Imaging x-ray fluorescence relevant to hydrodynamic mixing experiments at the National Ignition Facility

M.J. MacDonald[1], E.J. Gamboa[1], C.C. Kuranz[1], P.A. Keiter[1], R.P. Drake[1]

1. University of Michigan, 2455 Hayward St. Ann Arbor, MI, 48109

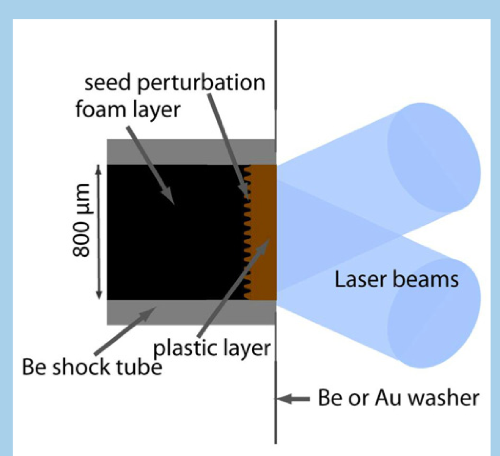
Project goals

- Create 2D images of material density using fluorescent imaging to resolve the structure at shocked interfaces
- Provide experimental results to test the validity of hydrodynamic codes for divergent geometries
- Measure flow velocity using particle image velocimetry (PIV) by taking several images of a single shock and tracking dopant particles over time
- Calculate dopant temperature and ionization using a 1D crystal spectrometer by measuring level shifts in the fluorescent radiation
- Develop a robust x-ray fluorescence imaging diagnostic for use in future experiments

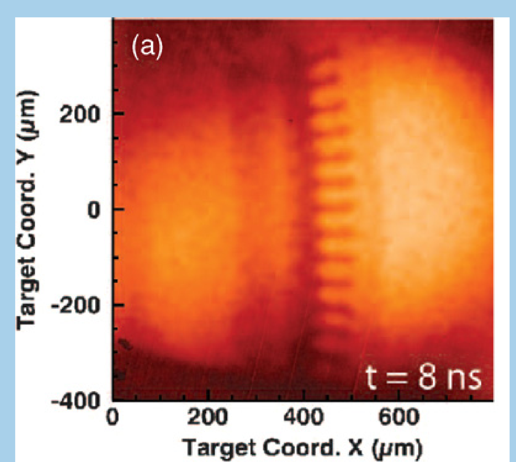
Previous work and hydrodynamic simulations

We are members of a team that has been awarded time at the National Ignition Facility (NIF) to perform a divergent, multi-interface Rayleigh-Taylor experiment. This work is relevant to core-collapse supernova, where a blast wave drives dense material into less dense outer layers.

Previous experiments, performed at the Omega Laser Facility, utilized a single, planar interface.



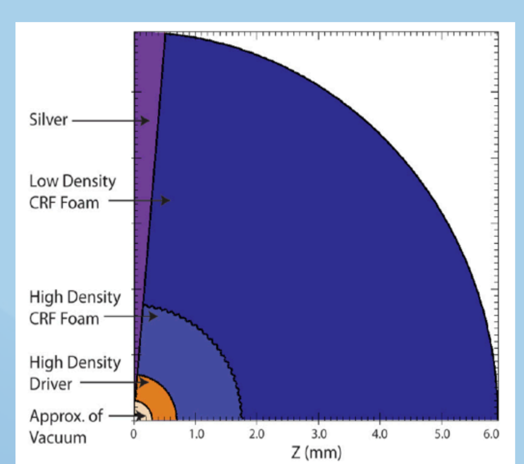
Planar interface setup



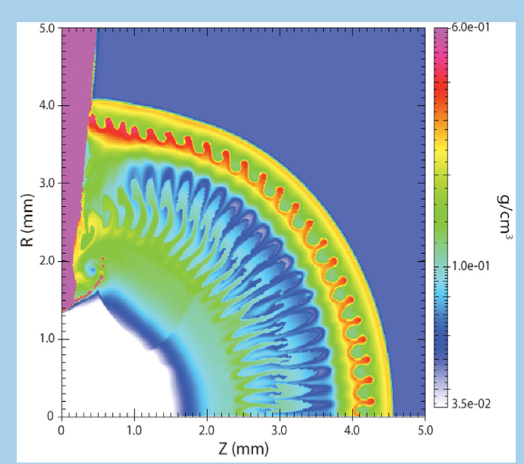
Transmission radiography data with planar interface

Kuranz CC et al. Astrophysical Journal, 696 (2009)

Grosskopf et al. performed numerical simulations with the CALE code to predict the hydrodynamic behavior of this system (see images below). We propose a technique to observe these instabilities experimentally using fluorescent imaging.



