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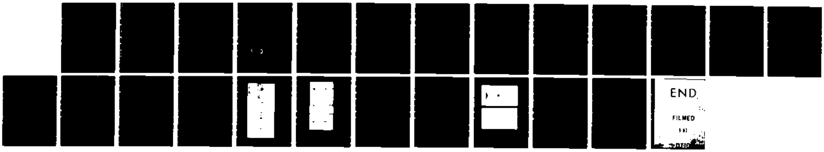

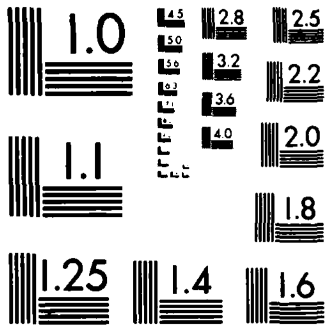

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NRL Memorandum Report 4945

A Broadband High Power Millimeter to Centimeter Spectrometer

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A simple spectrometer is described for measuring directly both a high electric field (0.1- 100 kV/cm) and wavelength over a broadband (0.1- 10 cm). The combination of interference and gas breakdown are utilized in measuring the electric field and wavelength. Electron diffusion and the characteristic breakdown relation limit resolution of sub-millimeter wavelengths by requiring very high electric fields ($>$100 kV/cm).

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A BROADBAND HIGH POWER MILLIMETER TO CENTIMETER SPECTROMETER

I. INTRODUCTION

Over the last several years there has been considerable interest in generating high power microwaves from relativistic electron beams.[1] One of the most important parameters to be determined in such experiments is the power spectrum. Interferometers have been used for spectral measurements,[2] but they are only useful over a very narrow band of frequencies. An improved bandwidth is obtained with a grating spectrometer[3] but noise and expense then become issues. Dispersive lines have also been used but they are impractical for long pulses (> 1 μs). Also, all of the above mentioned devices must be calibrated for absolute power. In the beginning of a microwave experiment quick but less precise information about the entire power spectrum are of primary importance. To fit this purpose, we have developed a simple and inexpensive spectrometer which is insensitive to noise and can directly measure selected wavelengths at full power.

II. SPECTROMETER DESIGN

Figure 1 shows a schematic of the spectrometer. Radiation is collected in the horn on the left. It then travels through a high pass filter and expands through the horn on the right to a collimating or weakly focusing lens. The microwaves are reflected from a metallic boundary which is located inside the gas filled chamber. Gas breakdown occurs at the spatially periodic peaks in the electric field which result from interference between the reflected and

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incident waves. Gas breakdown occurs at about half wavelength intervals apart. The wavelength is related to the spot spacing d and the angle of incidence α_i (see Fig. 1) by

$$\lambda = 2\ d \cos \alpha_i. \tag{1}$$

Thus, by measuring from a photograph of the breakdown region the spot spacing and diameter, and knowing the gas pressure, then the electric field, power and wavelength can be determined. A relationship between breakdown electric field and gas pressure will be given later. It should be noted that the chamber length does not determine the wavelength since the radiation is reflected from only one highly reflecting boundary. For low power microwaves the focusing lens increases the electric field to facilitate gas breakdown.

The aluminum horns are conical with an inside diameter that is reduced from 12.5 cm to 5 cm. An aluminum taper matches the end of the horns to the high pass filter. Focusing is accomplished with one of three lucite lenses having focal lengths of 12, 24, and 48 cm. Focusing inside and outside the chamber end plate has been tried; however, the clearest interference patterns are observed when focusing is outside the 30 cm long, 14 cm i.d. lucite chamber.

III. EXPERIMENTAL RESULTS

In the present experiment microwaves are generated when a 130 A, 550 keV, 2 μs long electron beam is passed through a "wiggler" magnetic field. The wiggler field is produced from the eddy currents induced in a set of spatially periodic conducting rings when an axial magnetic field is pulsed. In this particular case the rings are made of aluminum and have an inside diameter of 7.5 cm, a radial thickness of 0.6 cm and an axial extent of 1 cm. The ring period is 6 cm and the composite ring structure and axial guide field are 200 cm long.

Figure 2 is a time integrated photograph of the resulting interference pattern. Microwave radiation has entered from the left of the photograph, where the lens is located (but cannot be seen), and is reflected off a copper plate located at the right of the photograph (arrow indicates copper plate). The white spots are due to light produced from the gas breakdown. Type 57 (ASA 3000) Polaroid film was used with a Graphflex camera (f/4.5) to obtain these results. The gas density was selected experimentally so that enough light was available to be recorded photographically but not high enough to allow microwave reflections from the plasma.

From Fig. 2 the spot spacing is measured to be 2.25 cm which corresponds to a frequency of 6.67 GHz. The breakdown electric field E_b is estimated from the semi-empirical formula

$$E_b = AP\{1 + (a/P\lambda)^2\}^{1/2}, \qquad (2)$$

where $A = 3000\ \mathrm{Vm^{-1}Torr^{-1}}$ and $a = 0.9$ Torr-m for air or nitrogen, P is the gas pressure in Torr, and λ is the wavelength in meters.

Equation (2) has been derived semi-empirically from McDonald's precision data[4] and agrees in the worst case to within 30%. This formula is valid on the high pressure side of the breakdown curve, i.e. for $P\lambda > 0.26$ Torr-meters, pulse lengths >1 μs, low repetition rate (< 100 pps), and for no electron collisions with the chamber walls. For the results of Fig. 2 the measured pressure is 25 Torr and the wavelength is 4.5 cm, corresponding to an electric field of about 1 kV/cm. From the spot diameter of 2.5 cm the power is estimated, for a plane wave, to be 8 kW.

