Final Progress Report of the PSI-Center (DOE # DE-FG02-05ER54811)**(Mar 2014 – Feb. 2017)**

by

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This is the Final Progress Report of the Plasma Science and Innovation Center (PSI-Center) covering March 2014 through February 2017. The Center has accomplished a great deal during this period. The PSI-Center is organized into four groups: Edge and Dynamic Neutrals; Transport and Kinetic Effects; Equilibrium, Stability, and Kinetic Effects in 3D Topologies; and Interface for Validation. Each group has made good progress and the results from each group are given in detail.

Edge & Dynamic Neutrals Group *(U. Shumlak, S. Taheri, P. Norgaard)*

Accomplishments:

- Started implementing the nonlinear part of the momentum equation for neutral fluid.
- Working with Jacob King and Scott Kruger of Tech-X to develop implementation plan and consistent style for plasma-neutral model in NIMROD.
- Added the nonlinear calculations for neutral momentum equation without coupling it to plasma momentum to finish the momentum implementation. Completed the coding of momentum equation for both neutral and plasma species.
- The complete system of equations for plasma and neutral momentum was added to the NIMROD. Debugged the code and made sure that the solution is stable. Some test cases were run to make sure that the interaction of species was captured.
- Set up the infrastructure for neutral temperature inside the NIMROD. Since a whole equation is being added into the governing equations, an infrastructure for it in needed. J. King outlined the steps to add advance subroutines for neutral temperature equation. Work is proceeding on the subroutines that should be called to solve the temperature equation.
- Started adding neutral temperature. After setting up advance subroutines, initial implementation has begun for the integrand subroutines for neutral temperature. Plasma temperature has not been coupled to neutrals at this point.
- The temperature advance for both plasma and neutrals is completed. Finished the implementation of neutral temperature equation and added the related source terms in plasma temperature. At this point the plasma-neutral model is nearly implemented with constant cross-section terms.
- Elementary results for plasma-neutral interaction in a poster were presented it in APS-DPP, EPR, and Sherwood conferences, as well as presented the results at NIMROD team meetings.

Transport and Kinetic Effects Group ***(C. R. Sovinec, E. D. Held, J.-Y. Ji, K. Lee, J. Maddox, Z. Riford, and O. Ohia)***

Over the period of this report, the Transport and Kinetic Effects Group has conducted analytical and numerical work on closures for plasma moment equations and for coupled plasma-neutral systems. We have also contributed to a publication on current-sheet instability.

Accomplishments:

- John O'Bryan completed his PhD research and successfully defended his thesis on modeling current-filament injection for startup in the Pegasus Toroidal Experiment. Previously reported findings include information on magnetic reconnection, current-ring formation, poloidal flux development, magnetic topology evolution, and formation of closed flux surfaces after cessation of current-drive. His thesis also provides a detailed comparison of NIMROD results from MHD and two-fluid models (both with separate ion and electron temperatures), addressing thermal transport, the rate of increase of fluctuations during the growth phase of the poloidal flux, and the cross-power spectra from magnetic fluctuations. As shown in Fig. 1, the two-fluid results show weaker nonlinear growth of kinetic fluctuations, relative to the MHD prediction. There is also less power in correlated high-frequency fluctuations in the two-fluid results than in the MHD results. The difference is attributed to two-fluid effects that allow separate electron dynamics, leaving ion dynamics at larger spatial scales during similar reconnection events in the two models.

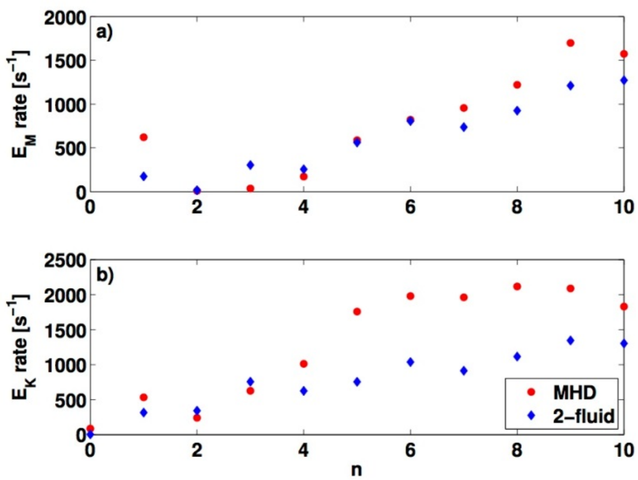


Figure 1. Comparison of nonlinear growth rates in a) magnetic and b) kinetic fluctuations during development of the poloidal flux for Pegasus startup, according to MHD and two-fluid modeling. [From J. B. O'Bryan, Numerical Simulation of Non-Inductive Startup of the Pegasus Toroidal Experiment, PhD thesis, University of Wisconsin-Madison, 2014.]

