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Mr. John Greenewald, Jr.

Dear Mr. Greenwald

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1. Request Ltr, 13 Apr
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AD 339084

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ASD-TN-61-22

OCTOBER 1961

AFSC Project 3805
Secondary Report Nr 0445-01(12)QP
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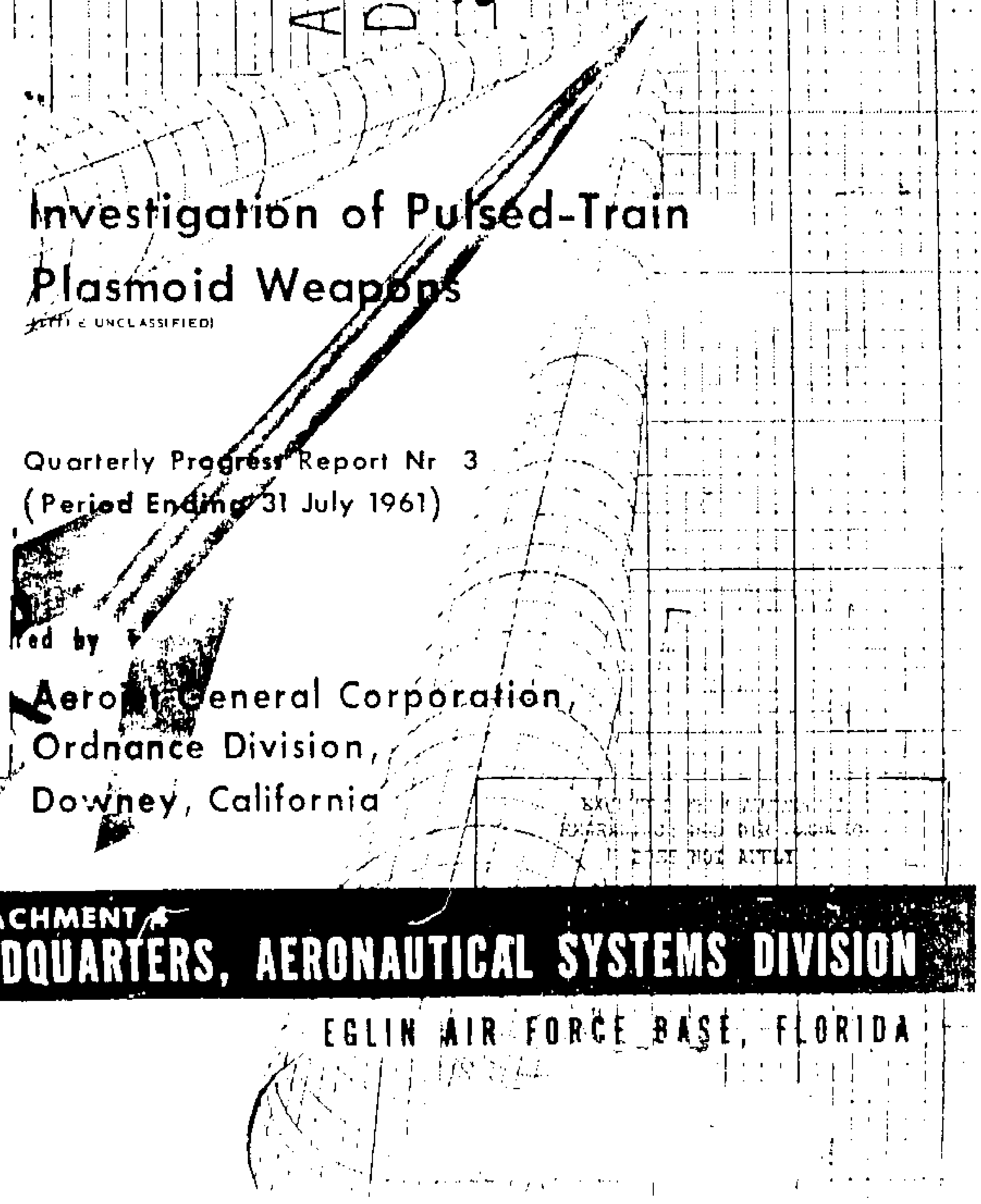

Investigation of Pulsed-Train Plasmoid Weapons

(TITLE UNCLASSIFIED)

Quarterly Progress Report Nr 3
(Period Ending 31 July 1961)

ed by

Aero[illegible]-General Corporation,
Ordnance Division,
Downey, California

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for

DETACHMENT 4
HEADQUARTERS, AERONAUTICAL SYSTEMS DIVISION

EGLIN AIR FORCE BASE, FLORIDA

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HEADQUARTERS, AERONAUTICAL SYSTEMS DIVISION
Air Force Systems Command
United States Air Force
Eglin Air Force Base, Florida

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ABSTRACT

This report contains a summary of the Investigation is made of the Pulsed-Train Plasmoid Weapons program and ~~intro~~duces some new ideas in projectors and nozzles are introduced. The experimental program is described, and test results are illustrated and presented in tabular form. A schedule of experiments is also given.

Catalog cards with abstracts may be found at the back of this publication

CONTENTS

1. INTRODUCTION

(U) 1.1 PURPOSE OF REPORT

This report contains a description and analysis of work completed under the program, Investigation of Pulsed-Train Plasmoid Weapons, included in Contract AF 08(635)-1671 during the quarter ending 31 July 1961.

~~(C)~~ 1.2 PROGRAM OBJECTIVES

~~(C)~~ 1.2.1 General Objective

The objective of this program is to theoretically and experimentally investigate the generation, projection, stability, and terminal effect of plasmoids for the purpose of obtaining preliminary weapon-system designs for use against enemy targets in the exosphere. It is essential that the gas making up the plasmoid retain sufficient directed kinetic energy (approximately 10 kilojoules/cm^2) to cause significant material damage to targets impacted at distances of 10 to 30 kilometers. The study of terminal ballistic effects from the impact of such high-speed plasmoids against representative target materials is included within this area of investigation.

(U) 1.2.2 Current Objectives

In order to evaluate the feasibility of plasmoid weapon designs that are conceived during the program, an experimental facility has been established so that prototype systems may be readily evaluated. An accelerated program of experiments is currently in progress to measure the performance of the various system configurations. A description of work completed thus far and a schedule of the experiments planned for the next period are contained in this report.

~~(S-RD)~~ 1.3 SUMMARY OF TECHNICAL PROGRAM

Parallel theoretical and experimental work is being continued. Theoretical analyses, combined with review of related studies by other investigators, are providing guidance for the experimental program, and also are being used in an attempt to provide possible solutions to current problems in ways which are not presently being studied experimentally. An important function of the theoretical work is also to suggest new concepts which may be useful in solving the problems of a continuing plasma weapon program.

Manuscript Released
10 October 1961

The plasma experiments have as their objective the investigation of various important phenomena or concepts involved in each of the weapon-system components or problem areas (i.e. power, acceleration, stabilization, impact damage).

(S-RD) 1.3.1 Theoretical Work

During the current report period, emphasis was placed on efforts to answer the following question: Is it possible, given hydrodynamic expansion of the plasmoid, to maintain sufficient energy density to cause damage at distances of tactical signficance? Limitations on the energy input to the system are set by the power source considered, and this source must be kept within reasonable bounds from the standpoints of payload and tactical considerations.

The hydrodynamic expansion of the plasmoid was investigated in greater detail, with results which generally confirm the acoustic approximations found in the last quarterly report. This analysis, combined with results of target-damage studies, has served to re-emphasize the need for increased translational velocity and confinement in order to achieve significant impact-damage effects. A number of approaches, varying in their possible ease of attainment, have been examined for achieving stronger damage effects.

a. Charge exchange and magnetic, adiabatic expansion nozzles have been previously described. Further analysis is given in this report (These concepts are being incorporated into the experimental program at present, and initial results are outlined in Section 3.2).

b. Biconical accelerators (after Phillips), which reduce the parasitic inductance associated with longer coaxial systems and also serve to compress the plasmoid prior to expansion in a nozzle, are discussed.

c. A double azimuthal pinch accelerator and compressor is discussed, and it is shown that its use would result in reductions in discharge energy losses by producing a current sheath near the walls, thereby preventing wall electron losses.

d. The hot plasma can possibly be used as a propellant for solid projectiles (Reference 1), thereby eliminating the need for collimation of the plasma discharge in a weapon system.

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e. [redacted] This would provide an energy source perhaps adequate for very long-range directed energy systems, but would not require such a large yield as to make its tactical use impractical, as is apparently the case for the device discussed in Reference 2.

It is concluded on the basis of theoretical work to date that gaseous plasmoid impact can be a feasible short-range (1-10 km) kill device against light space-vehicle structures or instruments. For long-range kill possibilities (10-100 km), use of hot plasma (produced either by novel electrical means or by low-yield nuclear systems) as a propellant for solid projectiles appears to be feasible.

~~(0)~~

1.3.2 Experimental Work

In view of what has been said previously about the importance of collimation of the ejected plasmoid, most of the experimental effort has been directed toward devising a suitable arrangement to do this effectively for gaseous plasmoids. The theoretical development suggests that, depending on the effective value of γ for the gas, gaseous plasmoids could still effect kills at short ranges. Since γ is not known with certainty, we have to carry through experimental measurements of the plasmoid expansion rate for various magnetic-nozzle configurations. For this purpose, we have begun high-speed optical measurements of the axial and radial velocities of the plasmoids as they are ejected from different magnetic-nozzle configurations. The configurations are produced by solenoidal or "pancake" coils, which may be arranged in series.

The measurements carried out so far indicate that reductions in the radial velocity of the plasmoid can be attained even by a simple solenoid nozzle in conjunction with a coaxial gun. Work on optimum nozzle configurations is continuing, and photographic studies of two-dimensional flow phenomena occurring during target impact have been made. These latter are important in showing the extent to which the effective area of contact between plasmoid and target is increased during impact.

Photographic evidence has also been obtained of the existence of a reverse current-flow filament discharge between the electrodes of the coaxial gun after firing, indicating existence of a reverse-field stabilized arc. This is discussed theoretically in Section 2.2.

Installation of a new vacuum chamber and associated electronic equipment has been carried out simultaneously with the above work at the Chino Hills Research Laboratories. Development work is proceeding on the probe system for measuring masses of charged particles in the plasmoid.

2. THEORETICAL PROGRAM

~~(S-RD)~~

2.1 EXPANSION AND TARGET-DAMAGE EFFECTS OF A GASEOUS PLASMOID

In the previous quarterly report we had attempted to discuss cloud expansion into a vacuum, rather crudely, by an acoustic approximation, assuming that the velocity of expansion of the cloud boundary was the local sound velocity. This assumption was found to describe very well the one-dimensional rate of expansion of a gas into a vacuum, when compared with the numerical calculations in Reference 3. However, it is necessary to sharpen the approximation somewhat for a discussion of a three-dimensional nozzle flow. In Reference 4 the expansion of a cloud of nuclear-weapon debris is discussed on the assumption that the density of the cloud remains uniform. This follows if the energy of random motion of the particles making up the cloud is uniformly converted almost completely to radially directed motion.

This is the condition which we are trying to achieve in our magnetic nozzle. In the ideal case, all the gas will be moving outwards radially in a conical segment of solid angle ω. The true position coordinate, r', transforms to an equivalent spherical radial coordinate, r, by the relation:

$$r' = \frac{4 \pi r}{\omega} \tag{1}$$

The velocity along the cone axis of symmetry then transforms to a one-dimensional radial velocity. ω is determined by the geometry of the nozzle, but its exact determination is not relevant for the present discussion. Working in terms of the r coordinate and assuming uniform density, at any given time one gets for that density:

$$\rho(t) = \frac{M}{\frac{4}{3} \pi R^3} \tag{2}$$

and

$$R = V_o t \tag{3}$$

where V_o =hydrodynamic velocity at the gas boundary.

We use V for hydrodynamic (bulk) velocity, v for molecular velocities.

