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EFFECT OF MICROWAVE RADIATION ON A SHOCK-PRODUCED ELECTRON PRECURSOR

by

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ABSTRACT

This paper presents some results of experiments in which a small pressure driven shock tube was used to produce shocks in Argon above Mach 10. This was strong enough to produce low level precursor ionization ahead of the shock. At the same time, the shock tube was used as a waveguide for pulsed X-Band microwave radiation with a peak power of a few kilowatts. This further ionized the gas in the precursor region, resulting in an ionization wave which propagated very rapidly toward the microwave source. The velocity of this wave was measured as a function of the microwave power and an interpretation and comparison with other data is given.

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I. INTRODUCTION

The interaction of microwave energy with plasmas and particularly with plasmas produced by shock waves in shock tubes has been utilized for diagnostic purposes for a long time. Reflection of microwaves from a shock front has been used to measure shock velocity[1]. The transmission and attenuation of a microwave signal have been utilized in a number of ways to determine two very important plasma parameters: the number density of ionized particles and the electron collision frequency in transient plasmas generated behind strong shocks in shock tubes[2]. The interaction of microwave fields in resonant cavities with plasmas in shock tubes has also been used to determine electron densities and collision frequencies both behind the shock[3,4] and in precursors found in front of strong shocks[5]. The effect of the power of the microwave signal in most cases was neglected since the power was low and the effect insignificant.

In a series of experiments by Bethke and Ruess[6] it was shown that a microwave signal, transmitted towards a preionized medium, causes the preionized gas to absorb part of the microwave energy generating a "plasma shield" which propagates towards the r.f. source. The velocity of propagation of the "plasma shield" was found to be a function of the r.f. power. In this work an attempt was made at obtaining the ionization front propagation velocity as a function of applied r.f. power with the preionized gas being the electron precursor of a strong shock. The effects of the electron precursor number density, the ambient pressure in front of the shock and the shock Mach number on the velocity of the ionization front were investigated.

II. PHENOMENOLOGICAL BACKGROUND OF THE EXPERIMENT

Precursor ionization is a well-established phenomenon. It was first observed around meteors[7] and during re-entry of manned satellites[8] and has been theoretically treated by a number of scientists[9-11]. These treatises, encompassing a variety of phenomena ranging from diffusion to ultraviolet radiation, were always unable to predict exactly or even approximately the measured electron densities in front of strong shocks in shock tubes. In an attempt to reconcile the observed phenomena with theoretical predictions, a number of laboratory experiments were conducted. These included experiments in glass shock tubes using magnetic pickups or modified electrostatic probes[12] and stronger shocks in metallic shock tubes with microwave resonant cavities as the primary pickup devices[5].

This is not the place for a complete discussion of the previous experiments but let us just briefly review some of the results and conclusions from the last reference[5]. The electron number density of the precursor was measured there using microwave cavities. That method of measurement has the advantage that no interfering probes of any kind were introduced in the measurement region. The conclusions resulting from all the measurements were as follows:

1. The shock wave moves into the driven gas with a certain electron precursor distribution preceding it.

2. The electron precursor velocity is equal to the shock velocity.

3. The precursor ionization is caused by radiation emanating from the shock heated gas behind the shock front.

Typical electron precursor profiles as obtained by these experiments are reproduced in Fig. 1. A comparison with prevailing theories does not bring the theoretical and experimental results together, which is not surprising since a complete theoretical treatment of the experimental conditions is simply too complicated. However, the general behavior of the experimental and theoretical precursor profiles agree quite well. The electron density in front of the shock appears to decrease exponentially with distance from the shock front. This feature is of some importance in the experiments described here.

III. EXPERIMENT

A schematic diagram of the experimental setup is given in Fig. 2. A one-inch i.d., pressure driven shock tube with hydrogen at 350 psi as the driving gas was used to generate shocks in Argon at pressures of 0.5, 1.0 and 3.0 Torr and shock Mach numbers of 13.4, 11.9, and 10.1, respectively. These were strong enough to produce a low level of precursor ionization ahead of the shocks. The free electrons thus produced were heated to produce further ionization by a pulse of microwave radiation delayed by approximately 150μsec after initiation of the shock. This allowed for complete formation of the shock and precursor. The microwave source was an X-Band magnetron capable of delivering 40kw peak power in a 2.33μsec pulse at 9.375ghz. This was coupled to the shock tube through standard X-Band waveguide by a "tee" as shown in Fig. 3 with a mylar window, 0.014 inches thick, to seal the shock tube pressure (vacuum) system. This tee with the mylar window had a VSWR of approximately 1.6 which permitted sufficient power to be coupled to the shock tube to cause microwave breakdown of the gas in the precursor region.

