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.

[1]J.-F. Bonnal, G. Briffod, and C. Manus, Phys. Rev. Letters 6, 665 (1961).
[2]G. Briffod, M. Gregoire, and C. Manus, Phys. Letters 2, 201 (1962).
[3]A. W. Trivelpiece and R. W. Gould, J. Appl. Phys. 30, 1784 (1959).
[4]B. Agdur, Proceedings of the Symposium on Electronic Waveguides (Interscience Publishers, New York, 1958), pp. 177-197.

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.

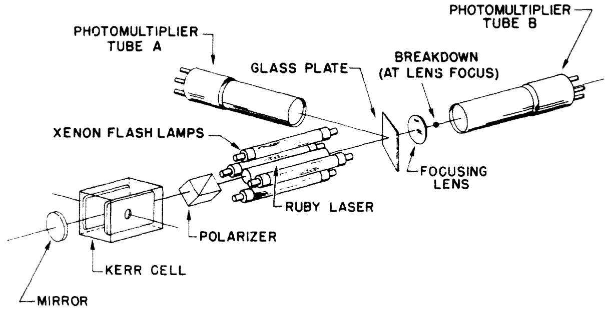

FIG. 1. Gas breakdown apparatus.

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

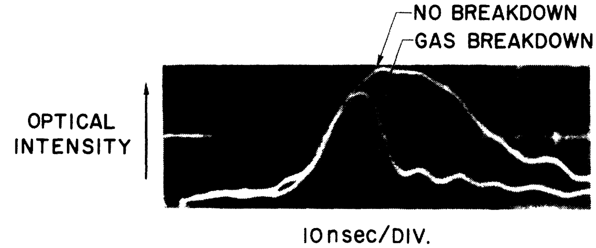

FIG. 2. Attenuation of laser beam by breakdown plasma.

establishes that the attenuation of the laser beam is indeed produced by the breakdown plasma.

This attenuation could arise from a scattering of the laser light by the plasma and, as a result, a series of photomultiplier measurements were made covering the entire solid angle around the breakdown region. It was observed that increased scattering of the 6943Å laser radiation did occur when breakdown took place. However, integrating over the total solid angle, the increased scattering was negligible compared with the one-half joule of energy removed from the transmitted beam, and thus scattering at the laser frequency is not responsible for the observed attenuation.

If the energy lost from the laser beam were absorbed in the plasma, this absorption should be observable as a temperature and pressure rise in a fixed-volume test gas. To test for such an absorption, the breakdown was produced within a small closed cell connected to a sensitive pressure transducer. When breakdown did not occur, no pressure change within the cell was observed. However, when breakdown did occur, a 2-psi pressure increase was measured. This pressure rise in a cell volume of 23 cm^3 corresponds to an energy increase of approximately one-third joule, and is, within the accuracy of the experiments, the energy removed from the incident beam. This experiment establishes unambigously that the energy was truly absorbed from the optical beam as it passed through the breakdown plasma. It should be noted that even if the gas in the 0.2-mm diameter, 0.6-mm long breakdown volume[4] (argon at atmospheric pressure was used in this series of experiments) were fully ionized by the laser beam, the ionization would require only 3×10^{-3} joule. Thus the energy absorbed is far more than that required simply to ionize the gas within the focus region.

Experimentally, then, it is observed that the incident optical-frequency beam is severely attenuated by the breakdown plasma. The energy withdrawn from the beam is far greater than that required to ionize the atoms of the plasma, and most of the energy is neither scattered at the laser frequency nor reradiated by excited atoms but instead is truly absorbed, leading to an increase in the electron density and temperature of the plasma.

The rate of energy absorption by the electrons necessary to produce this attenuation may be compared with that predicted by classical microwave breakdown theory. At a time $\tau = 9$ nsec after the start of the incident laser pulse of Fig. 2, the electrons of the forming breakdown plasma are absorbing about one tenth of the laser-beam power. On the basis of microwave theory, in this 9 nsec an electron in argon at atmospheric pressure would gain only 190 eV of energy from this pulse, a 40-MW laser pulse focused to the 0.2-mm diameter, 0.6-mm long focus region. Assuming 30 eV/(ion pair), this energy gain would result in the increase of electron density by only 100 fold, that is, a production of some 10^2 ion pairs within the focus volume.[5] However, according to classical microwave-absorption theory 10^{14} electrons would be required to produce the observed attenuation,[6] and on the basis of 30 eV/(ion pair) an energy gain of at least 1400 eV would be needed to produce this amount of ionization. Therefore, it appears that conventional microwave theory falls short of explaining the observed ionization rates for the early portion of the breakdown.[7]

Within the range of validity of the present experiments, the discrepancy could result from an anomalously large energy-absorption cross section for electrons in the very high-intensity optical-frequency fields, or a lower energy required for the production of an ion pair than obtained at microwave frequencies.[8] Mechanisms involving quantum mechanical effects as well as classical models are being studied in an attempt to explain this apparent discrepancy.

