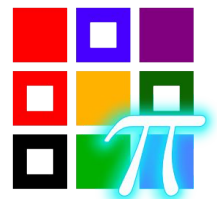
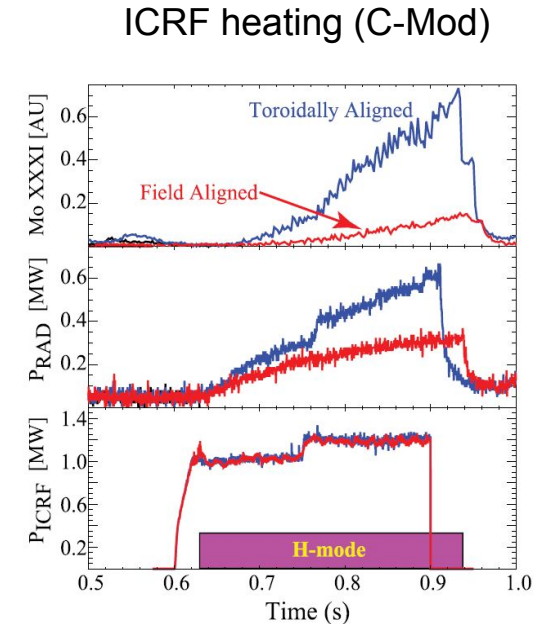
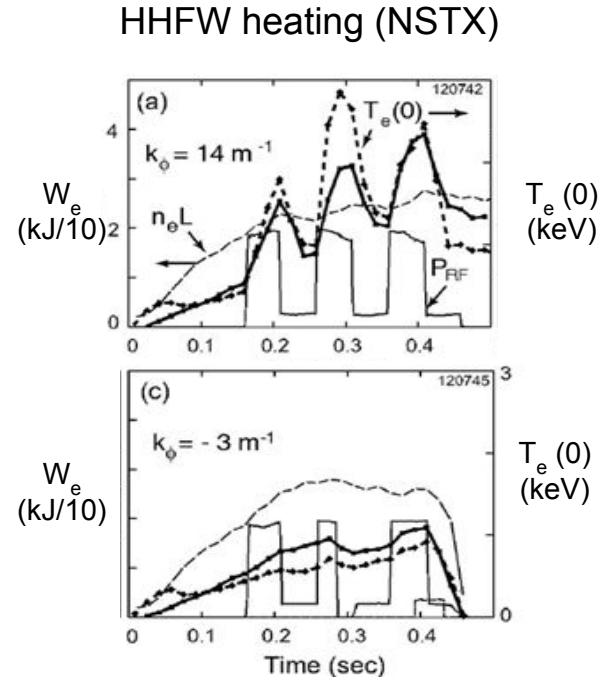
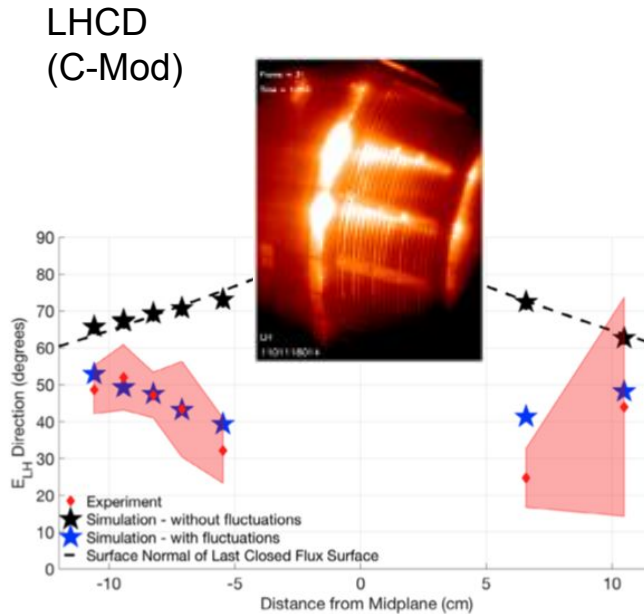


TOWARDS INTEGRATED RF ACTUATOR MODELING: WHOLE DEVICE SCALE RF FULLWAVE SIMULATION INCLUDING HOT CORE AND 3D SOL/ANTENNA REGIONS

S. Shiraiwa, N. Bertelli (PPPL), J. C. Wright (MIT)
P.T.Bonoli (MIT), T. Kolev, M. Stowell (LLNL)
J. Hillairet (CEA), J. Myra (Lodestar), M. Ono (PPPL),
R. Ragona (LPP), and RF SciDAC



Wave-plasma interaction in SOL regions needs to be better understood



Ubiquitous among various RF waves and fusion devices

- (Left) LHCD polarization changed possibly due to the density fluctuation[1].
- (Middle) Proper antenna phasing significantly improved HHFW heating[2].
- (Right) Field-aligned ICRF antenna reduced the impurity injection[3].

Computational modeling can play a major role to understand and extrapolate the present experiments to reactors

See also L. Colas (ID: 1033)

RF actuator simulation needs to take an integrated approach



Must integrate multiscale-multiphysics processes such as

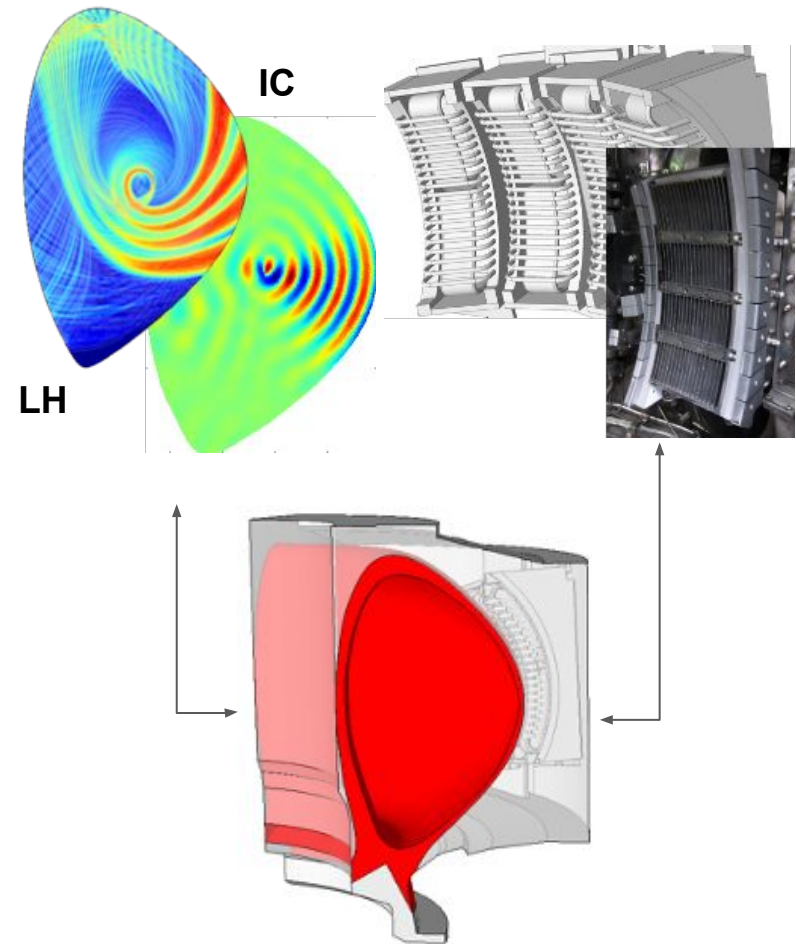
- Slow wave and PSI due to RF sheath.
- Wave scattering by the background plasmas.
- RF could modify the background plasma through transport and turbulence.
- non-local hot plasma response to RF electric field.

Must be 3D and “whole device” to include

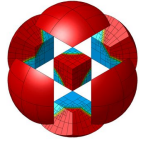
- Accurate 3D antenna and SOL geometry.
- Far-antenna sheath.