Since in each test the input power was a single pulse, a crystal detector was used to monitor the input power as shown in Fig. 2. This detector's response was calibrated using a Hewlett Packard Model 431A thermistor bolometer to measure average power while pulsing the magnetron at rates up to 500 pulses per second. The peak power was then calculated from the average power and the duty cycle and the corresponding detector response measured. Input power for a single pulse could then be measured from oscilloscope pictures of the detector's response. In the same way another crystal detector was used to monitor reflected power from the tee. Typical recordings are shown in Fig. 4a.

In the shock tube the microwave power propagates in the dominant TE_{11} mode since the size of the tube does not allow propagation of other modes at the applied frequency. In this mode the electric field is strongest at the center of the tube. If the field is strong enough, breakdown occurs in the gas. Breakdown in the shock tube was detected by two photomultiplier tubes which monitored the light radiated by the ionized gas through windows 1/16-inch i.d., approximately 130 cm apart, and by two small probes which monitored microwave power at two positions, also approximately 130 cm apart, along the tube.

Breakdown was said to have occurred at a photomultiplier station when light was first detected there. A typical response is shown in Fig. 4b. The difference in time τ_L, between breakdown at the two stations indicates an ionization wave traveling from the shock toward the microwave source and serves to measure its velocity. These measurements were checked with the microwave probe responses of which typical examples are given in Fig. 4c. In these, breakdown was said to have occurred at cutoff of the microwave power at the probe and again the time difference, τ_M, between cutoff at the two stations indicates the velocity of the ionization wave. Figure 5 gives a comparison of the two measurements as a function of input power at a driven pressure of one Torr and the agreement is seen to be very good though not exact. It is also compared with an extrapolation of data reported by Bethke and Ruess[6].

It may be noted in Fig. 4b that there is a fluctuation in power before cutoff at the probes (in this case especially evident in the second probe response). Sometimes two minima would be observed in the response of probe 2 and often a small dip would be observed in the probe 1 response. The cause (or causes) of these fluctuations is uncertain at this time but they may be produced by a phase shift resulting from the developing plasma, a change in polarization of the TE_{11} mode or a resonance effect. In any case, they made the probe measurements ambiguous in some tests so that the photomultiplier measurements are thought to be the more reliable of the two. These are plotted in Fig. 6 for pressures of 0.5, 1.0 and 3.0 Torr.

In addition to measuring the ionization front velocity, the photomultiplier tubes were used to measure the shock velocity. This, of course, required a much slower sweep rate and a separate oscilloscope. All effects of the ionization caused by the microwave pulse had apparently vanished by the time the shock wave reached the fist photomultiplier approximately 200μsec after the pulse.

IV. RESULTS AND INTERPRETATION

Figure 6 shows the measured velocities of the ionization wave as a function of the input power flux, i.e., input power divided by the cross-sectional area of the shock tube. The velocity range in this case was limited on the low side by the length of the pulse and the separation of the phototubes to velocities greater than 5.5 x 10^7 cm/sec. On the high side it was limted by resolution of the data traces and nonuniformity of the microwave pulse. In Fig. 6, it is seen there is a large amount of scatter in the data. This is not surprising since it is a characteristic of breakdown experiments and in addition, with the available shock tube there were the usual difficulties controlling impurity levels and reproducing shock strengths within a few percent. Nevertheless, the data indicate the general behavior. As expected, the higher the power the faster the ionization front propagates. Also, within the pressure range used here the lower the pressure the higher the power needed to produce an ionization front moving at a given velocity. Note, however, that these pressures were below the minimum of the breakdown field versus pressure curves for Argon at this frequency, Fig. 7 and Ref. 13. Therefore, at the lower pressures a higher breakdown field could be expected. An attempt also was made to get data at a pressure of 10 Torr, but was generally unsuccessful because either the gas did not break down at all or, if the power level was raised sufficiently, it broke down in the tee section. These difficulties were probably due to the fact that a strong enough shock and hence a strong enough precursor could not be generated at this pressure.

Our interpretation of the ionization wave is that it represents microwave breakdown in the gas which has the appearance of a wave traveling from the shock front because the initial electron density is highest close to the shock. When the preionized gas in the precursor region is irradiated with microwave energy, the region of highest initial electron density will break down first and breakdown will proceed in a wave toward the microwave source. If $n_o(x)$ is the electron density at position x upon initiation of the microwave pulse and ν is the net production rate of free electrons in the gas in the microwave field, and if we assume that ν is independent of x, then we may say the electron density at x is given as

$$n(x,t)= n_o(x)e^{\nu\tau} \qquad (1)$$

where time t is measured from initiation of the pulse and is no greater than the pulse length. In time τ the electron density will reach a critical breakdown level n_c, so

$$n_c=n_o(x)e^{\nu t} \qquad (2)$$

Clearly the difference in times to achieve breakdown at the different stations and hence the measured velocity of the ionization front is an indication of the initial electron density profiles, i.e., precursor profile.

