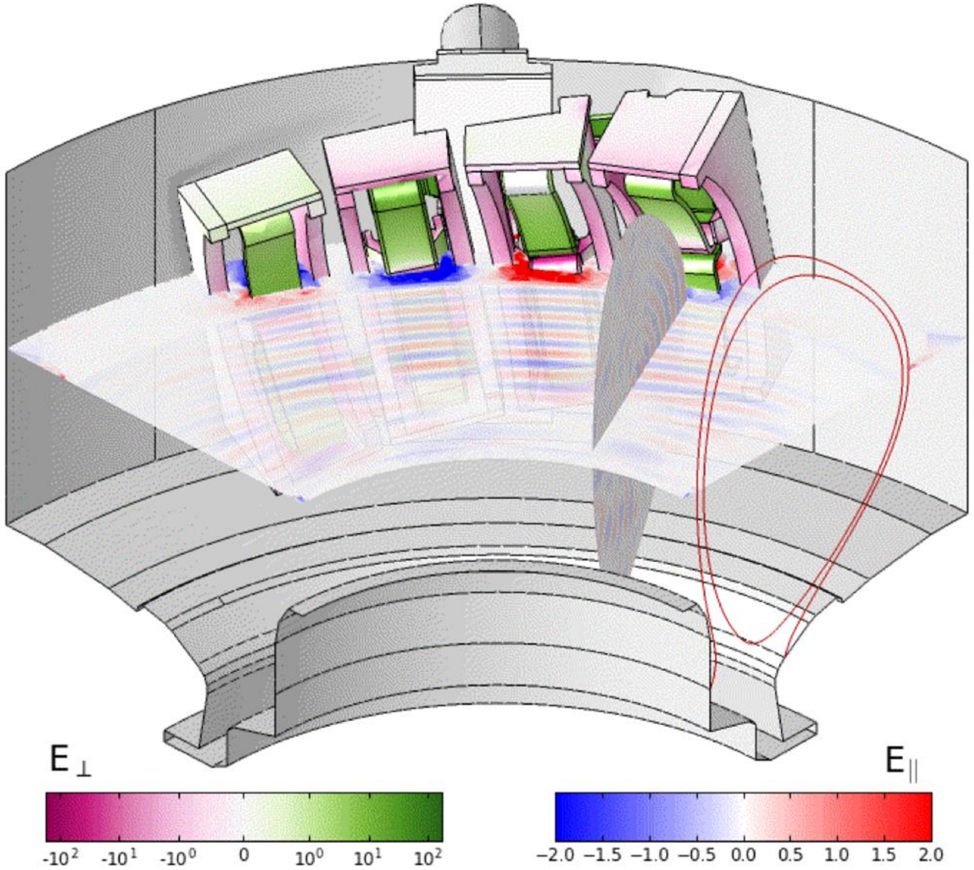
From hot core to antenna: towards whole device RF actuator modelling

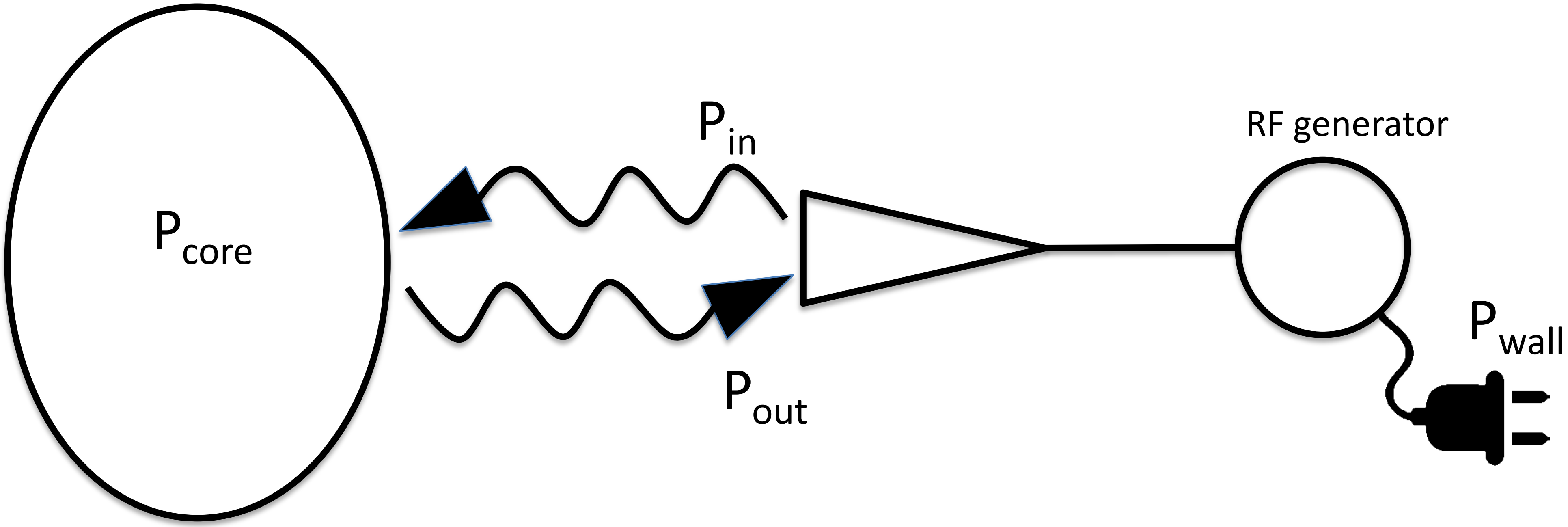
Syun'ichi Shiraiwa

Ackowlegement: **J. C. Wright, N.Bertelli[1]**, P. T. Bonoli, J. Myra[2], T. Kolev[3], M. Stowell[3], Y. Lin, C. Lau[4], O. Meneghini, G. Wallace, S. Wukitch, L. Zhou, W. Beck, the Alcator C-Mod team and the RF-SciDAC team

PSFC-MIT, PPPL[1], Lodestar[2], LLNL[3], and ORNL[4]



RF actuator in the ideal world

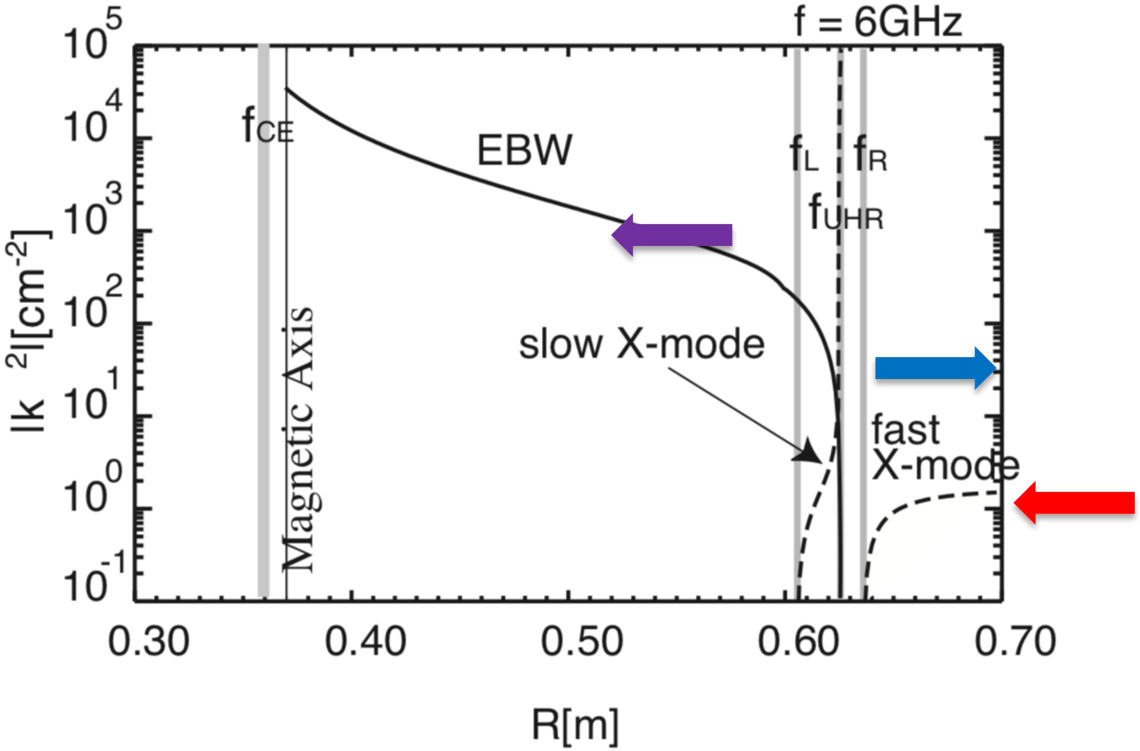


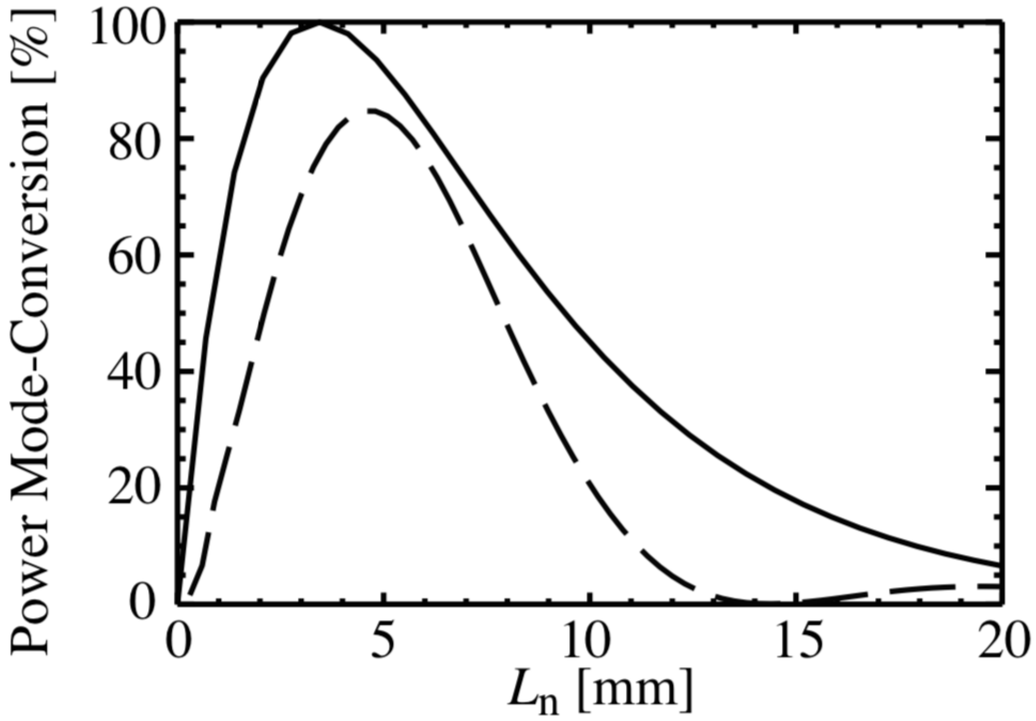
Power injected to the plasma (P_{in})

Power reflected from the plasma (P_{out})

Power absorbed in core plasma (P_{core})

Example: excitation scenario for electron Bernstein waves

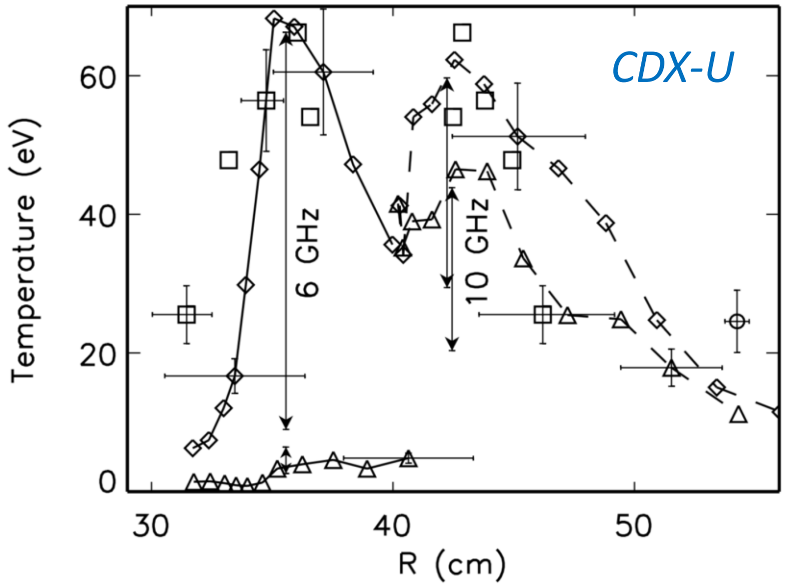


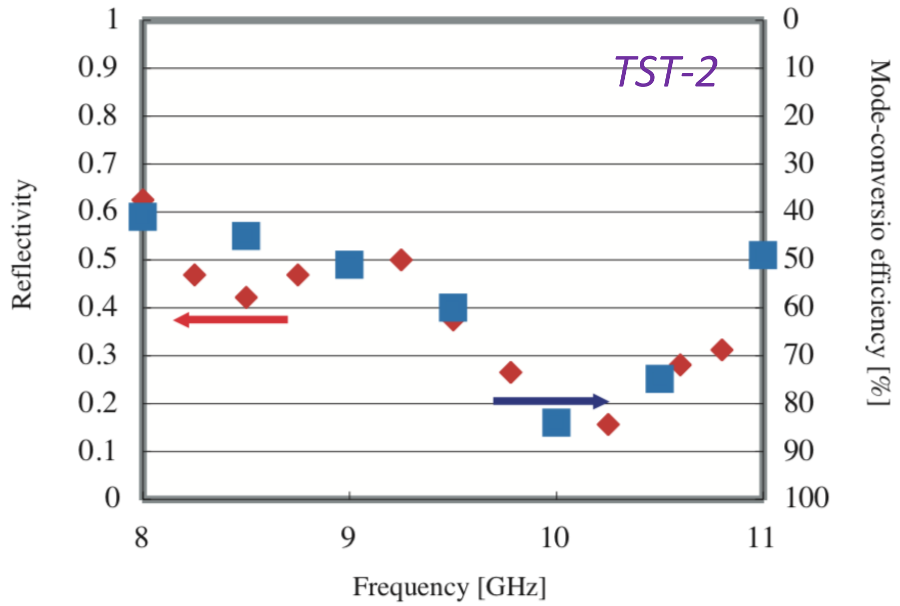


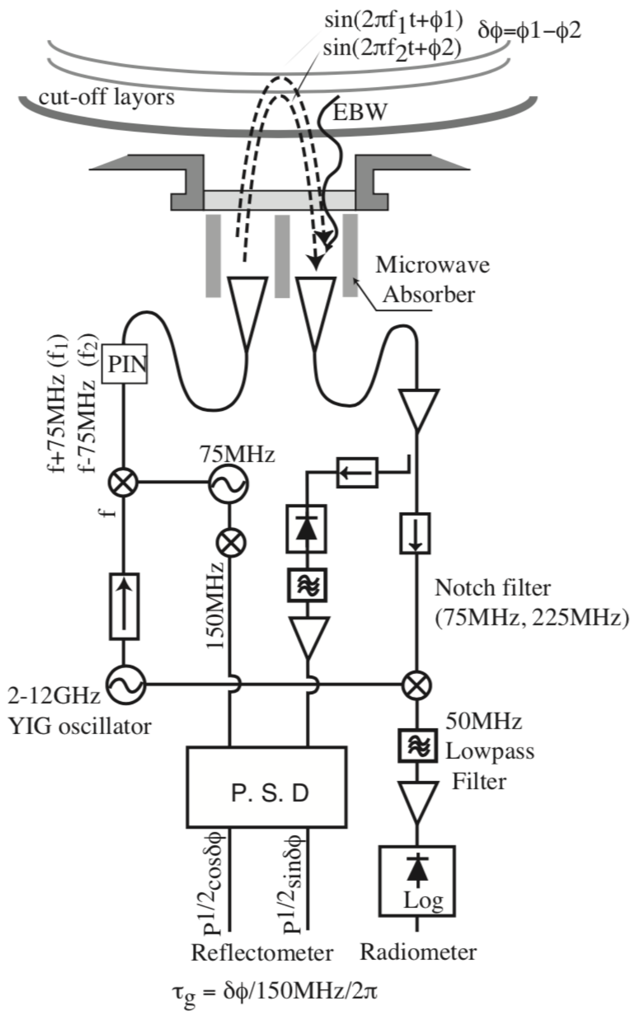
X-B mode conversion scenario

- Width of L_{cutoff}-UHR-R_{cutoff} triplet determines the transmission efficiency
- $P_{in} = P_{absorbed} + P_{reflected}$

1D theory explained well low power experiments





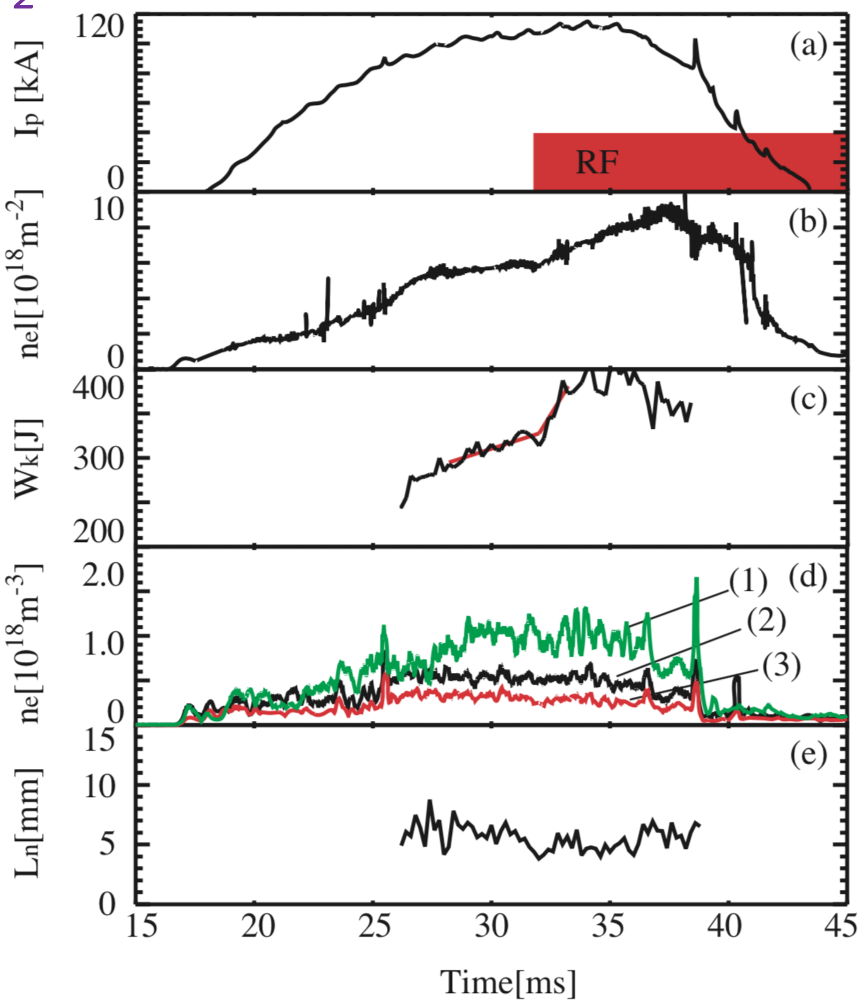


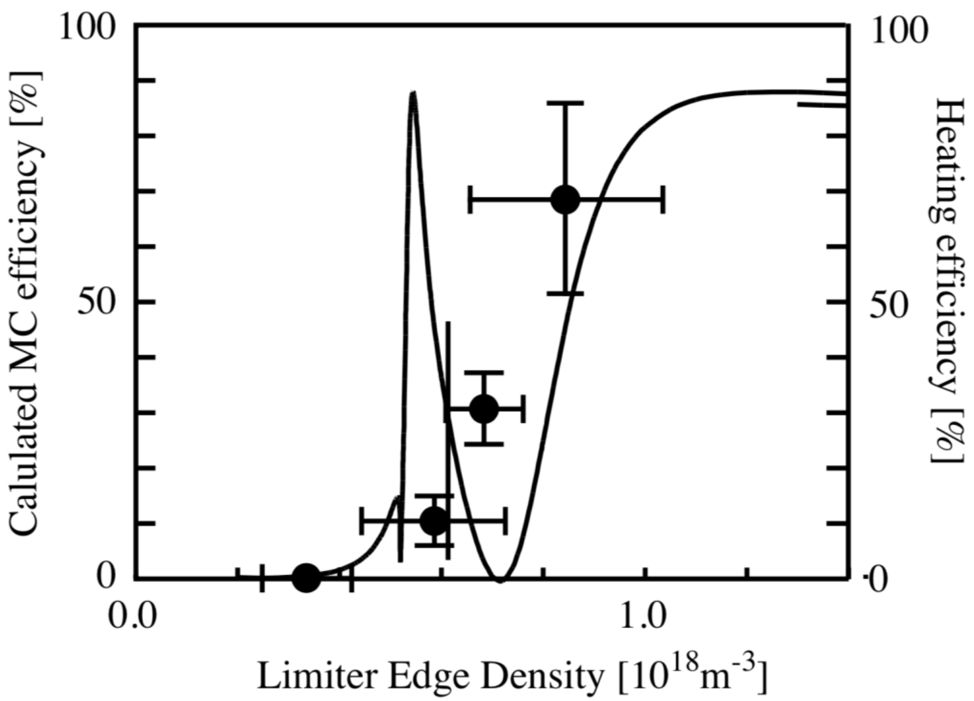
(right) EBW power emission measurement on CDX-U[1] (left) Comparison of power transmission efficiency and reflectivity measured by radio-reflectometer[2],

1) B. Jones, et al., Phys. Rev. Lett. 90, 165001 (2003)
2) S. Shirawia, et. al., Rev. Sci. Instrum. 74, 1453 (2003)

