RFASciDAC

SciDAC Center for Fusion Relevant RF Actuators: Particle-based approaches to RF induced impurity generation, and an MFEM based far-SOL transport solver. T. G. Jenkins, D. Curreli, M. Stowell, T. Kolev, D. L. Green, P. T. Bonoli, on behalf of the RF-SciDAC team (listed below).

*Work supported by US DoE contract numbers DE-SC0018090, DE-SC0018275, FWP 3ERAT952, FWP 2017-LLNL-SCW1619, and Work Proposal 3203.

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Scientific Objectives & Organization of the **RF-SciDAC Project**

- Develop an integrated simulation for quantitative prediction of the antenna + sheath + scrape-off-layer + core plasma system which fully utilizes leadership class computing.
- Validate this predictive capability on appropriately diagnosed experiments including dedicated RF test stands, linear devices, and existing tokamaks.
- Project organized into 4 thrusts:
- Thrust 1: RF WDM Components & Thrust Common Efforts (other poster)
- Thrust 2: RF + Turbulence (other poster)
- Thrust 3: RF + Equilibrium Transport (this poster)
- Thrust 4: RF + Impurity Generation (this poster)
- Use these tools to inform design of robust, impurity-mitigating RF heating and current drive sources for future fusion devices.



RF-SciDAC

Thrust 3 focuses on the coupling of RF with the physics of equilibrium time-scale transport to the antenna/wall



Codes used and under development in Thrust 3

- Transport codes (production)
- UEDGE: 2D fluid plasma and neutral transport
- EMC3-EIRENE: 3D Monte Carlo fluid plasma, kinetic neutrals
- Simple / surrogate RF models - New 1D coupled code (ORNL)
- Analytic models (Lodestar, Tech-X)
- RF solvers
- PETRA-M (RF solver based on MFEM)
- MFEM





RF-SciDAC

COMSOL based 3D simulation

R [m]

3D heat fluxes from RF anteni

 \mathbf{G}

on NSTX (Perkins 2

convective

•Single-species fluid momentum equation – use current, not velocity, form $m_{\alpha}n_{\alpha}\frac{\partial V_{\alpha}}{\partial t} + m_{\alpha}n_{\alpha}(\vec{V}_{\alpha}\cdot\vec{\nabla})\vec{V}_{\alpha} + \vec{\nabla}\cdot\vec{P}_{\alpha} = \rho_{\alpha}\left[\vec{E}+\vec{V}_{\alpha}\times\vec{B}\right] + collisions + sources$

•Has both slow and fast timescale quantities; products of fast-timescale perturbations es) can beat down into slow-timescale dynamics (Spectrally decompose into fast and slow dynamics with high/ low-pass filtering (retaining all nonlinearities); sum over species:

ectromagnetic pressure $\left(\frac{\partial}{\partial t}\left[\Sigma_{\alpha}\frac{m_{\alpha}\vec{J}_{\alpha0}}{q} + \epsilon_{0}\left(\vec{E}_{1}\times\vec{B}_{1}\right)\right]\right)_{\mu} + \vec{\nabla}\cdot\left(\vec{P}_{\alpha0} + \Sigma_{\alpha}\frac{m_{\alpha}J_{\alpha0}J_{\alpha0}}{q_{\alpha}\rho_{\alpha0}}\right)$

 $= \langle [\rho_0 E_0 + J_0 \times B_0] \rangle_{LP} + \langle collisions \rangle_{LP} + \langle sources \rangle_{LP}$ -Products of RF terms will be passed to transport codes as source terms

-Effective pressure terms can alter density near antenna, modifying RF accessibility and propagation -Later in project, two-way coupling: pass evolving background profiles to RF codes

A first step in coupling is to use surrogate models for the RF sheath in 2D and 3D transport simulations

- RF sheath potentials cause additional heat fluxes to surfaces and can drive convective cells
- Sheath boundary conditions are influenced by the time-averaged RF sheath potential
- Requires specification of the time-averaged RF sheath potential on flux tubes in the SOL To be provided by project RF codes, once they have
- implemented the fast-time-scale RF sheath BC For development and testing, we use a biased flux
- tube projected uniformly along **B** Surrogate models are guided by probe and gas-puff imaging velocimetry measurements in C-Mod; and probe measurements in LAPD

