NIMROD Team Meeting Minutes
October 31, 2009
Atlanta, Georgia

Model Development

Tom Jenkins presented work to couple NIMROD into the Integrated Plasma Simulator, a set of scripts developed by the SWIM group that organizes computations requiring more than one code and/or task. This relies on the Plasma State file for sharing data and has already been used successfully to couple TSC and TORIC. The revised implementation does not require NIMROD to start and stop when coupling with GENRAY. Each code just uses the most recently available data by subscribing to an 'events channel.' The first coupled run with NIMROD did not lead to power deposition; the physical parameters were such that the RF wave traveled into the NIMROD simulated plasma and was reflected by it. Revised parameters for the RF led to deposition but were only temporarily stabilizing for the magnetic island. The RF hit the O-point as intended but generated a 4/2 island after suppressing the original 2/1. Future work will incorporate modulation.

Jianhua Cheng gave an update on using simulation particles for majority ion species closure. To avoid limitations of existing gyrokinetic models, the computations use Vlasov ions with fluid-based electrons. The testbed is the GEM code [see Chen's 2009 PoP paper]. The Ohm's law is left in terms of the ion current computed from an implicit delta-f method; though, ion currents are not in the iterations. Cheng has made the algorithm second-order accurate, and tests on compressional Alfven, shear Alfven, and whistler waves show almost no numerical damping with temporal centering. He has also run computations for the Harris sheet magnetic reconnection problem.

Jeong-Young Ji presented recent work on closure theory based on the moment approach to the kinetic equation. He emphasizes the difference between fluid closure theory, which finds the traceless stress, heat flux, friction, and heating in terms of the evolved low-order moments, and transport theory, which finds all fluxes (including 1st-order moments) in terms of thermodynamic drives. The present effort to develop a general closure theory starts from a small-gyroradius expansion. What is unique is the way that the ordering is applied directly to the general moment equation, i.e. the ordering is carried-out for all moment equations in one derivation. One can then look at particular moment equations for a given order, and equations to second order have been presented. Future work includes comparing results with standard neoclassical theory.

Charlson Kim summarized progress on the FLR-PIC model for minority ion kinetics. He noted that the particle search-and-sort is the most computationally intensive part of the algorithm. Different background distribution functions are now available including the slowing distribution, Maxwellian, and a mono-energetic beam. The RF tail distribution will be added. He is presently looking at toroidicity effects in the RFP using NIMEQ to generate parallel current profiles that are the same functions of poloidal flux as cylindrical cases. In particular, he is considering m=0 modes. He is finding evidence of numerical inaccuracy near the trapped/passing boundary. ICC computations may actually be more sensitive to the magnetic field representation than tokamaks, because the toroidal field does not dominate.

Motivated by the HIT-SI application, Cihan Akcay is developing a more general algorithm for generating logically rectangular meshes for geometrically complicated regions. He first defines separate 'blocks' (not NIMROD grid blocks) and weights to control how the mesh is distributed. Segments are defined, parameterized, and splined to force certain mesh-vertex locations. A 'blending' step then fills in the meshing between sides and other segments. The approach still allows mesh packing near edges. Akcay also noted that the present version of NIMFL expects nimrod grid-blocks to be conforming.

Alfonso Tarditi reported on progress on different aerospace applications of NIMROD including propulsion, lightning strikes, and plasma aerodynamics. Lightning is of concern to NASA in different scenarios such as on the launch pad and during flight through the atmosphere, and NASA would like to assess the worst-case scenarios. The conductivity of the exhaust plume during flight expands a nearly constant potential region, and this concentrates electric field around the edge of this region, increasing the likelihood of a strike. The modeling is done using spatially varying resistivity with sources for plasma particles, momentum, and energy. The neutrals are modeled as having a constant velocity (relative to the rocket), and there is ionization and recombination. Plasma thruster modeling is investigating the launching of neutral plasma rings through a magnetic de Laval nozzle.

Analysis and Benchmarking

Carl Sovinec described analysis for the 'implicit leapfrog' two-fluid algorithm. He reviewed von Neumann-type computations of the eigenvalues of the time-step operation, which showed: 1) the algorithm is stable with implicit centered advection, 2) centered advection is compatible (unconditionally stable) with the semi-implicit operator for MHD, 3) centered Hall and gyroviscosity are also compatible, and 4) centered or backward differencing of dissipation is unconditionally stable. A new use of the von Neumann results is for benchmarking the NIMROD implementation at large time-step. Eigenvectors from the analysis are used to initialized NIMROD computations, and the measured frequencies agree well. Differential approximation has been applied to better understand the stability results. The time staggering can be considered directly for equations defined at different times in the stepping when synchronization effects are considered. Results for advection show a term that leads to an ill-posed problem for one of the two waves that propagate with respect to background flow—consistent with the von Neumann results. Other conclusions from the differential approximation are also consistent with the major findings of the von Neumann analysis and help to explain them.

