From core to coax: extending core RF modelling to include SOL, Antenna, and PFC

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PSFC-MIT, PPPL$^1$, Lodestar$^2$, LLNL$^3$, and ORNL$^4$
Leading-class computing facilities allow for accurate RF wave physics simulations in core and edge regions with great detail.

These models compute 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…
Requirements for self-consistent (hot core + realistic 3D antenna) RF simulations have been widely recognized

Many physics issues require to couple a hot core plasma with an edge (antenna and SOL) model having high geometrical fidelity

- Edge parasitic losses observed on many experiments (Alcator C-Mod ICRF\textsuperscript{[1]}/LH\textsuperscript{[2]}, NSTX HHFW\textsuperscript{[3]})
- Antenna coupling in 3D geometries (C-Mod field aligned ICRF, stellarators)
- Multiple-pass absorption regimes
- Impact of edge turbulence (See next talk).

- "monolithic " approach?
  - Half torus ICRF simulation on Alcator C-Mod using a FDTD code (cold core plasma)
  - FEM (finite element method) simulation of LH waves (iterative inclusion of electron Landau damping)

4) T. G. Jenkins and D. N. Smithe, 26\textsuperscript{th} IAEA FEC (2016) TH/P4-34
Outline

• HIS (Hybrid integration SOL) approach
  • Formulation/implementation
  • Verification using a stand alone TORIC simulation

• 2D Simulation and comparison with Alcator C-Mod experiment

• 3D Simulation
  • w/o 3D antenna structure
  • with 3D antenna structure

• Future plans and conclusion
HIS (Hybrid integration of SOL)-TORIC

**Core**

- **Axisymmetric** flux surface regular grid
- Hot plasma conductivity
- Dense Matrix Solver
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- **Unstructured mesh** with complicated geometry (either 2D or 3D)
- Cold plasma with collision.
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How to stitch to two regions...

Let's follow the power flow....

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

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 standalone simulation (right) providing verification of the method.
- There is only vacuum outside LCF.
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- There is only vacuum outside LCF.
- Mode amplitude of superimposed solution (blue) spread wider than the antenna excitation amplitude (red).
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: $T_{e_{\text{SOL}}} = 15$ev, 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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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 \(\rightarrow\) 100 M DoF for resolving slow waves.
SOL RF wave simulation built on Petra-M; an FEM modeling tool using the scalable MFEM library

- Scalable MFEM library
  - [http://mfem.org/features](http://mfem.org/features)

- Petra-M physics based FEM modeling interface

- Workflow management using πScope
  - [http://piscope.psfc.mit.edu](http://piscope.psfc.mit.edu)

Image uses cold plasma in the entire domain and solved by MFEM
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\textsuperscript{(1)}.
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D-(H) case on Alcator C-Mod

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

1) N. Tsujii, PhD thesis (2010)
J-port antenna RF geometry model built from engineering CAD drawing

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.
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
HIS realized high degree of geometrical fidelity with hot core.

Validation is on-going using Alcator C-Mod experimental data
  • RF voltage/current probes
  • PCI diagnostics
LAPD, high density data points
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)

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Conclusions

A new RF modeling capability permits exploration of core – edge interactions in many areas

• Technique applies to any full wave RF simulation in any frequency regime.
• Builds upon existing code infrastructure, algorithms and methods.
• Newly developed SOL FEM simulation built on the scalable MFEM library
• 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

HIS approach adopted by “Center for Integrated Simulation of Fusion Relevant RF Actuators”
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Detailed verification: $E_\psi$ continuity is retained at domain boundary

- 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.
RF sheath

Sheath rectifies RF electric field,