On the basis of the experimental measurements, then, it has been shown that a plasma can absorb a large fraction of the energy of an optical-frequency beam in a time of the order of a few nanoseconds. This rapid absorption leads to plasma heating rates of the order of tens of megawatts within very small volumes. With over 90% attenuation occuring at later times in the optical pulse, apparently complete ionization of atmospheric-pressure gases is achieved, and thus plasmas with electron densities of the order of 10^{19} cm^{-3} can be produced. Moreover, since optical irradiation introduces no impurities, clean, fully ionized plasmas of extremely high densities are for the first time available for experimental study.

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[1]R. G. Meyerand, Jr., and A. F. Haught, Proceedings of the Sixth International Conference on Ionization

Phenomena in Gases, Paris, 1963, edited by P. Hubert (S.E.R.M.A., Paris, 1964).

[2]R. G. Meyerand, Jr., and A. F. Haught, Phys. Rev. Letters 11, 401 (1963).

[3]A similar attenuation has been observed by William I. Linlor [Phys. Rev. Letters 12, 383 (1964)]. In his experiments, however, the plasmas used were generated by laser interaction with solid targets.

[4]The 0.2-mm focus diameter was obtained from a series of measurements of the hole diameter produced in extremely thin gold foils and is confirmed by calculations of the focus spot size resulting from the measured laser-beam divergence. Similar optical calculations give a length for the focus region about three times the focus diameter.

[5]In this discussion it has been assumed that initially only a single electron is present in the breakdown volume (from cosmic rays, etc.). The results are, however, not appreciably altered by assuming 1, 10, or even 100 electrons initially present within the focus region.

[6]The electron density required to produce the observed attenuation of the optical beam is so high that the Coulomb collisions must be included. A Coulomb collision cross section at an electron energy of 1.3 eV (the lowest temperature consistent with the electron density required for the observed attenuation) is used in this calculation.

[7]R. W. Minck, J. Appl. Phys. 35, 252 (1964), presents data on the optical-frequency breakdown threshold in agreement with microwave-breakdown theory. However, Minck did not measure the size of his focus region, and this agreement is based on an assumed focus diameter. The measurements of references 1 and 2 give a peak power flux for optical-frequency breakdown substantially less than that required by pulse-microwave theory, and both the charge-collection data of these references and the energy-absorption rate calculations of the present paper support this conclusion. It may well be that Minck's focus diameter was, in fact, larger than he assumed and that his results are actually in agreement with those of the present authors.

[8]This possibility has been suggested in a paper by J. K. Wright, to be published. In essence, his theory proposes atom excitation by electrons followed by further excitation and ionization by photoatom interactions. The relevant energy is then not 30 eV/(ion pair) for argon as in conventional breakdown theory, but instead the energy of the first excited state of argon, 11.5 eV.

LOW-FIELD de HAAS–van ALPHEN EFFECT AND FERMI SURFACE IN Ag AND Au[†]

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The first detailed measurements of the deHaas–van Alphen (dHvA) effect in the noble metals (Cu, Ag, Au) by Shoenberg[1] were made with pulsed magnetic field techniques. The results of these and other measurements[2] indicated that the Fermi surfaces of these metals could be represented by a single sheet which was multiply connected along the ⟨111⟩ directions, forming "necks" at the hexagonal faces of the Brillouin zone. Using the steady-field torsion balance technique, we have succeeded in making precise period and effective-mass determinations of the necks in Cu,[3] Ag, and Au, and in addition have discovered several new features. In all three metals, unusual behavior observed in the amplitude of the dHvA oscillations can be attributed to the effect of spin-splitting of the Landau levels.[3] We report also on a new set of dHvA oscillations in Ag which may be interpreted as arising from an overlap of the Fermi surface into the second Brillouin zone at the symmetry point L. With this assumption we estimate an approximate value for the energy gap across the hexagonal face of the first Brillouin zone in Ag.

The torsion balance used for the present experiment has been described in detail in previous publications.[3,4] The cylindrical samples (0.10-in. diam × 0.10 in. long) of Ag and Au were spark cut from single-crystal rods grown by K. R. Garr of Atomics International. The resistivity ratios of the as-grown crystals were 615 and ≈580 for Ag and Au, respectively. The specimens were mounted in both cases so that the magnetic field was in the {110} plane of the crystals.

The results of the dHvA period measurements associated with the neck orbits in Ag are plotted in Fig. 1(a). The maximum value of the period

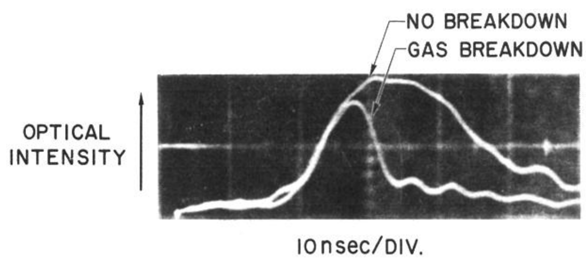

FIG. 2. Attenuation of laser beam by breakdown plasma.