…and even at high power to some extent

TST-2



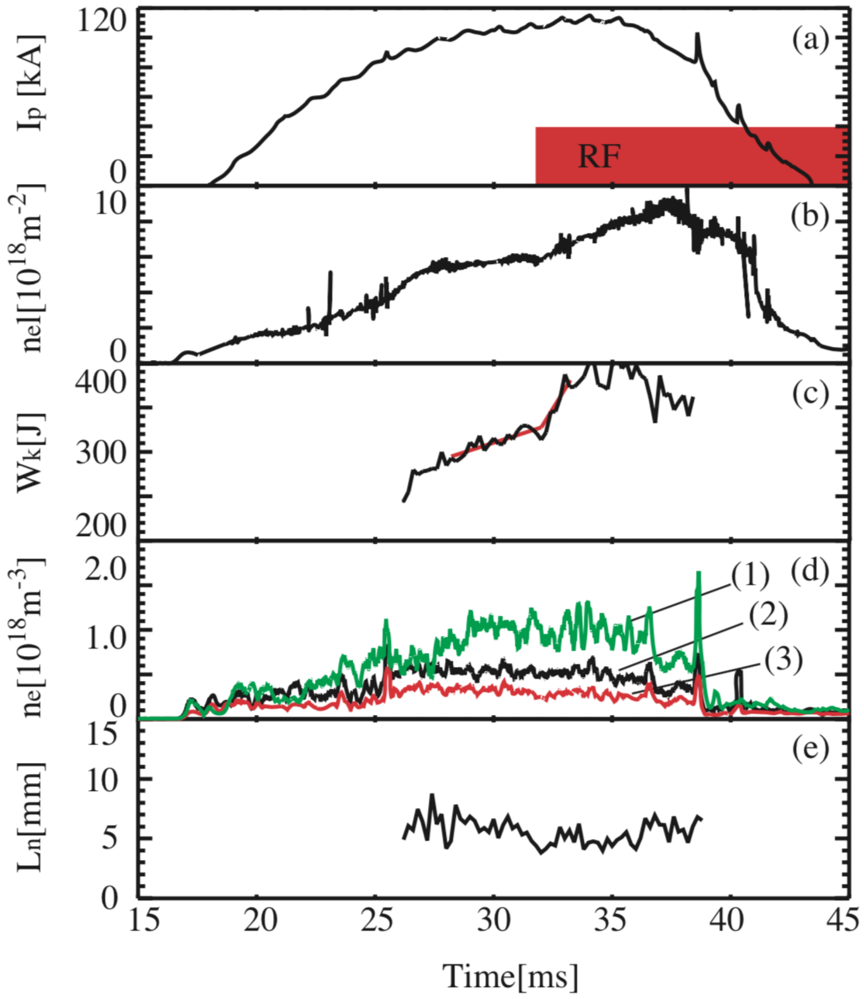


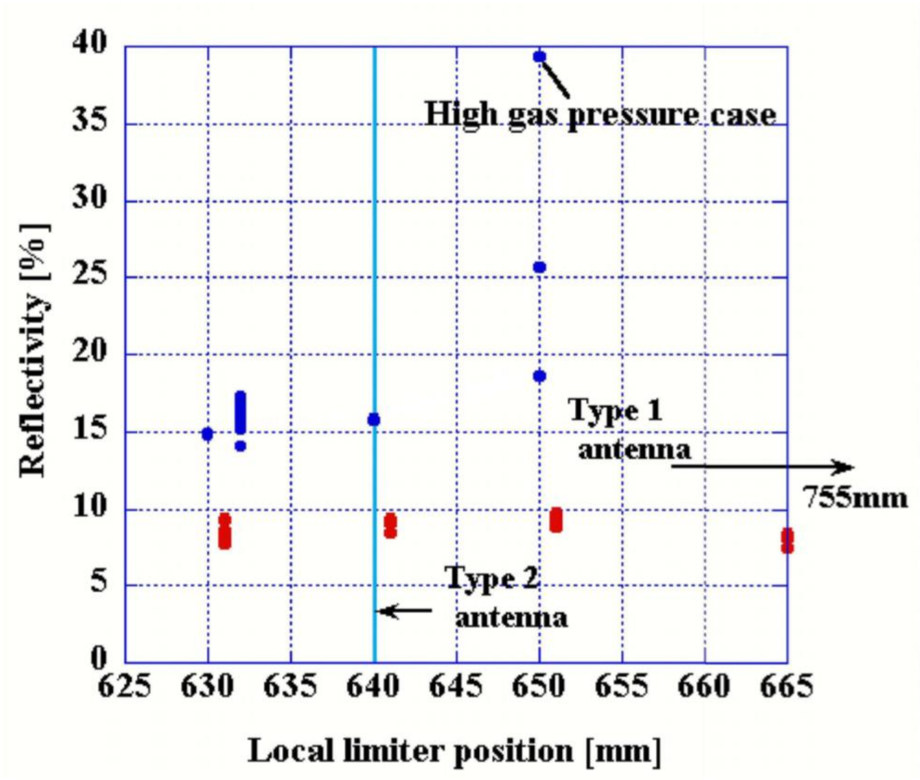
Reverse process was used to heat ST plasma, showing the core heating when the triplet with is suitable.

S. Shirawa, et. al., Phys. Rev. Lett. 96, 185003 (2006)

But a question remains

TST-2



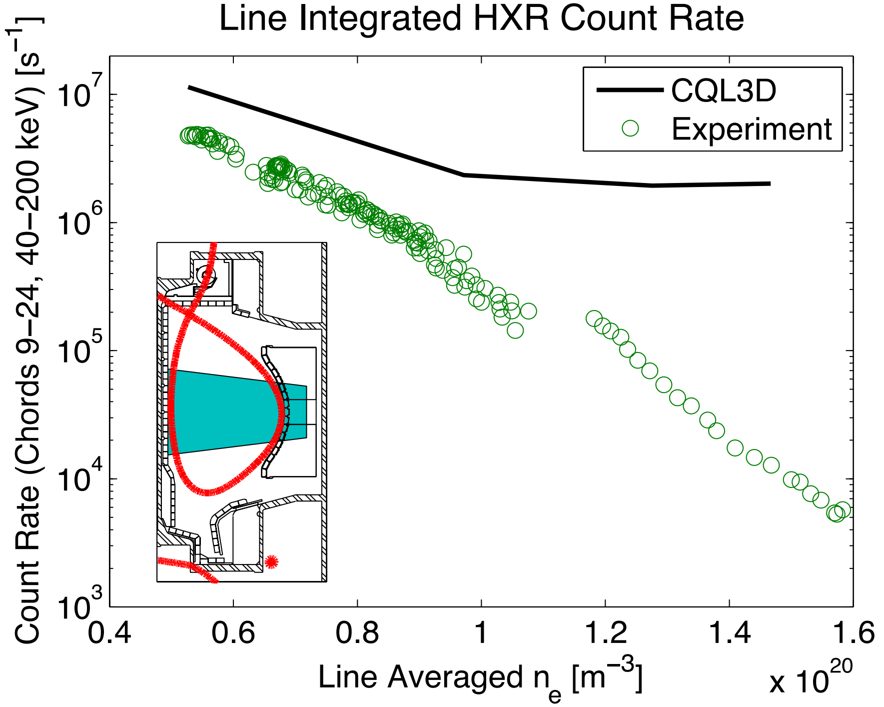


The power reflection is always low !

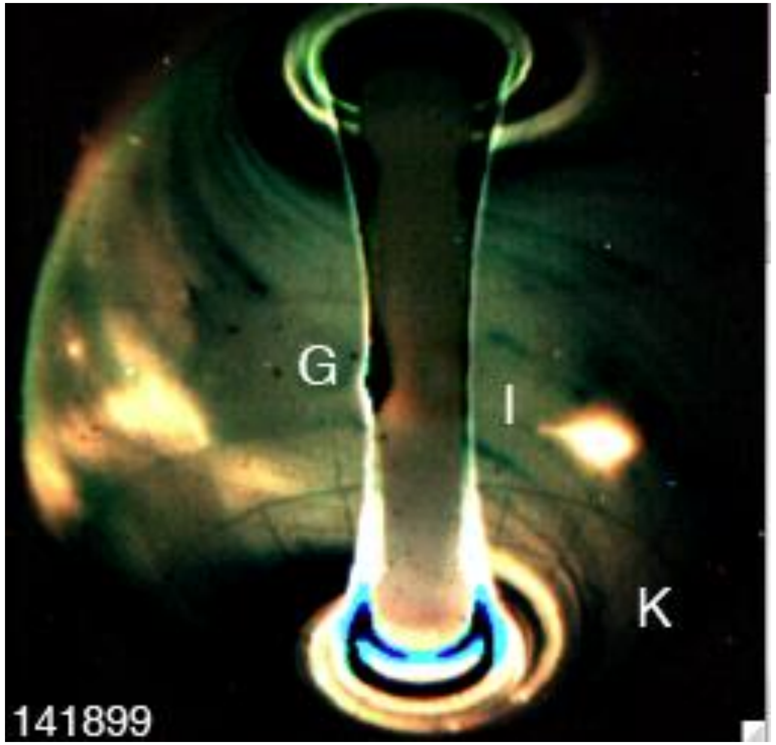
S. Shirawa, et. al., Phys. Rev. Lett. 96, 185003 (2006)

A key to understand and improve the RF actuators is to model parasitic losses and associated adverse effects on plasmas accurately

C-Mod[1,2, 3]



NSTX



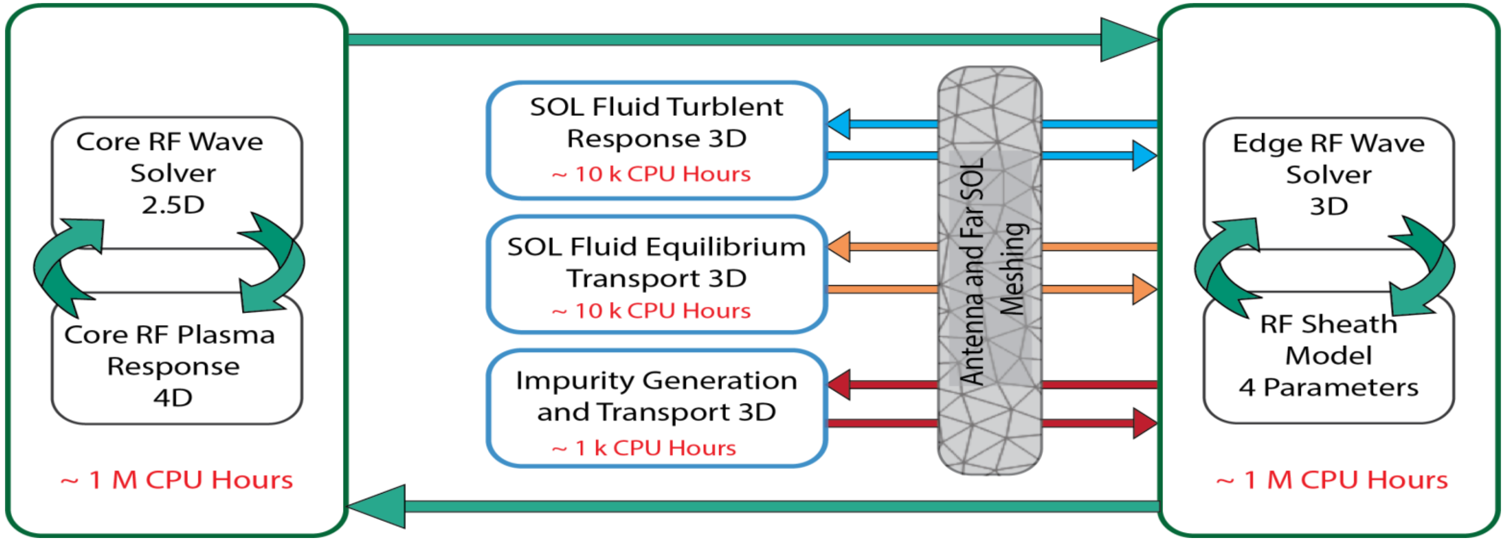
Common issue on many RF experiments

- ICRF : Alcator C-Mod, ASDEX, JET…
- LH : Alcator C-Mod, FTU, EAST, Toru Supra…
- HHFW : NSTX

1) G. M. Wallace, et al., Phys. Plasmas **17**, 082502 (2010)
2) S. Shiraiwa, Physics of Plasmas 080705 **18** (2011)
3) I. Faust, Ph. D thesis
4) R. J. Perkins, et al., Phys. Plasmas **22**, 042506 (2015)

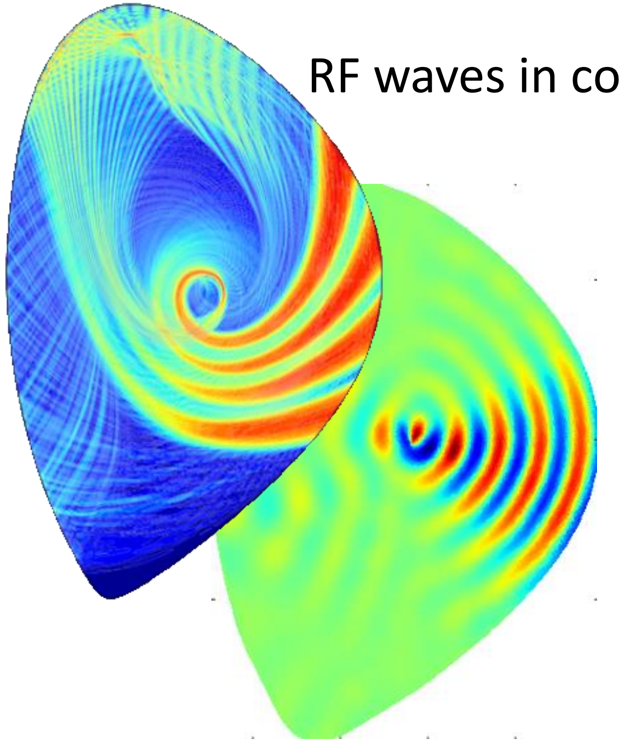
RF Modeling needs to handle a realistic 3D antenna, coupled with advanced physic models

- 3D geometry
  - Antenna coupling in 3D geometries (C-Mod field aligned ICRF, stellarators)
  - Open field line SOL plasmas
- Advanced physics
  - edge turbulence
  - RF stheath
  - …and more



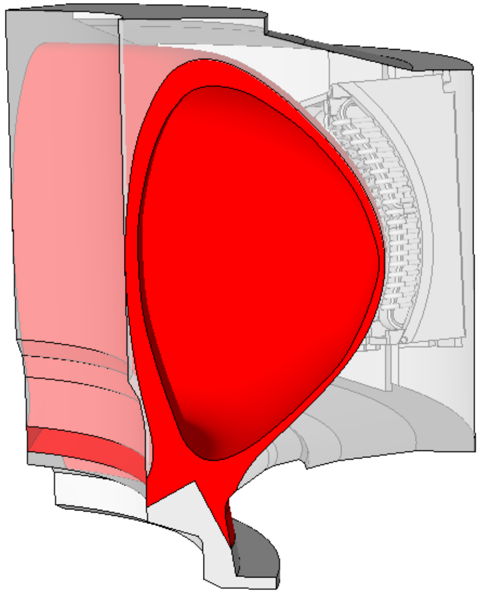
1) RF SciDAC-4 proposal

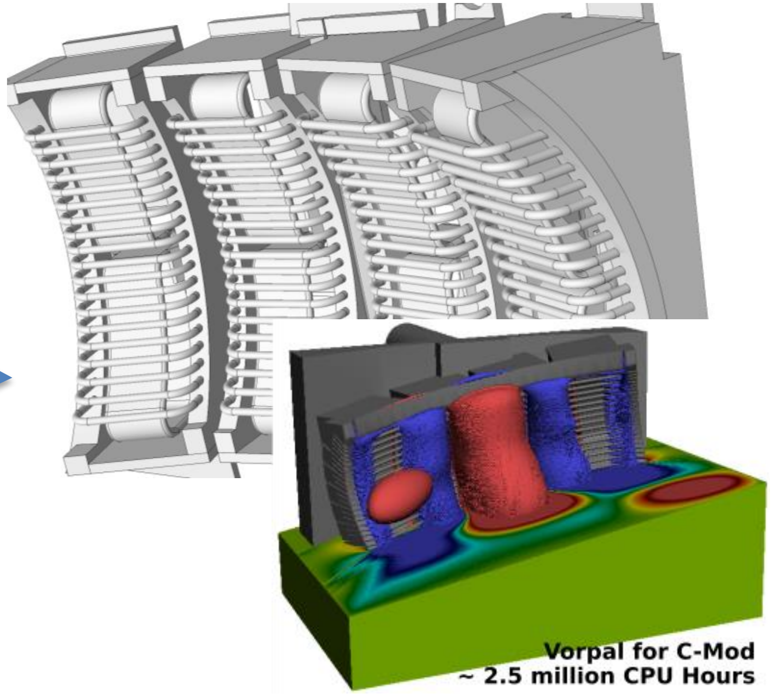
High fidelity (physics and geometrical) RF modeling requires an integrated approach



RF waves in core

SOL plasma





It is customary in RF simulations to handle hot core and antenna coupling separately.
We need to treat them self-consistently, which requres…

- A generic platform to implement technically transparent and scalable FEM application.
- Formulation to connect RF wave field between different regions.

LH grill launcher

Outline

- Petra-M platform on scalable MFEM library
- Whole device scale RF wave simulation [1]
- Integration of hot core plasmas [2, 3, 4]
- Future and summary

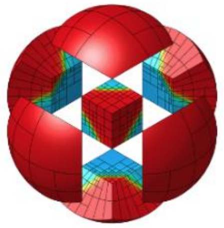
1) N. Bertelli, S. Shiraiwa, et. al. RF topical conf. 2019
2) J. C. Wright and S. Shiraiwa, RF topical conf. 2017
3) S. Shiraiwa, J.C. Wright et. al., APS 2017
4) S. Shiraiwa, J.C. Wright et al. N.F. (2017)
5) J. C. Wright, S.Shiraiwa, et. al. EPS 2018

MFEM

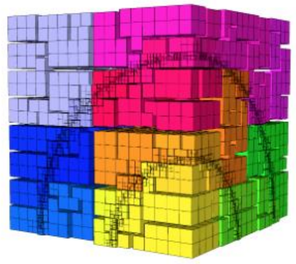
Lawrence Livermore National Laboratory

Free, lightweight, scalable C++ library for finite element methods. Supports arbitrary high order discretizations and meshes for a wide variety of applications.

- **Flexible discretizations on unstructured grids**
  - Triangular, quadrilateral, tetrahedral and hexahedral meshes.
  - Local conforming and non-conforming refinement.
  - High-order mesh optimization (ASCR Base).
  - Bilinear/linear forms for variety of methods: Galerkin, DG, DPG, …
- **High-order methods and scalability**
  - Arbitrary-order H1, H(curl), H(div)- and L2 elements. Arbitrary order curvilinear meshes.
  - MPI scalable to millions of cores. Enables application development on wide variety of platforms: from laptops to exascale machines.
- **Solvers and preconditioners**
  - Integrated with: HYPRE, SUNDIALS, PETSc, SUPERLU, …
  - Auxiliary-space AMG preconditioners for full de Rham complex.
- **Open-source software**
  - Open-source (GitHub) with thousands of downloads/year worldwide
  - Part of FASTMath, ECP/CEED, xSDK, OpenHPC, ...



