Picosecond framing photography of a laser-produced plasma[*]

M. C. Richardson and K. Sala[†]

Division of Physics, National Research Council, Ottawa, Canada

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Sequential two-dimensional photographs of a laser-produced plasma in air with effective individual exposure times of ∾ 5 psec have been obtained by utilizing a focal-plane optical Kerr effect shutter.

The study of highly transient radiant phenomena, particularly those induced by short laser pulses, has in recent years resulted in considerable progress being made in extending the capabilities of time-resolved photographic techniques. Electro-optic streak cameras capable of resolving pulses of radiation a few picoseconds in duration have been developed and have been used for the direct measurement of mode-locked laser pulses.[1–4] Significant advances have also been made in fast framing photography, where the incorporation of short-duration voltage gating techniques with proximity diode image intensifiers has resulted in devices having exposure times of ~300 psec.[5,6] Recently, however, an alternative approach to short-exposure two-dimensional photography has been demonstrated.[7] This method employs an ultrafast optical shutter based upon the optical Kerr effect (OKE) induced in a transparent material by the intense electric field associated with high-power laser pulses. Resolution on a picosecond time scale has already been demonstrated in the direct photography of mode-locked laser pulses,[8] and, since the temporal resolution of this technique is principally governed by the laser pulse duration, the provision of much shorter pulses could ultimately lead to exposure times of $< 10^{-14}$ sec.[8,9] The OKE shutter has also been utilized in the measurement of picosecond fluorescence lifetimes[10,11] and in the picosecond resolution of broad-band absorption spectra.[12]

In this letter we wish to report some initial results on the use of an OKE shutter in a system capable of photographing high-density plasmas with exposure times of ~5 psec. This system permits the direct observation of luminous plasmas on a picosecond time scale and should find application in the analysis of highly transient plasmas, particularly those produced or heated by very intense short-duration laser pulses.

In the present study, the plasma produced in air by a train of picosecond light pulses from a mode-locked laser has been photographed by gating the OKE shutter with a portion of the same train of laser pulses, so that the plasma was photographed at time intervals equal to the separation between individual picosecond pulses in the train (~6.7 nsec). The general layout of the experiment is shown schematically in Fig. 1. A transverse gating beam geometry was adopted, in which an image of of the plasma was formed inside a quartz cell filled with CS_2. The train of gating pulses then traverses the CS_2 cell along the image plane. This approach differs from that previously employed,[8,10] and, for the purposes of photographing high-speed radiant phenomena, offers some distinct advantages. As long as the transverse dimensions of the gating pulse are greater than those of the image in the Kerr cell, the over-all aperture of the camera system is determined solely by the optics employed. Hence, with the use of powerful matched optics, this focal-plane transverse gating geometry permits the study of events of relatively weak intensity. In addition, this technique eliminates the increase in framing time encountered in collinear gating geometries due to the difference in group velocities of the gating pulse and the radiation from the source to be photographed.[8,13]

The laser used in the present experiment consisted of a $9 \times \frac{5}{8}$-in. Brewster-angle Nd : glass rod situated at one