Need to develop a platform which facilitates

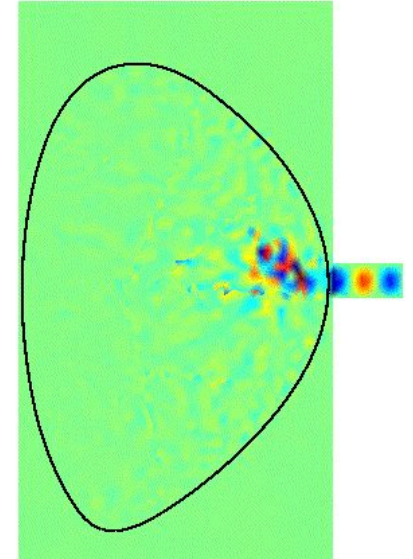
- communication with other codes.
- expansion of physics model.
- achieving good scalability.



Platform for advanced 3D RF wave simulation

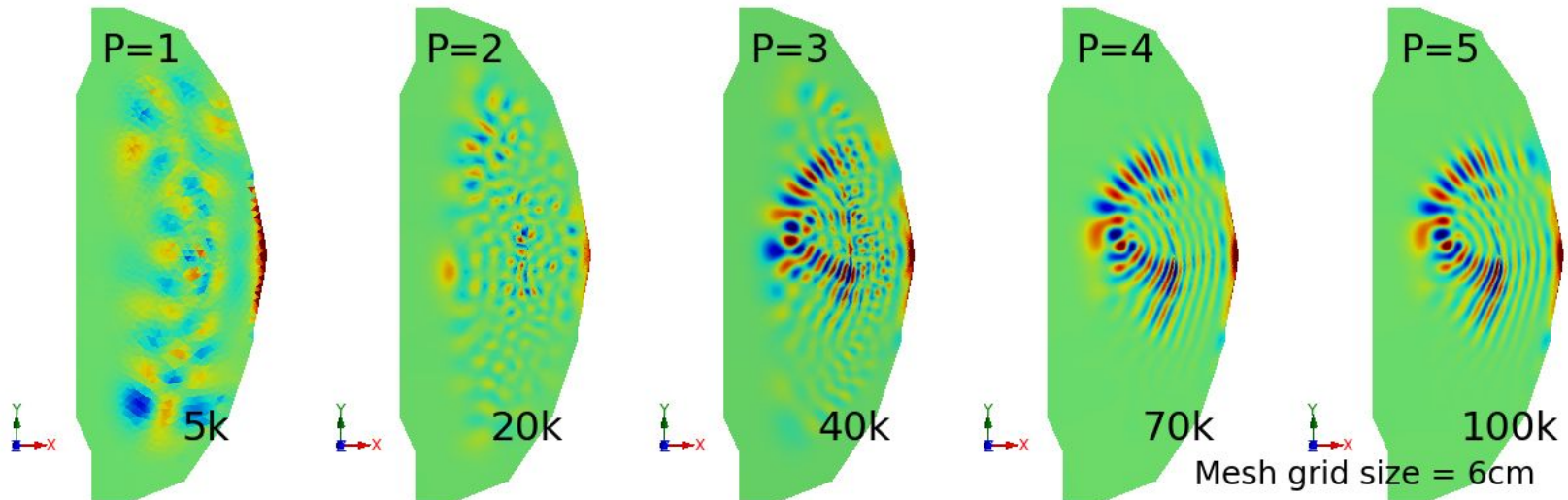


- Developed by MFEM team lead by LLNL.
- **Arbitrary high polynomial order (P)** for basis function and mesh elements.
- Various finite element basis functions.
- Scalable (MPI and GPUs).
- <http://mfem.org/>



Adaptive mesh refinement for LH waves [1]

P-scan for HHFW



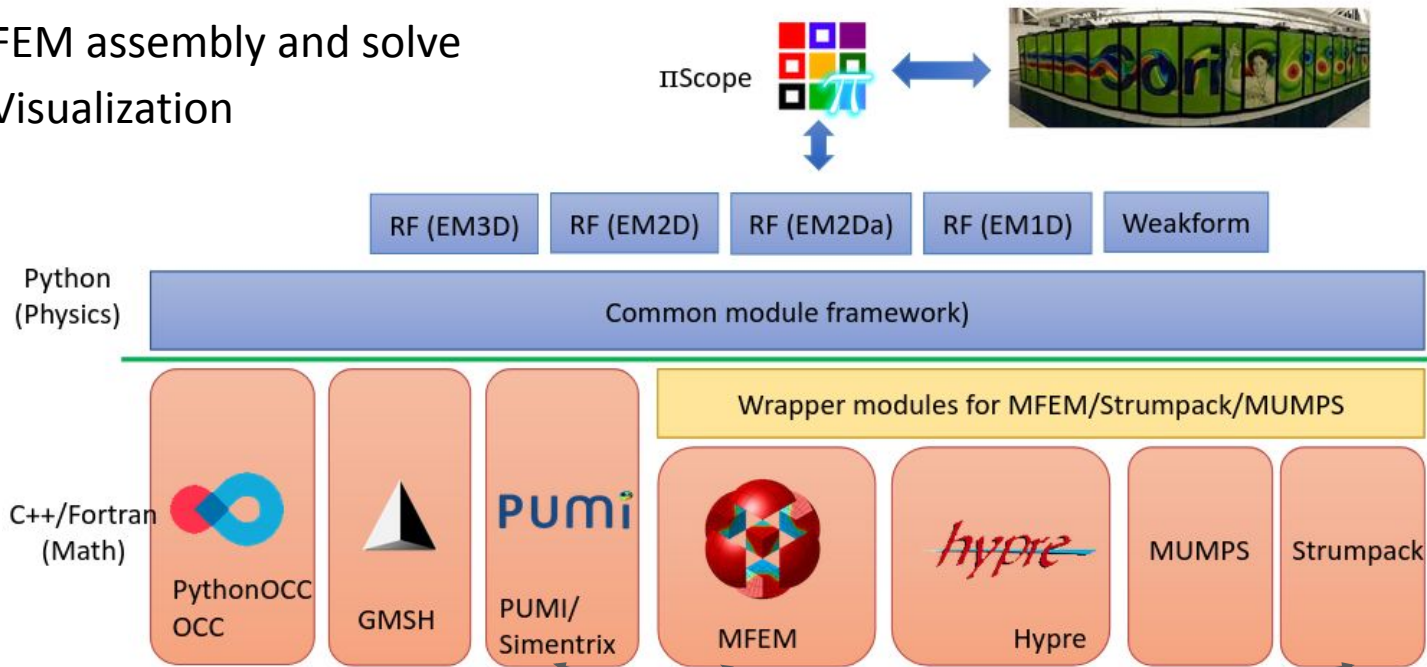


Combine high performance libraries in C++/Fortran with user friendly Python based physics interface.