Bonita Burke gave the 'final' presentation on the benchmarking of NIMROD to ELITE and GATO for ideal ballooning and kink in circular cross-section equilibria. She briefly reviewed the vacuum modeling of large resistivity and low mass density in the edge region. A new result shows a comparison of NIMROD linear results from interpolated equilibria (fluxgrid) with results from re-solved equilibria using NIMEQ. Near marginal stability for the more unstable case, there is as much as 30% difference in growth rates with the interpolated equilibrium results agreeing well with GATO while the re-solved equilibrium results agreeing well with ELITE. A new equilibrium has been developed to emphasize peeling drive. Without vacuum modeling, there is a clear peak in the growth-rate spectrum at $n<10$, which is convenient for nonlinear computation. With temperature-dependent resistivity, resistive ballooning at high-n dominates if the edge plasma is too cold. Preliminary nonlinear simulations use the more unstable ballooning case of the benchmark and the new kink-dominated case for comparison with each other and with nonlinear theory. Both cases have been run to the intermediate nonlinear stage, and analysis is underway.

Andrea Montgomery gave an update on her work to verify resistive wall results in cylindrical geometry. The computational domain includes a vacuum region where resistivity is high and density is low; both profiles are hyperbolic-tangent functions. She finds that having the resistivity transition beyond the sharp drop in her equilibrium current density profile helps prevent odd currents. The computations use a large aspect ratio and guide field, but they are not in the analytical limit, so she modifies her growth-rate formulas to account for this. With a conducting wall at the surface of the domain, S-interior=10^6, and S-edge=10, the computations quantitatively reproduce the ideal kink mode. For the resistive wall, she is concentrating on getting just the m=2 projection to act correctly. At present, the modes show sensitivity to the wall diffusion constant, but the computations have the normal component of magnetic field being larger at the wall than at the plasma/vacuum interface. Growth rate dependencies are also not yet correct, but there has been significant progress over the last few months.

Applications

Richard Milroy presented his simulation study of formation and sustainment of FRCs using rotating magnetic field (RMF) drive. The antennas are modeled through boundary conditions on magnetic field and electric field, and either even or odd parity with finite-length antennas can be modeled. He emphasizes that the Hall term is central to the RMF current drive effect. The parameters of the simulation are largely the correct ones for the experiment in Redmond, but the ratio of ion and electron masses is set at 100 to aid solver convergence. The initial formation is fairly violent, since the plasma is dominated by the antenna fields. The evolution of various signals, such as flux and B_z at the midplane are in qualitative agreement with the experiment. Fluctuation levels may be somewhat larger than experiment; though, they become smaller when resistivity is reduced. With even parity drive, field-lines remain open. The simulations show tilt or kink activity near the ends, beyond the antennas. Movies seem to show that the plasma rotates, but Milroy has found that most ion motion is axial, so the apparent rotation is a wave. With odd parity RMF, field-line tracing shows the formation of some regions of closed flux. Milroy also described simulations for the electrodeless Lorentz force (ELF) thruster—research that is supported by an AF grant. The simulations consider the acceleration of an FRC subject to magnetic field from a conical electrode.

Tom Bird described progress on his simulations of current filament injection in the Pegasus ST. An earlier simulation with the 0-beta model reaches relaxation, but the uniform resistivity makes the evolution very dynamic, hence computationally costly, and reversed currents take a long time to diffuse away. Newer simulations with temperature evolution, Ohmic heating, and temperature-dependent resistivity and thermal conduction have not shown current saturation. Two types of oscillations are apparent as the self-induced magnetic fields progressively overtake the vacuum field. There is a lower frequency oscillation as portions of the helical current channel slosh around, and there is a higher frequency spike when filaments interact and reconnect. The simulations show relaxation progressing with poloidal flux getting amplified with respect to the vacuum flux.

Dalton Schnack discussed progress and issues for the giant/monster sawtooth project. The giants result when neutral beams stretch the sawtooth period, resulting in very low safety factor on axis. He has conducted a thorough review of the theoretical literature. For particles with precession frequency that is comparable to MHD activity, the third adiabatic invariant tends to resist changes in the flux inside the precession orbit. When the Alfven frequency is comparable to the precession frequency, fishbones result, but when the precession frequency is much less than the Alfven frequency, kink stabilization is possible. Theory indicates that there is a minimum S required to see a stabilization gap in the kink before fishboning occurs; thus, simulations have to be at sufficiently large S. In the Choi paper that compares DIII-D results with the Porcelli sawtooth model, the experiments have hot particles accelerated by RF to well beyond 500 keV. Schnack has completed linear calculations for DIII-D shot 96043 at 1900 ms using the slowing-down distribution for all energetic particles (until an RF tail distribution is available). With a cutoff energy of 42 keV, the linear results are essentially identical to MHD, but with a cutoff of 281 keV, the growth rate is down by a factor of seven. Comparison with theory may be affected by the limited separation of scales in the NIMROD computations. There are also questions regarding whether 2-fluid effects and the Kruskal-Oberman contribution from thermal particles are needed. High priorities with respect to the modeling are: 2-fluid Ohm's law for particles, parallelization layers for particles, the RF tail distribution, and anisotropic equilibrium pressure.

