PRINCETON PLASMA PHYSICS LABORATORY

TOWARDS INTEGRATED RF ACTUATOR MODELING:

WHOLE DEVICE SCALE RF FULLWAVE SIMULATION INCLUDING HOT CORE AND 3D SOL/ANTENNA REGIONS `

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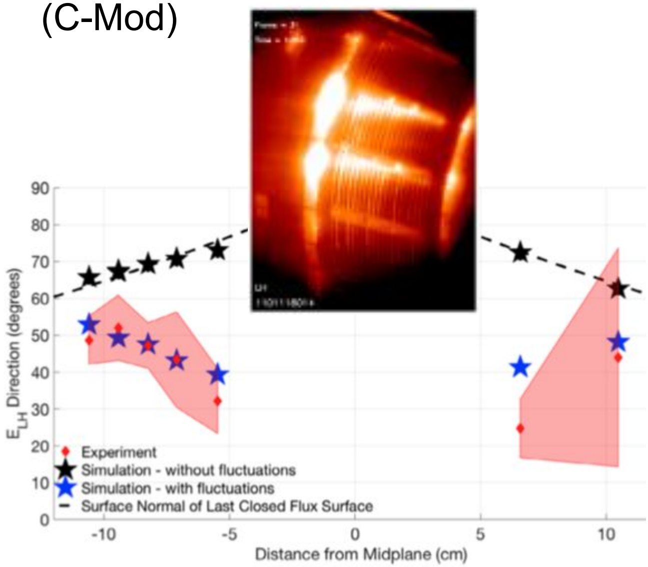
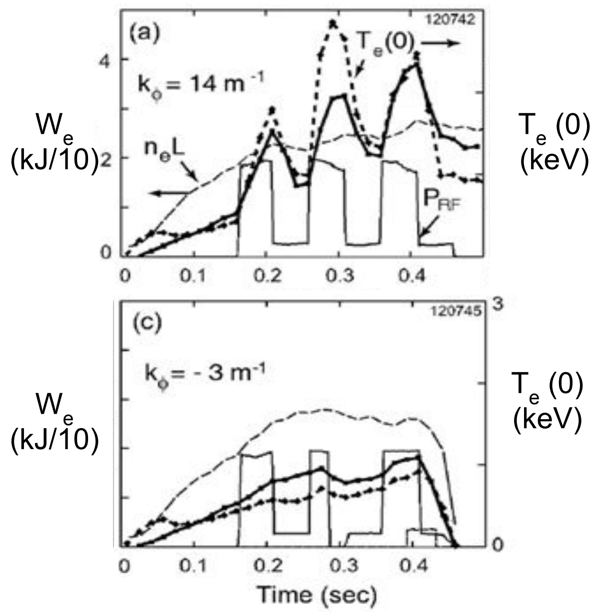
R. Ragona (LPP), and RF SciDAC

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

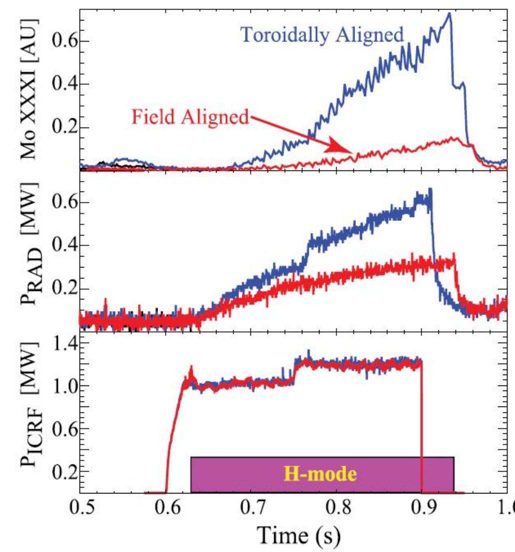
LHCD (C-Mod)



HHFW heating (NSTX)



ICRF heating (C-Mod)



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)

[1] E. Matin et. al., NF (2019), [2] J. C. Hosea, et al., PoP 15 (2008) 056104, R. J. Perkins, et al., PRL (2012), [3] S. Wukitch, PoP (2013)

RF actuator simulation needs to take an integrated approach

Must integrate multiscale-multiphysics processes such as

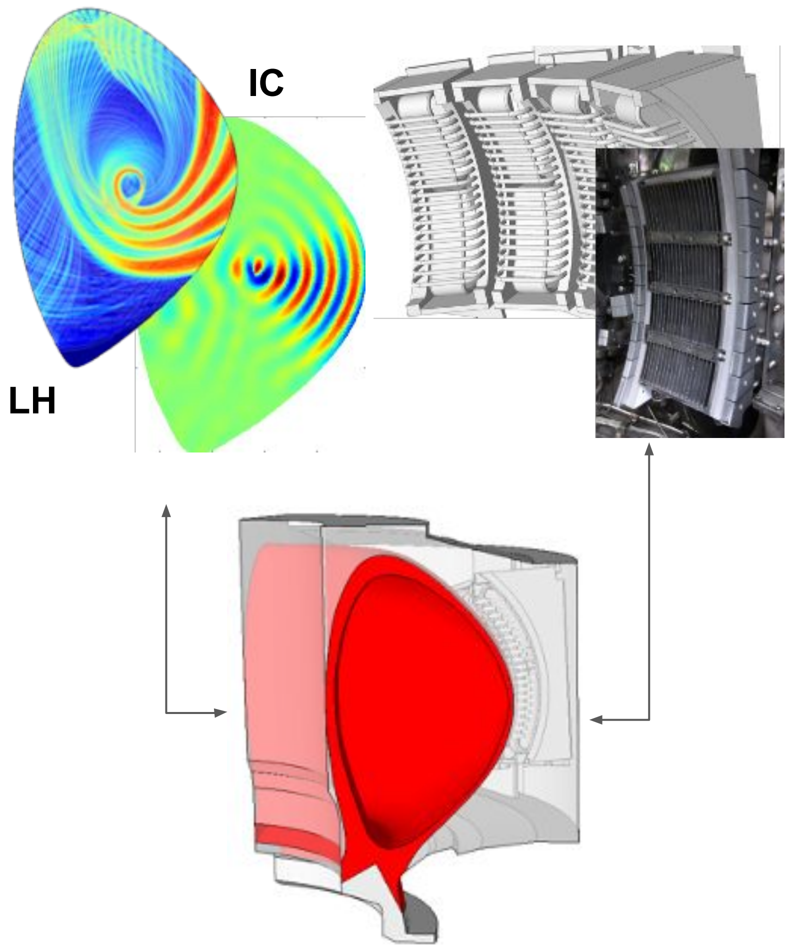
- Slow wave and PSI due to RF sheath.
- Wave scattering by the background plasmas.
- RF could modify the background plasma through transport and turbulence.
- non-local hot plasma response to RF electric field.