Wavelength discrimination is accomplished by utilizing the pressure and wavelength dependence of Eq. 2. That is, at a given pressure a shorter wavelength will require a higher electric field in order to achieve breakdown. As stated before, Eq. 2 is valid for $P\lambda > 0.26$ Torr-meter. In the other limit, i.e., for $P\lambda < 0.26$, it will be shown later that short wavelengths cannot be resolved as a result of diffusion.

Discrimination is not possible for all wavelengths in certain electric field versus wavelength distributions. If any two spectral lines in a discrete distribution satisfy the relation

$$\Delta E \approx E_1 \left\{1 - \left[1 + \left(\frac{Aa}{\lambda_1 E_1}\right)^2 \alpha \frac{(2-\alpha)}{(1-\alpha)^2}\right]^{1/2}\right\}, \qquad (3)$$

then discrimination is not possible. In Eq. (3), $\Delta\lambda = \lambda_1 - \lambda_2$, $\lambda_1 > \lambda_2$, $\Delta E = E_1 - E_2$, $E_1 < E_2$ and $\alpha = \Delta\lambda/\lambda_1$, where $E_{1,2}$ is the electric field for wavelength $\lambda_{1,2}$. Eq. 3 simply states that the two spectral lines satisfy Eq. 2 at the same pressure. Even if Eq. (3) is satisfied there is a way to circumvent this difficulty, provided the wavelengths are sufficiently separated. In such a case, a high pass filter can be used to eliminate the longer wavelength.

There are two more points to consider regarding Eq. 3. If ΔE is greater than the right hand side of Eq. 3 then the pressure can be adjusted so that E_2 is not large enough to breakdown the gas. However, if ΔE is less than the right hand side of Eq. 3 then the pressure can be adjusted to prevent breakdown by E_1. To resolve every wavelength in a continuous distribution $E(\lambda)$, it follows from Eq. 3 that

$$\frac{dE}{d\lambda} > - \frac{(aA)^2}{\lambda^3 E_b}, \tag{4}$$

for every λ.

In order to verify that the observed breakdown pattern is due to an interference effect, the boundary conditions on the incident wave are changed with the results shown in Fig. 3. In each case microwaves are focused by a lens located at the left of the photograph to a region in front of the boundary at the right. By comparing Figs. 3a and 3b, it is clear that the total electric field has increased by increasing the surface reflectivity. In Fig. 3a the boundary is composed primarily of graphite whereas in Fig. 3b the material is lucite (index = 1.63). It should be noted that the thickness of the lucite was selected not to satisfy the resonant reflection condition. In Fig. 3c an absorbing surface is used to eliminate the reflected wave. The interference pattern is absent but a single region of breakdown remains.

This residual breakdown region results from the method used to absorb the radiation. The absorber was constructed from Eccosorb (Emmerson and Cuming, Inc.) in the shape of a "V" and oriented so that microwaves enter the opening of the "V". This technique results in substantial reduction of the reflected wave. The gas breakdown now occurs within the "V" shaped absorber region.

IV. LIMITATIONS

There are several limitations which are inherent in the above type of spectrometer. Practical considerations limit both the wavelength and the electric field strength that can be measured. Long wavelength (>10 cm) operation is impractical while trying to maintain the geometrical optics condition. Short wavelengths (<1 mm) are bounded by the ability to resolve the spot spacing. Resolution is maximized by operating with a highly reflective chamber end plate and a high gas pressure, which limits electron diffusion. High pressures, however, require very high electric fields (> 100 kV/cm) for submillimeter resolution. At low electric fields (< 100 V/cm) a limit is set by the ability of the electrons to gain sufficient energy to breakdown the gas.

In order to make the wavelength measurements two conditions must be satisfied: the breakdown region must be visible and the wavelength must be resolvable. The dashed curve in Fig. 4 shows the total RMS electric field of the standing wave divided by the peak incident electric field. When the breakdown electric field is above the peak total RMS electric field (top line in Fig. 4), the gas does not breakdown. Also wavelength resolution is not possible if the breakdown electric field is below the minimum total RMS electric field (as in the bottom line), since breakdown occurs everywhere. Resolution is maximized when the breakdown field (solid line in Fig. 4) is just slightly below the peak total RMS electric field, so that the length of the breakdown region is considerably smaller than the wavelength. The length of the breakdown region can be determined from the total RMS electric field for two plane waves traveling in opposite directions,

$$E_{rms} = \{E_i^2/2 + E_r^2/2 - E_i E_r \cos(2kx)\}^{1/2}, \tag{5}$$

where E_i and E_r are the incident and reflected electric field amplitudes for a plane polarized wave incident normally on a partially reflecting surface located at $X = 0$, and $k = 2\pi/\lambda$ is the wavenumber. From Eq. 5 the length of the breakdown region is given by

$$L_b = \lambda/2 \left\{1 - \frac{1}{\pi} \cos^{-1} \left(\frac{E_i^2 + E_r^2 - 2E_b^2}{2E_i E_r}\right)\right\}, \tag{6}$$

where $E_i - E_r < 2 E_b < E_i + E_r$ for resolvable breakdown. An important observation here is that for a poorly reflecting boundary, the minimum E_{rms} approaches the maximum E_{rms} and breakdown will occur nearly everywhere or not at all, and again a wavelength measurement cannot be made. Figure 5 is a plot of the ratio of the total RMS electric field to the peak incident electric field versus position for three different values of E_r/E_i. It is clear that a highly reflecting boundary is desirable for wavelength resolution. It should be mentioned that a shallow focusing angle is necessary in order to keep the reflected wave amplitude comparable to the incident amplitude. This accounts for the fact that clearer interference patterns were observed when the radiation was focused beyond the end plate.