- To complete committed development work on the viscous stress tensor in NIMROD, O'Bryan is continuing as a postdoctoral associate over the summer months of 2014. He is implementing the viscosity model, which allows arbitrary ion magnetization, $x_i = \Omega_i \tau_i$ where Ω_i and τ_i are the gyrofrequency and mean time between collisions. Analogous to thermal conduction, the combination of the parallel and perpendicular stresses is isotropic at low magnetization. The gyroviscous part is linear in magnetization at low x_i-values. The figure shows coefficients from the standard Braginskii model, but like the implementation of thermal conduction, the code will have an option to use coefficients from Ji's K=2 model [Ji and Held, Phys. Plasmas **20**, 042114 (2013)].

- We completed ion parallel closures for arbitrary atomic weights and charge numbers.
  - For arbitrary collisionality, the heat flow and viscosity are expressed as kernel-weighted integrals of the temperature and flow-velocity gradients. The friction related closures for ions can be obtained from those of electron closures previously developed.
  - Simple, fitted kernel functions are obtained from the 1600 parallel moment solution and the asymptotic behavior in the collisionless limit. The inclusion of ion-electron collision operator significantly modifies the ion closures computed from no ion-electron collisions.
  - For $AZ^2 = 1$ and 2 (A is the atomic number and Z is the ion charge number), we adopted seven parameter fitted kernels which are highly accurate within 2% errors. For $AZ^2 > 2$, we adopted much simpler fitted kernels with four parameters sacrificing some accuracy, within 20% errors. Here we obtained general formulas for fitted parameters as functions of AZ^2 and temperature ratio.
  - A manuscript is complete and to be submitted to the Physics of Plasmas.
- In conjunction with the CEMM activity, we developed Mathematica code that computes closures for two fluid five-moment equations. Adopting a BGK-type collision operator we can compute closures that are accurate in the collisionless regime but approximate in other regimes. We modified the BGK operator by including a few lowest order Braginskii collision terms and adjusting collision frequency of the BGK operator. We tested the modified collision operator in the integral closures and found that the modified operator produces accurate closures in the collisional and collisionless limits and acceptable errors in the intermediate collisionality. We are comparing the analytical solutions that involve numerical integration with solutions of the finite difference method. The finite difference method is efficient but cannot produce an acceptable solution at the passing-trapped boundary due to a logarithmic singularity of the differential equation at the bouncing point at the boundary. This problem can be cured by using the analytical solution or by making the magnetic moment grid finer near the boundary. We are looking for the most efficient method to compute moments of the distribution function with satisfactory accuracy.
- We have started developing closures for (2+1) fluid models (two fluid with neutrals). As starting work we have built the general moment equations with Coulomb collision, charge exchange, ionization and recombination operators. For the high collisionality regime, we have written the algebraic system of moment equations for the (2+1) components. For a specific model computation, we are investigating parameter ranges of the operators for practical applications. We are also surveying methods computing the moments of the charge exchange operator for hydrogen ion-atom interaction, numerical integrations vs. analytical integration with fitted polynomials.
- With collaborator Dr. Bick Hooper of Woodruff Scientific, we have completed and revised a paper on a helical current-sheet instability of the expanding flux bubble of coaxial helicity injection (CHI) in spherical tokamaks (STs). The instability was observed in simulations of CHI in NSTX when reducing the modeled impurity density to simulate cleaner conditions that achieve higher temperature and, hence, larger current density. Numerical and delta-

prime analysis of the linear mode shows that it is a current-gradient driven tearing mode, which is similar to the current-sheet instability that leads to plasmoid formation during magnetic reconnection. The paper has been published as E. B. Hooper and C. R. Sovinec, "A current-driven resistive instability and its nonlinear effects in simulations of coaxial helicity injection in a tokamak", *Physics of Plasma* **23**, 102502 (2016).

