

Single-shot spatially resolved characterization of laser-induced shock waves in water

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We have developed an optical method for single-shot spatially resolved shock-wave peak-pressure measurements. A schlieren technique and streak photography were used to follow the propagation of the shock wave. The shock position r as a function of time was extracted from the streak images by digital image-processing techniques. The resulting $r(t)$ curves were differentiated with respect to time to yield shock-wave velocities that were converted to shock pressures with the aid of the equation of the state of the medium. Features and limitations of the technique are demonstrated and discussed on the basis of measurements of shock-wave amplitudes generated by laser-induced breakdown in water. For this purpose, laser pulses of 6-ns duration and pulse energies of 1 and 10 mJ were focused into a cuvette containing water. Complete $p(t)$ curves were obtained with a temporal resolution in the subnanosecond range. The total acquisition and processing time for a single event is ~ 2 min. The shock-peak pressures at the source were found to be 8.4 ± 1.5 and 11.8 ± 1.6 GPa for pulse energies of 1 and 10 mJ, respectively. Within the first two source radii, the shock-wave pressure $p(r)$ was found to decay on average in proportion to $r^{-1.3 \pm 0.2}$ for both pulse energies. Thereafter the pressure dropped in proportion to $r^{-2.2 \pm 0.1}$. In water the method can be used to measure shock-wave amplitudes exceeding 0.1 GPa. Because it is a single-shot technique, the method is especially suited for investigating events with large statistical variations. © 1998 Optical Society of America

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1. Introduction

Early studies of the propagation of shock waves in water have been undertaken because of their importance in underwater explosions,¹ and, on a smaller scale, because of their role in cavitation erosion.^{2,3} Interest was renewed with the advent of medical procedures accompanied by shock-wave emission, such as extracorporeal shock-wave lithotripsy (ESWL),^{4,5} intraocular laser microsurgery,^{6,7} and short-pulsed laser ablation.⁸ In ESWL the shock wave is used to create the primary surgical effect but has also been linked to unwanted side effects such as hemorrhage, rupture of cell membranes,⁵ and the fragmentation of DNA.⁹ In ocular laser microsurgery, tissue is evaporated by the generation of a microplasma, often in close proximity to delicate cell structures. The plasma formation is accompanied by the creation of a cavitation bubble and by the emission of shock waves

with pressures in excess of 100 MPa, which are potential sources for unwanted side effects.^{7,10,11} More recently the potential of shock-wave-enhanced drug and gene delivery on a cellular level has been discussed.¹² All these areas share the need for a method characterizing shock waves and their propagation in aqueous media. In this paper a new measurement technique is applied to shock waves emitted during laser-induced breakdown in water—a typical situation in intraocular microsurgery.

The methods previously used for characterizing shock waves include pressure transducer measurements^{13,14} as well as optical techniques.^{7,10,14–18} Transducer measurements yield reliable results only at distances from the source that are large compared with the size of the sensor,¹⁷ which is typically at least 1 mm. A few millimeters from the source the peak pressures are also lower, and therefore the risk of damage to the transducer is minimal. Noninvasive optical techniques in contrast are especially useful in the vicinity of the source where peak pressures are very high and changes in the optical properties of the medium are sufficiently large to be detected. Depending on the design, the spatial resolution of optical techniques can be as low as a few micrometers. In intraocular microsurgery, this allows the

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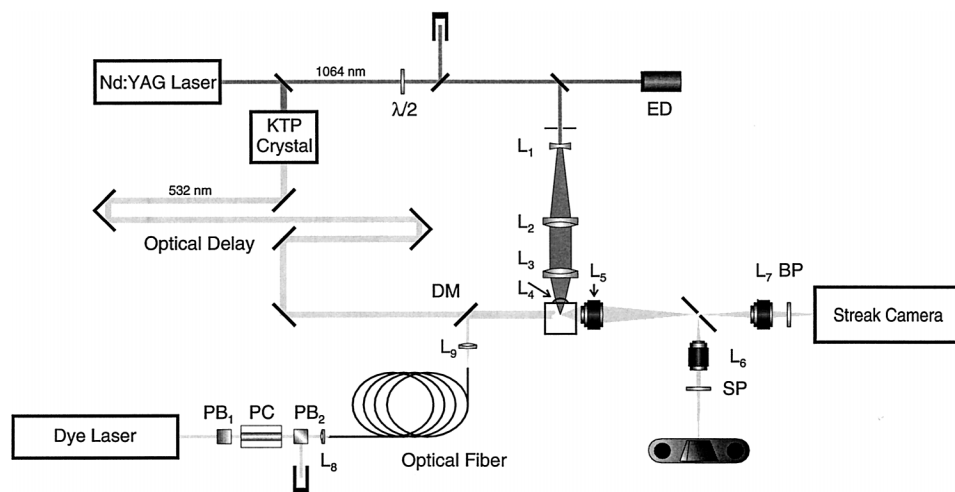