Target design



Simulation of shocked target

Grosskopf MJ et al. Astrophys Space Sci, 322 (2009)

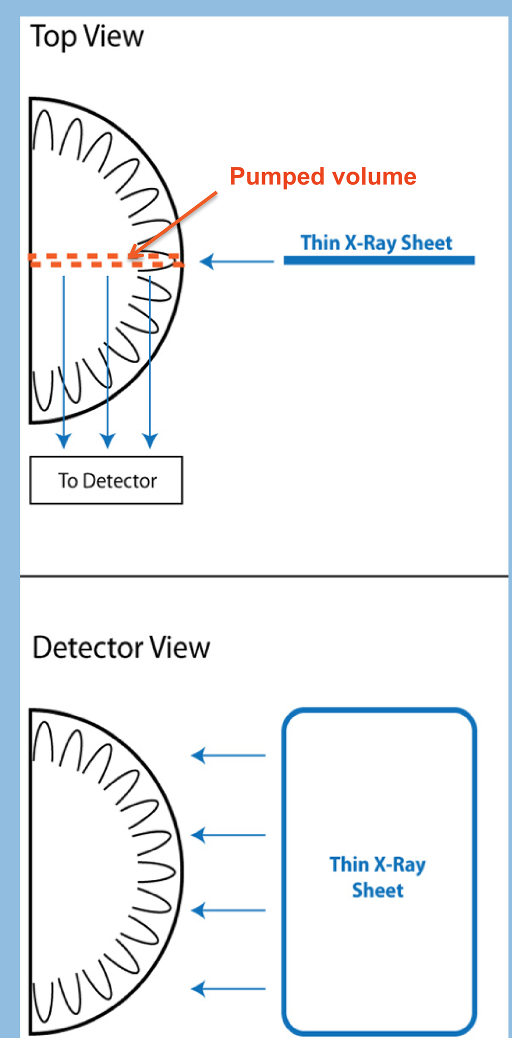
Fluorescene imaging allows a thin sheet within the hemispherical target to be imaged without the problems associated with line integrated techniques such as transmission radiography.

Abstract

The National Ignition Facility (NIF) is capable of providing enough energy to explore areas of physics that are not possible on any previous laser system. This includes large-volume, geometrically complex hydrodynamic and radiation hydrodynamic experiments in which traditional, line-integrated radiographic techniques limit the quality of the results. As an example, we are involved in divergent hydrodynamic experiments at the NIF, motivated by supernova hydrodynamics, that cannot be diagnosed in detail with transmission radiography. X-ray scattering has been considered for this purpose and appears feasible [1]. Here we consider fluorescence imaging, a better candidate as the cross section of photoabsorption in the several-keV range is roughly 100 times larger than that of scattering. A single layer of the target will be uniformly doped with a fluorescent tracer, which will be pumped by a sheet of x-rays. The fluorescent intensity will be measured to create a density map of the doped material as it mixes with other layers. Developing this diagnostic will create a powerful tool to characterize hydrodynamic experiments with complex geometries.

[1] Huntington CM et al. High Energy Density Physics 6, 194 (2010)

Design of the fluorescent imaging system



Pump x-rays entering target from two orthogonal views

Grosskopf MJ et al. Astrophys Space Sci, 322 (2009)