The velocity distribution <u>within</u> the cloud follows from the mass continuity relation

$$\partial\rho/\partial t + \nabla\cdot\rho\vec{V} = \partial\rho/\partial t + \rho\nabla\cdot\vec{V} + \vec{V}\cdot\nabla\rho = 0 \tag{4}$$

Since $\nabla\rho = 0$ (uniform density) and $\rho \propto R^{-3}$

$$\partial\rho/\partial t = \frac{9M}{4\pi R^4} \cdot \frac{dR}{dt} = \frac{3}{R} \cdot \rho \frac{dR}{dt} \tag{5}$$

But, from (4)

$$\nabla\cdot\vec{V} = \frac{3}{R} \frac{dR}{dt} = \frac{3}{R} V_o = \frac{\partial V}{\partial r} + \frac{2}{r} V \tag{6}$$

and

$$\vec{V}(r) = \frac{\vec{r}}{R} V_o \tag{7}$$

The kinetic energy per unit volume is

$$E = \frac{1}{2} \rho(t) V^2 \tag{8}$$

By integrating this, one gets the total directed hydrodynamic energy:

$$Y = \frac{1}{2} \int_0^R \frac{3M}{4\pi R^3} \cdot \frac{r^2}{R^2} \cdot V_o^2 \cdot 4\pi r^2 \, dr = \frac{3}{10} M V_o^2 \qquad (9)$$

$$V_o = \sqrt{\frac{10}{3} \frac{Y}{M}} \qquad (10)$$

Y is the fraction of energy converted into motion along the conical nozzle axis, and is given by

$$Y = \frac{T_2 - T_1}{T_1} E \qquad (11)$$

Here E is the initial input of energy into the device; T_1 is the temperature at the nozzle throat, calculated as E/MC_V; and T_2 is the temperature at the end of the expansion process, calculated on an ideal gas model, from

$$B \propto T^{\gamma/(\gamma-1)} \qquad (12)$$

where B is the applied magnetic field along the nozzle.

Not all the available energy is made available for motion along the symmetry axis of the system, however. Some remains as random thermal energy and is responsible for the dispersion of the plasmoid. Then the particles move outwards in an isotropic distribution given by the Maxwell distribution for molecular speeds:

$$N(v)dv = \frac{4\pi N}{v_c^3 \pi^{3/2}} \exp\left[-(v/v_c)^2\right] v^2 \, dv \qquad (13)$$

Here N = total number of particles,

$$v_c = \sqrt{\frac{2kT}{m}} = \text{ most probable velocity,}$$

m = mass of a particle,

and N(v)dv = number of particles having velocities in the range dv about v.

The kinetic energy corresponding to v_c is $1/2\ mv_c^2 = \frac{3}{2}\ kT$. But the total energy available thermally is

$$E - Y = Q = N \cdot \frac{3}{2}\ kT \tag{14}$$

since $\frac{3}{2}$ kT is the average energy per particle.

So

$$v_c^2 = \frac{2kT}{m} = \frac{4}{3}\ \frac{Q}{Nm} \tag{15}$$

Thus

$$V_o/v_c = \frac{5}{2}\ \frac{Y}{Q} \approx \frac{5}{2}\ \frac{T_1 - T_2}{T_2} \tag{16}$$

if C_v is assumed constant.

Values of between 10^2 and 10^3 for the above ratio seem quite feasible, given a favorable value of γ.

The plasmoid expansion process may be traced in more detail by using a transformation derived from P. Molmud (Reference 5). Writing (13) as

$$N(v)\,dv = 4\pi\ (\beta/\pi)^{3/2}\ e^{-\beta v^2}\ v^2\,dv = \phi$$

where

$$\beta = \frac{m}{2kT}$$

we see that the particles with the velocity range from v to v + dv are contained in a region of volume $4\pi v^2 t^3$, where t is time.

The particle density at $(|\vec{r} - \vec{r}'|, t)$ is

$$\rho = \phi\ dN\ (4\pi v^2\ t^3\ dv)^{-1} \tag{17}$$

Setting $v = \frac{|\vec{r} - \vec{r}'|}{t}$, we get

$$\rho = (\beta/\pi)^{3/2}\ t^{-3}\ dN\ \exp\left[-\frac{|r - r'|^2\ \beta}{t}\right] \tag{18}$$

Compare this with the point-source solution of the heat conduction equation:

$$T = Q(4\pi kt)^{-3/2}\ \exp\left[-(r - r')^2/4kt\right] \tag{19}$$

where

k : diffusivity

Q = source strength

Then (18) and (19) transform to each other (Q is equivalent to dN) if

$$t^2/\beta \rightleftharpoons 4kt \tag{20}$$

By this transformation, we can utilize known solutions of the heat-flow equation, as pointed out by Molmud. For the present case, assume cylindrical symmetry, a cylindrical jet, radius a, emerging from the nozzle mouth, $\rho = \rho_o$ in the interior of the cylinder.

Then

$$\rho(r, t)/\rho_o = 2\beta t^{-2} e^{-\beta r^2/t^2} \int_o^a x e^{-\beta x^2/t^2} J_o(i 2 x r \beta/t^2) dx \tag{21}$$

where J_o is the zero order Bessel function. A plot of ρ/ρ_o vs r/a is given (Figure 1).

The physical picture given by the above discussion follows: The plasmoid has acquired a non-random translational motion equivalent to the radial velocity along the symmetry axis, but its particles retain a random velocity component which is responsible for a diffusional expansion. The change in energy distribution in the nozzle is the critical factor in its behavior and, if the ideal gas law holds, the effective value of γ is highly important. It is this which we are now trying to determine experimentally, since if we know the ratio of V_o/v_c (axial to radial velocity) we can, from Equation 16 and our knowledge of the energy input, calculate the temperature drop in the nozzle.

Regarding target-impact phenomena, we note that in Reference 6 it is calculated that the greater part of the energy contained in plasma incident to a target is transferred to the reverse-flow vapor layer over the target. In Reference 6 this energy absorption is calculated from data on energy loss during sputtering which was obtained at Oak Ridge National Laboratory. At densities comparable to ours, 95% to 99% of the energy is transferred to the vapor layer. Our hydrodynamic calculation had indicated that a minimum of 85% of the energy was being so transferred, appearing in the form of thermal energy as the vapor layer is compressed against the solid surface. As the vapor recoils from the surface, most of this thermal energy will be recovered in

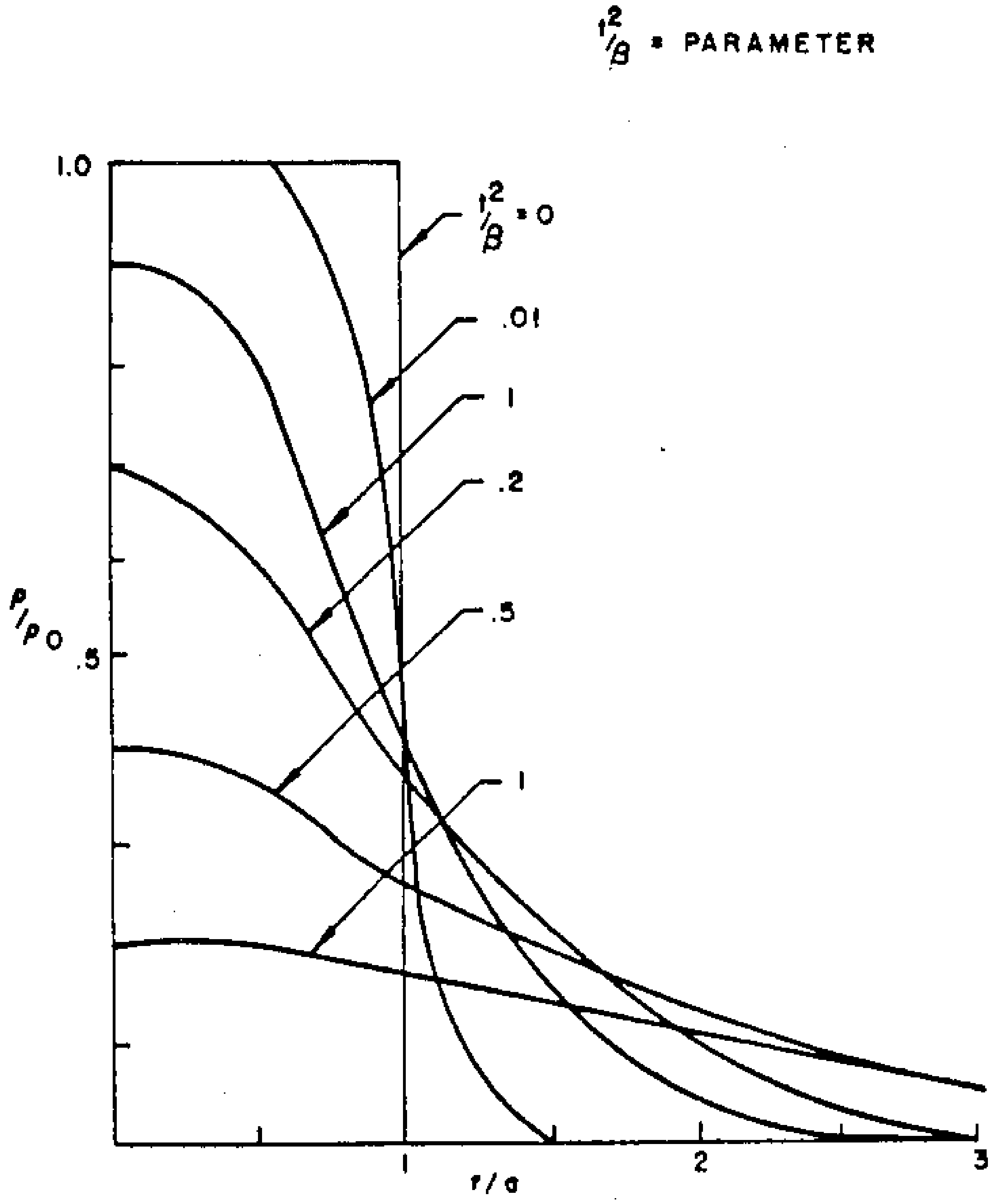

Figure 1. Plots of Dimensionless Density vs Time for Hydrodynamic Diffusion.

the form of kinetic energy. During the period of contact, however, a pressure pulse is introduced into the solid target material. The momentum of this impulse is transmitted into the target material or structure as a shock wave. The impact velocity and gas density determine both the pressure magnitude in this pulse and its duration. Analysis of this relationship for both the one-dimensional and bounded cases will be pursued during the next quarter.

(S-~~RD~~) 2.2 PLASMA HEATING PROCESSES

It has been noted previously that the expansion process plays a rather crucial part in accelerating the plasmoid and reducing its radial dispersion. To obtain adequate expansion ratios, we need a high degree of initial compression of the plasma, which is not possible in the coaxial gun. Moreover, in order to compress the plasma adequately without suffering excessive energy losses, the manner in which energy loss occurs in high-temperature discharges must be considered. Loss phenomena which were not anticipated had a disastrous effect on the stability of linear and toroidal pinches studied under the Sherwood program. The explanation of this effect seems to be that under the influence of a directional electric field, a large proportion of the energy of the plasma is carried off by electrons in the high-energy tail of the Boltzmann distribution, the so-called runaway electrons. Reference may be made to papers by Giovanelli (Reference 7), and Dreicer (Reference 8), for a discussion of the topic. In the presence of a strong electric field along, say, the Z axis of a system, one has a displaced Maxwell distribution; thus

$$F(c,\, c_2,\, t) = (m/2\pi kT)^{3/2}\ \exp\left\{(m/2kT)\left(c^2 + \left[c_2 - v(t)\right]^2\right)\right\} \qquad (22)$$

where v is the electron-drift velocity.