Fig. 1. Setup for simultaneous streak and framing photography of laser-induced breakdown.

measurement of shock pressures very close ($\sim 10 \mu\text{m}$) to the plasma.^{7,10,17}

Only streak photography^{10,15,19} and streak holography²⁰ are able to follow the shock wave emitted by a single event. With other techniques this information must be gathered over a large number of reproducible events, which is always tedious. Whenever large statistical variations are present, such as in the case of the pressure transients emitted by collapsing cavitation bubbles,³ they cannot be applied at all. The method presented in this paper is capable of partly closing this gap, because in regions close to the source it allows us to perform spatially resolved pressure measurements on a single-shot basis.

Schlieren streak photography of shock waves in gases was used in 1969 to estimate the energy content of shock waves in gases.¹⁹ In liquids the dependence of the shock velocity on shock pressure is much weaker owing to the smaller compressibility; thus a much higher spatial and temporal resolution is required for quantitative measurements of the shock pressure.^{10,15} In contrast to earlier streak photographic investigations of shock-wave propagation^{15,19} that relied on the manual analysis of the photographic records, we used digital image-processing techniques to extract the shock-wave trajectories from the streak images. Even though schlieren streak photography is not new, only the combination with digital image-processing techniques allows quantitative parameter studies of the shock-wave propagation to be performed within a reasonable time.

2. Streak Photographic Determination of Shock Pressure

The shock wave is visualized by the refractive-index change arising from the shock-wave-induced compression of the medium by means of a shadowgraph technique. A combination of the visualization with streak photography then allows the position of the shock to be followed through time, and the speed of

the shock can be obtained directly by differentiation of the trajectory of the shock wave.

In water the shock-wave peak pressure p is related to the propagation speed u of the shock through the equation of state²¹ and the jump conditions at the shock front²² by^{10,17}

$$p = A\rho_0 u[10^{(u-c_0)/B} - 1], \quad (1)$$

where $c_0 = 1483 \text{ m s}^{-1}$ and $\rho_0 = 998 \text{ kg m}^{-3}$ denote the sonic velocity and the density of the undisturbed water, respectively. $A = 5190 \text{ m s}^{-1}$ and $B = 25306 \text{ m s}^{-1}$ are empirical constants determined from Rankine-Hugoniot data.²¹

Earlier investigations^{10,16-18} found significant deviations of the shock-wave velocity from sonic velocity during the first 50–200 ns after the breakdown event. The time window of the streak camera must therefore cover this regime, requiring a very intense illumination with a constant brightness for the same period of time. This was achieved by the use of a flashlamp-pumped dye laser.

The laser-generated plasma is conical, and the shock waves emitted from the tip of that cone have different characteristics from those emitted at the base. Therefore the measurement position given by the location of the streak slit must be documented. For events exhibiting large statistical variations the slit location must be known for each individual event. Therefore simultaneous streak and framing photography were performed.

Short measurement and processing times are essential for investigations of the parameter dependence of shock-wave characteristics or for statistically varying events in which large numbers of streak images must be evaluated. Therefore electronic image readout of the streak camera was combined with digital image-processing techniques to determine the position versus time from the images. This allows a single event to be analyzed in $\sim 2 \text{ min}$.

3. Experimental Setup

The experimental setup shown in Fig. 1 consists of two parts: The first part was used to generate the plasmas, whereas the second part was used to measure the speed of the shock waves emitted.

For plasma generation, laser pulses with 6-ns (FWHM) duration emitted from a Nd:YAG laser (Continuum YG 671-10) were focused into a cuvette containing distilled and filtered water. The beam profile was Gaussian, slightly modulated by a ring structure. The focusing optics were designed with great care to minimize spherical aberrations.¹⁷ They consisted of a biconcave lens, L_1 ($f_1 = -40$ mm), two laser achromats, L_2, L_3 ($f_2 = 200$ mm, $f_3 = 120$ mm), and an ophthalmic contact lens, L_4 (Rodenstock RYM) built directly into the wall of the cuvette. The setup is identical to the one used previously to investigate shock-wave emission by framing photography.¹⁷ The focusing angle was 22° , which is similar to focusing angles used in ophthalmic laser applications, and the spot diameter was measured to be $7.7\text{ }\mu\text{m}$.²³ Pulse energies delivered into the cuvette were 1 and 10 mJ, respectively. The pulse energy was adjusted by means of a rotatable $\lambda/2$ plate between two polarizers without affecting the beam profile. Part of the laser pulse energy was coupled onto a pyroelectric energy meter (Digirad R-752/P-444) that was calibrated to yield the laser pulse energies delivered into the cuvette.

