DRACO Development for Modeling 3D Instabilities

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Summary

Abstract

Additional features have been included in the *DRACO* Lagrangian hydrodynamics code enabling realistic 3D simulation of laser driven ablation, shocks, and fluid instabilities in low-Z plasmas. Since last reported (Fatenejad and Moses, Bull. APS 51, 209 (2006)), *DRACO* now includes 3D laser ray tracing to model laser absorption and hydrodynamic restoring forces to counteract artificial grid distortions. Two temperature (electron and ion) flux-limited thermal transport has been included. *DRACO* is now being used to model the acceleration of a slab of Cu-doped Be into liquid deuterium via laser ablation. The slab has single mode perturbations imposed on it both at the ablation from and at the D-Be interface. Preliminary simulations of fluid instability growth will be presented using the improved *DRACO* 3D modeling. These simulations are motivated by similar recent experiments performed at the OMEGA laser facility.

Summary of Results

Fluid Instability Simulations

- The evolution of a Richtmyer-Meshkov instability is shown in 3D
- Multiple re-shock Richtmyer-Meshkov instability growth is shown
- 3D and 2D versions of the code and show good agreement at early times when the growth is linear

Code Development

- Features have been added to the thermal diffusion, Lagrangian hydrodynamics, and rezoning in 3D
- Refractive laser ray-tracing has been added to 3D
- Results of simulations validate 3D *DRACO* against 2D

Future Work

Simulation of Experiments

- Simulate the acceleration of a Cu doped Be slab via laser ablation
- Simulate the deceleration of Be slab by impact with a fixed slab of liquid D_2
- These simulations are designed to study instability growth for NIF target implosions

Code Development

- Add 3D radiation transport using multi-group flux-limited diffusion
- Parallelize the 3D code to decrease simulation run time

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3D Richtmyer Meshkov Simulations

Decelerating ICF targets are subject to the Richtmyer-Meshkov instability

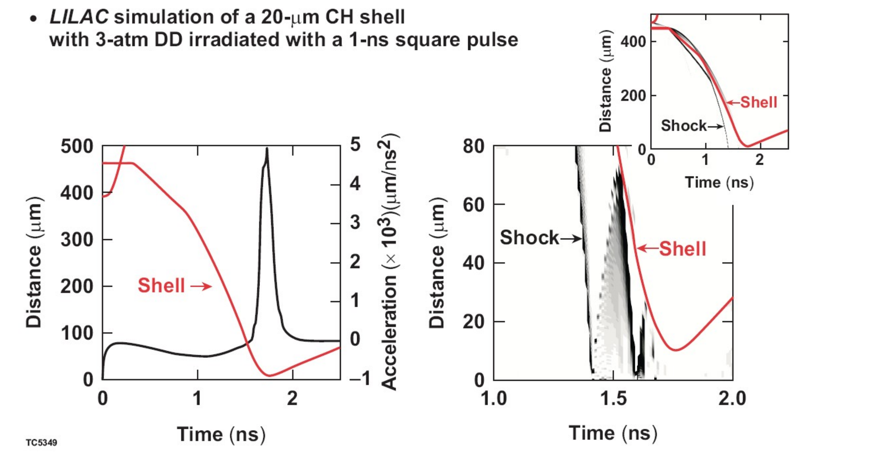
- Direct-drive ICF target implosions are driven by two main shocks, timed to meet interior to the shell
- The deceleration phase of the implosion is initiated when the combined shock passes through the origin and impacts the inward moving shell[1]
- The shock continues to reflect between the origin and the shell,impulsively decelerating the target
- The increasing pressure of the material interior to the shell causes continuous deceleration of the target

Each shock/shell interaction causes growth of modulations on the inner edge of the shell via the Richtmyer-Meshkov instability

[1]R. Betti *et al., Phys. Plasmas* 8, 5257 (2001)

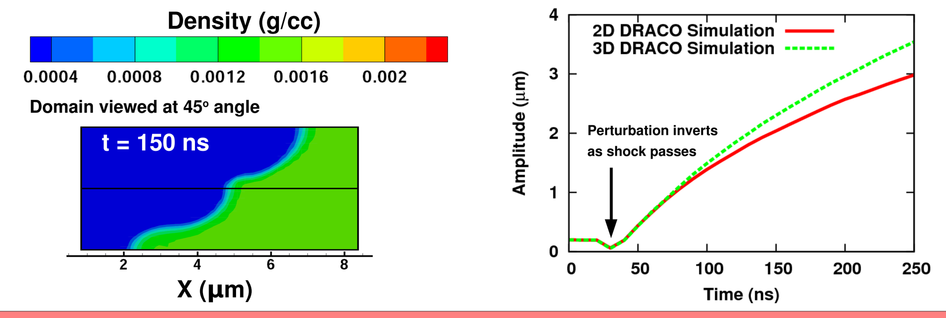
An ICF target is decelerated impulsively by multiple shock reflections

