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PHYSICAL PROCESSES IN A CO-AXIAL PLASMA GUN*

by

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I. Introduction

The coaxial plasma gun program at General Dynamics/Astronautics has been guided by two points of view concerning the MHD propulsion problem. The first is that in view of the poor state of knowledge of plasma behavior in impulsive discharge systems, a fairly basic program of plasma measurements in such an environment is a proper first step. Only after such work has yielded substantial information will it be possible to design a propulsion engine intelligently.

The second view, which in a sense contradicts the first, is that there are some guesses concerning desirable gun parameters which one may venture now; at least, it appears reasonable to work in certain directions in selecting trial values of acceleration length, storage capacitance, and atomic number of propellant. Thus, we have decided to employ as short an accelerating channel as possible because 1) the formation of interchange (Rayleigh-Taylor) instabilities at the field-plasma interface is less advanced as acceleration to a given velocity is accomplished in shorter times, 2) fewer ions are able to migrate to the wall and lose their directed energy, and 3) the transfer of thermal energy from electrons to ions may be very small for sufficiently brief acceleration, thus reducing further the transverse thermal migration loss of ions. (This reasoning does, of course, involve assumptions about the physical processes which operate in the plasma, and which may turn out to be quite wrong; nevertheless it gives some guidance toward a starting point in the program.) Corollary to the short acceleration length is a low value of energy storage capacitance. We believe this to be desirable on independent grounds, however, since it appears that the development of units of light weight and the extremely high requisite Q-values is easiest for low C.

II. Problem Areas

In employing a plasma gun for propulsion, one anticipates problems of certain predicable kinds, almost all of which are detrimental to engine efficiency. Assuming that the "engine" behaves to any extent like its near relatives in other areas of plasma research, it is reasonable to expect trouble from 1) instability, 2) electrode and insulator losses and erosion, and 3) "frozen flow" loss due to internal thermal and quantum excitation of the expelled plasma.

But aside from dealing with such troubles one must also determine how the actual acceleration of the plasma is accomplished. There are few theoretical analyses which are useful here; most involve quite unrealistic assumptions such as a plasma which is either fully ionized before application of driving current, collisionless, or else in thermal equilibrium. In practice none of these approximations apply. At the very least, it is usually assumed that electrons carry nearly all of the conduction current. Such a condition is crucially important in order that losses of energetic ions to the electrodes may be held to a minimum; yet, it appears, in the light of recent work, that ions may be very important carriers of current.

Accordingly, the first major activity in the GD/A plasma gun program has been the detailed probing of the electromagnetic field system within the gun as the acceleration proceeds.

III. Momentum Transfer, Ion Density, and Current Carriers

All of the work described here has been performed on a series of coaxial plasma guns which employ gas switching, i.e., the capacitors are connected directly to the barrel, and the discharge is initiated by injection of propellant gas into the annular interelectrode region.[1] Various barrel lengths from three to twelve inches have been employed, and storage capacitors of one and five microfarads have been used, the latter being standard for most of the work presently reported. For 12 kilovolts on the bank, the total discharge current rises to about 200 kiloamperes in 0.4 μs.

The field measurement program involves determination of the various components of E and B in the gun, and the inference of plasma properties from these. The techniques used have been reported elsewhere, but we will summarize here the general procedure and the inferences drawn from the data.

1) The measurement of $\vec{B}(\vec{r}, t)$ is accomplished, as usual, with small loop probes, moved from point to point in the barrel on successive discharges of the gun.[1] The current density is then obtained by invoking Maxwell's equation $\mu_o \vec{j} = \text{curl } \vec{B}$, and neglecting displacement current.

2) $\vec{E}(\vec{r}, t)$ is similarly plotted by the use of a differential floating potential probe.[1]

3) Since the electromagnetic forces per unit volume applied to the ion and electron components of the plasma are

$$n_{i,e} m_{i,e} \vec{r}'' = \pm n_{i,e} e \vec{E} + j_{i,e} \times \vec{B} \quad ,$$

where our propellant pressure and probably plasma temperature allow the neglect of viscous drag forces, one may make an estimate of ion and electron density (assumed equal). This estimate involves a further assumption on the relative magnitudes of $\vec{j}_i$ and $\vec{j}_e$; if we suppose that $j_e \gg j_i$, as is usually done, the result is

$$n\, e\, \vec{E} = \frac{1}{\mu_o} (\nabla \times \vec{B}) \times \vec{B} \quad ,$$

or

$$n_i\, e\, E_z = \frac{B_\theta}{\mu_o} \frac{\partial B_\theta}{\partial z}$$

in the cylindrical coordinates of the coaxial gun.

