

# Temporal evolution of thermoacoustic streaming around a spatially confined temperature gradient

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The ability to precisely control the localization of individual cells or other microscopic biological particles in aqueous suspension inside a microfluidic confinement is essential for the realization of future tools for single-cell studies in basic biology and medicine. We previously demonstrated that thermoacoustic streaming stemming from interactions of an acoustic field with a thermal gradient induced by focused light can produce fast, confined, and modular local flow fields. In this work, we study the buildup and decay of thermoacoustic streaming generated by a focused laser directed into an acoustic half-wavelength standing wave. For a pre-established sound field, we observe the timescale for buildup and decay of the thermoacoustic streaming upon activating the laser, and vice versa. For the system investigated, we find that while the buildup of thermoacoustic streaming takes only 2 ms for sound field-controlled thermoacoustic onset, laser-irradiation-controlled onset is ten times slower. This is explained by the relatively slow thermal diffusion in the system compared to the fast buildup of the acoustic resonance. Furthermore, we demonstrate how the combination of fast timing control by the sound field and the subsonic-wavelength spatial control offered by the confined temperature gradient makes it possible to move a single particle a distance of 100  $\mu\text{m}$  at 350  $\mu\text{m/s}$  while leaving the trajectory of another nearby particle, less than 25  $\mu\text{m}$  away, unaffected.

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## I. INTRODUCTION

Precise control of single cells and microscopic particles in microfluidic confinement presents opportunities for emerging single-cell technologies in biology and medicine. Acoustofluidics is a well-established tool for biocompatible cell handling and analysis [1–9]. Standing sound waves in a liquid having a spatially varying density and compressibility field allow for size-insensitive separation of micro-objects based on their intrinsic acoustic properties [10–12]. In this context, acoustic radiation forces move suspended cells to their isoacoustic positions, namely the location of zero acoustic contrast factor between the cell and fluid, providing insights into the phenotypical properties of cells. Media inhomogeneities also lead to acoustic body forces acting directly on miscible or immiscible liquids [13–16], which has been demonstrated to greatly suppress acoustic streaming by the presence of solute molecular gradients that slowly degrade due to diffusion [17,18].

Another way to generate and sustain media inhomogeneities is by local heating inside the acoustofluidic cavity [19,20], and we recently showed that heating through absorption of laser light induces thermoacoustic streaming in a microresonator [21]. The resulting thermoacoustic streaming strongly depends on the light absorption and position of the laser spot. The acoustic body force  $\mathbf{f}_{\text{ac}}$  describes how the streaming field generated is affected by the inhomogeneities of the fluid's acoustic properties due to an imposed temperature field  $T_0$  [19]:

$$\mathbf{f}_{\text{ac}} = -\frac{1}{4}|p_1|^2\nabla\kappa_0 - \frac{1}{4}|\mathbf{v}_1|^2\nabla\rho_0 \quad (1)$$

$$= -\frac{1}{4}\left[|p_1|^2\left(\frac{\partial\kappa_s}{\partial T}\right)_{T_0} + |\mathbf{v}_1|^2\left(\frac{\partial\rho}{\partial T}\right)_{T_0}\right]\nabla T_0. \quad (2)$$

Here  $p_1(\mathbf{r})$  and  $\mathbf{v}_1(\mathbf{r})$  denote the complex-valued first-order acoustic pressure and velocity amplitudes, and the corresponding actual (time-dependent) fields are defined as  $\tilde{p}_1(\mathbf{r}, t) = \Re[p_1(\mathbf{r})e^{-i\omega t}]$  and  $\tilde{\mathbf{v}}_1(\mathbf{r}, t) = \Re[\mathbf{v}_1(\mathbf{r})e^{-i\omega t}]$ . The body force is averaged over one acoustic period, and  $\kappa_0$  is the compressibility and  $\rho_0$  the density of the fluid. Both  $\kappa_0$  and  $\rho_0$  decrease within the temperature range from 15°C to 50°C, causing  $\mathbf{f}_{\text{ac}}$  to point towards the heat source. However, in water-based media, the compressibility exhibits a greater variation than the density over

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the temperature range considered here, making the term  $|p_1|^2 \nabla \kappa_0$  the dominant contribution [19].

In this study, we extend our recent work on thermoacoustic streaming induced by focused laser light [21] by investigating the temperature development and timescales for the onset and decay of thermoacoustic streaming to assess its applicability for dynamic control of a localized flow field in microfluidic systems.

## II. MATERIALS & METHODS

### A. Experiment

The chip and setup have been described in Ref. [21]. In brief, a rectangular microchannel was etched through the silicon layer of a glass-silicon-glass chip. A piezoelectric transducer, actuating on top of the chip, generated a half-wavelength standing wave across the channel width. To induce localized heating inside the cavity, a focused 785-nm-wavelength laser beam was guided to the floor of the microchannel, off-center along its width (Fig. 1). The channel was filled with an aqueous solution of indocyanine green (ICG) dye, absorbing around 30% of the laser light [21], fluorescent 1.1- $\mu\text{m}$ -sized polystyrene particles to trace the flow, and BCECF temperature-sensitive fluorescent dye. Laser light, LED illumination, transducer, and camera were triggered using digital signals. The whole setup, including triggers, a syringe pump, and a valve, was coordinated through a LabVIEW program enabling hundreds of repeated experiments for each condition. The buildup and decay of thermoacoustic streaming were recorded according to the time scheme described in Appendix B. Images were acquired at a frame rate of 100 fps. The tracer particle streaming recordings were processed using *DefocusTracker* [22–24] in MATLAB, by averaging over 800 repeated acquisitions per setting.

The temperature fields were processed as previously described [20].

### B. Temperature measurements

We used BCECF as thermosensitive fluorophore, which decreases its fluorescence with increasing temperature. We employed a thermoelectric cooler controller (TEC-1123, Meerstetter Engineering, Switzerland) to drive two Peltier elements (CP40136, Same Sky, USA) placed in contact with the side of the chip by two custom-made aluminum plates. On each plate, a resistance temperature detector (Pt1000, JUMO GmbH & Co., Germany) was glued close to the chip. Good thermal contact between all the components was assured by using thermal paste (MasterGel Pro v2, Cooler Master Europe BV, The Netherlands) at each interface. By measuring the temperature next to the chip and feeding it back to the controller, we could maintain the temperature on the chip constant at the desired value. First, we calibrated the relation between temperature and intensity by setting the temperature in the chip and recording fluorescent images of the channel. We did so from 20°C to 44°C, in steps of 4°C. Second, after smoothing with a Gaussian filter ( $5 \times 5$ ), we extracted the relationship between intensity and temperature for each pixel in the image. We then confirmed the linear change in intensity as function of temperature  $I = mT_{\text{set}} + q$  and we obtained two matrices with the  $m$  and  $q$  coefficients for each pixel,  $I(x, y) = m(x, y)T_{\text{set}} + q(x, y)$ . The pixelwise calibration was necessary to account for the uneven illumination from the LED. We could then measure the temperature during the transient dynamic of the thermoacoustic streaming, both for the laser and the sound turning on, respectively. We set the temperature of the chip to 24°C to avoid variations of the room temperature influencing the measurements. After recording the images, we used the inverse

