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USE OF Z-PINCH RADIATION SOURCES FOR HIGH-PRESSURE SHOCK WAVE STUDIES

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Abstract

There is a continuing need to determine the equation of state (EOS) and constitutive properties of materials to multi-megabar pressures in support of both weapons and non-weapons applications. Shock wave techniques have been a principal tool for determining the high pressure EOS of materials in regimes inaccessible by other methods (1). A variety of shock wave techniques have been developed for producing well-controlled shock planar shock waves to study dynamic material response. For ultra-high pressure EOS measurements, underground nuclear tests (2) have also been used to produce shock wave pressures up to about 3000 Mbar.

High-velocity launchers remain the standard tool for making these measurements. However, conventional gun technology is limited to launch velocities of about 8 km/s. Projectile impact at these velocities will produce shock pressures in materials ranging from about 1 Mbar in low-Z materials to approximately 7 Mbar in high-Z materials. Existing scientific and programmatic problems, however, require EOS studies at shock pressures of up to tens of megabars. This results in a need to increase the capability of gun launchers to significantly higher velocities and to develop other sources of shock wave drive for high-pressure EOS studies.

A variety of radiation sources are being explored for accessing the extremely high-pressure states of matter. The leading approaches include high intensity lasers and pulsed power methods. Recent results obtained with laser driven shock waves have produced promising results for high-pressure EOS studies in plastics and deuterium. For example, Evans et al. (3) have developed direct-deposition laser techniques using impedance matching to produce shock waves in copper to pressures of about 20 Mbar. More recently, Cauble et al. developed laser back-lighting technique for making absolute shock wave measurements of low atomic number materials at extremely high pressure (4). Experimental loading conditions, however, pose limitations on the sample sizes possible with laser sources. This size restriction also limits the experimental possibilities for studying a broader range of material properties other than EOS. For example, measurement of compressive strength in shocked states is of intense interest in developing constitutive models needed in 3-D computer simulations of dynamic material response. Typically, such measurements require samples of several centimeters in diameter and several millimeters in thickness.

Recent developments in pulsed power technology (5,6) have demonstrated the use of intense radiation sources (Z pinches) for driving planar shock waves in samples with spatial dimensions larger than possible with other radiation sources. Initial indications are that the use of Z pinch sources to produce Planckian radiation sources in secondary hohlraums is effective for producing planar shock waves in samples with diameters of a few millimeters and thicknesses approaching one half millimeter. These sample dimensions allow increased accuracy of both shock velocity and particle velocity measurements. In addition, the peak temperatures of nearly 150 eV in primary hohlraums now possible with Z pinch sources result in shock wave pressures approaching 45 Mbar in high impedance materials such as tungsten and 10-15 Mbar in low impedance materials such as aluminum and plastics. Experimental developments are in progress to use this technique for absolute shock Hugoniot measurements on aluminum at pressures of 1-3 Mbar with accuracies comparable to that obtained with gun launchers.

This technique uses imploding metal plasma produced by self-magnetic fields applied to wire arrays to produce high temperature x-ray environments in hohlraum enclosures, thus resulting in ablation-driven shock waves. Previous experiments have demonstrated that planar shock waves can be produced with this approach. (6). In the present experimental approach, stepped aluminum samples, ranging in thickness from 100 μm to 300 μm thickness and with lateral dimensions of about 9 mm in diameter, are being studied. VISAR interferometry is used to measure particle velocity behind the shock wave and active fiber optic breakout "pins" are used to determine shock velocity between prescribed steps in the target. Under the assumptions of uniform, steady planar shock compression, the combined diagnostics provide absolute measurement of the shock Hugoniot and allow EOS information on isentropic unloading response.

A photograph of a primary vacuum hohlraum with two secondary hohlraums attached at right angles is illustrated in Figure 1. The typical secondary hohlraum diameter being developed for shock wave experiments is 11 mm in outside diameter and about one centimeter long. Also shown in the central part of Figure 1 is an X-ray diode (XRD) measurement of a typical Z pinch, which is formed after implosion of the tungsten wire array in the primary hohlraum. Typical diameters of the imploded plasma are about 2 mm. This imploded condition produces temperatures in the primary hohlraum to nearly 150 eV with present capabilities. Typical primary and secondary hohlraum temperature histories are illustrated on the right side of Figure 1. The X-ray temperature in the primary hohlraum is not Planckian (blackbody) because of significant line radiation produced during wire implosion, but the secondary hohlraum temperature is nearly blackbody due to re-emission of radiation.

