High accuracy Hugoniot measurements at multi-megabar pressure utilizing the Sandia Z accelerator

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Abstract. The Hugoniot response of materials is centrally important in the field of high pressure science. Highly accurate Hugoniot measurements not only provide better material references but also allow for the detection of subtle material phenomena. A process has been developed utilizing the Sandia Z accelerator to measure Hugoniot response at multi-megabar pressure resulting in extremely high accuracy data. Key considerations are the use of large surface area flyer plates allowing measurement configurations with multiple targets and diagnostics. This allows for greatly reduced uncertainty in the data. The details of this process are given and each aspect is closely examined focusing on the individual contributions to the overall accuracy of the result.

1. Introduction
The Hugoniot response of materials is critical to understanding the high pressure performance in many applications including internal confinement fusion, weapons design, and planetary science. Historically, experiments were conducted on large (~ centimeter thick) samples using explosives, to generate the high pressures [1]. To achieve higher pressures, samples have become much smaller. Light gas guns typically shock a several millimeter thick sample up to ~1 Mbar although it is possible to reach much higher pressures ~ 6-7 Mbar with high impedance materials [2]. Laser facilities, which use high power lasers to generate pressures up to 1-10 Mbar, have typical sample thickness of tens of microns due to the energy density requirements [3, 4, 5]. Using the Z accelerator at Sandia National Laboratories relatively large samples (~ 500 – 1500 microns thick) can be loaded to pressures up to ~15 Mbar [6]. The thickness of the samples is important as this, combined with the resolution of the timing data, determines the overall accuracy of the measurement.

2. Experimental details
The Sandia Z accelerator is a pulsed power device capable of producing extremely large current (~25 MA) by releasing approximately 22 MJ of stored energy through an electrical short circuit. This current flows over parallel anode and cathode plates and generates a large magnetic field density (~12 MG) in the vacuum between them. The interaction of the current and magnetic field results in a large Lorentz (\( J \times B \)) force which acts to repel the plates and results in a magnetic pressure wave (>4 Mbar) being produced in the circuit materials over a short time (~hundreds of nanoseconds) which accelerates the anode at high velocity. With careful design [7, 8, 9], the accelerator can be used to launch large flyer plates (several square centimeters area) at velocities in excess of 40 km/s. The large flyer allows for simultaneous impact on multiple targets which will be shown in the following section to be important to improving the accuracy of the results.
The experimental geometry is illustrated in figure 1. This configuration, known as a strip-line, is slightly different than the coaxial design often used in the past. In this configuration, a large (17 x 40 mm) flyer plate is magnetically launched. The large size of the flyer allows for simultaneous impact on several targets. As shown in the figure, the two outermost targets are transparent quartz or sapphire windows. The inner three targets are test samples with windows affixed to the rear surfaces. Samples are generally 6 mm lateral dimension while windows are 4 mm. Each sample and window is monitored with multiple VISAR [10] diagnostic probes.

Using the two outer windows, and in the case of transparent test samples the inner targets as well, flyer velocity and impact planarity are determined. An advantage of observing the flyer through transparent windows without any reflective coating is that the velocity is recorded over the entire trajectory. Shock wave transit time through the samples is determined from the recorded shock break out at the sample window interface and the impact time recorded for each transparent sample or inferred from the outer window data in the case of opaque samples. This information is then used to determine the Hugoniot state of each sample.

3. Quantification of uncertainty
Determination of the Hugoniot state of a material requires the measurement or calculation from measured quantities of the material stress, shock velocity, and particle velocity. Other commonly used descriptors of the state (e.g. density, strain, volume compression, etc.) can be derived from these basic properties. Ultimately, the accuracy of the end results is based on the accuracy of the measured parameters used. The following sections examine each measurable quantity that is used to determine the Hugoniot state and the uncertainty associated with each measurement. In the final section the results are combined into a single uncertainty for the determined Hugoniot state.
3.1. Impact velocity

The velocity of the flyer is measured directly with multiple VISAR diagnostic probes from launch through impact. At a minimum, two VISAR probes, spaced 23 mm apart, observe the flyer looking through the outermost windows on the target. In the case of transparent samples, an additional three VISAR probes are used looking through the central sample-window stacks. When used to determine the Hugoniot state, there are two main sources of uncertainty in the impact velocity measurement; VISAR resolution and velocity gradients due to tilt.

The resolution of the VISAR instrument limits the precision of the data collected. It is determined by the VISAR sensitivity to motion, controlled through the velocity required to generate one fringe shift (velocity per fringe or vpf) and also the fringe resolution of the data. For experiments of this nature, the typical vpf setting is 500 m/s/fr or less. A conservative estimate of the fringe resolution is 0.1 fringe meaning that the minimum detectable motion is 0.1 fringe. These limits combine to give an absolute uncertainty of 50 m/s which is typically 0.2 – 0.4% of the measured flyer velocity. For the uncertainty analysis described later, a more conservative value of 0.5% is used for the VISAR resolution.

Since the flyer velocity is very sensitive to the anode-cathode gap distance, a slight misalignment of the coaxial load will result in a velocity gradient. Where the gap is smaller, greater force acts on the flyer resulting in greater acceleration and ultimately a greater velocity at impact. The effect is similar to that of projectile tilt in a traditional gas gun experiment. In this case however, effects from both the initial misalignment (tilt) and the resulting velocity gradients are observed. Corrections to the data are made following a similar approach to that of tilt correction.

Figure 2 shows typical velocity data recorded during an experiment. In this experiment, all samples were transparent and hence five VISAR records were recorded spaced laterally approximately 6 mm apart. VISAR resolution affects the width of the curves shown. The impact timing pattern and monotonic decrease in velocity at impact, sweeping across the target from bottom to top, indicate the flyer was tilted relative to the plane of the targets with a smaller anode-cathode gap at the bottom of.

