On the scaling of the magnetically accelerated flyer plate technique to currents greater than 20 MA

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Abstract. In this article we discuss scaling the magnetically accelerated flyer plate technique to currents greater than is available on the Z accelerator. Peak flyer plate speeds in the range 7-46 km/s are achieved in pulsed power driven, hyper-velocity impact experiments on Z for peak currents in the range 8-20 MA. The highest (lowest) speeds are produced using aluminum (aluminum-copper) flyer plates. In either case, the ≈1 mm thick flyer plate is shocklessly accelerated by magnetic pressure to ballistic speed in ≈400 ns; it arrives at the target with a fraction of material at standard density. During acceleration a melt front, due to resistive heating, moves from the drive-side toward the target-side of the flyer plate; the speed of the melt front increases with increasing current. Peak flyer speeds on Z scale quadratically (linearly) with current at the low (high) end of the range. Magnetohydrodynamic simulation shows that the change in scaling is due to geometric deformation, and that linear scaling continues as current increases. However, the combined effects of shockless acceleration and resistive heating lead to an upper bound on the magnetic field feasible for pulsed power driven flyer plate experiments, which limits the maximum possible speed of a useful flyer plate to <100 km/s.

1. Introduction
The first experiments to magnetically accelerate aluminum (Al) flyer plates on the Z accelerator occurred at the end of 1999 [1-3]. By 2007, peak flyer plate speeds up to 46 km/s had been achieved (greater than 100,000 mph, 3-4 times greater than gas gun capability, over 2 times greater than the speed of meteor impacts). To-date, pulsed power driven, hypervelocity impact (HVI) experiments on Z have produced many groundbreaking findings on the high-pressure behavior of materials [4-10].

Figure 1 plots measured flyer velocity vs. time from experiments that represent milestones in the development of platforms that produced the highest velocity possible for the available energy [3,7,8]. Because the objective of these experiments is to measure pressure and density on the principal Hugoniot (the locus of all possible shock states from the ambient state) of some material, the flyer plate must arrive at the target in a known state; its velocity must be nearly ballistic (constant), the impact surface must be coplanar with the target surface, and a layer of flyer material on the target side must be at standard density. Then, measurements of flyer velocity and shock speed in the target are used in conjunction with shock jump conditions to obtain density and pressure in the shocked material [3,4]. However, as illustrated in figure 2, current flowing on the drive side of the flyer plate (up to ≈20 MA) is large enough to melt and vaporize aluminum by resistive (Joule) heating, thereby creating a melt front that moves from the drive-side toward the target-side during acceleration [7,8,11]. Material is plasma/vapor/melted in region R, compressed solid in region G, and undisturbed solid in region S.
Also, shocks large enough to significantly change the state of aluminum must be avoided. This is accomplished on Z by shaping the rise time of the current pulse (magnetic pressure drive) so that the flyer plate compresses quasi-isentropically during acceleration [8,12]. Thus, the flyer plate must be thin enough to avoid shocking up during acceleration, yet thick enough so that the melt front doesn’t reach the free surface before impact with the target. We show that these two constraints produce an upper bound on the peak flyer velocity that can be achieved via magnetic acceleration, regardless of available energy.

2. The maximum feasible velocity of a magnetically accelerated aluminum flyer plate

Figure 1 illustrates the advances in flyer velocity that were achieved as the capability evolved for designing and performing pulsed-power driven, HVI experiments on Z. Before pulse shaping was possible, the maximum velocity of a useful flyer was about 20 km/s [3]. By 2004, a validated, 2D, resistive MHD model with predictive capability had been developed [11,13] that could accurately produce experimental results, scope out high pressure configurations, and design the pulse shape required for quasi-isentropic acceleration of the flyer. This quickly led to an experiment that produced a peak flyer velocity of ≈34 km/s, the maximum possible for the available energy on Z [7]. In 2006, the accelerator was refurbished in order to double the capacitor energy to 22 MJ, thereby increasing the current. The refurbished Z (initially called ZR, now called Z) came back online in 2007. Soon after, an experiment using a planar stripline platform produced a flyer plate velocity of ≈46 km/s, about the highest velocity possible for a useful flyer plate for the available energy [8].

