PLASMA DYNAMICS*

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RESEARCH OBJECTIVES

This heading covers all of the work that is supported in part by the National Science Foundation and is under the over-all supervision of the Plasma Dynamics Committee of the Massachusetts Institute of Technology. The general objective is to combine the technical knowledge of several departments, in a broad attempt to understand electrical plasmas, to control them, and to apply them to the needs of communication, propulsion, power conversion, and thermonuclear processes.

XIV. PLASMA PHYSICS†

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RESEARCH OBJECTIVES

The aim of this group continues to be the study of the fundamental properties of plasmas with particular emphasis on plasmas in magnetic fields. In emphasizing our interest in high-density plasmas, we have spent a great deal of effort on production of plasmas of high-percentage ionization at low pressures under steady-state conditions, the achievement of which will allow us to carry on the fundamental studies in which we are most interested. We have achieved plasmas of high-percentage ionization by means of cesium discharges and a hollow-cathode, low-pressure arc discharge.

We are also studying ways of determining the characteristics of plasmas by means of microwaves, infrared optics, and the diamagnetic effect of electrons. Along with these production and diagnostic studies, we are continuing measurements on the fundamental physics of loss and gain mechanisms of electrons in plasmas in magnetic fields. Emphasis is also being placed on the study of microwave radiation from plasmas, with and without magnetic fields, both as a tool for measuring the plasma temperature and thermal properties and as a means of understanding more about the motion of electrons and ions in magnetic fields.

Theoretical work has been concentrated on the study of waves in plasmas and of statistical theories of the nature of a plasma.

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A. HARMONICS OF ELECTRON-CYCLOTRON EMISSION FROM A MERCURY-VAPOR DISCHARGE

An increase in the radiation at the electron-cyclotron harmonic frequencies was observed in the microwave emission from the positive column of a low-pressure, high-current, mercury-vapor discharge immersed in a magnetic field. Previous measurements,[1,2] which were made with low currents and at higher pressures in mercury vapor and other gases, showed increased emission only at the first (that is, fundamental) harmonic.

The radiation was received from a section of the positive column, 50 cm long, immersed in a uniform magnetic field oriented parallel to the axis of the column. The plasma column with a 1-inch diameter was enclosed in a rectangular S-band waveguide by inserting the discharge tube through the broad sides of the waveguide at an angle of 8° to the waveguide axis. Thus the propagation vector of the waveguide mode and the applied magnetic field were roughly parallel.

The radiation from the plasma was observed at a fixed frequency ω equal to 3100 mc, within a bandwidth of 2 mc. The magnetic field was varied from 2000 gauss to zero. As the magnetic field was decreased, an increase in the microwave emission was observed whenever the fixed frequency ω was equal to a multiple integer, n, of the electron's orbital frequency $\omega_b = eB/m$. Figure XIV-1 shows the power radiated

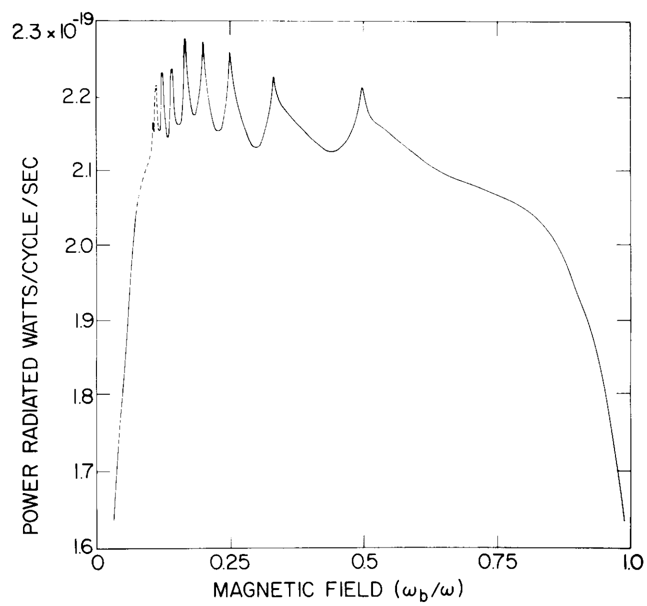

Fig. XIV-1. Power radiated from the positive column as a function of the axial magnetic field. Discharge current, 1 amp; axial dc field, approximately 0.7 volts cm^{-1}; vapor pressure in discharge, 0.0054 mm Hg.