An explicit measurement of the $\vec{E}$ and $\vec{B}$ distributions then allows an estimate of $n_i(\vec{r}, t)$.

4) The neglect of ion current and viscous drag forces leaves the ion acceleration to the space-charge separation field E_z. An integration of E_z over the time of the gun pulse should then yield the momentum transferred to each ion, and hence, its velocity, i.e.,

$$\Delta v_z = \frac{e}{m_i} \int E_z \, dt \quad ,$$

where the integral is evaluated along the trajectory of the ion.

The results of the employment of these probe procedures are the following:

1) As expected, a layer of radially-flowing current is observed to form near the rear of the gun – either over the gas input ports in the center electrode, or on the rear insulator, depending upon gas influx conditions – and to advance toward the gun muzzle. This current distribution also contains strong axial components as inferred from the

failure of B_Θ to decrease as $1/r$ during parts of the acceleration. Some preliminary distributions shown in Fig. 1 indicate a flow of current toward the rear of the gun as well as radially inward, particularly for the case of $z = 4$ cm, and $t = 0.5$ μsec.

2) A pulse of E_z accompanies the current layer downstream. However, when the integral over time is performed, it appears that this field cannot, in general, accelerate ions to the velocity of the current sheet. Typically $(e/m_1) \int E_z \, dt$ is about a half of the sheet speed.

3) n_i, as calculated from the combined E and B distributions, appears to be somewhat higher than our estimates of the injected gas load would imply, although the uncertainties in our gas pressure estimate are such as to make the significance of this difference uncertain.

We have, until quite recently, interpreted these data, and particularly the E_z *integrals as indicating that the current layer does not* act in "snowplow" fashion, but rather has more of the character of an ionizing shock which imparts some forward momentum to the plasma but does not bring the ions to its own speed. This conclusion was reinforced by a direct transit-time measurement of emerging plasma in which the plasma speed, as inferred from the drift time until collision with a downstream vacuum window, agreed roughly with the E-field integral, but disagreed markedly with current sheet speed.[1]

Recently, however, we have found, through direct ion energy analysis, that an appreciable number of ions do acquire a velocity just equal to the sheet speed. This measurement was accomplished by the use of a curved-plate electrostatic energy analyzer which had between itself and the gun sufficient collimation to reduce the plasma density to a level allowing separation of ions and electrons in the applied field.

The instrument was placed 3 meters from the gun muzzle, and on the system axis. This long drift distance, which gave drift times long compared to the gun discharge, then allowed a simultaneous determination of the velocity and energy of the plasma constituents passing into the detector at the output of the curved plates. Typical output signals from the photomultiplier are shown in Fig. 2, where for four deflection voltages the four corresponding ion energies are being examined. The first large deflection at time zero results from some direct feed-through of light from the gun. Subsequent to this, one observes two distinct pulses on each trace except that for v = 300, where the first has coalesced with the tail of the t = 0 pulse. Plotting the velocities of the two components (from transit time) against $\sqrt{V}$, we obtain the two distinct straight-line groups of Fig. 3. Now, the slope of each line is just $\sqrt{(e/m)(r/d)}$, where r is the mean deflection plate radius, and d is their spacing. We obtain here e/m values equal to 1/14 and 2/14 of that for the proton which correspond, clearly to singly and doubly ionized nitrogen.

Velocity distributions obtained by plotting indicated pulse sizes against velocity seem to peak at velocities near the sheet speed, i.e., about 10 cm/μsec. However, it must be borne in mind that a measurement of this sort taken on the gun axis will be highly preferential for the fastest ions; if we attribute to all ions the same distribution of transverse thermal speeds, it is clear that the ions having low axial speeds will be spread over a much wider emergent cone than the fast ions which tend to cluster on the axis. In order to obtain the actual velocity distribution of ions in the expelled plasma, the above measurement must be done as a function of angle with respect to the gun axis.

Only when each axial velocity component is integrated over all exit angles will the results be meaningful in terms of specific impulse and efficiency. The analyzer system is accordingly being modified to allow the taking of angular distributions.

In spite of the probability that the single axial measurement of the velocity distribution is biased in favor of faster components, it appears that the assumption that all the discharge current is in electrons may still be untenable. Clearly, a substantial number of ions are moving at the sheet speed, and the E_z field is insufficient to do this by itself. Some recent work on hydrogen discharges, however, gives a hint of where the discrepancy may lie.(2) In this instance, it was discovered that a flat current sheet moving between parallel plates and into a static filling of hydrogen exhibited an almost complete absence of an axial space-charge field. The current in the sheet was found to be almost pure ion current resulting not from an organized drift, but rather from the polarization of electron-ion pairs when the neutrals are ionized in the crossed E and B fields and then proceed to drift at the sheet speed. It is, in a quite proper sense, pure displacement current. No space charge field in the sheet motion direction results, since after ionization, the guiding centers of the ion and electron separate only along a line parallel to the sheet. In the case of the nitrogen accelerator under study here, however, the gyro radius of the ion is not small compared to either the sheet thickness or the electrode spacing; hence, the ion gyration subsequent to ionization is generally incomplete ($\omega\tau < 1$), and some space charge field will again appear. The result is a partitioning in which both ions and electrons may carry a significant fraction of the current.

