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LA-UR- 01- 5036

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Author(s): R. L. Gustavsen, S. A. Sheffield, R. R. Alcon, and R.S. Medina
Los Alamos National Laboratory, Los Alamos, NM

Submitted to: 52nd Meeting of the Aeroballistic Range Association, Sept. 9-14, Quebec City, Quebec, CANADA

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Form 836 (10/96)

Changes to the LANL gas driven two stage gun: projectile velocity measurement and etc.[†]

R. L. Gustavsen, S. A. Sheffield, R. R. Alcon, and R.S. Medina

Los Alamos National Laboratory, Los Alamos, NM 87545

We have tried a number of optical methods for measuring projectile velocity on our gas driven two stage gun. It was necessary to use optical methods because electrical shorting pins damaged the projectile, turned the projectile causing tilted impacts, and sprayed the target with bits of broken pin. The first optical method involved cutting shallow grooves in the sides of the projectile at precisely measured intervals. The projectile passed through a single light beam focused in such a way that the grooves would alternately block and transmit light to a sensing system. This system didn't work because the grooves filled with smoke, blocking the light at all times after the projectile first broke the beam. The second method used light reflected off the projectile at four different positions. Light from a 400 mW laser was split into four optical fibers. Half of the light reflected from the end of each fiber was returned to a photomultiplier. When the projectile passed in front of a fiber the amount of returned light increased. This system had a very poor signal to noise ratio: the amount of light returned when the projectile passed in front of the fiber was scarcely larger than the noise on the signals. The third system used four stations at which laser light was transmitted from one optical fiber to another. The projectile passed close by the sending or receiving fiber, rapidly cutting off the transmitted light. This method suffered from a laser speckle pattern which changed with time thereby giving a constantly changing intensity. The fiber optic beam splitter used to split the laser light in methods two and three was also very unstable: the amount of light split into any particular fiber varied with temperature, vibration, and any movement of fibers. The method which was ultimately successful used a 5mW, 670 nm laser diode at each of four positions. A small lens focused this light to a point through which the projectile passed. Transmitted light was imaged into 700 micron plastic fibers which relayed the light to a bank of photomultipliers. The combination of imaging the luminous area of the laser diode and the end of the sensing fiber onto the same plane, through which the projectile passed, provided very good rejection of stray light, a very fast light cutoff as the projectile passed through the focal point, and efficient use of light. Projectile velocities were measured with an accuracy of 1 part in 1,000. In addition to our optical projectile velocity measuring system, we have significantly changed our projectiles, our transition section diaphragms, and developed a new honing technique. These will be briefly discussed as well.

1: In which a focused beam is cut by a grooved projectile

The LANL gas driven two stage gun was developed primarily for studying shock initiation of insensitive high explosives. One of our primary diagnostics is embedded electromagnetic particle velocity gauges. Flash x-ray measurement of the projectile velocity is precluded because of the large electromagnet used to create the magnetic field. Additionally, we use an aluminum tube used to protect the magnets and target chamber from shrapnel. It is for these reasons, and because of the havoc caused by electrical shorting pins that we have developed optical methods for measuring the projectile velocity.

Early on we realized that any system in which the projectile passed through the small focal point of a light beam would result in fast light cut-off times. The same effect could be achieved if the projectile passed very close to a small aperture emitting or collecting the light. The end of an optical fiber would provide such an aperture. This principle was applied through all our work and eliminated the long light cut-off time observed in systems where the projectile cuts through a collimated beam.

[†] Work performed under the auspices of the U.S. Dept. of Energy.

The first system we used is shown in Figure 1. A beam from a diode laser is focused to a point near the edge of a grooved projectile. As the projectile passes through the beam, the light is either blocked by the projectile or transmitted through a groove and thus to collection optics. The light is thus modulated on and off at a rate proportional to the spacing of the grooves and the speed of the projectile.

In detail the system is constructed as follows. An aluminum blast shield, which is a 1 inch thick 6 inch diameter disk with a 2 inch hole cut in the center for the projectile to pass through, is used to protect the muzzle from shrapnel. A hole drilled through the blast, shield perpendicular to and near the top of the central projectile hole, contains the electronics and optics. A 28 mW laser diode was focused to a spot on the plane bisecting the center of the projectile, and about 0.5 mm from the projectile's edge. At the focal point, the image of the laser diode's luminous area is less than 100 microns in width.

