

Visualizations of ultrafast bubble dynamics

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Experimental high-speed visualization techniques are evolving rapidly and provide valuable tools for learning about ultrafast bubble dynamics that cause unwanted but also desirable damage, such as cavitation and acoustically driven bubbles and droplets relevant for biomedical applications. This article offers my personal perspective on the quest to illuminate the hidden physics of externally stimulated bubbles that have a remarkable ability to focus energy.

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I. INTRODUCTION

Bubbles are fascinating objects that appear in countless instances in nature and find applications in numerous technologies. A particularly interesting feature of bubbles that has intrigued scientists and engineers in the past century is their unique ability to focus energy by, for example, converting acoustic energy into highly localized flows or kinetic energy in liquid flows into surface damage and even light emission. A typical example of such extreme bubble activity is cavitation, which is the formation and collapse of vapor bubbles resulting from low pressures in a liquid medium, such as those caused by pressure fluctuations in high-speed liquid flows or by the rarefaction phase of underwater acoustic waves. The term cavitation is often used also to describe the strong dynamics of bubbles containing noncondensable gases driven by high-amplitude pressure fluctuations in liquids. The violent events occurring as a result of the associated energy focusing can be harmful in hydraulic and naval engineering systems, such as pumps, propellers, turbines [1], and high-speed sailing boats [2], but it can also be leveraged in numerous beneficial applications such as cleaning (e.g., ultrasonic dental scalers [3]), industrial processing (e.g., chemical and food processing [4]), and biomedical applications (e.g., lithotripsy [5], histotripsy [6], targeted drug delivery [7]).

The experimental study of cavitation and fast bubble dynamics is often done using visualization techniques. However, optical imaging of cavitation is severely challenged by their three-dimensional (3D) nature, their curved and complex interfaces, overlapping of bubbles within a cloud, the random spatial and temporal distribution of nucleation events, their multiscale nature both in space and time, the extremely high speeds and the micrometric scales of the smallest bubbles across a wide depth of field, and blurriness induced by a plane wall obscuring bubble activity near surfaces. In the meanwhile, computational methods to simulate such fast dynamics, especially when involving multiple bubbles, are limited by the prohibitively high computational costs caused by the multiple spatiotemporal scales spanning through orders of magnitude, which prevent resolving all scales

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simultaneously in a single simulation. Combined with the complexities in modeling compressible flows involving interfaces and phase change, numerical methods, which are being developed extensively, are also severely challenged in the study of cavitation. Theoretical approaches, on the other hand, often have to rely on assumptions that are too bold to capture the complexities arising from, for example, bubble deformations in extreme energy-focusing events. Due to such experimental, numerical, and theoretical limitations that the field faces, many open questions remain in the physics of ultrafast bubble dynamics. Given the large number of important applications of such dynamic bubbles, as listed above, there is a need to control them, which in turn requires precise prediction tools and, as a prerequisite, understanding of the physics. Especially in applications where highly localized cavitation-induced damage is desired, such as in focused ultrasound therapy, it is of the utmost importance to exert control on the cavitation to avoid off-target adverse effects. As of today, despite over a century of research on the broader topic of cavitation, cavitation bubble nucleation and dynamics (and their consequences to the surroundings) remain difficult to predict and control even in simple media such as water, let alone in complex environments such as biological tissues.

This article describes how advanced imaging techniques, such as high-speed microscopy and high-speed x-ray phase contrast imaging, can overcome many of the aforementioned measurement challenges in the different cavitation experiments we have recently performed. I do not intend to cover the field comprehensively, but I report on a selection of interesting techniques that we, together with many colleagues and collaborators, have come across when facing the challenges specific to our ultrafast bubble dynamics visualization experiments in the past decade. Here, “ultrafast” refers to events happening within timescales well below a millisecond.

I will also discuss what such visualization techniques can teach us about the extremely rich fluid dynamics related to ultrafast bubble motion, with a key focus on collapsing and/or ultrasonically excited bubbles, which manifest a plethora of fascinating interfacial phenomena such as Faraday instability, Rayleigh-Taylor and Richtmyer-Meshkov instabilities, curious flow-focusing singularities causing fast jetting events and extremely violent thermodynamic processes, history force effects, among others. These studies have been motivated by the need to understand, predict, and control cavitation bubble dynamics.

II. TECHNIQUES FOR IMAGING ULTRAFAST BUBBLE DYNAMICS

A. High-speed optical imaging of bubbles

Imaging a bubble, like any other object, in a satisfactory manner signifies overcoming or circumventing challenges associated with the target being too small, too fast, too far, obstructed, or offering too little contrast. There exist many ways to image a gas bubble in a liquid as a result of the mismatch in refractive index between gases and liquids. The appearance of the bubble in the image strongly depends on the choice of illumination and the imaging lens. With direct, collimated backlight illumination, where the bubble is placed between the light source and the image detector, one may obtain a sharp-edged projected shadow of the size and shape of the bubble, enabling shadowgraphy [examples in Fig. 2(c) and Fig. 3]. More information on the topographic features of the interface (e.g., to visualize surface waves) or optical access to the interior of the bubble (e.g., to visualize jets inside the bubble) can be obtained using noncollimated light, as some of the nonparallel light rays refracting on the bubble interface can reach the image sensor (examples are in Fig. 4). The refraction on the curved interface causes the bubble in the image to appear with thick, black bands at its edges, which can be made smaller using a larger numerical aperture (NA) of the imaging lens, with the best performance reached when it matches the NA of the illumination. At sufficient light intensities, front lighting can also enable dark field imaging of bubbles with detectable light reflections from the interfaces (an example is in Fig. 2). Optical distortions caused by light refraction can become troublesome when visualizing objects behind curved interfaces, but correction methods based on optical ray tracing exist to overcome such challenges. Successful

examples of these include the localization and sizing of cavitation bubbles inside spherical droplets [8], extracting exact shapes of liquid jets inside cavitation bubbles [9], and reconstructing complex bubble shapes from experimental images in combination with computational fluid dynamics [10].

When bubble dynamics and the associated flows are fast, their visualization requires high-speed imaging. For a comprehensive introduction to the available technologies and useful guidelines for the experimental design using high-speed imaging, I refer to the review articles by Thoroddsen *et al.* [11] and Versluis [12] written more than a decade ago. Much of them is still relevant today, with the exception that commercially available high-speed cameras have become even faster, more sensitive, more accessible, and overall better performing. The main factor bounding the performance of a high-speed camera is the limited data transfer rate, which forces the user to find a compromise between spatial resolution (number of pixels in an image), temporal resolution (time between individual frames), and bit depth (level of accuracy for the grayscale level on each pixel). This explains why the fastest high-speed cameras are typically monochrome (as color requires three values for each pixel), only capture a finite number of frames, and have a limited image resolution at the highest speeds. As an example, one of the fastest cameras in the market today, Shimadzu HPV-X3 (Shimadzu Corporation, Japan), which was released in 2025, reaches 20 million frames per second capturing 256 frames with an image size of 648×480 pixels, is monochrome, and has a bit depth of 10 bits. Further challenges that the user has to address are triggering the recording at the right time, especially if the number of frames is limited, and providing an amount of light sufficient for an appropriate signal-to-noise ratio within a typically very short exposure time.

