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TITLE AIR BREAKDOWN PHOTOGRAPHY IN THE PICOSECOND DOMAIN

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Air breakdown photography in the picosecond domain

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ABSTRACT

We have studied the breakdown of air using the Los Alamos Bright Source KrF laser at an irradiance of 1.36×10^{16} W/cm^2 and pulse length of 700 fs. Results of the temporal evolution of various regions of the spark, recorded with an S-20 streak/framing camera, are presented.

2. INTRODUCTION

In the past years considerable effort has been made in the study of laser-induced optical breakdown of gases and liquids.[1,2,3,4] The investigations have centered on the measurement of the threshold power density required for the breakdown of gases at different wavelengths and at different pulse lengths. The initial formation of the plasma spark has been modeled using an electron-cascade scheme where the laser produces seed electrons that absorb energy through inverse bremsstrahlung. The seed electrons collide with the rest of the gas, producing further electrons through ionizing collisions. The previous studies have used a variety of lasers for the production of the breakdown. A few of the investigations used 4-20 ps lasers,[5] 30-100 ps lasers,[6,7] and 20-100 ps flashes.[8] Those experiments, however, used modelocked pulses. The interaction of the modelocked train with the plasma was influenced by the residuals of previous pulses in the train. In the present work the 0.2 s time between the laser pulses is much longer than the plasma clearing time of a few tens of microseconds. Furthermore, we used 0.7 ps pulses to cause the breakdown.

3. DESCRIPTION OF THE APPARATUS

The apparatus consisted of a laser system capable of delivering 30 mJ pulses at 5 Hz with pulse lengths of 0.7 ps FWHM at a wavelength of 248 nm.[9] The air breakdown was induced by an irradiance of 1.36×10^{16} W/cm^2, which is at least an order of magnitude more than irradiances used in previous work. The 15 ns amplified spontaneous emission (ASE) pulse was a factor of $\sim10^{-6}$ of the main pulse and was insufficient to cause breakdown. The laser was focused using a 5 cm diameter Plano Convex lens with a focal length of 20 cm (see Figure 1). The laser beam filled the central 2.5 cm diameter of the lens. The optical breakdown region was viewed by a streak/framing camera with an S-20 photocathode whose measured temporal resolution was 1.2 ps. The image of the discharge in air was coupled to the streak camera with diffraction limited optics of diffraction limited resolution. The streak camera output was intensified using a proximity focused reducing fiberoptics array. The resultant images were recorded on Polaroid Type 47 film (ASA 3000) or on TMAX film (ASA 400). The resolution of the optics/streak camera combination was less than 10 μm.

4. EXPERIMENTAL PROCEDURE

Red beam pulses from the front end of the laser with an autocorrelation width of 650 fs were used to calibrate the streak camera. A single red pulse was selected and delayed by varying the path length in air. The electronic trigger relative to the red beam was varied using a 20 ps resolution delay generator. The streak was then recorded at different streak speeds and delays. The next process was to measure the spatial magnification of the streak/framing camera. A piece of thin pencil lead was used, and its recorded image was measured. The last process was to measure the spatial resolution of the optics-streak-camera combination. Various bolts with different pitches were back-illuminated and their groove shapes were recorded and examined. The laser energy was measured, but the laser pulse length was not measured on each shot since the laser pulse length has been observed to be stable over periods much longer than it took to record the present data. The spark, i.e., the air breakdown region, was observed at three different axial positions: away from the lens, also called the head, at the center of the spark, and at the end closest to the lens, also called the tail of the spark (see Figure 1).

5. RESULTS

The time integrated self emission of the spark region is shown schematically in Figure 1. The focal spot is ~1 mm behind the tip of the "head". The "middle" section is the brightest, followed by a l g "tail" which decreases gradually in brightness. The length of one spark is approximately 2.5 mm, with a filament in the tail extending another 2 mm, and a short filament extending ~0.5 mm beyond the head. Figure 2 shows a framing record of the spark. The interframe time is 6.67 ns, the framing times is 4 ns, time axis is upwards. Each division on the scale corresponds to 0.17 mm. The five top images are the actual frames indicating plasma expansion and intensity decay. (The other bright portions on the figure are instrumental artifacts.) The laser is incident from the right. The figure indicates that the plasma exists for a duration of ~34 ns.

