Progress toward x-ray Thomson scattering of warm dense matter on the Z accelerator

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Abstract. Experiments on the Z accelerator have demonstrated the ability to produce warm dense matter (WDM) states with unprecedented uniformity, duration, and size. Significant progress to combine x-ray Thomson scattering (XRTS), a powerful diagnostic for WDM, with the unique environments created at Z has been accomplished. The large current of Z is used to magnetically launch Al flyers to impact CH$_2$ foam ($0.12$ g/cm$^3$) samples. The uniformly-shocked CH$_2$ foam volume is about 10 mm$^3$ and the steady shock state lasts up to about 100 ns, which are approximately 1000 & 100 times larger, respectively, than typical laser shocked samples. The Z-Beamlet laser irradiates a 5 µm thick Mn foil near the load to generate 6.181 keV Mn-He-$\alpha$ x-rays that penetrate into the CH$_2$ foam and scatter from it. A high sensitivity x-ray scattering spherical spectrometer with both high spatial and spectral resolution is fielded, which enables benchmark quality data by simultaneously measuring x-rays scattered from shocked and ambient regions of the CH$_2$ foam, and the Mn x-ray source. Experimental efforts have achieved low x-ray background and mitigation of load debris, and measured high quality XRTS data of ambient CH$_2$ foam have validated the technique.

1. Introduction

The Z accelerator at Sandia National Laboratories is a pulsed-power generator used to create extreme states of matter by rapidly delivering a shaped current pulse (25 MA, 100–700 ns) into a target load. The immense currents and magnetic fields generated within the load launch flyer plates to velocities up to 40 km/s that are used to impact samples. These shock compressed states are large, uniform, long-lived and precisely characterized. The purpose of this work is to combine powerful x-ray Thomson scattering (XRTS) measurements with the unique warm dense matter (WDM) samples that Z is able to create, thus provide benchmark quality data to test WDM theory [1].

1.1. Warm dense matter

Measuring the physical properties, such as temperature, density, phase, structure factor, and ionization state, of dense plasma and WDM states is experimentally challenging [2]. With temperatures about 1–100 eV and electron densities of order $10^{20}$–$10^{24}$ cm$^{-3}$, these high energy density (HED) states are comparable to conditions within brown dwarf stars and Jovian planets [3, 4], and of interest to inertial confinement fusion research [5, 6]. Generating such extreme states have been achieved through isochoric heating of samples using high-power lasers [7],
and radiation from synchrotron sources [8]. Shock compression of samples to pressures up to tens of Mbar using high-power lasers has been developed as a complementary approach to access the HED regime [9]. However, the typical size of laser-driven shocked samples are small ($\sim O(0.01 \text{ mm}^3)$) with short durations ($\sim O(\text{ns})$) for the high-pressure steady-state conditions. By contrast, high velocity flyer impact of samples such as the magnetically launched plates on Z [10] generate HED states more macroscopic in size ($\sim 5–10 \text{ mm}^3$) that exist for longer durations ($\sim 10–100 \text{ ns}$). In these Dynamic Materials Properties (DMP) experiments on Z, velocimetry such as VISAR has been the main shock compression diagnostic, which has enabled pressure and density to be characterized with accuracy and precision of about 1–2%. To expand the diagnostic capabilities on Z, an x-ray Thomson scattering (XRTS) diagnostic has been implemented, which is described in this paper.

1.2. X-ray Thomson scattering

The development of powerful x-ray sources from high-power lasers and 4th generation synchrotrons have spurred the growth of techniques that are able to penetrate and diagnose dense matter including x-ray radiography [11], x-ray diffraction [12], x-ray absorption spectroscopy [13], and XRTS [14]. In XRTS, incident x-rays are directed into a sample and the spectrally resolved scattered x-rays reveal the atomic structure, electron density, electron and ion temperatures, and ionization state of the sample [15]. Some x-rays scatter from individual electrons (or ions), producing spectral shapes such as the elastic Rayleigh peak, and inelastic Compton and bound-free features. These are known as non-collective scattering features to distinguish them from x-rays scattering from large-scale, collective plasma motions across lengths greater than the electron screening length. The collective scattering features include the elastic Rayleigh peak, and down- and up-shifted plasmon wave shapes. Generally, the XRTS signals are weak because the scattering cross sections are small, so spectrometers and crystals with high collection efficiencies are important. The vast majority of XRTS measurements performed to date have employed highly oriented pyrolytic graphite (HOPG) crystals in the Von Hamos configuration [16–18]. However, HOPG has the significant disadvantages of relatively low spectral resolution ($E/\Delta E \sim 300–1000$), and negligible spatial resolution [19]. The latter problem implies that it is difficult or impossible to be certain that the scattering arises from a homogeneous WDM state. Without this certification, true benchmark quality data cannot be obtained, thus spatial resolution is an essential requirement for x-ray scattering measurements.

