OPTIC CAVITATION

W. Lauterborn

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Drittes Physikalisches Institut, Universität Göttingen, Bürgerstr. 42-44, D-3400 Göttingen, Fed. Rep. Germany.

Résumé.- On présente une revue des travaux relatifs à la cavitation optique qui est la création, par la lumière, de bulles de cavitation dans les liquides. On s'intéresse également à la dynamique de ces bulles.

Abstract.- A survey is given of the new field of optic cavitation, i.e. the formation of cavities in liquids by light and their dynamics.

1. Introduction.- The phenomenon of cavitation has a long history. Perhaps the first to care about this effect, the rupture of liquids, was Leonhard Euler as early as 1754 in his work on the theory of turbines /1/. But it was not until 150 years later, at the turn of the century, that it really became a problem in connection with ship propellers. Nowadays cavitation presents a problem in all kinds of hydraulic machinery, especially ship propellers, turbines, pumps and hydrofoils. This type of cavitation is called hydraulic cavitation and can be said to be effected by the Bernoulli underpressure in high speed fluid flow.

Acoustics entered the field later in the history of cavitation mainly in connection with sonar systems. When water is irradiated by sound of high intensity, cavitation may occur, called acoustic cavitation (see e.g. /2/). The cause for the rupture or breakdown of the liquid is again the lowering of the pressure in the liquid, this time due to the underpressure phase of the sound wave.

Shortly after the invention of the laser optics entered the field as cavitation phenomena are also observed in high intensity light fields /3/ /4/. This type of cavitation has been called optic cavitation /5/ /6/. The cause for liquid breakdown in this case is the local deposit of energy which leads to a " hot spot " and a kind of microexplosion. Starting point for the breakdown, also called optic breakdown, seem to be absorbing impurities, but also the pure liquid will rupture in high enough intensity light fields due to multiphoton ionization and electron avalanche processes.

In optic cavitation photons are used to rupture a liquid. But indeed, any sort of high energy particles may be used. This type of cavitation has been known since the 1950's and is utilized in the bubble chamber. The name particle cavitation is suggested for this case. At lower intensities or particle flux (below the cavitation threshold) sound waves are generated in the liquid via the thermo-acoustic effect (see the paper of Westervelt in the proceedings). In the photon case the breakdown is accompanied by shock wave emission. The same can be predicted for high energy particles.

The preceding unified view of cavitation phenomena has been given as a background to the following survey of optic cavitation.

2. Dynamics of laser produced bubbles.- High light intensities are needed to produce bubbles in liquids by light, but nowadays several laser systems exist being capable of delivering the necessary intensity and energy in a short time like ruby, neodymium and of course any laser planned for nuclear fusion studies if the liquid under study is transparent enough for the wavelength of the laser.

In our experiments a ruby laser was used. Fig. 1 shows the set-up. Giant pulses emitted by a Q-switched ruby laser with a beam cross section of about $1 cm^2$, a duration of about 30 to 50 nsec and a total energy of up to 1 joule are focused into the liquid under investigation by a single lens of short focal length. The bubbles produced in the vicinity of the focal point of the lens are diffusely illuminated by a flash lamp through a ground glass plate and photographed by a rotating mirror camera with framing rates up to a million frames per second. In a series of experiments bubble oscillations in the bulk of the liquid (water and silicone oil), bubble dynamics near plane solid boundaries and the dynamics of interacting bubbles

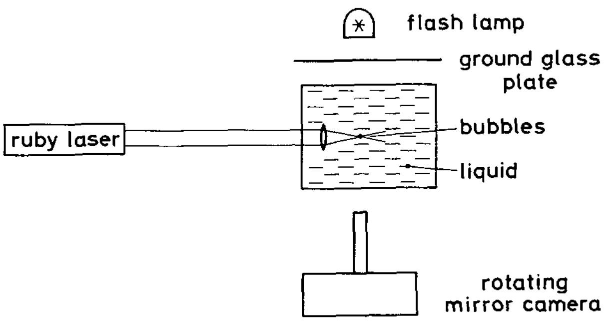


FIGURE 1 : Set-up for high-speed photography of laser-induced cavitation bubbles.

have been investigated /5/, /6/, /7/. The main results of this high speed photographic study have also been documented in a film available from the Institut für den Wissenschaftlichen Film /8/. The film has been shown at the conference, but it is of course difficult to give a reproduction in a few pictures or even words. The main impression one gets from the film is that jet formation plays a dominant role in the life of a cavitation bubble. Indeed this seems to hold very generally. It is conjectured that interacting bubbles always develop jets if the viscosity of the liquid is not too high. As an example just one series out of the film is shown in Fig. 2, where a bubble in water collapsing in the vicinity of an expanding bigger bubble develops two jets in opposite directions. The collapse of a bubble of similar shape as that in Fig. 2 has been calculated by Chapman and Plesset /9/ up to near collapse. Qualitatively the same form of the collapse is observed, and two jets develop as expected from an intuitive extrapolation of the calculation.