Because of joule heating, any weak electric field becomes transferred into a strong field with time and change of conductivity. Also, a diffusion of electrons into the high-velocity region is proceeding with time. These high-velocity electrons carry considerable energy to the walls of the discharge and lead to detachment of high Z impurities from the wall, greatly increasing the radiation loss. A possible method of eliminating this source of loss, which also suggests an explanation of the efficiency of the coaxial gun under the correct pressure condition follows. It is suggested by the mode of operation of the thetatron or azimuthal-pinch (Reference 9) device in which a rising current in a solenoid is used to induce an azimuthal current ring in a gas column enclosed in the solenoid. The combination of azimuthal current and axial magnetic field gives a radial body force which compresses the gas. The compression is carried out in the initial stages at least, by a sheath of ionized gas in the form of a ring. This is a single-sided sheath; the electron-ring current leads to a discontinuity in the radial distribution of the magnetic field; i. e., the value of B_Z drops to zero inside the ring. Now suppose we can provide a field distribution in which the B_Z field goes to a negative value, going through zero. This can be done (as in Reference 10) by inducing opposing current rings in the gas in rapid succession, one within the other, by feeding oppositely directed current pulses through the solenoid in succession. The first pulse would be a weak pre-ionization pulse; the second would be the main pulse. So we have a double-sided sheath, a region of zero magnetic field trapped between two current rings. The thickness of the sheath, in the two-sided case, has not yet been calculated. For the one-sided sheath, we can calculate it as follows:

Taking the y axis as parallel to the sheath front, $E_y = (v/c)\, B$ and the electrons are accelerated for a time, λ/v, where λ = sheath thickness, and v = sheath velocity. Then the average electron velocity in the sheath is

$$v_y \quad e\,B\,\lambda/mc \qquad (c = \text{velocity of light}) \tag{23}$$

But

$$B/\lambda = 4\pi j_y = 4\pi n e v_y/c \tag{24}$$

So

$$\lambda = (mc^2/4\pi n e^2)^{1/2} \tag{25}$$

depending only on the number density of electrons.

Thus the sheath thickness is a function mainly of the electron density, n. Such a double-sided sheath will act as a barrier to prevent the flow of runaway electrons transversely to the direction of motion of the sheath; and since the sheath is moving radially inward, it will prevent the movement of such electrons to the walls, and thus the loss of energy from the discharge.

The longitudinal movement of electrons along the sheath or inside it parallel to the walls is not, of course, prevented. Shear developing in the electron flow in this direction may be responsible for sheath instabilities. Such shearing instability is not likely to develop if the configuration of the sheath changes rapidly with time. Under practical conditions with an imploding sheath this happens near the center of the implosion, where the thickness of the sheath is not too much less than the radius of the imploded system, which is changing rapidly. The density of the electrons will increase; likewise, the rate at which they acquire kinetic energy for longitudinal motion by collision with the potential wall of the sheath. Thus, local shear flaws will develop. This can be prevented at least to some extent by arranging the geometry so that the implosion contracts onto an expanding annulus of sizeable radius, so that large values of dr/dt are not reached as the two sheaths converge. This double-sided arrangement has the additional advantage of providing an inner as well as an outer sheath to trap the electrons.

It has been pointed out by Longmire, Ebel, and Treiman (Reference 11) that electrostatic-charge sheaths can develop on the electrodes of a configuration such as that of a coaxial discharge gun. These can occur at low pressures through the motion of polymerization effects in a low-density plasma which functions effectively as a dielectric. Such sheaths can isolate runaway electrons from the walls, in the same manner as the magnetically induced sheaths discussed previously. This fact may explain the relatively high efficiency of hydrogen-loaded coaxial guns and their absence of electrode-impurity lines in the discharge spectra. From this discussion, the obvious experimental development is the double azimuthal pinch, or double thetatron. This consists of an annular system with induction coils outside and inside to produce simultaneous implosion and explosion of thetratron sheaths (Figure 2). Longitudinal leakage of electrons must be prevented, and this is done by injecting plasma from a coaxial gun system immediately upstream of the thetatron configuration. In the downstream direction, the hot plasma will be ejected, either into a nozzle or a gun barrel. In view of the above remarks on electrostatic-sheath formation in the coaxial gun discharge, it may be better to achieve the injection effect by shortening the coaxial electrodes to stubs at one end of the thetatron annulus.

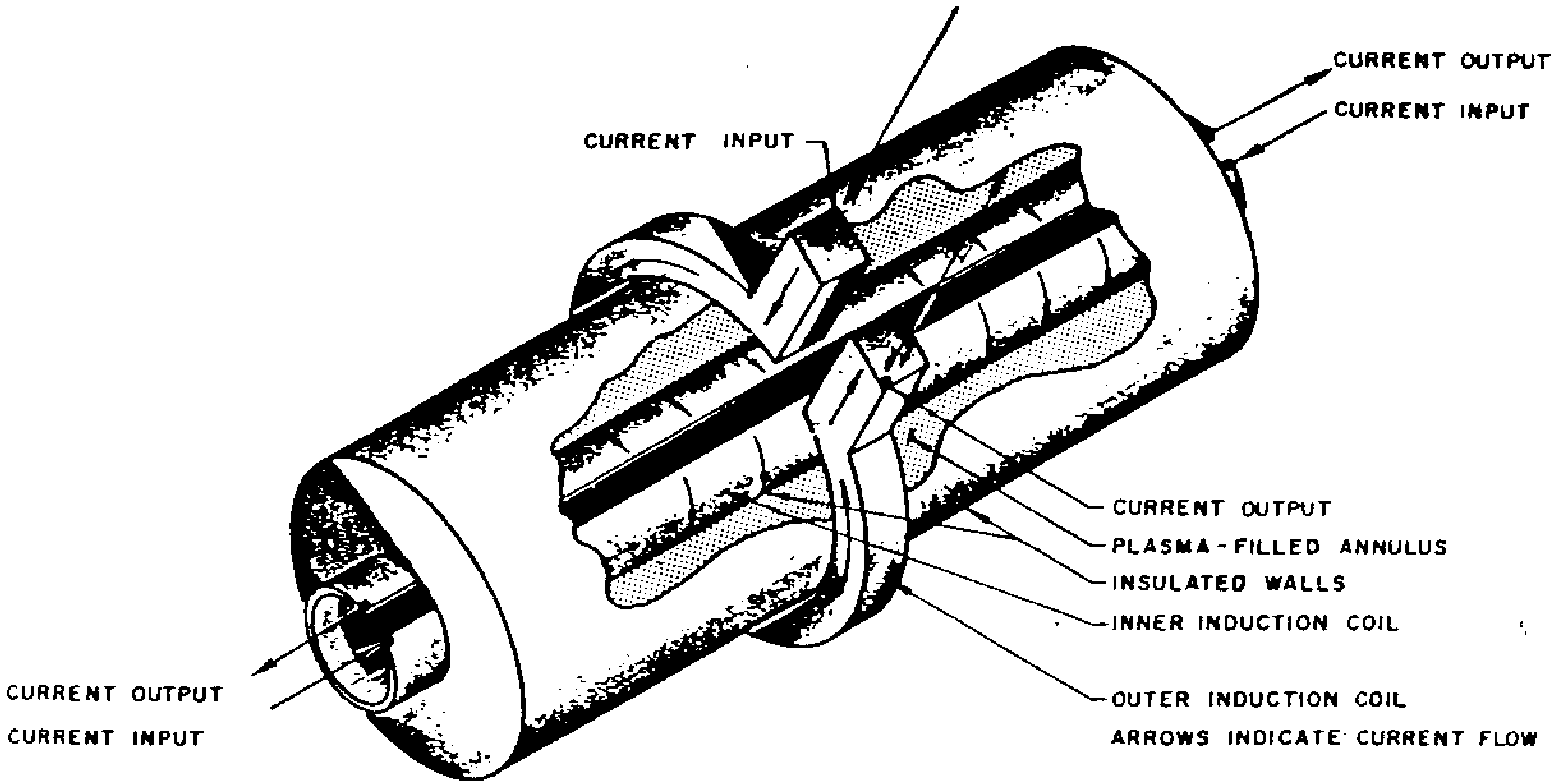

Figure 2. Double Thetatron.

By firing these prior to the thetatron discharge a form of arc, stabilized by reversed B_θ magnetic fields, is created around a central annulus. Here we have a double sheath being produced by B_θ, rather than B_Z, magnetic fields (Figure 3).

Upon application of the double-thetatron pinch, the sheath system so formed will be compressed by B_Z sheaths. Intermixing of the magnetic fields will follow, with heating and energizing of the plasma. While the detailed mechanism of plasma heating by field intermixing is not known, it is believed to occur by direct heating of ions by plasma oscillations (Reference 12). In any case, it appears experimentally to be an effective method of energizing a plasma.

The alternative to using a coaxial stub discharge is to use a coaxial gun which achieves sume precompression of the plasma while in the gun. Such a device is the biconical gun (Figure 4) in which the accelerating force is applied to the gas in annuli between two coaxial conical electrodes of different half-angle. This achieves the effect of precompression (by converging flow at the cone tip). At the same time, since the inductance of the gun varies as $\log \frac{d_2}{d_1}$, the parasitic inductance of the gun back of the moving slug of ionized gas is less than in a coaxial-type cylinder gun. Finally, in an expendable system, the magnetic pressure exerted by the thetatron sheath may be explosively augmented by driving the inducing sheath inwards by an explosive charge, in the manner indicated by Fowler et al (Reference 13). Since the magnetic field, B, varies as $1/R^2$ in such a device, it is apparent that combined explosive-magnetic compression would be much more effective than magnetic compression alone in heating the plasma. In the double-azimuthal pinch, however, a collapse of the solid core containing the induction coil must be prevented until the hot plasma has been squeezed out of the system longitudinally. This may be done by detonation of a line charge in the core, the expansion of which delays completion of the implosion. It may be remarked that simple cylindrical implosion without any magnetic effects has been used by the Orion group (Reference 14) to accelerate explosively derived plasmas in vacuum to $4\text{-}5 \times 10^6$ cm/sec.

To summarize, the following experimental developments have been suggested, based on the key idea that a plasma can be most effectively energized by implosion or acceleration within a charge sheath:

a. The double-thetatron pinch, which may be explosively augmented by combined explosive-magnetic effects.

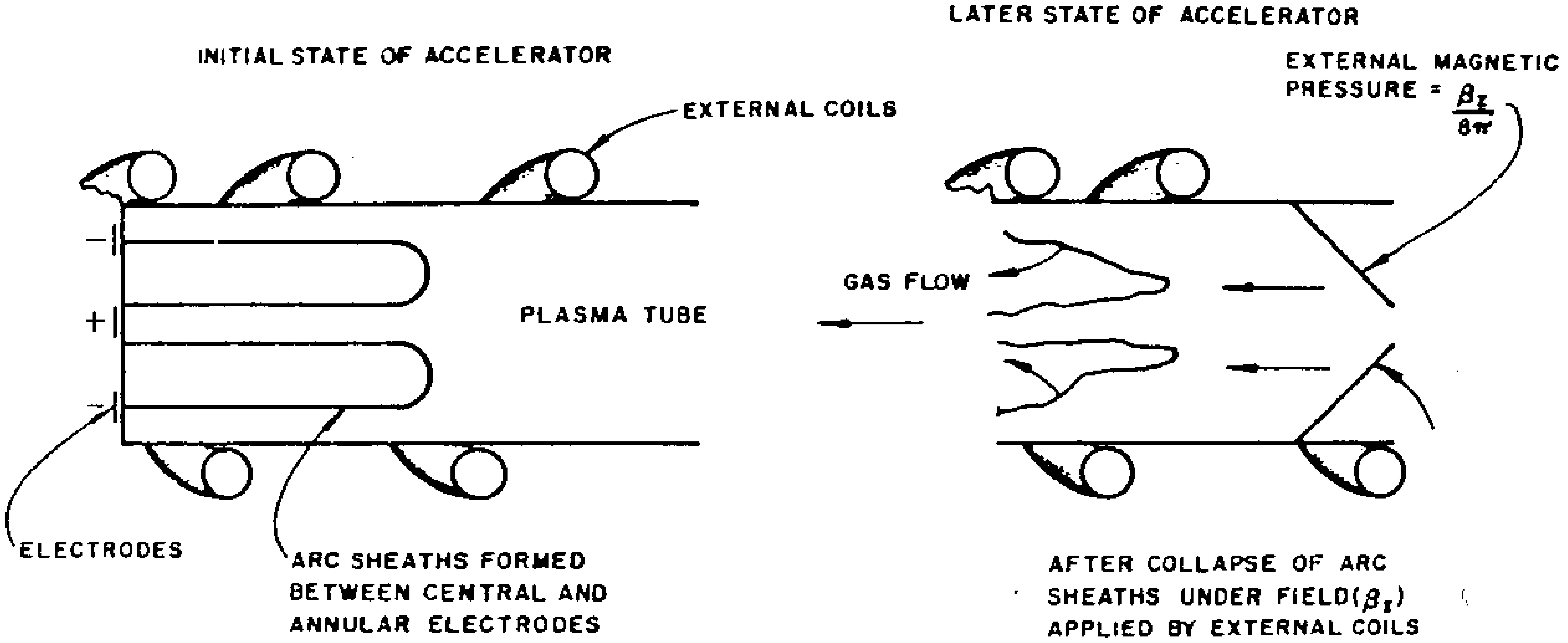

Figure 3. Superposed Magnetic Gun Barrel and Accelerator.