At microscale, which requires high-magnification imaging, challenges related to illumination for short exposure times are amplified. First, one needs an extremely powerful light source, examples being pulsed xenon flash lamps or laser light sources. A short working distance, in the (sub)millimeter range for standard microscope objectives, can enable the use of large NAs, for which more light from a wider angle can reach the image detector, and therefore one may obtain more information on the bubble interface (see examples in Fig. 4). The NA can be increased by 33% by immersing both the lens and the light source in water due to the higher refractive index in water compared to air. On the other hand, long-distance microscope objectives enable detection of micrometric bubbles centimeters away but offer a smaller NA and therefore receive light from a small angle, only capturing bubble shadows [example in Fig. 2(c)]. Further imaging challenges are faced when the size of the bubble is comparable to the wavelength of the light used for illumination, as interference between the bubble and the light passing around it generates a Fresnel diffraction pattern that appears as concentric circles around the bubble and compromises the bubble size measurement [13]: in our microscope, we found this to result in a systematic error of around $0.15 \mu\text{m}$ [14]. One way to overcome this problem is to load the bubble with a fluorescent label, which is possible if the bubble is coated with surfactants or a shell, where the interference problem in bubble size measurements is removed as light is produced directly on the microbubble surface [14]. Sub-micron-sized bubbles become challenging to image using optical microscopy because of the physical limit due to diffraction as we approach the wavelength of light, which limits the spatial resolution to about 200–300 nm, which can be slightly improved by increasing the NA or decreasing the wavelength. A facility worth mentioning when discussing ultrafast microscale imaging of bubbles is that of Brandaris 128, a custom-built device consisting of a high-speed rotating mirror projecting the image onto 128 individual CCD sensors and offering imaging frame rates up to 25 million frames per second (fps) [15], having pioneered and pushed forward the study of ultrasonically driven microbubble oscillations for two decades. Only relatively recently have commercially available cameras reached a similar performance. High-speed microscopes can be assembled by equipping commercial microscopes with a high-speed camera, which might be simpler but possibly more constraining and certainly more costly in terms of incorporating additional features into the system. Alternatively, one can build the microscope from scratch with off-the-shelf optical components, offering more versatility and the possibility to add features such as optical tweezers to manipulate the bubbles, fluorescence imaging at different wavelengths, or additional

views using multiple cameras and beam splitters. A detailed description of the components to build such a microscope is provided in Ref. [14].

A true game-changer in the microscopy of bubbles has been extending the microscope to offer a side-view perspective. Unless they are kept away from walls with appropriate acoustic or optical trapping technology [14,16,17], bubbles are typically close to a boundary by floating against a top surface due to buoyancy or remaining attached to a surface, and their interactions, especially in terms of the bubble shapes, its contact with the substrate, and substrate deformation, are mostly visible from the side. An example of a schematic of a side-view microscope used for acoustic bubble experiments is provided in Fig. 4.

The main drawback of high-speed cameras is their high cost. There are, however, many cheaper alternatives to measure ultrafast bubble dynamics. Smart illumination techniques can enable slower cameras—even those only capturing a single frame—to detect fast bubble events without motion blur, primarily through short, pulsed light sources (such as pulsed lasers or xenon flashes). One may also use multiple pulses in a single frame, or perform multiframe-multiexposure imaging if one has access to a pulsed laser source with a high repetition frequency or a sufficiently fast driver to modulate the output of continuous light, such as a continuous-wave laser [18]. There are multiple ways to overcome the nonuniform illumination from speckle patterns caused by the coherence of the laser due to phase interference, including the use of very short laser pulses such as femtosecond lasers, the use long multimode optical fibers to induce temporal decoherence that decorrelates the phases, or by leveraging pulsed laser-induced fluorescence of a dye as an illumination source [19]. An even cheaper, “single pixel” (corresponding to a fast photodetector sensor) alternative is the laser beam deflection probe method that can detect rapid changes in bubble sizes [20–22], and when combined with translational scanning, it can also probe bubble displacements and bubble asymmetry. Light scattering techniques have enabled the detection of extremely fast radial excursions of microbubbles oscillating at MHz frequencies with extremely high sensitivity, resolving tiny radial amplitudes down to the order of nm. Initially this required averaging over 100 000 signals to achieve a sufficient signal-to-noise ratio [23], but the technique was later refined to capture microbubble responses to a single impulse by letting the laser pass through the bubble twice [24], which offers an exceptional spatiotemporal resolution for oscillating microbubble experiments. Finally, yet another cheap alternative, possibly the cheapest, to perform ultrafast imaging of bubbles using only a standard single-frame camera without the need for extremely short illumination sources, although constrained to rather stringent conditions, is the virtual frame technique [25], which extracts the dynamic information from the grayscale resulting from motion blur. It requires the imaged process to be binary and monotonic. Shadowgraphy of a bubble, where the bubble appears black and the background is white, is well suited for this technique as long as the dynamic changes are monotonic, i.e., the bubble only grows, only shrinks, or only moves in one direction. The virtual frame technique has already been successfully applied to visualize the fast collapse of a vapor cavity [22].

B. High-speed x-ray imaging of bubbles

What about when the medium is opaque, or one needs to see through highly curved or perturbed interfaces, or the target finds itself within a dense cluster with overlapping bubbles? The challenges related to refraction, diffraction, or multiple scattering that cause image artifacts or reduce the signal-to-noise ratio can greatly limit optical visualization of bubbles. Using x-ray-based imaging techniques can overcome many of these challenges, and they have been extensively used in bubble visualizations, such as bubbles in liquid sprays [26], fluidized beds [27], and bubbly columns [28]. I refer to a comprehensive review article by Aliseda and Heindel [29] on the use of x-rays in imaging multiphase flows. The most common technique is x-ray densitometry, an absorption-based technique to measure line-of-sight projected density of the fluid and thereby quantify the (projected) spatial concentration of the different phases within the medium (e.g., to visualize the time evolution of internal fractures in opaque, dense cornstarch suspensions caused by air bubble injections [30]).