So far, only the initial breakdown region has been considered. wever, electron diffusion will increase the length of this initial region, hence further restrict the ability to resolve a given wavelength. Diffus- contributes a length given by

$$x_d = (Dt)^{1/2}, \qquad (7)$$

where D is the diffusion coefficient and t is the time. In order to relate the diffusion length to properties of the gas and the electrons, the diffusion coefficient must be evaluated. From elementary kinetic theory the diffusion coefficient for a Maxwellian distribution of electrons can be shown to be in MKS units

$$D = 2eU/(3mf_c), \qquad (8)$$

where m is the electron mass, eU is the mean electron energy (U is in eV), and f_c is the electron-neutral collision frequency. From Reference 4, a simple relation is available that connects the collision frequency to the pressure and is given by,

$$f_c = bP, \tag{9}$$

where $b = 5.3 \times 10^9$/sec-Torr for air or nitrogen. Also, from Reference 4 the measured electron energy is typically a couple of eV. When Eqs. (7)-(9) are combined it becomes clear that for long pulses and short wavelengths a high pressure is required in order to achieve wavelength resolution. Higher pressures will then require high electric fields to obtain gas breakdown.

Figure 6 demonstrates the combined effects of diffusion and breakdown field, on wavelength resolution. In Fig. 6a the image is cloudy which makes a wavelength determination dubious. By raising the pressure (from 2 to 20 torr) the image becomes clear as shown in Fig. 6b. A lucite wall was used as a reflector in Fig. 6a and 6b. At 20 torr the one dimensional diffusion length is from Eq. (7) equal to 0.26 cm. Since diffusion occurs in both directions from the center of the breakdown, the calculated spot thickness will be twice the one dimensional diffusion length, namely 0.52 cm. The measured spot thickness (Fig. 6b) is 0.5 cm which is in very good agreement with the calculated value. At 2 torr the two directional diffusion length is 1.6 cm which accounts for smearing of discrete spots. However, there may be an additional effect which clouds the image of Fig. 6a. Plasma motion has been observed when the electric field is substantially above the breakdown electric field.[5] The conditions for Fig. 6a are such that the electric field is three times the breakdown field which is sufficient for plasma motion to occur, and since this is a time integrated photograph plasma motion could account for some of the image clouding.

In general, the breakdown field versus pressure exhibits a minimum. This fact combined with diffusion imposes a limit on the minimum resolvable wavelength. This electric field minimum corresponds to a maximum transfer of energy to the electrons from the electromagnetic field, which occurs when the time between collisions is some fraction of half the wave period. That is

$$1/f_c = T/(2i), \tag{10}$$

where T is the wave period and i is a number that depends on the electron-neutral scattering angle. For a 180° angle, $i = 1$; for smaller angles, i becomes larger than 1. For electrons with a low energy (< 5 eV) the scattering angle is large, thus i will be of order 1. By combining Eqs. (9) and (10) a relation for the pressure at the minimum breakdown field can be obtained. When this is done and the results are compared with the data of Reference 4, then $i = 1.86$ is obtained for air.

At the minimum breakdown field the shortest resolvable wavelength can now be calculated. By setting $x_d = \lambda/4$ in Eq. (7) and solving Eqs. (7), (8), and (10) for the wavelength, the shortest resolvable wavelength is found to be

$$\lambda_s = 16\ eUt/(3\ mic), \tag{11}$$

where c is the speed of light. This result represents a rather fundamental relationship for any gas and only a knowledge of the mean electron energy and scattering angle constant is required. But since the mean electron energy for any gas is less than 5 eV, the scattering angle will be large and i will be of order 1. For the present experiment, $t = 2\ \mu s$, $i = 1.86$, and $U = 1.5$ eV, so that $\lambda_s = 0.5$ cm.

If it is desirable to resolve shorter wavelengths, then shorter pulses and/or higher electric fields could be used as shown in Fig. 7. The dotted curve is a plot of the diffusion relation (Eq. 7) with $x_d = \lambda/4$, $U = 1.5$ eV, and $t = 2\ \mu s$. The solid lines are plots of the higher pressure side of the breakdown curve (Eq. 2) for air at different electric field strengths. Since $x_d < \lambda/4$ is required for resolution when diffusion is considered, only wavelengths above the diffusion curve can be resolved. Also, for a particular electric field, λ must lie on the breakdown curve in order for the gas to breakdown only at the standing wave peaks. Thus, the minimum resolvable wavelength at any particular field is given by the intersection of the breakdown and diffusion curves. When the curves do not intersect, diffusion is not a limiting factor and the minimum wavelength is just determined by the field strength. It should be noted that very large electric fields are required as one approaches submillimeter wavelengths.

An expression for the minimum resolvable wavelength in air versus electric field can be found by eliminating the pressure in Eq. (2), (7), (8) and (9) and is given by

$$\lambda^2 = \frac{1}{2E_b^{\,2}} \left\{ (aA)^2 + \left[(aA)^4 + \left(\frac{64eUtAE_b}{3mb} \right)^2 \right]^{1/2} \right\} . \qquad (12)$$

For high electric fields, Eq. (12) reduces to

$$\lambda = \left(\frac{32eUtA}{3mbE_b} \right)^{1/2} . \qquad (13)$$

This very slow dependence on electric field gives a practical limit to the minimum resolvable wavelength.

In order to use this spectrometer for longer wavelengths a larger chamber and lens would have to be built in order to preserve the geometric optics condition. This then sets a practical limit on the utility of this spectrometer for long wavelengths. Effects from electrons hitting the chamber wall and ion motion occur at such low frequencies that they are not a limiting factor in view of the diffraction condition.

V. CONCLUSION

In summary then, a simple spectrometer has been described which is capable of both high power and broadband wavelength measurement. Wavelength resolution has been shown to depend on the reflectivity of the chamber end plate and electron diffusion. Electron diffusion and the characteristic breakdown curve limits the resolvability of submillimeter wavelengths by requiring very high electric fields (> 100 kV/cm). At high fields, the minimum resolvable wavelength is proportional to the reciprocal square root of the breakdown field. This slow dependence on electric field gives a practical limit to both electric field and submillimeter wavelength measurements.