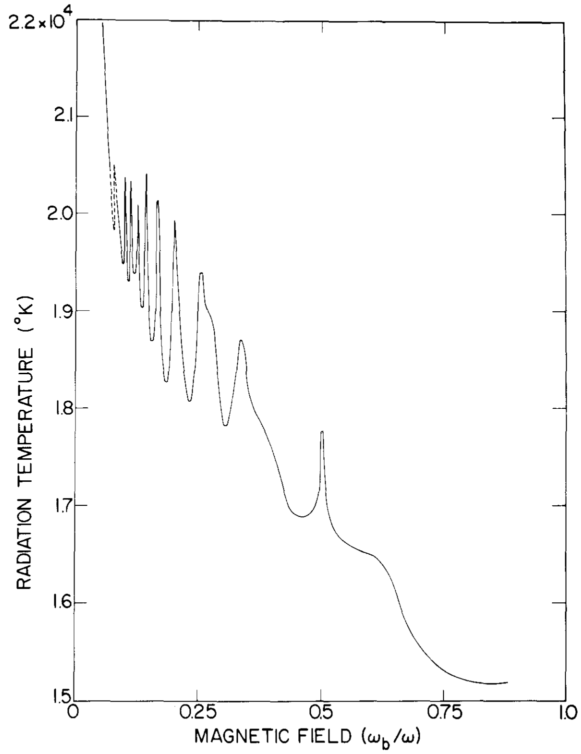

Fig. XIV-2. Radiation temperature of the positive column as a function of the axial magnetic field. Discharge current, 1 amp; axial voltage, approximately 0.7 volts cm^{-1}; vapor pressure, 0.003 mm Hg.

as a function of ω_b/ω. The first harmonic n = 1 was not observed, probably because of large internal reflections of the radiation in the vicinity of $\omega_b/\omega = 1$. As B decreases, the separation between harmonics decreases and harmonics beyond the eighth are not easily distinguishable. The peaks of the harmonics are located at the harmonic numbers $n = \omega/\omega_b = 2, 3, 4, 5 \ldots$, within an accuracy of ±1 gauss.

In Fig. XIV-2 we have plotted the radiation temperature T_r as a function of the magnetic field, ω_b/ω. If the free plasma electrons had a Maxwellian distribution of velocities, the radiation temperature T_r would equal[2] the electron temperature T_e. The pronounced harmonics superimposed on a monotonically decreasing background, as shown in Fig. XIV-2, give strong evidence of the non-Maxwellian distribution of electron velocities. The monotonic decrease of the radiation temperature with increasing magnetic field is indicative of the decrease of the mean electron energy with increasing B; this is in agreement with theory and experiment.[3]

The mechanism of the generation of the observed higher harmonics is not understood. Harmonics produced by the relativistic motion of electrons with energies of several electron volts in the positive column are much too small to account for the observed intensities. Two possibilities are:

(a) The helical electron orbits are distorted by the strong space-charge fields in the plasma sheath.

(b) Higher harmonics resulting from the propagation of a wave through a "temperate plasma" in which the finite size of the Larmor orbit must be considered in the computation of the complex conductivity of the plasma.[4]

G. Bekefi, J. D. Coccoli

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B. BREMSSTRAHLUNG FROM AND RESISTIVITY OF A HIGHLY IONIZED PLASMA

Percentages of ionization in an arc discharge in cesium vapor as high as 20 per cent were reported previously.[1] The pressures at which the arc operated varied from 3 to 29 microns.

The experiment has been continued and we have obtained a discharge in cesium vapor at pressures as low as 2×10^{-4} mm Hg in a tube with a radius of 1.7 cm, with a constant magnetic field applied along the axis of the tube in order to make the breakdown conditions easier to fulfill. Once the discharge is started it can be maintained without the magnetic field.

At these low pressures we could obtain electron densities that closely approached a fully ionized plasma. However, as soon as the frequency for electron-ion collisions is large compared with the frequency for electron-atom collisions, the electrical transport coefficients of the plasma do not change much with an increasing percentage of ionization. The low pressures thus enabled us to decrease the electron density to values at which the plasma frequency is less than or equal to the frequency of electromagnetic waves that can propagate in X-band waveguides, and still maintain approximately 20 per cent ionization. Since the diameter of the tube was just small enough for the tube to fit into an X-band waveguide, the electron temperature could be determined with the use of an X-band radiometer.

