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ABSTRACT

A set of closely related devices for generating a highly ionized hydrogen plasma is described. In each device a hydrogen plasma is created in a cylindrical tube immersed in an axial magnetic field of from 4 to 20 kgauss. The plasma is formed by a switch-on ionizing wave, driven from an external capacitor bank. In a typical tube 14.6 cm in diameter and 86.4 cm long, with a magnetic field of 15 kG, an ion density of $>5 \times 10^{15}$ cm^{-3} is attained in hydrogen of initial atomic density 6.6×10^{15} cm^{-3}. The temperature of this plasma is between 10,000 and 30,000° K, and the plasma decays in several hundred microseconds by a volume-recombination process.

DEVICES FOR GENERATING HIGHLY IONIZED HYDROGEN PLASMA*

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INTRODUCTION

One of the problems encountered in the design of plasma physics experiments is that of producing a highly ionized plasma containing only minimal quantities of impurities. These two desired plasma properties—high degree of ionization and low impurity content—must generally be compromised because substantial quantities of energy are required to produce a highly ionized plasma. The dissipation of an appreciable fraction of that energy at electrodes and containing walls introduces impurities in objectionable amounts.

The purpose of this article is to describe several closely related devices capable of producing a hydrogen plasma with ion densities greater than 85% and with total impurity concentration less than 1%, respectively, of the initial neutral gas density. The following sections describe the plasma preparation in the basic device, the properties of the plasma produced, and the various modifications that have been applied to the basic device.

PLASMA PREPARATION IN THE BASIC DEVICE

The plasma is produced within an electrically conducting tube, 86.4 cm long and 14.6 cm in diameter, as shown in Fig. 1. The tube is placed in a uniform axial magnetic field of about 15 kgauss. One end of the tube is closed with a Pyrex plate in which is mounted a coaxial molybdenum electrode 5 cm long and 5 cm in diameter. The opposite end of the tube is also closed with a Pyrex plate. The introduction of a conducting screen at this end to improve plasma uniformity will be discussed later. Hydrogen gas is introduced to a pressure of 0.1 torr and flows continuously through the tube. The ionizing energy is supplied by a lumped-constant pulse line which has been charged to 10 kV. The pulse line is connected as shown in Fig. 1 through a series resistor R and an ignitron switch to the coaxial electrode. The ground side of the pulse line is connected to the tube.

When the high voltage is applied to the coaxial electrode a local electrical breakdown of the gas occurs and a radial current flows. This radial current, crossed with the axial magnetic field, exerts an azimuthal force on the plasma ($F_\theta = j_r \times B_z$), causing the plasma to rotate and thus develop a back emf which tends to reduce the radial current flow. A well-defined ionization front develops and proceeds axially through the tube. Magnetic-probe measurements have indicated that the width of the ionizing front (i.e., the transition region between a warm highly ionized rotating plasma and an essentially neutral gas) is a few centimeters. This process has been discussed in some detail by Kunkel and Gross.[1]

The progress of the ionizing front down the tube is observed with radial current detectors (Fig. 2). Each of these detectors is a 1/4-in.-diameter metal button mounted in a hole in the tube wall and insulated from the wall. A radial current passing from the plasma to the button is returned to the tube through coaxially mounted resistors, and the resulting resistive voltage drop is observed with an oscilloscope. When the ionizing wavefront reaches a radial current detector, we observe a sharply rising signal. The progress of the front down the tube as measured in this way is shown in Fig. 3. The velocity of the front, which in this case is 5 cm/μsec, can be changed by varying the ionizing-current, gas density and magnetic field. The front velocity increases with increasing magnetic field and with decreasing initial gas density.

If the ionizing current continues to flow after the wavefront has reached the far end of the tube, impurity lines characteristic of elements in the Pyrex plate are observed spectroscopically. Therefore the ionizing current is shorted out (crowbarred) with the ignitron switch shown in Fig. 1 just as the ionizing wave reaches the end of the tube. This short circuit stops the energy flow from the pulse line to the tube, and also stops the gross rotation of the plasma. Figure 4 shows oscilloscope traces of the voltage and current supplied to the plasma. In this case the crowbar was applied 20 μsec after the ionizing current began to flow. A reversed current associated with the braking of the plasma rotation can be clearly seen. This current oscillates with a period controlled by the inductance of the crowbar circuit.

PLASMA PROPERTIES

The properties of the plasma produced as described above have been deduced from Alfvén-wave-propagation experiments, spectroscopic observations, magnetic probe observations, and Kerr-cell and framing-camera photography. The details of these measurements are given elsewhere,[2-7] and are summarized here. The ion density as a function of time has been measured by observing the Stark broadening of the first three hydrogen Balmer lines. The results of these measurements are shown in Fig. 5. We may note that the ion density extrapolates to approximately 6 or 7×10^{15} ions/cm^3, which is very nearly the density of neutral atoms present before the gas is ionized. From the measurements of the attenuation of Alfvén waves it is possible to set a lower limit of about 10,000° K to the temperature of the decaying plasma soon after the short circuit is applied.