Must be 3D and “whole device” to include

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

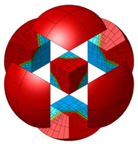
Need to develop a platform which facilitates

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

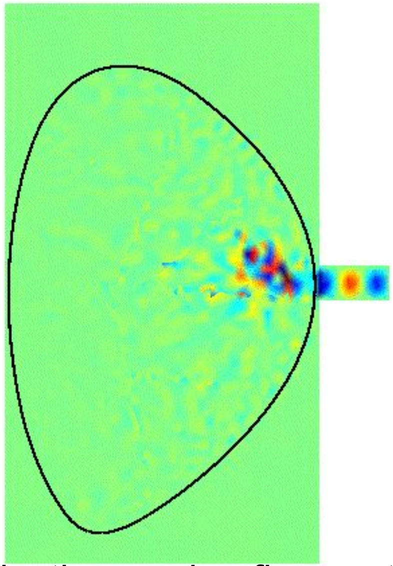


Platform for advanced 3D RF wave simulation

MFEM : modular finite element library

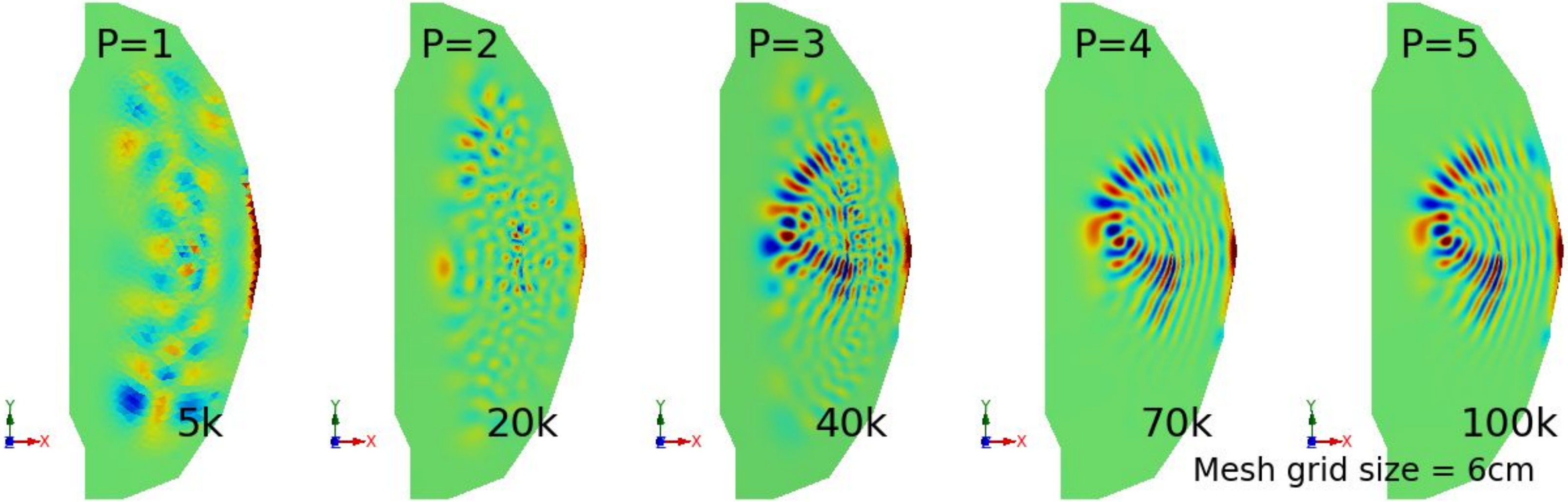


- Developed by MFEM team lead by LLNL.
- Arbitrary high polynomial order (P) for basis function and mesh elements.
- Various finite element basis functions.
- Scalable (MPI and GPUs).
- http://mfem.org/



Adaptive mesh refinement for LH waves [1]

P-scan for HHFW



[1] M. Hakim et. al, to be submitted

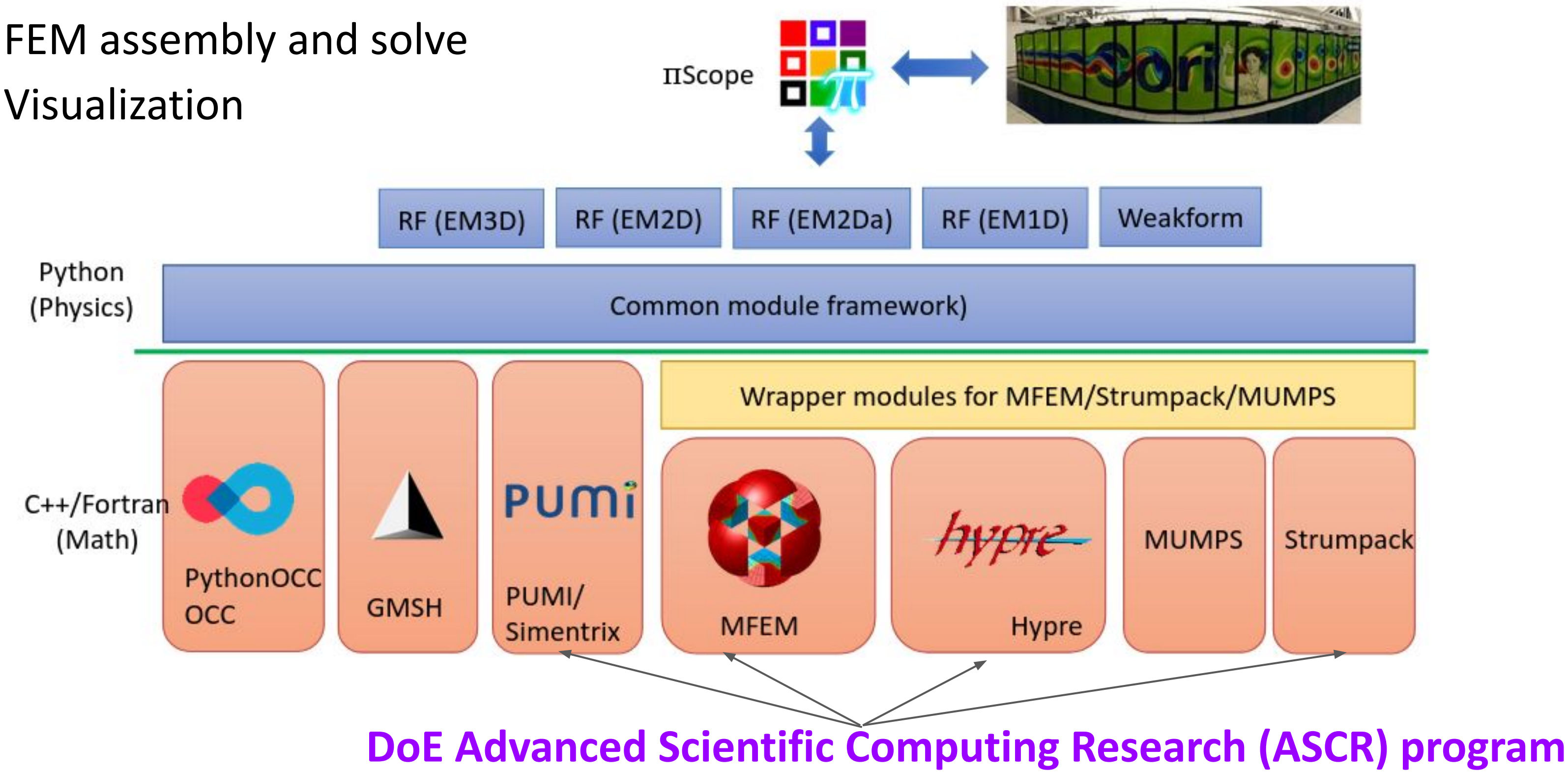
Petra-M : integrated multi-physics FEM platform

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

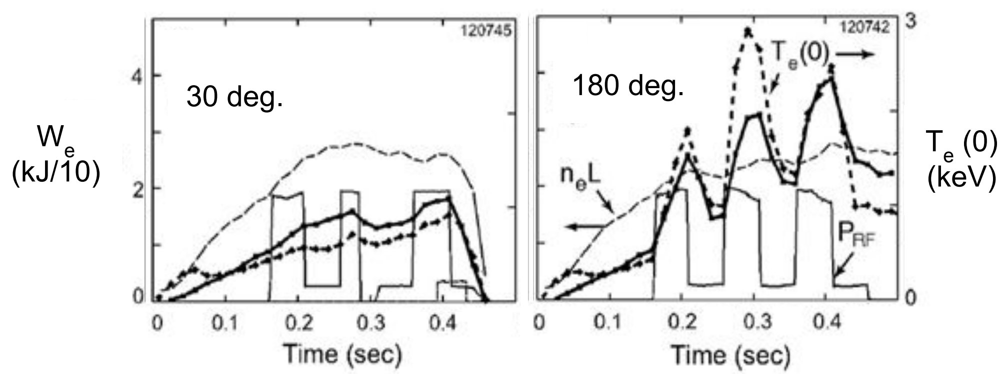
- Geometry creation
- Mesh generation
- FEM assembly and solve
- Visualization

