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Controlled Thermonuclear Processes

THE EFFECT OF A PRESSURE GRADIENT ON A MAGNETICALLY COLLIMATED ARC

R. V. Neidigh

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THE EFFECT OF A PRESSURE GRADIENT ON A MAGNETICALLY COLLIMATED ARC

Rodger V. Neidigh

Charles H. Weaver, Consultant
University of Tennessee

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The purpose of this report is to describe the experimental observations associated with an unusual gaseous discharge phenomenon. This phenomenon was first observed in connection with a study of possible mechanisms for the transport of plasma ions and electrons across a magnetic field.

A simplified schematic diagram of the apparatus used is shown in Figure 1. The magnetic field is uniform and can be varied between 0 and 8000 gauss. The end plates are either metal or carbon and are at ground potential, as is the vacuum chamber. All other potentials are measured with respect to ground. The pressure gradient along the arc is obtained by feeding the gas directly into the defining slot, while the lower side of the vacuum chamber is open to a 20-in. oil diffusion pump. In these experiments, H, D, N, Ne, A, Kr, and Xe were all used as feed gases; no significant differences were observed under the conditions being investigated. The only potential applied is the negative bias to the heated cathode; the bias is usually about -150 volts. The insulated electrode at the other end of the arc floats at a negative potential which varies according to the conditions of the experiments.

MODE I vs MODE II

The usual operation of the arc is characterized by nearly uniform pressure along the length of the arc column. With a pressure of 10^{-3} mm Hg in the region where gas is fed into the defining slot and a pressure greater than about 10^{-4} mm Hg beyond the defining slot, the arc column is sharply defined and much brighter than the plasma surrounding it (Figure 2, upper). Ionization in the plasma surrounding the central arc is 1 per cent or less;

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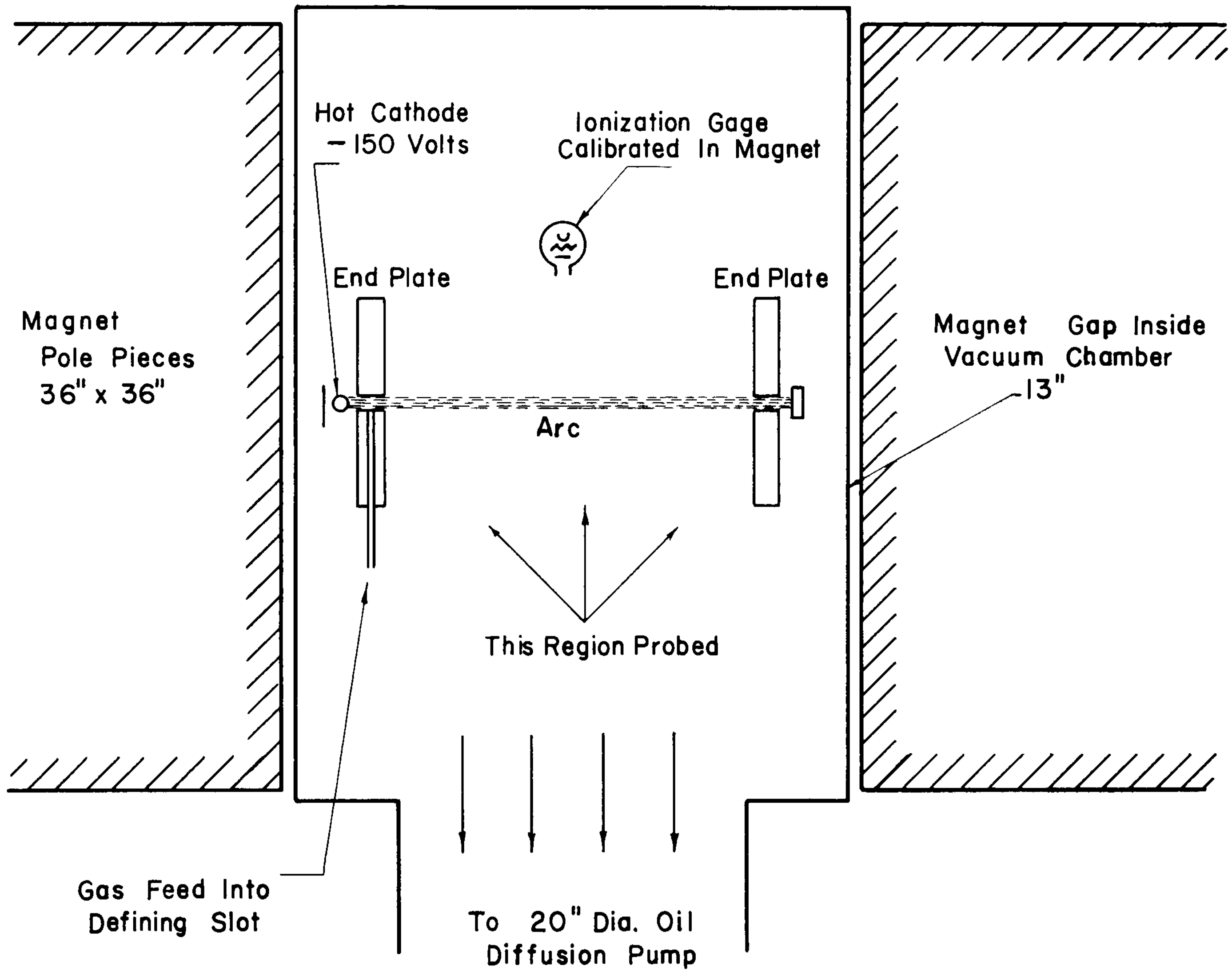

Fig. 1. Schematic diagram of the apparatus.

