Center for Extended Magnetohydrodynamic Modeling

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The Center for Extended Magnetohydrodynamics Modeling[1] (CEMM) is the nation's premier research organization for simulating macroscopic dynamics in magnetically confined plasmas. With support from the SciDAC initiative, CEMM has brought together leading researchers in fluid-based plasma simulation, plasma theory, computational meshing, and parallel solver algorithms. Originally separate efforts, the M3D and NIMROD code development teams now interact productively on a number of applications through CEMM. A notable example is the simulation of edge localized modes (ELMs), where the sharing of equilibrium data and simulation strategies led to successful completion of office-wide annual program performance targets for FY05 and 06, the first ever for theory and computation. On the computational side, synergism from sharing experience and ideas on energetic particle methods, spatial representation, implicit algorithms, and solver strategies has led to improvements in both codes. As envisioned for the SciDAC program, CEMM has received invaluable assistance from leading computational groups, such as APDEC, ITAPS and TOPS. Their contributions have boosted the performance of the two large codes and have spawned test-beds, such as the AMRMHD code, that explore new approaches, which is essential for continued improvement in the area of macroscopic plasma simulation. In turn, CEMM's efforts have motivated the computation collaborations to develop new methods for our challenging applications.

The applications being addressed are characterized by having a wide range of both space and time scales and by extreme anisotropy associated with the strong background magnetic field. The space scales arise from the need to describe highly localized reconnection layers as well as the global configuration. The time scales arise from the need to include the fast timescale physics associated with Alfven and whistler waves as well as the long timescales associated with instabilities growing on the slow dissipative timescales. The combination of these leads to an extremely demanding computational problem that requires the best algorithms and the most powerful computers available. The multiple time and space scales require the use of implicit algorithms, which imply solving large sparse algebraic systems of equations each time step. Our Center has become one of the major drivers for developing efficient and scalable sparse matrix solvers at the teraflop scale and beyond.

The equations we use do not make any approximations related to simplified geometry, small amplitude disturbances, or ratios of the self-generated to background magnetic fields. As a result, the extended MHD description has been extraordinarily successful in describing the macroscopic equilibrium and non-linear stability properties of a wide range of fusion experiments, including tokamaks, stellarators, reversed-field pinches, and spheromaks. [We have attached a bibliography from our Center for the FY04-07 funding period.] The application areas we are currently concentrating on are a balance between opportunities for verification and validation of our codes in new regimes, opportunities for supporting the U.S. experimental program in magnetic fusion, and opportunities to address unresolved issues for the international ITER experiment, presently under construction.

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The two workhorse simulation codes M3D and NIMROD, and the AMRMHD code being developed jointly by CEMM and APDEC, use very different numerical representations and algorithms and have different strengths and capabilities. However, there is a large range of overlap in the problems they can address. We have effectively used these codes together to perform a series of benchmark problems that serve as both linear and non-linear verification exercises for all codes. Recent benchmark exercises include computing the interaction of a fast ion component with the internal kink mode, computing fast collisionless reconnection, and computing the stabilization of the gravitational instability due to the gyroviscous force. However, our most notable success is the detailed M3D/NIMROD nonlinear benchmark calculation of three complete sawtooth cycles in a small tokamak. This significant benchmarking achievement has given us great confidence in the nonlinear results in both codes, and we are building on this new credibility by undertaking a number of important extensions.

During the last year we have improved the underlying extended MHD description of the plasma we use by including the gyroviscous force, improving the calculation of long-mean-free-path parallel closures, and by developing an improved formalism for further closures development. The M3D team is developing and testing new representations: one that uses higher continuity finite elements and is more strongly implicit (M3D-C^1) and one that involves high order spectral finite elements. We have also made great progress in extending the M3D partially implicit algorithm to allow a 5-times increase in timestep. The NIMROD team developed and implemented a new algorithm for solving the two-fluid plasma model. Both codes have improved their parallel scaling efficiencies so that the codes can now effectively use 4000-5000 processors, resources permitting. We have addressed cutting-edge applications in the areas of the internal kink mode (sawtooth and fishbone), Edge Localized Modes (ELMs), and mass redistribution after pellet injection.

To ensure a high level of reliability, we are now embarking on a number of critical verification and validation benchmark problems that test the new extended MHD closures, some of which have been recently implemented and some which we will be implementing in the near future. The M3D-C^1 effort is being taken from 2D to 3D so that it can be fully evaluated against the existing M3D approach, which itself is being improved through further extensions in the implicit algorithm and the completion of the introduction of spectral finite elements. We are also investigating a technique known as FETI-DP which shows promise for dramatically improving the parallel scalability and preconditioning in M3D. The NIMROD code will investigate an improved class of spectral basis functions and preconditioning methods, and will also evaluate a nonlinear implicit time advance based on the Newton-Krylov method.

