Boosting Sonoluminescence with a High-Intensity Ultrasonic Pulse Focused on the Bubble by an Adaptive Array

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Single-bubble sonoluminescence is characterized by a great concentration of energy during the collapse of a gas bubble, which leads to the generation of photons from low-frequency ultrasound. The narrow stability domain of sonoluminescence has limited previous attempts to reinforce this inertial confinement in order to generate photons of higher energy or to ignite a nuclear fusion reaction. We present a new experimental approach where an ultrasonic pulse of high frequency is adaptively focused on the bubble during the collapse. Using an array of eight transmitters, a pressure pulse of 0.7 MPa doubles the flash intensity; this technique can easily be extended to higher pressure.

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In the classical single-bubble sonoluminescence (SBSL) setup, a monochromatic sound field is used to trap a gas bubble in a resonant cavity filled with a liquid [1]. The bubble undergoes large periodic nonlinear oscillations characterized by an expansion stage followed by a violent collapse. At the end of the collapse, the acoustic energy stored by the bubble is converted into a short flash of light [2,3]. This process achieves a very efficient inertial confinement leading to plasma formation in the gas of the bubble. State-of-the-art models predict that the temperature and pressure inside the bubble reach several tens of thousands of degrees and atmospheres, respectively, at the end of the collapse [4–9]. To achieve light emission, the amplitude of the stationary sound field must be greater than 1.2 atm. At this level, the brightness of the bubble increases rapidly with the pressure field. When the amplitude of the stationary sound field exceeds 1.4 atm, the bubble disappears due to bubble shape instabilities and diffusive processes [7,10–12].

These figures have led several teams to investigate the possibility to further increase the energy concentration by modifying one or several parameters of the experiment: pressure, temperature, and the nature of the gas or the liquid (for a review, see [3]). One goal was to reach the conditions required to initiate a nuclear fusion reaction. Most of these trials have rapidly reached the boundaries of the narrow stability domain discussed above, and water remains the best liquid to achieve sonoluminescence. Simultaneously, several studies have tried to control the pressure field in order to improve the concentration of energy. From these studies, two approaches can be distinguished: periodic and transient methods.

Holzfuss *et al.* [13] used a biharmonic sound field and showed that a gain of intensity can be obtained near the low threshold of sonoluminescence. However, it is not clear if the bubble is actually brighter than for the case of a monochromatic excitation of higher amplitude. Seeley [14] performed the same type of experiment but did not detect any increase in the brightness. All these techniques are based on a periodic modification of the sound field. Therefore, they are seriously limited by the narrow stability domain of the bubble, which results from equilibrium being reached after several cycles of the sound field [7,10–12,15–19].

The transient technique was first proposed by Moss *et al.* [20] in the context of thermonuclear fusion reaction. However, his paper is only a numerical evaluation of the effect of a pressure pulse during the collapse of a deuterium bubble and relies on the shock hypothesis. Several teams have attempted to enhance the flash of light according to this technique [14] (Ref. [15] of [20]). Hargreaves and Matula [21] reported a doubling of the intensity of the flash for a negative pulse impinging on the bubble during the phase of expansion of the bubble. They showed that this pulse results in a transient increase of the maximum radius of the bubble. However, their technique is limited by asymmetrical effects since they used only one transducer. Indeed, one limitation of a pulse technique is that it may induce instabilities of the spherical shape of the bubble. These instabilities are smoothed during the growth of the bubble, whereas they will develop during the collapse of the bubble. Another difference between the two pulsed techniques is the amount of water vapor trapped inside the bubble before the collapse. Indeed, the technique developed here does not modify the gas content of the bubble, whereas the amount of water vapor will increase with the maximum radius of the bubble. This modification of the gas content affects the heating at the collapse due to the low polytropic exponent of water vapor. To our knowledge, no evidence of light increase has been reported with a positive pressure pulse.

In this Letter, we present a new experimental device that leads to a much higher incident sound field and overcomes the classical stability domain of sonoluminescence. The principle is to apply a strong acoustic pressure pulse at the bubble in order to increase the speed of the bubble collapse.