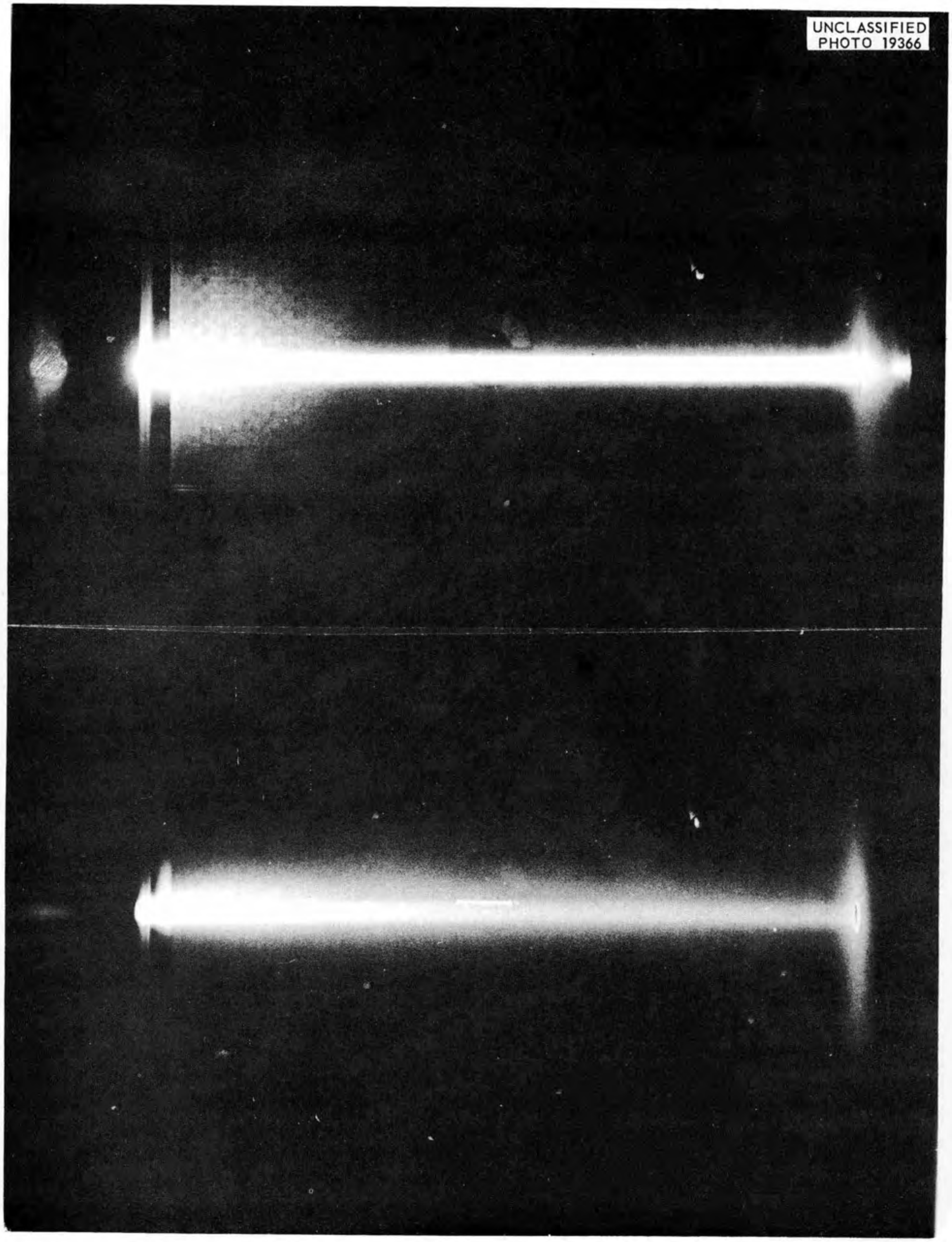

Fig. 2. The upper photo is the normal arc without a pressure gradient along its length. The lower photo is the corresponding arc with the pressure gradient. All other parameters are the same.

ion diffusion out from the arc is by collisions between ions and neutral particles and is random. This condition is identified as Mode I. Ion diffusion outward from this arc has been analyzed previously, ORNL reports 1890, 1960, and 2024.

The phenomenon described in this report occurs only when there is a pronounced pressure gradient along the arc column. With the same gas-feed rate and an increased pumping speed, the pressure in the vacuum chamber can be lowered to less than 5×10^{-5} mm Hg. At a pressure of about 10^{-4} mm Hg, the appearance of the arc changes discontinuously. The central arc column becomes diffuse and nearly as dim as the surrounding plasma, which has suddenly become brighter (Figure 2, lower). The arc column is still bright near the defining slot to which gas is admitted, however. This type of operation, called Mode II, is described in this report.

Additional contrast between Mode I and Mode II is shown in the graph of the cold-cathode potentials (Figure 3). In Mode II, the high-energy tail of the electron distribution is considerably higher than in Mode I. Since the cold cathode is insulated, $n_+ = n_-$, equal numbers of positive and negative particles strike it. But in Mode II, n_+ and n_- are each nearly zero, as compared with Mode I where they impinge upon the cold cathode to such an extent that it shows an excessive wear pattern. In Mode I, a tantalum cold cathode which is insulated thermally as well as electrically is heated to nearly electron-emission temperature by ion bombardment. No such heating occurs in Mode II. The energy (in excess of 100 watts) must now be going into the surrounding plasma and then to the cold-cathode end plate. The outgassing and sputtering of this end plate, which will be discussed in another section, supports this conclusion.

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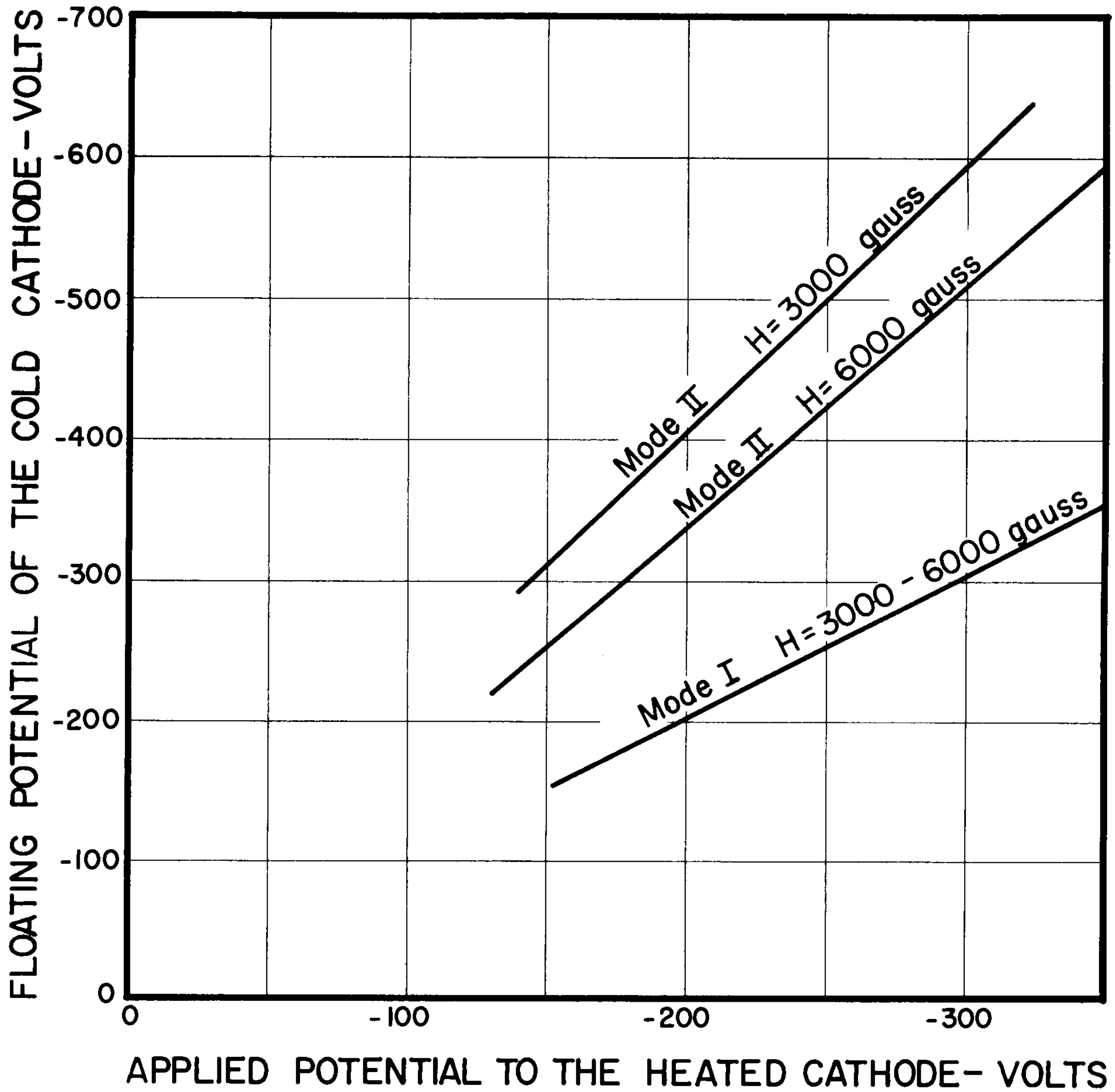

Fig. 3. The floating potential of the cold cathode with respect to the negative bias on the hot cathode. Note the difference between Mode II and Mode I.

