NSTX-U

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U.S. Department of Energy Office of Science
Fusion Energy Sciences

3D full wave fast wave modeling with realistic antenna geometry and SOL plasma

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and RF SciDAC Team

20th International Spherical Torus Workshop (ISTW-2019)
Bruno Brunelli Hall - ENEA Frascati Research Center, Italy, Oct. 28-31, 2019

PPPL MIT RF-SciDAC

Outline

- Introduction and motivation
- Petra-M & MFEM
- 3D HHFW simulations in NSTX-U plasma
  - Mesh details
  - Full 3D torus simulation + different antenna phasing
  - Petra-M + SPIRAL: first results
- Conclusions and future steps

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Interaction RF waves with SOL plasma

- The interaction between the SOL plasma and the RF waves is important for all frequency regimes
  - EC: edge density fluctuations could affect the EC beam with possible deleterious effects for NTM suppression
  - LH waves: edge density fluctuations, collision, PDI can affect the LH wave penetration in the core
  - **IC & HHFW: edge density fluctuations, RF sheaths, etc. can affect the IC & HHFW performance (loading, coupling)**

NEED TO STUDY AND UNDERSTAND THIS INTERACTION

Combine RF wave physics in core and edge plasma regions

- Our community has "well-established" tools for hot core plasma
- However, we need to incorporate the SOL region
  - With a realistic antenna geometry
  - In 3D geometry
  - With SOL physics
- Here we show a recent tool, Petra-M, developed within the RF SciDAC project (https://sites.google.com/view/rfscidac4/) and SPARC (CFS) (https://www.psfc.mit.edu/sparc)

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Petra-M (Physics Equation Translator for MFEM) is an integrated FEM analysis environment

Geometry/Mesh generation
Physics equation setting
FEM assembly
System equation solve,
Plotting

πScope

Python (Physics)

RF | Thermal | Eddy | Weakform

Common module framework

Main developer:
S. Shiraiwa (MIT)

C++/Fortran (Math)

GMSH | PUMI/ Simmetrix | PyMFEM | MFEM | Hypre | MUMPS | Strumpack

S. Shiraiwa, et al., EPJ Web of Conferences **157** , 03048 (2017), APS 2017

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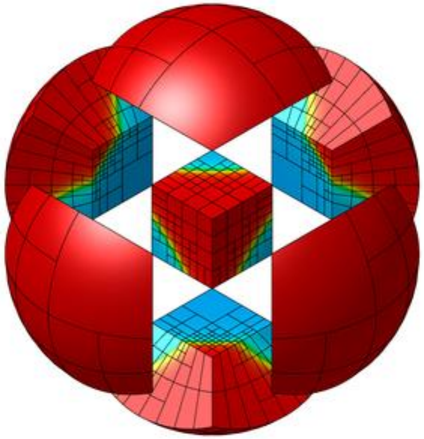
What is MFEM?

- *A free*, *lightweight*, *scalable* library for finite element methods (see http://mfem.org/features for detail)
  - Higher-order Finite Element Spaces: H1-, H(div)-, H(curl)-conforming spaces, L2, Discontinuous Galerkin spaces
  - Triangular, quadrilateral, tetrahedral and hexahedral elements
  - Tightly integrated with Hypre scalable solver library
  - MPI-based parallelism throughout the library
  - Various examples including Maxwell. eq.
  - Written in C++.
  - GPU implementation has been recently released
- Powerful library
- Developed by LLNL



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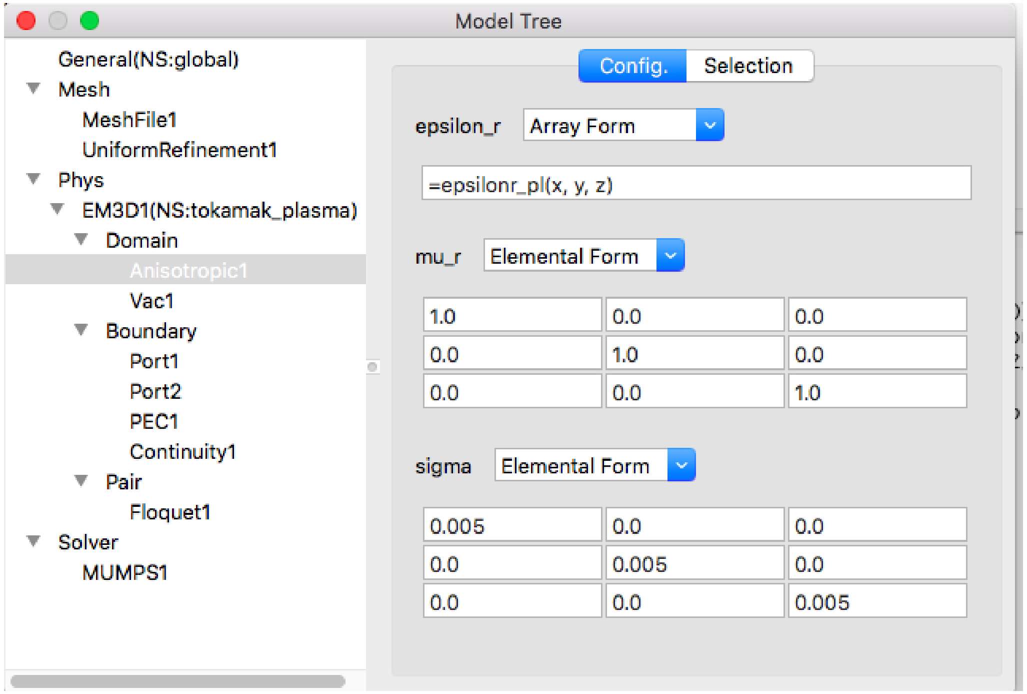
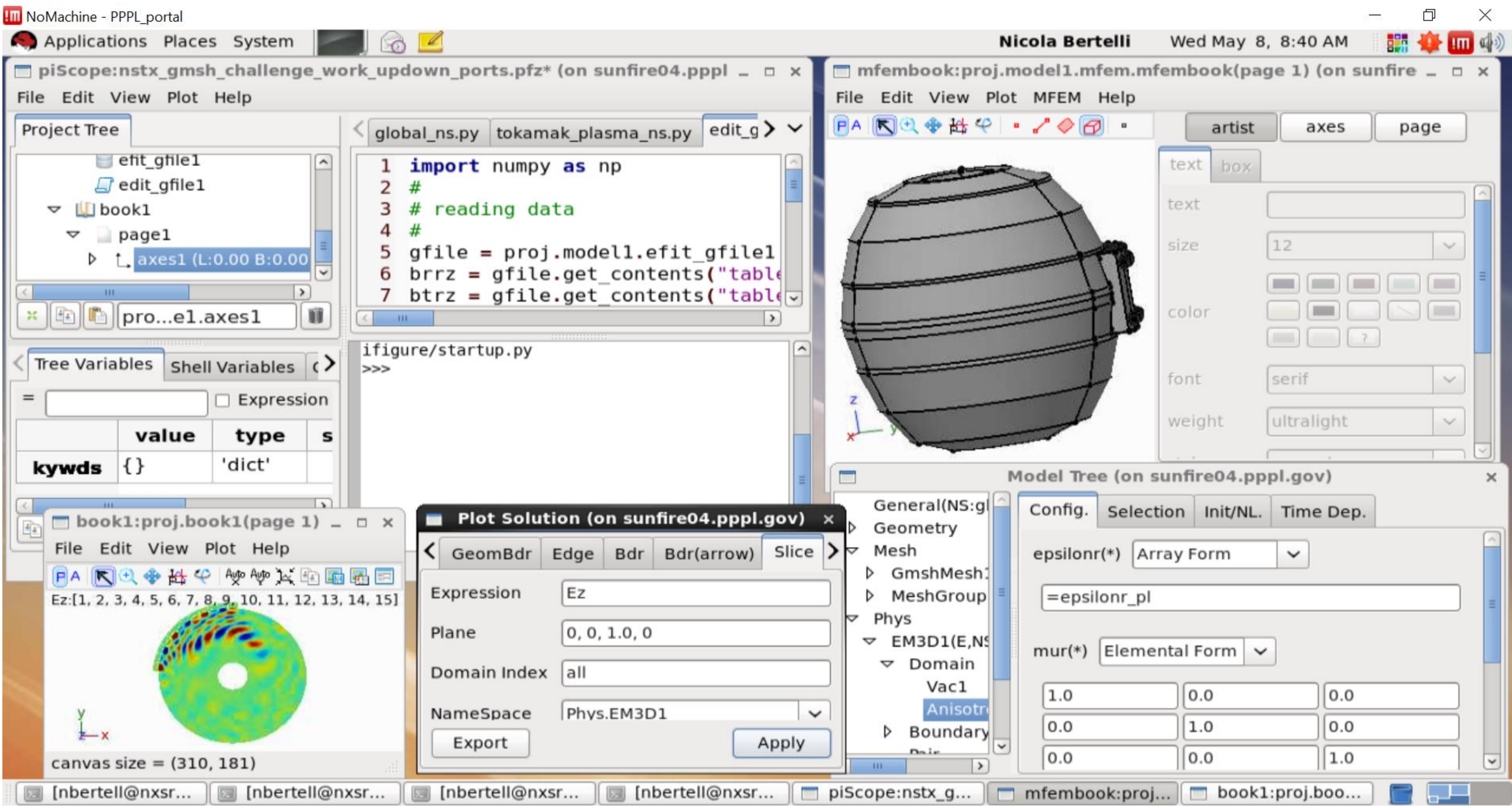
S. Shiraiwa, et al., EPJ Web of Conferences **157** , 03048 (2017), APS 2017