High order curved elements

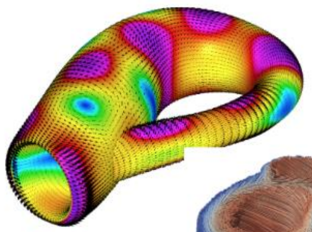


Parallel non-conforming AMR

CEED EXASCALE DISCRETIZATIONS

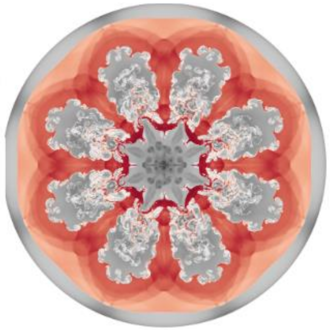
FASTMATH

ASC



Surface meshes

Heart modelling



Compressible flow ALE simulations

http://mfem.org

RF-SciDAC

C++ and Fortran layer is wrapped for rapid application development using Python

PyMFEM

Auto-generate C++ wrapper codes from mfem header files using SWIG

Wrapper allows to use C++ objects in MFEM from Python,

(c++)

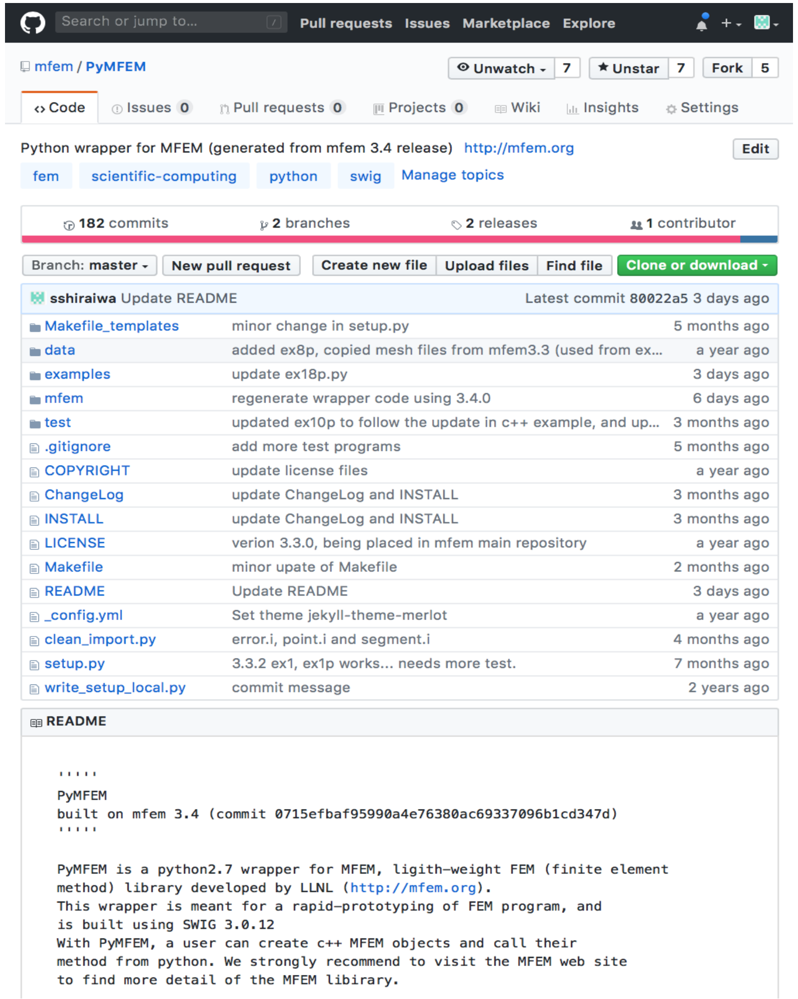
```
double data[] = {1,2,3};
o = Vector (data, 3);
```

(python)

```
v = mfem.Vector(np.array([1,2,3.])
```

Distributed from mfem.org

Using the same technique for linear solvers (MUMPS, Strumpack), and mesh adaptation (PUMI)



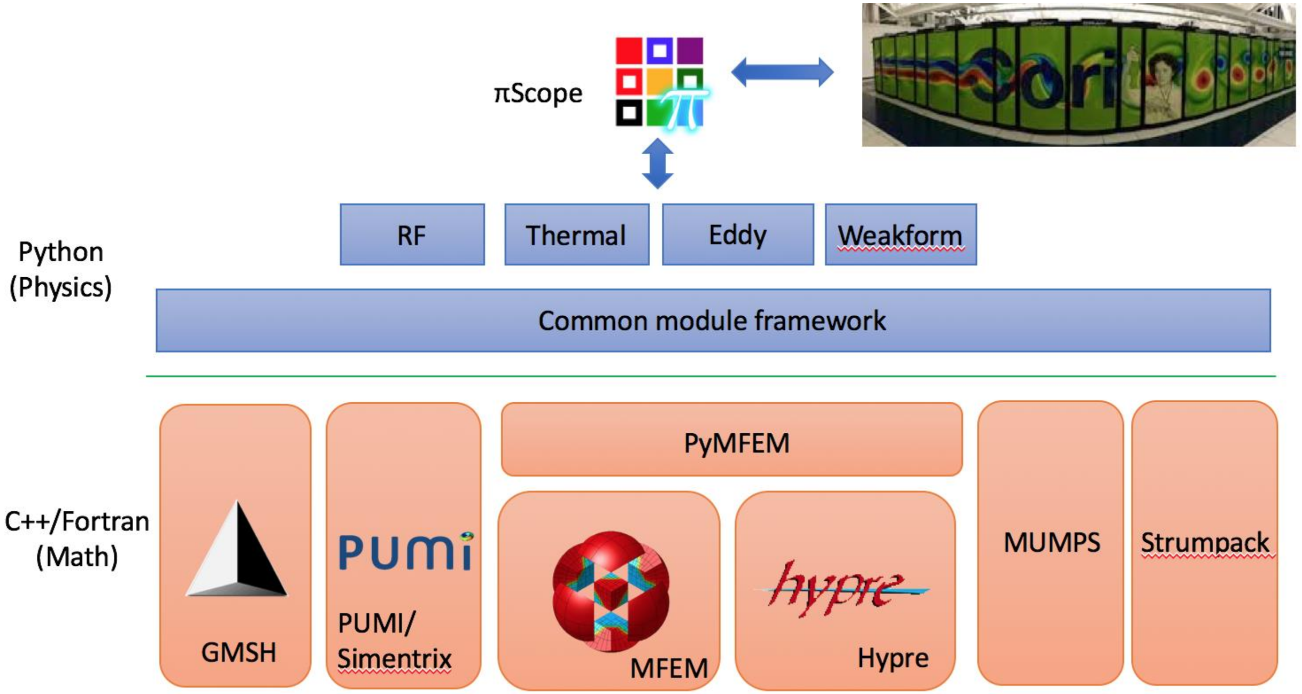
Available under MFEM site (LGPLv2)

Petra-M (Physics Equation Translator for MFEM)

FEM analysis platform

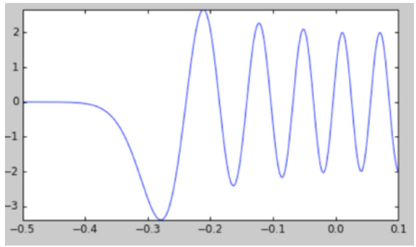
Front-end interface to open source software

- Integrated FEM modeling from geometry to FEM assembly and solve.
- Deployment tool for our advanced physics model

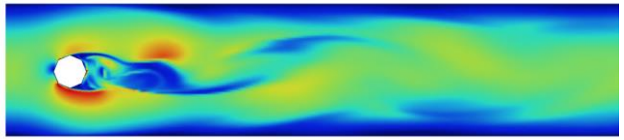


Started as RF modeling tool

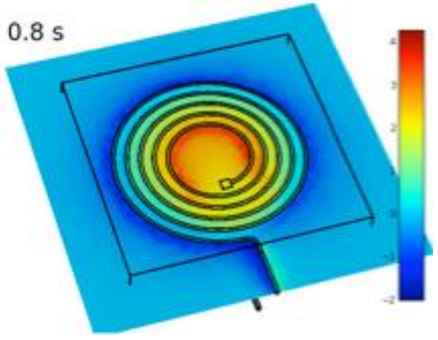
Use case is expanding even outside RF waves such as SPARC magnet.



1D RF wave



Navier-Stokes

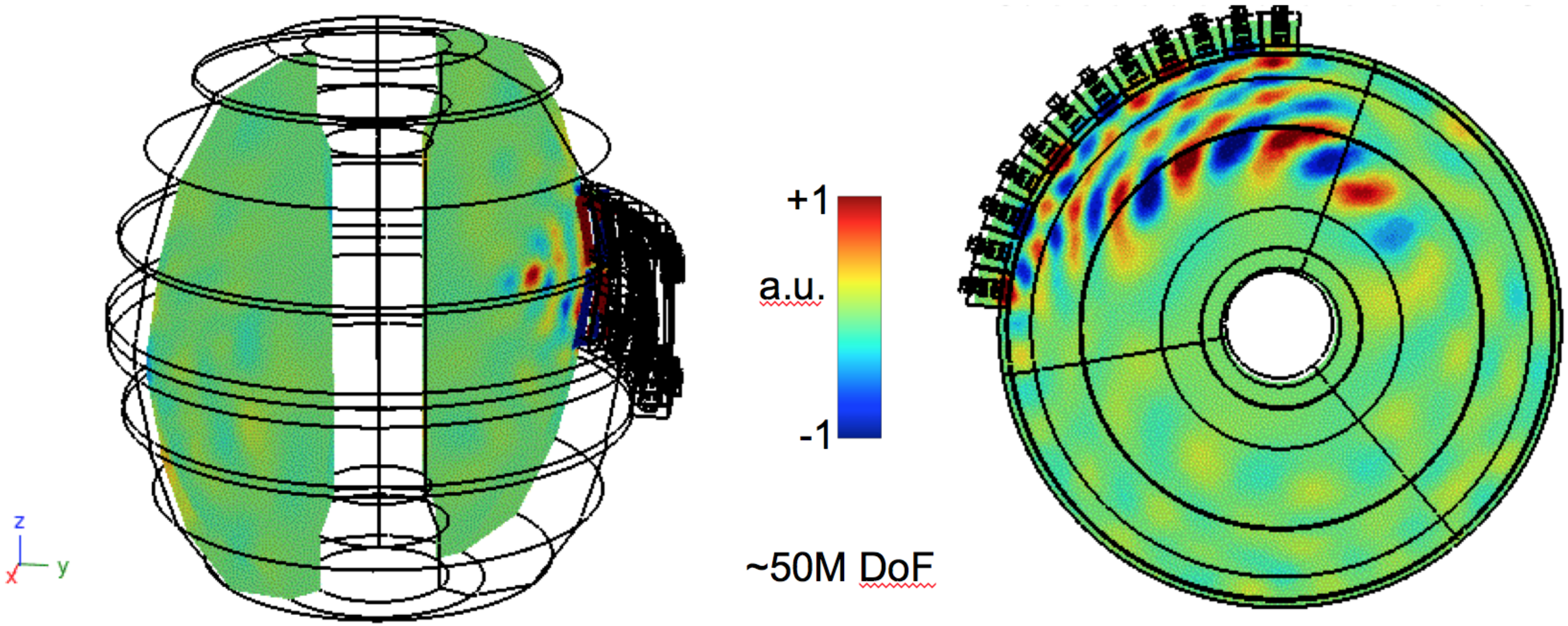


EM-thermal coupled PDE

Scalable RF wave solver with high geometrical fidelity

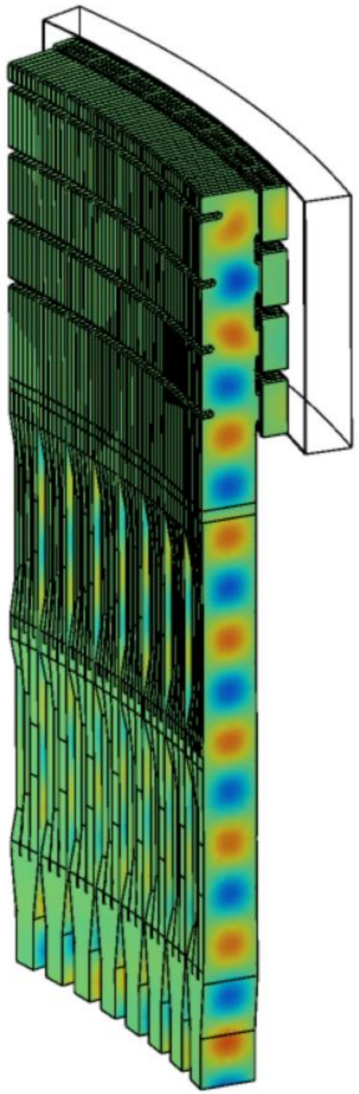
First full 3D torus simulation including realistic antenna geometry

E_z component for 90 degree antenna phasing



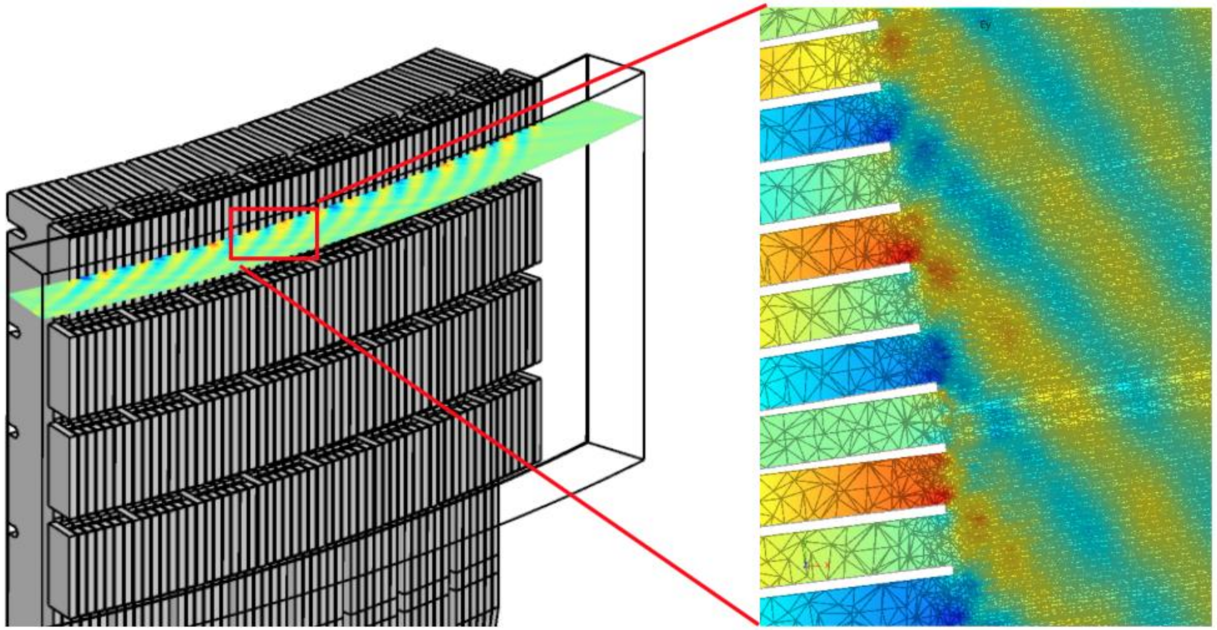
- Equilibrium B field from EFIT as well as the diverted geometry
- Analytical density profile with exponential decay in the SOL plasma
- Vacuum in the antenna box and anisotropic cold plasma in the torus with artificial collision

Preconditioners : Reduced Precision II



DIII-D high field silde lower hybrid launcher being designed/built by MIT

- 15-20 GMRES iteration
- Possible to resolve LH wave scattering in 3D
- 110 M DoFs (exceeding project 5th year milestone)

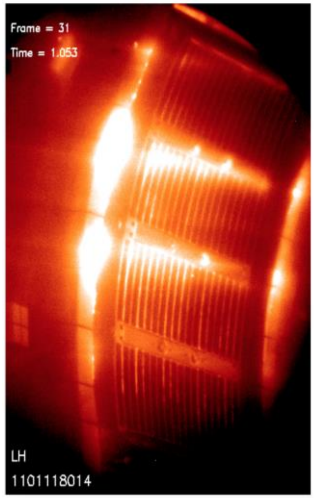


RF-SciDAC

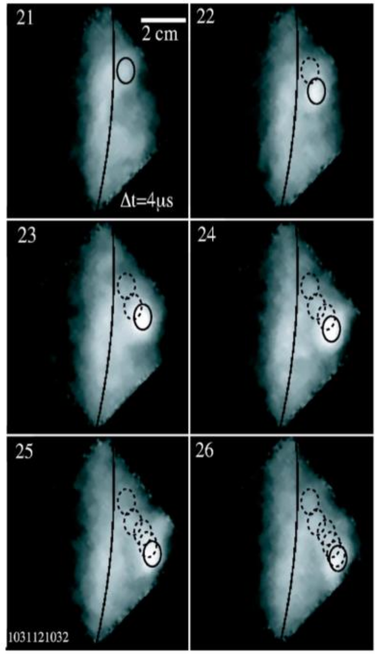
LH-wave scattering due to 3D density perturbation in front of antenna impacts RF wave propagation

- Experiment shows various field-line aligned density perturbations
  - Striation (stationary)
  - Turbulent blobs

C-Mod

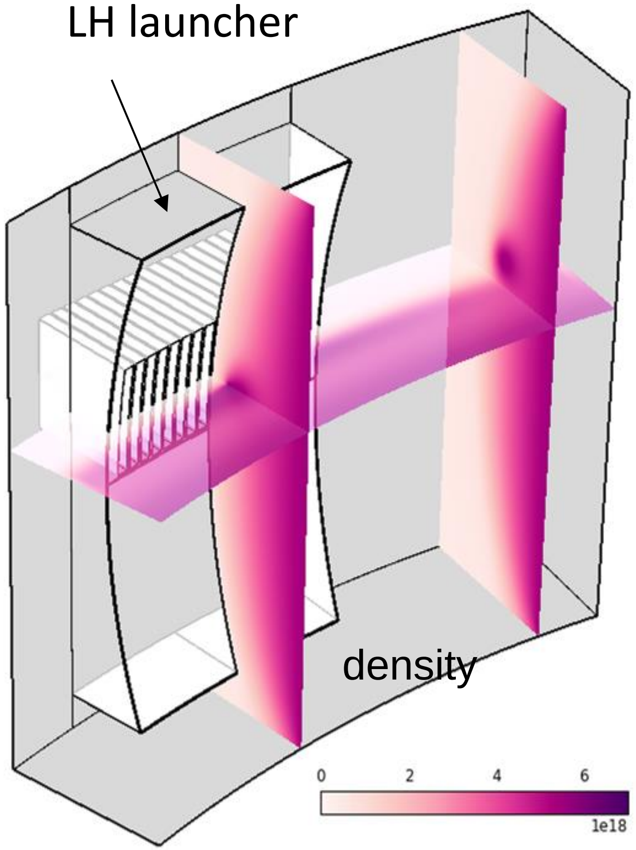


Glowing striations at LHCD launcher[1]



High speed movie of blob I SOL[2]

Simulation geometry with model blob perturbations

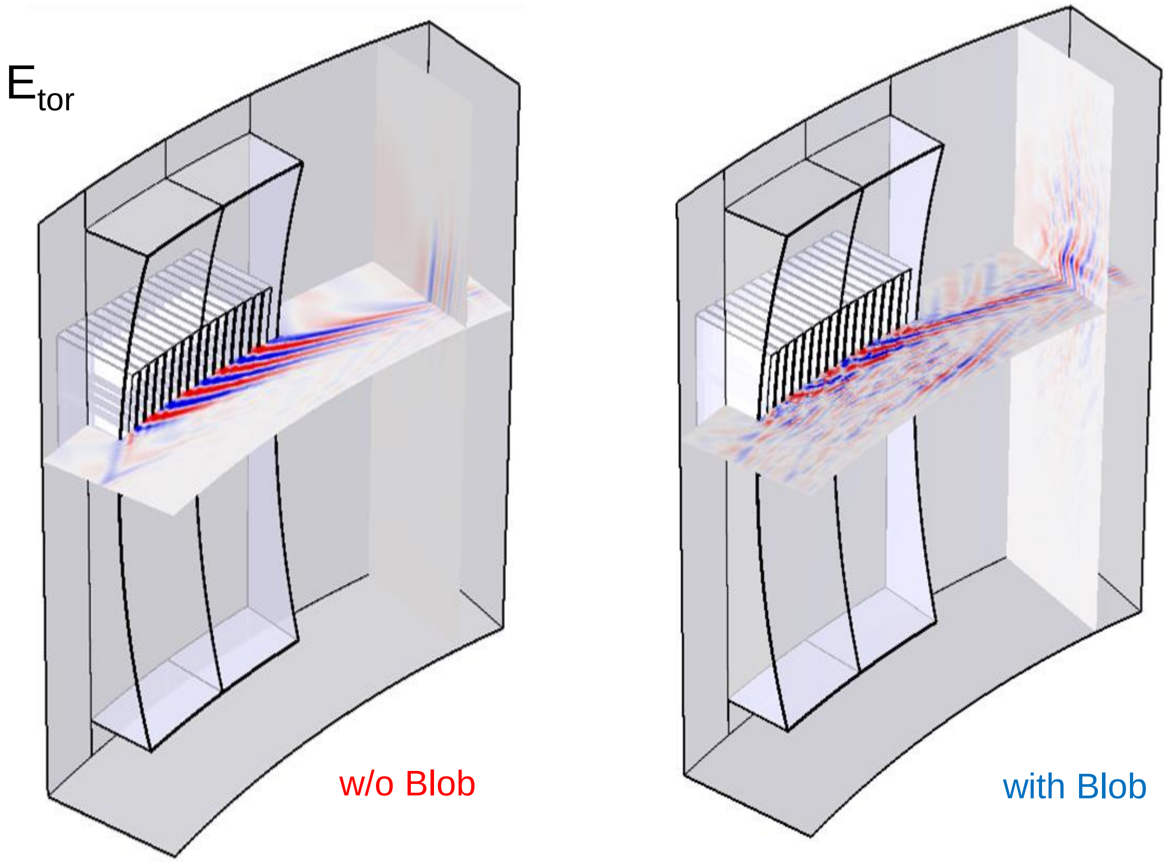


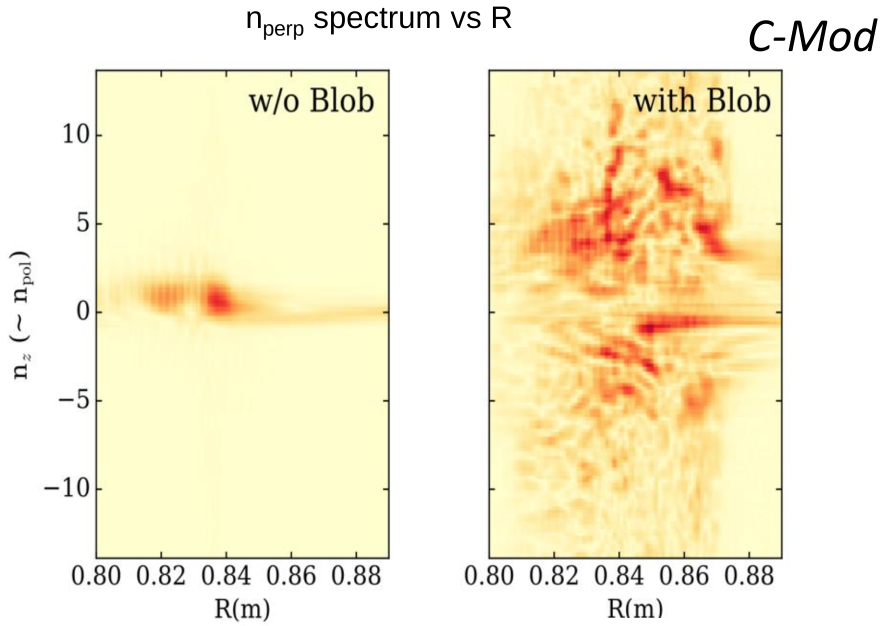
Field aligned density modulation placed in front of LH launcher

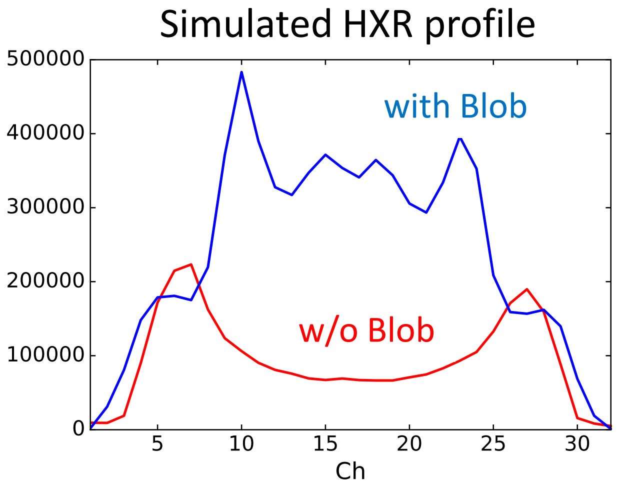
The modulation was computed by solving diffusion eq. from particle source in front of the launcher

