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Advances in Pulsed Power and MHD Technology to Enable High Pressure Material Dynamics Studies

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Abstract. Pulsed power devices are quite efficient at producing very large pulsed current and magnetic field densities. The corresponding Lorentz forces enable these devices to be used very effectively in driving implosion experiments; both wire array Z-pinch experiments and liner implosion experiments. In these cases, the relatively low mass cathode (the wires or the liner) are accelerated ($>10^{12}$ g) to high velocity in a convergent geometry. Recently, researchers at Sandia National Laboratories have investigated the use of the Z accelerator to perform "liner explosion" experiments. In this case, a relatively low mass anode is accelerated to high velocity in a divergent geometry. These experiments have been directed toward highly accurate dynamic material studies. In particular, emphasis has been placed on the launching of planar, solid density flyer plates to velocities approaching 30 km/s for use in equation of state studies at ultra-high pressure. Several advances in pulsed power and magneto-hydrodynamic technologies required to perform these experiments will be discussed.

INTRODUCTION

Pulsed power devices are capable of producing extremely large current and magnetic field densities. The associated Lorentz forces enable these devices to be used very effectively in Z-pinch and liner implosion experiments. Recently, researchers at Sandia National Laboratories have investigated the use of the Z accelerator [1] to perform "liner explosion" experiments using aluminum liners. In these experiments a short circuit, square or rectangular load is used to obtain several hundred GPa magnetic pressure, which can accelerate a relatively low mass anode outward at high velocity. These high pressures, and associated Giga "g" accelerations, are sufficient to launch the anode to velocities approaching 30 km/s.

The kinetic energy of a liner accelerated to these velocities is of order several hundred kJ/gm. This energy is approximately 50 times that required to melt and vaporize the anode material. Thus the high-pressure loading, resulting from the Lorentz force, must be tailored to maximize the transfer of energy in the form of kinetic rather than internal energy. This requirement necessitates the ability to finely control the current pulse shape of the Z accelerator discharge. To accomplish this, the triggering system of the accelerator was modified to allow independent firing of the transmission lines, and the circuit model for Z was modified to accurately predict the resulting time-dependent voltage.

Furthermore, a fully self-consistent, 2-D magneto-hydrodynamic (MHD) simulation capability is needed to determine suitable anode/cathode geometries to ensure planarity of the expanding liner. This simulation capability is also necessary to accurately account for the electrode deformation and significant load inductance increase that occurs during the discharge of the accelerator; this inductance increase significantly influences the shape and peak of the current pulse obtained from the applied voltage.

These advancements in pulsed power and MHD technologies will be discussed in the following sections.

PULSE SHAPING

The optimal pressure profile for accelerating the anode is one that results in isentropic compression of the anode material. Since isentropic compression is adiabatic, the thermal loading of the plate is minimized. Furthermore, since isentropic compression is reversible, the released state of anode is considered to be at ambient density and temperature. In solids the longitudinal stress differs from the hydrostatic pressure because of resolved shear stresses that produce an entropy increase from the irreversible work done by deviator stresses, and thus the loading is properly referred to as quasi-isentropic. Nevertheless, it is estimated that the resulting temperature increase and density decrease is minimal for materials with low elastic limits, such as aluminum.

The optimal pressure profile is also one that maximizes the propagation distance of the isentropic compression wave, or ramp wave, prior to shock formation. Due to the non-linearity in material sound speed with pressure, a ramp wave tends to steepen with propagation distance, and will ultimately form a shock wave. The significant increase in dissipation associated with the shock results in significant heating of the material, and can ultimately result in vaporization of the material upon unloading. Given the material sound speed as a function of pressure, the optimal pressure profile can be determined by requiring that the material characteristics all converge at a single position in the sample, with the propagation distance such that it is larger than the thickness of the anode, as shown in Fig. 1(a). These requirements dictate the rise-time and shape of the pressure profile. In these experiments the optimal rise-time is ~200 ns with a strongly concave shape, similar to that shown in Fig. 1(b).