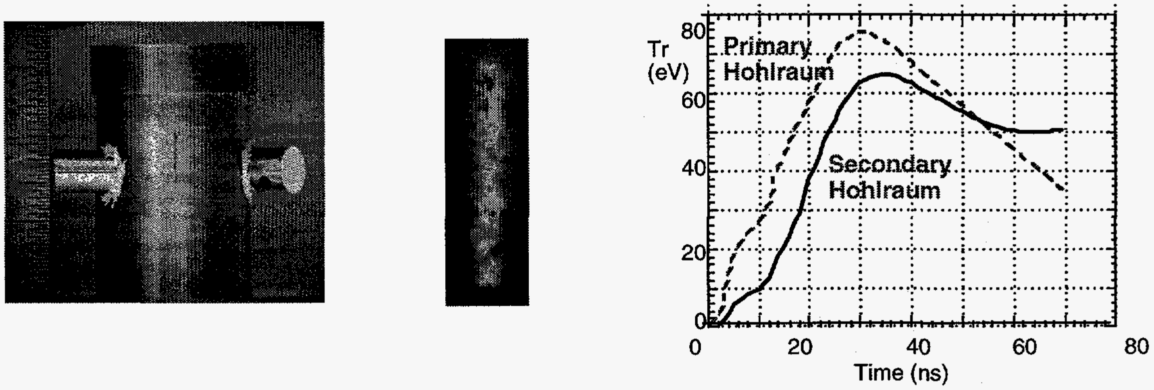

Figure 1. Hohlraum configuration and typically x-ray temperatures obtained in primary and secondary hohlraums during Z pinch experiments. An XRD measurement of a pinch after implosion is also shown.

A photograph of the actual wire array located inside the vacuum hohlraum is shown in Figure 2. Typically, a few hundred individual wires are used to produce the Z pinch source. For the shock wave experiments presently being, designed, arrays of 120 to 240 tungsten wires with individual diameters of about 10 μm are used to produce the Z pinch source. The overall diameter of the wire array is 40 mm.

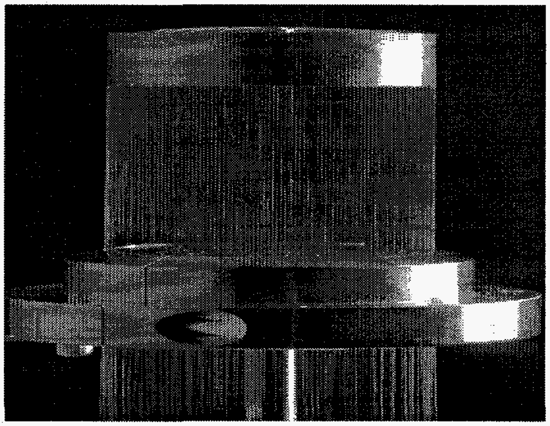

Figure 2. Wire array used for Z pinch experiments.

A cross-sectional view of the type of hohlraum being developed for shock physics experiments is illustrated in Figure 3. The primary hohlraum being proposed for shock wave experiments is about 5 cm in diameter. This contains the radiation produced by the imploded Z pinch. XRD diagnostics are used to characterize the radiation temperature history in the primary hohlraum through a Line-of-Sight (LOS 5/6 in the figure) in the accelerator.

Three secondary hohlraums are attached to the primary in this configuration. These are identical, with outer diameters of about 11 mm, inner diameters of 9 mm, lengths of about 1 cm and with a small shield at the entrance to prevent direct shining of the pinch radiation onto the sample surface. EOS samples are located transverse to the end of the secondary hohlraums. One secondary, S1, contains a specimen with a VISAR (8) interferometer and fiber optic shock breakout diagnostics. A second hohlraum, S2, contains an array of fiber optics to measure shock uniformity and shock speed through a stepped aluminum sample. A second stepped aluminum sample allows another measurement of shock velocity. A third hohlraum, S3, is capped at the end and has a 4-mm diameter hole for to measure the

The configuration being developed for the VISAR experiments is illustrated in Figure 4. The sample is a "hat-shaped" specimen of aluminum that has a diameter ranging from 6-9 mm and a thickness of a few hundred μm. It is located on the end cap of a secondary hohlraum perpendicular to the axis. The objective of this configuration is to uniformly radiate the full ablation surface, thus causing a planar shock wave. The finite time duration of the radiation pulse illustrated in Figure 1 produces a ramping pressure history at the input surface of the specimen, followed by an attenuating pressure pulse. It is desirable to choose the first step height so that a shock is formed by the time it arrives at this point. The second step height is chosen so that the shock pressure is not significantly attenuated at that propagation distance. A series of fiber optic breakout detectors are used to measure shock arrival at the first step. The combined measurements can be used to determine shock pressure and density through the shock jump conditions (1):

