Modeling Capabilities for Inertial Confinement Fusion

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Executive Summary

The computational models used in Inertial Confinement Fusion (ICF), which have been developed by the community over several decades and in multiple institutions, are indispensable tools for interpreting experiments, suggesting new experiments and designing new approaches to fusion energy production. An ability to predict experimental outcomes in advance, to a high degree of accuracy, is nevertheless a goal that is yet to be achieved. If the complexity of our current codes could be improved to the level required to reach a truly predictive capability, this would undoubtedly represent a game changing moment in inertial fusion research, greatly accelerating our current experimental programs and opening the door to the design of new facilities with confidence.

Introduction

The physics models used in ICF research are multi-scale meaning they commonly contain physics packages that describe physical processes that occur on different temporal and spatial scales. Our current computational models for ICF can be split into three broad categories:

(a) Radiation-Hydrodynamics and Magnetohydrodynamics (MHD) for long-pulse laser-plasma interactions and z-pinch physics. Examples include the 3D radiation-hydrodynamics code Hydra developed at LLNL, the 3D Gorgon radiation-MHD code developed at Imperial College (UK) and the FLASH MHD code (now at University of Rochester). These are the workhorse codes of the laser-plasma and z-pinch communities

(b) Particle-In-Cell codes for simulating short-pulse laser-plasma interactions at relativistic intensity, and wave-particle interactions relevant to long-pulse ICF. Such codes exist in every major plasma physics institution around the world and are the workhorse codes of the short-pulse laser community. They are also the principal tool for studying the generation, acceleration, temporal compression, and chamber propagation of ion beams for Heavy Ion Fusion, though these applications' needs are distinct and different codes are employed.

(c) Specialized codes and hybrid models. These include paraxial wave solvers for understanding parametric instabilities (e.g. Pf3D at LLNL), Vlasov-Fokker-Planck codes for understanding the thermal and magnetic transport properties of electrons and ions in laser fusion plasmas (e.g. K2 at LLNL), and first principles light wave solvers valid in a broader range of parameter space (e.g. LPSE at LLE).

These models work well within their area of applicability. Most of the current development focus is on the refinement of the existing algorithms or the addition of new physics packages that operate within the same level of fidelity. The challenge facing the community is the need to integrate the physics from several distinct categories into a single code. This is difficult not only from the perspective of computational expense (and the associated need to improve algorithm speed), but also in answering the fundamental questions regarding how to achieve the merging or cooperation of models that operate in different regimes of time, space and plasma approximations.

Next generation models

The main approaches to IFE being advocated in the US (and elsewhere) are: (1) laser-driven fusion (both direct and indirect, possibly with externally applied magnetic fields), (2) z-pinch driven fusion (e.g. MAGLIF), (3) the Fast Ignition of laser driven targets by intense electron or ion beams, and (4) Heavy-Ion Fusion (that is, heavy ion beam-driven fusion. Here we list, for each of these major approaches, the ideal set of new features that would be required to take the computational models to the next level of predictive capability.

Laser-fusion: The key physics concepts include: electron transport in hohlraum and capsule coronas; magnetic field generation and transport in the non-local regime; radiation production and transport in high-Z plasmas; coupling between thermal transport and radiation production; ion transport in hohlraum coronas and imploded cores (in multiple materials); alpha particle transport and particle scattering in the core; laser-plasma-interaction physics such as cross-beam-energy-transfer in multiple dimensions and in magnetized environment; wave-particle interactions; material properties including equation-of-state and opacity; hydrodynamic instabilities and possibility of turbulence.

Laser-fusion codes currently lack sophisticated electron and ion transport models. A Vlasov-Fokker-Planck treatment for multiple species coupled to Maxwell's equations would increase modeling confidence. This would more accurately account for effects such as non-local thermal transport, non-local magnetic field generation and advection, ion interpenetration and diffusion, and non-local ion transport. A combination of grids and Maxwell solvers are probably needed to account for distinct physical processes such as electron non-locality and ion-acoustic turbulence, which operate on vastly different temporal and spatial scales. Coupled to this is a need to greatly improve the propagation of lasers and the associated parametric instabilities including cross-beam energy transfer, magnetization effects on instability growth rates, and laser speckle physics in multiple dimensions.

Higher fidelity atomic kinetics and equation of state models would also be important developments. A kinetic treatment of fusion reactivity is emerging as a possible source of error in current models and this connects to non-local ion transport. A crucial feature of each of these models, which increases the complexity of the development process, is the need to work on irregular meshes for fully integrated simulations. Most kinetic treatments of laser fusion scenarios use idealized conditions for simplicity, so there is a need to move toward employing these in realistic conditions (i.e. simulating fully integrated experiments).