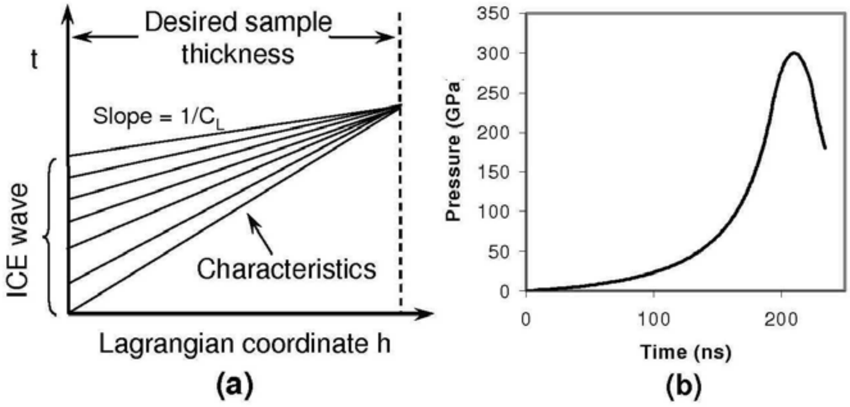

FIGURE 1. (a) Position-time diagram showing characteristics emenating from a ~200 ns shaped ramp wave. (b) Ideal pressure profile to launch an aluminum flyer plate to ultra-high velocity.

In contrast, the typical pressure profile obtained from the Z accelerator is nominally ~100 ns and quite linear in time. Thus, the current profile must be altered. This is accomplished by staggered triggering of the individual transmission lines of the accelerator. Z is comprised of 36 capacitor banks which energize an equal number of intermediate storage capacitors (ISC). Each of the ISCs is connected to a pulse forming line by a laser triggering switch (LTS). The pulse forming network feeds energy to four levels of magnetically insulated transmission lines (MITLs), which direct energy to the load. Shaping the current pulse is accomplished by staggering the timing of the LTS in 9 groups of 4 (one line to each level of the MITLs) in such a way that magnetic nulls in the MITLs and current reversals at the insulator stack are both minimized [2]. The triggering optimization relies heavily on PIC simulations of the MITLs to identify the location of magnetic nulls [3] as wells as a flexible circuit model for Z to predict the resulting time-dependent voltage [4].

MHD MODELING

The expected time-dependent voltage, either from the Z circuit model or from an experimental measurement for a similar timing configuration, is used as the input for a fully self-consistent, 2-D MHD simulation to predict the performance of a particular load geometry using the Sandia developed code ALEGRA [5]. A 2-D slice of the typical load geometry is shown in Fig. 2(a). The magnetic field is uniform in the 3rd dimension (experimentally verified), which enables the problem to be simulated accurately in 2-D. Fig. 2(b) shows the large deformation of the load that occurs during the discharge of the accelerator. The load becomes an element of a simplified LR circuit of the accelerator, shown in Fig. 2(c). Values for the inductances L_c and L_{ext} are determined from geometrical considerations. The inductance of the MHD load is calculated self-consistently in the simulation using an effective transverse length representative of the actual experimental load.