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

https://github.com/piScope/PetraM_Base

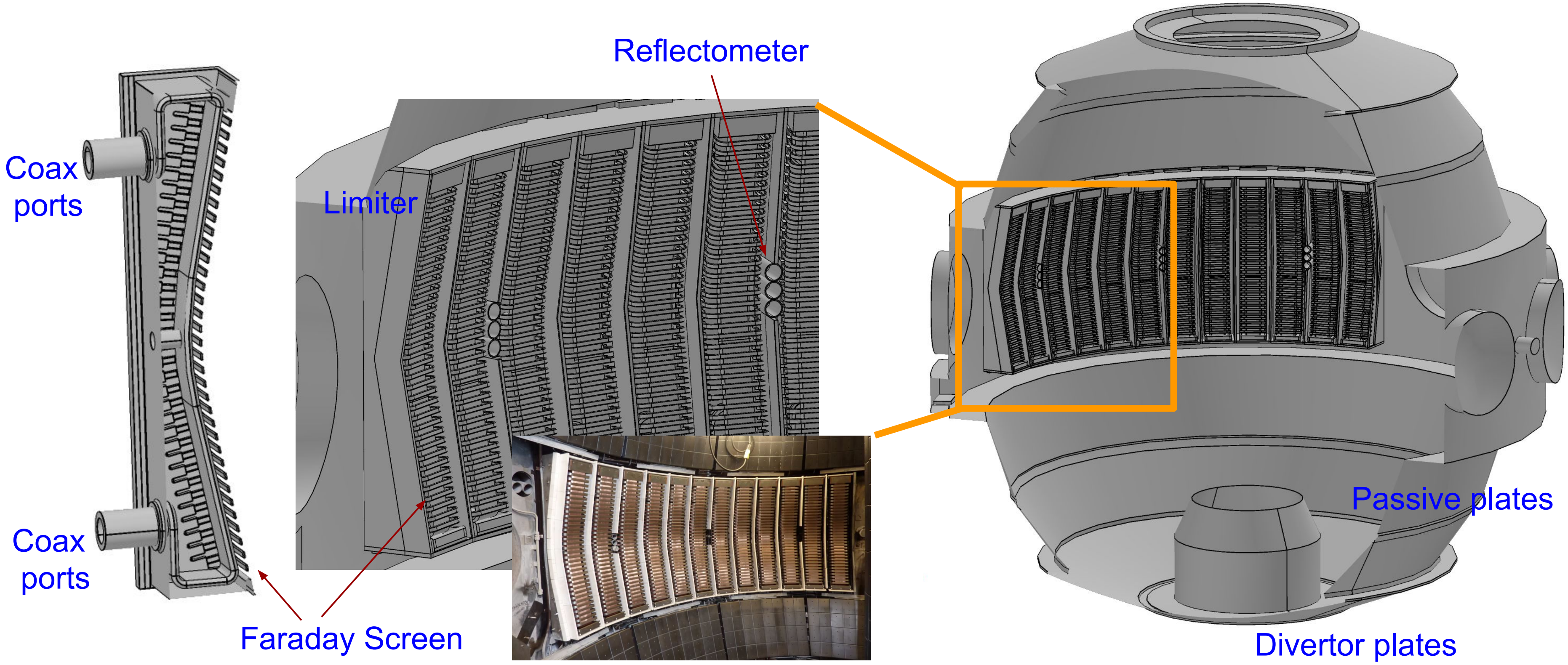


RF Wave field on plasma facing components



[1] J. C. Hosea, et al., PoP 15 (2008)

Simulation geometry was generated from original engineering CAD data

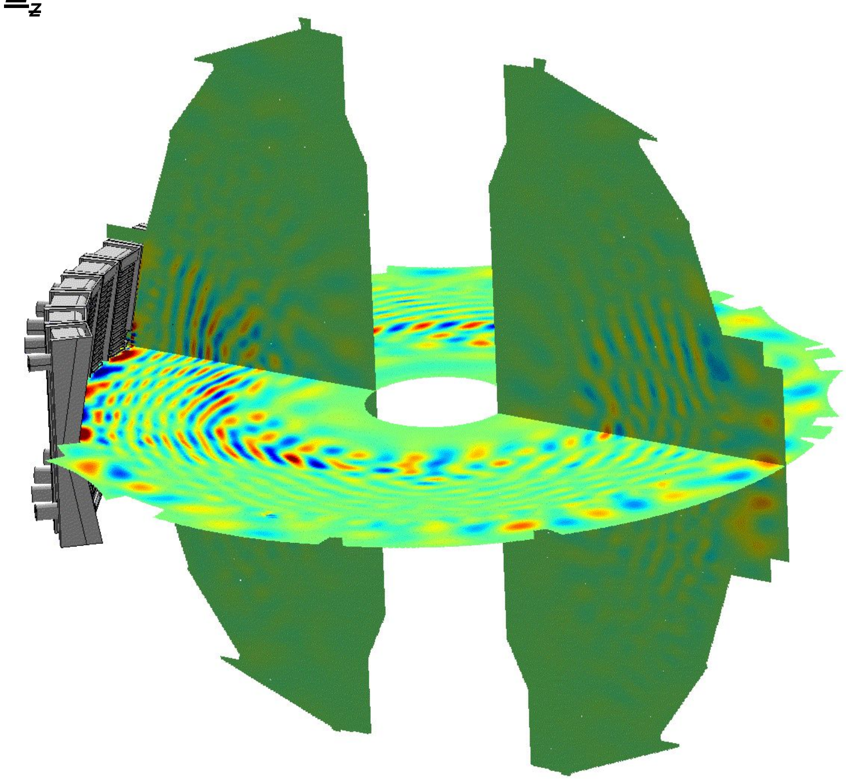


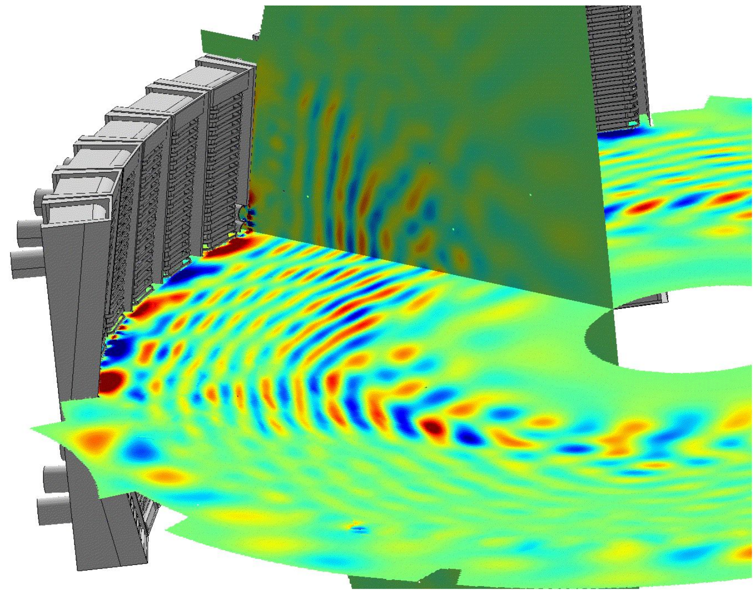
Model geometry includes everything we need for RF propagation from coax to plasma.