[1]O. Meneghini, et. al.,"Modeling Non-linear Plasma-wave Interaction at the Edge of a Tokamak Plasma", (2011)
[2]J. L Terry. et. al., "High speed movies of turbulence in Alcator C-Mod", RSI, (2004)

Initial results indicate that the LH wave field pattern can be significantly altered, potentially improving the agreement with experiment



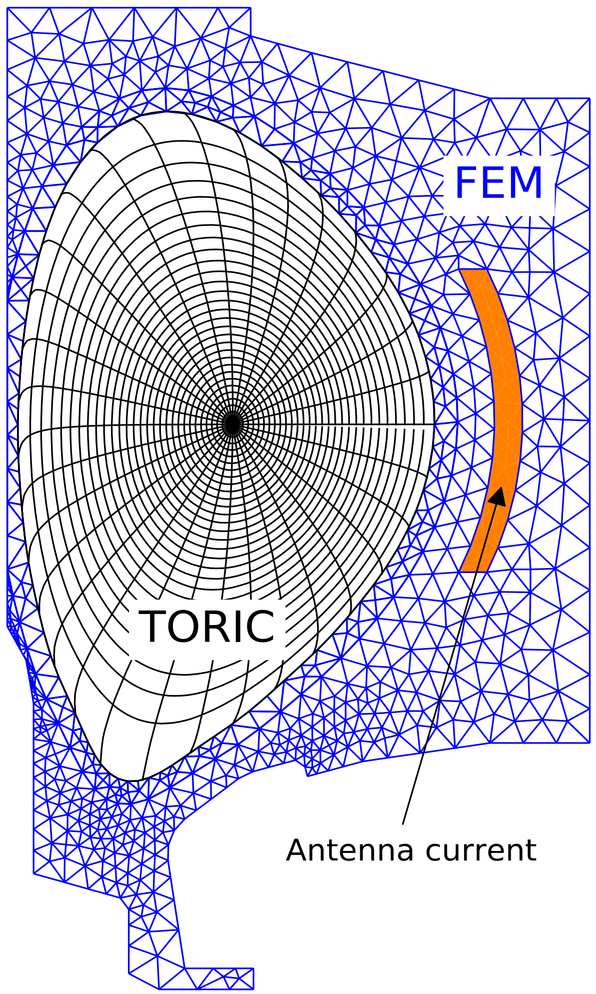




- LH resonance-cone propagation is largely destroyed, leading to broadening of the vertical wave-number (n_{perp}) spectrum.
- K-vector rotation impacts the core power deposition filling it in. S. Shiraiwa APS (2018), S. G Baek, RF conf. (2019)

Integration with hot-core wave solver

Hybrid integration of SOL

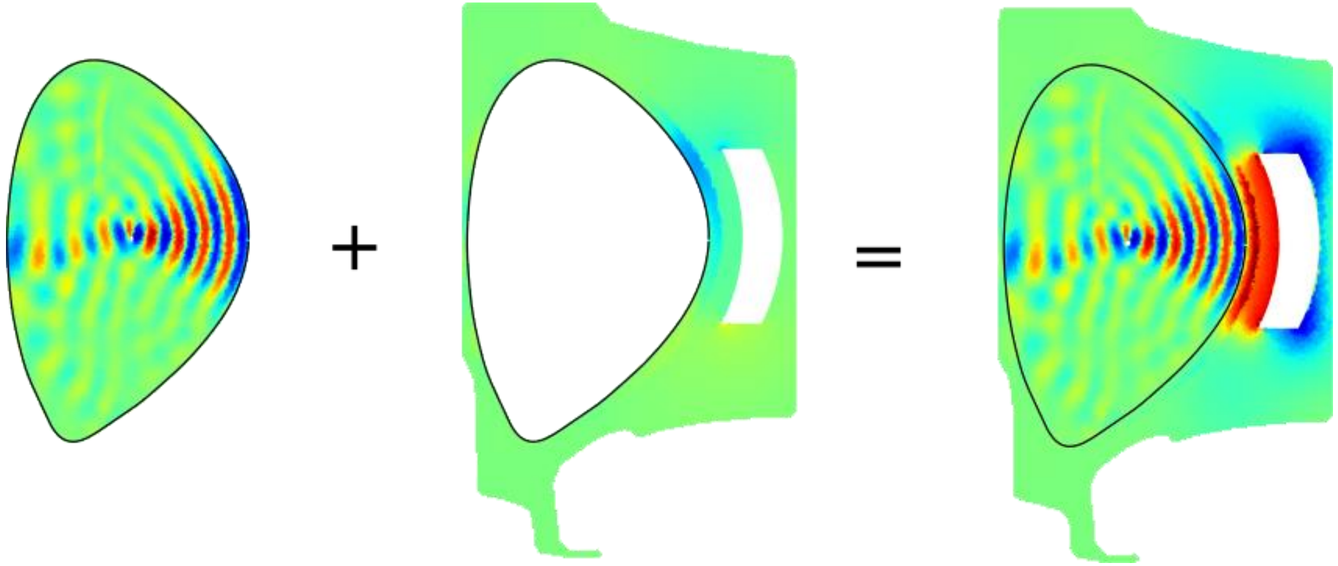


Core

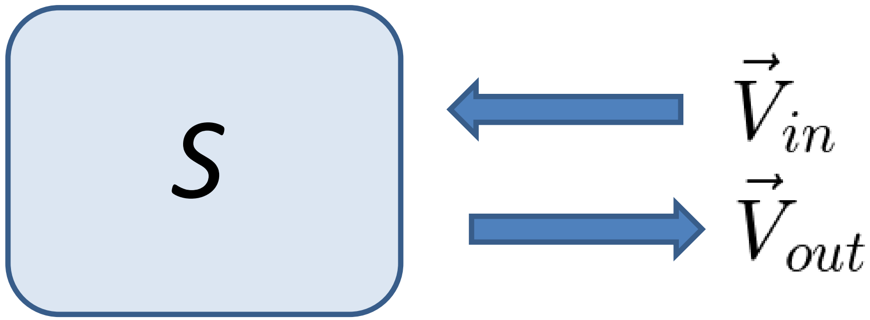
- **Axisymmetric** flux surface regular grid
- Hot plasma conductivity
- Dense Matrix Solver

Edge

- **Unstructured mesh** with complicated geometry (either 2D or **3D**)
- Cold plasma with collision.



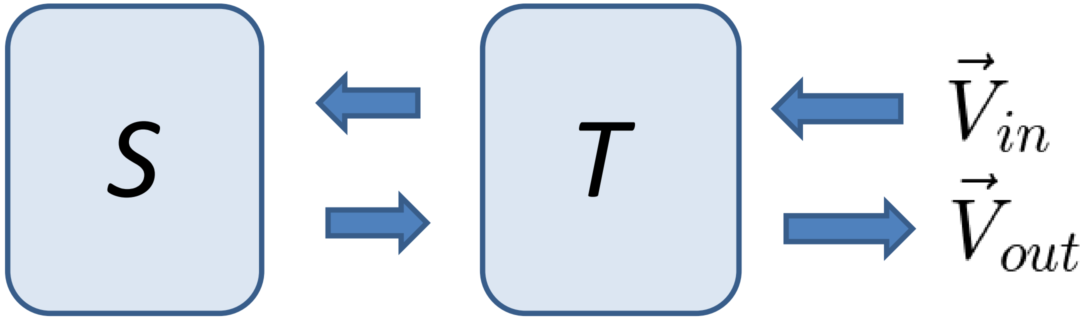
Core and edge connecting rule = cascading of RF components



RF network characterized by the Scattering matrix, S

$$\vec{V}_{out} = S\,\vec{V}_{in}$$

When connecting two networks…

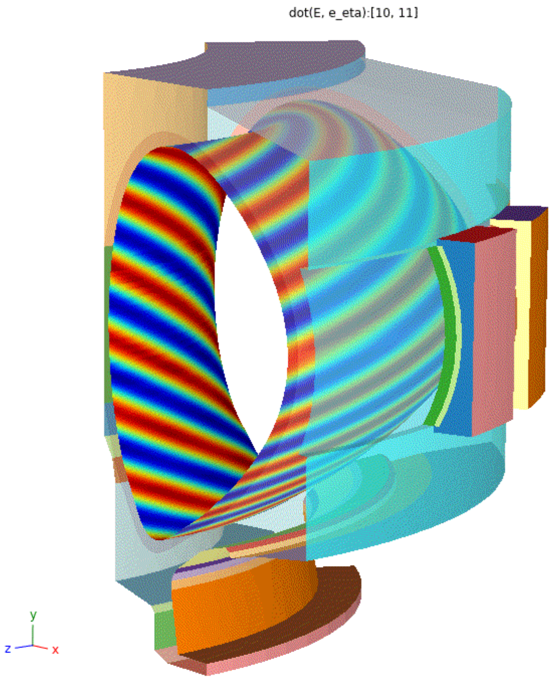


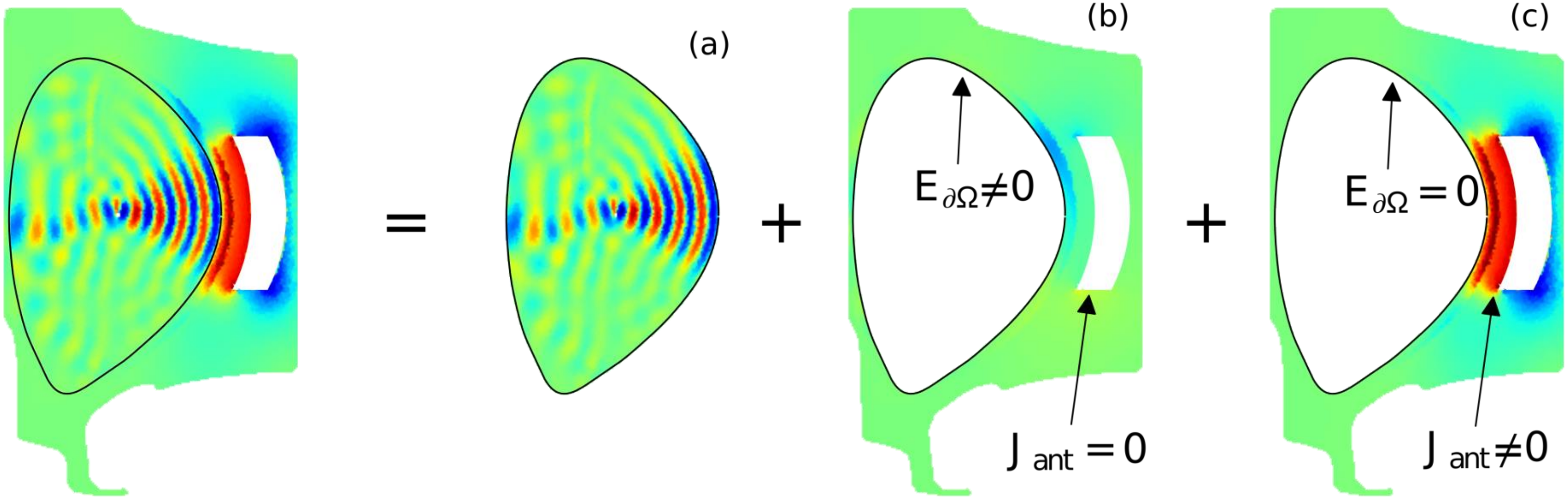
$$\vec{V}_{out} = U(T_2, S) \cdot T_1 \vec{V}_{in}$$

T_1: response to the power from the external input

T_2: response to the power from S

Final solution constitutes from three components

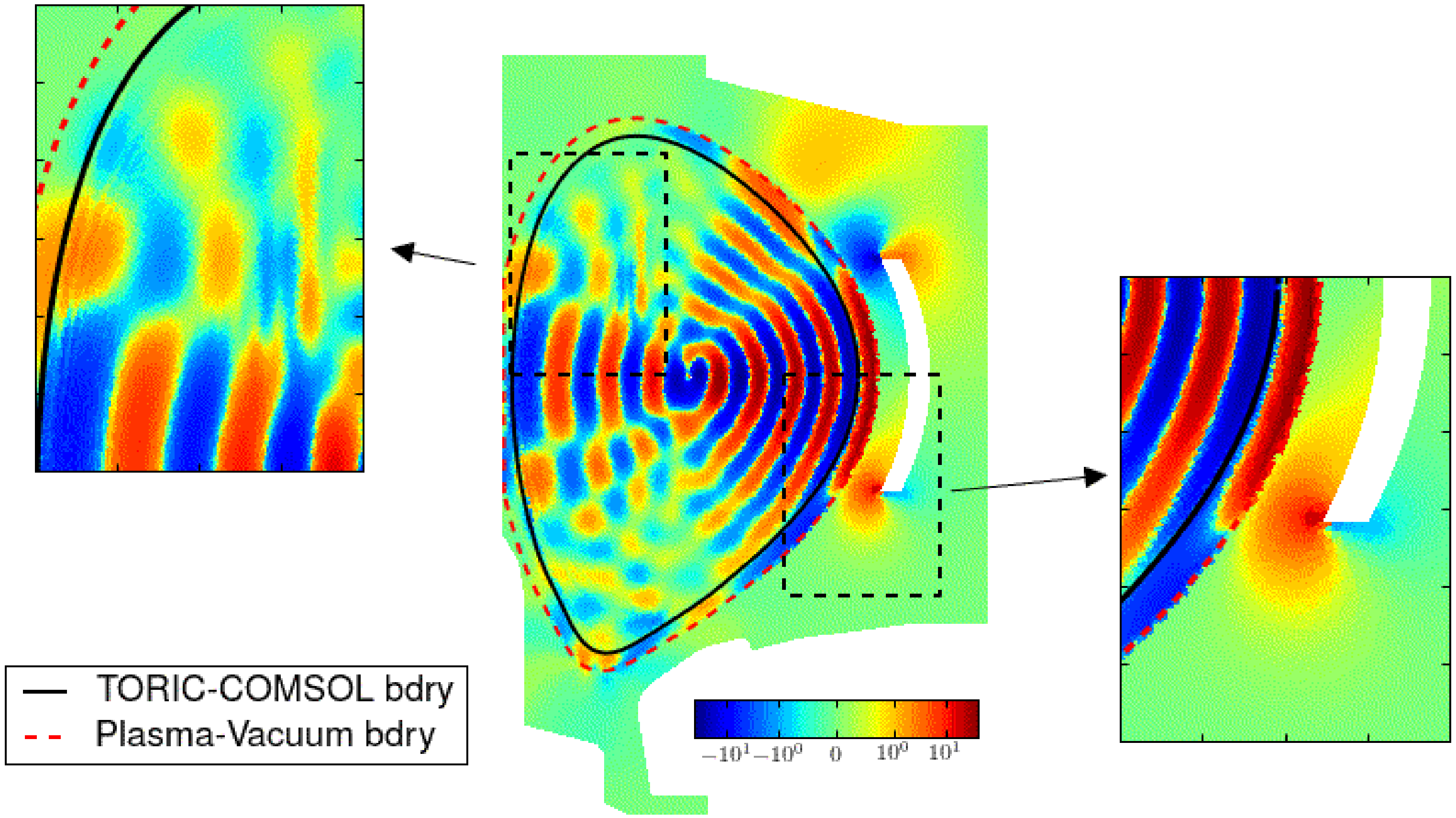




- Fourier decomposed modes (poloidal/toroidal) , not discrete RF port voltages.
- This method is exact – no approximations.
- Equivalent for requiring the continuity of tangential E and B on the connecting boundary.
- Changing antenna excitation does not require re-computing (b)

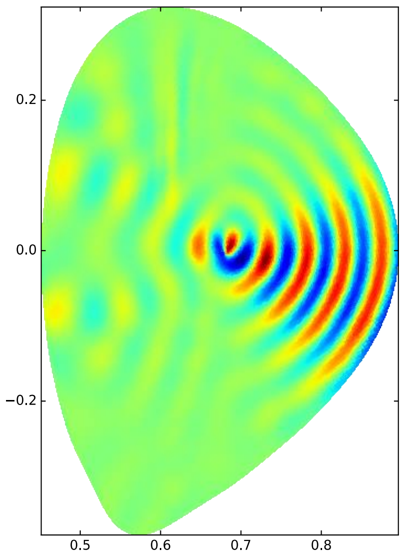
S. Shiraiwa et. al, et al. N.F. (2017), J. Wright et. al., RF conf. (2017)

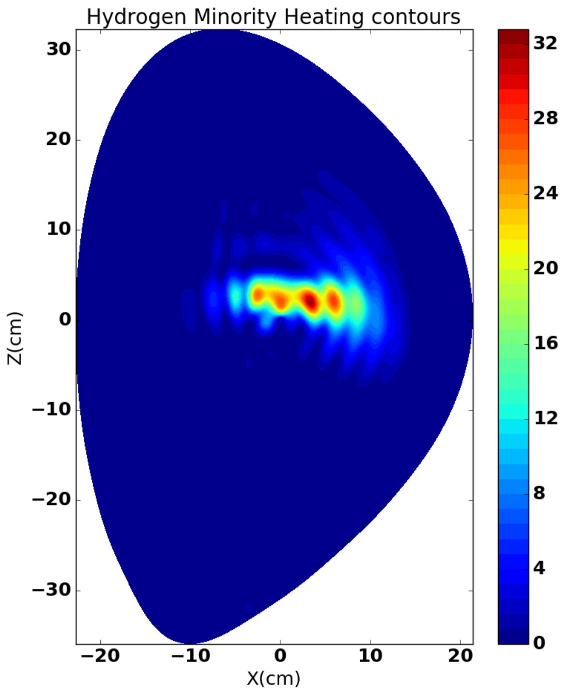
E_ψ continuity at domain boundary can be used for verification

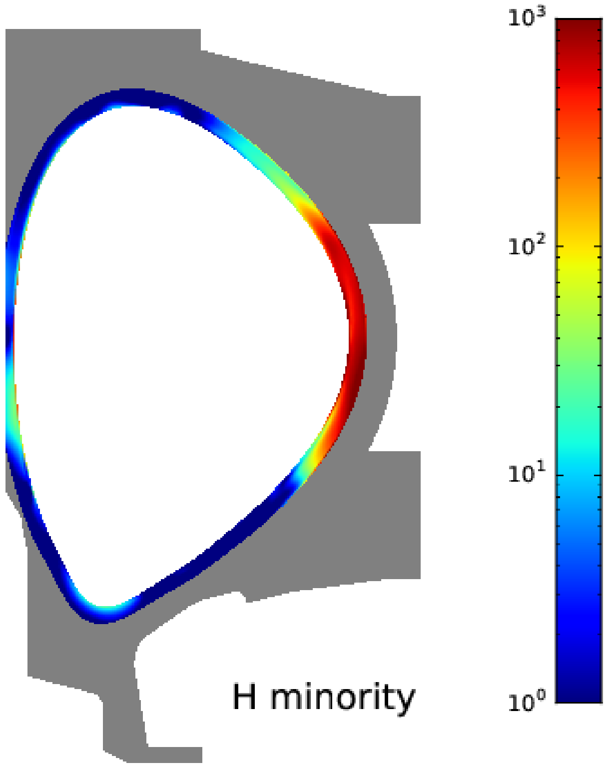


- Continuity of radial component is not given by construction and provides a way to verify the approach.
- Smoothly connected at TORIC/FEM boundary, but it is not at vacuum/plasma boundary.
- Consistent with a continuous dielectric at the former boundary, while it is not at the latter.