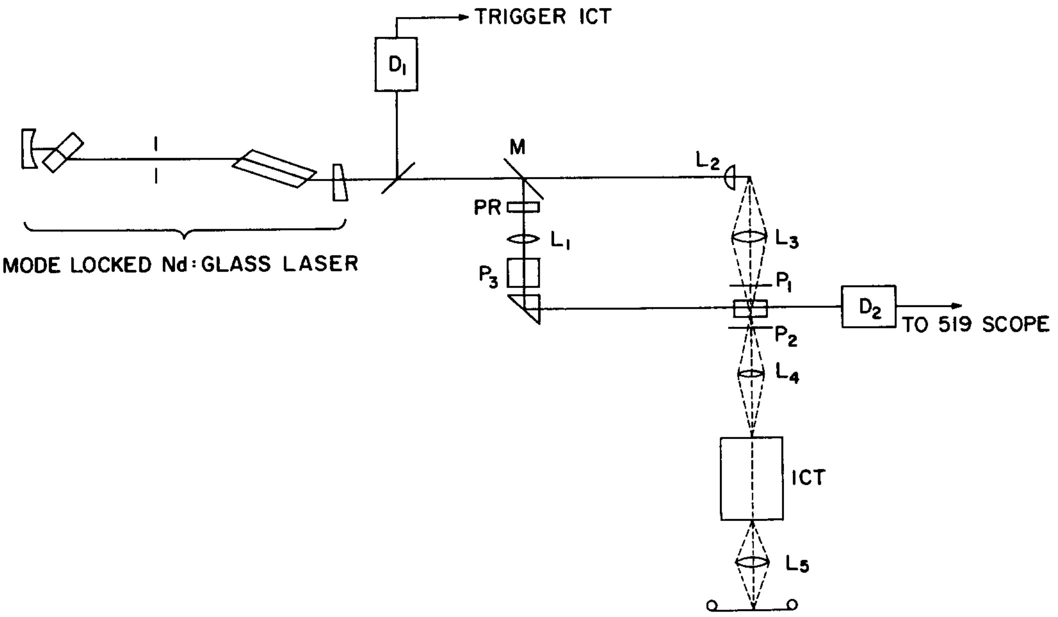

FIG. 1. Schematic of the experimental arrangement. Legend: M, 50% beam splitter; PR, polarization retarder; P_1, P_2, and P_3, polarizers; L_1, L_2, L_3, L_4, and L_5, lenses; ICT, electro-optic streak camera; D_1 and D_2, biplanar photodiodes.

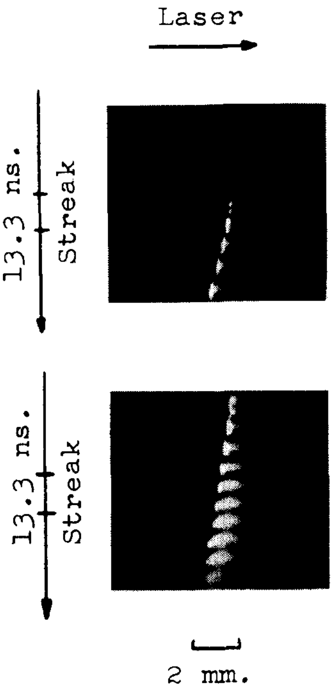

FIG. 2. Sequence of picosecond frame images of optical breakdown in atmospheric air with a streak duration of 100 nsec. These show (a) the initial breakdown and (b) the subsequent expansion of the plasma.

end of a 1-m optical resonator formed by a fully reflecting concave mirror with a 10-m radius of curvature and a wedged 60% reflecting plane output mirror. A 12.9-mm-thick cell containing Kodak 9740 saturable absorber in chlorobenzene and situated in close proximity to the concave mirror served as the mode-locking element. A typical output of the laser consisted of a 400-nsec-long train of picosecond pulses separated by 6.7 nsec and having a peak energy of ~ 10^{-2} J/pulse. Studies of the pulse duration using this OKE camera system to photograph individual second-harmonic picosecond pulses have shown that the pulse duration increases from ~4 psec at the beginning of the train to ~20 psec in the latter part of the train.[14] This finding is in close agreement with results obtained for a similar laser system with the aid of a picosecond streak camera.[15]

The horizontally polarized laser output was divided into two equal-amplitude beams by mirror M (Fig. 1). The gating beam was then passed through a polarization retarder, PR, and polarizer, P_3, to ensure the vertical polarization necessary to achieve optimum shuttering efficiency. Lens L_1, of focal length ~40 cm, reduced the full diameter of the gating beam within the 2-cm-long CS_2 cell to ~6 mm. The second beam was focused in air by a 20-mm–focal-length lens, L_2, to produce optical breakdown. An image of the spark was centered in the CS_2 cell with the aid of an $f/0.8$ lens L_3, and the two polarizers P_1 and P_2 (type HN-22) were carefully crossed with their axes at 45° to the vertical polarization of gating beam. The gated two-dimensional images transmitted by the second polarizer were then relayed by means of an additional lens, L_4, onto the (S11) photocathode of an image converter camera (ICT) operating in the streaking mode. In this manner, the individual gated images of the spark were spatially separated by the streak camera. Since the maximum streak velocity of the ICT was 2.5 mm/nsec and the effective exposure time of the gating system is ~5 psec, the individual images are unaffected by the streaking operation. Each image then results from the activation of the OKE shutter by a single picosecond pulse in the mode-locked pulse train. Thus, in addition to this method producing individual images with picosecond exposure times, the incorporation of a streak camera to spatially separate these images also provides resolution of the event on a nanosecond time scale. The resulting train of images was recorded on Polaroid Type 47 film (ASA 3000). In order to increase the sensitivity of the system, a two-stage electrostatically focused image intensifier with direct fiber optic coupling to the film was sometimes incorporated in the image plane of lens L_5. Although the spatial resolution of the present system was limited solely by that of the ICT (~ 6 line pairs/mm), a separate investigation of gated images of a test target without the use of the latter has failed to detect any degradation in image quality, to a resolution of better than 16 line pairs/mm, due to incorporation of the focal-plane OKE shutter.[14] Synchronization of the streak camera with the production of the spark was achieved by triggering the ICT with a pulse from a fast biplanar photodiode, D_1.

