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# Controlling Chamber Expansion in Miniature Electrothermal Guns for Increased Velocity and Efficiency

by W Casey Uhlig, Peter Bartkowski, Paul Berning, and Matthew J Coppinger

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Matthew J Coppinger**

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<b>13. SUPPLEMENTARY NOTES</b> ORCID ID(s): 0000-0003-1815-0106 (Uhlig)					
<b>14. ABSTRACT</b> The performance of an electrothermal research gun capable of firing small projectiles of less than 1 g at velocities over 3000 m/s was significantly increased to nearly 4000 m/s by controlling chamber expansion. The gun is powered via a high-voltage electrical discharge up to 20 kV and 38 kJ, evaporating a copper electrode and creating pressure in the breech to propel the projectile. A reduction in insulator volume in the chamber, thus reducing the potential for expansion in the breech region, resulted in a velocity increase of an additional 15% over previous gains attained by barrel hardening alone. The multiphysics code ALEGRA was used in design and characterization, and agrees very well with experimental results obtained via Photon Doppler Velocimetry and high-speed video measurements.					
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## 1. Introduction

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The US Army Combat Capabilities Development Command Army Research Laboratory has developed an electrothermal research gun capable of firing small projectiles for hypervelocity impact studies, using an electrical arc to produce a rapid expanding gas via vaporization of a pointed copper anode.<sup>1</sup> Significant velocity gains for given energy inputs were made in earlier work<sup>1,2</sup> by comparing projectile velocity profiles from Photon Doppler Velocimetry (PDV),<sup>3</sup> barrel expansion, and pellet erosion as benchmarks with ALEGRA magnetohydrodynamic (MHD)<sup>4</sup> results. One of the main conclusions from the earlier work was the significant dependence of final velocity on barrel strength and thus radial expansion. Further control of expansion of the chamber, particularly a reduction in chamber diameter and decrease in insulator fill, has led to increased velocity and efficiency, which is reported in this work.

## 2. Chamber and Barrel Design

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The initial barrel design used 4340 steel with a 50.8-mm-long, 9.5-mm-diameter chamber. The copper anode, which provided copper vapor as the working fluid during firing, consisted of a 6.35-mm-diameter rod with a region of reduced diameter (nominally 3.2 mm), leading to the vaporizing tip (total length of the reduced diameter region of 25.4 mm). The tip was conical with a length-to-base diameter ratio (LD) ranging from 2 to 5. The steel barrel and aluminum projectile acted as the cathode. A polyethylene sleeve insulated the copper electrode, and epoxy was used to fill the void surrounding the tip. Figure 1A shows a depiction of the assembled electrothermal gun (capacitive power supply omitted). Version two is identical to the initial design, with the addition of hardening the barrel to a yield strength of approximately 1200 MPa (Fig. 2B), which yielded a velocity increase of 15%. This increase is attributed to the reduction in expansion of the chamber due to the stronger steel. A direct comparison between post-experiment sectioned barrels of the unmodified and hardened barrels is shown in Figs. 2A and 2B, respectively. Attempts to further reduce the effective chamber size by using more rigid insulating sleeves (Mika and Bakelite) proved to be unfruitful (decreases in velocity of 14% and 24%, respectively).

A third barrel design (Fig. 1C), reducing the chamber diameter to the barrel bore diameter (4.78 mm) and length to 20 mm, was then constructed of hardened 4340 steel (1250 MPa to 1600 MPa). The total barrel length and location of the projectile/tip interface were kept constant. Thus, the effective breech face or chamber opening was moved approximately 30 mm into the steel barrel assembly.

