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Title: An experiment to measure the EOS of WDM Aluminum.

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Measurement of the EOS of WDM aluminum.

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Abstract: The warm dense matter (WDM) regime is one of the most uncertain in terms of our knowledge of the equation of state (EOS) of materials. This is not only because it is difficult to calculate the properties of WDM, but also because we have so little data from that parameter regime. To address this need, we are developing an experimental platform to measure the EOS of WDM. This platform relies on using the shock and release technique with the addition of non-traditional diagnostic capabilities. Our experiment platform utilizes the Omega laser to drive a very strong shock into an aluminum sample. The shock is then released into 0.2 g/cm^3 aerogel foam which is used as a pressure standard. A shock breakout measurement is used to determine the shock velocity and pressure in the foam and released sample. We have also developed an imaging x-ray Thomson spectrometer to measure Compton scattered x-rays from the released aluminum sample. This information can be used to determine the temperature and density of the released aluminum, providing the necessary measurements to determine the EOS. Simulations predict the conditions of the released aluminum will be ~ solid density at 10-15 eV. We will present our experimental results of pressure measurements along with preliminary data from the imaging x-ray Thomson spectrometer.

An experiment to measure the EOS of WDM Aluminum

Presented by John F. Benage

Collaborators are

Robert G. Watt & Dave Montgomery, LANL

and Eliseo Gamboa, Univ. of Michigan

Summary

- Brief discussion of WDM and EOS issues
- Description of our experimental design
- Presentation of experimental results
- Issues yet to be resolved for EOS determination
- Future plans

What is warm dense matter and where does it occur?

Warm dense matter is material too hot to be considered a solid, but too cool to be considered plasma.

- usually considered hot enough that electrons are only partially degenerate (i.e. zero temperature theories not applicable).

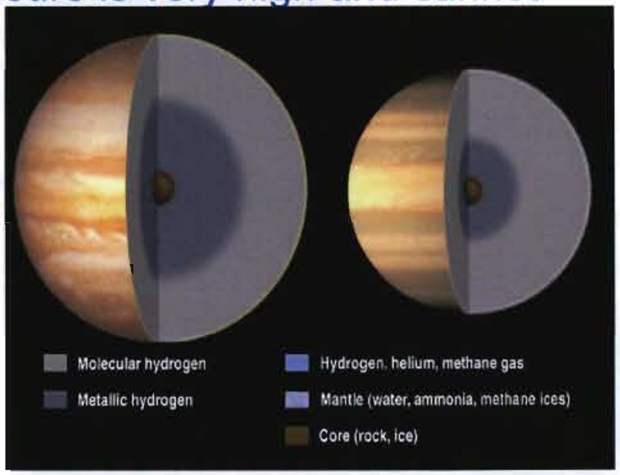
From an experimental point of view, there is a another distinction: WDM must be studied dynamically!

- the system is hot enough and dense enough that the pressure is very high and cannot be statically contained

Results in conditions that fall between plasmas and solids

- key solid state diagnostic tools must now by fast
- plasma diagnostics must penetrate at solid density

In nature, many astrophysical objects such as giant planets or brown dwarfs are made up of material in the WDM state



In laboratory systems, we find WDM whenever near solid density conditions at temperatures from a few to tens of eV are produced, such as in ICF fuel regions before ignition

Warm Dense Matter EOS Experiment: Requirements and Approaches

- **All EOS experiments require measuring three independent thermodynamic variables to determine the state of the material**
  - Typically, this means measuring density, pressure, and temperature or internal energy
  - Principle Hugoniot techniques only require two measurements because conservation equations can be used to determine the other variable under steady shock conditions
  - This is the technique used to provide a large fraction of the EOS data we have for dense material
  - Unfortunately, principle Hugoniot experiments do not typically produce conditions in the WDM regime
- **We evaluated five types of experimental techniques for their application to WDM EOS**
  - Shock driven experiments with initial conditions far from STP
    - Could measure 3 variables, but accuracy is not very good and sensitive to initial conditions
  - Isochoric heating using x-rays or beams
    - Very difficult to measure 3 variables of the same state, since a release always occurs
  - Double or multiple shocks/isentropic compression
    - This technique doesn't produce WDM conditions without preheating and it is difficult to measure 3 variables
  - Slow heating and isobaric expansion (pulsed power)
    - Can measure 3 variables, but accuracy is poor and densities are typically low
  - Shock and release, using standard drivers and lasers
    - Can measure 3 variables, requires better diagnostics of released material
- **One technique, the laser driven shock and release, meets our requirements and is being pursued**

There are several reasons we have focused on the laser driven shock and release technique.