Application areas we are now addressing include further sawtooth studies in larger machines with a more complete physics model and more demanding parameters, the introduction of an energetic ion component into the sawtooth studies, the calculation of the excitation and control of neoclassical tearing modes (NTMs), further studies of ELMs with the improved extended MHD equations, resistive wall modes, error field studies, and disruption mitigation studies. Each of these applications has a validation component in which the simulation results are compared with experimental data in CDX-U, DIII-D, C-Mod, and NSTX. We see these applications as not only opportunities to clarify the physical processes in these complex nonlinear phenomena, but also as essential steps in building a credible simulation tool for ITER. We continue to have strong collaborations with many other SciDAC centers and will extend and build on these.

CEMM Bibliography (FY04-07)

[Brennan05] Brennan DP, Kruger et al, “A categorization of tearing mode onset in tokamaks via nonlinear simulation”, Nucl. Fus. 45 1178 (Sep 2005)

[Brennan06] Brennan DP, Kruger SE, Schnack DD, Sovinec CR, Pankin A, “Computing nonlinear magnetohydrodynamic edge localized instabilities in fusion plasmas,” *JOURNAL OF PHYSICS: CONFERENCE SERIES* 46, 63 (2006).

[Breslau06] Breslau, J.A, Park W., Jardin, S.C. “Massively parallel modeling of the sawtooth instability in tokamaks”, J. Phys.: Conf. Ser. 46, 97-101 (2006)

[Breslau07] Breslau, J, Jardin, SC, Park, W., “3D modeling of the sawtooth instability in a small tokamak”, Phys Plasmas (to appear 2007)

[Chen04] J. Chen, J. Breslau, G. Fu, S. Jardin, W. Park, “Symmetric Solution in M3D,” *Comp. Phys. Communications* **164**, 468 (2004)

[Chen05a] Chen, J, Jardin, SC, Strauss HR “Solving anisotropic transport equation on misaligned grids”, Computational Science-ICCS 2005, PT 3 3516 1076 (2005) in Lecture Notes in Computer Science

[Chen05b] Chen J, Strauss HR, Jardin S, et al, Application of Mass Lumped Higher Order Finite Element”, PPPL-4128

[Chen05c] Chen J, Strauss HR, Jardin SC, et al, “Higher Order Lagrange FiniteElements in M3D”, PPPL4032

[Cohen05] Cohen BI, .., Sovinec CR, et al, “Simulation of spheromak evolution and energy confinement”, Phys. Plasmas 12 056106 (May 2005)

[Ferraro06]Ferraro N and Jardin S, “Finite element implementation of Braginskii’s gyroviscous stress with application to the gravitational instability”, Physics of Plasmas, 13: 092101 (2006)

[Ferraro07] N. M. Ferraro, “Finite Larmor Radius Effects on the Magnetorotational Instability”, to appear in The Astrophysical Journal, (2007)

[Fu06a] Fu GY, Park W, Strauss H, et al, “Global Hybrid Simulations of Energetic Particle Effects on the n=1 Mode in Tokamaks: Internal Kink and Fishbone Instability”, Phys. Plasmas **13** 052517 (2006)

[Fu06b] Fu GY, Breslau JA, Park W, Jardin SC, Chen J, “Nonlinear Simulations of Fishbone Instability and Sawteeth in Tokamaks and Spherical Torus”, IAEA EX/7-4Rb

[Fu07] Fu G, Breslau J. Fredrickson E. et al, “Global Hybrid Simulations of Energetic Particle-driven Modes in Toroidal Plasmas”, PPPL 4029, Phys. Plasmas **13** 052517, (2006)

[Held04] Held, ED; Callen, JD; Hegna, CC; Sovinec, CR; Gianakon, TA; Kruger, SE. 2004. Nonlocal closures for plasma fluid simulations. *PHYSICS OF PLASMAS* 11 (5): 2419-2426.

[Hooper05] Hooper EB, …, Sovinec CR, et al, “Magnetic reconnection during flux conversion in a driven spheromak”, Phys. Plasmas 12 092503 (Sep 2005)

[Hudson07] S. R. Hudson, “Steady state solutions to the advection-diffusion equation, and ghost coordinates, for a chaotic flow.”, submitted to Phys. Rev. E (2007)

[Izzo06] V.A. Izzo, “A numerical investigation of the effects of impurity penetration depth on disruption mitigation by massive high-pressure gas jet,” Nuclear Fusion **46** (2006) 541.

