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

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and RF SciDAC Team

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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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Interacting 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
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

Common module framework

RF        Thermal        Eddy        Weakform

Python (Physics)

C++/Fortran (Math)

GMSH

PUMi/ Simmetrix

MFEM

PyMFEM

Hypre

MUMPS

Strumpack

Main developer: S. Shiraiwa (MIT)

S. Shiraiwa, et al., EPJ Web of Conferences 157, 03048 (2017), APS 2017
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GMSH
PUMi
PUMI/Simmetrix
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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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Main developer:
S. Shiraiwa (MIT)
RF/EM3D physics layer

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

![Model Tree diagram](image-url)
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 90° toroidally

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

• Well-defined spectrum

• $|k_{\phi}| = 3, 8, \text{ and } 13 \text{ m}^{-1}$
  or
  
  $n_{\phi} = 5, 12, \text{ and } 21$
  when

  $\Delta \phi = 30^\circ, 90^\circ, \text{ and } 150^\circ$
Previous studies of heating efficiency showed large amounts of HHFW power missing from core

• Strong interactions between HHFW and SOL plasma

• 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

NSTX: Visual images of the RF “hot” zone.
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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

~50M DoF
Lower antenna phasing has stronger interaction with SOL plasma

150 degree

$E_z$ component of the wave field

90 degree

30 degree

Strong interaction with the SOL

reductions in $W_e$ and $T_e$ for low $k_\phi$

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 $\rightarrow$ low cut-off density ($n_{\text{cut-off}} \propto N^2/|B\omega|$)
- E field on the surface in 3D will be important for studying the antenna impurity generation and RF sheath effects
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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: \( \frac{d\mathbf{v}}{dt} = \frac{q}{m} (\mathbf{v} \times \mathbf{B} + \mathbf{E}) \)
  - \( \mathbf{B} = \mathbf{B}_{\text{eq}} + \mathbf{B}_{\text{RF}} \)
  - \( \mathbf{E} = \mathbf{E}_{\text{eq}} + \mathbf{E}_{\text{RF}} \)

\[ E = 80 \text{ keV} \]
\[ v_{\parallel 0} = 0 \text{ m/s} \]
\[ R_0 = 0.95 \text{ m} \]
\[ Z_0 = 0.6 \text{ m} \]
\( (n=4 \text{ D resonance}) \)

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.

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

Blue: strong interaction
Red: some interaction
Yellow: no interaction

20k particles
$E = 80$ keV
$v_{\parallel0} = 0$ m/s
$R = 43-155$ cm
(2 cm step)
$\phi = 0-2\pi$
(1 deg step)
$Z = 50$ cm
Strong interaction close to $5^{th}$ D resonance similar to AORSA simulation

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

Fast ions pow. deposition
By AORSA assuming single $n_\phi$ and Maxwellian distribution func.

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

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<th>Solver/Post-processing</th>
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<td>• Steady State and Time dependent solver</td>
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</table>

**- 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.
MFEM provides the foundation for scalable FEM analysis

- **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, ...

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

http://mfem.org
Antenna

RF spirals

Gas injection

G

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K