The optical axis of the optics used for the measurement of shock-wave speed was perpendicular to the optical axis of the delivery system. The events occurring in the cuvette were imaged with a two-stage imaging system. The first stage with a four-fold magnification consisted of a 63-mm lens, L_5 (EL-Nikkor optimized for 8:1 magnification). The aperture of this lens ($F = 4$) determines the minimum detectable refractive-index gradient. Only refractive-index gradients deflecting light out of the aperture can be visualized by the shadowgraph technique.

A reflectively coated glass substrate with a $20\text{-}\mu\text{m}$ -wide uncoated slit in its center was placed in the intermediate image plane under 45° with respect to the optical axis. The part of the image that was transmitted through the slit was reimaged onto the photocathode of a streak camera by a Nikon 2.8/105-mm macro-objective, L_7 . The streak camera (Hadland Photonics Imacon 792) was operated at a streak speed of 2 ns/mm and had a total recording time of 140 ns. The temporal resolution was better than 200 ps. Total magnification from the object to the fluorescence screen of the streak camera was $16.6\times$. The spatial resolution in the object plane was measured to be $6.4\text{ }\mu\text{m}$.

The part of the intermediate image deflected by the reflective substrate was imaged by another imaging lens, L_6 (Leitz Photar, 40 mm) onto the film plane of a camera back. Total magnification from object to film was $31.25\times$. This allows the slit position to be

monitored with respect to the shock-wave generating event.

Illumination of the streak images was provided by a flashlamp-pumped dye laser (Vuman PDL-20, $\lambda = 630$ nm) emitting pulses with a duration of $2.75\text{ }\mu\text{s}$ (FWHM). To avoid overexposure of the photocathode of the streak camera, the dye laser pulses were shortened by a Pockels cell, PC, located between two polarizing cubes, $PB_{1,2}$, outside the resonator. The resulting 200-ns pulses were coupled into an optical fiber (with a $300\text{-}\mu\text{m}$ core diameter) with a 40-mm plano-convex lens, L_8 . The remote end of the fiber was imaged into the object volume with a magnification of 9:1 by a 50-mm lens, L_9 . The dye laser pulse energy delivered to the object volume was of the order of $250\text{ }\mu\text{J}$. The large bandwidth ($\Delta\lambda = 2.3$ nm) of the dye laser in combination with the path-length differences of different modes in the optical fiber resulted in a speckle-free, top-hat intensity distribution at the exit of the fiber.

Backillumination of the framing photographs was obtained by frequency doubling part of the 6-ns Nd:YAG laser pulses by a potassium titanyl phosphate, KTP, crystal and combining it with the output of the flashlamp-pumped dye laser by using a dichroic mirror, DM. An optical delay of 23 ns between the pulse generating the event and the illuminating pulse was used to obtain framing photographs of the shock wave within the time window of the streak camera. Separation of the illumination for streak and framing photographs was achieved by a suitable bandpass filter centered at 630 nm, BP ($\Delta\lambda = 10$ nm) between the slit and the streak camera and a short-pass filter, SP ($\lambda_{\text{cutoff}} = 600$ nm) between the slit and the framing camera, respectively.

The streak images were recorded with either a CCD (Photometrics S200 with Kodak KAF1600 chip, 1536×1024 pixels) adapted to the streak camera or Kodak TMAX 400 sheet film mounted directly onto the fluorescence screen of the streak camera. The camera back used to document the slit position was loaded with Kodak TMAX 400 film. All photographic material was developed to its specified sensitivity. Photographic streak images (containing maximum spatial frequencies of 5 lp/mm) were digitized with 300 dpi, i.e., without loss of spatial and temporal resolution.

4. Data Processing

A flow diagram of the data-processing steps is in Fig. 2. On the photographic images the shock wave appears as a dark shadow on a bright background with an abrupt transition between bright and dark. Detecting the shock front is thus equivalent to finding the location of the sharp intensity transition between the bright background and the dark shock-wave image, a classical task for edge detection in digital image processing.