A streak record of the middle section of the spark using different neutral density filters is shown in Figure 3a. The ND values of 0, 0.3, 0.8 are from bottom to top, respectively. The vertical scale shows the radial dimension of 0.171 mm per small division and the horizontal scale is 120 ps per small division. At the earliest time, one notes the rapid radially accelerating expansion of the self-emission front. This expansion occurs long after the laser has turned off. No scattered laser light appears in any of the framing or streaking images (the collecting optics being opaque to KrF light). We observe a central bright emission region surrounded by a less luminous region. Similar results (shown in Figures 3a, b, and c) are observed for the head and tail region, except that the emission regions were smaller in radii and lasted for shorter durations.

The radial position of the self emission front at early times is plotted as a function of time in Figure 4 for the three axial positions. The self emission velocity (indicated by the slope of the r-t plot) is largest for the tail region and increases with time. A power law fit to the data in the expansion gave roughly a $t^{1.2\pm0.1}$ dependence of the radius, where t is time after the peak of the laser pulse. The average velocities were 3×10^8 cm sec at the tail, 1.6×10^8 cm/sec at the middle, and 1.4×10^8 cm/sec at the head. Isodensity contours of the decay of the self emission region are shown in Figures 5a, b, and

c. A typical value for the decay of the most luminous portion in the middle of the spark is $\sim 1.25 \times 10^6$ cm/s.

Streak records of the axial expansion are shown in Figure 6 for the head (left image) and middle (right image) regions of the spark. In this case, the slit was parallel to the laser axis. This laser was incident from the right. Each small division corresponds to 0.5 mm on the horizontal axis and 1.4 ns on the vertical axis. The location of the geometrical focus is indicated by the arrows in the figure. The self emission front in both images propagates towards the laser with an average speed of 3.5×10^8 cm/s. The emission duration varies with the axial position in accordance with the radial streaks shown earlier (see Figure 3).

6. DISCUSSION OF THE DATA

In the present series of investigations we have resolved the initial stages of the discharge. Two different theories have been proposed to describe this initial stage. The first is a blast wave, where the plasma expands rapidly into the remaining gas and forms a strong shock front. An accurate theory for spherical, cylindrical and plane waves has been given by Sakurai.[10] The radius of the front is not a linear function of time. For a spherical blast wave, where the energy is deposited instantaneously at a point source, Sedov gave the solution:[11]

$$r_s = t^{2/5}\,[W/d_0]^{1/5}\ \ Y(\gamma)$$

where γ is the gas adiabaticity ratio, W is the absorbed energy, d_0 is the initial mass density and Y is approximately one. For a cylindrical wave the radius varies as $t^{1/2}$ and as $W^{1/4}$. The second case is that of a shock wave driven by radiation emitted by the hot plasma after the laser pulse ceases.[12] For a blackbody-radiation-driven wave the radius is predicted to vary as $t^{1/5}$. If the absorbed energy was 1 mJ at a Los Alamos atmosphere (560 Torr), then the equations become:

$$r_s(\mu m) = [t(ps)/0.08]^{2/5}$$

and:

$$r_c(\mu m) = [t(ps)/2.447]^{1/2}$$

where the s and c subscripts refer to spherical and cylindrical blasts respectively.

