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FINAL REPORT

ADDITIONAL DEVELOPMENT OF A PROBE TO MEASURE VELOCITY DISTRIBUTIONS IN THE EXHAUST OF STEADY-STATE PLASMA ACCELERATORS

by

L. Liebing

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SECTION 1

INTRODUCTION

The development of the velocity probe was at first a small effort to satisfy the need for a better diagnostic tool in the pulsed arc gun development.[1,2] Later on a probe development program[3] started with particular emphasis on the application of the velocity probe in MPD arc plasmas. As a result of that effort a velocity probe was developed which is applicable in a variety of steady-state plasma exhausts.
Some problems became apparent which resulted in the probe not working completely satisfactorily in the MPD arc plasma. These problems were related to the relatively long period of time for which the probe was exposed to the plasma and to the nature of the MPD arc plasma itself.

The principle of operation of the probe, the mathematical treatment of the data, and the physical sources of error have been discussed in detail.[3,4] This report presents those particular problems which are related to the probe's application in the MPD arc plasma and describes their solution. The result is a new probe with new measuring equipment. However, as seen later in Figure 9, the essential features of the device remain unchanged. That is, the velocity data is acquired through the measurement of the time-of-flight of the ions between an electrical plasma shutter and an ion collector.

SECTION 2

IMPROVEMENTS OF THE VELOCITY PROBE WITH RESPECT TO THE MPD ARC DIAGNOSIS

2.1 HEAT LOADING

The earlier probe design contained a water cooling system which allowed the probe to be permanently located in the steady-state plasma beam if the distance between the gun and the probe was large enough (more than 1 meter). When it became necessary to make measurements closer to the thrustor the probe had to be moved across the plasma beam within a few seconds in order to protect the probe entrance from the increased heat flux density of the thrustor exhaust. A more convenient probe operation was the use of a probe pendulum, which eliminates the water cooling completely.

2.2 PENDULUM APPARATUS

A photograph of the probe pendulum is shown in Figure 1. The pendulum axis is mounted close to the top of the tank. The momentary position of the pendulum is indicated by some electrical pulses which are triggered by a light beam passing through the slots of an interceptor plate. At the top of the pendulum a gear and a motor have been installed which allow an axial location control of the probe from outside the tank.

The block diagram of the electronics which operate the probe at a certain pendulum position is shown in Figure 2. If the pendulum swings across the plasma beam a number of low voltage pulses are originated in the light sensor and fed into the trigger pulse generator (Figure 3). Since the light sensor has a recovery time which is larger than the pulse interval, only the first pulse in the sequence is steep. This steep pulse is used to operate a trigger pulse. (The total sequence of pulses can be observed at the pendulum position readout of the trigger pulse generator.) The trigger pulse is then delayed to coincide with the desired pendulum position before it is fed into the probe operation unit.

The probe operation unit generates the probe command pulse. It contains a delay unit which triggers the scope 50 μsec in advance of the measurement. This allows us to observe a larger portion of the plasma flux and both velocity measurements (switch-on and switch-off mode) on one trace. The probe operation unit also contains two low capacity isolating transformers to avoid closed electrical loops which are a hazard for high frequency signals. The schematic of the probe operation unit is shown in Figure 4 and 5. It is a version of the corresponding unit of Reference 3.

2.3 NEW SHUTTERS

It has been observed that charges are accumulated at the shutter electrodes if they are exposed to the steady-state plasma beam of the MPD arc.[3] Those accumulated charges change the electric field between the shutter electrodes and deteriorate the shutter performance. No charge accumulation was observed in experiments with pulsed beams which existed only for a small period of time of the order of 100 μsec, even at high plasma densities of the order of 10^{13} particles per cc.

In order to avoid the longer exposure times of the shutter electrodes to the MPD arc plasma, a fast-operating mechanical shutter was designed which could be attached to the entrance of the probe. This mechanical shutter is schematically shown in Figure 6. A 150 μF capacitor is discharged into a magnetic field coil which accelerates an aluminum disk to a velocity in the order of 100 meter/sec. A small steel projectile is initially resting on the aluminum disk. After awhile the disk comes to a stop whereas the projectile continues to travel along a steel tube for a few centimeters until it hits a small titanium arm which then opens the probe entrance hole. The steel projectile was used in order to provide a delay time between the capacitor discharge and the opening of the shutter which eliminates electromagnetic pickup from the magnetic field coil during the measurement. It also physically separates the relatively large shutter driving mechanism from the probe entrance in order to keep the shutter section of the probe as small as possible. The shortest opening time of the mechanical shutter was 50 μsec, which was achieved at a capacitor voltage of 2 kilovolts. This opening time was short enough to avoid effective charge accumulation.

The procedure of the probe operation is as follows. The probe pendulum is released from the tank wall. After it has reached a certain place inside the plasma beam the mechanical shutter is operated. Immediately after the probe entrance hole is thus opened, the electrical shutter is commanded to close.

Though the MPD arc is a steady-state device, its plasma turned out to be highly modulated and less steady than the pulsed plasma beams in which the probe was operated before.[3] This is demonstrated in Figure 7 which shows a collector signal with the probe on beam axis. The duration of the signal is determined by the opening time of the mechanical shutter. (The electrical shutter was permanently open.) The electronics has been set up such that a negative going signal is due to positive particles and a positive going signal is due to negative particles. It is evident that the ion flux is strongly modulated at a frequency of about 100 kHz. Rise and fall times are a few μsec. Less frequent, but as steep, are peaks of negative particles. Those peaks are properly related to bursts of energetic electrons which likely originate at the thrustor cathode. The collector bias voltage to separate ions from electrons was 22 volts. When this bias voltage was increased to about the thrustor terminal voltage (60 volts) the electron peaks disappeared. The ion peaks, however, remained essentially unchanged as shown in Figure 8.

From these observations in the MPD arc plasma, it may be concluded that the collector bias voltage has to be close to or higher than the thrustor terminal voltage. Besides this we have to recognize that the strong fluctuations in the plasma may electrically interfere with the sensitive collector signals and also cause additional problems for the electrical shutter. The MPD arc plasma indeed is a rough environment for a sensitive probe.

After the collector bias voltage had been increased the performance of the electrical shutter was checked out and was still found to be unsatisfactory. The previous conclusion that the malfunction of the electrical shutter is related only to the plasma exposure time of the shutter electrodes must, therefore, be modified to include some particular properties of the MPD arc plasma.

This finding renewed the experimental effort to improve the electrical shutter. First, the shutter bias voltage was varied and its polarity changed. It was found that the shutter performed slightly better at a negative bias voltage (with respect to the probe body). The reason is that a negative voltage avoids the relatively large electron current (100 mA) which is drawn from the plasma through the probe entrance hole if the bias voltage is positive. It has been observed that this electron current causes small erosion spots at the negative shutter electrode which may increase the gas density between the shutter electrodes significantly.

A considerable improvement of the electrical shutter was obtained by the incorporation of an additional shutter electrode. This is shown in Figure 9 which is a scale drawing of the new probe (without details).

The new shutter consists of a long negatively biased electrode, a short ground electrode being connected to the probe body and a short positively biased electrode. When the plasma enters the probe it is first exposed to a negative voltage gradient which keeps the electrons out of the shutter section. Also, part of the ions are run into the negative electrode. After the plasma has passed the short ground electrode it is exposed to a strong perpendicular electric field which is built up by the positive and the negative electrode. This perpendicular electric field then destroys the plasma beam completely.

