URDC

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CO-AXIAL PLASMA GUN STUDY

Contract NAS 9-9584

FINAL REPORT

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I. INTRODUCTION

This report reviews the work accomplished by Utah Research & Development Co., Inc. on NASA Contract NAS 9-9584, Co-Axial Plasma Gun Study. The study was initiated to determine the feasibility of accelerating small projectiles to meteor velocities by exposing them to a stream of high density, fast moving plasma. Co-axial plasma guns have been developed for use in many areas of physics, but their use to drive high density plasmas has been restricted, as far as we are aware, to the work URDC has done.

The work reported here is the result of a study in which the final velocity of the particles which were accelerated determined feasibility of the method. Diagnostic techniques were simple and only a rudimentary attempt was made to determine the integrity of the projectiles after they had been accelerated. The question of particle ablation as the projectile traveled through the range was not considered to be pertinent at this time, although that question must indeed be considered before the co-axial plasma accelerator can be used in impact studies.

The goal of this project was to accelerate projectiles whose diameter was 100 microns or greater to velocities of at least 20 km/sec. Present techniques are available for accelerating 50 micron projectiles to about 17 km/sec occasionally. In order to be of worth the co-axial gun acceleration techniques should demonstrate a probability of obtaining significantly better results than those currently attainable.

This final report will review the simple theory of co-axial plasma guns and some of the problems which may be encountered. The experimental approach used by URDC will be presented as well as the results of the firing program. Those results will be analyzed and recommendations of future work will be listed.

II. THEORY

The theory of co-axial plasma accelerators is relatively simple in concept. A co-axial gun consists of two electrodes, one a hollow cylinder, arranged co-axially as shown in Figure 1.

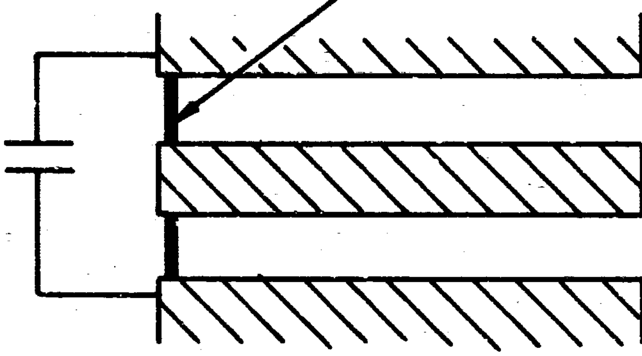


Figure 1. Sketch of Simplified Co-Axial Gun

A voltage is impressed across the electrodes by a power source such as a capacitor. An arc is struck between the electrodes allowing current to flow in the circuit. The magnetic force that is generated due to the current flowing, exerts a pressure on the plasma (arc) and forces it down the co-axial gun. The initiating foil shown in Figure 1 is used to strike the arc. The foil vaporizes and the metal atoms ionize to form the plasma. The plasma maintains its shape as it moves down the gun and sweeps whatever gas is in the gun ahead of it in much the manner of a snow plow. Local pressure can be expressed as

$$P = BXI \tag{1}$$

where B is the magnetic flux density and I is the local current density. If radial symmetry is assumed and we confine the current to a thin disk in the gun annulus, there is no field in the annulus beyond the current-carrying disk. The plasma is accelerated down the gun by the pressure

$$P = \frac{B^2}{2\mu} \tag{2}$$

Experimenters have reported that co-axial guns do behave in this relatively simple way. There have been reports that up to 40% of the energy stored in the capacitors has appeared as plasma kinetic energy. Most of the work of this type has been done with relatively large guns and low density gas.

Particle accelerators need to have a more dense gas in order to drag a projectile to interesting speeds. Rough calculations, assuming free molecular flow, show that a small particle should assume a velocity of about 63% of the stream velocity after a mass per unit area of the gas equal to approximately the particle's has passed. The size of the projectile that can be accelerated is related to the density of the plasma in the following way:

(Mass/area) projectile = (Mass/area) plasma

or

$$kd = \rho_g t$$

where

- d = diameter of the projectile
- ρ_g = density of the plasma
- t = thickness of the plasma
- k = constant for a given projectile material.

therefore

$$d \propto \rho_g t \qquad (3)$$

The obvious way to increase the density of the plasma is to increase the size of the foil that is vaporized or to increase the density of the foil. Any increase of this nature, however, requires a corresponding change in the power source driving the plasma and likewise increases the complexity and cost of the gun system.

A method of increasing the density of the plasma without increasing the mass of the foil is to drive the plasma down a tapered gun into a smaller area. A sketch of such a gun is shown in Figure 2.

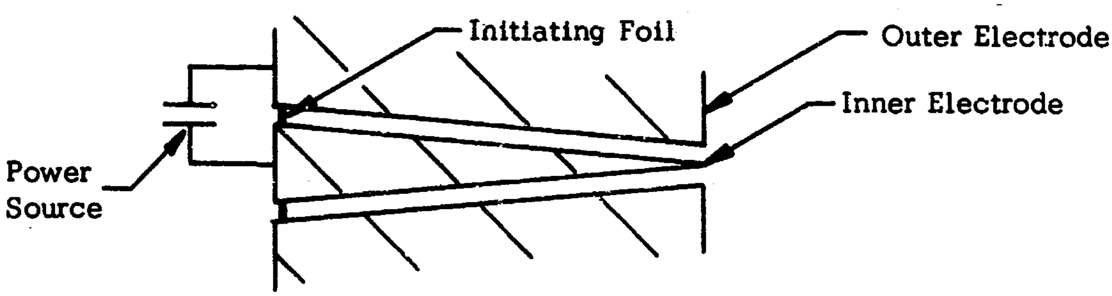


Figure 2. Sketch of a Tapered Co-Axial Gun

The tapered gun ought to provide an effective increase in the plasma density in direct proportion to the ratio of the area of annulus at the foil to the area of the exit of the gun chamber. This would be true for the ideal case of no energy losses to the walls of the gun. In practice there is a loss which occurs, but there is an effective increase in plasma density which is helpful.