Solves user defined PDEs.
Scales from laptop to cluster.
Open-source

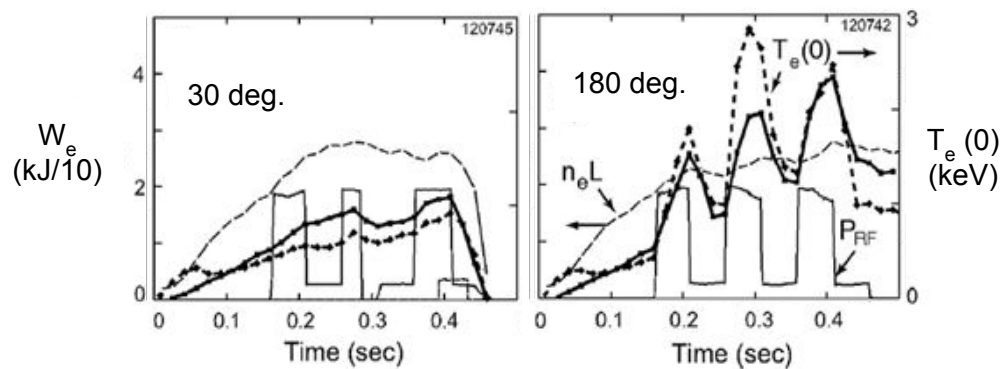
https://github.com/piScope/PetraM_Base

- Geometry creation
- Mesh generation
- FEM assembly and solve
- Visualization

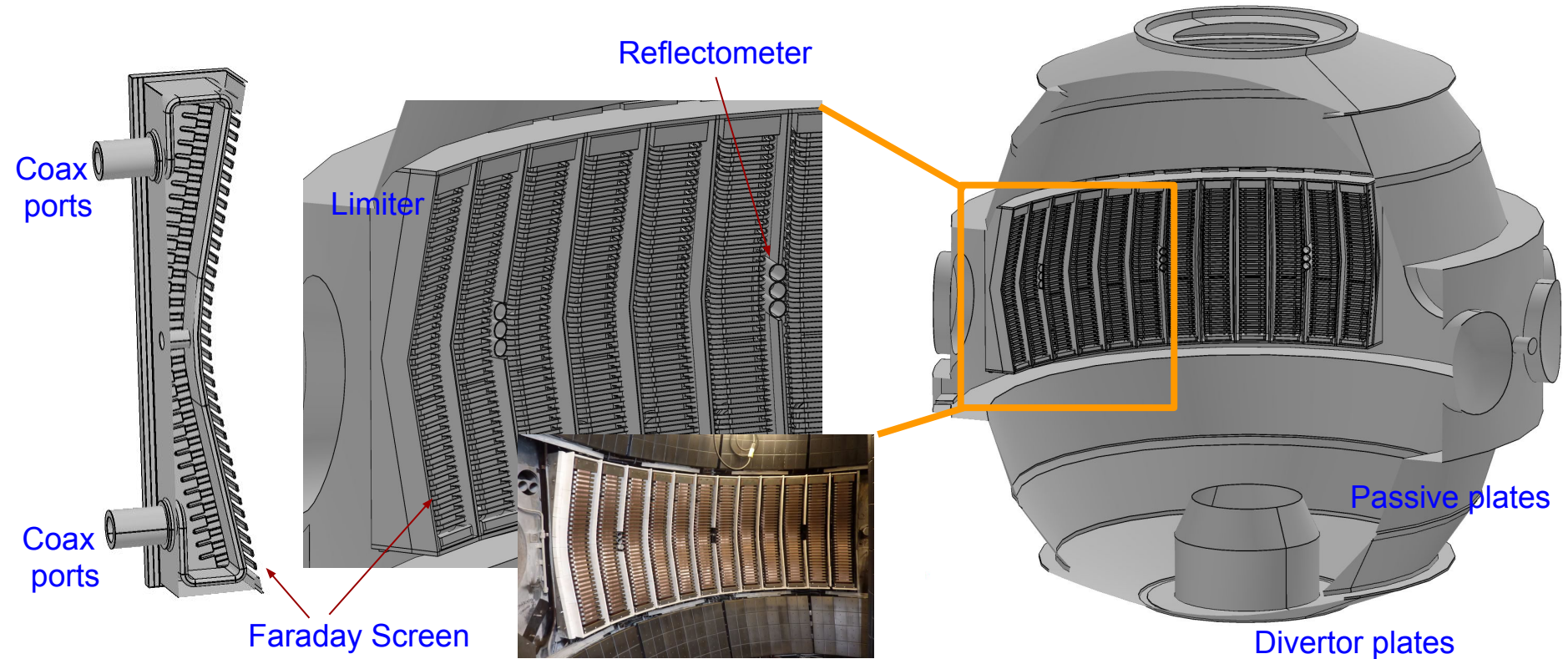


DoE Advanced Scientific Computing Research (ASCR) program

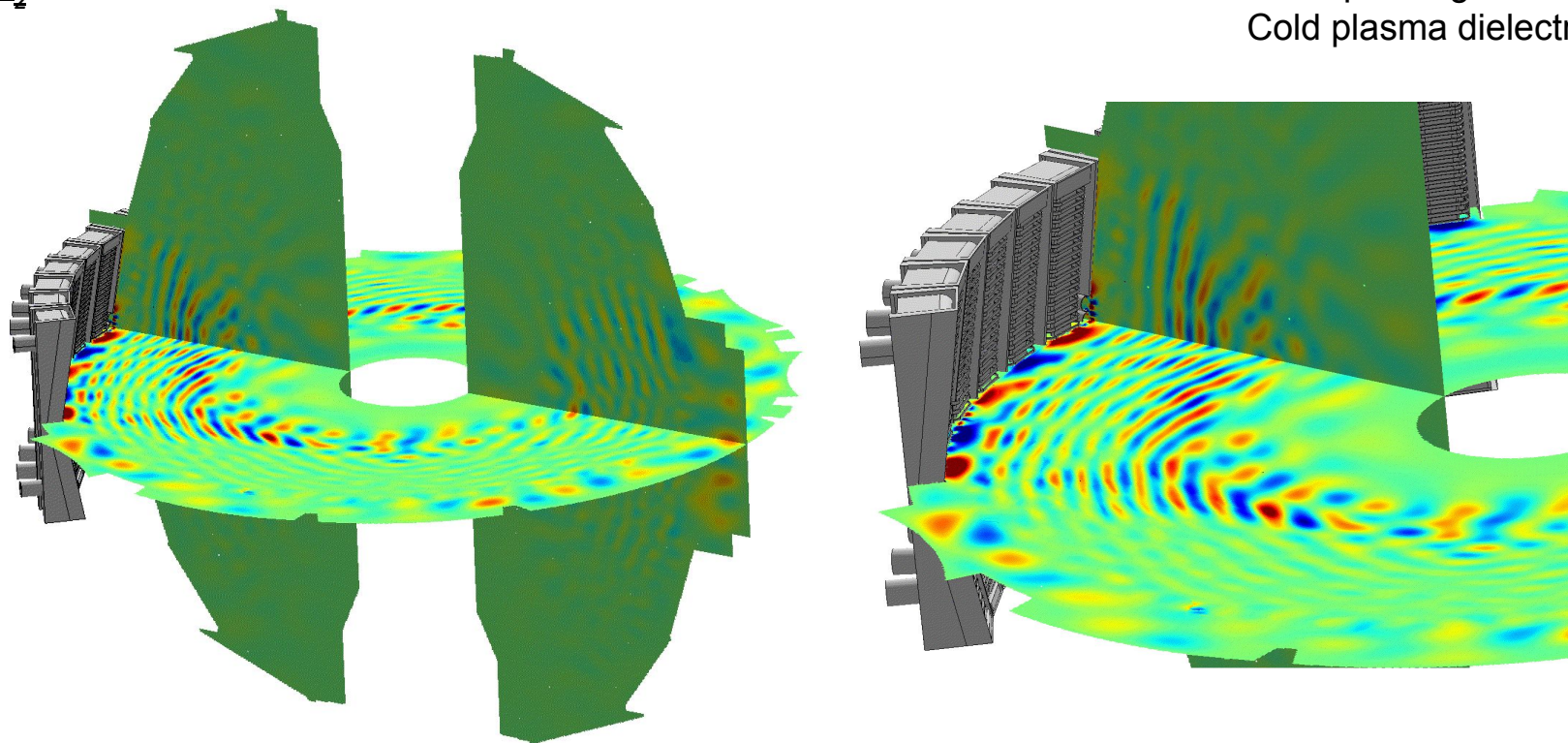
RF Wave field on plasma facing components



Simulation geometry was generated from original engineering CAD data



Model geometry includes everything we need for RF propagation from coax to plasma.