The use of x-ray densitometry has also been extended with tomographic modalities [31] (with the object or the source-detector assembly rotating). The speeds associated with ultrafast cavitation and acoustic bubble dynamics, however, are typically too high to permit time-resolved visualizations using standard x-ray imaging techniques, let alone tomography that requires multiple projections. Laboratory x-ray imaging tools have been used to image cavitating flows in constraining geometries [32,33] and in cavitating fuel injectors [34,35], but they typically measure time-averaged vapor fractions using densitometry, the best time resolutions offered on the laboratory scale being of the order of milliseconds [32,36]. Faster x-ray imaging capabilities are offered by large-scale facilities providing high-brilliance light sources, such as synchrotrons and free-electron lasers. Synchrotrons can produce highly collimated x-rays at high flux and, in addition to absorption contrast, enable high-speed phase contrast imaging because of their partial coherence (thanks to their small source size) and long propagation distance, which is an interferometric technique that captures refractive index gradients at interfaces due to the interference patterns from the weak refraction of x-rays, allowing the interfaces to appear sharply on the image. x-ray free-electron lasers can provide a higher resolution compared to a synchrotron, their higher flux enabling the use of very thin scintillators and approaching the diffraction limit resolution, where the fringes appear much sharper due to the high coherence. Their narrow energy band allows quantitative information to be extracted from phase-contrast images. However, x-ray free-electron lasers typically offer a very small field of view (around 1 mm²). Within the past decade, experiments have started to leverage high-brilliance light sources to visualize cavitation and fast bubble dynamics [37,38] and used the improved visual access to reveal, for example, air bubble entrapment beneath droplets impacting on solid surfaces [39], the Kelvin-Helmholtz instability triggered by hydrodynamic cavitation in a micro-venturi channel to be a primary mechanism enhancing mixing for oil-water emulsification [40], laser-induced fragmentation dynamics of cavitating droplets [41], the role of cavitation in the exfoliation of 2D materials [42], and the physical mechanisms that cause detrimental air bubble entrainment within piezoacoustic ink-jet printheads [43].

Indeed, synchrotron sources, free-electron lasers, and other large-scale research facilities that provide extremely powerful illumination are hidden gems and underused in the field of fluid dynamics. The beauty of most of such facilities is that some are open to all through a beamtime application system, and in case of help and collaboration with the beamline scientists, one does not necessarily need to be an expert in the imaging technique. In the past three years, we have had multiple opportunities to perform ultrafast x-ray phase-contrast imaging at the European Synchrotron Radiation Facility (ESRF) [44], which is one of the brightest synchrotron x-ray sources in the world, offering us visual access to hidden details in many ultrafast bubble phenomena. The methodology for a typical experiment that we would conduct can be described as follows. The high energy (i.e., mean energy of 30 keV) and high photon flux (i.e., in order of 10¹⁴ ph/s/mm²) of the ID19 beamline at the ESRF enables single bunch temporal resolution of 60 ps. The source properties, combined with the long propagation distance, result in a spatially coherent beam that is quasiparallel over a relatively large field of view (10 mm²), enabling propagation-based phase contrast imaging by moving the detector away from the sample to enhance the visibility of edges between media with different complex refractive indices, such as vapor/air and water, while fulfilling near-field conditions. After the x-ray has passed through the sample, its detection is enabled by a single-crystal scintillator, which converts the x-rays to visible light, coupled to a microscope objective and an ultrahigh-speed imaging camera (Shimadzu HPV-X2 or Photron SA-Z). Typical acquisition speeds range from 100 kHz up to 5.68 MHz with pixel sizes from 3.2 to 32 μm/px. Imaging at high speeds with hard x-rays utilizing indirect detector assemblies relies on scintillating elements for its resolution and efficiency. When the application requires higher magnifications and high speeds, the system typically requires a compromise on spatial resolution to improve the signal-to-noise ratio (e.g., using thicker scintillators with higher conversion efficiency). This results in images with less sharply defined interfaces compared to what one might achieve in optical imaging. Magnifications can also be achieved using compound refractive lenses to create a secondary source [45]. When

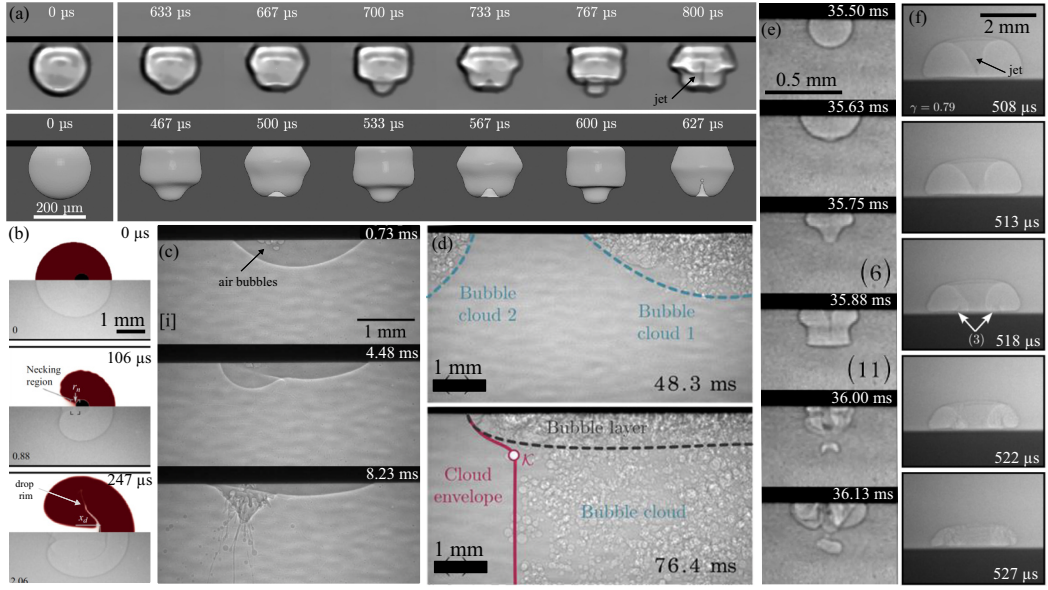


FIG. 1. Examples from cavitation activity visualized through synchrotron x-ray high-speed phase contrast imaging: (a) Shape oscillations and jetting from acoustically driven gas microbubbles, compared with 3D simulations using the boundary integral method [47], (b) shock wave-triggered release of a droplet contained inside an air bubble, here compared with 3D-axisymmetric compressible hydrodynamic simulations using the open-access solver ECOGEN [48], (c) effect of trapped air bubbles on the onset of ultrasonic atomization of pendant droplets [49], (d) cavitation bubble clouds, (e) zoomed-in individual bubble activity beneath an ultrasonic horn [50], and (f) laser-induced cavitation bubble collapse near a rigid wall, producing a broad jet and “Blake splashing” (frame 3) [46].

imaging bubbles in water, we must consider the distance of water through which the x-rays have to travel because of their strong absorption. Depending on the used magnification and flux, this distance in our experiment has typically been of the order of 1–3 cm either by using small test chambers or by equipping larger ones with telescopic windows that allow us to adjust the distance according to need [46]. We typically perform these measurements simultaneously with visible light illumination applied in a direction perpendicular to the incoming x-ray beam to complement missing information, in particular with regard to the location of the imaged events in 3D. Although x-ray imaging only provides a 2D projection of the bubble events, everything in the field of view remains sharply in focus as the experiments exploit an effectively infinite depth of field. This is because most materials have a refractive index of around 1 at the associated wavelengths, making it very difficult to bend x-rays.

