Radio Frequency tools for Breakthrough Fusion Concepts

BETHE Kickoff Virtual Workshop
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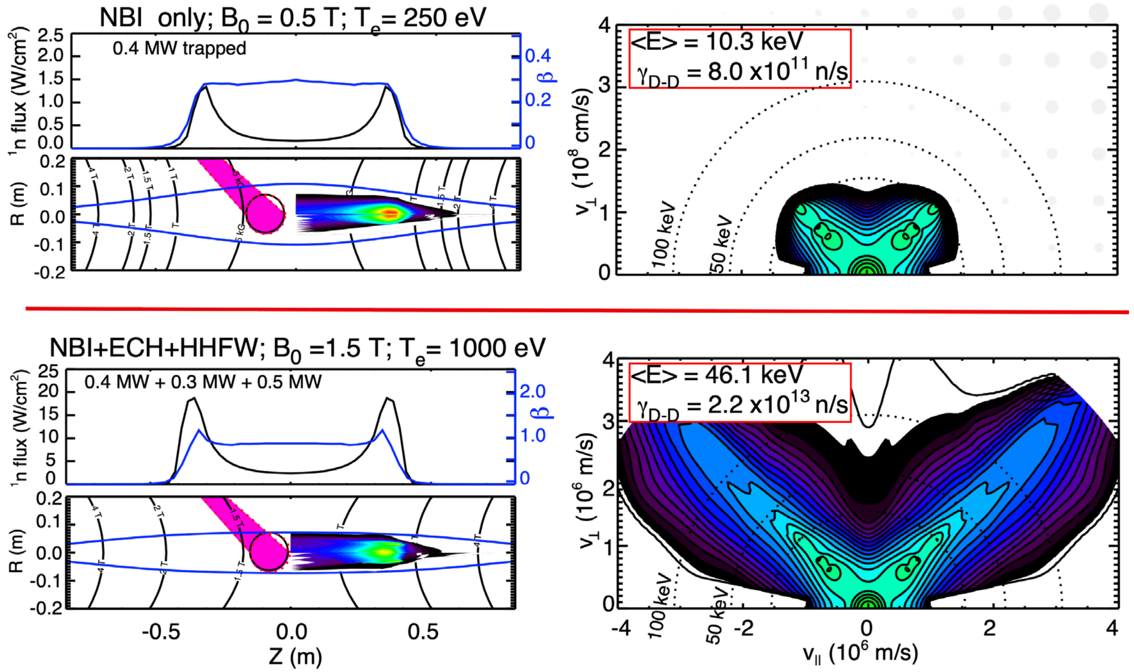
David Green, ORNL; Mark Stowell, LLNL; Bob Harvey, Comp-X

