Inverse Ray Tracing on Icosahedral Tetrahedron Grids for Nonlinear Laser–Plasma Interactions Coupled to 3-D Radiation Hydrodynamics

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Three major avenues to inertial confinement fusion (ICF) are currently being explored worldwide:[1] laser direct drive (LDD), laser (x-ray) indirect drive (LID), and magnetic drive using pulsed power. These approaches have in common the use of laser beams and face challenges related to laser–plasma instabilities (LPI's). LPI's are nonlinear microscopic processes that couple plasma eigenmodes (electron or ion plasma waves) to the laser beams or scattered light or each other.[2] In the case of LDD and LID, the main LPI's at play are cross-beam energy transfer (CBET), stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and two-plasmon decay (TPD). Their consequences for large-scale plasma hydrodynamics are often important, leading to significant loss of laser/target coupling, introducing asymmetries in target compression, and generating suprathermal-electron populations.[3]

While LPI's have a paramount influence in ICF, they are also difficult to model in radiation-hydrodynamic (RH) codes that describe the plasma motion at fluid scales. This relates to an incompatibility of dimensions between the typical plasma size (~mm) and driver duration (~ns) compared to the scales required to resolve the kinetic processes at play in LPI's (~nm and ~fs). These six-orders-of-magnitude differences in time and space prevent direct numerical calculations of LPI's in 3-D geometries at fluid scales. As such, they are often computed at reduced scales, for short periods of time, in a reduced number of dimensions, and/or for a limited number of laser beams. For these reasons, models for laser propagation in hydrodynamic codes have long been limited to the linear process of collisional absorption. This is usually modeled in the geometrical optics (GO) framework for computing laser trajectories,[4] which offers adequate performance at fluid scales, even in 3-D geometries.

Given the importance of LPI's in ICF, significant efforts have been made in the last 10 to 15 years to include reduced LPI models in fluid codes, mainly based on GO models for numerical efficiency. These reduced models must address two main questions: (1) how to compute laser intensities or fields in the GO framework, key properties for LPI's, and (2) how to account for the microscopic processes. The first issue stems from the infinitely thin property of GO rays, which prevents a straightforward definition of ray intensity. The GO framework also breaks down at laser caustics, which are prominent in LDD. The second issue relates to the formulation of theoretical models that reproduce microscopic physics from macroscopic quantities. Such models have been notably proposed for CBET by considering the laser wave as locally plane and homogeneous[5] and are used across a variety of codes. Significant technical difficulties arise, however, in coupling these models with the intensity calculation methods of GO. Usually, such details are handled with the introduction of free numerical parameters in CBET models, thereby allowing one to tune results of calculations to match experimental data. In this summary, we aim to propose a fluid-scale laser model, *IFRIIT*, which consistently follows the GO framework to compute laser fields and eliminates such free parameters. In addition, we present the coupling of *IFRIIT* to the *ASTER*[6] RH code for the specific spherical geometries of LDD. Calculations presented here were conducted in the framework of the OMEGA Laser System configuration and diagnostics.[7]

Our algorithm differs significantly from other methods implemented in RH codes on several key points: First, we make use of inverse ray tracing (IRT) to compute the laser propagation, as opposed to the method of forward ray tracing (FRT), which is usually employed. This is the first time an IRT method has been used for laser calculations coupled to plasma hydrodynamics in

RH fusion codes. Second, we decouple the laser grid from the hydrodynamics grid. This allows us to tailor a grid that is optimized for the resolution of the ray equations, leading to a better load balance for parallel computations. In addition, the laser grid itself is split into two grids: one for calculating ray electric fields and one for calculating ray trajectories. Furthermore, we employ a geodesic laser grid structure, contrary to the standard polar grids employed in 3-D RH codes. It is the first time that such a three-grid scheme has been employed for laser calculations. Third, we make use of the Etalon Integral method to compute laser fields in places where the GO framework breaks down.[8] This is also a new technique for RH codes, which is enabled by the use of IRT and allows us to remove the free parameters used in standard codes to set caustic fields. Fourth, the fields reconstructed from GO using IRT are at a higher order in space than conventional grid binning methods used to compute absorption and fields. While it is possible to achieve a higher order in space for fields using FRT through interpolation or local derivative estimation, the IRT method natively obtains this higher order. This is an important point in 3-D ICF implosions, where noise issues stemming from low convergence in the number of rays per cell for some FRT schemes, or low-order field estimation methods, will often be detrimental. Fifth, the laser code and the RH codes are also decoupled in time, allowing both codes to iterate asynchronously. Indeed, laser computations are often more costly than hydrodynamic ones (when including LPI's) but do not need updating as often. This is also the first time a RH code implements a desynchronized laser scheme. Finally, the use of IRT has additional advantages: e.g., it allows a native separation of the laser field between the various reflected components (so-called "sheets") that, for example, enable one to precisely account for self-interaction of the incident and reflected fields of beams through CBET. It also considerably speeds up pump-depletion iterations in CBET algorithms by allowing us to update only part of the ray equations.