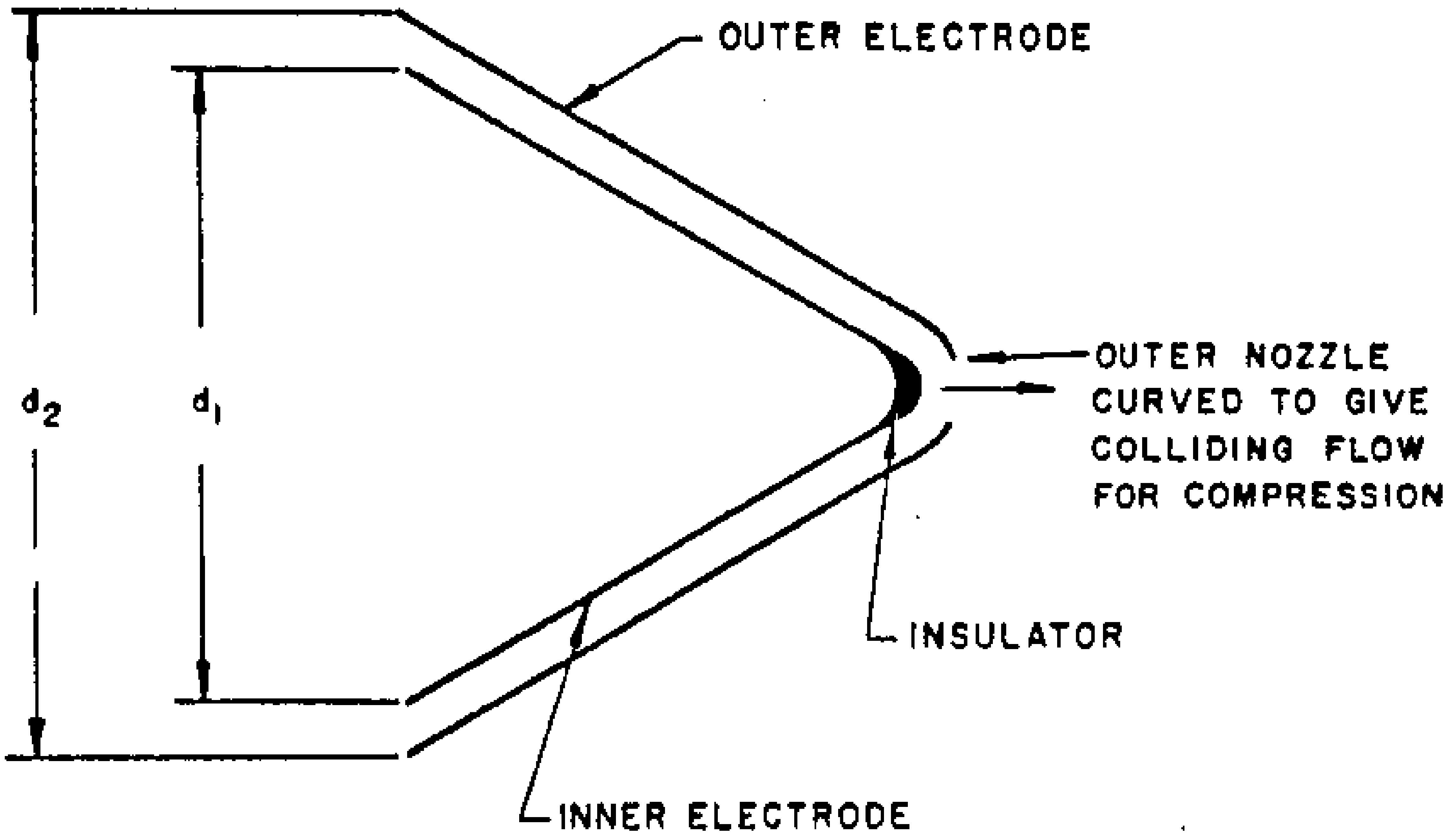

Figure 4. Schematic Diagram of Biconical Gun.

b. Injection of plasma into this system by (1) the biconical precompression device, or (2) a coaxial stub discharge to produce a magnetically stabilized plasma filament within the thetatron sheath.

The heated plasma moving out of the collapsing thetatron system can be expanded into a nozzle to produce a gaseous plasmoid, as is now being done, or it can be used as propellant for a group of solid particles. The experimental program anticipates first substituting a biconical-type gun for a coaxial gun, in conjunction with the magnetic nozzles now being developed. The biconical gun would inject compressed plasma into the nozzle throat. Later development would involve construction of a double-thetatron pinch, and finally an explosively augmented device.

(S-~~RD~~) 2.3 LONG-RANGE KILL POSSIBILITIES

To obtain a weapon capable of killing at a range of 10 to 100 km, a method of using plasma energy other than as a dilute gaseous blob must be considered. Also, the possibility of increasing the energy input by some form of staging in conjunction with an economical low-yield nuclear device must be considered. As to the first point, the plasma can be used as propellant for a single solid projectile or, more usefully, a shotgun spray of small projectiles. The hydrodynamic behavior of such a system can be calculated as follows, in terms of the net rate of addition of energy to the system, i.e., the gross rate of addition from external sources minus the radiation loss.

The motion of a particle being propelled by plasma proceeds thus: As the gas or plasma expands, a rarefaction wave caused by the motion of the body develops. After reflection, this reaches the propelled particle and the following mode will be established in the gas.

$$v = (x + \ell)\,\Phi(t) \qquad (26)$$

$$P = P(t)$$

Thus, if the pressure, and hence the density, in the gas does not depend, on the average, on the coordinate and only varies with time, the kinetic energy of the gas may be expressed as follows:

$$E_1 = \frac{1}{2} \int_{-\ell}^{\infty} \rho \, u^2 \, dx = \frac{1}{6} \rho \, (x + \ell)^3 = m \, u_b{}^3/6$$

where

$$m = \rho \, (\ell + x_b)$$

(m is the mass of propellant, M is the mass of the projectile, and the subscript b refers to conditions at the surface of the propelled body).

The potential energy, E_2, is then

$$E_2 = \frac{P_b \, (x + \ell)}{\gamma - 1} \tag{28}$$

Taking into account the fact that the pressure at the wall of the system can be higher than at the surface of the projected particle, E_1 can be expressed as

$$E_1 = \frac{m \, u_b{}^2}{6 \, \theta} \tag{29}$$

where $\theta > 1$ is a coefficient. In the case of escape into a vacuum, this should be equal to $\theta = \frac{2\gamma}{3(\gamma - 1)}$, which follows from the law of conservation of energy.

$$\frac{m \left(\frac{2}{\gamma - 1} \cdot c\right)^2}{6 \, \theta} = \frac{mc^2}{\gamma(\gamma - 1)} \tag{30}$$

where c = velocity of sound.

As time goes to infinity, the ratio $\frac{E_2}{E_1} \longrightarrow 0$, and so the entire energy becomes kinetic.

The energy equation for the gas may be written

$$E = \frac{P_b (x_b + \ell)}{\gamma - 1} + \frac{mu^2}{6\theta} + \frac{Mu^2}{2} = E(t, x) \tag{31}$$

Since

$$M (du/dt)_b = P_b \tag{32}$$

$$E(t, x) = \frac{M \ddot{x}_b (x_b + \ell)}{\gamma - 1} + \frac{1}{2} (\frac{m}{3\theta} + M) \dot{x}_b^2 \tag{33}$$

Differentiating with respect to time,

$$\frac{1}{M} \frac{\partial E}{\partial t} = \frac{\ddot{x}_b (\ddot{x}_b + \ell) + \ddot{x}_b \dot{x}_b}{\gamma - 1} + (\frac{m}{3\theta M} + 1) \ddot{x}_b \tag{34}$$

On the boundary of the propelled body this becomes

$$\frac{1}{M} \frac{\partial E}{\partial t} = \frac{u_b}{M} \frac{dE}{d x_b} = u_b \left[\frac{d}{d x_b} \left(\frac{d u_b}{d x_b} \cdot \frac{u_b (x_b + \ell)}{\gamma - 1} \right) + \left(\frac{m}{3\theta M} + 1 \right) \frac{d^2 u_b}{2 d x_b^2} \right] \tag{35}$$

This equation must be solved numerically, if the value of dE/dt is known as a function of t and of x. This must be calculated on the basis of the energy flow from outside, and the radiation loss from the gas. This has not yet been computed, for it will depend on the particular method of energy addition used, and on the opacity of the gas.

The second point, that of obtaining a more powerful energy source than the explosive generator, leads immediately to this result. The only transient energy source more powerful than an explosive or transient magnetohydrodynamic generator is a nuclear source.

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6.1 (a)

(U) 3. EXPERIMENTAL PROGRAM

Progress of the experimental work during this reporting period was marked by completion of the new test setup for the evaluation of prototype systems and the beginning of the series of associated experiments. Development of the various electronic diagnostic techniques was also completed, except for the mass-measurement probes. The high-speed photographic diagnostic techniques were developed prior to this period.

3.1 PROTOTYPE SYSTEM

Work on the prototype system was divided into the following parts:

a. Power source for the plasmoid gun

b. Plasmoid accelerator

c. Various stabilizer configurations

d. Diagnostic equipment

e. Target impact effects

f. Test setup

3.1.1 Power Source

The power source for the plasmoid gun was described in Section 3.1 of the previous quarterly report (Reference 15). No modifications have been made, since the power source has been operating satisfactorily in the experiments conducted during this period.

3.1.2 Plasmoid Accelerator

The coaxial gun was also described in Reference 15 (Section 3.2). This gun was used in all of the experiments during this period. In addition, however, a second gun was fabricated, utilizing essentially the same construction except that the barrel length is 10.00 in. instead of 1.00 in. It is anticipated that this longer gun will produce higher exit velocities, since a greater portion of the input energy from the condenser bank will be transferred to the plasmoid before it emerges from the gun. This improved performance, however, may be countered by the occurrence of destructive instabilities and the increase of parasitic inductance associated with long guns. Experiments utilizing this long gun will be conducted during the next reporting period.

3.1.3 Stabilizer

3.1.3.1 Magnetic Nozzle

Three coils were fabricated to provide various magnetic-nozzle configurations immediately downstream from the end of the plasmoid gun. The dimensions of the three coils are:

a. 3-in. long x 6-1/2-in. ID solenoid, 16 turns

b. 6-in. long x 6-1/2-in. ID solenoid, 32 turns

c. 3/4-in. long x 6-1/2-in. ID x 10-in. OD pancake coil, 40 turns

These coils were wound using No. 10 insulated wire (~3/16-in. dia) and are slipped over the outside of the Lucite test chamber. The power source for the coils consists of two 15-μf, 20 kv condensers, a 20-kv power supply, and a high-current sparkgap switch. The electrical circuit is similar to that shown in Figure 10 of Reference 15. The experiments completed thus far and those planned for the next period using these coils are described in Section 3.2 of this report.

3.1.3.2 Charge Exchange

As reported previously, a quick-release valve for injection of the neutral gas has been successfully tested. Experiments using this device to evaluate the neutralized plasmoid concept in conjunction with the best magnetic nozzle configurations are planned.