Relay optics image the laser diode onto the end of a 700 μm plastic fiber which takes the light to a photomultiplier. The first prototypes used a narrow band pass filter to block light from sources other than the laser diode. Additionally, shielding windows were placed in front of the optics in the hope that the shot would not destroy the apparatus.

Good signals were obtained in tests in which a projectile was shot down the barrel at about 10 m/s using 100 PSI compressed air. A real shot with a projectile speed of about 2.2 km/s also gave very encouraging results. First, good modulation was observed for more than half of the projectile's length. Second, the velocity was measured with an accuracy of $\approx 0.1\%$. Finally, all of the optics were undamaged.

A second shot at ≈ 3 km/s gave poor results. The light was not modulated by the grooves and only the front edge of the projectile was sensed. Lynn Barker suggested that, at the higher velocity, all of the grooves had filled with smoke from the projectile which was so dense that light could not penetrate it. Additionally, all of the electronics, optics, and even the blast shield were destroyed in this shot.

At that time we thought of stacking up multiple blast shields each containing systems such as are shown in Figure 1. Even if each system only sensed the front of the projectile, we could still obtain the projectile velocity because of the spacing of the beams. Difficulties in machining the hole to contain the optics and in measuring the distance between beam centers discouraged us from pursuing the idea at that time.

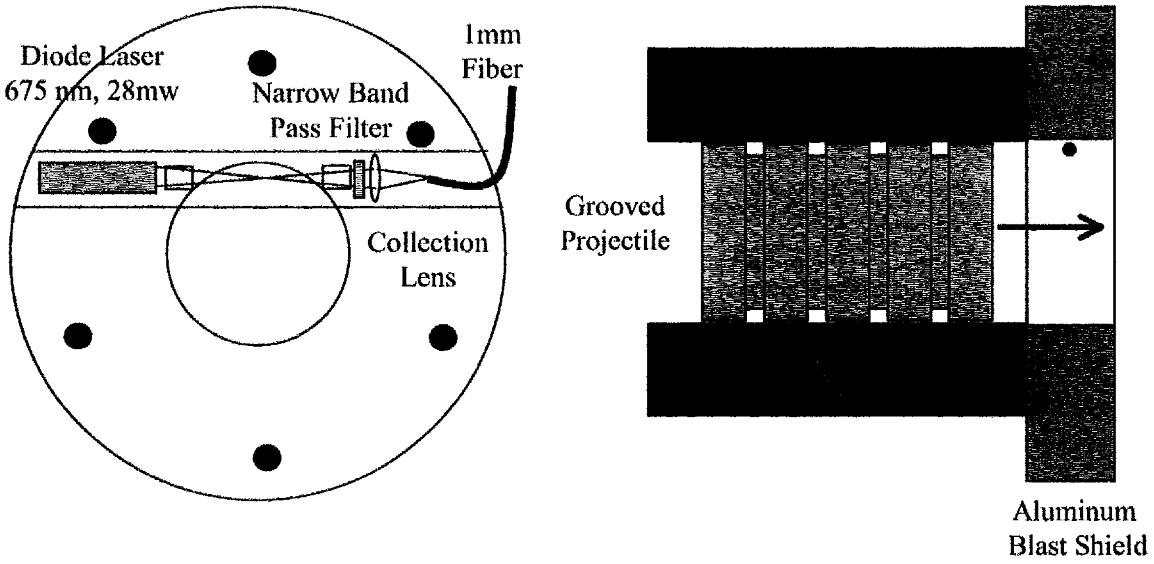

Figure 1. The focused beam and grooved projectile system.

2. In which light is retro-reflected off the projectile

The method in which light is retro-reflected off the side of the projectile is shown in Figure 2. In summary, light emanating from an optical fiber is reflected back into the same fiber by the side of the projectile as the projectile passes in close proximity to the end of the fiber.