3. Collapse studies. - The film clearly demonstrates that the collapse of a cavitation bubble in water under atmospheric pressure is a very fast event. Even framing rates of about a million frames per second seam to be insufficient to resolve the motion of the bubble at collapse /7/. We therefore started a project to have an even closer look at bubble collapse. An image converter camera with a framing rate capability of up to 20 million frames per second is used for this purpose. Of course, also the breakdown phase has been investigated with this camera. Cavity formation and shock wave radiation upon breakdown in water taken at 5 million frames per second have already been reported /10/.

For bubble collapse studies a special set-up to trigger on the collapse had to be developed as shown in Fig. 3. A He-Ne laser (15 mW) light beam passes the focal region of the focusing lens for the ruby light pulses and is picked up by a photodiode. The bubble or bubbles formed in the focal region scatter the He-Ne laser light out of the path giving rise to a modulation of the electric output of the diode. The trigger of an oscilloscope is used to select a certain part of the bubble motion, e.g. its collapse, to be photographed at high framing rates. The cavities are illuminated from behind so that they appear black on a bright background. The set-up of Fig. 3 is an extension of the relatively simple configuration of Fig. 1 and allows the simultaneous recording of bubble motion at two different framing rates. It is intended to take the whole life cycle (or at least the most interesting part of it) of a bubble with the rotating mirror camera at moderately high framing rates (up to a few hundred thousend frames per second) and simultaneously the collapse at high framing rates (up to 20 million frames per second) with the image converter camera. By now, bubble collapse studies are quite easily done at a million frames per second (by R. Timm, working for his masters degree). At higher framing rates the triggering is more difficult and not quite repeatable due to the slightly different trigger signals at different collapses. Fig. 4 shows an example of a bubble collapse and rebound in the bulk of water taken at one million frames per second. The width of the frames is about 3mm. As far can be concluded from the frames the collapse is spherical and a spherical shock wave is radiated. But the very final stage of collapse has not been caught. We hope to succeed in the near future in taking bubble collapses at 20 million frames per second. The more detailed information will become available. Of special interest is the collapse of bubbles near solid boundaries and their shock wave radiation properties.

4. First steps towards the investigation of the interaction of bubbles in three dimensions. - In real cavitation bubble fields many bubbles are present in close proximity. The question immediately arises of how e.g. the collapse of a bubble is

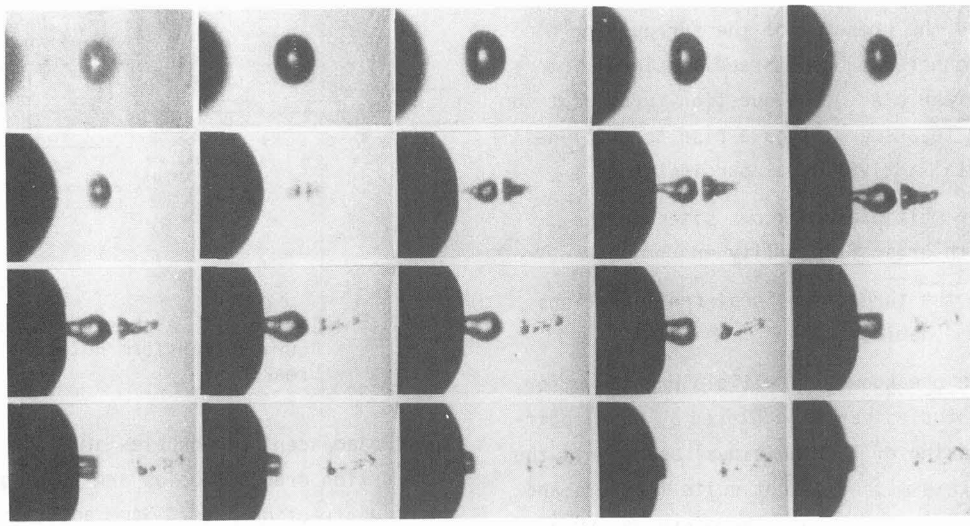


FIGURE 2 : Double jet formation upon collapse of a bubble in the vicinity of another expanding bubble (75 000 frames per second, frame size 2.25mm x 3.5mm).

