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Considerations For Generating Up To 10 Mbar Magnetic Drive Pressures With The Refurbished Z-Machine (ZR)

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Abstract. The intense magnetic field generated in the 20 MA Z-machine is used to accelerate flyer plates to high velocity for EOS experiments. A peak magnetic drive pressure on the order of 2 Mbar can be generated, which accelerates an approximately 0.2 g aluminum (Al) disc to 21 km/s. In a planned refurbishment of Z, called ZR, it is expected that up to 26 MA will be delivered to certain loads (e.g. dynamic hohlraums). We have used magneto-hydrodynamic (MHD) simulation to predict the peak magnetic drive pressure (and flyer velocity) that can be generated in a shock physics load on ZR. MHD simulations show that motion of the electrodes during the rise to peak current significantly increases the load inductance, which limits the peak current to values less than the expected maximum. This reduces the peak drive pressure to a value below what would be estimated using the expected peak current in a static geometry. However, MHD simulations show that starting with a load geometry that maximizes magnetic flux on one wall of the anode, it is possible to reduce dynamic geometry effects by tapering the rise of the voltage pulse in combination with using a stiff material for the cathode. Simulations predict that peak magnetic pressures of 6 Mbar in Al, and 10 Mbar in tungsten are possible on ZR. In addition, it is predicted that flyer velocities of 40 km/s and larger can be achieved.

2D MHD SIMULATIONS AND RESULTS

Material science experiments on the Z machine have yielded: (1) equation of state (EOS) measurements of deuterium for pressures up to 700 Kbar in conventional shock experiments [1], (2) measurements of the isentrope of Al up to 1.5 Mbar [2], and of Cu up to 400 Kbar in isentropic compression experiments (ICE) [3] and (3) flyer velocities up to 28 km/s. Indeed, experiments on Z have set benchmarks for future performance. We have performed a computational study using 2D MHD simulation to determine how material science experiments on Z will scale to ZR, the refurbished Z machine. In this paper we discuss physics and design issues at multi megabar magnetic pressures, and present results of 2D MHD simulations which constitute predictions for the performance of material science experiments on ZR.

The main physics issue is a consequence of the compressibility of the conductors that form the load for material science experiments. A typical load is shown in Fig. 1, and is comprised of a stainless steel cathode and Al anode (for example). The deformation that the electrodes undergo due to compression by the magnetic pressure results in significant inductance increase during the current rise time. The time dependent inductance is an effective resistance that creates kinetic energy at the expense of magnetic energy. Thus, significant conductor motion during the rise time of the current pulse reduces peak current and magnetic pressure.

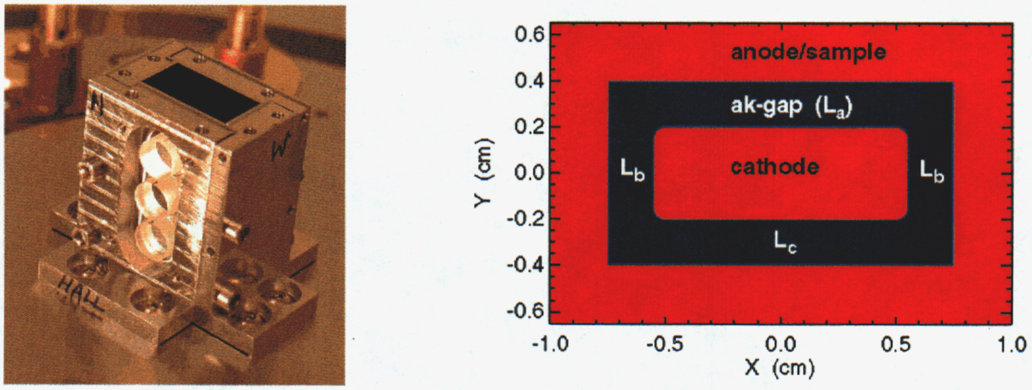

FIGURE 1. (a) Photograph of material science experiment load showing anode housing. Cathode (not shown) is centered on duct formed by anode walls and is connected to top of anode in a short circuit, which is accomplished with a cap. (b) Top down schematic of load showing cathode and anode. The material sample of interest is part of the anode. The L_i represent inductances of various current paths.

