Quarterly Progress Report of the PSI-Center (Oct. – Dec. 2007)

by

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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. Alan Glasser will be at the University of Washington for a 12-month sabbatical, starting January 2008.

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

Accomplishments

- Finite Element Code Development
  - Added support for Dirichlet and Neumann boundary conditions for all conserved variables
  - Added support for Dirichlet and Neumann boundary conditions to non-conserved variables of the Pseudo-1D Euler equations
  - Modified the non-linear function and Jacobian to handle the B.C. support
  - Verified code functionality with new boundary conditions by running several pseudo-1D Euler test problems
    - Supersonic inflow and outflow
    - Supersonic inflow and Subsonic outflow
    - Subsonic inflow and Supersonic outflow
    - Subsonic inflow and outflow
    - Euler Shock tube problem
  - Investigated adding support for continuous modal basis functions
    - Wrote theoretical report of how modal basis functions could be incorporated into the finite element code.
- ZaP simulations with MH4D have been found to qualitatively agree with MACH2 simulations in the acceleration region of the ZaP device. However, to date, MH4D runs have had insufficient resolution to capture the Z-pinch behavior seen in MACH2.
- An inflow boundary condition has been developed and used to simulate gas inflow in the ZaP experiment. During the acceleration phase of the ZaP discharge, simulations show that the initially non-azimuthally-symmetric plasma symmetrizes during acceleration. This highlights MH4D's capacity to simulate asymmetric phenomena.
- Initial HIT-SI simulations with vacuum fields have been conducted with MH4D. For these simulations, the domain is the entire HIT-SI machine, and all boundaries are conducting.
- Assisted Alan Glasser in the implementation of the FETI-DP preconditioning algorithm in the context of the SEL code; following that, successfully merged and tested that implementation with the latest version of the code.

- Developed a general "plan of attack" on how to go about extending the existing SEL code to its new multi-block 3D implementation.
- Multiple upgrades to the SEL code in preparation for extending it to a 2D multi-block and then 3D code:
    - restructuring of the input stack: completely decouple declaration and reading of job specific (i.e. physics specific) input parameters from the core of the code. Now, any new set of PDEs, initial, and boundary conditions can be implemented without even opening any of the algorithmic files;
    - modified the code to compute quadratures cell by cell;
    - in the process of generalizing the Fortran data structures, quadrature routines etc. to allow for a discontinuous spectral element representation of the solution (will also greatly help in generalization to multi-block formulation and improved implementation of FETI-DP algorithm);
- Attended ICNSP and APS-DPP conferences (Slava gave an invited talk at ICNSP) presenting previous results on magnetic reconnection, self-organization and sawtooth instability.
- In collaboration with Luis Chacon and Andrei Simakov of LANL, continued work on the generalized magnetic reconnection problem -- this time in the context of electron-positron reconnection -- by implementing electron-positron fluid approximation within the SEL code and running simulations to investigate the behavior of the system in various limits.
- External vacuum fields were computed for HIT-SI on a tetrahedral mesh for use with MH4D to begin simulations of that experiment.
- A 2D MHD equilibrium code was written using mimetic numerical operators and is being incorporated into Nimrod to generate FRC equilibria for initialization. A set of numerical operators is called mimetic if they preserve curl(grad)=0 and div(curl)=0 as exact identities. The mimetic operators were found to significantly improve the accuracy over an earlier version that used finite area operators.
- A set of 3D mimetic operators is being installed into the M4 MHD simulation code. The expected improvements in speed and accuracy should help solve some of the problems that have so far prevented successful implementation of the insulated conductor boundary condition.

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

Over the quarter of funding ending on 12/31/07, the Two-fluid and Transport Group has focused on preparing material for publication on closure modeling and on simulation applications to HIT-II and SSPX. We have also implemented a ‘mixed method’ computation for the temperature evolution equation to reduce resolution requirements when the integral heat-flux closure is used.

Accomplishments

- We are preparing to submit three papers on various aspects of the moment approach to deriving closures. The first discusses moment equations and collision operators when the random velocity (as opposed to the total velocity) is used in the moment expansion. The second paper uses a systematic method to derive a form of classical collisional closure that is more complete than Braginskii. The final paper discusses the general heat flux closure developed from the moment method and its application to heat transport studies of SSPX. These papers will be submitted prior to the Sherwood meeting. As a final note on analytical progress, we have developed the necessary formulas for tensor products in preparation for calculating nonlinear collision operators in the moment expansion.