In D-(H) MH, the power is absorbed dominantly in the core

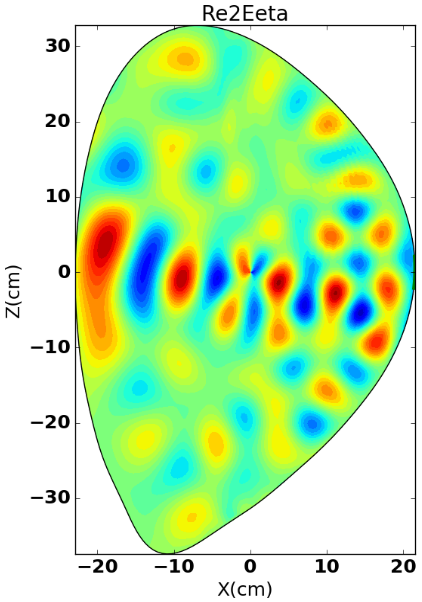


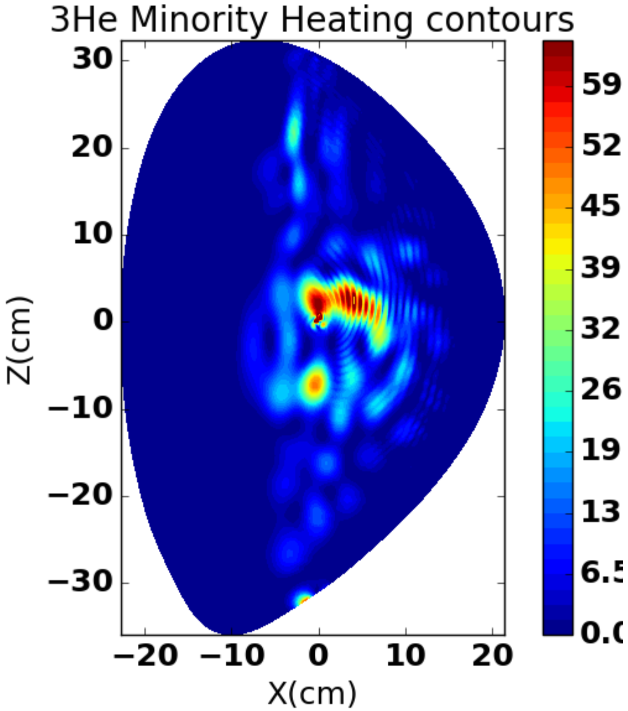


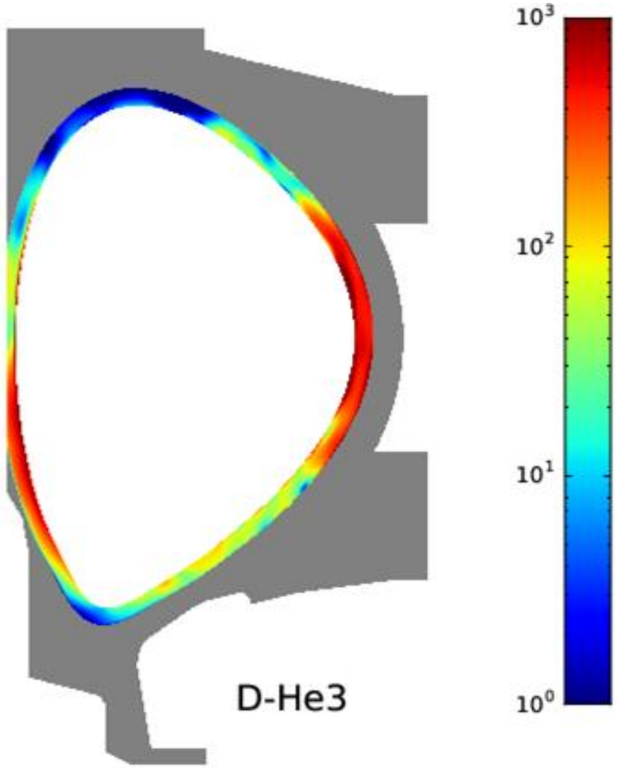


- D-(H) loading 16.1 Ω, power partition: 15% edge, 85% core.
  (note: Te_{SOL}= 15ev, which is low for C–Mod experiments)
- D-(3He) loading 14.5 Ω, power partition, 50% edge, 50% core.
- Loading is different than efficiency: power does not necessarily go into the core.
- In D-(3He), significant power lost in far SOL – possible source of far field RF sheath rectification

In D-(3He) MC, absorption in SOL increases due to weaker absorption







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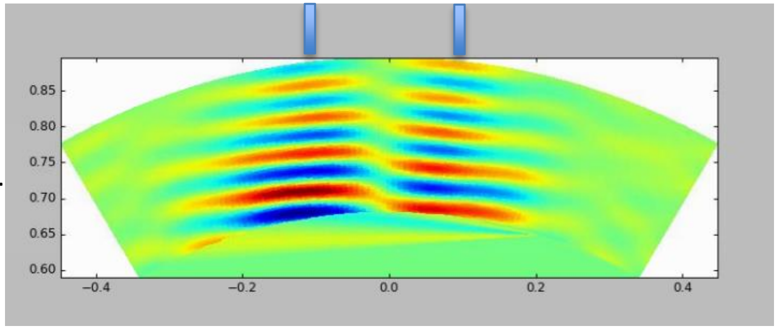
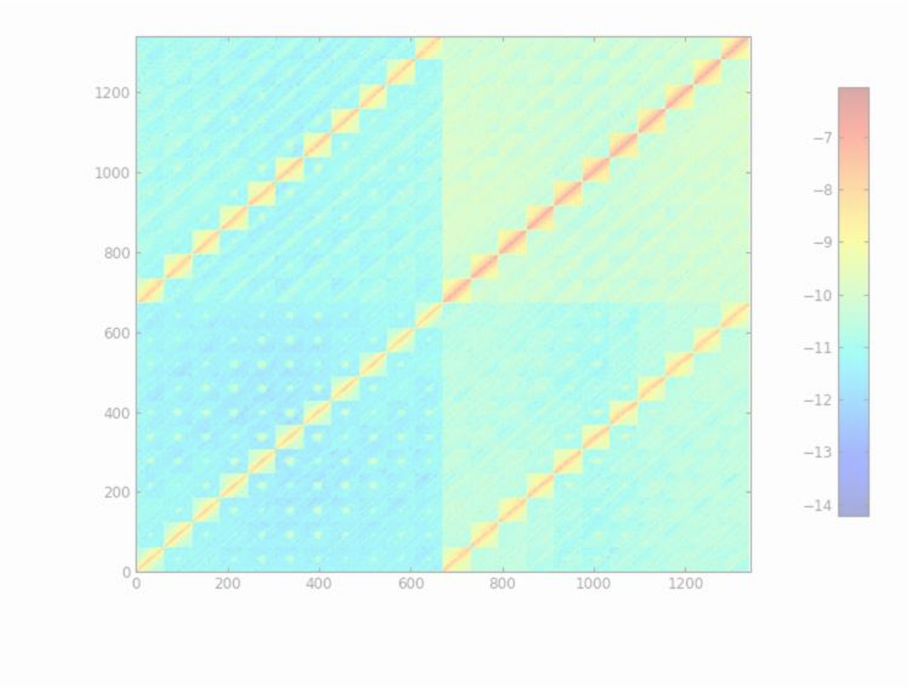
3D simulations using simply revolved 3D geometry indicates we need more realistic antenna structure

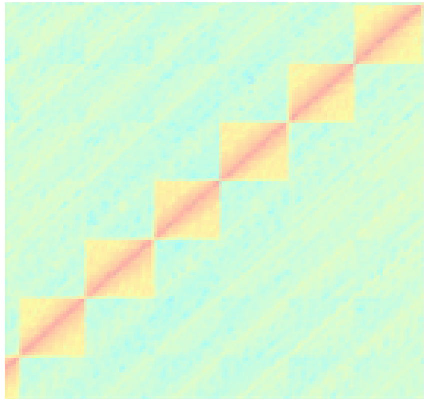
D-(H) case on Alcator C-Mod

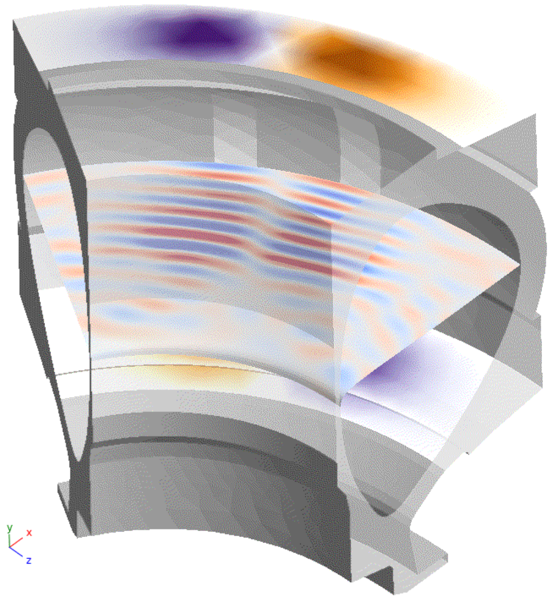
Accurate toroidal spectrum can be essential for finding RF amplitudes 'far' from antenna[1].

Midplane cut of low field side





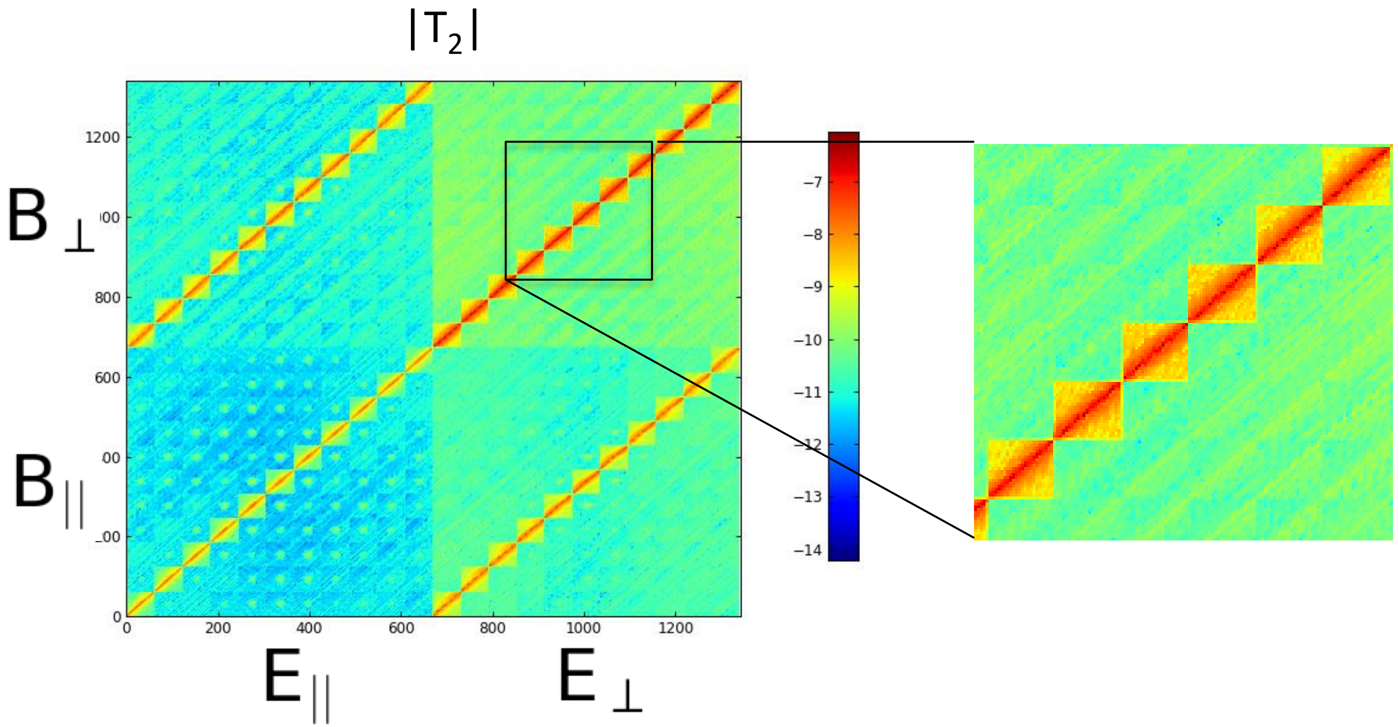




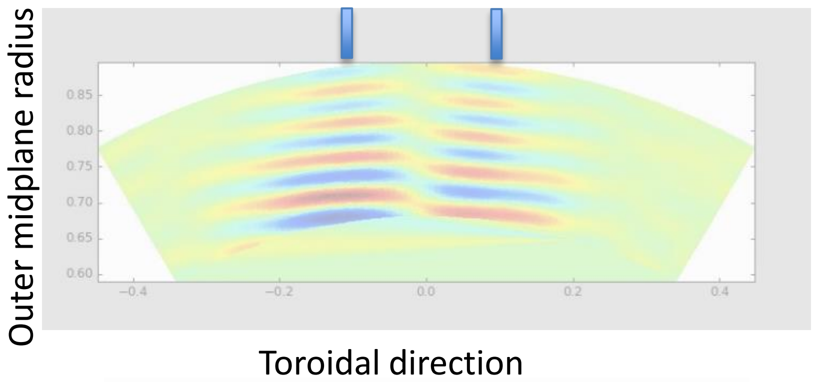
3D simulations using simply revolved 3D geometry indicates we need more realistic antenna structure

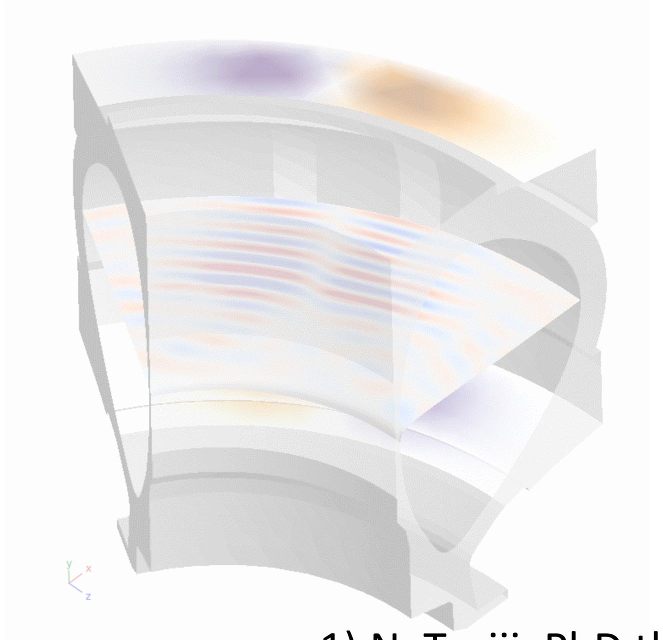
D-(H) case on Alcator C-Mod

Accurate toroidal spectrum can be essential for finding RF amplitudes ‘far’ from antenna[1].



Midplane cut of low field side

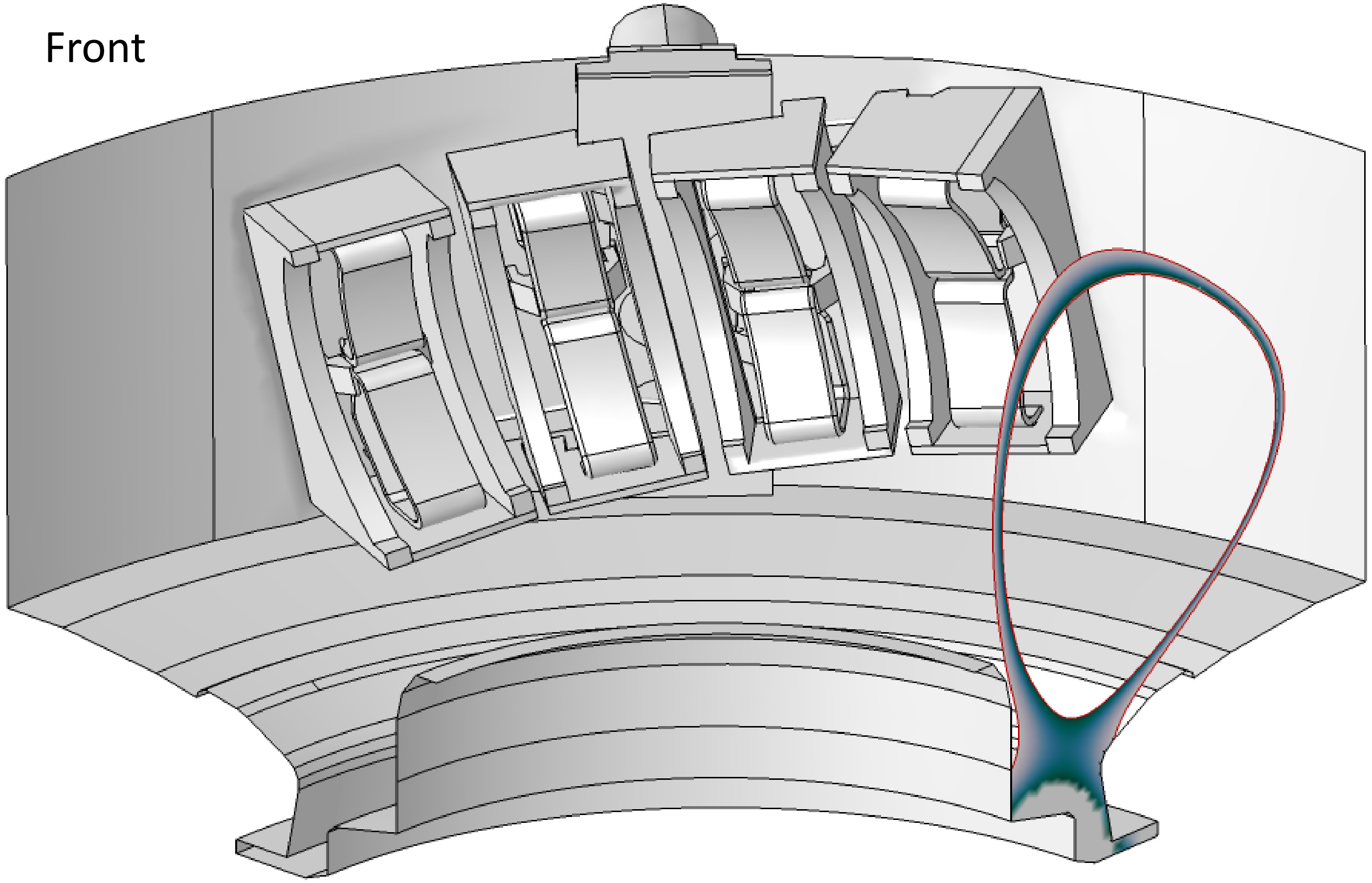




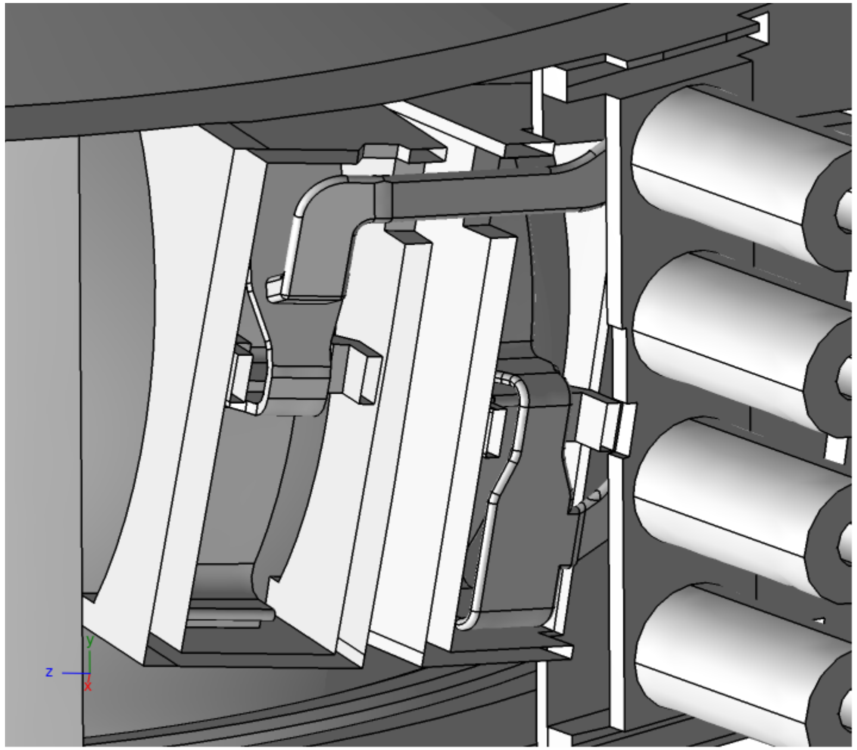
1) N. Tsujii, PhD thesis (2010)

J-port antenna RF geometry model built from engineering CAD drawing

Front

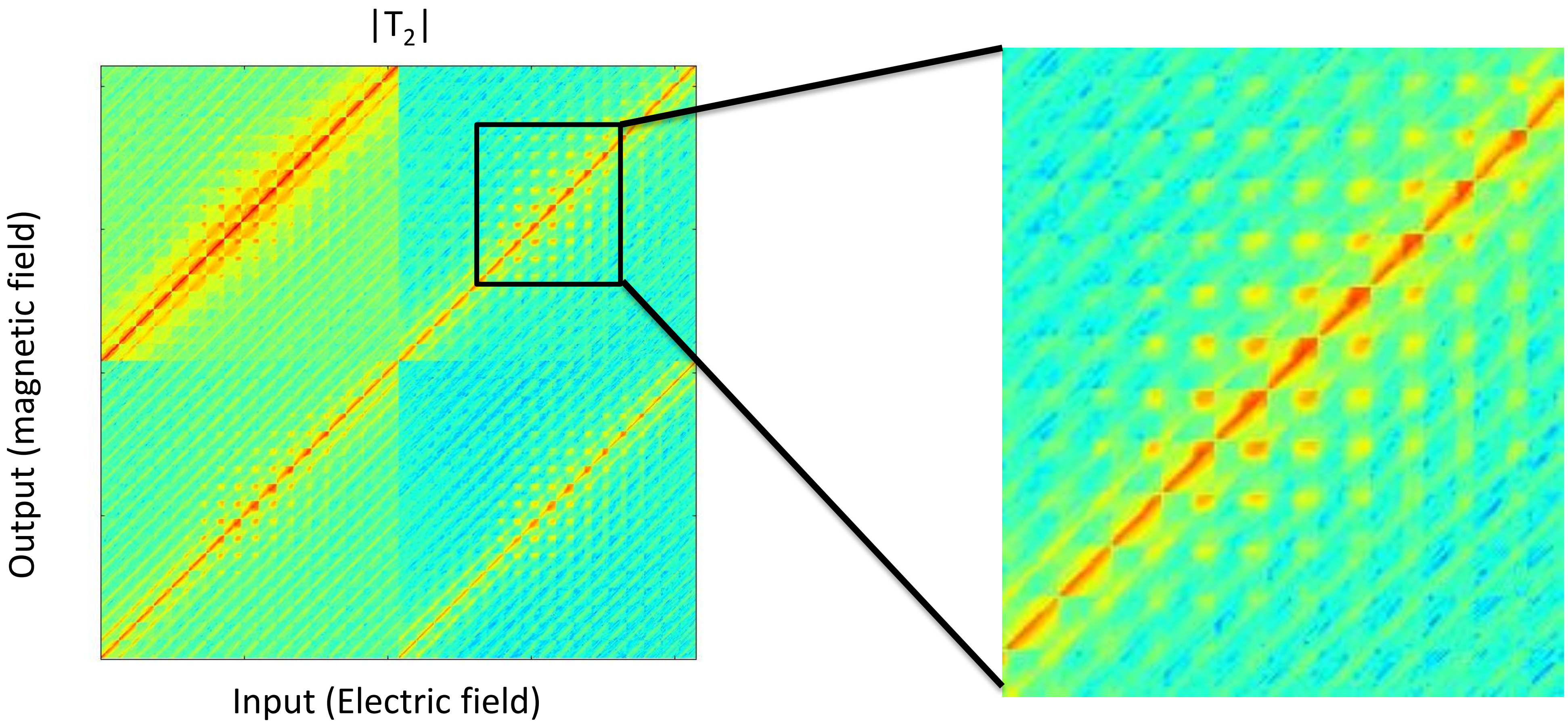


Back



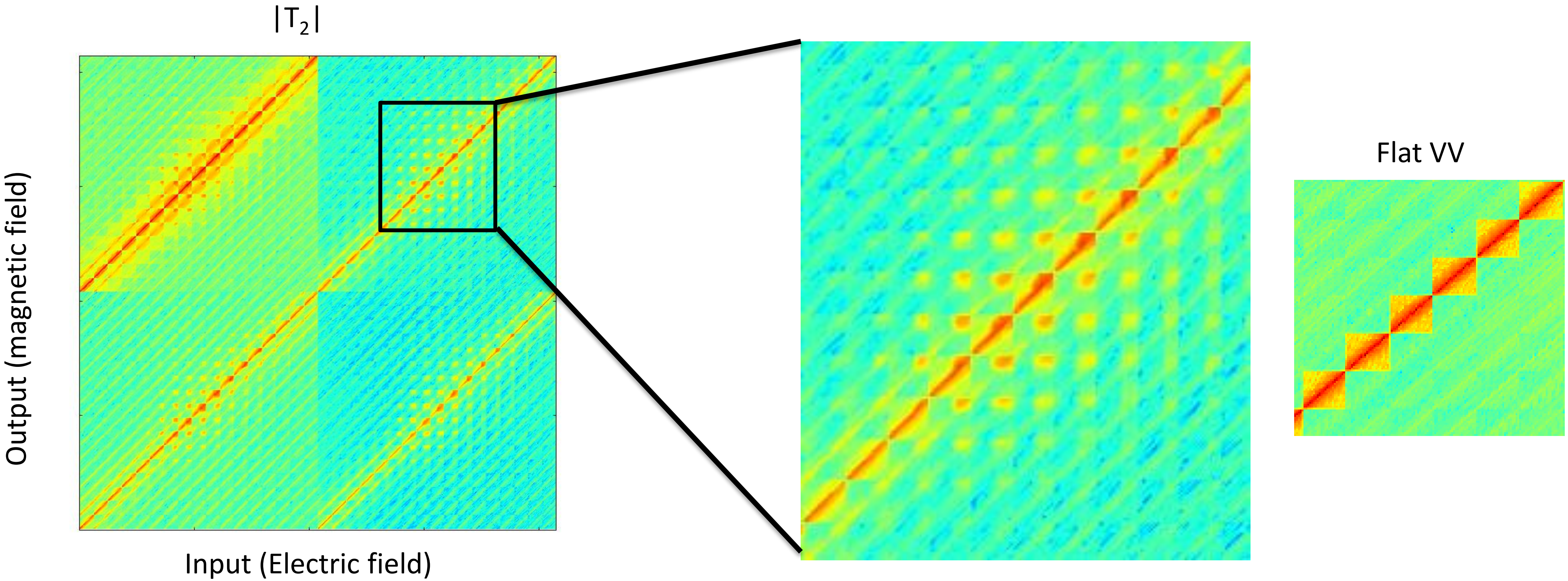
3D antenna structure and SOL plasma (diverted geometry is made from EFIT) is added

3D geometry introduces coupling among toroidal modes.



