Progress in the Plasma Science and Innovation Center

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Abstract:
Highlights of recent progress in the Plasma Science and Innovation (PSI) Center include adding reacting neutrals in the MHD model, providing capability from CAD description to grid generation to MHD simulation, incorporating energetic particles in extended MHD modeling, simulating 3D physics with Hall MHD, such as rotating magnetic field (RMF) current drive and inductive asymmetric current drive. The PSI Center is a collaborative effort to refine existing computational tools with the goal of improving computational predictability. The Center collaborates with experimental research groups to test the codes and to support the experiments. The Center refines primarily NIMROD and HiFi to have sufficient physics, boundary conditions, and geometry to be calibrated with experiments to achieve predictive capabilities. This paper describes some of the recent code advances, applications to experimental devices, and comparison to experimental data. By collaborating with a wide variety of plasma physics experiments, the PSI Center is able to focus efforts on adding the appropriate physics capabilities to existing fluid codes and thereby provide computational support and eventually predictive capability for experiments.

1 Introduction

Highlights of recent progress in the Plasma Science and Innovation (PSI) Center include adding reacting neutrals in the MHD model, providing capability from CAD description to grid generation to MHD simulation, incorporating energetic particles in extended MHD modeling, simulating 3D physics with Hall MHD, such as rotating magnetic field (RMF) and inductive asymmetric current drive. This paper describes some recent code advances, applications to experimental devices, and comparison to experimental data.

The PSI Center is a collaborative effort to refine existing computational tools with the goal of improving computational predictability. The Center collaborates with experimental research groups to test the codes and to support the experiments, which include smaller
Emerging Concept (EC) experiments that target well-focused fusion research topics. The Center adds capability to existing codes, primarily NIMROD and HiFi, to have sufficient physics, boundary conditions, and geometry to be calibrated with experiments to achieve predictability. The PSI Center works closely with other centers like the CEMM, the National Laboratories, and the NIMROD team to incorporate the physics of two-fluid/Hall effects, kinetic and FLR effects, transport, interacting neutrals, and sheath boundary conditions into the codes in a computationally tractable manner. The PSI-Center works with scientists from EC experiments at Auburn, Caltech, LANL, LLNL, MIT, Swarthmore, UWisc, and UWash.

2 Inductive Current Drive in the HIT-SI Spheromak

The HIT-SI bow tie spheromak uses geometrically asymmetric injectors to provide steady, inductive helicity injection, as shown in Fig. 1. The experiment has been simulated using NIMROD, which discretizes space using 2D finite elements in the poloidal plane and a Fourier expansion in cylindrical/toroidal direction. The experiment is simulated with an axisymmetric grid and replacing the asymmetric injectors with appropriate boundary conditions. From experimental data and Hall-MHD NIMROD simulations, the spheromak is formed and sustained by a combination of reconnection and quiescent dynamo drive. At first the n=1 injectors builds up an n=1 structure that then undergoes a large reconnection to form the n=0 spheromak as shown in Fig. 2. The spheromak current then increases through more quiescent dynamo action and the level of n=1 becomes only that imposed by the injectors.

![FIG. 1: Geometry of the HIT-SI spheromak and the multi-block grid used by HiFi.](image)

The NIMROD calculations closely capture the general characteristics of HIT-SI as shown by the comparison of NIMROD output to measurements by the internal magnetic probe. The calculated profiles had to be scaled down by 10% because NIMROD slightly overestimates the current amplification in this case. When scaled to the record current amplification (2.8), the cycle-averaged profiles overlay quite well, as seen in Fig. 3.
3 Rotating Magnetic Field Current Drive in the TCSU FRC

The translation, confinement and sustainment upgrade (TCSU) device was a rotating magnetic field (RMF) driven field reversed configuration (FRC) experiment that was...
terminated in 2011, however in its final year of operation it produced a wealth of detailed magnetic data that is still being analyzed. A series of extended MHD simulations of this experiment have been made, with magnetic boundary conditions tailored to closely match those of the most recent experimental measurements. These calculations are an extension of previous RMF calculations, and use the NIMROD code. To more closely model the experiment, the $n=0$ flux on the radial wall is set to closely match the measured flux, and the $n=1$ fields imposed are made to approximate the boundary fields measured by the 3-axis probe. In NIMROD, the $n=1$ RMF is imposed through the specification of the tangential electric field and the resultant boundary magnetic field is dependent on the interior solution. Hence it is not possible to specify RMF boundary conditions that are an exact match, but we have matched the effects of the antennas as closely as possible.