- It can readily produce WDM conditions.
  - Conditions reached are lower density and higher temperature than on the principle Hugoniot
  - Reaching ~ solid density and 10's of eV requires very strong initial shock and deep release, which the laser drive can provide.
- This approach has a well-established technique for the pressure measurement
  - Uses a low density standard (0.2 g/cc aerogel foam)
  - Measurements by Knudson, Asay, and Deeney at SNL, J. Appl. Physics, 97, 073514 (2005).

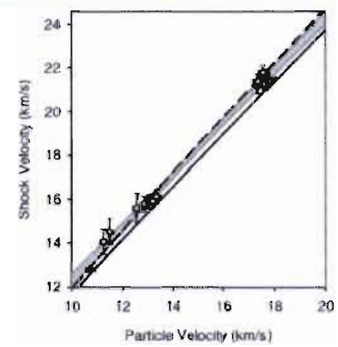
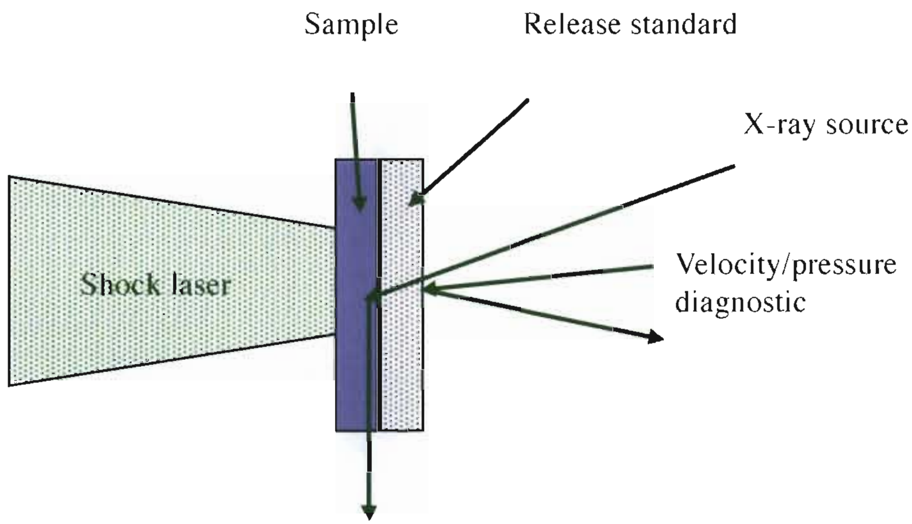


FIG. 5. Detailed view of 200-mg/cc silica aerogel U_s-u_p Hugoniot in the 25–100-GPa range. Lines and symbols as in Fig. 4. Gray band indicates the linear fit to the present data, with uncertainty, which was used in the aluminum release analysis.

- With the addition of imaging X-ray Thomson scattering, one can obtain density and temperature measurements, thereby obtaining a complete EOS measurement.