Consider, for example, an exponential precursor profile as found in Fig. 1 and Ref. 5,

$$n_o(x)=N_o e^{-\beta x} \qquad (3)$$

where β is a constant and consider two stations at x_1 and x_2. Then, from Eq. (2) we get

$$n_c=N_o e^{\nu\tau_1-\beta x_1}=N_o e^{\nu\tau_2-\beta x_2}$$

or

$$\nu\tau_1-\beta x_1 = \nu\tau_2-\beta x_2$$

so

$$\frac{\nu}{\beta} = \frac{x_2-x_1}{\tau_2-\tau_1} \qquad (4)$$

This is just the measured velocity of the ionization front. In this case the measured velocity determines the ratio of the net electron production rate to the decay rate of the precursor electron density and is independent of the position of the two monitoring stations with respect to the shock.

In general, it is expected that the precursor profile will not be a strict exponential[10]. Then we may write the precursor profile as

$$n_o(x) = N_o e^{-\beta f(x)} \tag{5}$$

so

$$\nu\tau_1 - \beta f(x_1) = \nu\tau_2 - \beta f(x_2)$$

or

$$\frac{\nu}{\beta} = \frac{f(x_2) - f(x_1)}{\tau_2 - \tau_1} \tag{6}$$

Then the measured velocity will depend on the position of the measuring stations with respect to the shock front as well as on the net electron production rate and decay rate in the precursor profile. An attempt was made to investigate this effect with the driven pressure at 3 Torr, and while there definitely was a dependence of measured ionization front velocity on position of the shock front, scatter in the data made it impossible to interpret it quantitatively in terms of finding f(x). It is suggested, however, that this may be a way of probing the precursor profile to lower electron densities than is possible by other means.

V. CONCLUSIONS

The experiments described here have shown that an ionization wave is produced when the precursor region associated with a strong shock in Argon is irradiated with microwaves of sufficient power density. This ionization front propagates very rapidly toward the microwave source and prevents the radiation from further heating of the gas behind it. The dependence of the ionization front velocity on the microwave power density has been investigated experimentally at several pressures and the results are given. These results and an interpretation of the phenomenon indicate that it is strongly dependent on the precursor electron density profile. The effect is important at very low electron densities and, in fact, it may offer a means of probing low density plasmas.

