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FOCUSSED DISCHARGE FROM PULSED PLASMA GUNS

By Dah Yu Cheng*

NASA-Ames Research Center, Moffett Field, California

page 14
code 1
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ABSTRACT

High-speed blobs of hydrogen plasma are focussed by means of a coaxial gun having a convergent barrel in the shape of a frustum of a cone. The focal point is at the virtual vertex. The plasma area at the focal point is about 1/100 the breech area, and about 1/4 the muzzle area. About one milligram of cold gas introduced through a fast-acting valve initiates an electric discharge at the breech between the conical barrel and a cylindrical cathode rod on the axis; the barrel initially being evacuated to a pressure of 10^{-7} torr. Plasma and discharge propagate to the muzzle where the plasma is expelled into vacuum. When the barrel is emptied of plasma, the discharge extinguishes. Image-converter camera pictures indicate a muzzle velocity not less than 5×10^{7} cm/sec. Impulse measurements from target discs at the plasma focus suggest an average velocity of about 2×10^{8} cm/sec, and an energy flux of about 200 megawatts/cm^2. Of the 5000 joules initially available in the capacitor-bank driver, about 1200 joules are transferred to the plasma.

*NAS-NRC Research Associate

This paper discusses design features of a unique plasma gun and reports results of preliminary tests that indicate a very high performance capability. Experiments with converging anode-barrel designs indicate that the plasma beam can be focused through a small area. Plasma gun performance is presented in terms of measurements of plasma velocity. The converging barrel design produced plasma velocities of the order 10^8 cm/sec as indicated by preliminary experiments. This surpasses the performance of any existing plasma gun. The performance tests are reviewed with consideration given to various techniques which were employed to measure these high plasma velocities.

The focusing effect and the acceleration of plasma to high speeds are both goals of primary importance in plasma gun research and development. For example, these features are of great importance in controlled thermo-nuclear reaction research. In addition, for plasma thrusters in space power applications, the performance indicated by the results reported here would yield specific impusle values of 10^5 seconds with an accompanying thrust force of the order 400-500 newtons.

The plasma guns that were built and tested are shown in figure 1. Three anode barrels had a common breech that consisted of the gas injection mechanism and a coaxial cylindrical cathode. The anode barrels consisted of a straight tube design and two tapered tubes of 3 and 5-degrees half angle having identical muzzle diameters. The 5-degree tapered anode barrel was shorter by 10 cm.

Certain differences exist in the design of the present gun and other types of plasma guns. First, with attention directed to the breech mechanism of Figure 1, this design permits introduction of an extremely small gas load. This is accomplished by using the "puff" valve-coil arrangement shown. By means of the puff valve and the gas pocket configuration, the particle front expands into the gun chamber with a uniform, high-pressure front. In operation, the chamber containing the plasma gun is evacuated to a pressure of the order $5X10^{-7}$ mm Hg. A high voltage (about 15 kv) is applied between anode and cathode. A switchless discharge scheme is employed; consequently, the necessary electrical transmission lines between the capacitor bank and the plasma gun can be extremely short. The inductance of the system is contributed mostly by the gun parts themselves rather than by the cables. This feature should result in a high efficiency of energy transfer. A puff of hydrogen is introduced into the pocket at the breech. The gas is injected by means of a valve disc actuated by a very high speed solenoid valve. The valve is opened by discharging a capacitor into the three-turn coil. The ringing frequency of the capacitor-coil-combination is about 55 kilohertz. However, a nonlinear damping scheme is used to produce a single, high current pulse and a rapidly damped oscillation thereafter. Therefore, only a single impulse is delivered to the valve disc. A description of the valve characteristics including the independence of operating voltage as well as the overall reproducibility is contained in reference 1.

After leaving the "puff" valve, the gas charge enters the gas pocket volume in the breech section. The gas pocket is an annular cavity at the base of the cathode. As the gas leaves the valve ports, it expands radially to build up the stagnation pressure in the gas pocket cavity before it expands into the barrel.

