Quarterly Progress Report of the PSI-Center (July – September 2008)

by

Thomas Jarboe, Alan Glasser, Richard Milroy, Brian Nelson,
Uri Shumlak, and Carl Sovinec

The Plasma Science and Innovation Center (PSI-Center) has accomplished a great deal this quarter. The PSI-Center is organized into four groups: Boundary Conditions and Geometry, Two-Fluid and Transport, FLR and Kinetic Effects, and Interfacing. Each group has made good progress and the results from each group are given in detail. On June 23 the PSI-Center had its annual meeting in Reno in conjunction with the ICC meeting. Presentation can be found on our website.

Progress Report for the BC&G Group (*U. Shumlak, W. Lowrie, V.S. Lukin, G. Marklin, and E. Meier*)

Accomplishments

- Added the ability to read CUBIT generated 3D hexahedral meshes into the HiFi code.
- Wrote a resistive MHD (with viscosity and isotropic heat conduction) module to HiFi, advancing density, momentum, pressure and magnetic field
    - Verified that the ideal MHD waves had the correct wave periods.
    - Incorporated a numerical eigensystem solver to compute the correct wave frequencies and wave perturbations
    - Verified that waves with dissipation (resistivity, viscosity, isotropic heat conduction) had the correct decay rates
    - Set up a spheromak tilt problem and determined that divergence of B errors were dominating and destroying the solution
- Rewrote the resistive MHD module for HiFi to include vector potential rather than magnetic field
    - Verified correct MHD wave period and decay for the vector potential formulation
    - Wrote spheromak initial condition solver module for the vector potential with magnetic field as the input
- Branginskii anisotropic thermal conduction has been implemented in SEL with proper transition from isotropic to anisotropic conduction as plasma magnetization varies.
- A flux injection boundary condition has been developed in which flux diffuses into the domain and normal and tangential velocities are not allowed. A resistive layer or Chodura resistivity can be used to allow the rapid diffusion in a quasi-vacuum region.

- An open boundary condition (i.e. a boundary that artificially truncates the computational domain) is under development, and has been implemented for the 2D Euler equations. Our approach involves decomposing the hyperbolic system and using Roe's flux-difference splitting method to use physical b.c. information for waves that are entering the domain while using numerical b.c. for waves exiting the system.
- Incorporated the PETSc SNES Newton solver interface developed by Alan Glasser into the primary SEL and HiFi code branches, to be used to solve both the main physics and the grid adaptation PDE systems. This has shown to make the code both more robust and often more efficient, particularly so in solving the grid adaptation equations.
- Reorganized the implementation of the relationship between the main code algorithm and particular physics modules in the SEL code to make its use and development of new physics modules even more user friendly. Developed a template for creating new physics modules for the code.
- Added new flexibility to have spatially dependent left hand side of the general boundary condition equation solved by SEL and HiFi. This has enabled using Cartesian vector components and Cartesian coordinate system for specifying time-dependent boundary conditions in arbitrary geometry. The feature has already been used successfully by George Marklin for implementing insulated conductor b.c. in a square cross-section torus.
- Continued improvement and maintaining high quality of the SEL/HiFi code organization as new features are added to the code by the developers; the same regarding post-processing modules for both codes.
- Assist new users of SEL and HiFi within the PSI-Center.
- Assist Alan Glasser in the development of FETI-DP with physics-based preconditioning for the SEL code.
- Begin to work on the multi-block version of HiFi.
- A resistive MHD equation module was written for HiFi to simulate an RFP with a square cross section and insulated conductor boundary conditions. The code seemed to be working but could not be run with sufficient resolution to produce any meaningful results.
- Mimetic operators have been incorporated into the M4 resistive MHD code and initial testing is in progress.

Scalable Extended-MHD Solver work (*Alan Glasser*)

Made major progress on a scalable solver for the 2D SEL code, based on FETI-DP domain substructuring and Physics-Based Preconditioning.

- First wrote a new code module to use the PETSc SNES nonlinear solvers, both because they provide a more advanced and robust nonlinear solver than our previously-used simple Newton solver, and because they provide a framework for the Physics-Based Preconditioner. Initially, the previously-used exact linear solvers were implemented as preconditioners to a matrix-free GMRES Krylov iteration.

- Another new code module was then developed for the Physics-Based Schur complement approach, using FETI-DP to solve the preconditioning matrix because of its scalability. This was first tested for a simple problem of sound waves in a 2D doubly-periodic plane. The code is organized such that the problem-specific Schur complement is expressed in flux-source form in a new subroutine of the problem-specific module, while the Schur complement module contains general-purpose code for any such problem.
- After successfully demonstrating the method for sound waves, I then developed and successfully tested it for the much more complicated and relevant case of ideal MHD waves. Scaling tests on the NERSC BASSI parallel computer show that the condition number and Krylov iterations to convergence remain constant as the number of processors and the problem size are scaled up (weak scaling).from 1 to 64 processors. There is a slow increase of cpu time, by less than a factor of 2 from nproc = 1 to 64, which is probably due to imperfections in the parallel implementation, which can be improved with the help of profiling studies. These scaling tests will be extended to 1024 processors on the FRANKLIN computer once a minor compiler problem is solved. The condition number and Krylov iterations increase as the angle between the wave propagation vector k and the magnetic field B approach 90 degrees, but are still quite manageable at 89 degrees.

This work is now being extended to include the Hall terms and its more challenging whistler wave, then dissipative, nonuniform, and nonlinear effects. Results will be presented at the APS and CEMM Meetings in November.

Two-fluid and Transport Group *(C. R. Sovinec, E. D. Held, R. A. Bayliss, J.-Y. Ji J. B. O'Bryan)*

Over the quarter of funding ending on 9/30/08, the Two-fluid and Transport Group has formulated meaningful subsets from our general moment model, developed Monte Carlo type calculations to make better use of data from integral-closure computations, implemented a demagnetization model for heat flux, and reordered data and loops to improve parallel scalability.