RF/EM3D physics layer

- Solve inhomogeneous Maxwell eq. in 3D in frequency domain
  - Cartesian coordinate system
  - Time harmonics term follows the physics convention : ~exp(-iωt)
- Domain
  - Uniform dielectric media
  - Anisotropic (matrix) media
  - External J
  - DivJ constraints in vacuum
- Boundary
  - Perfect electric conductor (Et=0)
  - Perfect magnetic conductor (Bt=0)
  - Waveguide port (TE, TEM modes, Coax)
  - Periodic boundary
  - Surface current/Magnetic field/Electric field



Petra-M: on the screen



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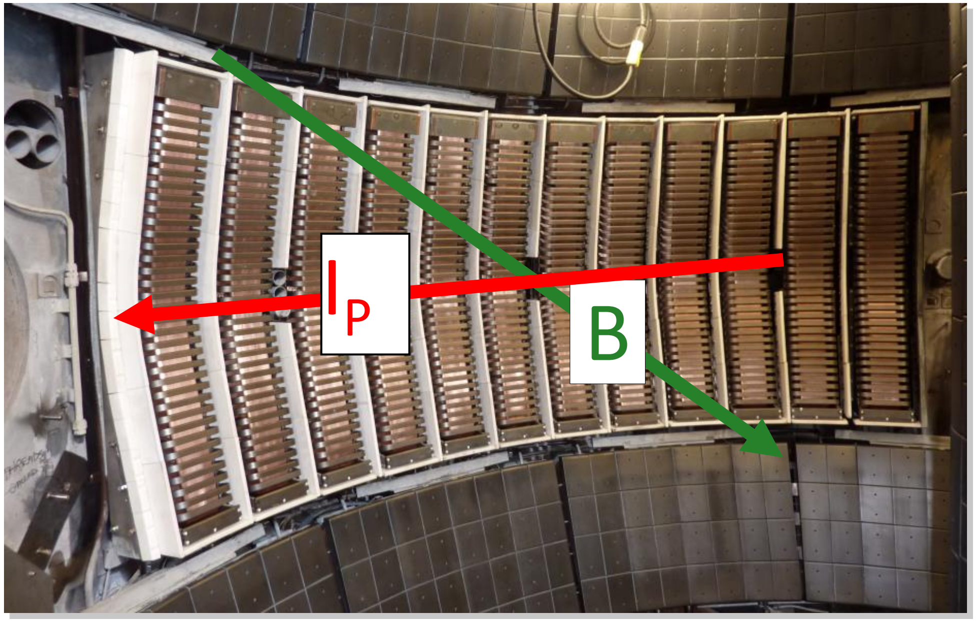
High Harmonic Fast Wave System in NSTX-U

- 12-strap antenna located on the outboard midplane and extends 90º toroidally

- Wave frequency = 30 MHz, up to P_{RF} = 6 MW

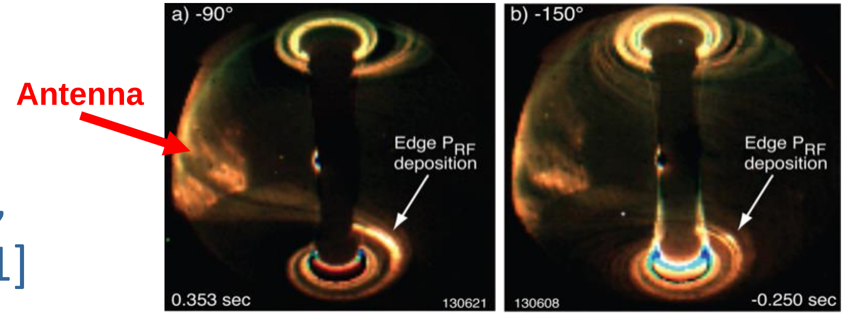
- Well-defined spectrum

- $|k_\phi|$ = 3, 8, and 13 m^{-1}
  or
  n_ϕ = 5, 12, and 21
  when
  $\Delta\phi$ = 30º, 90º, and 150º



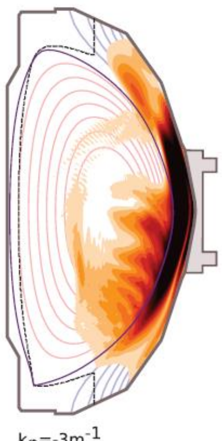
Previous studies of heating efficiency showed large amounts of HHFW power missing from core

- Strong interactions between HHFW and SOL plasma
  - [J. C. Hosea, et al., PoP 15 (2008) 056104,
  - R. J. Perkins, et al., PRL 109 (2012) 045001]

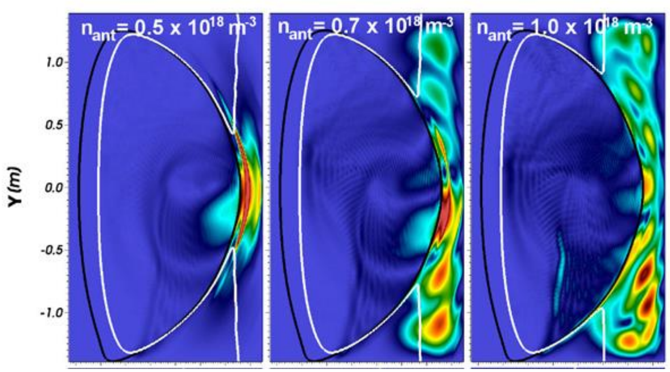


NSTX: Visual images of the RF "hot" zone.