![Figure 2: Typical VISAR data. This experiment had transparent samples so five traces are shown; one trace each from the samples and the two outer windows. The inset shows detail around the moment of flyer impact. Top and bottom refer to the vertical location along the strip.](image-url)
the panel. Based on the measured velocities and the time difference between impacts at the outermost windows, the flyer is 135 µm away from the top window at the time of impact at the bottom window indicating tilt of ~5 mrad or ~0.28 degree. The observed change in velocity of 0.4 km/s across the 23 mm lateral span of the targets corresponds to a gradient of approximately 0.09 %/mm or approximately 0.5% across each 6mm diameter samples.

Impact tilt mostly affects results on opaque samples where the impact time and velocity at each sample must be interpolated from data recorded at the outer window locations. In the case of transparent samples, these quantities are measured directly at each sample location. In that case the VISAR resolution becomes the main source of uncertainty in the measurement.

3.2. Shock velocity
Shock velocity is determined by dividing the sample thickness by the shock transit time through the sample. Each of these measured quantities has an associated uncertainty.

The sample thickness is determined by making multiple measurements with a through the lens laser autofocus system with a resolution of 1 µm. This results in an absolute measurement uncertainty of 1-2 µm or 0.4% or less for typical sample thicknesses in the range of 500 – 1500 µm.

For transparent samples, the shock transit time is determined directly from the raw VISAR data. Figure 3 shows one of four quadrature signals recorded for a typical experiment. The signal intensity is observed to drop at impact and increase when the shock enters the window. This provides clear timing fiducials from which to determine the shock transit time.

In order to most precisely and reproducibly determine the transit time, a differential approach is used. A copy of the data in the vicinity of the signal drop is inverted, scaled, time shifted, and subtracted from the original data in the vicinity of the signal increase. The time shift is varied to minimize the residual and thus determine the shock transit time.

To estimate the uncertainty in the transit time, we consider the range of time shifts over which the residual changes by one. These values are typically 100 – 200 ps, however, for the uncertainty analysis, a time of 400 ps is used to be conservative. This corresponds to an uncertainty of approximately 1.3% when compared with typical transit times of 30 ns. Combining the uncertainties in thickness and transit time, the shock velocity is determined to within 1-2% in transparent samples.

Figure 3: Typical raw VISAR data used to determine the shock velocity. Data shown is from one of four quadrature signals obtained from a single VISAR measurement.

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For opaque samples, impact time and velocity is determined by interpolating the data recorded at the window only locations. As discussed in the previous section, this adds 1-2 % uncertainty depending on the interpolation length. For reduced uncertainty, a third window only or transparent target is placed in the center location to reduce this length.

3.3. Density
Sample density is determined from measurements of the sample dimensions and mass. The dimensions are measured as previously described with an uncertainty of 1-2 um. Mass is measured with a high precision balance with a resolution of 1 µg. For typical samples, these measurement uncertainties result in uncertainty in the density of less than 0.01%.

3.4. Impactor Hugoniot
In addition to the measurable quantities discussed, the impedance matching technique used to determine the shocked state relies on knowledge of the impactor Hugoniot. Data taken from several studies of copper using explosive or nuclear drives over the range of 400 – 2500 GPa were used to determine the Hugoniot to be described by the relation $U_s = 4.57 \pm 0.24 + 1.36 \pm 0.04 u_p$.

3.5. Determination of the Hugoniot state
The Hugoniot state following impact is determined graphically using a standard impedance matching technique. A Rayleigh line with slope equal to density times shock velocity passing through the origin is intersected with the impactor Hugoniot centered on the impact velocity as shown in figure 4. The widths of the lines in the figure indicate uncertainty in the values. The intersection gives the target pressure and particle velocity. Propagation of the previously discussed uncertainties results in an uncertainty of approximately 1% in the particle velocity and pressure determined for a single measurement.

![Graphical determination of the Hugoniot state](image)

Figure 4: Graphical determination of the Hugoniot state. Line widths indicate uncertainty.
In order to further reduce the uncertainty in the measurement, multiple measurements are made. Each experiment consists of 2-3 identically loaded samples and each sample is observed with 2-3 independent VISAR probes. Thus there are up to nine independent measurements of the target material which allows for weighted averaging of the results which improves the measurement uncertainty to better than 1%. The effects of averaging can be seen in figure 5 which shows (a) the results of 45 individual sample measurements on diamond and (b) 15 data points resulting from averaging the three samples on each panel.

![Figure 5: Hugoniot response of diamond [11] illustrating the effect of averaging multiple measurements of identically loaded samples. Individual data points from 45 measurements are shown in (a). The resulting 15 averaged data points are shown in (b).](image)

4. Significance of results
The ability to determine the shock response of a material to better than 1% accuracy has allowed the detection of subtle features in data. As an example, consider the recently observed triple point in the carbon phase diagram [11]. Figure 6 compares (a) Hugoniot data on carbon collected by other means and (b) data collected as described above. The data across all techniques generally agree within the quoted experimental uncertainties. However, the technique described here allows for the observation of a faint discontinuity in the melt region corresponding to a diamond-liquid-bc8 triple point which is completely unobservable in the other results. This underscores the extreme importance of high accuracy when making detailed measurements, especially at high pressures where subtle effects can be caused by complex material response.
Figure 6: Hugoniot response of diamond. Published data from other sources [3, 5, 12] is shown in (a) while recent data from Z [11] is shown in (b) along with the quantum molecular dynamics computed response [11].

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