The electronics which simultaneously switches the positive and negative shutter voltages is shown in Figure 10. It contains the previous shutter electronics which was presented in Reference 3. Figure 11 also presents the collector electronics indicating the new collector bias voltages.

The improvement of the electrical shutter made the mechanical shutter obsolete. It turned out that the pendulum swing provided a short enough time to avoid charge accumulation at the shutter electrodes. No improvement of the shutter performance was found with the additional use of the mechanical shutter. This result was rather fortunate because of the involved measuring procedure which is required by the use of the mechanical shutter.

The density fluctuations in the plasma as seen by the probe are accompanied by potential fluctuations.[5] Since the probe body is in direct electrical contact with the plasma, these potential fluctuations tend to be transmitted into the interior of the probe to be picked up by the sensitive collector. Though the interior of the probe has been carefully shielded this pick up becomes apparent at small collector currents (1 to 10 μA) and at strongly modulated plasmas.

The pick up problem can be avoided if the collector signal is kept above the interference level. This requires a controllable probe entrance aperture because the plasma flux in the gun exhaust may be changed from experiment to experiment. Such a controllable aperture has been incorporated into the probe as shown in Figure 11. The aperture is a slot which can be variably covered by a small arm. The location of this arm is controlled by a motor.

2.4 BACKGROUND PRESSURE

The neutral gas pressure inside the probe has to be small enough such that the ion flux is not affected by charge exchange collisions. If this background pressure stays below 10^{-4} Torr the measurement is generally not affected. A particular example is given in Reference 3 for an argon exhaust at the velocity of 1.2 cm/μsec. In this case, the maximum allowable argon background pressure inside the probe was 2×10^{-4} Torr.

MPD arc facilities with good pumping speeds provide tank pressures below 10^{-4} Torr, even if non-condensable propellants are used. In this fortunate situation the measurement can be done without any additional pumping. This follows because the time-of-flight chamber of the probe will come into pressure equilibrium with the tank when the probe is pulled out of the plasma beam. When the probe pendulum swings across the beam, additional gas enters the probe. The background pressure increase due to this effect, however, is negligible because of the short pendulum swing-through time and the small ion flux that enters the probe.

An additional probe pumping is provided for the case that the background pressure is not low enough. As shown in Figures 1 and 11, the time-of-flight chamber of the probe can be connected to a vacuum pump. Convenient pumps for this purpose are ion or getter pumps. Ion pumps have to be used in case of a noble gas. The pumping speed should be about 10 liters per sec. For non-noble gases, getter pumps are very efficient. Figure 1 shows a titanium getter pump which is hooked up to the pendulum and connected to the probe. The inside of this getter pump contains a tungsten-titanium filament which is flash heated (10 volts, 50 amperes) for a few seconds. During this time a titanium layer is formed at the inside wall of the pump which actively pumps for about 10 more secs which is more than enough for the velocity measurement procedure.

SECTION 3

VELOCITY MEASUREMENTS IN THE MPD ARC PLASMA

Velocity measurements with the improved probe shown in Figures 9 and 11 have been performed in MPD arc facilities at Convair and at NASA Langley. At both places the plasma flux has been found to be strongly modulated with only some rare exceptions of a smaller degree of modulation which lasted over a period of at least 100 μsec. Those modulations complicate the velocity measurement because their rise and fall times are almost equal to the time-of-flight inside the probe. To compensate for this interference a number of velocity measurements have to be obtained and the proper velocity distribution has to be determined by a statistical procedure. This situation is less fortunate than it has been in the case of the non-modulated pulsed plasmas[3] where the complete velocity distribution could be obtained with one single measurement. The average ion velocity in the MPD arc plasma, however, can still be obtained with at least a few measurements. Examples of those measurements are presented in Figures 12 and 14.

Figure 12 shows three velocity measurements which have been done in the Convair laboratory. The upper beam is the ion flux signal at the collector (negatively going), the lower beam is the command pulse for the probe shutter. The shutter is opaque during the positive pulse. The three measurements show successively larger degrees of ion flux modulation. The trace of the upper beam returns to the base line (no current) when the shutter is closed. The first photograph is one of the rare examples where the modulation is relatively small. The closing and the opening event are indicated by the time marks superimposed on the collector signals. (These time marks are faint, but clearly visible in the original photograph.) The time intervals between the time marks and the switch-off or switch-on process of the ion flux indicates a velocity of 1.2 cm/μsec (at a flight path of 6 cm). This is consistent within 20% for the six measurements (switch-off and switch-on).

At those measurements the MPD arc was running on nitrogen at 20 mg/sec at a power level of 12 kW (300A). The location of the probe was on axis 14 cm downstream. No differential probe pumping was required because of the low background pressure (3×10^{-4} Torr).

Similar velocity measurements have been made at NASA Langley. The MPD arc there was running on argon at a power level of 4 kW (100 A). The argon propellant was fed into the thrustor through a hollow cathode and a porous anode at a total of 10 mg/sec. The background pressure was again 3×10^{-4} Torr. The distance between the gun and the probe was only 2.5 cm on axis. Figure 13 shows a complete probe swing through at a slow time sweep, i.e., ion flux vs. probe position. The upper beam presents the collector signal (negatively going) and the lower beam the command pulse. Because of the slow time sweep the command pulse and the operation of the electrical shutter are shown as dots in the center of the photograph, indicating the probe position during the measurement. The dot at the collector signal is in line with the no-plasma signal indicating that the electrical shutter closes completely. The broad width of the collector signal at the center of the beam indicates again a high degree of ion flux modulation.

Figure 14 presents the actual velocity measurements at the center of the beam. Four subsequent probe operations are shown in order to demonstrate the interference of the plasma modulation. The average velocity can be easily analyzed to be 1.5 cm/μsec.

SECTION 4

SUMMARY AND CONCLUSION

The improvement of the velocity probe and the probe equipment has yielded a diagnostic instrument which is now well usable in the MPD arc exhaust. Once set up, velocity measurements can be obtained very fast at variable locations inside the plasma beam. The fast responding collector circuit (50 nanoseconds) also senses the 100 kHz plasma fluctuations which have been found to be a dominating feature of the MPD arc plasmas. These oscillations complicate the measurement of the ion velocity distribution and statistical procedures have to be employed for their elimination. The average ion velocity, however, is obtainable by a few probe operations.

A fast-operating mechanical shutter (50 μsec) has been built to shield the faster electrical shutter (30 nsec) in the interval between measurements. This was done to avoid a charge accumulation problem on the shutter surfaces. A pendulum system was built to swing the probe traverse to the exhaust beam and to record the probe position. In typical measurements at a distance of 10 cm from the thrustor the pendulum intercepts the cross section of the plasma beam for 30 msec. This time is short enough to ease problems of heat loading, charge accumulation, and background pressure due to neutrals within the probe chamber. Auxiliary pumping has been provided for the probe interior, however.

For the experimental conditions reported, it was unnecessary to use the mechanical shutter once the pendulum and the new three electrode shutter were in use. Also, there was no heat loading problem and no auxiliary pumping was necessary.

Measurements in regions of higher magnetic fields (500 Gauss) have not indicated any deterioration of the probe performance. The influence of a magnetic field on the probe measurement, however, should be investigated in more detail. It can be expected that even larger magnetic fields (10 kGauss) are tolerable if the plasma polarization inside the probe is properly utilized.

SECTION 5

ACKNOWLEDGMENT

I wish to thank Alan V. Larson for his advice and Orley Neller who assisted in building the probe and performing the measurements.

SECTION 6

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4. L. Liebing, "Probe for the Measurement of Ion Velocity Distributions in Low Density Plasma Beams," AIAA Paper 67-706, Sept. 1967.