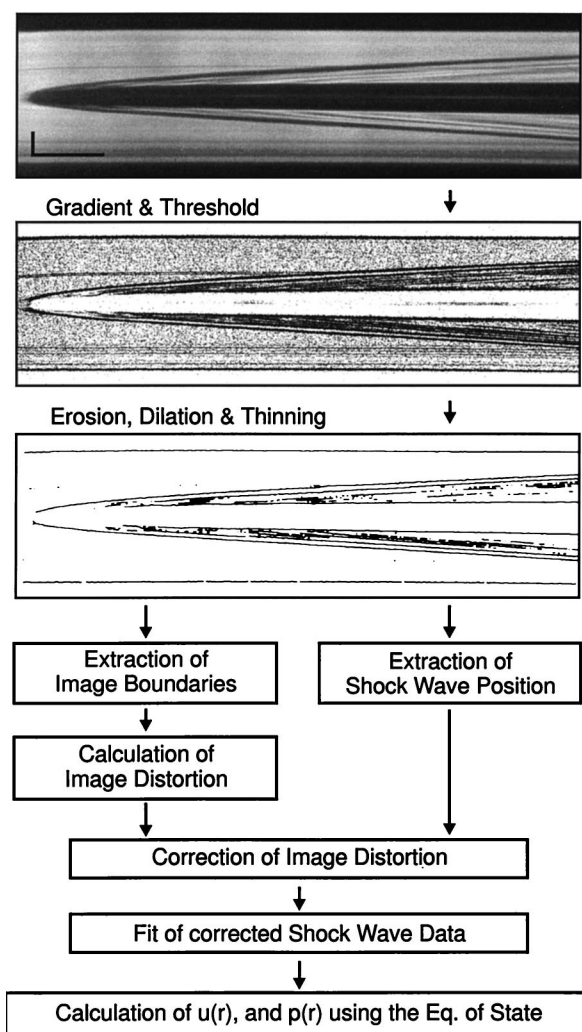


Fig. 2. Overview of the image- and data-processing steps used to obtain the shock pressures. The images acquired after laser-induced breakdown with a 10 mJ-pulse. The length of the bars corresponds to 100 μm (vertical) and 10 ns (horizontal), respectively.

For edge detection, spatial gradient images were calculated from the pixel values $p_{x,y}$ of the original image according to

$$g_{x,y} = (p_{x-1,y-1} + 2p_{x,y-1} + p_{x+1,y-1}) - (p_{x-1,y+1} + 2p_{x,y+1} + p_{x+1,y+1}). \quad (2)$$

The resulting gradient image was thresholded at 10% of the maximum absolute gradient amplitude within the image. The binary image contains bands of pixels corresponding to the edges of the streak image, the upper and lower shock-wave image, and the boundaries of the cavitation bubble as well as some noise arising from the graininess of the fluorescence screen. Owing to the limited spatial resolution of the image converter tube, the width of the bands in the binary image (5–6 pixels) is slightly larger than the kernel used for calculating the gradient. These bands can be isolated from the background noise caused by the coarseness of the

fluorescence screen (isolated pixels) by morphological erosion with a 7×3 kernel. This erosion removes all pixel groups with dimensions smaller than the size of the kernel. Larger pixel groups experience a reduction in size by the erosion that is compensated by a morphological opening operation with the same kernel. After the morphological operations all features in the gradient image with a dimension smaller than 7 pixels along the x axis and smaller than 3 pixels along the y axis are removed (Fig. 2). The pixel bands corresponding to the shock wave and the image boundaries, however, remain almost unaffected, owing to their width of 5–6 pixels in the y direction. They are finally reduced to lines (1 pixel wide) by use of a thinning algorithm.²⁴ From the resulting image the locations of the upper and the lower image boundaries (uppermost and bottommost pixels in each image column) and the upper and the lower shock position (second pixel from top and bottom, respectively) were extracted.

Image distortions by technical imperfections of the streak camera were corrected, and appropriate scaling factors for the spatial and the temporal axes of the streak image were deduced from the optical magnification and the streak speed.

From physical principles the speed of a spherical shock wave can be expected to be monotonously decreasing and to approach the sonic velocity in the long time limit. The exact functional relationship of the decrease in velocity (pressure) is not known, however. We therefore fitted the following series expansion to the shock-wave position r as a function of time t obtained from the images:

$$r(t) = a_0 + a_1 t + a_2 \ln t + \sum_{i=3}^n \frac{a_i}{t^{(i-2)}}. \quad (3)$$

The derivative of the fit function [Eq. (3)] is a power series in $1/t$; hence it will rapidly decrease and approach sonic velocity (given by parameter a_1). Monotonicity is not guaranteed by the choice of the function. In practice, however, the use of Eq. (3) with $n = 8$ on experimental data was found to yield monotonicity in the measurement interval. The use of a global fit function such as Eq. (3) was found to discriminate much better between physically relevant trends and noise artifacts in the data than the use of optimal frequency filtering²⁵ or piecewise local quadratic fits.¹⁰

Analytic differentiation of Eq. (3) was used to obtain the speed of the shock front as a function of time and position. The measurement uncertainty in the speed of the shock front was calculated based on the covariance matrix of the fit parameters.²⁶

The shock peak pressure p can be calculated from the propagation velocity u of the shock wave by Eq. (1).

