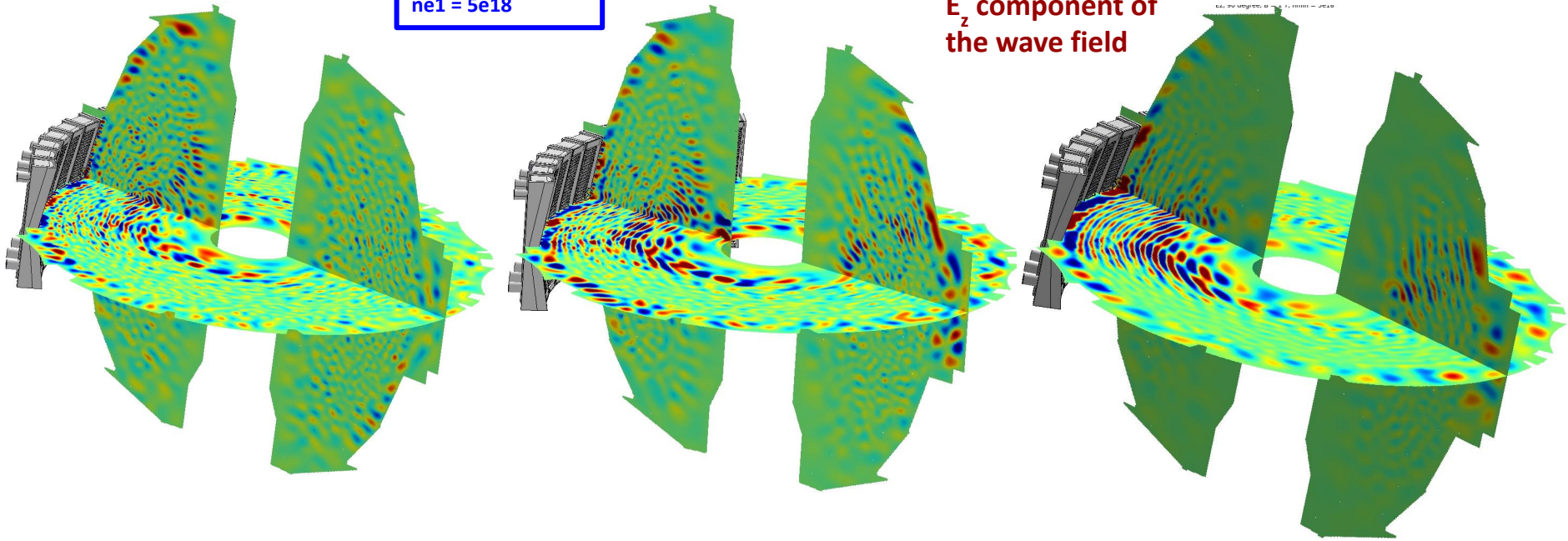
E_z component of the wave field



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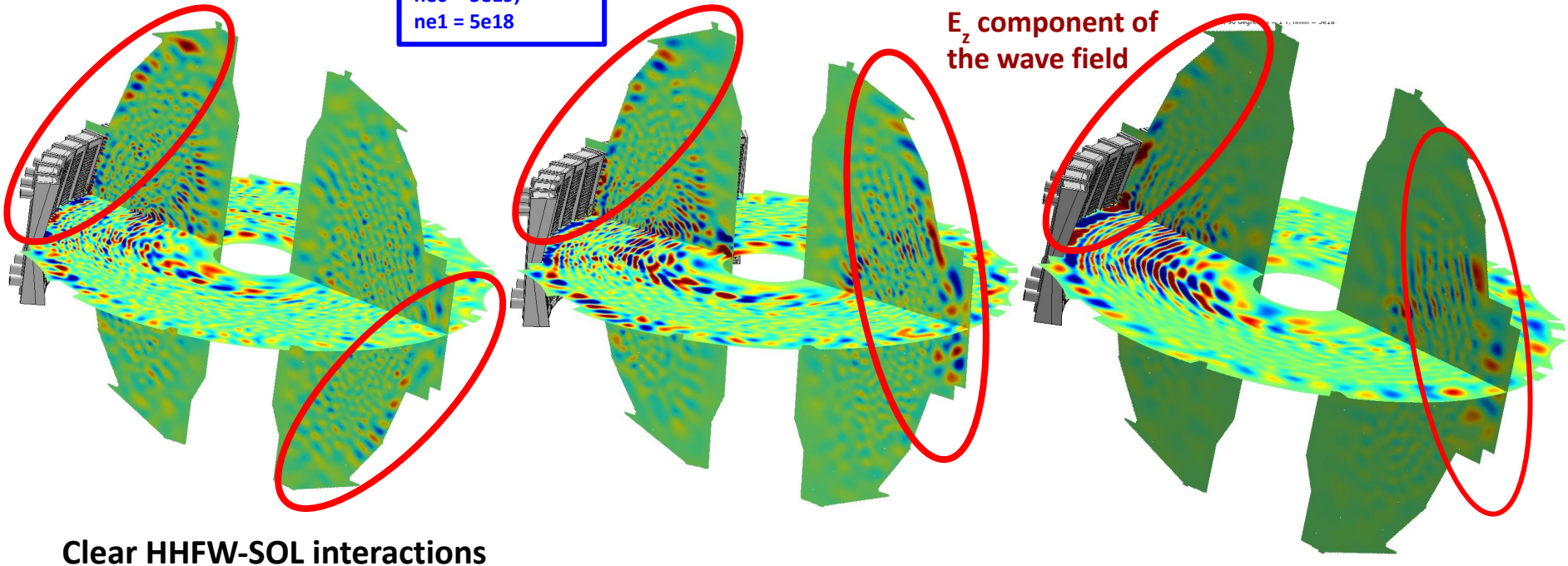
E_z component of the wave field