We are, then, in a position where our earlier conclusions of relative velocity between plasma and the current sheet may be quite wrong, since before, we had assumed that only electrons carried current and only E_z accelerated ions. The answer will be in hand when we are able to obtain angular distributions of the ion energies with the analyzer described above.

IV. Energy Losses

We have been able to insert a voltage probe through the insulator assembly of the gun in such a way that it measures the inter-electrode potential at the rear end of the accelerating column. This, together with a measurement of total current, and probe plots of the magnetic field distribution in the barrel, has made possible an inventory of the energy content and flow in the electrical circuit at any time.

We combine with the breech voltage measurement the voltage measured at the capacitor studs, and are thus able to determine the parasitic inductance of the transmission line; the capacitor inductance was previously measured by short-circuit ringing of the separate units. With these parameters and the field quantities in hand, we are able then to calculate, as functions of time 1) the energy present in circuit inductances, 2) remaining capacitor electrostatic energy, 3) the energy which has passed into the barrel, and 4) the energy present in the magnetic field within the barrel.

Fig. 4 shows oscillograms of capacitor voltage, breech voltage, and total current. (These are overlays of several traces which demonstrate good shot-to-shot stability.) In Fig. 5, the breech V and I are combined to give an input power curve. We find that at the end of the first "half cycle" of the power curve, ($t \simeq 0.5\ \mu$sec) the energy is accounted for as follows:

Energy initially in capacitors	390 joules
Remaining in capacitors at $t = 0.5\ \mu s$	15 joules
Energy in parasitic inductance	85 joules
Energy dissipated in capacitors due to finite Q	40 joules
Energy entering barrel ($\int V_b\, I\, dt$)	250 joules
Energy in B-field in gun	60-80 joules

The important conclusions to be drawn from the above data are that about 65% of the energy has actually entered the barrel, but that all but a small fraction of this has gone into the plasma, and is no longer electromagnetic. However, we also conclude from the field distribution that the directed plasma velocity is still small at this time; hence, it seems inescapable that we have sustained a severe loss to the electrodes and insulator during this rising phase of the current. (The energy cannot be present as internal plasma energy at this time, since it would correspond to several hundred electron volts per ion; nitrogen, at least in terrestrial surroundings simply cannot be made this hot with present technology.)

While our earlier observation that the 60-80 joules of field energy is subsequently transferred to the directed plasma with fair efficiency seems still to be true, it is small consolation when nearly 200 joules were lost in accomplishing it. There is evidence, however, that this 150-200 joule loss may be a fixed penalty to be paid for establishing the plasma, and that if the rise in I were continued past the peak in Fig. 4, the subsequent transfer of energy would be largely into directed kinetic motion. With this hope before us, we are increasing the storage capacitance by about a factor of 2, leaving all other parameters about the same: (and actually decreasing the parasitic L); if the "fixed penalty" hypothesis turns out to be true some increase in efficiency should then be evident.

We have used conical copper-sheet calorimeters to measure the total energy content of the emerging beam. Thermistors are employed as temperature sensors, and in taking measurements, as many as ten shots of the gun are collected on the calorimeter in quick succession in order to average out the effect of statistical fluctuations and also to improve the absolute accuracy of the temperature measurements.

A large-mouth cone was used at various distances from the gun in order to determine the angular spread of the beam. In Fig. 6, the collected energy, expressed as a fraction of that stored in the capacitors, is plotted against the half-angle subtended by the calorimeter at the gun. It seems from these data that the beam spread is about 30° off axis. This collected energy is, of course, the sum of the internal and translational energy, and so cannot be properly interpreted as an efficiency.

V. Instability

The radial current sheet in a coaxial gun is hydromagnetically unstable against sweeping up into a single spoke or pinch on one side of the barrel. One hopes to operate such a device in a manner which will not allow this instability to grow to disastrous proportions before the acceleration is complete. The fatal attributes of such a spoke are that 1) it sweeps up very little of the gas which uniformly fills the barrel cross-section, and 2) it develops very violent secondary instabilities of its own which consume large amounts of energy in driving the randomly directed fluctuations.