5. P. Brockman, J. Burlock, R. V. Hess, F. W. Bowen, "The Effect of Various Propellants and Propellant Mixtures on an MPD Arc Jet," AIAA Paper 67-684, Sept. 1967.

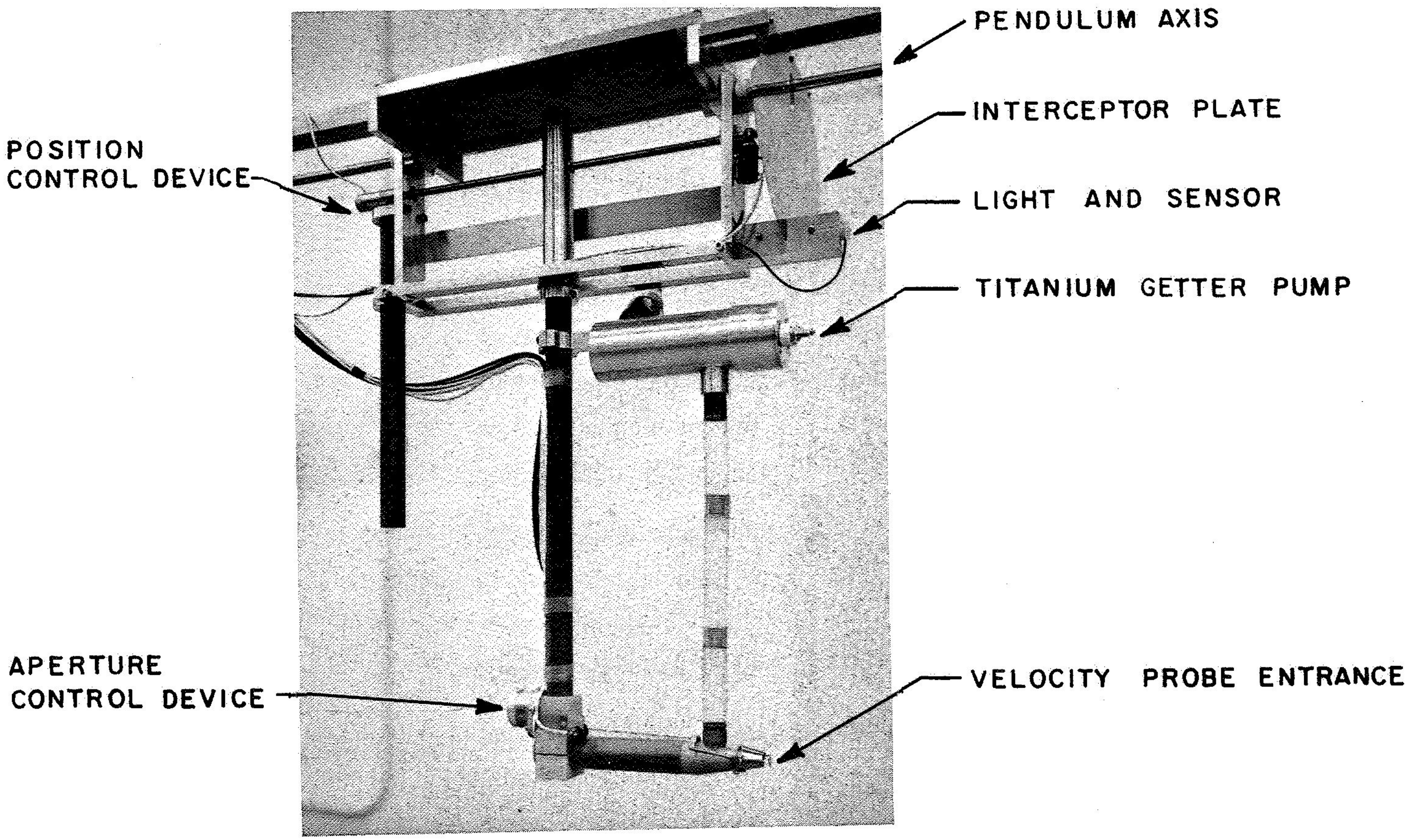


FIG. 1 : PROBE PENDULUM WITH PROBE AND PUMP