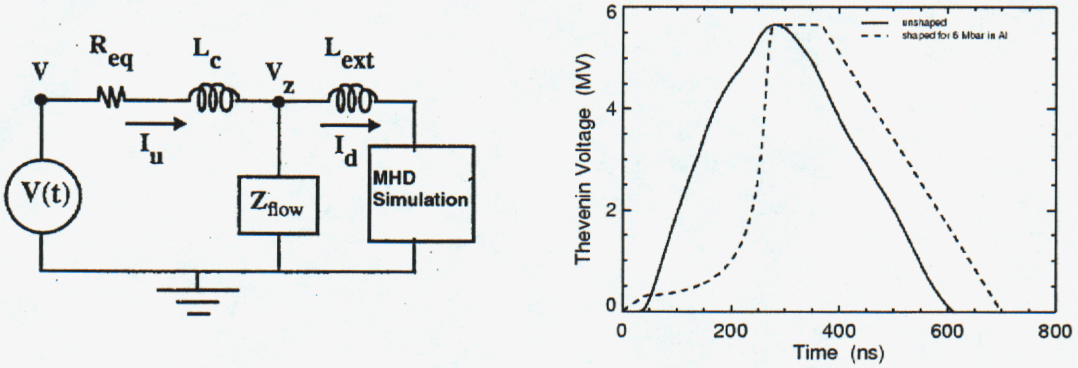

FIGURE 2. (a) Schematic of circuit driven 2D MHD simulation. Values of circuit parameters appropriate for ZR are: R_{eq}=0.18 Ω, L_c=10.18 nH and L_{ext}=2.3 nH. (b) Time dependent voltages V(t) used to drive the MHD simulation. The solid curve is the anticipated raw (unshaped) ZR voltage, and the dashed curve is an ideal waveform that contains the same amount of energy. The rise time of the ideal pulse is shaped to achieve isentropic compression to 6 Mbar in Al. Power enters the simulation from the 3rd (transverse) dimension in Fig. 1a. The effective length in this direction is 3.6 cm.

We have used the Sandia developed, radiation magneto hydrodynamic, finite element code ALEGRA [4] to investigate time varying inductance (L-dot) effects on ZR. Simulations are 2D MHD and are driven by an external circuit model of ZR. The simulation model is shown schematically in Fig. 2a. The Z_{flow} loss element is ignored, which can result in an over-estimate of the load current of about 5% (depending on voltage). The dynamic load feeds back on the circuit to affect the input power. Voltage waveforms used to drive the simulations are shown in Fig. 2b. Sesame equations of state are used for materials [5], in addition to models for the thermal and electrical conductivities [6,7]. The Ohm's law used includes the resistive electric field and the velocity cross magnetic field term.

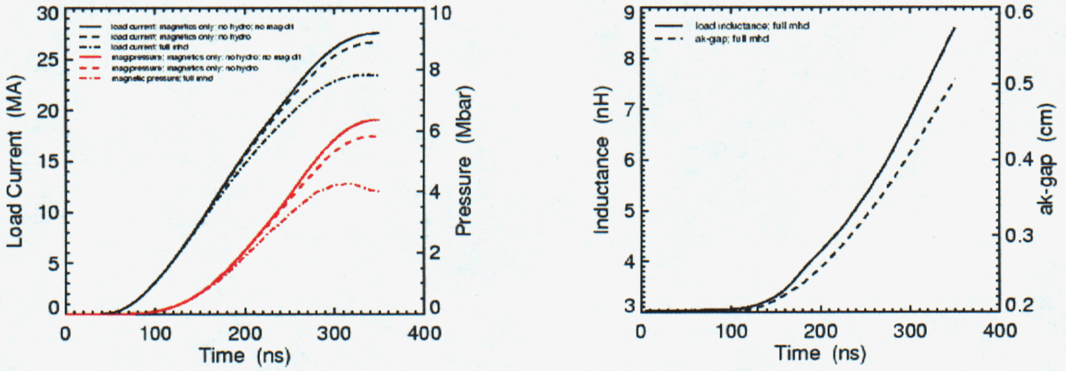

FIGURE 3. (a) Load currents (black curves) and magnetic pressures (red curves) from 2D MHD simulations with: (1) no hydro motion, magnetic diffusion minimized, magnetics only (solid lines), (2) no hydro motion, magnetics with magnetic diffusion (dashed lines) and (3) full MHD (dash-dot lines). (b) Load inductance and ak-gap vs. time in full MHD simulation.