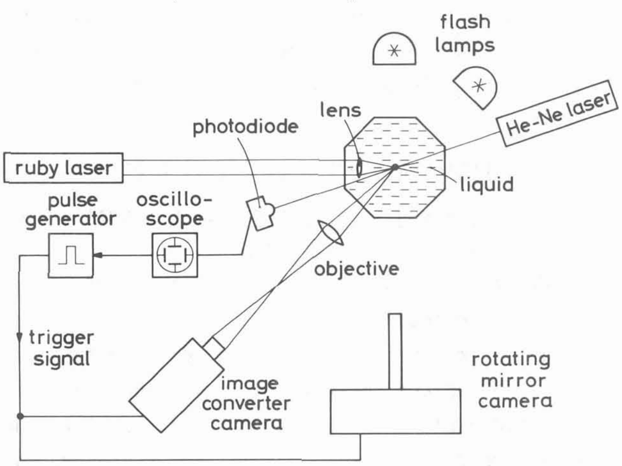


FIGURE 3 : Set-up for the simultaneous high-speed photographic recording of laser-induced bubble motion and bubble collapse at two different framing rates with triggering on collapse.

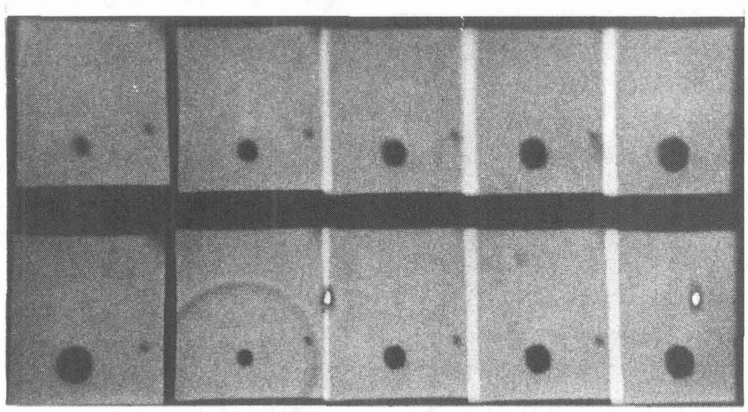


FIGURE 4 : Collapse of a laser-induced cavity in water under atmospheric pressure taken at one million frames per second. The width of the frames is about 3mm. Apparently spherical collapse and shock wave radiation (Sequence taken by R. Timm).

influenced by the presence of the surrounding ones and in general of how threedimensional interaction may take place. The question turnes out to be difficult to answer. It gave rise to two lines of experimental activities at our institute :

1. to achieve multiple breakdown sites in the liquid with great flexibility and
2. to record the threedimensional configurations and their dynamics.

4.1. Multiple breakdown.- Multiple breakdown for interaciton studies can be achieved by beam splitting and focusing of the individual beams into the liquid. But this method is not quite flexible and limited to just a few beams. Therefore we try a holographic approach. The idea is to use holographic lenses (i.e. holograms with just a few points in space as image) to get simultaneous optic breakdown in the liquid at different points. The experimental set-up will then remain as simple as before.

Strong difficulties are encountered when trying to realize this idea. Only phase holograms can be used due to the high light intensities. Up to now we have used phase holograms made in photoresist which is reasonably stable against ruby laser light. But due to enormous difficulties in fabrication we did not yet succeed in getting multiple breakdown from such holograms. That this approach will work once the technological problems are overcome can be seen from a feasibility study with a grating-lens assembly to focus the ruby laser light (Fig.5). A contact copy of a grating has been made in photoresist (Shipley AZ 1350) and put in front of the focusing lens (built into the wall of the container) for the ruby pulses. The phase grating can be considered as a Fourier transform hologram whose image (the different diffraction orders) is formed in the back focal plane of the focusing lens. When the intensity of the giant pulses is high enough multiple breakdown will occur at these points. Fig. 6 shows an example. Rather viscous silicone oil is used as liquid which is decomposed at the sites of breakdown. Thus the cavities formed are permanent bubbles due to gaseous decomposition products and stick for some time to the places where they have been formed. The picture is a still photograph taken about a second after breakdown (by W. Hentschel on his way to his masters degree). The big bubble in the middle stems from the zeroth order.