Another approach to concentrating the plasma is to deliberately make the plasma disk assymetrical. When this approach is used, that part of the disk that is heavy lags behind the rest of the plasma and creates an effective "low" place in the disk. The faster, lower density plasma flows into the "low" area and is concentrated in such a manner as to increase the plasma density. In practice this technique is very difficult to control and hence to use.

Another approach to concentrating the plasma is to use magnetic fields which interact with the plasma. A sketch of a gun using such an approach is shown in Figure 3. The electrodes are the usual conducting material, such as

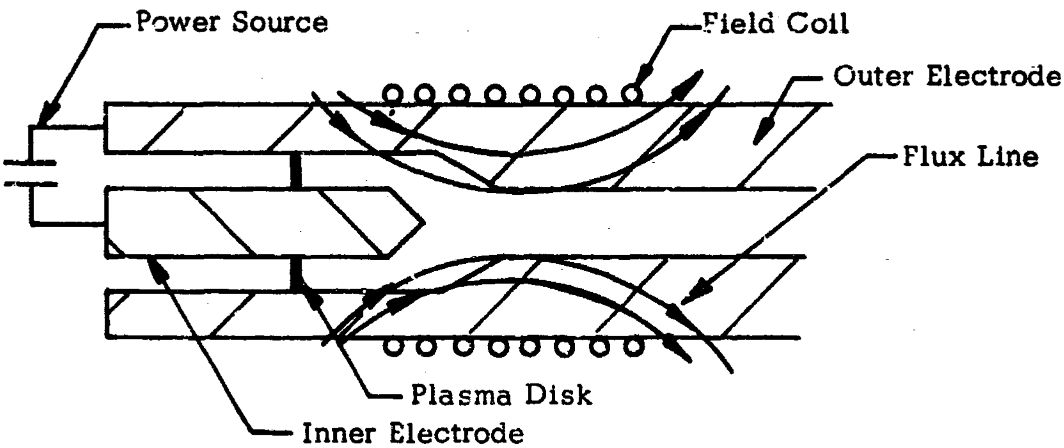


Figure 3. Sketch of a Co-Axial Gun with a Magnetic Field Concentrating Coil

brass, from which the guns are customarily made. The coil is wound at the tapered section of the gun in order to set up a magnetic field between the plasma and the wall of the gun. A heavy plasma will attempt to push the field lines out of the way and will be resisted by a pressure of $B^2/2\mu$. The pressure will act to push the plasma toward the center of the gun. The highest practicable field is approximately 10 MKS units. The pressure resulting from this field is about 400 atmospheres, which is rather small. The field cannot, however, be pushed back in the conducting outer electrode in the times during which this process occurs. Flux in the tapered section of the gun will be pushed back against the walls, but will not change much. The flux density, B, will rise to whatever value is necessary to balance the plasma pressure. This whole process effectively shields the plasma from the energy-absorbing electrode walls and allows the plasma to be conce trated without losing too much energy.

All of the three methods mentioned above should lead to a concentration of the plasma which will permit a ˙ rger (about 100 microns) projectile to be accelerated. This report describes only the results of the work done with small tapered guns. Although the other methods are feasible, there was not time to investigate them under the present contract.

III. EXPERIMENTAL PROGRAM

The experimental program employed during this study reported here was directed at developing a co-axial plasma accelerator that would accelerate small particles to meteor velocities. The main components of the accelerator are the capacitor bank, charging supply, initiating switch, vacuum range and gun. These components will be discussed in some detail in this section of the report.

A. Capacitor Bank and Power Supply

The capacitor bank is made up of 24 capacitors rated at 15 μf and 20 KV. These capacitors are connected in parallel and have a maximum energy rating of 72,000 joules when they are charged to full voltage. Although it is not necessary to have an ultra-fast discharge, it is desirable to match the discharge of the bank with the velocity of the plasma in the gun. Since the co-axial gun is roughly 10 cm long and the desired plasma velocity is 40 km/sec, the ringing frequency of the bank must be longer than 2.5 microseconds. It is not desirable to have the discharge time too long either. The ringing frequency of the URDC bank is approximately 50 khz. The voltage falls to zero in about five microseconds.

The capacitors are mounted in a vertical frame made of 2 x 8's. Attached to one side of the frame by wooden supports are the aluminum leads which connect the capacitors in parallel. The leads are 30 mil thick sheets of aluminum separated by 17 layers of 6 mil polyethylene. Holes have been cut in the ground lead to allow tabs from the high voltage lead to be connected to the plus side of the condensers. Connecting the capacitors in this manner gives the low inductance lead system which is necessary. A rough calculation of the inductance gives a value of about 0.028 microhenrys in the leads. The connection of the bank to the guns is described in Section D which discusses the guns.

The power supply is a simple transformer and rectifier circuit. The current charging the capacitor bank is controlled by a variac on the primary side. The operator manually charges the bank by controlling the variac setting to control the charge rate while observing a current meter and a bank voltage meter.

B. Initiating Switch

The most common way to discharge a high voltage capacitor bank is to use a spark gap technique. This is a relatively easy system to operate, but a little more expensive to build than URDC felt was warranted during this contract. A more inexpensive system was therefore devised.