[Jardin04] Jardin, SC. 2004. A triangular finite element with first-derivative continuity applied to fusion MHD applications. *JOURNAL OF COMPUTATIONAL PHYSICS* 200 (1): 133-152.

[Jardin05] Jardin, S.C; Breslau, J.A. , 2005, “Implicit solution of the four-field extended-magnetohydrodynamic equations using high-order high-continuity finite elements”. *PHYSICS OF PLASMAS* 12, 056101 (2005)

[Jardin07] Jardin, S.C., Breslau, J. A., Ferraro, N, “A High-Order Implicit Finite Element Method for Integrating the Extended-Magneto-Hydrodynamic Equations in Two Dimensions”, PPPL 4209 to appear J. Comp. Phys (2007)

[Ji06] Ji, J-Y, Held, ED. “Exact linearized Coulomb collision operator in the moment expansion,” *PHYSICS OF PLASMAS* 13, 102103 (2006).

[Kim04] Kim, CC; Sovinec, CR; Parker, SE. NIMROD Team. 2004. Hybrid kinetic-MHD simulations in general geometry. *COMPUTER PHYSICS COMMUNICATIONS* 164 (1-3): 448-455.

[Kruger04] Kruger, SE; Sovinec, CR; Schnack, DD; Held, ED. 2004. Free-boundary simulations of DIII-D plasmas with the NIMROD code. *COMPUTER PHYSICS COMMUNICATIONS* 164 (1-3): 34-39.

[Kruger05]Kruger SE, Schnack DD, Sovinec CR, “Dynamics of the major disruption of a DIII-D plasma”, Phys Plasmas 12 056113 (May 2005)

[Menard05] Menard JE,Park W, et al “Internal kink mode dynamics in high-beta NSTX plasmas”, Nucl. Fus. 45 539 (Jul 2005)

[Pankin05] Pankin A. Y. Bateman G., Brennan DP, et al., “Elm triggering conditions for the integrated modeling of H-mode plasmas”, Czech. J. of Physics 55 367 (Mar 2005)

[Ramos04] A. Sen, D. Chandra, P. Kaw, M.P. Bora, S. Kruger and J.J. Ramos, "Effect of sheared flows on neoclassical tearing modes", 20th IAEA Fusion Energy Conference, Vilamoura, Portugal, 2004, TH/6-1.

[Ramos05a] Ramos JJ, “General expression of the gyroviscous force”, Phys. Plasma 12 112301 (Nov 2005)

[Ramos05b] Ramos JJ, “Fluid formalism for collisionless magnetized plasmas”, Phys Plasma. 12 052102 (May 2005)

[Ramos06] A. Ishizawa, N. Nakajima, M.Okamoto and J.J. Ramos, ", "Multi-scale nonlinear interactions among micro-turbulence, magnetic islands and zonal flows" (with A. Ishizawa et al.), 21st IAEA Fusion Energy Conference, Chengdu, China, 2006, TH/P2-21.

[Ramos07] Ramos,JJ “Fluid theory of magnetized plasma dynamics at low collisionality”, Phys. Plasmas, **14**, 052506 (2007).

[Reynolds06] Reynolds D., R. Samtaney and C. S. Woodward, “A Fully Implicit Numerical Method for Single-Fluid Resistive Magnetohydrodynamics”, J. of Comput. Phys. **219:**144-162, 2006.

[Ryutov05] Ryutov DD, …, Sovinec CR, et al, “The effect of artificial diffusivity on the flute instability” Phys. Plasmas **12** 084504 (Aug 2005)

[Samtaney03] [9] R. Samtaney, Suppression of the Richtmyer-Meshkov instability in the presence of a magnetic field. Phys. Fluids, **15**(8):L53--56, 2003.

[Samtaney04]Samtaney, RS; Jardin, SC; Colella, P; Martin, DF. 2004. 3D Adaptive Mesh Refinement simulations of pellet injection in tokamaks. *COMPUTER PHYSICS COMMUNICATIONS* **164** (1-3): 220-228.

[Samtaney05a] Samtaney R. , S. C. Jardin, P. Colella, and D. F. Martin, Adaptive Mesh Refinement Methods for Magnetic Fusion Applications. Published in Adaptive Mesh Refinement: Theory and Applications, Lecture Notes in Computational Science and Engineering. Editors: Plewa, Linde and Weirs. Springer-Verlag, 2005.

[Samtaney05b] Samtaney R., P. Colella, T. J. Ligocki, D. F. Martin and S. C. Jardin, An adaptive mesh semi-implicit conservative method for resistive MHD. Journal of Physics, Conference Series, SciDAC 2005, **16**, pp: 40-48, 2005.