The laser we used simulated a blast quite accurately, i.e., the pulse length of 0.7 ps and the focal spot of 10 μm in diameter is a close simulation to blast. The energy deposition time of < 700 fs is at least an order of magnitude shorter than that used in any previous investigations.[13] The initiation phase is distinct and lasts a few hundred picoseconds. All of these developing processes last much longer than the laser deposition time. What is surprising, as seen in Figure 3, is that the self emission front travels with an increasing lateral speed even after the laser has turned off! The velocities (1-3x10^8 cm/s) are much too fast for regular shock waves. Assuming that the plasma in the spark is at equilibrium. Korobkin et al.[14] gave a relationship between the plasma temperature and the lateral expansion velocity V_l:

$$T(K)=1.25\times10^{-2}V_l(cm/s)^{8/7}$$

as well as a relationship with the axial expansion velocity $U=1.75\ V_l$. At the tail this relationship gives 6.1×10^7 K, or 5.25 keV, and 3×10^7 K or 2.6 keV at the center of the spark. Such plasma temperatures may be over-estimates. If the absorbed energy from the laser were about 0.1 μJ, it would correspond to a density of 4×10^8 eV/molecule which then corresponds to an equilibrium temperature of 6 keV. What causes such high temperatures?

If a blackbody source is created instantaneously at zero time, and its temperature drops to 100 eV in 70 ns, then the extrapolated initial temperature should be ~1 keV. Since these conditions are similar to our experimental results, it indicates that a 1 keV plasma is reasonable. This estimate gives a lower bound on the temperature at the core of the spark.

At a KrF laser irradiance of 1.36×10^{16} W/cm^2 a free electron oscillates at the laser frequency with a maximum energy of 40 eV. The corresponding electron velocity is 7.5×10^8 cm/s. The electron-neutral collision mean free path would be 5 μm. Thus what we are observing is the electrons that have gained some energy from the laser and have drifted with an average velocity of 4×10^8 cm/s. The electrons ionize more molecules until the electron energy ceases to be capable of further ionization and the process terminates. The electron-electron equilibration time for these electrons is less than 10^{-15} s. A plasma at 40 eV has an x-ray emission peak around 100 eV. The range of a 100 eV x ray is approximately 170 μm in air at STP. This roughly matches the width of the weakly luminous region around the spark.

7. SUMMARY

In conclusion, we have presented data on the temporal evolution of self emission from a subpicosecond laser produced spark in air. The main characteristics are similar to experiment performed with longer pulse lengths. However, the speeds cannot be explained by using a blackbody source which indicates that the spark plasma is not in thermodynamic equilibrium. Further analysis using code calculations will be required to understand the details.

8. ACKNOWLEDGMENTS

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REFERENCES

1. C. Grey Morgan, "Laser gases," Report Progress Physics, vol. 38, pp. 621-665, 1975.

2. A. J. Alcock, "Experiments on self-focusing in laser-produced plasmas," in *Laser Interaction and Related Plasma Phenomena*, Vol. II, Ed. H. J. Schwartz and H. Hora, (New York, Plenum Press), 1972.

3. Yu. P. Raizer, *Laser Induced Discharge Phenomena*, (Consultants Bureau, New York and London), 1977.

4. T. P. Hughes, *Plasmas and Light*, (John Wiley & Sons, New York), pp. 145-272, 1975.

5. M. C. Richardson and K. Sala, "Picosecond framing photography of a laser produced plasma," Appl. Phys. Lett., vol. 23, pp. 420-422, October 1973.

6. I. K. Krasyuk and P. P. Pashinin, "Breakdown in Argon and Nitrogen under the influence of a 0.35 M picosecond laser impulse," Soviet Physics JETP Letters, vol. 15, pp. 333-334, April 1972.

7. I. K. Krasyuk, P. P. Pashinin, and A. M. Prokhorov, "Investigation of breakdown in argon and helium produced by a picosecond ruby laser light pulse, " Soviet Physics JETP, vol. 31, pp. 860-861, November 1970.

8. F. V. Bunkin, I. K. Krasyuk, V. M. Marchenko, P. P. Pashinin, and A. M. Prokhorov, "Structure of a spark produced by a picosecond laser impulse focused in a gas," Soviet Physics JETP, vol. 33, no. 4, pp. 717-720, April 1971.

9. J. P. Roberts, A. J. Taylor, P. H. Y. Lee, and R. B. Gibson, "High-irradiance 248-nm laser system," Opt. Lett., vol. 13, pp. 734-736, September 1988.

