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Using xRage to Model Heat Flow for Experiments to Measure Opacities in HED Plasmas

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Outline

- Introduction & Motivation
- Pleiades Platform at NIF
- xRage Simulation Overview
- Simulation Data
- Comparison with Previous Simulation Results
- Analysis
- Conclusions & Future Work
- Acknowledgements & References

Solar Abundance Problem

- Recent solar models find significantly lower abundances of C, N, and O than previous models.
- The difference in the sound speed between the models and the sun more than tripled beneath the convection zone.
- Solar models using the updated abundances do not agree with measured data from neutrinos and helioseismology.
- Small differences in sound speed correspond to large revisions to elemental abundances, opacities, or other properties of matter in the solar interior.

Impact of Opacities on Solar Abundances

- Possible explanations for solar abundance discrepancy include:
 - A
 - B
 - C
- Ad-hoc revisions to opacities of [list elements & % increase] yield solar abundances in agreement with [helioseismic and &&] measurements; however, there is no physical justification.

The histogram is the fractional contribution to the Rosseland mean evaluated near the base of the solar convection zone using the OPAS opacity model. (Bailey 2009)

Opacity Models Do Not Agree

NIF Can Achieve Conditions Relevant to BCZ

Temperature and density from $r = 0.6 R$ (on the right end) to $0.7 R$ (on the left end), which corresponds to just below the base of the CZ, which is at $0.71 R$ in the GN93-based model and $0.73 R$ in the AGS05-based model.

Fig. from Chris Orban

Proposed Experiment & Aims

- Measure opacities of C, O, N at temperatures & densities corresponding to base of solar convection zone.
- Compare data with existing opacity models; validate models or inform development of new models
- Will use _____ spectrometer to measure “flat” parts of opacity spectra (not resolve peaks)
- Use measured opacities in solar evolution models and see if this yields abundances consistent with helioseismology data

From OP model
Reference?
Temperature for plot
above??

Pleiades Platform

Moore et al 2013.

- Laser-driven half-hohlraum emits X-rays that drive supersonic radiation wave in foam targets.
- Previous experiments at NIF [ref] have demonstrated a high-temperature ($>340\text{ eV}$) X-ray radiation source with a quasi-Planckian distribution.
- Radiative transfer in foam target approximated by analytic solution for Marshak wave (constant temperature source driving a diffusive radiation wave).

Pleiades Platform & Opacity Measurements

- Density of cold foam measured beforehand.
- X-ray source from hohlraum creates highly supersonic radiation wave that heats foam target.
- Density of heated foam remains constant and equal to density of cold foam over a time scale of a couple ns, before hydrodynamic effects create temperature and density gradients.
- During this brief time window, opacities of both the hot and cold material are measured.

Target Used in Simulation

- 200 mg/cc Carbon foam.
- SiO_2 disk absorbs M-band radiation emitted from hohlraum.
- Gold tube with 25 μm wall thickness serves as a tamper.
- No diagnostic slots in tube (cylindrically-symmetric geometry enables 2D simulation).

Hohlraum Emission & X-Ray Source

Fig. 3. Measurement of the hohlraum temperature through the LEH shown for two separate shots at 37 deg (dark-gray line and open circles) and 64 deg (light-gray line). Line widths are representative of the error bar in the measurement. NYM simulations of the emission are shown as solid black lines. The percentage difference between two shots is shown on the right axis (dotted gray line).
Moore 2013.

