Overview of the Plasma Science and Innovation Center (PSI – Center)

Thomas R. Jarboe\textsuperscript{1}, Adam Bayless\textsuperscript{2}, Eric Held\textsuperscript{3}, Jeong-Young Ji\textsuperscript{3}, Charlson Kim\textsuperscript{1}, Angus Macnab\textsuperscript{1}, George Marklin\textsuperscript{1}, Richard D. Milroy\textsuperscript{1}, Brian A. Nelson\textsuperscript{1}, Uri Shumlak\textsuperscript{1}, Carl Sovenic\textsuperscript{2}, Srinath Vadlamani\textsuperscript{1}, and Simon Woodruff\textsuperscript{1}

\textsuperscript{1}University of Washington, Seattle, Washington 98195
\textsuperscript{2}University of Wisconsin, Madison, Wisconsin 53706
\textsuperscript{3}Utah State University, Logan, Utah 84322

http://psicenter.org/
Abstract

The Plasma Science and Innovation Center (PSI-Center) has recently formed. The principal goal of the PSI-Center is to achieve significantly improved predictive capability for smaller-scale devices. This is being accomplished through the refinement of existing computational tools by adding sufficient physics modeling, boundary conditions, and geometric capabilities to benchmark results against experimental data. The developments emphasize the modeling needs of emerging concept (EC) experiments, but improved simulation capabilities for all innovative confinement concepts (ICC) are expected. A special emphasis is placed on physics effects that may extend beyond the standard analysis applied to the mainline programs. The PSI-Center is presently concentrating on five focus areas that have been identified as being very important for various EC experiments. The key physics issues are: 1) two fluid / Hall physics, 2) kinetic and FLR effects, 3) reconnection and relaxation physics, 4) transport, atomic physics, neutrals, and radiation, and 5) boundary conditions and geometry. All of these effects are also important in mainline fusion devices, but one or more tend to dominate in particular EC configurations. In some cases, important effects may result from high-frequency electron dynamics or kinetic effects that can not be calculated from first-principles in a practical manner during global simulations. Here, well benchmarked phenomenological modeling may be the best approach for some applications.
Abstract-Cont

There are numerical simulation codes having some subset of these important features, but no existing code covers all of the special needs of innovative/emerging concepts. We plan to develop the needed features within existing codes to avoid the resource requirements and delays associated with developing completely new models. We have started with two codes: 1) NIMROD\textsuperscript{1} which is a 3D code that is periodic in one dimension and employs finite elements in the other two dimensions; and 2) MH4D\textsuperscript{2} which employs a full 3D unstructured mesh.

While the entire EC community is invited to participate in this Center, nine experimental programs are providing the initial database and test bed for the theoretical and computational efforts of the PSI-Center. These nine experiments are: 1) Caltech reconnection experiments, 2) FRX-L, 3) HIT-SI, 4) MBX, 5) PHD, 6) SSPX, 7) SSX, 8) TCS, and 9) ZaP. This set of experiments has many overlapping areas of physics that complement the PSI-Center’s focus. Experimental data will be used to test and calibrate the numerical predictions generated by the computational tools developed by the Center.


\textsuperscript{2}Schnack, D. D., and Lionello, R. Eos Trans. AGU,85(47), Fall Meet. Suppl., Abstract SH13A-1158
Mission

In concert with smaller innovative plasma physics experiments, refine and optimize existing MHD codes to achieve significantly improved predictive capability.

- Collaborate closely with experimental groups to test and calibrate codes by utilizing data from several Emerging Concept (EC) experiments.
- Add sufficient physics, boundary conditions, and geometric capabilities to benchmark results against experimental data.
- To the greatest extent possible, use existing codes and code development of the mainline programs.
- Facilitate information exchange with collaborating partners
To make the fastest progress, we will improve existing codes instead of building new ones.

- **NIMROD**
  - A proven macroscopic simulation code having several critical features for EC experiment modeling.
  - The “NIMROD Team” continues to enhance this code with features of interest to the EC community – as well as the mainline program.