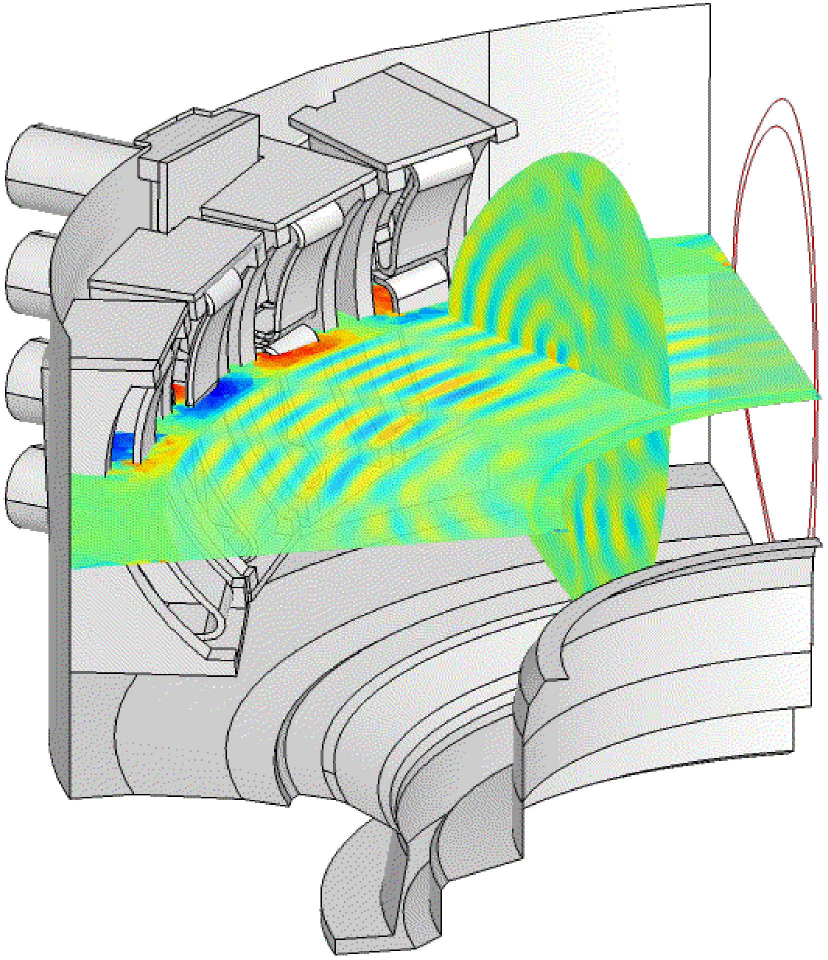
Different toroidal modes communicate each other via surface RF current on the antenna structure

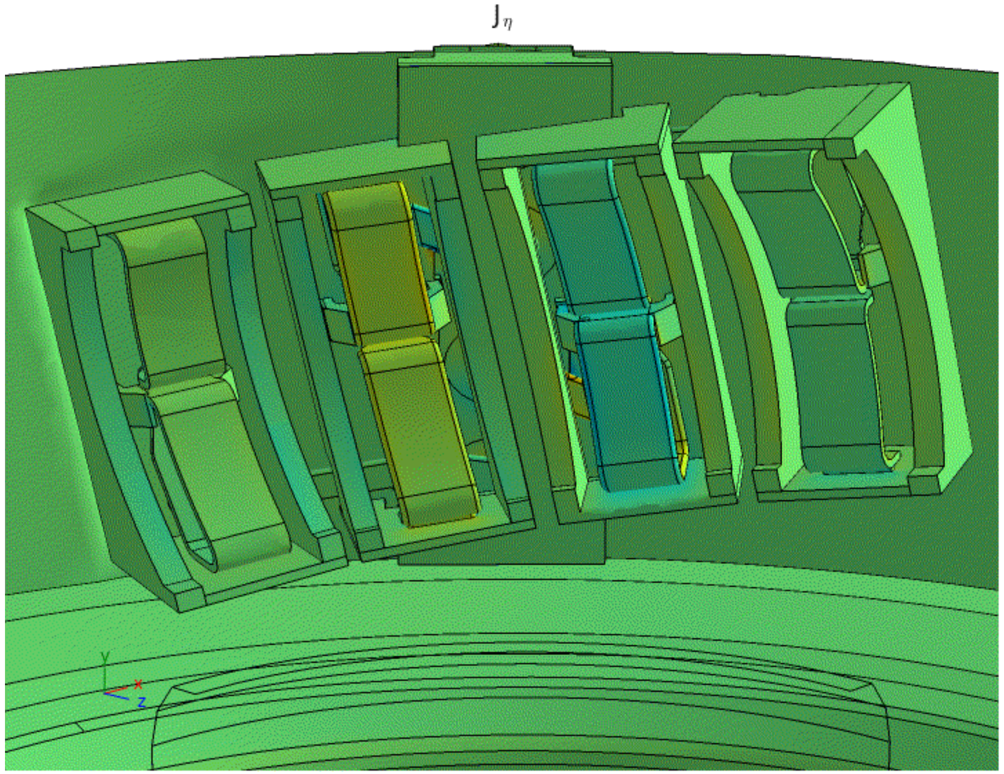
3D geometry introduces coupling among toroidal modes.



Different toroidal modes communicate each other via surface RF current on the antenna structure

Core-edge integrated solution for C-Mod field-aligned ICRF antenna

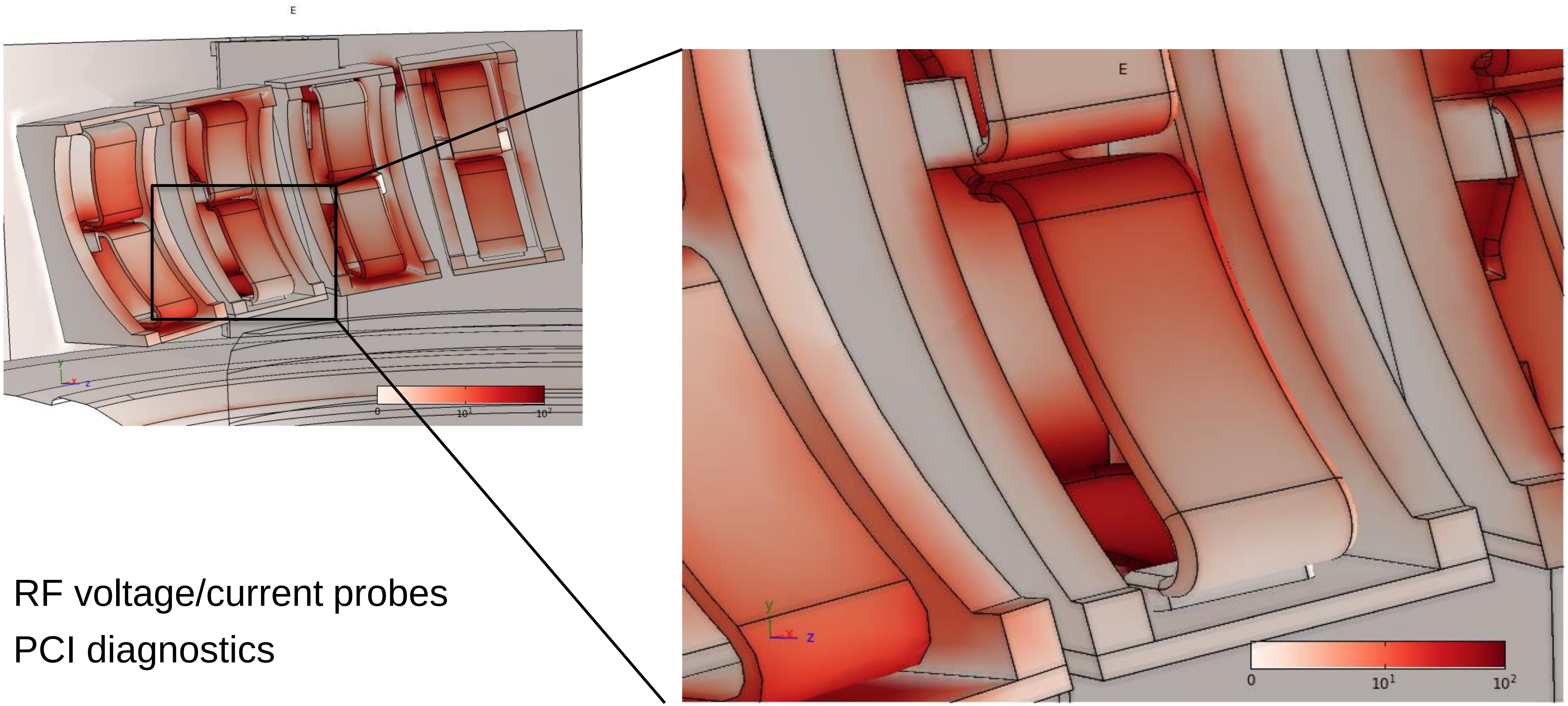




- Wave propagates smoothly from antenna to the core
- Surface currents indicates phasing is not exactly 0-pi-0-pi

Future plan

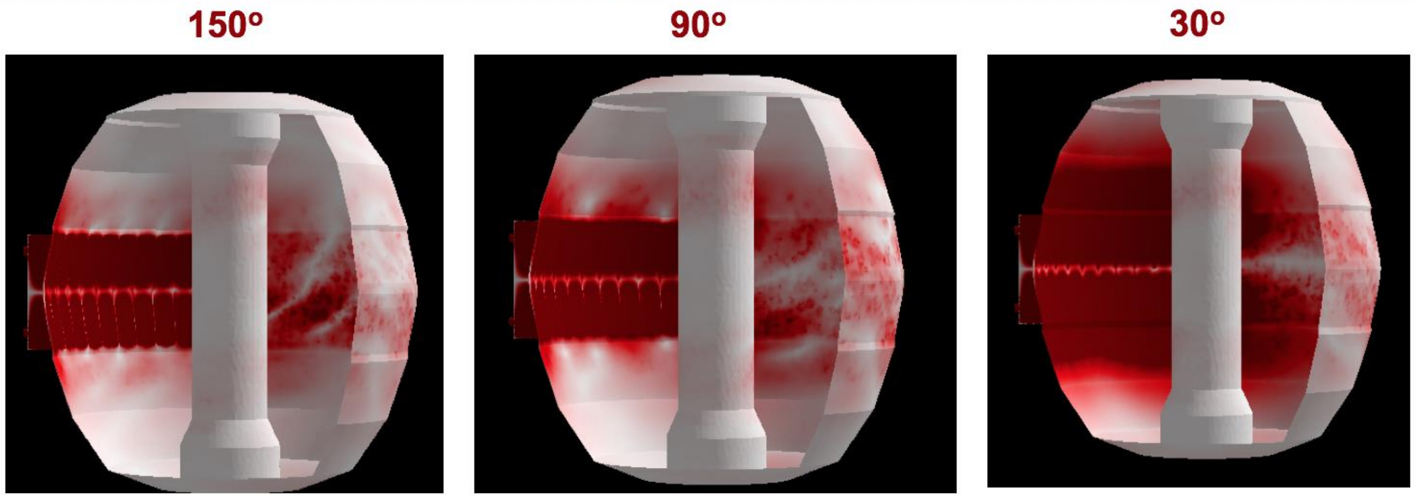
Moving on the validation using existing C-Mod experimental data



- RF voltage/current probes
- PCI diagnostics

… and future experiments

Very strong E field on the wall surface even far away from the antenna



- E field also on the center stack surface
- E field on the surface is stronger for lower antenna phasing
  - Low antenna phasing has also generally a poorer RF heating performance
    - From experiments and AORSA modeling
- Low antenna phasing ⟶ low cut-off density ($n_{cut\text{-}off} \propto N^2_{//}\, B\, \omega$)
- E field on the surface in 3D will be important for studying the antenna impurity generation and RF sheath effects

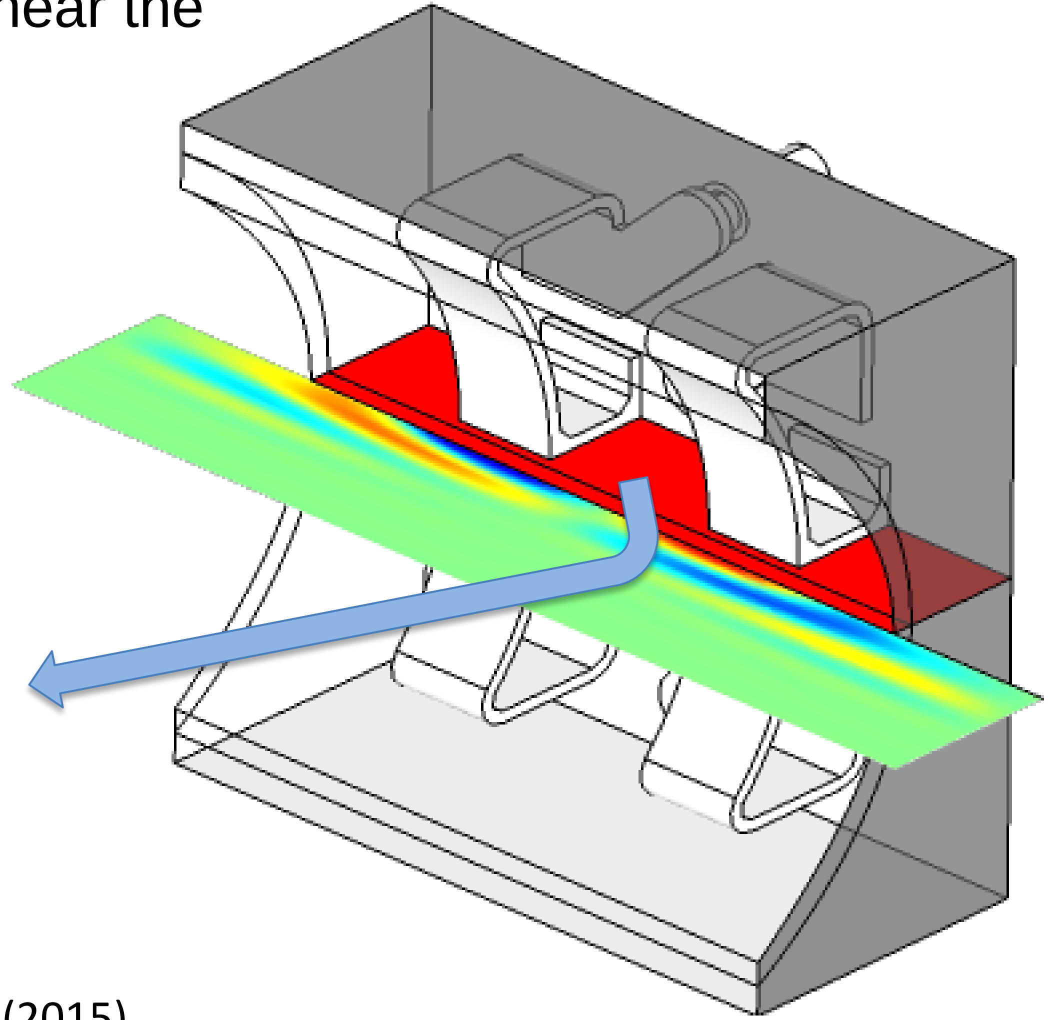
NSTX-U N. Bertelli, et al. , 23rd Topical Conference on Radiofrequency Power in Plasmas. Hefei, China, May 14-17, 2019 23

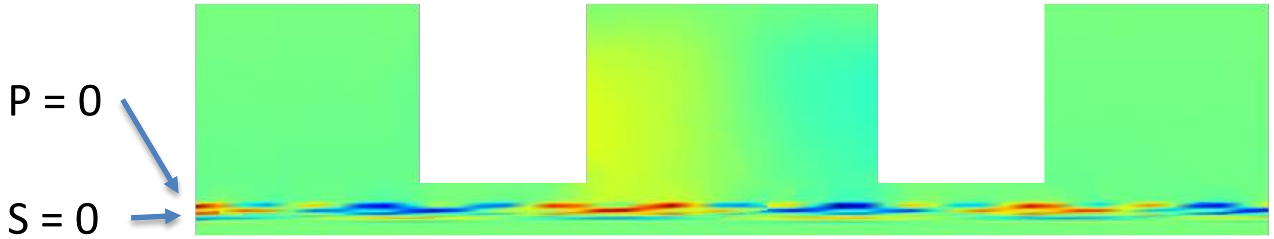
Investigation of slow wave has begun

Slow wave excitation in the low density region near the antenna structure

- has very short wave length
- produces nonlinear RF rectified potential
- responsible for impurity regeneration

Work with J. Myra (Lodestar)





1) J. R. Myra and D. A. D’Ippolito, Phys. Plasmas **22** , 062507 (2015)
2) H. Kohno, J.R. Myra, and D.A. D'Ippolito, Phys. Plasmas **22**, 072504 (2015)

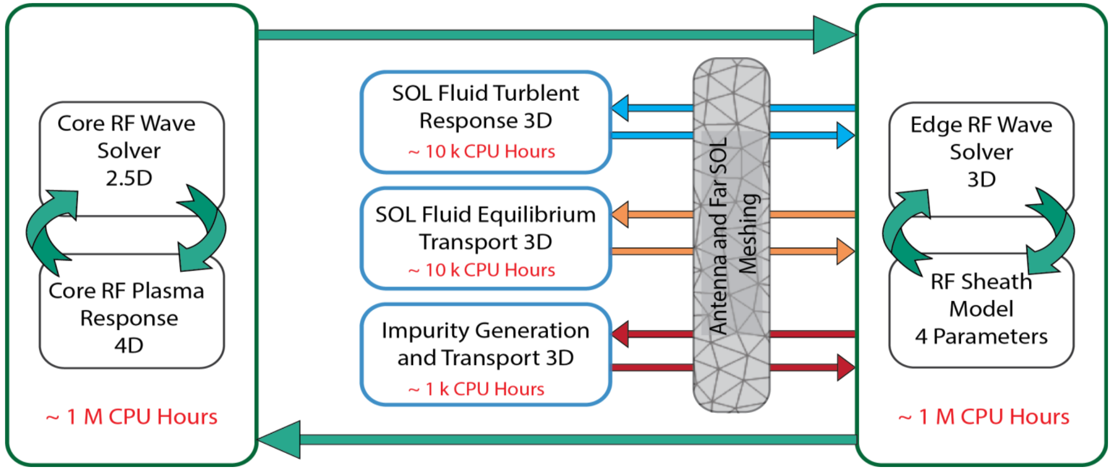
Conclusions

A new RF modeling capability permits exploration of RF wave physics at whole device scale

- Petra-M FEM platform
  - built on the scalable MFEM library
  - designed to be versatile allowing for integrating advanced RF physics such as RF sheath
- Hot core – cold edge coupling
  - built upon existing code infrastructure, algorithms and methods.
  - applicable to any full wave RF simulation in any frequency regime.
- Integrates for the first time, antenna coupling, SOL propagation with realistic geometry, and hot core plasma.

A step towards whole device scale RF modeling

- RF sheath models
- Core Fokker-Planck models
- SOL fluid and turbulence models
- Impurity generation and transport models



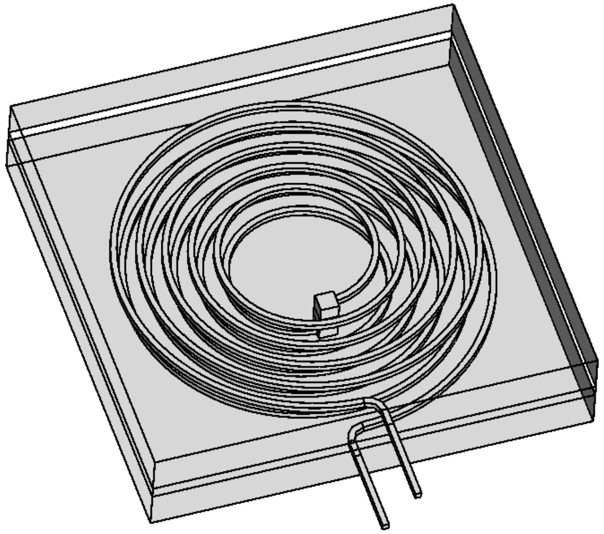
Validation is critical

Collaboration domestic and international

Back up slides

Question : any possible application of Petra-M to different field ?

