Breakdown and Self-Focusing Effects in Gases Produced by Means of a Single-Mode Ruby Laser

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***Abstract*—Using a passively *Q*-switched ruby laser, operating in a single axial and transverse mode, sparks produced in a number of gases at pressures ranging from 760 to 9000 mmHg have been studied. Breakdown threshold measurements for both single and multimode laser radiation have been made and in addition, the characteristics of the sparks produced with single-mode radiation have been investigated.**

Photography at 90° of the scattered laser light showed the existence of scattering regions with transverse dimensions not exceeding the 5-μ resolution of the optical system. Furthermore, a large amount of laser light is scattered in the forward direction. The intensity, angular distribution, and spectral characteristics of this scattered radiation have been determined. Various possible mechanisms that could account for these phenomena are discussed, and it is concluded that self-focusing of the laser beam after the initiation of the breakdown process may be occurring.

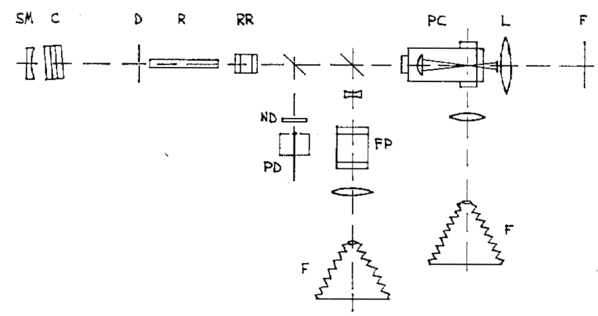

Fig. 1. Experimental setup. *SM*—spherical mirror, *C*—dye cell, *D*—diaphragm, *R*—ruby, *RR*—resonant reflector, *PC*—pressure cell, *L*—lens, *F*—camera, *ND*—neutral filters, *PD*—photodiode, *FP*—Fabry–Perot interferometer.

Introduction

ALTHOUGH laser-induced breakdown of gases has been investigated extensively during the last six years, most experimental studies have been carried out with lasers having an uncontrolled and undefined mode structure. An investigation of the influence of the laser modes on the breakdown threshold has been reported in only one paper [1], and until recently [2] no attempt had been made to study any other properties of the sparks produced by radiation from a single-mode laser.

The present paper contains a number of new experimental observations that were obtained by extending the investigation described in [2] to include a number of gases at pressures ranging from 760 to 9000 mmHg. In addition, breakdown threshold measurements were made in three gases and both the pressure and focal volume dependence were investigated. The results obtained differ significantly from those obtained by means of multimode lasers and a number of mechanisms that might be responsible for the characteristics of the sparks produced are discussed.

Experimental Setup

The laser and pressure cell in which sparks were produced are shown in the diagram of the experimental arrangement (Fig. 1). The select quality Czochralski ruby, which had a diameter of $\frac{3}{8}$ inch and a length of 6 inches, was antireflection coated at each end and situated within a ~1-meter-long optical cavity. One reflector was a 1-meter-radius spherical mirror with a 99-percent-reflectivity coating while the other consisted of a pair of high-quality quartz flats optically contacted to a $2\frac{1}{4}$-inch quartz spacer. The active volume of the laser rod was limited by means of a 1.6-mm-diameter aperture placed within the cavity and Q switching was achieved by means of a solution of cryptocyanine in methanol contained in a 1-mm-thick cell. In order to obtain operation in a single axial and transverse mode, the absorber cell and the ruby had to be misaligned with respect to the resonant reflector even though the rod was antireflection coated. Although its position in the cavity was not important, the pinhole had to be centered with respect to the ruby. This latter requirement may have resulted from the nonuniformity of the double elliptical pumping geometry. The optical quality of the ruby was by far the most important factor involved in obtaining single-mode operation. In addition, it should be noted that in contrast to previously published results [3], single-mode operation could not be achieved when a flat rather than spherical 99-percent-reflectivity mirror was used.

The temporal variation of the laser output was observed by means of a photodiode and Tektronix 519 oscilloscope while a plane Fabry–Perot interferometer, having a free spectral range of 1500 MHz was used to monitor the spectrum. Operation in a single mode resulted in a measured finesse of 15 with an additional indication being the very high reproducibility of the almost Gaussian pulse shape. As has been already noted by others [4] a number of superimposed oscilloscope traces could not be distinguished from the trace obtained with a single pulse. A typical

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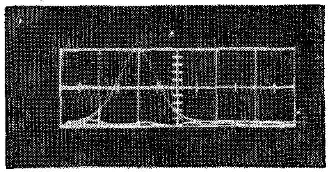
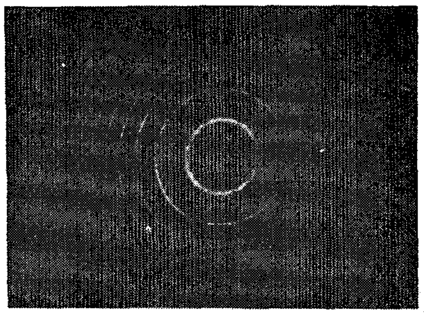


(a)

10 ns/div



(b)

$\Delta\bar{\nu} = 0.05\ \text{cm}^{-1}$

Fig. 2. Oscilloscope trace of a typical single-mode pulse (peak power 4 MW) and corresponding Fabry–Perot interferogram (measured finesse ~15).