We have examined the growth and conditions of occurrence of these instabilities through the use of double-coil magnetic probes and Kerr-cell photography.[(3)] Our conclusions may be summarized as follows:

1) The pressure at which the propellant gas is injected into the barrel is the single most sensitive parameter affecting instability occurrence. If it is about a certain "critical" value, a very fast, violent spoking occurs, and the output energy is negligible. For lower pressure, the discharge tends to be symmetrical for the acceleration period.

2) The use of stainless steel for electrodes is to be avoided, since even though nominally non-magnetic, continued discharging on the electrodes sets up small magnetic "spots", and these drastically affect the breakdown characteristics of the tube.

3) A rough qualitative criterion for stability against spoking seems to be that the rate of neutral gas flow into the advancing sheet should not decrease in time at a faster rate than the driving pressure

$B^2/2\mu_o$. This requires that the distribution of gas in the barrel prior to the shot should not be too peaked; such peaking naturally occurs for high injection pressures, as mentioned in item 1. It further implies that the sheet should not be allowed to accelerate, but rather, move at a constant, or even a slightly decreasing speed.

We have achieved a gas distribution which gives very uniform azimuthal current density through the use of multiple gas ports spaced along the inner barrel in the axial direction. These have variable openings, thus allowing a "tailoring" of the pre-shot density profile.

References

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2. "Private communication", R. H. Lovberg, General Atomics, San Diego.
3. "Instabilities in a Co-axial Plasma Gun", T. J. Gooding, B. R. Hayworth, R. H. Lovberg, A.R.S. 17th Annual Meeting, Paper No. 2665-62, Nov. 1962.