3.1.4 Diagnostics

Development and construction of all the photographic and electronic diagnostic equipment was completed, except for the mass-measuring probes. These are now utilized as desired in the newly completed test setup.

3.1.4.1 Optical Diagnostics

Optical observations of the plasmoid are made with the Beckman & Whitley high-speed framing and streak cameras. These techniques, which were developed early in the program, were previously reported.

3.1.4.2 Electronic Diagnostics

3.1.4.2.1 Ballistic Pendulum

The design of the ballistic pendulum system was improved over that reported in Section 3.3.4 of Reference 15. Fabrication of a device in accordance with this improved design was completed. This device is a 4.3-gm nonmetallic pendulum which carries a Clairex CL-403 cadmium selenide photoresistor. The resistance of this device varies with the intensity of light incident upon it. A small nondirectional flashlight lamp is mounted at a fixed distance from the equilibrium position of the pendulum.

From bench calibration tests it was determined that the midpoint of the linear portion of the resistance-source distance characteristic (on a log-log plot) corresponds to a resistance of 270 Kohm. For stable response a balanced bridge circuit is being used, in which the photoresistor is incorporated as one element. Before each experiment, the pendulum is quiescent and the bridge is balanced by adjusting the intensity of the light source to a fixed value. The output of the bridge is directly coupled to a Tektronix Model 555 oscilloscope. The circuits for both the light source and the photoresistor must be isolated from ground at the time the plasma gun is fired, to prevent discharge of any part of the main capacitor-bank energy to these circuits. The light source is powered by a heavy-duty storage battery which is isolated from ground.

The pendulum is suspended by limp nylon strands from a plastic support which fits in the vacuum system. The support also carries the light source on an adjustable rigid extension. The photoresistor leads are 4-mil wire, wound in a loose spiral about the suspension strands. Preliminary experiments showed that if wire leads were used for suspension, their stiffness would introduce undesirable perturbations in the motion of the pendulum bob. The pendulum bob is a hollow plastic tube with the cadmium selenide resistor mounted below it.

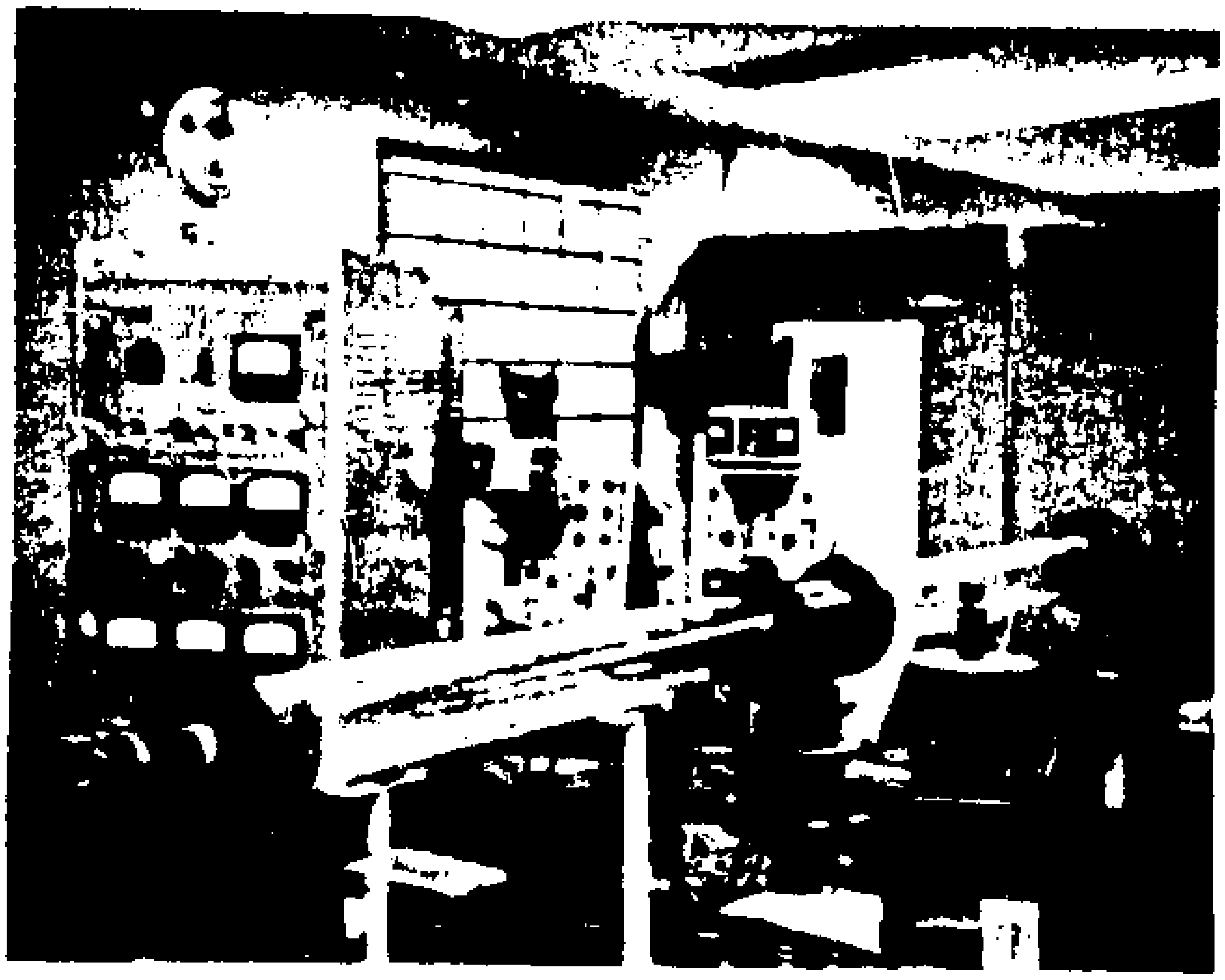
3.1.4.2.2 Velocity Probes

The velocity-probe geometry has been modified so that the probes are now in the form of a square-based U of No. 20 bare wire, with a separation of 1 in. and height of 1-1/4 in. The base section and support for the coaxial signal cable are now below the major part of the plasma stream. The wire subtends an insignificant cross-sectional area of the plasma stream. No serious corona problems have been encountered, and no significant velocity degradation is now observed.

3.1.5 Vacuum Chamber and Test Setup

The recently completed vacuum chamber is 116 in. long with an inside diameter of 5.6 in. It is constructed from two 52-in.-long Lucite tubes connected by a 12-in.-long steel T section. The T section includes a 4-in.-ID side outlet covered by a Plexiglas disc. Five vacuum coaxial feed-throughs are mounted on this disc so that instrumentation cables may be brought out of the chamber. Two high-vacuum pumping systems are used to evacuate the chamber; one is mounted at the T section and the other is mounted at the end by means of a steel elbow section. Each pumping system consists of a Welch 1402-B mechanical pump, a Consolidated Vacuum MCF-300 diffusion pump, and a Consolidated Vacuum BLN-40 liquid-nitrogen baffle. A Consolidated Vacuum GIC-110 gage is used to monitor the pressure in the chamber. Test-chamber pressures of 10^{-7} mm Hg are attainable with this setup.

Tektronix Model 555 and Model 551 oscilloscopes are currently being used to monitor the ringing frequencies of the coaxial-gun circuit and the magnetic-coil circuit and to measure the system delay between the condenser-bank discharges to the gun and to the coil. Oscilloscopes will also be used to monitor the outputs from the probe pulse circuits and from the ballistic-pendulum readout circuit. Two views of the test setup are shown in Figure 5. Figure 6 shows the condenser bank



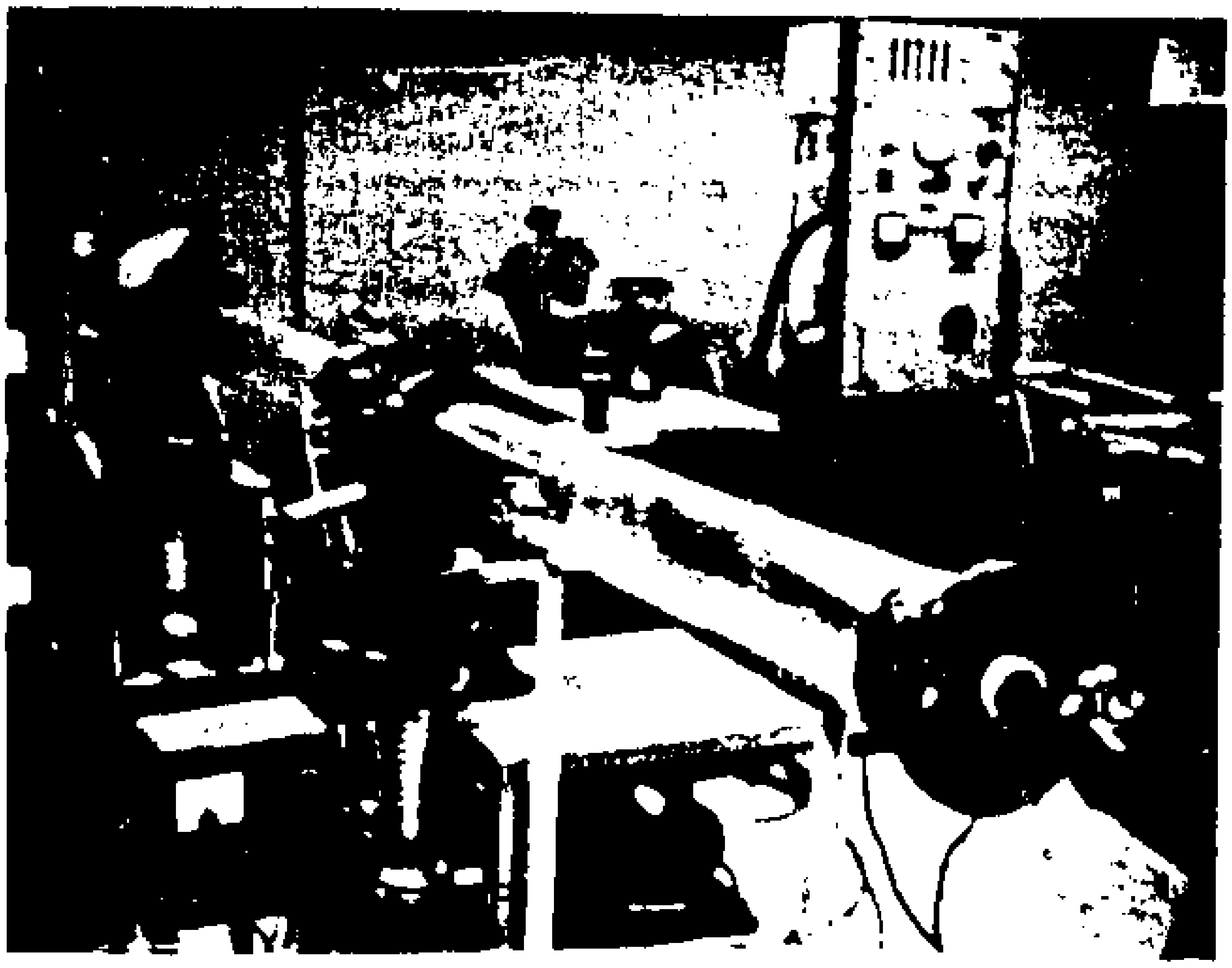


Figure 5. Test Setup for Prototype System.

and exploding-wire switch for the coaxial gun. A rear view of the power supply and sparkgap switch for the magnetic coil is shown in Figure 7. A block diagram of the major components of the prototype system is shown in Figure 8.

3.2 PLASMOID EXPERIMENTS

An accelerated program of experiments was conducted to measure the performance characteristics of the traveling plasmoid and to assess the target-impact effects under various input conditions and magnetic-nozzle configurations.