Figure 1 displays examples of various experiments visualizing cavitation and acoustic bubble activity with high-speed x-ray imaging where the time evolution of bubble shapes is the key observable: (a) shape oscillations and jetting of ultrasonically driven air bubbles resting against a wall [47]; (b) shock wave-induced release of a drop encapsulated within a bubble [48]; (c) sonicator horn-induced atomization of a pendant droplet affected by cavitating bubble activity confined within [49]; (d) formation and evolution of cavitation bubble clouds beneath an ultrasonic horn and (e) individual air bubbles initiating the cavitation activity beneath an ultrasonic horn [50]; and (f) the collapse and jetting of laser-induced vapor bubbles near a rigid wall [46]. Although the experiments exhibit different timescales, they are all very short, ranging between 10 μs and 1 ms, and sufficient signal is achieved without spurious boiling of the liquid due to x-ray absorption. All x-ray images are clearly free of artifacts related to optical refraction, which typically causes black bands on

curved surfaces, such as spherical bubbles, when visible light is used as back illumination. Hence, all interfaces present in the x-ray beam are revealed, including those that would be inaccessible to conventional optical imaging. Interface folding in the complex interfacial shapes as well as fluid structures positioned within bubbles, such as drops and jets, are clearly visible in Figs. 1(a)–1(c) and Figs. 1(e) and 1(f). These structures can be clearly identified despite perturbed interfaces, such as those in Fig. 1(f), which shows new nonaxisymmetric features such as “Blake splashing.” Figures 1(a) and 1(c)–1(f) show a very clear surface for the wall, which would typically be blurred in an optical image and prevent accessing information near the contact line. Figure 1(d) resolves all individual vapor bubbles within highly dense bubble clouds, as well as those in contact with the surface, such as in Fig. 1(e).

III. ILLUMINATING THE HIDDEN PHYSICS OF FAST BUBBLE DYNAMICS

So what can one learn using such fascinating, ever-improving visualization techniques to probe ultrafast bubble dynamics? There is still a plethora of open questions around cavitation and fast bubble dynamics as much of their physics “hides” behind challenges they still pose for experiments, numerical simulations, and theoretical modeling. Many studies use visualization techniques to quantify cavitation events, and as fast imaging tools continue to be developed simultaneously with computational tools enabling numerical simulations with increasingly complex configurations (through better computational power, parallelization, better algorithms, etc.), more direct comparisons can be made between them. This will help us improve our prediction tools, understanding, and therefore control of the fast bubble dynamics, whether it is harmful or desirable depending on the application. Recent reviews discuss challenges related to the extremely broad field of fast (and slow) bubble physics by Garbin *et al.* [51], Lohse [52], and Dollet *et al.* [53]. In the following, I focus on selected topics of personal interest that have caught my attention over the past decade.

A. Jetting from collapsing bubbles

An interesting feature of an inertially collapsing bubble is that if it does so in a nonsymmetric way, it can produce a liquid jet that pierces the bubble and can be so fast that it can cause damage to a neighboring object or wall, generating, for example, pores on a cell membrane [54] and significant deformations on thin metallic foils [55], or providing useful flow actuation [56]. Figure 2 shows

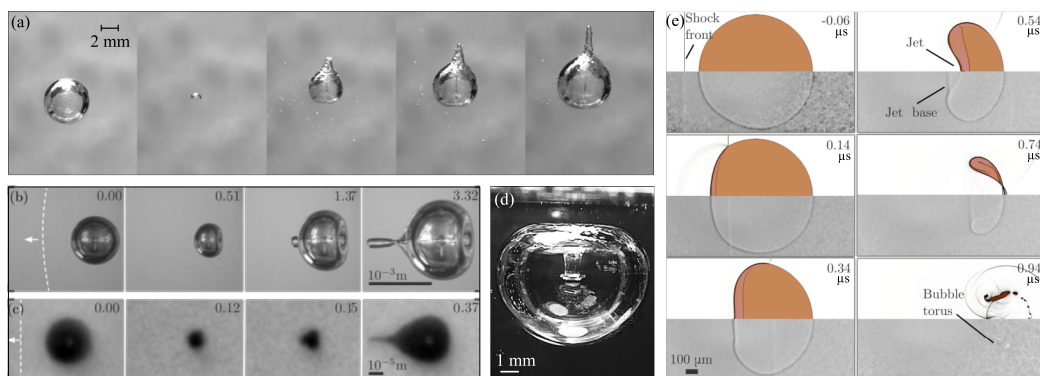


FIG. 2. Examples from jets from collapsing bubbles in water: (a) jet from laser-induced cavitation bubbles produced by the hydrostatic pressure gradient [9]; (b) jet from a laser-shock-driven collapse of an air bubble and (c) a hydrogen microbubble [57]; (d) jet from a laser-induced vapor bubble collapsing near a free surface [9]; and (e) jet from a nitrogen bubble driven by a planar, high-amplitude shock from an exploding copper foil, comparing x-ray phase contrast images with numerical simulations using a multicomponent compressible flow model [58].

examples of jets from collapsing bubbles of various sizes in water driven by different sources of bubble deformation, i.e., hydrostatic pressure gradient, traveling shock wave, and a neighboring boundary (free surface), visualized using different imaging and illumination techniques. Figure 1(f) shows possibly the most extensively studied configuration for jets from single cavitation bubbles, which is a bubble collapsing near a flat, rigid wall, here imaged with x-rays. The early formations of the jets are challenging to visualize because of their high speed, small size, and propagation in the bubble interior to which the optical access is limited. Typically, jets are instead observed once they have pierced the bubble and become visible by entraining gas (whatever the bubble contains) with them, such as in Figs. 2(a)–2(c).