Katie Mussack

xRage Simulation: Physical Model & Inputs

- “Cut-off” problem:
 - Hohlraum not included
 - 350 eV Planckian temperature source applied at target boundary
- Multi-group diffusion model, 2T NLTE
- Opacities & EOS from LANL [unclassified] Sesame tables

xRage Simulation: Data Output

- 2D data measured every 1 ps:
 - Density (ρ)
 - Material Temperature (tev)
 - Radiation Temperature (rev)
 - Pressure (prs)
 - Sound Speed (snd)

Radiation Front Location

120 mg/cc SiO_2 disk + 200 mg/cc $\text{C}_{1000}\text{O}_{48}\text{H}_{65}$ foam
350 eV Planckian Temperature Source

Radiation Front Mach Number

Material Temperature at BCZ

Comparison with Previous Results

- 200 mg/cc Carbon target
- Implicit Monte Carlo (IMC) Simulation
- 320 eV Frequency-Dependent Source

- 200 mg/cc Carbon target with SiO₂ disk
- Multi-Group Diffusion Simulation
- 350 eV Planckian Temperature Source

Frequency-Dependent Source vs. Planckian

FDS

Planckian

*Figures from
Katie Mussack*

Implicit Monte Carlo vs. Multi-Group Diffusion

For $t < 2.5$ ns, not much difference between IMC & MGD.

Diffusion Approximation

- Analytic solution (1D, Cartesian) for supersonic diffusive radiation wave with constant temperature drive:

$$\kappa = \kappa_0 \left(\frac{T}{T_0} \right)^{-n}$$
$$\varepsilon = \varepsilon_0 \left(\frac{T}{T_0} \right)^m$$

Diffusive Limit (optically thick):

$$y_{RF} = \sqrt{\frac{32}{3(n + 4 - \frac{3}{2}m)} \frac{t\sigma T^4}{\kappa\rho^2\varepsilon}}$$

Free-Streaming Limit (optically thin):

$$y_{RF} = \frac{t\sigma T^4}{\rho\varepsilon}$$

Temperature Source Function & Opacity

Diffusive Limit (optically thick):

$$y_{RF} = \sqrt{\frac{32}{3(n + 4 - \frac{3}{2}m)} \frac{t\sigma T^4}{\kappa\rho^2\varepsilon}}$$

Free-Streaming Limit (optically thin):

$$y_{RF} = \frac{t\sigma T^4}{\rho\varepsilon}$$

Rosseland Mean Opacity:

$$\kappa_R(T) = \frac{\int_0^\infty \kappa_\nu \frac{dI}{dT} dE_\nu}{\int_0^\infty \frac{dI}{dT} dE_\nu}$$

Planckian Temperature Source:

$$I(E_\nu, T) = \frac{2e^4 E_\nu^3}{h^3 c^2} \frac{1}{\exp\left(\frac{E_\nu}{T}\right) - 1}$$

Limits of MGD Model & Temperature Source

- $y_{RF} \sim t$
- Free-streaming radiation
- Target material optically thin

- Neither optically thin nor thick
- $T(t)$ rapidly decreasing
- Diffusive model less accurate
- Differences in temperature source models amplified

Issues with Carbon Target

- Temperature source & target composition in this simulation did not achieve desired conditions at base of solar convection zone.
- Absorption spectrum of Carbon:
 - NIF does not currently have spectrometer for <600 eV
 - If hot target is transparent to X-ray spectrum from Hohlraum, it will likely be transparent to back-lighter source used for absorption spectroscopy (target may be too thin and too transparent to measure opacity)
- Gold tube ablation

Oxygen-Doped Targets

- New simulation for oxygen-doped target.
- More detailed analysis of radiation drive temperature, material temperature and density, and opacity.

Gold Tube Ablation

Temperature and Density Profiles

- Run 3D simulation with diagnostic slots in target

Conclusions & Future Work

- How accurate are source models?
- Oxygen-doped target
- More detailed analysis of oxygen opacity over temperature range achievable
- Available diagnostics: back-lighter source, spectrometer
- Modify target and/or source incident on target to achieve conditions at BCZ?
- 3D simulation with diagnostic slots in target

Summary

- This type of simulation useful for...
- But with limitations/caveats ...