First fully resolved 3D HHFW field on NSTX-U

Bt = 1T, n_{e0} = 5x10^{19}m^{-3}
150 º phasing
Cold plasma dielectric

E_z



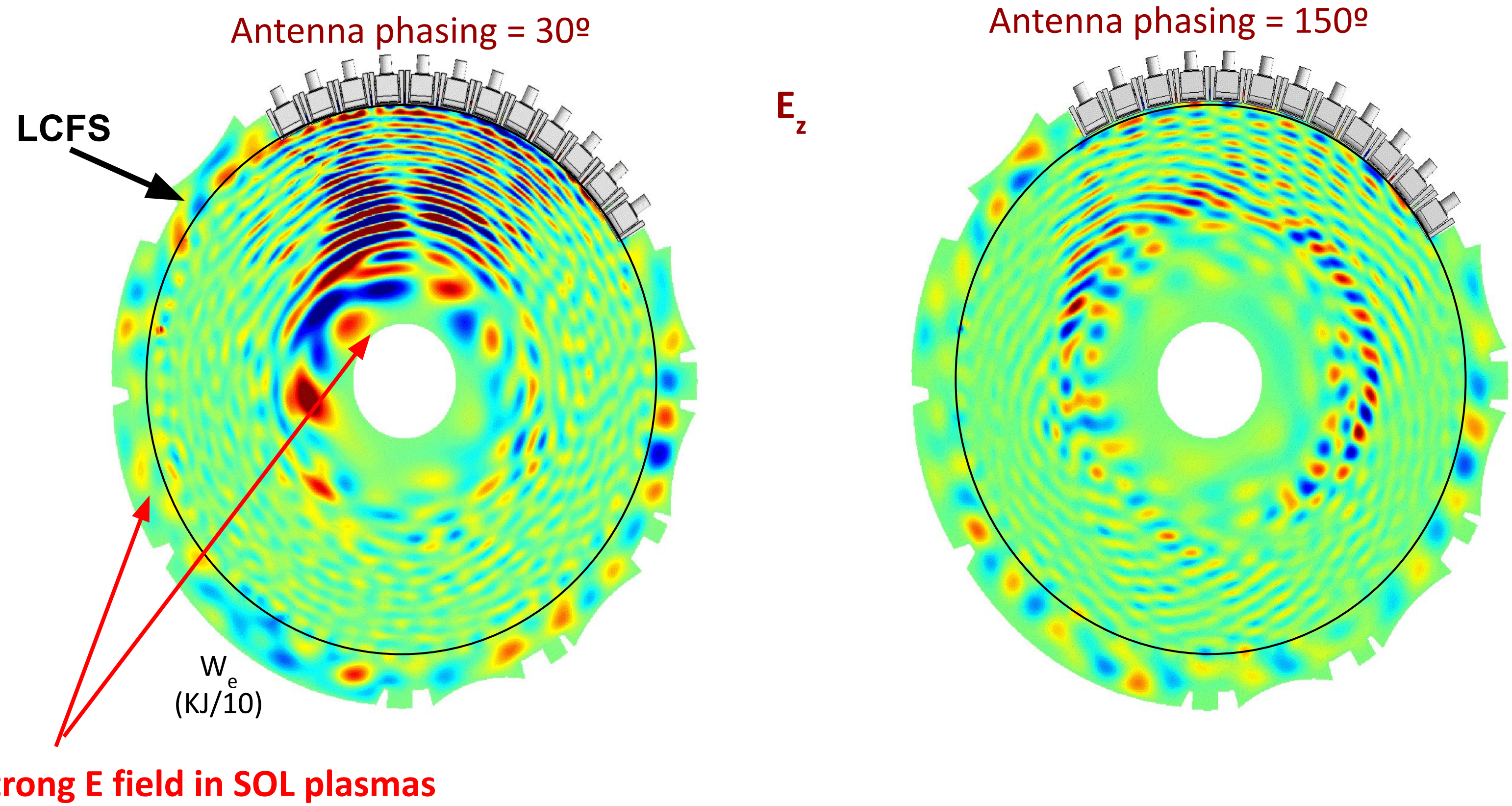


- Obtained using 4th order basis functions.
- 50M DoFs at 4th order basis, corresponding ~ 400M DoFs with usual 2nd order.
- λ/L ~ 15 is close to what is required for resolving ICRF wave field on ITER.

see also N. Bertelli (ID: 943)

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

Comparison of Ez with different antenna phasing



- 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).

see also N. Bertelli (ID: 943)

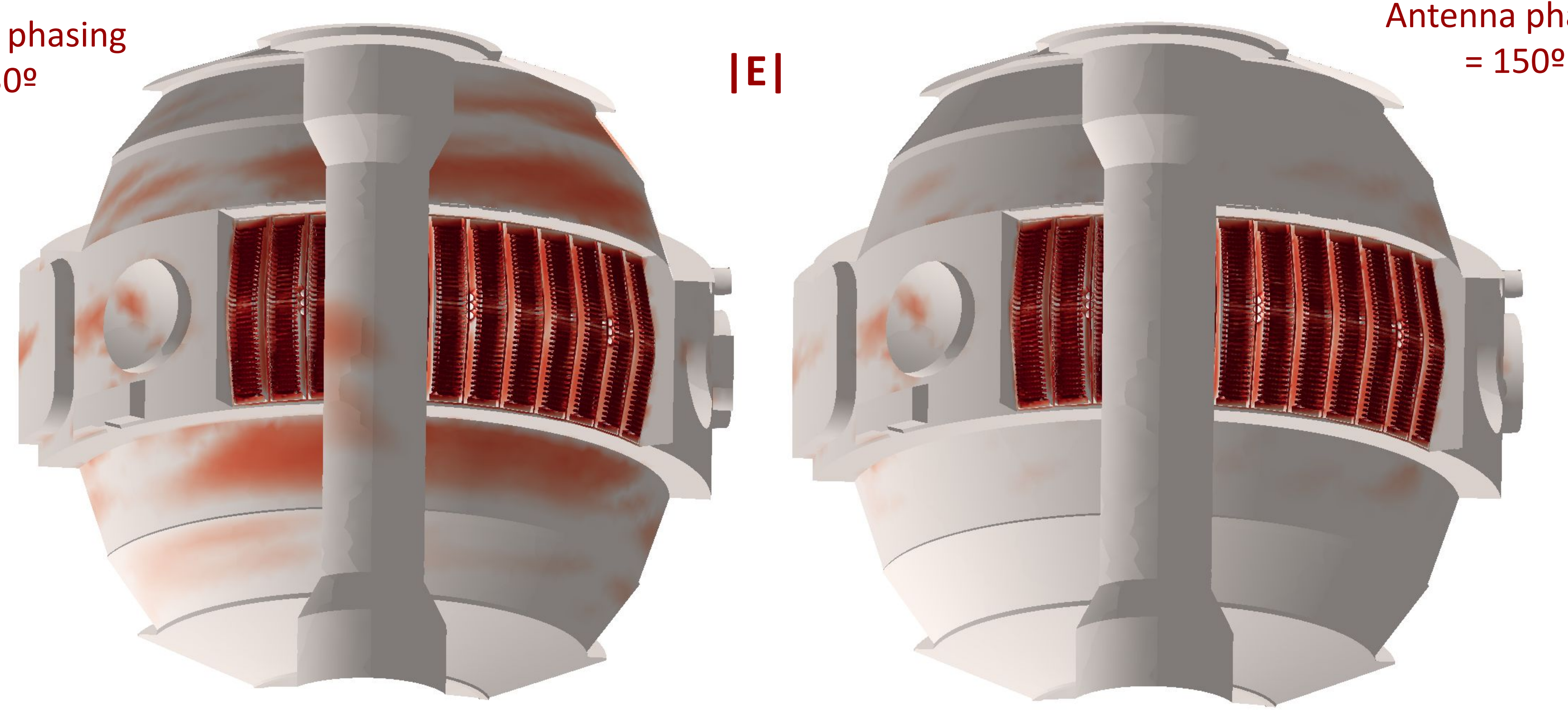
Antenna phasing (k_φ) impacts E field on passive plates...

