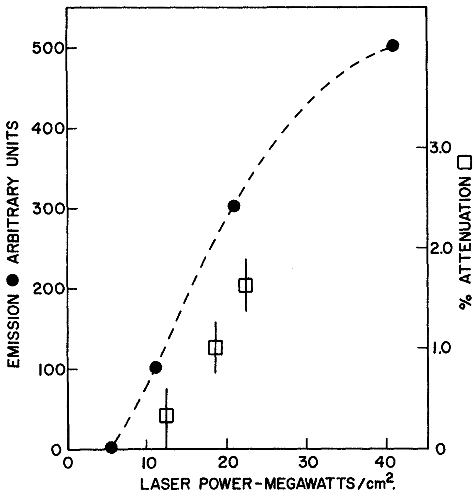

FIG. 2. Plot of percent attenuation (right-hand scale, squares) and emission (left-hand scale, black circles) against laser power for a 150-Å Ludox sample.

the absorption increased with particle size. The absorption varied roughly as the concentration of the particles. Also, the threshold for breakdown appeared to be inversely related to particle size in the range studied.

Dielectric breakdown in the neighborhood of a particle may occur for the following reasons. If the particle is opaque, rapid heating with release of electrons can occur in the field of an intense laser pulse.[5] If the particles are essentially transparent, the intense laser beam may induce a photoconductivity[6] leading to absorption. The creation of free electrons which subsequently absorb laser light may be facilitated by the presence of the colloidal double layer. Also, as is well known, a conducting sphere in an electric field concentrates or focuses the field at its surface by a factor of 3. This would facilitate breakdown.

In summary, we believe that the absorption, scattering, and emission result from dielectric breakdown at particle sites in the liquids. Careful filtering reduces these effects. We have not, even with the most careful preparation, been able to eliminate them entirely for powers above 100 MW/cm^2.

We are indebted to our colleagues, particularly R. G. Brewer and J. G. Swalen, for helpful discussions. The technical assistance of F. Rodgers is much appreciated.

[1]R. G. Brewer and K. E. Rieckhoff, Phys. Rev. Letters 13, 334 (1964).

[2]M. Born and E. Wolf, Principles of Optics (Pergamon Press, New York, 1959), p. 651.

[3]P. J. Regensburger and E. Panizza, Bull. Am. Phys. Soc. 12, 82 (1967). This work came to our notice during the preparation of this Letter.

[4]E. K. Damon and R. G. Tomlinson, Appl. Opt. 2, 546 (1963); R. G. Meyerand and A. F. Haught, Phys. Rev. Letters 11, 401 (1963); R. W. Minck, J. Appl. Phys. 35, 252 (1963); W. I. Linlor, Phys. Rev. Letters 12, 383 (1964).

[5]P. Langer, G. Tonan, F. Floux, and A. Ducauze, J. Quant. Electron. 2, 499 (1966).

[6]K. E. Rieckhoff and B. S. Shasma, Bull. Am. Phys. Soc. 11, 898 (1966).

POSSIBLE OBSERVATIONS OF COLLISIONLESS ELECTROSTATIC SHOCKS IN LASER-PRODUCED PLASMAS

D. W. Koopman* and D. A. Tidman*
Maryland Institute of Technology, Bethesda, Maryland
(Received 27 February 1967)

In an investigation of laser-produced plasmas, granules of LiD have been irradiated by 15-nsec, 3-J pulses from a ruby laser. The target material consisted of a cluster of 5- to 25-μ diam solid particles which were injected into the 400-μ diam laser focal region by an electromechanical apparatus. Expansion velocities of the luminous boundary of the high-density plasma were measured from streak photographs with an image-converter camera.[1] A similar phenomenon has been investigated by other authors.[2,3]

The apparatus is shown in Fig. 1. Langmuir probes with faces 1.6 mm diam separated by 1 cm were located 6.3 cm from the laser focal spot, and the signals to these biased probes were recorded on oscilloscopes. No magnetic fields were present and provision was made to produce a dc glow discharge in the chamber.