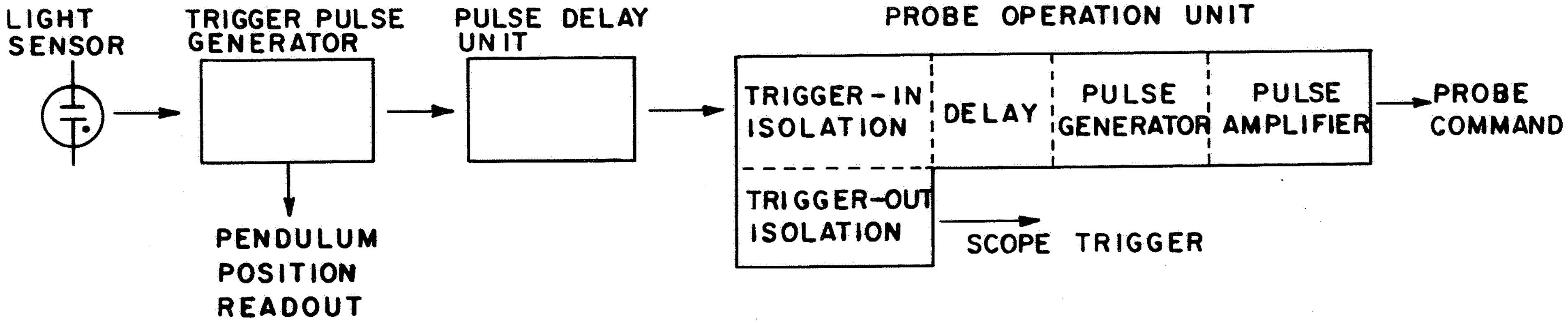


FIG. 2 : BLOCK DIAGRAM OF THE PROBE ELECTRONICS

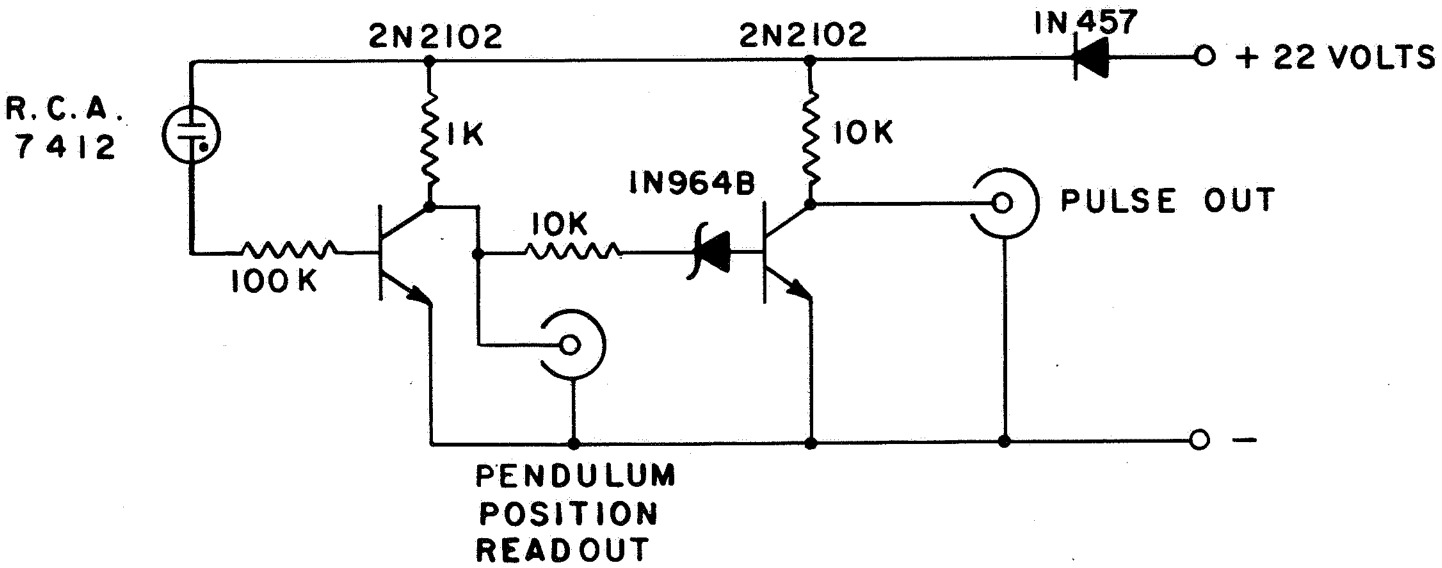


FIG. 3 : TRIGGER PROBE GENERATOR

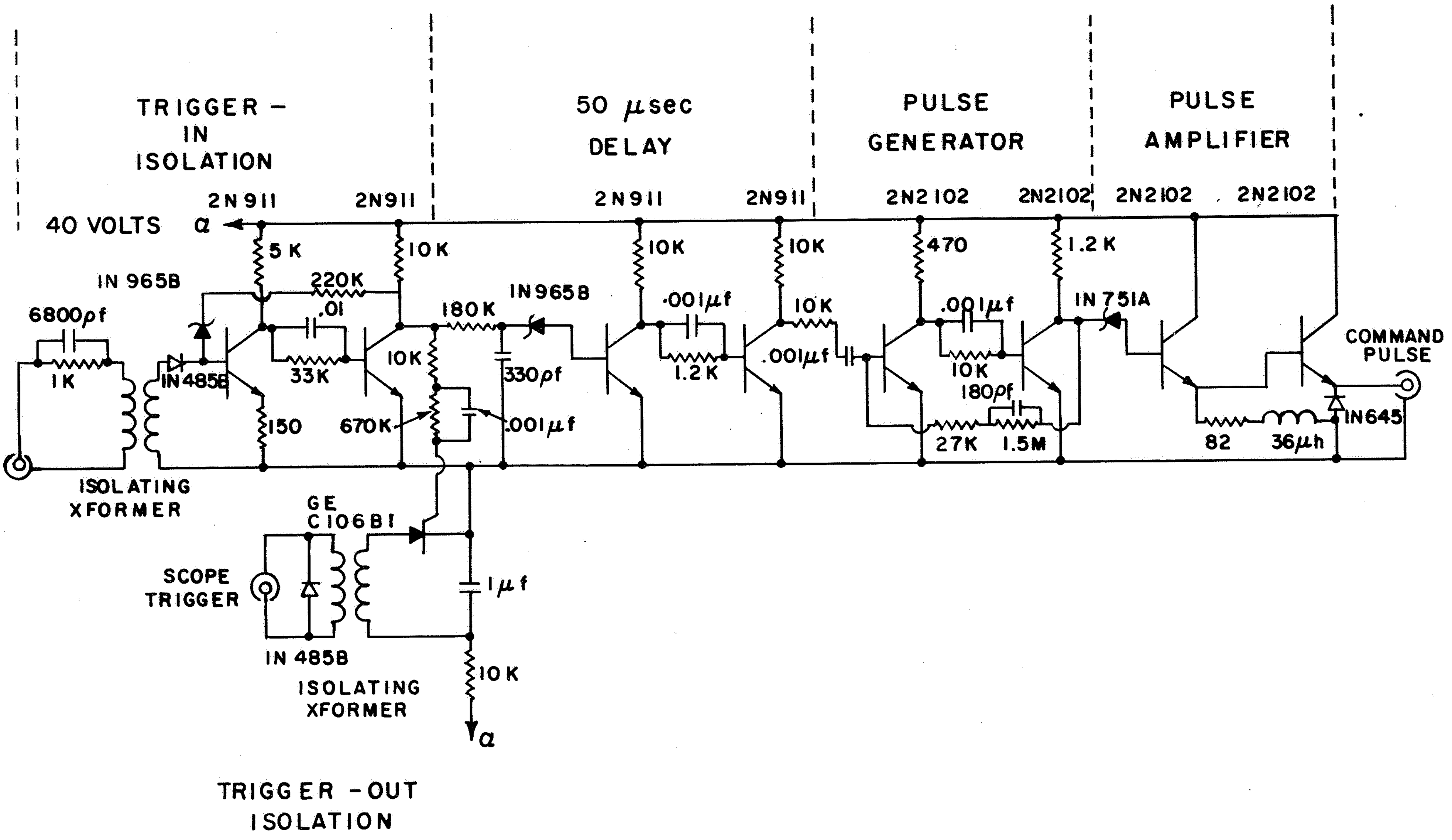


FIG. 4 : PROBE OPERATION UNIT