Controlling the fluorescent volume and timing

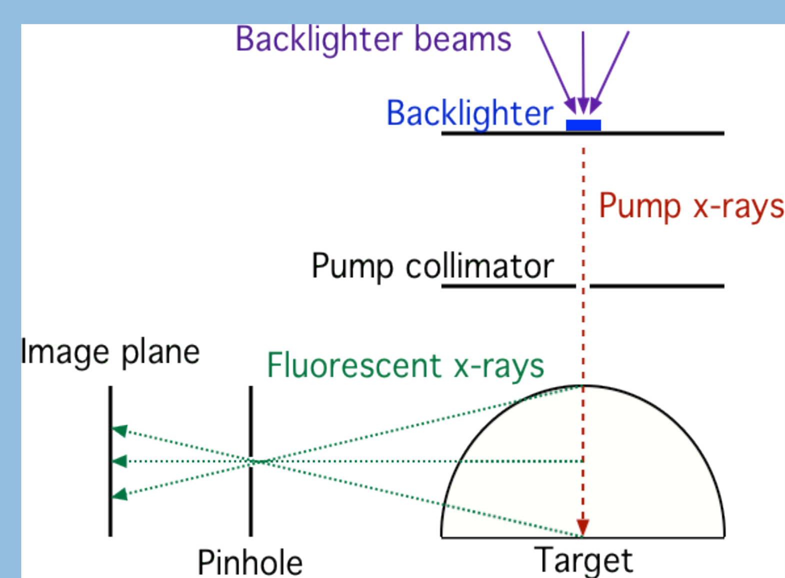
- A thin sheet of x-rays pumps a slice of material in the target
- The x-ray producing beams dictate the timing of the fluorescent pump, controlling the delay and exposure time for the imaging system
- Fluorescent intensity and signal levels are strongly affected by dopant density and x-ray energies

Fluorescent measurements

- A pinhole camera is used to image x-ray fluorescence intensity to create a 2D image of the material density, providing images of hydrodynamic instabilities
- Images can be taken at different times to study hydrodynamic behavior and obtain flow velocity measurements via particle image velocimetry (PIV)
- An imaging crystal spectrometer is used to measure level shifts in the K-α radiation, which will be used to calculate dopant temperature and ionization states

Experimental setup for 2D fluorescent imaging

1. Pump x-rays are generated by irradiating a high Z foil
2. Pump x-rays are collimated into a thin sheet using a thin slit
3. Pump x-rays induce K-α fluorescence from by knocking out inner (K) shell electrons from the dopant atoms
4. Fluorescent x-rays are detected using a pinhole camera or imaging crystal spectrometer

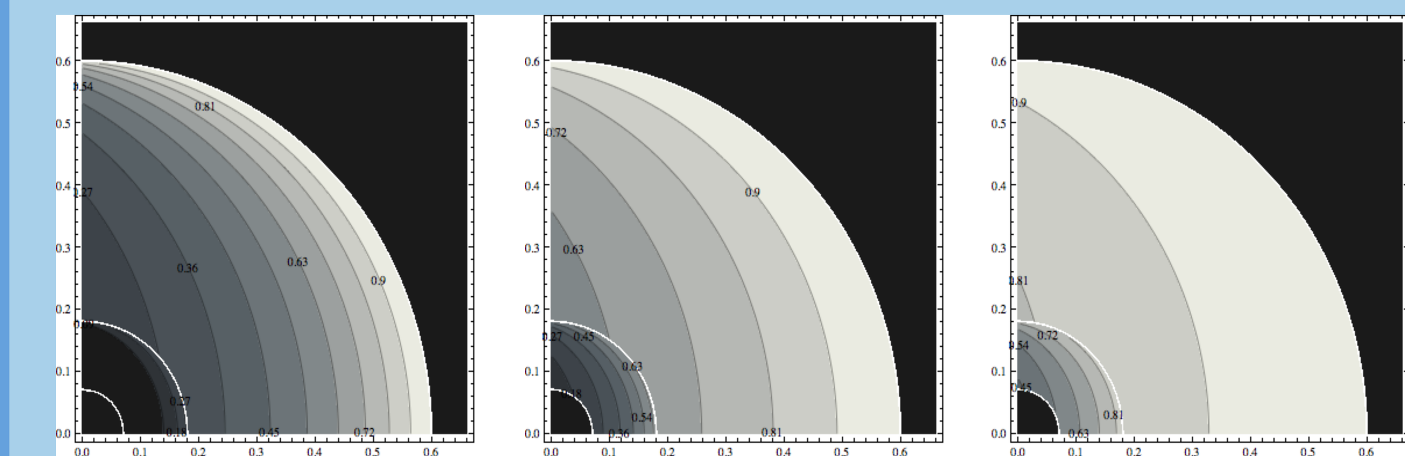


Experimental setup (top view). Pump x-rays are collimated into a sheet perpendicular to the page.