3.2.1 Measurement of Plasmoid Propagation Velocity

The axial velocity of the plasmoid is measured by means of the high-speed streak camera. A reproduction of a typical film record is shown in Figure 9. The following experiments were conducted with the 1-in. coaxial gun loaded with four 0.001-in. x 0.032-in. x 0.375-in. copper strips set 90° apart. An 0.125-in.-thick aluminum target plate was set in the chamber for some of these tests, so that measurements of the reflected plasmoid blowoff velocity were also obtained. The resulting data follow:

C (μf)	V (kv)	E (kj)	ν (kc)	v_i (cm/μsec)	v_r (cm/μsec)	d (in.)	P (10^{-5} mmHg)	U_s (rps)
85.53	15.0	9.62	-	3.94	-	8.5	9.0	1503
85.53	15.0	9.62	48.6	3.36	0.50	8.5	9.0	2003
58.11	15.0	6.54	52.8	2.99	0.24	9.0	9.0	2007
29.23	15.0	3.29	58.9	2.04	0.20	9.0	9.0	1970

C = capacitance of condenser bank
V = condenser-bank voltage
E = condenser-bank energy
ν = ringing frequency of gun circuit
v_i = axial velocity of plasmoid
v_r = reflected velocity of plasmoid
d = distance from gun to target
P = test-chamber pressure
U_s = streak-camera turbine speed

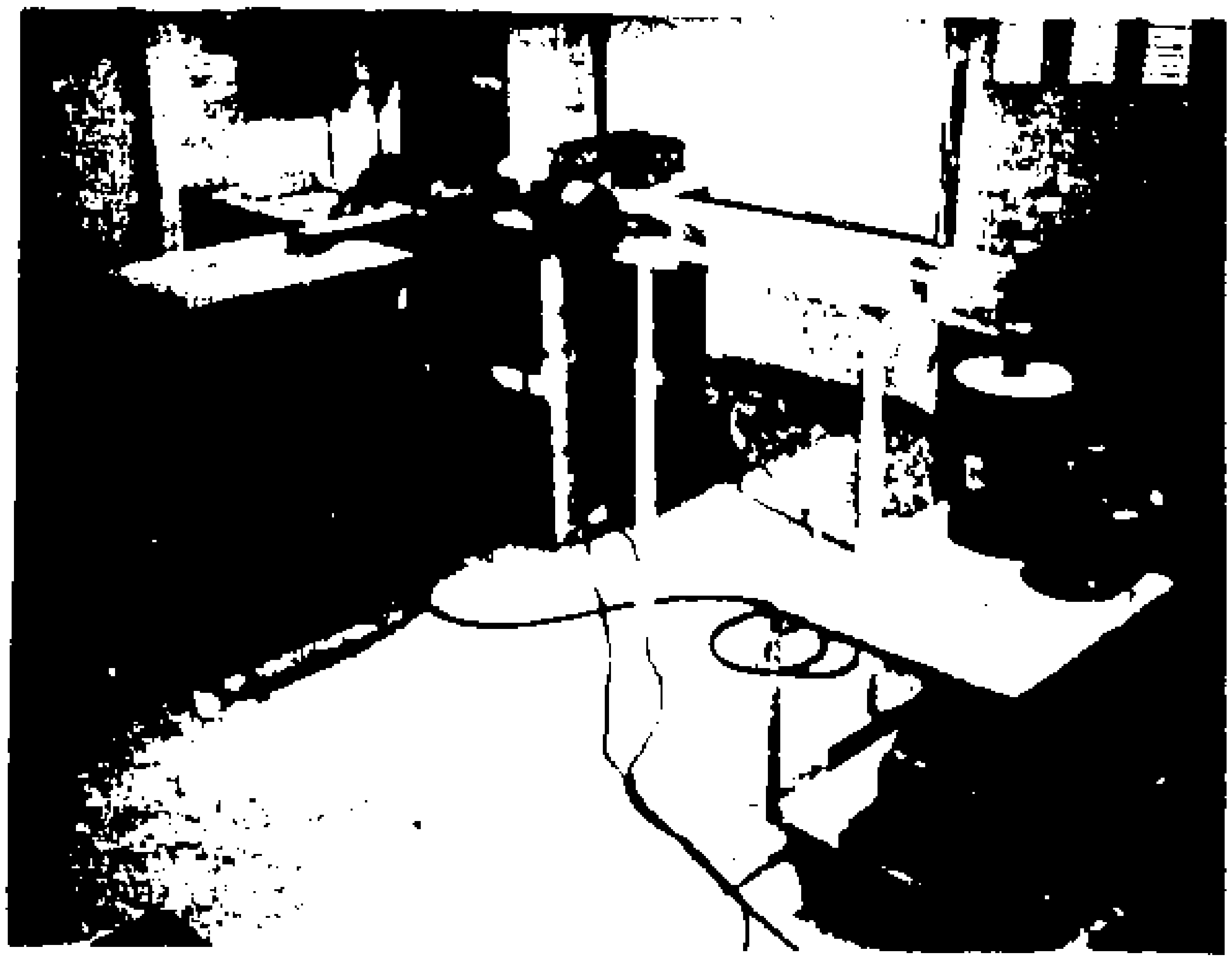


Figure 6. Condenser Bank and Exploding-Wire Switch for Coaxial Gun.

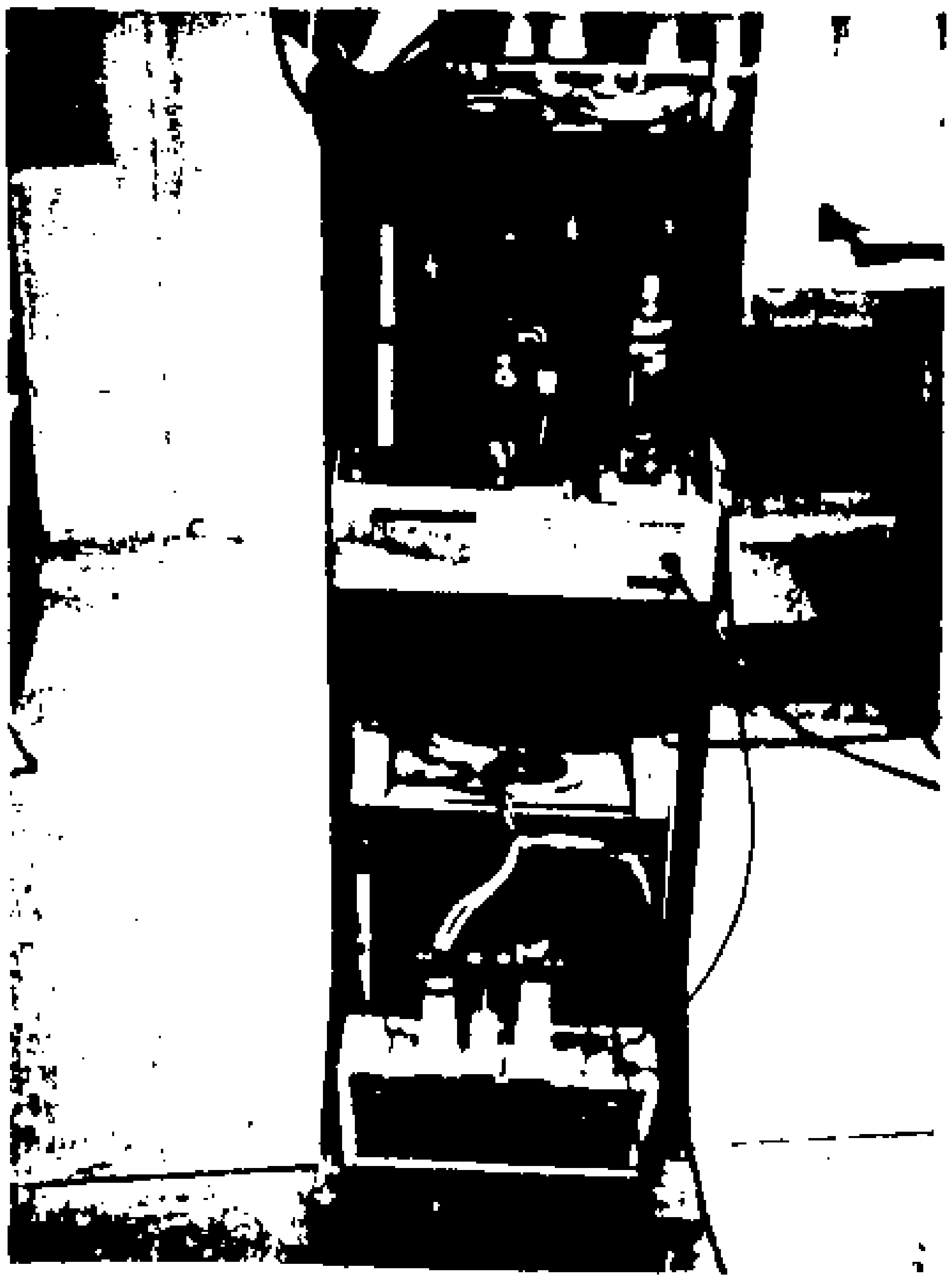


Figure 7. Power Supply and Sparkgap Switch for Magnetic Coil.

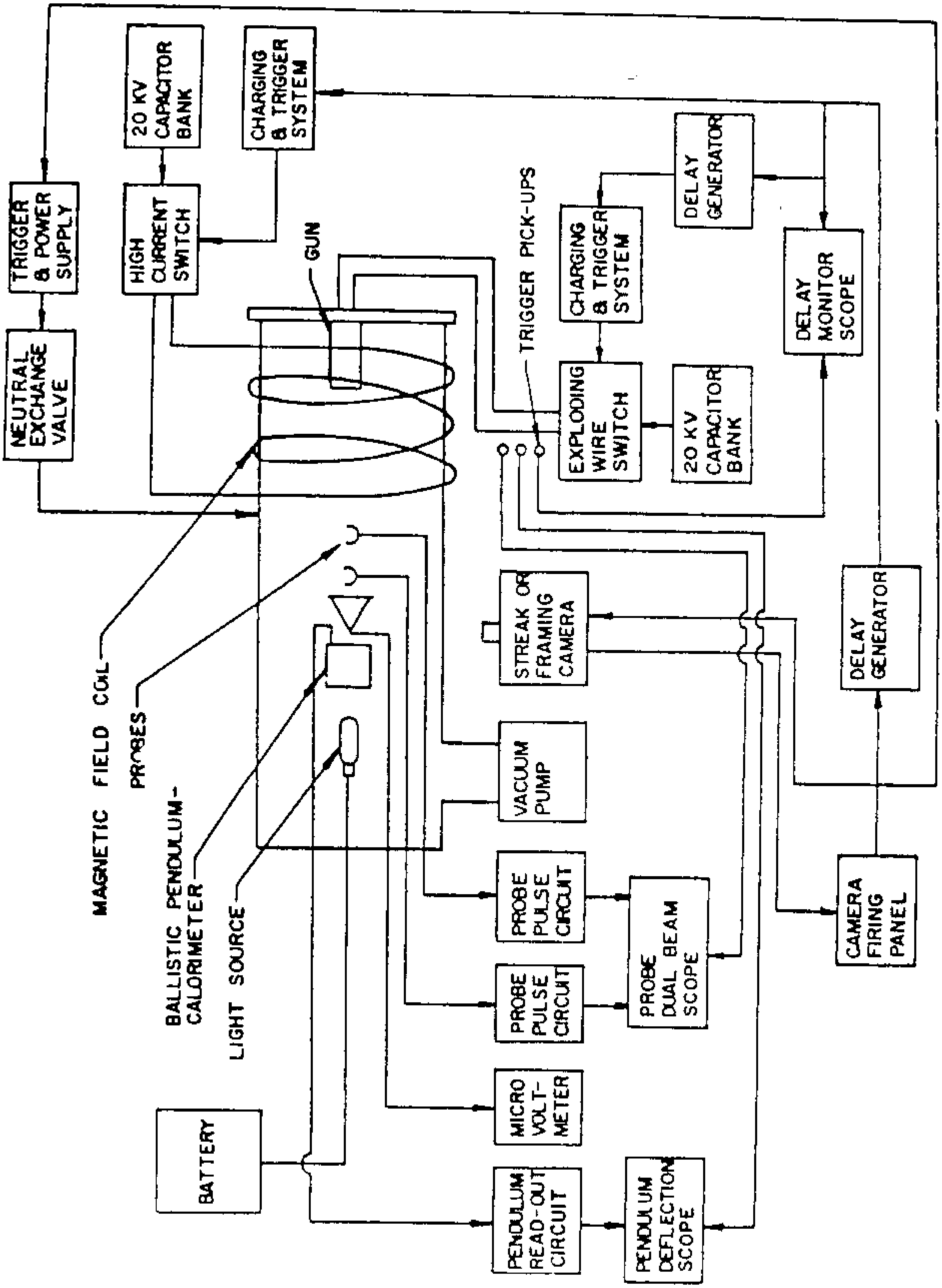


Figure 8. Block Diagram of Prototype System.