FIG. 4: Experimentally measured magnetic flux from TCSU compared to a NIMROD calculation.

The $n=0$ flux on the wall is set using a tanh function to interpolate between a series of coils. Figure 4 shows the measured flux on the flux conserving rings from a typical long mirror shot on TCSU along with the specified flux in a NIMROD calculation. The flux is normalized to the ring or wall radius, and is expressed in units of magnetic field (T). In the calculation the tangential component of the $n=0$ component of the electric field is zero on the boundaries, so this flux profile is fixed in time. The boundary flux imposed in the NIMROD simulations is a very close approximation to the experimentally measured values in the region where the FRC is formed and sustained. Figure 5 shows the corresponding vacuum magnetic field, which is assumed as part of the NIMROD initial conditions.

FIG. 5: Vacuum magnetic field for the initial conditions for the NIMROD calculation.

To make a detailed comparison with the experiment, a calculation was performed that assumes the even-parity antenna configuration had parameters adjusted to approximate those corresponding to experimental conditions where a full 3-axis probe scan. The calculation was initialized with a uniform fill plasma with a density of $2 \times 10^{18}$ m$^{-3}$, and the
vacuum magnetic field configuration illustrated in Figs. 4 and 5. The bias magnetic field at the axial midplane was 3 mT, rising to a value of 14.2 mT in the end regions. The full simulation volume had a radius of 0.4 m, and extended from -3.5 m to +3.5 m. The RMF boundary conditions were ramped up linearly over a period of 50 µs, with an RMF frequency of 122 kHz. A constant and uniform electrical diffusivity $\eta/\mu_0 = 64 \text{ m}^2/\text{s}$ is assumed, which is the smallest value that we can use without introducing new numerical difficulties, and is representative of the inferred average resistivity for the experiment. As with earlier simulations, we often only employ the $n=0$ and $n=1$ modes to reduce the computational effort, however the calculations reported here employ modes $n=0$ through $n=5$.

**FIG. 6: Toroidal magnetic field in TCSU comparing experimental data (top) and NIM-ROD simulation results (bottom) for even-parity RMF. Magnetic flux lines are superimposed.**

Figure 6 compares the experimentally measured steady magnetic field with the calculated $n=0$ magnetic field. The top figure is generated using 3-axis probe data, low-pass filtered at 10 kHz. To generate a field map as a function of $r$ and $z$, data from multiple shots are combined, as the axial position of the probe is moved between multiple experimental pulses. For comparison, Fig. 6 also shows the $n=0$ component of $B_\theta$ with field lines superimposed, from the simulation. The FRC generated in the simulation is similar in size (radius and length) to the experimental measurements, however the poloidal flux contours from the NIMROD simulations have a racetrack profile, while the experimental profile is more elliptical. The measured toroidal field profiles appear similar to the calculated profiles; however, the magnitude is larger in the simulation results (color scale is from -2.5 to +2.5 mT, compared with -1.5 to +1.5 mT for the experimental results). It is thought that the magnitude of the toroidal field on the open field lines depends on the plasma resistivity in the open field line region and on the details of the end-shorting process. A uniform resistivity with $\eta/\mu_0$ was assumed for the calculations.