The electron temperature of the plasma has been estimated spectroscopically by observing the frequency dependence of the Balmer recombination continuum (which should be very nearly proportional to $e^{-h\nu/kT}$).

A carbon arc was used as a radiation standard. During most of the decay period, temperatures of about 20,000° K were observed; 100 μsec after breakdown the electron temperature as measured by this method was 21,000° K (+8000° K, -4000° K).

The close agreement between the shapes of the experimental Balmer-line profiles and those calculated by assuming a uniform plasma density indicates that the plasma is fairly homogeneous along a magnetic field line. Magnetic probes with a sensitivity of 1 gauss at a frequency of 1 Mc immersed in the plasma do not display noise signals from the decaying plasma, which suggests that the amount of magnetic turbulence in this frequency range is very small.

Kerr-cell photographs of the decaying plasma show a pattern of swirls developing over a period of approximately 10 μsec. These swirls, which extend throughout the tube length, may be formed when the rotating plasma is abruptly stopped by the application of the crowbar. A 1/4-in.-mesh steel screen mounted just inside the receiving end insulator prevented the development of these swirls.[7]

The amount of impurities present in the plasma was estimated by admitting a small amount of methane or carbon dioxide into the tube and observing with a monochromator the resulting increase in intensity of a carbon or an oxygen spectral line. The particle density of carbon or oxygen determined in this way is about 0.2%.

It may be noted from Refs. 3 and 4 that the decaying plasma is electrically isolated from its container, even though the conducting tube has a much higher conductivity than the plasma. For instance, in the Alfvén-wave experiments it was found that the radial boundary condition to be applied was appropriate for a thin vacuum layer separating plasma from the conducting wall. As observed experimentally, however, a high-density current flow from plasma to wall can maintain electrical contact between them.

MODIFIED DEVICES

To demonstrate the applicability of the ionizing technique described above to other geometrical conditions, the basic device has been modified in two different ways.

The first such device is shown in Fig. 6 and is similar to the basic device except that the diameter and length have been approximately halved and the conducting tube walls are changed to Pyrex for most of the tube length. As in the basic device, an initial discharge occurs at one end within the coaxial electrode structure and an ionizing front propagates down the tube through the glass portion to the opposite end. When the front reaches the Pyrex end plate the electrodes are short-circuited, thus stopping the plasma rotation. Kerr-cell photographs of the front made perpendicular to the tube axis give front arrival times which agree with a signal from a magnetic probe near the passive end of the tube.

Time-dependent ion-density measurements were made by using a polychromator (a device capable of simultaneous, time-resolved intensity measurements in a number of adjacent wavelength intervals)[8] to observe the Stark-broadened H_β and H_γ line profiles. By use of a 6-kgauss magnetic field and an 8600-amp ionizing current, ion densities approximating the initial neutral hydrogen atom density of 6.6×10^{15} cm^{-3} are produced.[9] Density measurements were made both parallel and perpendicular to the tube axis.

Figure 7 shows density measurements made perpendicular to the axis along a tube diameter at three longitudinal positions; times are measured after initial breakdown. From these data one notes that the maximum ion densities exceed the initial neutral gas density. For the 6-kgauss magnetic field the density falls after passage of the front and is not in general uniform along the tube. Thus measurements made parallel to the tube axis represent a composite of a longitudinally variable density. At crowbar time, 23 μsec, the ion density at the passive end is still rising while at the other two positions nearer the electrodes it is falling slowly. However, the ion density at this time is nearly equal to the initial neutral density throughout the entire tube, with the possible exception of the center electrode region.

Carbon and oxygen impurity levels were determined by intensity comparison of the 4649-Å O^+ and 4267-Å C^+ lines from the plasma with those obtained by introducing known amounts of CO_2 gas into the system before ionization. The impurity levels of carbon and oxygen observed in this manner are approximately 0.04% and 0.7% respectively.

The ion density and impurity levels indicate that a device of this modified type may have application as a preionizer in compression devices.

The second modified device, designed to determine the effects of the removal of the confining Pyrex walls to a larger radius, is identical with that shown in Fig. 6 except that the inside diameter of the Pyrex portion was increased from 3 in. to 6 in. The axial magnetic field was 16 kgauss and the electrode current was 8000 amp.

The presence of a conducting screen similar to that used to reduce swirling after crowbar in the basic device proves to be a critical factor in the operation of this device. Figure 8 is a typical pair of Kerr-cell photographs of the plasma in this modified device at approximately 80 μsec after initial breakdown. It is clear that the conducting screen prevents the spread of plasma beyond the radius of the outer coaxial electrode. Photographs taken from a somewhat different aspect confirm that the effects displayed in Fig. 8 are not surface phenomena but are distributed throughout the plasma volume.