Initial results using solid density materials

Pump x-ray source and dopant comparison

Pump and fluorescent x-ray transmission through each point of the target

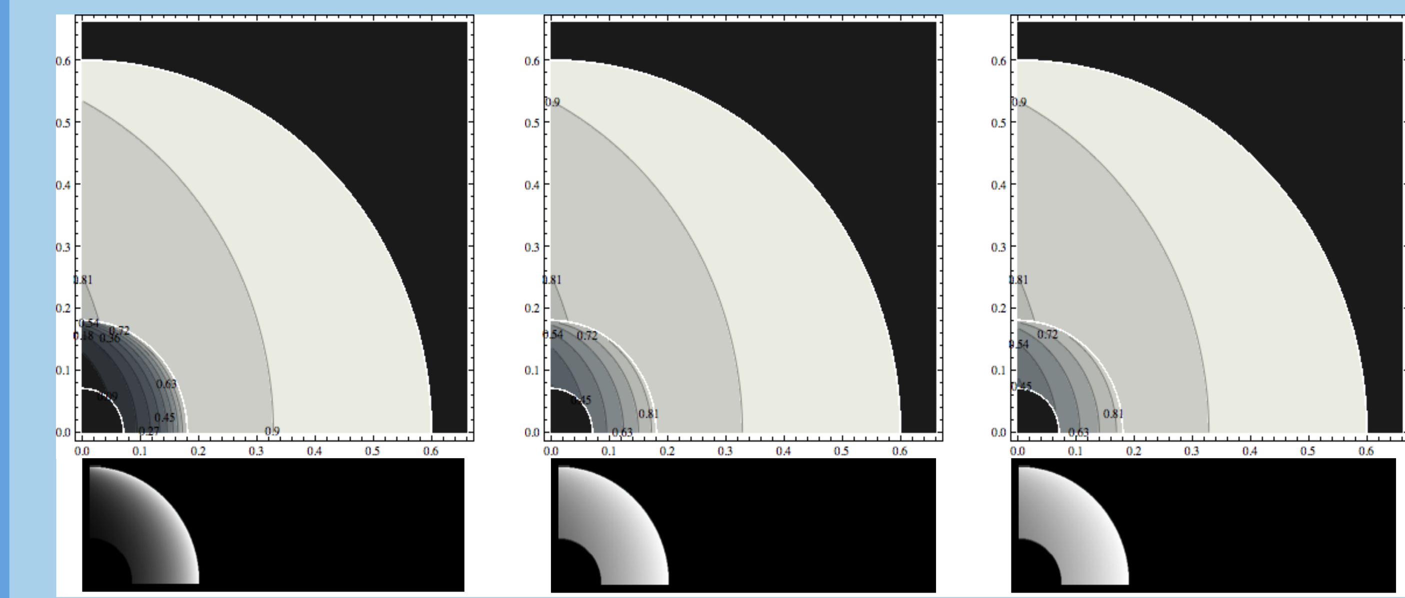


Pump: Ti (4.75 keV)	**Pump:** Fe (6.75 keV)	**Pump:** Zn (8.99 keV)
Dopant: Sc (4.10 keV)	**Dopant:** Mn (5.90 keV)	**Dopant:** Cu (8.05 keV)

Observation: Higher energy x-rays are attenuated less by target material. Note that moving to higher energy pump x-rays results in a lower number of pump x-rays due to the higher energy cost per photon.

Dopant density

Top: X-ray transmission through each point of the target
Bottom: Fluorescent signal from the doped layer



50 mg/cm³ Cu | 5.0 mg/cm³ Cu | 0.5 mg/cm³ Cu

Observation: Lower dopant concentrations provide a more even signal along the path of the pump x-rays at a price of lower signal levels to the detector. This balance will be optimized using the spatial resolution and response characteristics of the detector.

Future work

- Determine detector specifications to calculate the optimal materials and densities to produce high quality images
- Include shocked material in the simulations to account for the effects of ionized foam and density gradients within each layer
- Add unstable interfaces to create a more realistic model to optimize the diagnostic for measuring hydrodynamic instabilities

Funding acknowledgements

This work is funded by the Lawrence Livermore National Laboratory and by the Defense Threat Reduction Agency, Basic Research Award #HDTRA1-10-1-0077 and the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-FG52-09NA29548.

National Nuclear Security Administration