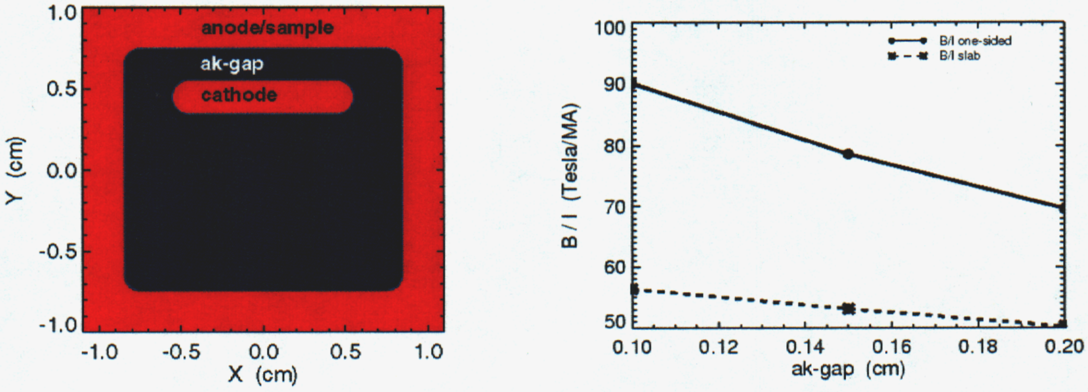

FIGURE 4. (a) Schematic of material science load optimized to reduce alternative current paths thereby concentrating magnetic flux under material sample region (ak-gap) where maximum magnetic pressure is desired. (b) Comparison of magnetic field per unit current for Fig. 4a (solid curve) and the analogous slab geometry (see Fig. 1b).

Figure 3 shows results from a simulation of an unoptimized geometry (similar to Fig. 1b) in which the electrodes are Al; cathode dimensions are 11x4 mm, anode inner dimensions are 15x15 mm and the ak-gap is 2 mm. The plots show that in the case of a purely inductive static geometry 28 MA peak current is delivered to the load. However, in the full MHD case conductor motion during the current rise time produces an L-dot that reduces the peak current to ~23.5 MA, with a corresponding 33% reduction in peak magnetic pressure. Comparison of Figs. 3a and 3b shows that the inductance increases by factor of 2.3 during current rise time, which reduces peak current (and magnetic pressure) relative to ideal case.

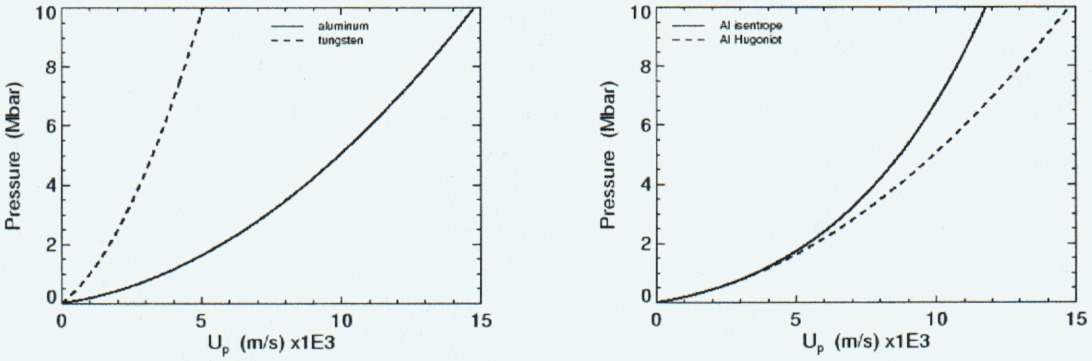

FIGURE 5. (a) Shock hugoniots for W and Al (solid curve) in pressure vs. material velocity space. Plot shows that there should be much less material motion (due to compression) for the same pressure when a stiff material (W) is used for the electrodes. In addition, a much higher pressure can be achieved for the same material velocity when W electrodes are used. (b) Hugoniot and isentrope (solid curve) for Al. Since shock formation is to be avoided, it is necessary to compress the material sample isentropically. The plot shows that this further reduces the material motion for the same pressure.