We show that, if the pressure pulse is adaptively focused on the bubble at the time of collapse, a significant increase of the emitted light can be achieved.

Experimental setup.—The experimental setup is based upon the one first developed by Gaitan *et al.* [1]. However, we use a spherical glass cavity, as described in [22], filled with degassed water and driven at resonance (frequency 27.6 kHz) by two piezoelectric transducers glued opposite each other along a circumference. A large nonspherical lens and photomultiplier are used to collect and measure the light. This now classical setting is adapted to incorporate eight high-frequency piezoelectric transducers (central frequency of 700 kHz) operating in pulse mode (see Fig. 1). The eight transducers are oriented perpendicularly to the surface of the spherical cavity and paired opposite each other along planes that cut the sphere into quarters. The glass cavity has been cut at the eight locations of the transducers to optimize the acoustic coupling to the water. A remotely programmable multichannel electronic drives the high-frequency transducers. Each of the eight channels consists of a pulse generator in transmission along with a numerical acquisition system in receive mode.

Method.—The aim of the experiment is to focus the eight high-frequency acoustic pulsed waves onto the sonoluminescing bubble at the time of collapse.

This requires two steps. First, the eight acoustic pulsed waves must arrive on the bubble at the same time in order to obtain constructive interference. Since the precise location of the bubble depends on several parameters of the experiment, the focusing must be adaptive. Second, the pulsed wave must be synchronized with the 27.6 kHz frequency dynamic of the bubble in order to reach the bubble at a predetermined phase of its cycle.

The principle of adaptive focusing is the following. The acoustic time of flight between each transducer and the bubble is determined by acoustic scattering. Each transducer sends a pulsed wave onto the bubble and records the backscattered waves. The pulsed waves are weak enough to avoid the destruction of the bubble. Time cross-correlation between the backscattered signals gives the eight times of flight between each transducer and the bubble. It should be noted that the scattered wave is difficult to detect because the wavelength of the incident wave is large compared to the radius of the bubble (Rayleigh scattering). Moreover, the amplitude of the scattered wave strongly depends on the radius of the bubble. As the radius of the sonoluminescing bubble varies from less than 5 μm at equilibrium to 50 μm [3], the amplitude of the scattered wave varies by a factor greater than 100. In order to obtain the maximum scattered pressure, the incident wave must reach the bubble when the bubble is large. However, the scattered signal is still too low to be detected in the acoustic noise background of the cavity (see Fig. 2a). This noise comes from the echoes of the incident acoustic wave on the walls of the cavity and from the acoustic emission of the bubble itself, which oscillates nonlinearly in the 27.6 kHz sound field. In order to obtain the scattered signal of the bubble, this background noise has to be subtracted (see Fig. 2b). As mentioned above, one source of noise comes from the sound emitted by the bubble itself at each cycle. However, because of the high-quality factor of the SBSL cell, each emission reverberates a long time in the cavity and, consequently, is mixed together. This prevents the use of the signal emitted by the bubble in order to measure the time of flight.

After this first step, the eight high-frequency transducers are synchronized with the dynamic of the bubble. The multichannel electronics are triggered by the monochromatic generator working at 27.6 kHz and the flash of light is taken as the time reference. We point out the synchronization between the acoustic pulse and the dynamic of the bubble is crucial for the success of the experiment. Indeed,

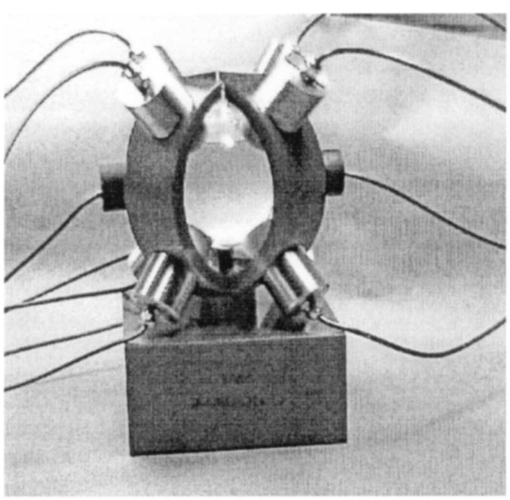

FIG. 1. Photograph of the sonoluminescence cell with its eight high-frequency piezoelectric transducers, held by hoops, and its two low-frequency transducers, in black.