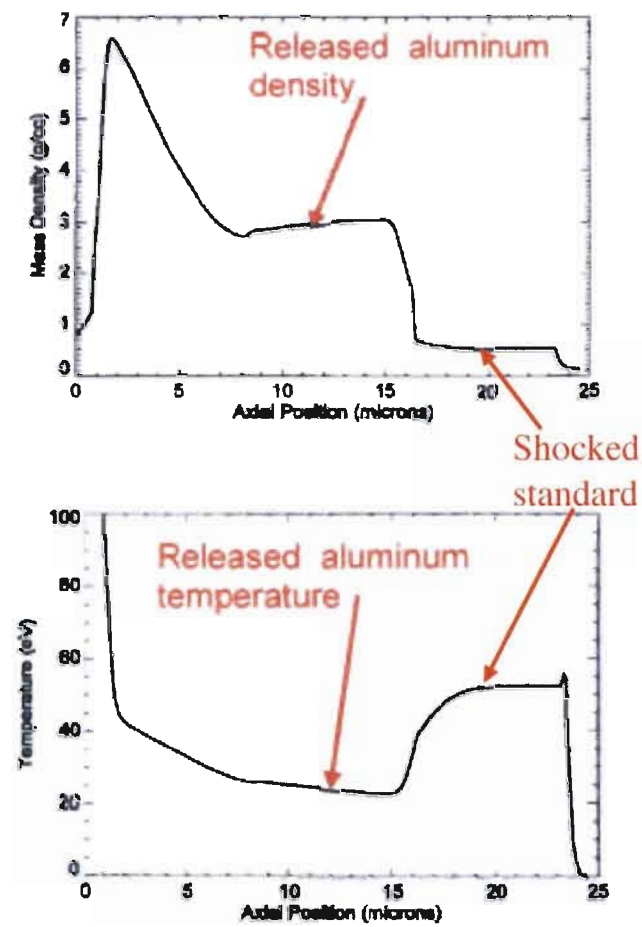
Laser Driven Shock and Release Approach to WDM EOS

Simple schematic of possible laser driven shock and release experiment



Imaging x-ray Thomson scattering diagnostic to determine temperature and density of released material

Calculated spatial profile of shock and release conditions calculated for Al at a laser intensity of 10^{15} W/cm^2



X-Ray Thomson scattering is being used to measure many properties of dense plasmas

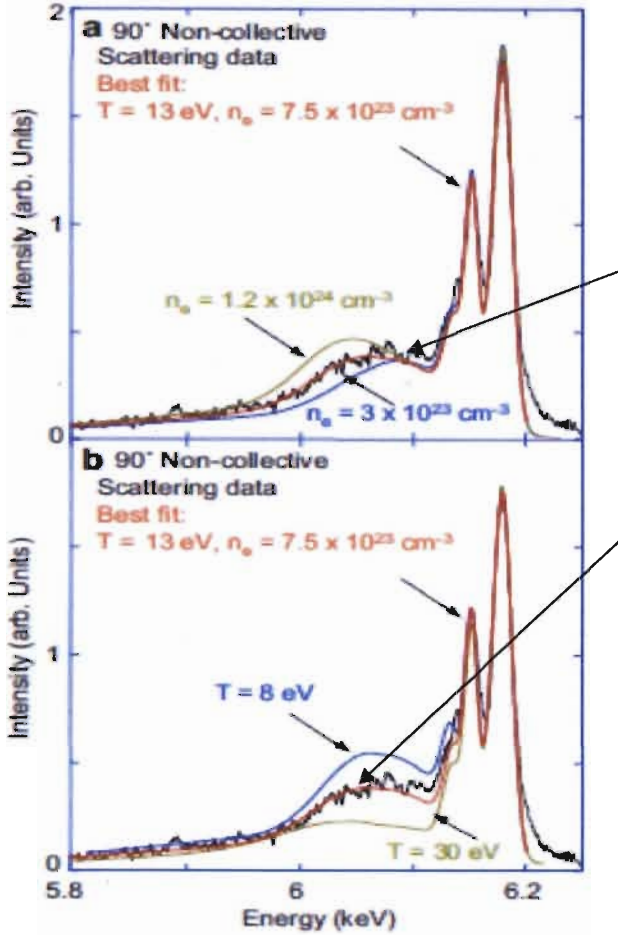


Fig. 3. (a) X-ray scattering data for 90° scattering angle are shown along with theoretical spectra for various electron densities. (b) Same as in (a) for various ion temperatures.