- Progress on analytical modeling based on the general moment method includes:
    - We have recovered the Braginskii closure formulas from a 21-moment approximation and reproduced Braginskii's tabulated transport coefficients.
    - We have explicitly written a 29-moment system and compared its predictions with Balescu's transport theory and also checked its results with Kaneko's 49x49 calculations.
    - We find that the ion transport is significantly modified by the ion-electron collision effect when the electron temperature is lower than ion temperature, an important regime for some emerging concept experiments. In addition, the perpendicular friction coefficients converge slowly in some ranges of gyrofrequency.

- Two papers that summarize these results are in preparation.

- For the integral-closure approach, we have experimented with Monte Carlo type calculations that use all of the data generated along magnetic field lines to approximate the integrals needed for NIMROD's finite element computations. Preliminary results show that importance-sampling based on the form of the integrands, which involves the product of the 2D finite-element basis functions, the Jacobian, and the closure data, yields superior convergence to that obtained in a crude Monte Carlo approach. This work may lead to greater efficiency in the integral closure calculations for cases with multiple significant Fourier components.

- Our temperature-dependent (fluid) thermal conductivity has been modified to include the demagnetization effect. It is based on the Braginskii model, which makes perpendicular diffusivities transition to their parallel values as the collision frequency exceeds the gyro-frequency. So far, the implementation is two-dimensional, and it is being used in computations of flux compression in the Pegasus experiment. The model will be generalized to 3D.

- A branch of the NIMROD code has been modified to improve parallel scaling through data and loop reordering. The quadrature-point and element indices have been switched to allow fewer collective mpi_alltoallv communication calls with more data, thereby reducing latency. Initial results show improved weak scaling as the number of Fourier components is increased with the number of processors. Further development will eliminate an extra data storage step.

FLR and Kinetic Effects Group *(R. Milroy, C. Kim, and G. Cone)*

The FLR and Kinetic effects group continues its collaboration with the MST group on FLR effects on RFP tearing modes, and on improving the performance of including particle effects in NIMROD. We continue with FRC formation simulations including calculations with a shaped radial boundary.

Accomplishments

- Charlson has collaborated with D. Brennan and R. Takahashi of U. Tulsa leading to the submission of the following paper to PRL. "Kinetic effects of energetic particles on resistive MHD stability" by R. Takahashi, D.P. Brennan, and C.C. Kim.

- Implement a fast high order particle integrator for a rectilinear finite element mesh. This was achieved by evaluating the Lagrange polynomials in standard form as a sum of n successive powers instead of a product of n linear terms. This implementation will be generalized to the general geometry available with NIMROD's finite elements.

- Charlson visited the University of Wisconsin to collaborate with the MST group on FLR effects on RFP tearing modes. He worked with V. Mirnov to discuss the physics of FLR effects and tearing modes in RFPs, and has begun a discussion with the experimentalists.

- We have begun a series of calculations using NIMROD to help the SSX team characterize the stability of an FRC formed by merging two spheromaks. These

FRCs are oblate and reside in a shaped flux conserver with little flux between the separatrix and the conducting wall. Preliminary calculations show the FRC is MHD stable to the tilt mode, but remains unstable to an n=1, m=1 *mushroom* mode. These calculations will continue with an effort to characterize the stability boundary, and investigate the effects of including two fluid terms, etc.

- We continue to investigate the effect of the Hall term on FRC formation in a θ-pinch. In particular we have begun calculations to simulate FRC formation in a conical θ-pinch, and are looking for the generation of toroidal field, and perhaps poloidal flow. This study will continue into the next quarter.
- Some effort was expended to adopt the developer version of NIMROD as a standard for the PSI center. All FRC specific initialization routines were ported to the developer version of NIMSET, and it was set up to compile and run on a PC with Visual Studio. However it has been decided that the effort required to complete this task will be too great for the expected benefits, and we have put this port on hold for now and have returned to the NIMPSI version of NIMROD as a standard for the Ψ-Center.

Interfacing Group (*B. A. Nelson, C. C. Kim, A. P. Cassidy, S. D. Griffith*)

Accomplishments:

- The IG is tasked with assisting in computational support for the twelve collaborating ICC experiments (along with the three physics groups).
- Work has continued with Jay Kesner of MIT to set up LDX runs on NERSC.
- Carleton College undergraduate student Ben Haynor worked this summer with the PSI-Center to improve “NimPy”, the Python-based NIMROD post-processor. Finite Element manipulations are being added in Python, allowing accurate reduction of data (FE-based curls and divergences of fields, etc.). Speed-ups in writing VTK files for VisIt have been implemented, as well as general code refactoring to make NimPy more “object-oriented”.
- After moving towards the NIMDEVEL version of the NIMROD code, some issues specific to modeling ICCs were found to require some code reworking. Thus for the present, we are going back to the NIMPSI version of NIMROD. NIMPSI will also be merged with the NIMlite version of the code (mentioned in previous progress reports).
- The Caltech spheromak simulations are restarting, investigating formation studies.
- The Interfacing Group is continuing support of HIT-SI NIMROD simulations, such as assisting in refining boundary conditions for the HIT-SI injectors and merging the HIT-SI version with NIMPSI.
- Profs. Nelson and Jarboe were invited to write a paper describing the activities of the PSI-Center for the Journal of the Japan Society of Plasma Science and Nuclear Fusion Research (which is included as an appendix).

Activities of the Plasma Science and Innovation Center

B. A. Nelson and T. R. Jarboe
PSI-Center, University of Washington, Seattle WA, USA

Abstract

The Plasma Science and Innovation Center (PSI-Center) is refining and developing codes to accurately simulate innovative confinement concept (ICC) experiments, with the goal of achieving predictive capability. The PSI-Center development focuses on geometries, boundary conditions, atomic physics, and two-fluid, collisional, and kinetic effects, appropriate for ICCs. Simulations are performed in collaboration with twelve ICC experiments at seven institutions, and are compared with experimental data. The results of these comparisons guide further code development and refinement for improved predictability.