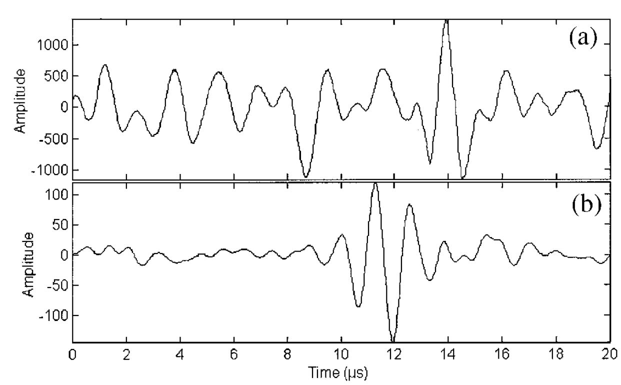

FIG. 2. Signal measured by one high-frequency transducer in pulse-echo mode: (a) before subtraction of the ambient acoustic noise and (b) after subtraction. The echo of the bubble when it reaches its maximum radius is more than 20 dB below the ambient acoustic noise.

the acoustic pulse produced by the high-frequency transducers is not a pure positive pressure pulse. Rather, its precise shape is determined by the bandwidth of the transducers, and the acoustoelectric response of one of these transducers is displayed in Fig. 3. While a positive pressure pulse increases the speed of the collapse, a negative pressure pulse slows down the collapse and prevents the light emission. The duration of the bubble collapse is about 3–4 μs [3], which is larger than the duration of the positive part of the acoustic pulsed wave (400 ns). Therefore, the acoustic pulsed wave has to reach the bubble during the last 400 ns of the collapse.

Results.—The driving voltage of the low monochromatic frequency was increased up to the threshold for which the bubble disappears while monitoring the intensity of the flash. Then, the voltage was set just below this threshold so that the pressure inside the cell was close to the upper boundary of SBSL and, hence, that the intensity of the flash of light was close to its maximum for a monochromatic excitation. When the high-frequency transducers are adjusted to focus on the bubble and synchronized with the bubble dynamic, an acoustic pulsed wave of high power is sent to reach the bubble at the collapse. In our experiment each channel can deliver 85 V peak-to-peak. Figure 3 displays the time dependence of the pressure three centimeters away from the aperture of one of the piezoelectric transducers. This measurement was made with a calibrated bilaminar hydrophone. Each element generates the same signal of which we used only the first half cycle of this acoustoelectric response (90 kPa amplitude). This results in a maximum pressure pulse of 0.7 MPa on the bubble. Figure 4 displays the recordings of the light emitted by the sonoluminescing bubble before and after the application of the pressure pulse.

Before $t = 16$ T, where $T = 36.2$ μs is the driving period, the flashes of light correspond to the classical SBSL. At time $t - 400$ ns, the positive pressure pulse reaches the bubble. This leads to a strong increase of the flash of light. With a pressure pulse of 0.7 MPa, we have been able to obtain a gain of 90% of the light intensity emitted by the bubble. The gain is defined as the ratio of the light intensity emitted by the bubble when the pressure pulse is applied to the light intensity emitted by the bubble without the pressure pulse at the high threshold of sonoluminescence. This means that the light emitted by the boosting bubble is twice as large as the maximum intensity obtained with the classic SBSL setup.

After the arrival of the acoustic pulsed wave, the dynamic of the bubble is strongly modified, in particular the next flash of light is absent. This certainly comes from the unavoidable negative pressure pulse, which follows the positive one. This negative pulse reaches the bubble after the collapse and is not in phase with the 27.6 kHz sound field, which induces a transient dynamic of the bubble. However, the bubble is not destroyed by our transient boosting. This implies that, in that range of pressure amplitude, sonoluminescence is not limited by instabilities at the collapse, such as the Rayleigh-Taylor instability.