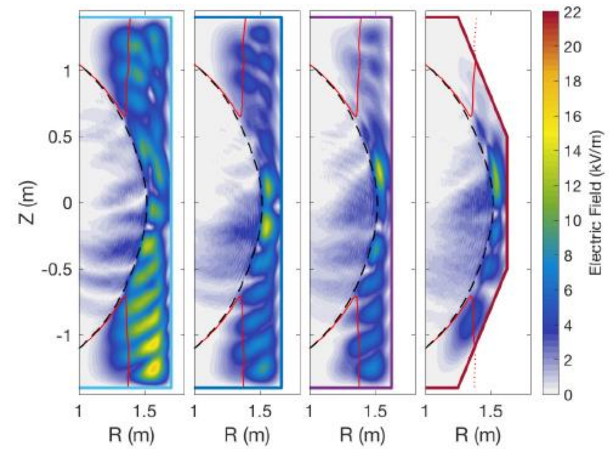
- Larger SOL losses for high plasma density in front of the antenna
- 2D AORSA simulations shown cavity modes in SOL plasma



Green, et al, PRL 2011



Bertelli et al, NF 2014



Kim et al, accepted to PoP 2019

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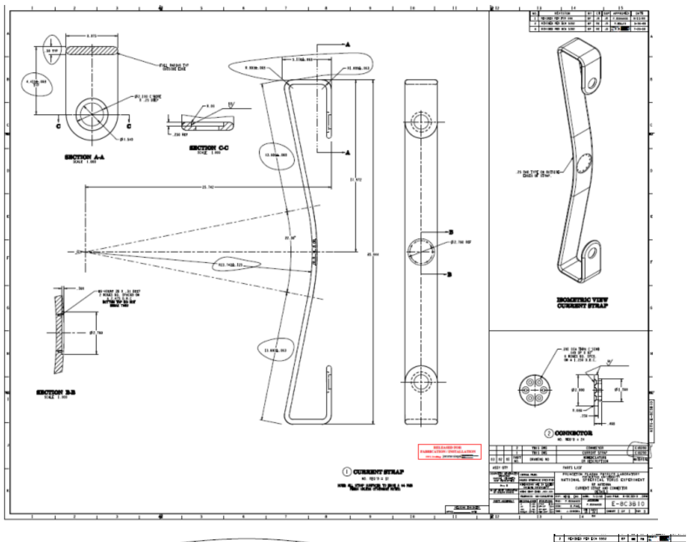
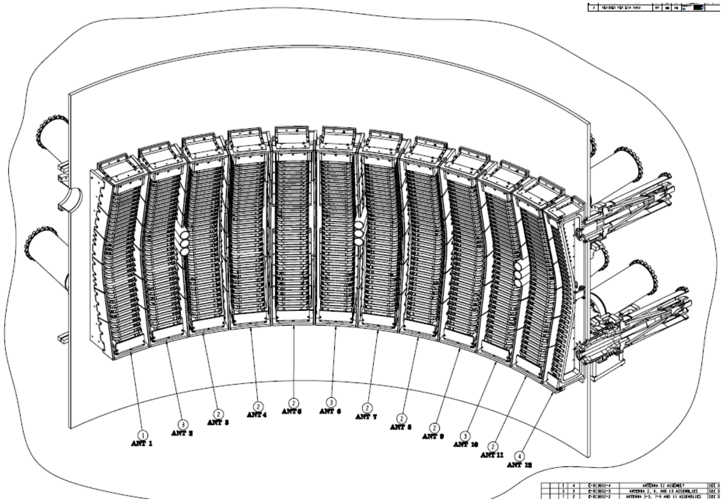
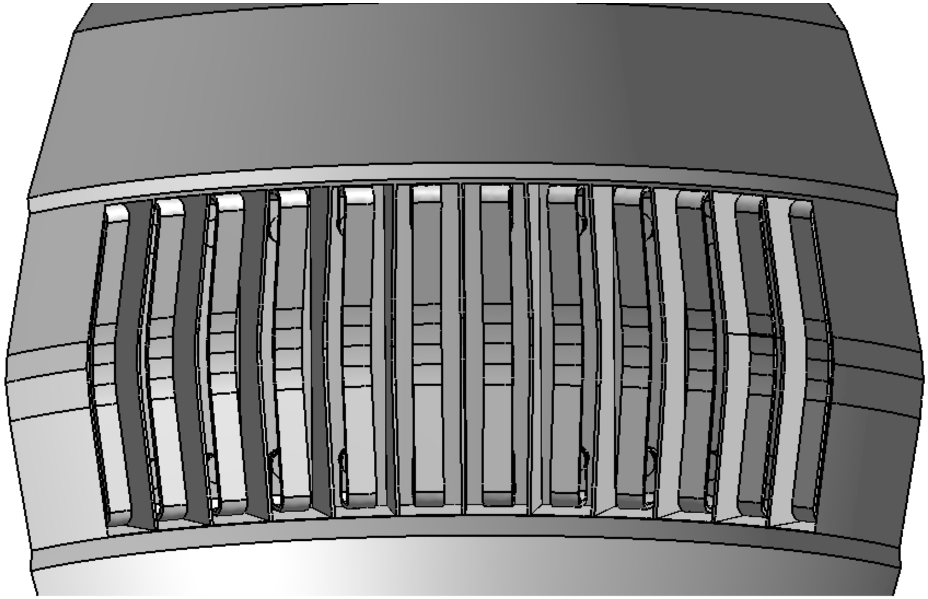
Build the NSTX-U and HHFW antenna meshes