Introduction

The Plasma Science and Innovation Center (PSI-Center) is a U.S. Department of Energy-funded program to improve computational predictability of innovative confinement concept (ICC) experiments. The PSI-Center is adding the necessary physics and algorithmic capability to extended magnetohydrodynamic (MHD) codes, and is working with experimentalists to validate code results with experimental data. The computational groups work closely with the experimentalists to iterate this process, summarized in this Mission Statement: "In concert with smaller innovative plasma physics experiments, refine and optimize existing MHD codes to achieve significantly improved predictive capability." The PSI-Center emphasizes physics that may extend beyond the standard analysis presently applied to the mainline (*e.g.*, tokamak) fusion programs. This specifically includes strong flow effects, kinetic effects, reconnection and relaxation phenomena, transport, atomic physics, radiation, FLR effects, two-fluid or Hall physics, more realistic boundary conditions and geometry, and other physics that must be included in models to achieve the needed predictability. All of these effects are also important in mainline fusion devices, but one or more tend to dominate effects in particular ICC configurations, which makes those effects particularly amenable to ICC study with their existing diagnostics. The goal of the PSI-Center is to capture the dominant effects of many different ICC experiments, covering most of ICC physics.

PSI-Center Organization

The PSI-Center is based at the University of Washington, Seattle WA, the University of Wisconsin-Madison, Madison WI, and Utah State University, Logan UT, and organized in four groups (codes and methods mentioned in this section will be described in detail in subsequent sections):

The *Boundary Conditions and Geometry Group* works on more realistic geometries, boundary conditions, atomic physics, neutrals, and radiation. They work on the development of the 2D SEL/3D HiFi codes and also a 3D tetrahedral mesh MHD code, to accurately model the complex geometry of many ICC experiments.

The *Two-Fluid, MHD Transport, and Relaxation Group* works on two-fluid/Hall, relaxation/reconnection, and MHD transport. They develop capabilities for modeling 3D dynamics in plasmas that are either collisional or in transition to low-collisionality behavior. These tasks build upon the mature MHD algorithms and Hall-MHD algorithms in the NIMROD code to produce self-consistent two-fluid simulation models for the lower-temperature plasmas found in ICC experiments.

The *FLR and Kinetic Effects Group* works on kinetic and FLR effects, primarily focusing on adding the physics needed for modeling field-reversed configurations (FRCs) with 3D codes. Energetic particles are simulated using a δf particle-in-cell (PIC) model. Time-dependant boundary conditions have been implemented in NIMROD to accurately simulate the external coils used in theta-pinch formation, translation, compression, and RMF current drive experiments.

The *Interfacing Group* works with the ICC experiments, and the other three PSI-Center Physics Groups. They lead the PSI-Center's interactions with the participating experimental groups. In coordination with the collaborating experiments, the best applicable code and equations to be solved are selected. Interfaces to code output are developed, and continually refined for data presentation and analysis packages. The Interfacing Group performs ICC experiment outreach and information dissemination through the PSI-Center web site, and presentations at conferences and workshops.

PSI-Center Code Development

The PSI-Center is concentrating its efforts on two major extended MHD codes, NIMROD and SEL/HiFi, as well as other developmental/testing codes.

<u>NIMROD:</u>

The Non Ideal Magnetohydrodynamic with Rotation, Open Discussion code, NIMROD,[i,ii] is a macroscopic simulation code solving compressible nonlinear magneto-fluid equations with electric-field terms selected to represent either the non-ideal single-fluid MHD model or two-fluid models of magnetized plasmas. The NIMROD code is 3D, using high-order finite elements to represent a non-periodic plane and Fourier series for the periodic direction. The finite elements provide a flexible description of the poloidal plane, so NIMROD is suitable for a variety of ICC configurations. The code also has flexibility in the polynomial degree of the basis functions used for the finite elements, so that spatial convergence can be achieved through the most efficient combination of mesh resolution and basis function order. High-order basis functions have proven important for simulating the extremely anisotropic thermal transport associated with magnetized plasmas[1], particularly when the magnetic field is not aligned with the computational mesh, as is common in dynamic ICC experiments.

Two complementary approaches to modeling plasma kinetic effects are being implemented in NIMROD: First, a semi-analytical approach addressing long mean-free-path physics for parallel kinetics of the majority species, and second, a hybrid kinetic-MHD approach, capturing the effects of minority energetic ions.

The semi-analytical approach determines closure relations by solving perturbed drift kinetic equations through a basis function expansion in velocity space along characteristic trajectories in *physical* space and accumulating the non-local effects that impact the fluid moments[iii,iv,v,vi,vii,viii]. This approach has already been implemented for electron and ion parallel heat fluxes and is valid over a range of collisionality extending from short-mean-free path to collisionless behavior.

The kinetic effects of the energetic minority ions are treated with a δf PIC model. A δf pressure moment is calculated and added to the MHD momentum equation. This minimal modification to the MHD equations is valid in the limit of $n_{HOT} << n_{BULK}$ but with $\beta_{HOT} \sim \beta_{BULK}$[ix,x,xi].

The PSI-Center is adding new physics features to NIMROD, as well as improving existing features. These include mixed finite elements to improve temperature evolution, collisional closures, using high-order finite-elements in the PIC calculations, and improving boundary conditions (BCs) to better simulate ICC experiments. These BC improvements include time-varying external coils for FRC formation and translation (as well as a wall radius that can vary along the Z-axis), and end-shorting/Hall physics to capture FRC spin-up effects.

SEL/HiFi

The PSI-Center is presently developing the 3D high order finite (spectral) element code HiFi, based on the existing 2D SEL code[xii]. The distinguishing capabilities of the code will include fully 3D adaptive spectral element spatial representation with flexible multi-block geometry, highly parallelizable implicit time advance, and general flux-source form of the PDEs, and boundary conditions that can be implemented in its framework. The 2D SEL code has been extensively validated and used for simulations of various multi-fluid plasma physics phenomena, including magnetic reconnection, cylindrical tokamak sawtooth oscillations, and FRC translation. SEL/HiFi use the hierarchical data format (HDF5) for parallel data I/O which can also be read by the 3D visualization software VisIt (described later). SEL/HiFi is also interfaced to the Sandia CUBIT meshing program (http://cubit.sandia.gov) for automatic grid generation. Present development includes self-consistent boundary condition formulations, adding cylindrical geometry, neutrals as a static fluid, Hall effect terms, and a Spitzer/Chodura resistivity model. Scalability studies are being pursued, using the "FETI-DP"[xiii] method of domain substructuring, and physics-based preconditioning. This is anticipated to greatly expand scalability of HiFi to computational clusters with very large core counts.