Ryoji Takahashi is investigating the stabilization of tokamak 2/1 tearing modes from energetic particles and has already published results in PRL and Nuclear Fusion. Results show that complete stabilization may be possible for sufficiently large energetic-particle betas. He would like to combine the energetic particle and 2-fluid models, but so far, they have been treated separately. His 2-fluid computations require the finest resolution due to smaller spatial scales. A point of discussion is that his resistive modes at $S=10^6$ are slower than predictions for ideal instability, but this may be due to the viscosity at Pm=100. He compares nonlinear results for MHD only and for MHD with particles. Particle noise is a non-trivial issue during initialization for the energetic particle computations. Nonetheless, the growth rate decreases when particles are added.

Jacob King presented results for 2-fluid tearing and magnetic island evolution in RFP-relevant pinch profiles. 'Two-fluid' includes the generalized Ohm's law and gyroviscosity (when ions are not cold). Linear computations show that with cold ions, the tearing growth rate increases monotonically with rho_s from the MHD limit. With warm ions, the gyroviscosity first leads to a lower growth rate before ions are completely decoupled at large rho_s. With nonlinear saturation in single-helicity computations, the ratio of perturbed kinetic energy to perturbed magnetic energy decreases relative to the linear mode. With cold ions, the saturated island width is independent of rho_s, but it decreases with rho_s with warm ions. Analysis of the gyroviscous stress shows that it contributes to saturation by opposing the linear drive forces. This supplements the Rutherford nonlinear JxB forces, hence the small island. Multi-helicity two-fluid computations with pinch parameter of 1.6, aspect ratio of three, and S=5000 are reversing.

Ping Zhu described initial work on ballooning in equilibria with a separatrix. He has modified NIMEQ to generate equilibria with an X-point. The mesh and pressure current profiles inside the separatrix are based on results from the ESC code, which does not have the separatrix. Zhu has considered three different equilibria with the divertor in locations ranging from inboard to outboard. The growth rate of the ballooning mode increases as the divertor is moved outward. Expectations are that ideal results should be sensitive to the divertor location, while resistive results in the collisional regime should not be sensitive. Zhu has completed preliminary nonlinear simulations. The ideal-regime computation shows significant localization of the distortion of total pressure to the region near the X-point, and the dissipative-regime computation shows distortions spread around flux surfaces near the separatrix.

Fatima Ebrahimi is performing a simulation study for the plasma Couette flow experiment that will investigate kinetically driven dynamo processes. Use of plasma as the working fluid will allow larger magnetic Reynolds numbers than what is possible with liquid sodium. She has performed computations of the MRI instability in an idealized configuration and simulations with boundary conditions for the cusp fields from the permanent magnets. She has obtained the MRI mode in annular NIMROD simulations with periodic boundary conditions, and there is growth at parameters expected for the experiment. Nonlinear computations show sustainment of a small-scale dynamo. The cusp fields have been implemented for more comprehensive simulations. They show the development of poloidal flows and toroidal magnetic field when the effective potential is not a flux-function. This can be suppressed by imposing toroidal rotation at the inner boundary of the annulus; the resistive wall in the experiment is expected to serve the same purpose. Ebrahimi also presented some initial results from Ivan Khalzov that show a kinematic dynamo developing from a hydrodynamically unstable von Karman flow.

Scott Kruger led a discussion regarding the physics applications drivers for the Fusion Simulation Project. He thinks that among the initial set of drivers, disruption physics is likely the most relevant for NIMROD.

<u>CEMM meeting on 11/1/09: Izzo and Held presented there.</u>

Valerie Izzo presented her work on simulating runaway electron confinement during disruptions. There are two approaches to reducing the problem—increasing number density or reducing confinement time. Her computations solve the drift orbits of relativistic electrons, including radiation effects, subject to the electric and magnetic fields computed in 3D NIMROD simulations. She finds that the drift effects of the energetic electrons lead to better confinement than what would be expected from the magnetic topology alone. When resonant magnetic perturbations are added, there is a spike of radiation, similar to what is seen in DIII-D experiments. However, she finds that with the way RMP alters the magnetic evolution during a disruptive crash, it increases runaway electron confinement. The likely next step in the modeling is to include a model for secondary avalanche-electron generation.

Eric Held discussed his group's work to use NIMROD for solving kinetic equations for electromagnetics directly as a continuum approach. Investigations by student Andy Spencer use the 2D finite elements for parallel velocity and energy dimensions with the Fourier direction for gyro-angle. Initial continuum computations have the test-particle part of the linear Coulomb collision operator and show the slowing and thermalization of a beam of particles. Future work will generalize the collision operator and combine the modeling with spatial dimensions. Held also described how his recent drift model in NIMROD represents the 0-th order of the Hazeltine recursive calculation, i.e. it is the gyro-angle independent part. He is considering new temporal centerings for the kinetic distortions relative to the fluid moment centerings. Completed tests include stress damping of sound waves with varied background temperature, i.e. collisionality.