 E_z 

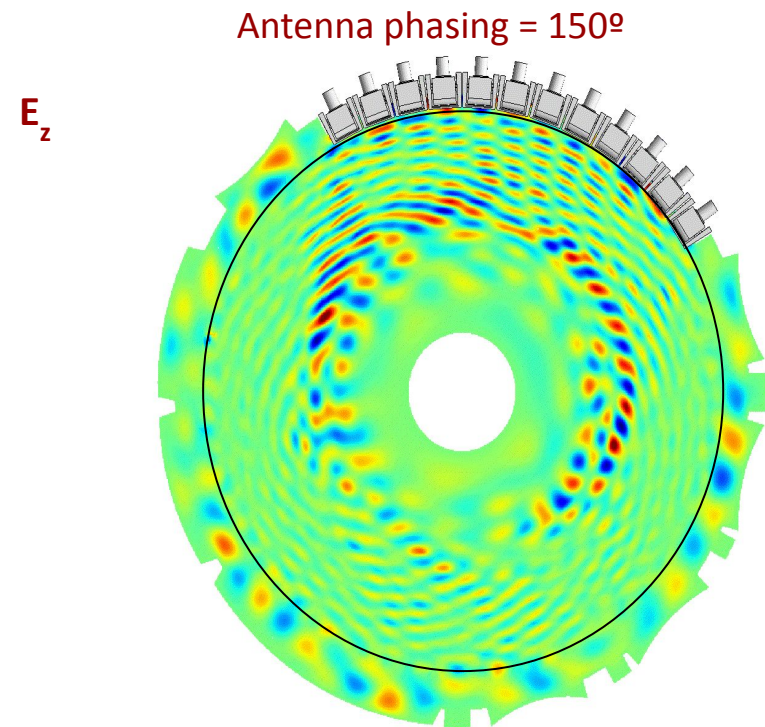
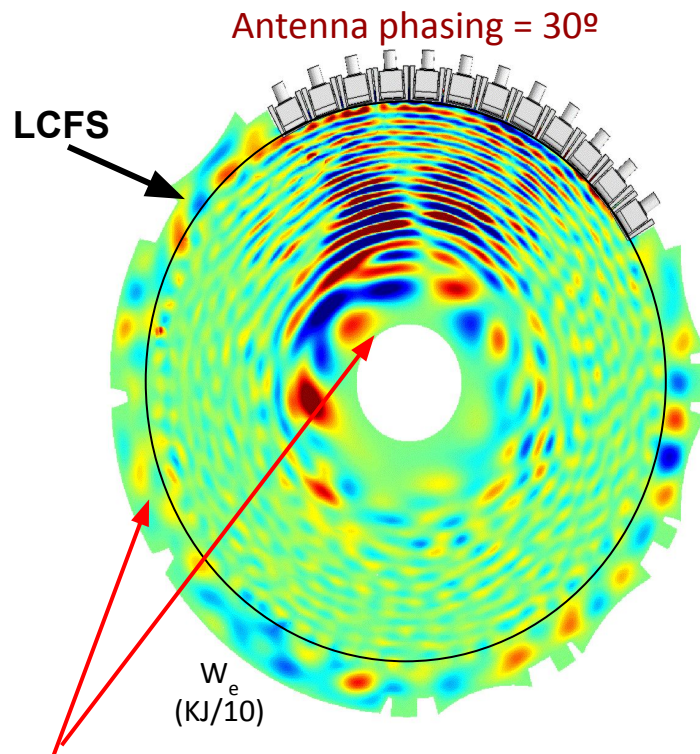
$B_t = 1\text{T}$, $n_{e0} = 5 \times 10^{19}\text{m}^{-3}$
150° phasing
Cold plasma dielectric

- Obtained using 4th order basis functions.
- 50M DoFs at 4th order basis, corresponding $\sim 400\text{M}$ DoFs with usual 2nd order.
- $\lambda/L \sim 15$ is close to what is required for resolving ICRF wave field on ITER.

Lower antenna phasing (k_ϕ) case indicates stronger interaction between RF and SOL plasmas



Comparison of E_z with different antenna phasing



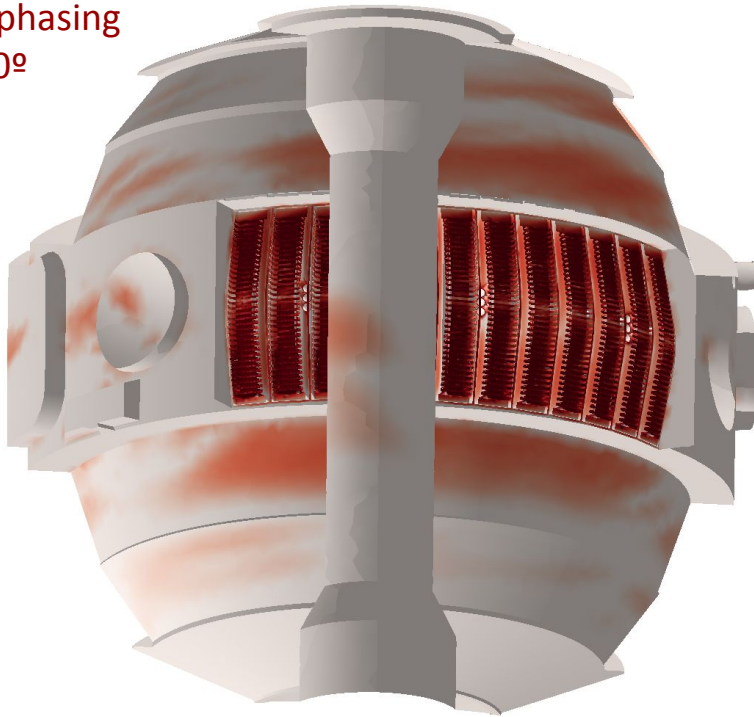
Strong E field in SOL plasmas

- Strong wave field in SOL regions both on the low field side and the high field side.
- Consistent with NSTX experiment where reductions in W_e and T_e for low k_ϕ (i.e, low antenna phasing).



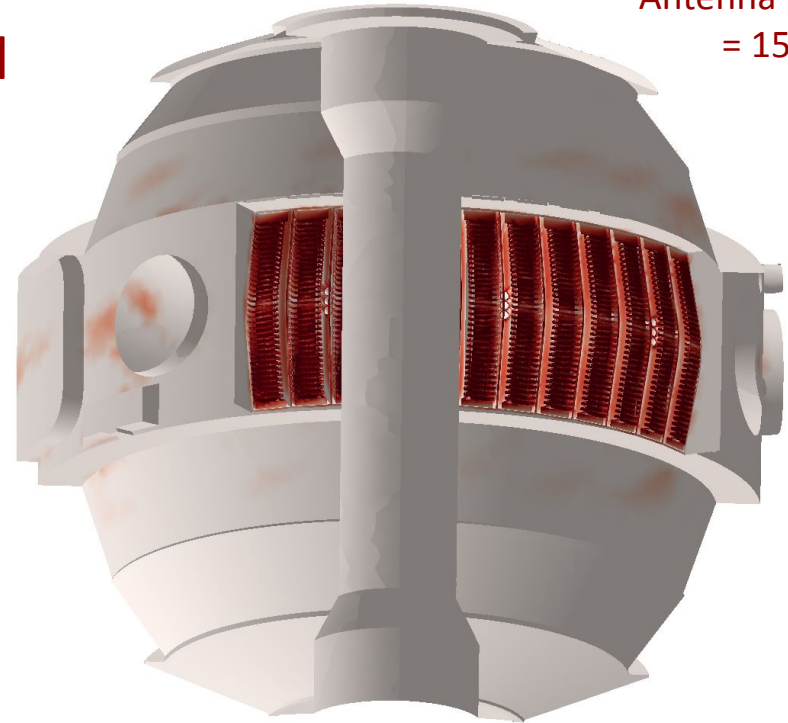
Comparison of $|E|$ with different antenna phasing