Equilibrium, Stability, and Kinetic Effects in 3D Topologies (*T. Benedett, C. Hansen, G. Markland, V.S. Lukin, A.H. Glasser, and D. Sutherland)*

Accomplishments:

- **MHD stability with non-axisymmetric boundaries (collaboration with HBT-EP)**
  Work is continuing, in collaboration with the High Beta Tokamak Extended Pulse (HBT-EP) experiment, to investigate simulating passive conducting structures, such as passive stabilization plates and first wall components, coupled with an MHD plasma model. This allows the study of finite conductivity wall interaction in linear and non-linear regimes. Material domains are specified through the CAD interface to the CUBIT code allowing simple use of realistic experimental geometries. Linear stability simulations of HBT-EP discharges with different non-axisymmetric wall configurations have been performed using PSI-Tet. Comparison with experimental results, earlier reduced models using DCON+VALEN and physics study are underway.

- **Hall MHD simulations of Steady Inductive Helicity Injection (collaboration with HIT-SI)**
  Validation work and physics study of the HIT-SI device is continuing with a focus on high frequency operation of the injector circuits. Poor agreement has been seen in this regime previously between experimental data and numerical simulations with uniform density and temperature. Improved agreement has been achieved by improving the match between simulated and experimental injector waveforms. Simulations with density and temperature evolution are now being conducted and preliminary results have shown improved agreement in some regimes. Runs at 14.5 kHz injector frequency with anisotropic fluid viscosity were completed in this period and compared to isotropic cases.

- **Wall eddy current effects in PSI-Tri equilibria (collaboration with LTX)**
  A model to capture the toroidally symmetric effect of eddy currents, induced in close fitting metal walls, on plasma equilibria has been added to experimental reconstruction in the PSI-Tri code. This model adds a small set of fixed-shape eddy current structures to the reconstruction, where the amplitudes of the induced currents are free parameters. Current structures are determined from a filament model (derived from a CAD model) of nearby conducting regions. This method is actively being applied to equilibrium reconstruction from experimental data from the Lithium Tokamak eXperiment (LTX).

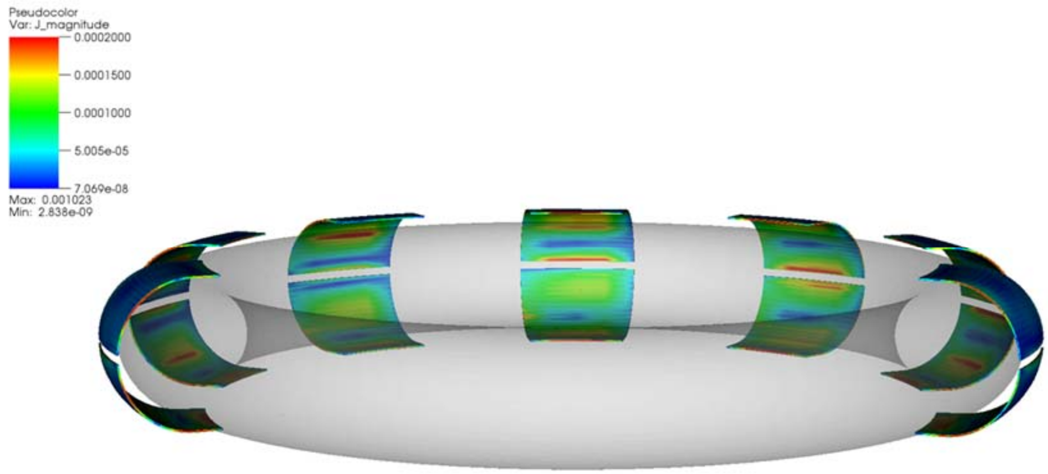


Figure 2- Amplitude of eddy currents induced in HBT-EP passive plates due to a growing, unstable 3-1 mode. Plasma boundary shown in gray. Nearest plates removed for visualization.

- **Interacting Plasma-Neutral model in PSI-Tet**
  A fully interacting dynamic plasma-neutral model previously tested in HiFi is being implemented in the PSI-Tet code by Derek Sutherland. Neutral density and energy evolution and plasma coupling with a static (zero velocity) neutral fluid has been implemented and verified. Simulations are currently underway for comparison with existing neutral measurements on the HIT-SI device. During this period verification simulations were completed of the decay phase of HIT-SI was simulated for comparison with experimental measurements.