- Numerical progress has focused on improving the efficiency of the integral closure calculation in NIMROD. This work is needed in light of the prohibitive time spent calculating the closures in the SSPX confinement studies. We are developing a mixed finite element formulation for advancing temperature, which solves for an auxiliary variable related to the diffusive, parallel heat conduction in concert with the temperature update. Previous SSPX computations suggest that this may provide improved spatial resolution at a fixed number of elements and Fourier components when the magnetic field is stochastic. This would in turn speed up the integral closure calculation for a given accuracy level by allowing lower polynomial degree and fewer Fourier modes for the expanded variables, hence resulting in fewer locations where the closures need to be calculated. At present, the implementation works for n=0 only cases, and the behavior of the iterative solves for non-symmetric systems without preconditioning in the Fourier direction is being studied.
- We are preparing a manuscript on a numerical study of DC helicity injection in HIT-II for conditions that do not produce significant flux amplification. These cases were performed on the experiment as part of an investigation of the bias flux distribution, and the laboratory database is very useful for validation purposes. Numerical parameter scans over injected current, rod (toroidal field) current, and magnitude of the poloidal flux are now near completion. Simulations of HIT-II with three different poloidal-flux footprints have been run on the new NERSC machine Franklin and will provide information for direct comparison with the experimental results. Simulations for a second manuscript that will describe results with temperature-dependent transport coefficients and conditions of strong relaxation are also progressing.

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

Over this quarter the FLR and Kinetic Effects group has focused on finishing up work on the n=2 rotational instability in the FRC, and on the continued enhancement of particle simulations with a focus on understanding the importance of the details of the energetic particle distribution. A new graduate student, Giovanni Cone will be joining the FLR and Kinetic Effects Group at the beginning of January.

Accomplishments

- We have resumed our study of the n=2 rotational instability in a collaboration with Loren Steinhauer. A paper titled "Toroidal field stabilization of the rotational instability in field-reversed configurations", by R.D. Milroy, and L.C. Steinhauer has been submitted to the Physics of Plasmas. Here, a modest toroidal magnetic field is predicted to provide a strong stabilizing influence on the m = 2 rotational instability in FRCs. This result is consistent with experimental observations that the rotational mode often does not appear in translating FRCs which tend to have a net toroidal field. A stability threshold for the toroidal field was derived using a quasi-analytic model.

$$(B_{\theta,\max})_{st} = 0.65\sqrt{\mu_0 m_i n_m}\, r_s \Omega ,$$

where $(B_{\theta,\max})_{st}$ is the threshold toroidal field (at its maximum point) for stability, n_m is the maximum FRC density at the magnetic null, r_s is the separatrix radius, and Ω is the rotation rate. NIMROD calculations show a basic agreement with the analysis but instabilities persist in the open field-line region, even well above the derived stability threshold. However the growth rate is significantly reduced from the cases with no toroidal field, and the persistent mode is largely limited to the open-field-line region. Several effects that could stabilize the disturbance in the open-field-line region are missing from the present treatment.

- Attend the APS meeting and present two papers.
  - "The Effect of a Weak Toroidal Field on the n=2 Rotational Instability in an FRC", by R.D. Milroy, L.C. Steinhauer, A.I.D. Macnab, C.C. Kim, and C.R. Sovinec.
  - "Impact of velocity space distribution on hybrid kinetic MHD simulation of the (1, 1) internal kink mode", by Charlson C. Kim.
- Energetic particle simulations were performed to study the impact of increasing the energy cut off of the particles loaded into the simulation. A slowing down distribution function ($f_h(\vec{x},\vec{v}) = \frac{n_h(\vec{x})}{v^3 + v_c^3}$) was used for the energetic (or hot) particles. It was observed in the drift kinetic hot particle simulations that the n=1 projection of δf in velocity space peaks at the extreme values of velocity (see figure 1). To follow up on this observation, simulations were performed where the velocity cut off was increased from $1\text{x}10^6$m/s to (1.1,1.2,1.3,1.5)$\text{x}10^6$m/s. It was observed that as the velocity cut off is increased, the relative amplitude of δf for passing region to trapped region decreases. Stabilization at β_{frac} =.5 was found to increase (almost linearly) with increasing velocity cut off, with a velocity cut off 1.5m/s entirely stabilizing the (1,1) mode. The real frequency was also observed to increase (linearly) with increasing velocity cutoff (see figure 2). It is also worth mentioning that for the fixed β_{frac}, as the velocity cut off is increased, the energetic particle density is decreased to maintain the constant particle pressure. These simulations show the importance of the details of the energetic particle distribution. These results may be significant when applying the hybrid kinetic-MHD method to ICC devices such as FRCs and RFP (particularly extensions of MST tearing mode simulations with realistic geometry).