Common measurements are used to determine n_e, T_e, and Z^*

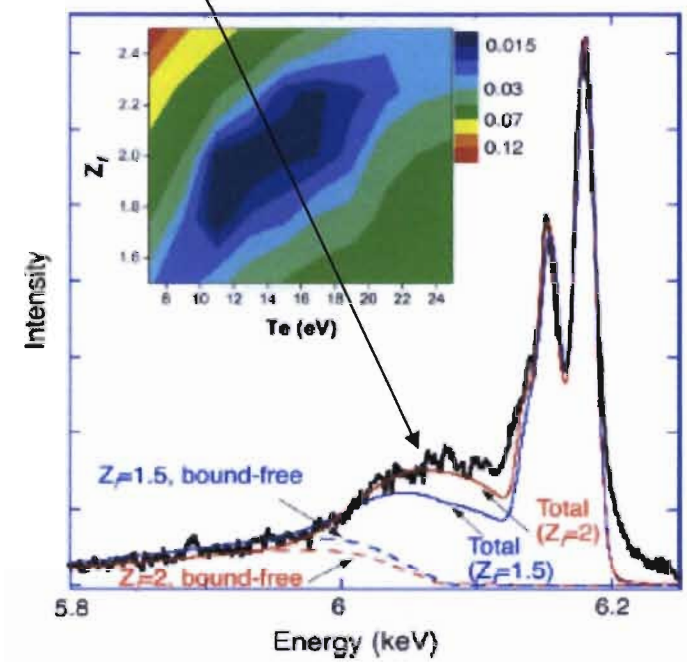


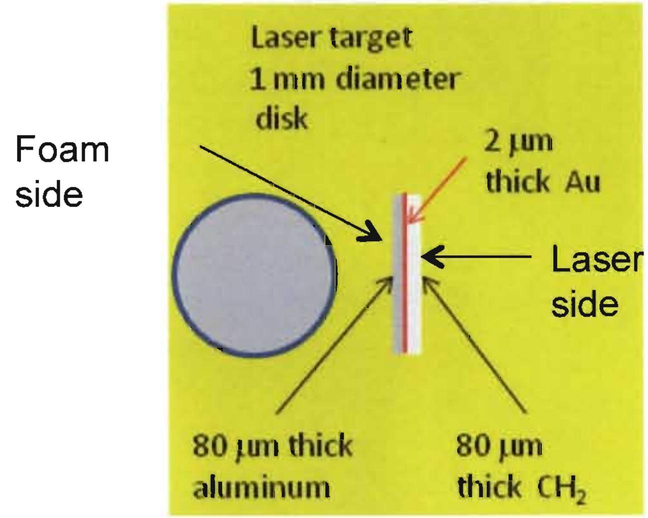
Fig. 4. x-ray scattering data for 90° scattering angle are shown with ionization state variation in the theoretical spectra. Best fit with $Z_i = 2$ is compared to a fit with $Z_i = 1.5$. Here, $T_e = 13$ eV and $n_e = 7.5 \times 10^{23}$ cm^{-3}. Inset shows the rms values between fits and data indicating the sensitivity to varying temperature and ionization state.

Both figures from Glenzer, et al., HEDP **6**, 1, (2010).

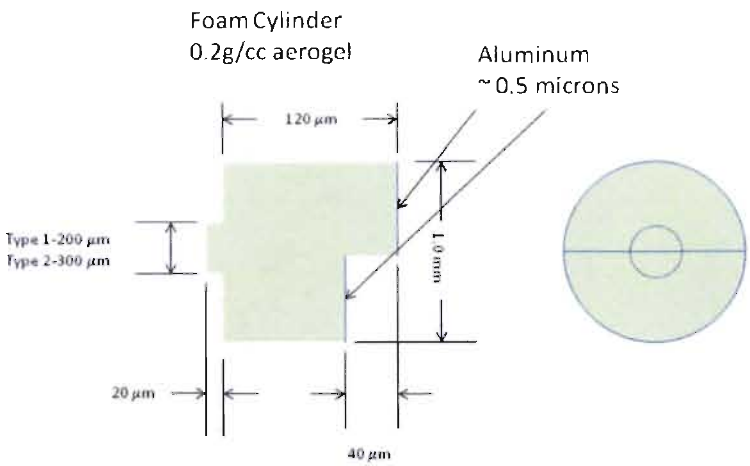
DPEOS Experimental Goals and Target Configuration

