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INSTABILITIES IN PENNING DISCHARGES

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This Letter describes some experimental studies of the generation of electromagnetic energy in the microwave region in a cold-cathode Penning discharge operating at gas pressures of a few microns. Studies of electromagnetic radiation from Penning discharges in this frequency region have been reported by several authors. The work described by Bonnal, Briffod, and Manus[1] and by Briffod, Gregoire, and Manus[2] seems to have the closest relation to our work.

The experiments reported here have been carried out with the Penning discharge tubes shown in Figs. 1 and 2. The dimensions of the tubes are given in the figures. The distance between the two cathodes could be varied in tube 1. The cavity (operating in the TM_{010} mode) in tube 1 was introduced in order to measure the electron density in the discharge and the movable rf probe in tube 2 to measure the fields outside the central region of the plasma. Aluminum and graphite were used as cathode materials. This made it possible to work with anode-cathode voltages from 400 to 2000 volts. The dc magnetic field, which was directed along the axis of the tubes and had a constant value in the discharge volume, could be increased up to 2500 gauss in continuous operation. The tubes were operated in a current region of 1-100 mA, and most measurements were made in air at pressures of 1-10 mμ.

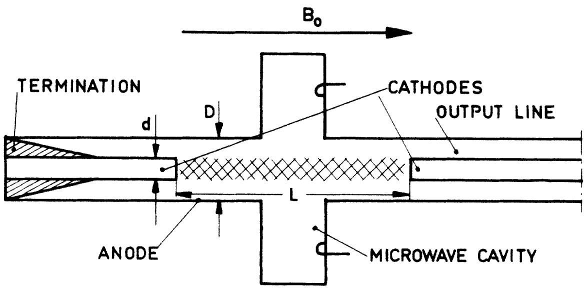

FIG. 1. Tube 1 with dimensions $d = 9$ mm; $D = 21$ mm; $L = 39$-189 mm.

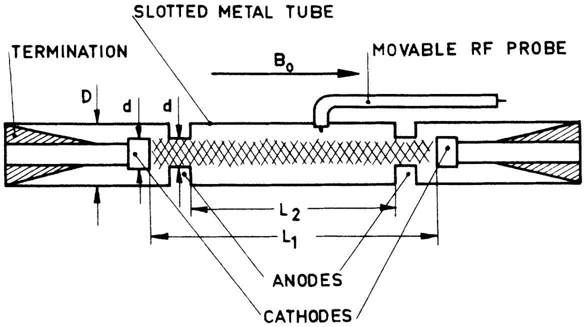

FIG. 2. Tube 2 with dimensions $d = 12$ mm; $D = 21$ mm; $L_1 = 140$ mm; $L_2 = 120$ mm.

The discharge current generally had a low-frequency component of 20 kHz or higher—not caused by the external circuits—and the rf signals appeared as pulses around the maxima of the modulated current. The external low-frequency circuits did not materially affect the generation of the rf noise. The spectrum of the microwave noise could be analyzed by a receiver connected to the coaxial output of the tubes. The peak level of the pulsed noise detected was generally above 10 μW/MHz.

Measurements on tube 1 in the frequency range 0.5-10 GHz with magnetic fields of up to 2500 gauss showed that there is a difference of several orders of magnitude between the amplitudes of the noise for frequencies below and above the cyclotron frequency of the electrons. In fact, noise could not be detected at frequencies above the electron-cyclotron frequency with the receiver used.

The microwave cavity measures the number of electrons in the volume given by the axial length of the cavity and an equivalent diameter of the plasma, probably larger than the diameter of the cathode and smaller than the diameter of the anode. The cavity measurements thus allow an estimate of the electron density, N, from which the plasma frequency for electrons, $f_p = (2\pi)^{-1}(e^2N/\epsilon_0 m_e)^{1/2}$, can be calculated. The measurements show that noise is detectable only for frequencies

Table I. Measurements made on tube 1 with the following parameters: $f_{\text{noise}} = 1.5\text{-}2.2$ GHz; $f_c = 4.2$ GHz; $f_p > 8$ GHz; $p = 2$ μ (air); $V_{\text{disch}} = 500\text{-}800$ V.