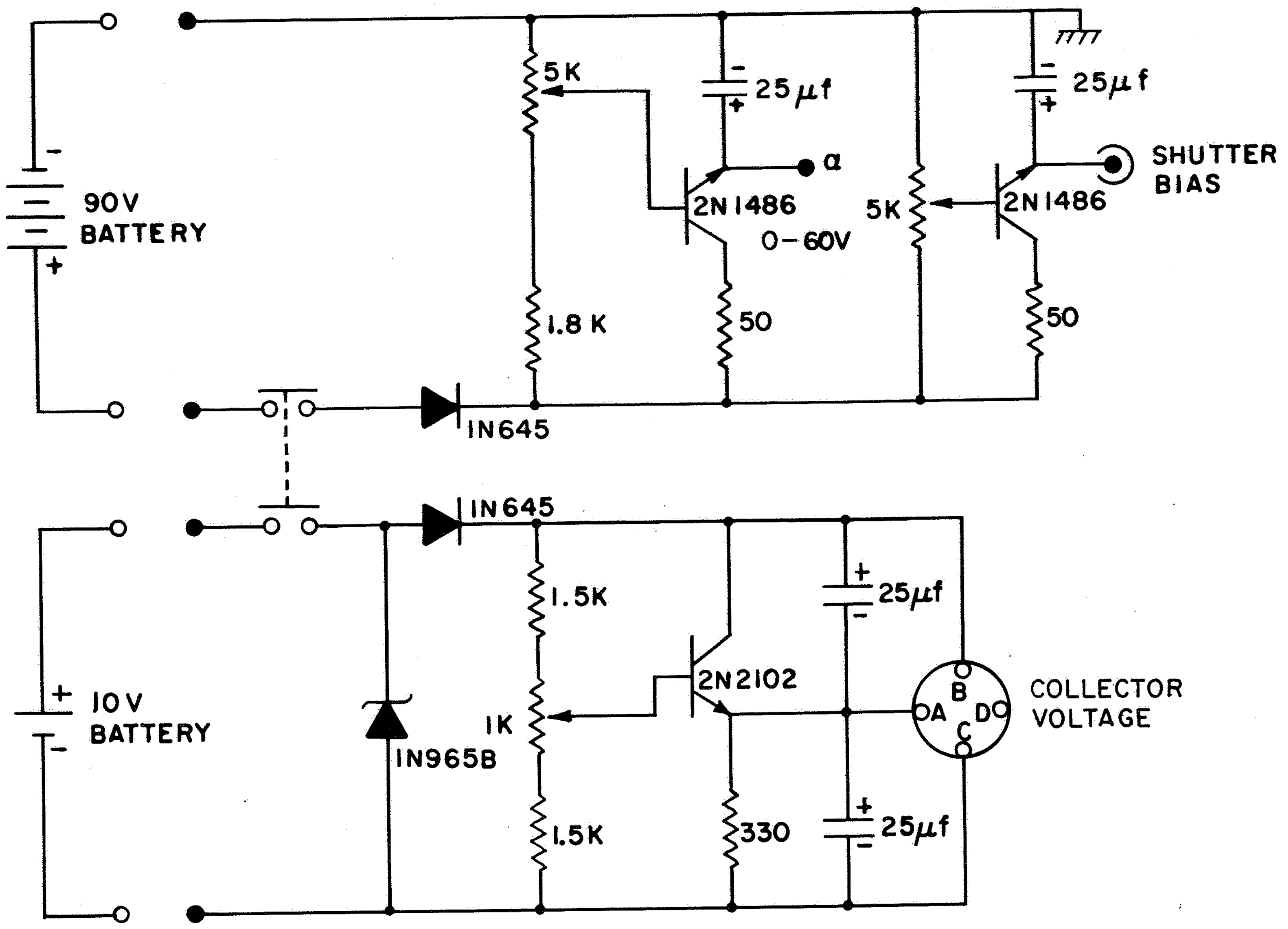


FIG. 5 : POWER SUPPLY FOR PROBE OPERATION UNIT

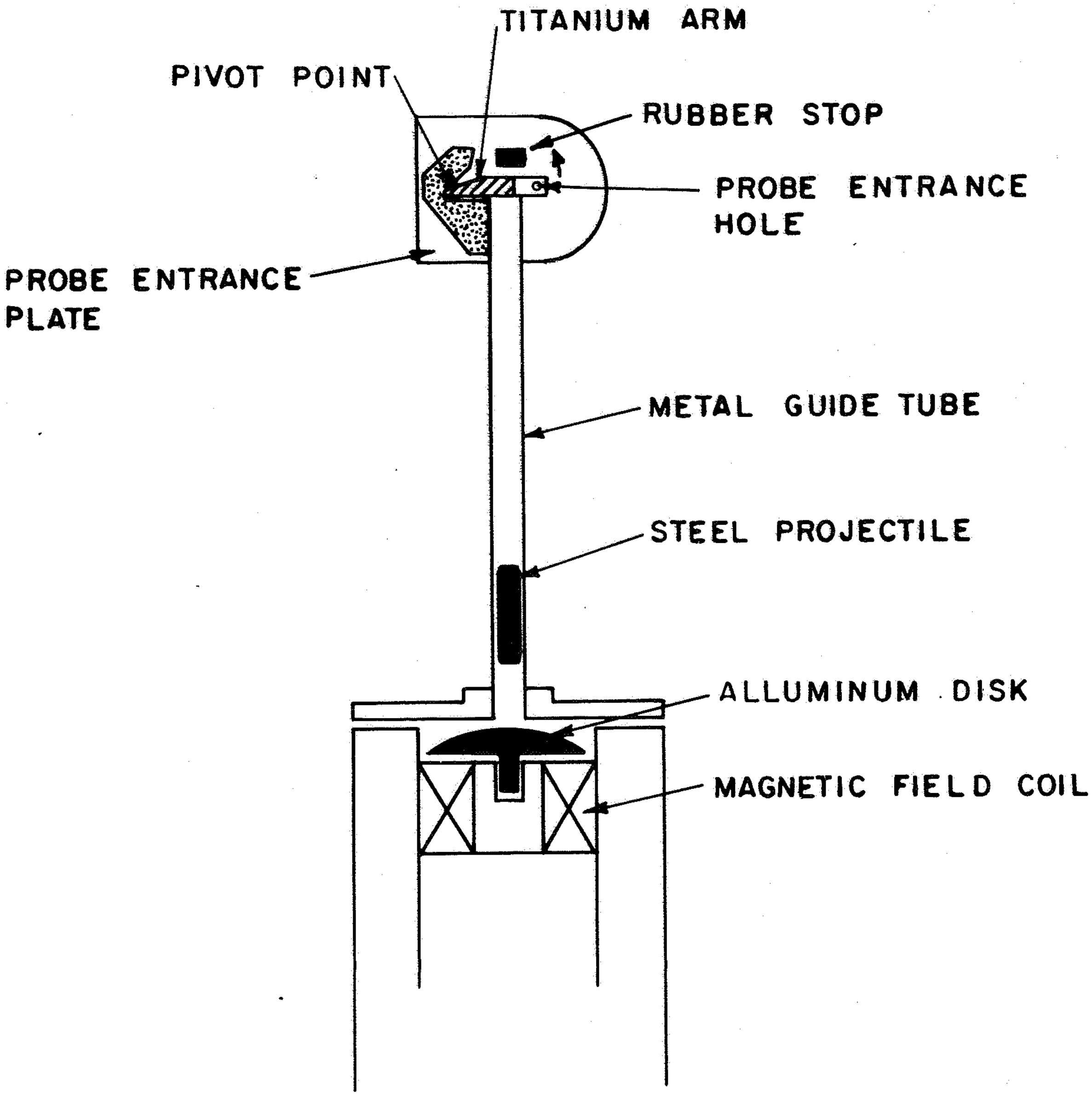


FIG. 6 : MECHANICAL SHUTTER ATTACHMENT

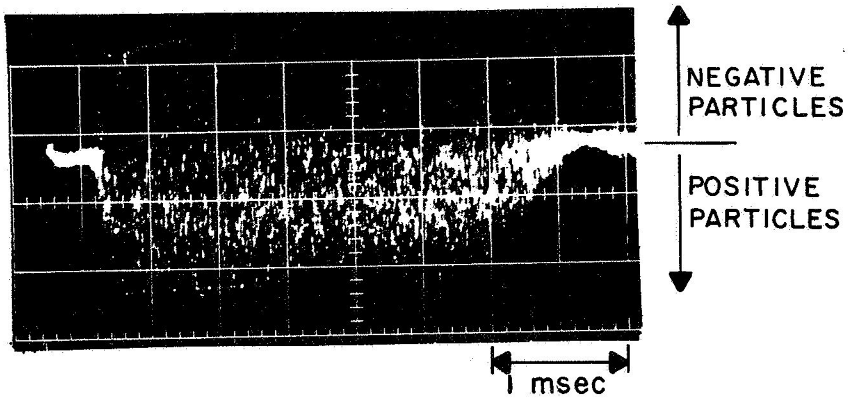


FIG. 7 : OSCILLATIONS IN THE COLLECTOR CURRENT