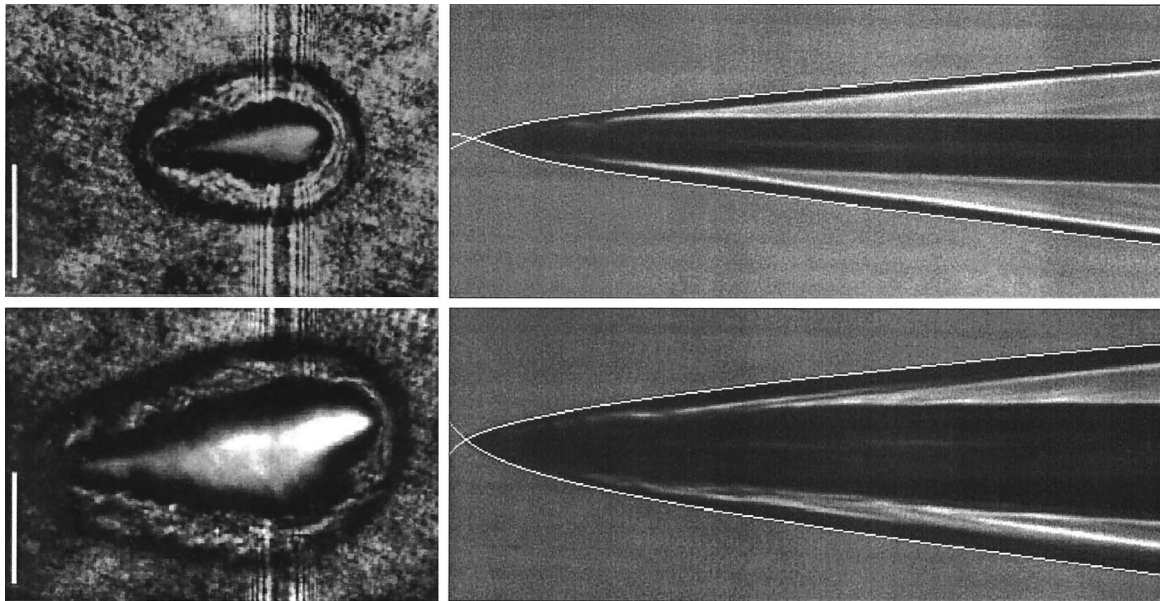


Fig. 3. Representative framing and corresponding streak images of laser-induced breakdown with 1-mJ (top) and 10-mJ (bottom) pulses. The framing images (left) indicate the location of the streak slit (dark line). The streak images (right) show an enlarged view of the first 100 ns of the streak window. The horizontal bars correspond to 10 ns (horizontal), and the vertical bars correspond to 100 μm (vertical). The white lines indicate the position of the shock wave as determined by the image-processing algorithm. The small steps in the fitted function are an artifact introduced by drawing the smooth fitted function into the discrete pixel grid of the original image. The arrows indicate the time and place at which the shock wave leaves the luminescent plasma.

5. Results and Discussion

A. Plasma, Cavitation Bubble, and Shock-Wave Formation

Figure 3 shows examples of typical breakdown events at 1 and 10 mJ as well as the corresponding streak images.

The framing images were obtained with an open shutter in a dark room, with illumination of the scene by the frequency-doubled pulse 23 ns after breakdown. The laser light is incident from the right. The plasma radiation is visible because of the open camera shutter, although it lasts only 15 ns and has already ceased when the shock wave and cavitation bubble are imaged. The cavitation bubble appears as a dark area surrounding the plasma, and the shock wave is visible as a dark ring around the bubble. Even though the sizes of the plasma and the cavitation bubble vary significantly with pulse energy, the general characteristics are quite similar: For both pulse energies the plasma has a conical shape with a wing on the top right. The shape of the plasma reflects the light-intensity distribution near the laser focus, and the wing corresponds to an asymmetry in the ring structure modulating the Gaussian beam profile.