Other Developmental and Testing Codes:

The PSI-Center is developing and implementing other codes used for numerical testing and for equilibria/stability studies. M4 is a 3D tetrahedral mesh MHD code for testing algorithms, boundary conditions, *etc*. It is being adapted to include "mimetic operators", which "mimic" analytic operators for improved accuracy, while preserving vector relations such as the curl of a gradient and the divergence of a curl being identically zero. Boundary conditions are being developed for insulated conducting boundaries and also including circuit equations for external power supplies. The T4 code is a 3D tetrahedral mesh Taylor-state solver which successfully predicts the field structure in the HIT-SI spheromak. A MATLAB-based mimetic Grad-Shrafranov solver (which can include vacuum regions) is used to calculate initial equilibria for input to other codes.

Code Post-processing and Visualization:

VisIt (http://www.llnl.gov/visit/) is a powerful, open-source, 3D visualization code whose use is rapidly growing throughout the scientific community. It runs on many computer platforms and can read a wide variety of data formats. It is run as client/server processes, where the server can be a remote machine, including running on many processors in parallel. Fast 3D OpenGL graphics are displayed on the client machine using the visualization toolkit (VTK) package. The SEL/HiFi codes write HDF5 data which can be read *via* an easily-produced XDML file. A Python-based module "NimPy" can read standard NIMROD dumpfiles, as well as "nimplot", and "nimfl" post-processor output, and produce VTK files that can be read by VisIt. NimPy also allows interactive viewing, plotting, and manipulation of NIMROD data. This script-driven approach allows a standard NIMROD install to produce output without modifying/recompiling NIMROD. The M4 code directly writes VTK files for post-processing in VisIt. This model of using powerful open-source software (and scripts to make input files for VisIt) provides a common platform across codes and experiments, easing the learning curve, and saving costly commercial 3D visualization licensing.

Collaborating ICC Experiments

The PSI-Center is actively collaborating with the following twelve ICC experiments at seven institutions: the Caltech Plasma Group[xiv] (spheromak, helicity injection: Caltech), the field-reversed experiment FRX-L[xv] (FRC formation, translation, and active compression, Los Alamos National Laboratory), the steady inductive helicity injection spheromak HIT-SI[xvi] (Univ of Wash: UW), the coaxial helicity injection (CHI) spherical torus HIT-II[xvii] (UW), the levitated dipole experiment LDX[xviii] (M.I.T.), the Madison symmetric torus MST[xix] (reversed field pinch, Univ of Wisc-Madison: UW-M), the Pegasus low aspect ratio spherical torus[xx] (UW-M), the pulsed high-density experiment PHD[xxi] (FRC translation and compression, UW), the sustained spheromak physics experiment SSPX[xxii] (coaxial helicity injection spheromak, Lawrence Livermore National Laboratory), the Swarthmore spheromak experiment SSX[xxiii] (dual, coaxial-source spheromak/FRC, Swarthmore College), the translation, confinement, and sustainment upgrade TCS-U[xxiv] (FRC translation and rotating magnetic field formation/sustainment, UW), and the ZaP flow-shear stabilized Z-pinch[xxv] (UW).

Initial Results for Selected ICC Collaborations:

All four PSI-Center Groups are involved in simulations of the collaborating experiments. A brief description of initial results of some of these experiments follows.

HIT-II is being modeled using NIMROD. CHI requires two insulators, thus separate boundary conditions are implemented for the "injector" and "absorber" insulators. The voltage across the absorber insulator is first specified. The current flowing from one side to the other of the injector insulator is then adjusted to flow only from the inner electrode to the outer electrode (and not out the absorber insulator). The injector flux is scanned over conditions leading to weak relaxation (but large current amplification) in resistive MHD computations, and numerical results agree well with results from the experiment. A manuscript on this numerical study is in preparation. Knowledge gained through these simulations will be applied to other electrode-based collaborating experiments (Pegasus, Caltech, SSX, and ZaP).

MST is being modeled by NIMROD. Investigations of energetic-particle stabilization of tearing modes for the MST RFP, are proceeding, exploring the parameter space and performing convergence studies. The simulations show that for an idealized phase space distribution, sufficiently energetic ions stabilize the tearing mode. These simulations show good agreement with analytic theory and demonstrate the FLR physics capability of the hybrid kinetic-MHD model[xi].

The collaborating FRC experiments are being simulated using NIMROD. These include rotation stabilization[xxvi], translation[xxvii,xxviii], the physics of end-shorting[xxix], and rotating magnetic field (RMF) studies. When the tangential electric field on the end boundaries (open field lines) is set to zero and the Hall term is included in the calculation, the open field-line plasma spins up due to end-shorting effects, which in turn couples to the main FRC plasma through shear viscosity. The spin-up rate is found to be sensitive to the open field-line plasma profile. uyaInitial formation studies with Hall terms show toroidal field generation. Investigations are being made into recent observations[xxx] that imply a small toroidal field could help stabilize the n=2 rotational instability. It is found that a combination of a relatively weak toroidal magnetic field and the inclusion of the Hall term in the calculation can lead to a change in the character of the mode and a dramatic reduction to its growth rate. Recent modifications to the radial boundary conditions capture most of the effects of multiple discrete coils found in many FRC experiments. This allows translation studies of FRCs with non-uniform radial boundaries (such as PHD, FRX-L, and TCS-U), see Figure 1, as well as simulations of theta-pinch FRC formation studies. The previously mentioned mimetic Grad-Shafranov solver is used to create equilibria for NIMROD, see Figure 2.