COLLECTOR BIAS 22 VOLTS, MPD PLASMA SOURCE

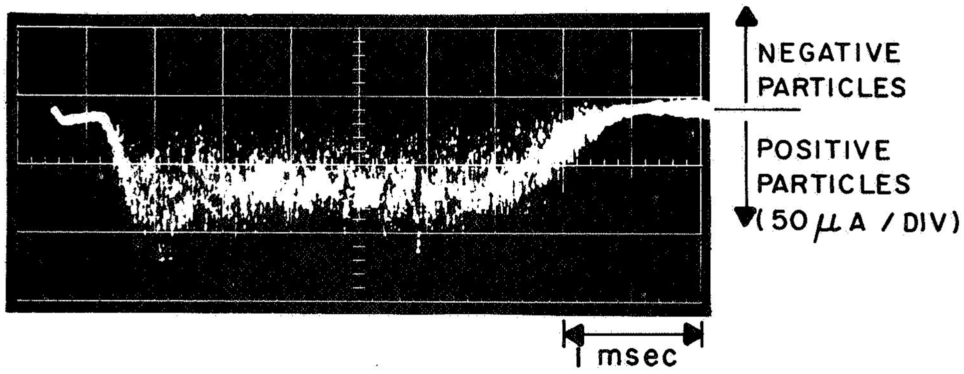


FIG. 8 : OSCILLATIONS IN THE COLLECTOR CURRENT
COLLECTOR BIAS 60 VOLTS, MPD PLASMA SOURCE

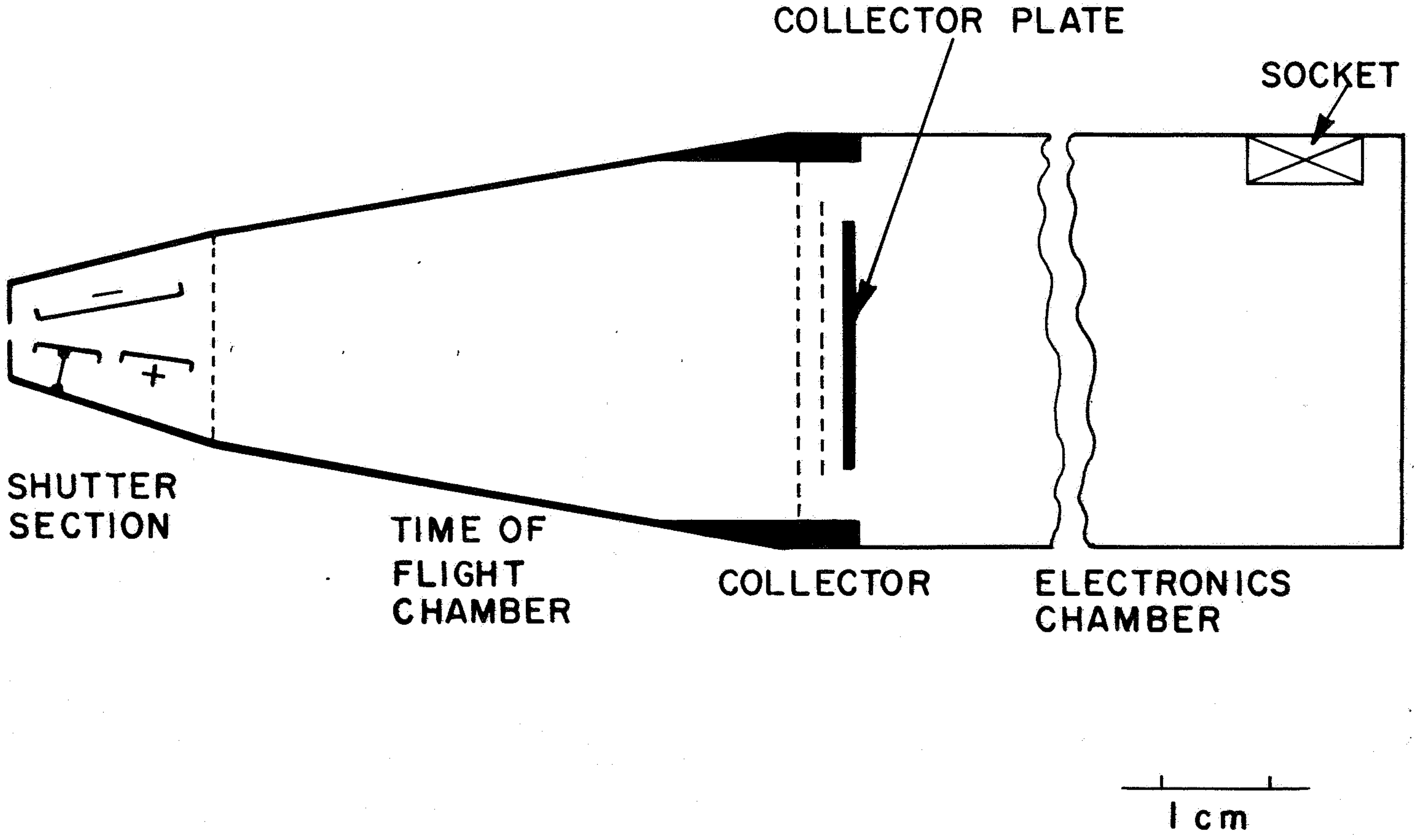
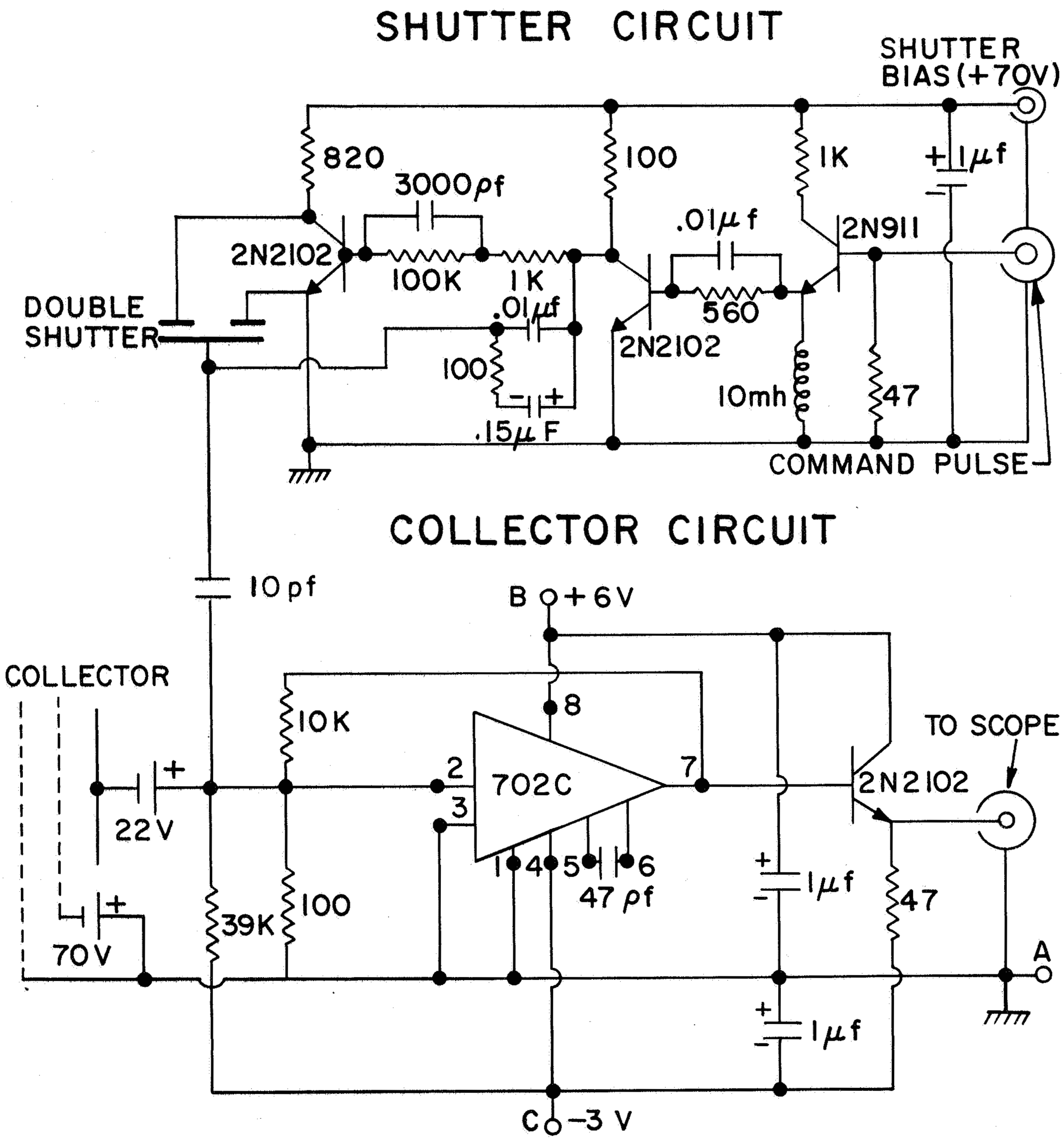


