Ultrasonic cavitation with laser-generated bubbles

T. Kurz, D. Kröninger, T. Wilken, L. Wißmann, W. Lauterborn
University of Göttingen, 3. Phys. Inst., 37077 Göttingen, Germany, Email: tkurz@dpi.physik.uni-goettingen.de

Introduction

The laser generation of single bubbles has been used in the past to study their collapse dynamics under a variety of experimental conditions, e. g., with bubbles close to rigid or compliant walls [1,2]. In this way, specific features of bubble collapse like liquid jet formation, and the emission of shock waves, could be elucidated [3]. Laser-generated bubbles typically last for at most a few oscillation cycles, until either the energy imparted by the laser pulse is dissipated, or the bubble breaks up due to instabilities. If the bubbles are produced in an ultrasonic field they can gain energy by the acoustic driving and thus be expanded to a much larger size at least transiently [4,5]. This leads to a stronger collapse that cannot be realized easily, e. g., by using acoustic bubble traps alone. Furthermore, the method permits to investigate the long-term evolution of bubble parameters as well as bubble movement in the acoustic field under conditions, at which the bubble oscillates stably.

Experimental Setup

The experimental setup used in our experiments is shown in Figure 1. The bubbles are produced by an amplified femtosecond (fs) laser system delivering single pulses of 130 fs duration ($\lambda = 780\,\mathrm{nm}$) with energies of a few μJ. The laser light is focused to the center of a cubical cuvette (30 mm face length) filled with clean water. The cuvette is driven at its first fundamental mode (frequency $f \approx 44$ kHz) by a piezoelectric transducer glued to the bottom face. The acoustic drive is phase locked with the laser oscillator. By suitably selecting the pulses feeding the laser amplifier the seeding phase φ_s of the bubble in the sound field can be defined precisely while maintaining the resonance condition for the cuvette. The bubbles are observed through a long-distance microscope and can be imaged, using back illumination, with a CCD camera. Alternatively, their cavitation luminescence is observed by a gated ICCD camera or by a sensitive photo multiplier tube (PMT). A hydrophone is used to measure the collapse time of the bubbles, thus allowing to sort measurement results according to the actually obtained maximum bubble sizes.

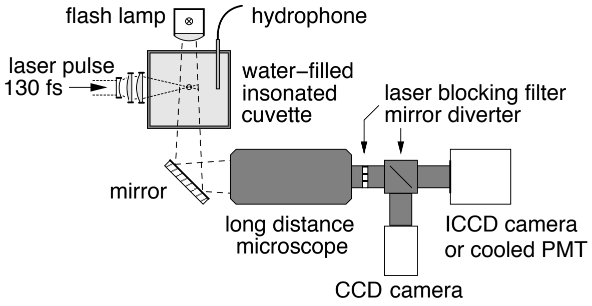

Figure 1: Experimental setup to generate bubbles in a standing wave field by a femtosecond laser.

Results

Typically, bubbles produced by fs laser pulses do not have spherical but cylindrical shape and thus collapse without emitting light or strong acoustic waves. At low laser energies, due to the low breakdown threshold of fs pulses, the maximum effective bubble radius is of the order of 10 μm, the collapse time of the order of a few μs. This is a distinctive advantage of fs laser bubble generation when it comes to the production of bubbles with low initial gas content in a sound field.

Transient dynamics at strong driving

Bubbles that are seeded at the beginning of the low-pressure phase of the sound field inherit the elongated shape of the producing laser plasma, as it is is expanded immediately. However, if the laser shot is set at the start of the high-pressure half-cycle, the generated bubble nucleus has sufficient time to stabilize. This leads to an initially well-defined spherical bubble shape even at high acoustic driving amplitude with correspondingly strong succeeding collapse (Figure 2).

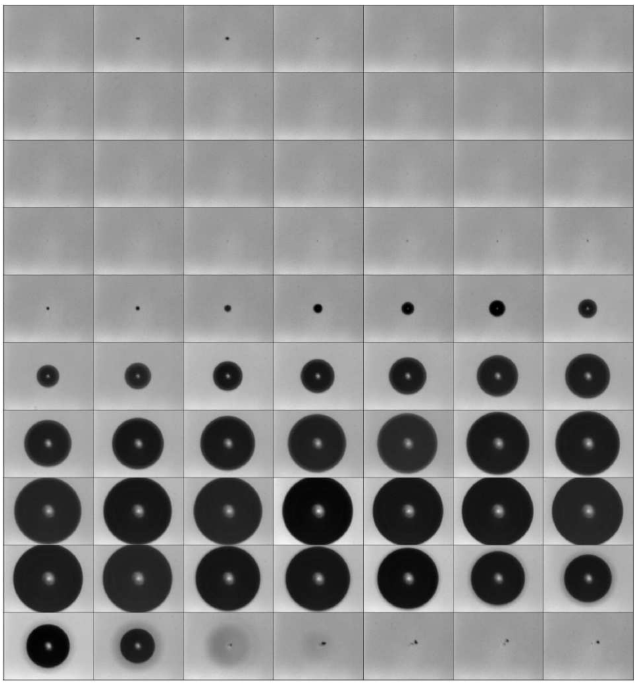

Figure 2: Delayed expansion of a bubble shot at the beginning of the high-pressure phase of the sound field ($\varphi_s = 353.5°$, $f = 43.7\,\mathrm{kHz}$, $p_a = 3.7\,\mathrm{bar}$, image width 346 μm, image separation 500 ns, exposure time 200 ns).