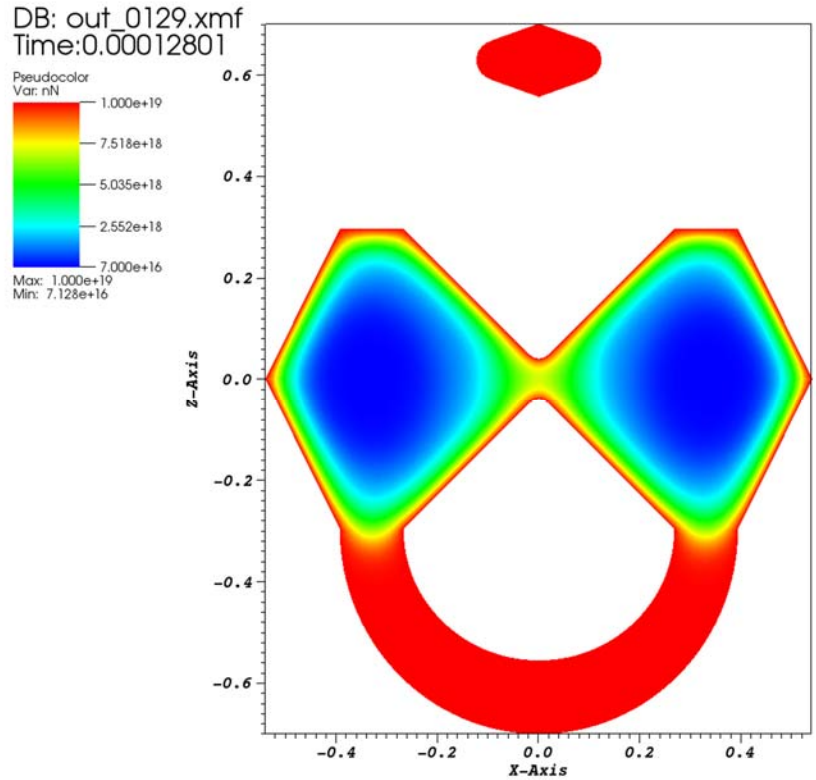


Figure 3- Neutral density profile from a PSI-TET simulation using the new plasma-neutral model for a decaying spheromak test case in HIT-SI.

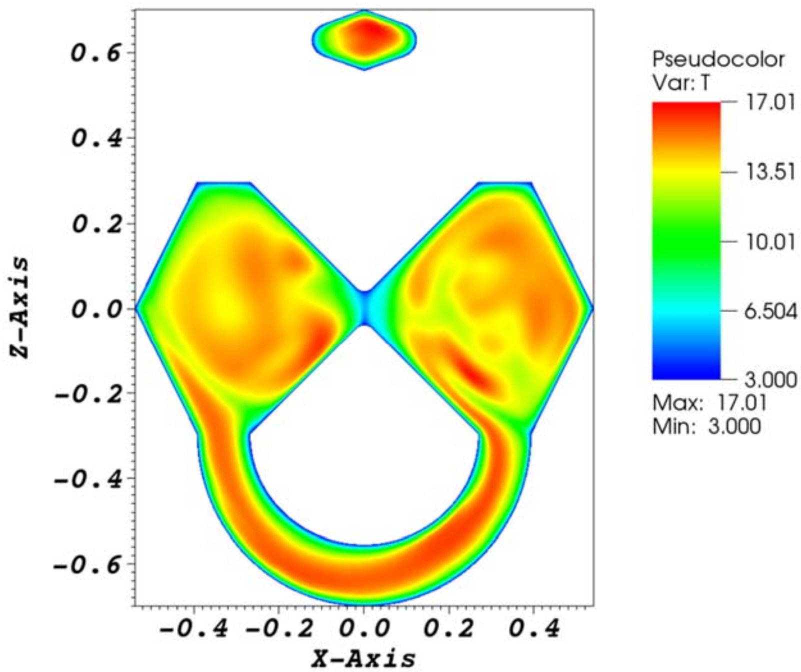


Figure 4- Ion temperature profile in HIT-SI from a recent PSI-TET Full MHD simulation at 14.5 kHz.

