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Measuring the EOS of a Dense, Strongly Coupled Plasma; Description of the Technique *

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INTRODUCTION.

One of the most fundamental properties of materials is the relation between thermodynamic variables as a function of the material state, designated the equation of state(EOS). For most materials under many conditions, this relation is fairly well known, and there has been much experimental work to determine this relation. One region of parameter space that is not well known is the strongly coupled plasma regime. In this regime the EOS physics is quite complicated due to the strong interaction of individual particles with each other. Many theories attempt to calculate the EOS of a dense plasma, from one component plasma models and density functional models to the standard Thomas-Fermi models which are widely used to produce EOS tables. A lack of experimental data prevents a determination of the accuracy of these models in the dense plasma regime.

This paper describes a new experimental design which we believe can produce reasonably accurate data for the EOS of a dense plasma. This design takes advantage of the standard shock technique used for determining the high pressure EOS of solids. It also utilizes recently developed experimental techniques for producing dense, strongly coupled plasmas^{1,2} as well as new diagnostic techniques³ for measuring the properties of these plasmas. The results should be able to distinguish among theoretical models for plasmas at just under solid density and temperatures of 10's of eV.

DESCRIPTION OF THE TECHNIQUE.

The standard shock technique for measuring the EOS of a material consists of producing a steady shock in a solid by colliding a flyer plate at high velocity with a solid sample of the material of interest. The flyer plate velocity and the shock velocity are the variables measured in the experiment. If the flyer plate and the sample are the same material, the material velocity behind the shock can be determined using the conservation of momentum. These two measurements along with the equations for conservation of mass, momentum, and energy across the shock allow one to determine the pressure, density, and energy of the shocked material. The locus of points produced by a set of such experiments is called the standard hugoniot, where the variable changed is simply the flyer plate velocity. This technique has been the major source of EOS data in the high energy density regime.

When using the shock technique for determining the EOS of a material, the conservation equations across the shock interface must be utilized. These are written as

$$\rho = \rho_0 / (1 - v_p / v_s) \quad 1)$$

$$P = P_0 + \rho_0 v_s v_p \quad 2)$$

$$\mathcal{E} = \mathcal{E}_0 + P v_p / (\rho_0 v_s) - v_p^2 / 2 \quad 3)$$

where ρ_0 and ρ are the densities ahead and behind the shock, v_s is the velocity of the shock, v_p is the velocity of the material behind the shock, P_0 and P are the pressures ahead and behind the shock, and $\mathcal{E}_0$ and $\mathcal{E}$ are the internal energies ahead and behind the shock. These equations are applicable at the shock interface but only apply to the entire sample if the shock produced is planar and steady in time. Here we have three equations and eight unknowns. If the initial pressure and internal energy are very small compared to the final, then approximating them as zero reduces the number of unknowns to six. In the case of solids, the initial density is known. Then one only needs to measure two variables to determine the other three. If the initial density is not known, then three variables must be measured to determine the rest. Such is the case for this experiment and we will measure ρ , ρ_0 , and v_s and use the equations above to determine the pressure and internal energy of the material behind the shock.

Using the shock technique on materials initially in the solid state is not very useful for studying dense plasma effects on EOS. This is because the physics issues that dominate the EOS of materials along the standard Hugoniot are issues of solid state physics, not dense plasma physics. One would therefore like to do experiments in a region of parameter space where the strong coulomb coupling plays a more significant role. This region of parameter space lies in densities less than solid but at temperatures of a few eV. One way to reach these types of conditions is to start off with lower density material not in the solid state. This is what we will attempt to do.

A schematic of our experiment is shown in figure 1. In this experiment, we create a uniform dense plasma by electrically heating an aluminum wire to a temperature of $\sim 4\text{eV}$ and allow this plasma to expand into the vacuum through a rectangular slit. The slit is removed from the end of the wire a few wire diameters to allow the expanding plasma flowing through it to be uniform. This should produce a plasma at densities of a few percent solid and temperatures of $\sim 1\text{ eV}$. We will use a high power laser incident on this plasma plume from the side to launch a shock into the plasma. This laser will deposit its energy at the critical surface, producing a hot, high pressure plasma which drives a shock into the plume. By increasing the intensity of the laser and therefore the pressure, we can obtain EOS measurements along a Hugoniot starting from initial conditions much different than the standard Hugoniot. This should provide some of the first EOS measurements of a dense, strongly coupled plasma.

To measure the material conditions, we will use two variations of the same technique. This technique involves using a short pulse laser incident on a solid target to produce a hot plasma source of x-rays. If the intensity of the laser on target is set to the appropriate value, a significant amount of k-shell lines will be produced. By measuring the absorption of these x-rays through the plasma along with the spatial extent of the plasma, we can determine the mass density, assuming we know the absorption cross section. To insure we are confident of this cross section value, we will use a specific high energy line for this absorption measurement. In our case, we plan to use the 4.7 keV line

from TiXXI. The production of this line requires an intensity on target of $\sim 10^{15} \text{ W/cm}^2$. Also, the absorption of photons at this energy through aluminum should not be affected due to the low ionization state of aluminum at these conditions.

Figure 1. Schematic for Dense Plasma Diagnostic Setup

The same x-ray absorption technique can be used to measure the propagation of the shock through the plasma. In this case a longer pulse of x-rays must be used along with a streak camera to obtain a time history of the shock position in the plasma. The line need not be Ti in this case since an absolute absorption number is not required. Thus, we intend to use the 1.3 keV line from MgXII for this measurement. Production of this line only requires an intensity of $\sim 10^{14} \text{ W/cm}^2$, but since it is needed for a much longer time, the energy in the laser is similar. Both cases require accurate measurements and therefore we need very high spatial resolution when imaging the x-ray absorption through the plasma. To make these measurements, two x-ray microscopes are being constructed. These microscopes will produce a spatial resolution of $\sim 2 \mu\text{m}$ at the plasma. This spatial resolution should provide sufficient accuracy in our measurements to determine the density within 5% and the energy and pressure within 15%.

The initial conditions we expect to produce in the plasma plume are aluminum densities of $\sim 0.1\text{-}0.2 \text{ g/cm}^3$ at a temperature of $\sim 1 \text{ eV}$. The laser intensity available to produce a shock in this plasma will be 5×10^{12} to $5 \times 10^{13} \text{ W/cm}^2$, producing aluminum densities of $\sim 1 \text{ g/cm}^3$ and temperatures of $\sim 25 \text{ eV}$. The Γ for these plasmas, which is the ratio of the average potential energy between ions to their temperature, will be of order 10. At similar conditions for Be the theory of Perrot⁴ differs from the Thomas-Fermi model⁵ by $\sim 25\%$ in energy. This difference should be outside the error bars of our experiment, therefore determining which EOS theory is most accurate in this regime.

Presently we are completing work on the pulsed power machine being used for heating the aluminum wires. Soon production of the aluminum plasma plumes will begin with subsequent measurements of their spatial extent, expansion rate, and temperature using a visible framing camera. The construction of the x-ray microscopes for imaging the plume and measuring the density has begun and should be completed shortly. This will be used to measure the density of the plasma plume and determine when the conditions we seek are produced in this plasma. Subsequently we will complete the construction of the laser for driving the shock in the plasma along with the construction of the second x-ray microscope. This will enable us to begin the EOS measurements in earnest.

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