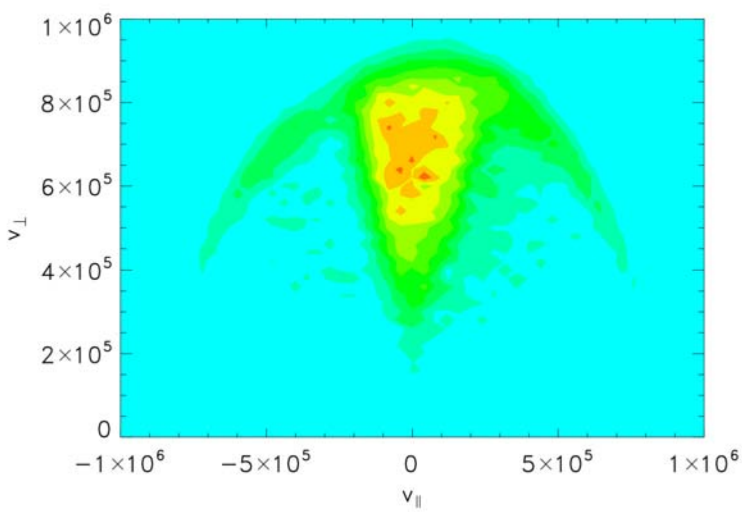


Figure 1. n=1 projection of δf in velocity space shows activity dominantly in trapped region and extremes of passing region

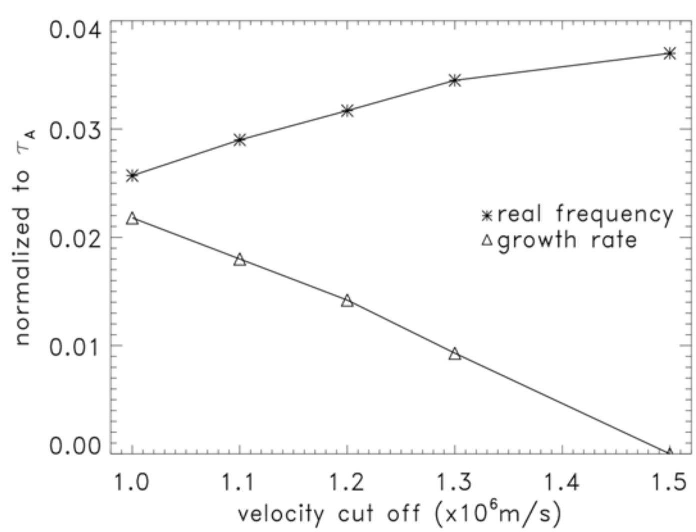
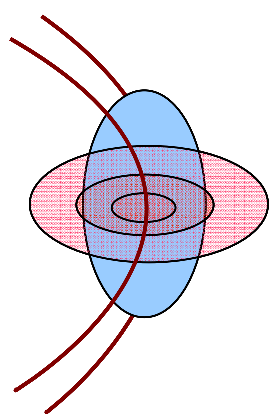


Figure 2. shows velocity cut off scan and impact on linear growth rate and real frequency of (1,1) mode for β_{frac}=.5. Note near linear dependence.