10. A. Sakurai, "On the propagation and structure of the blast wave," Journal of the Physical Society of Japan, vol. 8, pp. 662-669, 1953.

11. L. I. Sedov, *Similarity and Dimensional Methods in Mechanics*, Transl. M. Friedman from the 4th Russian edition, Infosearch Ltd., London, 1959.

12. B. Ahlborn and J. D. Srachan, "Dynamics of step heat waves in gasses and plasmas," Canadian Journal of Physics, vol. 51, pp. 1416-1427, 1973.

13. A. J. Alcock and M. C. Richardson, "Creation of a Spark by a single Subnanosecond Laser Pulse," Phys. Rev. Lett., vol. 21, pp. 667-670, September 1968.

14. V. V. Korobkin, S. L. Mandel'shtam, P. P. Pashinin, A. V. Prokhindeev, A. M. Prokhorov, N. K. Sukhodrev, and Ya. M. Shchelev, "Investigation of the air spark produced by focused laser radiation III," Soviet Physics JETP, vol. 26, pp. 79-85, 1968.

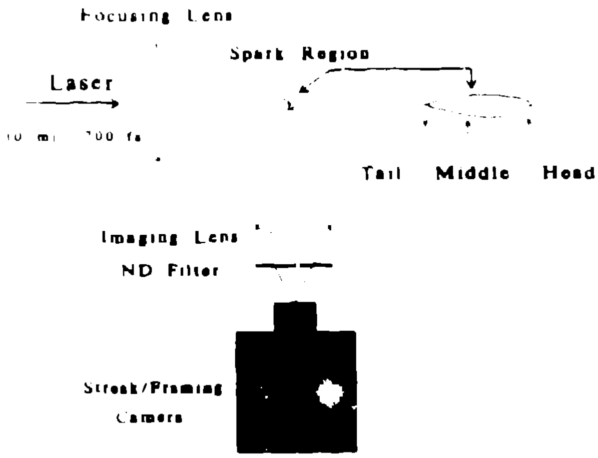


Fig. 1. A schematic diagram of the experiment.