LDX is being modeled using NIMROD. Stability to interchange and high-n ballooning modes is of interest, particularly when the pressure gradient in the bad curvature region is steeper than that of an adiabatic profile[xxxi]. The NIMROD grid has been refined and an axisymmetric equilibrium is evolved using density and heating source terms, as shown in

Figure 3. When the bad curvature region pressure gradient exceeds that of an adiabatic profile, the code is then run with non-axisymmetric modes destabilized. With 6 toroidal Fourier modes, [0, 5], a (mostly) n=5 interchange-like structure is seen to develop. The Interfacing Group is transferring this work to M.I.T. personnel and will continue to assist them in further investigation into these results.

SSPX has been modeled for several years using NIMROD, by personnel at LLNL, University of Wisconsin-Madison, and Utah State University[xxxii,xxxiii,xxxiv]. The PSI-Center is improving NIMROD simulations by including parallel heat-flow closures at arbitrary levels of collisionality. Comparison of core SSPX temperatures obtained with the diffusive parallel heat flow model indicates that a 10% increase results from nonlocal collisionless effects in the integral closure. While the discrepancy in this application is small quantitatively, these calculations point to necessary improvements in spatial resolution as well as the need for a more numerically efficient algorithm for computing the integral closures. Improved agreement with experiment will likely require time-dependent simulations, which are planned for future work. Also the PSI-Center works closely with SSPX personnel to refine the NimPy code to produce output for analysis with VisIt, shown in Figure 4.

HIT-SI NIMROD simulations[xxxv,xxxvi] are being refined by a HIT-SI graduate student, Cihan Akcay, with help from the PSI-Center. This effort has resulted in improved gridding, better resolution of the resistive wall boundary, and refinement of injector BCs. Mr. Akcay also helped develop the mimetic Grad-Shafranov solver for the NIMROD grid, which is used to create HIT-SI equilibria for NIMROD. In addition, the T4 3D Taylor-state solver code has been applied to HIT-SI, Figure 5, which agrees remarkably well with experimental measurements of surface and internal magnetic fields[xxxvii].

Summary

The Plasma Science and Innovation Center (PSI-Center) focuses on improving computational predictability for innovative confinement concept (ICC) experiments. Three computational physics groups develop codes with physics and boundary conditions appropriate for ICCs. These groups and a fourth “interfacing” group collaborate with twelve ICC experiments at seven institutions on simulations of their experiments. Budget constraints make it difficult for most ICC experiments to pursue computations on their own, thus a modest, purposed effort such as the PSI-Center provides a synergistic path for improved understanding of the physics of ICCs. Improved predictability for ICCs provides a more direct and cost-effective path towards larger ICC-based experiments with improved chances for success.

Acknowledgements

The authors would like to thank their PSI-Center colleagues for their contributions to this manuscript: R. D. Milroy, U. Shumlak, G. A. Cone, A. H. Glasser, G. J. Marklin, C. C. Kim, W. B. Lowrie, V. S. Lukin, and E. T. Meier of the University of Washington, Seattle WA, USA, C. R. Sovinec and R. A. Bayliss of the University of Wisconsin-

Madison, Madison WI, USA, and E. D. Held and J.-Y. Ji of Utah State University, Logan UT, USA.

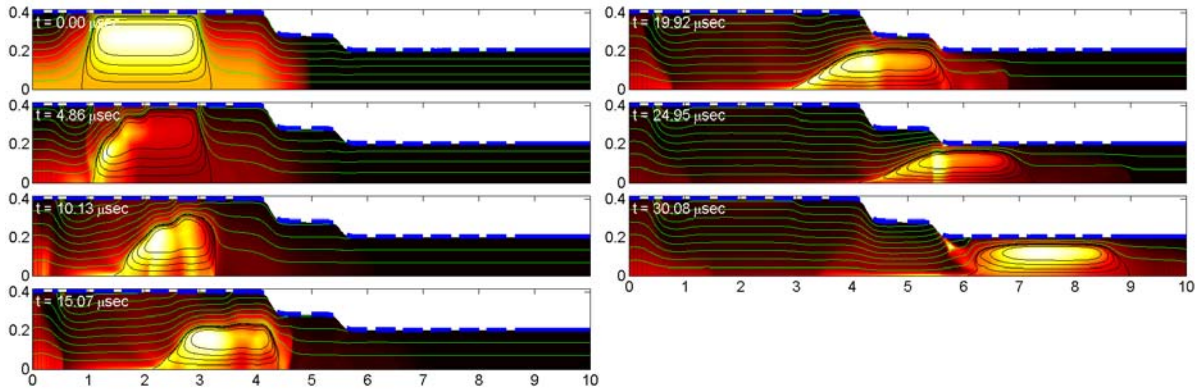

Figure 1: Illustration of FRC translation in the PHD experiment's shaped flux conserver. External coils (blue segments) are activated sequentially to accelerate and compress the FRC.

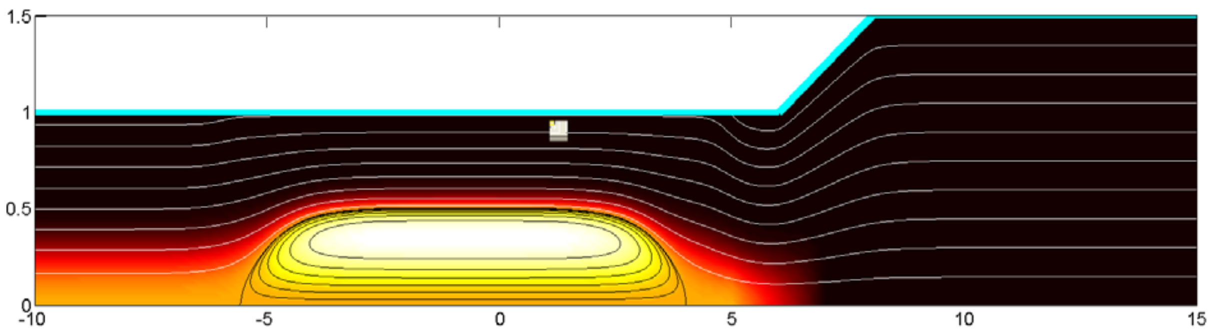

Figure 2: Illustration of an FRC equilibrium in a shaped region and confined by mirror fields. The plasma pressure is shown as a solid color with field lines superimposed The FRC transitions to a vacuum region on the right side.