1. Bremsstrahlung from Weakly and Highly Ionized Plasmas

If the electrons have a Maxwellian velocity distribution function, the power that results from free-free transitions and that is emitted in a frequency interval $d\omega$ in all directions and in both polarizations and in the absence of self-absorption, is for a fully ionized plasma:[2]

$$dP(\omega) = 1.09 \times 10^{-51} N_e N_i Z^2 T^{-1/2} G\, d\omega \qquad wm^{-3}$$

where

N_e = electron density/m^3

N_i = ion density/m^3

T = electron temperature in °K

Z = ionic charge

G is a slowly varying function of T, ω and N_e; in our case it is approximately equal to 7.

For discharge currents at which the plasma radiation is well below that of a plasma radiating as black body the attenuation coefficient is small; thus, since $N_i \sim N_e$, the detected power varies as N_e^2 if the temperature is a constant.

For a weakly ionized plasma the bremsstrahlung that results from electron-atom interactions is significant. The temperature dependence of the radiated power is determined by the temperature dependence of electron-atom interactions. As far as the particle densities are concerned, however, we can expect the emitted power to be proportional to $N_e \times N_a$, when N_a is the number of atoms/m^3.

Comparing the emitted power from a fully ionized plasma with that from a weakly ionized plasma, we find a proportionality with N_e^2 and N_e, respectively. If we plot log P as a function of log N_e or as a function of the log of the current density, the difference in slope for the curves should be a factor of approximately 2, provided that the temperature does not change much with the current. In Fig. XIV-3, P is plotted as a function of the current density on a double logarithmic scale for pressures of 0.2×10^{-3} and 14.5×10^{-3} mm Hg. The angle changes in the anticipated direction. The fact that the difference is less than a factor of 2 means, probably, that at the higher pressure electron-ion interactions are not negligible. Furthermore, the neglect of the temperature effect makes it unlikely that the results will be very close to the theoretical prediction.

2. Resistivity of a Fully Ionized Plasma

Spitzer and Härm[3] find for the resistivity of a fully ionized plasma

$$\eta = 6.53 \times 10^3 \frac{G}{T^{3/2}} \text{ ohm-cm.}$$

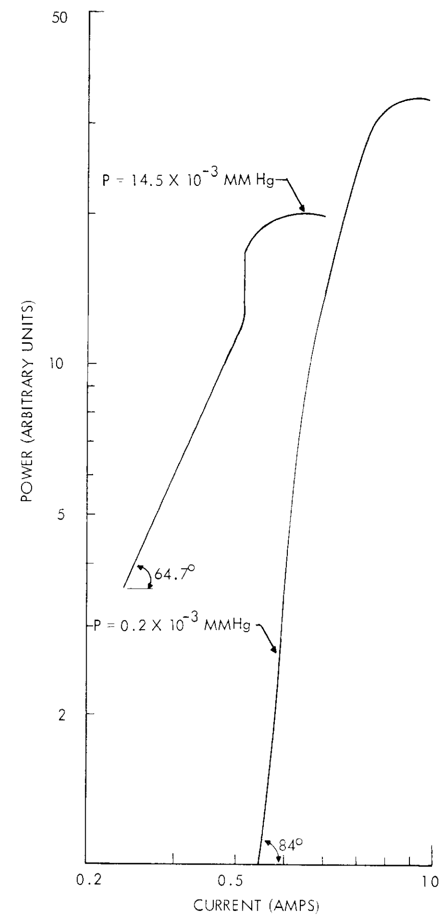

Fig. XIV-3. Intensity of the bremsstrahlung from the positive column of an arc discharge in cesium vapor as a function of the discharge current.

This equation is based on the assumption that the electric field is so small that the potential energy gained across one mean-free path of the electrons is negligible as compared with kT. Here, G is a slowly varying function of the electron density and the electron temperature. In the region of values for N_e and T_e that we have measured we introduce only a small error if we set G = constant, equal to 7. Then we have

$$\eta \sim 45.7 \times 10^3 \times T^{-3/2} \text{ ohm-cm} \tag{1}$$

a relation in which the electron density does not appear.

