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Zero to 1,600 m/s in 40 microns: Sensitive pulse shaping for materials characterization on Z

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Abstract

Dynamic materials properties experiments on Sandia National Laboratories Z Machine require increasingly precise electrical current pulse shaping. In the experiment described here, a copper flyer plate is accelerated from rest to 1,600 m/s over a 40 micron flight gap in 50 ns. This flyer then impacts a cerium sample, shock melting the cerium, before subsequent quasi-isentropic ramping to mega-bar pressures. Through predictive simulations, postdicted analysis, and a new computational tool for characterizing inherent Z Machine timing accuracy, qualitative estimates of pulse controllability and experimental design robustness are arrived upon.

Keywords: high energy density; dynamic material properties; pulse shaping; equation of state; Z Machine; laser triggered gas switch; timing

1. Introduction

The Z Machine (Z) at Sandia National Laboratories is capable of delivering 26 MA of pulsed electrical current with a 1 µs rise time to a load. By shaping the current pulse it is possible to quasi-isentropically compress materials to multi-Mbar pressures, allowing for direct observation of high energy density (HED) states of matter. Dynamic materials properties (DMP) experiments on Z are now at a stage where high-fidelity control of the pulse shape and micron-scale machine tolerances are enabling the exploration of materials in regions of phase space not previously

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accessible by experiments, and data at off-Hugoniot conditions and extreme pressures for various materials is routinely obtained. Data acquired on Z are used to construct more accurate equations of state at HED conditions than theory alone may currently allow. We will consider cerium here, which is of particular interest because attempts to build equations of state at even relatively low pressures using computational methods have proved problematic [1]. The present work will outline the design procedure for shot Z3005, which involved particularly tight design tolerances in an attempt to probe the melt line of cerium.

DMP experiments on Z utilize a set of standardized load hardware that is adjusted as necessary, which greatly accelerates design time and increases experiment success rate. The present experiment utilized the standard 11 mm stripline configuration, which resembles a thin inverted U-shaped load with current flowing along the inside shorted loop with the material samples mounted on the outside of the structure. Due to a taper engineered into the load, the magnetic field has a high degree of uniformity along the z-axis, ensuring nearly identical loading profiles to all six sample locations (three each on the cathode and anode sides) [2]. The specifics of the samples mounted to the exterior of the stripline varies between experiments and depends on the desired loading profile and material being studied. Cerium samples of 8.0x7.3 mm with thicknesses ranging from 0.8 – 1.1 mm are impacted by a 2.5 mm thick copper flyer. The exterior surface of the cerium samples (opposite the flyer impact side) are tamped to 3.0 mm thick lithium fluoride windows.

The experiment considered here is termed a shock-ramp, in which a flyer plate of well characterized material is thrown at ballistic velocity and high planarity into a sample material to be probed. Upon impact the current continues to flow through the flyer, further accelerating it, thus imparting a carefully designed ramp loading profile to the sample material. Through this method of shocking and subsequent quasi-isentropic ramping it is possible to explore off-Hugoniot states for a large variety of materials [3]. If the initial shock is designed to exceed the sample's shock-melt pressure then subsequent ramp compression of the liquid may be used to probe the location of the fusion curve at higher pressure for materials that possess a melt line with positive Clapeyron slope, aiding in construction of a multi-phase equation of state (EOS). Velocimetry data – obtained via Velocity Interferometer System for Any Reflector (VISAR) [4] or Photon Doppler Velocimetry (PDV) [5] – is captured from the sample-window interface over the course of the experiment and, through computational physics models, can be interpreted to yield insight into the material state [3].

The successful design and execution of a DMP experiment on a pulse power platform relies on the verifiable accuracy of sophisticated computational physics models that can predict both the platform's performance under a given load configuration as well as the dynamic material response of the flyer-sample mass under the proposed magnetohydrodynamic (MHD) load. The two workhorse codes utilized for shot design are the Z Circuit Model – a transmission line circuit model that can accurately reproduce the electrical response of Z [6] – and the Alegra MHD shock multi-physics code that can predict the load response in one, two, or three dimensions through MHD/solid dynamics coupling [7]. Both codes were developed at Sandia National Laboratories.

The remainder of this paper is laid out as follows. In section two the basic design process for a planar shock-ramp Z experiment will be explained using Z3005 as an example. In section three the analysis of data from Z3005 will be presented and observations made. In section four a new tool for characterizing design robustness will be described and demonstrated before moving to overall conclusions in section five.

2. Typical Design Process

DMP experiment design typically begins with a desired one-dimensional (1D) hydrodynamic loading profile for a target sample material. This design incorporates a number of target criteria and is simulated in a one-dimensional solid dynamics code. Under hydrodynamic loading, a prescribed pressure is applied to the drive side of the flyer, which deforms according to the validated material models for the drive material, which here is pure copper. On Z, the pressure is applied via the Lorentz force as multi-mega-ampere currents flow through the drive surface, which results in rapid phase transition from solid to plasma, reducing the thickness of ambient (solid) flyer over time, thus increasing the acceleration as a function of time due to mass loss. Accordingly, the initial hydrodynamic pressure profile must be adjusted to account for these effects, which is done through 1D Alegra MHD simulations. The initial design for our MHD drive is shown in Figure 1, in which three distinct regions can be identified. The initial ramp