Clear HHFW-SOL interactions

- **"Cavity modes" travelling poloidally in SOL**

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SOL density scan

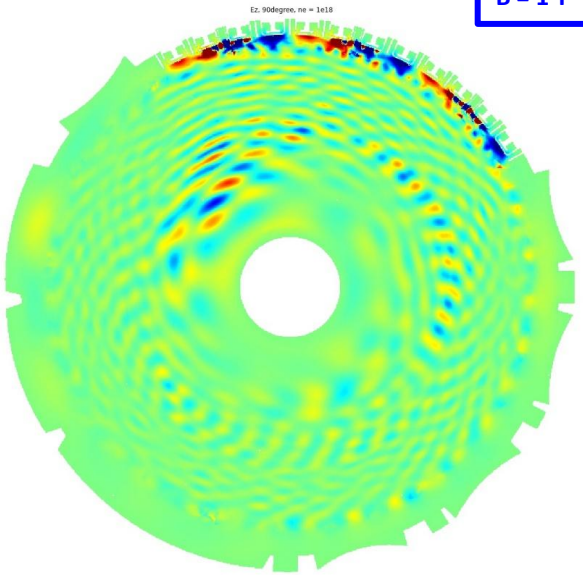
$n_{e,min}$ = 1.0 x 10^{18}/m3

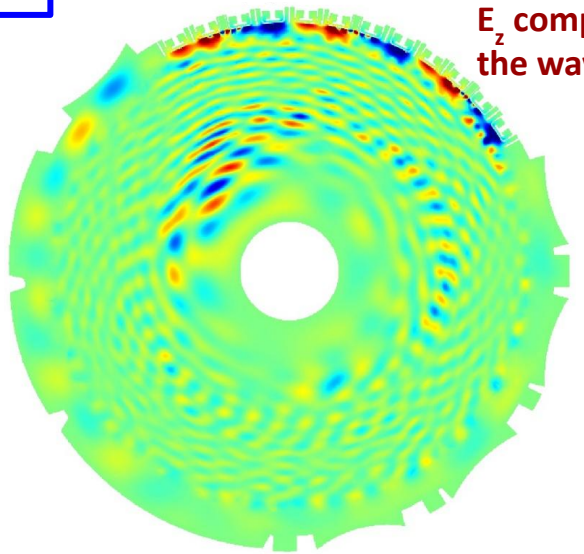
90 degree antenna phasing
B = 1 T

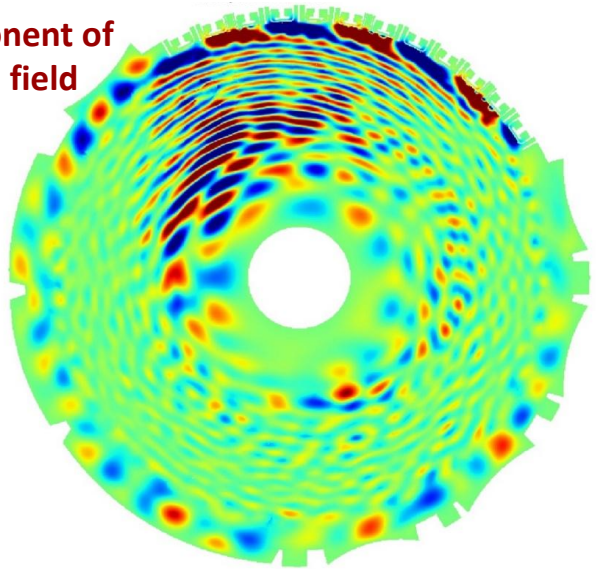