The actual discharge occurs when the gas from the gas pocket cavity (reservoir) expands into the barrel region to provide a favorable breakdown condition. It is conjectured that the gas pocket cavity design causes a slug of high pressure gas to move into the barrel where electrical breakdown and the actual discharge occurs. The improvement in the measured gun performance is consistent with this flow model. Therefore, with this gun design a high pressure breakdown occurs inside the barrel where the plasma is expanding. This discharge is initiated by a "reverse-Paschen curve" phenomenon.

The actual discharge phenomena within the gun barrel is not well understood. The details must be considered as conjecture at this point. Just before breakdown, an electrostatic field, $\vec{E}$, exists that is normal to both cathode and anode surfaces. After breakdown occurs, there will arise a current-induced electro-magnetic field, $\vec{B}$, that is normal to the local $\vec{E}$ field. The plasma then is accelerated in the direction dictated by the local $\vec{E} \times \vec{B}$ direction. For this model, a focusing of the plasma occurs when the $\vec{E}$ vector field assumes a curved shape due to the conical barrel boundary. To test this discharge model, a series of tests were made with the three gun barrel configurations to obtain evidence of plasma convergence. The test setup is shown in figure 2. The entire plasma gun was enclosed in a long pyrex tube and the pressure was lowered to 5×10^{-7} mm Hg. Evidence of focusing was obtained by examining a metal target located up to 1 meter from the plasma gun muzzle. The metal target could be placed at various stations by means of a sting support system. The straight (parellel bore) anode barrel showed no evidence of focusing. The metal target showed a "doughnut-shaped" damage zone which was the same size as the gun muzzle. In tests with the two converging anode barrels, a focusing effect was achieved. In figure 2, one can see the damage area confined to a region about 1 cm in diameter on a tungsten metal target. Tungsten was chosen as the target material after preliminary tests with aluminum had indicated convergence. Due to the high surface melting temperature and hardness of tungsten, a sharper gradient in the surface ablation zone results which yields a better definition of the focused plasma beam. Further evidence of the plasma configuration was obtained from image converter camera pictures which are shown on the bottom of figure 2. The first picture shows a copper metal target which is about 7.5 cm in diameter. The pyrex envelope is 10 cm in diameter and the two coils are dimagnetic probes which are 10 cm apart. The second picture in the sequence was made by triggering the image converter camera as early as possible; inherent internal delay in the system, however, was about 150 nanoseconds. The shape of the self-luminous plasma on the surface of the target indicates that the plasma indeed is focused into a small area and then flows radially outward from a stagnation zone. The area between the target and the plasma gun appears to contain no significant radiation source. Due to distortion effects at wider lens openings and camera limitations, it was not possible to make exposures at lower f numbers to increase the radiation sensitivity.

The plasma flow at the target is shown some 300 nanoseconds later in the third picture. Operating conditions of the gun for this test were identical with those considered previously. One can see that the intense plasma was confined to a small zone (less than 2 cm in diameter as indicated by the bright zone at the target). The luminous zone consists chiefly of ablated surface material. The ablated area is somewhat larger than the focused plasma spot due to the stagnation flow indicated in the second photograph. The plasma has flowed up to the tube boundary and has reflected back toward the muzzle which illuminates the entire volume. (The shadow of the upstream dimagnetic probe appears at the left in the picture.) Note that the plasma has no tendency to flow between the target and the pyrex tube.

The bottom right picture shows the damage zone of the metal (copper) target. The effects of three firings are shown. The target was initially highly polished; hence, only a rough zone will show scattered light. Notice that the center portion of the impact area on the target shows diffuse light scattering. Under close examination, this zone shows the same characteristics of an ablated copper surface which undergoes melting and subsequent flow as well as ebullition.

The remainder of this paper considers the techniques employed to measure the energy content of the plasma as it leaves the gun. Since the "puff" valve arrangement delivers a fixed amount of gas into the system, the velocity of the plasma becomes a measure of energy. Three methods have been used:

1. Time of flight which employed the image converter camera which is operated at very small time intervals between exposures.