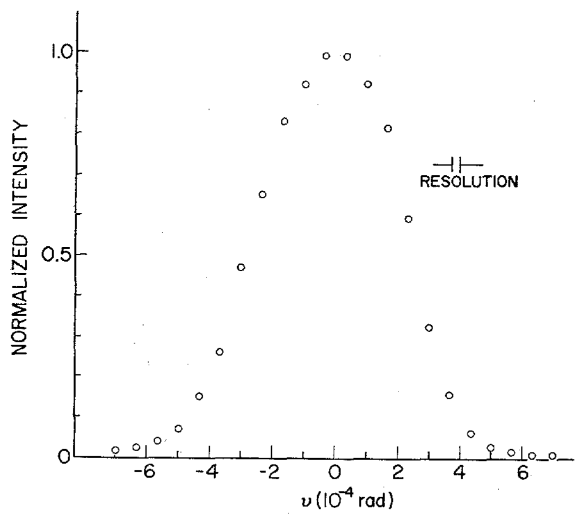


Fig. 3. Intensity distribution of the single-mode laser far-field pattern. The $1/e$ beam divergence is 0.63×10^{-3} radian, full angle.

pulse having a peak power of 4 MW, and the accompanying Fabry–Perot interferogram are shown in Fig. 2. The presence of a single transverse mode was demonstrated by investigating the near- and far-field patterns, the former photographically and the latter by means of a photodiode behind a 20-μ pinhole that was used to scan the intensity distribution at the focus of a 1-meter focal length lens. This permitted the distribution to be plotted as shown in Fig. 3 where it can be seen that it is very nearly Gaussian with a $1/e$ beam divergence of 0.63×10^{-3} radian, full angle. Although each point in Fig. 3 corresponds to a different laser shot it is unlikely that this resulted in a significant error in view of the extremely high reproducibility of the laser output.

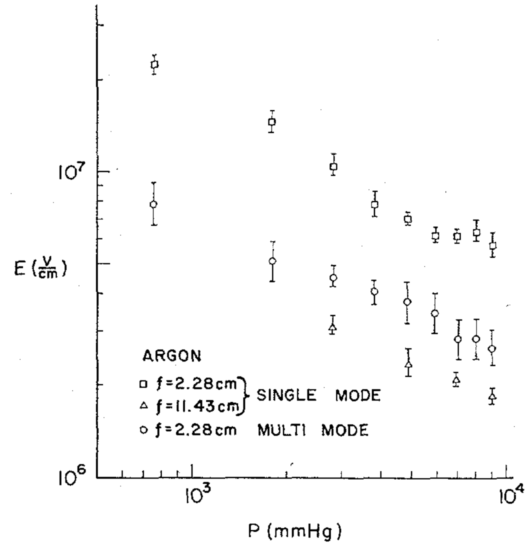


Fig. 4. Breakdown threshold electric field versus pressure in argon for single-mode and multimode ruby laser radiation.

The single-mode radiation emitted by the laser was focused in the pressure cell by lenses with focal lengths varying from 1 to 13 cm. In addition to the entrance window, the cell had four side windows permitting observations in a plane normal to the laser beam axis, and one large exit window. A number of diagnostic techniques were used to investigate the sparks and will be described in the following section together with the experimental results.

Experimental Observations

The first investigation carried out with the experimental arrangement described above was a study of the breakdown threshold in argon at pressures ranging from 760 to 9000 mmHg. Sparks were produced by focusing the beam with lenses of 2.28- and 11.43-cm focal lengths, and threshold fields are plotted in Fig. 4 where it can be seen that when the longer focal length lens was used the threshold field was approximately one third of the value required with the short focal length lens. A series of measurements was also made using the short focal length lens and with the laser operating in the multimode regime. This was achieved by reducing the length of the cavity, removing the pinhole, and replacing both the resonant reflector and spherical mirror with plane dielectric coated mirrors. With this cavity, the Fabry–Perot interferograms indicated that more than 10 axial modes were present and measurement of the beam divergence yielded a value of $(4.11 \pm 0.45) \times 10^{-3}$ radian. The error is due both to shot-to-shot variation of the beam divergence and to the irregular shape of the focal spot. As can be seen from Fig. 4, the breakdown thresholds obtained for the multimode case are 50 percent higher than those measured when the single-mode laser was focused with the 11.43-cm focal length lens, even though the beam-divergence measurements indicate that the focal spot diameter is larger in the multimode case. Both single and multimode meas-