Figure 4 is a drawing of the gun assembly area of the capacitor bank. The various elements of the gun assembly area are labeled. The front plate is an inch thick plate of aluminum which holds the gun and is in contact with the ground side of the capacitor leads. This connection between gun and capacitor bank puts the outer electrode of the gun at ground potential. Proceeding backward from the front plate, we have the aluminum sheet which constitutes the ground lead. Next to the aluminum lead is a thin copper sheet which makes an additional contact between the ground lead and the outer electrode. Next to the copper is polyethylene which is the insulator between capacitor bank leads. A six-inch hole has been cut in the polyethylene in which is placed a disk of fiberglass. This insulating disk is used to conserve the polyethylene, since it would be destroyed with one firing if it were closer to the gun. The fiberglass is easily replaced after each shot. In back of the fiberglass is a thin (1/16" thick) glass which also acts as an insulator. Behind the glass is another thin sheet of copper which makes contact with the positive lead of the bank and the back plate of the assembly. It can be seen in Figure 4 that there is a hole back of the center electrode through every piece of material except the glass and the positive copper sheet. When the bank is charged the only thing that prevents the copper sheet from arcing to the bank electrode is the glass insulator. If the glass is ruptured the bank will discharge through the gun and create a plasma accelerator.

The glass insulator in the URDC system effectively replaces the spark gap in more conventional systems. A spark gap is generally triggered by a third electrode which has a voltage spike induced on it in such a way that an arc is initiated which allows the gap between the two main electrodes to break down. In the URDC system we use a blasting cap to break the glass insulation and allow an arc to be established between the positive lead of the capacitor bank and the center electrode of the gun. The system is inexpensive and sure. If proper care is taken it is also a safe system.

C. Vacuum System

When very small projectiles are accelerated they are subject to high aerodynamic drag forces unless the atmosphere through which they travel is substantially reduced. URDC built up a ballistic range for the plasma accelerator experiments from six-inch glass tubing. The range was connected to a small roughing pump and a diffusion pump. A free flight length of 3.5 meters is possible in the range. The entire range is small enough in volume that the pumping time is negligible. We generally fire at pressures between 1 and 500 microns of Hg. The pressure is measured by an Alphatron and by a McLeod vacuum gage.

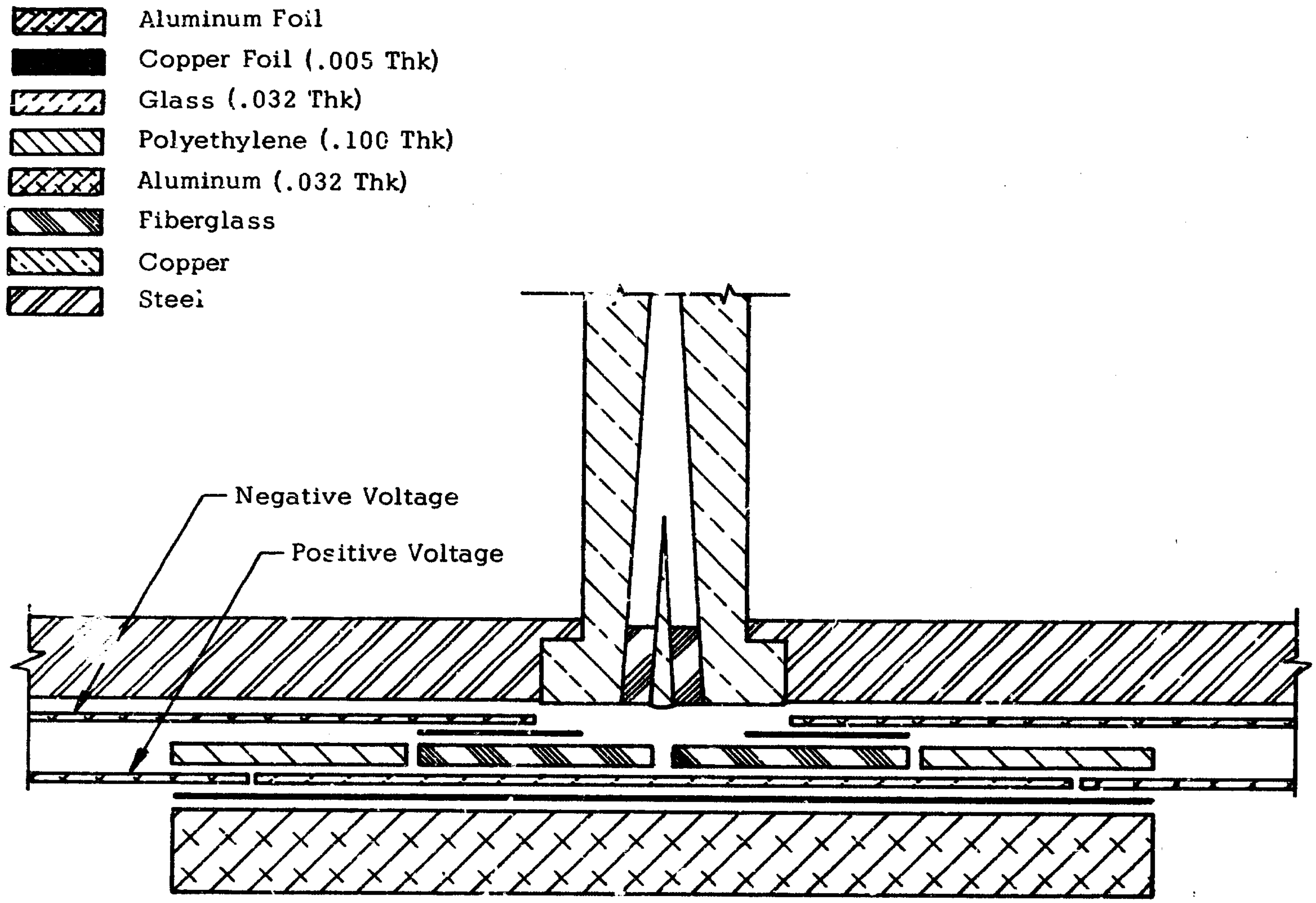


Figure 4. Gun Assembly Area of the Capacitor Bank Showing the Connections of the Gun to the Bank