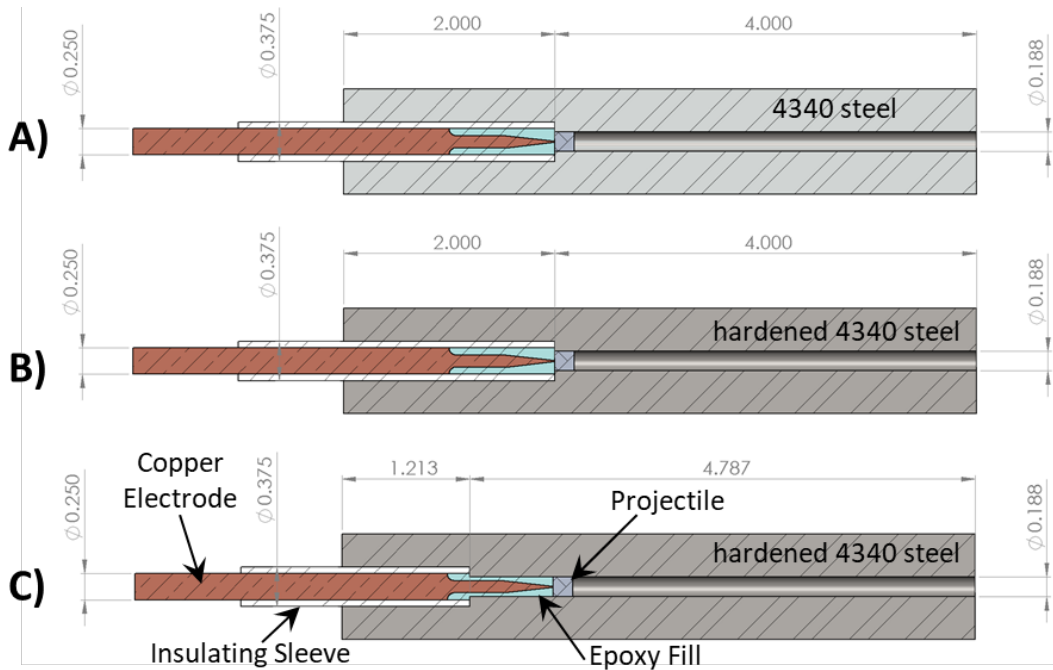


Fig. 1 Cross section of barrel assembly (units are in inches)

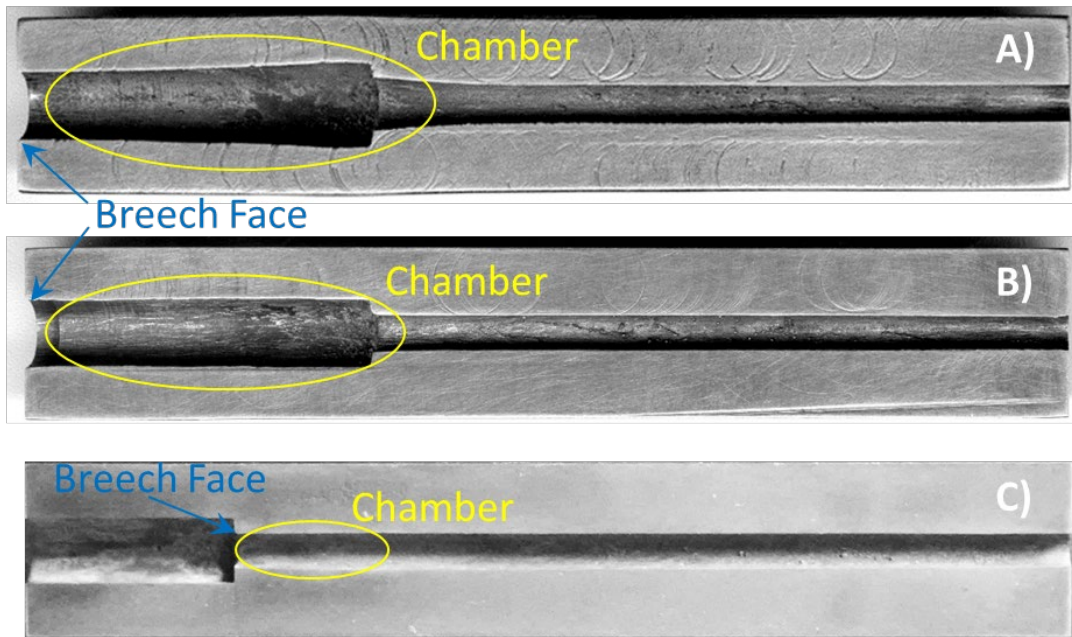
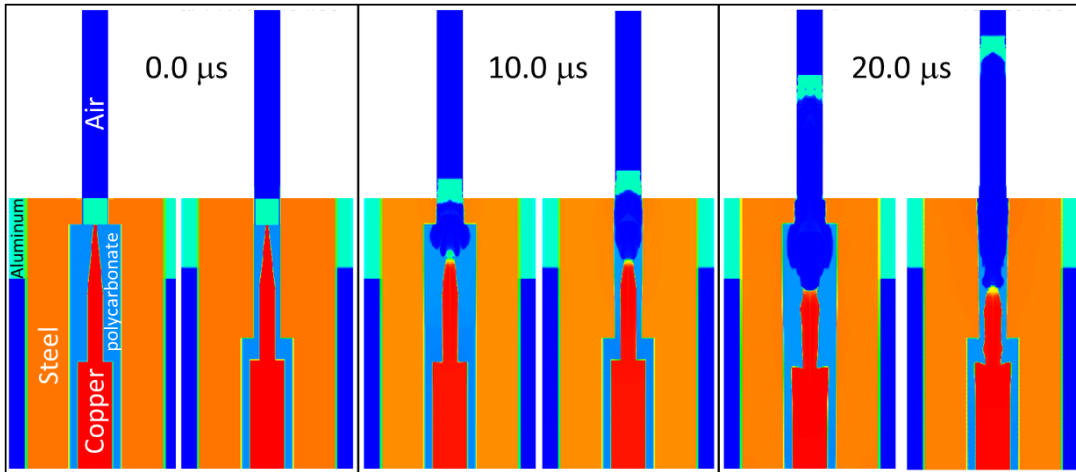