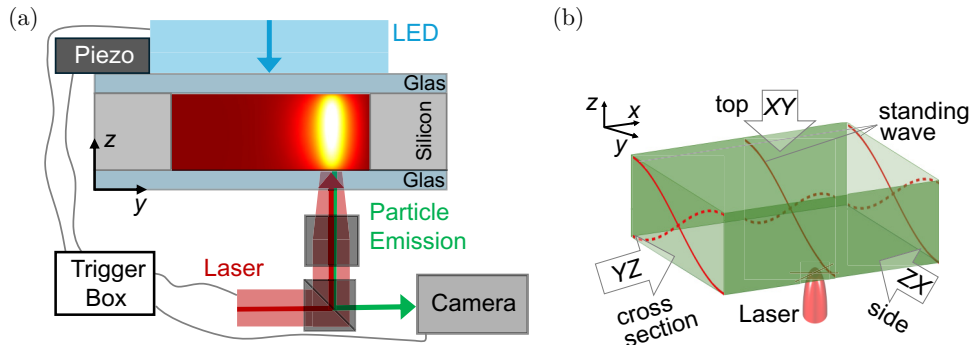


FIG. 1. (a) Experimental configuration with a laser spot near the wall, entering the glass-silicon-glass channel from below (red). LED light excites fluorescence in tracer particles from the top (blue) and tracer particles emission is imaged by a fluorescence microscope (green). Coordinated triggering of ultrasound, laser, LED, and camera is employed. The simulated temperature field in the cross-sectional view of the glass-silicon-glass chip is exemplified for a total ICG dye absorption of 30%. (b) Chip schematic indicating the standing pressure wave, laser spot position, and definition of the coordinate system and projections.

formula to estimate the temperature from the intensity for each pixel as  $T(x, y) = [I(x, y) - q(x, y)]/m(x, y)$ . Thus, we could obtain a temperature map for the whole field of view at every frame. The images were cropped, excluding the edges of the channel, to avoid optical artifacts, such as reflection, from the side walls.

### C. Optics

The power of the laser (Near-infrared NIR, CW, Topica, IBEAM-SMART-785-S) was set to 10 mW, resulting in a power of 6 mW at the channel. Green fluorescent polystyrene particles (Thermo Fisher, Fluoro-Max Dyed Green Aqueous Fluorescent Particles) are used to track the thermoacoustic streaming inside the channel. Their fluorescence is activated with an LED (Thorlabs: SOLIS LED, 470 nm and filter FESH0500). The camera (CMOS, Hamamatsu, OrcaFusion BT) records images at 100 fps with an exposure time of 6 ms.

### D. Electronics and sound

A piezoelectric transducer (Pz26, Ferroperm™ piezoceramics, Meggit A/S, Denmark), with dimensions  $30 \times 4.0 \times 1.0$  mm, generated the ultrasonic pressure field at a frequency of 1.975 MHz and set amplitude  $10 V_{pp}$  over the piezoelectric transducer. During the recording, the timing of all the system parts and the generation of the electrical signal to the piezoelectric transducer was handled by an Analog Discovery device (Digilent, Analog Discovery 2) using its software WAVEFORMS (Digilent, v.3.22.2).

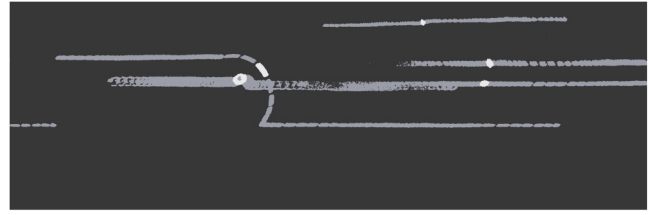
### E. Sample preparation

ICG dye (Thermo Fisher, IR-125, laser grade, CAT: 412545000) was diluted in ultrapure deionized water and dimethyl sulfoxide (DMSO), and also BCECF (B1151, Thermo-Fisher Scientific, USA) was dissolved in DMSO. The stock solutions were then mixed to a final concentration of ICG 0.395 mg/ml, BCECF 0.25 mg/ml and DMSO 5  $\mu$ l/ml and spiked with 1.1- $\mu$ m-sized tracer particles (Fluoromax Green, Fisher Scientific). For temperature measurements, the tracer particles were omitted.

After rinsing the channel with ethanol and then water, the mixture was injected. The channel was flushed and filled with new liquid before each recording to avoid photobleaching effects.

### F. Microfluidic channel and liquid transport

The straight microfluidic channel has a single-inlet, single-outlet structure (GeSim Bioinstruments and Microfluidics GmbH, Germany). The cavity is 375  $\mu$ m wide, 150  $\mu$ m high, and 4 cm long, etched through the silicon layer. The glass-silicon-glass layers were anodically bonded to make the microfluidic chip. They have a thickness of 760  $\mu$ m, 150  $\mu$ m, and 500  $\mu$ m, respectively,



**Video 1.** Realtime recording of transient thermoacoustic streaming to selectively transport a 1- $\mu$ m-diameter fluorescence polystyrene particle in the vicinity of other, unaffected, particles. In total 95 frames were recorded at 20 fps.

with holes for fluid inlet and outlet drilled in the thicker glass. The sample was supplied to the channel using a syringe pump and valve to stop the flow during acquisition (neMESYS, Cetoni GmbH, Korbussen, Germany). The streaming and temperature experiments were conducted in stop-flow. Video 1 shows a flow that was manually controlled through pushing on a syringe.

### G. Simulations

A numerical model was implemented in COMSOL MULTIPHYSICS [25] that simulates the whole chip in three dimensions for a 1-mm section along its length. The time-dependent simulation comprised the modules *Laminar Flow*, *Heat Transfer in Fluids*, and *Radiative Beam in Absorbing Media*. We assumed an ideal sound plane standing half-wave across the width of the channel with a pressure node located in the center. Boundary-driven acoustic streaming was implemented in the *Laminar Flow* module as a slip velocity, directed along  $y$  on the top and bottom boundaries [26,27], and the acoustic body force [Eq. (2)] was implemented as a volume force in the same module. The laser heating was modeled as an incident Gaussian beam intensity absorbed by the water for an overall absorption of 30% of the incoming light. The temperature of the outer boundaries of the chip was set to 24°C.

The numerical model assumes a perfect pressure half-wave standing wave along the channel width dimension  $y$  whose first-order fields are

$$p_1 = p_a \sin(k_y y), \quad (3)$$

$$\mathbf{v}_1 = \frac{p_a}{\rho_0 c_0} \cos(k_y y), \quad (4)$$

in which  $p_a = \sqrt{4\rho_0 c_0^2 E_{ac}}$ ,  $E_{ac}$  is the acoustic energy density,  $k_y$  is the wavenumber, while  $\rho_0$  and  $c_0$  are the medium density and speed of sound at 24°C, respectively. The material properties were taken from the COMSOL material library [25], including water for the fluid domain, borosilicate glass and silicon for the chip. We employed the *Laminar Flow* module for the fluid domain, which

also included the acoustic effects. Rayleigh streaming was implemented as a wall velocity  $u_w$  in the  $y$  direction at the bottom and top walls of the channel:

$$u_w = \frac{3}{8c_0} \left( \frac{p_a}{\rho_0 c_0} \right)^2 \sin(2k_y y), \quad \max = 5 \mu\text{m/s}, \quad (5)$$

and we added a no-slip boundary condition for the fluid. The acoustic body force was implemented as a volumetric force according to Eq. (1). We employed the *Heat Transfer in Fluids* module for the whole system. The top and side boundaries of the chip were kept at  $24^\circ\text{C}$ , which was the also the initial temperature of the whole system. The laser was implemented with the *Radiative Beam in Absorbing Media* module. The fluid domain was set as absorbing medium, while the incident laser intensity was set at the bottom of the channel, with deposited beam power of 14.65 mW. The *Heat Transfer in Fluids* and *Radiative Beam in Absorbing Media* modules were coupled by the *Heat Transfer with Radiative Beam in Absorbing Media*

multiphysics. The *Heat Transfer in Fluids* and *Laminar Flow* modules were coupled by the *Nonisothermal Flow* multiphysics. The timing for enabling or disabling either the laser or the sound was implemented as *Events*. To reduce the computing time, a  $y$ - $z$  symmetry plane was placed in the center of the model, at the location of the laser spot.