Front-light illumination enables visualization of the jet inside a deformed bubble, as long as the bubble interface remains smooth, as in Figs. 2(a), 2(b), and 2(d). The optical access to the final stages of the collapse of cavitation bubbles, combined with the exceptionally high initial sphericity of the laser-induced bubble (achieved with careful optical design of the experiment [59]), has allowed us to determine, for example, the shape of the bubble at this stage and the exact instant at which the bubble is pierced by a high-speed liquid jet. This has confirmed the approximate geometrical similarity of the bubble at this specific instant for different degrees of bubble deformation described by a dimensionless pressure anisotropy parameter ζ [9], defined as

$$\zeta \equiv -\nabla p R_0 \Delta p^{-1}, \quad (1)$$

which represents a dimensionless version of the effective pressure gradient deforming the bubble, where ∇ is the pressure gradient, R_0 stands for the bubble radius at its maximum size, and $\Delta p = p_\infty - p_v$ is the pressure difference between the outside and the inside of the bubble that drives the bubble collapse. Here, ζ can also be regarded as the dimensionless version of the Kelvin impulse [60–62], which quantifies the linear momentum acquired by the liquid throughout the growth and the collapse of the bubble.

For bubbles deformed by the hydrostatic pressure gradient caused by gravity, $\nabla p = \rho g$, where ρ is the liquid density, g is the gravitational acceleration. In environments where the bubble deformation cannot be described by an external, constant ∇p , we can define a ζ that describes an equivalent ∇p such that the Kelvin impulse is correct. For example, if the bubble is deformed by a flat rigid or free surface located at a stand-off parameter $\gamma = h/R_0$, where h is the distance from the initial bubble center to the boundary and R_0 the maximum bubble radius, we can find an expression for ζ for boundary-deformed bubbles as $\zeta \approx 0.195\gamma^{-2}$. Expressing ζ as a function of γ in this way approximates the bubble deformation with an equivalent uniform pressure gradient ∇p (first term of the Taylor expansion of any nonuniform pressure field) that yields the same Kelvin impulse as a rigid/free surface at a stand-off distance γ . What makes the pressure anisotropy parameter so convenient to describe jetting vapor bubbles is that different quantities describing the jet dynamics, such as jet speed, the instant of the jet piercing the bubble, the volume of the bubble at that instant, and the displacement of the bubble all conveniently reduce to power laws of ζ regardless of the origin of bubble deformation [9]. It becomes challenging to define a corresponding pressure anisotropy parameter for more complicated sources of jets, such as neighboring bubbles, shock waves or ultrasound that are strongly time-dependent, or boundaries with complex geometries. Some efforts have been made for, e.g., bubbles jetting near porous plates [63], and numerically determining ζ for other complex geometries [64]. Other works have extended the use of ζ or the Kelvin impulse to describe bubble deformations and jetting for bubbles collapsing near liquid-liquid interfaces [65], multiboundary systems [66,67], granular boundaries [68], ultrasound-driven microbubbles [69], among others.

The optical access to the bubble interior has also enabled the determination of scaling laws describing jets from collapsing air bubbles subject to shock wave driving [57,58], see Figs. 2(b), 2(c), and 2(e). Shock-bubble interaction is a well-studied but very complex problem [70], and serves as a typical case study to probe the performance of computational compressible multiphase flow solvers [71–73], but lacks experimental validation data for bubbles in water mostly due to the difficulty of the experiment, both in terms of visualization technique and the controllability of the single

bubble-shock-system. This is a challenge we have been trying to tackle in recent years [48,58,74]. Jets from shock-driven gas bubbles in water are a beautiful manifestation of the Rayleigh-Taylor, or perhaps even Richtmyer-Meshkov instability, developing from a single-mode perturbation. The instability is driven through the combined effect of the shock-induced translational acceleration (driven by a pressure gradient) and that of the radial acceleration of the collapsing bubble (driven by the pressure jump). The jet onset and characteristics depend on the relative amplitudes and durations of each type of interfacial acceleration. Indeed, a criterion for a shock-driven bubble to form a jet is related to the collapse speed of the bubble interface: the bubble does not jet if the driving impulsive pressure wave or shock wave results in simple linear oscillations at their natural frequency due to the compressible gas core. For higher-amplitude driving, the pressure wave can cause the bubble to collapse nonlinearly, and in this case the mean jet speed approximately scales with the bubble's mean collapse speed [57]. Synchrotron x-ray phase contrast imaging enables precise measurements of jet growth rates and comparison with interfacial stability theories [57]. The resulting jet may also enhance the release of a payload carried by the bubble, such as in the example in Fig. 1(b), where a liquid droplet contained inside the bubble is released as a result of the shock wave driving, which is potentially interesting for fluidic transport applications.

B. Underwater pressure waves and cavitation nucleation

Another example in which improved optical access enables us to learn about the physics of violent bubble events is the visualization of pressure waves. High-amplitude pressure waves may contain sufficiently strong density gradients for the resulting changes in local refractive index, related to density via the Gladstone-Dale equation, to deflect collimated light and to produce detectable intensity changes on the image pixels. Classical Schlieren visualization techniques can amplify these effects using a knife edge, providing clear images of shock waves produced at the collapse of cavitation bubbles and their reflections from complex boundaries [77]. However, sufficiently collimated simple shadowgraphy illumination can also enable the visualization of shock waves and the enormous pressures near the wall of a collapsing bubble, although the detector's pixel intensities provide only the second-order differential value of the local density in the liquid ($\nabla^2 \rho$) and therefore do not suffice to quantify pressure. An example of a process producing changes in the liquid's refractive index detectable via shadowgraphy is shown in Fig. 3(a). The collapse and compression of the highly spherical laser-induced vapor bubble is so violent that not only it produces a visible luminescent flash as the bubble reaches its minimum size due to extreme heating [78] and a clear, spherical shock wave upon its rebound, but the illuminating backlight near the bubble wall in the last stages of the collapse is also deflected, indicating pressures of the order of thousands of bars. This significant pressure rise near the bubble wall agrees with Lord Rayleigh's prediction over a century ago [75], the model being directly compared in Fig. 3(b) with corresponding hydrophone measurements that also detect the rise preceding the shock front despite the detection being done several centimeters away from the bubble [76]. This pressure increase was experimentally detected more than three decades ago with single-shot images using Mach-Zehnder interferometry [79]. If we could refine the measurement with techniques such as background-oriented Schlieren [80,81], one could access the pressure field during this most violent stage of the bubble dynamics, which could provide insights into, for example, cavitation-induced crystallization of liquids [82] that finds applications in industrial processing. Such strong light deflection may also prevent optical access to the bubble wall at its smallest radii. This can be overcome using more advanced imaging techniques such as x-ray imaging with femtosecond free-electron laser pulses, which has also enabled spatiotemporal quantification of the pressures around an expanding laser-induced vapor bubble [83].

