Final report: GRANT NO. DE-FG02-04ER54743
"Validation of Numerical Two-Fluid and Kinetic Plasma Models"
D. C. Barnes, Principal Investigator
Center for Integrated Plasma Studies
University of Colorado at Boulder

March 25, 2011

Executive Summary:

This was a four year grant commencing October 1, 2003 and finishing September 30, 2007. The funding was primarily used to support the work of the Principal Investigator, who collaborated with Profs. Scott Parker and John Cary at U. Colorado, and with two students, N. Xiang and J. Cheng also of U. Colorado. The technical accomplishments of this grant can be found in the publications listed in the final Section here. The main accomplishments of the grant work were:

- Development and implementation of time-implicit two-fluid simulation methods in collaboration with the NIMROD team
- Development and testing of a new time-implicit delta-f, energy-conserving method

The basic two-fluid method, with many improvements is used in present NIMROD calculations. The energy-conserving delta-f method is under continuing development under contract between Coronado Consulting, a New Mexico sole proprietorship and the Oak Ridge National Laboratory.

Work items per FY:

During the period October 1, 2003 through September 30, 2004, the following work items were completed:

- Current version of NIMROD obtained and ported to local computer resources
- Warm two-fluid dispersion relation analyzed
- Various implicit time step algorithms for two-fluid were investigated
- Warm two-fluid modes were reproduced by NIMROD code
- Papers were presented to NIMROD meeting 2003 APS Albuquerque and 2004 Sherwood meeting Missoula

During the period October 1, 2004 through September 30, 2005, the following work items were completed:

- The time-centered two-fluid algorithm was upgraded to include a General Minimum Residual (GMRES) iterative solver.
- The time-centered two-fluid algorithm was applied to uniformly long FRC equilibria.
- Two-fluid FRC modes were obtained. Results seem in agreement with previously published numerical results.
- A collaboration with the PSI (Plasma Science Initiative) Center of the University of Washington was initiated.
- Two versions of the FRC time-centered two-fluid code were transferred to the PSI Center.
- FRC stability results were presented at the Tahoe Sherwood 2005 meeting.
- FRC algorithm and results were presented at the Summer NIMROD meeting in Madison, WI in August, 2005.
- An extended analytic uniformly-long FRC two model is being developed to include the coupling between axial (tilt) polarization modes and radial (shift) polarization modes.
- A poster in collaboration with the PSI Center researchers will be presented at the Denver APS meeting.

During the period October 1, 2005 through September 30, 2006, the following work items were completed:

- The General Minimum Residual iterative solver was applied to Sovinec's time-centered leap-frog two-fluid algorithm.
- A paper describing Sovinec's time-centered leap-frog two-fluid algorithm was published in *Journal of Physics: Conference Series*, **16**, pp. 25-34 (2005).
- A fully non-linear two-fluid algorithm based on Sovinec's algorithm was developed and applied to FRC two-fluid modes.

- The non-linear two-fluid algorithm was transferred to the PSI (Plasma Science Initiative) Center of the University of Washington.
- Implementation of time-implicit, low-noise (Quiet Implicit Pic or QIP) particle ion methods for FRC physics studies into NIMROD was begun.
- The IMP (Implicit Moment Particle) code was written to explore algorithm issues associated QIP ion implementation.
- IMP was applied to the classical, Roberts-Taylor gravitationally-driven interchange mode.
- A paper describing QIP ion algorithms and IMP was presented at the Dallas Sherwood/April APS meeting.
- Particle ion work was described at the winter Boulder NIMROD meeting, at the Dallas CEMM meeting, and at the summer Seattle NIMROD meeting.

During the period October 1, 2006 through September 30, 2007, the following work items were completed:

- The IMP algorithm was improved to exactly conserve energy and applied to the gravitationally driven mode
- Papers were presented to the NIMROD meeting at 2007 Sherwood Annapolis, the Sherwood meeting
- An invited paper was presented at the 2007 APS meeting Orlando
- The invited paper was published in the Physics of Plasmas (May, 2008)

Publications:

1. D. D. Schnack, D. C. Barnes, C. R. Sovinec, *et al.*, "Extended fluid models and their implications for simulation algorithms," Paper 1C50, 2004 Intl. Sherwood Fusion Theory Conf., April 26-28, 2004 Missoula, MT.
2. D. C. Barnes, "Two-fluid applications of NIMROD," Paper HP1.010, APS DPP 2004 Meeting, Savannah, GA
   http://flux.aps.org/meetings/YR04/DPP04/baps/abs/S1305010.html
3. D. C. Barnes, "Kinetic modeling of electron Bernstein waves," Paper PP1.083, APS DPP 2004 Meeting, Savannah, GA
   http://flux.aps.org/meetings/YR04/DPP04/baps/abs/S2090083.html
4. D. C. Barnes, *et al.*, "One- and two-fluid computational studies of Field-Reversed Configuration (FRC) formation and stability," Presented at 2005 Intl. Sherwood Fusion Theory Conf., April 11-13, 2005 Stateline, NV.
5. D. D. Schnack, D. C. Barnes, *et al.* , "Computational modeling of fully ionized magnetized plasmas using the fluid approximation," Tutorial Paper GI2a.00001 APS DPP 2005, Denver, CO
   http://meetings.aps.org/Meeting/DPP05/Event/35084
6. D. D. Schnack, D. C. Barnes, *et al.*, "Computational modeling of fully ionized magnetized plasmas using the fluid approximation," *Phys. Plasmas* **13**, 058103 (2006).
7. D. D. Schnack, D. C. Barnes, *et al.*, "Validation of 2-fluid and gyro-viscous terms in NIMROD," Paper UP1.00040 APS DPP 2006, Philadelphia, PA
   http://meetings.aps.org/Meeting/DPP06/Event/52950
8. C. R. Sovniec, D. D. Schnack, D. C. Barnes, *et al.*, "Two-fluid modeling with the NIMROD code," Paper JP1.00019 APS DPP 2006, Philadelphia, PA
   http://meetings.aps.org/Meeting/DPP06/Event/52389
9. Nong Xiang, John Cary, D. C. Barnes, *et al.*, "Self-interactions of electron Bernstein waves in an inhomogeneous plasma," Paper BP1.00072 APS DPP 2006, Philadelphia, PA http://meetings.aps.org/Meeting/DPP06/Event/51759
10. N. Xiang, J. R. Cary, D. C. Barnes, and J. Carlsson, "Low-noise electromagnetic delta-f particle-in-cell simulation of electron Bernstein waves," *Phys. Plasmas* **13**, 062111 (2006).
11. D. C. Barnes, "IMP – symmetric, energy-conserving, time-implicit, low-noise kinetic algorithm," Paper 1E-21, 2007 Intl. Sherwood Fusion Theory Conf., April 23-25, 2007, Annapolis, MD.
12. D. C. Barnes, "Closure of computational fluid models with evolving background delta-f kinetics," Invited Paper BI2.00001, APS DPP 2007, Orlando, FL
    http://meetings.aps.org/Meeting/DPP07/Event/69762
13. D. C. Barnes, J. Cheng, and S. E. Parker, "Low-noise particle algorithms for extended magnetohydrodynamic closure," *Phys. Plasmas* **15**, 055702 (2008).