The model was tuned to the experiments by the following approach. The laser beam location, power, and diameter were tuned until the simulated temperature field matched the measured steady-state temperature field. Subsequently,  $E_{ac}$  was tuned to  $5 \text{ J/m}^3$  such that the simulated maximum velocity of the thermoacoustic streaming matched the maximum velocity in the experimental steady-state velocity field.

### III. RESULTS

To characterize the dynamics of thermoacoustic streaming, we measured the temporal evolution of the streaming and temperature fields in a region around the laser's point

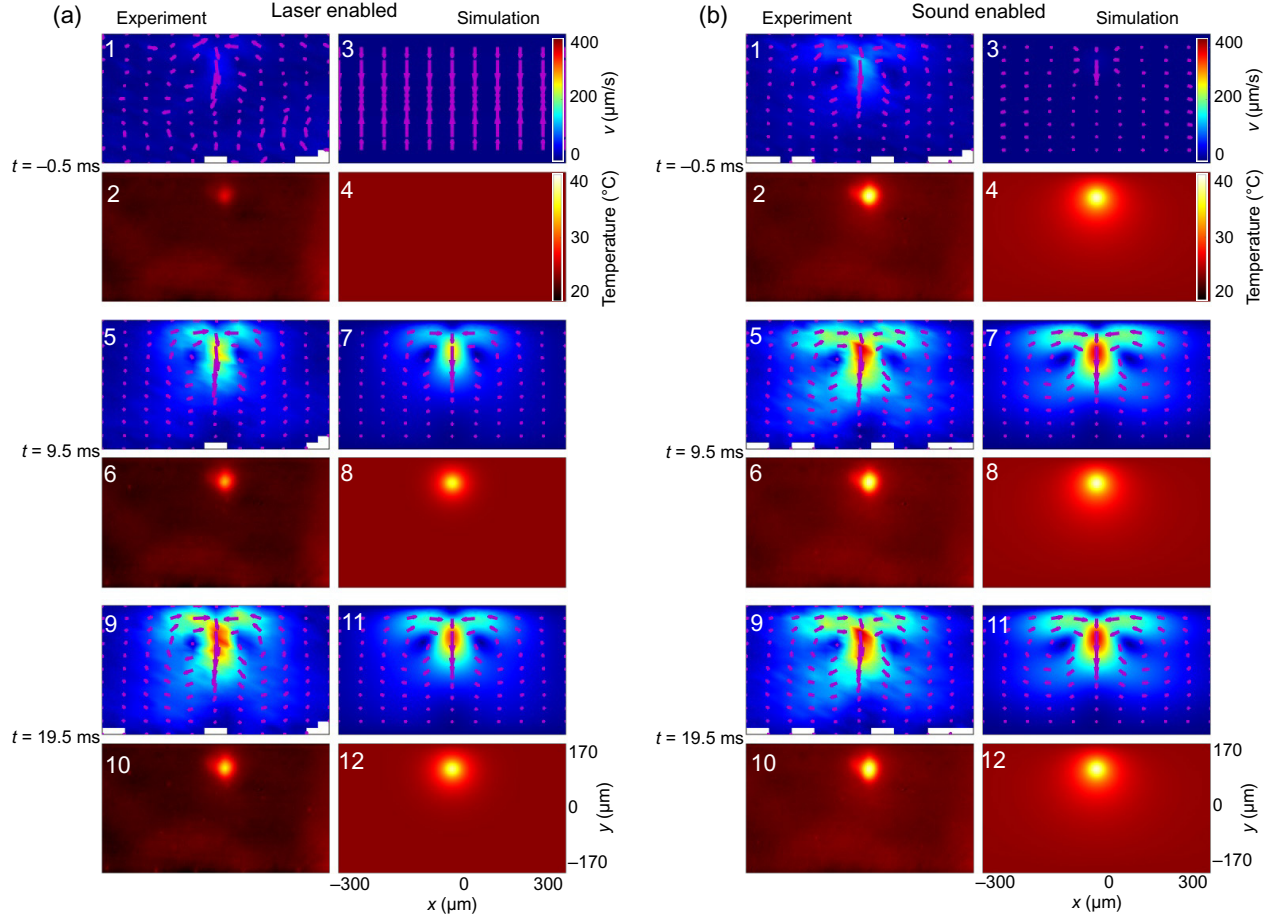


FIG. 2. Buildup of thermoacoustic streaming for the two different configurations: (a) laser ON at  $t = 0$  s and (b) sound ON at  $t = 0$  s (for timing scheme, cf. Fig. 6). The left columns of (a) and (b) show experimental results of thermoacoustic streaming and temperature at three different times  $t$ . The right columns show the corresponding simulation results for thermoacoustic streaming and temperature. All arrows are normalized to their respective frame.

of incidence. As the thermoacoustic streaming buildup depends on the establishment of a temperature field as well as a sound field, we studied both the effect of toggling the laser for a constant sound field and the effect of toggling the sound field for constant laser irradiation. The constant field was enabled at  $t = -200$  ms, while the toggled field was enabled at  $t = 0$  ms and disabled at  $t = 2000$  ms. The temperature field was acquired for 90 ms each during the buildup and decay, while the velocity field was measured throughout the whole sequence. One frame represents the mean particle positions during the 6-ms exposure time, and the recording of the following frame started 4 ms after the previous one ended. The detailed timing scheme is shown in Appendix B, Fig. 6.

Figure 2 shows the evolution of the thermoacoustic streaming during its buildup while the (a) laser or (b) ultrasound is toggled on, experimentally and numerically. In both scenarios, the thermoacoustic streaming pattern appears in the experiment already in the first recorded frame at  $-0.5$  ms after activation [Fig. 2(a)(1) and (b)(1)].

This is because the velocity and temperature measurements extend in time such that the measurement at  $t = -0.5$  ms starts before the trigger and ends after the trigger, and thus the measured field has some component of thermoacoustic streaming. The simulations, however, represent the instantaneous fields where the only velocity that can be observed at  $t = -0.5$  ms stems from the constant fields. In Fig. 2(a)(3) we observe the boundary driven acoustic, Rayleigh-type, streaming, and in Fig. 2(b)(3) the natural gravity-driven convection due to the lower density of the heated fluid in the laser spot. Arrows are scaled to the maximum velocity within each panel, while the velocity magnitude color scale is the same throughout all panels.

In Appendix C we provide a quantitative spatiotemporal comparison of the experimental and simulated results by plotting the temperature and the streaming velocity across the width of the channel.

The buildup of the thermoacoustic field for a preestablished acoustic field is slower than the buildup for a