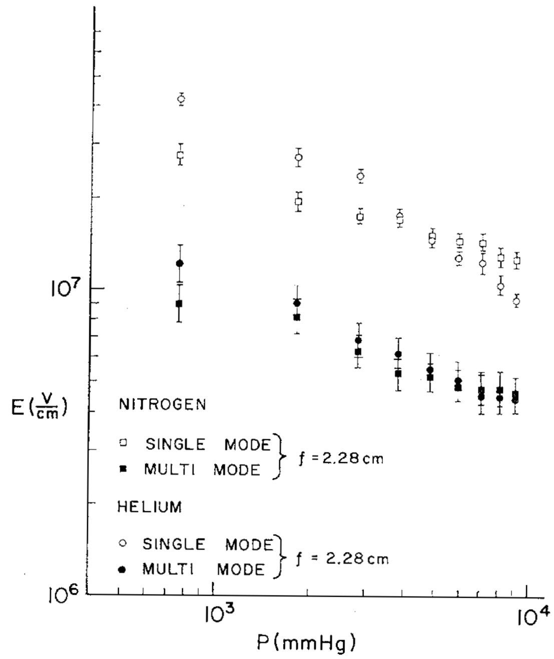


Fig. 5. Breakdown threshold electric field versus pressure in helium and nitrogen for single-mode and multimode laser radiation.

urements were also carried out in nitrogen and helium and the results obtained are presented in Fig. 5.

Although these results are in order of magnitude agreement with previous measurements of the breakdown threshold [5] they do demonstrate a noticeable difference between the multimode and the single-mode cases.

In order to check that the above effect did not result from the difference in diffusion losses, the diffusion length for a cylindrical breakdown region that is given by

$$\frac{1}{\Lambda^2} = \left(\frac{\pi}{l}\right)^2 + \left(\frac{4.8}{d}\right)^2$$

where

$$l = (\sqrt{2} - 1)\,\frac{f^2\theta}{\alpha} \qquad d = f\theta$$

and

f lens focal length,
θ beam divergence,
α beam diameter,

was calculated for the two cases. The two values of Λ ($1.5 \sim 10^{-3}$ cm and 1.58×10^{-3} cm) obtained do not differ sufficiently to account for the change in threshold, since E_{th} depends on Λ through the relation

$$E \propto (1/\Lambda^{0.75}).$$

Although this dependence of E upon Λ was obtained previously with multimode radiation [6], an investigation of the threshold in argon at pressures of 2800 and 8850 mmHg confirmed its applicability to the single-mode situation (Fig. 6).

Apart from the breakdown threshold measurements a number of other characteristics of the sparks produced in nitrogen, Freon, methane, helium, argon, neon, krypton, and xenon were investigated. As in the case of air [2] the first observations were made by using scattered laser radiation to obtain high-magnification (~100) time-integrated photographs showing the extent of the plasma's development along the laser beam axis. A narrow-band interference filter centered at the laser wavelength was used. The photographs revealed that the scattered light originated in regions running parallel to the beam and having a diameter that was not more than the 5-μ resolution of the optical system. (Note that the focal spot diameter was varied between 15 and 80 μ.) In addition it was found that, in general, the molecular gases were characterized by almost continuous filaments, whereas in the noble gases a number of widely separated scattering points were observed. This effect is illustrated in Fig. 7, which shows photographs obtained by focusing the laser output in argon and nitrogen with a 4.9-cm focal length lens; the laser power was just above the breakdown thresholds in the two gases. A series of photographs was obtained at pressures ranging from 760 to 9000 mmHg revealing a similar difference between molecular and noble gases at all pressures, although the separation of the scattering regions in the noble gases increased as the pressure was reduced. In addition, when laser powers well in excess of threshold were used, the scattering regions always had a fork-like structure, as has been noted previously by Savchenko and Stepanov [7]. It was also found that, contrary to these previous observations, the scattered light in xenon and krypton exhibited a similar structure although its intensity was approximately two orders of magnitude lower than in argon.

An investigation of the temporal development of the filaments was carried out by means of a Space Technology Laboratory (STL) image-converter camera, operating at the maximum streak rate of 2.5 mm/ns. A 1-mm slit was used to give a time resolution of approximately 0.4 ns, and examples of the streak photographs obtained in nitrogen at 3800 mmHg and argon at 1500 mmHg are presented in Fig. 8. In addition to illustrating the difference between the two gases mentioned above, it can be seen from the figure that the filament in nitrogen expands towards the laser with a velocity that decreases