Ion densities were determined by observation of Stark-broadened H_β line profiles. Densities greater than the initial neutral density of 6.6×10^{15} cm^{-3}

are present until about 50 μsec after the start of the discharge. This high density may be due to influx of neutrals from the region between the plasma and the outside wall, resulting in ionization and trapping.

Temperature measurements have not been made in the modified devices, although they are not expected to differ substantially from those observed in the basic device when comparable magnetic fields are used.

FOOTNOTES AND REFERENCES

* This work was performed under the auspices of the U.S. Atomic Energy Commission.

† On leave at the Royal Institute of Technology, Stockholm, Sweden.

‡ 1st Lt., U.S. Air Force. The opinions expressed by the Air Force author are his own and do not necessarily reflect those of the United States Air Force or of the Department of Defense.

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9. When the field was reduced to 4 kgauss, with 4300 amp ionizing current the maximum ionization was about 45%. Doubling the ionizing current increased the ionization to approximately 50%, in qualitative agreement with the predictions by Kunkel and Gross (Ref. 1).

FIGURE CAPTIONS

Fig. 1. Device geometry.

Fig. 2. Geometry of the radial current probe. The 1/4-in.-diameter button is connected to the adjacent wall through six parallel 5-ohm resistors. The maximum voltage drop is less than 1 volt.

Fig. 3. Position of the ionizing front vs time, as measured with radial current probes.

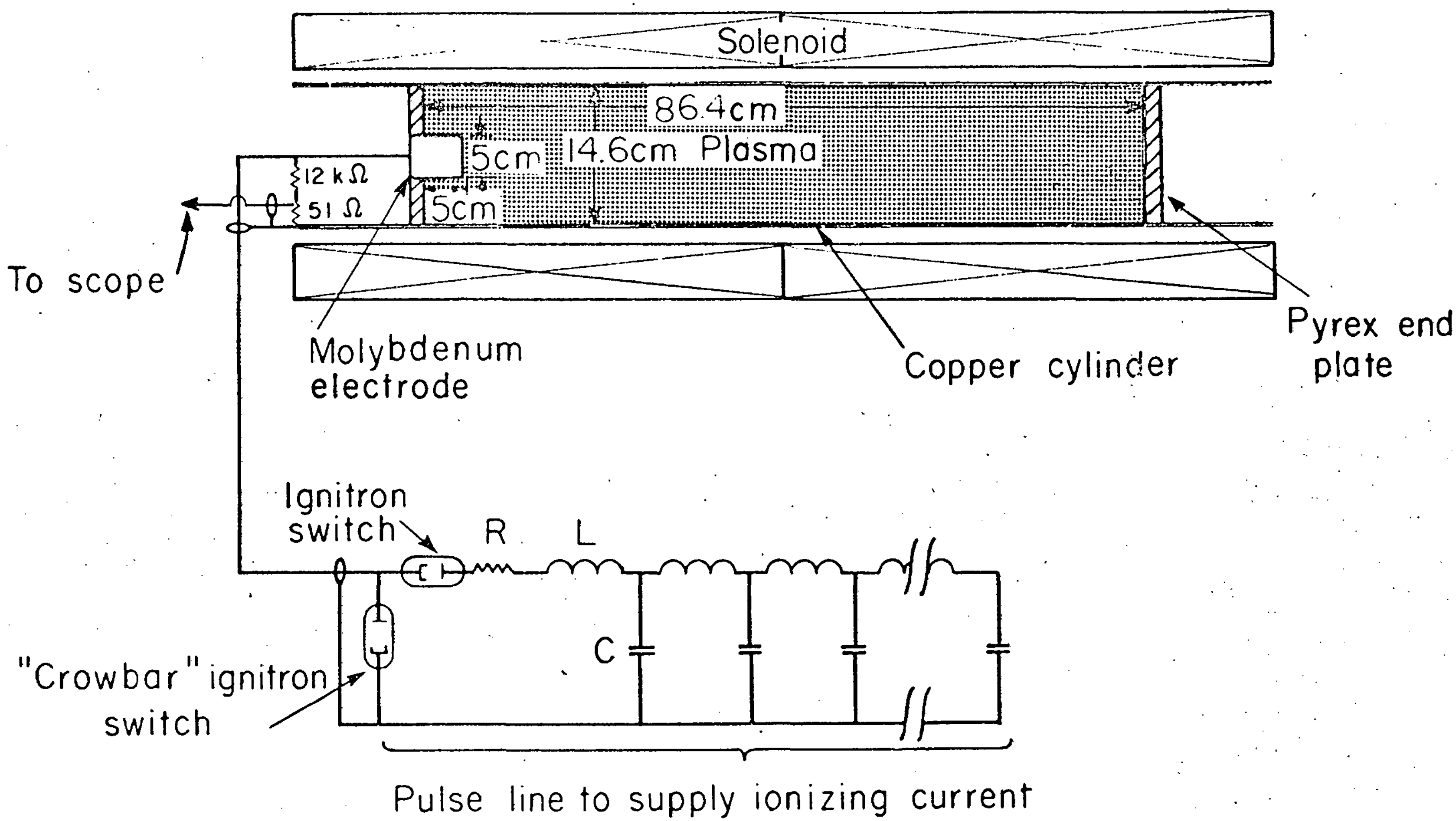
Fig. 4. Oscilloscope traces, showing ionizing conditions. The top trace is voltage on the driving coaxial electrode at 2400 volts/cm and the bottom trace is current from the pulse line at 10^4 amp/cm. The horizontal scale is 10 μsec/cm. The current was crowbarred 22 μsec after the voltage was first applied.