FIG. 9 : IMPROVED VELOCITY PROBE



SHUTTER CIRCUIT

COLLECTOR CIRCUIT

FIG. 10 : SHUTTER AND COLLECTOR CIRCUIT

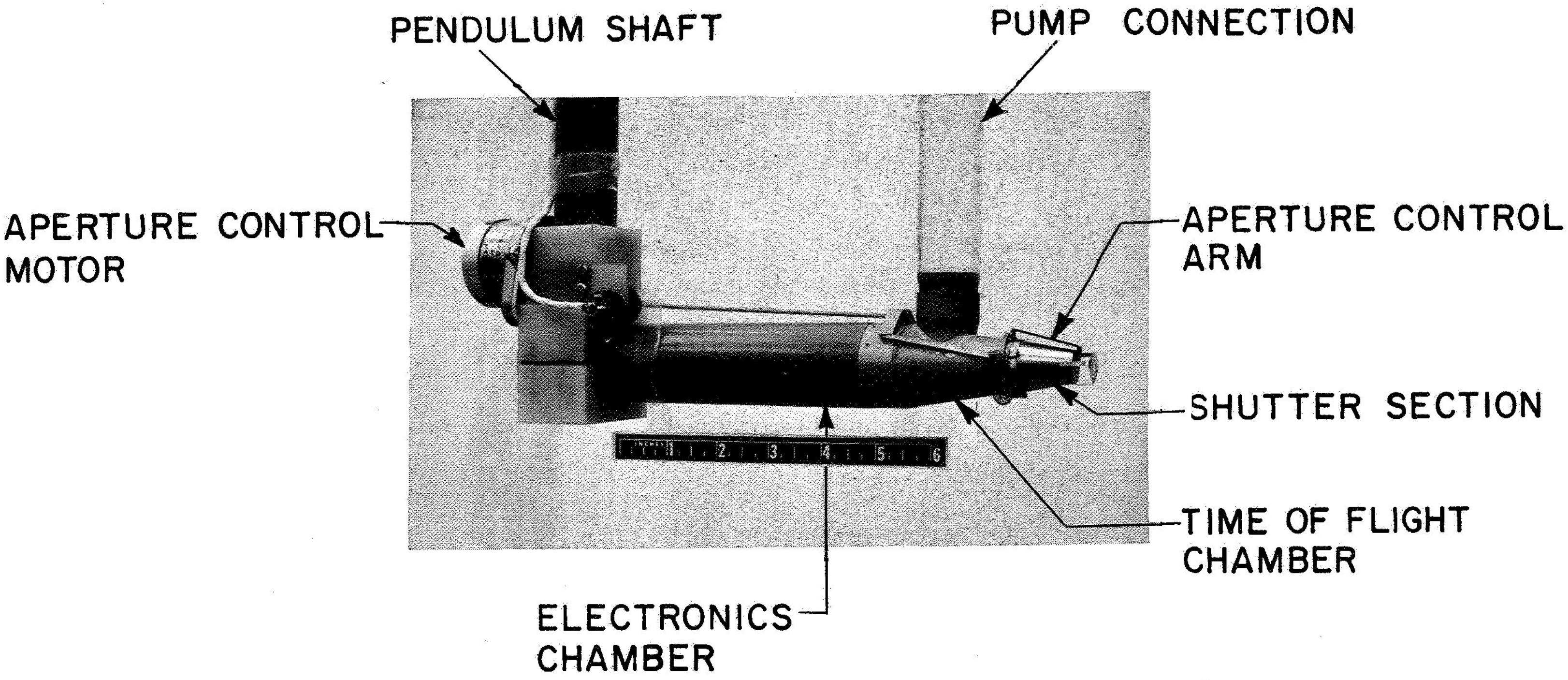


FIG. 11 : PHOTOGRAPH OF THE VELOCITY PROBE

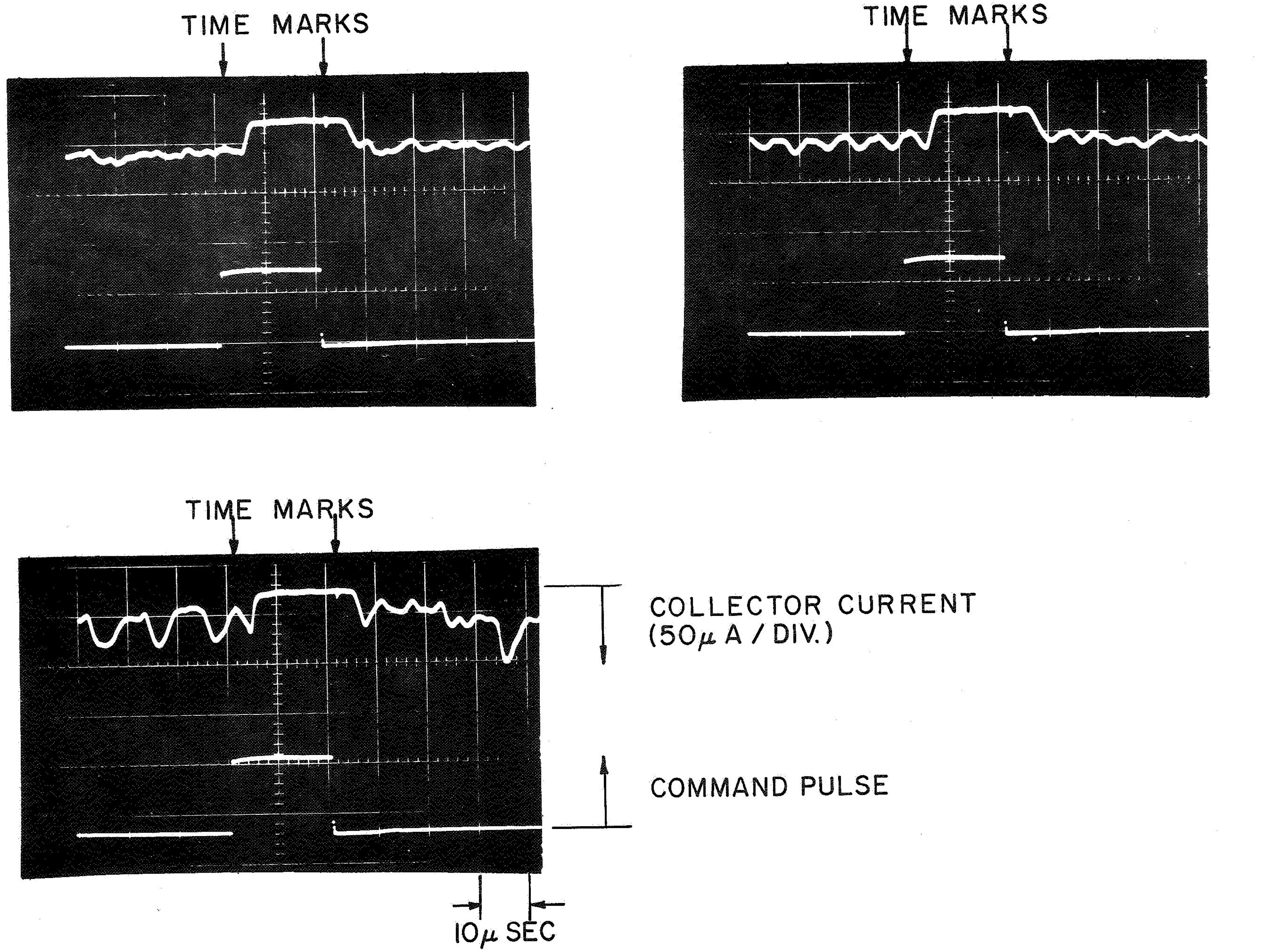


FIG. 12 : VELOCITY MEASUREMENTS IN AN MPD EXHAUST AT CONVAIR
THRUSTOR : 300A, 40V, 1.5 K GAUSS, N_2 AT 20 mg / sec