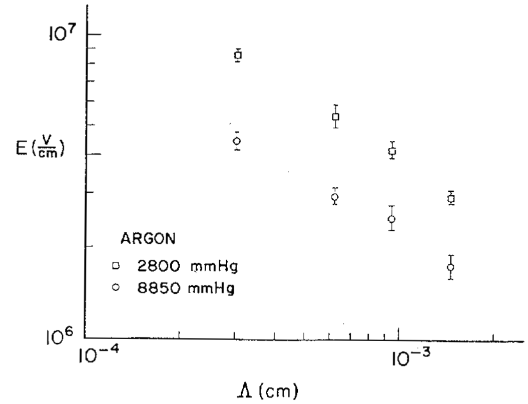
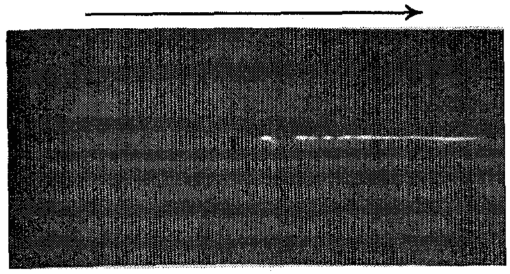
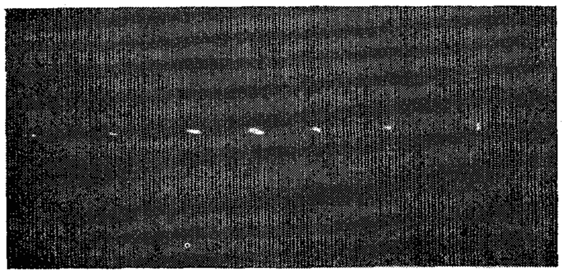


Fig. 6. Breakdown threshold electric field versus diffusion length for argon obtained with single-mode ruby laser radiation.



(a)



(b)

0.1 mm

Fig. 7. Photographs of ruby laser light scattered at 90°. (a) Nitrogen at 3800 mmHg. (b) Argon at 1800 mmHg. The arrow indicates the direction of the laser beam.

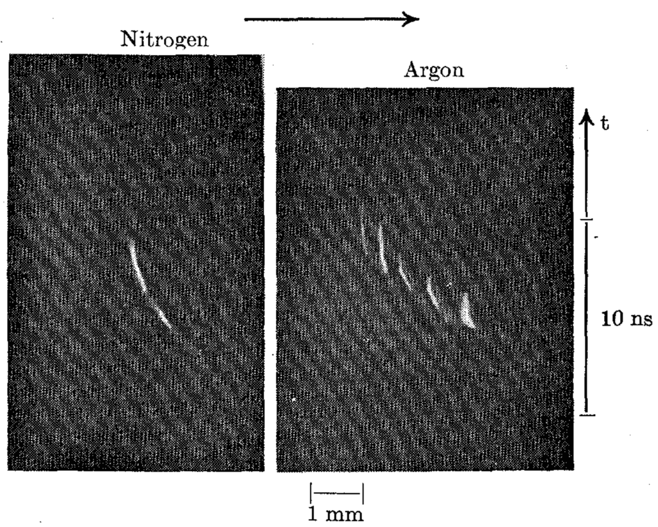


Fig. 8. Streak photographs of ruby laser light scattered at 90°. Nitrogen at 3800 mmHg; argon at 1800 mmHg; time resolution 0.5 ns. The arrow indicates the direction of the laser beam.

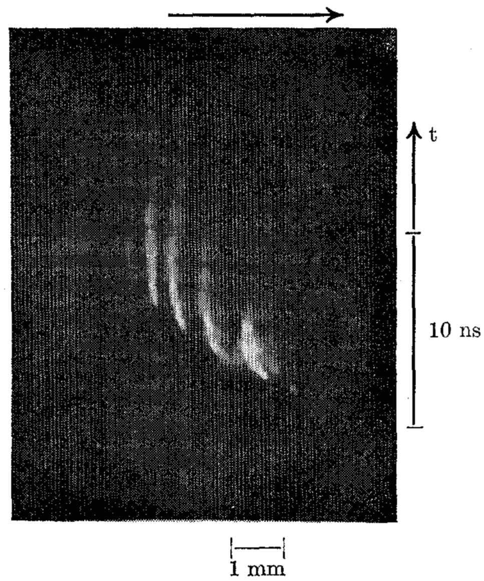
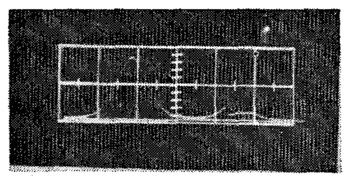
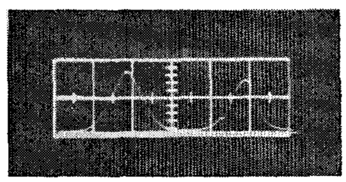


Fig. 9. 90°-streak plasma development. Argon at 1800 mmHg; time resolution 0.5 ns. The arrow indicates the direction of the laser beam.



(a)



(b)

