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

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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
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

P=1  P=2  P=3  P=4  P=5
5k  20k  40k  70k  100k

Mesh grid size = 6cm

[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

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

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

$B_t = 1T, n_{e0} = 5 \times 10^{19} m^{-3}$

150 ° phasing
Cold plasma dielectric

see also N. Bertelli (ID: 943)
Lower antenna phasing ($k_\phi$) case indicates stronger interaction between RF and SOL plasmas.

Comparison of $E_z$ 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 $k_\phi$ (i.e., low antenna phasing).

see also N. Bertelli (ID: 943)
Antenna phasing \( (k \phi) \) impacts E field on passive plates...

Comparison of \(|E|\) with different antenna phasing

Antenna phasing
\[ = 30^\circ \]

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

Antenna phasing
\[ = 150^\circ \]
Antenna phasing \((k_\phi)\) impacts E field on passive plates...

**Comparison of \(|E|\) with different antenna phasing**

- **Antenna phasing = 30°**
- **Antenna phasing = 150°**

\(|E|\) field is stronger in the lower antenna phasing \((k_\phi)\) 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

- $= 30^\circ$
- $= 150^\circ$

$|E|$ 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.

- \( \frac{\Delta n}{n_e} \sim 50\% \)
- \( d_{blob} \sim 1\text{cm} \)

(w/o Blob)

- Clean resonant cone propagation

(w/o 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

(w/o Blob)
- Large distortion of wave field pattern

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

GENRAY/CQL3D predicts very different CD profiles.
Petra-M edge simulation is coupled with the TORIC solver using admittance matrix. Symmetric wall (no 3D) leads to 2x2 block diagonal matrix.
3D antenna also modifies antenna spectrum

**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.

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

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J. Wright and S. Shiraiwa, EPJ Web of Conferences 157, 02011 (2017)
S. Shiraiwa, APS 2017, J. Wright, EPS 2018
Ongoing collaborations and future works
## Verification and validation (V&V) through worldwide collaboration

<table>
<thead>
<tr>
<th>Device</th>
<th>Wave</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIII-D (GA)</td>
<td>LH/Helicon</td>
<td>Slow wave excitation. LH launcher coupling</td>
</tr>
<tr>
<td>WEST (CEA)</td>
<td>LH/ICRF</td>
<td>Wave field comparison, impurity generation</td>
</tr>
<tr>
<td>JET (EU)</td>
<td>ICRF</td>
<td>Verification on ITER-like antenna</td>
</tr>
<tr>
<td>NSTX-U (PPPL)</td>
<td>HHFW</td>
<td>Support HHFW experiments in NSTX-U</td>
</tr>
<tr>
<td>LAPD (UCLA)</td>
<td>ICRF/HHFW</td>
<td>Slow wave/Alfven wave comparison with experiment</td>
</tr>
<tr>
<td>C-2W (TAE)</td>
<td>HHFW</td>
<td>HHFW wave propagation in FRC</td>
</tr>
<tr>
<td>ASDEX (IPP)</td>
<td>ICRF</td>
<td>Comparison with RAPLICASOL and SSWICH</td>
</tr>
<tr>
<td>C-Mod (MIT)</td>
<td>ICRF/LH</td>
<td>Field aligned antenna modeling / coupling with TORIC</td>
</tr>
<tr>
<td>KSTAR (NFRI)</td>
<td>Helicon</td>
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Extensive verification & validation is in-progress

LH1 launcher (WEST)

2-strap antenna (AUG)

Waves in the limiter shadow

LH waves in reverse direction (counter-I\textsubscript{\text{plasma}})

LH wave in the forward direction (co-I\textsubscript{\text{plasma}})

DSELF RF E-field diagnostics\textsuperscript{[1]}

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.
3D antenna also modifies antenna spectrum

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

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.

\[ \text{Admittance matrix} \]

Antenna currents couple m/n modes