Fig. 5. The observed time dependence of the ion density. Errors (not shown) in the experimental points are estimated to be $\pm 1.0 \times 10^{15}$ cm^{-3} late in the decay period. Solid line: least-squares fit, decay rate assumed proportional to the square of the ion density; dashed line: exponential decay assumed.

Fig. 6. Geometry of the first modified device.

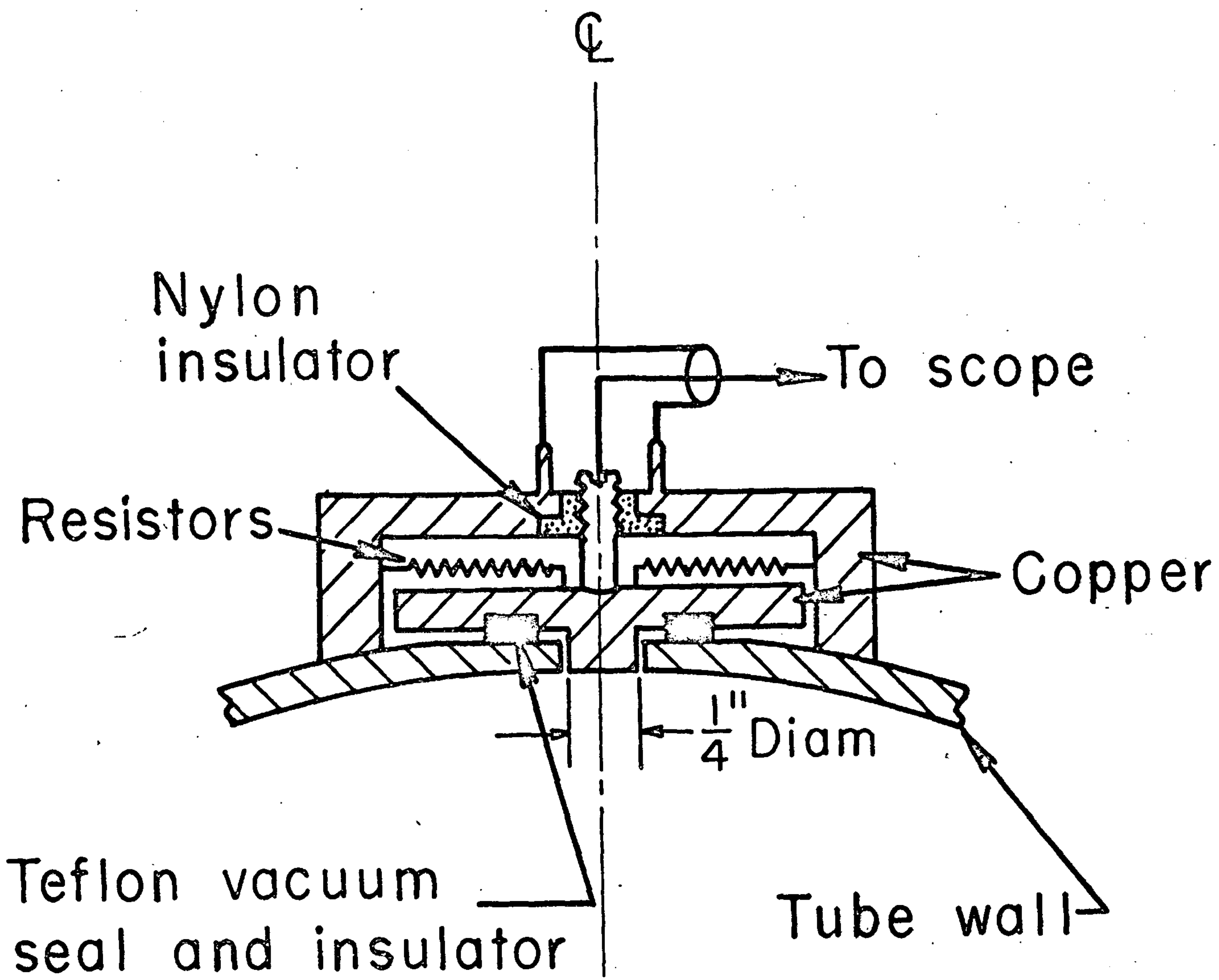
Fig. 7. Time-dependent ion density in the first modified device. Viewing direction is perpendicular to the tube axis.