10 ns/div

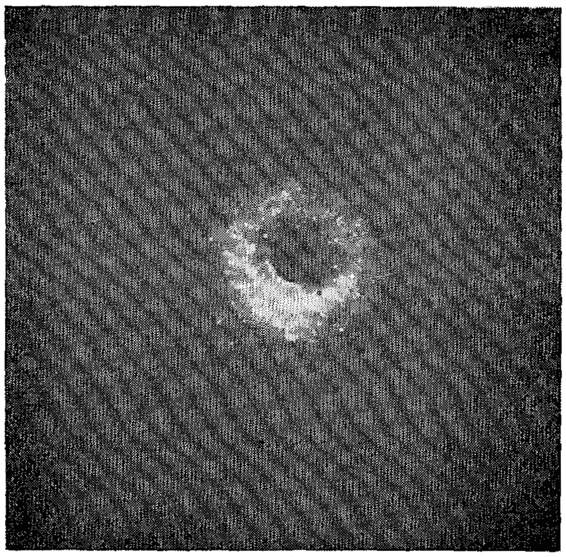
Fig. 10. Oscilloscope traces showing forward-scattered ruby laser light in argon at 8300 mmHg. The first signal on each trace corresponds to the incident laser pulse, while the second delayed signal corresponds to the forward-scattered laser light. (a) Accepting only light traveling in the same direction as the incident laser beam. (b) Accepting all light of laser wavelength emerging from the breakdown region at angles up to 30° to the forward direction. The two photodiodes are normalized to give the same signals when no spark is produced. Peak power of the incident pulse is 4 MW.

smoothly from an initial value of approximately 1.5×10^7 cm/s. However, in the case of argon, a filament only expands for a few nanoseconds before there is an abrupt decrease in its velocity and another filament appears several hundred microns ahead of it.

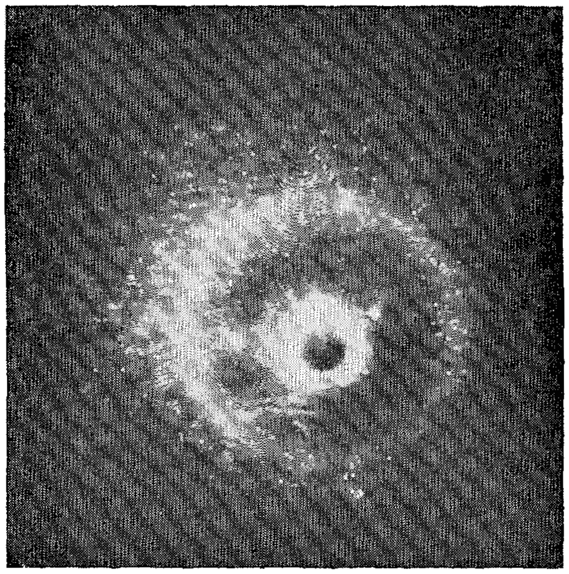
Streak photographs were also obtained with a blue filter that transmitted the visible radiation emitted by the plasma and excluded the scattered laser light, and as can be seen in Fig. 9, these confirmed that the small scattering centers seen in argon did in fact correspond to separated plasma regions formed at intervals of 1 or 2 ns.

In addition to the photographic observations made by means of the light scattered at ~90° to the laser beam direction, scattered light emerging in the forward direction was also investigated. This was done both photoelectrically and photographically, and oscilloscope traces showing the forward-scattered light in the case of an argon spark are presented in Fig. 10. In this figure the incident laser pulse occupies the first half of each trace while the second, delayed, photodiode signal shows the forward-scattered light transmitted by a narrow-band interference filter centered at the laser wavelength. Without any spark, equal signals were obtained from both photodiodes. Fig. 10(a) was obtained by placing in front of the second photodiode an aperture that transmitted only the radiation traveling in the same direction as the incident beam and shows that the occurrence of breakdown is accompanied by the apparent absorption of approximately 80 percent of the remainder of the pulse. In contrast to this, Fig. 10(b) shows both the incident pulse and the signal observed when light emerging at angles up to ~30° from the forward direction is detected. It can be seen that over 80 percent of the incident pulse now reaches the photodiode and thus the true absorption is, in fact, quite small. Similar effects were observed when sparks were produced in all other gases, although the fraction of the scattered light reaching the second photodiode was always less than that observed in argon. In all cases the polarization of this radiation was found to be the same as that of the incident light, irrespective of the polarization of the latter. Within the range of pressures and incident powers employed, it was found that the ratio of the peak of the scattered light to the peak of the incident light did not vary by more than ~10 percent. However, when the forward-scattered light was detected photographically it was found that the angle of maximum emission was strongly pressure dependent. This effect is illustrated in Fig. 11, which shows the scattered radiation emerging from argon sparks at pressures of 760 and 9000 mmHg. The two photographs were obtained by using an obstacle to block out the direct laser radiation transmitted through the focal region and permitting any radiation that passed the obstacle to fall on the photographic film after passing through a narrow-band interference filter. At the higher pressures the laser power required for breakdown was sufficiently low such that no detectable radiation leaked past the obstacle when the power was just below the breakdown threshold. However, as can be seen from Fig. 11(a), scattered light emerging at angles up to ~5° from the forward direction was observed when a spark was produced. At lower pressures the higher laser power required for breakdown resulted in a noticeable leakage around the obstacle; however, the scattered light emerging at angles up to 9°, Fig. 11(b), could be distinguished from it.