532 nm CW laser light is focused into the end of a 100 μm core optical fiber. This is split 4 ways, then passes into directional fiber optic beam splitters and finally to the end of the fibers. Light coming back from the end of each fiber is split by a beam splitter; part returning to the laser and part going to a photo-multiplier for recording. Under most conditions, light is reflected merely by the end of the fiber, the joints at the ST connectors, and imperfections in the 2m fibers. This provides the background level. When the projectile is in close proximity to the end of the fiber, additional light is reflected from its surface and returned to the PMT. Thus the method senses changes in reflectivity as the projectile passes in close proximity to the end of the fiber.

The optical fibers were mounted in an aluminum block which, in turn, was mounted to the blast shield on the end of the barrel. Positions of fiber ends were measured using an optical comparator. The aluminum block was adjusted so the fiber ends would be about 0.1 mm away from the projectile as it passed by.

This system was used for a handful of experiments. In most experiments, we recorded very sharp breaks in the reflected light intensities when the front of the projectile passed over a fiber. Using these breaks, and the measured positions of the fibers we used a linear fit of position vs. time. The slope of this curve is, of course, the projectile velocity. Standard error in the velocity was typically 0.1%, that is, a few m/s out of 2 – 3 km/s.

The problem with this system was the signal to noise ratio. Background level reflections from the end of the fibers and the joints typically resulted in signal levels of around 50 mV. In good experiments we might see signal levels change by 5 – 10 mV when the projectile passed a fiber. However, in other experiments the signal level change would be so small as to be barely distinguishable from background noise. That is, there might be 3 mV of random noise, and only 4 mV of signal change when the projectile passed a fiber. We began searching for other methods.

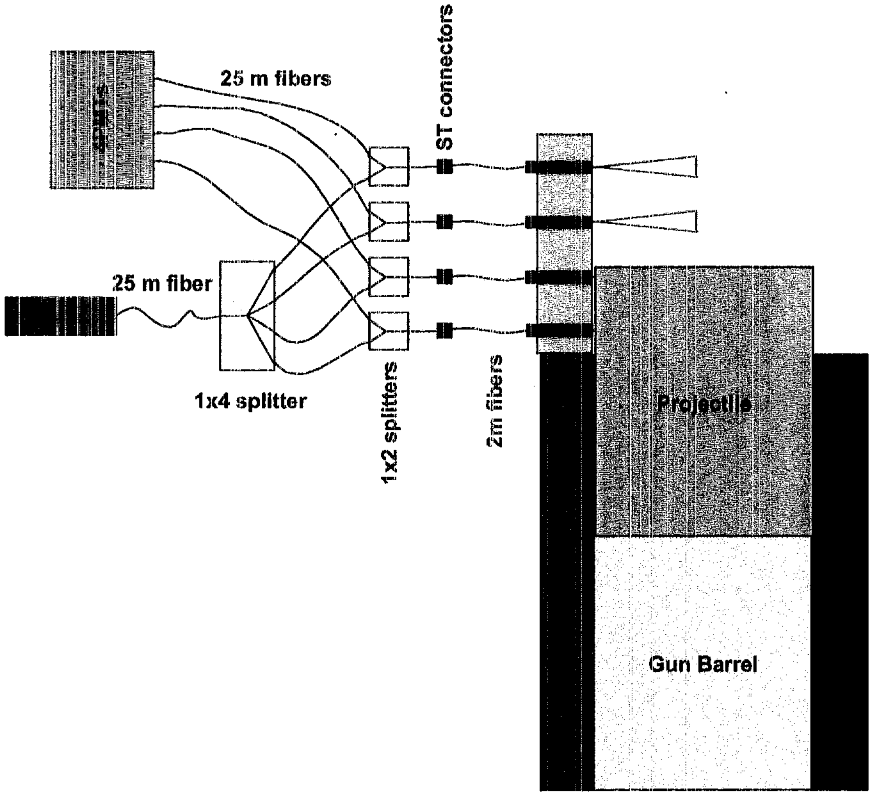

FIGURE 2. Diagram of the system in which light is retro-reflected off the side of the projectile. The view is from above and in cross section. The fibers are located on the centerline of the projectile.

3. In which the projectile cuts light transmitted between two optical fibers

It was at this time that we realized that we could transmit light between two fibers. One variation of this system is shown in Figure 3. As in the retroreflection system, light from a 532 nm laser is split 4 ways by a fiber optic splitter. This is transmitted to the fiber ends using short, disposable, optical fibers. Light is collected into optical fibers on the other side of the barrel. As the projectile passes through the beams it blocks light from entering the receiving fibers. From the collection point, the light is transported to 4 photomultipliers for recording. Sending fibers and receiving optics were mounted in blocks attached to a simple blast shield.