Typical photographs of sparks obtained by using this technique are shown in Figs. 2 and 3. Each photograph shows a train of separate images obtained at 6.7-nsec intervals. Since the optical path of the gating beam was equal to that in the image arm of the system, framing photographs were obtained at a time concurrent with the incidence of an additional picosecond pulse on the plasma. The first bright spot in the train of images shown in Fig. 2(a) corresponds to the initial breakdown of the gas. The remaining framed images in Fig. 2(a), as well as those in Fig. 2(b), show the subsequent expansion of the plasma and the effect of the incidence of further picosecond pulses during the first ~100 nsec. As can be seen, the mean expansion velocity toward the lens is ~2×10^6 cm/sec; however, previous studies have shown that upon incidence of each picosecond pulse the

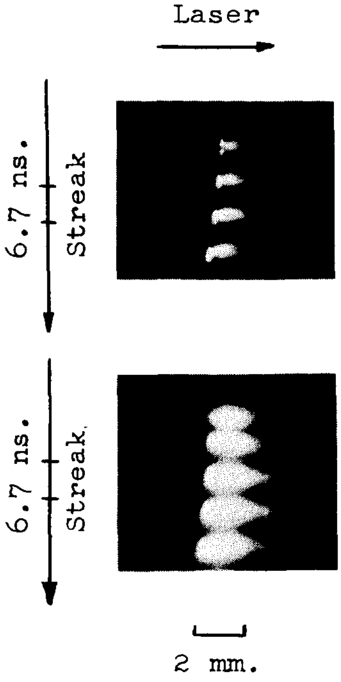

FIG. 3. Picosecond framed images of the spark with a streak duration of 50 nsec showing (a) the bright region at the expanding plasma front present in the first 100 nsec, and (b) the appearance of the plasma approximately 200 nsec after breakdown.

plasma expands with an initial velocity of $\sim 10^8$ cm/sec for a short period (~ 1 nsec) and then subsequently expands with a velocity of $\lesssim 10^6$ cm/sec.[16,17] Also visible in photographs of the plasma produced during the first ~ 100 nsec after breakdown [Fig. 2(b)] is the existence of intense bright regions at the plasma boundary nearest the laser. These may well arise as a result of optical breakdown produced at the plasma boundary by the subsequent laser pulses incident on the plasma. Although these bright regions exist at distances up to 1 mm from the focal point, where the laser power density would apparently be $\sim 10^{12}$ W/cm^2 and therefore would be well below the measured breakdown threshold for a single picosecond pulse,[18] the existence of self-focusing effects associated with sparks produced in air by a train of picosecond pulses has already been postulated.[19] However, as is more easily seen in Fig. 3(a), no history of these breakdown sites is visible in subsequent images of the plasma. Figure 3(b) shows a series of framed images of the plasma taken several hundred nanoseconds after initial breakdown. At this time, the plasma has expanded to ~ 3 mm in length and nearly 2 mm in diameter and absorbs most of the incident laser light.

In summary, the present investigation demonstrates the potential of focal-plane OKE photography for the study of laser-produced plasmas, and it implies that further development of this technique with either a single picosecond pulse or a train of pulses should have important implications for the analysis of other high-speed radiant phenomena.

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