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RADIATION SCATTERED FROM THE PLASMA PRODUCED BY A FOCUSED RUBY LASER BEAM

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Is is now well known that gas breakdown at optical frequencies can be produced in the focused beam of a ruby laser. In the present communication we wish to report observation of scattering of the laser beam itself by the plasma so formed. The observations are consistent with scattering by the free electrons in the plasma, under conditions such that the spectral distribution of the scattered radiation is governed by cooperative interactions between the ions and electrons. Rather surprisingly, the wavelength of the scattered radiation is observed to be shifted slightly with respect to that of the laser beam. This is interpreted as a Doppler shift due to a motion of the plasma during the initial phase of the spark.

The experimental arrangement was as shown in Fig. 1(a). The beam from a Q-spoiled ruby laser was focused at the point P by a lens L_1 of focal length approximately 8 mm. At output powers of 5 MW and above, a spark was produced at P. Most of the work was done using sparks in air, although breakdown has also been observed in a jet of helium, directed towards the focal point P.

Radiation from the spark was observed in a direction at right angles to the beam and focused onto the slit of a spectrograph, equipped for both photoelectric and photographic recording, by a lens L_2. A light trap served to reduce stray light from the laser beam itself.

In the visible region of the spectrum, the radiation from a spark in air consisted of an intense continuum upon which were superimposed a few N II lines. The radiation scattered from the laser beam appeared as a sharp line close to the laser wavelength, but shifted from it by up to 3 Å. This line was absent when breakdown was prevented—by attenuating the laser beam slightly—showing that it was not due to scattering from the air itself. The observations also rule out any possibility that the line is due either to stray light entering the spectrograph slit or to deviation of the laser beam by changes in refractive index in the region of the spark.

The variation with time of the scattered radiation, the laser emission, and the radiation from the spark was as shown in Fig. 2(a). The measurements had a time resolution (as determined using a short-duration pulsed light source) of 20 nsec, and a time jitter of ±5 nsec. The scattered radiation occurred only after breakdown had taken place—as determined from the onset of radiation from the spark—and only during the latter part of the laser pulse.

When the laser beam was recollimated after the spark, delayed 30 nsec by sending it around a 9-meter optical path, and then refocused onto the spark in a direction at right angles to both the primary beam and the direction of observation, a second scattering signal was obtained [Fig. 2(b)].

By using a long (50-cm) focal-length lens to refocus the laser beam onto the spark it was possible to establish that the second scattering sig-

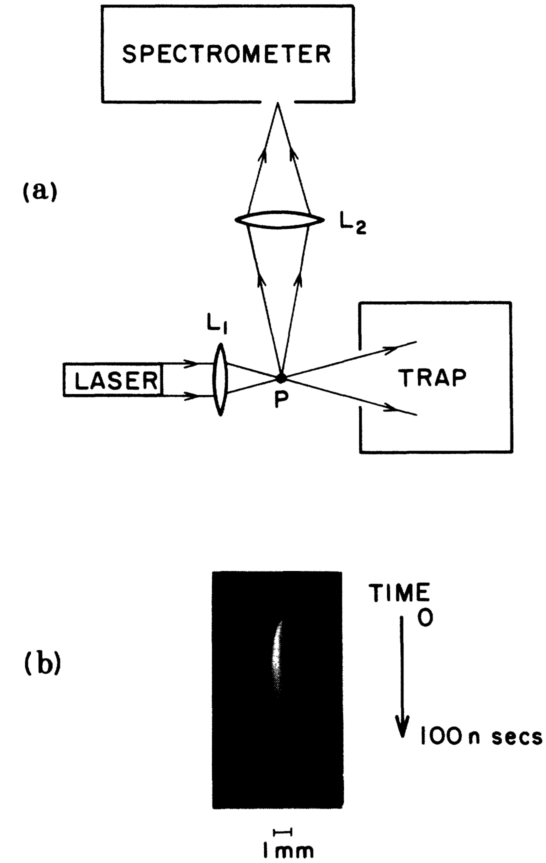

FIG. 1. (a) Diagram of apparatus. (b) Streak photograph of the spark.