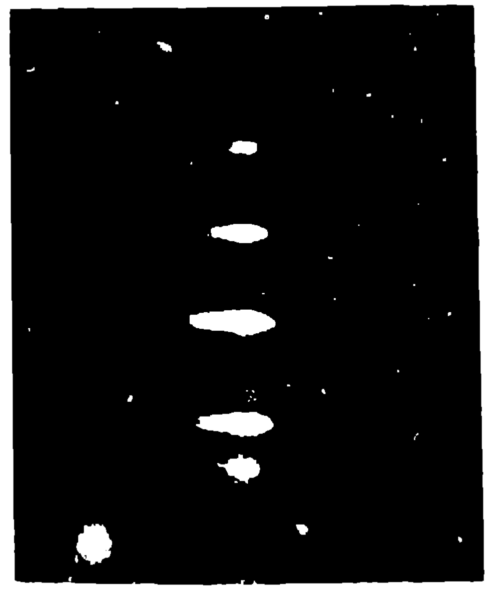
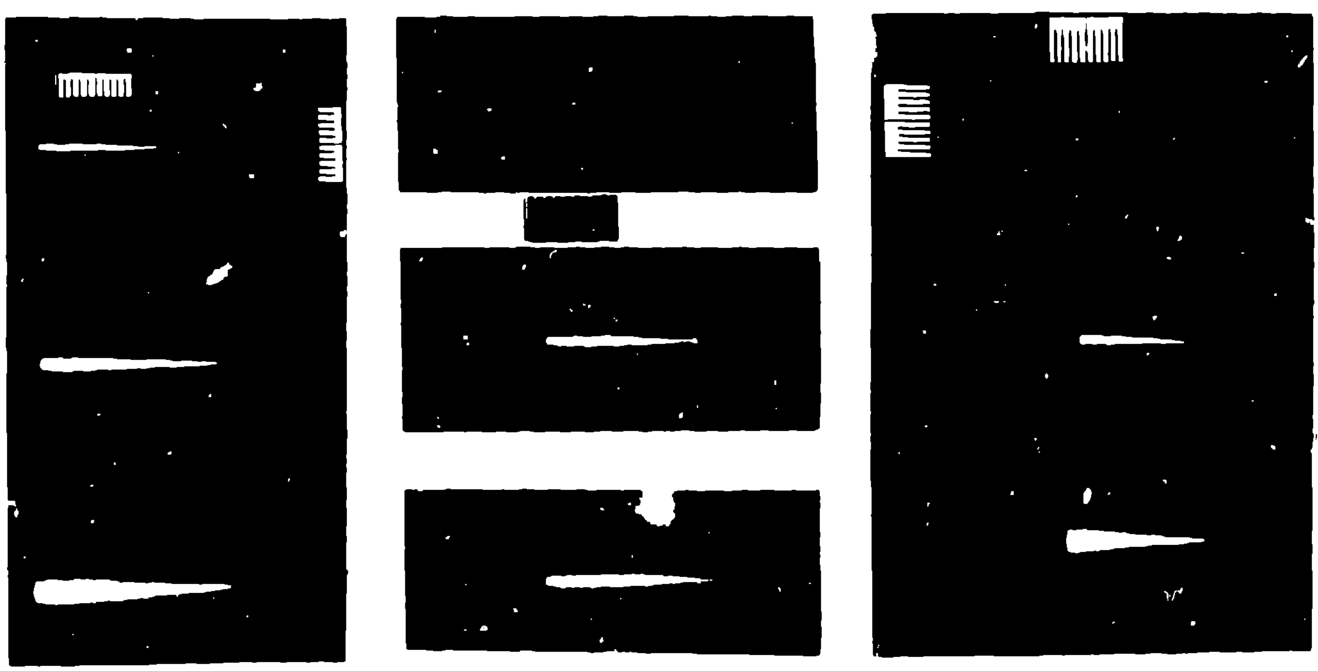


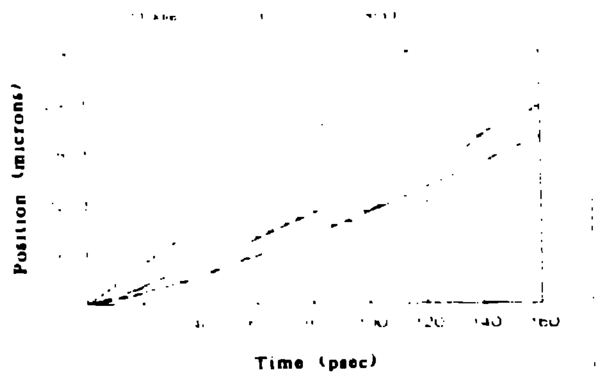
Fig. 2. A framing picture of the plasma emission. The framing rate was $1.5x10^8$ frames per second. Each frame had an exposure time fo 4 ns. The first frame begins at the fifth bright image from the top. Time axis is upwards. Scale is .17 mm/div.

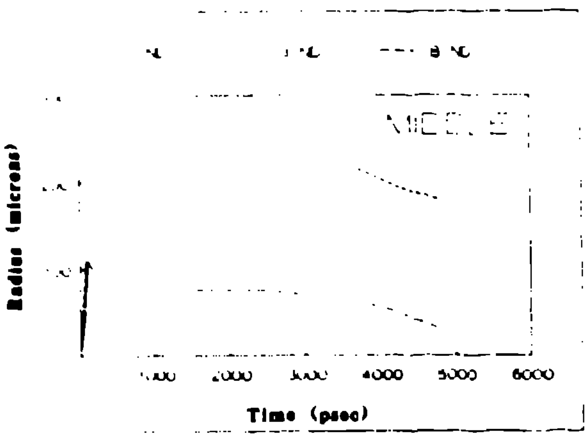


3a 3b 3c

Fig. 3. A streak record at various axial positions of the spark. Different records are taken with attenuation of 0, 0.3, 0.8 ND from bottom to top, respectively. The streak speed was 120 ps/div. The horizontal scale is .17 mm/div. a) middle, b) head, and c) tail.