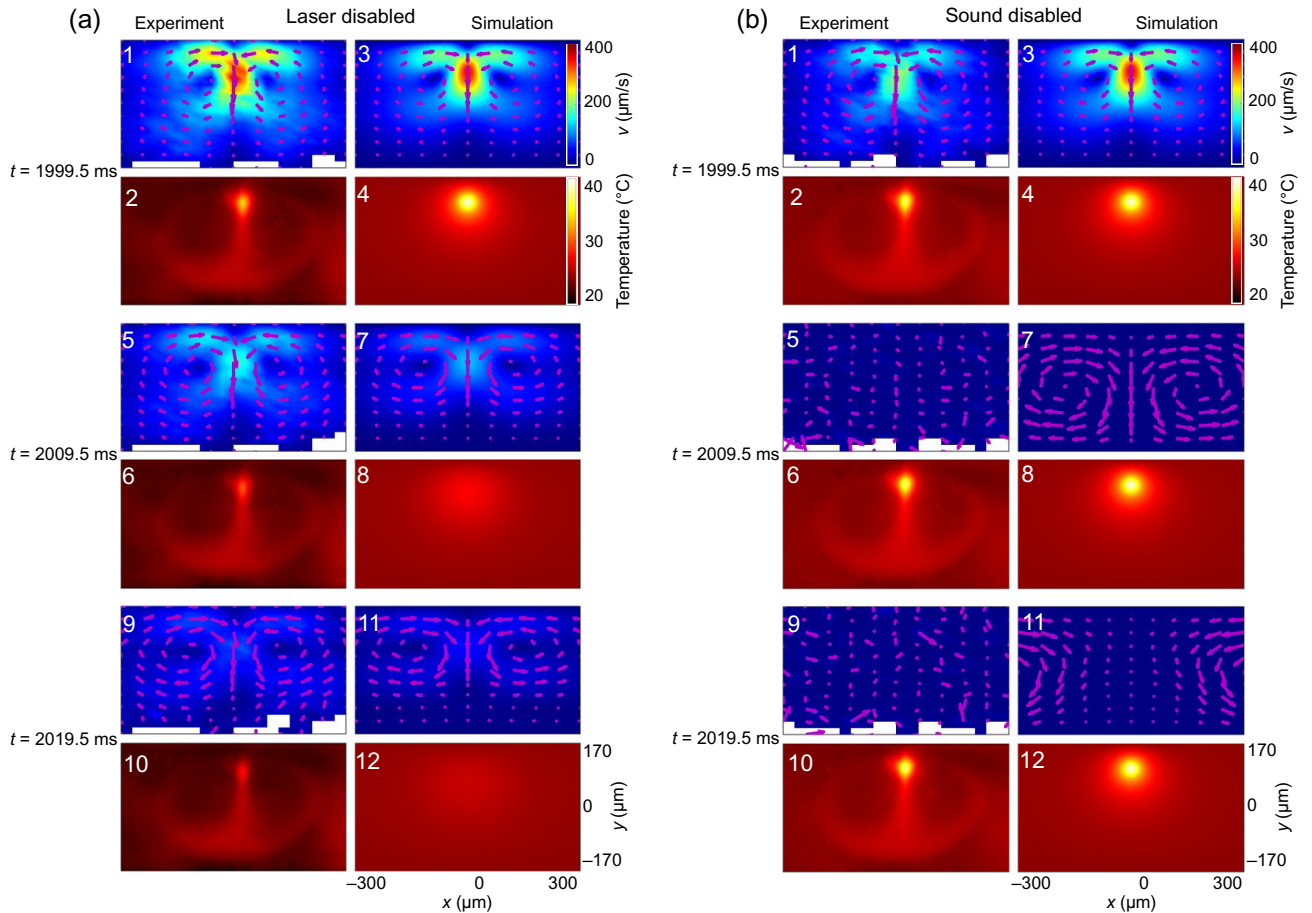


FIG. 3. Decay of thermoacoustic streaming for the two different configurations: (a) laser OFF at  $t = 2$  s and (b) sound OFF at  $t = 2$  s (for timing scheme, cf. Fig. 6). The left columns of (a) and (b) show experimental results of thermoacoustic streaming and temperature at three different times  $t$ . The right columns show the corresponding simulation results for thermoacoustic streaming and temperature. All arrows are normalized to their respective frame.

preestablished temperature field, which is particularly evident in the experimental velocity data at  $t = 9.5$  ms [Fig. 2(a)(5) and (b)(5)]. In Fig. 2(b)(5) the velocity is already fully established, relative to Fig. 2(b)(9), while Fig. 2(a)(5) is still underdeveloped relative to Fig. 2(a)(9).

Laser toggling is slower because the buildup of the temperature gradient is slower than both the establishment of the acoustic resonant pressure field and the response of the system due to momentum diffusion. The characteristic time  $\tau_T$  for the development of the temperature field can be estimated from the thermal diffusion constant of water at room temperature  $\alpha \approx 0.15$  mm<sup>2</sup>/s, assuming two-dimensional diffusion, as  $\tau_T = L^2/(4\alpha)$ . Under the assumption that the shortest possible time to reach equilibrium is through heat diffusing from the laser source to the nearest silicon side wall, we insert  $L = 70$   $\mu$ m, which leads to a low estimate for the characteristic buildup time  $\tau_T \approx 8$  ms. This time is long compared to the buildup time of the sound field which can be estimated from the frequency and  $Q$ -value of the resonator  $\tau_{\text{sound}} = Q/(2\pi f)$  [28]. Even for a conservatively chosen high  $Q$ -value of 1000, the buildup time is less than 1 ms. Further, the momentum diffusion time  $\tau_{\text{momentum}} \approx L^2 \rho/\eta$  describes the time for the fluid velocity field to develop some distance  $L$  away from a source [28]. The average minimum distance of a fluid element to any wall is  $L = H/4$ , where  $H$  is the channel height. This

yields  $\tau_{\text{momentum}} \approx 1$  ms, which is also faster than  $\tau_T$ . The experimental temperature and streaming fields are thus in very good agreement with the simulations and some simple scaling laws both in terms of the temporal development and the flow field patterns.

When toggling the laser off [Fig. 3(a)], we observe a decay in thermoacoustic streaming over tens of milliseconds, while when toggling the sound off [Fig. 3(b)], the thermoacoustic streaming is below the detection limit already in the second frame. Notably, the laser decay is not just a reversal of the onset. During the onset, the thermal profile grows from a tiny spot with associated small thermoacoustic streaming rolls [Fig. 2(a)(5) and (a)(7)], until reaching a thermal equilibrium. Deactivating the laser leads to decaying but further enlarged streaming rolls [Fig. 3(a)(9) and (a)(11)] as the temperature field diffuses in all directions over time. The temperature fields measured during the decay reveal a deformation and a faint arc-shaped pattern that appears to follow the velocity field. We do not observe this in the simulations and we think it could be an artifact in the experiment or an effect that is unaccounted for in the simulation, or both, see Sec. IV.

To quantify the evolution over time, we extracted the thermoacoustic velocity and temperature versus time within a small region of interest (ROI) of similar size to the laser spot size (Fig. 4). The maximal streaming