According to the moving-breakdown model,²⁷ the plasma grows toward the laser as long as the light intensity increases. The trailing edge of the incident laser pulse leads to heating of the plasma but not to further growth. The energy density in the plasma is therefore most likely to be higher on the side oriented toward the incident laser beam. The high-energy density leads to high pressure inside the

plasma resulting in high shock peak pressures in the liquid surrounding the plasma. Since we expected the highest peak pressure to occur in the region of the plasma oriented toward the laser, we located the streak slit (indicated by the dark vertical line in Fig. 3) near the estimated center of mass of the plasma. The streak slit that is properly focused onto the streak camera appears slightly defocused in the framing images owing to chromatic aberrations of the imaging optics, L_5 , and the wavelength difference used for illuminating the streaks (630 nm) and the framing images (532 nm).

In the streak images, no plasma radiation can be seen because it was blocked by the bandpass filter. Instead the breakdown event appears as a dark shadow in the center of the streak images. This initial shadow corresponds to the plasma being formed.

Approximately 4–5 ns after its first appearance the homogeneous shadow separates into three distinct objects: The expanding plasma starts to form the cavitation bubble that is now the central structure in the image. Above and below, two distinct dark lines with gradually decreasing slopes can be observed. These lines correspond to the shock wave. At the cavitation bubble wall and at the shock front the refractive-index gradient is large. This leads to a deflection of the illuminating light from the imaging aperture, resulting in the dark appearance of bubble and shock waves. In contrast, the plasma appears dark owing to absorption rather than deflection of the background illumination.

Initially, the plasma and the shock wave both appear as a single dark object in the streak images. It

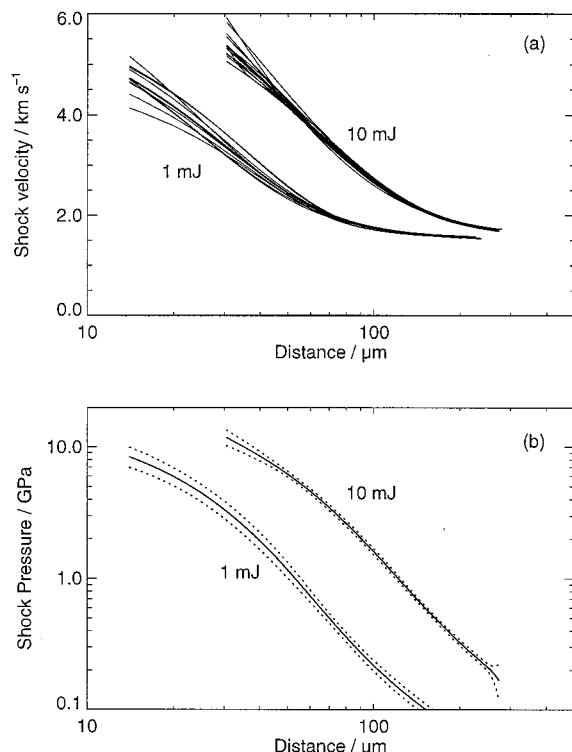


Fig. 4. (a) Shock-wave velocity and (b) shock-wave peak pressure as a function of distance from the optical axis. (a) Each curve represents a shock wave emitted after laser-induced breakdown with laser pulses of 1 and 10 mJ, respectively. (b) The solid curves were obtained from the average shock velocity for each pulse energy. The dashed curves indicate the standard deviation.

is therefore difficult to decide whether the edge of this object corresponds to the edge of the plasma or to the detached shock front. The dimensions of the plasma, however, can be measured from the time-integrated framing images. The plasma radii r_0 at the location of the streak slit thus obtained are 14 and $30.5 \mu\text{m}$ for pulse energies of 1 and 10 mJ, respectively. The time when the radius of the dark object in the streak images equals the plasma radius is indicated by arrows in Fig. 3. At earlier times, the increasing size of the dark object in the streak images corresponds to the lateral plasma growth in the streak slit. Consequently the speed of the shock wave can be determined only after the shock wave emerges from the luminescent plasma.

The speed of the shock wave extracted from the streak images is shown in Fig. 4(a) for different breakdown events with pulse energies of 1 and 10 mJ. The average shock-wave velocity at the plasma rim was $4.7 \pm 0.3 \text{ km s}^{-1}$ for 1-mJ pulses and $5.4 \pm 0.3 \text{ km s}^{-1}$ for 10-mJ pulse energy. For both pulse energies the shock-wave velocity decreases rapidly, approaching sonic velocity within the first $300 \mu\text{m}$ from the optical axis. Variations in the shock-wave velocity are most pronounced near the source.

