Numerical Algorithms for Magnetohydrodynamics of Multifluid Systems

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The purpose of this project is to develop novel mathematical models, numerical algorithms, and computational software optimized for modern supercomputers for the numerical simulation of free surface multiphase magnetohydrodynamic (MHD) flows at low magnetic Reynolds numbers, and to perform simulations in support of magnetically confined fusion and advanced accelerator applications. Our primary goal is to gain through mathematical modeling and numerical simulations a better understanding of physics, and improve the design of experiments and devices critical for the DOE mission. The research is being performed in close collaboration with General Atomics, Neutrino Factory/Muon Collider Collaboration, and the SciDAC Center TSTT (ITAPS).

Development of Models, Algorithms, and Computational Software

Specialized numerical algorithms, optimized for modern computer architectures such as BlueGene, and new models for complex MHD processes in multiphase systems are necessary in order to advance numerical simulations of nuclear fusion devices such as the International Toroidal Experimental Reactor (ITER) and future accelerators. Mathematical models, algorithms, and software being developed under this project enable the simulation of ITER fueling through the injection of small frozen deuterium-tritium pellets, striation instabilities of the pellet ablation channel, liquid hydrogen or lithium jets proposed for the tokamak plasma disruption mitigation, and the simulation of a mercury jet interacting with intense proton pulses in the target system for the Neutrino Factory/Muon Collider.

FronTier-MHD, a code for 3D compressible free surface MHD flows at low magnetic Reynolds numbers, has been recently developed by our group based on the method of front tracking. The explicit tracking of interfaces allows us to apply different mathematical approximations and numerical discretizations in domains occupied by different materials, and thus to resolve material properties and multiple time scales. In FY06, the embedded boundary method for elliptic problems in geometrically complex 3D domains was developed for the FronTier-MHD code.

An accurate description of multiphase mixtures and phase transitions such as the surface ablation and cavitation is a key problem in modeling and simulation of targeted applications. In FY06, we developed a heterogeneous (discrete vapor bubble) numerical model for cavitation, a model for the ablation of solid surfaces, multi-component equation of state accounting for atomic processes in plasma, and the corresponding computational software for the FronTier code. Future development of numerical algorithms will focus on scalable elliptic solvers in complex domains with interface constraints, adaptive mesh refinement in 3D, and optimization of the code for modern computer architectures such as BlueGene. We will also work on the coupling of the FronTier-MHD code with MHD codes for tokamak plasmas in order to

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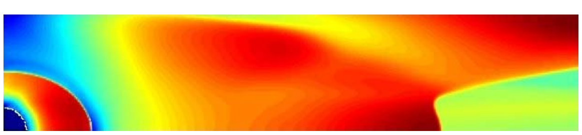
achieve advances in the simulation of such multiphysics processes in tokamaks as the pellet fueling.

Application Highlights

Fueling Technologies for ITER

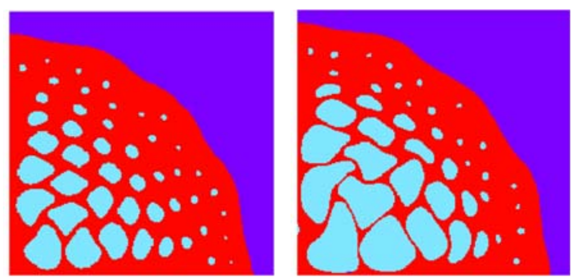
Our numerical models and the software enable large scale numerical simulations of complex physics processes associated with the injection of frozen deuterium-tritium fuel pellets in tokamaks. This research, being performed in close collaboration with General Atomics, addresses detailed ablation physics. Therefore it complements global plasma simulations currently being performed at the SciDAC Center for Extended MHD Modeling (CEMM). In our recent work, the pellet ablation rate and lifetime in magnetic fields were systematically studied for the first time and compared with theory and existing experimental databases. We showed that a common expectation of the nuclear fusion community regarding the role of the anisotropic heating and magnetic field on the pellet ablation rate was incorrect. The study of striation instabilities, impossible without resolving the detailed physics in the ablation cloud, will be the focus of our future research. These instabilities are not well understood and have a significant impact on the pellet-plasma interaction that will occur in the fueling of burning plasmas in ITER. In the future, we will work with PPPL scientists on the coupling of the M3D code with FronTier-MHD as a subgrid model for detailed pellet ablation physics, and performing simulation on the BlueGene.



Mach number distribution of the pellet ablation flow demonstrating double transonic layers.

Targets for Advanced Accelerators

The design of liquid mercury targets able to generate high-flux beams is among the most important problems of the design of advanced accelerators such as the Neutrino Factory / Muon Collider, and the Spallation Neutron Source. The Muon Collider target has been proposed as a pulsed jet of mercury interacting with strong proton beams in a 20 Tesla magnetic field. We have performed simulations in support of MERIT, a future targetry experiment at CERN. Simulations have shown the proton pulse induced cavitation, instability, and breakup of the jet. We have also shown numerically that the magnetic field reduces cavitation and the Richtmyer-Meshkov type instability in the mercury jet.



Simulation of cavitation in the mercury target with FronTier-MHD code.

We have demonstrated that at the design parameters, the distortion of the jet entering a non-uniform magnetic field is significant, and that reduces the effective cross-section of the interaction with the proton pulse. The study has led to the change of design parameters of the future experiment MERIT. Current work is focused on large scale 3D MHD simulations of the mercury jet interaction with proton pulses.

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