- **Anisotropic fluid viscosity for PSI-Tet**
  Simulations of HIT-SI using the NIMROD code have indicated a significant difference between isotropic and anisotropic models for plasma viscosity. The PSI-Tet MHD module has been updated to include anisotropic viscosity. During this period verification of this new capability was completed.

- **Model verification for PSI-TET using GEM challenge reconnection**

  The widely used GEM challenge reconnection benchmark is being used to further verify the PSI-TET extended MHD model. Simulations are being conducted by Tom Benedett for comparison with previous cross code verification studies.

- **Free boundary equilibrium fitting in PSI-Tri**

  Development has continued on free boundary equilibrium fitting in the PSI-Tri. The PSI-Tri fitting module is being applied to equilibrium reconstruction from HBT-EP, HIT-SI and LTX data. Improvements in this period include improved boundary condition evaluation, vertical position control, performance, and additional synthetic diagnostics for fitting constraints.

- **User focused code documentation for PSI-Tet and PSI-Tri**
  One of the primary goals of PSI-Tet and PSI-Tri is to develop a complete set of companion documentation for each code. This documentation includes descriptions of the code elements themselves as well as detailed examples that demonstrate the use and

implementation of different physics modules. This work is ongoing and is currently being used to successfully improve the learning curve for new users.

- **Resistive DCON and Beyond**
  Great progress has been made in the past few years, extending the DCON MHD stability code from ideal to resistive instabilities. In the ideal case, the Euler-Lagrange equations for minimizing the energy principle δW are reduced to a coupled system of ODEs and integrated numerically from the magnetic axis to the plasma edge. Attempts to extend this method to determine the outer region matching data for resistive instabilities convert it from a numerically stable initial value problem to an unstable shooting problem, causing it to fail. The avoid this, we have developed a new solution procedure in the GAL module, based on the singular Galerkin method of Pletzer and Dewar, but with major improvements in the choice of Galerkin basis functions to improve speed, accuracy, robustness, and range of validity. The outer region matching data are matched to the resistive inner region matching data based on the equations of Glasser, Greene and Johnson (GGJ). The inner region solution procedures of Glasser, Jardin, and Tesauro have been improved with a new inner region module DELTAC. The MATCH code combines data from GAL and DELTAC to obtain complex growth rates and global eigenfunctions. Benchmarks against the MARS code show excellent agreement for both eigenvalues and eigenfunctions over a broad range of parameters, but with the resistive DCON package running about 100 times as fast.
- Future efforts will be devoted to extending these methods to extended MHD. A more complete set of moment equations will be incorporated in the inner region DELTAC module. In addition to resistive MHD, these include sheared equilibrium toroidal rotation, electron and ion visccosity, anisotropic thermal conductivity, and Hall and electron pressure terms in Ohm's law. The required closures for determining these new terms will be obtained from full Braginskii in the collisional regime and the drift kinetic equation in the banana regime. In the collisional regime, these equations can be solved by incorporation into the DELTAC inner region code. This can be accomplished during FY 2016. It will provide fast and accurate benchmarks for the M3D-C1 and NIMROD codes in the linear regime.
- In the banana regime, a new derivation has been developed to merge the systematic ordering assumptions of the GGJ inner region with finite Larmor radius to provide a consistent form of the drift kinetic equation applicable to the inner region. New methods will be developed to solve these equations in phase space in a numerically efficient procedure that retains the speed and accuracy of resistive DCON.
- Because the outer region solutions become singular at the mode rational surface, the largest values are localized to the inner region. Each nonlinear inner region has helical symmetry, reducing the dimensionality from 3 to 2, coupling different toroidal Fourier harmonics. Different inner regions couple to each other through the linear ideal outer region. The resulting code can be used to treat neoclassical tearing modes in both the linear and nonlinear regimes.

- **Presentations and papers**
  Results were presented by Benedett, Hansen, and Sutherland at the APS Annual Meeting in San Jose (November 2016). A paper on the LTX equilibrium model (Hansen) was submitted

for publication. Several papers containing work from this group were submitted for publication by collaborating groups (HBT-EP, HIT-SI, and LTX) during this period as well.

Interfacing Group *(B. A. Nelson, R.D. Milroy, K. Morgan, and S. D. Griffith)*

Accomplishments:

Merging FRC Studies

- Features that were in the PSI-Center's NIMPSI version of NIMROD and required for FRC calculations have now all been ported to the NIMDEVEL version of the code and tested.