There is visual evidence of excessive drain to the edge of the defining slot in Mode II. A bright ring of incandescent graphite particles appears, whereas no such ring appears in Mode I (see Figure 2). It has not been possible to measure this current directly because of the interference of the primary electron beam. Metered concentric rings around the defining slot indicate, however, that this is electron drain.

An indication of the minimum energy of the most energetic ions is their sputtering ability. The material of the plate at the cold-cathode end is sputtered away by the ions which are formed in the central arc column. If the plate is made of copper and is water-cooled so that sublimation by heating is negligible, the copper is sputtered away at the rate of 0.001 in. an hour over the area of the glow. At least 100-ev ions are required for this rate of sputtering. No quantitative measurement of the energy can be made since the angle of incidence is variable. No sputtering occurs at the hot-cathode end plate.

An obstacle placed in the discharge near the cold-cathode end plate casts a shadow on the sputtered region of the end plate. Figure 4 shows the result of such an experiment. Note the radial and azimuthal displacement of the shadow with respect to the obstacle. Shadow experiments were quite sensitive to "exposure" time; ions with large angles of incidence tended to remove the shadow when the experiment was overexposed. Analysis of this shadow experiment indicates that the radial component and the z-wise component of the ion energies were about equal and that their orbits pass through the arc column.

It was possible to adjust the magnetic field so that the field strength at the anode end was twice that at the cathode. This 2:1 ratio reflected

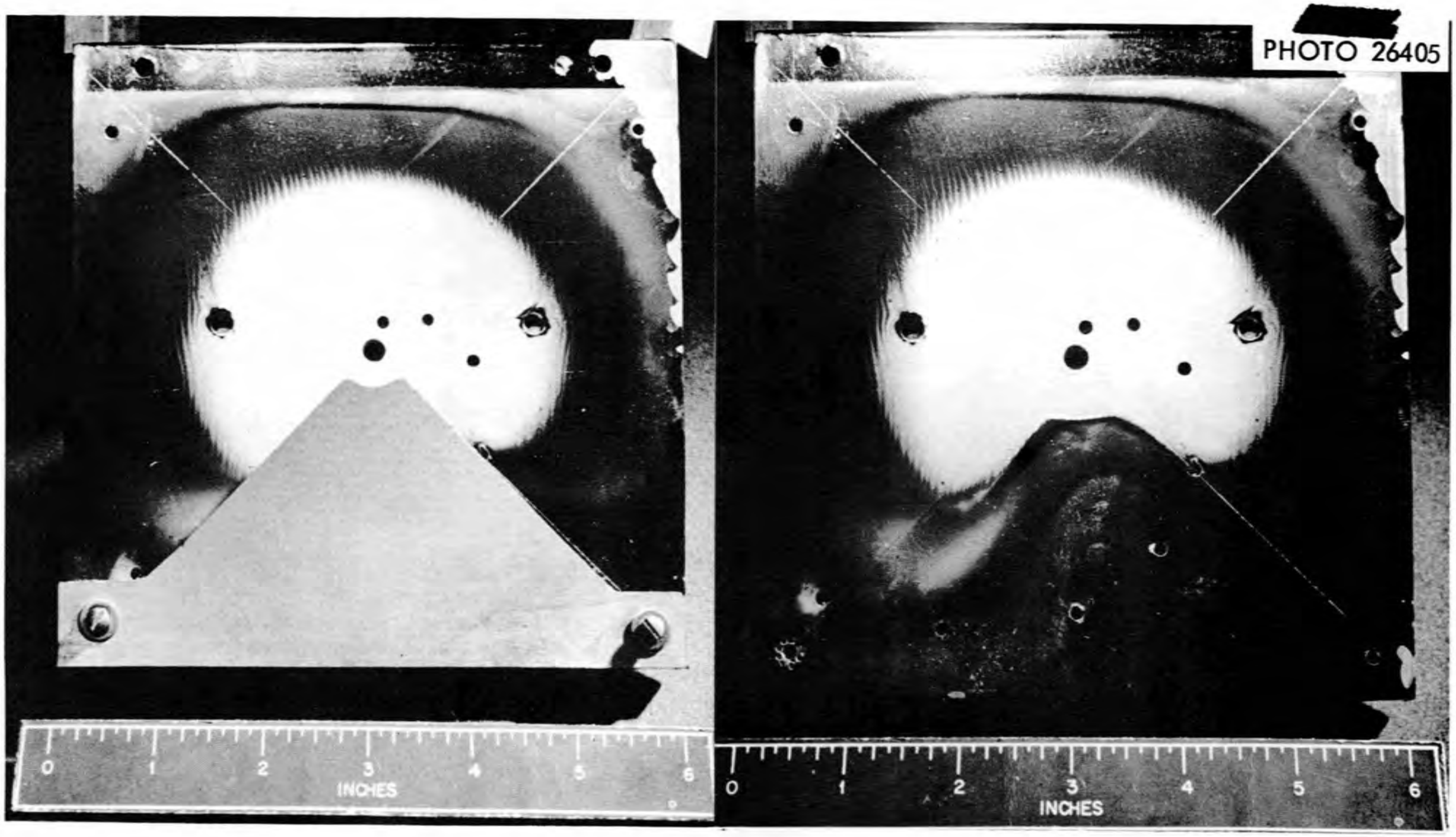

Fig. 4. Cold cathode end plate with the obstacle in place (left), and with the obstacle removed (right). Note the azimuthal displacement of the shadow with respect to the obstacle.

approximately 50 per cent of the ions, and the hot-cathode end plate was sputtered in a ring pattern. The diameter of the ring indicates it was sputtered by ions of about 300 ev energy.

The potential of an electrically insulated probe placed in the plasma surrounding the arc was used as a reference, and current measurements to a biased probe were used to locate the regions of maximum ion or electron density with respect to the reference probe. The regions of maximum ion and electron density are indicated on the oscilloscope trace of the floating-probe potential (Figure 5). Maximum ion current to a negative probe occurs at the bottom of the potential drop and the beginning of the flat portion of the floating probe potential. The most energetic ions are at the positive peak of the floating-probe potential curve as indicated by a positively biased probe. Most of the ion current is neutralized by the electron current peak to the positive probe, but the probe records an ion current just before the avalanche of electrons to it. This type of measurement not only indicates the existence of the energetic ions, but establishes the fact that they are present before the electron breakdown and probably give rise to it.

For all feed gases used, some ions emerging from the central arc column possess energy considerably in excess of the floating cold-cathode potential, i.e., greater than 400 ev. Singly-charged positive ions emerging from the arc were collimated and magnetically analyzed. The radial component of the energy of the ions collected was 400-500 ev. The peak current to the collector in the channel in the magnetic analyzer was 30 times background. A schematic diagram of the apparatus, with the magnetic analyzer in place, is shown in Figure 6. Figure 7 is a photograph of the apparatus. For

