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Three-Dimensional Radiation Transport Hydrodynamics

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ABSTRACT

Radiation transport hydrodynamics codes have many applications in high-temperature physics, including the study of laser matter interactions [LMI] with applications ranging from design of high-gain inertial confinement fusion [ICF] pellets to the design and diagnosis of near-term laboratory experiments at such facilities as the NRL Nike KrF Laser Facility and the NOVA laser at LLNL. Realistic LMI simulations offer one of the best means of learning how to control the ablative Rayleigh-Taylor [RT] instability, which is one of the most dangerous hydrodynamic instabilities of laser fusion.

We here report the development of the *RAD3D-CM*¹ radiation transport hydrodynamics code, and the first results from well-resolved multimode simulations of the evolution of the laser-driven, ablative Rayleigh-Taylor instability on planar, plastic targets. *RAD3D-CM* is a compressible hydrodynamics code which contains the following effects relevant for the simulation of high-temperature plasmas such as ICF-regime RT unstable laser targets: inverse bremsstrahlung laser energy deposition; classical Spitzer thermal conduction; real (table look-up) equation-of-state with either separate or identical electron and ion temperatures; and, multi-group variable Eddington radiation transport. On the CM-5, LMI simulations with *RAD3D-CM* exhibit more than seventy-fold increase in speed over comparable simulations with its serial XMP-running predecessor *RAD3D*. Combined with the large CM-5 memory, this enables us to simulate a wide range of three-dimensional [3d] multimode LMI problems that have hitherto been impossible.

The serial version of *RAD3D* code uses an operator splitting approach to solve the hydrodynamic equations, basically solving each physical process separately and combining the result. The hydrodynamic transport is solved using an operator-split Flux-Corrected-Transport [FCT] algorithm.² FCT is a high order monotone explicit algorithm well-suited for compressible flows. For the LMI simulations of the ablative RT instability, we consider a small region surrounding a small section of the target so that Cartesian geometry is valid. We take the direction of the incident

laser beam as the x -direction. In the directions normal to the laser, (y, z) , we employ periodic boundary conditions. The laser radiation is treated as a source term in the energy equation. We also assume that the scattering of laser energy normal to the laser direction is small so that the amount of energy deposited in the material at a given location is determined only by the amount of laser energy reaching that location from the x -direction. The thermal diffusion step is discretized implicitly in time and with finite volumes in space. This produces a system of non-linear equations in which each equation involves the seven nearest neighbors. These equations are solved iteratively. Linearization of the equations produces a block banded matrix equation. The iteration process treats the diagonal and the non-diagonal elements of this matrix associated with the x -direction discretization implicitly and the other four bands explicitly. As a result the algorithm iteratively updates and inverts a set of tridiagonal matrices. The diffusion equations for the variable Eddington radiation transport are solved by a similar technique. Table look-ups and logarithmic interpolation are implemented to obtain the appropriate thermodynamic variables from the tabulated equation of state. The same look-up routines are employed to obtain the opacities used in the radiation transport routines.

For an explicit algorithm such as FCT, data parallelism is easily accomplished up to boundary conditions. Periodic boundary conditions are ideal for SIMD computing since the equations at each point look the same and the toroidal mesh communications network for the CM-5 makes the exchange of neighbor data uniform across processors. Only the x -direction requires special processing for the boundary conditions. Hence, the transport phase of the calculation will benefit from a data layout that places all of the x -direction within processor and the y, z -directions across processors. This can be accomplished within CM-FORTRAN using the CMF\$LAYOUT directive, specifying that each 3d array be (:SERIAL, :NEWS, :NEWS), where the :SERIAL axis is associated with the x -direction. In order to make efficient use of a 256-node partition, we must also have adequate resolution in the (:NEWS, :NEWS) direction. A typical ablative RT LMI calculation uses a 128x128 grid in the (y, z) directions, thus placing 16 x -direction pencils in each vector unit of a 256-node partition. Each vector unit then operates on vectors which are sixteen times the length of the :SERIAL direction. Finally, a standard split scheme FCT code algorithm² integrates one pencil at a time, and thus uses only one-dimensional arrays for scratch storage. In order to utilize the SIMD nature of the algorithm and because of the large memory on the CM-5, these arrays were promoted to three dimensions.