The purpose of this note is to describe some preliminary results of an experiment in which

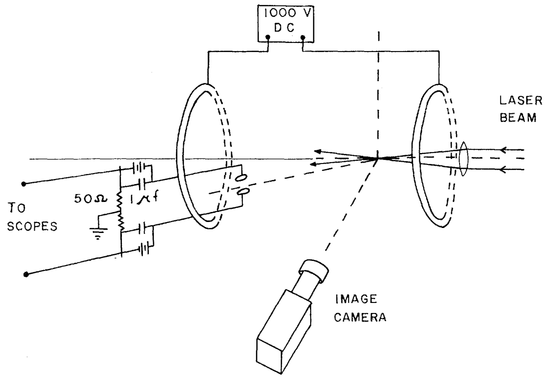

FIG. 1. Experimental apparatus, showing relative positions of laser focus, probes, discharge electrodes, and camera. The vacuum chamber, target control apparatus, and laser electronics are omitted.

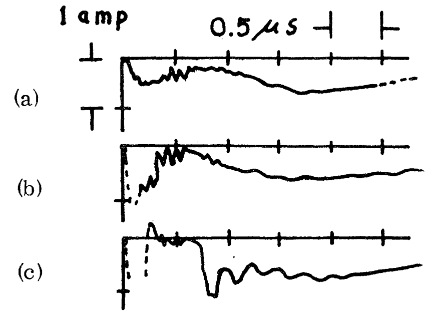

FIG. 2. Typical oscilloscope traces from the positive probe. Chamber conditions: (a) 0.2 μ; (b) 25 μ; (c) 25 μ, with glow discharge. The signals during the first 0.5 μsec are due to photoionization.

the plasma ball expands into an ambient plasma. Our results suggest that we have observed a thin, "collisionless," electrostatic shock front propagating radially at the leading edge of the plasma ball.

The phenomenon is in many respects analogous to a blast wave.[4] The expanding sphere of laser-produced plasma acts as the piston and under appropriate conditions the tenuous background plasma swept up is expected to give rise to a spherical ion-wave shock.[5,6] For a plane-wave shock the mechanism of the transition can be visualized in the rest frame of the shock as follows. Relatively cool plasma streaming into the shock transition layer becomes unstable leading to the growth of ion waves. The relative stream velocity U_1-U_2 of the incoming plasma of velocity U_1 plowing into the plasma and leaving the back of the shock with velocity U_2 drives this instability. The turbulent spectrum of ion waves thereby maintained inside the shock gives a shock thickness characterized by a particle-wave scattering mean free path instead of the much longer particle-particle scattering length.

Among the conditions derived[5] for the existence of such a shock at high Mach numbers is the requirement that ion waves become unstable in the leading edge of the shock, i.e.,

$$\beta=\frac{e^3}{128}\left(\frac{U_1}{V_{i1}}\right)^2\left\{\frac{3m_eT_{i1}^{\ 3}}{2m_iT_{e1}^{\ 3}}\ln\left(\frac{m_iT_{e1}^{\ 3}}{m_eT_{i1}^{\ 3}}\right)\right\}^{1/2}\ll 1, \quad (1)$$

where U_1 is the shock velocity, T_{e1} and T_{i1} are the upstream electron and ion temperatures, and $V_{i1}=(KT_{i1}/m_i)^{1/2}$. For example if $U_1/V_{i1}=50$, $T_{e1}/T_{i1}=50$, and for typical background ions $(m_e/m_i)^{1/2}\cong 1/200$, then $\beta\cong 0.04$ and the condition is satisfied. If conditions are suitable for propagation, the shock thickness is $L_s=A(U_1/\omega_{i1})$, where $\omega_{i1}=(4\pi N_1e^2/m_i)^{1/2}$ and A is not known exactly but is probably of order 10. Thus for ionized air with upstream ion density N_1,

$$L_s\cong O(U_1/28\sqrt{N_1}\ \mathrm{cm}). \quad (2)$$

Currents from probes biased at ± 90 V were measured, and typical oscilloscope signals are shown in Fig. 2. This was done for pressures of 0.2 and 25 μ of air in the experimental chamber, and the character of the signals in these cases was identical. In contrast, when a glow discharge was induced in the chamber at 25 μ to provide a background plasma, a sharp onset of negative current was observed on the positive probe. Table I compares typical rise times of the positive probe current with and without the background plasma.

The sharp onset in the presence of background plasma corresponds to an abrupt change in the

Table I. Observed negative-probe signal rise times.