By collecting the forward-scattered light emerging at angles up to 30° and focusing it on a ground-glass screen, the spectral characteristics of this radiation were investigated by means of Fabry–Perot interferometers having plate separations of 2.5, 1, and 0.3 cm. The interferograms revealed a broadening of the spectrum towards longer wavelengths in the case of air [8] and other molecular gases while both anti-Stokes shifts and broadening were observed in noble gases. An example of the results obtained in argon at a pressure of 760 mmHg is shown in Fig. 12, where interferograms produced in the absence of breakdown [Fig. 12(a)] and in the presence of breakdown [Fig. 12(b)] are presented. As can be seen from the figure, the scattered light has a spectral width of ~0.1 cm^{-1} and is shifted toward shorter wavelengths by ~0.2 cm^{-1}. Interferograms obtained over the pressure range from 760 to 9000 mmHg revealed that the broadening changed slightly, but that the shift decreased rapidly as the pressure increased. This effect is illustrated in Fig. 13, where the experimentally observed shift versus pressure is plotted for three noble gases.



(a)

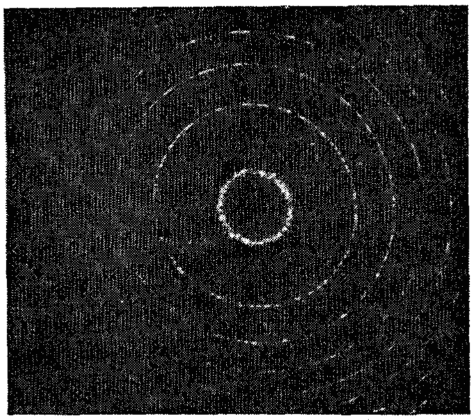


(b)

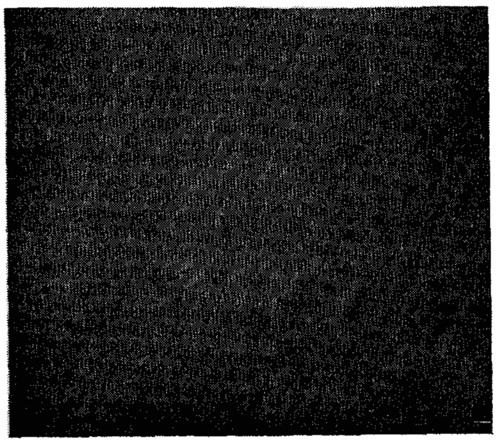
Fig. 11. Forward-scattered laser light in argon. (a) Pressure of 9000 mmHg. (b) Pressure of 760 mmHg.

An investigation of the backward-scattered radiation was also carried out. However, in the presence of a stray light signal corresponding to approximately 0.25 percent of the incident light, no backward scattering from the spark could be detected.

An attempt was made to investigate, with the same diagnostics, the sparks produced by a multimode laser. For this experiment a conventional 100-MW ruby laser, Q switched by means of a Pockels cell, was used. Although the same experimental setup was used, the conditions were now changed considerably due to the larger beam diameter ($\frac{5}{8}$ inch) and beam divergence (2 mrad). With this laser, time-integrated photographs, taken by means of the 90°



(a)



(b)

$\Delta\bar{\nu} = 0.5 \text{ cm}^{-1}$

Fig. 12. Fabry–Perot interferograms of forward-scattered laser light. (a) Without spark. (b) With spark in argon at 760 mmHg.

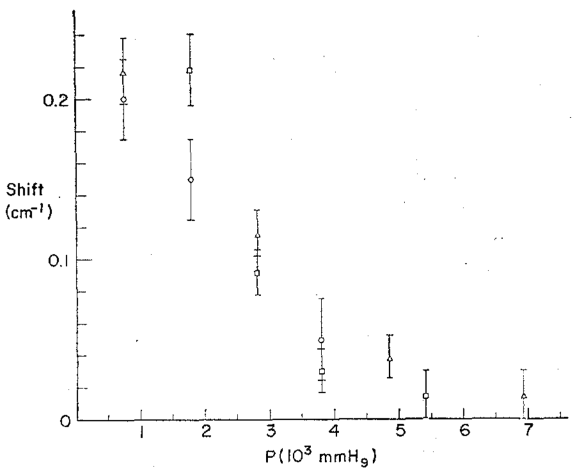


Fig. 13. Experimentally observed frequency shift of forward-scattered laser light versus pressure for sparks in argon, krypton, and xenon. Δ—argon; □—krypton; ○—xenon.

scattered laser light transmitted through a narrow-band interference filter, revealed the existence of many small scattering regions occupying the entire focal volume as shown in Fig. 14. Although it was possible to detect some

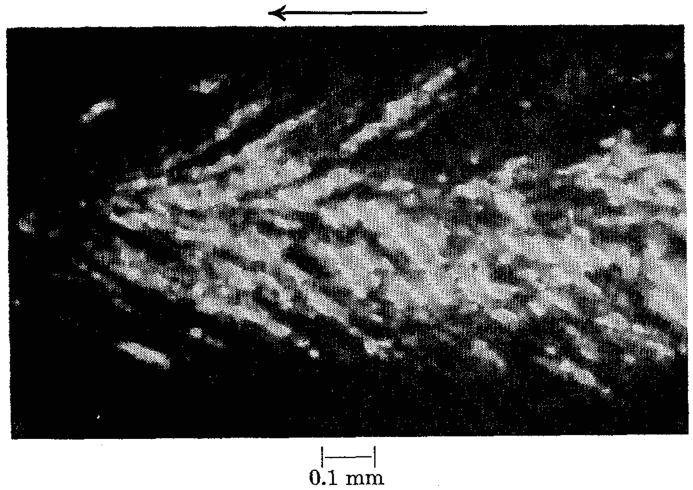


Fig. 14. Ruby laser light scattered at 90° when a multimode laser is used; argon at 7800 mmHg. The arrow indicates the direction of the laser beam.

forward-scattered light, its relatively low intensity precluded a detailed study of its characteristics.