2. Momentum exchange between plasma and target which was measured with a calibrated piezo-electric probe.

3. Velocity measurement by observation of the doppler-shifted wavelength of H_α radiation using photographic spectroscopy. The plasma leaving the gun muzzle is probably in a non-equilibrium condition. Therfore, there is no definite front that one can associate with the plasma. Moreover, each of the three methods used probably measures a different energy level of the moving plasma. Consequently, the measurements should be viewed as establishing limits or order of magnitude as opposed to specifying exact velocity measurements. The three methods discussed here did, however, produce the same order of magnitude for the plasma velocity - which is approximately 10^8 cm/sec.

Figure 3 shows the first method which employed an image converter camera to measure time of flight for the luminous plasma. As the plasma leaves the gun muzzle, a light sensor actuates a trigger for the STL image converter camera. The image converter camera takes a series of pictures with 5 nanoseconds exposure time and with a preset delay between pictures. The picture in the middle shows the relation between the muzzle and target; flow is from left to right. On the bottom left row of figures is shown results of a test in which there was 500 nanoseconds between exposures. The first picture shows the plasma has emerged from the gun but has not yet arrived at the target. (The relative position of the plasma can be compared with the middle picture of figure 3.) At a time 500 nanoseconds later, the plasma has arrived at the target and has undergone reflection back towards the gun. After another 500 nanoseconds, the plasma has reflected back into the gun muzzle. From the known dimensions and time intervals, one calculates a plasma velocity of $3X10^7$ cm/sec. In an attempt to obtain improved time resolution, the test was repeated with 200 nanoseconds delay time between pictures. These pictures are shown in the lower right column in figure 3. The top picture shows that the plasma arrived at the target in about 200 nanoseconds. After another 200 nanoseconds, the plasma jet is reflected back towards the nozzle. This indicates a velocity cf $7.5X10^7$ cm/sec.

Momentum measurements were made with a piezeelectric probe arrangement shown in figure 4. The piezoelectric probe was mounted behind a brass disc which was mounted at the focal point of the conical-barreled plasma gun. The output of the probe is recorded directly on a Tektronics Type 555 dual-beam oscilloscope. Prior to each discharge, the probe was calibrated with a cold gas impulse. The top two oscilloscope traces show the probe output for two time scales - 5 μsec/cm and 100 μsec/cm. From the top trace, the peak voltage output (32 volts) is obtained. The second trace - with a long time base - shows that a very clear sharp pulse was obtained. The third trace is for the cold flow only (no discharge). The signal consists of the spike at the left of the trace. The bottom trace is the current trace corresponding to the first two pictures. Notice that the probe gives a continuous signal for a much longer time than that during which current flows; i.e., a probe signal is observed beyond 20 μsec when the current is no longer flowing. This is due to inertia of the probe which results in an apparent mass integration effect. Provided that the mass injected into the gun is the same under both discharge and cold-flow conditions, the change in momentum will be proportional to the change in velocity. For the measurements shown, this indicates an average plasma velocity of 1.9×10^8 cm/sec.