D. Co-Axial Guns

The co-axial gun was the part of the experimental system which was of the most concern in this study. We first built a non-tapered co-axial gun of the type shown in Figure 5. This gun was not expected to be particularly effective

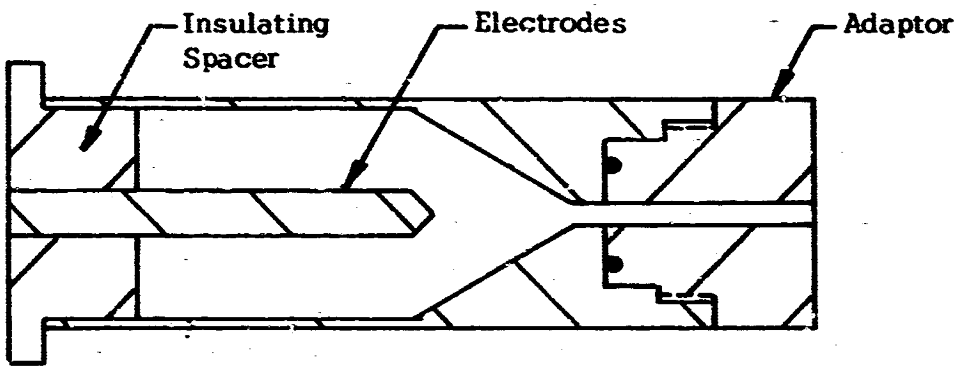


Figure 5. Non-Tapered Co-Axial Accelerator for Use in Checking Plasma Velocities

as a particle accelerator, but was useful in accelerating a plasma and determining how the overall system was operating. Plasma velocities of approximately 30 km/sec were obtained with this gun. This velocity fit very well with that which was expected for the plasma. Some shots were fired with this gun in an attempt to accelerate projectiles, but it was found to be very unsatisfactory. The projectiles, in this and other guns, were put on a mylar film with a thin coating of vacuum grease. The mylar film was placed at the interface of the outer electrode and the adaptor. In this position the projectiles were exposed to the plasma which melted the mylar and accelerated the particles by drag forces.

A tapered gun of the type shown in Figure 6 was next used. The electrodes were quite large in order to get a larger compression ratio for the plasma.

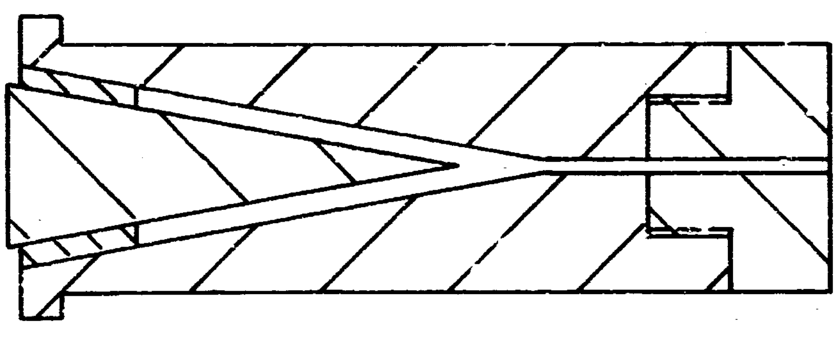


Figure 6. Large Tapered Co-Axial Gun

A provision was also made to introduce hydrogen into the annulus. The annulus was first evacuated and then filled with one atmosphere of hydrogen. When the firing occurred the hydrogen was compressed and swept ahead of the plasma and acted as an accelerating gas to the projectiles. Very few shots were made with this gun as it was found to produce unsatisfactory results.

The gun configuration which was used for most shots is that shown in Figure 7. This gun is very similar to that used in the experiments URDC performed at Wright-Patterson Air Force Base in the Materials Laboratory. The main difference between this gun and the one shown in Figure 6 is the electrode size. An effective size of 1/2" is used at the larger end of the tapered center electrode. A variation of this gun was obtained by using a center electrode that was 1/4" at the large end of the tapered section. The gun shown in Figure 7 has less volume than the gun in Figure 6 and will not have quite the density concentrating characteristics. The actual results using this gun were much better than those obtained using the larger gun, however.

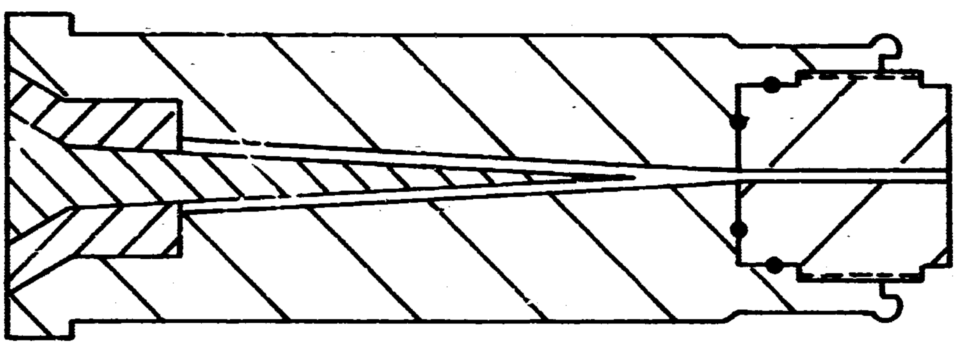


Figure 7. Tapered Gun Using a Small Center Electrode

E. Velocity Determination

A very simple velocity measuring system was used to determine the velocity of the projectiles. Time of flight measurements were made by observing the plasma issuing from the gun with a photocell. An oscilloscope trace was started with this signal. The light caused by the impact of the projectiles on the target (5 mil aluminum) was observed by a photomultiplier and the output was fed on the scan trace. Only those projectiles which penetrated the target were observed since the photomultiplier was looking at the back side of the target. There was generally more than one hole in the target and it was not possible to correlate a particular hole in the target with the impact flash associated with it. This study was only meant to be a feasibility study and these diagnostic techniques are suitable to determine trends in the data. When the co-axial accelerator is used as a laboratory tool better diagnostic techniques will have to be applied.