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

Accomplishments

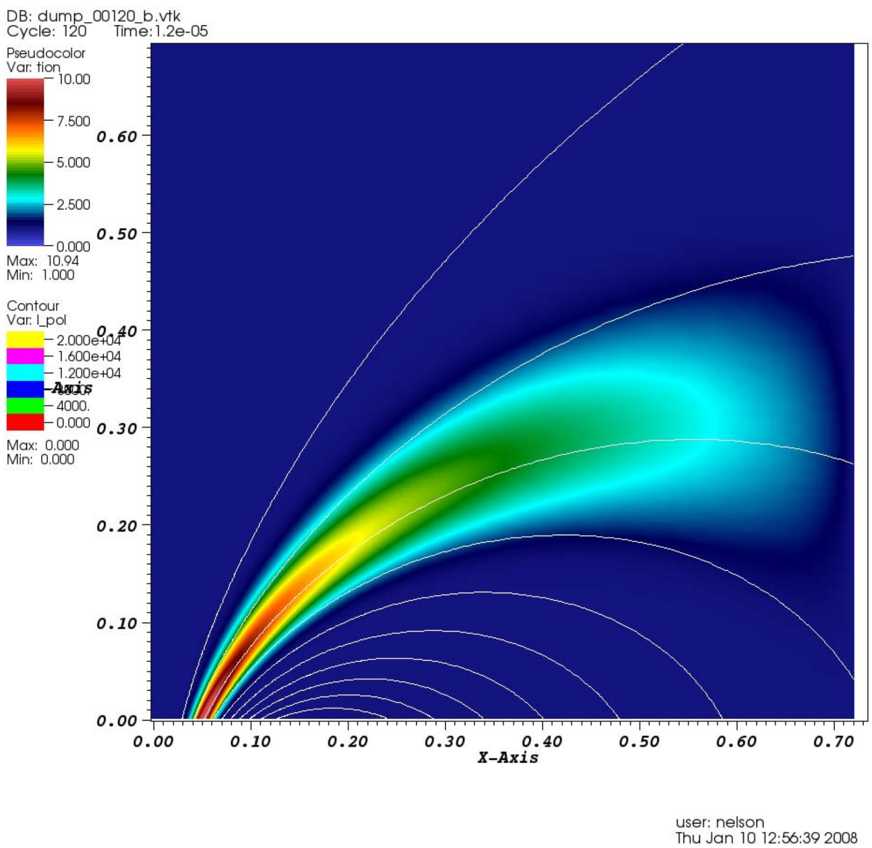
- The IG is tasked with assisting in computational support for the twelve collaborating ICC experiments (along with the three physics groups). All collaborating PIs have been contacted, and development of plans for proceeding with simulations is ongoing.
- IG results were presented at the 2007 APS DPP Meeting in Orlando Florida. Discussions of results were made with off-site collaborators: LDX (Drs. Kesner and Garnier), the Caltech experiment (Prof. Bellan and graduate students), SSX (Prof. Brown), and SSPX (Drs. Hooper and B. Cohen).
- Work is continuing on the **Levitated Dipole Experiment** (LDX):
    - After twiddling with reading in equilibria and massaging the grid, the problem has been reverted back to growing an equilibrium using a heating source. Reading in an equilibrium proved to be troublesome. Obtaining a smooth current profile proved difficult. Also, there were interpolation errors that resulted in "anomolous" fields at the cryodonut boundary and along the R=0 boundary. We are presently working on an in-house equilibrium solver that may be more compatible with the NIMROD grid. Instead "consistent" equilibria has been evolved by using a temperature heat source.
    - The runs use modest amounts of diffusivity, **elecd=**10, **kin_visc**=1000. To grow the initial equilibrium, a significant density diffusion is used to prevent the flow from advecting the density away from regions of high temperatures.
    - It was discovered that it is preferable to use a prolate heating spot as opposed to oblate spot. The oblate spot was found to cause a small secondary peak.