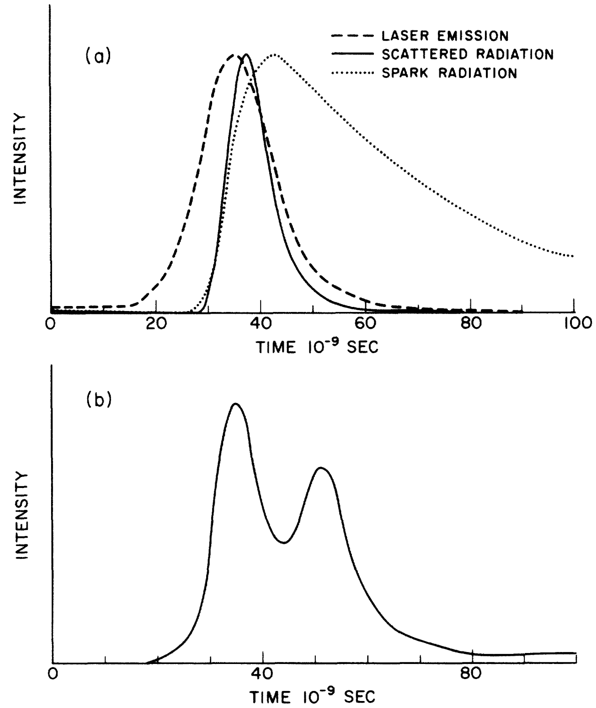

FIG. 2. (a) Traces of oscillograph recordings normalized at the peak and showing the variation of intensity with time of the laser emission, spark radiation, and scattered radiation, for a spark in air. Sweep speed 20 nsec/cm. (b) Trace of oscillograph recording showing second scattering signal. Sweep speed 40 nsec/cm.

nal was plane-polarized with the electric vector at right angles to both the direction of the refocused beam and the direction of observation, as should be the case for scattering from free electrons. The first scattered signal was essentially unpolarized. This was attributed to the high aperture of the lens L_1 and the highly convergent nature of the primary focus.

A photograph of a spark in air showed a central, highly luminous, pear-shaped region, approximately 1.5 mm long and 1 mm in diameter, with the rounded end towards the lens L_1. When photographed through a narrow-band interference filter centered on the laser wavelength, 6943 Å, the scattering volume appeared as a small central region approximately 0.1 mm in diameter and 0.5 mm long, corresponding to the region of maximum power density ($>10^{11}$ W/cm^2) in the focal spot. If the extent of the plasma is greater than that of the scattering volume, the fraction of the beam scattered is independent of the cross section of the beam and, for scattering by free electrons, is given by $8\times 10^{-26} n_e l \Omega$, where n_e is the average electron density and l is the length of beam scattered in the direction of observation into solid angle Ω. In our case, for $l = 0.01$ cm, $\Omega = 1/46$, this fraction was measured to be $\sim 10^{-9}$, yielding a value of $n_e \sim 5\times 10^{19}$ cm^{-3}. Support for this figure is obtained from the observation that ~0.2 joule, representing 60 % of the energy in the laser beam, was expended in producing a spark in air—an amount sufficient to fully ionize the air within the focal spot.

For a spark in helium the fraction of the laser beam scattered in the direction of observation was measured to be $\sim 10^{-11}$, corresponding to a value of $n_e = 5\times 10^{17}$ cm^{-3}, in good agreement with the electron density determined independently from the Stark-effect broadening of HeI 5876.[1] To within the accuracy of the measurements (±10 % of the energy in the laser beam) there was no appreciable absorption of the laser beam for a spark in helium.

To within the resolution of the spectrograph (0.4 Å) the linewidth of the scattered radiation was no greater than that of the laser beam. In earlier work[2] on the scattering of a laser beam from a plasma of lower density it has been observed that the scattered radiation is broadened by the thermal motion of the electrons. This cannot be so in the present case, since the upper limit of 0.4 Å on the width of the scattered line corresponds to an electron temperature $T_e \leq 4°$K. A possible explanation of this anomaly is that the linewidth is governed, through cooperative effects[3] within the plasma, by the motion of the ions. This is so if the parameter $\alpha = 1/KD > 1$, where $K = 4\pi\lambda_0^{-1} \sin\frac{1}{2}\theta$ and $D = (kT_e/4\pi n_e e^2)^{1/2}$, the Debye length in the plasma. Here θ is the angle of observation of the scattered radiation with respect to the incident beam, λ_0 the wavelength of the laser beam, and T_e the electron temperature. For $\lambda_0 = 6943$ Å, $\theta = \frac{1}{2}\pi$, $n_e = 5\times 10^{19}$ cm^{-3}, $\alpha > 1$ if $T_e < 10^8$ °K. The upper limit of 0.4 Å on the linewidth of the scattered radiation would then correspond to an ion temperature $T_i \leq 10$ eV.