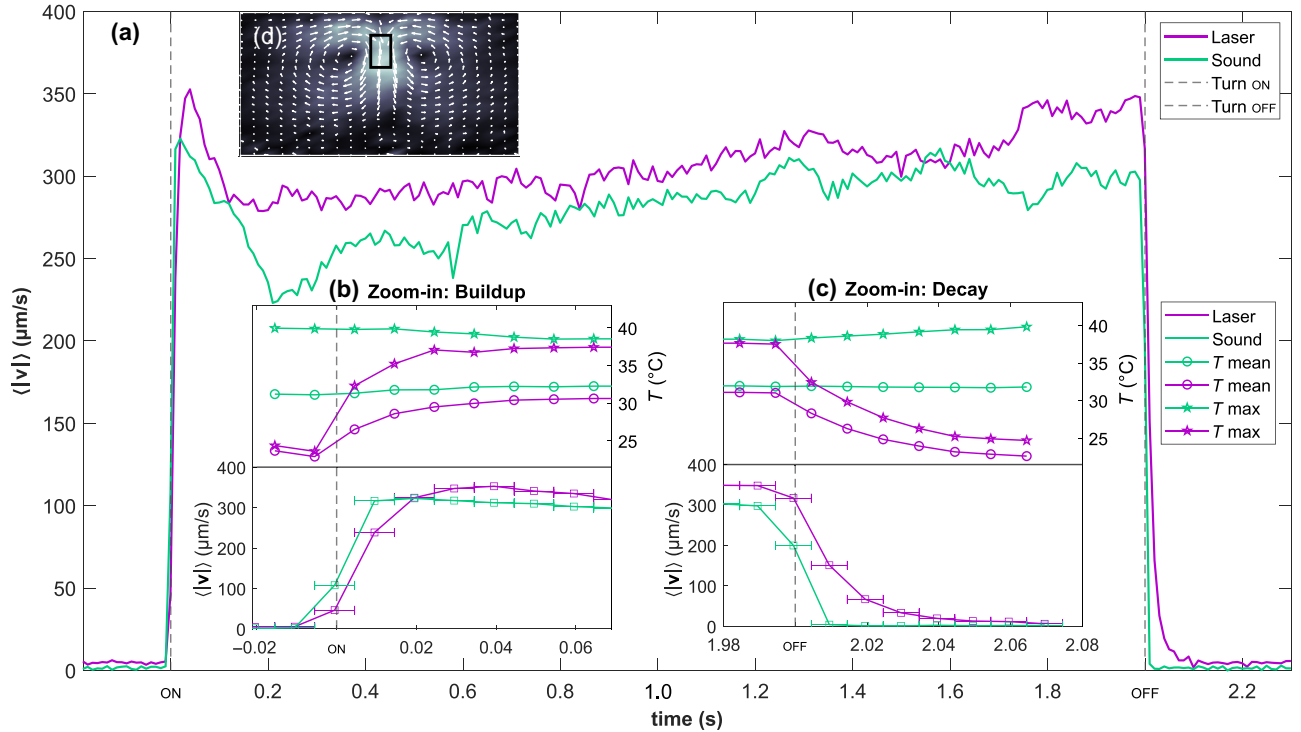


FIG. 4. Measured (a) streaming velocity and (b)(top) temperature in the laser spot for laser (pink) or sound (green) enabled at 0 s and disabled at 2 s. The velocity is extracted only from the ROI (d, black rectangle). Insets (b) and (c) show details for buildup and decay velocity evolution as well as the measured temperature in the ROI, as mean (circles) or max (stars). The dashed lines indicate when the laser or sound was enabled or disabled.

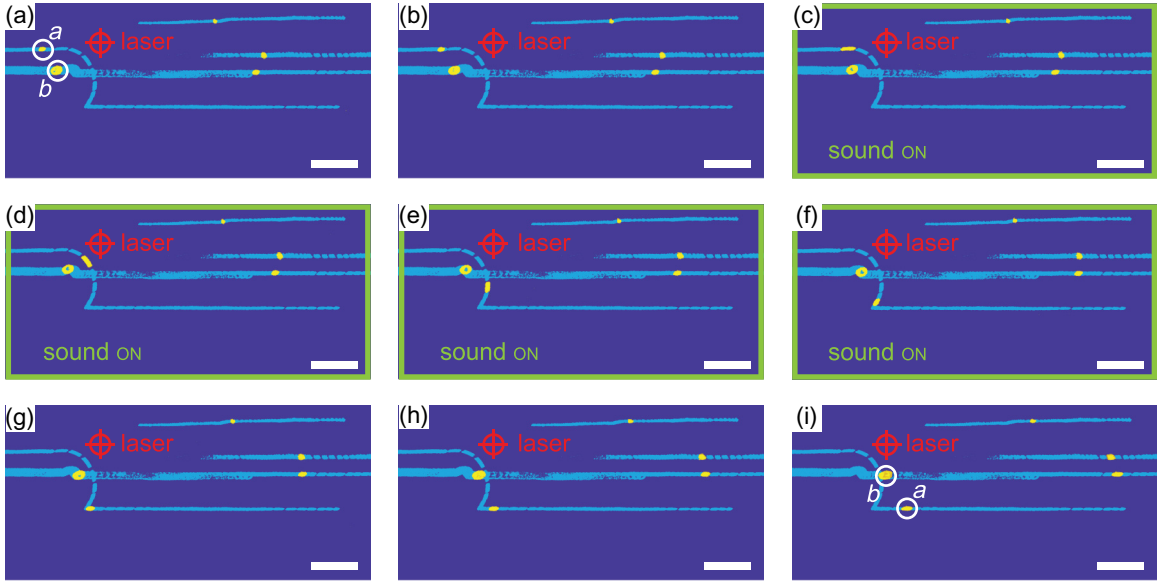


FIG. 5. False-colored image overlay from extracted frames of Video 1 showing the trajectories (light blue) and positions (yellow) of two nearby particles referred to as *a* and *b*, in (a) and (b) before, (c)–(f) during, and (g)–(i) after sound-toggled thermoacoustic streaming. The laser’s point of incidence is indicated by a circled red cross. Scale bars 100  $\mu\text{m}$ .

velocity plateaus at 350  $\mu\text{m/s}$  after 30 ms (laser-toggled) and 9.5 ms (sound-toggled) [Fig. 4(b)]. Due to the limited frame rate, we cannot measure rise-times shorter than about 10 ms, but we believe the actual rise-time for toggling the sound is close to 2 ms, as suggested by the simulations (Appendix D). The temperature measurements show an increase of about  $12^\circ\text{C}$  upon activating the laser, with development over time similar to the thermoacoustic streaming [Fig. 4(b)].

After the velocity reaches its peak, we observe a dramatic decline after which the velocity gradually increases [Fig. 4(a)]. The effect is more pronounced for toggled ultrasound (30% drop over 200 ms) than for toggled laser (20% drop over 100 ms). This effect was unexpected and we cannot fully explain it and we did not observe it in the simulations (Appendix D). In a high-Péclet-number system, where advection dominates over thermal diffusion, we would expect such a drop, caused by the onset of thermoacoustic advection of cold fluid into the laser-heated region, leading to a flatter temperature gradient and a resulting reduced streaming. However, at the measured fluid velocity of 300  $\mu\text{m/s}$ , it takes  $\frac{1}{3}$  s to cross the 100- $\mu\text{m}$  large laser-heated region and thus exchange the heated fluid. But the measured temperature field across the channel converges within 25 ms, which is roughly ten times shorter than the advective timescale [Fig. 9]. For a three-dimensional system, heat diffuses in all directions, including into the top and bottom glass substrates, which lowers the relative influence of advective heat transport. Hence, the Péclet number is indeed low and we presently have no satisfactory explanation for the thermoacoustic streaming decay in the first 200 ms.

Laser-induced transient thermoacoustic streaming can be a viable approach to implementing single cell sorting or cell rearrangement inside a microcavity. As a proof of concept, we fed a dilute suspension of 1- $\mu\text{m}$ -diameter fluorescent polystyrene microparticles through the cavity with constant laser irradiation while toggling the acoustic field ON and then OFF (see Video 1).

Figure 5 highlights the events of Video 1 where the position of a particle (*a*) is changed without affecting a nearby particle (*b*) while they both flow left to right through the thermoacoustic cavity. In Figs. 5(c)–(f), the sound field is activated resulting in thermoacoustic transport of particle *a* in an arc-shaped trajectory passing just in front of particle *b* which is only minimally affected by the thermoacoustic flow. After turning off the flow in Fig. 5(g) both particles continue along their trajectories along the channel. Downstream, three other particles follow straight trajectories unaffected by the thermoacoustic field.

#### IV. DISCUSSION AND OUTLOOK

We investigated the buildup and decay of thermoacoustic streaming. The realization that the buildup of the temperature field occurs on a slower timescale than the buildup of the sound field has potentially useful implications. While our previous work [21] could show that the thermoacoustic streaming field can be shaped by a laser-induced temperature gradient, we now show that the time modulation can be done by toggling the sound field. Combined, this opens up the possibility of achieving a spatial resolution of the generated velocity field that is not

limited by the wavelength of the sound field which normally defines the spatial resolution in acoustic systems. At the same time, the streaming field can be activated and deactivated on a timescale that is defined by the relatively fast buildup time of the sound field rather than by the relatively slow thermal diffusion. It is possible to operate under constant laser irradiation, since the natural convection is much slower than the thermoacoustic streaming, and thus particles will not be significantly affected by this stationary flow field. Further, the thermoacoustic streaming is much faster than boundary-driven acoustic streaming and the direct radiation force acting on suspended microscopic objects. Therefore, objects outside the direct vicinity of the temperature gradient will be subjected to very small acoustophoretic displacements during the onset of the sound field.