Fig. 8. Kerr-cell photographs of the second modified device taken along the tube axis, (a) without and (b) with screen wire at end of tube.



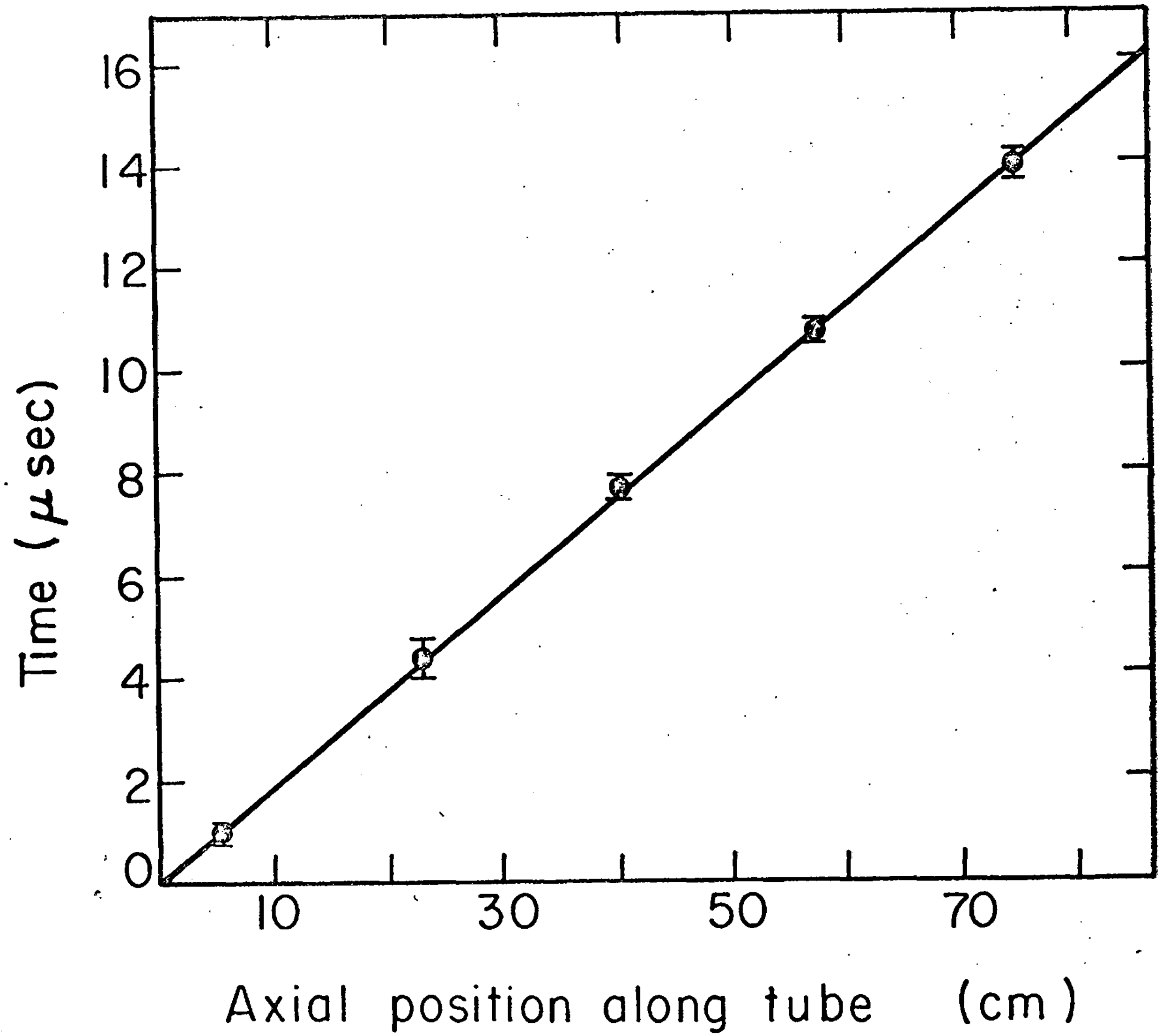
MU-22165-A

Fig. 1



MU-20358

Fig. 2



MU-20359

Fig. 3