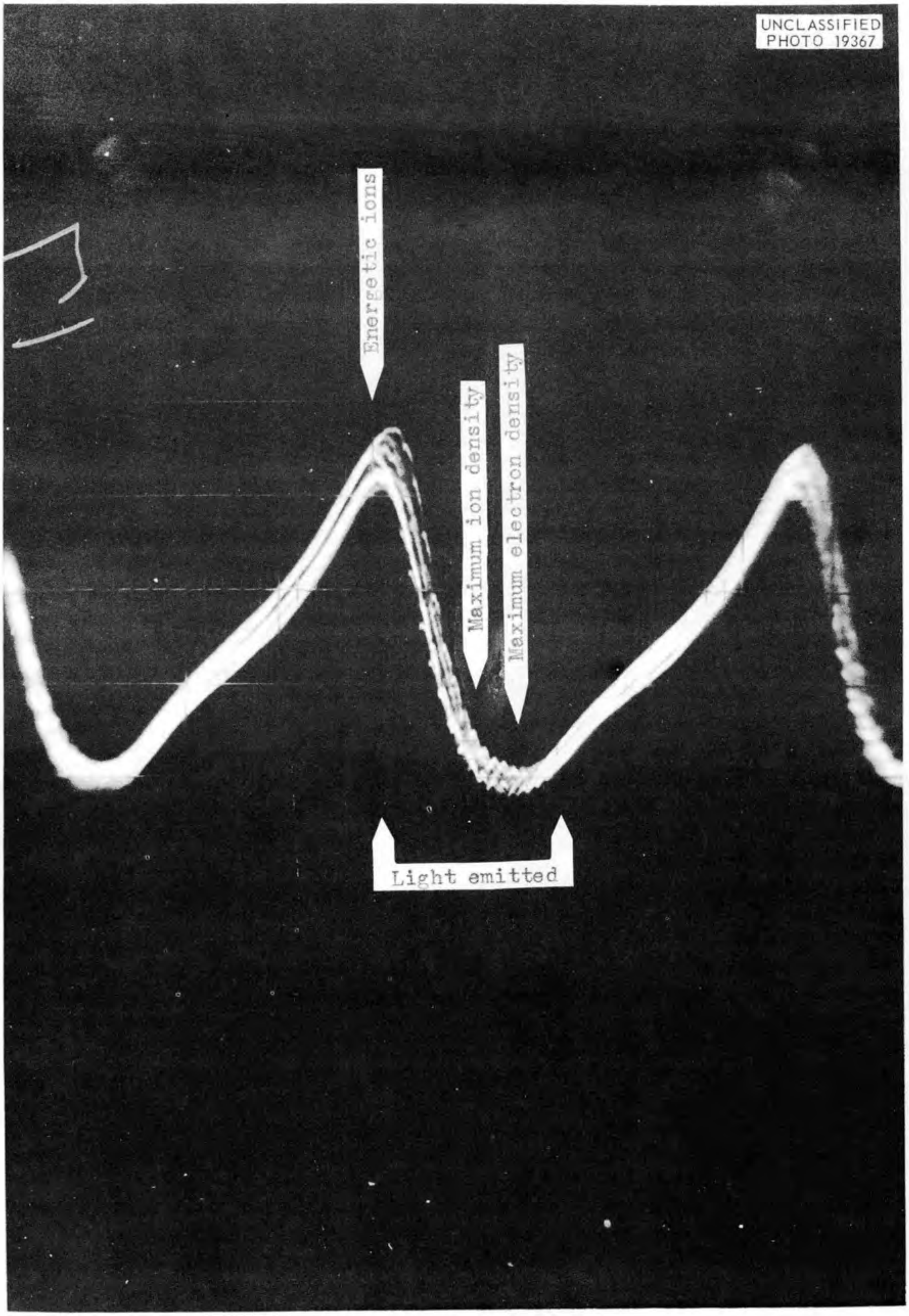

Fig. 5. The floating-probe potential as a function of time. This is a photo of several oscilloscope traces superimposed by triggering the oscilloscope at a given probe potential. Time is from left to right. The period of the fundamental component of the signal is 40 microseconds and represents one revolution of the plasma potential. The peak-to-peak potential is about 70 volts in this case. Current measurements to biased probes located ions and electrons in positions shown. Light emitted was observed with a photo-multiplier.

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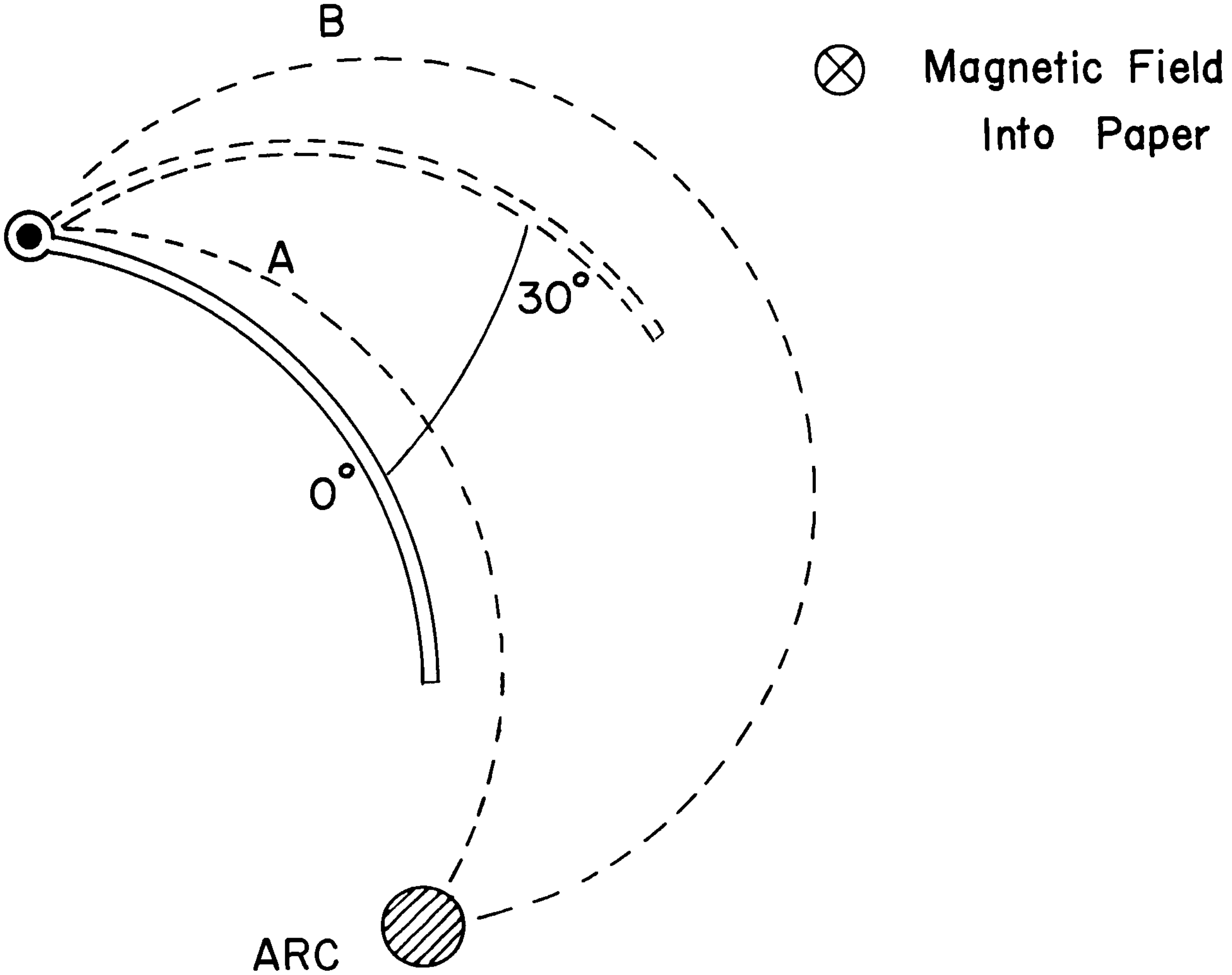

Fig. 6. Schematic diagram of the magnetic analyzer. Note that collection of mono-energetic ions from the arc is possible in two positions, A and B. The ion collector was moved from 0° to 30°. A typical plot of collected current is shown in Fig. 8.