Comparison of |E| with different antenna phasing

Antenna phasing = 30º

|E|

Antenna phasing = 150º

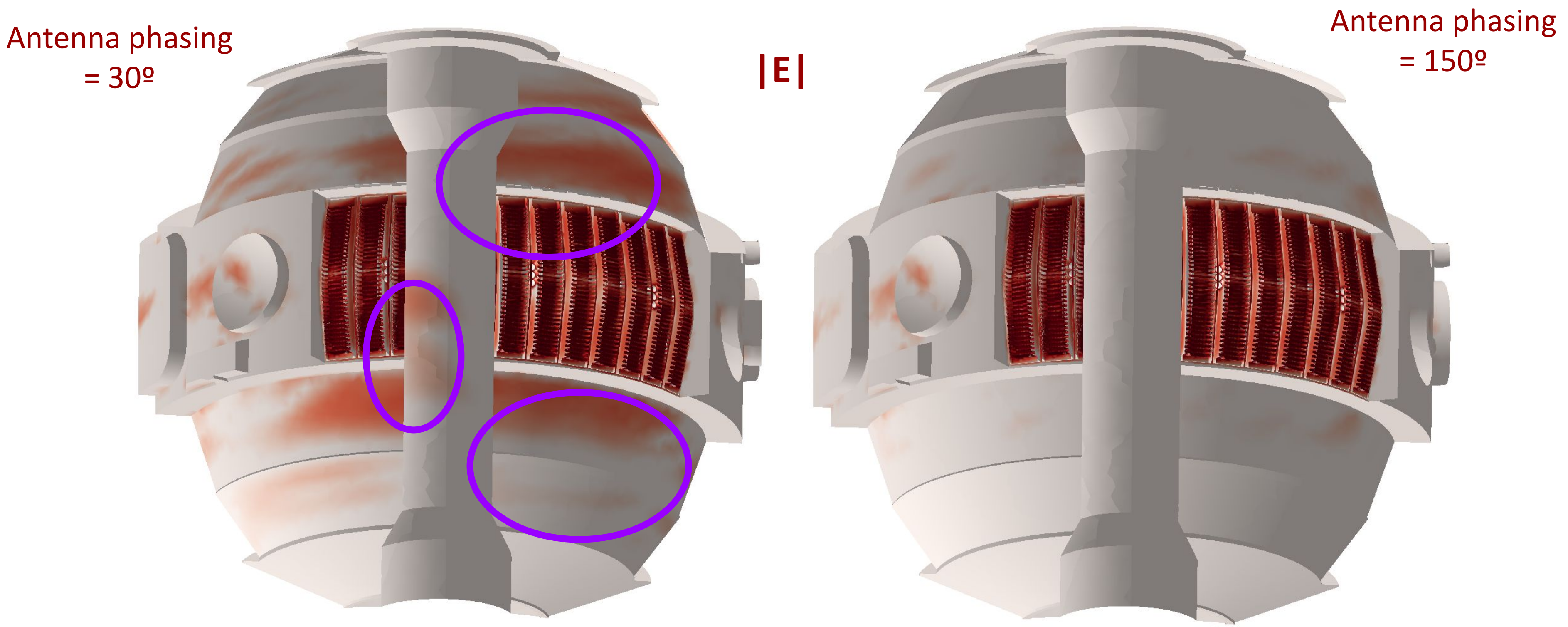


|E| field is stronger in the lower antenna phasing (k_φ) case

- On top and bottom passive plates
- On CS wall

Antenna phasing (k_φ) impacts E field on passive plates...

Comparison of |E| with different antenna phasing



|E| field is stronger in the lower antenna phasing (k_φ) case.

On top and bottom passive plates.

On CS wall.

Double null equilibrium and CS is not magnetically connected.

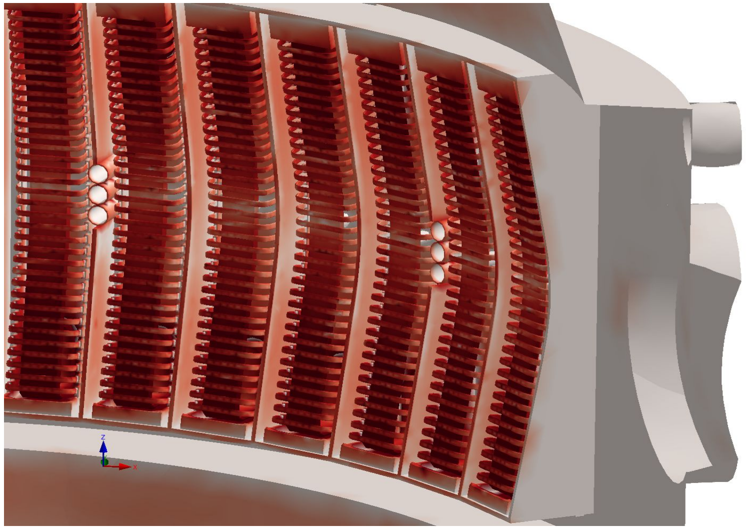
… but not so much on the antenna

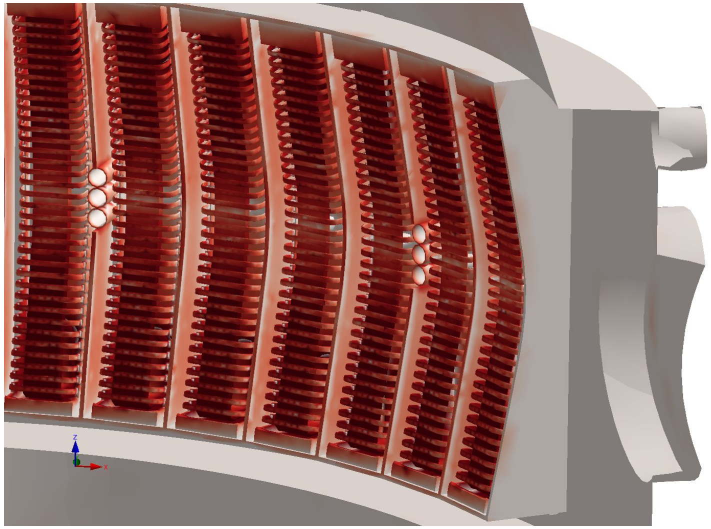
Comparison of |E| with different antenna phasing

Antenna phasing
= 30º

|E|

Antenna phasing
= 150º





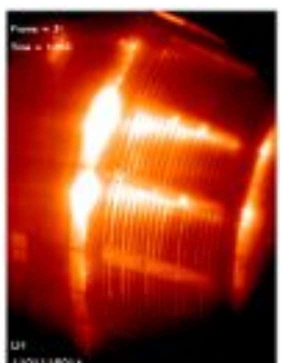
|E| field strength is similar on antenna region.

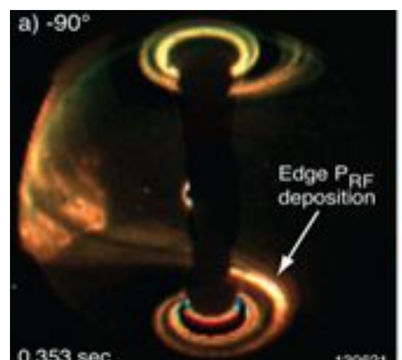
- RF-PWI interaction far away from the antenna is important?
- Even if not magnetically connected?