Combining simultaneous visualizations and acoustic measurements of cavitation events in controlled experiments is useful to help interpret acoustic cavitation data, which are typically complicated but often serve as the only measurable signatures of cavitation in systems with no direct visual access, such as in medical therapies [84,85] or in hydraulic machines [1]. Figure 3

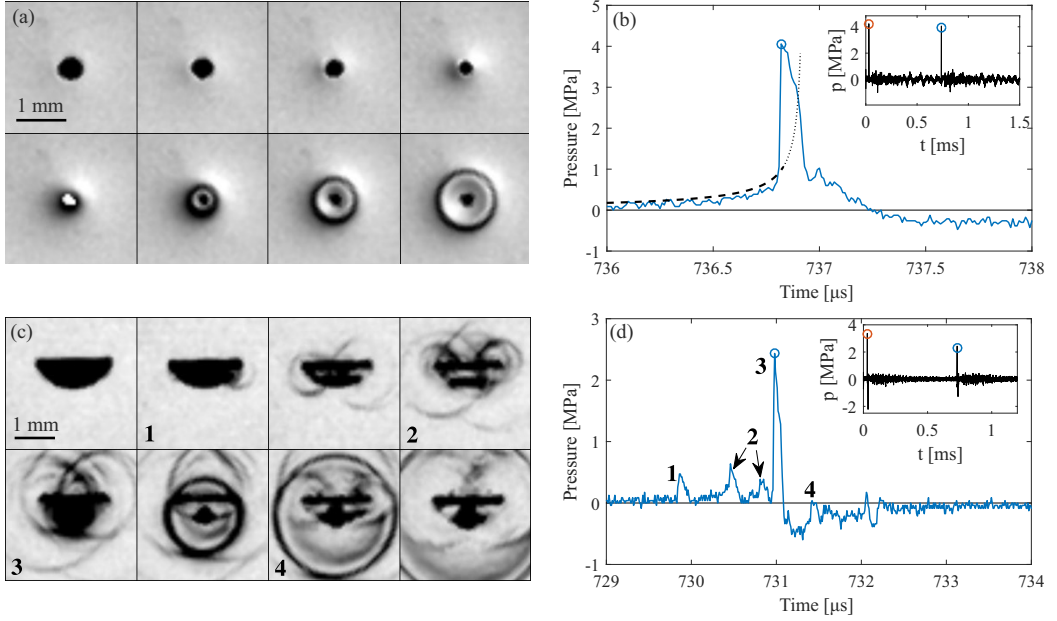


FIG. 3. Simultaneous imaging and acoustic measurements of a laser-induced vapor cavity collapsing (a) spherically and emitting a single shock wave ($R_{\max} = 3.8$ mm, interframe time is 100 ns). (b) Pressure recorded by the hydrophone. The inset shows the whole bubble oscillation, where the orange and blue circles refer to generation and collapse shock wave peak pressures, respectively. The dashed line shows $p(t) - p_0$, where $p(t)$ is the Rayleigh pressure model [75] up to the shock peak, and the dotted line extends the curve to the time at which the bubble is estimated to reach a radius of $R = 100$ μm . (c) Near a free surface, at a stand-off distance $\gamma = h/R_{\max} = 2.1$ (where h is the distance from bubble center to surface) and $R_{\max} = 3.6$ mm, interframe time is 300 ns. The shock waves are denoted as (1) jet impact, (2) torus collapse, (3) tip bubble collapse, and (4) second torus collapse shock waves. The black bars show the 1 mm scale. Figure adapted from Ref. [76].

shows an example of such an experiment for a single bubble, where direct shadowgraphy of bubble-induced shock emission can identify the exact mechanisms producing the shocks, which can become complex especially as the bubble collapses in a nonspherical way. The deformed bubble displayed in Fig. 3(c) collapses near a free surface and generates four distinct shocks: the first one caused by the water hammer effect from the jet piercing the bubble, and others from the individual collapses of the various parts that the bubble has split into. Combining these visual observations with quantitative pressure measurements using a distant hydrophone [Fig. 3(d)], it is possible to determine their relative contributions to the total shock energy and how they vary for different levels of bubble deformation [76]. This example shows a relatively simple configuration, but as visualization techniques improve and more complex, multibubble cavitation events can be captured, coupled with the continuing development of advanced acoustic signal processing algorithms and machine learning methods, I believe that cavitation detection will drastically improve in the coming years, which will be crucial for its control in different applications.

With improved techniques to quantify instantaneous pressure fields from an image, one can study acoustic cavitation nucleation in a more controlled way, which is relevant in cavitation in power ultrasound processes and in biomedical therapies using focused ultrasound or shock waves. High-amplitude acoustic waves may rupture the liquid medium by generating negative pressure in the bulk of the liquid through their rarefaction phase. With better, noninvasive pressure field

quantification, such as using background-oriented Schlieren [81], one could characterize the onset of the so-called *Gouy phase shift* in focused underwater acoustic waves and its role in enhancing cavitation nucleation. Upon reaching the acoustic focus, a wave focusing in 3D will have accumulated a shift in phase of π , which causes an inversion of its polarity and transforms the compressive wave into a rarefaction wave [77,86]. This is a well-known effect in optics, yet the consequence of such a phenomenon happening with underwater pressure waves and shock waves is the fact that one can generate tension in liquids and therefore form cavitation bubbles by focusing positive pressure waves into a medium [87,88]. This observation might have interesting implications in the design of acoustic driving strategies to safely initiate cavitation for medical therapies, where one should minimize the amount of negative pressure traveling through human tissue in the risk of off-target effects in healthy areas. Indeed, it has been observed through ultra-high-speed imaging that highly distorted ultrasound waves promote the vaporization of micron-sized phase-change agents, or cavitating liquid droplets, both because higher frequency components (which appear when waves are distorted) can focus efficiently inside the droplets and amplify the negative pressure created in them [89], and also because the positive portion of the ultrasound wave contributes to generating the negative pressure required to initiate vaporization [87], which could well be due to the Gouy phase shift. We are currently working on demonstrating this effect by focusing impulsive shock waves that have mostly positive pressure waveforms inside spherical droplets to generate cavitation [88].