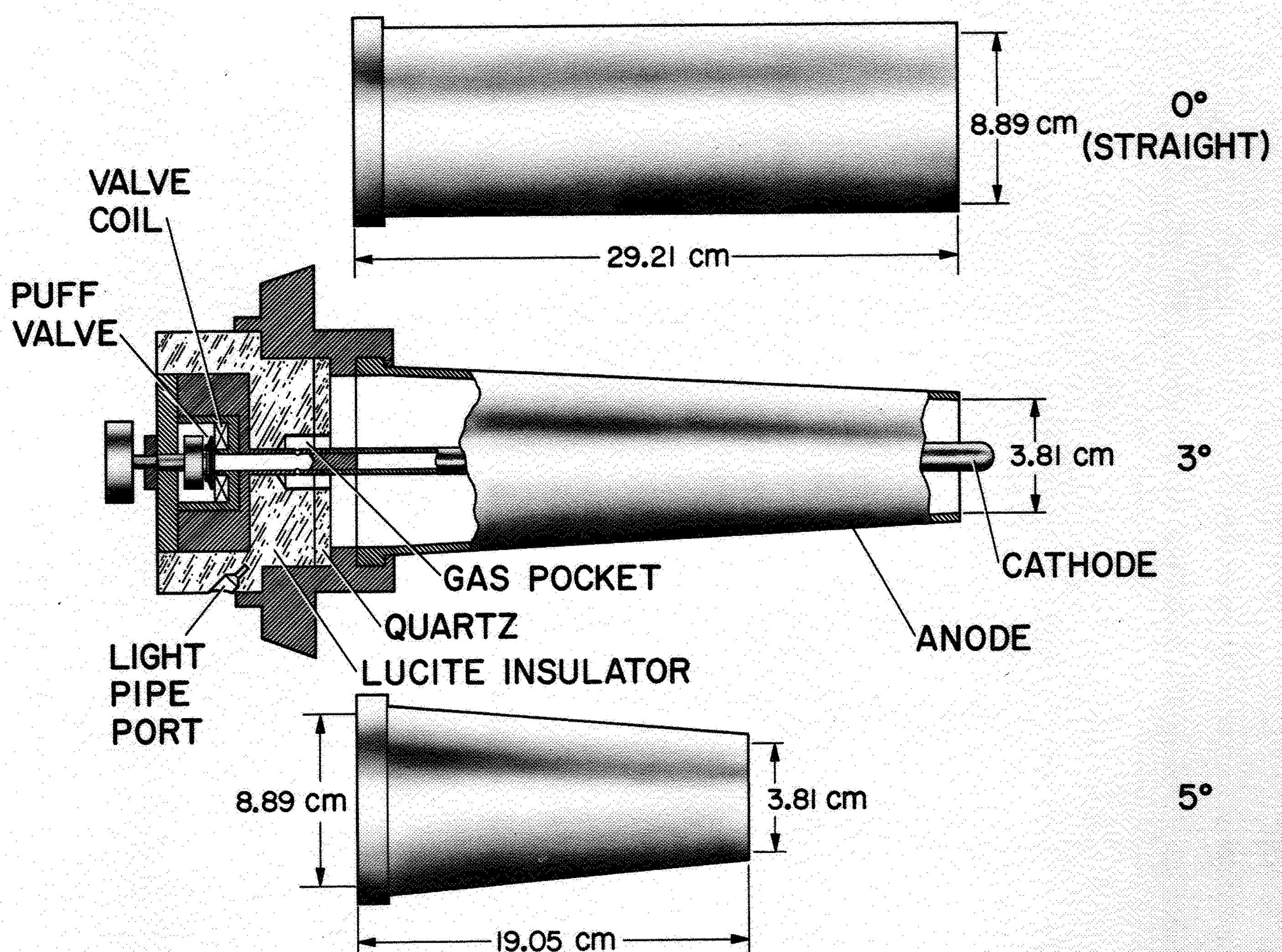
In figure 5 the arrangement for measuring velocity by the doppler shift method is shown. Doppler shift spectra of the H_α line radiation were obtained at the focus point of the converging barrel system. By means of a beam splitter plate, it is possible to simultaneously focus two beams that are oriented 90° and 45° relative to the gun axis onto the entrance slit of a spectrograph. For these tests a high resolution 2.5 meter Jarrell Ash spectrometer was used. A slit width of 500 μ and a slit height of 2 mm confined the measurement to discrete radiating volumes on the plasma trajectory at the focal point. The relative motion that exists between the two beam directions results in a doppler shift of radiation from the plasma. A spectrograph of the emission in the region of the H_α line at 6563Å is shown on the lower half of the figure. A doppler shift of approximately 21 Å is observed for the H_α line. For the instrument dispersion of 7.4 Å/mm, this corresponds to a plasma velocity of 1.4×10^8 cm/sec.