Fig. 2 Sectioned barrels corresponding to the designs in Figs. 1A-C that were fired using identical energies from a 20-kV and 38-kJ capacitor bank

Close analysis of the chamber from Fig. 2B shows that some deformation still occurred. Figure 2C shows a cross section for the third barrel design after being fired with a 20-kV capacitor pulse identical to that used for the barrels shown in Figs. 2A and 2B. While some barrel erosion is evident, very little chamber expansion is observed. Compression of the high-voltage insulation (sleeve and epoxy) allows significant expansion of the working fluid *within* the chamber for the second design in Fig. 2. The reduced chamber of the third design does not allow the same magnitude of expansion. The differences are evident in simulations. Figure 3 compares ALEGRA simulations of the second and third designs at 0.0, 10.0, and 20.0  $\mu\text{s}$ . At 0.0  $\mu\text{s}$  the density color scheme results in dark blue (air), light blue (polycarbonate), cyan (aluminum), orange (steel), and red (copper). Further information on the simulations is included in Section 4, while the details of the simulations are outlined in Uhlig et al.<sup>5</sup>



**Fig. 3** Density cross sections from ALEGRA simulations, original design hardened (left) and reduced chamber (right), at 0.0, 10.0, and 20.0  $\mu\text{s}$

The total volume of the expanding plasma region behind the projectile rapidly expands due to both projectile motion and compression of the insulating material within the chamber. While the reduced chamber design propels the projectile at higher velocities, creating a larger vacated bore volume (e.g., the projectile at 25  $\mu\text{s}$  has moved 47.3 mm down the barrel compared to 36.7 mm for the original hardened design), the total opening volume behind the projectile increases even faster for the larger chamber as illustrated in Fig. 4. Thus, a higher pressure is maintained for the faster projectile throughout the launch for the reduced chamber design.