F. Projectile Size Determination

Projectiles which were fired during this study were commercially obtained and had a wide range of size distribution. In order to obtain projectiles that had a smaller spread in size URDC made a small wind tunnel to use in separating projectiles. A large (12-inch diameter) tube was filled with two-inch diameter paper tubes. A fan was placed at one end and was used as the constant velocity wind source. An opening was cut in the middle of the large tube approximately six feet from the fan and a space provided for the collection of the projectiles. When the fan was turned on, glass projectiles were allowed to fall singly into the tube and were separated in distance at the bottom of the tube by the drag force associated with the air acting on them. The projectiles were dropped through the air tunnel several times. A size classification of $\pm$ 15% was obtained by this procedure.

G. Experimental Methods Summary

The operation of the co-axial plasma accelerator to obtain data for this study proceeded in the following way.

1. The co-axial gun was assembled with the sorted glass spheres mounted on a mylar film in the gun barrel.

2. The gun was mounted in the vacuum range with connection of the outer electrode to the ground side of the capacitor bank and the plus side of the bank separated from the center electrode by a sheet of insulating glass.

3. The range was pumped down to a pressure between 1 and 500 microns of Hg.

4. The annulus of the gun was evacuated and then filled with one atmosphere of hydrogen gas.

5. A blasting cap was connected and placed behind the glass sheet to act as the initiator of the firing.

6. The capacitor bank was charged to a voltage between 10 KV and 20 KV.

7. The blasting cap circuit was initiated and the cap was fired.

8. The glass was broken by the cap and the bank discharged through the gun.

9. The metal foil between the two electrodes was evaporated and ionized by the discharge of the bank through it, and a plasma was formed.

10. The plasma was forced down the annulus of the gun by magnetic forces, sweeping the hydrogen gas before it.

11. The projectiles suspended on the mylar film in the gun barrel were accelerated by means of the plasma dragging them along into the range.

12. The sweep of one oscilloscope was triggered by the output of a photo cell that observed the plasma coming out of the gun.

13. The projectiles impacted against the target and the impact flash noted by a photomultiplier observing the back side of the target. Only those impacts which produced a penetration were recorded. The output of the photomultiplier was fed on the oscilloscope trace.

14. The velocity was computed and penetrations in the target were observed through a microscope.

This procedure was followed for the data which are reported in the following section of the report.

IV. RESULTS AND ANALYSIS

The experimental results of this study are reported in terms of the work done with the three types of guns which were used. Gun A, the non-tapered gun of Figure 5, was used for the preliminary work. Gun B, the large tapered gun shown in Figure 6, was used for relatively few shots. The main work was done with Gun C, the smaller tapered gun of Figure 7.

A. Gun A Results

During the early phases of the work of this study Gun A was the main accelerator that was used. The foil that was used to initiate the current between the electrodes and that was ionized to become the plasma was a 0.002 inch thick aluminum disk as shown below. The foil was used for most of the shots with Gun A. The projectiles used were generally those which were not sorted by

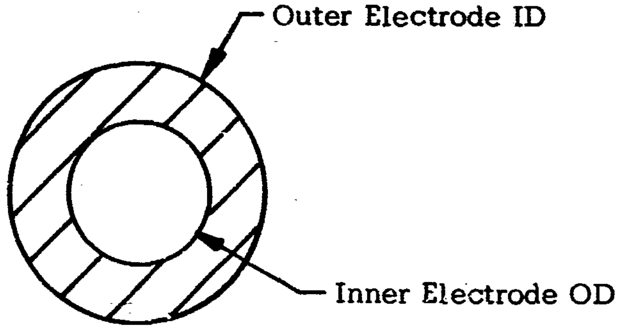


Figure 8. Shape of Foil Usedin Early Experiments to Initiate Current Flow Between Electrodes

URDC and were screened by the supplier to be between 125 and 177 microns in diameter. Results from the firings of Gun A were somewhat ambiguous. The velocities which were recorded were generally low (< 5 km/sec) and seemed to be independent of the bank voltage. Examination of the holes in the targets showed many irregular shaped penetrations which were not consistent with those to be expected with spherical glass projectiles. Several shots were fired where no projectiles were suspended from the mylar in the gun barrel. The velocities obtained on these shots were comparable to those where projectiles were used. It was obvious that material other than glass projectiles was being accelerated down range. One of the offenders in the physical set-up was tnought to be the mylar from which the projectiles were suspended. In the early shots this mylar was 10 mils thick. The thickness was reduced to one mil for the subsequent shots and much of the trouble disappeared. It was determined that the projectile velocity obtained with Gun A was lower than that desired and the work on this gun was concluded.

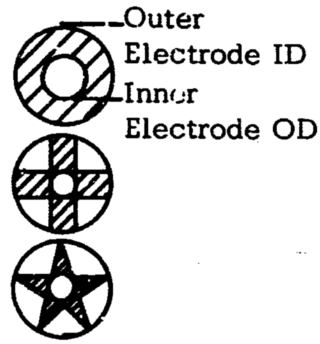
B. Gun B Results

Gun B was used for only a few shots. A change was made to a lithium foil, 10 mils thick, for the initiating action. The shape of the initiating foil was that shown in Figure 8. The change to lithium was to take advantage of the decreased density of the foil material. Projectile size was also reduced from 125-177 micron balls to 62-88 micron balls. The results from Gun B were discouraging, since the maximum velocity obtained with 20 KV on the bank was only 5.4 km/sec.