Video 1, where one particle crosses the path of a second particle within a distance of just 25  $\mu\text{m}$ , is a clear example of the potential of transient thermoacoustics where strong velocity gradients are combined with high temporal resolution. The sideways translation of about 100  $\mu\text{m}$  takes 250 ms during which the path of the other particle remains almost unaffected.

It can be concluded from the data of Fig. 4 that the current setup, with a temporal resolution of 10 ms, does not fully resolve the dynamics of the thermoacoustic streaming, in particular for the case of toggling the sound ON and OFF. In Fig. 4(b) the velocity reaches a plateau already at the first measurement point after onset ( $t = 9.5$  ms). Furthermore, the decay in velocity from 180  $\mu\text{m/s}$  to almost 0  $\mu\text{m/s}$  between 2.01 s and 2.02 s in Fig. 4(c) makes the decay time estimation uncertain. Increasing the frame rate from 100 Hz by a factor of 5–10 would likely be sufficient. A shorter exposure time would also lead to a more accurate determination of the position and velocity of the particles. Even with the current dataset, the accuracy could be slightly improved by taking into account that the time interval of the exposure of each line on the camera sensor is known.

In this work, we implemented temperature measurements through the fluorescent tracer BCECF. This enabled us to measure the magnitude and the characteristic time for the buildup and decay of the temperature gradient. However, the measurements are challenging due to the significant influence of photo bleaching which requires pixelwise time-resolved calibration. This means each measurement time was captured in separate experiments by imposing different delay times after activating the fluorescence excitation light. A less convoluted temperature measurement would enable more reliable and extensive temperature measurements spanning all time points of the experiment. Furthermore, we can observe in the decay temperature fields [Fig. 3] an arc-shaped pattern corresponding to a few degrees of elevated temperature that we cannot explain. If this was an effect of hot fluid ejected

from the laser by the thermoacoustic streaming we would expect it to diffuse away quickly after the thermoacoustic streaming has stopped. While we conclude a very fast decay of thermoacoustic streaming, there is no sign of the pattern becoming dimmer in the investigated time. We have observed that it disappears on the timescale of a second and we therefore think it may be associated with the intense laser irradiation leading to a photo-bleaching effect or vesicle formation obscuring the light. Such photo-bleached molecules or vesicles would diffuse much more slowly than the thermal field. Future work should focus on improving the temperature measurement to ensure accuracy and precision by optical methods such as multispectral fluorescence, fluorescence lifetime measurements, or chip-integrated sensors [29].

We envisage that the localized fast transient thermoacoustic streaming presented can be employed to achieve label-free sorting of biological micro- and nano-objects. This could be achieved by activating the sound, for constant laser heating, in short bursts, enough to develop the streaming and thus affect the trajectory of the selected object, which would be deflected by the highly localized thermoacoustic streaming without affecting nearby objects.

## ACKNOWLEDGMENTS

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There are no conflicts of interest to declare.

## DATA AVAILABILITY

The data that support the findings of this article are openly available [30], embargo periods may apply.

## APPENDIX A: SIMULATION DETAILS

The temperature field  $T$  was solved by the following equations, which couple the advective and diffusive heat transport:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q, \quad (\text{A1a})$$

$$\mathbf{q} = -k_{\text{th}} \nabla T, \quad (\text{A1b})$$

with density  $\rho$ , specific heat capacity  $c_p$ , velocity field  $\mathbf{u}$ , heat flux  $\mathbf{q}$ , heat source  $Q$ , and thermal conductivity  $k_{\text{th}}$ .

TABLE I. Boundary conditions.

| Boundary type             | Equation                                                             |
|---------------------------|----------------------------------------------------------------------|
| Thermal isolation         | $-\mathbf{n} \cdot \mathbf{q} = 0$ , with normal vector $\mathbf{n}$ |
| Temperature               | $T = 293$ K                                                          |
| No slip                   | $\mathbf{u} = 0$                                                     |
| Slip                      | $\mathbf{u} \cdot \mathbf{n} = 0$                                    |
| Boundary streaming        | $u_y = u_w(y)$ [as in Eq. (5)]                                       |
| Pressure constraint point | $p = 0$ Pa (assigned to a corner of the fluid domain)                |

The thermoacoustic streaming field  $\mathbf{u}$  was solved by the following equations:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mathbf{K}] + \mathbf{f}_{ac} + \rho \mathbf{g}, \quad (\text{A2a})$$

$$\rho \nabla \cdot \mathbf{u} = 0, \quad (\text{A2b})$$

$$\mathbf{K} = \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^T). \quad (\text{A2c})$$

The boundary conditions are shown in Table I.

Constant temperature was implemented on the sides, top, and bottom of the chip, while the other boundaries were thermally isolated. The no-slip boundary condition was applied to the side walls of the fluid cavity. The slip condition was applied to the boundary corresponding to the truncated fluid cavity, ensuring that no fluid leaves

the domain. The slip velocity at the top and bottom of the fluid cavity implemented Rayleigh streaming without resolving the boundary layer. The pressure point constraint is necessary to obtain stable solutions from the solver.

The mesh was a free tetrahedral mesh with a maximum element size of  $7.1 \mu\text{m}$  in the laser spot,  $21.4 \mu\text{m}$  in the fluid domain away from the laser, and  $143 \mu\text{m}$  in the solid domains as validated via a mesh convergence test to within 5% compared to the finest mesh by probing the thermoacoustic streaming velocity field across the  $y$  direction. The parameters used in the model are specified in Table II.

## APPENDIX B: TIME SCHEMES

Two schemes were employed to investigate the buildup and decay of the temperature and thermoacoustic streaming fields (Fig. 6). Time  $t = 0$  ms is defined as the first instance when the trig signals to both ultrasound and laser are activated, which is when the thermoacoustics starts. In the first scheme, the ultrasound and the imaging sequence was first triggered at the time  $t = -200$  ms, the laser was turned ON at  $t = 0$  ms and OFF again at  $t = 2000$  ms, and the recording stopped at  $t = 3000$  ms. The temporal resolution is limited by the camera frame rate, the duration of the exposure, and the readout sequence of the camera pixel rows. Each pixel row (oriented along  $x$ ) is read out in parallel and the exposure of a frame starts at the top

TABLE II. Simulation parameters.

| Parameter            | Expression                | Value                   | Description                          |
|----------------------|---------------------------|-------------------------|--------------------------------------|
| <b>Geometry</b>      |                           |                         |                                      |
| $L_{\text{channel}}$ |                           | 1 mm                    | Length of chip/fluid channel ( $x$ ) |
| $W_{\text{channel}}$ |                           | $375 \mu\text{m}$       | Width of fluid channel ( $y$ )       |
| $H_{\text{channel}}$ |                           | $150 \mu\text{m}$       | Height of fluid channel ( $z$ )      |
| $W_{\text{chip}}$    |                           | 5 mm                    | Width of chip ( $y$ )                |
| $H_{\text{chip}}$    |                           | 1.5 mm                  | Height of chip ( $z$ )               |
| $x_{\text{laser}}$   |                           | $100 \mu\text{m}$       | Laser $x$ position                   |
| $y_{\text{laser}}$   |                           | $115 \mu\text{m}$       | Laser $y$ position                   |
| $d_{\text{laser}}$   |                           | $20 \mu\text{m}$        | Laser spot diameter                  |
| <b>Heat</b>          |                           |                         |                                      |
| $T_{\text{bnd}}$     |                           | 297.15 K                | Ambient temperature                  |
| $P_{\text{laser}}$   |                           | 14.65 mW                | Laser power                          |
| $\text{Trm}$         |                           | 0.7                     | Transmittance                        |
| $A$                  | $\ln(\text{Trm})$         | 0.35687                 | Absorbance                           |
| $a$                  | $A/H_{\text{channel}}$    | $2377.8 \text{ m}^{-1}$ | Attenuation coefficient              |
| <b>Sound</b>         |                           |                         |                                      |
| $E_{ac}$             |                           | $5 \text{ J/m}^3$       | Acoustic energy density              |
| $c_0$                |                           | 1500 m/s                | Speed of sound (first-order field)   |
| $\rho_0$             |                           | $1000 \text{ kg/m}^3$   | Density (first-order field)          |
| $\kappa_0$           | $1/(\rho_0 c_0)$          | $444 \text{ MPa}^{-1}$  | Compressibility                      |
| $p_a$                | $\sqrt{4E_{ac}/\kappa_0}$ | 212 kPa                 | Acoustic pressure amplitude          |
| $v_a$                | $p_a/(\rho_0 c_0)$        | 0.1414 m/s              | Acoustic velocity amplitude          |
| $k_y$                | $\pi/W_{\text{channel}}$  | $8377.6 \text{ m}^{-1}$ | Wavenumber (half wavelength)         |