- **MH4D**
  - Employs an unstructured 3D mesh, which is appropriate for simulating complex geometries and non-symmetric details such as gas injection and diagnostic and vacuum ports.
Key Physics Issues

- Initial concentration on five fundamental issues that appear essential in developing predictability for EC experiments:
  - Two fluid / Hall physics
  - Kinetic and FLR effects
  - Reconnection, relaxation physics
  - Transport, atomic physics, neutrals, and radiation
  - Boundary conditions and geometry
Two Fluid / Hall Physics

◆ Generalized Ohm’s law:

\[
E = -v \times B + \eta j + \frac{1}{en} j \times B - \frac{1}{en} (\nabla P_e + \nabla \cdot \Pi_e)
\]

– Resistive MHD includes first two terms.
– Third and forth terms (Hall and \(\nabla P_e\)) are often neglected.
– Hall effect is very important to physics of some EC experiments:
  » Leads to toroidal field generation when a spheromak is generated in a conical \(\theta\)-pinch.
  » Is responsible for current drive in Rotating Magnetic Field current drive experiments.
– Accurate inclusion of these terms is numerically difficult, and is being developed by the NIMROD team and the CEMM.
Kinetic and FLR Effects

- Kinetic and FLR effects are very important for some EC experiments.
  - FRCs have a high $\beta$ (low field) interior with only a few ion gyro-radii separating the magnetic null from the separatrix.
- PIC codes are too time consuming to simulate a full experimental pulse.
- Include some kinetic / FLR effects into MHD models.
  - Use PIC to represent a minority species in hybrid model.
  - Gyroviscous effects will be incorporated into NIMROD.
- Collaborate with Elena Belova to incorporate advances that she has accomplished with the HYM code.
A clear understanding of magnetic reconnection is essential for several EC concepts.

Relaxation is challenging to model, since it results from fluctuation correlations, so the fluctuation turnover time-scale must be resolved.

NIMROD and MH4D will be optimized for the computation of relaxation physics problems.

Recent theoretical work on two-fluid relaxation in high-\(\beta\) plasmas would benefit from first principle simulations.
Transport, Atomic Physics, and Radiation

◆ EC experiments tend to be relatively small and low temperature.
  – Can be strongly affected by impurity radiation, Ionization, charge exchange, neutral dynamics, and collisional transport.

◆ We will implement an atomic-physics package into the MHD models.
  – We hope to take advantage of efforts by the National Transport Code Collaboration (NTCC), and the BALDUR impurity radiation model.
Boundary Conditions and Geometry

Realistic boundary conditions are essential to make quantitative comparison with EC experiments.

Ideal conducting boundaries are often employed in codes but we need to:

- Account for the finite conductivity of metal boundaries
- Allow for the insulating boundaries employed by some ECs
- Work toward including realistic coil geometries and external circuit equations.
- Be able to include effects of a thin layer of cold poorly conducting plasma close to a conducting boundary.
- Some experiments have an insulator between a close fitting metal wall and the plasma.
PSI-Center Organization and Funded Manpower

- Director (Jarboe)
  - Deputy (Milroy)
    - Admin. (Pareja-Klemisch)
      - Boundary Conditions and Geometry
        - Shumlak *
        - Marklin
        - Vadlamani
        - Gradstudent
      - Two-Fluid Transport
        - Sovinec*W
        - Held^U
        - Bayliss^W
        - Ji^U
      - FLR & Kinetic Effects
        - Milroy*
        - Macnab
        - Kim^s
        - Gradstudent
      - Interfacing Group
        - Nelson*
        - Griffith
        - Cassidy
        - Kim^s

* Group Lead
^W at Wisconsin
^U at Utah
^s shared post-doc
Tetrahedral meshes discretize complicated geometries more easily than hexahedral meshes.