C. Gun C Results

Most of the data that were useful in determining the potential of the coaxial plasma gun were obtained with Gun C. Three projectile sizes, three bank voltages, three foil configurations and two center electrode sizes were used in obtaining the data. These parameters are listed in the table below.

TABLE I. VARIOUS PARAMETERS USED WITH GUN C FIRINGS

Projectile Size	Bank Voltage	Center Electrode	Initiating Foil Configuration
50 μ	10 KV	1/2 inch	
75 μ	15 KV	1/4 inch	
150 μ	20 KV		

The data obtained from the firings while varying the parameters are plotted in Figures 9, 10 and 11. Figure 9 is a plot of the bank voltage vs. the velocity of the projectiles for 75 micron projectiles. Figure 10 shows the bank voltage vs. velocity for 50 micron projectiles. Figure 11 is a plot of diameter vs. velocity for a constant bank voltage of 15 KV.

Several things are evident when one examines Figures 9 and 10. The relationship between voltage and velocity does not appear to be that of one to one. A straight line curve is drawn for the relationship one might expect if the energy

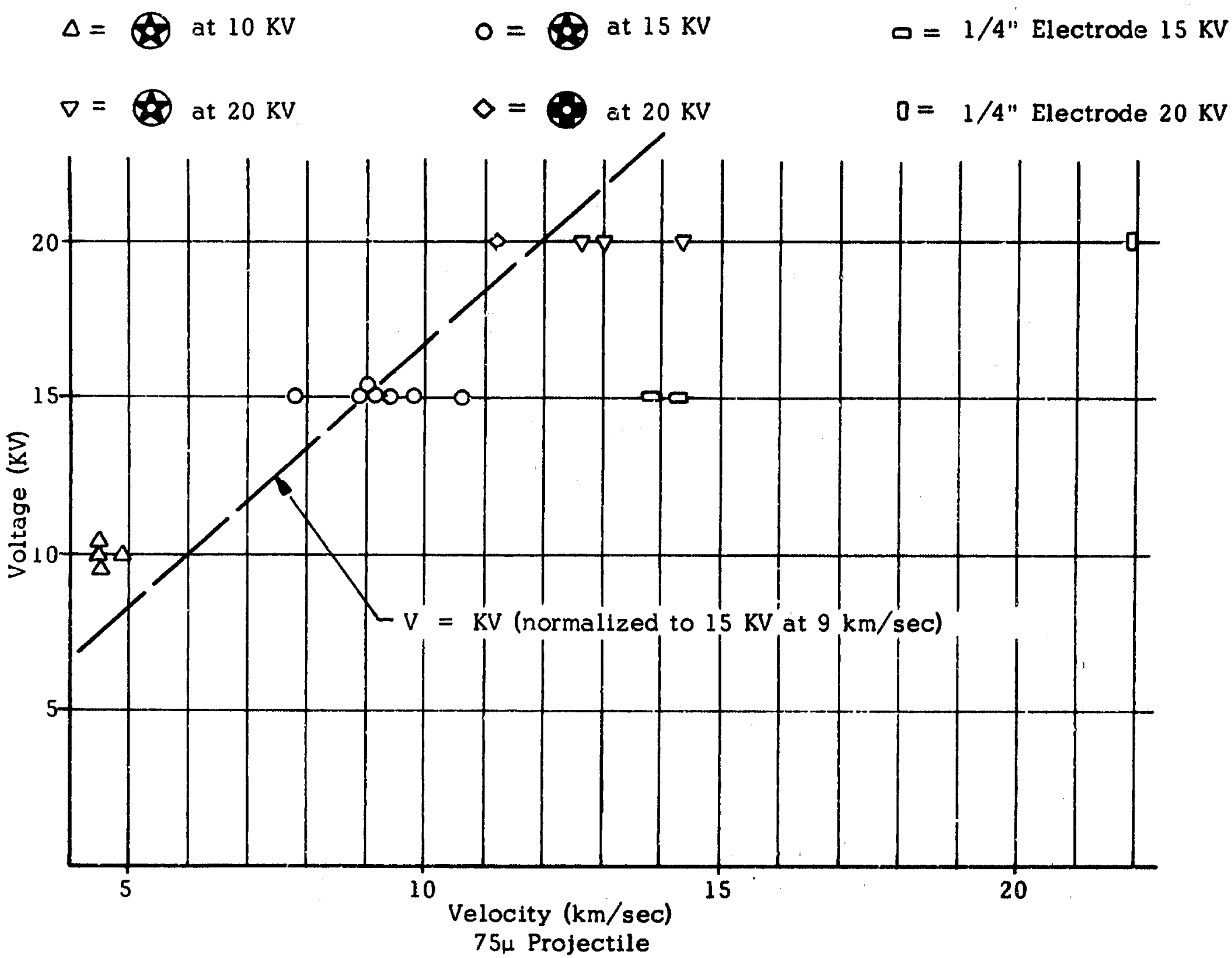


Figure 9. Bank Voltage vs. Projectile Velocity for 75 micron Projectiles
The Legends Indicate the Configuration of the Lithium Initiating Foil

