Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 00 (2017) 000–000

SAND2017-4617C

Procedia Engineering

www.elsevier.com/locate/procedia

14th Hypervelocity Impact Symposium 2017, HVIS2017, 24-28 April 2017, Canterbury, Kent, UK

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

Andrew J. Porwitzky[a]*, Christopher T. Seagle[a], Brian J. Jensen[b]

[a]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
[b]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

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

---

* Corresponding author. Tel.: 1-505-844-6423.
E-mail address: ajporwi@sandia.gov

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 Clapyeron 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 Bertha 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 begins at 2.2 µs due to current transit times through Z, with zero time referencing the initial discharge of the 36 Marx banks. From 2.2 to approximately 2.6 µs we have the initial ramp phase, in which the flyer is accelerated over the 40 µm flight gap up to a peak flyer speed before impact of approximately 1,600 m/s. From 2.6 to 2.75 µs is the pressure hold; it is at the start of this time that each flyer impacts its paired cerium sample. The pressure hold ensures that the shock is supported and steady as it transits the thickness of the largest sample, otherwise it is difficult to characterize the bulk state of the sample material and greatly increases the uncertainty in the resultant EOS construction. The region of the drive from 2.75 µs to peak current is responsible for ramping the sample to the ultimate target pressure (approximately 1.1 Mbar here). With a magnetic drive established, the corresponding load current is obtained through two-dimensional Alegra simulations which account for gross conductor motion. The details of such calculations have been described in detail elsewhere [8].

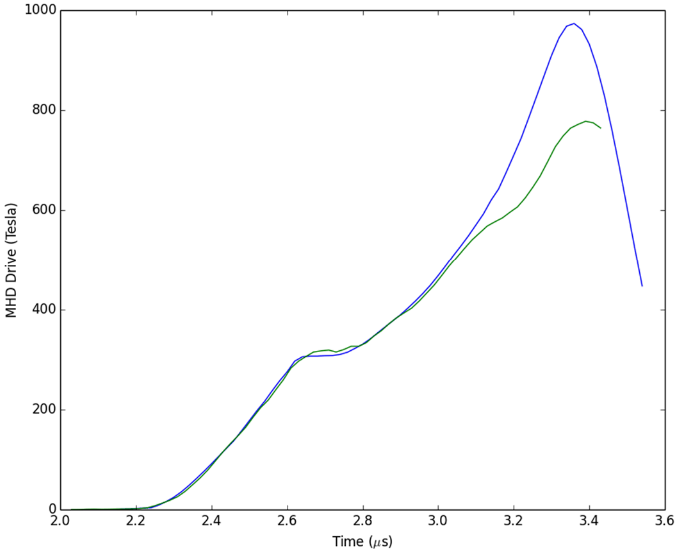

Fig. 1. Preliminary design for MHD field drive (blue) and the final experimental prediction based on pulse shaping (green).

Any loading profile can be drawn and simulated, but engineering reality enters during the pulse shaping step, in which the Bertha circuit model is used to simulate the dynamic response of Z for a given machine configuration. Z consists of 36 independent pulse lines, each of which can be configured to generate one of five pulse shapes of different rise times. Each line can have an advance discharge time ranging from approximately +650 ns to -50 ns, which is achieved by adjusting the sulfur hexafluoride gas pressure in the laser triggered gas switches (LTGS) [9]. The voltage held off by the spark gap in the LTGS increases (roughly) parabolically in such a way that peak voltage occurs for zero advance time. By decreasing the gas pressure in the LTGS, breakdown occurs before peak charge, resulting in an advanced firing of that line; correspondingly advanced lines have lower peak output current than do non-advanced lines of the same pulse type, making the pulse shaping process highly non-linear. Groups of four adjacent lines can be set to A or B Marx triggering which allows for two sets of initial Marx bank firings up to 600 ns apart, allowing for overall shaped pulse rise times on the order of 1 µs. Overall Marx charge voltage is adjusted nominally from 60 to 95 kV. All of these factors allow for high variability in pulse shaping, though not to an arbitrary degree. Not until the pulse shaping stage is it clear if a proposed design is producible on Z. The atypically small flyer gap used on this experiment was of concern because it necessitated an aggressive flyer ramp from rest to 1,600 m/s in 40 µm in order to impart a shock just above the melt line in cerium. If a linear acceleration to impact velocity is assumed, then the flyer experiences a constant acceleration of ~3 giga-g's. With such rapid acceleration necessary the risk of the flyer shocking prior to impact was accepted as a possibility.