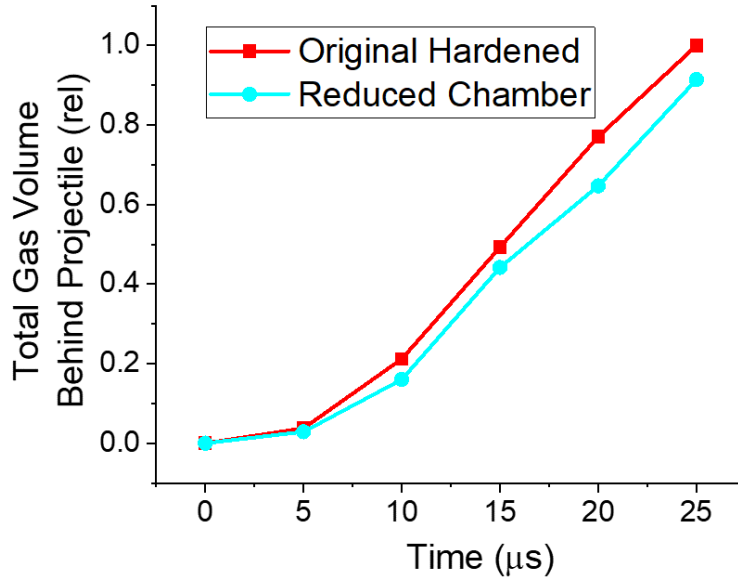


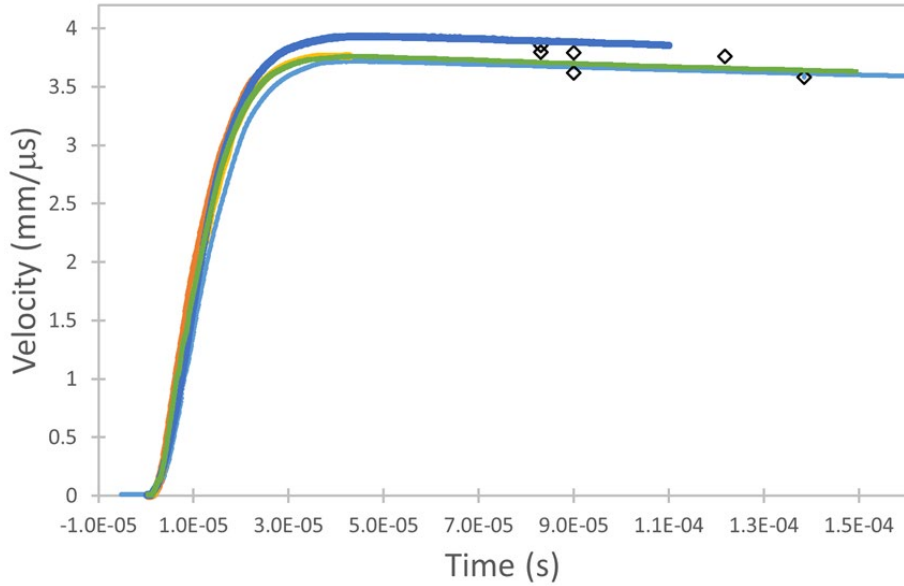
Fig. 4 Density cross sections from ALEGRA simulations, original design hardened (left) and reduced chamber (right), at 0.0, 10.0, and 20.0  $\mu\text{s}$