Indirect-drive fusion arguably represents the greatest modeling challenge within ICF.

Z-pinch fusion: The key physics includes: magnetohydrodynamics of pinch implosion; wire ablation, particle acceleration, magnetization and drifts in coronal plasma; interpenetration of precursor plasma; K-alpha radiation production; laser propagation and associated thermal transport including magnetic field.

Kinetic electron and ion transport models and speckled light wave solvers for understanding laser preheat in MAGLIF designs are important next steps. The physics of the coronal and precursor plasma in wire-array implosions also require kinetic packages that can handle regions of large Hall parameter. In order to resolve processes that occur on small length scales, for example wire ablation, improved gridding techniques are needed, for example Adaptive Mesh Refinement (AMR).

Heavy-Ion Fusion: The key physics includes: the generation, acceleration, pulse compression, routing, and final focusing of the ion beams; transport of the beams through the fusion chamber; beam interaction with “radiation converters” in hohlraum targets (though direct drive continues to be pursued in Japan); and integrated target physics calculations.

Fast Ignition: The key physics includes: integrated implosions with novel targets possibly including magnetic field generating experimental components; absorption of laser energy in coronal plasma over long timescales; ablation physics at high intensity; transport of electrons and ions through dense plasma; formation of sheath fields in complex geometries for ion acceleration; kinetic and collisional processes in transporting energy to the core; particle refluxing; generation of magnetic field in multi-material targets (e.g. resistivity gradients).

Fully integrated modeling of both electron and ion driven fast ignition concepts will require the inclusion of fully electromagnetic electron and ion kinetic models to describe the fast particle generation and transport, combined with radiation-hydrodynamics models to describe the implosion phase. Our current models treat the absorption and subsequent transport of energy to the core with separate models, but next level models will need to treat these processes simultaneously. Particle-In-Cell codes could be made to represent phase-space more efficiently by designing novel particle splitting and merging techniques, or other means of reducing the computational load in regions that are over-resolved with particles. Improvements in implicit field solvers for PIC are needed to better conserve energy and momentum on very long timescales. Techniques to remove noise in both advection and collisions are also beneficial, for example via phase-space remapping. Additionally, more accurate electron and ion stopping models are needed.

Discussion

Clearly there is considerable overlap in both the physics models and the research needed to understand how to couple multiple gridding techniques. The above list is non-exhaustive and highly challenging but it nonetheless serves as a useful goal for the next two decades of model development. A common theme is the need for integrated, electromagnetic kinetic models. A variety of approaches, for example particle and continuum methods, should be explored and benchmarked. Models for particle splitting and merging, and Adaptive Mesh Refinement in momentum-space will probably be necessary. Solutions may involve the use of multiple grids simultaneously, the merging of different grids, or the merging of physics models on a common grid (e.g. asymptotic-preserving schemes).

Many models can be perfected in one dimension before moving to 3D. The development time is usually significantly shorter for models that operate on relatively simple (i.e. uniform) computational grids. This highlights the need for experimental codes with simple grids which allow new models to be tested, as well as the production codes.

Modeling is currently in a transition phase due to the migration to new CPU/GPU computing architectures and this adds an additional layer of complexity faced by the community, as a number of legacy codes become unusable. Moreover, with the emerging capabilities of quantum computing, algorithms and codes should be developed to harness the computing power of QPU.

Although some of the algorithmic structure is similar in inertial and magnetic confinement fusion codes, in practice the codes are very different, largely due to the need to specialize to particular geometries (e.g. hohlraums vs. tokamaks) and regimes of plasma behavior (e.g. small vs large plasma beta). Both communities therefore have very different workhorse codes, for example MCF is largely focused on gyrokinetic models whereas ICF mostly makes use of radiation-hydrodynamics.

An often overlooked but important part of speeding up the development cycle is the need for less complex codes that are easily accessible to designers and students which can be used as a testbed for new physics packages and training. These less complex codes often use simpler computational meshes, operate in only 1D or 2D, and are run in lower resolution on less integrated systems.

Reduced models, for example inline LPI models or the SNB heat transport model will continue to play a role over the coming decades because truly “fully kinetic” simulations, which are able to resolve all relevant length and time scales, will likely require unaffordable computing power for the foreseeable future.

An essential component to developing more sophisticated codes is the need to make direct comparison to experiments for model verification. This requires relatively simple (“non-integrated”) experiments with well characterized and reproduceable plasma conditions and multiple diagnostics, but at high power. The Omega laser at LLE is a valuable platform for these types of systems.

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