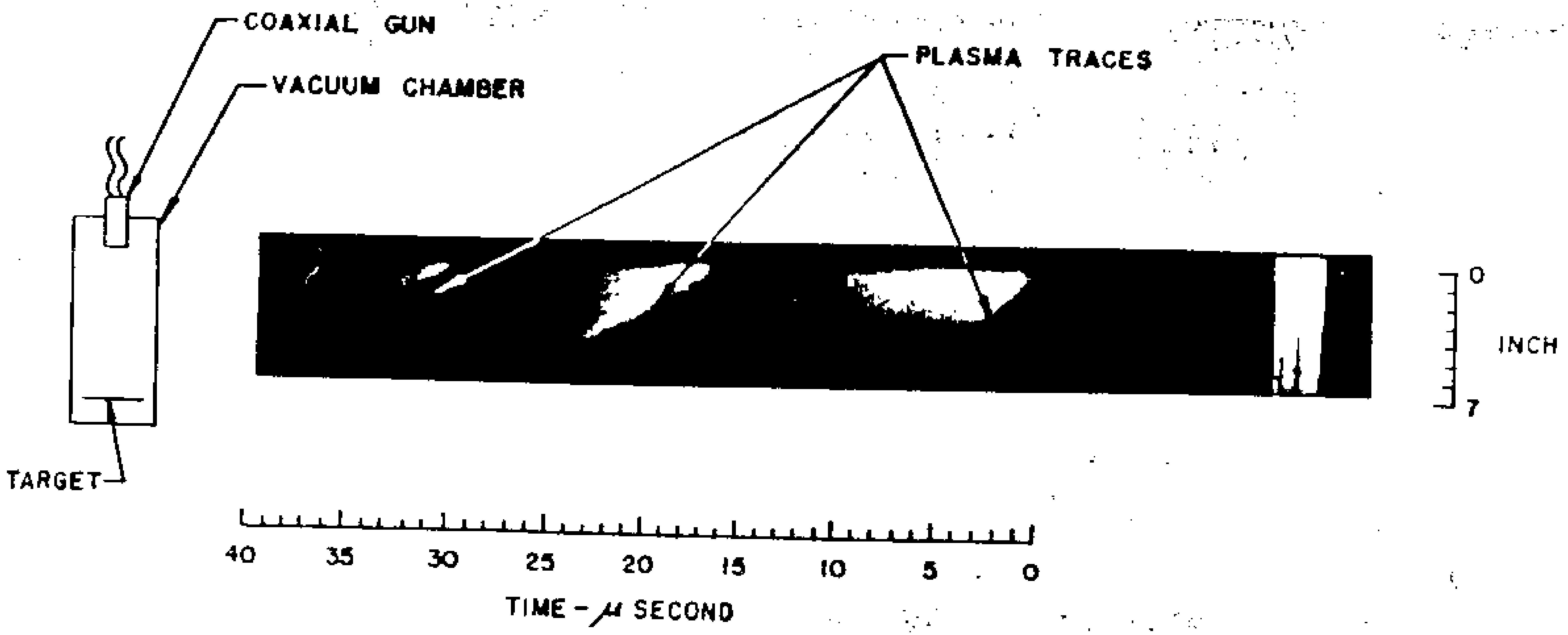


Figure 9. Streak-Camera Observation of Plasmoid Propagation Velocity.

The first magnetic-coil configuration tested was the 3-in. solenoid coil positioned at the end of the plasmoid gun. Two axial-velocity tests were completed, with the following results:

C (μf)	V (kv)	E (kj)	ν (kc)	C_c (μf)	V_c (kv)	E_c (kj)	ν_c (kc)	$\mathcal{T}$ (μsec)	v_i (cm/μsec)	a (in.)	P (10^{-5} mmHg)	U_s (rps)
85.53	18.5	14.64	-	28.55	15.5	3.43	-	45	4.75	1/2	16	1504
85.53	18.3	14.32	43.5	28.55	15.5	3.43	4.6	44	4.61	1/4	14	2011

Here the subscript, c, denotes the magnetic coil, and $\mathcal{T}$ is the system delay from the trigger pulse to the coil power supply to the trigger pulse to the gun power supply. The coil was positioned so that the end of the gun was inside the coil a distance, a.

3.2.2 Measurement of Radial Velocity

The first attempts to measure the radial expansion velocity of the plasmoid were made with the streak camera. One setup employed a mirror in the chamber positioned so that the streak camera viewed the gun head-on. The resulting film records showed the trace of the concentrated portion of the blob clearly, but the faint trace of the expanding plasmoid boundary was somewhat obscured by rewrite of the camera after the plasma had lighted up the whole tube. A second setup whereby the streak camera viewed the plasma normal to its path produced similar results. A framing-camera technique was then tried and this method produced excellent results, since the plasmoid cone angle was clearly defined. Since the propagation velocity was known, the radial velocity could then be calculated. This technique will be used to determine the radial velocity in future experiments. A representative framing-camera sequence is shown in Figure 10. Results of this series of experiments follow:

Streak-Camera Instrumentation, No Coil

C (μf)	V (kv)	E (kj)	ν (kc)	v_{rad} (cm/μsec)	P (10^{-5} mmHg)	U_s (rps)	View
85.53	19.0	15.44	--	0.80	15.0	1495	A
85.53	18.6	14.79	--	0.78	17.0	1003	A

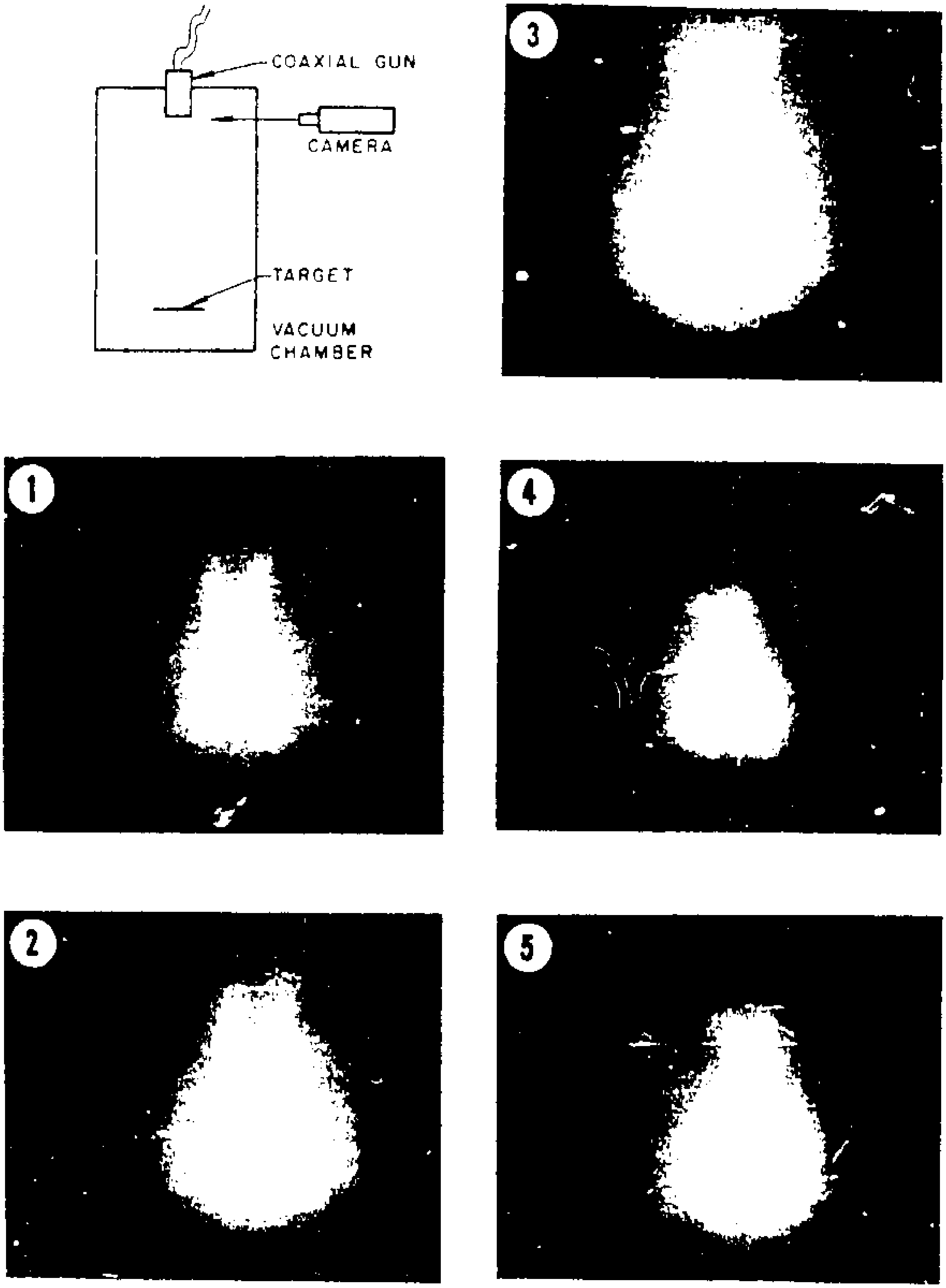


Figure 10. Framing-Camera Observation of Traveling Plasmoid (Selected Frames).

Streak-Camera Instrumentation, 3-in. Solenoid Coil

C (μf)	V (kv)	E (kj)	ν (kc)	C_c (μf)	V_c (kv)	E_c (kj)	ν_c (kc)	τ (μsec)	v_{rad} (cm/μsec)	P (10^{-5} mmHg)	a (in.)	U_s (rps)	View
85.53	18.5	14.64	48.8	28.55	15.5	3.43	4.6	48	0.3	10.0	1/2	802	B

Framing-Camera Instrumentation, No Coil

C (μf)	V (kv)	E (kj)	ν (kc)	v_{rad} (cm/μsec)	P (10^{-5} mmHg)	U_f (rps)
85.53	18.5	14.64	45.5	0.97	14.0	4322

Here v_{rad} is the radial expansion velocity and U_f is the framing-camera turbine speed. View A is looking directly into the gun; View B is looking normal to the plasmoid path.

3.2.3 Observation of Target-Impact Effects

Target impact is observed by means of the high-speed framing camera. The camera viewed the phenomena from the side normal to the plasmoid path (View A), looking nearly normal to the target (View B), or from a 30° angle off the target (View C). The pertinent data on the experiments conducted follow:

Test No.	C (μf)	V (kv)	E (kj)	ν (kc)	d (in.)	P (10^{-5} mmHg)	U_f (rps)	View	Source
22	29.23	16.6	4.03	59.9	6	8.8	1998	A	A
23	29.23	16.8	4.12	48.6	6	4.2	2004	A	B
24	58.11	16.5	7.91	52.8	6	6.5	1999	A	A
25	58.11	16.0	7.44	45.5	6	9.0	1999	A	C
28	85.53	17.5	13.10	52.5	8-3/4	9.0	2002	A	C
30	85.53	16.4	11.50	50.0	8-3/4	9.0	2002	A	C
35	85.53	18.5	14.64	50.0	28	18.0	2002	B	C
38	85.53	18.6	14.79	50.0	28	12.0	2003	C	C

Here Source A is a 0.001-in. x 1.1-in.-OD x 0.8-in.-ID ring of copper foil. Source B is a similar ring of 0.0007 aluminum foil, and Source C is four 0.001-in. x 1/32-in. x 3/8-in. copper strips set 90° apart. Tests 22 and 23 resulted in faint film records because of the low input energy. Test 24 gave improved results, although the foil was still not completely vaporized. However, on the remaining tests with Source C and higher input energies, the film records clearly showed the incident plasmoid striking the target and the reverse-flow blowoff. A representative record from View A was shown in Figure 1 of Reference 15. A portion of the film records from Tests 35 and 38 are shown in this report as Figures 11 and 12, respectively. Note how the initially concentrated blob in the center of the target rapidly spreads over the entire target surface. It is planned to perform densitometer readings to find the distribution of relative density with time and correlate these findings with the hydrodynamic code calculations.