- **Overall: Measure temperature, density, and pressure of aluminum at warm dense matter conditions.**
  - Knowledge of the equation of state of materials at WDM conditions is limited.
  - These experiments would be first success at obtaining a full EOS measurement at such conditions
- **Experiment will use a laser driven shock and release technique**
  - High pressure drive from laser enables reaching WDM conditions ($I=6\times10^{14}$ W/cm^2)
  - Should create conditions near 500 GPa, 3 g/cm^3, and 10-15 eV
- **Measurement techniques should determine thermodynamic state**
  - Utilization of imaging x-ray Thomson spectroscopy will enable measurement of temperature and density that is beyond the standard shock and release approach.
  - ASBO diagnostic will measure shock velocity in aerogel

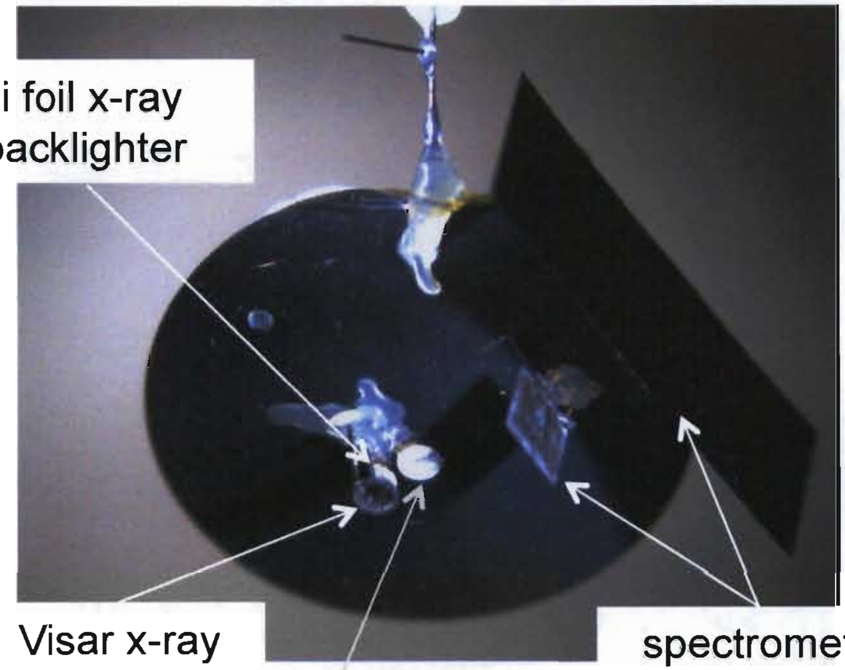
Schematic for laser target



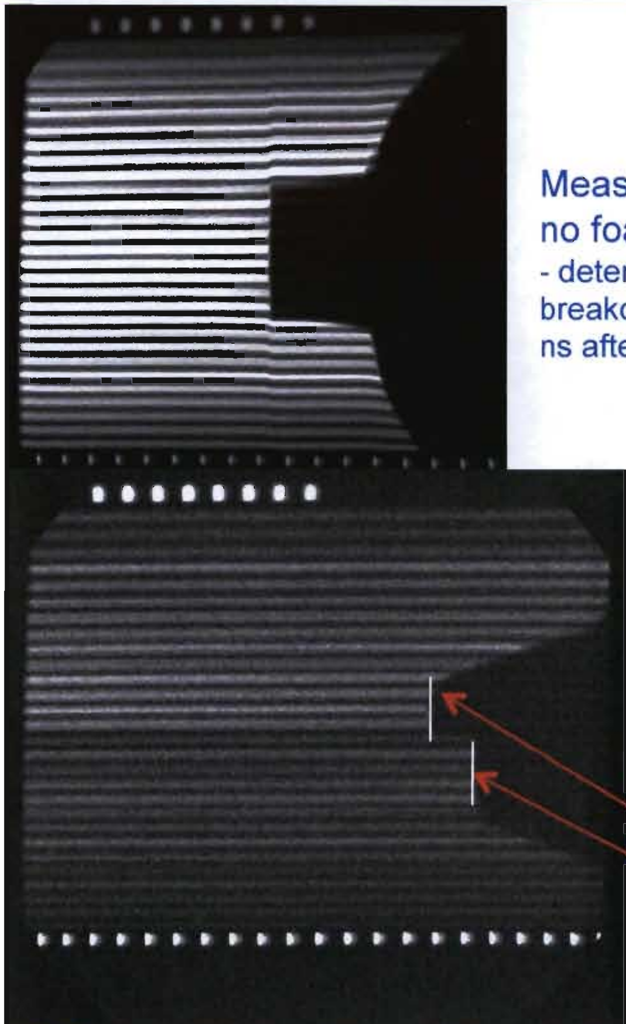
Detailed Foam design



DPEOS Experimental Configuration



Initial DPEOS visar results



Measurements with no foam standard
- determine shock breakout from Al, ~ 3.6 ns after T_0