Will be investigated in NSTX-U campaign (FY23)

Wave spectrum launched by 3D antenna and SOL

Striation (C-Mod)

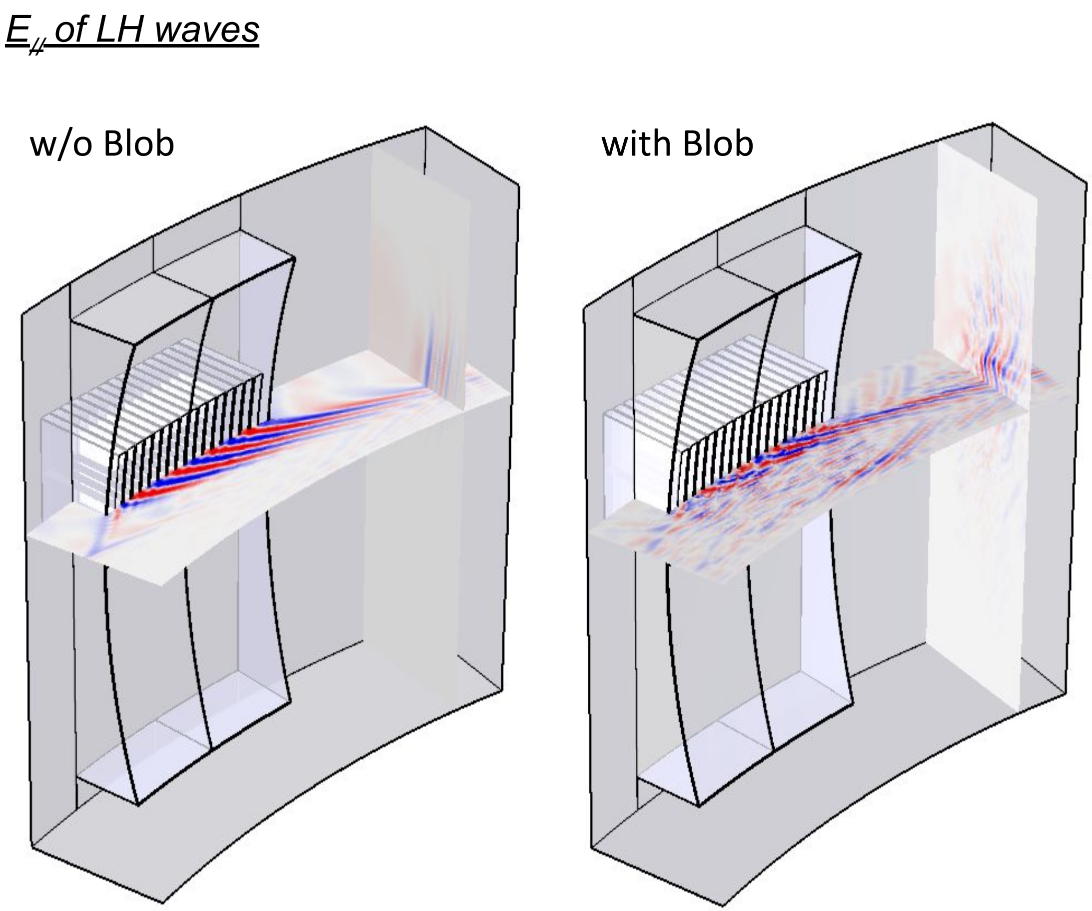




Spiral (NSTX)

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...



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

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

(w/o Blob)

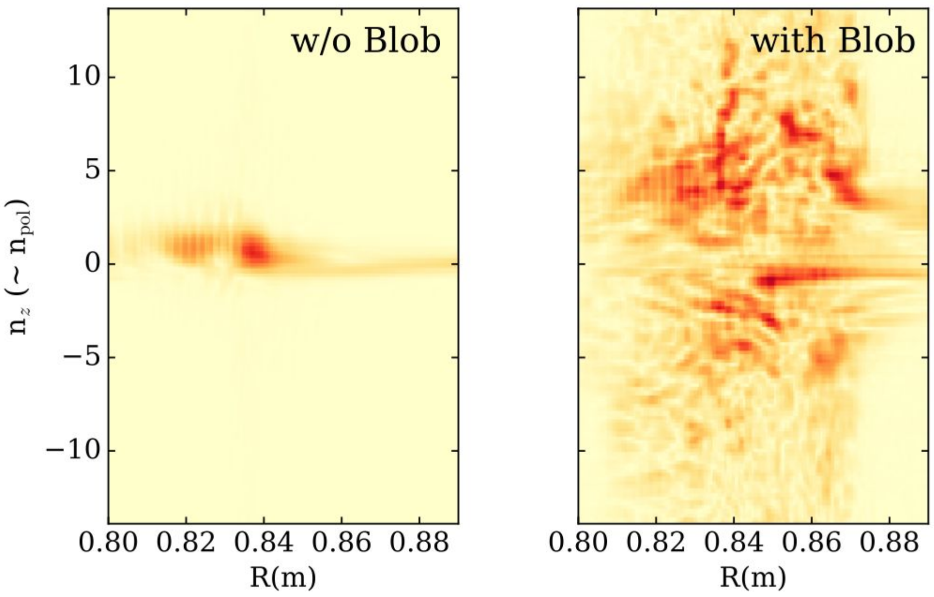
- Clean resonant cone propagation

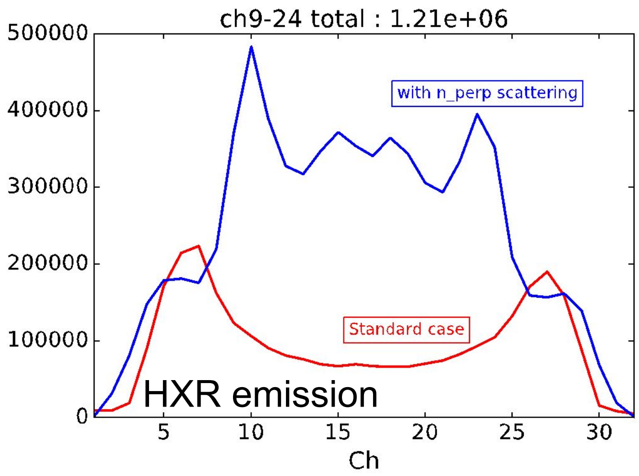
(with Blob)

- Large distortion of wave field pattern

...and impacts on LHCD profile

Comparison of Wavenumber spectrum





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

(w/o Blob)

- Clean resonant cone propagation

(with Blob)

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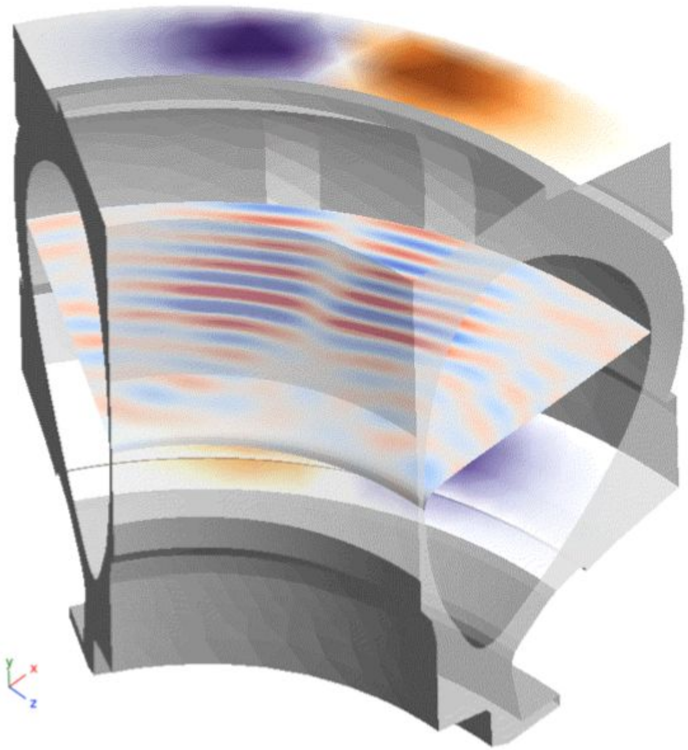
Wavenumber ($k_\perp$) spectrum is broaden significantly.