In addition to the even-parity calculations, a set of odd-parity calculations have been performed using the same parameters, except that an odd-parity antenna was assumed. These calculations are compared with a set of experimental data where the plasma was scanned axially with a 3-axis probe to generate a set of measurements of the magnetic field as a function of $r$, $z$, and $t$. The calculations for both the even and odd-parity used the same RMF frequency of 122 kHz to allow a direct comparison between the calculations. However, the experimental RMF frequency for the odd-parity case was 109 kHz due to an inductance change when the antennas were configured for odd-parity.
Figure 7 compares the experimentally measured steady magnetic field with the calculated \( n=0 \) magnetic field. A slight asymmetry is noted in the experimental data, with an apparent larger radius to the right. Also the experimental data shows a flux maximum near the axial center of the FRC, while the computed profiles have a local minimum at the axis of symmetry. Despite these discrepancies, it is interesting to note that the calculated \( B_\theta \) profile is similar to the calculated profile, including the structure inside the FRC. Note that the scale for the computed \( B_\theta \) ranges from -0.0025 to +0.0025 T, while the range for the experimental data is from -0.0015 to +0.0015 T. As with the even-parity case it is thought that the magnitude of \( B_\theta \) in the open field-line region depends on the plasma resistivity there and on the details of the end-shorting process.

An analysis of the TCSU experimental data continues, and an important part of this analysis is a comparison of measurements made with the 3-axis probe with extended-MHD simulations from the NIMROD code.

4 Plasma Neutral Interactions on the ELF

A model for a reacting plasma-neutral mixture has been developed. Complete dynamics are modeled for a singly-ionized plasma and a dynamic neutral gas. Fundamentally, the model is an extension of the viscous, resistive, single-fluid plasma model presented by Braginskii. Moments are taken of the Boltzmann equations for ion, electron, and neutral species to generate three coupled sets of fluid equations for mass, momentum, and energy. Species conversion reactions, including electron-impact ionization, three-body recombination, and resonant charge exchange (CX), are allowed in the derivation. The ion and electron fluids are combined, following Braginskii, into a single plasma fluid. Separate neutral fluid equations are maintained. Concise, accurate expressions for reaction collision operator moments have been derived. Excited states are not tracked; an effective ionization potential is used to account for the average ionization energy expenditure, including excitation/de-excitation losses. An optically thin plasma is assumed such that the radiation energy associated with excitation processes escapes from the system. Basic closures have been implemented, and more sophisticated closures are under consideration. The resulting model is suitable for capturing the primary fluid physics of ionization, recombi-
FIG. 8: ELF simulation with HiFi plasma-neutral implementation. Black contours indicate poloidal magnetic flux. Black and white arrows indicate the direction and magnitude of plasma and neutral momentum density, respectively.

The new model has been implemented into HiFi. HiFi uses a fully implicit time advance and has been used to model 3D reconnection in the SSX spheromak merging experiment in single-fluid MHD and Hall MHD regimes.

The plasma-neutral model has been applied to several specific problems. Simulations of the Electrodeless Lorentz Force (ELF) thruster are briefly summarized here. ELF is an electric propulsion (EP) concept involving the formation and acceleration of FRC plasmas. A crucial aspect of the ELF concept is the entrainment of a downstream neutral gas during FRC acceleration. In most EP devices, ionization energy investment is a significant burden on the overall efficiency of the device, that is, the conversion of input electrical energy into directed kinetic energy. If ions transfer significant energy to neutral particles via charge exchange during plasma acceleration, ionization energy investment can be maximized by accelerating many particles for each ionization. In Fig. 8 four snapshots show color contours of the total (plasma plus neutral) pressure in the cylindrical simulation domain as the FRC interacts vigorously with downstream neutral gas, transferring over half of the original FRC momentum to the neutral gas.

The application of the HiFi plasma-neutral model implementation to ELF provides insights useful for optimizing the ELF plasma-neutral coupling. Furthermore, the work provides verification that the implementation performs as expected, conserving mass, momentum, and energy in a complicated, highly non-linear simulation.
5 Summary

By collaborating with a wide variety of plasma physics experiments, the PSI Center seeks to develop broadly applicable computational tools. Capability is added to existing fluid codes required to capture the relevant physics and thereby provide computational support for these experiments. The quantitative comparisons in this paper represent a concerted effort to validate the recent code developments along the path to achieving predictability.

References