The first variant of this system used no receiving lenses, just bare 100 micron optical fibers on both sides. Sending and receiving fibers were located about 0.1 mm away from the projectile surface on the projectile center-line. Without lenses, this system suffered from very low collection efficiency. Additionally, a strong speckle pattern was produced. Any slight vibration would change the intensity of light at a particular spot, for example, the end of the receiving fiber, by a large amount. It was for this reason that we started using lenses.

The larger collection area of the lenses increased the signal collection efficiency and also decreased the sensitivity to a changing speckle pattern. In different shots we successfully used simple lenses and also gradient index (GRIN) lenses.

All variants of this system gave very sharp light cutoffs. This was despite the fact that the diameter of the collection lenses was as large as 6 mm. The sharp light cutoff arises from the projectile cutting off all the light at a single point, the point at which light exits the sending fiber. While the projectile begins to cover the receiving lens, light is cut off slowly. When the projectile crosses the sending fiber, the rest of the light is shut off almost instantly. When we realized this, we were also able to make the deduction that if we were able to focus the light to a small point, and pass the projectile through this point, that we would get very fast light cut-offs.

In the end, the major difficulty with these systems was the four-way fiber optic splitter. Any motion of the fiber entering the splitter would cause the splitting ratio to change. This caused the signal levels to constantly change, and it didn't matter if the motion was caused by temperature, or vibration.

4. In which light is transmitted from a laser

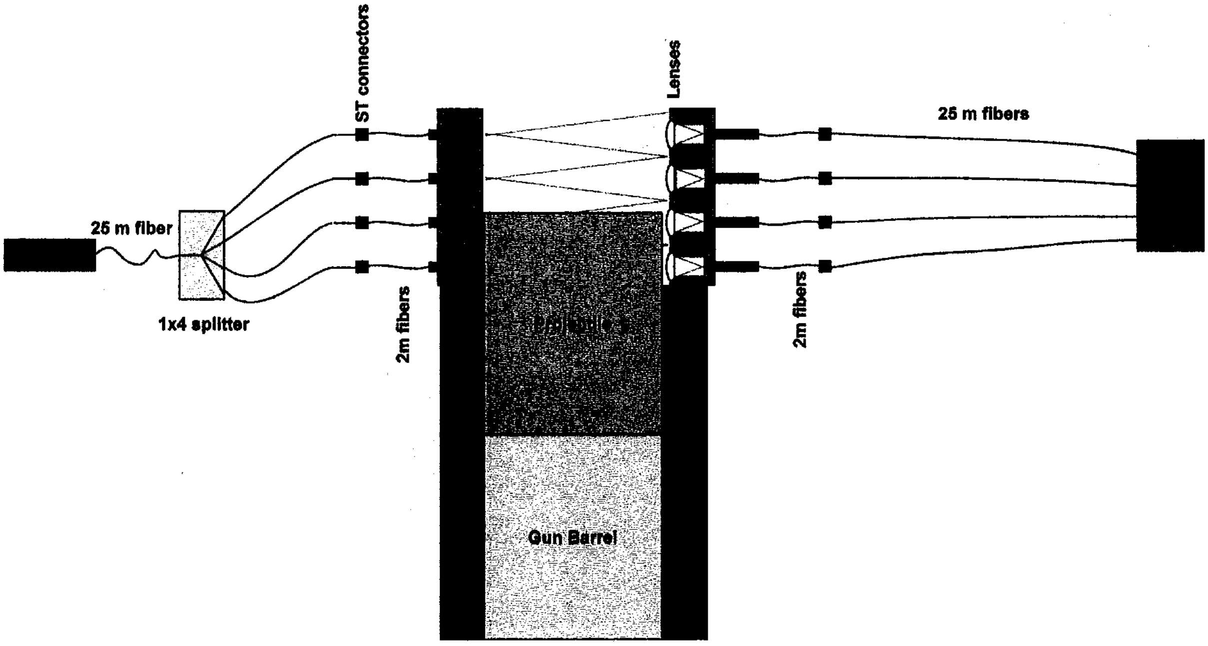

FIGURE 3. Diagram of the system in which light is transmitted between two optical fibers. The view is from above and in cross section. The sending and receiving fibers were located on the projectile's centerline.

diode to a photodiode detector

Because of the problems we were having with varying light levels caused by the fiber optic splitter, we decided to return to the use of laser diodes for the light source. The basic layout we used is similar to that shown in Figure 1, however there are some very major differences. The system is shown in Figures 4 and 5 below.