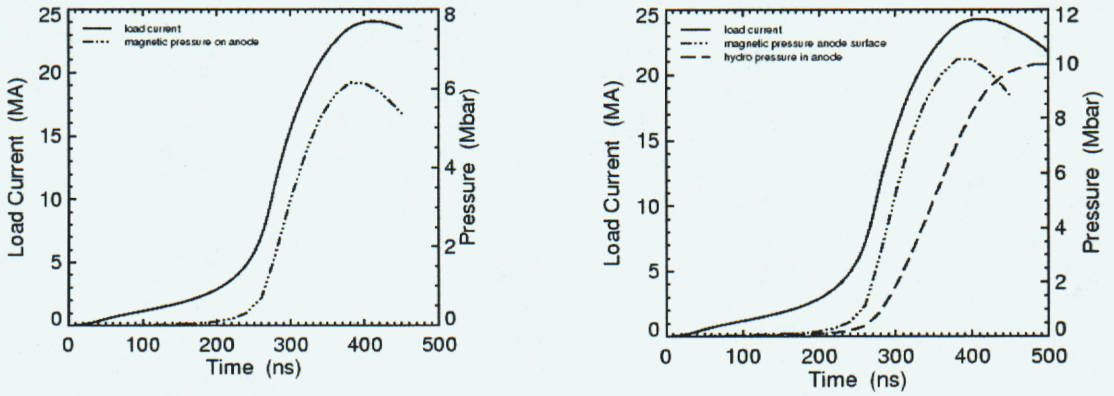

FIGURE 6. Results of full 2D MHD simulations for optimized load (Fig. 4a) with W cathode. Ideal voltage waveform for ZR (Fig. 2a) was used. Load current (solid curve) and magnetic pressure on anode surface vs. time for (a) Al anode and (b) W anode. In the latter case the hydrodynamic pressure in the material (anode) is also shown.

To achieve maximum magnetic pressure in material science experiments requires both electrical and hydrodynamic optimization of the load. An advantage of symmetric loads (as in Fig. 1b) is that data can be taken from multiple samples in one shot. However, the magnetic pressure on the sample can be maximized by minimizing alternative current paths, which produces a load like that shown in Fig. 4a. Figure 4b shows that this one-sided geometry yields a factor of 2.6 higher magnetic pressure for the same current when the ak-gap is 0.1 cm (compared to the symmetric design).