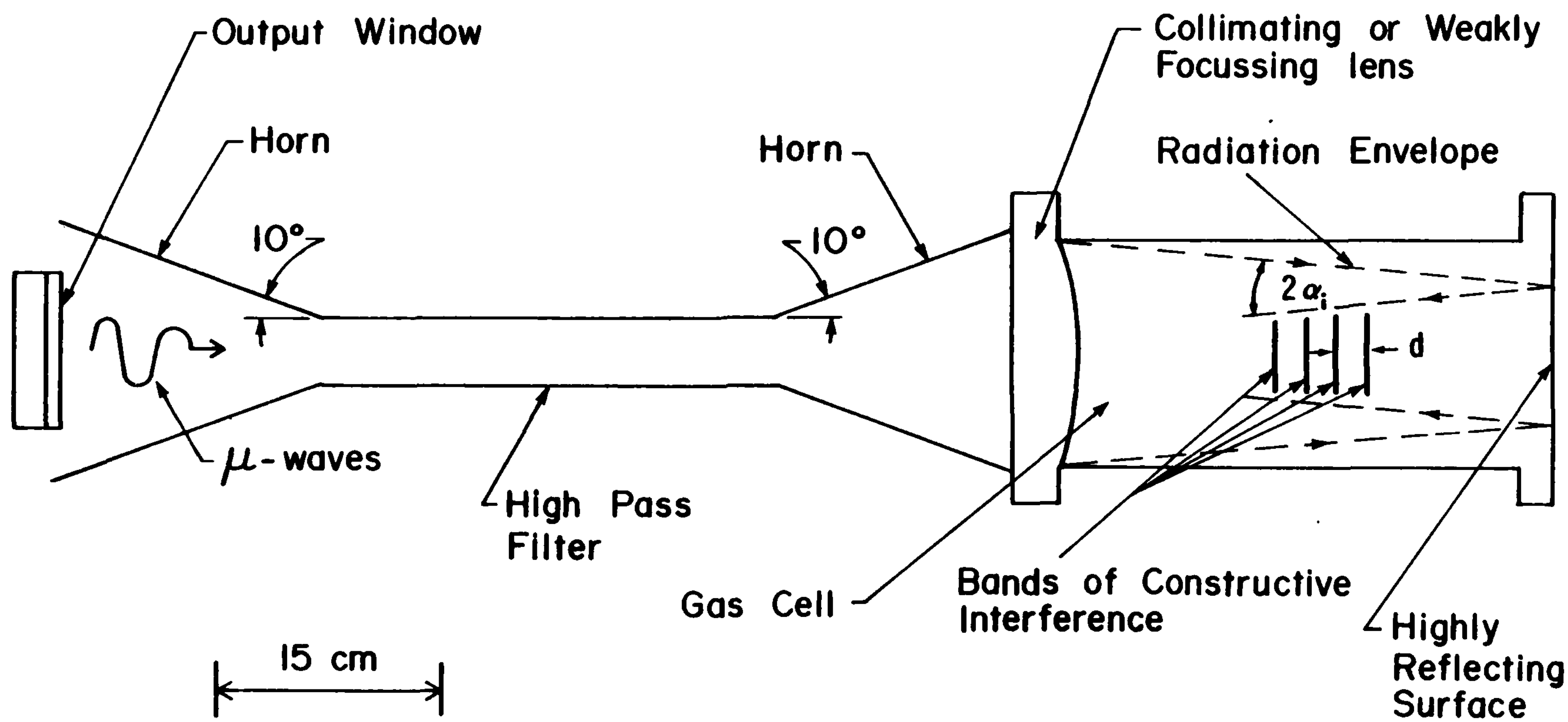

Figure 1. Schematic of the spectrometer.