- *LILAC* simulation of a 20-μm CH shell with 3-atm DD irradiated with a 1-ns square pulse



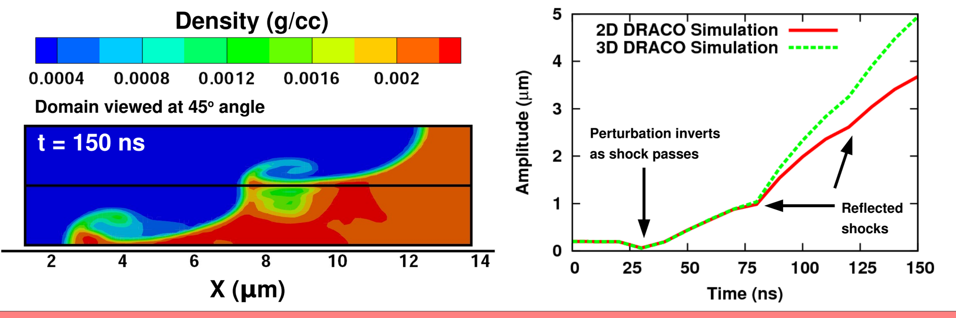
A 3D Richtmyer-Meshkov (RM) simulation demonstrates agreement with 2D early in time

- 2D *DRACO* has been benchmarked against other codes
- Shock (M = 1.3) passes from right to left through a perturbed interface with:
  $\gamma = 5/3$, $A_t = 0.753$, $\lambda = 5$ μm, $a_0 = 0.2$ μm
- 2D and 3D results diverge late in time due to greater surface area in 3D



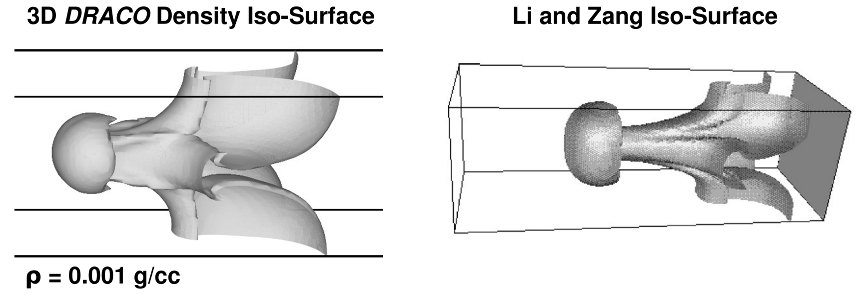
A shock-tube simulation is used to study the effect of multiple shocks on RM instability growth

- Shock reflects off fixed boundary at x = 0
- All other parameters identical to no re-shock simulation
- Multiple shocks cause the perturbation amplitude to increase



3D *DRACO* shows agreement with the morphology of Li and Zang[2]

- Different initial conditions were used preventing exact agreement; future simulations will have exact agreement
- Agreement was obtained at early times with analytic RM growth rate



[2]X. L. LI, Q. Zang, *Phys. Fluids, 9*, 3069 (1997)

Conclusions

Simulations show 3D *DRACO* can be used to model Richtmyer-Meshkov Instabilities

- RM instabilities are relevant in ICF target implosions
- At early times, the 3D and 2D amplitudes agree
- 3D results diverge at late times due to greater surface area
- Re-shock case confirms that successive shocks increase the growth rate
- Agreement is obtained with analytic growth rate at early times
- Qualitative agreement is obtained with Li and Zang

3D Code Development

Additional features have been added to the 3D thermal diffusion

- Two temperature, flux-limited thermal transport is an important effect in laser-driven ICF
- 3D *DRACO* can now fully implicitly solve the two temperature thermal diffusion equations shown below

$$\rho C_{v,\mathrm{ion}}\frac{\partial T_{\mathrm{ion}}}{\partial t} = \nabla\cdot K_{\mathrm{ion}}\nabla T_{\mathrm{ion}}+\rho\frac{C_{v,\mathrm{ele}}}{\tau_{ei}}(T_{\mathrm{ele}}-T_{\mathrm{ion}}) \ , \quad \rho C_{v,\mathrm{ele}}\frac{\partial T_{\mathrm{ele}}}{\partial t} = \nabla\cdot K_{\mathrm{ele}}\nabla T_{\mathrm{ele}}+\rho\frac{C_{v,\mathrm{ele}}}{\tau_{ei}}(T_{\mathrm{ion}}-T_{\mathrm{ele}})$$

- Two types of flux-limiters (min/max and harmonic) have been added and are shown below. The gradient is computed in a manner consistent with the differencing of the diffusion operator[3]

$$K_{harmonic}=\frac{1}{\frac{1}{K}+\frac{\nabla T}{fl}} \ , \quad K_{min/max}=\min\left(K,\frac{fl}{\nabla T}\right) \ , \quad fl_{\mathrm{ion}}=\left(\frac{K_B T_{\mathrm{ion}}}{m_{\mathrm{ion}}}\right)^{3/2}\rho \ , \quad fl_{\mathrm{ele}}=\frac{(K_B T_{\mathrm{ele}})^{3/2}\bar{z}\,\rho}{\sqrt{m_{ele}}\,m_{ion}}$$