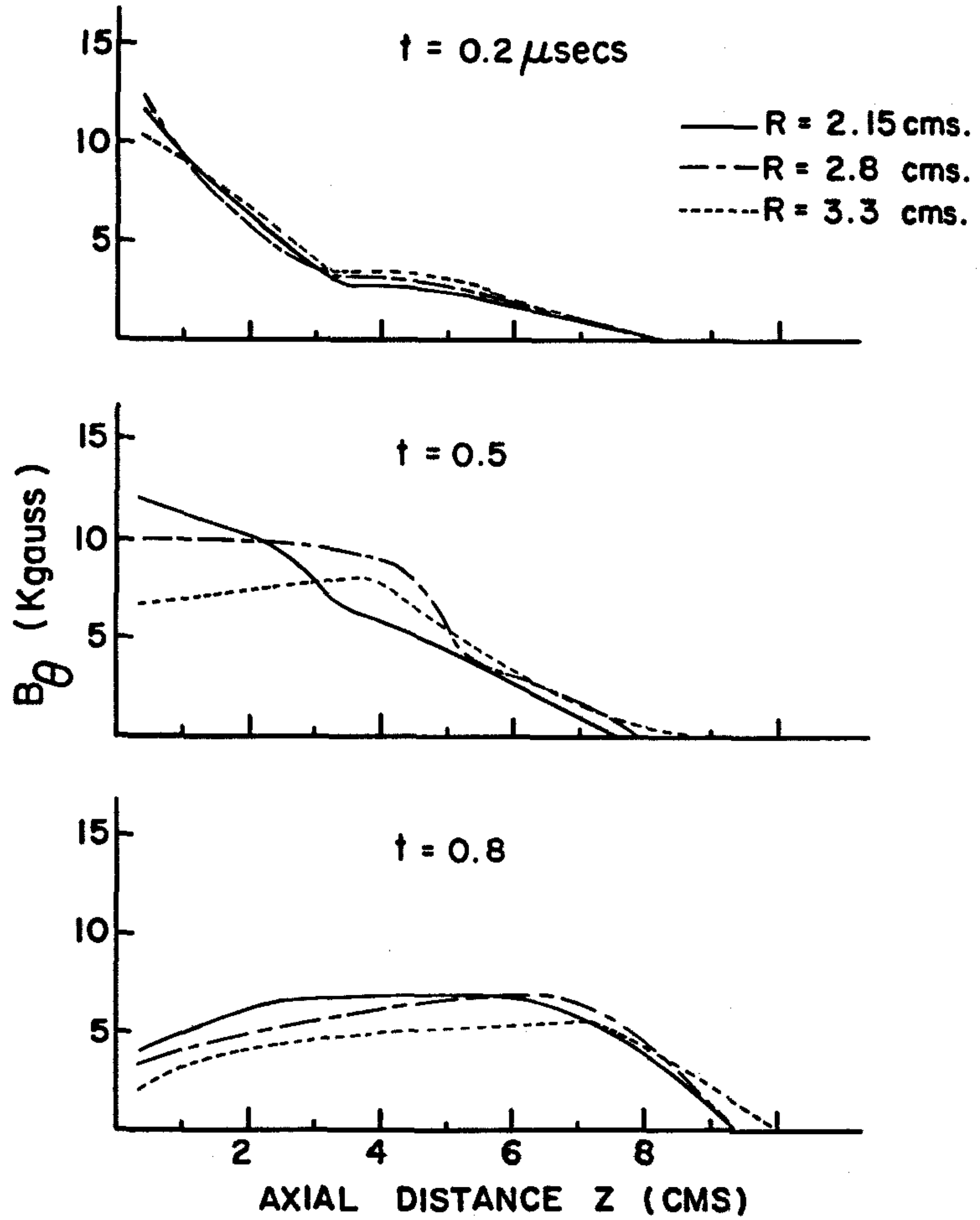


FIG. 1: MAGNETIC FIELD DISTRIBUTION ALONG THE GUN AXIS, NITROGEN PROPELLANT AT 12 kv., R = PROBE RADIUS.

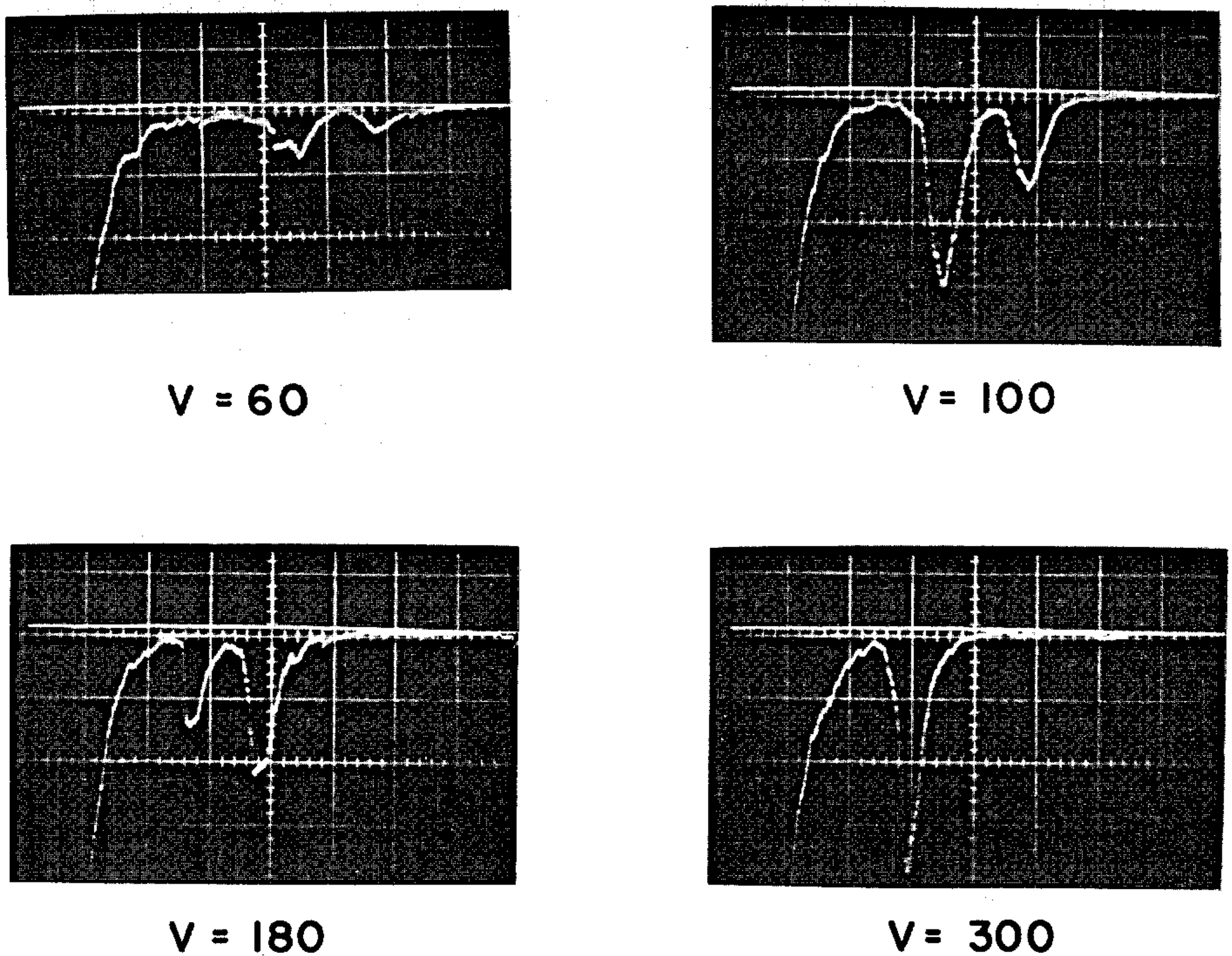


FIG. 2 : TIME DISTRIBUTIONS OF PARTICLE-ANALYZER OUTPUT.
t = 10 μsecs /cm V = DEFLECTOR VOLTAGE (VOLTS)