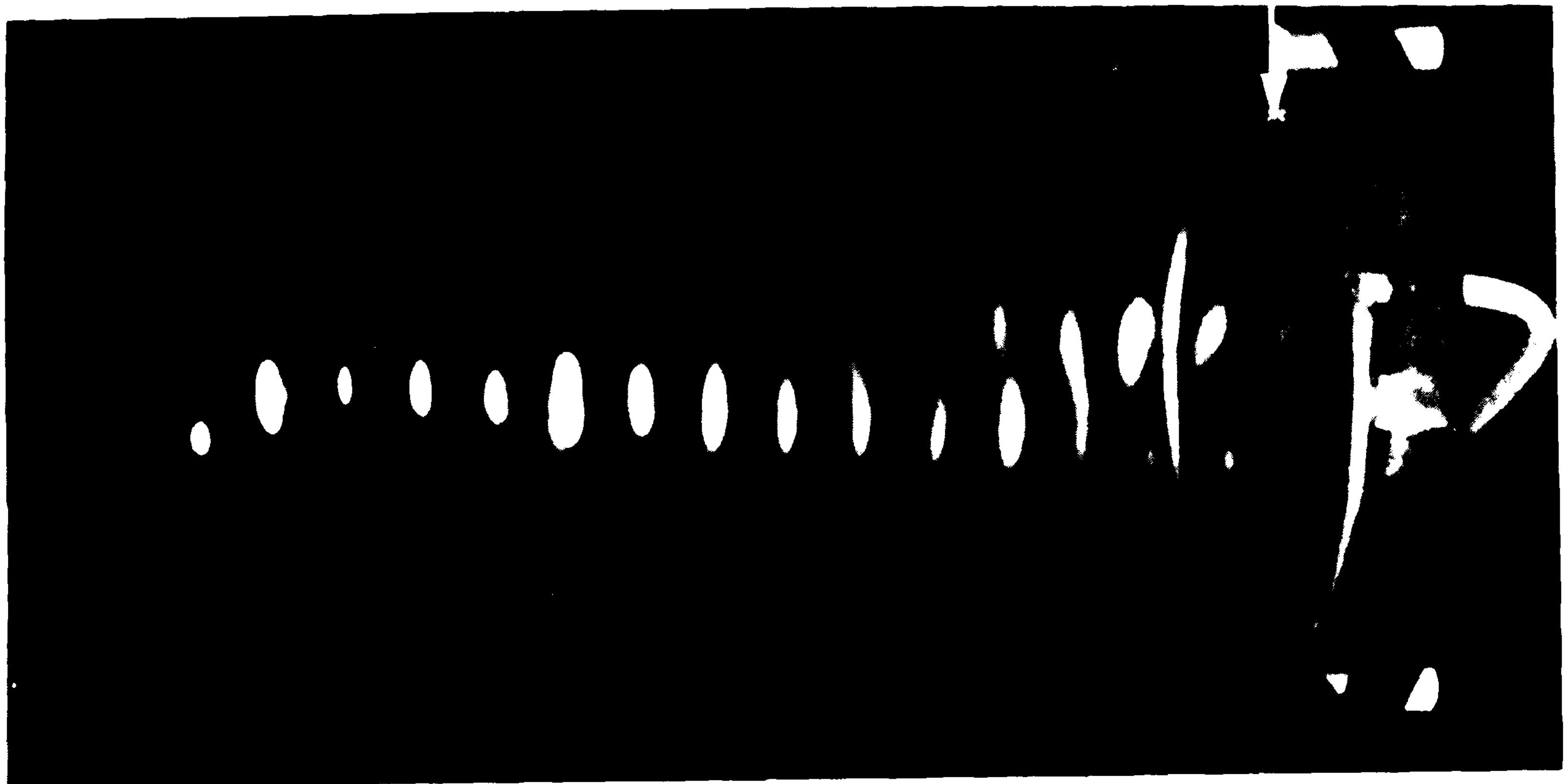

Figure 2. A time integrated photograph of the microwave interference pattern. Bright spots result from breakdown of the gas, in this case nitrogen at 25 Torr. The arrow indicates the location of the copper plate.

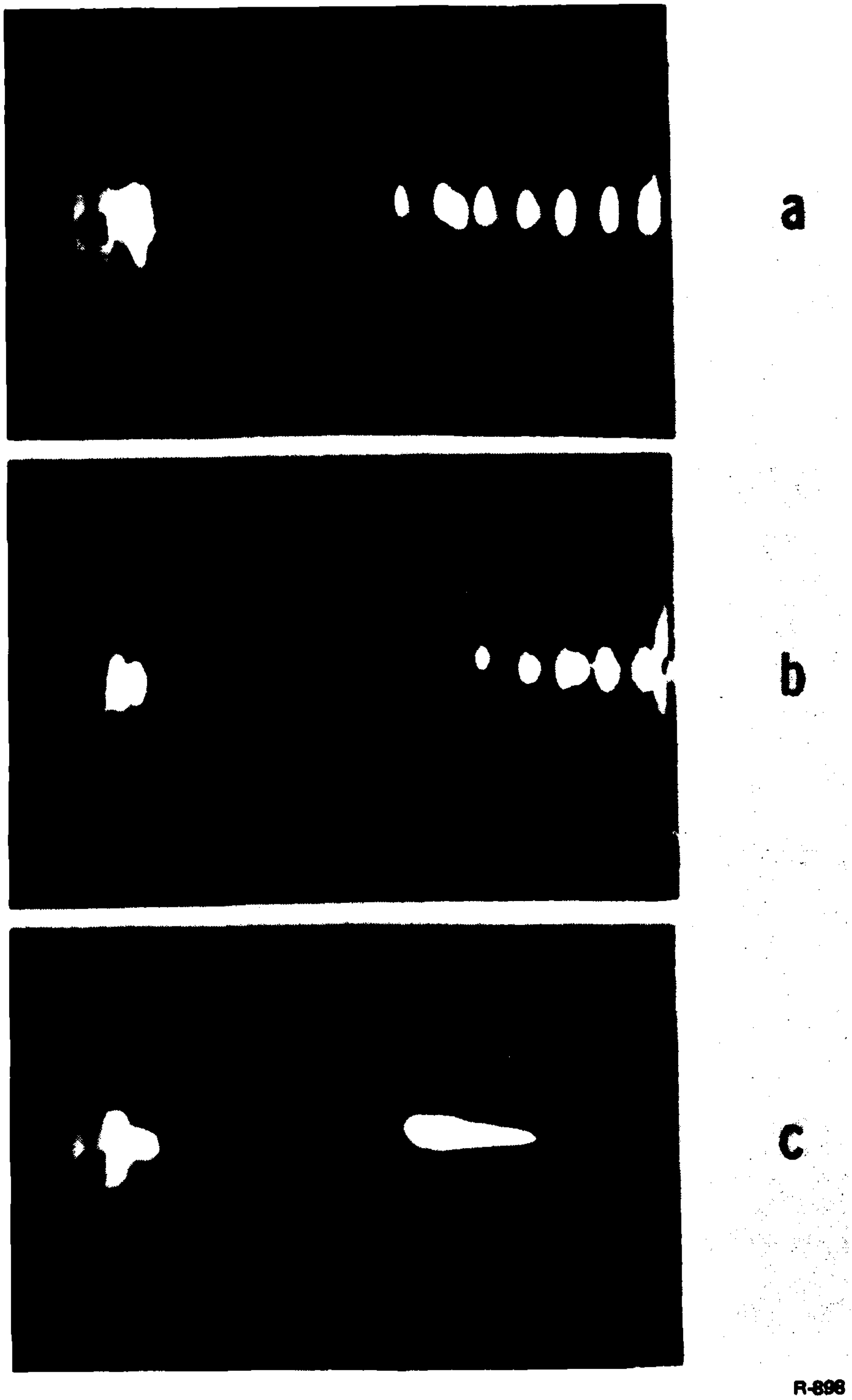

Figure 3. Microwaves entering from the left are focused in front of three different boundaries on the right. a) Highly reflecting boundary. b) Partially reflecting boundary. c) Absorbing boundary. In each case the pressure is 20 Torr.