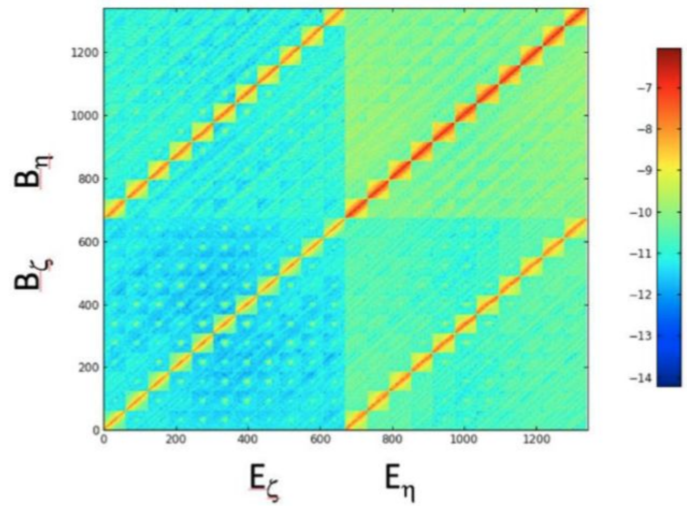
GENRAY/CQL3D predicts very different CD profiles.

3D antenna also modifies antenna spectrum

TORIC/Petra-M coupled simulation



|Admittance matrix|



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

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

J. Wright and S. Shiraiwa, EPJ Web of Conferences **157**, 02011 (2017)

3D antenna also modifies antenna spectrum

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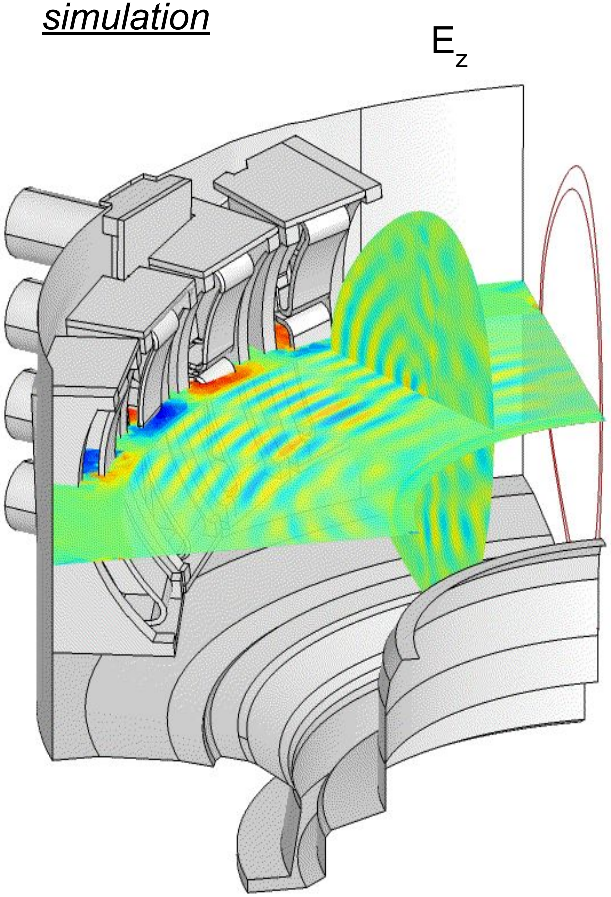

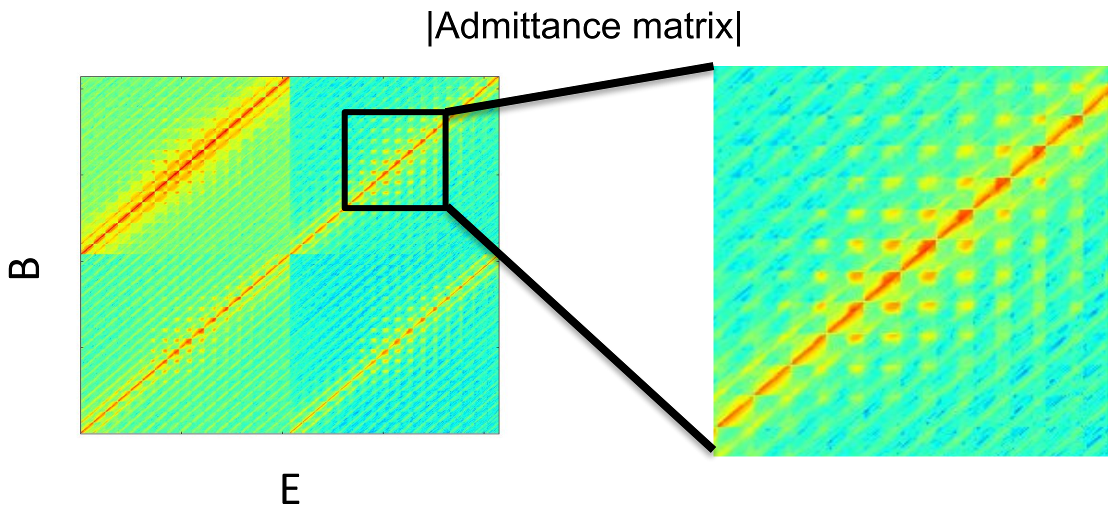

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S. Shiraiwa, APS 2017, J. Wright, EPS 2018

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)

Verification and validation (V&V) through worldwide collaboration

Device	Wave	Goal
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WEST (CEA)	LH/ICRF	Wave field comparison, impurity generation
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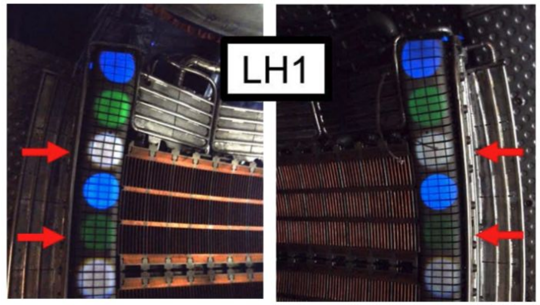
KSTAR (NFRI)	Helicon	Slow wave excitation (linked to DIII-D effort)

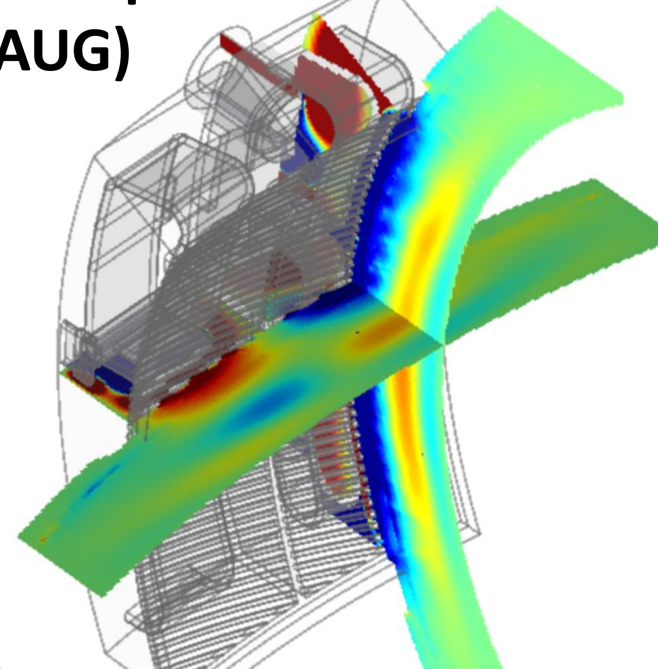
Extensive verification & validation is in-progress