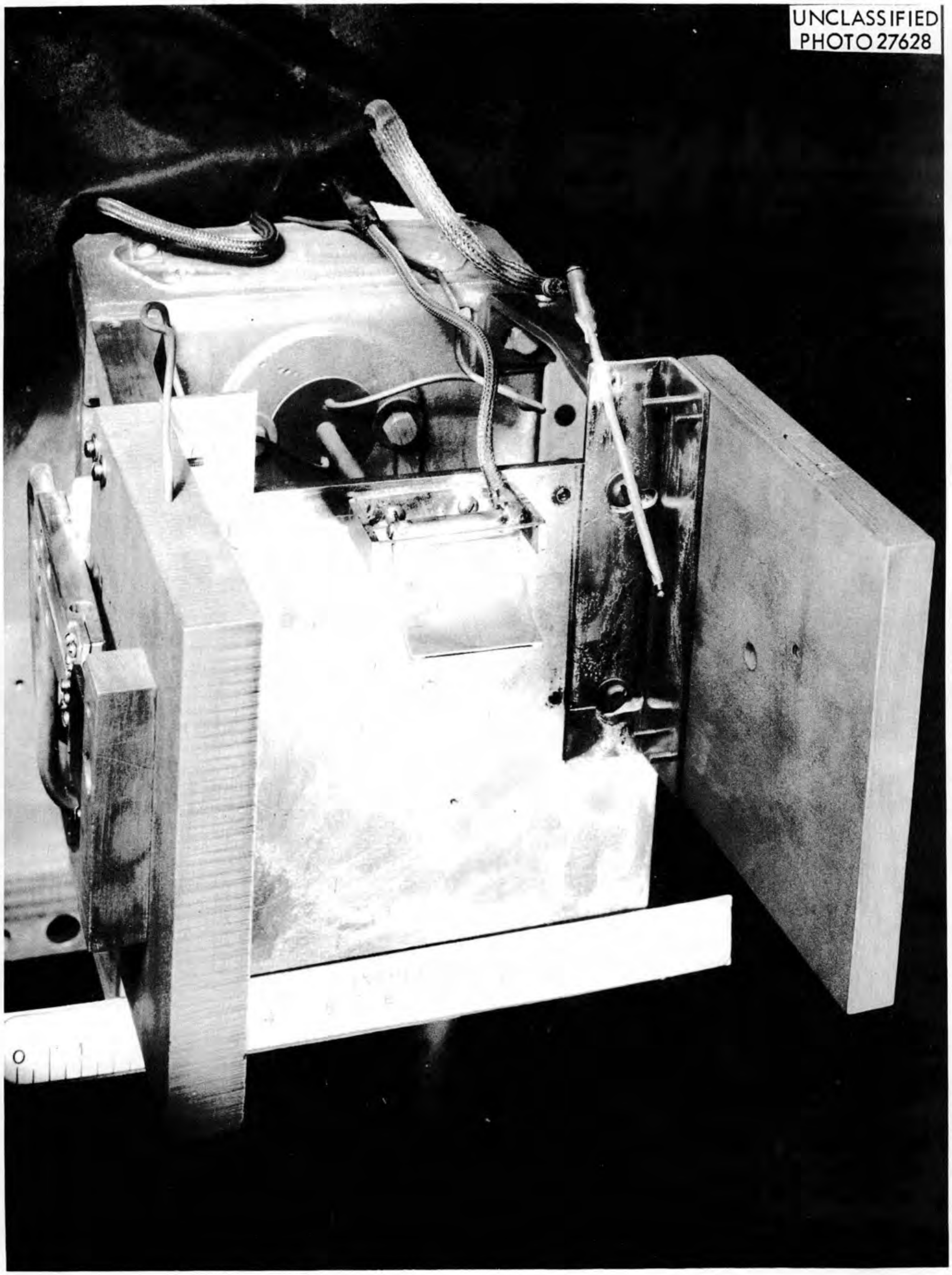

Fig. 7. The magnetic analyzer in place between the end plates.

argon ions in a magnetic field of 5000 gauss, the current to the collector, as a function of the collector position, is shown in Figure 8.

This is a conclusive piece of evidence. Ions whose radial component of energy is less than 400 ev would be lost on the walls of the magnetic channel. Also, no ions get to the collector by an ExH drift since no E can exist in the channel. The z-wise length of the channel limits the collection to ions with at least 50 per cent of their energy directed perpendicular to the magnetic field.

The percentage of the total number of ions which possess energy in excess of 400 ev can be only roughly estimated. The magnetic channel will accept only ions whose radial component is of the prescribed energy (400 ev in this case). If all the ions have approximately the same energy, but random directions, between z and radial, the aperture of the magnetic channel is considerably smaller than the area of its entrance slit. The current to the collector inside the magnetic channel integrated over the cylindrical surface of which the collector is a part is of the order of 20 ma. The total current to the cold-cathode end plate is approximately 200 ma. An estimate from the sputtering observations presented in the next section was approximately 50 per cent, and probably the more realistic of the two approximations.

Probe coils were inserted in the plasma for measurement of a change in magnetic field strength due to the circulating current. A complete analysis of the probe coil circuit was made to insure that it was giving evidence of a real effect. The maximum change in field strength observed was 0.1 gauss. This corresponds to a circulating current of more than 100 ma. Again the ion paths are not accurately known. Similarly the energy of the ion which

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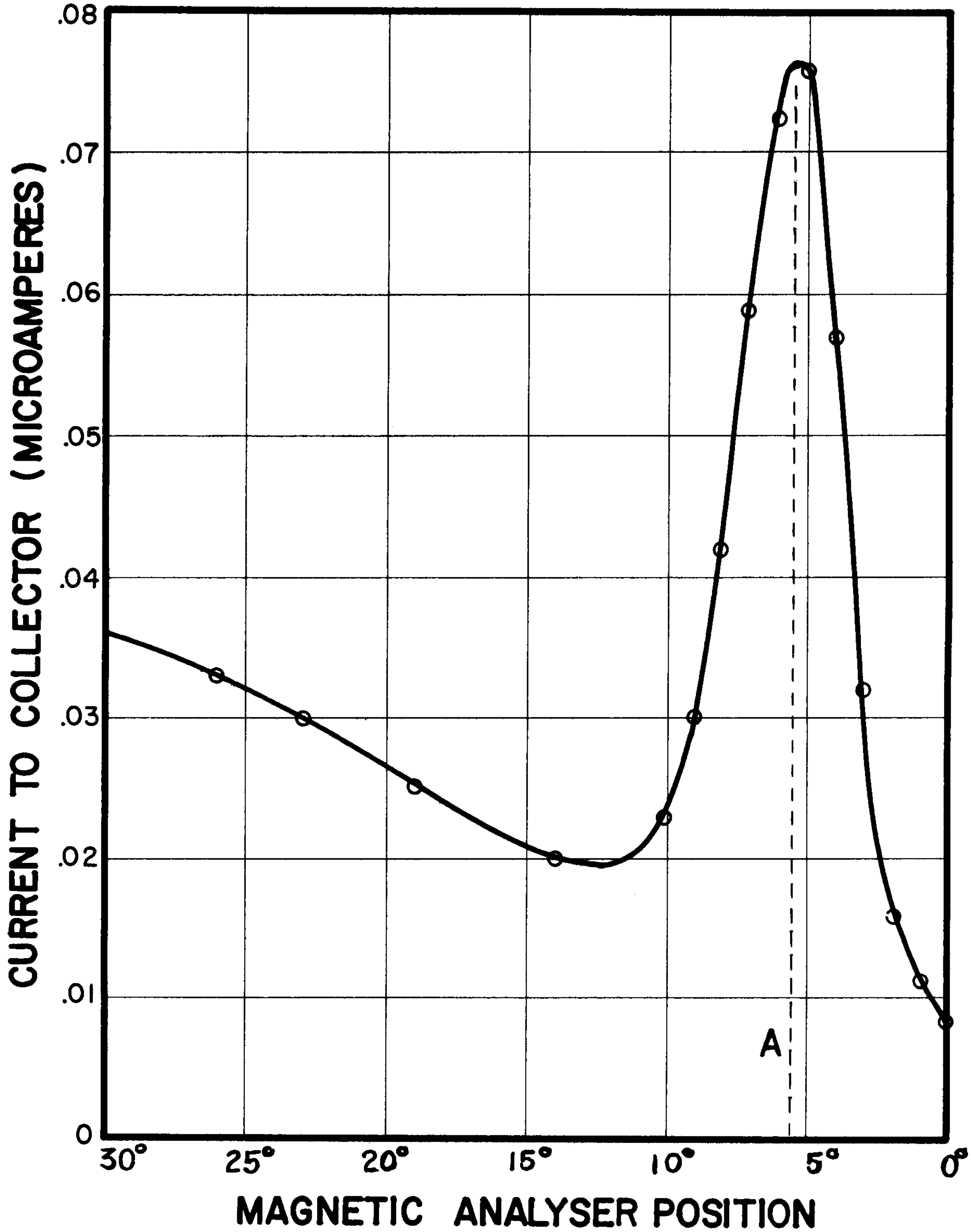