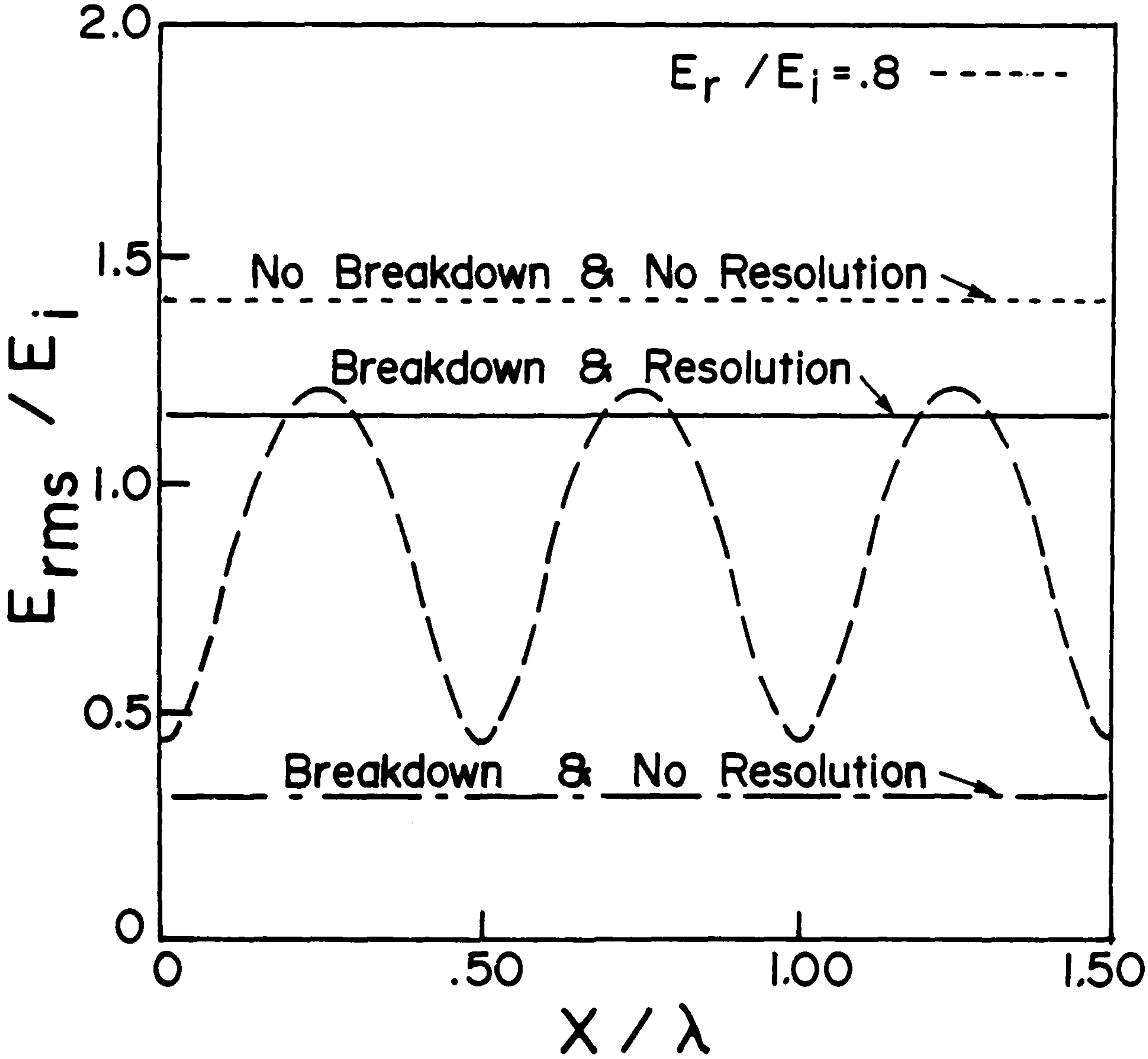

Figure 4. Conditions necessary for wavelength measurement. The dashed curve is the total RMS electric field normalized to the peak incident amplitude. When the required breakdown field is too high (top line) no breakdown occurs. When the breakdown field is too low (bottom line) breakdown occurs everywhere. The correct breakdown is indicated by the solid line. The reflecting surface is located at X = 0.