The wavelength shift of the scattered radiation was dependent upon the point of observation of the spark along the axis of the lens L_1. The shift was almost always towards shorter wavelengths, although on occasion a weak line has also been observed shifted slightly towards longer wavelengths. When a Dove prism was used to image the region of the spark lying along the axis of the lens onto the slit of the spectrograph, an inclined image was obtained, showing that the shift was least for points along the axis nearest the lens L_1.

We interpret the shift in wavelength of the scattered radiation as a Doppler shift due to a motion of the plasma as a whole towards the lens L_1 during the initial stage of the spark when scattering takes place. Such a motion is clearly seen on a streak photograph of the spark taken with an image converter camera [Fig. 1(b)]. The initial velocity of luminous front towards the lens L_1 is ~10^7 cm/sec, in good agreement with the maximum observed shift of 3 Å towards the blue. The velocity decreases as the plasma moves towards the lens L_1, in agreement with the observation that the wavelength shift is least for points nearest the lens L_1. The presence of a second, less luminous, front moving in the opposite direction explains the occasional observation of a weaker line shifted towards the red. A more detailed study of the expansion of the spark is under way and will be the subject of a further communication.

We would like to acknowledge that our interest in this problem arose initially out of a discussion with Dr. R. W. Minck of the Ford Scientific Laboratory, Dearborn, Michigan.

[1]H. R. Griem, M. Baranger, A. C. Kolb, and G. Oertel, Phys. Rev. 125, 177 (1962).
[2]W. E. R. Davies and S. A. Ramsden, Phys. Letters 8, 179 (1964).
[3]See, for example, E. E. Salpeter, Phys. Rev. 120, 1528 (1960).

EXCITATION OF CYCLOTRON HARMONIC RESONANCES IN A MERCURY-VAPOR DISCHARGE*

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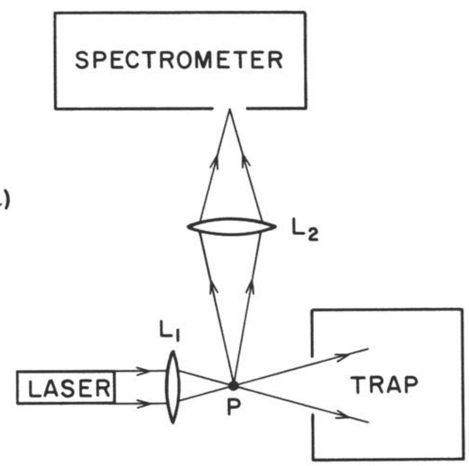
Measurements of the topside profile of the ionosphere have been made recently with the Canadian sounder satellite "Alouette." In these, the time delay of radar echoes from the ionosphere following the pulsed emission of signals of slowly varying frequency was studied. In addition to the expected results, a series of sharp resonances at integral multiples of the local electron cyclotron frequency, ω_c, with ringing continuing for many rf periods after the transmitter pulse had ceased, was observed.[1] The experiments to be described were carried out to determine whether these resonances could be excited in the laboratory, and to shed some light on their origin. There is already evidence that such effects occur in laboratory plasmas. Not only have many peaks in noise emission been observed at these frequencies,[2] but in addition, such noise output can be greatly enhanced by passing an electron beam from a shielded gun through the plasma.[3,4] Weak absorption of rf signals at these frequencies has also been seen.[5] We shall give results showing that the transmission between two probes immersed in a plasma exhibits strong resonances in a situation in which absorption effects are hardly measurable.

Our transmission measurements were made in the positive column of a mercury-vapor discharge, as shown in Fig. 1(a). Variation of magnetic field strength at a fixed working frequency, ω, resulted

(a)



(b)

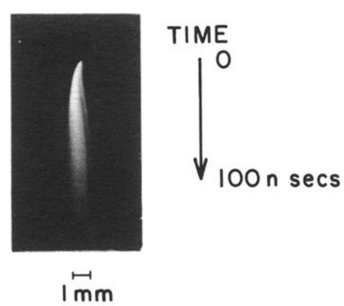


FIG. 1. (a) Diagram of apparatus. (b) Streak photograph of the spark.