- From antenna drawings to antenna mesh



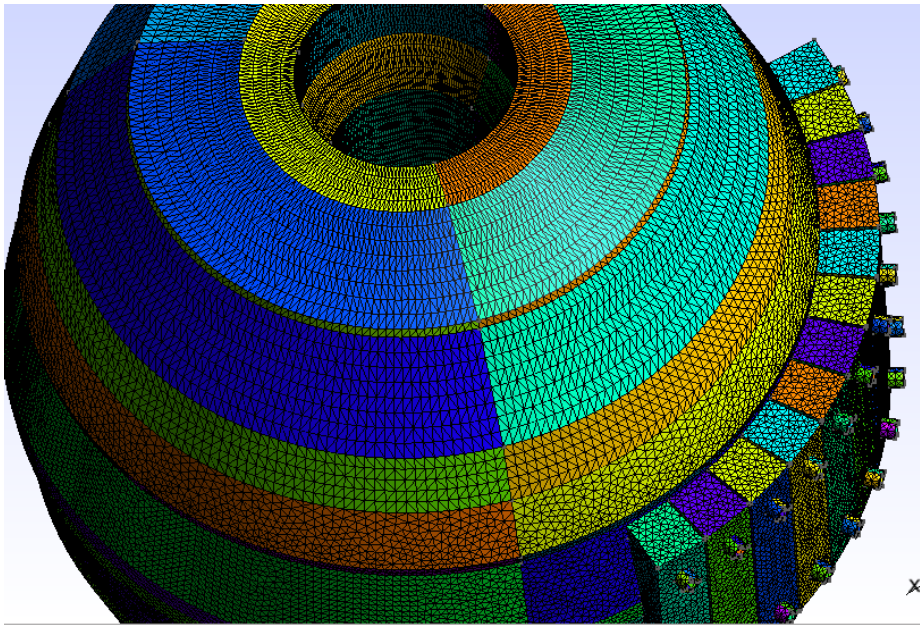


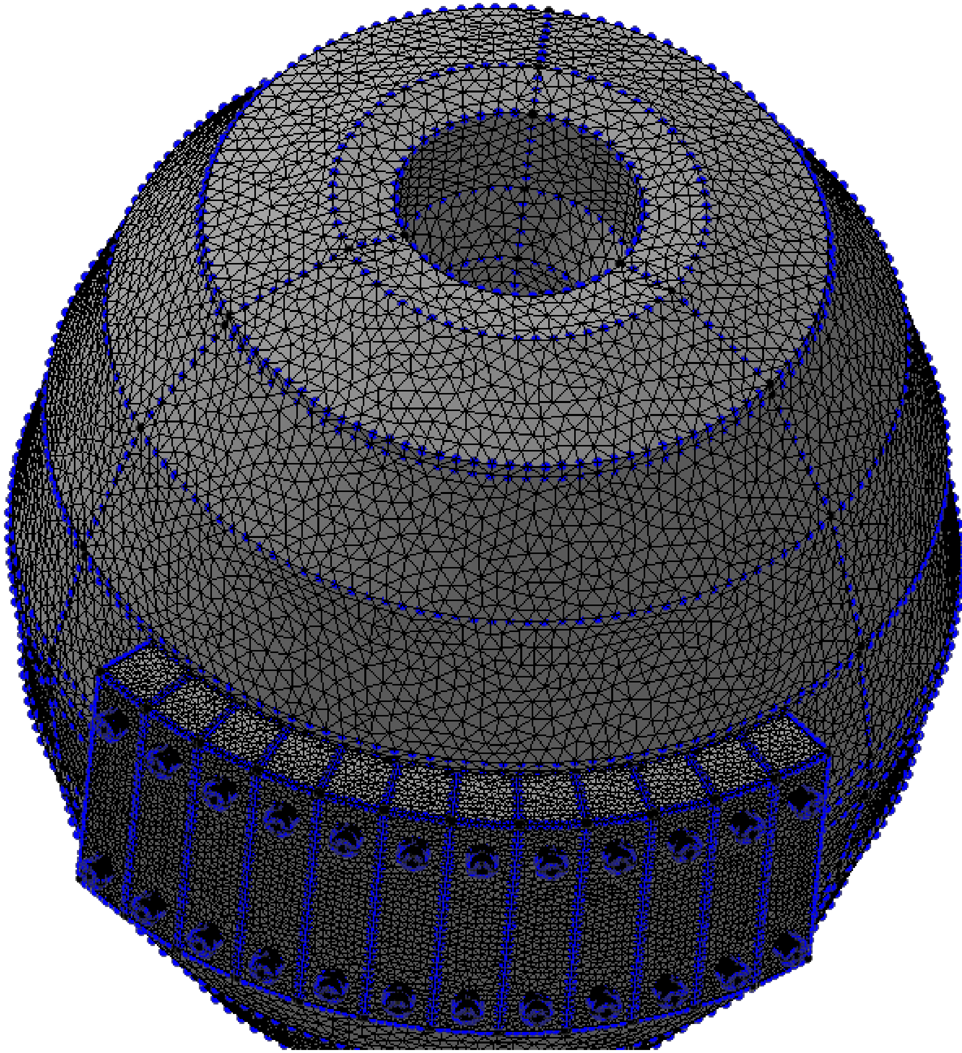
Used GMSH in Petra-M



NO Faraday screen included yet

3D mesh for NSTX-U (geometry from EFIT file)





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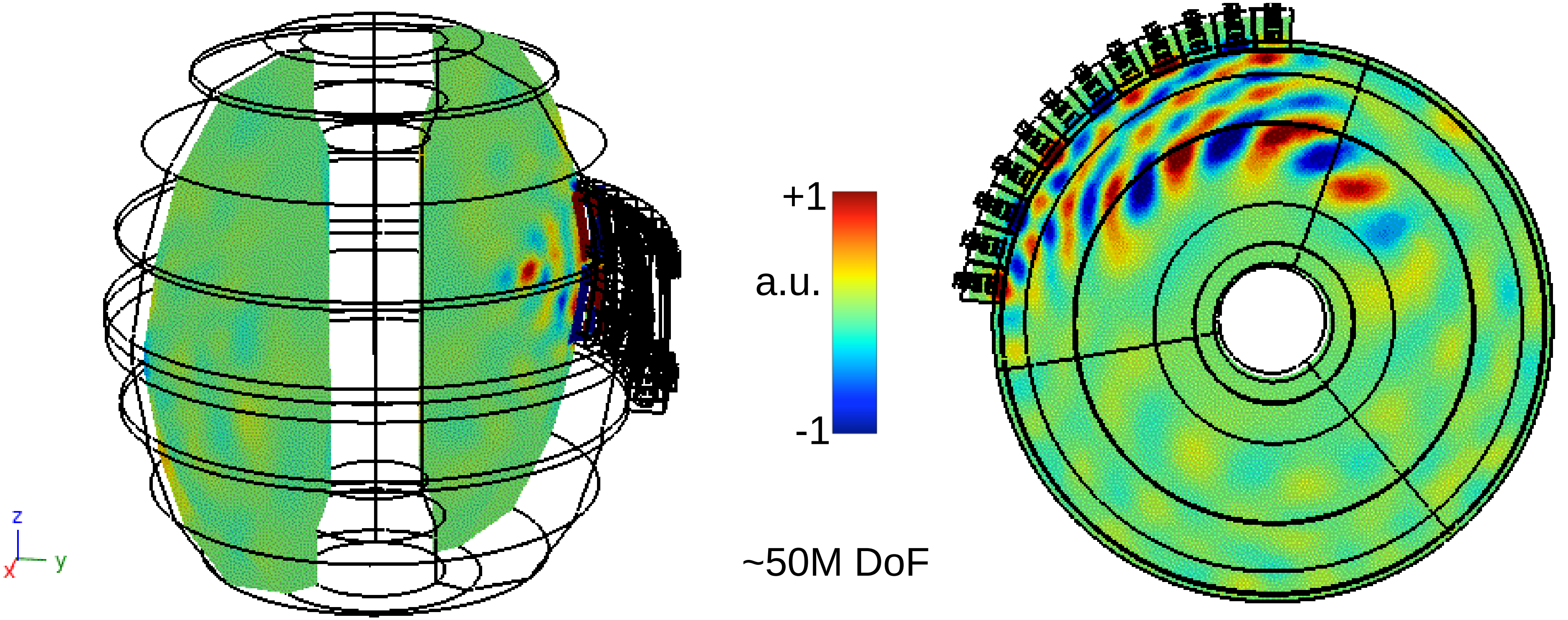
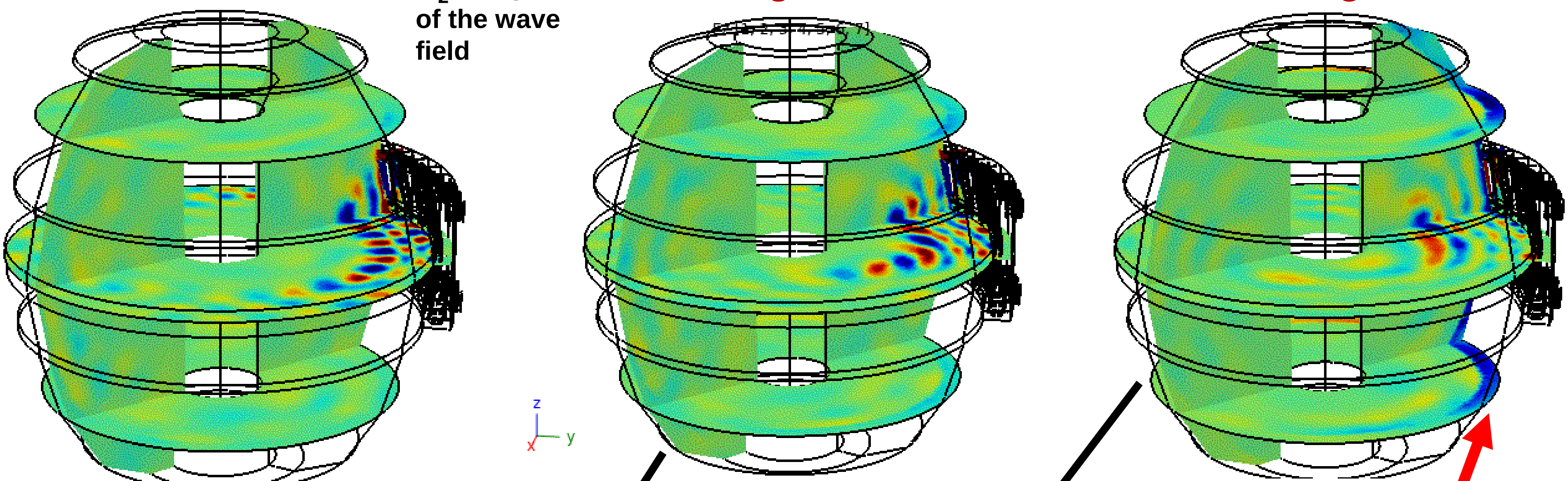
First full 3D torus simulation including realistic antenna geometry