Team members and roles

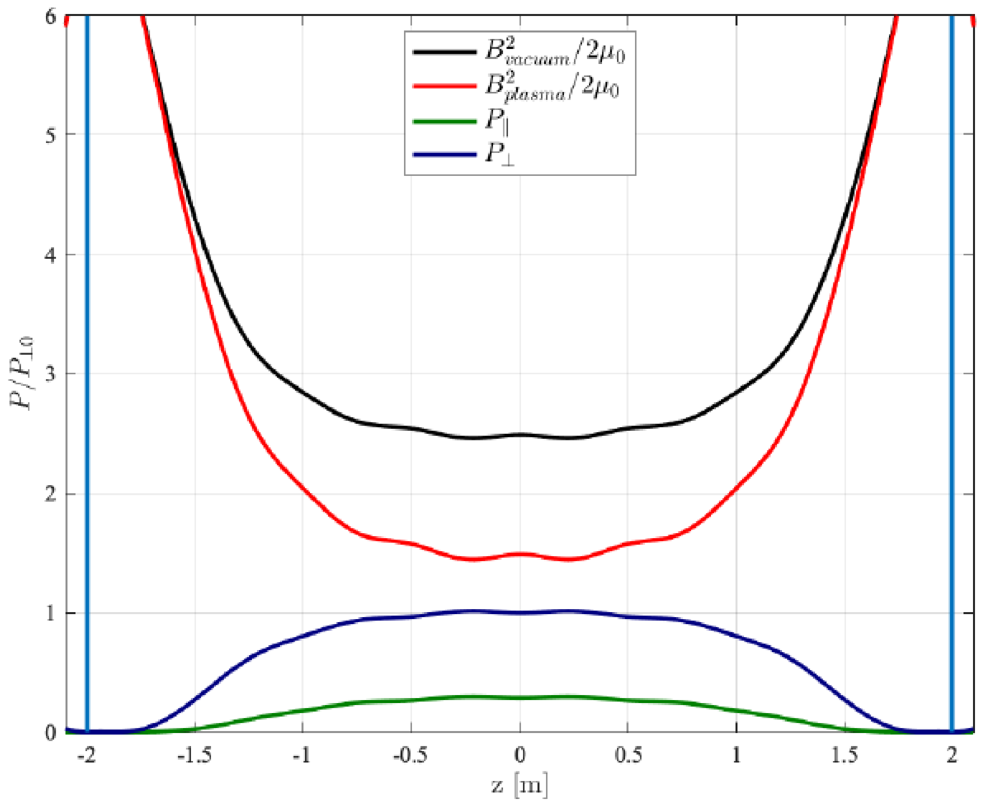
- **PI: Dr. John C. Wright (MIT):** Full wave solvers in FEM and spectral basis, parallel algorithms and computation, modeling of experimental RF scenarios in LH and ICRH. PI of RF modeling collaboration with WEST experiment.
- **Co-PI: Dr. David Green (ORNL):** Numeric methods and high performance computing of relevance to plasma simulation including spectral, DG finite element, FDTD, Monte-Carlo, etc. Is the co-PI of the multi institutional SciDAC center for Integrated Simulation of Fusion Relevant RF Actuators.
- **Dr. Juan Caneses Marin (ORNL):** Both experimental operation, modeling and simulation for linear magnetically confined plasma devices; Leads the ORNL LDRD team for developing 4-D Fokker-Planck computational tools for open magnetic geometries applications to materials with MPEX and neutron sources.
- **Co-Pi: Dr. Robert Harvey (CompX):** Fokker-Planck continuum and Monte-Carlo code development, modeling of mirror configurations and tokamaks, ray tracing models.
- **Co-Pi: Mark Stowell (LLNL):** Computer science and software design for high performance computing environments, finite element methods relevant to modeling of electromagnetic phenomena.



Synergy between neutral beams (NB) and ion cyclotron heating (ICH) shown in the ion distribution function, extending the mean energy 4x with a doubling of ion heating.

Our capability team will bring state-of-the-art RF modeling tools to ARPA-E experiments.

Metric	State of the Art	Proposed
Full wave ion and electron wave modeling	*Typically not done in non-tokamak geometries*	*Adapt and apply our robust RF simulation toolkit to BETHE concepts*
Plasma startup with RF	*Trial and error without a predictive or interpretive application of simulation*	*Optimize the density production rate via simulation and make RF plasma startup more robust for BETHE concepts*
Lost ion distribution, lost electrons and E||.	*Open systems like mirrors and divertors require 4D Fokker-Planck*	*Apply these existing approaches to particular ARPA-E BETHE geometries*



Pressure anisotropy on flux surface in mirror geometry using Matlab for initialization of PIC calculation– ORNL.

Major tasks for WHAM (Wisconsin) / Centrifugal Mirror (CM) (Maryland) / PFRC (PPPL)

- WHAM/PFRC: Evaluate HHFW and ECH performance in WHAM and RMP penetration in PFRC with **dispersion analysis**.
- WHAM: Optimization of ECH heating schemes with ray tracing and Fokker-Planck codes. **ECH breakdown** and plasma formation, determine rate of formation with ECH power < 1 MW.
- WHAM: Optimize ion cyclotron heating **antenna coupling** using cold plasma full wave codes. Aim for loading factor that couples > 50% of source power.
- WHAM: Optimize **HHFW and NBI synergies**, effect on plugging of ends.
- PFRC: Investigate **RMP ion-heating rate** in FRC with full-wave FEM and orbit code.
- CM/WHAM: **End loss calculations using 4D Fokker-Planck** with E|| effects. Scattered electron losses. Quantify if achievable Mach rotation numbers are sufficient to allow Q>1.
- Technical Risk:
  - Optimized electron-cyclotron heating (ECH) and ion-cyclotron RF (ICRF) scenarios **identified be optimum for existing sources** that experiments may already have.
  - **Instabilities** (MHD, kinetic) and transport (losses, changes in distribution function) that can reduce the effectiveness of RF heating (and profile control) and NBI.