### 3. Experiments

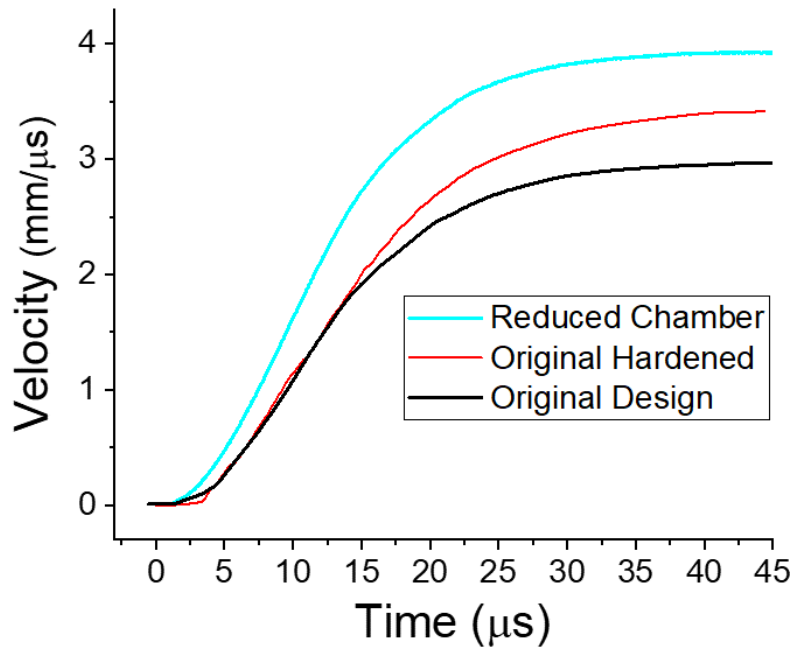
Experiments including 10 launches using the reduced chamber design were performed using a 191- $\mu\text{F}$  capacitor bank charged to 20 kV with nominally 0.24-g aluminum projectiles. Data were collected using high-speed video, PDV, magnetic sensor velocity detection, a Rogowski current monitor, and high-voltage probes at the gun mount. A standard tip LD 4 was chosen for most of the experiments based on previous work. To compare the reduced chamber design to previous work, one of the hypervelocity launches included an LD 2 tip, and one used a straight 20-mm-long, 14-gauge (1.6-mm) copper wire. In addition, one shot reused a previously shot barrel to test durability and repeatability. Thus, seven nominally identical launches with the standard LD 4 copper tip were available for comparison. PDV, high-speed video, and magnetic sensing velocity measurements<sup>6</sup> for the seven shots are shown in Fig. 5. Both high-speed video and magnetic sensing data (shown as open diamonds) occur at later times than peak velocity observed in PDV (solid lines) and are thus lower than peak velocities due to air drag. Additionally, there is a small offset between PDV velocities and the other methods where they overlap in time. In the four cases where both PDV and another method captured the velocity, PDV gave higher velocities (at equivalent times) by 1%–2%.

The velocity/time curves acquired by PDV for the reduced chamber barrels are very similar to the earlier gun designs, but the initial acceleration is significantly higher for the reduced chamber. From 5 to 10  $\mu\text{s}$ , the third design has an average acceleration 40% larger than the original design (0.230  $\text{mm}/\mu\text{s}^2$  and 0.164  $\text{mm}/\mu\text{s}^2$ ).

Figure 6 shows nominal velocity profiles for the three barrel designs and that the original and original hardened designs follow the same acceleration path until nearing 15  $\mu\text{s}$ , where they begin to diverge. ALEGRA simulations show that divergence begins when the softer barrel begins to expand in the region of the chamber/bore interface.

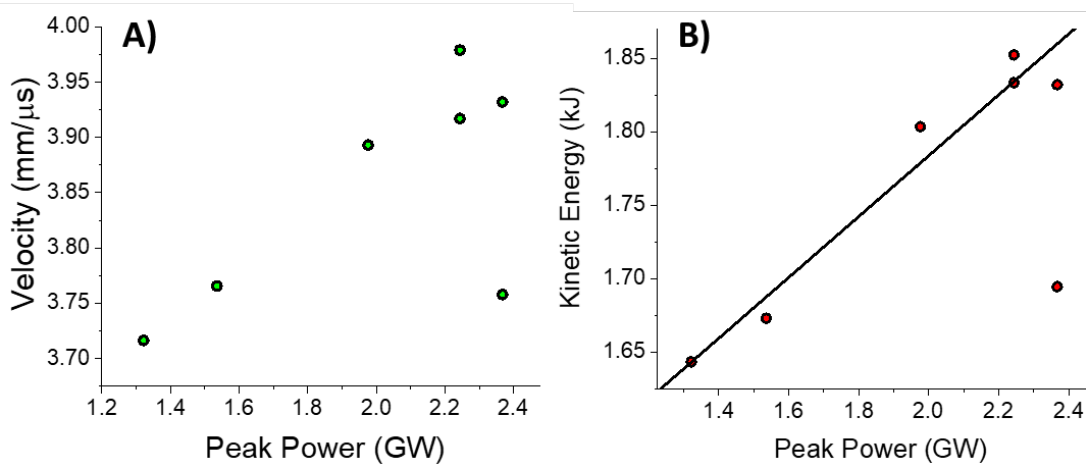


**Fig. 5** Velocity profiles for reduced breech design with LD 4 electrode tips. Solid lines are fits to PDV data. Open diamonds represent velocity measurements from high-speed video and magnetic sensing techniques.