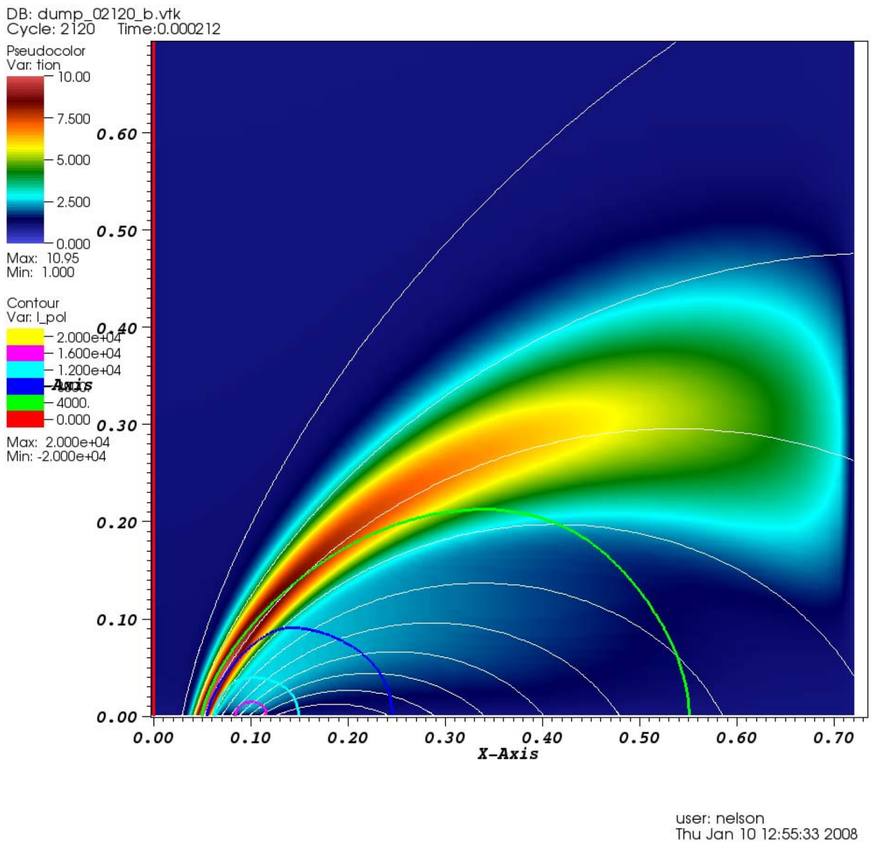


Sketch of prolate and oblate heating profiles (ovals) and LDX magnetic field lines (arcs).

    - Slower and longer heating is also preferable as this reduces the resulting flow. However, this must in turn be balanced with the perpendicular thermal conduction.
    - Preliminary simulations with multiple modes (0,1,2) show significant poloidal resolution is required. We've returned to the original 40x60 pd=4 mesh with strong packing near the cryodonut. This helps to resolve the strong fields that lie at the center of the cryodonut. Not surprisingly, proper resolution of the anisotropic thermal conduction relies on sufficient resolution. This would be much improved by flux alignment of the grid.
    - We have run nonlinear simulations with n=[0-2] and n=[0-5]. Higher n clearly shows larger growth rates. We are in the preliminary phases of diagnosing these runs.

- Work is continuing on the **Caltech experiment**:
  - Previous formation studies in NIMROD showed the current channel location very strongly depends upon the specific shape of the plasma resistivity profile, *viz*., the enhanced resistivity near the lower boundary. Unlike the experiment, the simulation current channel path is dominated by the edge resistive layer, rather than by the plasma and/or magnetic field.
  - To provide a low-resistivity channel for the current, temperature-dependent resistivity/thermal conductivity and Ohmic heating switches were enabled in further simulations. A temperature "hot spot" was introduced at the location of the experimental inner electrode gas injection port, and allowed to approach steady-state (see upper part of figure).





Caltech NIMROD results: Shaded levels are ion temperature, white contour lines are poloidal flux, and colored contour lines are driven poloidal current.

Upper: Initial temperature "hot spot"(R=0) is evolved with temperature-dependent thermal conductivity. Lower: 20 kA of current is applied, (insulator at R=0.1 m). Temperature is increased, and drawn out, into the channel, and also increases near the insulator.

  - While this low-resistivity channel lets the applied current to further penetrate, the lower boundary resistivity-shaping still affects the current path, (see lower part of figure). (Also, at high driving currents, the plasma heats near the insulating gap, which draws in some of the driven current.)
  - To resolve this issue, we are exploring the incorporation of a resistivity model different from Spitzer, *e.g.*, "Chodura" resistivity, which depends on density and the ratio of drift to sound speeds. Previous simulations using the Chodura resistivity model have been found to agree very well with theta-pinch and FRC experimental results, and should aid in Caltech experiment simulations.

- The Python-based "NimPy" post-processor is being updated, along with the Wiki page. NimPy converts NIMROD dump files to the Visualization Toolkit (VTK) format, which can then be read by the LLNL VisIt visualization program (http://www.llnl.gov/visit/). Work is progressing on a NimPy/VisIt tutorial that will be posted on the PSI-Center Wiki.