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Key techno-economic metrics of the project

- Our project is a capability team so its primary objective is to provide support to concept teams.
- The RF C-Team has one commercial component, CompX.
  - There has also been substantial support from:
    - industry (General Atomics, Tri-Alpha Energy) and
    - universities (UC San Diego, UC Los Angeles, University of Wisconsin/Madison, MIT),
    - and national laboratories (PPPL, ORNL, and LLNL).
- We anticipate that further opportunities for support of related modeling activities will be available at the end of its term.
- Tools and expertise developed under this BETHE funding will be available for the INFUSE program going forward if it supports universities in the future.

Thank you: RF Tools applied to BETHE program

Name	Physics Domain	Formulation/URL	Applications
Dispersioneering	All	0D hot & cold dispersion solver for Maxwellian plasmas https://github.com/ORNL-Fusion/dispersioneering	Determination which waves will propagate where.
AORSA	Full wave solver	All orders (harmonics) dielectric, physical optics, Fourier collocation https://github.com/ORNL-Fusion/aorsa	High Harmonic fast wave in mirrors, wavelength~ system
CQL3D-M	Coupled Fokker Planck for electron and ion responses in axisymmetric (mirror) geometry	Nonlinear, bounce-averaged continuum, 2D-in-V, 1D-in-generalized radius, time-dependent, includes radial diffusion. NFREYA NB and full-wave+GENRAY RF sources https://github.com/compxco/cql3d	Analytic or eqdsk-like equilibria, Must be generalized for multiple magnetic wells.
GENRAY-C	RF ray characteristics and power deposition in general 3D geometry	All frequencies geometric optics code, including hot and cold dispersion https://github.com/compxco/genray	Location of power deposition when wavelength<device size. Data for CQL3D QL operator, and QL absorption.
MCGO	Monte Carlo Guiding center/collisional Orbit code, alternatively full Lorentz orbits in 6D phase space	Parallelized, obtains ion distributions, and orbit losses. Coupled to NREYA NB source and AORSA-based full-wave RF kick operators. http://www.compxco.com/mcgo.html	Fast ion distributions due to combined NB and full-wave RF sources
DC	Diffusion Coefficient Calculator	Forms gyro- and bounce- averaged RF diffusion coefficients by direct integration of particle orbits in combined equilibrium and full-wave RF fields. http://www.compxco.com/dc.html	Used for coupling full-wave RF codes to the bounce-averaged CQL3D-M FP code, giving QL RF radial deposition and non-Maxwellian distributions
Prometheus++	Ion parallel transport and Fokker Planck	Hybrid Particle-In-Cell code with Coulomb collisions. Kinetic ions and fluid electrons. 1D in space along magnetic field lines and 3D in velocity space. Resolves parallel ambipolar electric field https://bitbucket.org/lcarbajal/prometheus-upgrade/src/master/	Ion parallel transport, ambipolar electric field and ion distribution function for mirror devices with RF and NBI heating.
STELLA	3D Fokker Planck solver for electron and ion responses along the magnetic field	Non-bounce-averaged, 1D-in- space along the magnetic field, 2D-in-velocity, with parallel streaming term. Self-consistent parallel electric field gives ambipolar flow. http://www.compxco.com/stella.html	Distribution function evolution with RF and NB in mirrors. 4D including radial dependence can be implemented
Stix2d	Cold plasma physical optics	FEM formulation, physics optics, general geometry https://github.com/mfem/mfem/blob/b0a250a18dd8d7b234c0957 79879658162fa63aa/miniapps/plasma/stix2d.cpp	ECH and ICH fields in complex geometries in cold plasma conditions

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