Fig. 8. Current to the collector in the magnetic analyzer as a function of collector position.

is responsible for this change in field strength is only approximately known. The implication is, however, that ions originating in the arc possess this maximum energy and about half of the energy is directed perpendicular to the applied magnetic field.

There is experimental evidence to indicate that most of the energetic ions in the Mode II plasma come from the high-pressure region jutting out from the defining slot. A hollow, cylindrical tantalum tube of just slightly larger diameter than the defining slot was placed as shown in Figure 9. This did not effectively lower the ion current to probes in the plasma, nor did the maximum radius of the glow decrease in the region radially outward from the part of the central arc column which was covered by the tube.

PLASMA POTENTIAL FIELDS EXTERNAL TO DEFINING SLOT

A plot of the floating-probe potential in the plasma surrounding the central arc column of Mode II is shown in Figure 10. The plot was made from a series of oscilloscope traces obtained with a probe placed at different radii. The pattern rotates as a whole. This was found by placing probes at different azimuthal positions and noting that the phase shift was always equal to the space angle between the probes. The direction of rotation is as shown in the figure and is always thus oriented with the magnetic field. A careful search was made for a phase shift parallel with the central arc column by operating an arc discharge in a long solenoid which permitted the distance between the end plates to be increased to 100 cm. It was estimated that as little as 3 deg. of phase shift should be detectable; no shift was

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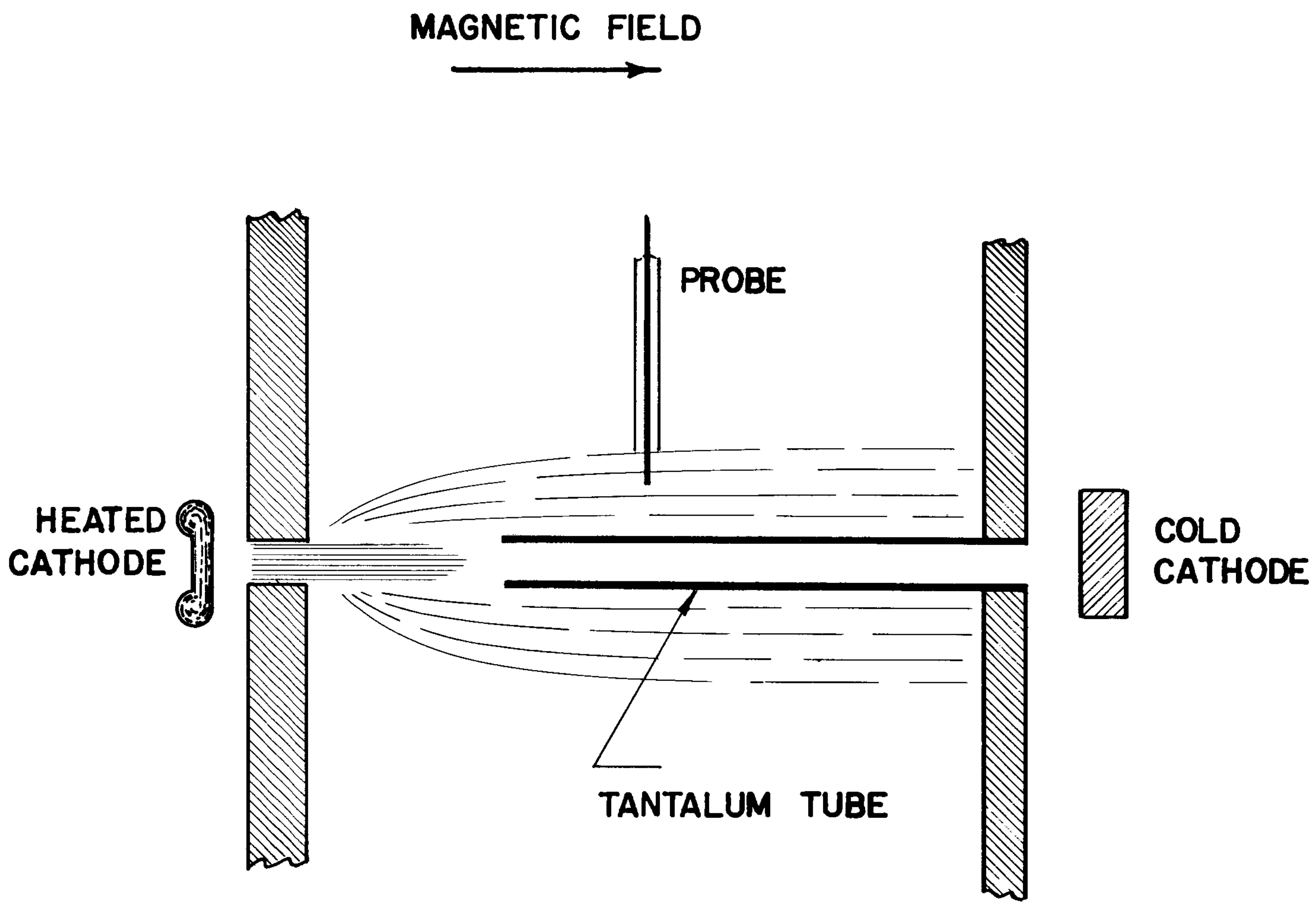

Fig. 9. Diagram of the experiment which located the origin of the energetic ions.