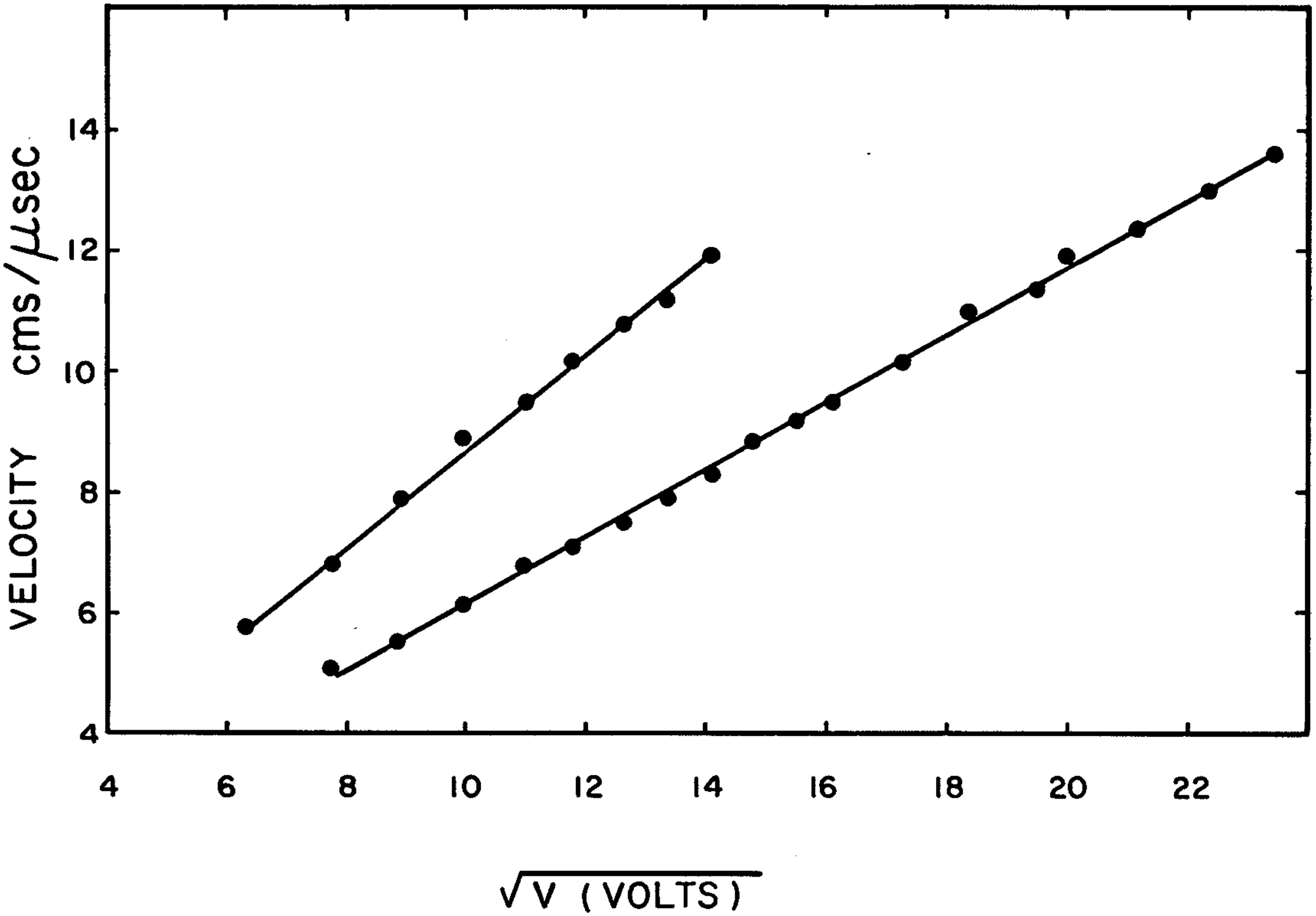
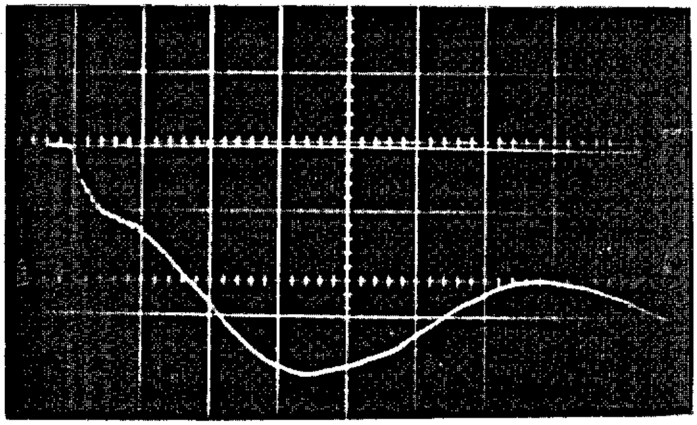
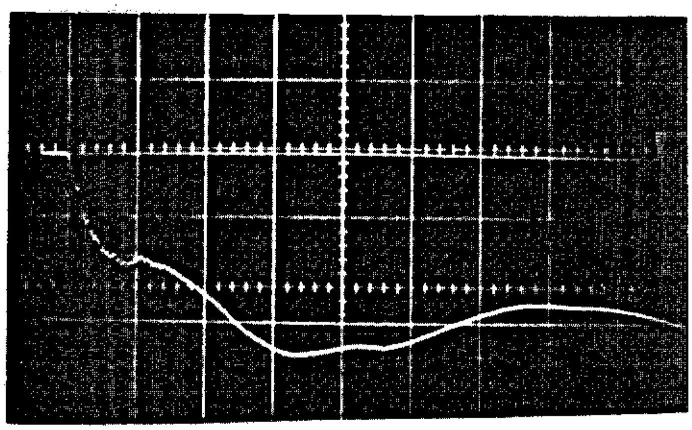