The laser energy deposition also benefits from this pencil layout of data. Since we assume no transverse scattering, all data dependencies in the algorithm involve multiply-scan operations along the x -direction, while depositing energy as specified by inverse bremsstrahlung at each location. By placing x -direction pencils within processor, each pencil is processed in parallel. The multiply-scan operations terminate at the critical electron number density surface to the laser side of the target, and a reflected multiply-scan operation begins. Within this model the surface of the target is denoted by a x -position function of the transverse coordinates. Location of this position is done with a search down the x -pencils until the appropriate density change is encountered. Again the (:SERIAL, :NEWS, :NEWS) layout allows this search to be conducted in parallel.

The iteration process in the thermal diffusion step also can be solved in parallel. Since the tridiagonal matrices involved in this step only couple data in the serial x -direction, all the data for inverting the tridiagonal lies within processor. Furthermore each tridiagonal is the same length, hence solving this set of tridiagonals can proceed in a SIMD fashion. The only communication needed in this step is for the explicit update of the coefficients and the right-hand-sides of the tridiagonal system.

Table look-up can be a difficulty for distributed memory computers. Our equation of state table consist of a few thousand entries, and the opacity tables consist of a few hundred elements for each radiation group. The memory capacity of each processor on the CM-5 is such that we can store a copy of each table on each processing node (SPARC plus four vector units). The four vector units on each processing node use the same table. The CM-5 software libraries include routines for building and accessing these duplicate tables in a SIMD fashion.

We here consider results from two CM-5 calculations using the parallel version of the code, *RAD3D-CM*. Each calculation took about 60 hours of CM-5 time to run, on meshes that were $220 \times 128 \times 128$ x, y, z grid points. Spitzer-Härm thermal conduction and inverse bremsstrahlung laser deposition of $0.249 \mu\text{m}$ (KrF) laser light are included, although we ran the simulations using the ideal gas equation of state and no radiation transport, so that we could directly compare them with our previous single mode serial code results.³ The initial mass density target perturbations are random, with a power law dependence of k^{-2} , a rms surface finish of $0.1 \mu\text{m}$, and perturbation wavenumbers ranging from $2\pi/d_{\text{max}}$ to $\sqrt{2 \times (12\pi/d_{\text{max}})^2}$, for $d_{\text{max}} = 128 \mu\text{m}$. At early nonlinear times, the perturbations grow to tilt the target with approximately hexagonal bubbles that are of the shortest, initially-seeded wavelengths not stabilized by density gradients. The

tiling occurs on a timescale that is comparable to the eddy turnover time of the dominant bubble diameter d_e . By this early nonlinear time, although the perturbation spectrum has evolved from the initial state to one that strongly resembles a 'turbulence' spectrum, the physical appearance of the target perturbation ρR is well-correlated with the initial ρR . On targets that are thick compared to d_e , the perturbation continues to evolve to conditions in which bubbles of larger and larger diameter dominate. The dominance at late times of initially seeded, nearly hemispherical bubbles can be seen in the figures below. Mode perturbation transfer to longer length scales takes place through shorter-wavelength bubble merger as well as through ongoing longer wavelength single mode growth.

Our *RAD3D-CM* ablative RT simulations contain essential dynamics of a fusion-regime laser-accelerated ablator. In future studies with the inclusion of radiation transport we hope to demonstrate a control of the instability to ensure the survival of ICF targets.

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1. D. E. Fyfe, J. P. Dahlburg, & J. H. Gardner, 23rd Anomalous Absorption Conference, Wintergreen, VA (1993).
2. J. Boris and D. Book, *J. Comp. Phys.*, 11, 38, (1973); J. Boris, *NRL Memorandum Report 3237*, (1976).
3. J. P. Dahlburg, J. H. Gardner, S. W. Haan, & G. D. Doolen, *Phys. Fluids B*, 5, 571 (1993).

Figure. The laser-direction (x) integrated mass density has been plotted as a function of the spatial directions transverse to the incident laser (y, z) initially (left), after 2.5 nsec (center), and after 4.0 nsec (right). Darkest shades of greyscale indicate regions of most mass.

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