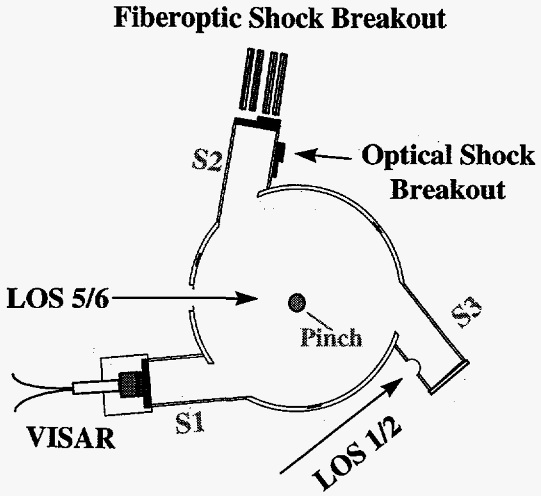

Figure 3. Hohlraum design for shock wave experiments. A primary hohlraum of about 5 cm in diameter is used to contain the radiation from the Z pinch implosion.

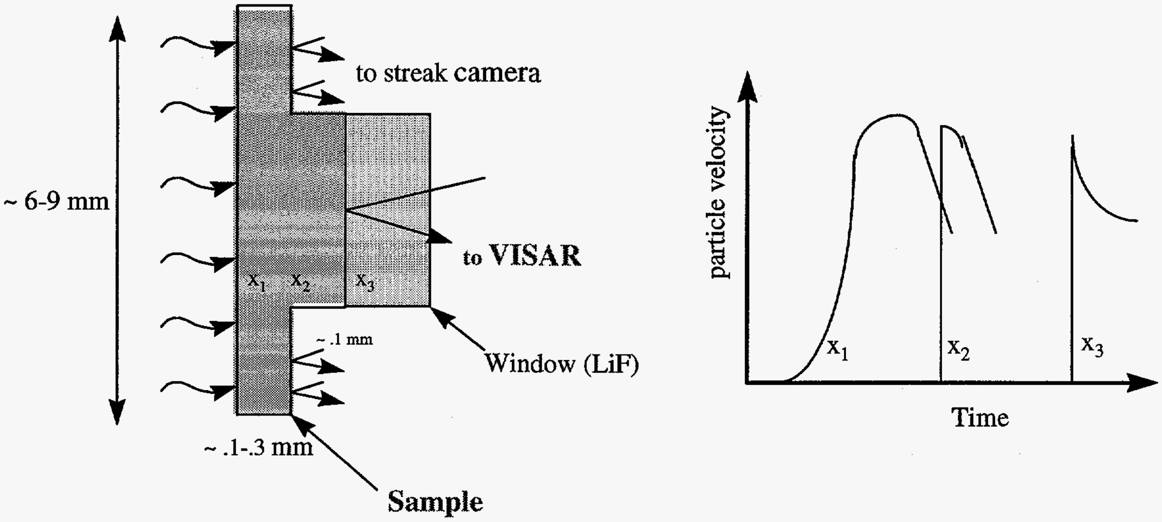

Figure 4. Sample configuration for EOS experiments.

Numerical simulations of the pressure profiles expected with the Z pinch drive conditions was performed with radiation hydrodynamics codes, including ALEGRA (7) and LASNEX (8). To estimate the pressure profiles generated by x-ray ablation in the secondary hohlraum, a time-dependent Planckian source radiation boundary condition was applied at one boundary of the specimen to simulate the source conditions expected in the secondary hohlraum. Maximum temperatures of interest using the assumed radiation pulse covered the range of 50-200 eV.

One of the goals of the simulations was to investigate ablation pressure scaling with atomic number of the target. Two types of calculations were undertaken. First, direct illumination of the target specimen by the secondary radiation was performed. Second, calculations were done with a polystyrene (CH) ablator on the ablation surface.