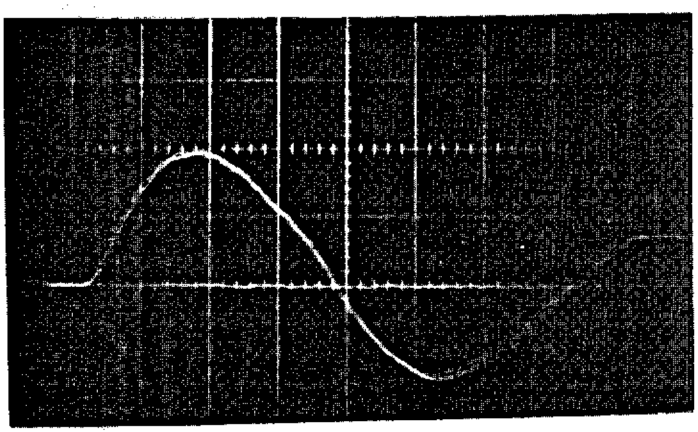
FIG. 3 : PLASMA VELOCITY VERSUS DEFLECTOR VOLTAGE.



CAPACITOR VOLTAGE



BREECH VOLTAGE



CURRENT

FIG. 4 : VOLTAGE AND CURRENT WAVEFORMS, NITROGEN PROPELLANT AT 12 kv.
V = 5 kv/cm   I ~ 125 ka/cm
t = 0.2 μsecs / cm .

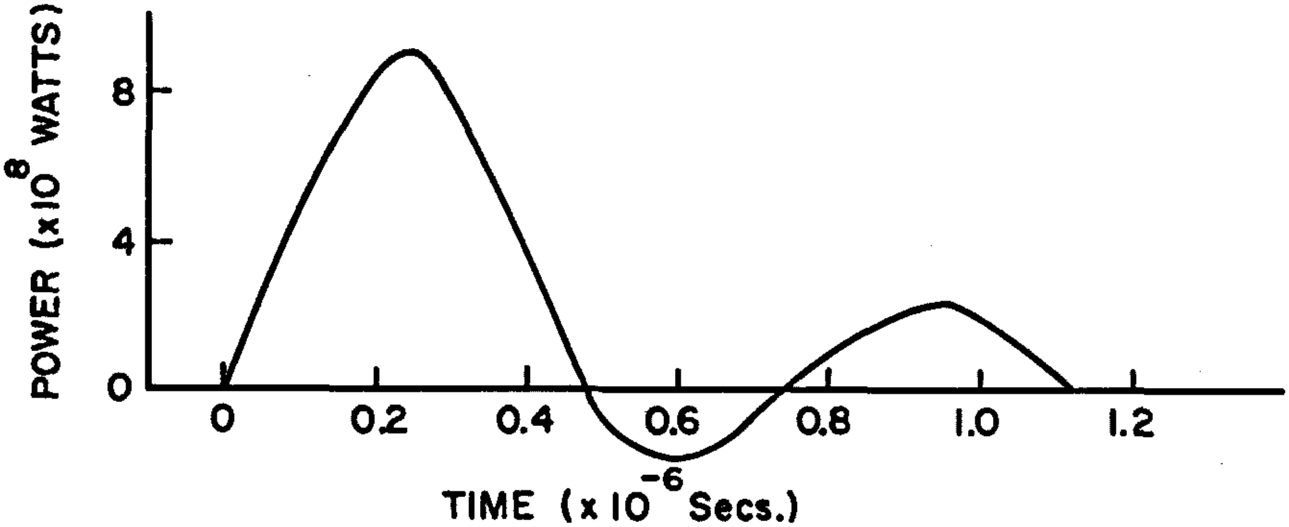


FIG. 5 : VxI POWER DISTRIBUTION CALCULATED FROM FIGURE 4.