The final magnetic field drive is shown alongside the design target in Figure 1 and a number of differences are clearly visible. In order to match the slope of the initial ramp using as few pulse lines as possible, a slight overshoot of the target hold pressure was found to be unavoidable. Accordingly, the ramp had to be shaped in such a way that the bend over to the hold had to be completed before sample impact. Unlike these early time differences, the substantial deviation between initial and final design in the sample ramp was an improvement over the initial design. During pulse shaping it was found that – according to the Mie-Grüneisen EOS used for the cerium – the ramp trajectory was such that a shock would develop in the sample. Compensating for this prediction led to the inflection point in the drive profile around 3.1 μs. Once through this region of the EOS a more rapid ramp could be resumed. Due to the simplistic nature of the Mie-Grüneisen EOS it is possible that this shock generation is an artifact, but a cautious design path was followed in favor of ignoring the simulation results in this region. Additionally, any current losses should be largest in this later region of the pulse (highest current load), further decreasing the slope of the sample ramp and adding a safety margin.

3. Shot Z3005 Analysis

If a sample is not included in one of the six available locations on the stripline load then it is possible to obtain velocimetry data from a “naked flyer” which can be used in conjunction with validated computational models for the flyer material to “unfold” a magnetic drive. A non-linear least squares method using Dakota [7] can be employed with the design drive as an initial guess to converge to the drive evident in the experiment. This unfold allows for the MHD drive to be obtained independent of sample EOS, instead relying on validated models for the drive material. It is also independent of all other diagnostic monitors deployed on Z and it is the most accurate method known for determining the current delivered to the load [10].

Figure 2 shows the final design prediction for the flyer free surface velocity compared to the experimental measurement. A shock appeared in the flyer during the ramp, though the sample impact timing and velocity were not significantly affected, so a stable pressure hold was achieved and usable material data successfully obtained. Non-linear least squares optimization identifies the magnetic field drive from the experiment, reproducing the measured flyer free surface velocity with maximum residuals less than 20 m/s, which is the experimental uncertainty in the VISAR measurement. The final design and experimental drives are shown in Figure 3 and show an intuitive correlation between velocity deviation and drive deviation. The unfolded drive ends before peak current due to a causality effect: the effect of the drive must propagate through the flyer in order to affect the surface velocity, thus late time drive information is irrelevant beyond a certain point. A two-stage loss mechanism is observed during the sample ramp that can not be accounted for by machine jitter (the subject of the next section) and is beyond the timing deviation postdicted from Z voltage diagnostic probes. This atypical loss is being investigated, and ongoing Z experiments continue to explore the mechanisms of current loss [11].

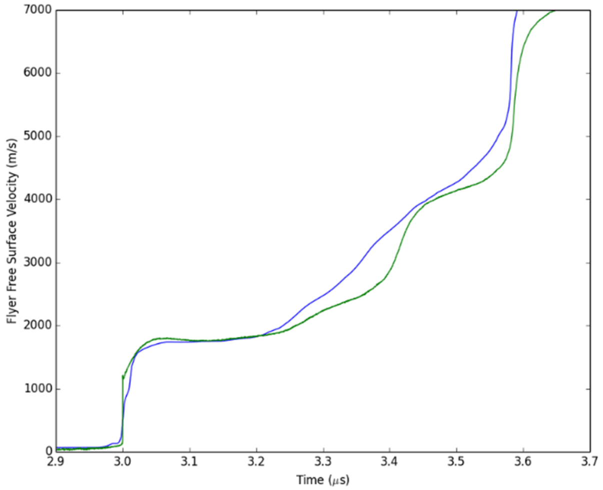

Fig. 2. Prediction of the flyer free surface velocity based on the final design (blue) and the VISAR recorded free surface velocity (green) from Z3005. Prediction depends only on the validated flyer (copper) material models and not on any cerium data. Differences are due to deviation from the design drive to the experiment drive.