E_z component for 90 degree antenna phasing

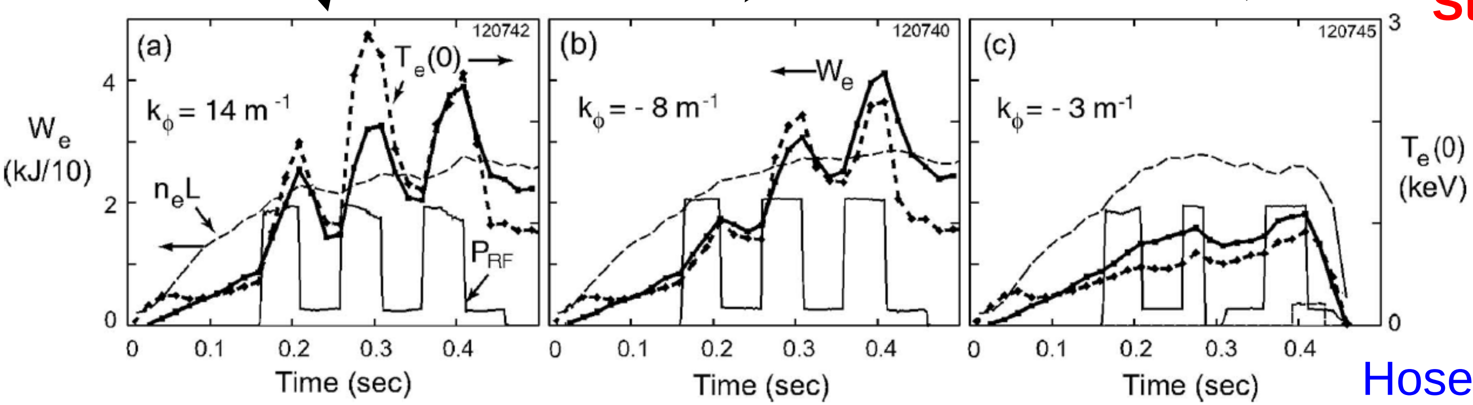


- Equilibrium B field from EFIT as well as the diverted geometry
- Analytical density profile with exponential decay in the SOL plasma
- Vacuum in the antenna box and anisotropic cold plasma in the torus with artificial collision

Lower antenna phasing has stronger interaction with SOL plasma



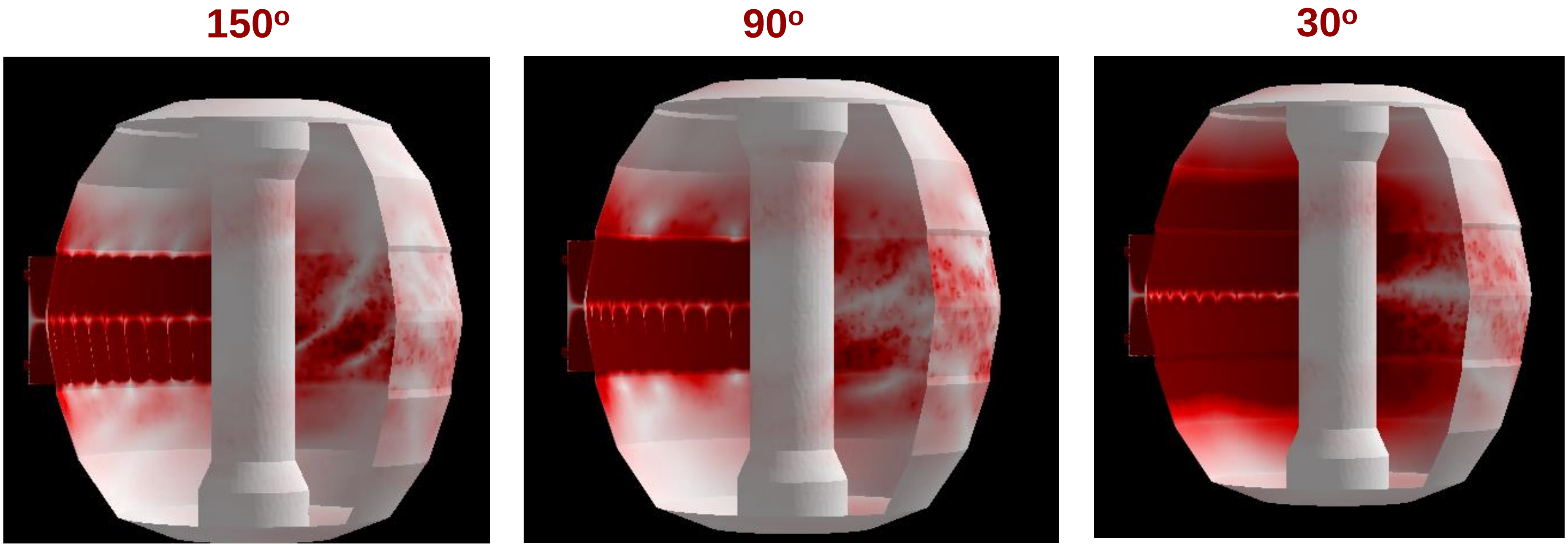
Strong interaction with the SOL



reductions in We and Te for low k_ϕ

Hosea PoP 2008

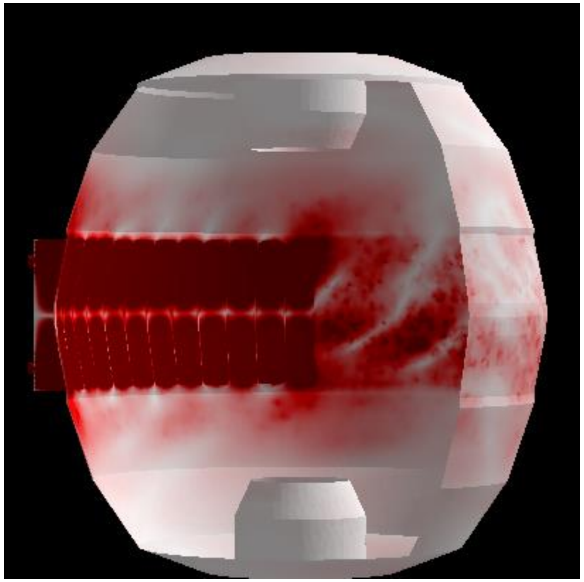
Very strong E field on the wall surface even far away from the antenna