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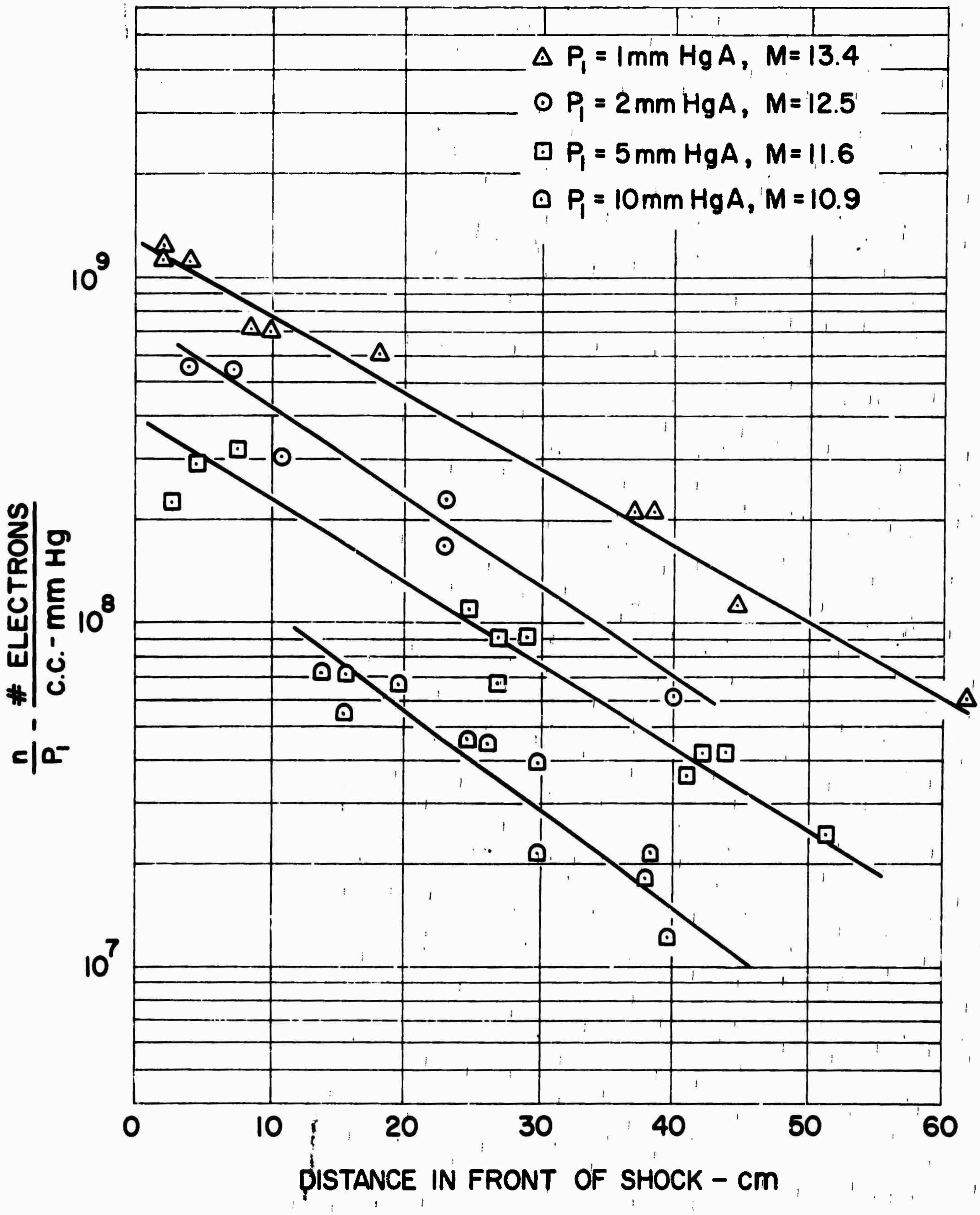


FIG. 1 NORMALIZED ELECTRON PRECURSOR NUMBER DENSITY AS A FUNCTION OF DISTANCE AS MEASURED BY MICROWAVE CAVITIES.