$n_{e,min}$ = 2.0 x 10^{18}/m3

$n_{e,min}$ = 5.0 x 10^{18}/m3

E_z component of the wave field







Clear HHFW-SOL interactions

- **"Cavity modes" tend to increase with SOL density**

SOL density scan

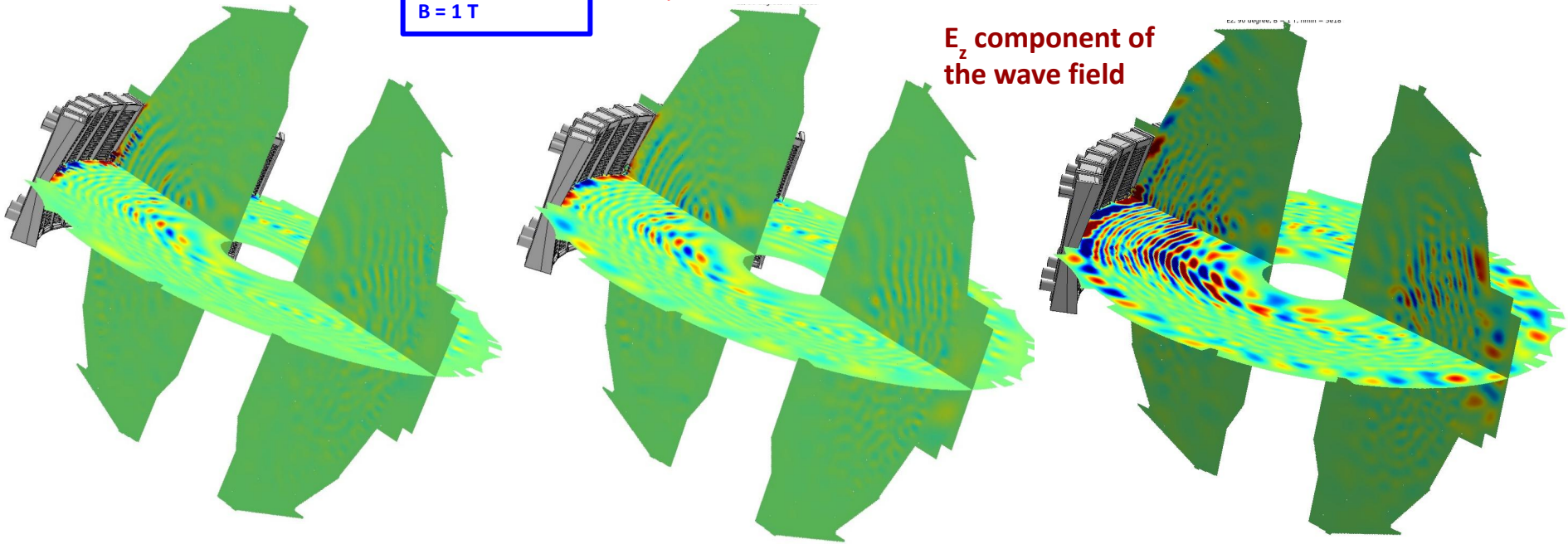
$n_{e,min}$ = 1.0 x 10^{18}/m3

90 degree antenna phasing
B = 1 T

$n_{e,min}$ = 2.0 x 10^{18}/m3