L (cm)	$\langle \Delta f \rangle$ (MHz)	$10^{-7} v_p$ (m/sec)	$10^{-7} v_e$ (m/sec)
3.9	170	1.33	1.3
8.9	84	1.49	···
13.9	55	1.53	···
17.0	47	1.59	···
18.9	44	1.66	1.7

below f_p.

The noise power emitted from tube 1 was measured as a function of frequency at given pressures and magnetic fields. Noise in the frequency range 1.2-4.0 GHz was detected by a receiver having a bandwidth of approximately 1 MHz. The curves of power/MHz versus frequency showed evenly spaced maxima and minima. If one assumes that the different noise maxima correspond to different numbers of half-wavelengths in a resonant structure formed by the plasma column and some appropriate end surfaces, and that the phase velocity of the waves does not vary significantly between two adjacent maxima, one can deduce the following simple formula for the phase velocity of the waves, in meters per second:

$$v_p = 2L\Delta f, \qquad (1)$$

where L is the distance in meters between the end surfaces of the resonant structure—taken below as the distance between the cathode surfaces—and Δf the frequency difference in hertz between two adjacent noise maxima.

Measurements were made at different spacings of the cathodes, and the phase velocities were calculated from Eq. (1). The results are shown in Table I together with the discharge parameters. The frequency differences between two adjacent maxima, Δf, were almost constant, and $\langle \Delta f \rangle$ in Table I gives the average values of Δf in the region 1.5-2.2 GHz. The anode-cathode voltage varied from about 500 volts at the smallest spacing to about 800 volts at the largest spacing of the cathodes. The velocities of electrons accelerated by those voltages are given in the last column of Table I.

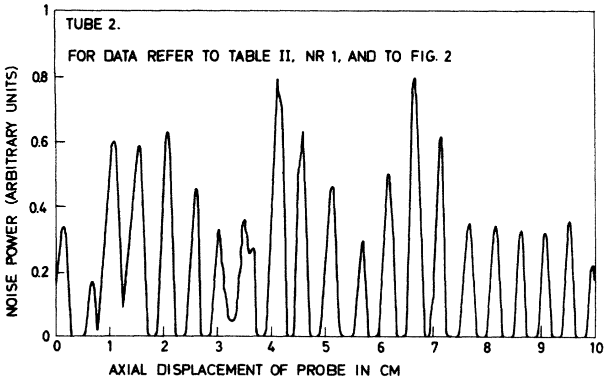

FIG. 3. Standing-wave pattern measured in tube 2 by a probe sensitive to the radial electric field.

The movable probe in tube 2 enabled direct measurements of standing-wave patterns to be made, from which the phase velocities could be calculated. The axial motion of the probe was transferred to the X axis of an XY recorder, and the amplified signal from the probe was fed to the Y axis through a power meter. Figure 3 shows a reproduction of a typical standing-wave pattern measured by a probe sensitive to the radial electric field. It should be pointed out that the phase velocity of the waves is constant along the main part of the discharge column.

The results from two measurements with different anode-cathode voltages are given in Table II together with the discharge parameters. v_e is the velocity of electrons accelerated by the anode-cathode voltage.

The measurements described above strongly indicate that the Penning discharge supports slow electromagnetic waves with a phase velocity roughly equal to the velocity of electrons accelerated in a potential drop equal to that between the anode and the cathode. This observation suggests that a possible explanation of the noise radiation is that the slow waves propagating in the discharge get energy from fast electrons. If we

Table II. Measurements on tube 2.