- The IPA experiment [J. Slough et.al, Nucl. Fusion **51**, 053008 (2011)] is used to validate this version of NIMDEVEL. These calculations include the θ-pinch formation and acceleration of two FRC's, using the dynamic formation methodology. Their translation to a central compression chamber where they merge and are magnetically compressed, is illustrated in the Figure. In the NIMROD simulations the two FRCs quickly merge to form a single FRC with a flux maximum at the axial midplane, in agreement with the experiment, based on detailed excluded flux measurements. However, in previous simulations using the Moqui code, reported in [J. Slough et.al, Nucl. Fusion **51**, 053008 (2011)], the FRCs did not completely merge. A key difference between these simulations is NIMROD's ability to include the Hall term. We find that if the Hall term is turned off prior to the merging, the field lines do not all connect and the resultant FRC has two distinct flux maxima on either side of the midplane – similar to the previous Moqui calculations.
  - Detailed calculations of the formation and translation phases continue as we document the effects that various boundary condition assumptions (enhanced resistivity, viscosity, etc.) have on the process. In particular, we will document the effect that these assumptions have on the generation of toroidal magnetic field and plasma rotation.

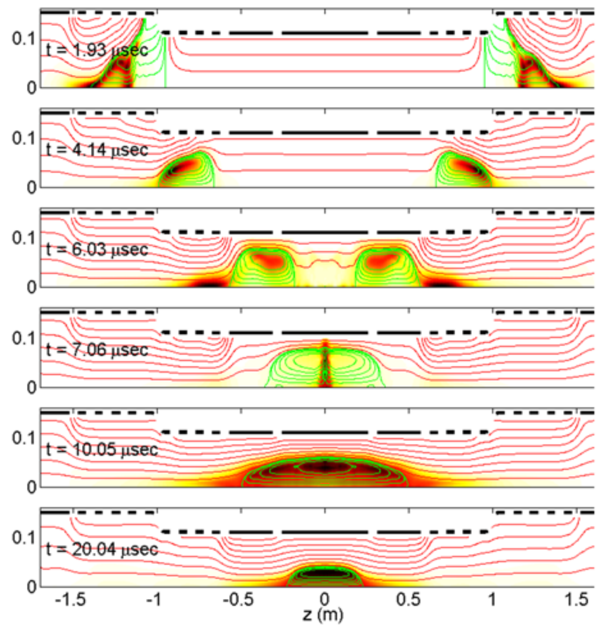
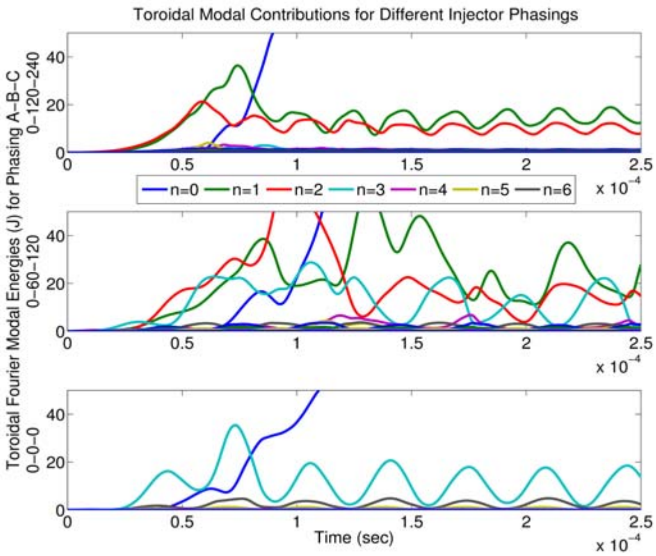


Figure 5. Field line and pressure contours from FRC formation, translation, merging, and compression simulation of the IPA experiment.