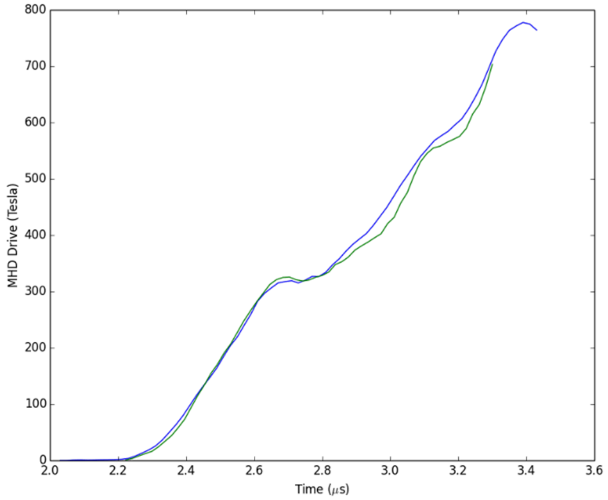

Fig. 3. Design MHD drive (blue) and experimental MHD drive (green) unfolded from naked flyer velocimetry data.

With the experimental drive determined, a forward simulation can be performed for the cerium sample, producing a sample-window interface velocity that can be used to help characterize a cerium EOS. Future work by the authors will outline the material science data obtained from this and subsequent cerium shock-ramp experiments.

It is clear from Figures 2 and 3 that a subtle deviation from the design drive during the ramp resulted in a shock forming in the flyer, leading to questions of design robustness. In order to characterize robustness for future designs, a new computational tool was developed to explore what is termed machine jitter – the error in the prediction of the LTGS firing times due to the sensitivity in the timing of the dielectric breakdown.

4. Design Robustness Analysis

The LTGS have a one sigma timing uncertainty of ±5 ns [12]. A framework for automated 1D DMP simulations has been developed to aid in experiment design that incorporates automated plotting scripts to visualize design parameters. By coupling that framework with a new capability to randomly perturb LTGS advance times inside a two sigma range we are able to assess experimental design robustness from a pulse shape control standpoint. The statistical analysis possibilities of this framework are just beginning to be explored, but a qualitative robustness estimate can be obtained with a relatively small sample size.

A random uniform distribution perturbation is applied to each of the 36 pulse lines in a ±10 ns window. The pulse shape that results from this configuration is captured from the Bertha circuit model and passed to the automated 1D design package so that the effect of the perturbation can be propagated through to the simulated experiment; thus we can observe how LTGS timing uncertainty affects design robustness. Ten randomly perturbed configurations were run on the design pulse and it was found that six generated undesirable shocks in the flyer ramp, while four exhibited smooth acceleration to impact. Repeating with different random seeds bore out consistent statistics on subsequent sets with ten samples each. From a qualitative standpoint we can conclude that the design had a 60% chance of flyer shock-up before impact. The simulations and shot data indicate that, due to the small flight gap, flyer shock formation does not significantly affect the flyer-sample impact time in this particular experiment. This is not the case for most shock-ramp experiments, where flight gaps are typically 200-400 μm. If the flight gap is of this order then shock formation in the flyer can result in the flyer-sample impact occurring earlier than designed, which can cause a mistiming of the pressure hold and its magnitude. For Z3005, machine jitter causing the flyer to shock may advance the sample impact time 5 ns or less, a magnitude that by necessity must result in an insignificant impact to the physics goals of the experiment, since we know that machine jitter defines the controllability of the pulse shape to have a one sigma of 5 ns.