Antenna phasing
= 30°



$|E|$

Antenna phasing
= 150°

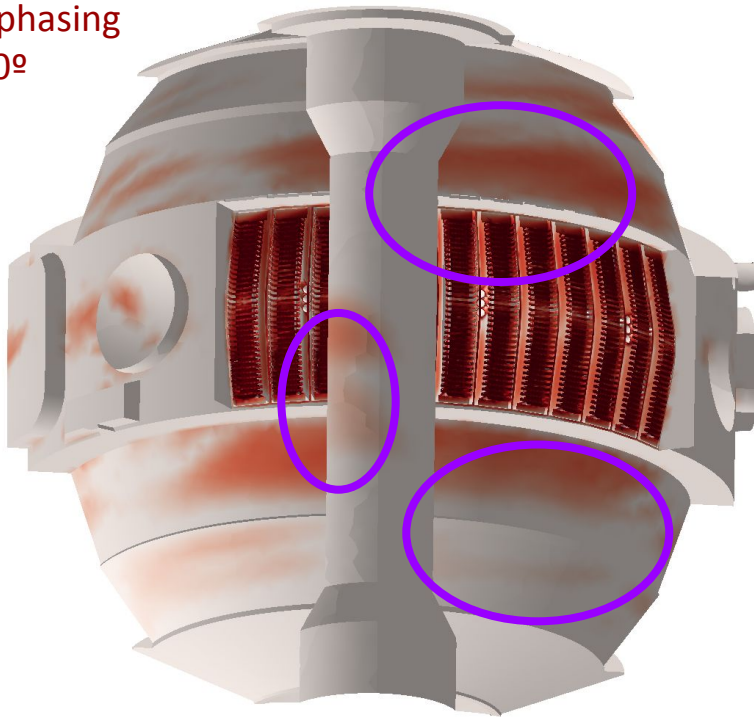


$|E|$ field is stronger in the lower antenna phasing (k_ϕ) case
On top and bottom passive plates
On CS wall



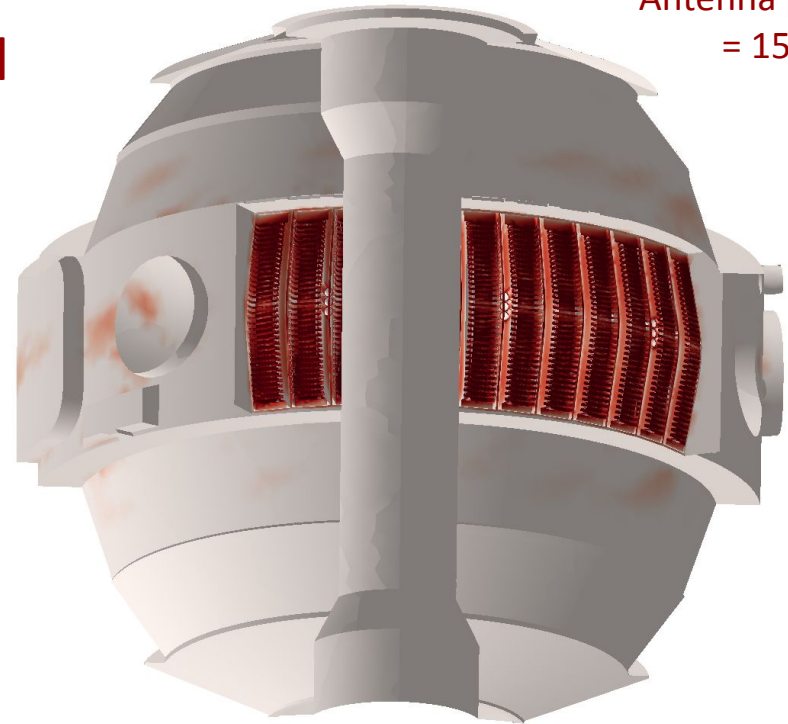
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$|E|$

Antenna phasing
= 150°



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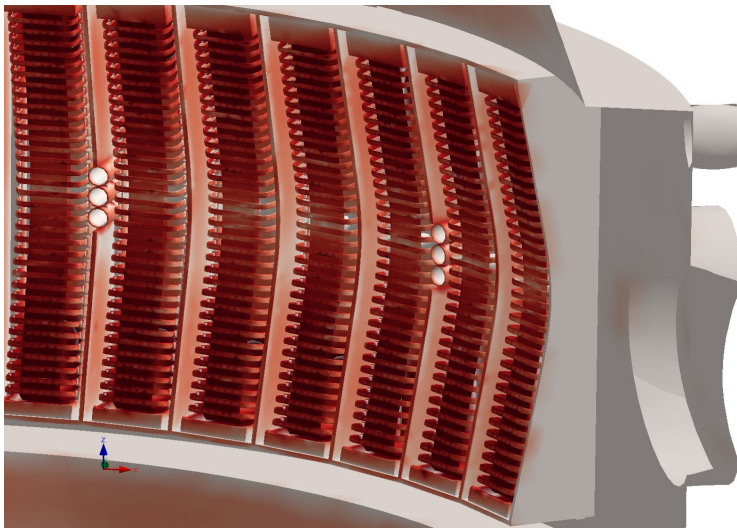
On top and bottom passive plates.

On CS wall.

Double null equilibrium and CS is not magnetically connected.

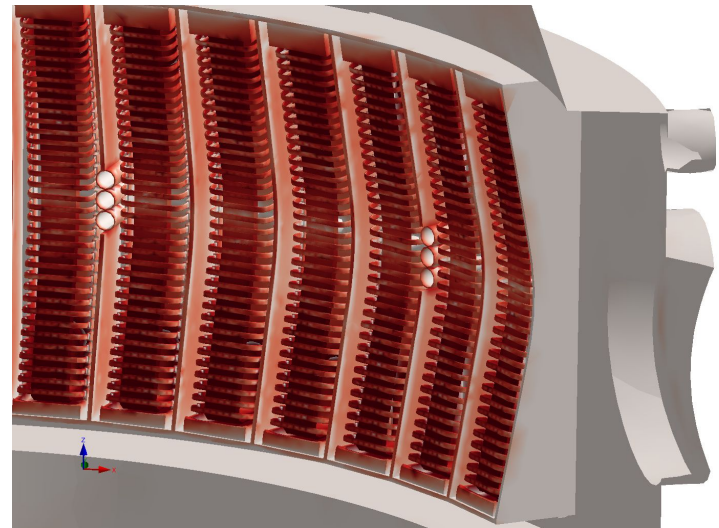
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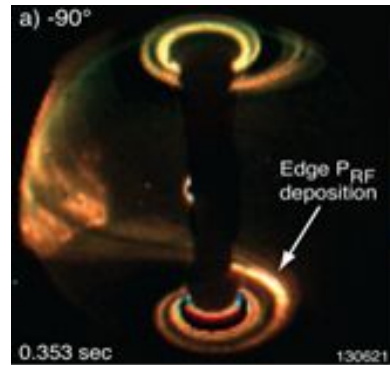
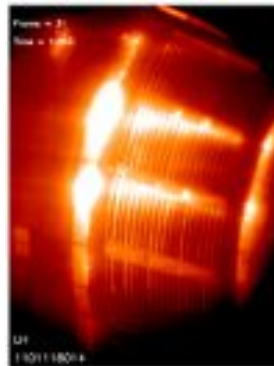
$|E|$ field strength is similar on antenna region.

- RF-PWI interaction far away from the antenna is important?
- Even if not magnetically connected?