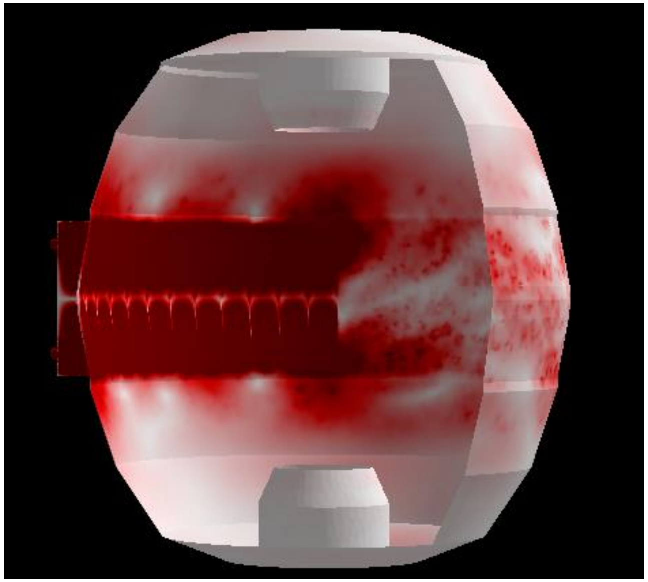
- E field also on the center stack surface
- E field on the surface is stronger for lower antenna phasing
  - Low antenna phasing has also generally a poorer RF heating performance
    - From experiments and AORSA modeling
- Low antenna phasing ➡ low cut-off density ($n_{cut\text{-}off} \propto N^2_{//}\,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

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

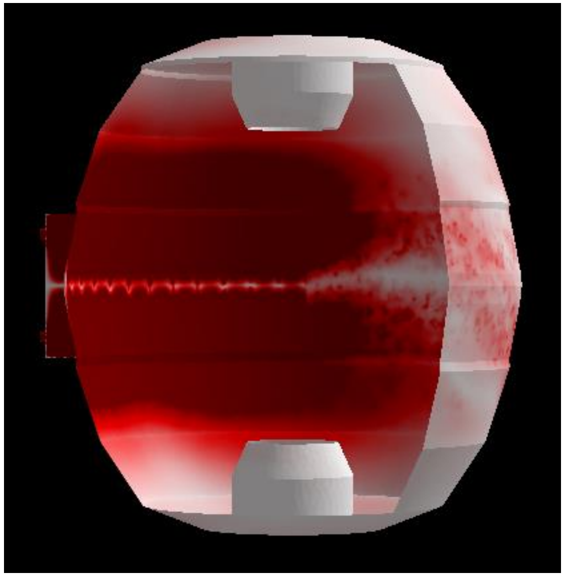
150^o



90^o



30^o



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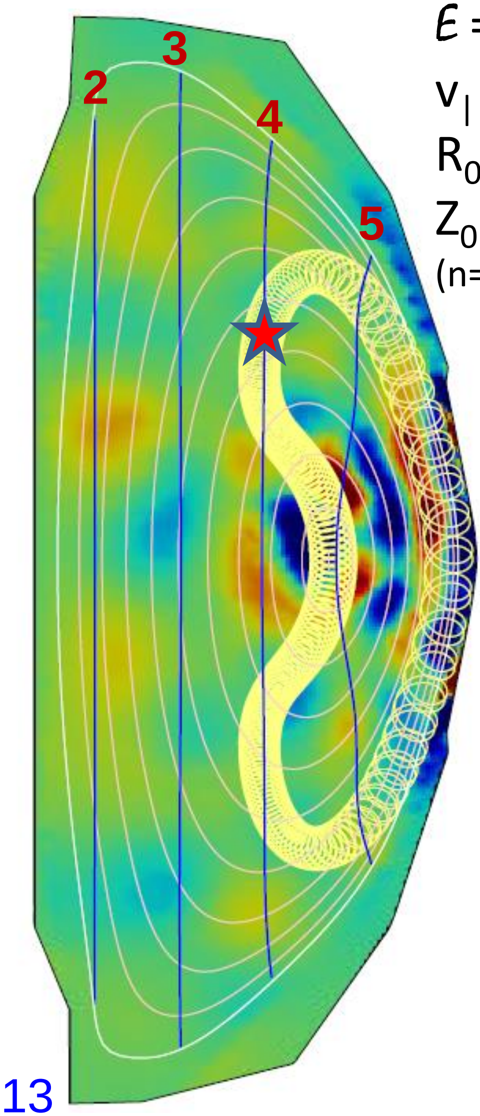
3D RF field (from Petra-M) combined with following particle code SPIRAL to study the interaction of FW with fast ions

Following particle code SPIRAL

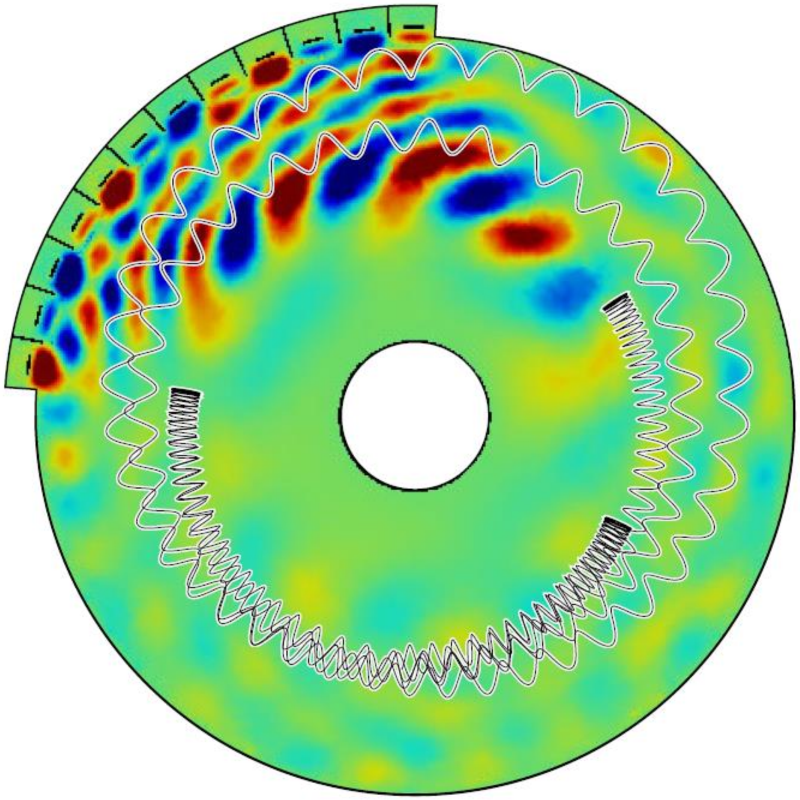
- The SPIRAL code is a test-particle code
  - Used to interpret and plan fast-ion experiments in tokamaks.
- Finite-orbit effects are important for fast ions studies
- Interaction between ICRF heating and fast ions depends on the gyro-motion of the fast ions and is captured in the SPIRAL code.
- Lorentz equation: d**v**/dt = q/m (**v** x **B** + **E**)
  - $\mathbf{B} = \mathbf{B}_{eq} + \mathbf{B}_{RF}$
  - $\mathbf{E} = \mathbf{E}_{eq} + \mathbf{E}_{RF}$