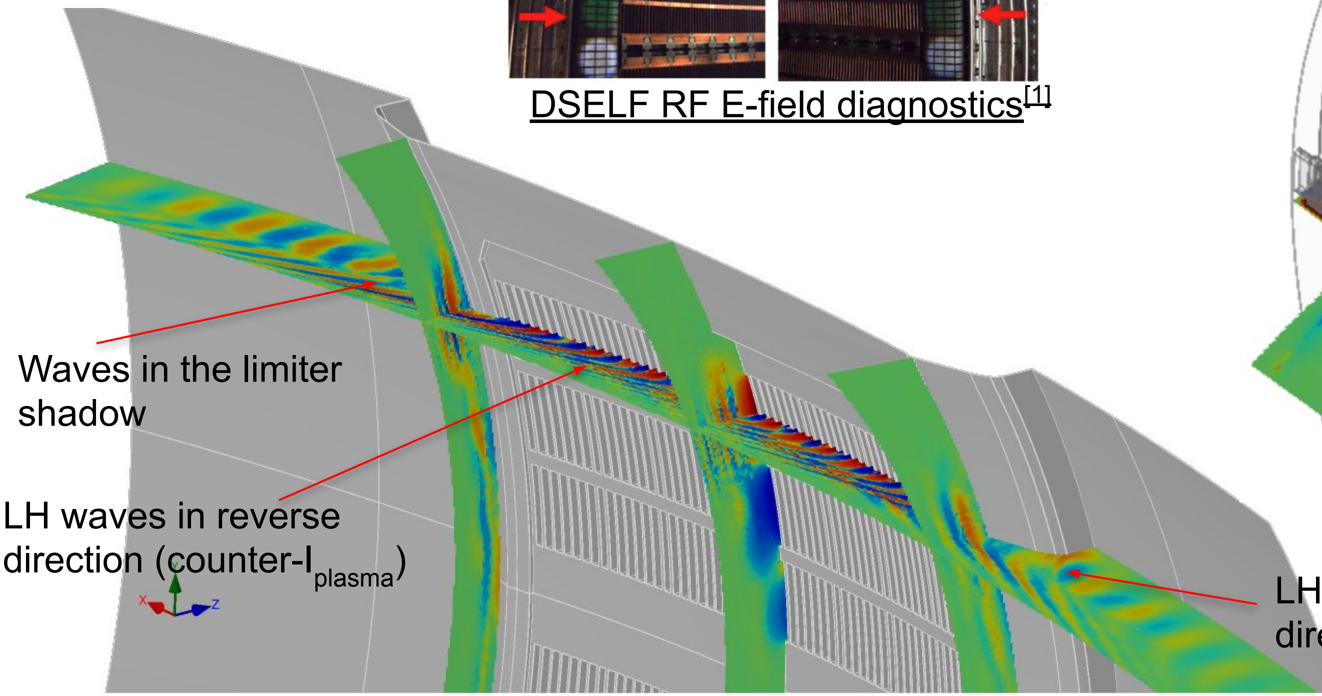
LH1 launcher (WEST)



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

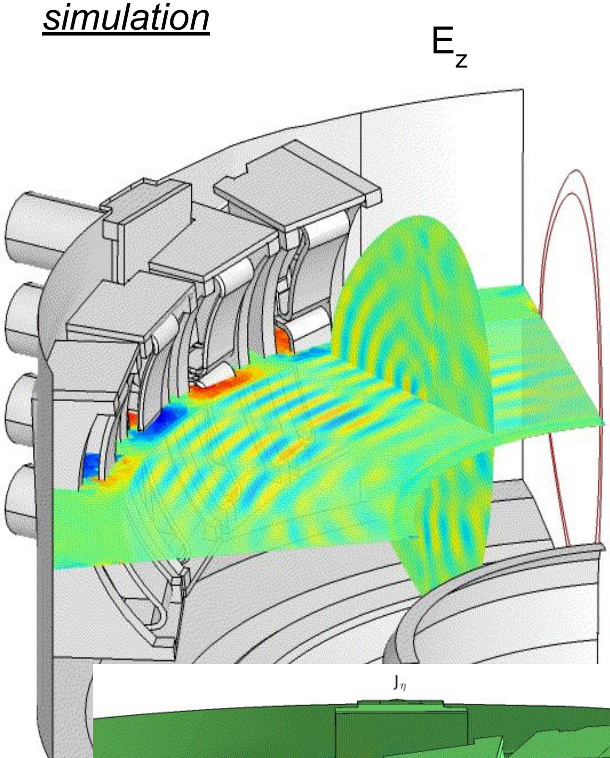
- Use MFEM scalable FEM library.
- Built on close collaboration with ASCR US applied math team.
- Collaboration with WW fusion experiments for verification/validation/extension in progress.

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

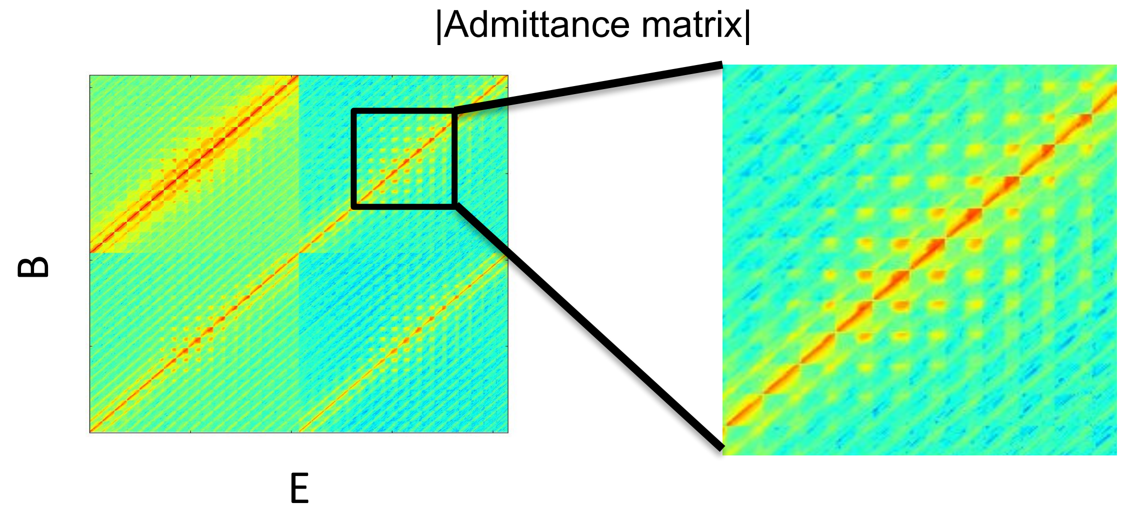
- First ever full torus NSTX-U HHFW propagation simulations
  λ/L ~ 15 is close to what is required for resolving ICRF on ITER.
  Show clear difference in E field pattern on far-antenna PFC between different antenna phasing
  Will be investigated experimentally in FY23 campaign
- Antenna spectrum modification due to
  Field-aligned density fluctuation.
  3D antenna structure and induced RF surface currents.

3D antenna also modifies antenna spectrum

TORIC/Petra-M coupled simulation



Antenna currents couple m/n modes



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