In Fig. XIV-4, η is plotted as a function of the measured temperature. The broken line represents the resistivity obtained from measurements of arc current and voltage. A total voltage drop of 4 volts resulting from cathode and anode fall was assumed.[4] The solid line represents η as obtained from (1). Temperature measurements could

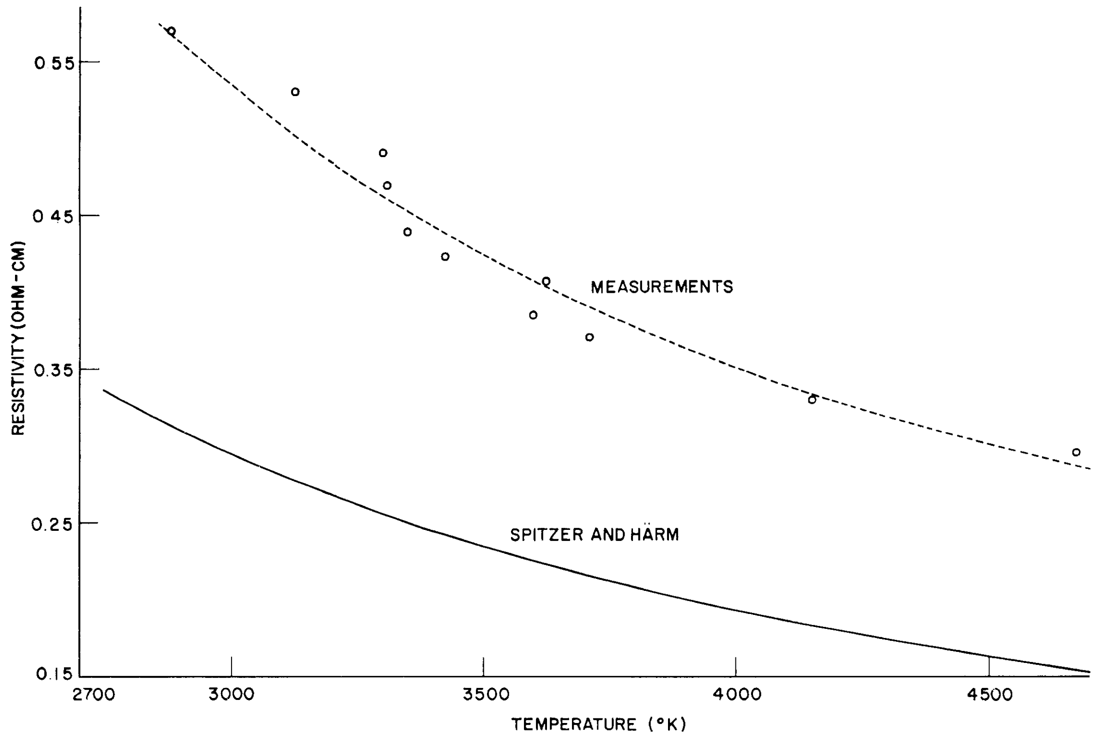

Fig. XIV-4. Electrical resistivity of a highly ionized cesium plasma as a function of the electron temperature.

be made only in a limited range of arc currents. A minimum current is determined by the condition that the plasma must radiate as a black body; that is, the electron density must be $\geq 8.5 \times 10^{17}/m^3$ for the frequency at which the radiometer was operating. An upper limit was introduced by the reflection coefficient on the plasma boundary, which became high at high currents. The measured temperature is higher by a factor of approximately 1.7 than the temperature predicted by Spitzer and Härm.

In order to reduce the diffusion losses (tube diameter was 1.7 cm) we applied a magnetic field of approximately 600 gauss along the tube axis. The presence of this magnetic field increased the electron temperature, probably a result of the Lehnert effect. This rise in temperature may explain the discrepancy between the two curves in Fig. XIV-4. The influence of a magnetic field on the discharge will be further investigated.

The question may be asked whether or not at the low pressures at which the measurements were made, impurities play an important role in the discharge. The tube was sealed off at a pressure of approximately 8×10^{-8} mm Hg; the oxide-coated cathode and also the tube walls must be expected to release gases in considerable amounts. We think, however, that the influence of these impurities is small. First of all, cesium is a good getter; second, the ionization potential of cesium (3.87 volts) is much lower than that of the foreign gases, and the average electron temperature in the discharge is so low (< 0.5 ev) that ionization and excitation of the foreign gases can hardly be expected; third, most measurements were made for values of current and pressure at which electron-ion collisions were the main interactions between particles in the discharge, and the frequency for these collisions is independent of the chemical nature of the gas; finally, no appreciable changes in the characteristics of the arc were found after approximately two months of use.

J. C. Terlouw

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C. A TRANSIENT MICROWAVE RADIATION PYROMETER

A microwave radiation pyrometer has been described[1] for measuring the radiation temperature[2] of a steady-state discharge placed in a waveguide. The system described below extends this technique to the measurement of the radiation temperature of a waveguide-contained plasma undergoing some transient process.