[Samtaney07] “Adaptive Mesh Refinement Extended MHD Simulations of Tokamak Refueling”.

To appear in Advanced Computational Infrastructures for Parallel and Distributed Applications. Editors: Li, Parashar and Chandra. Wiley Book Series on Parallel and Distributed Computing, Wiley, 2007.

[Schnack06b] Schnack DD, Barnes DC, Brennan DP et al, “Computational Modeling of Fully Ionized Magnetized Plasmas using the Fluid Approach”, Phys. Plasmas **12** 058103 2006

[Sovinec05a] Sovinec CR, Schnack DD, Pankin AY et al. “Nonlinear Extended Magnetohydrodynamics Simulation Using High-Order Finite Elements,” Journal of Physics: Conference Series **16**, 25 (IoP, London, 2005).

[Sovinec05b] Sovinec, CR; Cohen, BI; Cone, GA; Hooper, EB; McLean, HS. 2005. Numerical investigation of transients in the SSPX spheromak. *PHYSICAL REVIEW LETTERS* 94 (3): art. no.-035003.

[Strauss04a] Strauss, HR; Pletzer, A; Park, W; Jardin, S; Breslau, J; Sugiyama, L. 2004. MHD simulations with resistive wall and magnetic separatrix. *COMPUTER PHYSICS COMMUNICATIONS* 164 (1-3): 40-45.

[Strrauss04b] Strauss, HR; Sugiyama, LE; Fu, GY; Park, W; Breslau, J. 2004. Simulation of two fluid and energetic particle effects in stellarators. *NUCLEAR FUSION* 44 (9): 1008-1014.

[Strauss04c] H.R. Strauss, Linjin Zheng, M. Kotschenreuther, W. Park, S. Jardin, J. Breslau, A. Pletzer, Roberto Paccagnella, L. Sugiyama, M. Chu, M. Chance, A. Turnbull, Halo Current and Resistive Wall Simulations of ITER, Twentieth IAEA Fusion Energy Conference, Villamora, Portugal IAEA-CN-116/TH/2-2 (2004)

[Strauss06] H. Strauss, L. Sugiyama, C.S. Chang, G.Y. Park, S. Ku,W. Park, J. Breslau, S. Jardin “ELM Simulations with M3D,” 21st IAEA Fusion Energy Conference, Chengdu, China, TH/P8-6 (2006)

[Sugiyama05] L.E. Sugiyama, W. Park, H.R. Strauss, G. Fu, J. Breslau, J. Chen, S. Klasky, “Plasmas beyond MHD: Two-fluids and Symmetry breaking”, Journal of Physics: Conference Series 16: pp. 54-58 (2005)

[Turnbull05] Turnbull AD, Brennan DP, Chu MS, et al. , “Theory and simulation basis for MHD stability in DIII-D”, Fus. Sci. and Tech **48** 875 (Oct 2005)

[Wan05] Wan, W; Chen, Y; Parker, SE. 2005. Gyrokinetic delta f simulation of the collisionless and semicollisional tearing mode instability. *PHYSICS OF PLASMAS* 12 (1): art. no.-012311.

[Wheatley05a] Wheatley V, Pullin DI, Samtaney R, “Stability of an impulsively accelerated density interface in magnetohydrodynamics”, Phys. Rev. Lett. **95** 125002 (Sept 2005)

[Wheatley05b] V. Wheatley, D. I. Pullin, and R. Samtaney. “Regular shock refraction at an oblique planar density interface in magnetohydrodynamics.” J. Fluid Mech., **522**:179--214, 2005.

[Woodruff05]Woodruff S, …,Sovinec CR, et al, “Controlled and spontaneous magnetic field generation in a gun-driven spheromak”, Phys. Plasmas **12** 052502 (May 2005)

[Yamada06] M. Yamada, Y. Ren, H. Ji, S. Gerhardt, R. Kulsrud, A. Kuritsyn, and J. Breslau, “Experimental Study of Two-fluid Effects on Magnetic Reconnection in Laboratory Plasma with Variable Collisionality,” *Phys. Plasmas*. **13**, 052119 (2006).

[Zhu06] Zhu P, Hegna CC, Sovinec CR, “Nonlinear growth of a line-tied *g*-mode near marginal stability,” *PHYSICS OF PLASMAS* **13**, 102307 (2006).

[Zhu07] Zhu P, Hegna CC, Sovinec CR, Bhattacharjee A, Germaschewski K, “Intermediate nonlinear regime of a line-tied *g*-mode,” *PHYSICS OF PLASMAS* **14**, 055903 (2007).