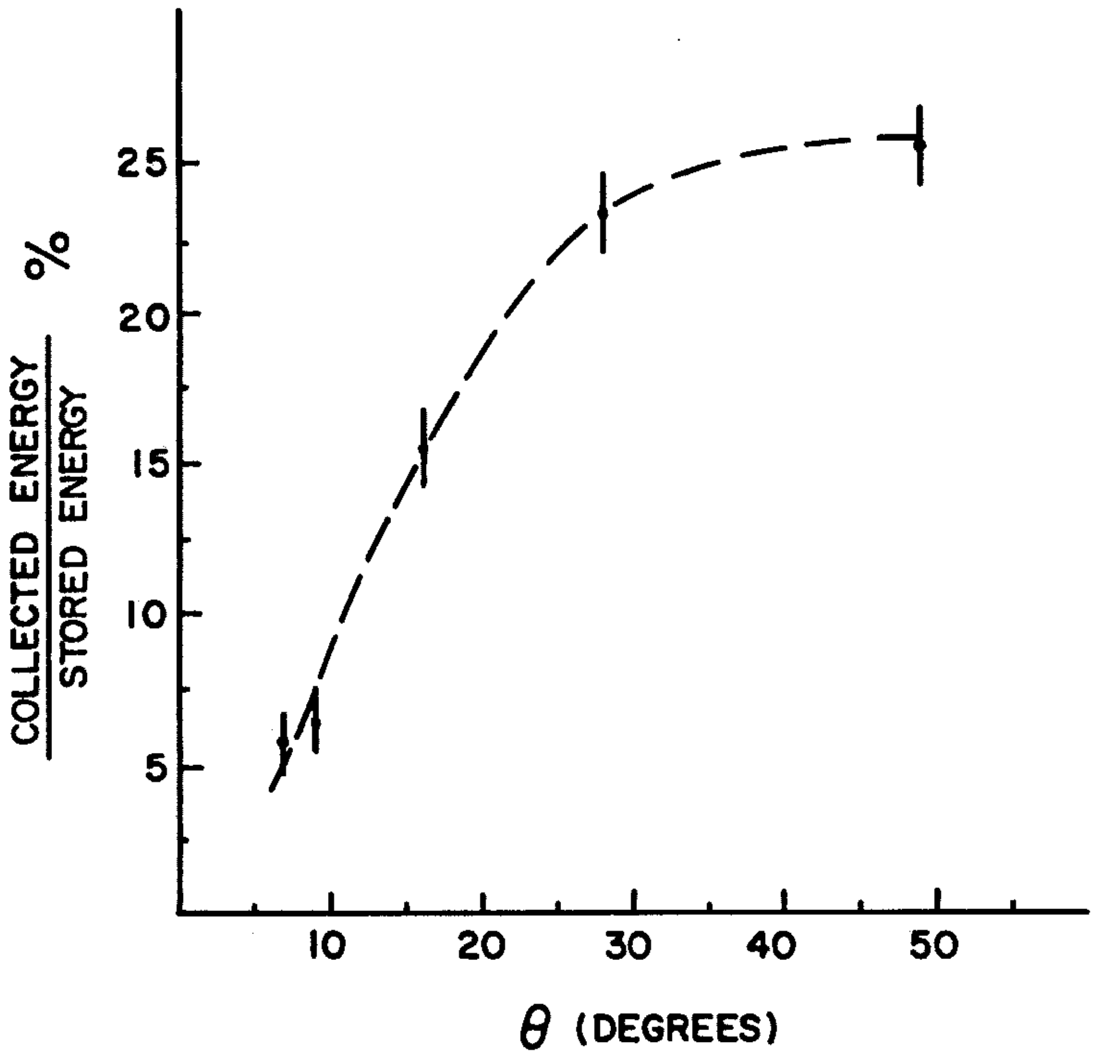


FIG. 6 : CALORIMETER ENERGY VERSUS CONICAL HALF ANGLE, NITROGEN PROPELLANT AT 12 kv.