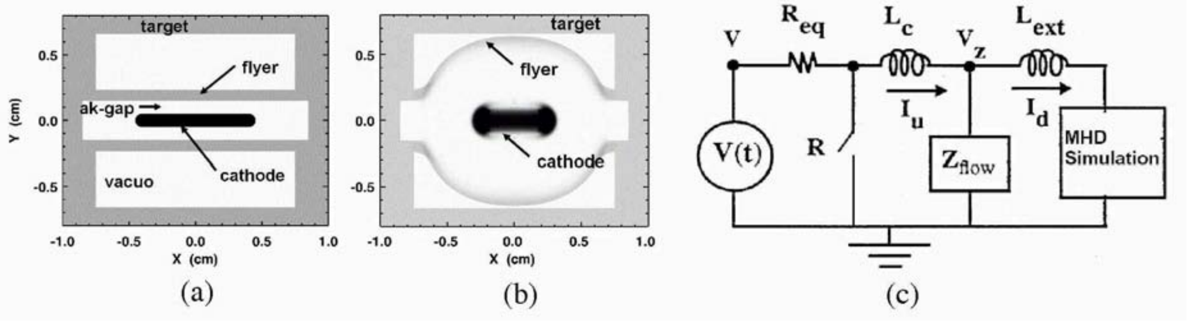

FIGURE 2. (a) 2-D schematic of the flyer plate load, a perpendicular slice through the coaxial geometry. (b) Snapshot of load just before flyer impacts target. (c) LR circuit model of the Z accelerator with the 2-D simulation as one of the circuit elements.

Results of these 2-D simulations are in excellent agreement with experiment. In particular, the load current, denoted as I_d (downstream current), is accurately reproduced, as shown in Fig. 3(a). This level of agreement indicates that the circuit model accurately reproduces the details of the electrodynamics involved in the discharge of the accelerator.

This is significant in that without explicitly taking into account the significant increase in load inductance (see Fig. 2(b)), the predicted peak current would be too large, and thus the driving pressure would be overestimated. Furthermore, the magnitude of the reverberation is dependent on the magnetic pressure just after peak current, when the reflected rarefaction wave from the initial driving pressure pulse interacts with the drive surface. These key features are necessary in being able to accurately predict the performance of an arbitrary load configuration.

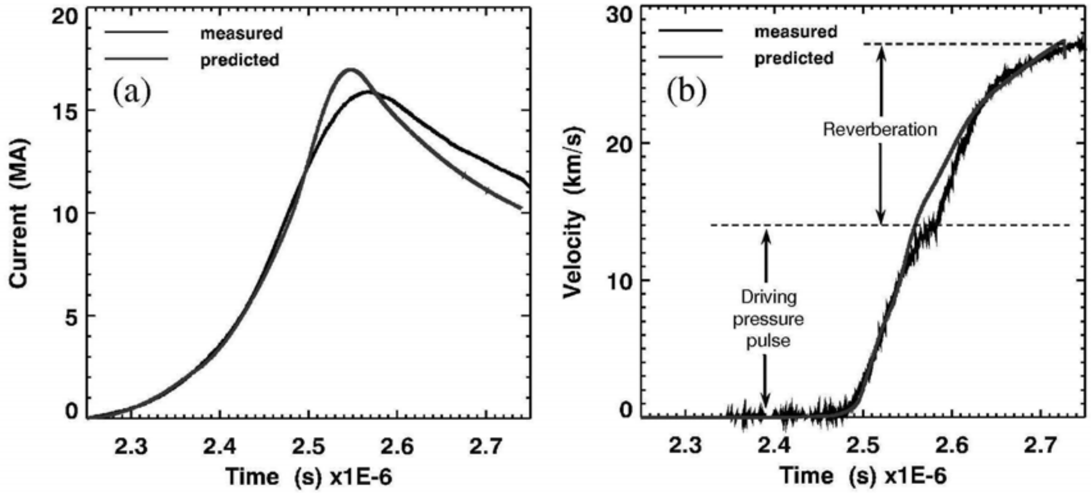

FIGURE 3. (a) Comparison of the simulated (gray) and measured (black) load current (I_d). (b) Comparison of the simulated and measured velocity profile of an aluminum flyer plate launched to over 27 km/s. Measurements of current and velocity have uncertainties of ~5-10% and ~1%, respectively.

ALEGRA simulations performed to optimize the load geometry suggests that an asymmetric configuration, similar to that shown in Fig. 2(a) but with the lower flyer plate removed, should significantly increase the flyer velocity. Simulations with such a configuration predict a shocklessly accelerated flyer plate with peak velocity of ~33 km/s

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