Measurements with stepped foam standard
- determine shock velocity in foam

Shock breakout points

We obtained successful visar shock breakout measurements

- Shock velocities measured between 4.8 and 5.7 $x10^6$cm/s
- Pressure ranges from 366 to 520 Gpa

Value predicted by simulation is ~ 450 GPa.

Some issues between experiment and simulation

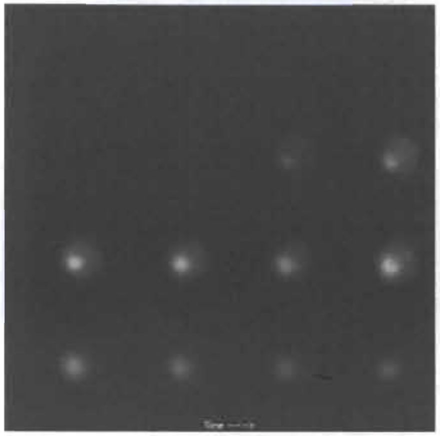
- we used different plastic ablators than simulation, a higher density, 50 micron thick and lower density, 75 micron thick
- The EOS model for the aerogel foam does not reproduce the hugoniot

One other issue:

-the shock breakout sometimes occurred late, possibly due to gaps in target

Initial DPEOS x-ray results

X-ray images of backlighter target



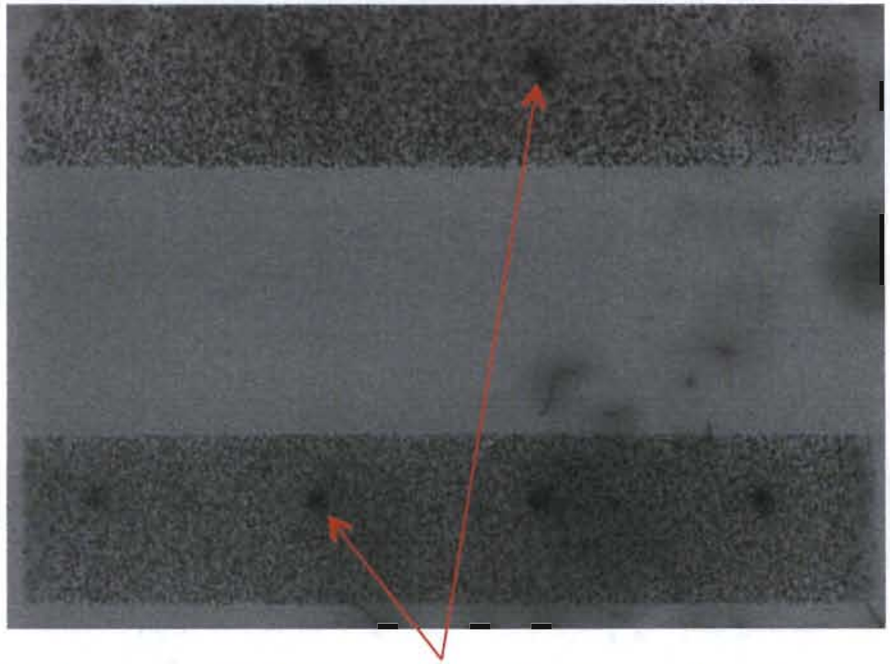
~ 750 μm at target

Streaked spectrum of Ni x-ray backlighter

-the He$_\alpha$ lines will be used for the Thomson scattering

-Spectral shape and image are consistent with peak conversion efficiency at ~ 2×10^{16} W/cm^2