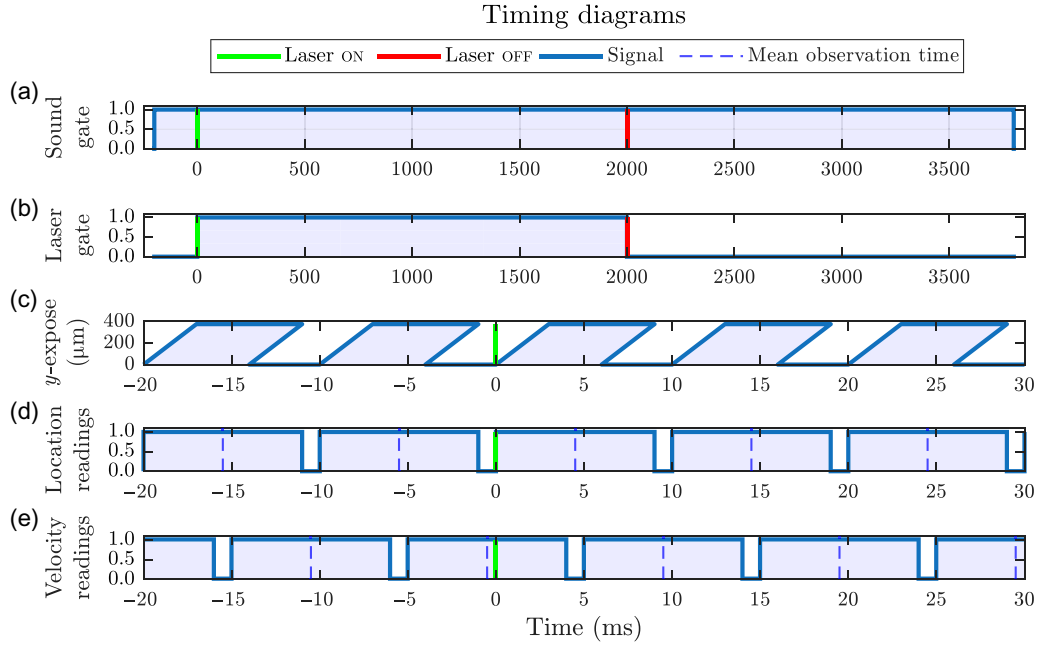


FIG. 6. Timing signals (blue solid lines) for constant actuation with ultrasound while the laser is switched ON and OFF. (a) The gate signal to the ultrasound. (b) The gate signal to the laser. (c) The exposed locations in the image across  $y$  in the channel. (d) The windows of observation of particles and temperature field. (e) The windows of observation for the velocity determination of particles. Red and green solid lines indicate the turn-ON and turn-OFF times of the laser, respectively. Dashed blue lines indicate the mean time for observing location or velocity within an observation window.

row (corresponding to  $y = 0$ ), while the last row exposure ( $y = 375 \mu\text{m}$ ) starts after a delay of 3 ms. Each row is exposed for 6 ms and therefore the mean time point of the overall exposure is shifted by  $(6 \text{ ms} + 3 \text{ ms})/2 = 4.5 \text{ ms}$  relative to the trig signal of a frame [Fig. 6(c)]. The recorded images of particles and temperature fields are thus shifted by 4.5 ms relative to the camera trigger. Moreover, the velocity fields are calculated between observations of a particle in two consecutive frames and therefore the average time point of the velocity observations is shifted by an additional 5 ms relative to the trigger of the first frame. Thus, the first temperature registration after onset occurs at  $t = 4.5 \text{ ms}$  while the first velocity registration occurs at  $t = 9.5 \text{ ms}$ . Notably, a registration of velocity also occurs at  $t = -0.5 \text{ ms}$ , and for this velocity the laser was OFF during the first 5 ms and ON during the last 4 ms. In Fig. 2 the temperature field has been interpolated in time to correspond to the time point of the velocity registration. In the second scheme, the gate signals to the laser and ultrasound were swapped such that the laser was instead activated at  $t = -200 \text{ ms}$ , the ultrasound was turned ON at  $t = 0 \text{ ms}$  and OFF again at  $t = 2000 \text{ ms}$ , and the recording stopped at  $t = 3000 \text{ ms}$ .

### APPENDIX C: SPATIOTEMPORAL VALIDATION OF SIMULATIONS VS EXPERIMENTS

We plotted the temperature and the  $y$ -component of the streaming field across the channel ( $y$ -direction) to enable a more detailed comparison between experiments and simulations, and to better highlight the link between the temperature field and the thermoacoustic streaming.

Figure 7 shows experimental data for toggling the sound during constant laser illumination. The velocity field builds up, and later decays, faster than a single velocity recording [Figs. 7(a),(b)]. Figures 7(c),(d) confirm that the temperature field is already established when the sound is toggled, but this field becomes distorted with time, presumably due to the thermoacoustic flow. A local velocity maximum is located near the thermal maximum, but shifted towards the pressure node. This makes sense as the thermoacoustic body force acts in the direction of the temperature gradient towards the temperature maximum, but since the acoustic pressure decays towards the centrally located pressure node a flow converges around the temperature maximum and is funneled along  $y$  towards the channel center.

Figure 8 shows the corresponding simulated results for toggling the sound with constant laser. We note that the