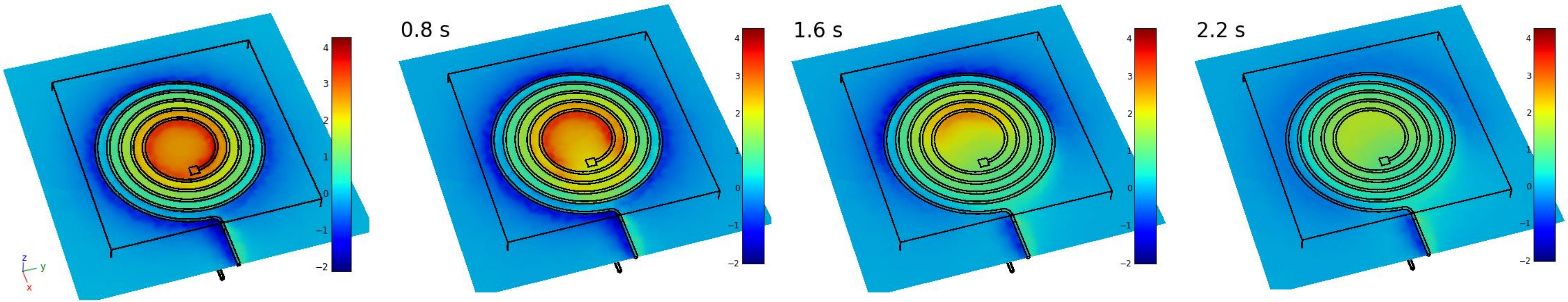
Petra-M is a generic FEM analysis tool, and application is not limited to frequency domain RF. Could be applied to broad range of physics and engineering issues.



HTS magnet modeling

MHD waves

What else?



Investigation of slow wave has begun

Slow wave excitation in the low density region near the antenna structure…

has very short wave length

produces nonlinear RF rectified potential

responsible for impurity regeneration

Work with J. Myra (Lodestar)

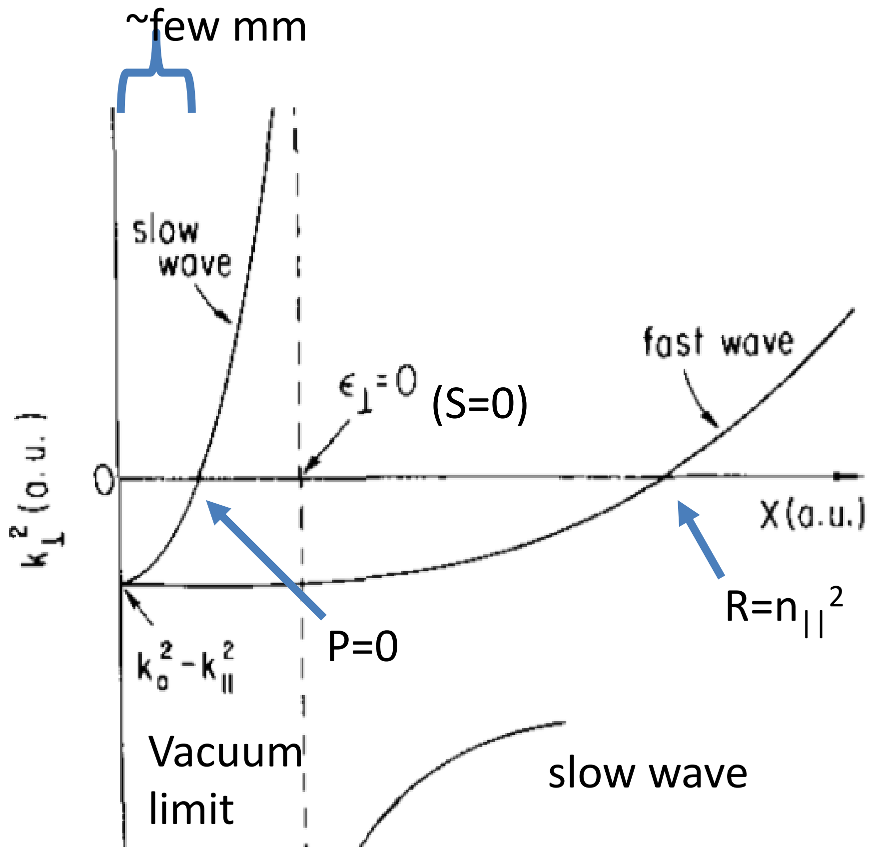


Fig.2 from Berro and Morales IEEE Trans. (1990).

1) J. R. Myra and D. A. D'Ippolito, Phys. Plasmas **22** , 062507 (2015)
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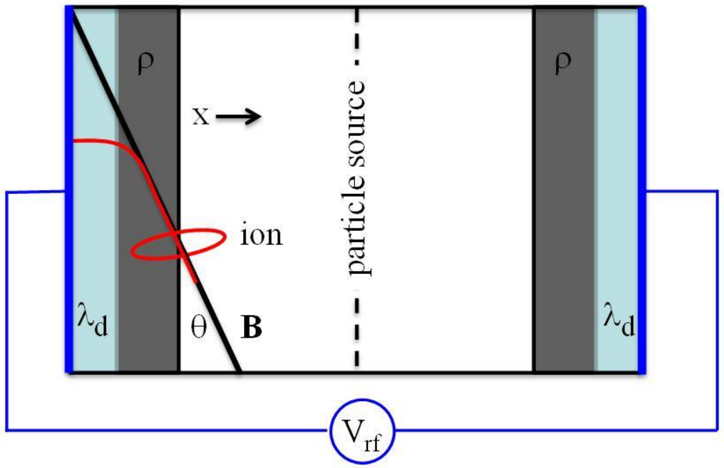
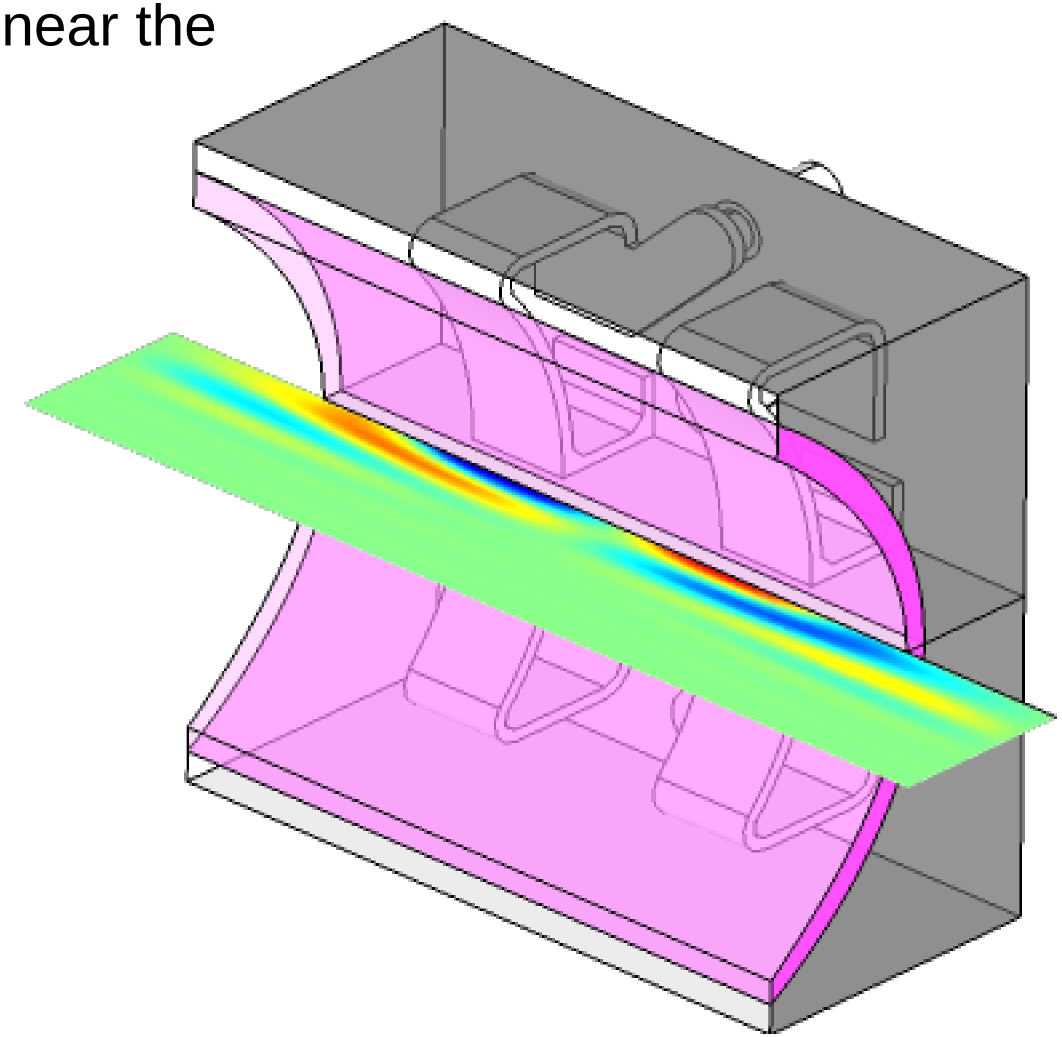
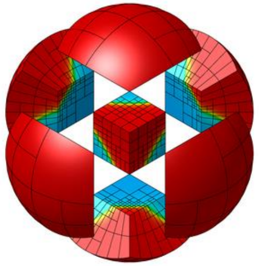




Petra-M (Physics Equation Translator for MFEM)

- Scalable MFEM library
  - http://mfem.org/features



- Petra-M physics based FEM modeling interface

- Workflow management using πScope
  - http://piscope.psfc.mit.edu

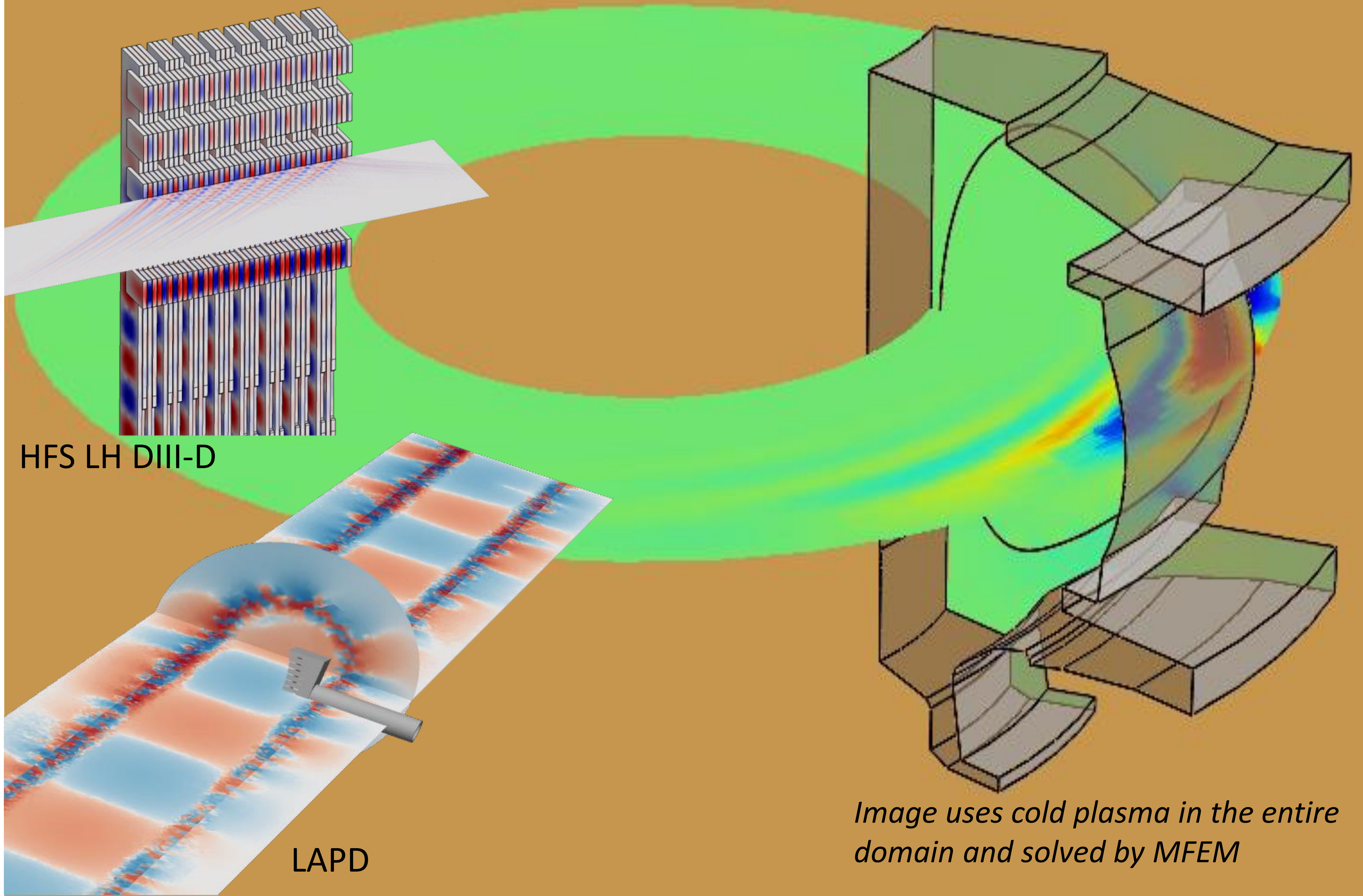


Image uses cold plasma in the entire domain and solved by MFEM

Petra-M (Physics Equation Translator for MFEM)

Geometry/Mesh

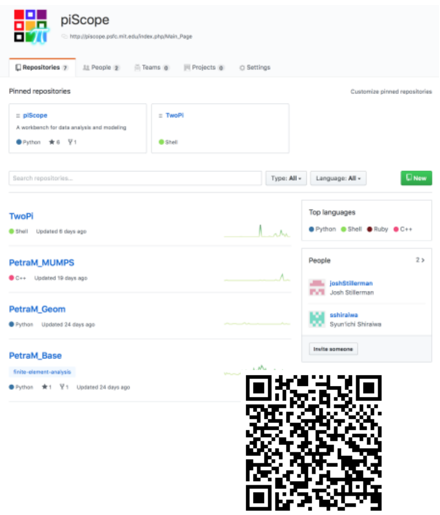
- Procedural geometry/mesh generation in 2D/3D
- NASTRAN file import
- Utilize GMSH/OpenCASECADE for backend
- On-going work to use RPI/Simmetrix mesh tools

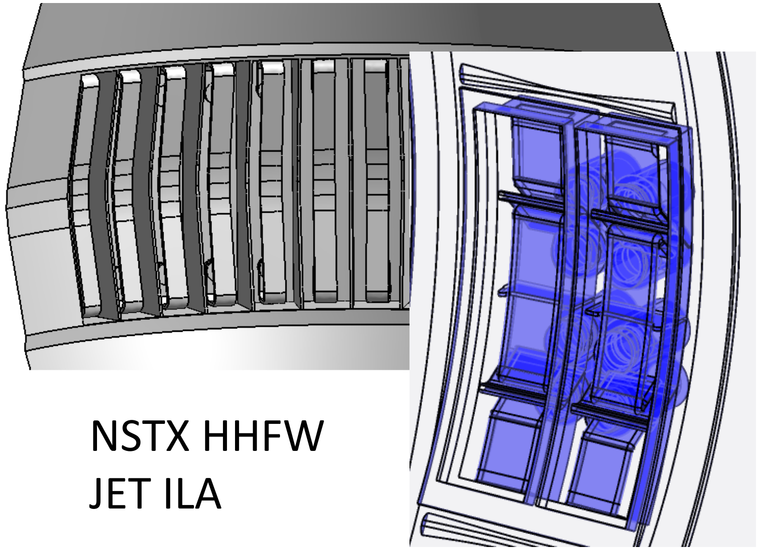
FEM interfaces for MFEM

- Tightly integrated with πScope Python workbench
- RF Physics module
  - 1D/2D axis-symmetric/3D
- Weakform module
  - Multiphysics coupling

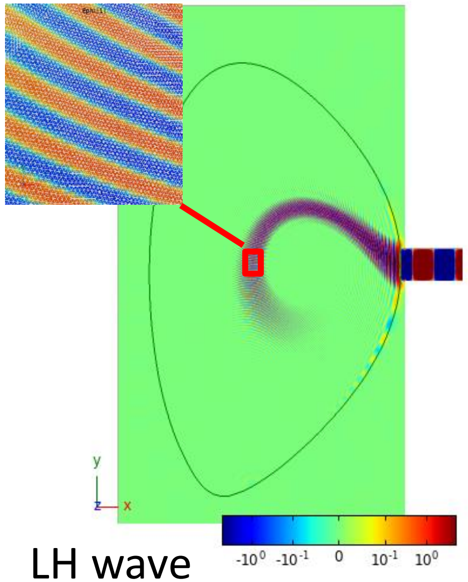
Solver/Post-processing

- Steady State and Time dependent solver
- MUMPS/Strumpack direct solver
- Hypre iterative solvers
- Visualization on πScope

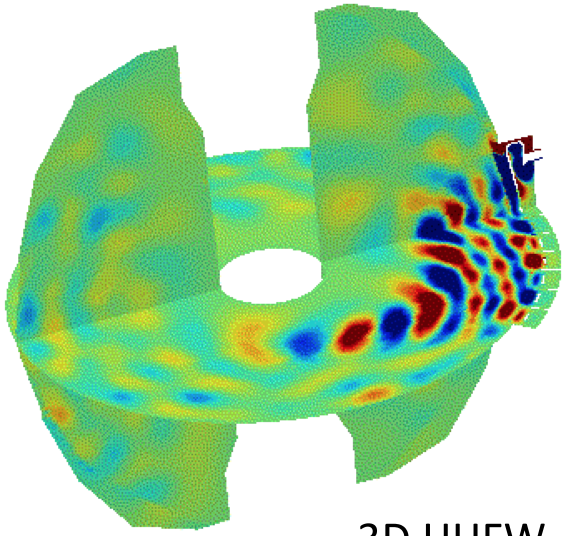




NSTX HHFW
JET ILA

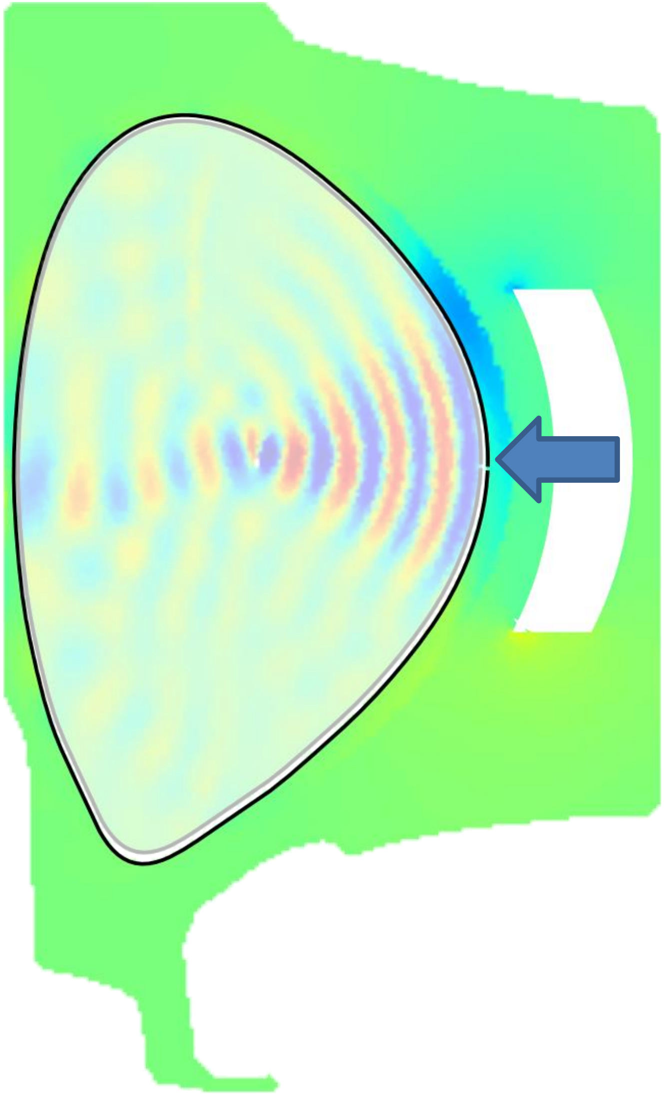


LH wave



3D HHFW

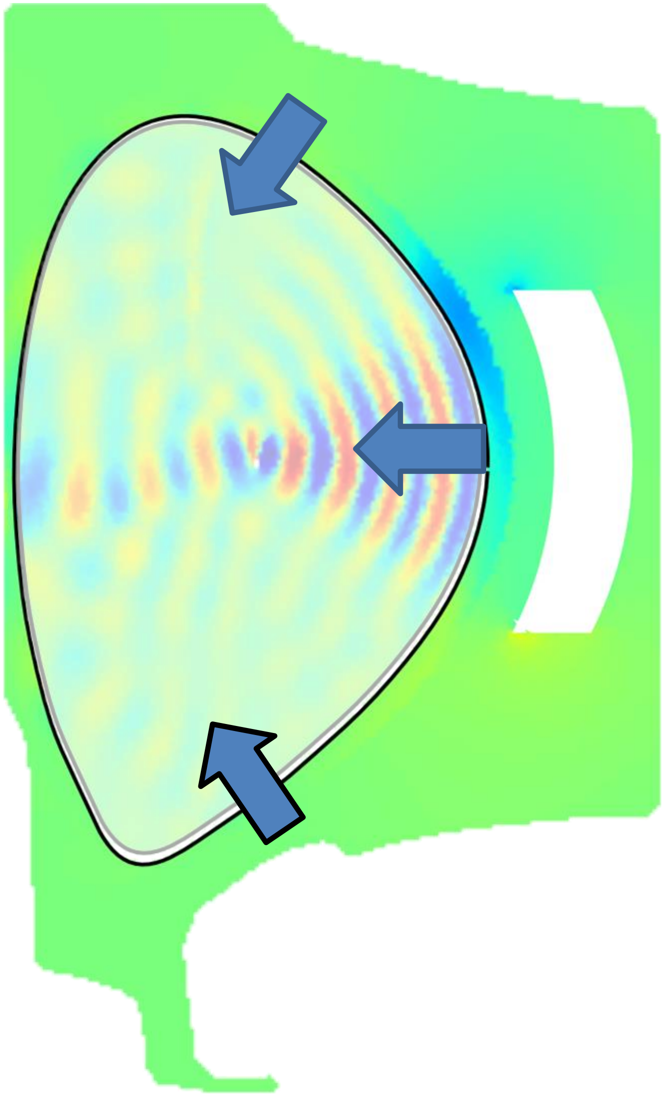
How to stitch to two regions…



Let's follow the power flow….