- **HIT-SI3 NIMROD Modeling Progress (Kyle Morgan)**
  Significant progress has been made on modeling of HIT-SI3 with NIMROD. The experiment consists of three semi-toroidal Steady Inductive Helicity Injectors which are driven with oscillating loop voltage and magnetic flux to inject magnetic helicity into a confinement region. These three injectors can be operated at a variety of relative phases, with the experiment focusing on three in particular. These three phasings are 1) all injectors in phase; 2) the three injectors 120º out of phase; and 3) the three injectors 60º out of phase, with the second two phasings providing constant helicity injection. Simulations have been

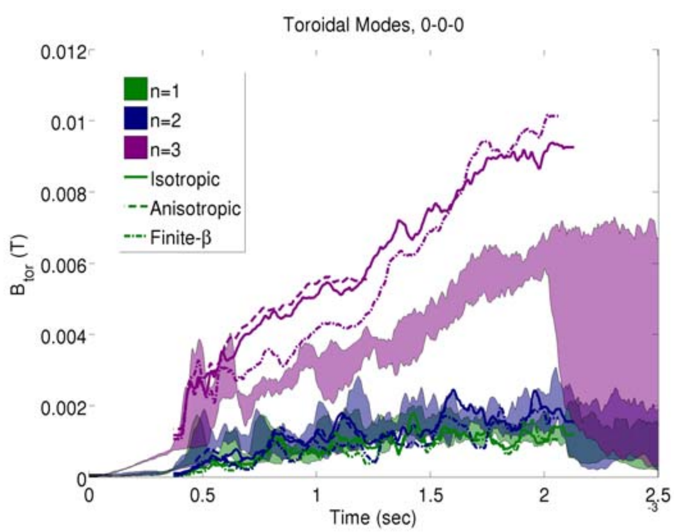
performed matching the injector settings of these three and comparisons with the experimental results are underway.



The primary difference between these simulations comes in the modal structure of the imposed perturbations. The figure shown above shows the toroidal energy spectrum of the plasma in simulations of the three phasings. While the non-axisymmetric portion of the spectrum changes significantly between the three phasings, it can be seen that an axisymmetrc (*n*=0 toroidal mode) object (the spheromak) always forms.

A set of three simulations have been performed at each phasing, leading to 9 total simulations. Two zero-β simulations, assuming uniform density, *n*, and temperature, *T*, with isotropic and anisotropic viscosities and one finite-β simulation with anisotropic viscosity. Comparisons are underway with experimental measurements of magnetic field (through surface and internal probes) and velocity (through ion Doppler spectroscopy) to compare the differences in models. Of interest is to validate agreement between the toroidal mode spectrum seen experimentally with that seen in simulation, to demonstrate the proper perturbation is being applied.

As an example, the comparison of toroidal mode spectrum between experiment and simulation for all injectors in phase is shown below. This spectrum is measured with a set of 16 surface probes located on the outboard midplane of the device. The experiment is plotted as the range of values seen for 5 similar experimental discharges while the lines represent the simulation values. As can be seen agreement with the overall rankings of the modes is achieved, with *n*=3 dominating in both cases, though the absolute value of the mode is overestimated in the simulations. This is thought to be due to small geometric features of the experiment not accounted for in the simulations.



- **Python Post-processing Progress**
  Progress has been made with Python post-processing scripts, including the NimPy post-processing code for NIMROD. Parts of the NimPy VTK output were used by Prof. Carl

Sovinec to guide independent coding for VTK out, and the NimPy class objects were used by Dr. Cihan Akcay for analysis of NIMROD files.

Dr. Nicholas Murphy of Harvard University started a "PlasmaPy" group on HipChat, inviting interested parties, include the PSI-Center Interfacing Group, to join in sharing and documenting Python scripts used for plasma physics.

Publications:

Jeong-Young Ji, H.Q. Lee, and E.D. Held, "Ion parallel closures", *Physics of Plasmas*, **24 (**2) 022127 (2017)

Jeong-Young Ji, Sang-Kyeun Kim; E.D. Held, and Yong-Su Na "Electron parallel closures for various ion charge numbers", *Physics of Plasmas*, **23** (3) 032124 (2016)

J.-Y. Ji and E. D. Held, "Ion closure theory for high collisionality revisited", *Physics of Plasmas*, **22,** 062114 (2015)

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Jeong-Young Ji and E.D. Held, "A framework for moment equations for magnetized plasmas", *Physics of Plasmas*, **21 (**4) 042102 (2014)

J. B. O'Bryan, and C.R. Sovinec, "Simulated flux-rope evolution during non-inductive startup in Pegasus" *Plasma Physics and Controlled Fusion*, **56** (6) 064005 (2014)

S.D. Knecht, W. Lowrie, and U. Shumlak, "Effects of a conducting wall on Z-pinch stability, *IEEE Transactions on Plasma Science* **42** (6), 1531 (2014)