Tetrahedral meshes typically require a higher resolution for the same accuracy.
Two-Fluid and Transport Group

◆ Improve efficiency of the NIMROD code for EC plasma conditions.
  – Developed for tokamak: MHD conditions that are extremely stiff, but laminar.
  – EC experiments with magnetic relaxation are less stiff but more dynamic; accurate simulation requires a smaller time-step relative to wave propagation times.
  – Improvement will result from reorganizing data structures and turning Gaussian integration into matrix operations.
Two-fluid and Transport Group

◆ Develop fluid modeling capability for collisional plasmas.
  – Two-fluid Ohm’s law (leveraged by CEMM effort)
  – Collisional closures

◆ Implement non-local closures for the free-streaming kinetic effects that are most important as a plasma becomes collisionless.
  – Parallel electron heat flux
  – Parallel ion stress
FLR & Kinetic Effects Group

◆ Will focus on simulating high-$\beta$ plasmas, where finite Larmor radius (FLR) and kinetic effects are very important.
  – Standard MHD theory does not always work well for predicting behavior of high-$\beta$ plasmas. For example, it does not predict the observed stability of an FRC.
  – Center codes will incorporate terms often associated with FLR effects including:
    » Hall / two-fluid effects
    » Gyroviscous effects
    » Fully kinetic minority ion species (hot ions, or a beam)
FLR & Kinetic Effects Group

- Responsible for some boundary condition enhancements to NIMROD:
  - For example, FRC simulation requires insulating boundary with realistic representations of external coils, including RMF antennae.

- Incorporate atomic physics and radiation models into NIMROD.
  - Utilize same algorithms (as much as possible) as will be used in the MH4D code.
Interface Group

- Strong interaction with EC programs is crucial to Center goals

- Adapt codes for participating experiments via on-site visits
  - Implement data/code communications with the Center
  - Establish uniform and easy to use code interfaces
  - Develop data analysis and visualization to compare with experiments

- Host Summer Study for experimentalists

- Maintain a web site for Center information, give conference presentations about Center activities, explore Center codes applicability to other plasma science issues
Interface Group

- Perform initial simulations of EC experiments (at PSI-Center)
  - Utilize appropriate code and physics for initial runs (with EC input)
  - Initial simulations will use NIMROD; MH4D when available/appropriate

- Visit experiments to facilitate them in performing simulations
  - Develop/maintain GUI for code input
  - Teach groups how to develop “numerical diagnostics” for their experiments (e.g., magnetic probes, line-integrated measurements)
  - They can then improve specific modeling and analysis issues

- Establish connectivity between the Center and experiments
  - MDSplus interfacing to experimental data and codes
  - Provide access to latest version of codes (CVS version control)
Participating experiments

- Caltech – Paul Bellan, Spheromak formation / Plasma Gun
- FRX-L – Los Alamos, High-density FRC source for MTF
- HIT-SI – U. of Washington, Helicity Injected Torus
- MBX – U. of Texas, Magneto Bernoulli Experiment
- PHD – U. of Washington, Pulsed High Density FRC
- SSPX – Lawrence Livermore, Spheromak
- SSX – Swarthmore Spheromak / merge → FRC
- TCS – U. of Washington, RMF sustained FRC
- ZaP – U. of Washington, sheared-flow stabilized Z-pinch
Boundary Conditions & Geometry Group

- Develop capability to handle complex geometries and realistic boundary conditions.

- Take the lead in development of atomic physics, neutral dynamics, and radiation models.

- Develop the MH4D model
  - Employs an unstructured tetrahedral mesh, making it appropriate for complex geometries and detailed boundary conditions.
## Participating experiments

Physics matrix showing areas of overlap among the experimental programs.

<table>
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<th>Caltech</th>
<th>FRX-L</th>
<th>HIT-SI</th>
<th>MBX</th>
<th>PHD</th>
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PSI-Center accomplishments

- NIMROD and MH4D running on the Center’s code-development computer.
- Progress made on eight experiments.
- All personnel on board.
- Achieved first results with insulating boundary conditions.
- Strategy in place to develop a model for neutrals and ionization.
- Semi-collisionless transport coefficients under development.
- Begun characterizing nature of linear two fluid FRC tilt to compare to analytic model.
- Linear n=1 two-fluid calculation started for FRC.
Summary

◆ The PSI-Center is to develop computational predictability for ICC/EC experiments
◆ It will mostly integrate existing and on-going work but some new development is needed
◆ The developed codes will greatly facilitate the exploration of the ICC/EC parameter space and increase the scientific output from experiments
◆ The work is underway.
Summary-cont

Experiment

Interfacing

Center Groups

Goal

Boundary Conditions + Geometry

FLR + Kinetics

Two fluid MHD + Transport + Relaxation

Predictive Modeling

Improved Performance