Will be investigated in NSTX-U campaign (FY23)

Wave spectrum launched by 3D antenna and SOL

Striation
(C-Mod)



Spiral
(NSTX)

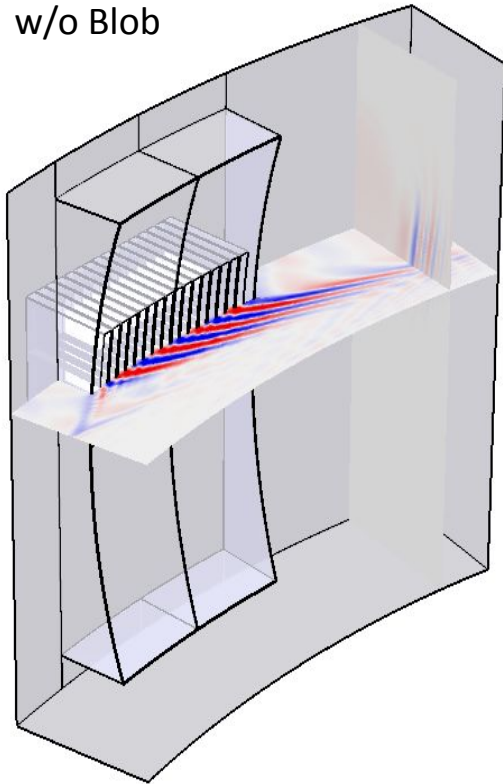
see also S. G. Baek (ID: 776), C. Lau (ID: 637)

Wave scattering due to density modulation could modify the LH wave field pattern significantly...

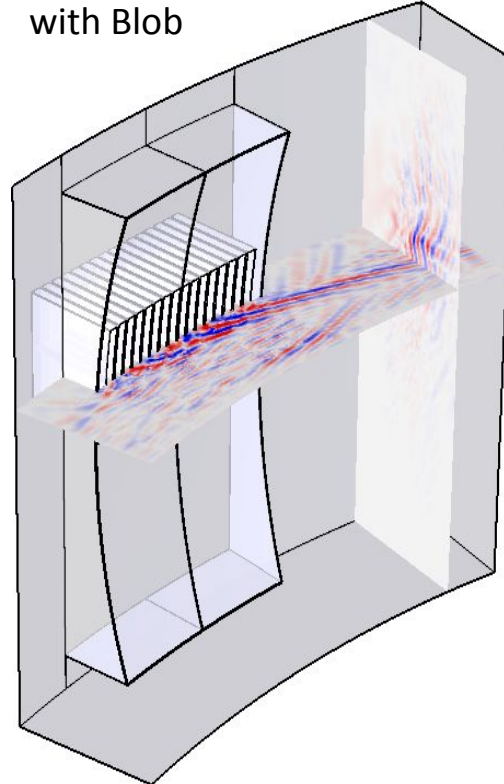


E_{\parallel} of LH waves

w/o Blob



with Blob



Lower hybrid (LH) waves on C-Mod with field-aligned density perturbation.

- $\langle \Delta n \rangle / n_e \sim 50\%$
- $d_{\text{blob}} \sim 1\text{cm}$

(w/o Blob)

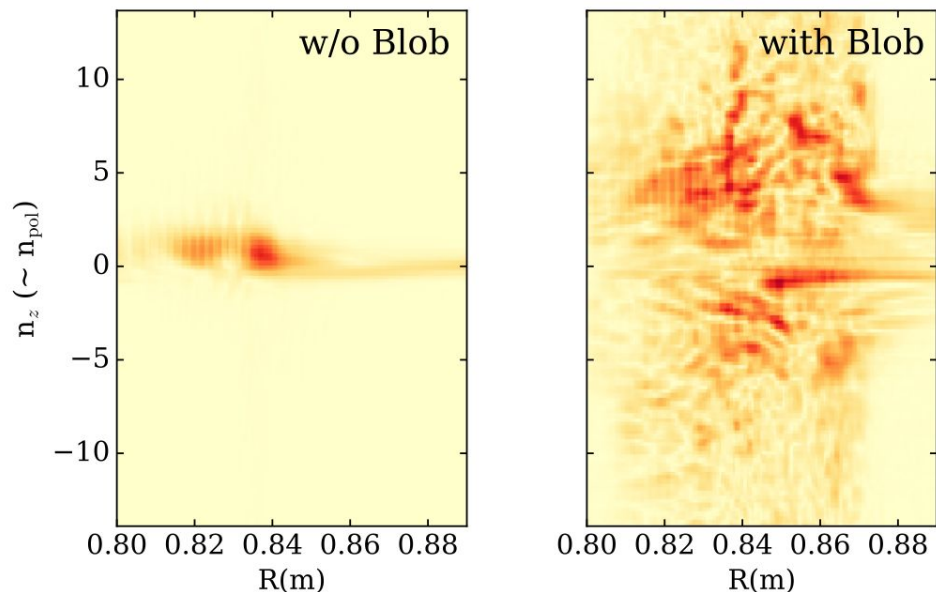
- Clean resonant cone propagation

(w/o Blob)

- Large distortion of wave field pattern



Comparison of Wavenumber spectrum



Lower hybrid (LH) waves on C-Mod with field-aligned density perturbation

(w/o Blob)

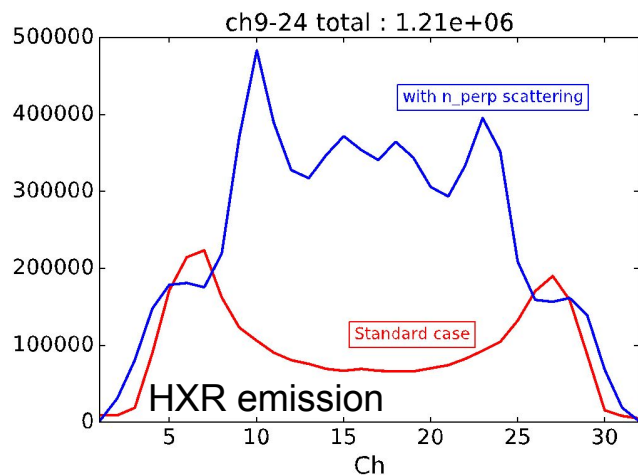
- Clean resonant cone propagation

(w/o Blob)

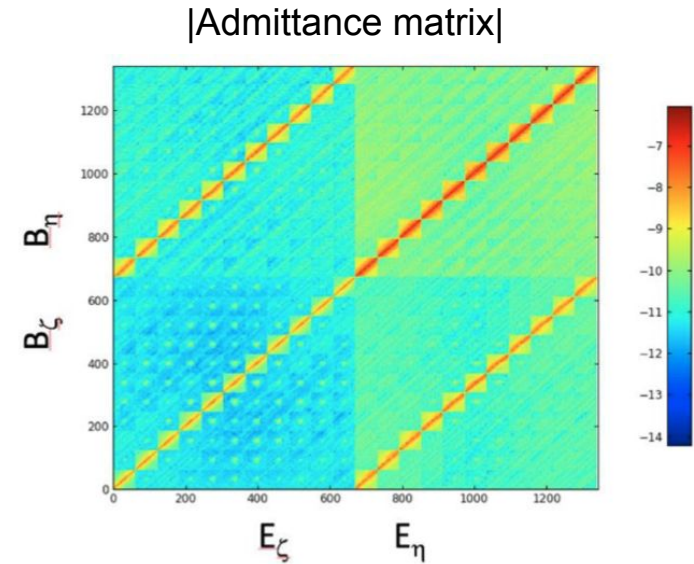
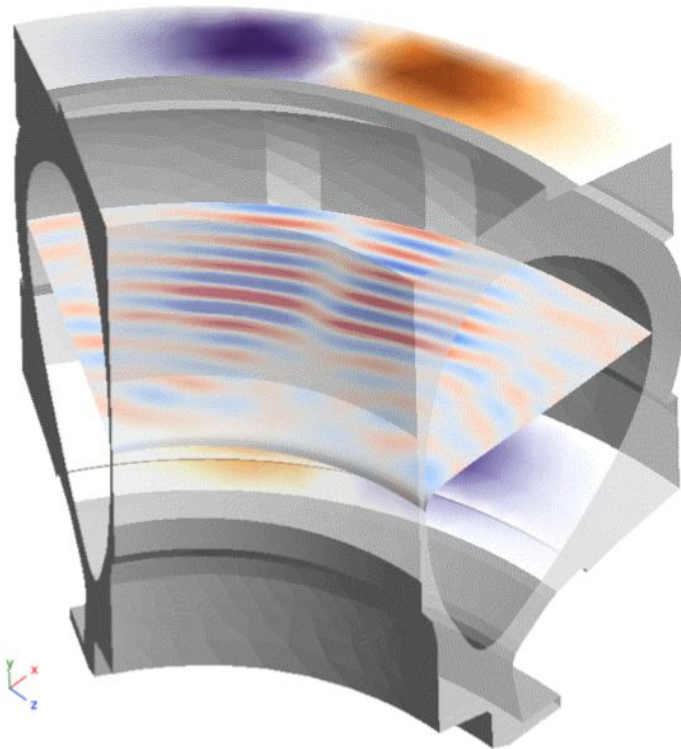
- Large distortion of wave field pattern

Wavenumber (k_{\perp}) spectrum is broaden significantly.