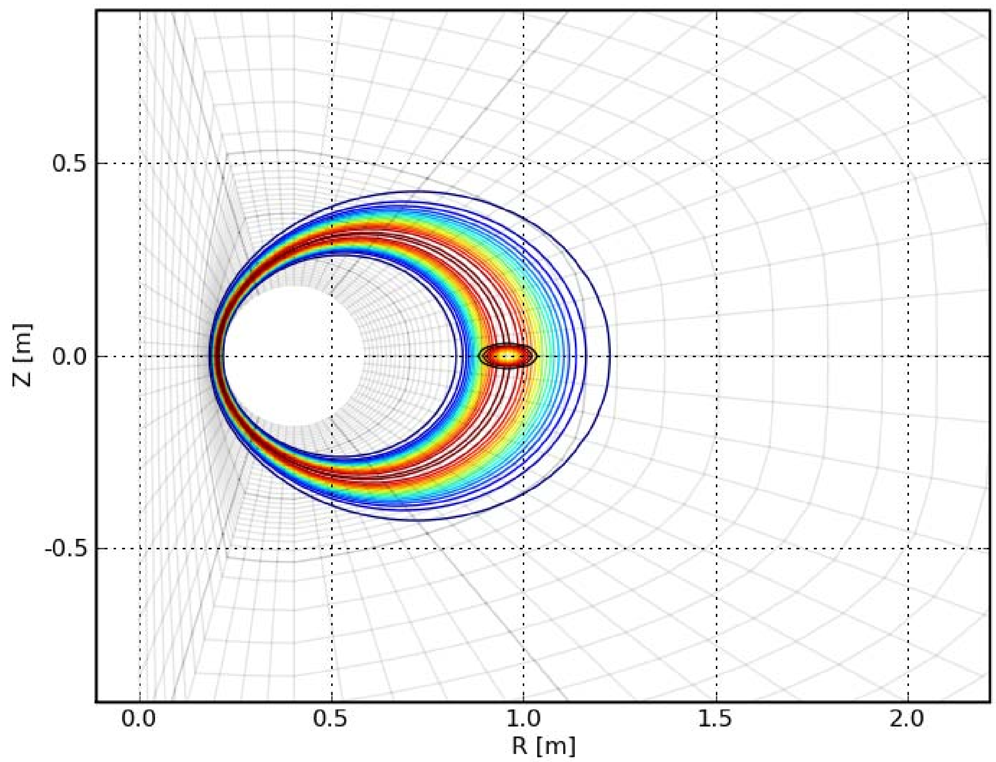

Figure 3: Example of contours of pressure (larger set of contours) and the generating heating profile (smaller set of contours). (The NIMROD grid can be seen as faint lines. The grid spacing can be adjusted to be more coincident with the pressure contours). Heat flows away from the source along the simple dipole field, produced by a current filament at the center of the levitating coil (hole in the grid).

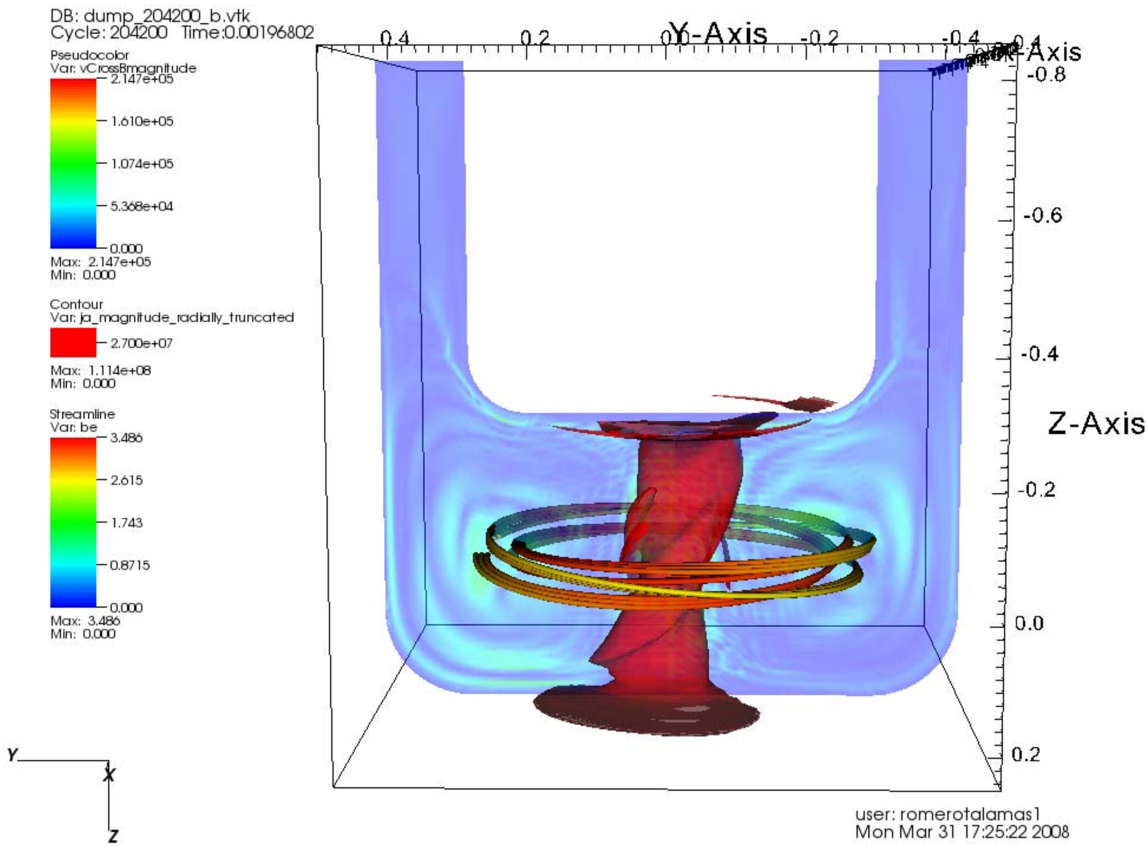

Figure 4: SSPX NIMROD data in VisIt: The semi-transparent slice in the y-z plane shows the structure of |V x B|, where discrete bands of higher amplitude appear to approximately follow poloidal contours. Approximate magnetic field streamlines are shown with color corresponding to strength (these are not *integrated in a finite-element sense). The red column in the middle represents a contour of constant current density. (Figure courtesy of Drs. Romero-Talamas and Hooper of LLNL, using the PIS-Center NimPy code to create VisIt input files..)*