Chamber pressure (μ)	Rise time (μsec)
0.2	1.1 ± 0.4
25	1.2 ± 0.3
25[a]	$0.062^{+0.032}_{-0.016}$

[a]Glow discharge.

average plasma characteristics that takes place in a length scale $L = U_1 \Delta t$, where U_1 is the velocity of the front and Δt is its duration on the oscilloscope trace. Typically the front arrives in a time 0.8 μsec. Thus $U_1 \cong 8\times10^6$ cm/sec and $L \cong 0.35$ cm after allowing for the 1.6-mm probe diameter. (Note that this is an upper limit for L since the shock may have slowed down before reaching the probes, and the response time of the circuit is about 10^{-8} sec.)

The length $L = 0.35$ cm contrasts with collision mean free paths in air at 25 μ which are of order 10 cm. If we tentatively identify the sharp front as due to an ion wave shock, we see from Eq. (2) that an ion density $N_1 \cong 10^{12}$-10^{13} cm^{-3} would give a shock thickness $L_s \cong 0.3$-0.1 cm, in reasonable agreement with what is observed. A density of 10^{13}/cm^3 corresponds to a degree of ionization in the glow discharge at 25 μ of $\sim 1\%$.

Using the relation $I = AeN_e(KT_e/2\pi m_e)^{1/2}$ for the current to the positive probe of area A, the observed 1-A signals are obtained if we assume that behind the shock front (subscripts 2) $N_{e2} \cong 4N_1 \cong 4\times10^{12}$/cm^3 and $T_{e2} \cong 5\times10^5$ °K. The high electron temperature T_{e2} should drop rapidly further behind the shock because of thermal conduction into the colder driver plasma of LiD, but this effect on the probe current is overcome by an increase in electron density as the LiD plasma arrives at the probe.

We are grateful to Mr. E. Jacobsen, Jr., for his generous and imaginative support of this work, and to Mr. J. Maloy who engineered much of the apparatus.

---

*Permanent address: Institute for Fluid Dynamics and Applied Mathematics, University of Maryland, College Park, Maryland.

[1]D. W. Koopman, Bull. Am. Phys. Soc. 11, 464 (1966).
[2]A. F. Haught and D. H. Polk, Phys. Fluids 9, 2047 (1966).
[3]J. M. Dawson, Phys. Fluids 7, 981 (1964).
[4]G. I. Taylor, Proc. Roy. Soc. (London) A186, 273 (1946).
[5]D. A. Tidman, Phys. Fluids 10, 547 (1967).
[6]D. A. Tidman, to be published.

EXCITATION OF ELECTRON-PLASMA WAVES BY THE INTERACTION OF AN ION BEAM WITH A PLASMA*

W. Herrmann and Th. J. Fessenden†
Institut für Plasmaphysik, Garching bei München, Germany
(Received 16 Fegruary 1967)

This paper reports the interaction of an energetic beam of ions with a plasma that is produced by the ion beam.

The experimental arrangement is given in Fig. 1. From a duoplasmatron ion source surrounded by an insulator, a beam of hydrogen ions is extracted by an accelerating electrode. The beam is focused and divided into mass components by a magnetic lens. Through the entrance aperture, 2 cm in diameter, practically only particles of one component enter the plasma chamber. Negative-potential electrodes in front of and behind the plasma chamber prevent the electrons from leaving the plasma chamber along the beam. The neutral gas pressure in the plasma chamber can be varied by a gas leak. In all experiments hydrogen was used. The pressure in the drift space depended a little on the gas pressure in the plasma chamber. Because the beam current, entering the plasma chamber, changed smoothly with the pressure in the drift space, an automatically driven gas leak in the drift space was provided which always adjusted the pressure to a given value (about 6×10^{-5} Torr). The beam current, entering the plasma chamber, was measured by a movable calorimeter.

The plasma chamber had an outer diameter of about 20 cm, was 125 cm in length, and was made of stainless steel. The end plates were of iron. The whole plasma chamber could be used as a cavity. Two loops were used to excite a TM mode. The quality Q of this cavity for these modes was about 500. In addition there was a Langmuir probe and, at the end of the chamber, a pin probe for detecting excited frequencies.

Normally the experiment was performed with a H_2^+ beam, because the highest currents at that time were achieved with H_2^+. Some exper-