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GAS BREAKDOWN AT OPTICAL FREQUENCIES

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A Q-spoiled ruby-laser system capable of generating a giant pulse of optical energy with a peak power of the order of tens of megawatts has been used to study the interaction of extremely high-intensity optical-frequency electromagnetic radiation with gases. The laser, shown in Fig. 1, consists of a $\frac{1}{2}$-in. diameter, 6-in. long ruby rod pumped by four E.G. & G. FX-47 lamps, each lamp individually powered by a 1200-μF capacitor bank. A polarizer–Kerr cell shutter was used to alter the Q of the laser cavity resulting in a single giant pulse of optical radiation from the laser.[1] The light emitted by the laser is incident on a lens which forms one window of a cell containing the test gas. At the focus of the lens, breakdown of the test gas by the focused laser beam is observed for suitable conditions of beam energy and gas pressure.[2,3]

The breakdown itself is evidenced by the appearance of a bright flash of light at the focus of the lens. The light is not simply scattered laser radiation, since it is readily seen through "band-block" interference filters designed to exclude the 6934Å ruby-laser output, and in addition, from photomultiplier and high-speed framing camera photographs, the breakdown luminosity lasts for a time of the order of 50 μsec compared with the 30-nsec duration of the exciting giant laser pulse.

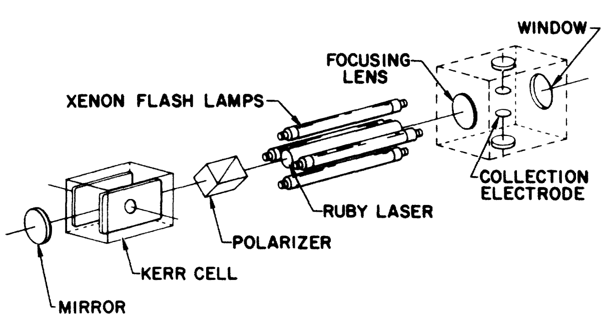

FIG. 1. Q-spoiled laser system.

A pair of electrodes placed on either side of the focus point were used to establish that electrical breakdown, that is, the production of ion pairs, was indeed achieved. Neither the current wave form nor the total charge collected, about 10^{13} electron charges, was affected by electrode potential differences from 100 V to 200 V, the range of the power supply used. Photomultiplier records show that the laser pulse and the breakdown occur simultaneously within less than 50 nsec, the time resolution of the dual-beam oscilloscope.

To compare the phenomena observed here with existing theories of electrical breakdown in gases, measurements have been made of the optical-frequency electrical field required for breakdown as a function of pressure for a number of gases. The electric field strength at the point of breakdown was determined from calorimetric measurements of the energy in the giant optical pulse, the time duration of the pulse as determined by photomultiplier records, and the focus diameter. For a typical case, the energy of the giant pulse was one joule and its duration 30 nsec, giving a peak power of 30 megawatts. The diameter of the focus point, determined by a series of measurements of the hole size produced in $5\text{-}\times10^{-6}$-cm thick gold foil, was 2×10^{-2} cm resulting in a peak power density of about 10^{15} W/m^2. This focus diameter was confirmed by calculations of the demagnification ratio of the optics using the measured laser-beam divergence. Both of these techniques give an optical-frequency electric field strength of approximately 10^7 V/cm at the focus.

The field strength necessary to produce breakdown in argon and helium is shown in Fig. 2 as a function of gas pressure. In each case the breakdown threshold is observed to decrease with increasing pressure, leveling off at the higher pressures. The field strengths required for breakdown in argon and helium are less than 10^7 V/cm, or 0.1 V across the dimensions of an atom. It should be noted that this field strength is less by two orders of magnitude than that required for a direct electric field stripping of an electron from an atom.

Similarly, since the laser photon energy is approximately 1.7 eV and gases with an ionization potential as high as 24 V (helium) have been successfully ionized by the laser beam, direct single-step photoionization is not possible. Successive photon absorption could conceivably produce the ionization. However, to reach even the lowest lying levels of argon and helium would require, respectively, 7 and 12 successive absorptions. Assuming even a 10% probability for each absorption step, this would imply a 10^5 ratio between the field strengths required for breakdown in argon and helium. The experimentally observed ratio is only 1.7, indicating that multiple photon absorption is not responsible for the breakdown.

The curves of Fig. 2 are threshold curves, that

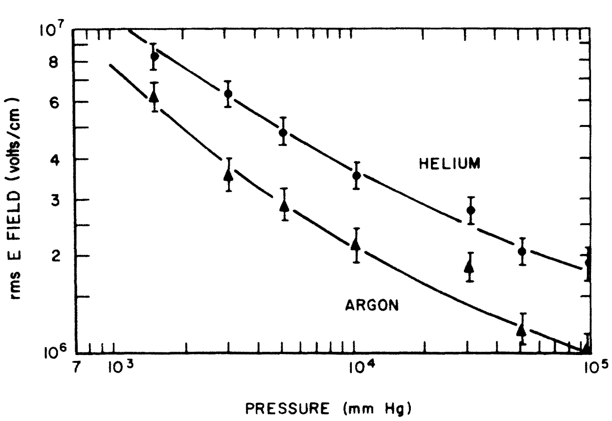

FIG. 2. Breakdown field strength as a function of pressure.

is, for values of pressure and field strength which lie below the curve for a given gas, no ionization is observed in that gas, while at a slightly higher pressure or field strength above the curve, breakdown results and a very large degree of ionization is produced. This abrupt change implies some form of cascade process with a critical level of energy input required to sustain the process, a condition not predicted by the photon-atom processes considered above.