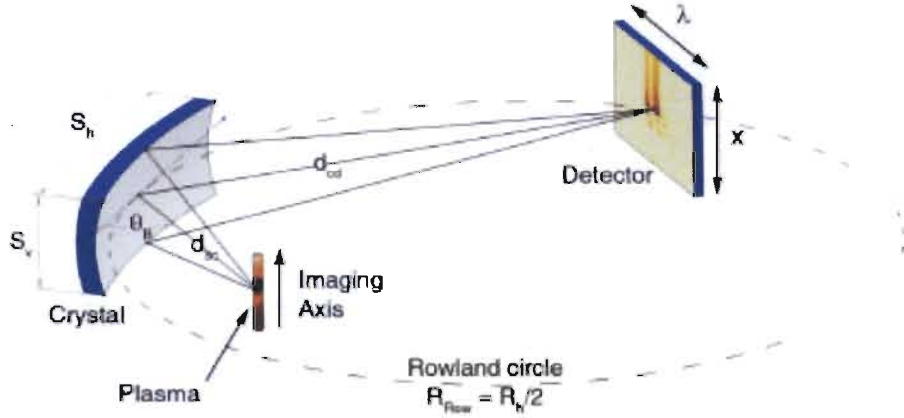
QXI X-ray images of foam target



Rectangular slot in 2 mil W shield which images foam/plasma to spectrometer position

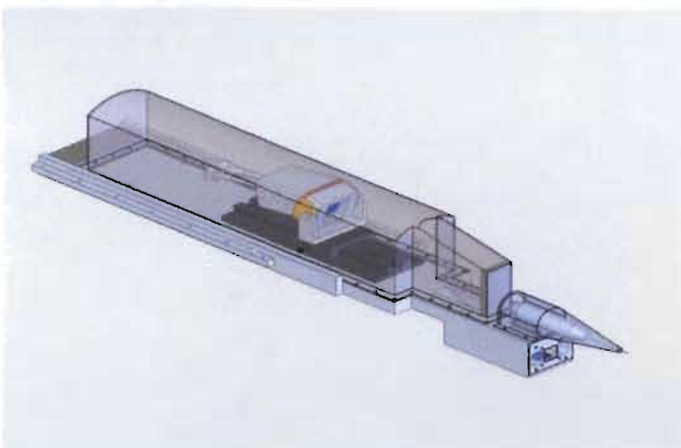
-Timing of images was before backlighter, during laser
- x-ray fog is coming from > 15 keV photons
- We believe this exposure is caused by gold x-rays from hot electrons
- In second series, gold cone was coated with CH and x-ray background disappeared

Imaging X-ray Thomson Spectrometer



Spectrometer uses a toroidally curved crystal

- Radii of curvature are very different
- Enables high throughput and reasonable resolution



Spectrometer designed for 2 energies

- Zn and Ni
- Only requires a change of crystal

Design characteristics are given below

Probe	Zn	Ni
Energy (eV)	9000	7800
Crystal	Ge(220)	Ge(220)
θ_B(°)	20	23.4
R_{int} (mrad)	0.137	0.087
M	1.85	1.85
R_v (cm)	10	10
R_h (cm)	121.818	90.346
S_v(cm)	2.2	2.2
S_h (cm)	(+1.5, -4.5)	(+1.65, -1.5)
d_{sc} (cm)	22.5212	19.395
d_{cd} (cm)	41.6442	35.8808
Ω_{act} (sr)	2.9×10^{-5}	2.15×10^{-5}
ΔE (eV)	(8250, 9350)	(7500, 8000)
δx (μm)	< 25	< 25
δE (eV)	< 4	< 4

Future efforts and summary.

- **We have tested our shock and release target and laser drive conditions and we are reaching the desired pressure range.**
  - Timing of shock breakout is still an issue (needs to be sooner).
  - There is some variability from target to target.
- **We also found our backlighter spectrum is near optimal**
  - The main issue is whether the backlighter intensity is high enough that scattered x-rays will be brighter than background
  - Evaluation of this based on measured x-ray efficiencies and expected reflectivity and detector response indicate we should have enough light
  - We require the Thomson spectrometer to verify this
- **The x-ray Thomson spectrometer has been tested at Trident and appears to be operating correctly**
  - The crystal (with x-rays) and CCD (with visible light) appear to be working correctly
  - The spectrometer has yet to be approved for operation at Omega
  - We expect to have that resolved before our next day of experiments