Using the small statistical sample size outlined above, we can qualitatively characterize the machine jitter for this experiment. The flyer free surface velocity during the pressure hold varies less than 100 m/s, which imparts a predicted shock pressure into the cerium of between 21 and 26 GPa. Critically, the minimum shock pressure as a result of jitter is above the 18 GPa shock melt [13]; for this reason, a buffer above the target phase transition pressure should always be incorporated into the design. If machine jitter pushed the cerium shock pressure below the melt target, then the cerium could be placed into a mixed phase which would be undesirable for the material science goals of the experiment. Due to the conservative design of the sample ramp region of the pulse, none of the jittered configurations resulted in a shock-up of the cerium sample. Though the jitter calculation clearly demonstrates a high probability of the flyer shocking during the ramp phase, the atypically small flight gap resulted in the pulse shape remaining robust for this particular design because impact timing was not significantly affected by the flyer acceleration profile.

5. Conclusion

Sensitive pulse shaping on the Z Machine is possible if considerations are made concerning the inherent uncertainty in laser triggered gas switch timings. The code infrastructure detailed here for Z Machine jitter analysis is simple and easily deployed, and as a result has become part of the design process for several shot designers. If incorporated early enough in the design process the jitter analysis can potentially improve Z Machine DMP experiment success rate.

Acknowledgements

The authors would like to thank Jean-Paul Davis for many useful discussions concerning pulse shaping, and Justin Brown for his assistance testing the robustness analysis tools described here.

References

[1] N. Devaus, M. Casula, F. Decremps, S. Sorella, Electronic origin of the volume collapse in cerium, Phys. Rev. B 91, 081101(R), 2015.

[2] D.B. Seidel, W.L. Langston, R.S. Coats, M.D. Knudson, R.W. Lemke, J.-P. Davis, T.D. Pointon, An optimization study of stripline loads for isentropic compression experiments, IEEE Pulsed Power Conference, 2009.

[3] C.T. Seagle, J.-P. Davis, M.R. Martin, H.L. Hanshaw, Shock-ramp compression: Ramp compression of shock-melted tin, Appl. Phys. Lett. 102, 244104, 2013.

[4] L.M. Barker and R.E. Hollenbach, Laser interferometer for measuring high velocities of any reflecting surface, J. Appl. Phys., 43, 4669, 1972.

[5] O.T. Strand, D.R. Goosman, C. Martinez, T.L. Whitworth, Compact system for high-speed velocimetry using heterodyne techniques, Rev. Sci. Instrum., 77, 083108, 2006.

[6] B.T Hutsel *et al*., Z machine circuit model development, IEEE Plasma Science (ICOPS), 2013.

[7] R.W. Lemke, M.D. Knudson, D.E. Bliss, K. Cochrane, J.-P. Davis, A.A. Giunta, H.C. Harjes, S.A. Slutz, Magnetically accelerated, ultrahigh velocity flyer plates for shock wave experiments, J. Appl. Phys. 98, 073530, 2005.

[8] J.-P. Davis, C. Deeney, M.D. Knudson, R.W. Lemke, T.D. Pointon, D.E. Bliss, Magnetically driven isentropic compression to multimegabar pressures using shaped current pulses on the Z accelerator, Phys. Plasmas 12, 056310, 2005.

[9] K.R. LeChien, *et al.*, 6.1-MV, 0.79-MA laser-triggered gas switch for multimodule, multiterawatt pulsed-power accelerators, Phys. Rev. ST Accel. Beams 13, 030401, 2010.

[10] R.W. Lemke *et al.*, Probing off-Hugoniot states in Ta, Cu, and Al to 1000 GPa compression with magnetically driven liner implosions, J. Appl. Phys. 119, 015904, 2016.

[11] G. Laity *et al.*, Experimental platform development for studying vacuum power flow physics at the Sandia Z Accelerator, submitted to IEEE Pulsed Power Conference, 2017.

[12] R. Focia *et al.*, Performance enhancements and results of testing a new 6.7 MV laser-triggered gas switch system on the refurbished Z accelerator, IEEE Pulsed Power Conference (PPC), 2013.

[13] B.J. Jensen, F.J. Cherne, J.C. Cooley, M.V. Zhernokletov, A.E. Kovalev, Shock melting of cerium, Phys. Rev. B 81, 214109, 2010.