This technique is being applied, at present, to the measurement of the radiation-temperature decay of a pulsed direct-current discharge in the afterglow. The radiation-temperature decay can be related to the decay of the average electron energy.[2] If the distribution function is Maxwellian, then the radiation temperature equals the electron temperature. When this condition prevails and when elastic recoil of the hot electrons with the cool gas atoms is the dominant cooling process, the energy dependence of $g\nu_c$, the fractional energy loss per second caused by elastic electron-atom collisions, can be determined. This energy loss is determined through the combined use of the expression for the cooling of electrons caused by elastic collisions with gas atoms[3] and a computer program that determines the best form of $g\nu_c$ to fit the temperature-decay curve.

The present system is capable of making radiation-temperature measurements at 1-μsec intervals over a time interval of 300 μsec after the discharge is terminated. The accuracy is approximately ±100°K over the range of 300°K to 20,000°K, if it is assumed that the standard noise source is exactly known. The discharge is pulsed at the rate of 1000 times per second and is on for one-fifth of the cycle. The microwave

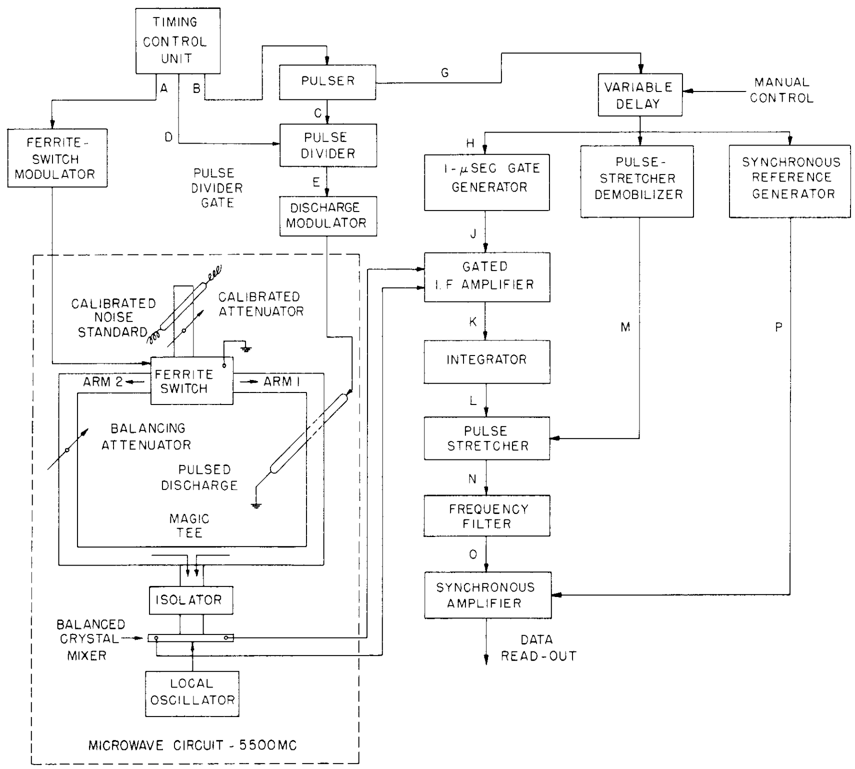

Fig. XIV-5. Transient microwave radiation pyrometer.

system operates at 5500 mc.

During the first half-cycle, the ferrite switch (Figs. XIV-5 and XIV-6(a)) sends the noise-standard radiation through the discharge (arm 1) as the discharge is being established and as it cools down. The discharge has reached room temperature at the beginning of the second half-cycle, during which the noise-standard radiation is sent through arm 2. The resultant signal received by the i-f amplifier is shown in Fig. XIV-6(f): in the first half-cycle the amplifier receives the discharge radiation plus that part of the noise-standard radiation that was not absorbed in traversing the plasma, and in the second half-cycle it receives the unattenuated noise-standard radiation. A 1-μsec variable-delay gate signal (Figs. XIV-5 and XIV-6(j)) then samples from each half-cycle (Fig. XIV-6(k)) of the i-f amplifier signal. These sample pulses are then integrated, stretched, and filtered until finally the waveform (Fig. XIV-6(o)) is identical with the waveform input to the synchronous amplifier for the steady-state pyrometer circuit.

The null measurement is now made by adjusting the calibrated attenuator until there is no signal at the synchronous amplifier. This adjustment results in the effective noise-standard temperature equaling the radiation temperature of the decaying plasma at the given time in the afterglow.