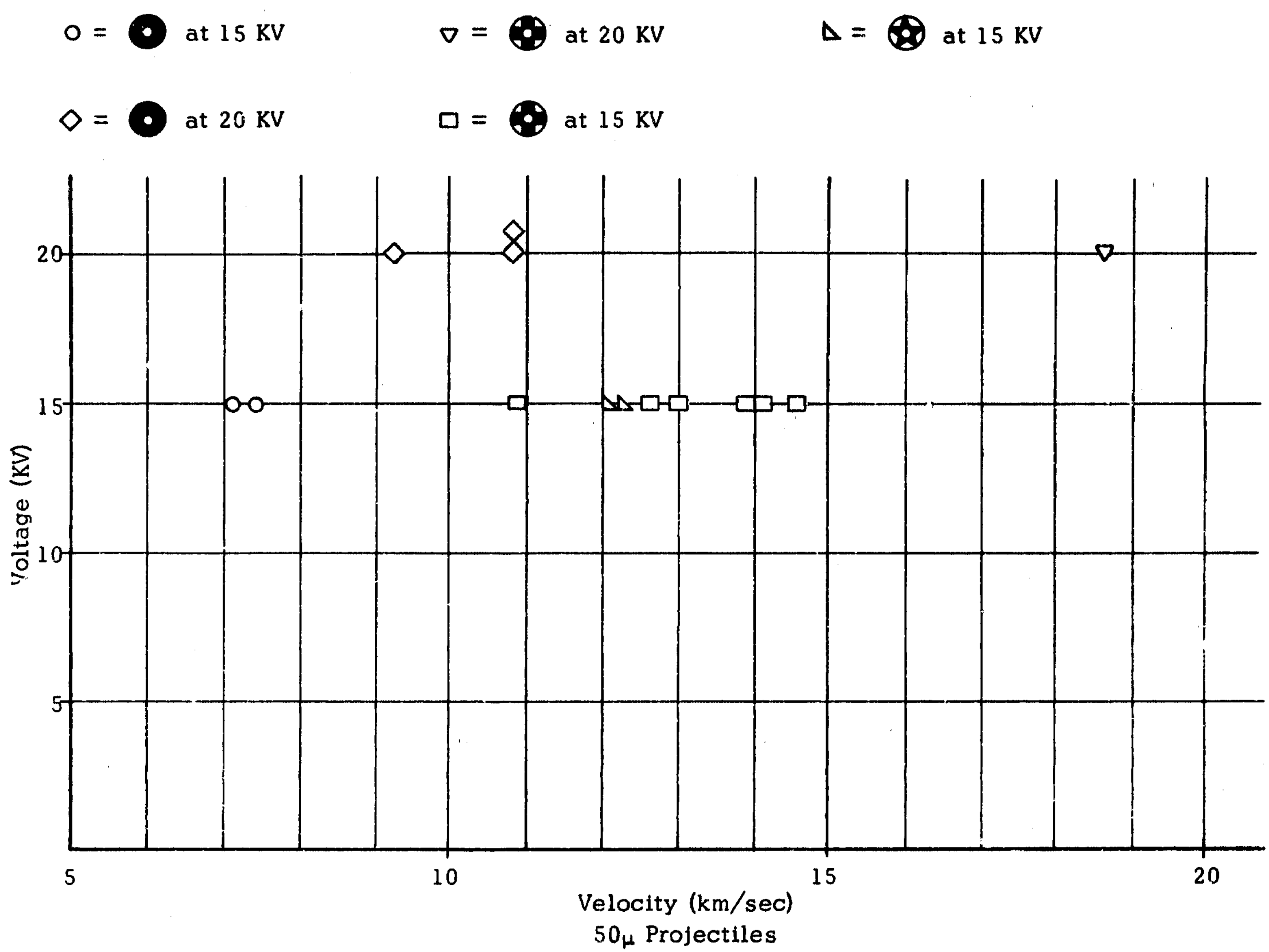


Figure 10. Bank Voltage vs. Projectile Velocity for 50μ Projectiles

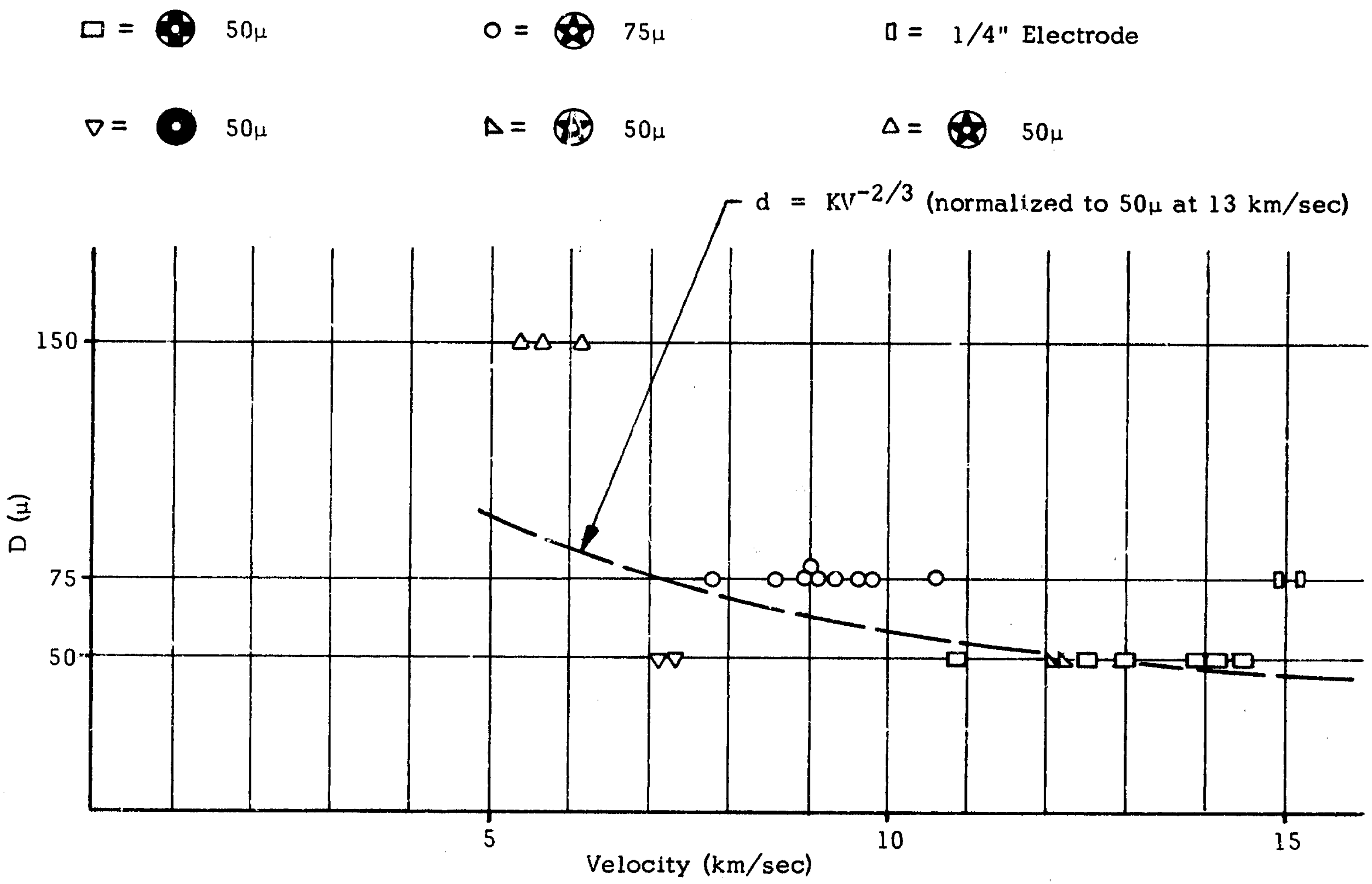


Figure 11. Projectile Diameter vs. Projectile Velocity for a Constant Bank Voltage of 15 KV

of the capacitor bank were transferred equally efficiently to the projectiles at all voltages. The curve was normalized for the condition of 9 km/sec at 15 KV. It is evident that the projectiles are accelerated more efficiently at higher bank energies than at lower. This could represent a less than optimum relationship between the lithium initiating foil and the bank. If the whole foil were not ionized at the lower voltages there would be a less dense plasma at the low voltages and less drag on the projectiles. It certainly indicates that the gun system has not been optimized and that one can expect at least some increase in performance.

There seems to be an effect on particle velocity due to the configuration of the initiating foil. This effect is particularly noticeable in Figure 10, which shows the effect of voltage on the 50 micron projectile velocity. It can be seen that the hollow disk configuration is much less effective than the cross configuration. The contrast between the cross configuration and the star configuration is not nearly so strikingly indicated in the data plots, although there may be a small difference. There are not enough data to make any positive statement about this relationship.

Figure 9 shows a marked improvement in results for the 75 micron particles when a 1/4 inch center electrode was used in the C type gun. Each of the three shots that were fired seemed to have results that were 50-60 percent better than with the 1/2 inch gun. There is a size of center electrode where the current density gets so high as to evaporate the metal of the electrode and cause a contamination of the plasma to occur. Apparently the 1/4 inch electrode is still not too small, although considerable ablation of the electrode was observed after firing. More firings of the gun in the configuration are required to ascertain the limits which are imposed on this gun.

Figure 11, a plot of the diameter of the particles vs. the velocity for a given voltage, suggests that the gun is more efficient at firing larger particles than smaller particles. The line in Figure 11 is a plot of the relationship that would be observed if the same kinetic energy were delivered to particles regardless of size. This particular curve is normalized at 50 micron particles and 13 km/sec. If one considers drag forces a relationship of diameter to velocity might be