The validated MHD model is used to determine peak flyer velocity for currents much greater than 20 MA. It includes a wide range equation of state (EOS) for Al, and a state-of-the-art model of electrical conductivity [14]; details can be found in the references [7,8,11,13]. Figure 3 plots peak flyer velocity (v_f) vs. peak magnetic field (B) from simulated experiments that accurately produce experimental results for plate thickness in the range 900-1200 µm. Two-dimensional simulation shows that the scaling of v_f with increasing B (or peak current) changes from quadratic (at very low currents) to linear (at the highest currents), which is a consequence of conductor motion. A linear fit to the data in figure 3 is given by v_f = 0.0464B – 17.18, with B in Tesla and v_f in km/s. We assume that linear scaling is valid for values of B much greater than can presently be obtained on Z.

The velocity of the melt front (v_m) in Al imposes a lower bound on flyer plate thickness (D). The flyer arrives at the target with a fraction of its material near ambient conditions if D > t_A v_m, where t_A
is the total acceleration time. Simulations show that $v_m$ is approximately constant during acceleration. Figure 4 plots simulated $v_m$ vs. peak magnetic field for the data in figure 3. The linear fit is given by

$$v_m = 0.001276B + 0.596$$

with $B$ in Tesla and $v_m$ in mm/µs, which we assume is valid for arbitrarily large values of $B$.

To preclude shocking the flyer plate during acceleration, the rise time to peak current is designed to compress it along an isentrope [8]. The Lagrangian sound speed ($C_L$) vs. pressure ($P$) on the cold curve of the EOS employed in the MHD model, plotted in figure 5, is used to calculate an ideal pressure vs. time for a desired peak pressure ($P_{\text{max}}$) and rise time ($t_R$). Lagrangian sound speed is defined as sound speed times the ratio of density at pressure $P$ and standard density. Figure 6 plots load current and magnetic pressure vs. time for one of the data points in figure 3, and shows the ideal pressure pulse used to develop the rise to peak magnetic field produced in the experiment. Shocks are precluded if the flyer plate thickness is less than the shock-up distance $X_S = t_R C_L (P_{\text{max}}) C_L (P_{\text{min}})/[C_L (P_{\text{max}}) - C_L (P_{\text{min}})]$, where $P_{\text{min}}$ is a non-zero value of pressure early in the ideal pulse. Thus, $X_S$ is an upper bound on the flyer plate thickness.

The constraints imposed on flyer plate thickness by the melt front, $D > D_{\text{lb}} = t_A v_m$, and shock-up distance, $D < D_{\text{ub}} = X_S$, produce an upper limit on the peak value of magnetic field ($B_{\text{lim}}$) that can be used to accelerate a flyer, while preserving a fraction of aluminum in a solid state. These constraints are plotted in figure 7 as functions of peak magnetic field for $t_R = [300 \text{ ns}, 400 \text{ ns}]$, and assuming that $t_s = A t_R$ with $A = 1.5$, which is consistent with experiments. The value of $B_{\text{lim}}$ is determined where curves with like values of $t_R$ intersect. For the stated assumptions $B_{\text{lim}} = 2414.3 \text{ T}$, and is independent of

Figure 3. Peak flyer velocity vs. peak magnetic field.

Figure 4. Melt front velocity in Al flyer plate vs. peak magnetic field.

Figure 5. Lagrangian sound speed vs. pressure on compression isentrope of aluminum.

Figure 6. Ideal pressure drive, simulated magnetic pressure, and current vs. time.
the value of $t_R$. However, increasing (decreasing) the value of $A$ increases (decreases) the slope of the diffusion constraint, which decreases (increases) the value of $B_{\text{lim}}$.