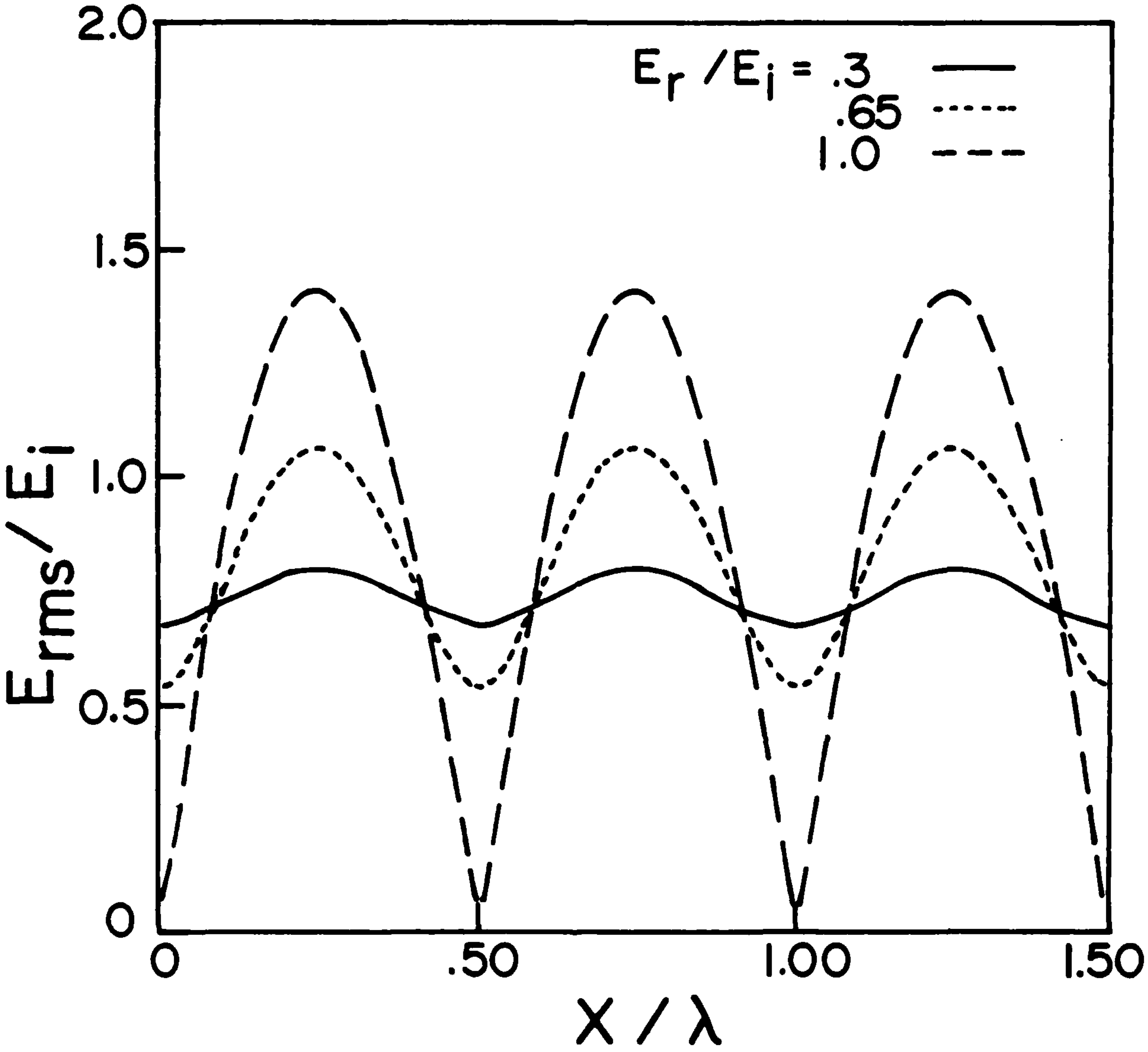

Figure 5. The effect of the boundary reflectivity on the total RMS electric field. Reflected to incident wave amplitude is indicated in the upper right hand corner. Low reflectivity greatly diminishes the ability to select the proper breakdown condition for wavelength measurement.