Figure 4(b) shows the shock-wave pressure as a function of distance from the optical axis. The solid curves were obtained by averaging velocity curves

from Fig. 4(a) and converting them to pressure by using Eq. (1). The dotted curves indicate pressures that result if the shock velocity deviates one standard deviation from the average value. The shock pressure at the plasma rim was $8.4 \pm 1.5 \text{ GPa}$ for 1-mJ pulses and $11.8 \pm 1.6 \text{ GPa}$ for 10-mJ pulses. The pressure decay for both pulse energies was approximately proportional to $r^{-1.3 \pm 0.2}$ up to distances as great as $2r_0$. At greater distances the average pressure decay was proportional to $r^{-2.2 \pm 0.1}$.

B. Accuracy and Reproducibility

The shock-wave peak pressure is determined from the shock-wave speed, which is obtained as the temporal derivative of the shock-wave position. Therefore high accuracy in shock position detection is essential for accurate measurements of shock peak pressure. The measurement accuracy of the method presented depends on the spatial and the temporal resolution obtained in the images, the accuracy of the shock-wave extraction during image processing, and the accuracy of the analytic fit through the extracted data.

The spatial resolution of the setup was measured to be $6.4 \mu\text{m}$ and is limited by the spatial resolution of the streak camera and the CCD readout. The temporal resolution is determined by the streak rate and the width of the slit image on the photocathode and is better than 200 ps. The shock-wave position determined by automated image processing was in most cases found to be identical within 1 pixel (corresponding to $3.2 \mu\text{m}$) with the shock-wave position determined visually. The use of a global fit function can be interpreted as a weighted average over the entire streak duration. Similar to local averaging it improves the overall accuracy in position detection, provided an adequate global model is used.

The measurement uncertainty of the shock speed and corresponding uncertainties in pressure were calculated based on the covariance matrix of the fit parameters in Eq. (3) by using error propagation theory.²⁶ Typical relative errors of the propagation speed of the shock wave are $\sim 5\%$, which is similar to the variation of the shock speeds obtained for different events with equal energies [Fig. 4(a)]. The non-linearity of the equation of state implies that the relative errors in shock pressure are higher for lower pressures. Typical errors at 0.1, 1, and 10 GPa are 87%, 20%, and 13%, respectively.

To check the reproducibility of the method, shock waves emitted by several breakdown events at equal pulse energies were investigated. Figure 4(a) shows the shock velocity as a function of distance from the optical axis for several pulses at each of the pulse energies investigated. In general, the agreement of the velocities obtained for different individual events is reasonable. At the source the standard deviation of the measured shock wave velocities is below 7%, and it decreases even further as the distance from the source increases. The good agreement of the shock-wave velocities obtained from different individual events is a result of the reproducibility of the break-

down event being very good if the spherical aberrations of the optics focusing the laser pulse into the cuvette were minimized.¹⁷

The variations in speed and pressure were greater for a pulse energy of 1 mJ, probably because variations in the breakdown process are larger at small energy values close to the breakdown threshold ($ED_{50} = 170 \mu\text{J}$): Plasma formation occurs only if the free-electron density created during the laser pulse duration is sufficiently high. Possible mechanisms for the creation of free electrons are multiphoton absorption and avalanche ionization.²³ The probability for both processes increases with increasing laser pulse intensity; i.e., they become more and more deterministic with increasing intensity. Near breakdown threshold, the plasmas created are thus expected to show some variation in size, shape, and electron density. Consequently the shock waves emitted during the plasma formation at 6 times the threshold (1 mJ) will also show some variation in pressure amplitude. At 60 times the threshold, in contrast, the plasma formation has lost most of its statistical nature. In fact, plasma shape and size were found to vary much more in the framing images obtained for 1-mJ pulses than those created with 10 mJ. The variation in pressure amplitudes for the higher pulse energy, where the breakdown process is almost deterministic, therefore allows a realistic estimate of the overall accuracy of the measurement technique.

With current magnification and temporal resolution, shock speeds as low as Mach 1.05 can be measured with 5% accuracy. In water, this corresponds to shock pressures of 100 MPa and relative errors of 87%.²¹ In air, the Mach number at the same pressure is 30.²⁸ The ability to measure Mach numbers of 1.05 as accurately as 5% implies that pressures as low as 0.1 MPa can be measured as accurately as 11% in air with high spatial resolution.²⁸ This might be useful for characterizing shock waves emitted during laser ablation in gaseous surroundings.