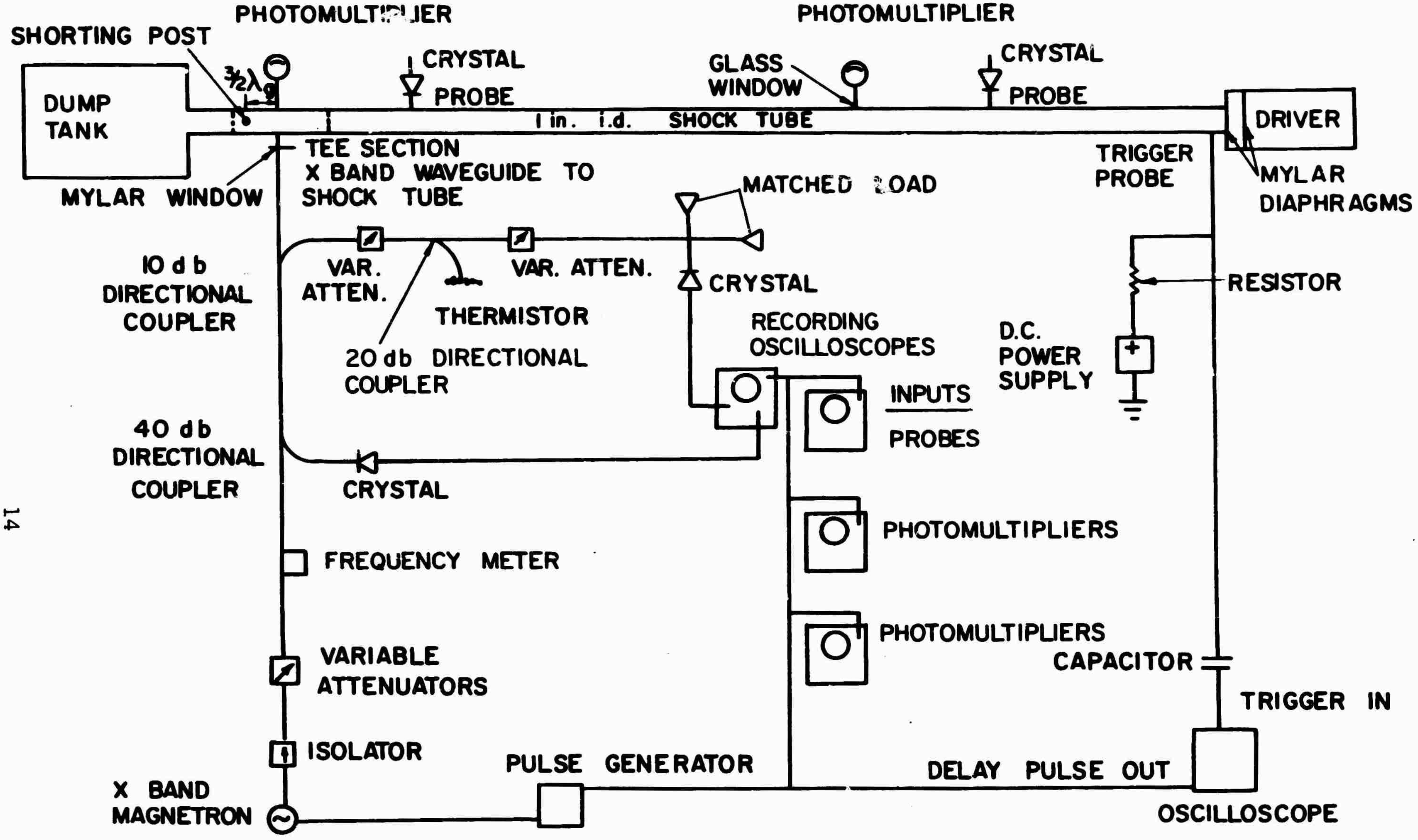
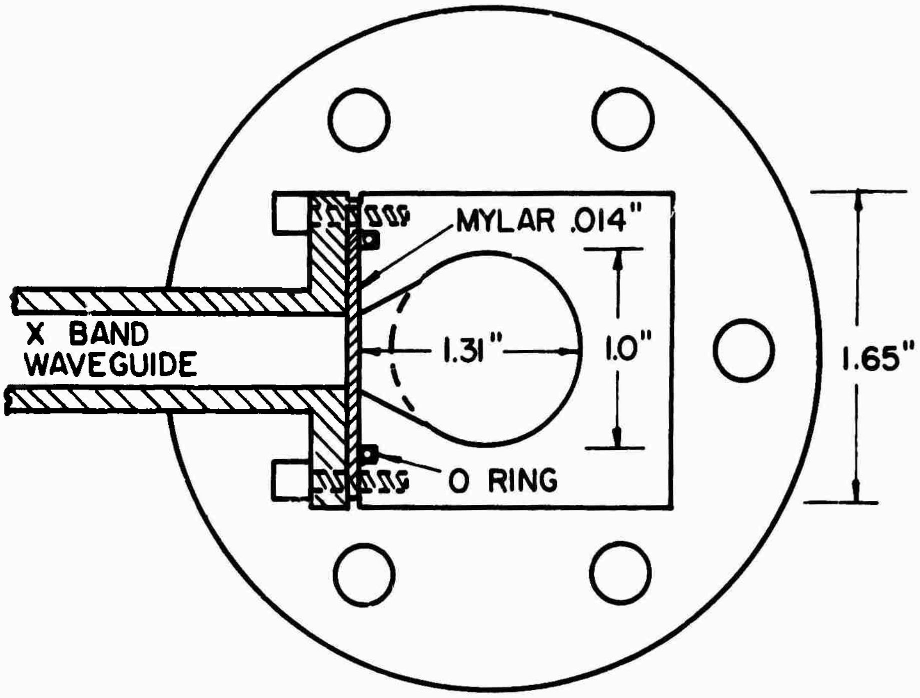