Measurement No.	f_{noise} (GHz)	f_c (GHz)	V_{disch} (V)	I_{disch} (mA)	p (μ)	$10^{-7} v_p$ (m/sec)	$10^{-7} v_e$ (m/sec)
1	1.43	1.67	660	7.0	3 (air)	1.47	1.52
2	2.80	3.02	2000	8.5	3 (air)	2.78	2.65

assume that most of the discharge electrons have comparatively low velocities, we would expect[3,4] that this magnetized "plasma" could carry slow waves for frequencies smaller than f_c and f_p. Further investigations have to be carried out, however, in order to clarify the behavior of this system.

The authors would like to express their gratitude to K. Bengtsson and L. Ståhle who assisted with the measurements.

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OPTICAL-ENERGY ABSORPTION AND HIGH-DENSITY PLASMA PRODUCTION*

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During the course of further experiments on the phenomenon of gas breakdown at optical frequencies, in which a focused laser beam is used to produce electrical breakdown in a gas,[1,2] a large attenuation of the laser beam has been observed.[3] The apparatus used is shown in Fig. 1; two photomultipliers (*A* and *B*) monitor the laser radiation both before (*A*) and after (*B*) it has passed through the breakdown plasma produced at the focus position of the lens. With the photomultipliers filtered so that they are sensitive only to the 6943Å laser light, it is observed that when breakdown occurs the transmitted laser light is severely attenuated during the later portions of the laser optical pulse. A double exposure of the transmitted laser radiation with and without breakdown is shown in Fig. 2. When no breakdown occurs, the transmitted light has the time history of the upper trace. When breakdown does occur, the laser beam is significantly attenuated as shown by the lower trace. For these experiments the beam power is slightly above the breakdown threshold of the test gas, argon at one atmosphere pressure, and above one half of the one joule incident optical energy is removed from the transmitted beam.

To establish that the appearance of the attenuation was not the result of a different manner of operation of the laser when breakdown occurred or that the breakdown luminosity did not affect the operation of the laser or photomultipliers, a monitor photomultiplier (*A*) was used to observe the laser output at all times. With a neutral density filter placed over the exit aperture of the laser, the beam intensity was reduced such that breakdown did not occur. Under these conditions, photomultipliers *A* and *B* both recorded the same signal. On moving the filter, and one identical to it, to a position just in front of each photomultiplier, the filtering of the light received by the photomultipliers remains unchanged, but the laser intensity at the focus of the lens is now sufficient for breakdown. In this configuration the signal observed by photomultiplier *B* is attenuated, as in Fig. 2, with no change observed in the signal from photomultiplier *A*. Since the filtering of the laser radiation received by the photomultipliers is not changed by shifting the filters, this experiment uniquely

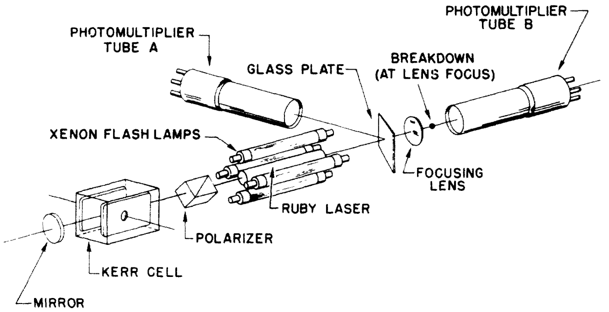

FIG. 1. Gas breakdown apparatus.

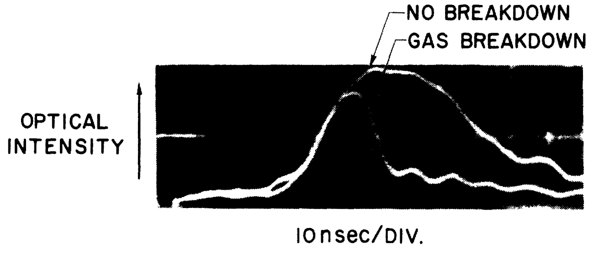

FIG. 2. Attenuation of laser beam by breakdown plasma.