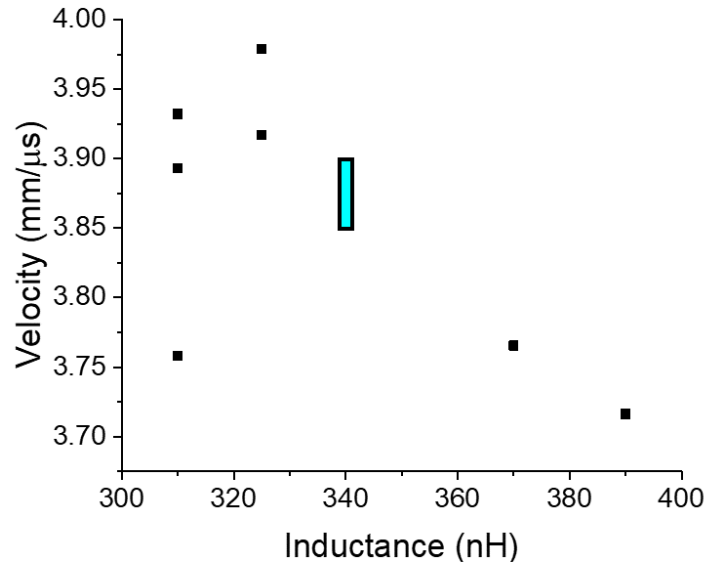


**Fig. 6** Nominal velocity profiles for the three barrel designs

There is some variance in peak velocities among the seven launches using the reduced chamber design as seen in Fig. 5 (average peak velocity 3851 m/s, standard deviation 102 m/s, maximum difference 263 m/s). Peak velocities are shown in Fig. 7. Data on shots that do not include PDV sufficient to obtain the maximum velocity were adjusted based on the acceleration from air drag observed in the other PDV measurements ( $-1.26 \text{ m/s}/\mu\text{s}$ ) and average offsets observed between the PDV, high-speed video, and magnetic velocimetry. While this does not give an exact maximum velocity, it should give a good estimate to compare all the data on similar footing. Plotting the velocity (Fig. 7A) and projectile kinetic energy (Fig. 7B) to account for differences in projectile mass reveals a clear dependence on the peak power attained in the circuit applied at the gun mount. The straight solid line in 7B was added to guide the eye and is a linear fit to the data excluding the outlier at 2.4 GW. While many factors can contribute to shot-to-shot variation, including electrode tip precision, bore flaws, potential voids from epoxy fill or loading, and electrical connection resistance, the largest variant between shots was the system inductance, which is largely affected by the electrical leads from the capacitor bank to the gun mount. Figure 8 shows the negative effect of increasing inductance on velocity.



**Fig. 7** Projectile peak velocity (A) and peak kinetic energy (B) from 20-kV shots using the reduced chamber gun design versus peak applied power to the gun mount



**Fig. 8** Projectile peak velocity from 20-kV shots using the reduced chamber gun design as a function of system inductance. The cyan solid rectangle shows the velocity range from the ALEGRA simulation.

Velocities attained using the LD 2 tip electrode and the 14-gauge wire were drastically lower than the nominal reduced chamber shots (~1000 m/s reduction and 1500 m/s reduction for the two electrodes, respectively). While it was expected that the LD 2 tip would not provide sufficient vaporized copper as a working fluid from previous work, it is assumed that the 14-gauge wire exploded from each end (at the contact with electrode copper rod and at the tip), thus causing deleterious effects on the launch process. No matter the reasons for the poor performance, velocities were significantly lower and any similar attempts were abandoned.