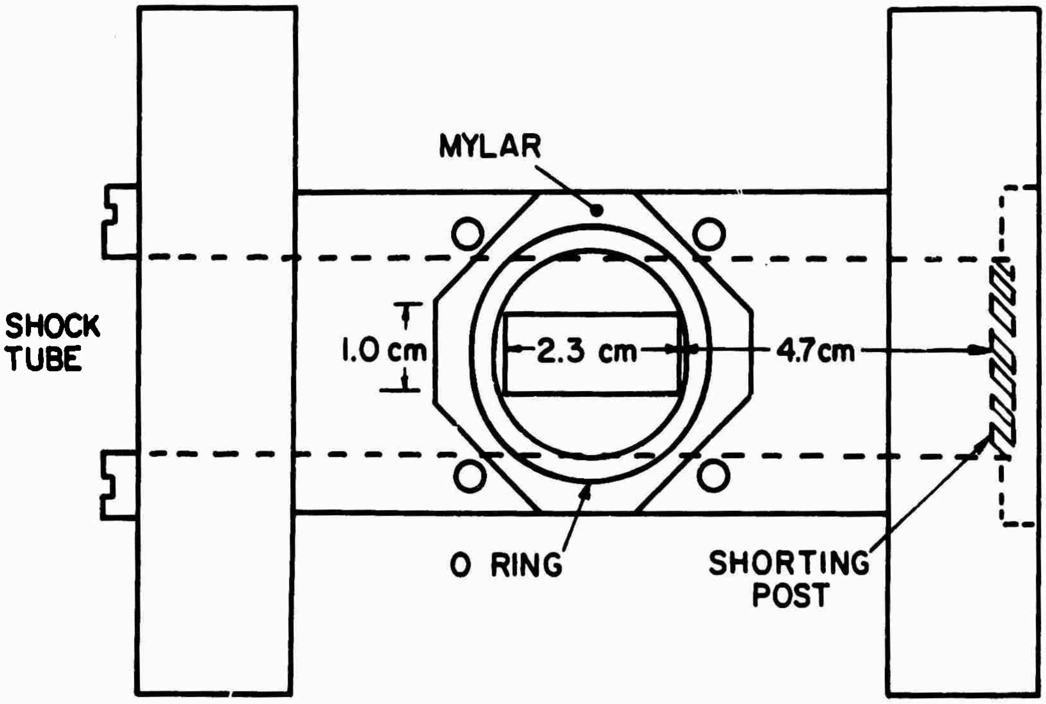