First, instead of a lens focusing light onto a receiving fiber to transmit light to a photo-multiplier, we used a fast (10 ns rise-time) silicon photodiode. (ThorLabs model FDS100 www.thorlabs.com). These photodiodes have a large, 3 mm, diameter, so that by changing the optical system slightly from that shown in Figure 1, we were able to dispense with the collection lenses. Light was collected directly onto the photodiode.

The second major difference was that the protection windows and filters were dispensed with. These were all destroyed in the shot anyway, and added to the expense. The entire system was, in fact quite inexpensive. The photodiodes cost about $10.00 each. The laser diodes (Sanyo model DL3149-055, $\lambda = 670$ nm, power = 5mW, obtained from ThorLabs) cost about $6.00 each, and the plastic aspheric lenses (ThorLabs model cax100) cost about $4.00 each.

The third, and perhaps most important difference, was that this system dispensed with the projectile grooves and recorded only the projectile front breaking a beam. The beam, however, was broken at four different locations rather than only one. As with the retro-reflection and fiber to fiber transmission systems, four stations was found to provide very good statistics and projectile velocities were measured with an accuracy of $\approx 0.1\%$.

Mounting the laser diodes and photodiodes in blocks or on circuit boards, also solved the difficult problem of machining holes sideways in blast shield disks and then stacking up blast shields, as we had imagined doing earlier (see section 1). Further, the positions of the laser diodes could be accurately measured using an optical comparator. Images of each laser diode's active area are clearly projected by the lenses and their positions can be measured.

In Figures 4 and 5, the laser diodes are shown mounted in a black plastic block. We soon found that if we mounted them in an aluminum block their output was much more stable. We ascribed this to the heat-sinking action of the aluminum block.

The one difficulty we found with this system was that the system was very sensitive to stray light. While we had several good shots using this system, there were two in which the sensors were blinded by stray light prior to impact, causing us to get no velocity measurement. We ascribed this to the non directional nature of the receiving photodiodes. Light from anywhere could cause signals.

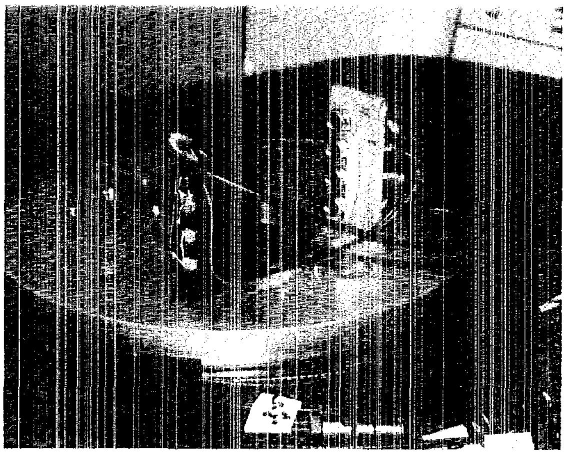

FIGURE 4. The system in which light is transmitted from a laser diode to a silicon photodiode detector. The lasers are contained in the black block on the left and the photodiodes are mounted on the circuit board on the right.

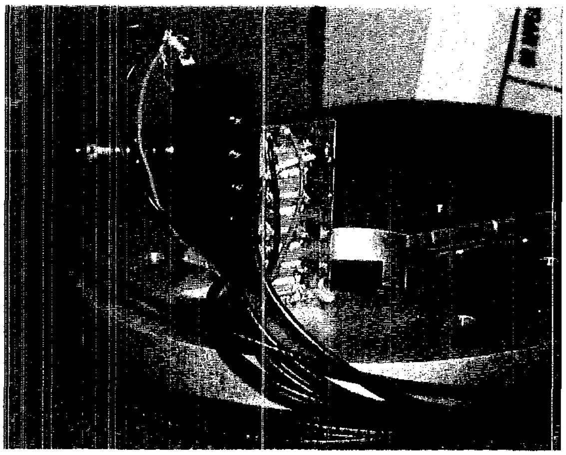

FIGURE 5. The lenses, shown in the black block, focus light from the laser diodes to the projectile center line. Photodiodes mounted on the circuit board collect the light. The aluminum disk with the hole in the center is the blast shield.

