Introduction

The advent of high-power laser facilities in the past two decades has enabled the creation of physical conditions that were heretofore inaccessible in the laboratory, opening a new field and providing new ways to explore the physics of high energy density laboratory plasmas (HEDLP). Computer modeling and simulation are crucial to the design, analysis, and interpretation of HEDLP experiments. To extract the best and the most science from experiments, modeling and simulation of experiments need to be the norm. This has not been the case in some areas of HEDLP because of a lack of open codes and/or funding for the development and use of such codes.

Computer modeling and simulations of HEDLP experiments and phenomena currently span the range from kinetic modeling to continuum fluid modeling. In the kinetic approach, a plasma may be modeled either by directly solving for the motions of individual electrons and ions, as determined from self-consistent electromagnetic fields, or alternatively, by solving the evolution equations for the electron and ion particle distribution functions. In the continuum approach, in contrast, one solves the evolution equations for local plasma properties – such as velocity and energy density – by treating the plasma as a fluid in which the electron and ion components may be regarded as separate but interacting components. Which approach is adopted depends on the level of detail that is required in order to understand the local physics. Hybrid approaches are receiving increased attention because HEDLP
experiments and phenomena are often multi-physics and multi-scale; spanning the broad range of both spatial and temporal scales encountered remains one of the outstanding challenges of this field.

Hydrodynamic and magneto-hydrodynamic simulations of HEDLP experiments face a particular challenge. Although a number of highly capable HEDLP codes exist at the defense program laboratories (Los Alamos National Lab, Lawrence Livermore National Lab and Sandia National Lab), most of these codes are classified, and the few that are not are export controlled. In the former case, the academic community members who happen to know about a particular code must ask people at the labs to run simulations for the design and analysis of their experiments, and after a lengthy interval, some data may be able to be provided to the academic who requested it. In the case of export control, foreign nationals may not be able to have access to the source code and, consequently, only the binary executable code is available. In the case of commercial codes, the purchase cost may be prohibitive, and usually it is only the binary executable that is available.

For these reasons, simulations of academic HEDLP experiments involving hydrodynamics and magneto-hydrodynamics have been rare. This has placed the academic HEDLP community at a great disadvantage in designing and analyzing novel experiments in many important areas of HEDLP physics. Open hydrodynamic and magneto-hydrodynamic codes with HEDLP capabilities are needed in order to extract the best and the most science from such experiments. In 2009, the Department of Energy (DOE) National Nuclear Security Administration (NNSA) selected FLASH to be such a code.

FLASH

FLASH\textsuperscript{1-3} is an open community code developed under the auspices of DOE/NNSA and DOE/Office of Science. It is a multi-physics finite-volume Eulerian code with multiple state-of-the-art hydrodynamics and magneto-hydrodynamics solvers and adaptive mesh refinement (AMR) on a block-structured mesh. It uses a variety of parallelization techniques, including domain decomposition, mesh replication, and threading to best utilize hardware resources, and scales to well over 100 K processors. It is extremely portable: it can run on platforms ranging from laptops and clusters to supercomputing systems such as the IBM BG/Q. It is professionally managed software with daily, automated regression testing on a variety of platforms, version control, coding standards, extensive documentation, user support, and integration of code contributions from external users.

FLASH has many physics modules relevant to astrophysics, cosmology, combustion, high energy density physics, and turbulence. FLASH has a large, world-wide user community: it has been downloaded more than 3,000 times, and more than 1,100 papers authored by more than 1,600 scientists have been published that directly use FLASH results.

FLASH HEDLP Capabilities

Current FLASH HEDLP capabilities\textsuperscript{4-8} include:

- Compressible hydrodynamics/magneto-hydrodynamics on an AMR mesh
- 3T (separate electron, ion, and radiation temperatures) hydrodynamics/magneto-hydrodynamics
- Multi-geometry support for unsplit hydrodynamics/magneto-hydrodynamics solvers
- General-purpose implicit diffusion solver
- Explicit/implicit thermal conduction (Spizer, Lee & More)
- Heat exchange (Spitzer, Lee & More)
- Explicit magnetic resistivity (Braginskii)
- Biermann battery effect in smooth flows and at shocks
• Multi-material tabular equations of state
• Multi-group radiation diffusion
• Multi-material, tabular opacities
• Optical ray tracing (Kaiser, bi-cubic 2D and tri-cubic 3D interpolation of electron number density, adaptive stepping and 2nd-, 3rd-, and 4th-order Runge-Kutta integration methods)
• Ability to represent rigid bodies of arbitrary shape in the computational domain
• Limited particle-in-cell capability
• Magnetic field diagnostics, including induction coils, Faraday rotation, and proton radiography
• Able to work seamlessly with Spect3D (Prism Computational Sciences)