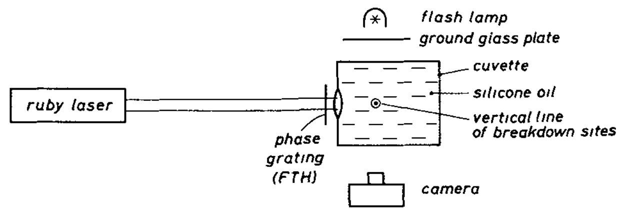
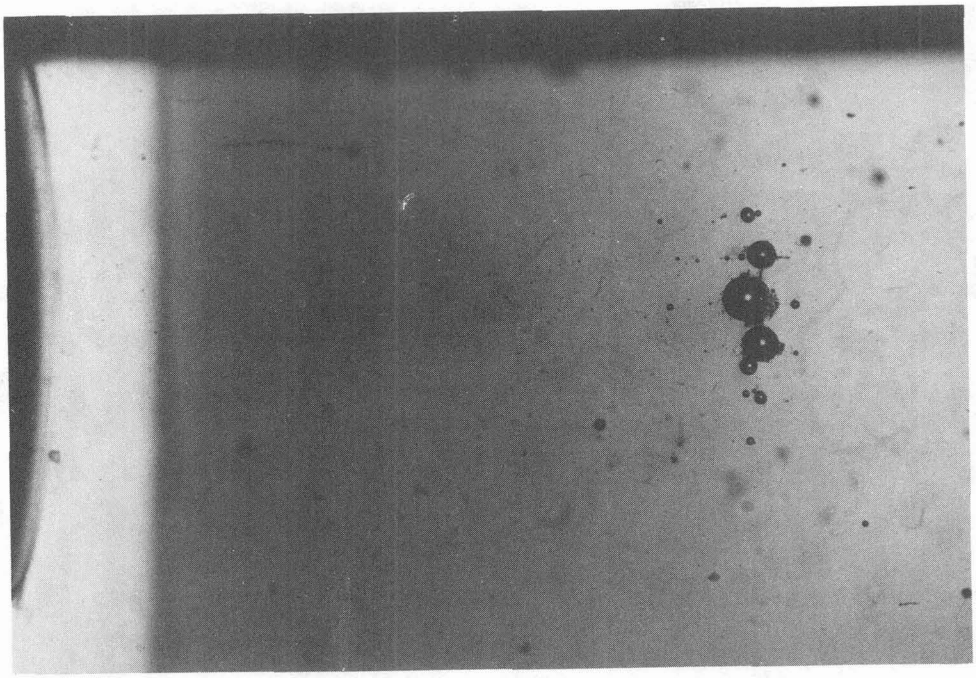


FIGURE 5 : Set-up with a phase grating (or FTH = Fourier Transform Hologram) for multiple breakdown.

The two adjacent big bubbles are the + and - first diffraction order. Bubbles are to be seen up to the third diffraction order. Some additional small bubbles appear near the main ones presumably due to impurities in the liquid facilitating additional breakdown.

The next step will be to produce not just phase gratings in photoresist but more complex holograms giving multiple breakdown in different planes in depth.

4.2. Recording of threedimensional bubble configurations and their dynamics.- For small threedimensional scenes that can be illuminated with coherent light holography is the way of recording. In our case the holographic equivalent to a rotating mirror camera would be needed. Unfortunately such devices are not yet available. Thus we spent a considerable amount of time and effort into the development of high-speed holocinematography. Mainly two devices, using spatial and spatial frequency multiplexing have been developed and used for bubble studies. For a detailed description see Ebeling /11/, /12/ and Lauterborn and Ebeling /13/, /14/. The state of the art is by now that four to eight holograms can be taken at a rate of 10 to 20 kHz. An example of a hologram series taken with one of our devices at a rate of 20 000 holograms per second is shown in Fig. 7. The object is a dynamic threedimensional scene made up of a laser produced bubble going through its first collapse and four gas bubbles in different planes in depth attached to screw tips and undergoing deformations due to shock waves and the flow field generated by the laser produced bubble. Noteworthy is the excellent quality of the pictures and the bunch of shock waves radiated upon the unsymmetric collapse of the central laser produced bubble. They seem to be



- FIGURE 6 : Bubbles remained after multiple breakdown from a Q-switched ruby laser pulse in viscous silicone oil at the diffraction points in the back focal plane of a grating-lens assembly. Height of the picture about 14mm. The lens is to be seen on the left (Picture taken by W. Hentschel).

produced by the liquid jet formed upon collapse and the remnants of which are to be seen in the last two columns.