This forced us to analyze our design once again.

5. In which light is transmitted from a laser diode to a fiber optic receiving system

The system we are currently using, and with which we are extremely happy, solves the stray light problem in a way suggested by the system of Figure 1. An image of the laser diode's active area is projected to the centerline of the blast shield. From the other side of the blast shield, an image of the 0.7 mm plastic receiving fiber is projected to the centerline of the blast shield. The two projected images overlap, and any light outside of the overlap region is unlikely to reach the receiving fiber.

A photograph of this system is shown in Figure 6. It is so much like our original system that we feel like we have come 359 degrees around a circle. The system is mounted on an aluminum blast shield bolted to the end of the gun barrel. The block on the top of the blast shield contains four 5mW laser diodes which are spaced ½ inch apart. The beams were focused at about the center of the projectile.

The collection apparatus, shown in the lower half of the photo consists of lenses and 0.7 mm plastic optical fibers. Again, the image of the fiber is projected to a point close to the center line of the projectile. The fibers can be seen just below the lower block. Light collected into the optical fibers is transported to four photo-multipliers for conversion into electrical signals.

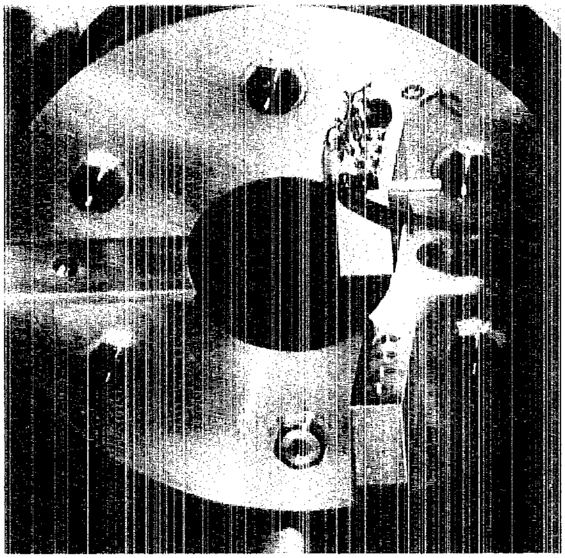

FIGURE 6. Photo of the essential parts of the velocity measuring apparatus.

Figure 7 shows photo multiplier records for Shot 2S-58. When the projectile cuts through a beam, the signal goes from a finite value to zero. (Note that the baseline signals are negative.) This experiment measured a projectile velocity of 2.379 ± 0.006 km/s. That is, the projectile velocity was measured with an accuracy of 0.25%.

As can be seen in Figure 7, this system demonstrates very good signal to noise characteristics. Additionally, it has very good rejection of stray light. We could take a 500 watt halogen lamp and aim it toward the collection fibers without noticing a change in the signal levels. Furthermore, it is easy to assemble, and contains a minimum of custom machined parts. We are very happy with this system.

6. Projectile modifications

Throughout the time we were developing the projectile measuring system we had a significant number of shot failures. Because of the nature of the magnetic gauge signals and the optical velocity signals, we attributed all of these to projectile failure; however, we did not know the cause of the failure. Perhaps the projectiles were not optimally designed, they were being accelerated too hard at launch, or there was "stuff" in the barrel causing sudden deceleration. We decided to attack the problem on all three fronts.