In summary, tests were made of a plasma gun system with anode barrel design as a primary variable. Characteristics of a straight-tube barrel and two conical barrels of 3° and 5° half angle were studied. It has been demonstrated that the straight-tube barrel design does not focus the plasma. The two conical barrels cause the plasma to focus (or converge) to a spot about 1 cm in diameter. The beam energy (in terms of plasma velocity) for the converging barrel design was measured by three methods. Results are summarized in the following table:

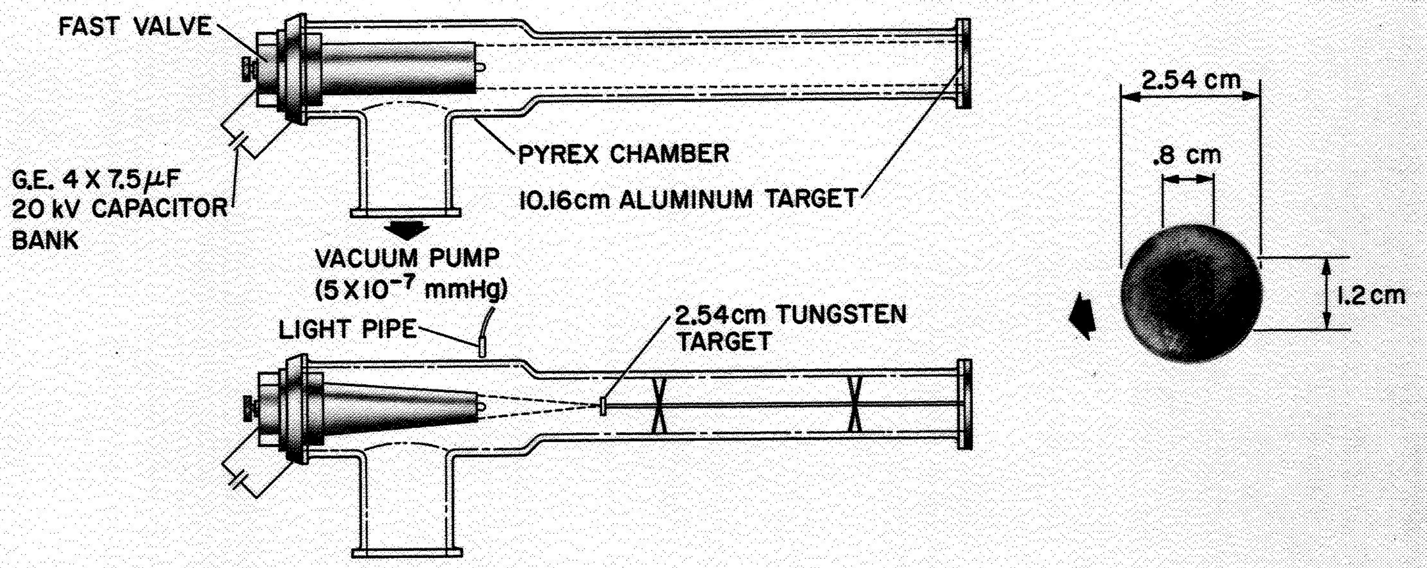
METHOD	INSTRUMENT	PLASMA VELOCITY, cm/sec
1. Time of Flight	Image Converter Camera (200 nanosec resolution	$0.8\text{X}10^8$
2. Momentum	Piezoelectric Probe	$1.9\text{X}10^8$
3. Doppler Shift of H_α	Photographic Spectrograph	$1.4\text{X}10^8$

All measurements indicate a velocity of the order 10^8 cm/sec. This level of performance exceeds the level reported for any other plasma gun.

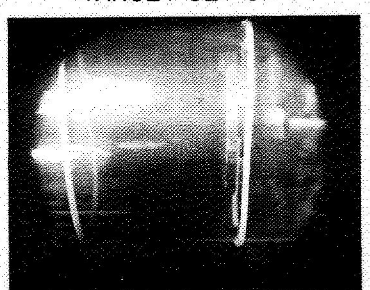
CONVERGING COAXIAL PLASMA GUN



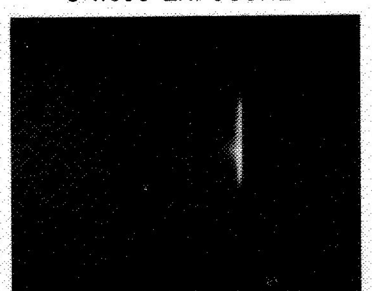
EVIDENCE OF CONVERGENCE OF PLASMA BY A COAXIAL GUN