The work on high-speed holocinematography is continuing.

5. Conclusion.- Optic cavitation is quite a new field only a few years old. But it may add substantially to our knowledge on cavitation bubble dynamics because

1. bubbles can be formed in the free liquid without any disturbing parts,
2. the location of the bubble is known,
3. the instant of generation is known, and
4. at least simple bubble configurations can be produced at will.

Thus the questions of single bubble collapse, jet formation, shock wave radiation, and bubble interaction can be attacked with great hope of success.

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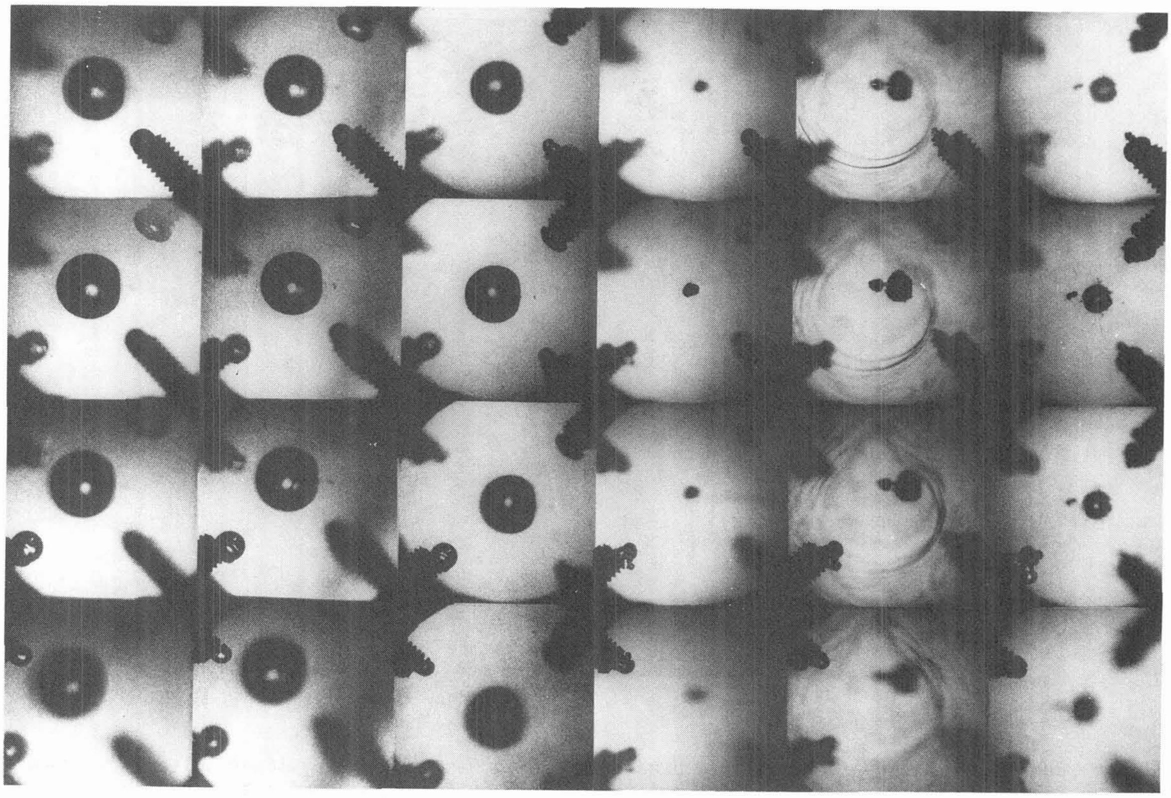

FIGURE 7 : Example of a hologram series taken at 20 000 holograms per second. The columns show different planes in depth at the same instant (from the top : 0mm, 5mm, 10mm, 20mm). The rows show one plane in depth at different instants in time (from left to right : 300µs, 350µs, 400µs, 500µs, 550 s, 650 s after breakdown). The frame size is 15mm x 15mm. The bubble in the middle is the laser produced bubble undergoing its first collapse.

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