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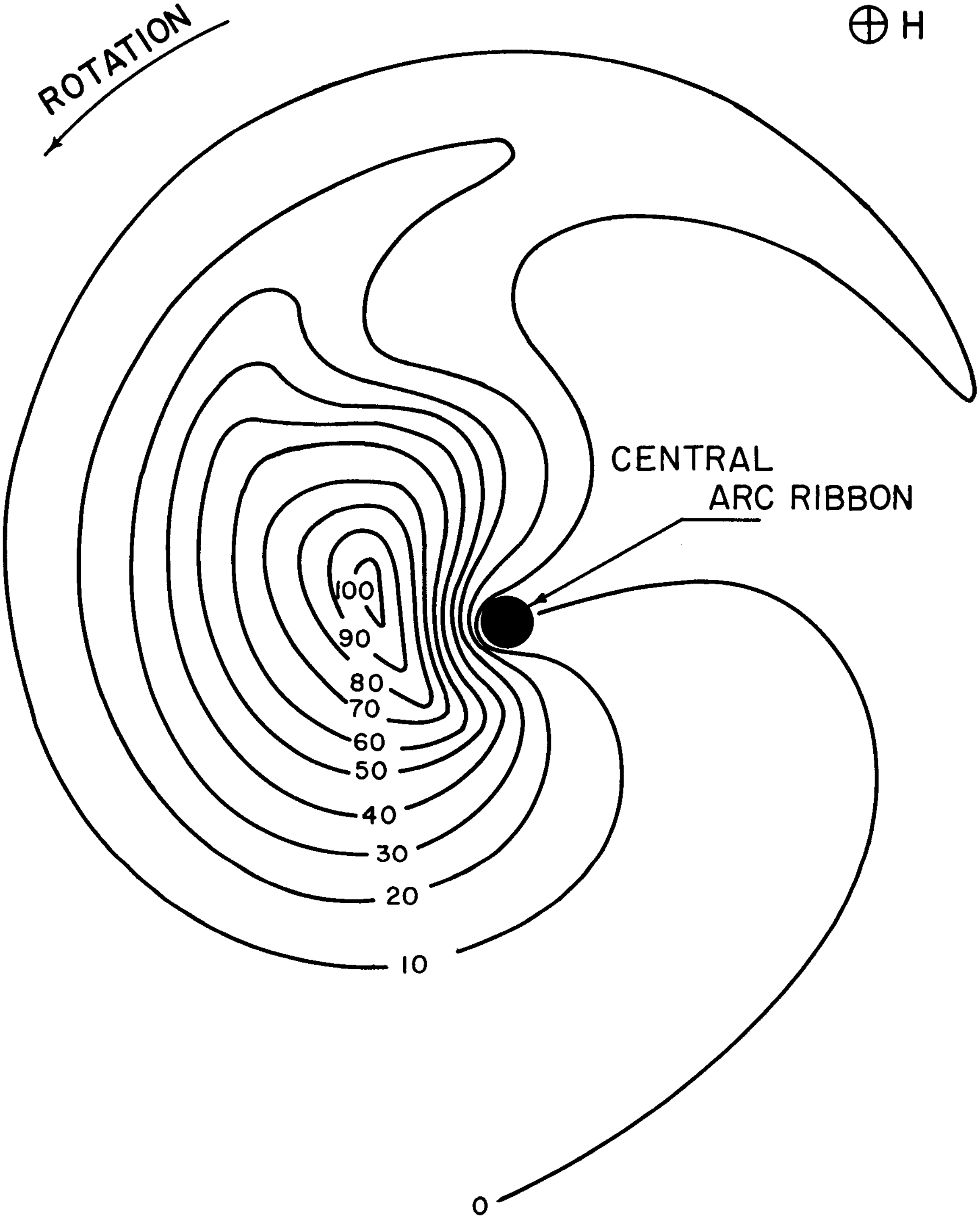

Fig. 10. Floating-probe equipotential lines in the plasma surrounding the arc in Mode II. The numbers indicate positive potentials with respect to the end walls. These are typical of the potentials assumed by a floating probe at any instant. The field rotates as a unit about the arc in the direction indicated.

detected. A decrease in amplitude was observed near the plate at the hot-cathode end. No other change in wave shape was seen.

The frequency of rotation of the dominant mode is always less than the Larmor frequency of the ion for the gas used. It is dependent, but not in any simple way, upon the following variables: (1) the mass of the ion, (2) the gas-feed rate, (3) the pumping speed of the vacuum system, (4) the bias to the hot cathode, (5) the heating current to the hot cathode, (6) the magnetic field, and (7) the material of the end plate. In general, the change of any one or more of the variables which would be expected to increase the ion production rate in the defining slot also increases the frequency of rotation of the potential in the surrounding plasma.

Figure 11 is typical of the variation in the floating-probe potential with time. The upper trace in each of the photographs is that of a fixed monitoring probe. The lower trace is that of a probe which is at the same azimuthal position but at different distances from the hot-cathode end plate. Note that the amplitude of the signal increases as the distance from the hot-cathode end plate increases and that the phase relation between the two signals does not appear to change with _z_ position.

The light emitted by the discharge is most intense along the zero equipotential line, Figure 10. The lower trace in Figure 12 is the output of a photomultiplier tube directed toward dispersed light from a portion of the discharge which is azimuthally displaced 90 deg. from the position of the probe yielding the upper trace. The light from both excited ions and excited neutrals is most intense at the same point in time and space. The most negative peak in the output of the photomultiplier is the point of greatest light intensity. Note that the output is essentially zero for