$n_{e,min}$ = 5.0 x 10^{18}/m3

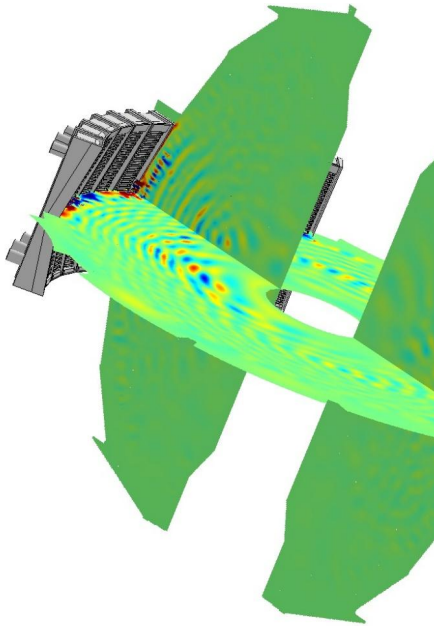
E_z component of the wave field



Clear HHFW-SOL interactions

- **"Cavity modes" tend to increase with SOL density**

$n_{e,min}$ = 1.0 x 10^{18}/m



Clear HHFW

- "(

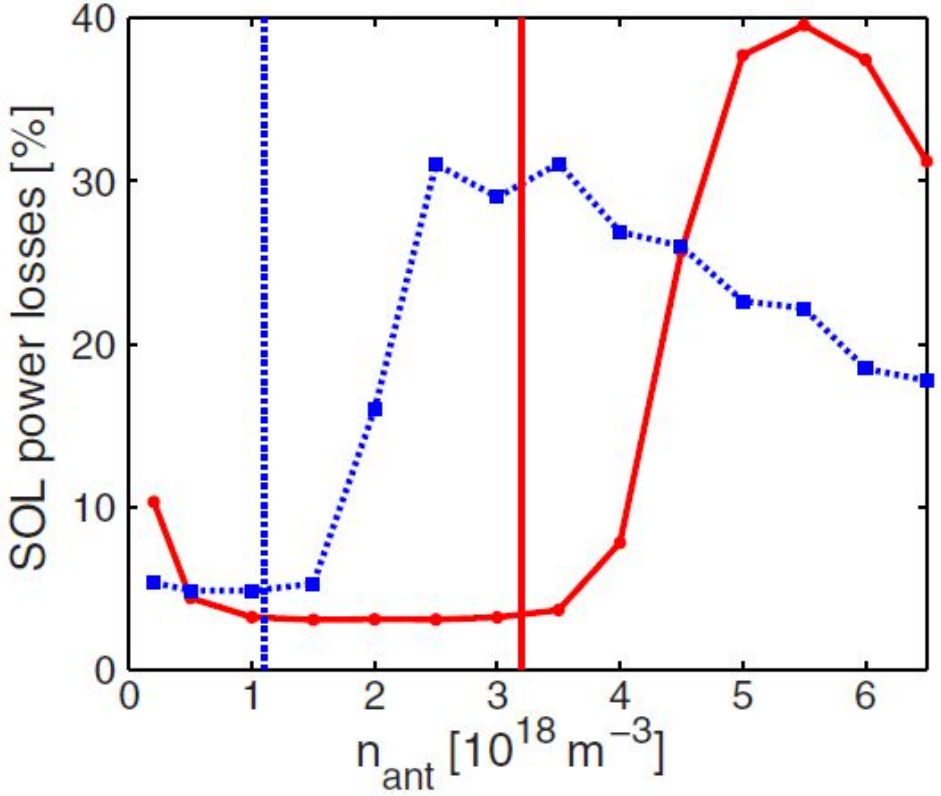
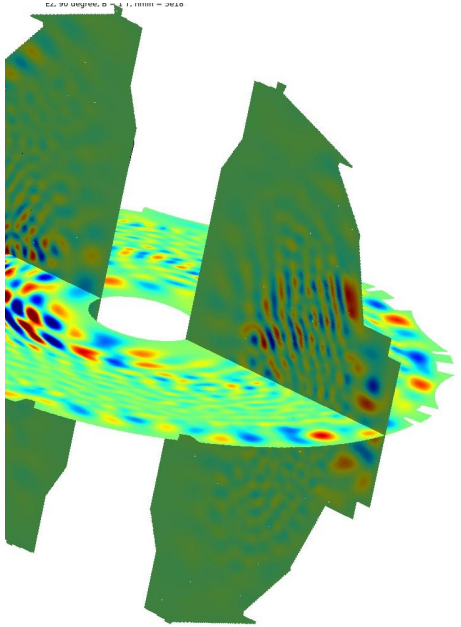