The projectiles we used back in 1999 were made of Lexan, had the impactor glued in with epoxy, and had a shallow cutout in the back. To at-

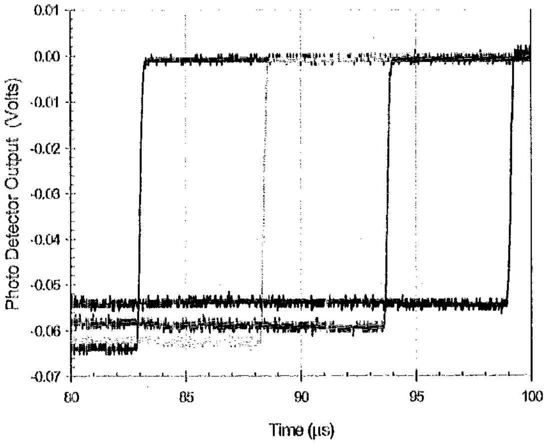

FIGURE 7. Photo-multiplier records for shot 2S-58

tach the Kel-F impactors more firmly to the projectiles, we put coarse threads on the outside of the impactors. The impact face of the projectile was made with a cup-like indentation with threads into which the impactor mated. The cup was painted with epoxy, the impactor threaded into place and the epoxy allowed to harden. The projectile was placed in a V-block and the impact surface machined perpendicular to the axis using a surface grinder.

While we felt that projectiles with impactors attached using threads failed less often than previous kinds, we still had a significant number of failures. The next thing we tried was a different material. Some literature from the manufacturer led us to believe that PEEK would be superior to Lexan for making projectiles. It is supposed to be very strong and tough. However, all three shots we did using PEEK projectiles failed because of projectile failure.

The last thing we did to improve our projectiles was to modify the back cup in the hope of reducing blow-by. These projectiles are shown in Figure 8 below. The cup is about 4 times deeper than previously used. The contours are also much smoother. We think that hogging out the back like this results in a better seal of the launch gasses. We have seen less evidence of blow by since we started using these projectiles with the larger cup.

7. Diaphragm modifications

In order to get a gentler launch, we changed our burst diaphragm design. Our original design used 0.200" thick Ni diaphragms scored with grooves 0.125" deep. We changed to a diaphragm that was 0.125" thick with 0.043" deep grooves. This seemed to help a great deal with keeping projectiles intact. We tried diaphragms with deeper grooves, however, these led to reduced projectile velocities and unacceptable extrusion of the polyethylene pump piston.

8. Cleaning and honing system modifications

When we first started using this gun we cleaned it out using a rod and rags. Soon we became convinced that we were leaving behind bits of plastic which had melted off the projectile and stuck to the barrel. Next, Lloyd Davis invented a technique whereby a long rod of polishing disks loaded with jeweler's rouge was turned using a high speed drill. This was deemed unsafe by almost everyone but Lloyd.

Following up on a wild idea, we started using a drain cleaning machine, a "Roto-Rooter" if you will, to turn cleaning tools. Figure 9 shows Bob Medina using the power feed Roto – Rooter to clean the gun. Now, after every shot we hone the gun using a Sunnen 5 stone hone loaded with C05 (600 grit) stones. After this, the gun is cleaned using a rod and rags. We feel that we are at least getting the gun very clean using this method. This should eliminate projectile breakup from hitting a bit of gunk and suddenly decelerating.

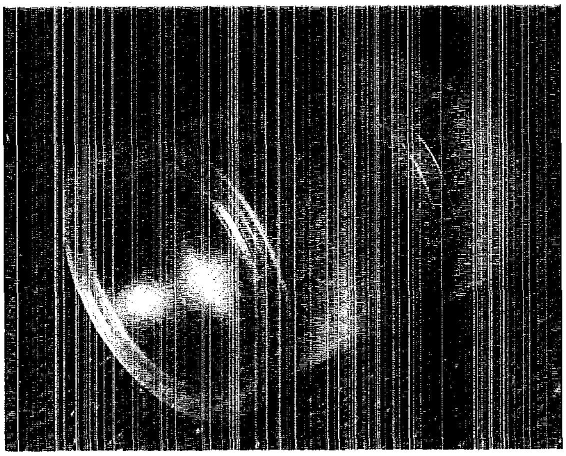

FIGURE 8. Projectile with modified back cup.

FIGURE 9. Using the Roto – Rooter to hone and clean the gun.

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1. S. Sheffield, S. Buelow, R. Gustavsen, Q. Pack, L. Davis, L. Hill, R. Alcon, and R. Medina **Progress in measuring projectile velocity on the LANL two-stage gas gun** in *Proceedings of 50thAeroBallistic Range Association Meeting, Pleasanton, CA, Nov. 8-12, 1999*