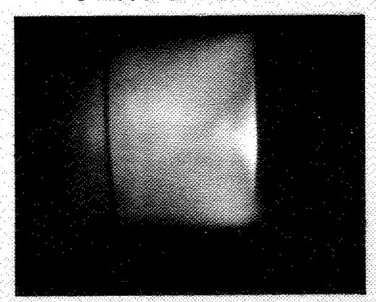
TARGET SET UP



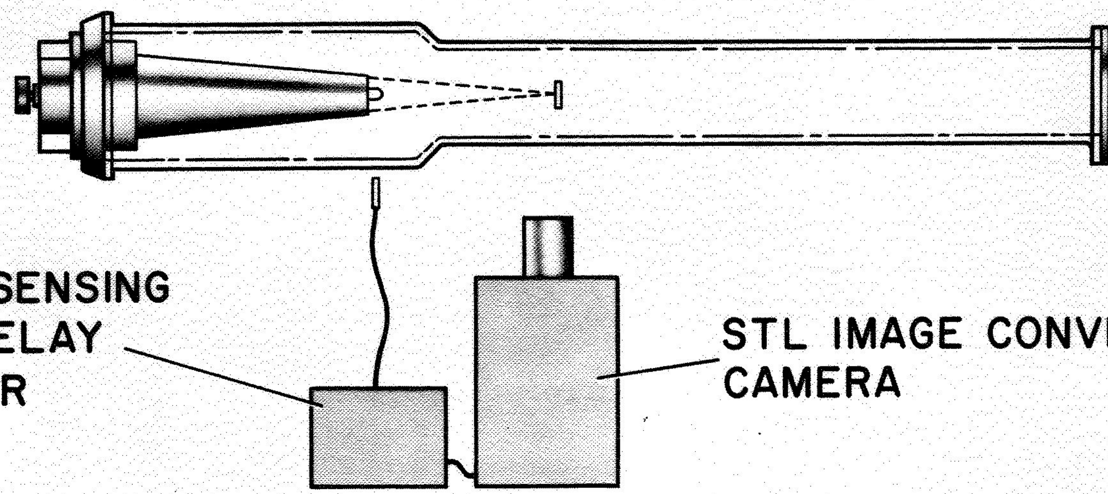
INTERNAL DELAY
≈150 nsec
NO EXTERNAL DELAY
f8/f1.7
5 nsec EXPOSURE