Figure 5. Fraction of power lost to the SOL as a function of the density in front of the antenna for $n_\phi = -21$ (solid curve) and $n_\phi = -12$ (dashed curve), for an NSTX-U case with $B_T = 1$ T. The vertical lines represent the value of the density for which the FW cut-off starts to be 'open' in front of the antenna.

n = 5.0 x 10^{18}/m3



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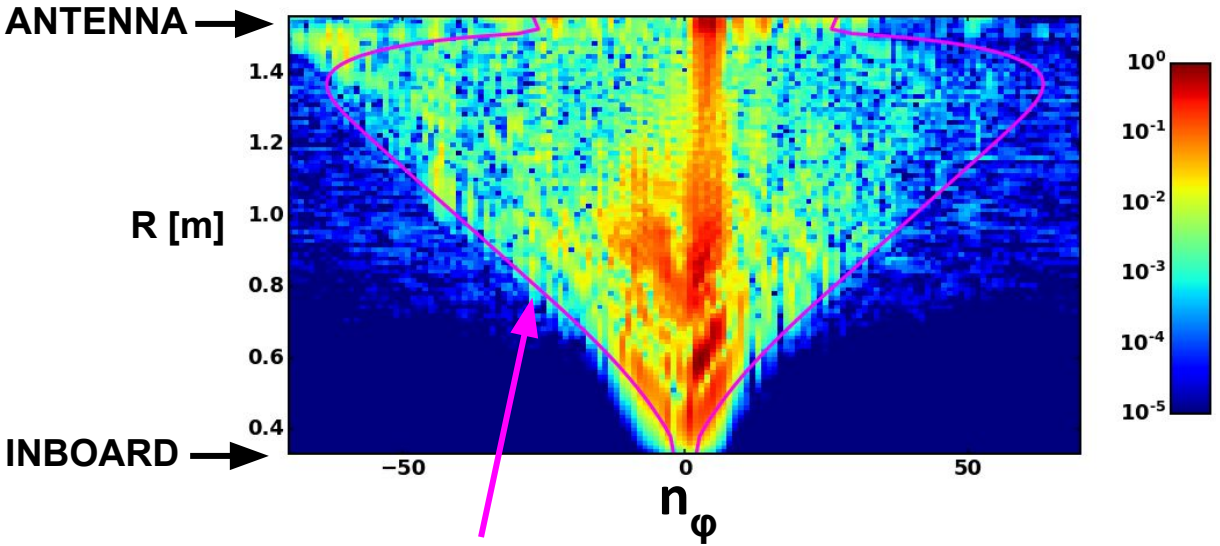
Conclusions

