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THE ELECTRIC GUN: A New Method for Generating Shock Pressures in Excess of 1 TPa

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ABSTRACT

By combining the electrically-driven, flying-plate, high-explosive initiator with well-known gas-gun technology, a novel method of generating and measuring shock pressures greater than 1 TPa has been developed. Called the electric gun, this system is competitive with laser or nuclear-driven, shock-wave, equation-of-state experiments in the 1-5 TPa range. Compared to those other methods, it has the advantage of simplicity, high precision, and low cost. In addition, its small size and low total energy allow it to be easily contained for experiments with toxic materials.

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Present experimental techniques reach pressures of ~ 1 TPa, and theory is generally reliable down to ~ 10 TPa. Equations-of-state have relied on interpolation schemes to fill in the intermediate range. Our electric gun gives promise that we may be able to experimentally investigate this intermediate region.

The design and operation of the gun is illustrated in Fig. 1. A capacitor bank discharges a high current pulse through the thin foil bridge, causing it to explode. This explosion punches out a section of the kapton-metal laminate, and accelerates it up the few millimeter-long barrel to strike the target. In the simplest case, the target is the same metal as the flyer and has a set of precisely cut steps in it. A Fabry-Perot interferometer measures the velocity of the flyer. At the time of flyer-target impact, this velocity is exactly equal to twice the material velocity (U_p) in the shocked target. At pressures < 0.1 TPa, luminescence from heating, due to shock arrival at the free surface, is sufficient to be detected by a fast streak camera. Measurement of shock velocity (U_s) then consists of measuring shock-transit time across the steps in the free surface of the target. Using these measurements of U_s and U_p , and the mass and momentum conservation conditions across the shock front, we can determine the pressure and volume on the Hugoniot.

This system has two very important differences compared to the electrically-driven, flying-plate, high-explosive initiator.⁽¹⁾ The thin metal layer placed on top of the kapton flyer increases the total mass of the flyer and therefore lowers its velocity. However, the shock impedance or "stiffness" (defined as the product of the density and the shock velocity) is so much greater

for a typical metal than for kapton, that even at the lower velocity the pressure induced in the target by the metal flyer is significantly increased. Because of this change, the electric gun can be viewed as a type of gas-gun, where the exploding metal foil, kapton insulator, and metal flyer are the counterparts to the high pressure gas or explosive powder, sabot, and flyer in a gas-gun. In addition, the air in the barrel and target chamber has been evacuated. This results in not only a stronger and sharper shock, but also removes a Taylor-unstable situation, thereby keeping the flyer flat when it impacts the target.

The gun can accelerate flyers to high velocities because the exploding foil acts like a super high-explosive (HE). Using a simple model based on energy and momentum balances, it can be shown that the terminal velocity of the flyer (V_f) is proportional to the square root of a characteristic specific energy E_g and to a factor which is a function of the mass per unit area of the flyer and the exploding foil or HE. E_g is the energy converted from internal energy in the foil or from chemical energy in the HE to kinetic energy of the flyer. Experiments show that V_f in the electric gun can reach 3-10 times V_g in a system where the same flyer is driven by an equal mass per unit area of HE. This implies that E_g in the electric gun is 10-100 times that in the equivalent HE.

The high efficiency in the electric gun is in part due to the pressure exerted on the flyer by the magnetic field. Both the exploding foil and HE drive the flyer hydrodynamically, but this pressure falls rapidly as the explosive products expand. On the other hand, while the pressure produced by the magnetic field is low (< 1 GPa), it is roughly constant, and acts for the entire time the flyer is moving through the barrel. Simple one-dimensional calculations using measured currents and accelerations have verified this concept.

The electric gun is competitive with the laser and nuclear-driven experiments in producing shocks in the 1-5 TPa range. In order to measure a point on a Hugoniot, two independent measurements must be made, e.g., U_s and U_p . The technique for measuring U_p in a nuclear-driven experiment is complicated and has a precision of only $\pm 5\%$.⁽²⁾ The laser system does not yet have a proven method of measuring U_p , so presently it must rely on theoretical calculations to supply the missing information.^(3,4) However, with the electric gun, we can use a precise method of determining U_p , i.e., measuring V_p . Finally, the low cost and relative ease of doing many laboratory experiments, even in a glove box, make the electric gun especially attractive.

Figure 2 shows a streak record made when a tantalum flyer impacted a tantalum target that had a step cut in the middle of the free surface. The measured shock velocity is $6.1 \text{ mm } \mu\text{s}^{-1}$. Using a flyer velocity of $5.7 \text{ mm } \mu\text{s}^{-1}$, estimated from previous experiments, the shock pressure is $\sim 0.3 \text{ TPa}$. The shock velocity at this pressure compares favorably with published data. In addition, this pressure is approximately equal to the maximum pressure that can be produced in tantalum with the fastest two-stage gas-guns.

Figure 3 shows the result of a similar experiment using a flat target. The simultaneity of the start of luminescence demonstrates the flatness or "one-dimensionality" of the gun over a diameter of $\sim 2 \text{ mm}$.

Recently, we measured a velocity of approximately $16 \text{ mm } \mu\text{s}^{-1}$ for a $12.7\text{-}\mu\text{m}$ -thick, 6.08-mm -diam. tantalum flyer. Had this flyer impacted a tantalum target, a shock of nearly 2 TPa would have been produced.

As can be easily seen in Fig. 2, the present streak camera is too slow to be useful in Hugoniot experiments. We have ordered a new camera with a maximum writing speed that is approximately 100 times faster. This should allow us to spread out our streak records in time and make precise shock-velocity measurements.

Our next immediate objective is to simultaneously measure U_p and U_s at several pressures between 0.1 and 0.5 TPa in a material with a well-characterized Hugoniot, such as tantalum or platinum. We will then vary a number of experimental parameters to maximize V_f , and thereby the shock pressure, but still allow ample space and time to make reliable velocity measurements.

The most effective way of increasing V_f is to put the most energy into the exploding foil in the shortest period of time. This requires a high-voltage, low-inductance capacitor bank coupled with minimum-impedance mismatch to the exploding foil. We have recently acquired such a bank and will soon determine the optimum coupling parameters, principally the thickness of the exploding foil.

In addition, we can decrease the total flyer mass to increase V_f . However, the thinner the metal flyer, the shorter the duration of the steady-state shock; the smaller the area, the less space available for making the measurements. Because of the relatively steady pressure generated by the magnetic field, increasing the length of the barrel increases V_f . However, it also increases the likelihood of instabilities in the flyer surface, and this could decrease the precision and reliability of the velocity measurements. Thus, only a continuing experimental effort will tell us what the optimum capabilities of the electric gun are.

In summary, the electric gun offers a unique method of producing high pressure shocks. Its low cost, ease of operation, and low total energy make it ideally suited for laboratory operation. This could allow high pressure shock-wave physics to be done at establishments where today cost, lack of space, or operational difficulties make such work prohibitive.

References

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Figure 1. Schematic of the electric gun showing the placement of the exploding foil, laminated flyer, barrel, target, and optical diagnostics. The metal flyer is typically a few tens of microns thick, and the target is $\sim 2-3$ times the thickness of the flyer.

Figure 2. Streak-camera record of the start of luminescence of a stepped tantalum target shocked to ~ 0.3 TPa.

Figure 3. Streak-camera record of the start of luminescence of a flat tantalum target shocked to ~ 0.3 TPa.