$$d = kv^{-1}.$$

The curve for this relationship is closer to the observed values although the data still indicate somewhat more efficient acceleration for large particles than for small ones.

The improvement in velocity due to the foil configuration and center electrode size are again noticeable in Figure 11.

The data show a tendency to follow the direction one might predict. The data obtained with the straight electrode gun, Gun A, and the large tapered gun, Gun B, were disappointingly low. In their present form they are obviously not the best guns available. The plots of data shown in Figures 9, 10 and 11 show a general consistency in results that is encouraging. There seems to be a trend toward better acceleration efficiency as the bank voltage increases and as the size of the projectile increases. The high velocities obtained with the gun configuration using a 1/4 inch center electrode are greater than we had expected. This effect should be investigated at greater depth.

V. CONCLUSIONS AND RECOMMENDATIONS

The results of the Co-Axial Plasma Gun Study may be summarized as follows:

1. A simple power supply and capacitor bank were built to power a co-axial gun system.

2. The plasma was accelerated to the expected velocity.

3. Projectiles were accelerated to interesting velocities by plasma drag technique.

4. The data showed that the guns were not optimized and that better results are probably possible with slight variations.

5. The larger guns did not perform as well as had been hoped because the plasma density was not increased to the degree hoped for.

6. Present co-axial gun techniques can be used to accelerate 75 micron projectiles to velocities in the 17-20 km/sec region.

7. The study did prove the feasibility of the method of accelerating small particles.

URDC recommends that the following work be done:

1. Optimize the present co-axial gun design. This work will require more extensive firing than has been done. The parameters that would be varied are the center electrode and the initiating foil configuration.

2. Concentration of the plasma by means of a magnetic field should be investigated. The method for doing this work is relatively simple and the potential results well worth the effort. A plasma concentration is necessary if much larger projectiles are to be accelerated by the co-axial gun technique.

The work of this study was encouraging and should be continued.