Substituting the value of $B_{\text{lim}}$ into the linear fit to the velocity data in figure 3 yields 94.8 km/s, which is the maximum feasible flyer velocity for HVI experiments using magnetic acceleration regardless of available accelerator energy. Actually, for practical applications we set $D_{\text{min}} = (1 + f)D_{ib}$ and $D_{\text{max}} = (1 - f)D_{ub}$ with $f>0$, which decreases $B_{\text{lim}}$ but ensures a feasible flyer.

For $f=[0.10, 0.15]$, $B_{\text{lim}}=[1935 \, \text{T}, 1728 \, \text{T}]$ with maximum feasible flyer velocities 72.6 km/s and 63.0 km/s, respectively. Figure 8 repeats the plot of $v_f$ vs. $B$ shown in figure 3, including the limiting values determined for different values of $f$ (i.e., for different constraints on flyer thickness).

3. Conclusions

The goal of magnetically driven, HVI experiments on Z is to obtain pressure and density on the principal Hugoniot of a sample of interest. Knowing the flyer plate velocity and density at impact, the initial density of the sample, and the shock speed in the sample, one can use the Rankine-Hugoniot conservation equations to calculate the shock pressure in the sample. Flyer velocity ($v_f$) and shock speed in the sample are measured; the initial density of the sample material is known. The flyer plate density is assumed to be known and in a solid state near ambient conditions. The latter requirement leads to an upper limit on the peak magnetic field ($B_{\text{lim}}$) that can be used to magnetically accelerate an Al flyer plate that is feasible for shock wave experiments.

Using aluminum flyer plate velocity data from HVI experiments on Z, and results from simulations of these experiments, we have shown that the upper limit on peak magnetic field is $B_{\text{lim}} \approx 2414.3 \, \text{T}$, which leads to an upper limit on peak flyer velocity $v_f \approx 94.8 \, \text{km/s}$. Thus, at the limiting magnetic field, it is not possible to shocklessly accelerate an aluminum flyer plate that remains in a solid state near ambient conditions. Therefore, in practice the maximum feasible flyer velocity is less than 94.8 km/s. For example, if measurement accuracy requires that the flyer plate arrives at the target with at least 15% of its original thickness near ambient conditions, then $B_{\text{lim}} \approx 1728 \, \text{T}$ and $v_f \approx 63 \, \text{km/s}$. To produce this velocity would require an accelerator that generates a peak current of $\approx 38 \, \text{MA}$, assuming performance on Z scales to this current.

Similar constraints apply to copper (Cu) flyer plates, despite its higher electrical conductivity relative to Al. In experiments on Z with pure Cu flyer plates, the melt front velocity inferred from measurements is $\approx 1.9 \, \text{mm/µs}$ for a peak magnetic field of $\approx 1020 \, \text{T}$, about the same as Al according to figure 4. Hence, as long as the magnetic field is large enough to produce a melt front in both Al and Cu, there is no advantage to using a pure Cu flyer plate to reduce the required thickness. Nevertheless,
because shocks with the same pressure are slower in Cu than in Al, flyer plates composed of Al and Cu (with Cu on the target side) are used in some HVI experiments on Z to increase the dwell time of the shocked state, which improves measurement accuracy. Also, because Cu has larger shock impedance than Al, the shock produced in a target by a Cu flyer plate is larger than that produced by an Al flyer plate with the same velocity. The maximum peak velocity of an Al/Cu flyer plate produced on Z is $\approx 28$ km/s.

With the present capability of the Z accelerator, it is possible to produce shock pressures of $\approx 30-40$ Mbar in magnetically driven, HVI experiments. Assuming a peak accelerator current of 38 MA, and a conservative value of 63 km/s for the limiting velocity of a feasible Al flyer (as in the example above), would make possible peak shock pressures of $\approx 69$ Mbar in a Cu target, for example. Thus, there is still much to be gained for shock physics research by scaling the magnetically accelerated flyer plate technique to currents greater than can be produced on Z.

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