RF physics can be added to EMC3-EIRENE to study **RF-SciDAC**

- 3D plasma evolution near plasma-facing component (a) 200 [..... • EMC3-EIRENE solves steady-state 3D fluid transport equations using field-aligned mesh
- Grid can extend radially to antenna structure and PFC structure.
- Meshing can be challenging due to structured grid requirements. Results in a large memory footprint. • 3D meshing of Alcator C-Mod antenna region in progress
- High geometric fidelity calculation will require advancements in meshing and reduced memory footprint





Far-SOL MFEM-based solver on non-field-aligned mesh is being investigated

- EMC3-EIRENE widely used to model 3D equilibrium transport code in tokamaks/ stellarators, but meshing can be challenging
- We need both high geometric fidelity to match RF antenna structures, and high-order basis functions 10⁻⁶ to capture the large anisotropy ($\sim 10^3$ - 10^9) in heat transport in the SOL
- Using MFEM and advanced meshing tools may provide us both.
- High order: Implemented NIMROD benchmarks Anisotropic transport problem with analytic solution to assess error (numerical diffusion)
- Tested Cartesian (non-aligned) grid using MFEM Demonstrates acceptable error at challenging anisotropy level
- Flux-based numerical approach results in order of magnitude improvement.



0.1 0.2 0.3

0.05 0.10 0.20







Same MFEM-based AMR algorithms can be applied to a variety of high-order physics models



Parallel AMR scaling to ~400k MPI tasks demonstrated **RF-SciDAC**



CPU cores weak+strong scaling up to ~400k MPI tasks on BG/Q • measure AMR only components: interpolation matrix, assembly, marking,

refinement & rebalancing (no linear solves, no "physics")

Current

straps





Future Work



- Thrust 3 focuses on the coupling of RF with the physics of equilibrium time-scale transport to the antenna/wall
- Progressive approach underway, leveraging reduced models & existing codes • Surrogate models in lieu of full coupled-to-RF simulations
- 1D model to test coupling and ponderomotive effects
- Implementation of surrogate models in 2D and slab models
- 3D transport simulations to wall including RF physics Long-term goal of scalable far-SOL transport code using MFEM
- Initial benchmarking shows promising results
- Advanced meshing techniques will allow extended meshing to wall • Near-term effort: exploring a mesh that transitions from field-aligned in core to
- PFC-conforming in far-SOL Validation exercises planned for LAPD and C-Mod geometries

Thrust 4 focuses on using the developed meshing and solver tools with sheath and sputtering models to calculate RF-rectified sheaths and impurity generation



Plasma sheath formation on RF antenna surfaces:



•Sheath formation on antenna surfaces is associated with sputtering of neutral wall atoms, and subsequent high-Z impurity contamination of the fusion reaction as these neutrals are ionized

•Sheath widths are small relative to characteristic RF wavelengths, but still drive relevant physics. Problem is highly multiscale: wide variation between various length scales { λ_{RF} , Δ_{sheath} , λ_{mfp} , L_{device}}, and timescales { ω_{pe} , ω_{RF} , Ω_{i} , v_{coll} }

•Both the ion distribution function in the sheath and the sheath structure itself are affected by magnetic fields and RF bias.



emission: sputtering, bubble surface, it can be ionized by rupture, cracking, thermal the plasma background and desorption, etc. Solid become responsive to particles leave the surface electromagnetic fields.

impurity is released from the now-charged impurity is subject to all the usual plasma forces (drifts, fluid, collisional). It may be re-deposited back to the surface, or flow far from the surface, cross the separatrix, and contaminate the core plasma.

Modeling RF physics with the Vorpal (VSim) code



•Vorpal (VSim) – electromagnetic/electrostatic PIC code, finite-difference time-domain (FDTD) methods, kinetic (Boris) particles, expanding GPU capabilities, good parallel scaling up to 100k+ cores (OLCF, NERSC) •Can model wave propagation in edge/SOL region, where temperatures are low

•Can import realistic machine geometries and plasma profiles



geometries for LAPD (above). Full-fidelity, long-term geometry for **C-Mod** (right).

Simple, near-term validation

2D simulation

planes

Parallel model Perpendicular model

a multiscale problem

RF-SciDAC





•Will also compare benchmark cases with other RF-SciDAC codes (RF-SOL, Petra-M, BOUT++) and models (generalized sheath BC) where possible

, T. G. Jenkins, and D. Curreli (for the SciDAC Center for Integrated Simulation of Fusion Relevant RF Actuators), 2018 SciDAC PI Meeting (July 2018)