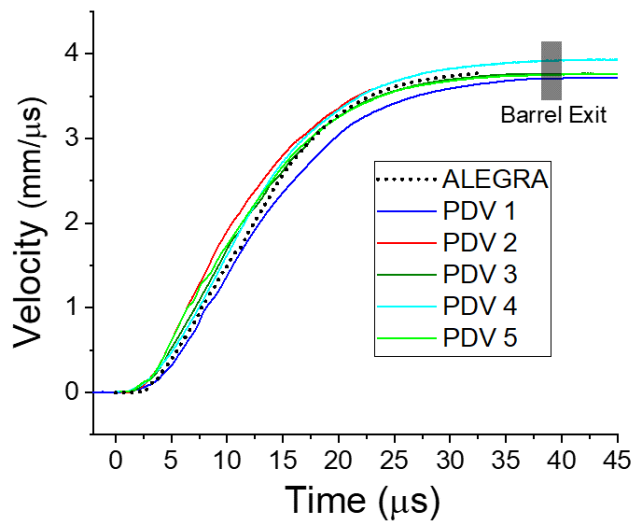
An attempt was made to ascertain how effective a previously shot barrel would be for a second firing. A barrel of the reduced chamber design that resulted in an original velocity of 3.77 mm/μs was reused with no alterations to the chamber and only light reaming to clear the bore. The resulting velocity was 2.99 mm/μs with significant “blow-by” passing the projectile before muzzle exit. The “blow-by” is a clear indicator of some slight expansion of the chamber/bore from the previous shot as well as evidence for the importance of precision-reamed barrels.

#### **4. Velocity Comparison to ALEGRA Predictions**

Three-dimensional simulations of the electrothermal launch were performed using the shock physics code ALEGRA with MHD capabilities developed by Sandia National Laboratories. A cylindrical trisection mesh, with one-quarter symmetry and cells with edges less than 0.1 mm in the region of the electrode tip, was used. A material model for polycarbonate was used in place of the epoxy and

polyethylene sleeve surrounding the electrode, a simple elastic-plastic model was used for the steel barrel in which the yield strength was set to the equivalent tensile strength from hardness measurements of the steel, and an elastic-plastic model with double the yield strength and Young’s modulus for aluminum 7075 (to prevent excessive breakup of the projectile and match soft captured pellets fired from the gun). Additionally, the simulations remove all material down the length of the barrel (besides the bore) beyond the initial location of the projectile to avoid excessive friction due to erroneous welding at the projectile/barrel interface inherent to Eulerian codes.<sup>5</sup> An external circuit was applied to the mesh to match the experimental components and median parameter fits to the current traces (340 nH and 10.4 mΩ).

The simulated velocity plot was produced by a Lagrangian tracer at the front center of the projectile. Figure 9 shows the velocity simulation results compared to the five PDV curves obtained from the LD 4 tip with reduced chamber shots. The velocity profile and acceleration path follow well within all the PDV curves. Also shown is the region of pellet exit from the muzzle in the experiments (gray shaded rectangle). To reduce the required computational resources and increase run time, the bore length in the simulations was only 80 mm as opposed to 100 mm for the experiments. Thus, the simulations are stopped at 33 μs, at which point the pellet approaches the mesh domain boundary. At this point, the projectile is traveling at 3.77 mm/μs, resulting in an estimated final velocity between 3.85 and 3.9 mm/μs from an extrapolation of the data based on the acceleration pattern from the PDV curves. This is in excellent agreement with the plot in Fig. 8, where a linear fit to the data results in a velocity of 3.86 mm/μs at an inductance of 340 nH. The simulation data point is plotted as a cyan solid rectangle at 3.875 ±0.025 mm/μs.



**Fig. 9** Velocity profile for a 3-D ALEGRA simulation of an LD 4 electrode tip compared to the PDV data from five launched aluminum pellets

## 5. Conclusions

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Efficiency and velocity in electrically launched millimeter-sized aluminum projectiles were significantly increased by further control of chamber expansion and reduction of the insulation fill and chamber diameter. This resulted in an increase in average velocity for LD 4 electrode tips from 2.99 mm/ $\mu$ s in the original barrel design to 3.85 mm/ $\mu$ s, a 29% increase. The largest contributor to variation in shot-to-shot velocity appears to be inductance changes. Careful control of the inductance has the potential to push the average velocity closer to 4 mm/ $\mu$ s. ALEGRA simulations add a substantial tool in not only velocity performance predictions but also design considerations for future work with the electrothermal gun and hypervelocity launch.

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## List of Symbols, Abbreviations, and Acronyms

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3-D	three dimensional
LD	length-to-base diameter ratio
MHD	magnetohydrodynamic
PDV	Photon Doppler Velocimetry

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