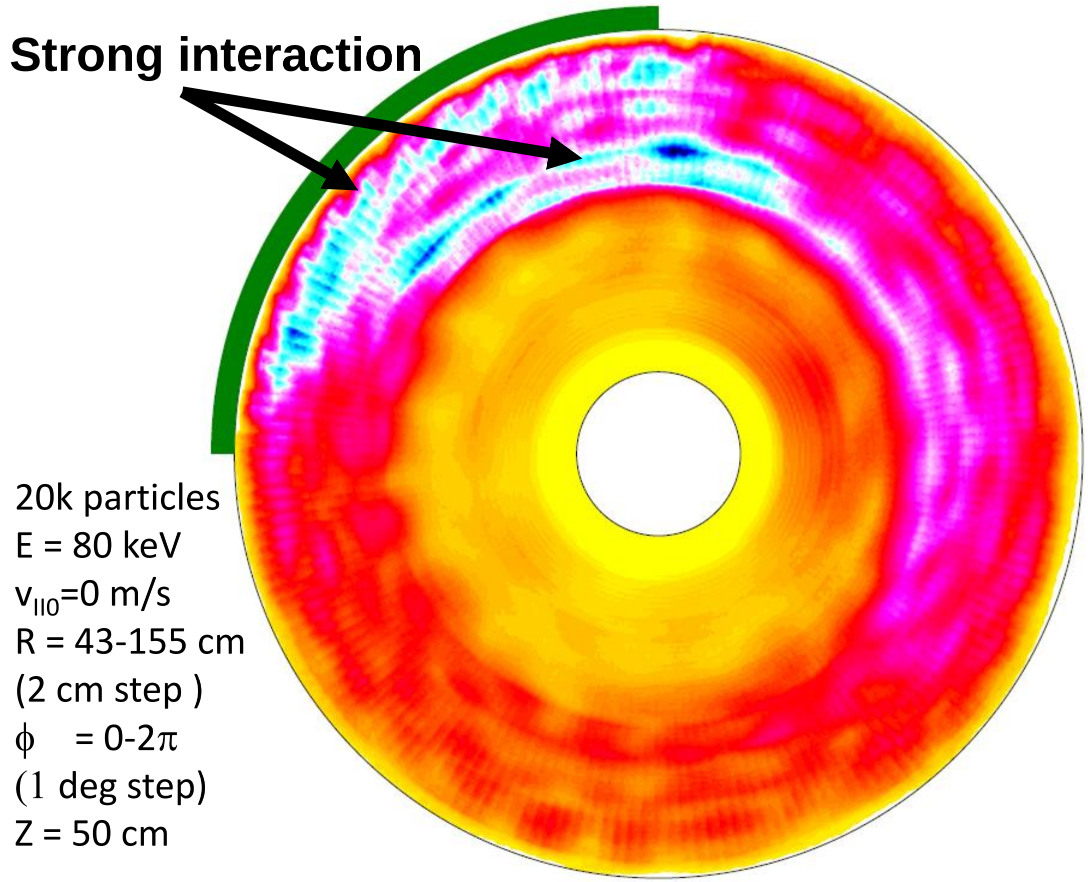
$\mathcal{E}$ = 80 keV
$v_{||0}$=0 m/s
R_0 = 0.95 m
Z_0 = 0.6 m
(n=4 D resonance)

G. J. Kramer et al, PPCF **55** (2013) 025013

Fast ions are mainly accelerated in front of the antenna region where the RF field is stronger



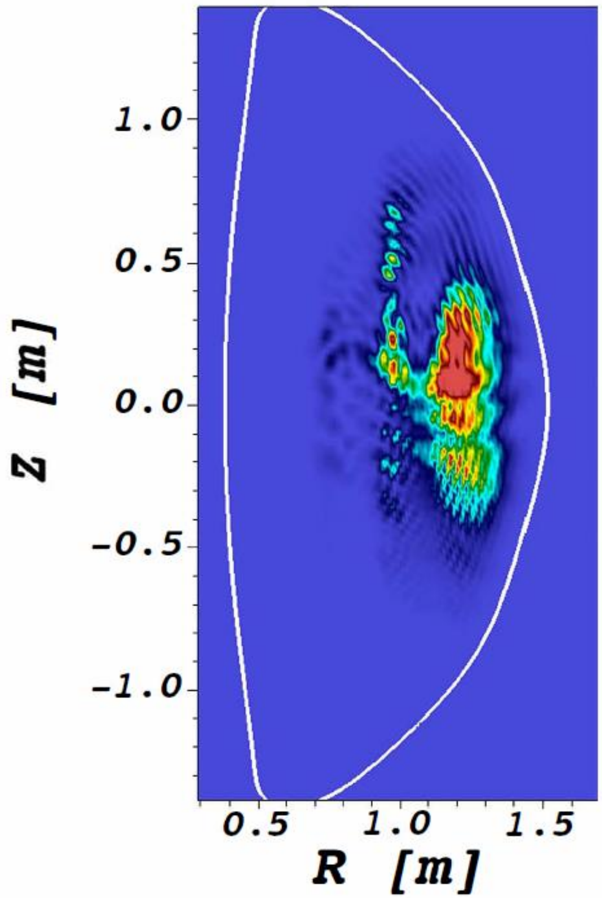
20k particles
E = 80 keV
$v_{||0}$=0 m/s
R = 43-155 cm
(2 cm step)
ϕ = 0-2π
(1 deg step)
Z = 50 cm



3D vs. 2D field can affect the interaction between FW and fast ions.

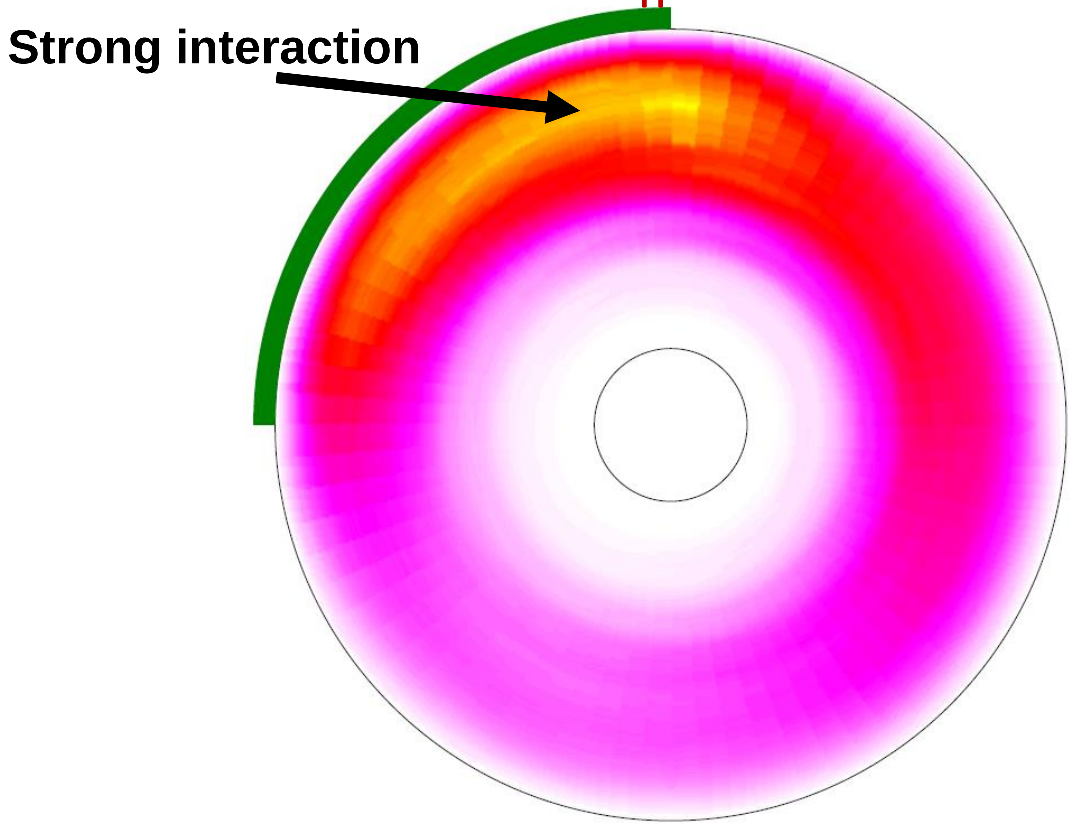
Blue: strong interaction
Red some interaction
Yellow no interaction