Fig. 4. A plot of the front position as a function of time. The continuous curves are fits using a $t^{1.2}$ power law.





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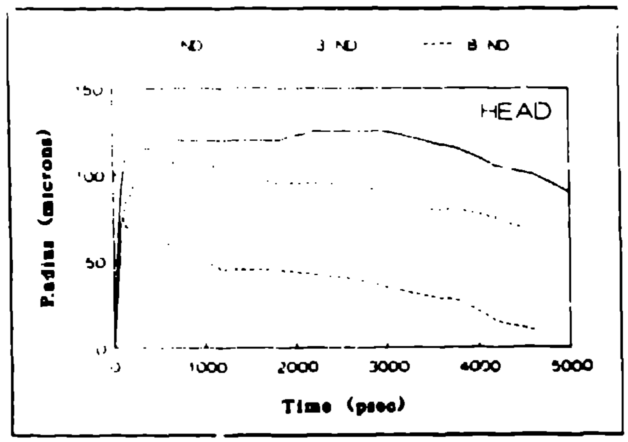

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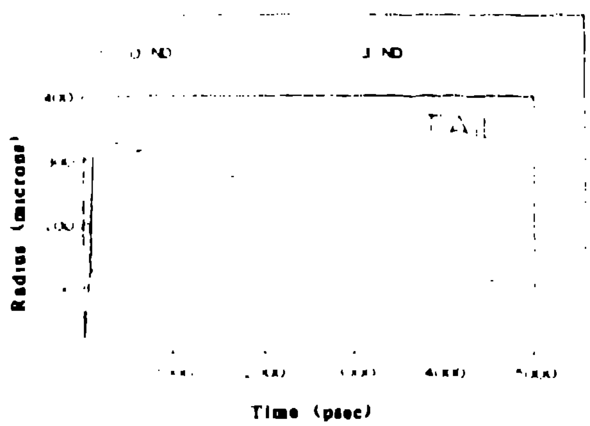

5c

Fig. 5. Isodensity contour plots of the streak records at the a) middle, b) head, and c) tail of the spark. The incident laser energy was 78 mJ. The laser pulse length was 0.7 ps.

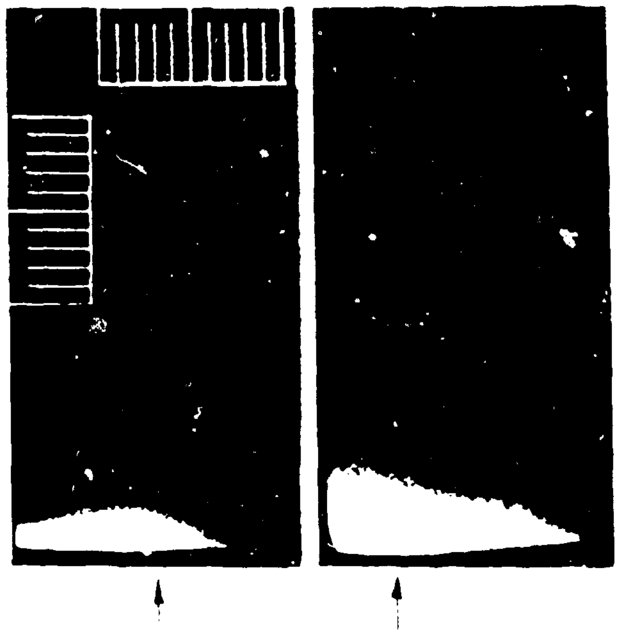

Fig. 6. A streak of two axial positions as a function of time. Head (left image), Middle (right image). The streak slit was parallel to the discharge axis and the laser was incident from the right. The horizontal scale is 0.5 mm/div and the vertical scale is 1.4 ns/div.