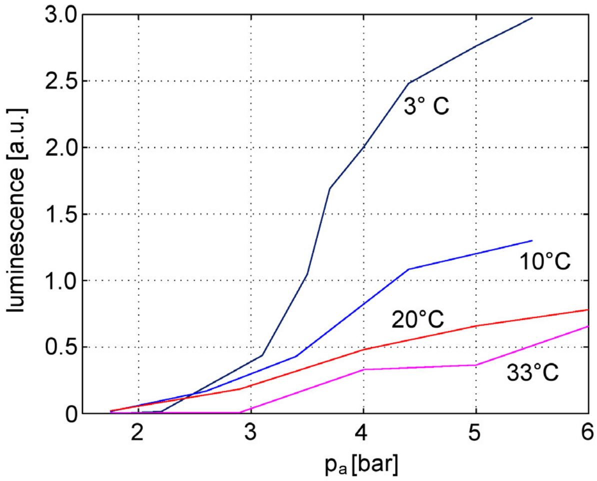

Figure 3: Temperature and pressure dependence of bubble luminescence at first strong collapse for bubbles generated at $\varphi \approx 0°$.

Bubbles generated in this way in fact do emit luminescence light upon collapse. The luminescence yield was measured as a function of driving pressure and liquid temperature and is shown in Figure 3. It can be stated that the light emission increases in a monotonous way with the acoustic pressure. It appears to level off at higher pressure amplitudes, an effect that also shows up clearly in other measurements not presented here. It can be attributed to the fact that a bubble cannot be expanded to arbitrary size within an acoustic half-cycle of given length. It is also evident that the light emission increases strongly when the water is cooled. This phenomenon was also observed in single bubble sonoluminescence (SBSL) [6] and the cavitation luminescence of non-driven laser-generated bubbles [7]. It probably is linked to the strong decrease of vapour pressure and a correspondingly smaller content of trapped vapour in the bubble at collapse.

Long-term evolution at SBSL conditions

If the gas content of the liquid and the acoustic driving are adjusted properly to realize SBSL conditions, a laser-generated bubble produced at the pressure anti-node of the sound field can be turned into a stably emitting SBSL bubble. During this process the bubble undergoes a characteristic change of its size, i. e., the amount of non-condensable gas it contains, its chemical composition and its light emission at collapse on the time scale of a few seconds. With the experimental technique used here it can be imaged sharply and investigated in detail over the whole time range of interest.

Figure 4 gives but one example of the measurement of bubble luminescence over the course of time as obtained by an ICCD camera. Initially, the laser-generated bubble, which is supposed to contain oxygen and hydrogen gas as by-products from the laser breakdown, even shrinks to a rather small size before rectified diffusion takes over. Then the bubble grows and starts to emit a significant amount of light only after it has collected enough gas (presumably, argon) and approaches its equilibrium size. The onset of stable SBSL is preceeded by a phase in which microbubbles are pinched off and the bubble dances around in an erratic way. With these data, models of gas diffusion for cavitation bubbles are to be validated experimentally.

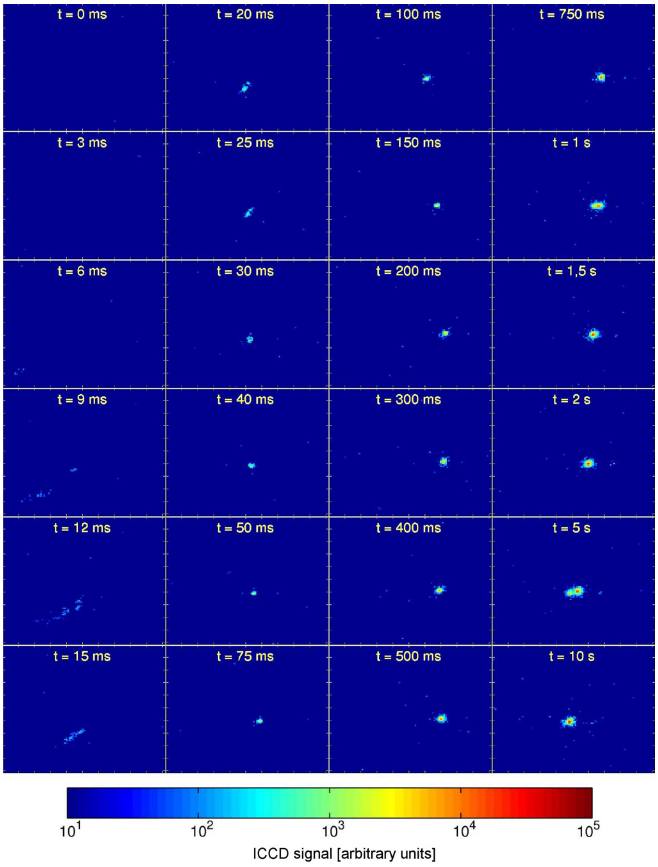

Figure 4: ICCD recordings of bubble luminescence (exposure time 2.28 ms, average of 5 acquisitions) at different times after laser generation of a bubble at SBSL conditions ($p_a = 1.55$ bar, $f_a = 43.68$ kHz).

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