Discussion of Results

The experimental results presented in the preceding section show considerable differences in the sparks produced by the output of a single-mode laser from those produced by that of a multimode laser. In addition to an apparent reduction in the breakdown threshold, these include such characteristics as the filamentary nature of the scattering regions, the large fraction of incident light scattered in the forward direction, and the spectral properties of this scattered radiation.

The difference in breakdown thresholds observed with single and multimode laser outputs is probably to be expected since the spatial and temporal fluctuations of the field distribution in the focal region, which occur in the case of multimode radiation, result in significant uncertainties in the actual breakdown threshold conditions. Previously reported measurements of the threshold field obtained with single-mode laser radiation [1] indicated that, to within the measurement accuracy, there was no difference in the threshold conditions for the single-mode and multimode cases. The results of the present experiment show a small, but measurable difference in the two thresholds. This may simply result from the use of space- and time-averaged measurements in defining the characteristics of the multimode laser radiation and consequently illustrates the importance of using single-mode lasers for the determination of accurate threshold values.

Considering now the nature of the scattered laser radiation emerging at 90° to the beam axis, a number of other authors have reported the observation of small isolated scattering regions and have concluded that the observed radiation is either refracted by the plasma [7] or reflected at its boundary [9], [10]. The small size of the observed regions, relative to the transverse dimensions of the focal volume, was explained in several ways. Ahmad *et al.* [9] suggested that reflection occurred in the spherical shock front of a radiation-driven shock wave and that the small apparent size of the scattering regions was a consequence of geometrical effects of the detecting optical system. An alternative explanation [7] is based on the existence of irregularities, such as refractive index fluctuations in the surface of the spark. These hypotheses could be applied to explain the present results and, on the basis of the 90° scattering alone, it is difficult to discriminate between them and the possibility that the scattering regions indicate the true transverse dimensions of the plasma and/or the beam of laser radiation.

It has also been suggested that the structure of the spark may result from intensity variations, within the focal volume, arising from the spherical aberration of the focusing lens [11]. This explanation appears to be less plausible since the small diameter of the single-mode laser beam (1.6 mm) would, according to this proposal, result in the predicted intensity maxima having a separation considerably larger than that actually observed. It also fails to account for the large effect that the type of gas and its pressure have on the separation of the scattering regions.

None of these proposed mechanisms, however, satisfactorily accounts for the large proportion of the incident laser light scattered in the forward direction. Certainly it is possible that radiation, striking at grazing incidence conical plasma regions pointing towards the source of radiation, could result in a cone of reflected light propagating in the forward direction. However, it seems unlikely that as much as 80 percent of the incident radiation would be reflected in this manner unless the transverse dimensions of the plasma were considerably larger than those of the observed scattering regions. Additionally, the spectral properties of the scattered radiation do not appear to correspond to any of the known stimulated scattering phenomena.

The possibility that the observed effects result from self-focusing of the laser radiation has been suggested already [2] and although this hypothesis cannot account for all of the experimental results it does provide a qualitative explanation for a number of them. For self-focusing to occur it is necessary for the refractive index to vary with the laser intensity. Such an effect could occur, prior to breakdown in the neutral gas, during the breakdown process when there exists a partially ionized gas containing atoms at various levels of excitation, or after breakdown in the resulting plasma.

The occurrence of self-focusing in the neutral gas is difficult to justify as a possible mechanism for several reasons. First, this would imply that all previous explanations of the breakdown process were no longer valid and that the observed threshold was in fact the self-focusing threshold and not that of cascade ionization as is generally believed. However, the agreement between the absolute breakdown threshold values and those predicted by the cascade ionization theory is reasonably good as is the agreement between the observed pressure dependence of the threshold and theory. In addition to the above reasons, any self-focusing mechanism invoked must have a threshold that corresponds to that normally required for gas breakdown. An estimate of the self-focusing thresholds can be obtained from the expression for critical power derived by Kelley [12]. Thus the critical power P_c is given by

$$P_c \approx \frac{(1.22\lambda)^2 c}{256 n_2},$$

where the refractive index of the gas is related to the field strength and n_2 by the expression

$$n = n_0 + n_2 E^2.$$

In a neutral gas the field-dependent term can arise from electrostriction or the optical Kerr effect. Values of n_2 and P_c for argon and nitrogen are presented in Table I. From this table it can be seen that the lowest threshold will be that due to electrostriction; however, even this is an order of magnitude higher than the observed breakdown thresholds. Furthermore, electrostriction is a bulk effect and the refractive index change cannot occur in a time shorter than that required for a sound wave to propagate across the focal spot. In the case of a spot diameter of 30 μ this results in a delay time of $\sim 10^{-7}$ second, which is considerably longer than the duration of the pulses used in the experiment. Although the Kerr effect does not suffer from this limitation, it can be seen that this mechanism would result in a much higher threshold. Thus, it appears that the probability of self-focusing occurring prior to the onset of ionization is extremely small.