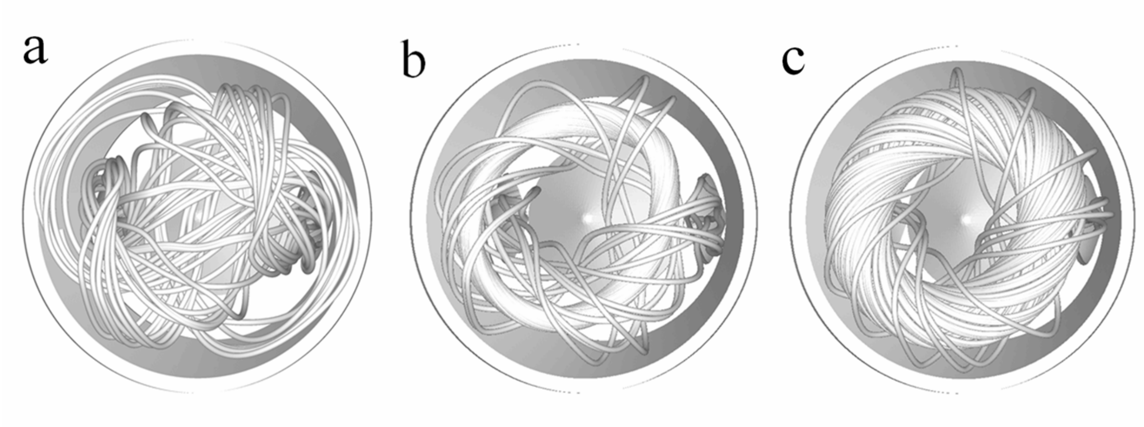

Figure 5: Magnetic flux tubes from HIT-SI 3D Taylor state code results for increasing values of helicity. (a) Injector current (I_{INJ}), without spheromak current (I_{TOR}), (b) I_{TOR} ~ 1.5 I_{INJ}, and (c) I_{TOR} ~ 5 I_{INJ}. (View is into one injector and flux conserver half, with the other removed.

---

[i] C. R. Sovinec, A. H. Glasser, T. A. Gianakon, D. C. Barnes, R. A. Nebel, S. E. Kruger, D. D. Schnack, S. J. Plimpton, A. Tarditi, M. Chu, and the NIMROD Team, "Nonlinear Magnetohydrodynamics Simulation using High-Order Finite Elements," J. Comput. Phys, **195**, 355 (2004)

[ii] C. R. Sovinec, D. D. Schnack, A. Y. Pankin, D. P. Brennan, H Tian, D. C. Barnes, S. E. Kruger, E. D. Held, C. C. Kim, X. S. Li, D. K. Kaushik, S. C. Jardin, and the NIMROD Team, "Nonlinear Extended Magnetohydrodynamics Simulation using High-Order Finite Elements", Journ. of Physics: Conference Series, **16**, 25 (IoP, London, 2005)

[iii] E. D. Held, J. D. Callen, C. C. Hegna, Phys. Plasmas **10**, 3933 (2003)

[iv] E. D. Held, Phys. Plasmas, **10**, 4708 (2003)

[v] J.-Y. Ji and E. D. Held, "Exact linearized Coulomb collision operator in the moment expansion", Phys. Plasmas, **13,** 102103 (2006)

[vi] J.-Y. Ji and E. D. Held, "Collision operators and general moment equations for an electron-ion plasma", to be published in Phys. Plasmas (2008)

[vii] J.-Y. Ji, E. D. Held, and C. R. Sovinec, "Moment approach to deriving parallel heat flux for general collisionality", in review

[viii] J.-Y. Ji and E. D. Held, "Moment approach to deriving a unified parallel viscous stress in magnetized plasmas", to be published in J. Fusion Energy

[ix] S. E. Parker and W. W. Lee, "A fully nonlinear characteristic method for gyrokinetic simulation", Phys. Fluids B, **5**, 77 (1993)

[x] C. C. Kim, C. R. Sovinec, S. E. Parker, and the NIMROD Team, "Hybrid Kinetic-MHD Simulations in General Geometry," Computer Physics Communications, **164**, 448, (2004)

[xi] C. C. Kim, "Impact of velocity space distribution on hybrid kinetic-magnetohydrodynamic simulation of the (1,1) mode", Phys. Plasmas, **15**, 072507 (2008)

[xii] V. S. Lukin, "Computational Study of the Internal Kink Mode Evolution and Associated Magnetic Reconnection Phenomena", PhD Thesis, Princeton University, 2007

[xiii] Axel Klawonn and Olof B. Widlund, "Dual-Primal FETI Methods for Linear Elasticity", Comm. Pure Appl. Math., **59**, 1523 (2006)

[xiv] S. C. Hsu and P. M. Bellan, "On the jets, kinks, and spheromaks formed by a planar magnetized coaxial gun", Phys. Plasmas, **12**, 032103 (2005)