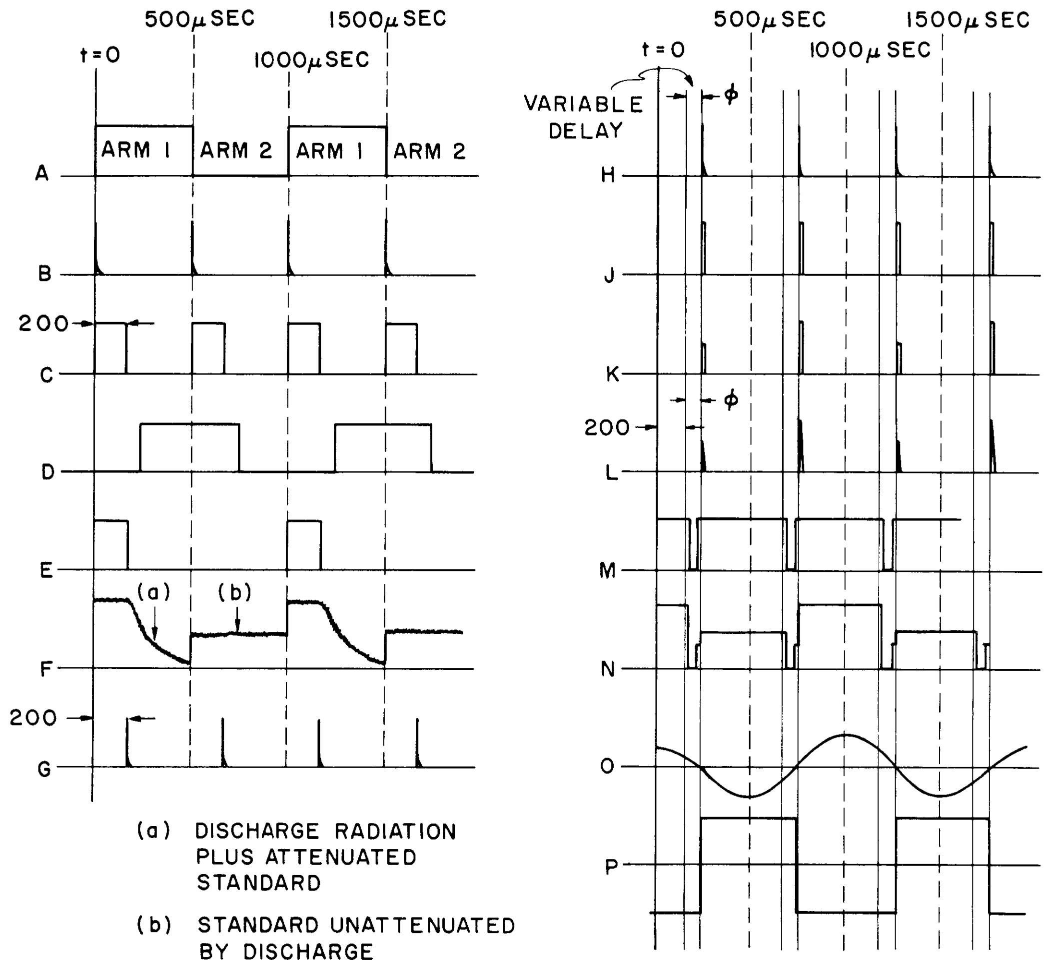

Fig. XIV-6. Waveforms for transient microwave radiation pyrometer. (Waveforms F, K, L, and O are shown for a non-null condition.)

Preliminary measurements have been made in helium at pressures of 0.1-6 mm Hg and with curents of 10-300 ma. Helium was chosen because its momentum-loss frequency is well known and could thus provide a check for the temperature-decay measurements. The temperature decay at higher pressures (0.3-6 mm Hg) is slower than that predicted by an elastic-recoil cooling mechanism. This slowness could be caused by any of a number of processes, the most likely being the collision between an excited helium atom and an unexcited helium atom which forms the molecule-ion and an electron with energy of approximately 1 ev. Generally, as the pressure is decreased, the temperature decay approaches the $g\nu_c$ decay curve. Deviations that depend on longitudinal magnetic field and discharge current are also noted at the lower pressures (0.05-1 mm Hg). Measurements of the discharge temperature before the afterglow period indicate that these deviations may be caused by plasma instabilities that are excited as a result of the breakdown transient. A longer cycle will be used to test this indication.

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