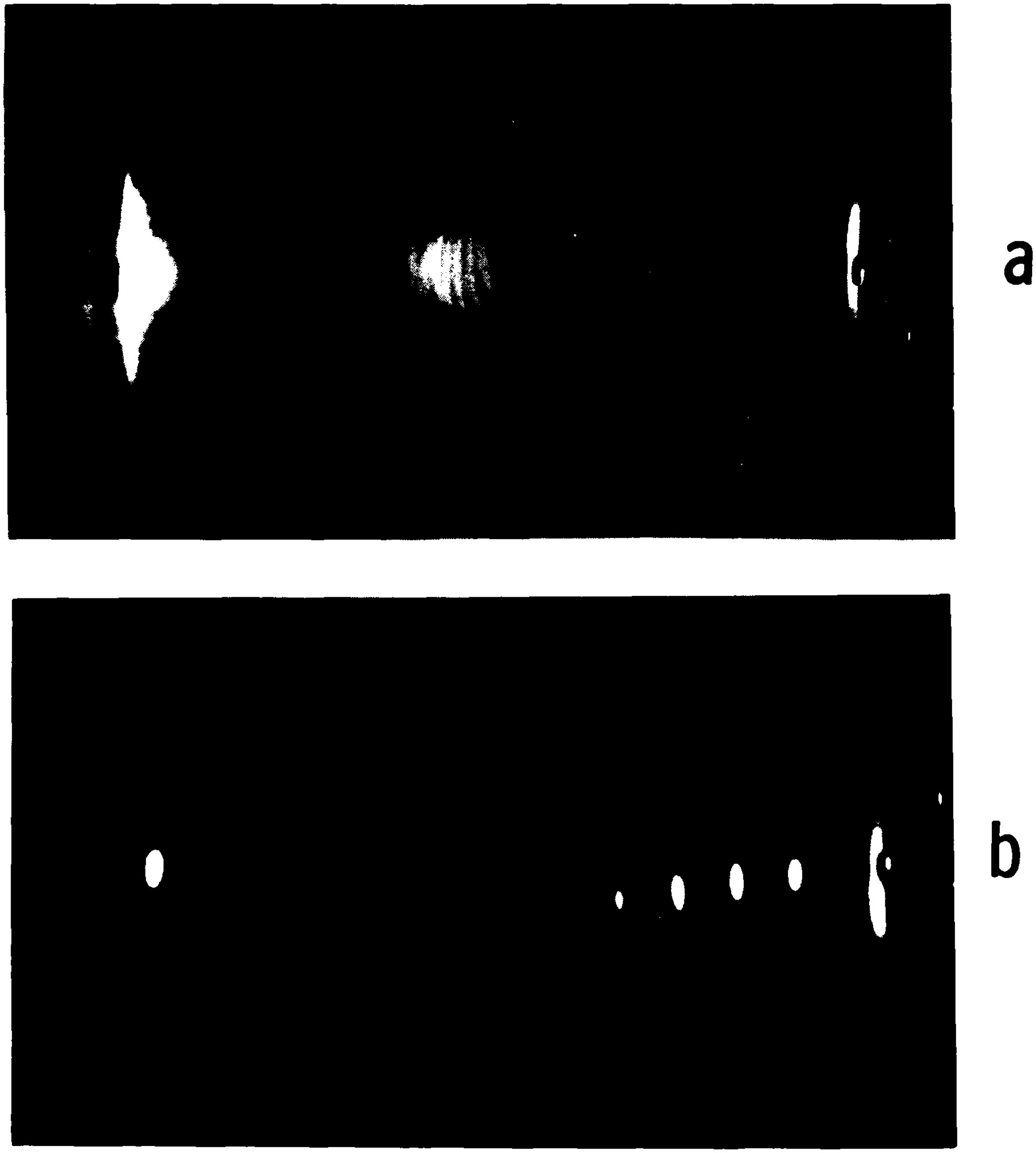

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Figure 6. The impact of low reflectivity and diffusion on wavelength resolution. In (a) a wavelength measurement is not possible; however, by increasing the pressure (b) a wavelength measurement is easily established.

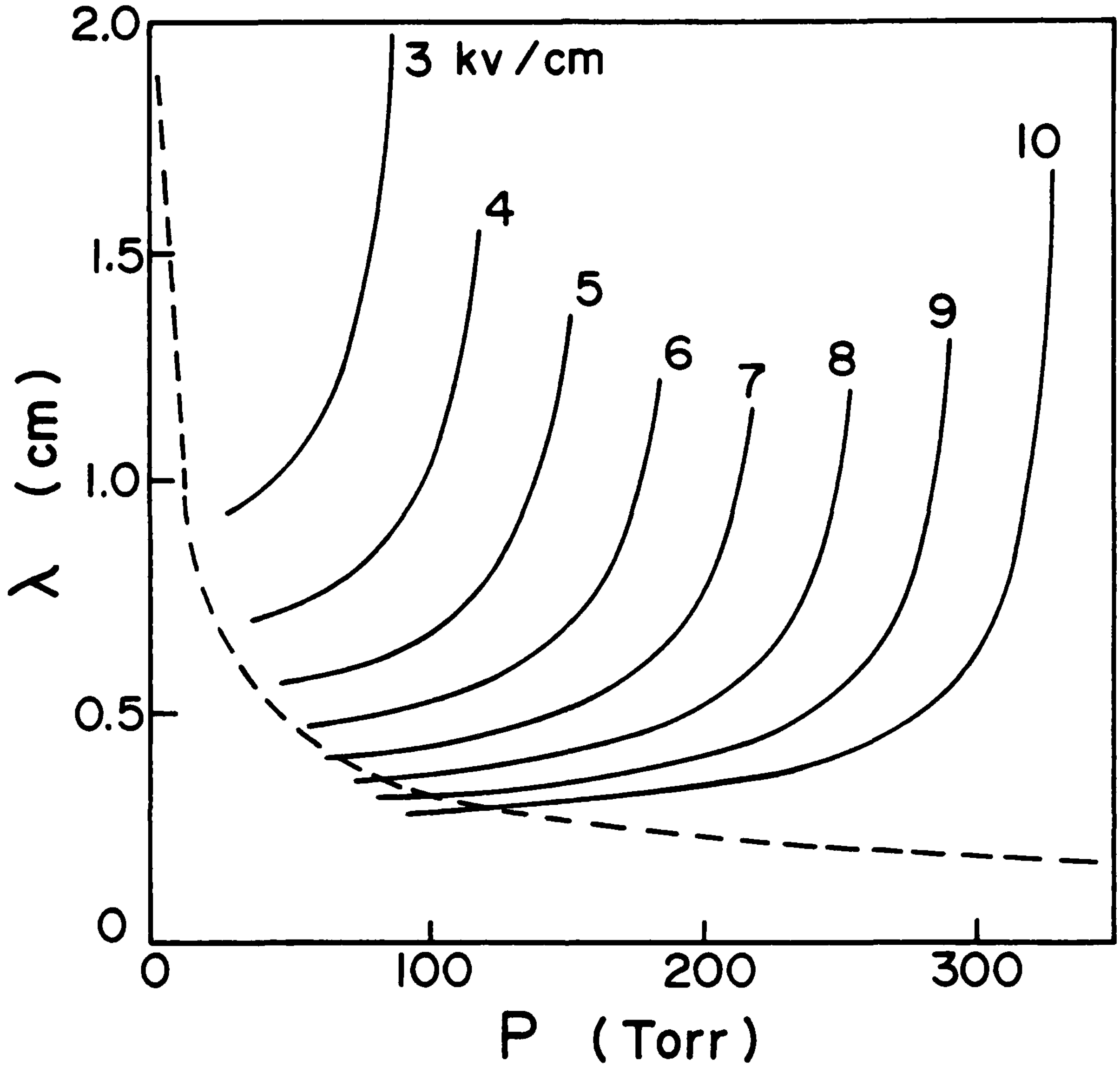

Figure 7. Shortest resolvable wavelength at various electric field strengths. The dotted curve is the diffusion length equated to λ/4, and the solid curves are the characteristic breakdown curves for different electric field strengths. Minimum resolvable wavelength is given by the intersection of the diffusion and breakdown curves, or simply by the bottom of the breakdown curves when the two curves do not intersect. The curves are for air with a diffusion time of 2 μsec and an electron energy of 1.5 eV.

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