GENRAY/CQL3D predicts very different CD profiles.



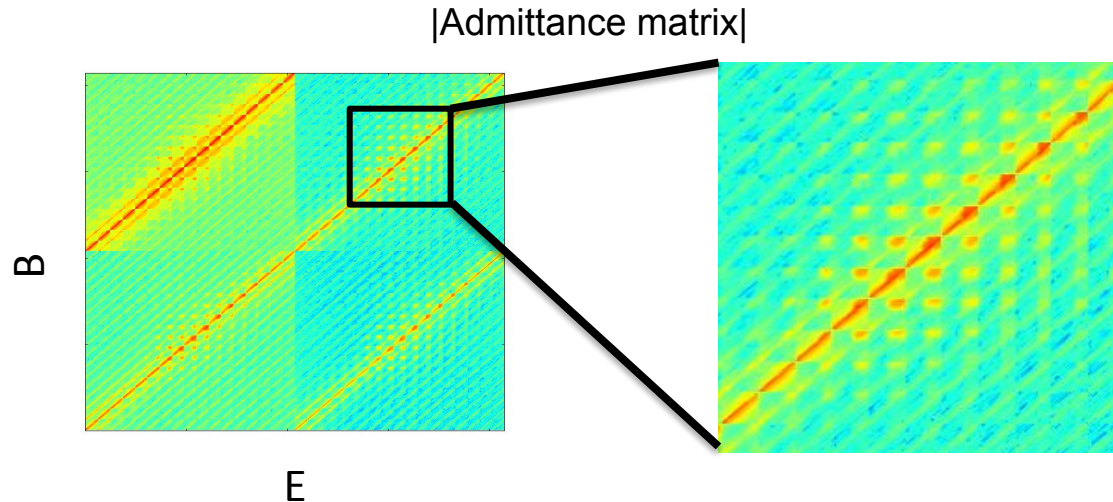
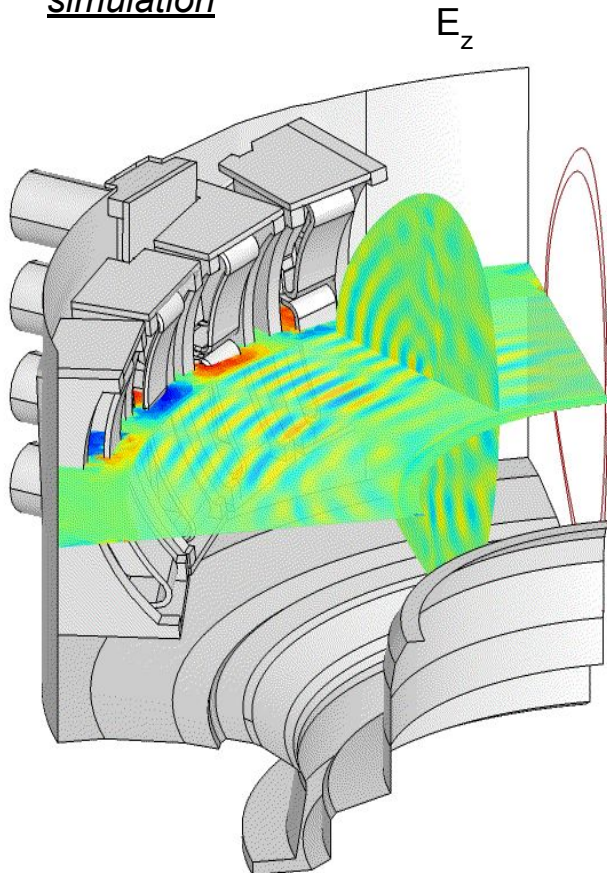
TORIC/Petra-M coupled simulation



Petra-M edge simulation is coupled with the TORIC solver using admittance matrix.

Symmetric wall (no 3D) leads to 2x2 block diagonal matrix.

TORIC/Petra-M coupled simulation



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Symmetric wall (no 3D) leads to 2x2 block diagonal matrix.

3D wall allows for different toroidal modes to communicate each other due to surface RF current on the antenna structure.

Ongoing collaborations and future works

Verification and validation (V&V) through worldwide collaboration



Device	Wave	Goal
DIII-D (GA)	LH/Helicon	Slow wave excitation. LH launcher coupling
WEST (CEA)	LH/ICRF	Wave field comparison, impurity generation
JET (EU)	ICRF	Verification on ITER-like antenna
NSTX-U (PPPL)	HHFW	Support HHFW experiments in NSTX-U
LAPD (UCLA)	ICRF/HHFW	Slow wave/Alfven wave comparison with experiment
C-2W (TAE)	HHFW	HHFW wave propagation in FRC
ASDEX (IPP)	ICRF	Comparison with RAPLICASOL and SSWICH
C-Mod (MIT)	ICRF/LH	Field aligned antenna modeling / coupling with TORIC
KSTAR (NFRI)	Helicon	Slow wave excitation (linked to DIII-D effort)