Applications to direct-drive implosions for ICF have been considered for which a geodesic icosahedron grid is implemented in *IFRIIT*. The performances of the *ASTER*/*IFRIIT* coupling have been demonstrated by conducting simulations of cryogenic implosions performed on the OMEGA Laser System, in the presence of various sources of 3-D effects: laser port geometry, cross-beam energy transfer, beam imbalance, and target misalignment [see Fig. 1, (p. 136)]. The code was found to have sufficiently low numerical noise to accurately model the high-convergence ICF implosions without introducing spurious modes. A comparison with neutron data for a cryogenic implosion experiment has also shown excellent agreement for the laser–plasma coupling (notably the measured bang time). More-recent developments (to be published in an upcoming paper) include the modeling of the polarized CBET interaction. In the latter case, simulations with the full post-shot data allow the magnitude of the measured DT flow to be reproduced, as well as approaching the measured direction of the flow.

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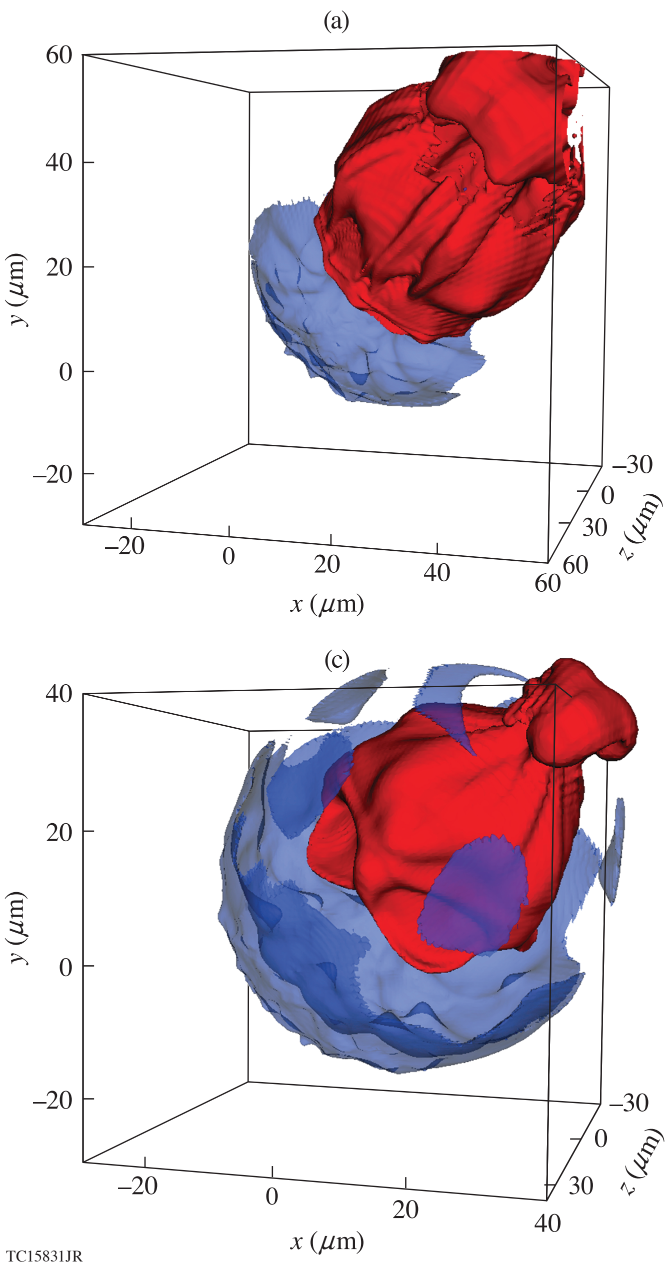

Figure 1
Academic test case of the effect of large offset and beam imbalance on cryogenic targets, illustrating how CBET can mitigate such effects. [(a),(b)] The target at stagnation in the presence of a 40-μm positioning offset in the $\theta = 65$, $\varphi = 45$ direction, and [(c),(d)] a 5% beam imbalance imposing a mode 1 in the same direction as the target offset. Run results without [(a),(c)] and with [(b),(d)] CBET enabled. In all figures, the 100-g/cm^3 density isocontour is shown in blue, the 50/50 DT ice/gas fractional volume isocontour is shown in red, and the axis ticks are in units of microns. The simulation setup is that of shot 94712.