BACKGROUND PRESSURE : 3 x 10^{-4} TORR

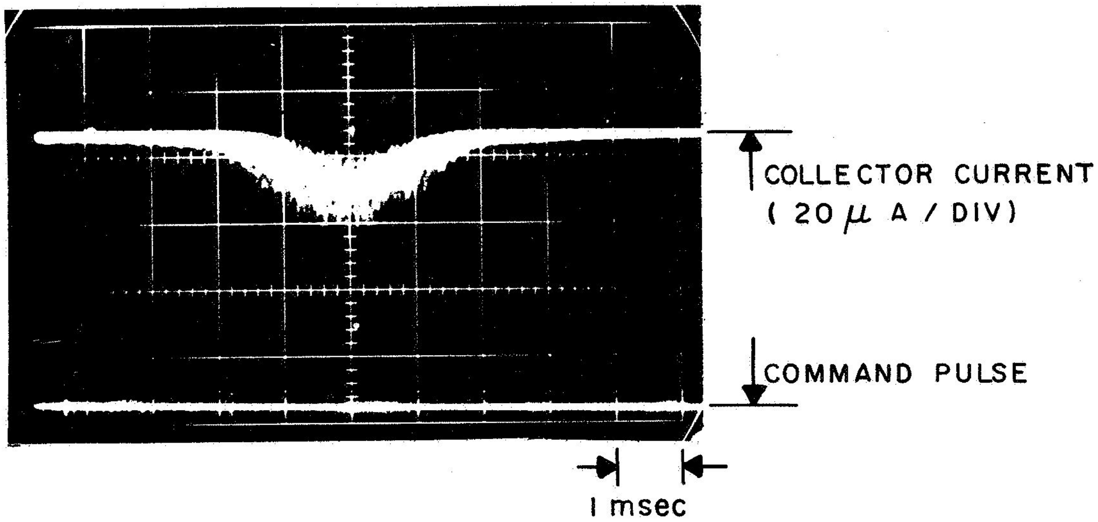


FIG. 13 : ION FLUX DURING TOTAL PENDULUM SWING

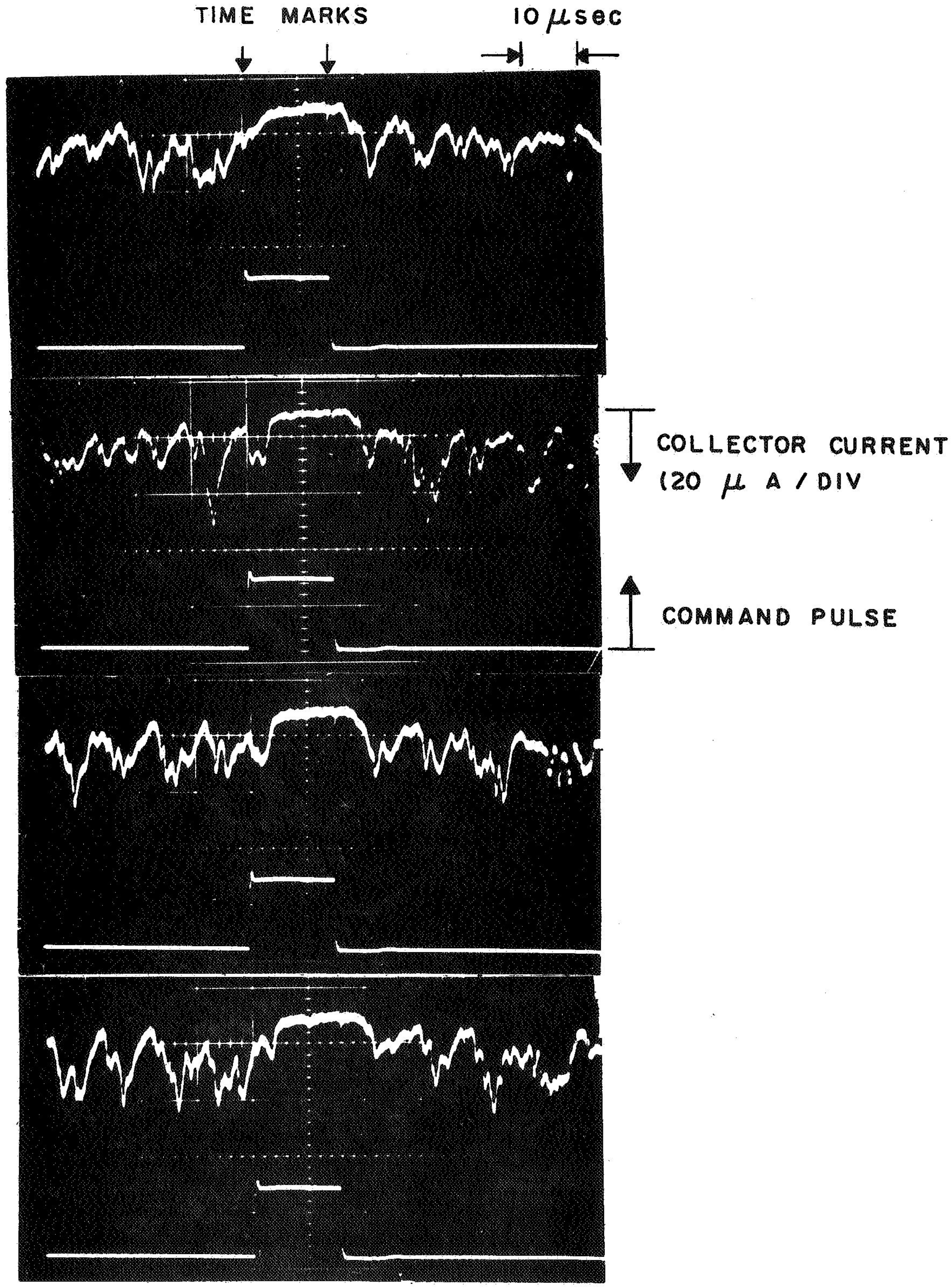


FIG. 14 : VELOCITY MEASUREMENTS IN AN MPD EXHAUST AT NASA-LANGLEY
THRUSTOR : 100 A , 40 V , 700 GAUSS
ARGON , 10 mg / sec
BACKGROUND PRESSURE : 3×10^{-4} TORR