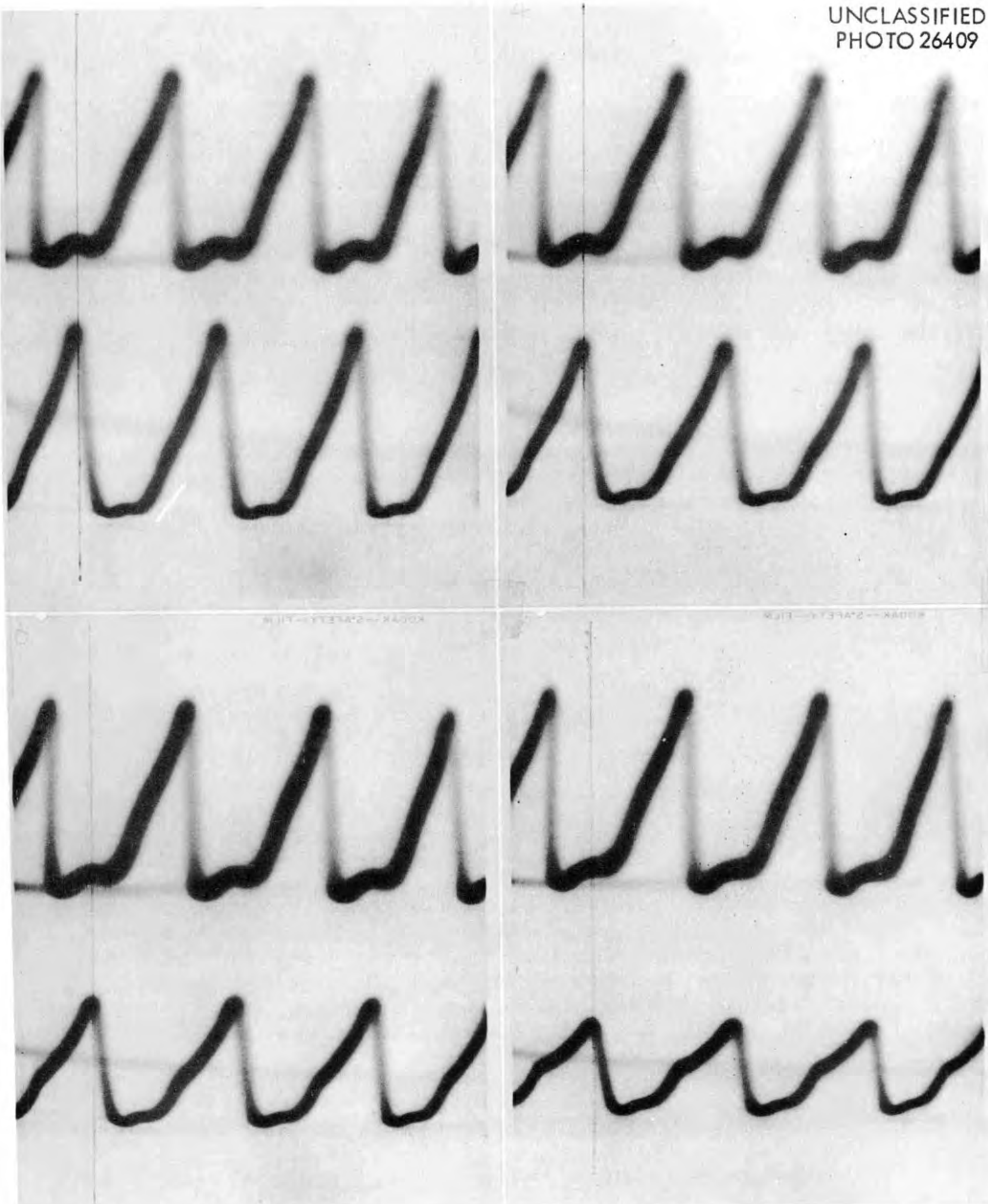

Fig. 11. Oscilloscope traces of the floating probe potential, taken on a DuMont dual-beam oscilloscope. The upper trace in each of the four photos is of the fixed monitoring probe. The lower trace is of the movable probe which was displaced 90° azimuthally from the monitoring probe; in the four photographs the amplitude decreases as the probe is moved toward the hot cathode. Maximum amplitude is 25 volts. The period is 40 microseconds.

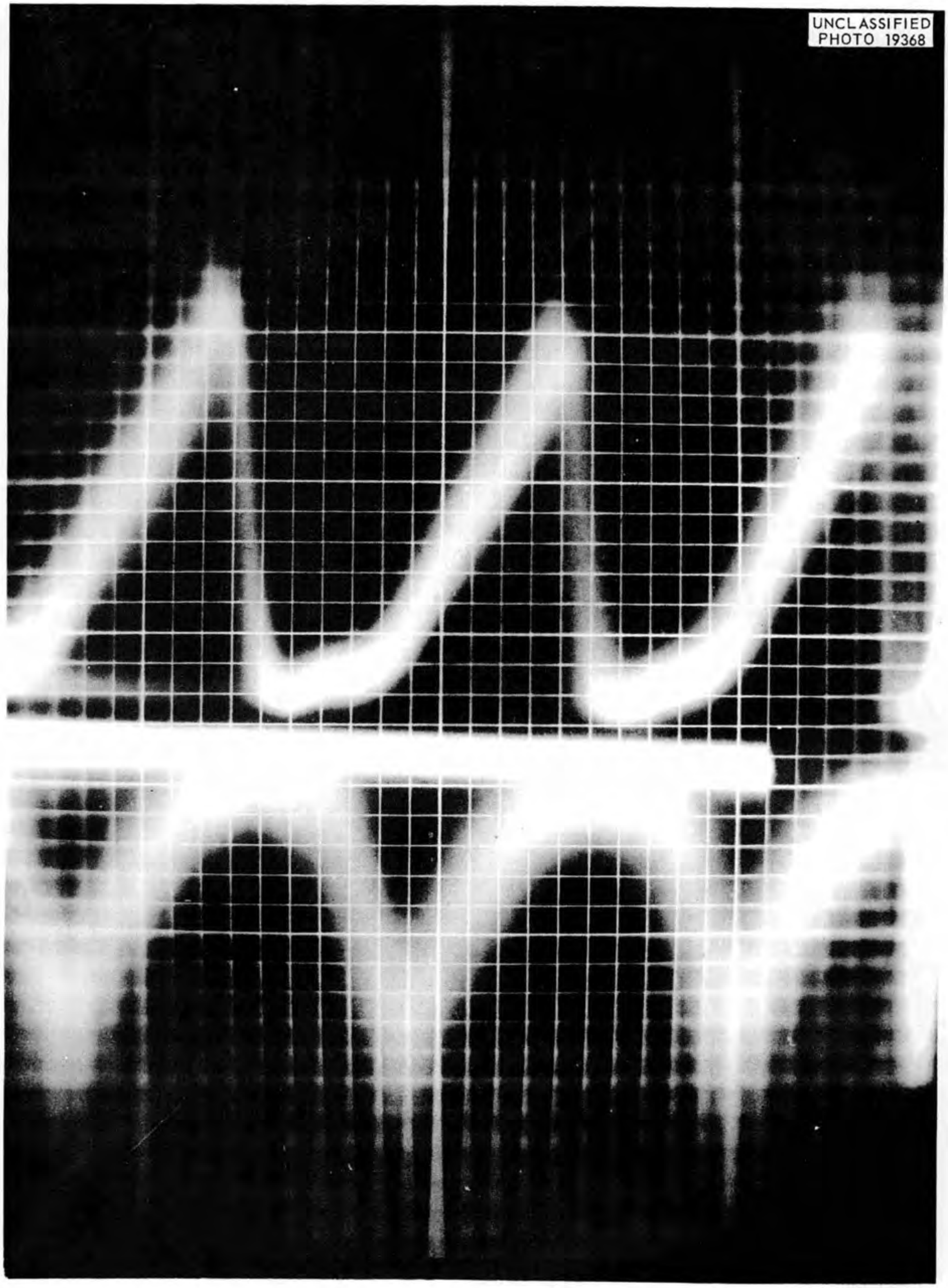

Fig. 12. Light output compared with floating probe potential. The probe was displaced 90° azimuthally from the region being observed by the photomultiplier. The horizontal line is the zero of the photomultiplier. Oscilloscope was a DuMont dual beam.

nearly 180 deg. of the cycle, and the maximum light intensity occurs at about the same time as the electron current peak. The light and the dark portions of the discharge are located with respect to the floating-probe potential trace in Figure 5.

The electrons released from the end plate may oscillate back and forth in the positive potential well of the plasma, producing additional excitation and ionization. This was positively demonstrated by placing another gas feed in the plasma region. The pressure gradient just beyond the nozzle of the gas line could readily be observed by the gradient in the intensity of the light emitted from this region.

In an experiment where the hot cathode was several inches removed from the end plate, so that Mode II could occur on both sides of the defining slot (i.e., the only connection between the two Mode II's was through the defining slot), the positive potential fields rotated together at the same frequency. Their phase relation depended on the adjustable parameters, gas-feed rate, length of the defining slot, etc. The phase difference could be varied from 0-180 deg. Another experiment with separate gas feeds to separate defining slots but with the same primary electron beam from the heated cathode produced two Mode II plasmas which were completely independent in their behavior.

SUMMARY

At present the following conclusions can be drawn from these experiments with an arc in the Mode II type of operation. A pressure difference of at least two orders of magnitude exists in the central arc column.

Electrons accelerated from the heated cathode are observed to possess an energy spread much greater than that observed in the usual arc. Ion energies increase linearly with hot-cathode bias, to the limit of its supply. Either constant or time-varying electric fields which exist in the central arc column accelerate some ions to at least twice the cathode bias. The phenomenon does not appear to be at all transient in any way. The results are entirely reproducible, and the apparatus can be run hour after hour, the only limiting feature being the wear on the hot cathode due to ion bombardment.

A degree of containment is effected for electrons. In the first place, they are constrained to move along magnetic field lines. Secondly, the lines are bounded at one end by the heated cathode, and at the other, by a floating cold cathode. The potential of the cold cathode is always about double the applied potential to the heated cathode.

The ion energy is comparable to and increases with the cold-cathode potential. In order for ions to have this energy in a grounded, field-free region, they must have been accelerated from a positive potential of this value in one step, or from a time-varying potential field in multiple steps. Exactly how this potential originates is not known. This acceleration of ions is always associated with the pressure gradient in the arc column and occurs only when ions and electrons are being produced faster than they can be removed at the ends of the arc.