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Extra Slides

Gold Tube Ablation: 2.8 ns

Rad. Temperature Images

2.4 ns

2.8 ns

Snd & Prs @ 2.4 ns

Rev images for movie

Use 'rev' images for $t=[0 : 0.1 : 6.5]$ ns to make movie

Introduction

We are developing a proposal for experiments at the National Ignition Facility (NIF) to measure opacities of elements with atomic number Z in the range of 6-10 at temperatures and densities relevant to the base of the solar convection zone (~ 350 eV, 0.2 g/cm³). Currently, there exist little data of measured opacities of materials within this high-energy-density (HED) regime. In astrophysics and ICF, scientists must rely on opacity models to predict radiation transport behavior in HED plasmas. However, for $Z > 2$ elements, opacity models do not agree. Experimentally measured opacity data are necessary to validate opacity models or provide physical insights to inform the development of new opacity models.

Fig. 1. Comparison of three widely used opacity models of carbon. Figure reproduced from [1].

Experimental Platform

Previous experiments at NIF² have demonstrated a high-temperature (>340 eV) X-ray radiation source with a Planckian distribution. Such a source is capable of generating a supersonic radiation front within foam targets, a necessary condition for our opacity measurements. With a sufficiently supersonic radiation front, the density of the heated foam (behind the front) remains constant and equal to the density of the cold foam (ahead of the front) over a time scale of a couple nanoseconds. Afterwards, hydrodynamic effects create temperature and density gradients within the heated material, which would obfuscate analysis of opacity data. Therefore, there exists a brief time window during which the opacities of both the hot and cold material may be measured at constant and well-known densities.

Fig. 2. Experimental platform for proposed opacity measurements. The X-ray radiation source is emitted from a laser-driven half-hohlraum. Targets consist of foams doped with the elements of interest (C, N, O). Opacities of these elements are found by measuring transmission spectra from X-ray backlighters through hot and cold regions of the foam targets.

xRage Simulation Results

We are using xRage to simulate heat flow within our targets in order to estimate the time scale over which significant temperature and density gradients evolve. These simulations will better inform our target design and requirements for the spectral, spatial, and temporal resolution of the diagnostics to be used in the proposed experiments.

Fig. 3. a) Target used in simulation. A thin SiO₂ disk absorbs M-band radiation emitted from the hohlraum. A gold tube with 25 μ m wall thickness surrounds the foam and serves as a tamper. b) Material temperature in target 2.4 ns after radiation source is applied.

Simulation data collected includes material temperature (tev), radiation temperature (rev), density (rho), pressure (prs), and sound speed (snd). From this data, the radiation front location was defined as the point where the radiation temperature decreased by 50% along the center axis of the target. The radiation front velocity and Mach number were then calculated.

Fig. 4. a) Radiation temperature along center of target. Circles indicate location of radiation front used to calculate Mach number, shown in b).

The heated foam reaches a maximum temperature 2.4 ns after the radiation source is applied. (This is consistent with the 2.5 ns laser pulse duration at NIF.) At 2.4 ns, the density of the heated foam is constant over a region 1.5 mm long (Figure 5a). The length of the target may be increased so that there is a similarly long region of constant-density cold foam. Looking at the cross section, density and temperature are uniform over a radial distance of 700 μ m at a distance 1.0 mm from the hot end of the target (Figure 5b).

Fig. 5. a) On-axis profiles of density and material temperature at 2.4 ns. b) Radial profiles of density and material temperature for times 1.6-2.6 ns at a distance 1.0 mm from the hot end of the target.

Conclusion & Future Work

Our simulations predict that the NIF laser source can drive a radiation front with Mach >8 over distances up to 2.5 mm within our foam targets. These conditions should enable the first opacity measurements of C, N and O at temperatures and densities comparable to the base of the solar convection zone and yield valuable data for the refinement of opacity models used in astrophysics and ICF research. Next, we will consider the specifications of X-ray spectrometers and detectors available for the NIF experiments and design an imaging system for the target chamber. We must ensure that the sensitivity, spatial resolution and range of the diagnostics are sufficient for these opacity measurements.

References

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