- 3D HHFW full wave simulation for NSTX-U plasma including realistic antenna geometry and SOL plasma
  - Strong interaction between HHFW and SOL plasma
  - Lower antenna phasing has stronger interaction with SOL plasma
    - agreement with previous 2D AORSA full wave simulations
  - B and ne scans showing “cavity modes” consistent with 2D AORSA and FW2D simulations
    - tend to increase with lower B and higher density
- **Future work/steps**
  - Study the impact of RF sheath effects
  - Coupling core-edge: TORIC-Petra-M
  - Antenna loading calculation
  - Impact of edge turbulence

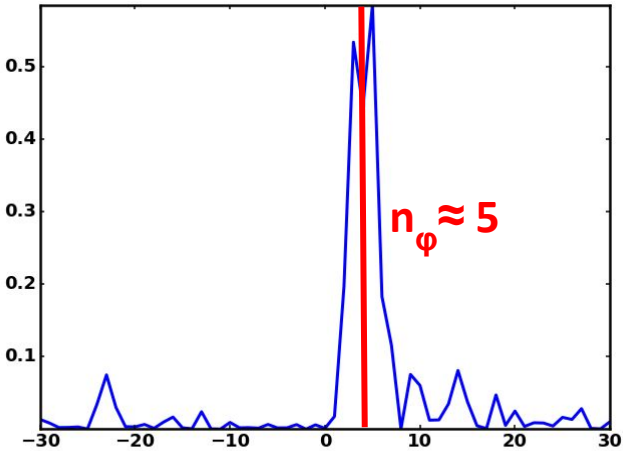
Thank you!

Launch power spectra are consistent with launch FW mode and the antenna phasing

Antenna phasing = 30º



Power spectrum at $R_{ANTENNA}$



Fast wave cut-off condition

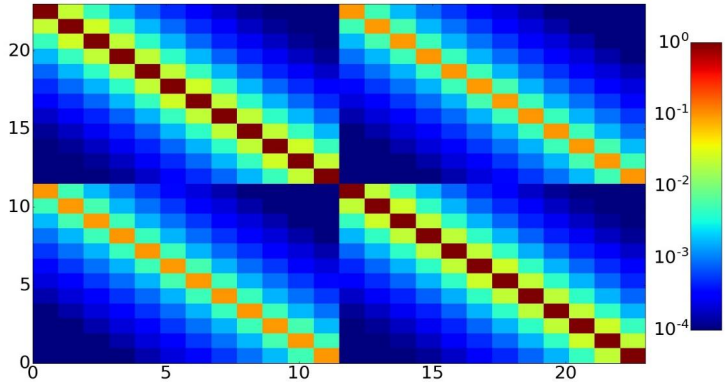
$$\frac{\omega^2}{c^2}(S+D) - k_\parallel^2 = 0$$

S and D are the components of cold plasma dielectric tensor

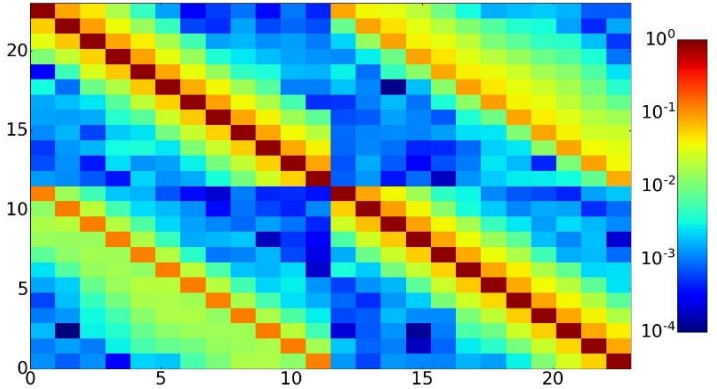
S-matrix: vacuum vs. plasma cases

- To be able to evaluate the coupling resistance of the HHFW system for different plasma scenarios to optimize the HHFW system, the 1st step is to evaluate the RF scattering (**S-matrix**).
- The S-matrix relates the voltage waves incident on the antenna ports to those reflected from the ports, in other words, $V_{reflected} = SV_{incident}$.