An alternative possibility is that of self-focusing occurring during the development of the electron cascade. During this stage, there exists within the focal region a mixture of electrons, ionized atoms, and neutral atoms at various levels of excitation. The presence of free electrons will result in a reduction of the refractive index, and if the electron density distribution corresponds to that of the radiation intensity, the refractive index gradient will have a defocusing effect. However, in many cases it appears likely that ionization occurs by photoionization of excited atoms, and as has been pointed out by Askar'yan and Rabinovich, the populations of ionized, excited, and overexcited atoms (i.e., atoms excited to within one or two laser photon energies of ionization) may be approximately equal [13]. Although little experimental data are available, one would expect the absolute polarizabilities of the excited atoms to be considerably greater than that of the unexcited or ionized atoms. This is borne out in the case of excited argon [14] ($^3P_2$ state), where the observed polarizability is $\sim 10^{-22}$ cm^3, which exceeds by approximately two orders of magnitude that of the ground state. This results in a refractivity, $(n - 1)_{AI}$, of $6 \times 10^{-22} N_{AI}$ while at a wavelength of 7000 Å the electronic

TABLE I

	Electrostriction*		Kerr Effect†	
	$n_2 \times 10^{15}$ esu	P_c MW	$n_2 \times 10^{15}$ esu	P_c MW
Argon	3.72	23.0	0.04	2140.0
Nitrogen	5.1	16.8	0.14	611.0

* The calculation of n_2 was made using values of density, sound velocity, and refractive index obtained from *American Institute of Physics Handbook* (New York: McGraw-Hill, 1963) and *Handbook of Chemistry and Physics* (New York: Chemical Publishing, 1964).

† The values of n_2 quoted for the Kerr effect were obtained from I. L. Fabelinshii, *Molecular Scattering of Light* (Reading, Mass.: Plenum, 1968, p. 555). Since neither gas possesses a permanent dipole moment it has been assumed that the optical Kerr constant is equal to the dc value.

polarizability is $-2.3 \times 10^{-22} N_e$ (where N_e and N_{AI} are the densities of electrons and excited argon atoms, respectively). Thus, it is not inconceivable that the presence of large numbers of excited atoms could cancel the effect of the electrons, yielding a refractive index gradient capable of inducing a self-focusing effect.

Finally the possibility of self-focusing occurring in the plasma itself must be considered. Here, as in the case of the neutral gas, a number of mechanisms can give rise to a nonlinear refractive index, and an obvious example is the inherent nonlinearity of an electron gas due to the Lorentz force [15]. This, coupled with relativistic effects, can lead to an intensity-dependent refractive index associated with local fluctuations in electron velocity. However, such effects are not likely to be appreciable at the power densities used in the present experiment [16], [17]. Nevertheless, there are a number of other processes such as density changes, induced thermally or by means of the gradient of the beam intensity, which may be important. Recently such mechanisms have been treated theoretically [16], [18] and the minimum powers required to sustain a self-trapped filament estimated. In both cases the powers required are comparable to, or lower than, those required to produce breakdown and thus self-focusing effects within the plasma certainly cannot be ruled out. However, in these theories, no attempts were made to estimate the self-focusing length and its dependence on the amount by which the critical power is exceeded. In addition, the predicted power for self-trapping due to ponderomotive forces is independent of the plasma density (provided $\omega > \omega_p$) and the conditions for self-trapping appear to have been satisfied in numerous experiments where scattered laser light has been used to study the parameters of laboratory plasmas with densities as high as $10^{17}/\text{cm}^3$. In no cases have anomalous results been reported and it therefore appears necessary to establish in more detail the conditions where such effects will definitely occur.

In conclusion, the investigation of sparks produced by single-mode laser radiation has revealed a number of new and interesting phenomena lacking a satisfactory explanation at the present time. Although a hypothesis based upon self-focusing appears to be a likely candidate, additional experiments are essential to confirm this explanation and throw further light on the type of mechanism involved.

Note Added in Proof: Evidence for self-focusing has also been reported recently by Tomlinson [19] who carried out an experimental investigation of laser light scattered at 90° from a gas breakdown plasma. Photomultiplier measurements of the scattered intensity coupled with time-integrated and time-resolved photographic observations indicated that the scattering is due to reflection by an extended core of high-density plasma having a diameter of a few microns. It is suggested that this effect is a result of self-focusing brought about by a nonlinearity that develops in the plasma after the ionization process has begun.

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