For a blackbody of about 100 eV and a FWHM temperature history of about 20 ns, the profiles shown in Figure 5 are expected for different propagation distances. It is noted that attenuation of the peak pressure is minimal over the distance of 50-200 μm. The effect of different peak hohlraum temperatures was investigated by scaling the peak temperatures and by keeping the same temporal form for the time dependence. Although the profile shown in Figure 5 are reasonable expectations of the pressures obtained with the Z accelerator, we found that the assumed early temporal dependence of the hohlraum temperatures has a major influence on the pressure wave profiles.

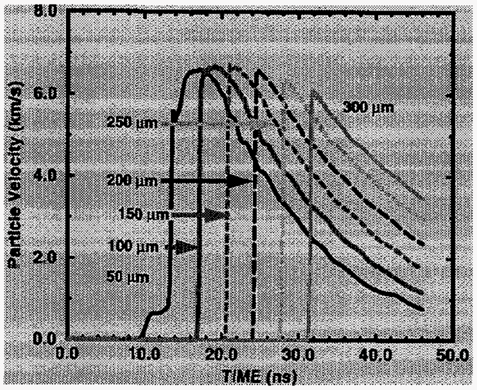

Figure 5. Calculated VISAR records for the baseline temperature drive, conditions over the range of 50-300 μm.

An additional series of simulations was performed with the radiation-hydrodynamics code, LASNEX (8), assuming a similar temporal dependence for the secondary hohlraum temperature. In this case, it was assumed that the temperature rose linearly to peak temperature in 10 ns, remained at the peak for 10 ns, then returned to zero in 10 ns. The peak pressures obtained for varying peak drive temperatures are illustrated in Figure 6. Also shown is a scaling relation (11) developed to give approximate peak pressures at different peak drive temperatures. Low Z materials such as aluminum and plastic, approximate the scaling relation fairly well, although high Z materials, such as tungsten, vary significantly from this relation at higher drive temperatures. However, it is found that this limitation can be minimized by using a relatively thick layer of CH (about 100 μm) at the ablation surface. This substantially increases the peak pressures produced in high-Z materials. Calculations performed with a 100 μm thick layer of CH on tungsten indicate that it should be possible to produce 45 Mbar in tungsten at a drive temperature of 150 eV.

Preliminary experiments have been performed on the Z accelerator to demonstrate the ability to obtain VISAR measurements in the Z accelerator environment. Analysis of these results indicate that another effect, not initially anticipated, is an apparent change in refractive index that occurs in the various optical components used in the system. This effect results in an apparent shift in the frequency of reflected laser light, and causes an error in the measured particle velocity. Experiments are presently in progress to understand and minimize this effect.

In summary, we are developing a new shock wave diagnostic using z pinch sources for high-pressure EOS measurements. Specifically, we are employing VISAR interferometry to measure the particle velocity of shocked materials and fiber optic probes to measure the shock speed. Combination of these measurements will allow absolute EOS data with Z accelerators. This report is a progress report on the development of this new approach to EOS measurements; however, preliminary data obtained with the diagnostics are encouraging. With further development of Z pinch sources, it is envisioned that a variety of EOS and constitutive property measurements can be made. Time-resolved wave profile measurements will then provide a variety of EOS and material property data, such as isentropic EOS, initial compressive strength and shock-induced compressive strength, dynamic tensile strength, kinetics of phase transitions, and surface stability studies.

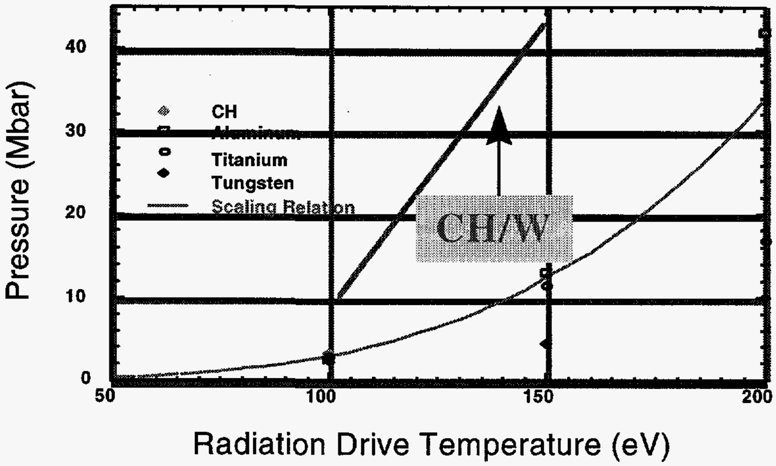

Figure 6. Peak pressures achievable with Z pinch sources as a function of radiation temperature.

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