Abs(S), B = 1 T, VACUUM



Abs(S), B = 1 T, $n_{e,min} = 5 \times 10^{18}/m^3$

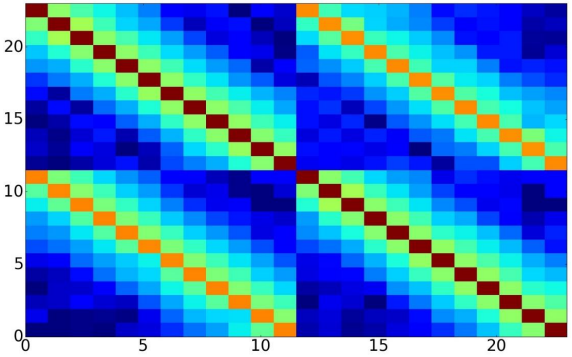


- S-matrix (24x24) for the front face HHFW antenna
- S-matrix in vacuum is symmetric unlike the plasma case
- Significant improvement w.r.t. the previous modeling efforts done in 2001-2003 with RANT3D [*Swain et al 2001-2003*]

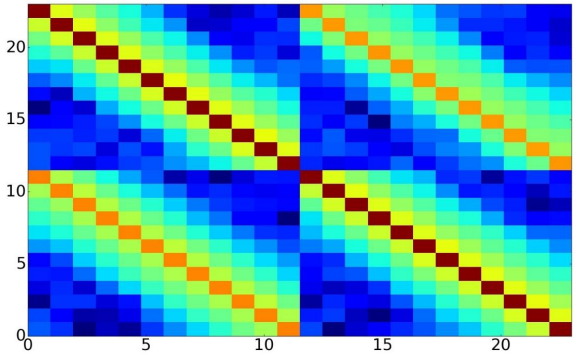
S-matrix: different SOL density plasma cases

- To be able to evaluate the coupling resistance of the HHFW system for different plasma scenarios to optimize the HHFW system, the 1st step is to evaluate the RF scattering (**S-matrix**).
- The S-matrix relates the voltage waves incident on the antenna ports to those reflected from the ports, i.e., $V_{reflected} = SV_{incident}$.

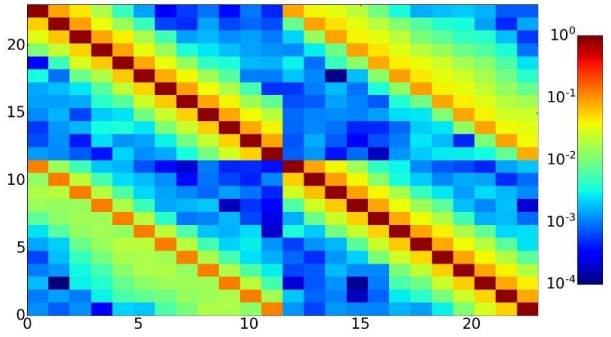
Abs(S), B = 1 T, $n_{e,min} = 1 \times 10^{18}/m^3$



Abs(S), B = 1 T, $n_{e,min} = 2 \times 10^{18}/m^3$



Abs(S), B = 1 T, $n_{e,min} = 5 \times 10^{18}/m^3$



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Next step is to incorporate backend RF circuit for direct comparison with measured RF antenna performance

In the experiment, the RF transmitter is connected with the antenna via RF coupling circuit

- Self and mutual inductances are measured behind backend RF circuit

Standard approach is to use S-matrix cascading