- Antenna current inject the RF power to SOL

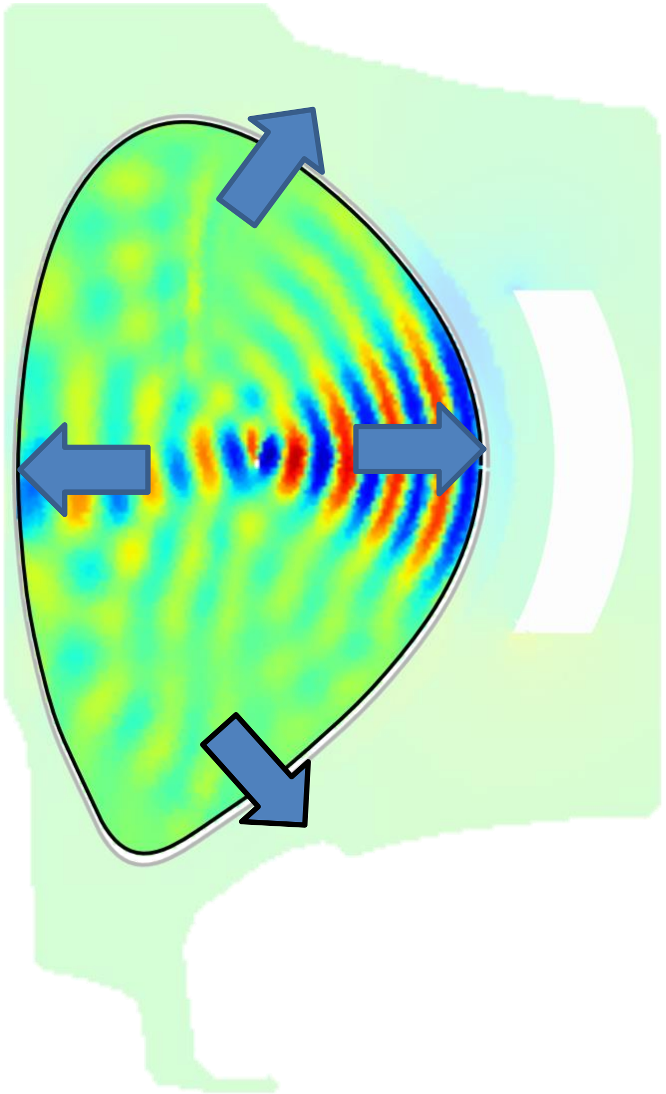
How to stitch to two regions…



Let's follow power flow….

- Antenna current inject the RF power to SOL
- The RF power goes through the SOL and across the connecting boundary to enter the core

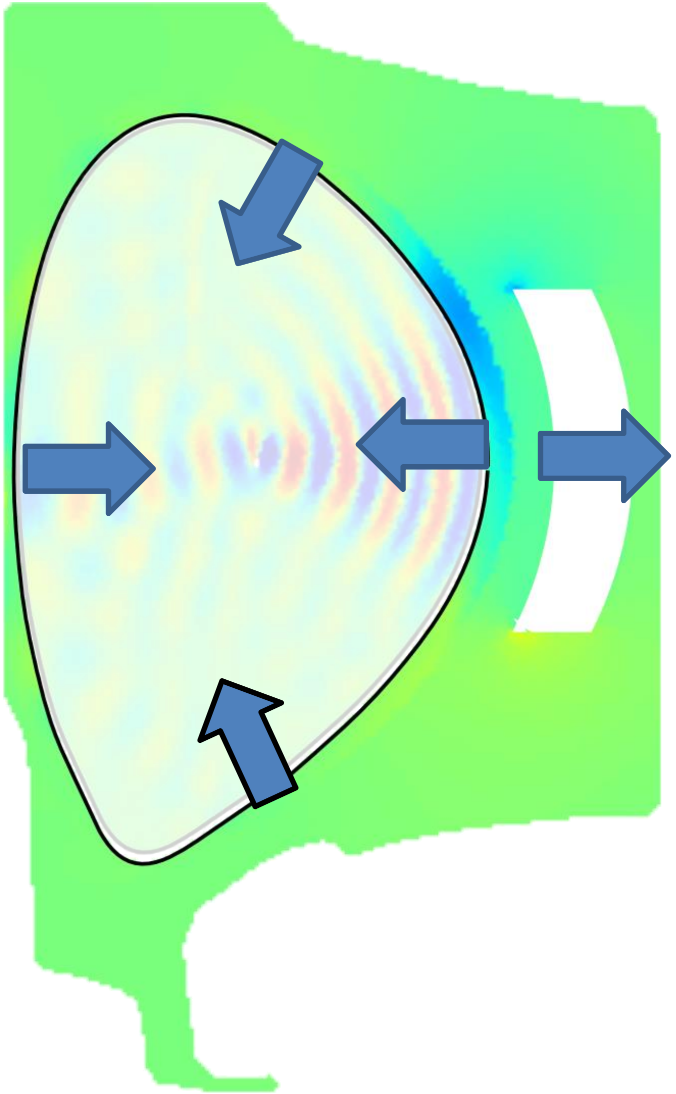
How to stitch to two regions…



Let's follow power flow….

- Antenna current inject the RF power to SOL
- The RF power goes through the SOL and across the connecting boundary to enter the core
- The power not being absorbed comes out to SOL

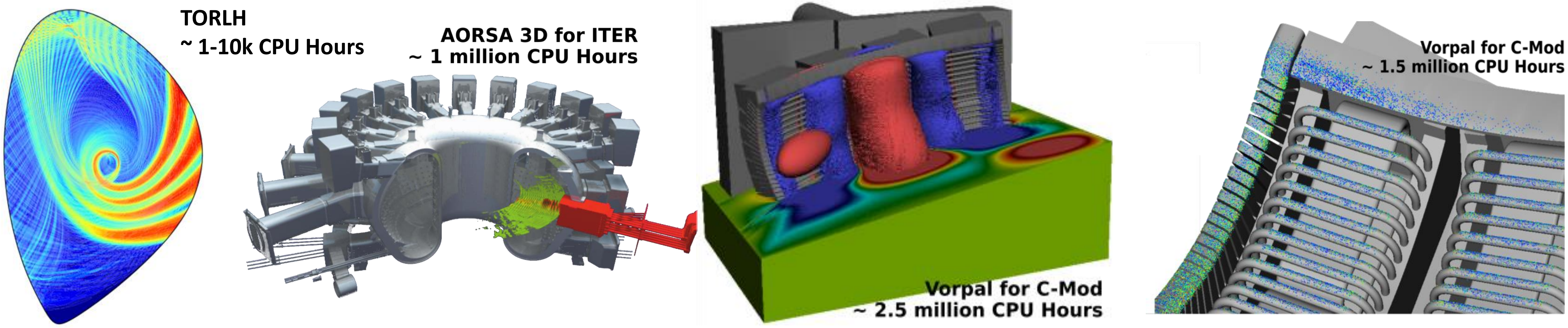
How to stitch to two regions…



Let’s follow power flow….

- Antenna current inject the RF power to SOL
- The RF power goes through the SOL and across the connecting boundary to enter the core
- The power not being absorbed comes out to SOL
- The power is sent back to core or to the transmitter

Leading-class computing facilities allow for RF wave physics simulations in core and edge regions with great detail



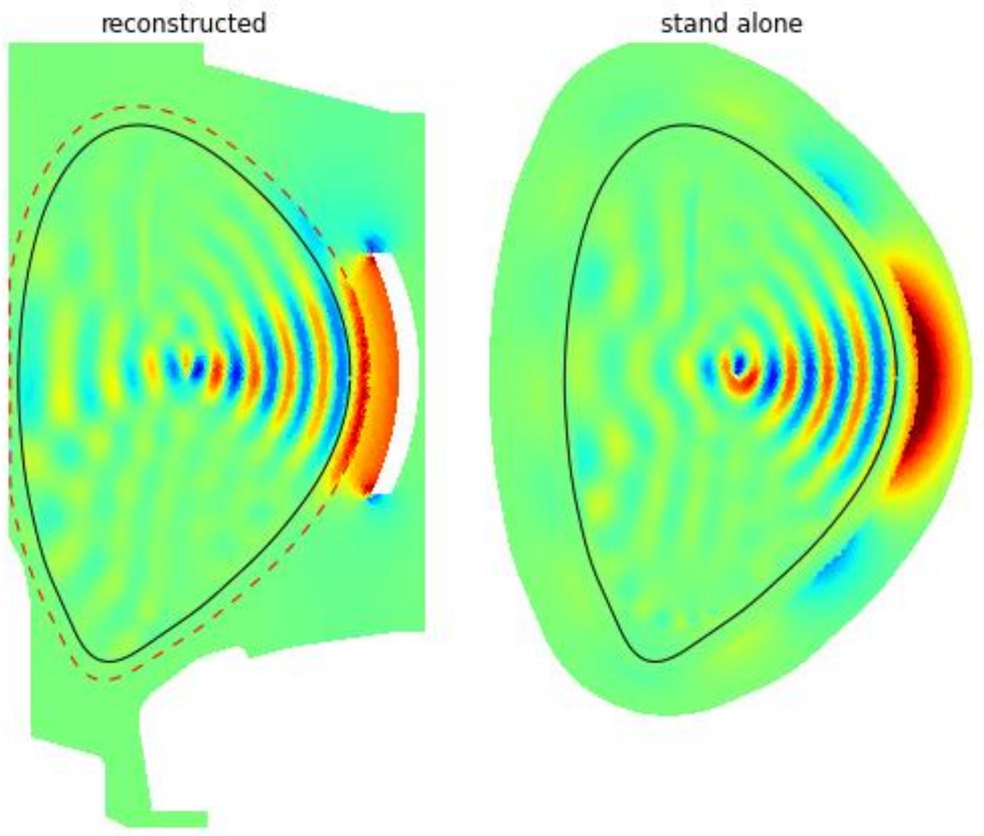
RF wave propagation and absorption including linear and non-linear effects

- Full wave spectral code simulations of core LH and IC waves
- FDTD (finite difference time domain) simulation of ICRF antenna on C-Mod

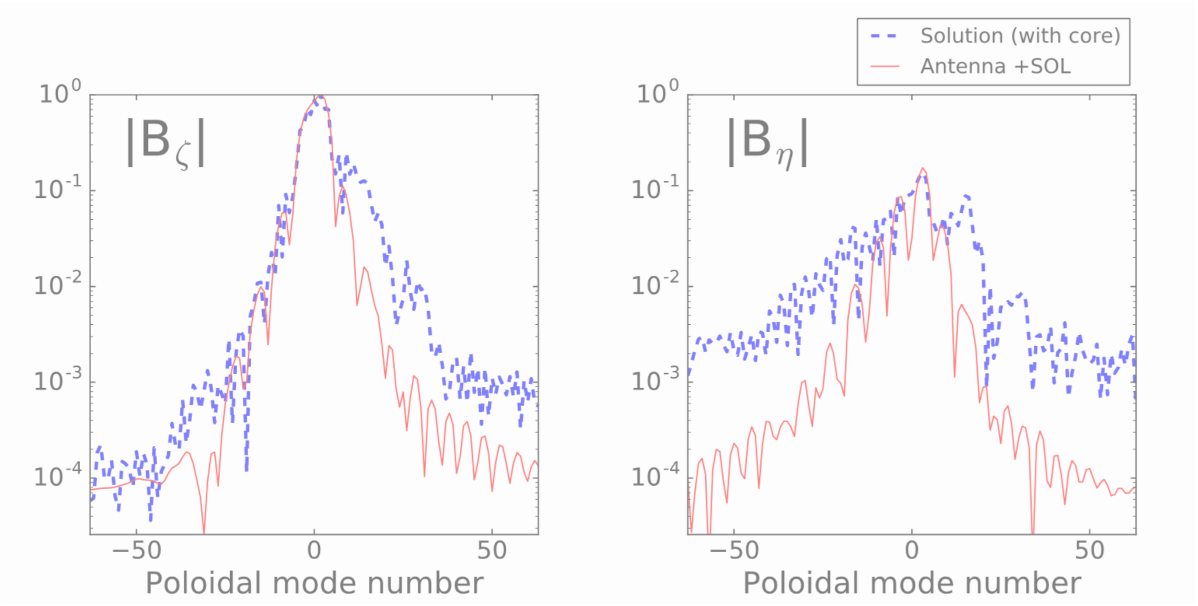
These models are now being able to couple RF non-linear effects such as modification of velocity distribution function and RF sheath rectified potential.

However, core and edge regions are modeled separately…

The reconstructed solution is very similar to a standalone TORIC simulation.



- In the core region, the superimposed solution (left) agrees well with the core solution of TORIC stand alone simulation (right) providing verification of the method.
- There is only vacuum outside LCF.



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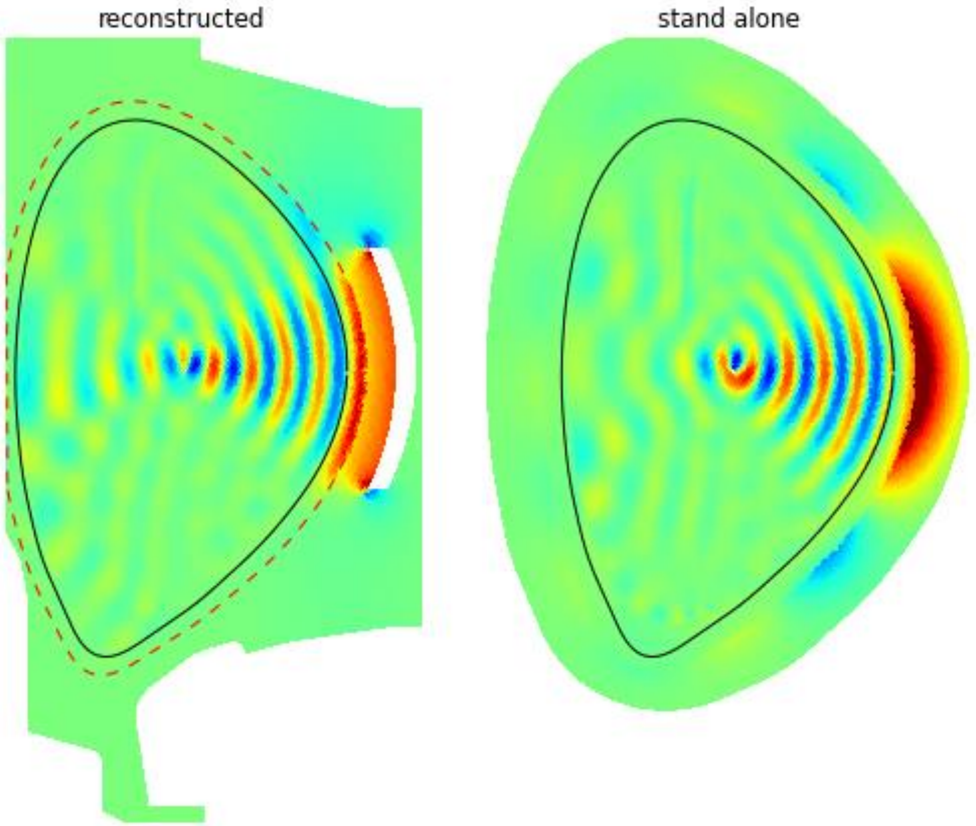
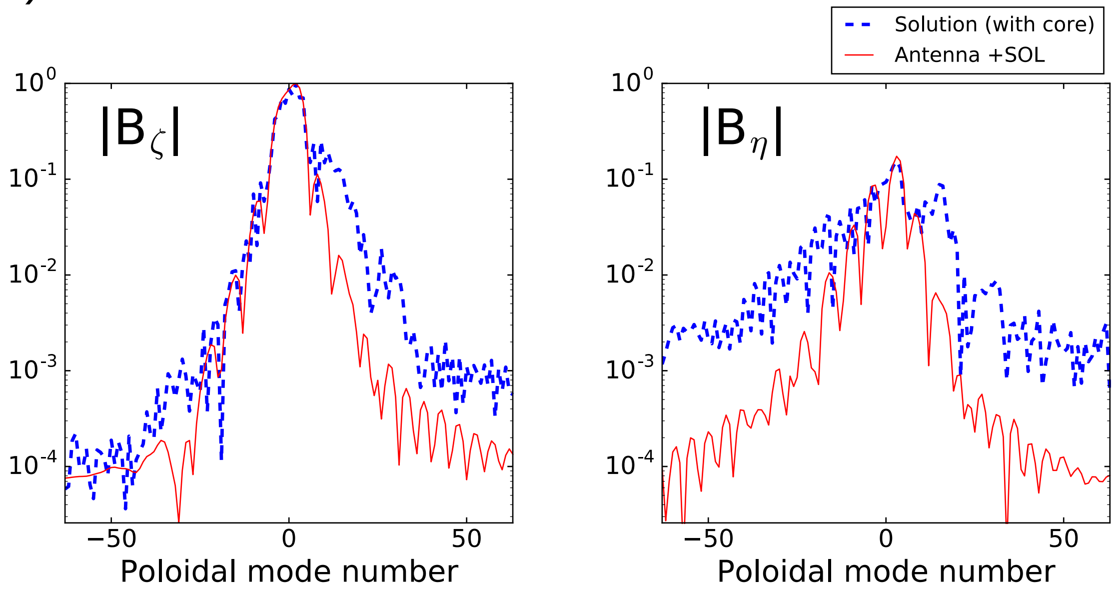


- In the core region, the superimposed solution (left) agrees well with the core solution of TORIC stand alone simulation (right) providing verification of the method.
- There is only vacuum outside LCF.
- Mode amplitude of superimposed solution (blue) spread wider than the antenna excitation amplitude (red).



Our HIS formulation extends to 3D naturally

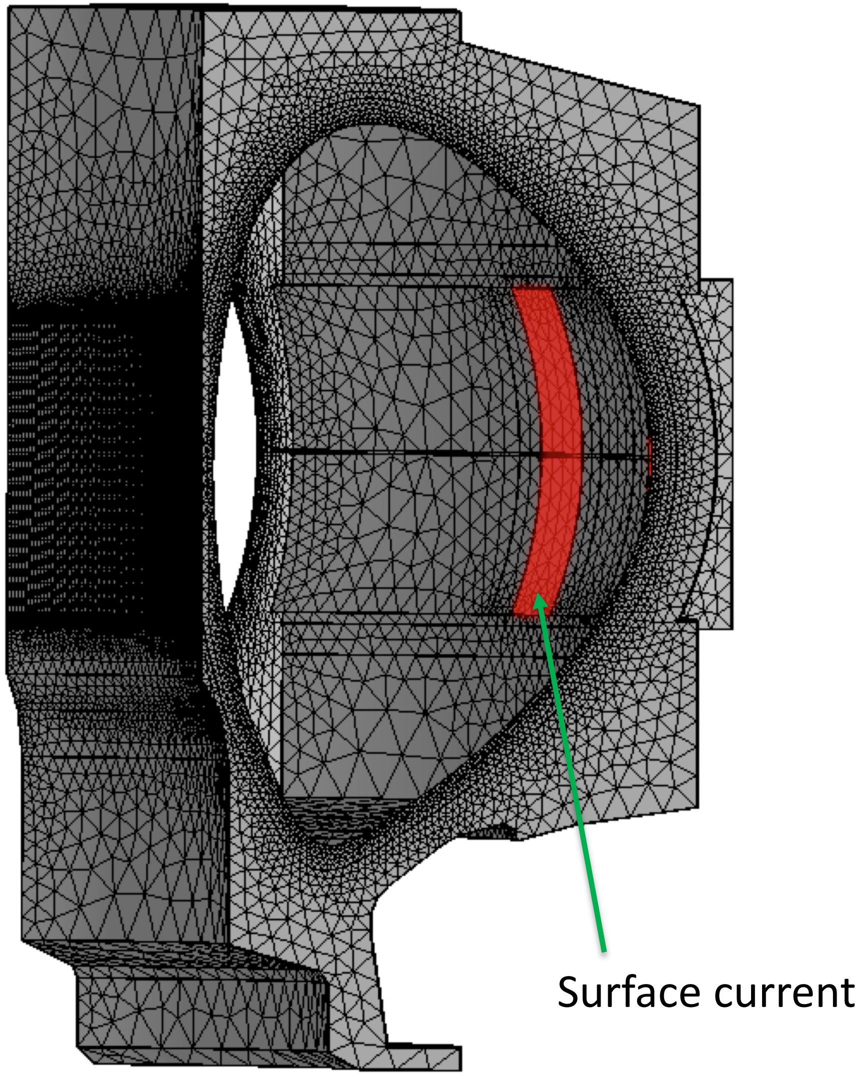
However, significantly larger resources are required

Geometry made by revolving previous poloidal cross section.

- 60 deg vessel section
- two strap antenna

Even a FE mesh, which is fine enough to resolve only the relatively long wavelength fast waves, yields a linear problem with ~5 M DoF.

Expecting 30 M ➔ 100 M DoF for resolving slow waves.



1342 x 2 solutions