Use of FLASH by the Academic HEDLP Community

FLASH has been used to design, analyze, and interpret academic HEDLP experiments in collaborations the Flash Center for Computational Science at the University of Chicago has with MIT, Michigan, Rice, Ohio State, Oxford, and the Laboratoire d’Utilisation des Lasers Intenses; and through an MoU with the UK Science Research Facilities Council. See Figures 1-6 for a description of some of these experiments.9-15

FLASH is being used to design many upcoming academic HEDLP experiments on large facilities, including:

• **Omega**: “Non-linear amplification of magnetic fields in laser-produced plasmas,”
  PI: D.Q. Lamb (University of Chicago)
• **Omega**: “Plasma jets,”
  PI: R. Petrasso (MIT)
• **Omega**: “Magnetized jets,”
  PI: E. Liang (Rice University)
• **NIF**: “Primordial magnetogenesis and turbulent amplification of magnetic fields on NIF,”
  PI: G. Gregori (University of Oxford)
• **NIF**: Generation of collisionless shocks and magnetic fields on the National Ignition Facility,”
  PI: Y. Sakawa (Osaka University)
• **LMJ**: “Primordial magnetogenesis and turbulent amplification of magnetic fields,”
  PI: G. Gregori (University of Oxford)
• **LMJ**: “Turbulent hydrodynamics experiments in high energy density plasmas,”
  PI: A. Casner (CEA)

Summary and Recommendation

Computer modeling and simulation are crucial to the design, analysis, and interpretation of HEDLP experiments. To extract the best and the most science from experiments, modeling and simulation of experiments need to be the norm. This has not been the case in some areas of HEDLP because of a lack of open codes and/or funding for the development and use of such codes. In particular, there is a need for open hydrodynamic and magneto-hydrodynamic codes. FLASH is one such code, but funding for its development and use was slashed in 2013. This situation underlines the need for increased funding to develop and use codes that can simulate academic HEDLP experiments. Such funding would produce a large impact at modest cost by greatly expanding the range of new and novel experiments that could be achieved and enabling the best and the most science to be extracted from them.
References


Figure 1: The University of Oxford experiments with the Vulcan laser generate a shock wave that crosses a grid, stirring turbulence. The magnetic field generated by the Biermann battery effect is amplified by the turbulent motion and is measured by 3-axis coils\(^9\).

Figure 2: To push the amplification towards the non-linear dynamo regime, we devised an experimental setup that consists of two colliding jets. The interaction region is significantly hotter and the resulting formation is akin to galaxy clusters\(^10\).

Figure 3: Study of the radiative properties of jets propagating in gases. The jets are driven using the Omega laser and advance inside a tiny tube. By changing the material properties of the plasma we can study radiative shock physics (source C. Li). 52 radiative MHD simulations of the experimental setup scan the parameter space to help design the laser experiment (left). The pseudo-color and simulated diagnostics show Sid 50 with a 10 µm polystyrene pusher in Xe gas at 300 mbar.
Figure 4: FLASH was used to design an experiment that created inertially confined jets. The laser configuration allows for the control of flow characteristics such as the jet velocity, density\textsuperscript{11} and self-generated magnetic fields\textsuperscript{12}.

Figure 5: Interaction between a central outflow and a surrounding wind is common in astrophysical sources powered by accretion. These experiments, performed at LULI, studied the collimation of the inner central outflow in the context of astrophysical jet formation\textsuperscript{13}.

Figure 6: Probing the equation of state of warm dense carbon with the laser-driven shock and release technique\textsuperscript{14,15} with the Omega laser. Left: experimental imaging of the shock propagating in the multi-layered target. Right: a FLASH Rad-Hydro simulation of the experiment, confirming a small shock curvature.