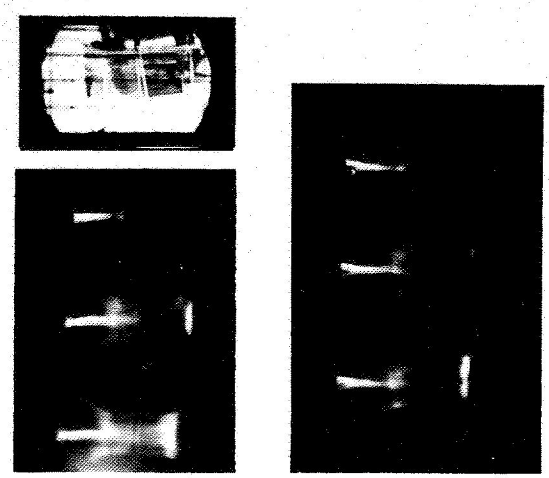


EXTERNAL DELAY
≈300 nsec
f8/f1.7
5 nsec EXPOSURE



TIME OF FLIGHT MEASUREMENT BY FRAMING IMAGE CONVERTER CAMERA





f8/f1.5
500 nsec DELAY
BETWEEN PICTURES

5 nsec EXPOSURE

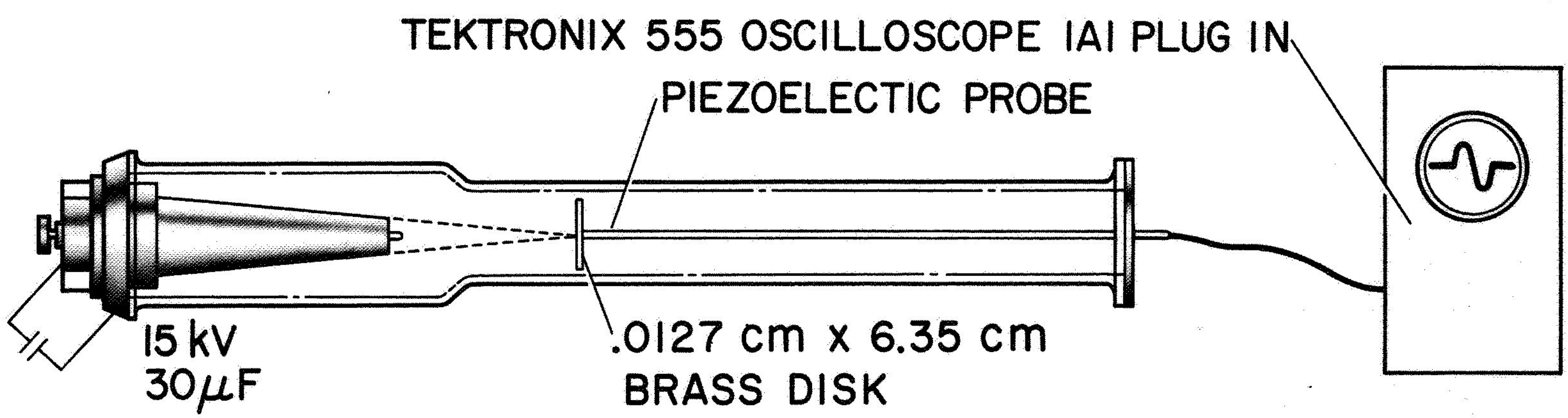
$v \approx .3 \times 10^{8}$ cm/sec

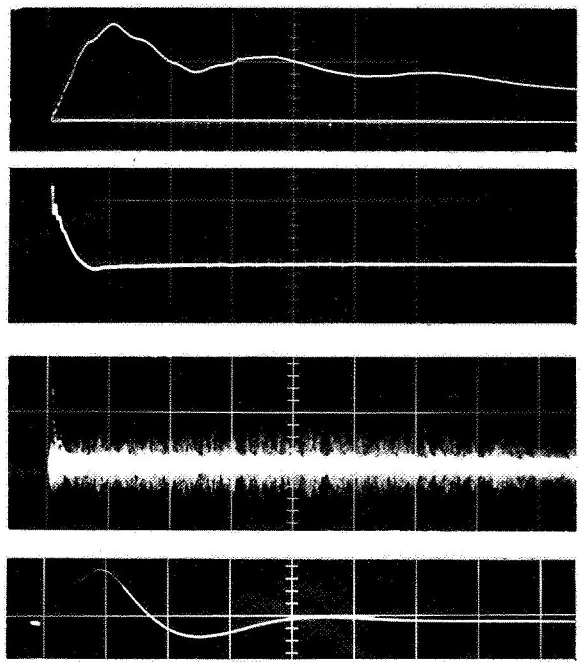
f8/f1.5
200 nsec DELAY
BETWEEN PICTURES

5 nsec EXPOSURE

$v \approx .75 \times 10^{8}$ cm/sec

IMPACT PRESSURE MEASUREMENT





5μsec/cm, 20 V/cm

100μsec/cm, 20 V/cm

10μsec/cm, .05V/cm
NO DISCHARGE

5μsec/cm, 20 V/cm
CURRENT TRACE

.056 V/psi

PEAK IMPULSE
NO DISCHARGE = 1.21 psi,
.068 V

PEAK IMPULSE
WITH DISCHARGE = 572 psi,
32V

$(V_{H_2})_{293°K} = .42 \times 10^6$ cm/sec

$V_{plasma} = 2 \times 10^8$ cm/sec

DOPPLER SHIFT MEASUREMENT