In a field as old as extracorporeal shock wave lithotripsy (ESWL), which was introduced in the early 1980s to treat kidney stones via focused shock waves, we can still uncover new physics related to the exact role of cavitation in the process [5] mainly due to the challenges related to optical access to the bubble activity being limited by dense vapor bubble clouds as well as to the stone that they cover during the treatment. Using x-ray phase contrast imaging one can distinguish individual bubbles within the dense cloud, as well as visualize all new interfaces created within the stone and correlate their opening with the cavitation bubble activity [90]. Such visualizations can enable easier comparison with simulations predicting cavitation-induced stresses and disclosing their exact origins on the stone, with an example being the peculiar interaction between bubbles that are attached to the stone and those further away leading to pressure amplification [90]. Such visualization techniques could be useful also in detecting cavitation in histotripsy [6], or ultrasound-induced ablation of soft tissue, where the combined visual information on the high-amplitude acoustic waves and the bubbles using shadowgraphy, x-rays to track individual bubbles, and finally x-ray tomography to characterize the damage could provide invaluable insights into the mechanical bioeffects of cavitation.

C. Periodically driven bubble dynamics

Many of the applications that rely on bubble-induced energy focusing use periodic forcing of the bubbles, such as ultrasound. Periodic pressure fluctuations drive the highly compressible gas bubble into a sequence of compressions and expansions. Because the noncondensable gas core of the bubble acts as a spring, the system represents a harmonic oscillator that has a resonance frequency at which the radial excursions of the bubbles can be significantly amplified. Coupled with acoustic radiation forces from traveling acoustic waves, volumetric oscillations also ensure that there is a net force applied on the bubble in one direction and resulting in bubble translations [69,91,92]. The history force, or the Basset force, becomes highly relevant in this process and must be considered in the force balance from which the translations can be modeled [92].

What do we know about periodically driven interfaces? When a liquid pool is vibrated vertically with periodic forcing, the free surface can become unstable to a well-known parametric instability called the Faraday instability, which produces a beautiful standing wave pattern on the interface. In case of acoustically driven bubbles, the volumetric compression-expansion cycles of bubbles cause periodically varying accelerations of their spherical interface, which can also become unstable to Faraday waves. Indeed, such shape oscillations on bubbles have been

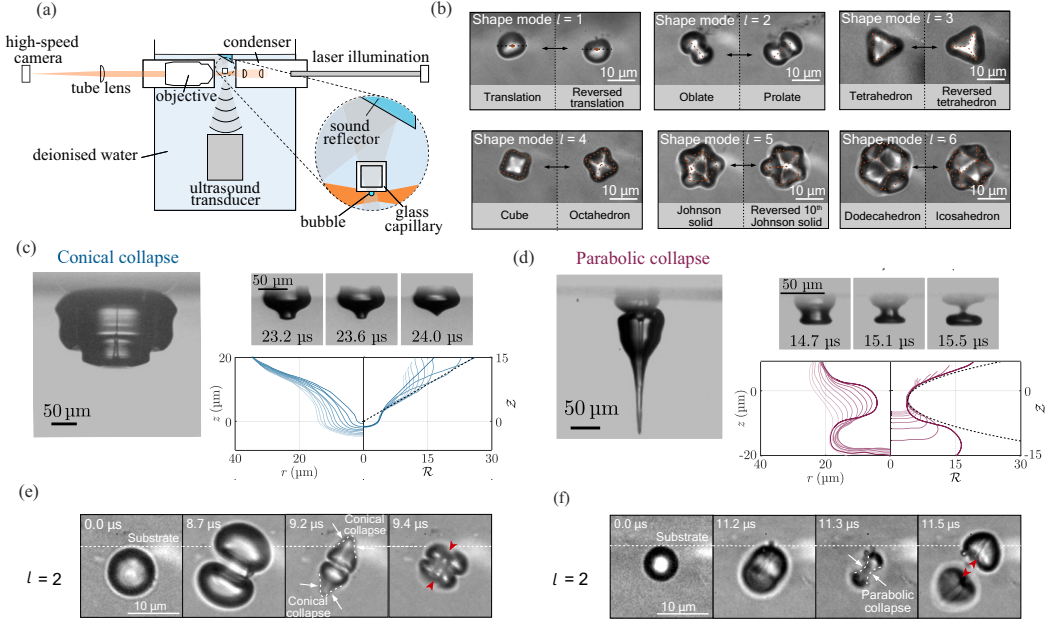


FIG. 4. (a) Typical setup for side-view microscopy of acoustically driven bubbles. (b) Stable shape modes induced by Faraday instability in lipid-coated microbubbles driven by ultrasound. The illumination enables visualizing the 3D shape of the bubble, and thanks to the highly hydrophilic nature and extreme softness (elastic modulus < 1 kPa) of polyethylene-glycol (PEG) substrate against which the bubble is resting, it barely feels any boundary effects and behaves as it were free [69]. (c) Upward jetting from acoustically driven wall-attached bubbles due to Faraday waves yielding a conical collapse of the bubble tip, causing a singularity and forming a Longuet-Higgins jet, with self-similar shapes at the location of jet formation upon collapse, and (d) at slightly different driving parameters, the bubble can undergo parabolic collapse that can also yield a singularity and produce a pair of Worthington jets, upward and downward, again with self-similar bubble shapes in the singularity point [105]. (e) Conical and (f) parabolic collapses of bubbles from lipid-coated microbubbles manifesting $l = 2$ shape mode at scales relevant to biomedical applications [69].

reported in the past [93–98], and their stability can be described with Mathieu-type equations. The combination of the acoustic driving frequency and the bubble size (as well as surface tension, and for wall-attached bubbles, wetting conditions [47]) determines the shape mode triggered for a bubble, described by spherical harmonics but, in simple terms, represented by a shape mode degree, which effectively represents a spherical harmonic wave number: the higher the shape mode degree l , the higher the number of interfacial “lobes” on the bubble interface. For a fixed driving frequency, l increases with the size of the bubble, since larger bubbles can accommodate more “lobes” of a size dictated by the driving frequency. It has been possible to observe the shapes of effectively free microbubbles (1–10 μm in radius) resting against a hydrophilic, ultrasoft PEG hydrogel substrate (elastic modulus < 1 kPa) driven with acoustic frequencies near their resonance (in the order of MHz, which conveniently matches the frequency range used medical ultrasound imaging), where the preferential Faraday wave patterns on a free bubble, which is initially a perfect sphere, correspond to polyhedral patterns and their duals, which happen to take the shapes of platonic solids up to dodecahedron and icosahedron [Fig. 4(b)]. The new visual access to these shapes has confirmed the theoretical predictions of Ebo-Adou *et al.* [99], who observed patterns corresponding to platonic solids for shape mode degrees 3 to 6 on spherical droplet interfaces.