Strong interaction close to 5th D resonance similar to AORSA simulation



Fast ions pow. deposition
By AORSA assuming single n_ϕ
and **Maxw. distribution func.**

Assuming a Maxwellian in SPIRAL code with $T_{FI} \approx 25$ KeV



Yellow strong interaction

40k particles used

Conclusions

- Petra-M tool: recently developed for RF physics studies and beyond
  - Full 3D torus with realistic antenna geometry
  - Powerful GUI interface
  - This new tool opens up several opportunities and applications
- First full NSTX-U 3D torus core + edge simulations for a cold plasma have been obtained
  - Found strong interaction between HHFW and SOL plasma at lower antenna phasing
  - Strong E field on the wall surface also far away from the antenna
  - First results with 3D RF solver + following particle code

Future steps

- Improve the 3D plasma geometry as well as the antenna geometry (Faraday screen, etc.)
  – CAD files
- Incorporate additional mechanisms in the SOL plasma
  – RF sheath boundary
  – Edge density fluctuations
  – Ponderomotive effect
  – Etc.
- New numerical schemes to incorporate warm effects in FEM model
  – TORIC (core) + FEM (edge) coupling
  – Within RF SciDAC project
- Validation with experimental data
  – Applications to different devices and wave frequencies

THANK YOU!

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 Simmetrix mesh tools
  - Collaboration with Rensselaer Polytechnic Institute (RPI), NY

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

- Petra-M has been developed by RF SciDAC project / SPARC (CFS)
- Main developer: S. Shiraiwa (MIT)
Shiraiwa et al, EPJ 2017

PyMFEM = python wrapper for MFEM

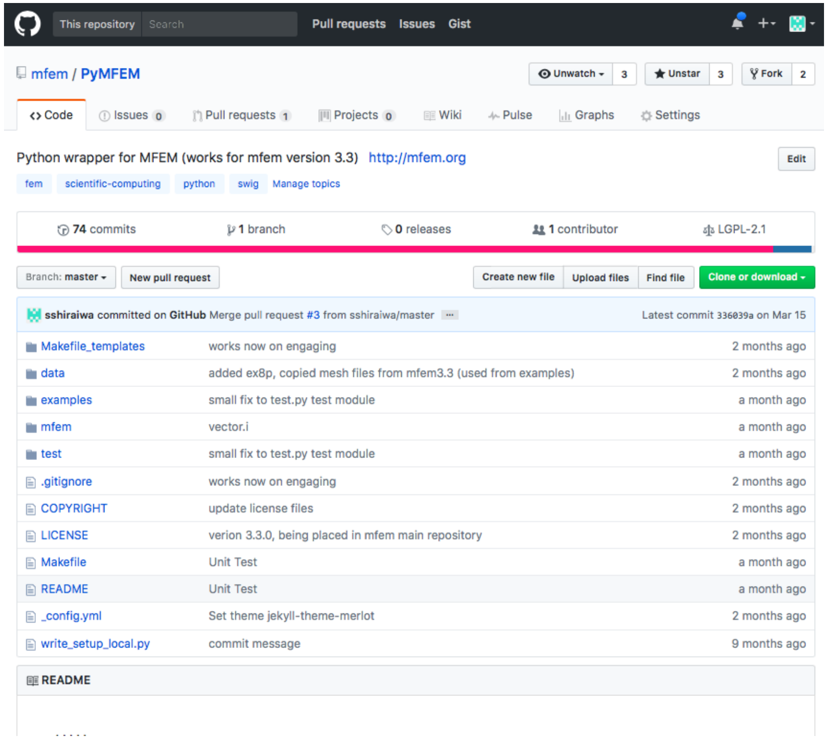
- SWIG (simple wrapper interface generator)
- Allows for construct, manipulate MFEM c++ objects
- Allows for defining FunctionCoefficient using python class
- (Partial) Supports passing numpy array as argument and return value

  (c++) double data[] = {1,2,3};

  o = Vector (data, 3);

  (python)

  v = mfem.Vector(np.array([1,2,3.]))
- Create HypreParCSR/HypreVector using distributed scipy.sparse matrix
- All 31 parallel/serial examples are translated in Python



Jul. 2016 Put on GitHub for review
Sep. 2016 Released under LGPL v-2
Feb. 2017 Became part of MFEM repo.

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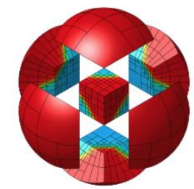
MFEM provides the foundation for scalable FEM analysis

MFEM

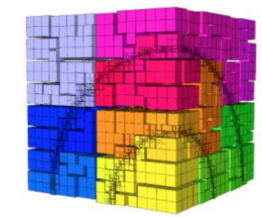
Lawrence Livermore National Laboratory

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, ...



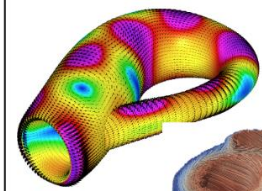
High order curved elements



Parallel non-conforming AMR

CEED EXASCALE DISCRETIZATIONS

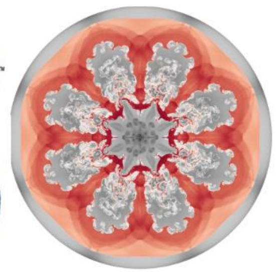
FASTMATH



Surface meshes

Heart modelling

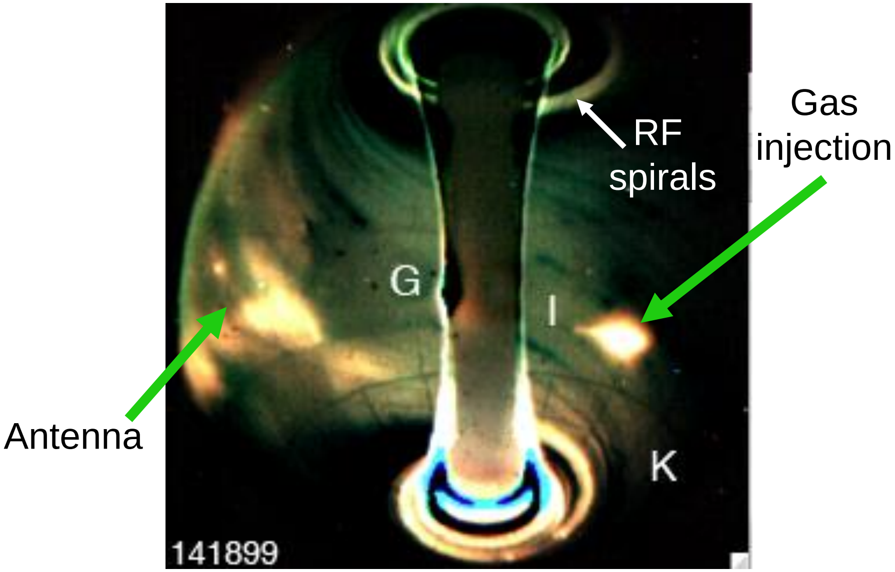
ASC



Compressible flow ALE simulations

http://mfem.org

RF-SciDAC


RF
spirals
Gas
injection
G
I
K
Antenna
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