Cascade theories have been developed for gas breakdown at microwave frequencies.[4] The theories predict an energy input to the electrons from the oscillating electromagnetic field through the mechanism of electron-atom collisions which convert the ordered oscillatory motion of the electrons in the field to random motion. The electrons gain random energy on each collision until they are able to make ionizing collisions with gas atoms leading to succeeding generations of electrons. These theories, however, cannot be applied to explain the breakdown at optical frequencies, since important differences exist between the two cases. In the microwave case, the maximum kinetic energy in the ordered oscillatory motion of the electron in the electromagnetic field corresponds to a kinetic energy of the order of 10^{-3} eV, while typical microwave photon energies are of the order of 10^{-5} to 10^{-6} eV. Thus, an electron oscillating in the electromagnetic field must absorb and emit many microwave quanta of energy every cycle, and its motion may be considered to be classical. In the optical case, for the field strengths used in these experiments, the oscillatory energy of the electron is classically also of the order of 10^{-3} eV, but the photon energy for a ruby laser is 1.7 eV. The classical oscillatory energy of the electron is thus small compared with the photon energy, and one might expect that the motion of the electron and its subsequent interaction with atoms and the radiation field is governed by quantum effects. In fact, from the uncertainty principle the energy of the electron during any one cycle of the oscillating electromagnetic field cannot be determined to better than $\Delta E \geqslant \hbar\nu$, and therefore, it is not meaningful to discuss an electron oscillation energy of 10^{-3} eV in a 1.7-eV photon field.

Even assuming that the electron behaves classically in an optical-frequency field, not enough energy is given to the electrons to account for the ionization observed. At a helium pressure of 1500 mm Hg and an optical field strength at which breakdown occurs, microwave breakdown theory predicts that an average electron would gain only 190 eV of energy during the optical pulse. Thus assuming 30 eV are required to produce an ion pair, the ionization produced during the pulse would be many orders of magnitude below the experimentally observed value of 10^{13} ion pairs, determined by the charge collection experiments.

In the classical theories for breakdown at microwave frequencies, an electron can receive at most only the 10^{-3} eV of ordered oscillatory energy from the electric field in an electron-atom collision. However, at optical frequencies the absorption can become a quantum-dominated process, and the possibility exists that a large fraction of the photon energy can be transferred to an electron during a collision. The process of bremsstrahlung, photon radiation from electrons during an interaction with an atom or ion, is well known. The reverse process may also occur in which an electron gains energy by absorbing either the entire photon or some significant fraction of its energy during a collision with an atom.[5] It is felt that a process of this inverse bremsstrahlung type is the mechanism responsible for the breakdown at optical frequencies.

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SCATTERING OF RUBY-LASER BEAM BY GASES*

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The advent of the laser[1,2] has at last made it possible to made a detailed study of Rayleigh scattering.[3] Earlier measurements giving the right order of magnitude of the Rayleigh cross section were made at 90° in argon.[4]

With the development of monochromatic, coherent light sources and sensitive photodetectors, it is now possible to determine the angular distribution of the molecular scattering of light. A preliminary study of the divergence of the laser beam showed that the intensity of the laser light even at an angle of 80° was only reduced by a factor of 10^{-5} with respect to that of the forward beam.[5] This was found to be many orders of magnitude larger than the expected intensity of the light scattered from gas molecules. Thus it was necessary to design an optical system which would prevent this light from scattering off the walls of the apparatus. The schematic diagram of the system which reduced the spurious scattering to a tolerable level is shown in Fig. 1. The ruby-laser beam is focused at the center of the observation chamber by means of a long focal-length lens (focal length is 23.3 cm). The exit window is placed at the Brewster angle, and the observation chamber is shadowed from both the lens and window by two irises.

Observations are made in the horizontal plane. The scattered light is detected by photomultiplier No. 1 (RCA 7102), placed at the observation tubes which are located at every 15° around the scattering chamber. The light scattered from the exit window is detected by photomultiplier No. 2 (RCA 7102). Its output is used as the reference signal, since it is a measure of a quantity proportional to the intensity of the laser beam. Both photomultipliers are provided with appropriate interference filters.

The angular distribution of the scattered light observed in argon at atmospheric pressure and room temperature (296°K) is given in Fig. 2 and Fig. 3. Figure 2 shows the intensity variation for a horizontally polarized laser beam, and Fig. 3 shows the variation when the beam is vertically polarized.

The dashed line in Fig. 2 shows the $\cos^2\theta$ dependence predicted by Rayleigh's theory, fitted to the average experimental values obtained at