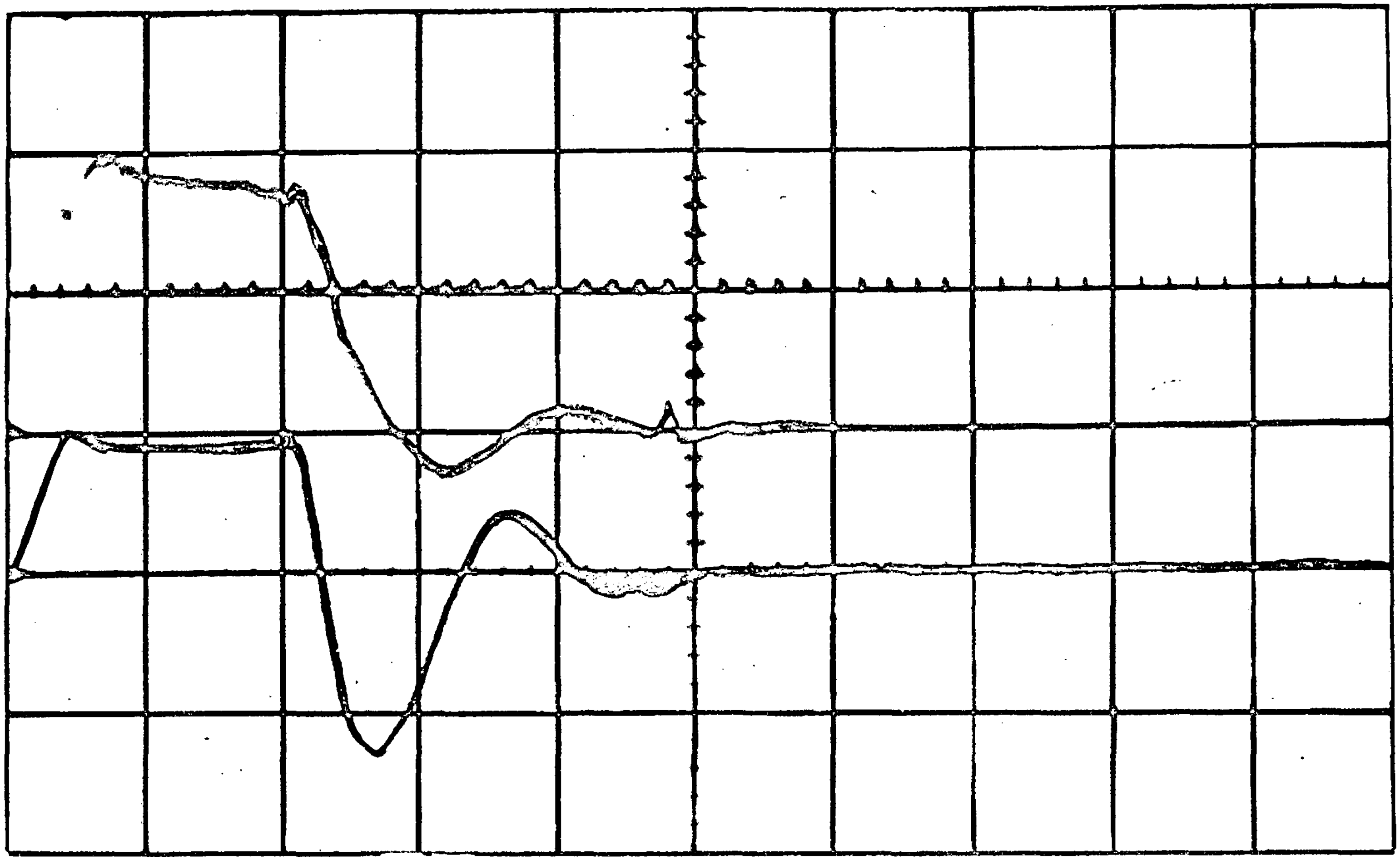
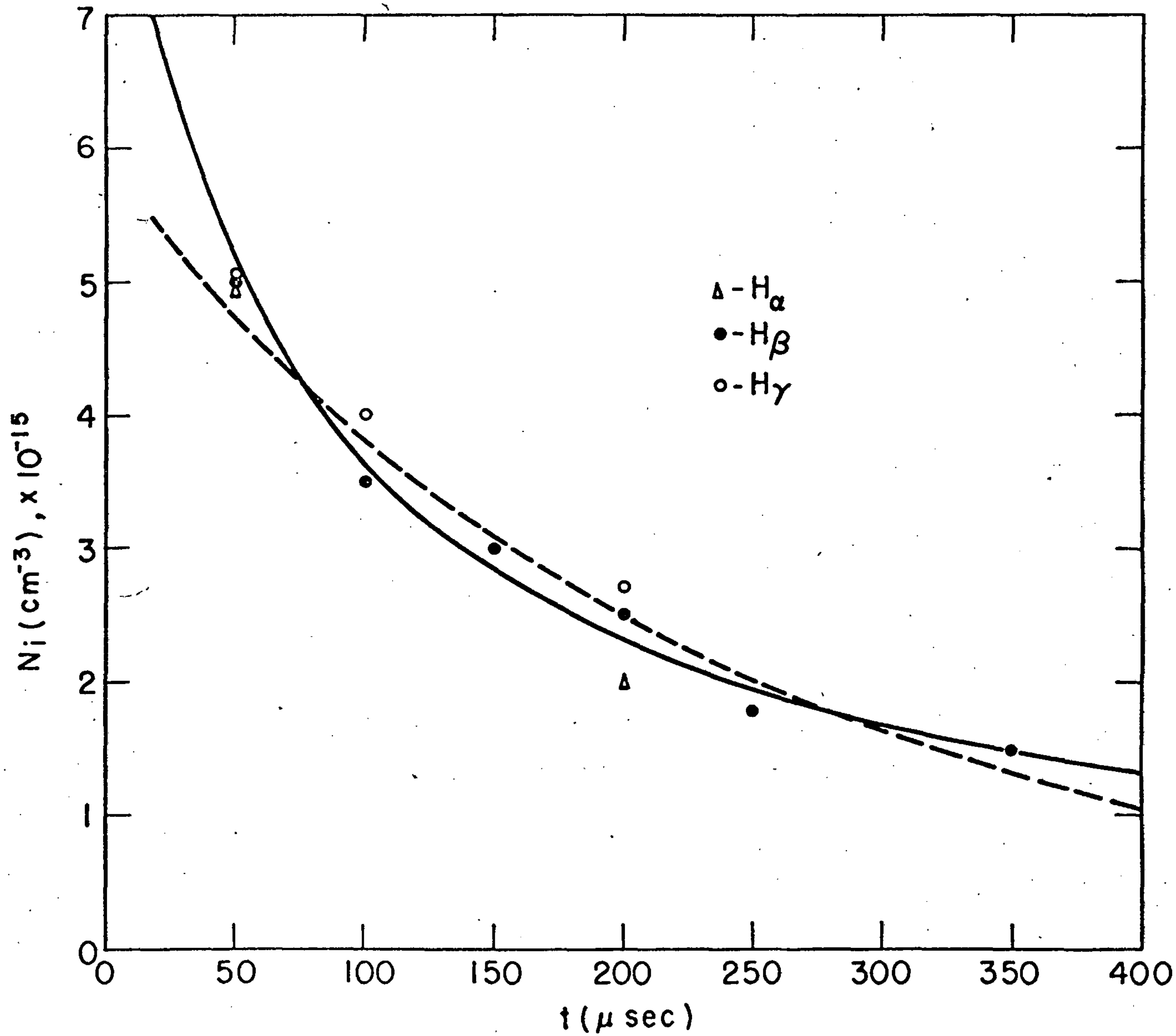
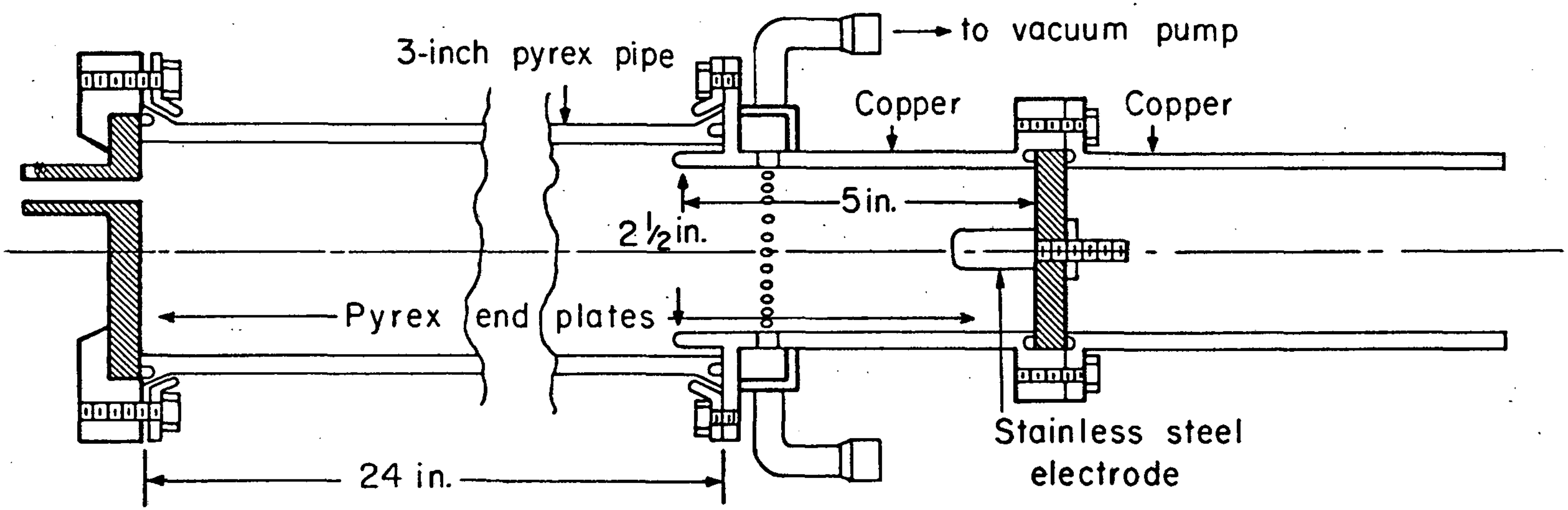