FIG. 2 SCHEMATIC OF SHOCK TUBE INSTRUMENTATION

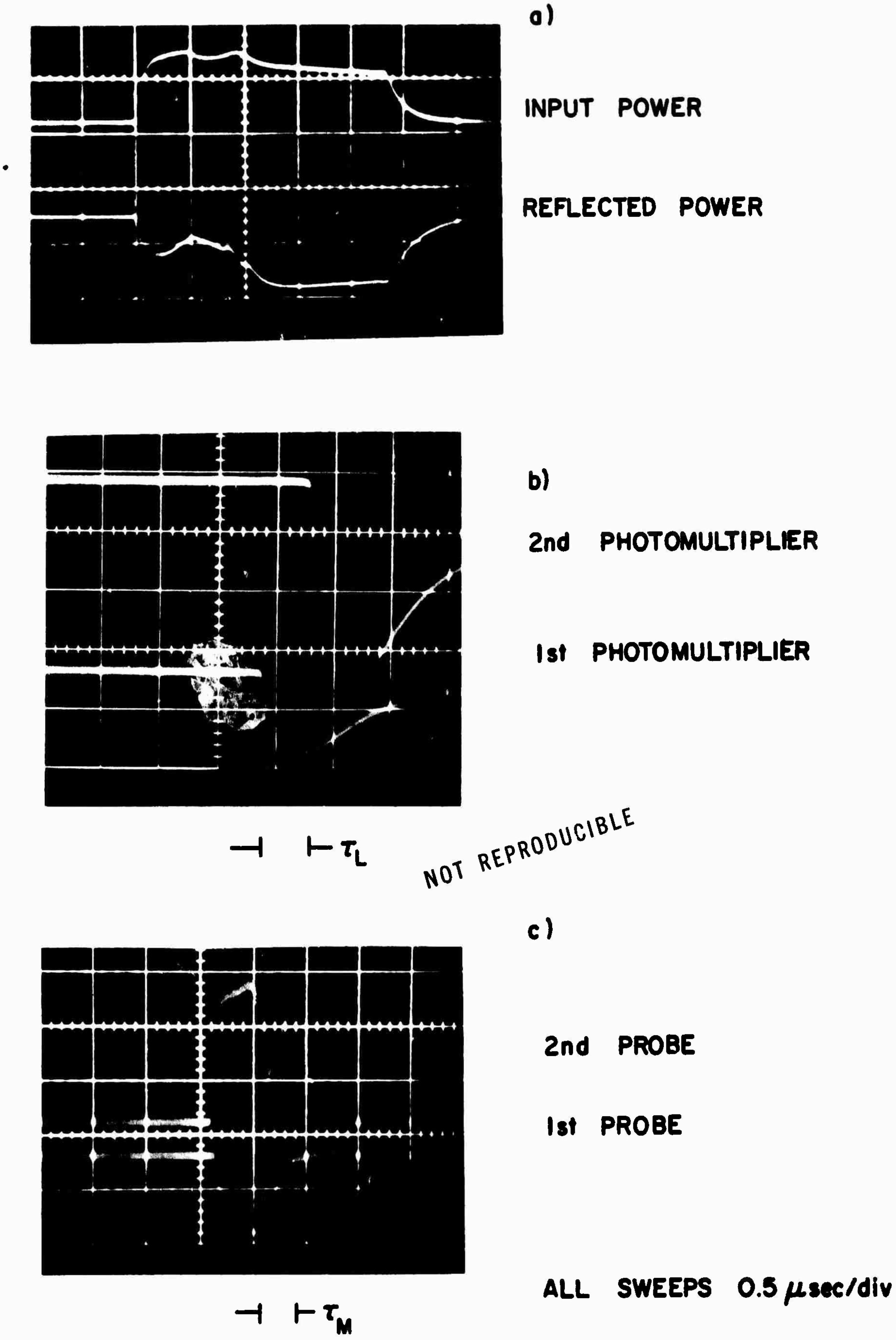


END VIEW



SIDE VIEW

FIG. 3 "TEE" SECTION COUPLING WAVEGUIDE TO SHOCK TUBE



ALL SWEEPS 0.5 μsec/div

FIG. 4 TYPICAL DATA TRACES