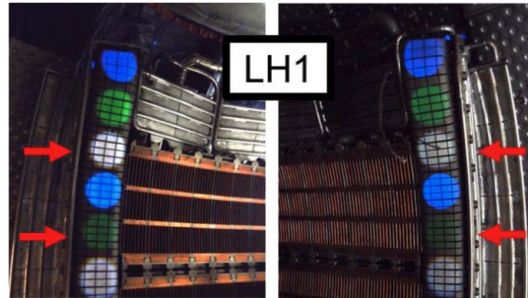
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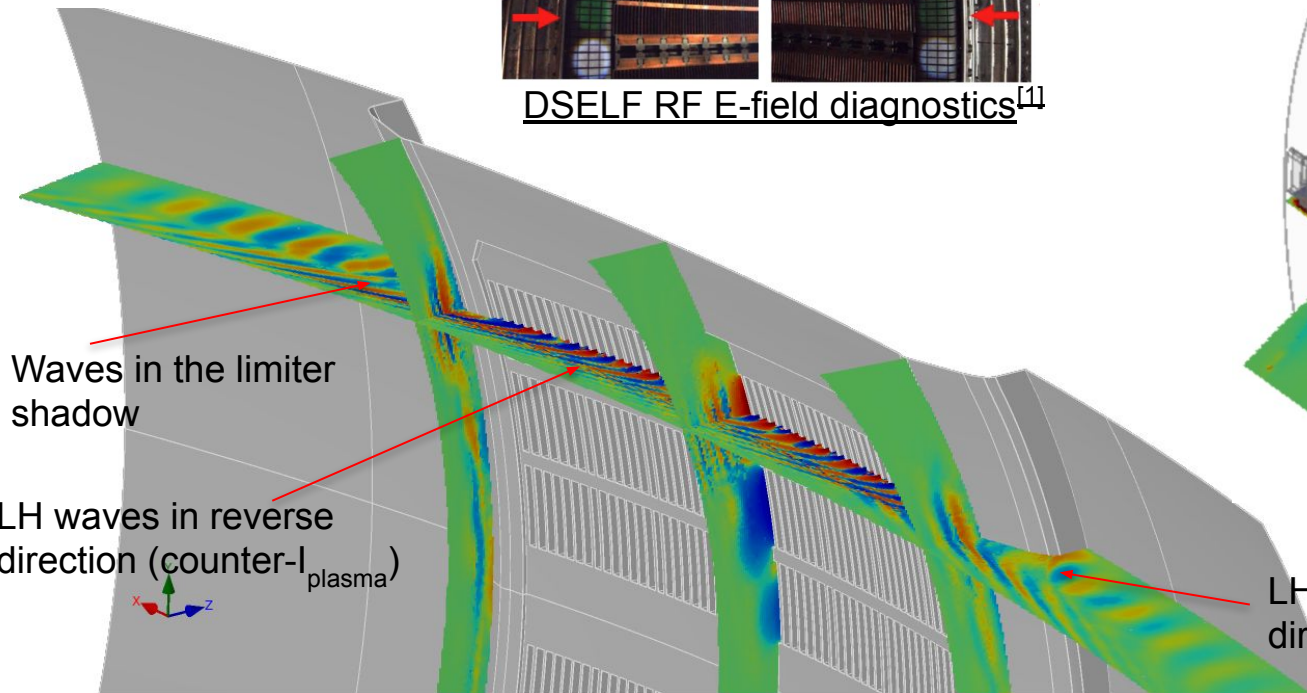
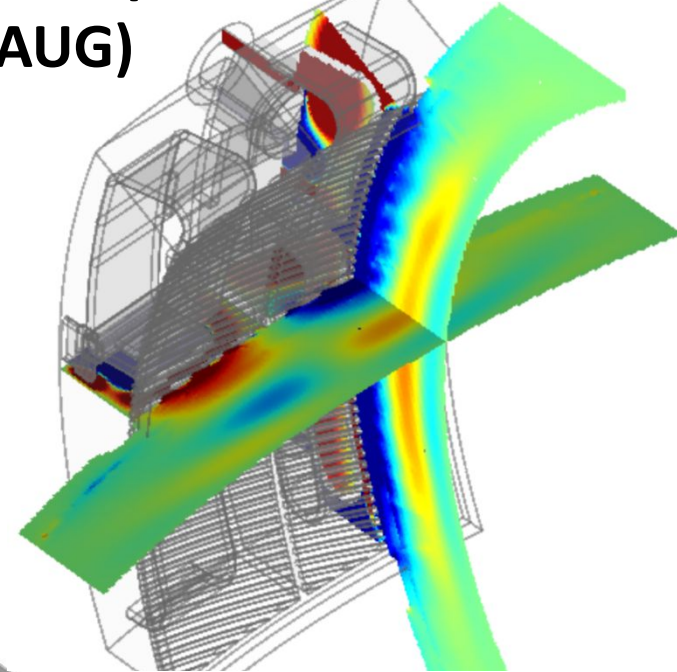


LH1 launcher (WEST)



DSELF RF E-field diagnostics^[1]

2-strap antenna (AUG)



[1] E. Martin, et. al., "Investigation of Lower Hybrid Wave Interaction with the Edge Plasma in WEST through Electric Field Vector Measurements", 2019 APS

Summary

Progress towards integrated whole device scale RF actuator modeling

- Includes whole torus with detailed 3D antenna/SOL
- Scales to resolve ICRF propagation on ITER.
- Integrates advanced RF-PWI physics models (RF sheath/impurity generation/ hot core/wave scattering)

Petra-M integrated FEM platform

- Use MFEM scalable FEM library.
- Built on close collaboration with ASCR US applied math team.
- Collaboration with WW fusion experiments for verification/validation/extension in progress.

New 3D full-wave simulation capability can directly address wave physics issues which were out-of-reach previously

- **First ever full torus NSTX-U HHFW propagation simulations**

$\lambda/L \sim 15$ is close to what is required for resolving ICRF on ITER.

Show clear difference in E field pattern on far-antenna PFC between different antenna phasing

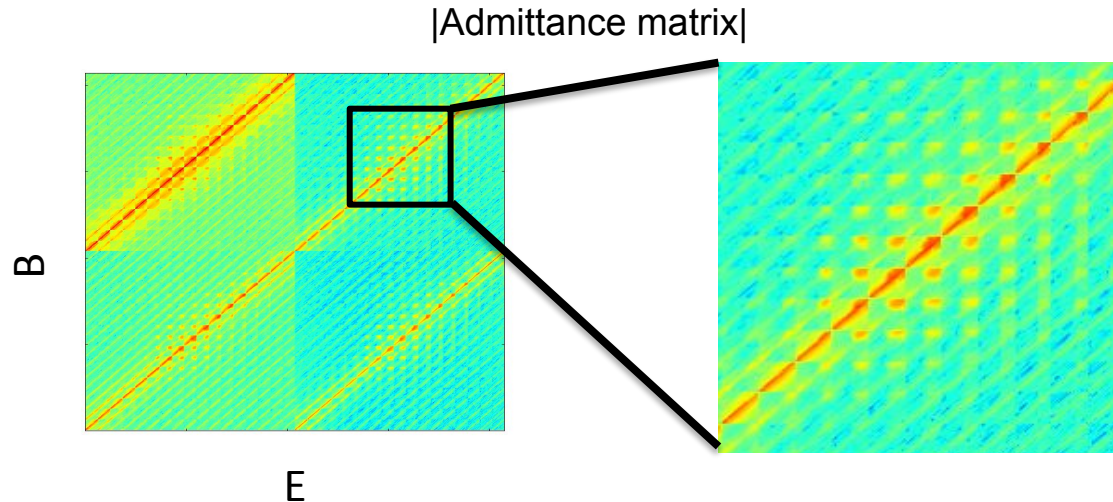
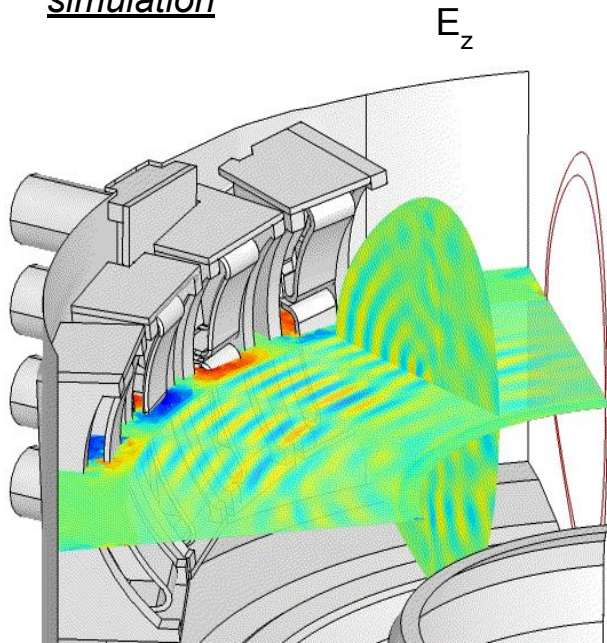
Will be investigated experimentally in FY23 campaign

- **Antenna spectrum modification due to**

Field-aligned density fluctuation.

3D antenna structure and induced RF surface currents.

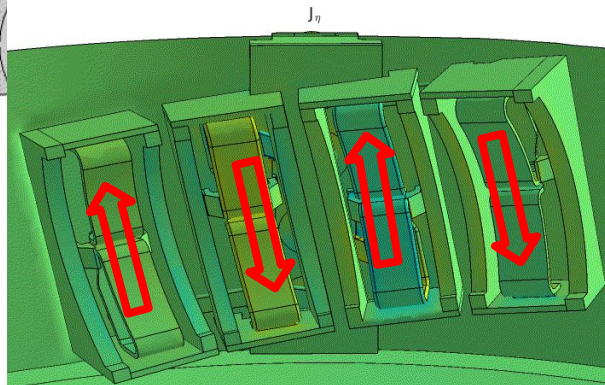
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Antenna currents couple m/n modes