Fig. 4



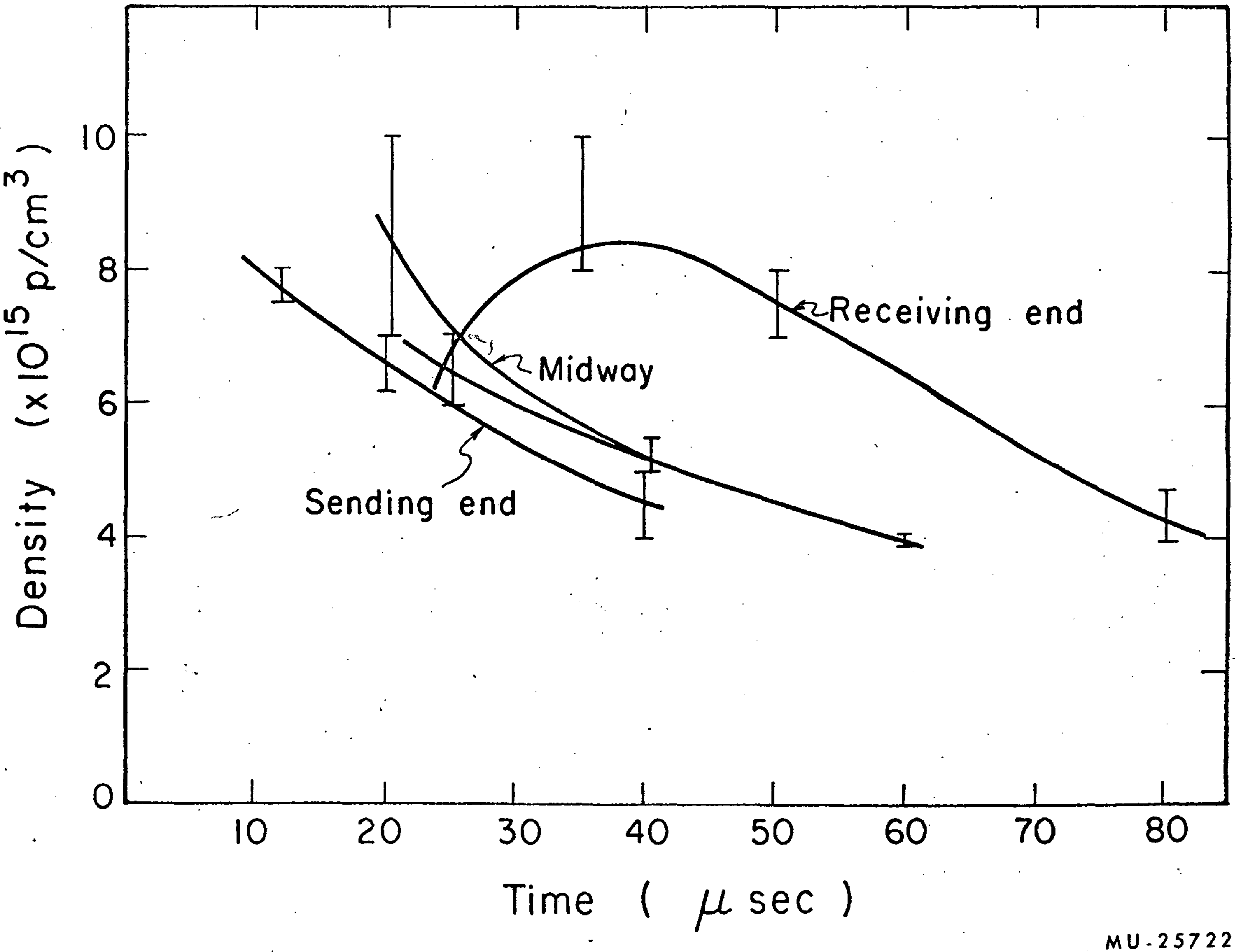
MU-22430

Fig. 5



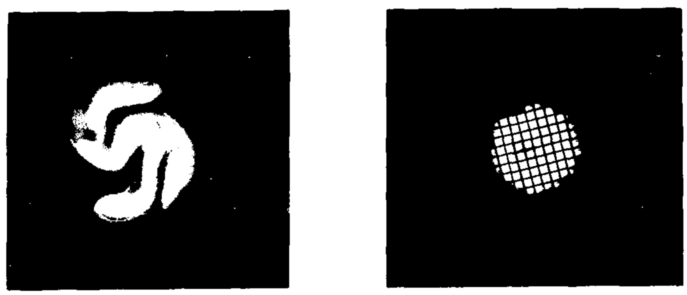
3-inch pyrex pipe
to vacuum pump
Copper
Copper
5 in.
2½ in.
Pyrex end plates
Stainless steel electrode
24 in.
MU-25694

Fig. 6



Density (x 10^15 p/cm^3)
10
8
6
4
2
0
10
20
30
40
50
60
70
80
Time (μ sec)
Receiving end
Midway
Sending end
MU-25722

Fig. 7



a b

Fig. 8.