2. Experimental setup of XRTS on Z

The overall Z-XRTS experimental setup is shown in figure 1. The three key components of XRTS on Z-DMP experiments are (1) the Z-DMP load, (2) the Z-Beamlet laser (ZBL), and (3) the x-ray scattering spherical spectrometer (XRS3). As shown in figure 2, ZBL will irradiate a x-ray source place near the back surface of a sample. The x-rays will penetrate the shocked sample and scatter out the side of the sample. The XRS3 diagnostic is setup perpendicular to the shock propagation direction to collect x-rays scattered from both shock and ambient states of the sample, and incident x-rays. This allows the uniformity of the WDM state to be verified, and the x-ray probe spectrum to be characterized simultaneously.

2.1. Z-DMP load

The magnetically accelerated flyer technique for shock compression experiments on Z has been thoroughly described by Lemke et al. [20]. Briefly, the Z-DMP coaxial load consists of two anode panels arranged around a central cathode stalk to form two anode-cathode vacuum gaps (see figure 2). A short circuit is created between the anode panels and the cathode stalk through a shorting cap at the top. The current $J$ flowing on the anode and cathode produces a planar magnetic field $B$ between them, and the $J \times B$ interaction results in a smooth mechanical
stress wave that is proportional to the current squared. The generated impulsive pressure provides sufficient momentum to launch the anodes panels at high velocities across a gap and impact load samples. The magnetohydrodynamics code ALEGRA [21] was used to predict the expected WDM states created by Z. In the initial Z-XRTS experiment, a shaped current pulse magnetically launches a solid Al flyer to a peak velocity of 16.7 km/s to impact a CH\textsubscript{2} foam (0.12 g/cm\textsuperscript{3}) sample. The shocked CH\textsubscript{2} (0.4 Mbar, 2.6 eV, 0.5 g/cm\textsuperscript{3}) WDM state will have large spatial extents along the shock propagation direction (270 \textmu m) and lateral directions (5 mm \times 5 mm), and long steady-state duration (90 ns), which will be highly accessible for probing by the XRS3 diagnostic.

2.2. Z-Beamlet laser
The ZBL beam originates in the ZBL facility [22] that is housed in a separate building next to the Z accelerator, and is transported 75 m along a relay telescope assembly between the two buildings before reaching the axis of the Z center section chamber. There the beam reaches a final optics assembly (FOA) consisting of a turning mirror and a 3.2 m focal length lens. The ZBL beam enters the Z-DMP load region through a hole in the blast shield top lid (see figure 1). Inside the blast shield, the ZBL beam passes through three baffle plates and an aperture block above the Z-DMP load, before being focused onto the x-ray source target. The target is fabricated from a 5 \textmu m thick manganese (Mn) foil backed by a 100 \textmu m thick layer of polyester. ZBL is optimized to provide 2 kJ of laser energy (\(\lambda = 527\) nm, 0.5 ns pre-pulse, 2 ns main pulse, focused to \(\sim 2 \times 10^{15}\) W/cm\textsuperscript{2}) to generate the bright Mn-He-\textalpha (6.181 keV) emission for XRTS. The firing of ZBL is timed so x-rays are generated 50 ns after the flyer impacts the CH\textsubscript{2} foam and 25 ns before the shock-breakout. With a 16.7 km/s Al flyer impacting a 1.5 mm thick CH\textsubscript{2} foam sample, the x-rays should penetrate into sample when the shock wave has propagated only 1.0 mm through it, so that 0.5 mm of foam remains ambient ahead of the shock front. This would enable simultaneous scattering from the 270 \textmu m thick layer of shocked CH\textsubscript{2} foam, and from the 0.5 mm thick region of ambient CH\textsubscript{2} foam.

2.3. X-ray scattering spherical spectrometer
The XRS3 is a focusing spectrometer with spatial resolution [23], in which collected x-rays are spectrally and spatially resolved by a spherically bent crystal, and recorded onto a Fuji-TR
image plate (IP), as shown in figure 1. The relative x-ray collection efficiency, spatial resolution, and spectral resolution of spherically bent quartz, mica, germanium, and pyrolytic graphite crystals were investigated using a Manson x-ray source [24]. A spherically bent germanium 422 crystal is fielded in the Z-XRTS experiment because it had the best combination of spatial and spectral resolution, and x-ray collection efficiency. The spherically bent crystal and IP are housed inside a 1” thick tungsten box for debris and x-ray background shielding. An entrance snout consisting of chevron (V-shaped) plates is meant to deflect load debris from entering the XRS3 spectrometer. In addition, several 1” thick tungsten internal crossover plates that only allow x-rays that are reflected off the crystal to reach the IP are used to further reduce x-ray background.