3.2.4 Schedule of Experiments

During the first few weeks of the next reporting period, experiments will be conducted to evaluate various magnetic-nozzle configurations and to assess the usefulness of the neutralized-plasmoid concept. The following schedule of experiments has been established:

a. For a given input energy, determine accurately the radial and axial velocity of the plasmoid.

b. For the same input energy, determine the radial and axial velocity of the plasmoid with the application of magnetic fields from the following coil geometries:

   (1) 3-in. solenoid coil.

   (2) 3-in. solenoid coil followed immediately by the pancake coil.

   (3) 3-in. solenoid coil followed by the pancake coil set 1 in. apart from the solenoid coil.

   (4) 3-in. solenoid coil followed by the pancake coil set 2 in. apart from the solenoid coil.

   (5) Other variations of the 3-in. solenoid coil and the pancake coil depending on the previous experimental results.

   (6) Similar experiments with the 6-in. solenoid coil replacing the 3-in. solenoid coil.

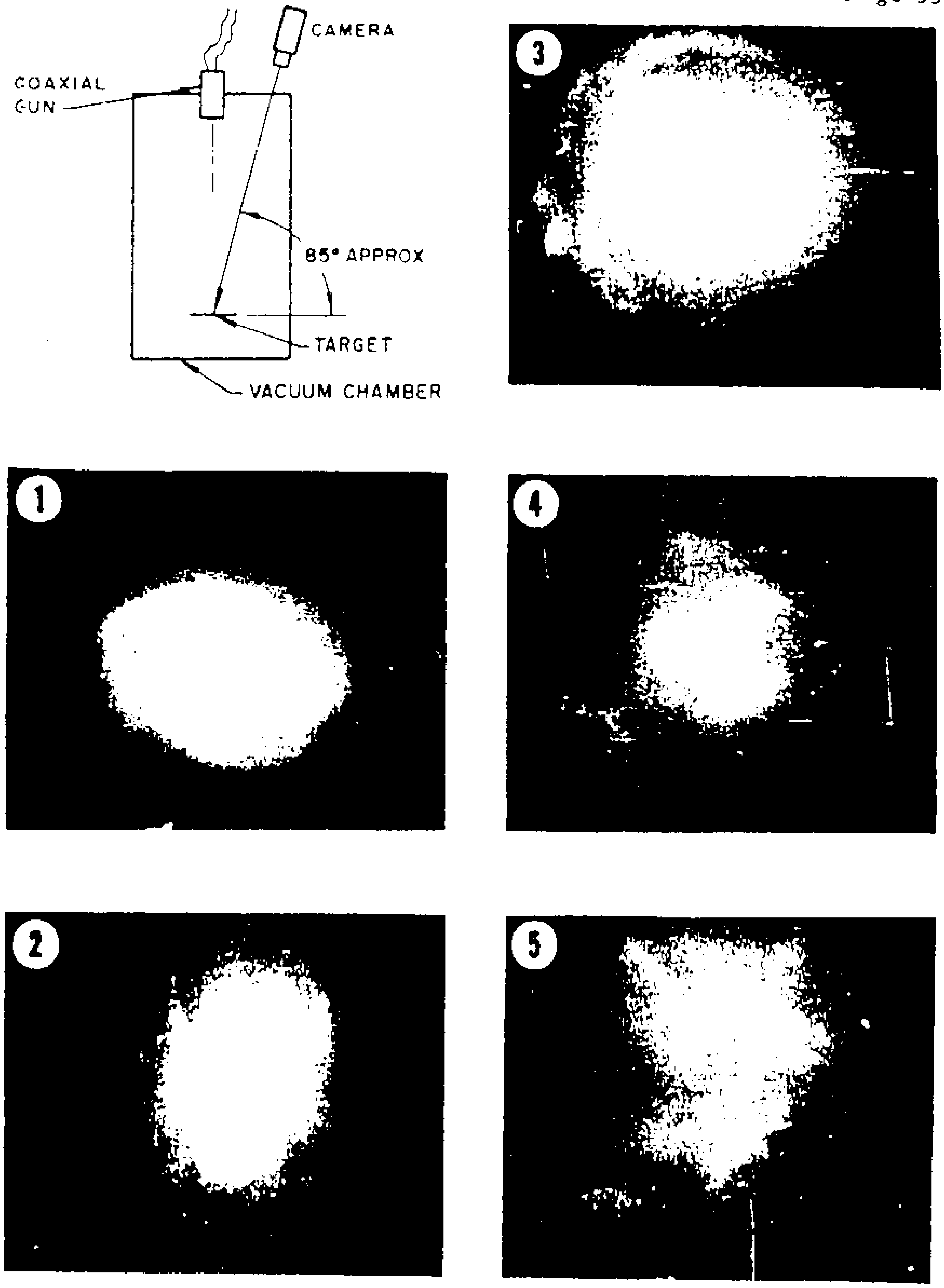


Figure 11. Framing-Camera Observation of Target Impact, Time Between Frames Shown - 8.4 μsec.

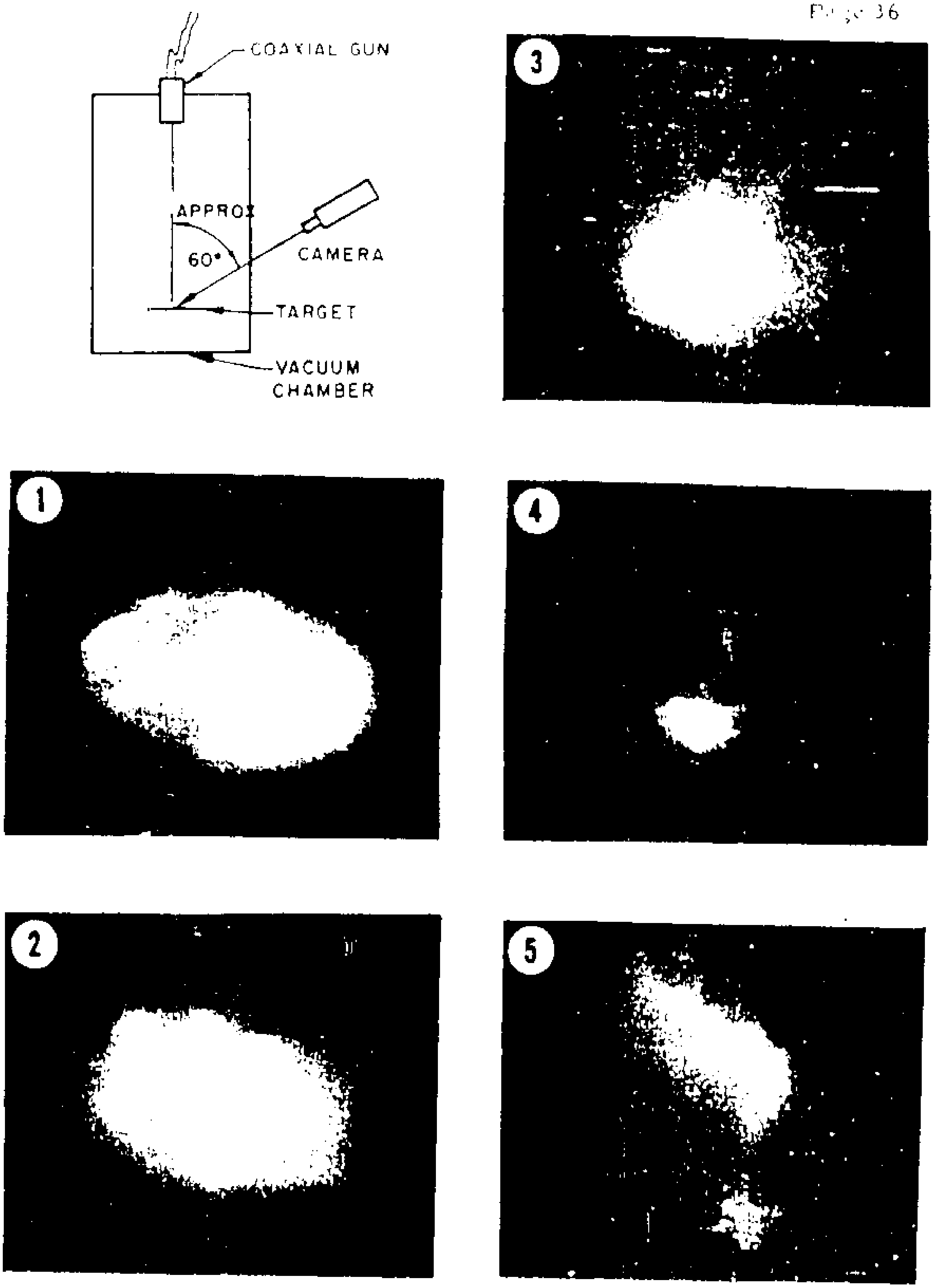


Figure 12. Framing-Camera Observation of Target Impact, Time Between Frames Shown - 0.3 μsec.

c. For a given input energy, determine accurately the radial and axial velocity of the plasmoid with the 10-in. -long coaxial gun.

d. For the same input energy, determine the radial and axial velocity of the plasmoid with the 10-in. -long coaxial gun for the most promising coil geometries.

e. Begin experiments with gas injection for charge exchange using the most promising gun-coil combinations.

   (1) Measure radial and axial velocity.

   (2) Measure efficiency of charge exchange.

f. Assess target damage from selected experimental configurations listed.

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1	SAC (DOCEO-T)
1	SAC (DM4A)
1	SAC (O/A)
1	SAC (DPLBC)
1	SAC (DAT)
1	SAC (DOSD)
2	TAC (TOD)
2	TAC (TMD)
2	TAC (TPL-RQD)
1	ATC (ATTWS)
1	PACAF (PFORQ)
1	5 AF (5FCAG-P)
1	5 AF (5FOPR-RQ)
1	USAFSS (CLR)
1	USAFSS (DCS/OPS)
1	AF Sp Comm Cen (SCP)
1	AAC (ACS/Intelligence)
1	AAC (OA)
1	AAC (XPR)
1	AWS (TIPD)
3	AU (AUL-9764)
1	MAAMA (MANE)
1	US Army War College
1	US Army CmlC Field Requirement Agcy
1	Dugway Proving Ground
1	US Army CmlC NDL
1	US Army CmlC R&D Lab(Tech Lib)
1	US Army CmlC Biological Lab (Doc Sec Tech Lib)
1	Ofc of Ord Rsch (ORDOR-IR)
2	Picatinny Arsenal (Tech Info Sec)
1	Picatinny Arsenal (RDBB-VC2)
1	ABMA (ORDAB-HT)
1	ARGMA (Tech Lib)
1	Chief of Naval Operations (Op-75)
2	OPNAV (OP-76)
2	Bureau of Naval Wpns (RT)
1	Ofc of Naval Rsch (Physics Div)
1	Bu Ship (Code 335)
1	US Naval Ord Lab (Lib)
1	US Naval Wpns Lab (Lib)
1	Marine Corps Eq, Bd
1	AFCRL (CRRDA)
5	Advanced Rsch Projects Agcy
1	Dir, USAF Proj RAND
1	US Atomic Energy Comm (Tech Info Ex)
1	Atomic Wpns Tng Fld Comd,DASA
1	General Electric TEMPO Div
1	Raytheon Company Advanced Development Lab
1	Goodrich High Voltage Astronautics
1	Aerojet-General Corp
	APGC
	1 PGF
	3 PGEH
	7 PGAPI
	Det 4, ASD
	3 ASQWR

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Secret-Restricted Data report

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1. Plasma physics
2. Particle accelerators
I. Det 4 ASD, AFSC
II. Contract AF 08(635)-1671
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