Shape oscillations from acoustically driven bubbles are interesting not only because they are half-harmonic in nature and may promote subharmonic acoustic signals and enhance contrast in contrast-enhanced ultrasound imaging [100], or tune acoustic microstreaming flows around them [101], but also because beyond a certain driving amplitude, they may form jets through the same mechanisms as the well-known Longuet-Higgins jets produced from vertically vibrating liquid pools [102,103]. This jetting is enhanced in shape-oscillating bubbles that are bounded by a wall and produce a flow-focusing singularity at the lobe located at the tip of the bubble, causing a conical collapse of the bubble interface [Figs. 4(c) and 4(e)]. The shape oscillations and subsequent jetting from acoustically driven wall-attached bubbles can be numerically modeled via 3D boundary integral method [47], as seen in Fig. 1(a), although the exact onset of shape oscillation is difficult to predict, as seen by the time offset between experiments and simulations. This jetting can also form for bubbles resting against a vibrating substrate, as seen in Fig. 1(e) (fourth frame). A striking feature of these jets is that they are cyclic in nature and can hit the same target repeatedly. At higher driving amplitudes, when the Faraday wave deformations become even more pronounced, the bubble may split in the middle due to a parabolic interfacial collapse, causing a singularity forming a pair of jets, upward and downward, also known as Worthington jets (such as those forming when an object falls into a liquid pool [104]), as shown in Figs. 4(d) and 4(f). Both conical and parabolic collapses exhibit self-similar scalings for the shapes near the singularity [location(s) of jet formation], which are governed by inertia and capillarity [105]. For wall-attached bubbles, the wall determines the jet axis. Free bubbles may also jet, but the number of jets and their direction is entirely dictated by the bubble shape and tend to follow the number of faces of the polyhedral pattern. In general, these visualizations help determine the conditions under which jets can be periodically and stably emitted from the microbubble interface and can impact, in a repeated manner, a neighboring substrate such as a cell membrane [69], with implications in targeted drug delivery. Only a carefully designed imaging system with side-view perspective can provide visual access to such jets [69,100].

Finally, periodically driven bubbles can find themselves in more complex systems, one example being ultrasonic drop atomization, where the fragmentation of a droplet excited with an ultrasonically vibrating substrate is drastically altered when cavitation forms within the drop [49]. Ultrasonic atomization processes typically aim at a monodisperse droplet production, yet the acoustically driven bubble activity induce additional interfacial accelerations that make the fragmentation more chaotic and the produced droplets sizes more varied. Figure 1(c) shows x-ray images of such a process. Bubble activity has also been shown to have significant enhancing effects on oxide de-agglomeration processes in the production of metal powders in additive manufacturing, as visualized with x-ray imaging [106].

IV. CONCLUSIONS AND THE WAY FORWARD

In this perspective article, I describe visualization techniques to probe ultrafast bubble dynamics and discuss how they can help us uncover important physics related to acoustically driven bubbles and cavitation. From an experimentalist perspective, I feel that we are living in an exciting period where the rapid development of high-speed imaging techniques that are becoming faster and more available can uncover fast fluid physics that remain otherwise hidden. Event-based sensing, which is already being applied to flow measurements [107], will become more prominent as it overcomes some of the key challenges of traditional high-speed camera technologies related to memory and data transfer rates. The increasing availability of these fast visualization technologies will allow more research groups to routinely use them, which, in turn, will enable more diverse perspectives on physics that have previously only been interpreted by a few. Furthermore, as techniques for image-based measurements of instantaneous pressure fields are being refined for liquid flows presenting sufficiently strong density gradients, it will be possible to acquire more precise information on the exact conditions that produce cavitation nucleation and acoustic bubble activity, which can significantly advance biomedical technologies leveraging underwater acoustics and shock waves

to induce desirable mechanical effects from bubble dynamics, such as targeted drug delivery, thrombolysis, biofilm removal, histotripsy, and lithotripsy [7,108]. This could also help to resolve important fundamental questions in the broader field of cavitation, such as distinguishing the relative contributions of shock waves (and their focusing), micro-jets, and shear flows in cavitation-induced erosion of materials.

As high-brilliance light sources are becoming more available, x-ray imaging at high speed will become a central tool to experimentally detect optically hidden events related to ultrafast bubble dynamics. While all of the reported works in this article tackle 2D projections of the imaged events, tomography techniques that enable 3D scans of the sample (an important field not covered in this article) are also being developed and become faster. Most of these techniques require the sample or the detection system to rotate. An interesting, emerging technique worth mentioning with particular interest for fast multiphase systems is multiprojection imaging [109,110], which can provide rotation-free 3D imaging of samples that are optically opaque at high speed, currently having been demonstrated up to 3000 frames per second. Developing this and the relevant reconstruction algorithms further could make three-dimensional, high-speed, high-resolution experimental data of complex multiphase flows a reality. Beyond bubbles and cavitation, high-speed x-ray imaging has a bright future in disclosing new physics related to a wide spectrum of other areas of fluid dynamics, such as drops, bursting, breakup and coalescence processes, aerosol generation, flows in porous media, interfacial instabilities, heat and mass transfer in multiphase flows, particle-laden flows, phase-change processes, turbulent multiphase flows, sprays, suspensions and non-Newtonian flows, shock waves, among others.

A valuable outcome from advanced visualizations of ultrafast interfacial flows is the high-quality reference data for validating computational models for complex flows. We can access highly complex shapes of interfaces and measure, for example, rapidly moving contact lines in surface-attached multiphase flow problems where wetting and adhesion effects are important (such as sessile or pendant droplets, bubble-induced drag reduction, or cavitation nucleation from surface roughness elements or particles). Combined with continuously developing computational tools and machine learning methods, these experimental data can drastically improve our monitoring and prediction tools for cavitation, especially when coupled with other measurements, such as acoustic detection. For example, “cavitation dose” in biomedical applications is an acoustic measure that vaguely describes, in real time, the extent of cavitation inside the body during an ultrasound treatment [111]. There currently exists no rigorous definition for it despite its key role in the treatment outcome, this being a challenge that requires the acoustic measurements to be directly compared with more precisely characterized cavitation activity under different acoustic conditions. The lack of a standardized cavitation measurement prevents cross-setup comparisons and streamlining safety and efficacy studies. Besides, the exact physical mechanisms enabling cavitation to cause a therapeutic effect still remain unclear precisely because of the difficulty to measure it, although many hypotheses have been proposed. I am hopeful that the ever-improving visualization techniques for ultrafast bubbles, and combinations thereof, as well as further efforts in unveiling the underlying fluid dynamics, will help address these urgent needs.

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DATA AVAILABILITY

No data were created or analyzed in this study.

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