[xv] T. Intrator, S. Y. Zhang, J. H. Degnan, I. Furno, C. Grabowski, S. C. Hsu, E. L. Ruden, P. G. Sanchez, J. M. Taccetti, M. Tuszewski, W. J. Waganaar, and G. A Wurden, “A high-density field reversed configuration plasma for magnetized target fusion”, Phys. Plasmas, **11**, 2580 (2004)
[xvi] T. R. Jarboe, “Steady inductive helicity injection and its application to a high-beta spheromak”, Fus. Tech., **36**, 85 (1999)
[xvii] A. J. Redd, T. R. Jarboe, W. T. Hamp, B. A. Nelson, R. G. O’Neill, and R. J. Smith, “Flux amplification in helicity injectec torus (HIT-II) coaxial helicity injection discharges”, Phys. Plasmas, **15**, 022506 (2008)
[xviii] D. T. Garnier, A. K. Hansen, J. Kesner, M. E. Mauel, P. C. Michael, J. V. Minervini, A. Radovinsky, A. Zhukovsky, A. Boxer, J. L. Ellsworth, I. Karim, and E. E. Ortiz, “Design and initial operation of the LDX facility”, Fus. Engr. and Design, **81**, 2371 (2006)
[xix] S. C. Prager *et al*., “Overview of results in the MST reversed field pinch experiment”, Nuc. Fusion, **45**, S276 (2005)
[xx] G. D. Garstka, S. J. Diem, N. W. Eidietis, R. J. Fonck, B. T. Lewicki, G. Taylor, D. J. Battaglia, M. W. Bongard, M. J. Frost, B. A. Kujak-Ford, B. J. Squires, and G. R. Winz, “The upgraded Pegasus Toroidal Experiment”, Nuc. Fusion, **46**, S603 (2006)
[xxi] J. Slough, S. Andreason, H. Gota, C. Pihl, and G. Votroubek, “The pulsed high density experiment: concept, design, and initial results”, J. Fusion Energy, **26**, 199 (2007)
[xxii] B. Hudson, R. D. Wood, H. S. McLean, E. B. Hooper, D. N. Hill, J. Jayakumar, J. Moller, D. Montez, C. A. Romero-Talamas, T. A. Casper, J. A. Johnson, L. L. LoDestro, E. Mezonlin, and L. D. Peralstein, “Energy confinement and magnetic field generation in the SSPX spheromak”, Phys. Plasmas, **15**, 056112 (2008)
[xxiii] C. D. Cothran, A. Falk, A. Fefferman, M. Landreman, M. R. Brown, and M. J. Schaffer, “Spheromak merging and field reversed configuration formation at the Swarthmore Spheromak Experiment”, Phys. Plasmas, **10**, 1748 (2003)
[xxiv] K.E. Miller, J.A. Grossnickle, R.D. Brooks, C.L. Deards, T.E. DeHart, M. Dellinger, M.B Fishburn, H.Y. Guo, B. Hansen, J.W. Hayward, A.L Hoffman, W.S. Kimball, K.Y. Lee, D.E. Lotz, P.A. Melnik, R.D. Milroy, Z.A. Pietrzyk, G.C. Vlasses, F.S. Ohuchi, and A. Tankut, “The TCS upgrade: design, construction, conditioning, and enhanced RMF FRC performance”, Fus. Science and Tech., **54** (2008)
[xxv] U. Shumlak, B. A. Nelson, R. P. Golingo, S. L. Jackson, E. A. Crawford, D. J. Den Hartog, “Sheared flow stabilization experiments in the ZaP flow Z pinch”, Phys. Plasmas, **10**, 1683 (2003)
[xxvi] R. D. Milroy and L. C. Steinhauer, “Toroidal field stabilization of the rotational instability in field-reversed configurations”, Phys. Plasmas, **15**, 022508 (2008)
[xxvii] R. D. Milroy, A. I. D. Macnab, C. C. Kim, and C. R. Sovinec, “FRC Simulations using the NIMROD Code”, J. Fusion Energy, **27**, 73 (2008)
[xxviii] A. I. D. Macnab, D. C. Barnes, R. D. Milroy, C. C. Kim, and C. R. Sovinec, “Simulations of the Field-Reversed Configuration with the NIMROD Code”, J. Fusion Energy, **26**, 113 (2007)
[xxix] A. I. D. Macnab, R. D. Milroy, C. C. Kim, and C. R. Sovinec, “Hall magnetohydrodynamics simulations of end-shorting induced rotation in field-reversed configurations”, Phys. Plasmas, **14**, 092503 (2007)
[xxx] H. Y. Guo, A. L. Hoffman, R. D. Milroy, K. E. Miller, and G. R. Votroubek, “Stabilization of interchange modes by rotating magnetic fields”, Phys. Rev. Lett., **95**,175001 (2005)
[xxxi] D. T. Garnier, J. Kesner, and M. E. Mauel, “Magnetohydrodynamic stability in a levitated dipole”, Phys. Plasmas, **6**, 3431 (1999)
[xxxii] C. R. Sovinec, B. I. Cohen, G. A. Cone, E. B. Hooper, and H. S. McLean, “Numerical investigation of transients in the SSPX Spheromak”, Phys. Rev. Lett., **94**, 035003/1 (2005)
[xxxiii] B. I. Cohen, E. B. Hooper, R. H. Cohen, D. N. Hill, H. S. McLean, R. D. Wood, S. Woodruff, C. R. Sovinec, and G. A. Cone, “Simulation of spheromak evolution and energy confinement”, Phys. Plasmas, **12**, 56106-1 (2005)
[xxxiv] E. B. Hooper, B. I. Cohen, H. S. McLean, R. D. Wood, C. A. Romero-Talamas, and C. R. Sovinec, “NIMROD resistive magnetohydrodynamic simulations of spheromak physics”, Phys. Plasmas, **15**, 032502-1 (2008)
[xxxv] V. A. Izzo and T. R. Jarboe, “A numerical assessment of the Lundquist number requirement for relaxation current drive”, Phys. Plasmas, **10**, 2903 (2003)
[xxxvi] V. A. Izzo and T. R. Jarboe, “Three-dimensional magnetohydrodynamic simulations of the Helicity Injected Torus with Steady Inductive drive”, Phys. Plasmas, **12**, 056109 (2005)

[xxxvii] T. R. Jarboe, W. T. Hamp, G. J. Marklin, B. A. Nelson, R. G. O'Neill, A. J. Redd, P. E. Sieck, R. J. Smith, and J. S. Wrobel, "Spheromak formation by steady inductive helicity injection", Phys. Rev. Lett., **97**, 11503 (2006)