Note that this pulse of pressure has no influence on the gas or vapor content of the bubble before the collapse. In these conditions, the intensity of the sonoluminescent light is usually linked to the speed of the bubble collapse and the maximum temperature inside the bubble [4–6]. It should be noticed that for a higher pulse amplitude and/or lower frequency, the 90% gain of light should be much more important. Here the amplitude of the pulse is too small to

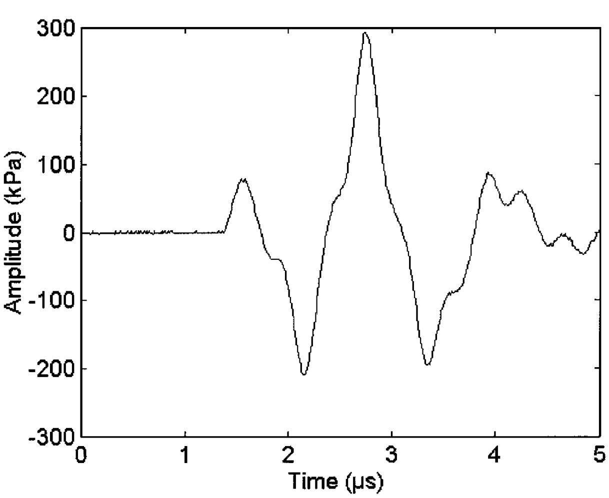

FIG. 3. Acoustoelectric response of one of the high-frequency piezoelectric transducers.

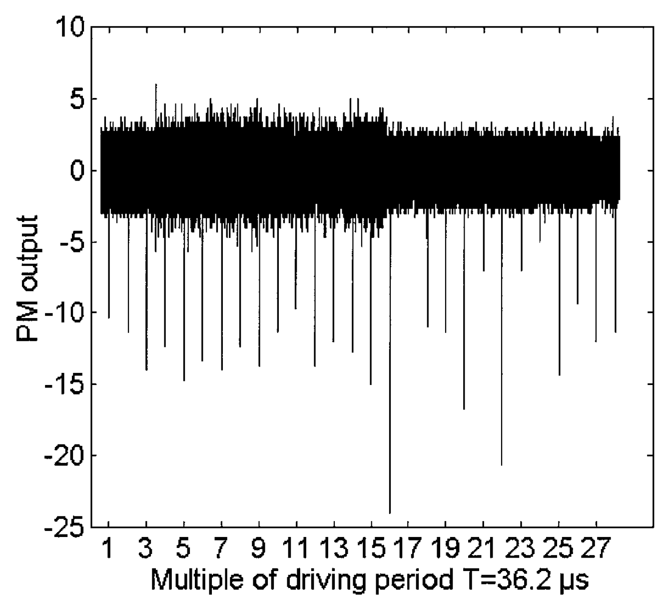

FIG. 4. Flash of light measured by the photomultiplicator when a pulse of pressure is applied at the end of the collapse. The acoustic pulse is sent 21.3 μs before the boosted flash at $t = 16$ T so that it arrives on the bubble 400 ns before the end of the collapse at time. A gain of 90% is obtained when this pressure pulse of 0.7 MPa and 400 ns of duration is applied. The gain is very sensitive to this timing.

shorten the duration of the collapse into half of the transient cycle. Therefore, the bubble is subjected to an overpressure only during the last 400 ns of the collapse, which is not very efficient. Previously Moss *et al.* [20] computed a gain of a factor of 100 for a weaker pulse (0.5 MPa and 500 ns of duration), but applied at the beginning of the collapse.

Other mechanisms have been proposed for sonoluminescence which have stressed the role of the nonsphericity of the bubble [23]. The increase of light reported here can provide a test for the different theories since the surrounding pressure and the light emitted are precisely measured.

Conclusion and perspectives.—The transient adaptively focused technique presented here is the first successful attempt toward a better inertial confinement in SBSL. A gain of brightness of a factor of 2 has been obtained, which was limited only by the power of the transducers. Since this transient boosting is no longer limited by the classical stability domain of SBSL, it could lead in the future to much higher temperatures inside the bubble. This experimental setup also provides a new domain of parameters for SBSL and, hence, a new test for numerous theories about light emission mechanisms.

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