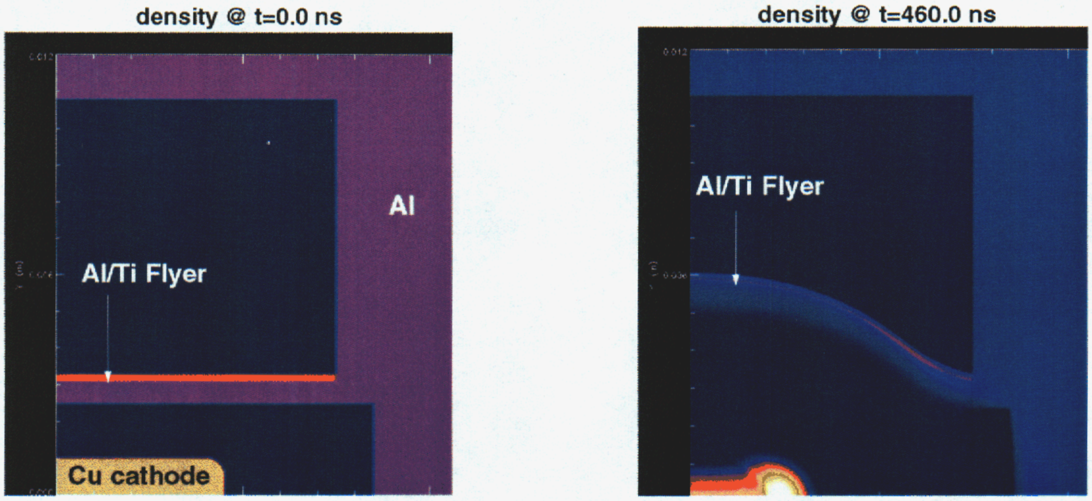

FIGURE 7. Configuration for 2D flyer simulation in quarter symmetry. Flyer is a slab comprised of 600 μm of Al and 200 μm of Ti (in red). Surrounding anode material is Al. (a) Configuration at t=0 ns. (b) Configuration just after peak current. Although the flyer is severely bowed away from the center, the central 2 mm remains uniform until impact with the target (top of plot). Bowing is a result of nonuniformity in the magnetic field in the horizontal direction.

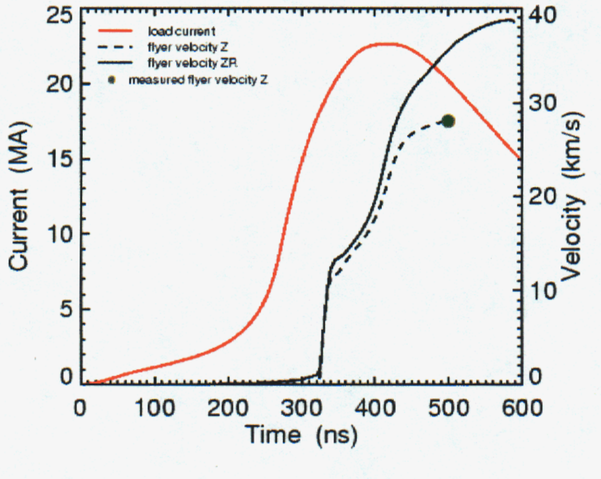

FIGURE 8. Comparison of simulated flyer velocities for Z and ZR (solid curve) voltage pulses with peak velocity measured on Z (the green dot). The ideal voltage waveform (Fig. 2b) was used for the ZR simulation. The simulated current for ZR (red curve) is superimposed. In view of the Z result, the peak velocity for the ZR simulation is probably accurate if the ideal voltage waveform is accurate.

Hydrodynamic optimization is necessary to minimize electrode motion during the current rise time, and to avoid shock formation. Figure 5a shows that using stiff materials for the electrodes results in significantly less conductor motion to achieve the same pressure. To avoid shock formation, which significantly modifies the material sample, isentropic compression is necessary. As shown in Fig. 5b this further reduces material motion.

Isentropic compression requires that the current rise slowly initially, which can be accomplished with a shaped voltage waveform. An example of an ideal shaped voltage waveform for ZR is shown in Fig. 2b.

To determine the maximum isentropic pressures that might be achieved on ZR simulations were performed using the Fig. 4a geometry with a tungsten (W) cathode, and the ideal shaped voltage waveform. Results for Al and W anodes are shown in Figs. 6a and 6b, respectively. The use of an optimized configuration results in peak isentropic pressures of 6.2 and 10.2 Mbar in Al and W, respectively (an increase of 48% relative to the unoptimized case for Al shown in Fig. 3a).

Simulations were also performed to determine the peak flyer velocity that might be achieved on ZR for conventional shock physics experiments. In this case a configuration that was shot on Z was used, which was driven by the ideal shaped voltage waveform for ZR. The simulation geometry is shown in Fig. 7. Figures 7a and 7b respectively show the initial geometry, and the geometry just after peak current when the flyer is traveling at ~35 km/s. As shown in Fig. 8, the peak velocity reaches ~39 km/s. Superimposed on the plot is the predicted velocity and measured peak velocity for the Z shot, in addition to the predicted load current for ZR. The peak velocity increases to ~41 km/s when the optimized geometry (Fig. 4a) is used.

Results of this computational study predict that a major impediment to achieving maximum magnetic pressure in material science experiments on ZR will be current reduction caused by the significant increase in load inductance associated with electrode deformation. This effect can be minimized, and maximum magnetic pressure achieved, through hydrodynamic and electrical optimization of the load.

ACKNOWLEDGMENTS

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