3. Results
To obtain sufficient XRTS signals, XRS3 needs to be placed very close to the Z-DMP load (crystal-to-source distance of 37 cm), as shown in figure 1. Thus, the two main experimental challenges for XRTS on Z are (1) x-ray background overwhelming the XRTS signal, and (2) damage from load debris. First, Z itself is a tremendous x-ray source, where photons with energies up to 10 MeV are produced in both the power feed sections and load region. Therefore, sufficient signal-to-noise for the XRTS measurement needed to be validated. Second, Z is a very destructive environment, where about 2–3 MJ (an energy release comparable to a stick of dynamite) is deposited into the load hardware which sends debris everywhere. The primary concern is vertically directed debris damaging the ZBL FOA and creating a catastrophic vacuum breach of the target chamber. Another concern is debris entering the XRS3 spectrometer and damaging the IP, thereby preventing retrieval of the XRTS data.

3.1. X-ray background
The Z accelerator is also used for other HEDP research such as inertial confinement fusion, radiation-driven hydrodynamic jets, and astrophysical phenomena in z-pinch radiation producing experiments [5]. On those types of experiments, very strong x-ray backgrounds have been measured within the Z center section chamber that easily saturate IP signals; i.e. > 25 PSL (photostimulated luminescence). The XRS3 with its thick layers of tungsten shielding was designed to suppress the x-ray background, and was tested as a ride along diagnostic on several Z-DMP experiments. It was shown that Z-DMP experiments have significantly lower x-ray background than z-pinch experiments. The x-ray background at the bottom entrance of the XRS3 box where the spherically bent crystal sits was about 0.3 PSL. This was further reduced by a factor of 30 using the internal tungsten crossover plates, so that at the IP only about 0.01 PSL x-ray background was measured. This low x-ray background makes XRTS viable for Z-DMP experiments.

3.2. Debris mitigation
Currently, a sacrificial 10 mm thick glass debris shield is placed below the ZBL FOA vacuum window (30 mm thick glass) to stop any debris from reaching it. The debris mitigation strategy for the Z-XRTS experiment is based upon previous hypervelocity penetration depth studies of particle impacts on glass/vacuum interfaces [25]. The penetration depth into the glass shield depends upon a projectile’s mass density, size and velocity. Increasing the thickness of the glass shield would prevent perforation, but would decrease the focusing quality of ZBL. The alternative is to decrease the mass density, size, and velocity of projectiles reaching the glass shield. This was accomplished using an aperture block near the load and baffle plates above it within the blast shield to limit the axial debris. The residual debris that impacted the glass shield was found to be mostly liquid, and some small solid fragments with low velocities that posed no danger to the ZBL FOA. The entrance snout deflected most debris from entering the XRS3,
thus the image plate was undamaged and XRTS data was recovered. However, the spherical crystal was still damaged by the remaining undeflected projectiles, so additional shielding to protect the crystal is being investigated.

3.3. Preliminary x-ray scattering data
The first fully integrated Z-XRTS experiment was recently completed in which spatially and spectrally resolved XRTS data was measured, as shown in figure 3. Unfortunately, during that shot there was current loss away from the load which reduced the flyer peak velocity to only 9 km/s and not the expected 16.7 km/s. As a result, ZBL generated x-rays about 190 ns early relative to shock arrival in the CH$_2$ foam and scattering was only from ambient CH$_2$ foam. In any case, this was the first XRTS data measured on Z, and it showed very good signal-to-noise. Furthermore, the x-ray source and x-ray scattered signals are spatially well resolved. In fact, the x-ray scattering as a function of depth into the CH$_2$ foam is clearly observed. In addition, the multiple satellite lines of the Mn-He-α emission are spectrally well resolved. Since the x-ray source spectrum was measured simultaneously, subtle scattering features such as the bound-free scattering are able to be distinguished.

![Figure 3. Spectrally and spatially resolved x-ray image of Mn x-ray source, and x-ray Thomson scattering from ambient CH$_2$ foam measured by XRS3 diagnostic.](image)

4. Summary
Significant progress has been made in combining XRTS with Z-DMP experiments, in which x-ray background and debris mitigation issues have been addressed. An XRTS measurement on Z with spatial resolution of an ambient sample has been demonstrated. In upcoming experiments, XRTS measurement from shocked CH$_2$ foams is anticipated, and XRTS from other shocked materials such as Be and LiD will be performed. In addition, there is continuing development of higher energy x-ray probes such as Ni-He-α (7.804 keV) emission, which will allow XRTS of materials with higher atomic number and mass density (i.e. higher x-ray opacity).

Acknowledgments
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000. Funding of this work was through the Sandia LDRD program (Project 141540).
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