C. Peak Pressure and Pressure Decay

The shock pressure at the rim of the plasma generated by 10-mJ pulses was larger than for 1-mJ pulse energy. This observation is consistent with earlier research¹⁷ and indicates a higher-energy density for larger laser pulse energies.

The spatial decay of shock peak pressure was similar for both pulse energies: In close proximity to the source the pressure decay is proportional to $r^{-1.3}$, whereas at great distances the pressure decay is roughly proportional to $r^{-2.2}$. The different form of the $p(r)$ dependence in the vicinity of the source is most likely due to the shape of the plasma. At distances that are small compared with the plasma length (112 μm at 1 mJ, 260 μm at 10 mJ, Fig. 3) the plasma appears as a conical source, whereas at greater distances it resembles a spherical source. As in the case of underwater explosions,¹ the pressure decay surrounding the laser-induced plasmas is reduced for a more elongated source geometry.

The shock wave propagates a significant distance ($\approx 30 \mu\text{m}$) during a laser pulse duration of 6 ns. The time required for the complete development of the shock front can also be associated with the smaller slope of the $p(r)$ curves near the source.¹⁷

D. Comparison with Other Authors

Vogel *et al.*¹⁷ determined the shock-wave velocity based on evaluation of the shock-wave position from framing images, which were obtained with the same laser parameters as in this study. The framing images were taken after separate events, with increasing time delay between the plasma generation and the photograph of the shock wave. They found a similar form and similar maximum slope of the $p(r)$ curves, but lower pressures, especially at the plasma rim (2.4 GPa compared with 8.4 GPa for 1-mJ pulses and 7.2 GPa compared with 11.8 GPa for 10-mJ pulses). At greater distances, pressures obtained from analysis of the streak images are in good agreement with those obtained from framing images: At 100 μm the shock pressures for 1- and 10-mJ pulses were 0.2 and 1.6 GPa, whereas Vogel *et al.* reported 0.4 and 1.6 GPa, respectively. The discrepancies close to the plasma can be explained by considering the exposure duration of the shock-wave images. If the shock position is evaluated from framing images illuminated by the frequency-doubled laser pulse, the measured position will be averaged over the exposure duration (6 ns). If the shock-wave position is obtained from the streak images, however, the averaging period is much shorter (≈ 200 ps). Hence the shock-wave position is determined much more accurately. This is of particular importance close to the source where the propagation and the decay of the shock wave are very rapid. The measured shock-wave speeds and corresponding pressure values will therefore be higher in the case of streak photography.

A comparison with the measurements of Doukas *et al.*¹⁶ who used two probe beams separated by 30–40 μm can be performed only for a great distance from the source, because the technique can be used only at distances greater than the separation of the probe beams. At a 120- μm distance from the optical axis Doukas *et al.* obtained a peak pressure of 1.53 GPa with a 14.7-mJ pulse. This is in reasonable agreement with a pressure of 1.0 GPa obtained with 10-mJ pulses in this study. The slope of the $p(r)$ curves in Fig. 4(b) appears to be smaller than the average value of -2.2 for greater distances. This is consistent with the $1/r^2$ dependence found by Doukas *et al.*¹⁶ for distances as great as 1500 μm .

The peak pressure amplitudes measured in this study are similar to those in an earlier streak photographic investigation performed in our laboratory.¹⁰ The quality of the pressure data obtained, however, was significantly improved:

The use of a flashlamp-pumped dye laser provides bright homogeneous illumination over the entire streak window. This allowed a CCD readout to be combined with largely automated image-processing

algorithms, making it feasible to obtain complete $p(r)$ curves for single events within minutes.

Additionally the use of a global fit instead of local approximations improved the signal-to-noise ratio of the $p(r)$ data significantly. Furthermore the measurement location with respect to each individual event can now be documented, which proved useful in the interpretation of the $p(r)$ curves for events with statistical variations (1-mJ pulses).

6. Conclusion

We have demonstrated the feasibility of single-shot spatially resolved streak photographic pressure measurements of shock waves in liquids. The measurement accuracy of the shock-wave velocity was $\sim 5\%$, allowing shock pressures down to 0.1 GPa to be measured in water.

The single-shot determination of complete $p(r)$ curves allows, for the first time to our knowledge, investigation of shock-wave emission in aqueous media for events with poor reproducibility and large statistical fluctuations; a possible example is the shock-wave emission during the collapse of cavitation bubbles. Furthermore the relative ease and the speed (a single event can be analyzed in less than 2 min) of obtaining spatially resolved pressure amplitudes allows parameter studies of shock-wave emission such as investigations of the pulse energy and pulse duration dependence of shock-wave emission during laser-induced breakdown.

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