[3] L. Stein *et al., Comput. Methods Appl. Mech. Eng.* 11, 57 (1977)

Additional restoring forces and rezoning options have been added to the 3D Hydrodynamics

Artificial Grid Distortions

- Artificial grid distortions such as 2dx instabilities that occur when zones have high aspect ratios can prematurely terminate Lagrangian fluid dynamics calculations
- An additional artificial restoring forced based on tetrahedralizing the 3D Lagrangian cell has been added to alleviate this problem[4]
- Additional rezoning options have been added to

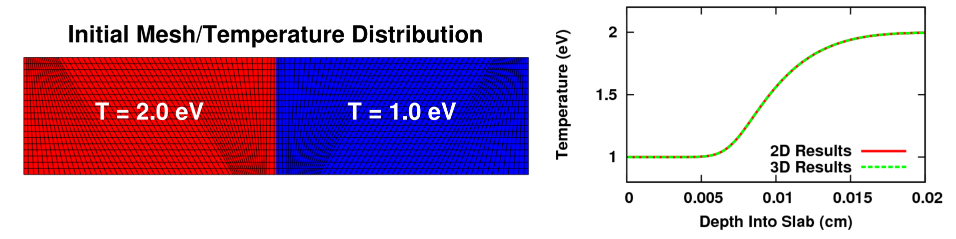
Rezoning

- Additional rezoning options have been added to 3D DRACO to allow direct comparison of and validation against results in 2D.

[4] M. Wilkins, *J. Comp. Phys.* 36, 281 (1980)

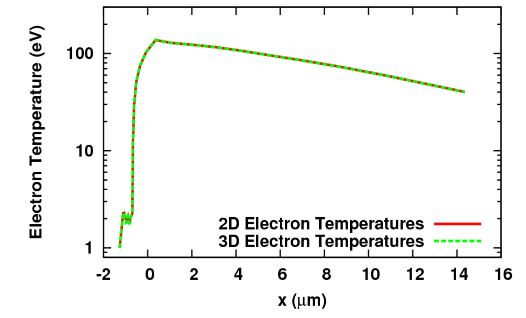
The 3D thermal diffusion routines have been tested against 2D on non-orthogonal grids

- A step discontinuity in temperature was allowed to diffuse
- 1-Temperature, flux-limiter thermal transport was used



Preliminary simulations involving laser ray-tracing, hydrodynamics and thermal transport agree with 2D

- The simulation was run using two temperatures
- A planar target was accelerated using a laser energy dump at critical density



Refractive laser ray trace is being implemented in *DRACO* for 3D planar geometry

- A 3D refractive ray trace is necessary for realistic simulation of experiments in planar geometry
- The ray trace is based on Kaiser's method[5]:
  - Fit a linear profile to the electron number density n_e within each cell (not continuous at faces)
  - Take a single step across the cell using $dt = ds / (cn_e)$:

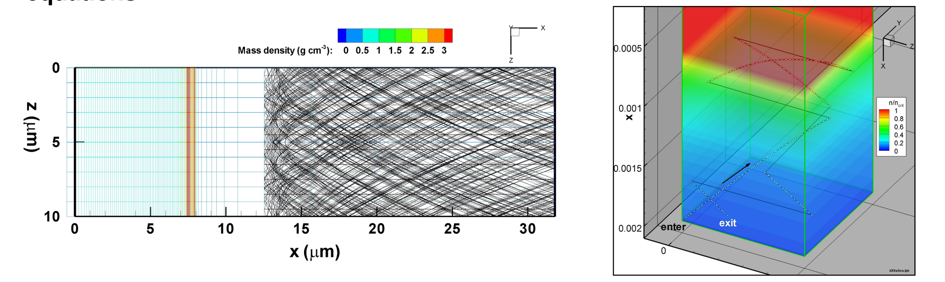
$$\vec{v}(\Delta t) = \vec{v}_0-\frac{c^2}{2n_c}\left(\vec{\nabla} n_e\right)\Delta t \ , \quad \vec{x}(\Delta t) = \vec{x}_0+\vec{v}_0\Delta t-\frac{c^2}{4n_c}\left(\vec{\nabla} n_e\right)(\Delta t)^2$$

  where c is the speed of light, s the arc length, v_o the group velocity, x_o the ray path and n_c the critical density
  - Snell's law refraction is used at the boundaries

[5]T. B. Kaiser, *Phys. Rev. E,* 61, 895 (2000)

Ray launching algorithm and boundary conditions are chosen to model laser-driven planar targets

- The ray trace has been calibrated vs. analytic solutions to the geometrical-optics equations



- “Wrapping” boundary conditions are used since the simulation size is much smaller than the laser spot size