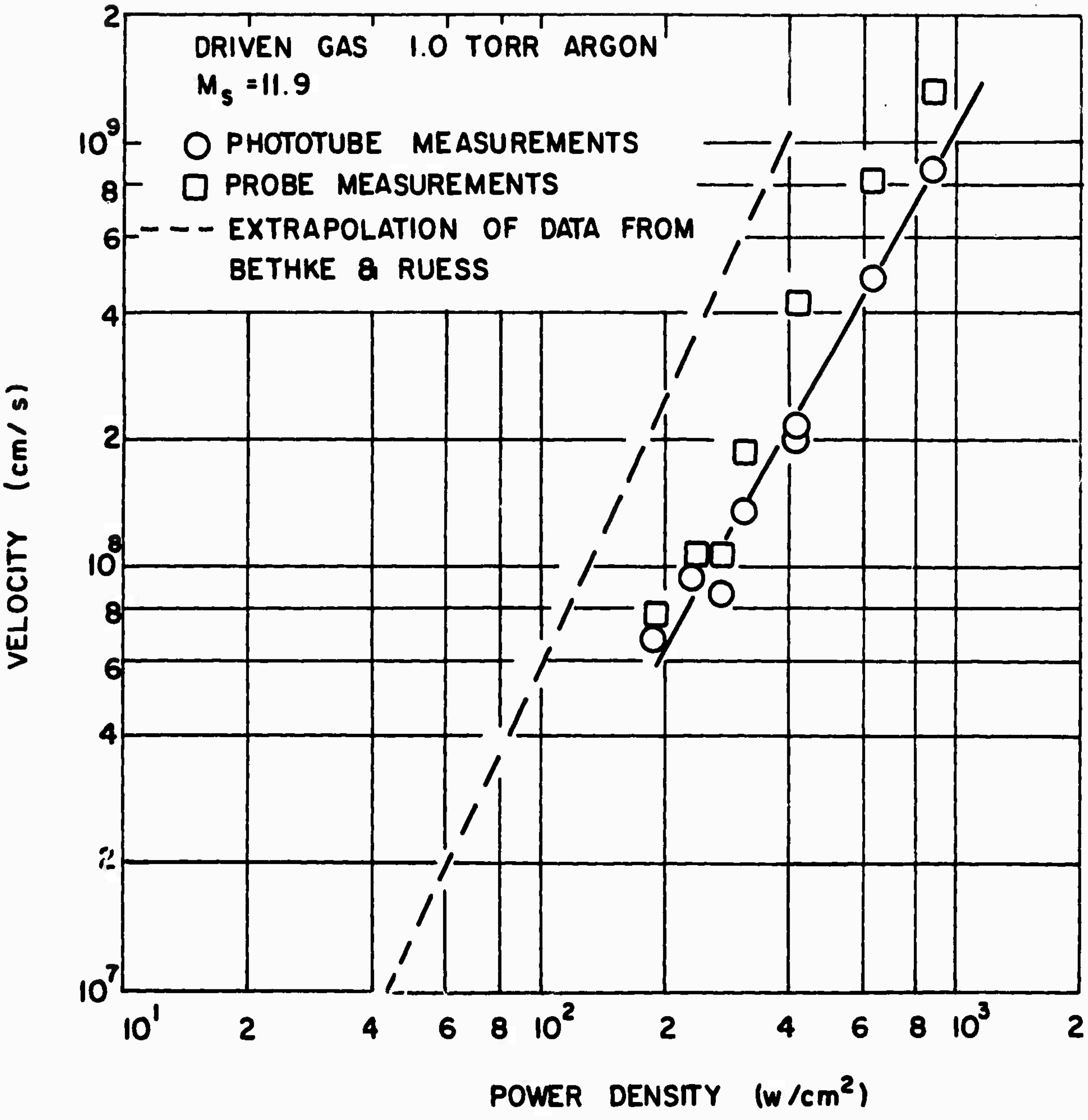


FIG. 5 COMPARISON OF MEASUREMENTS OF IONIZATION FRONT VELOCITY AS A FUNCTION OF INPUT POWER FLUX

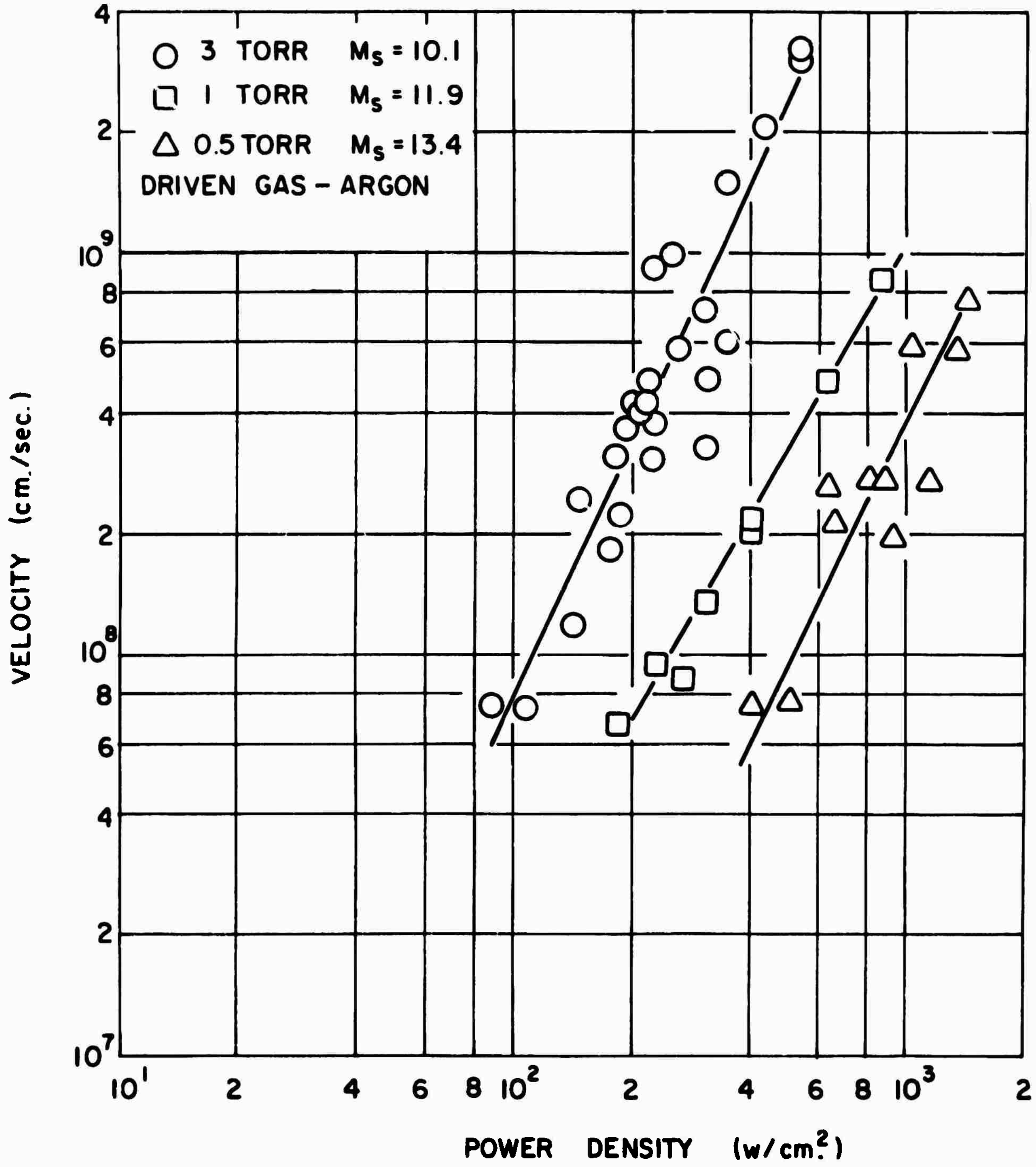


FIG. 6 IONIZATION FRONT VELOCITY AS A FUNCTION OF INPUT POWER FLUX