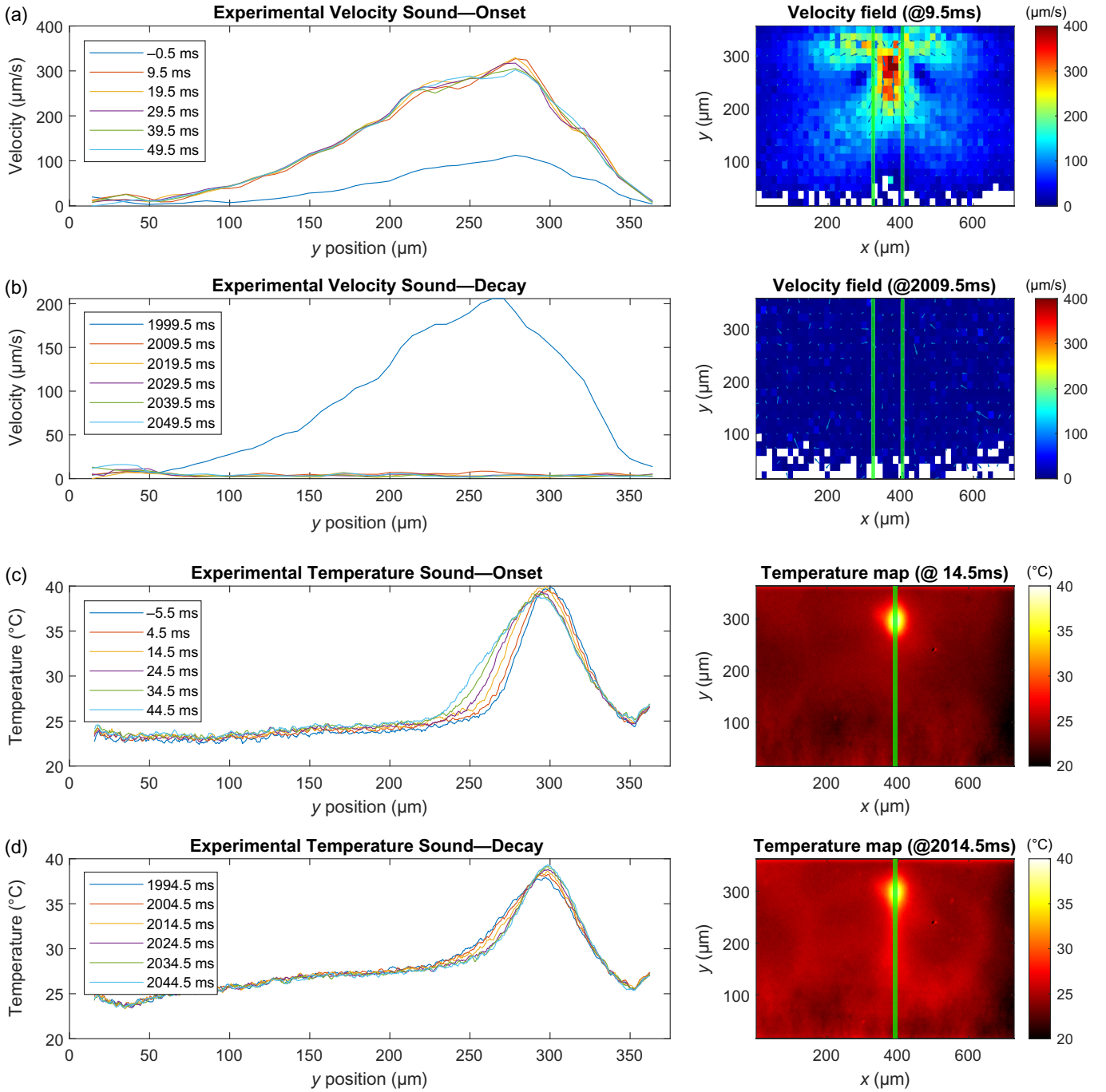


FIG. 7. Plots of measured absolute velocity  $y$ -component along  $y$  for (a) buildup and (b) decay when toggling the sound while having constant laser irradiation. Corresponding plots for the measured temperature along  $y$  for (c) the buildup and (d) the decay. To the right of each plot is shown the location of the extracted data overlaid with a corresponding two-dimensional field.

velocity fields and temperature fields match well regarding both magnitude and spatial distribution. The matching magnitudes are expected, since, in the simulation, the laser power and position were tuned until matching the peak temperature in the experiments and the acoustic energy density was tuned so as to generate the same maximum

velocity magnitude in simulations and experiments. When observing the temporal evolution of the temperature field, there is a notable discrepancy. The simulated temperature field displays only a very small evolution over time after toggling the sound field and this is indicative of thermal diffusion dominating over advective transport of

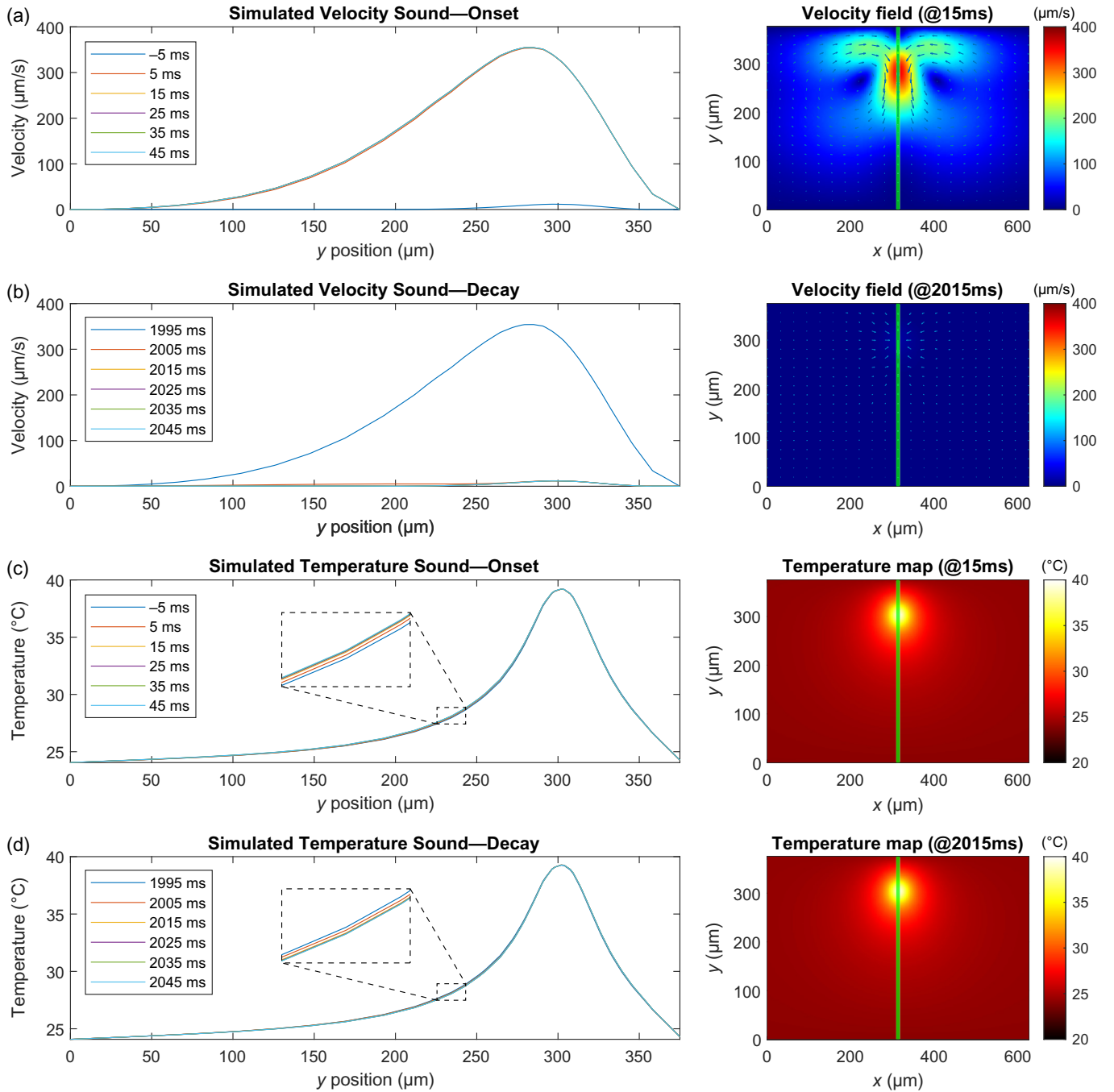


FIG. 8. Plots of simulated velocity  $y$ -component along  $y$  for (a) buildup and (b) decay when toggling the sound while having constant laser irradiation. Corresponding plots for the simulated temperature along  $y$  for (c) the buildup and (d) the decay. To the right of each plot is shown the location of the extracted data overlaid with a corresponding two-dimensional field.

heat in our model. However, the experimental temperature field (Fig. 7) appears to gradually develop with time over the first 45 ms after streaming onset. During the decay sequence, however, the temperature field seems to recover the initial shape as the thermoacoustic streaming has stopped. We currently have no explanation as

to why the model does not predict this. Such discrepancy, between simulated and experimental temperature data, was previously reported when describing thermoacoustic streaming [31] but it can possibly also be due to experimental artifacts when measuring the temperature field.

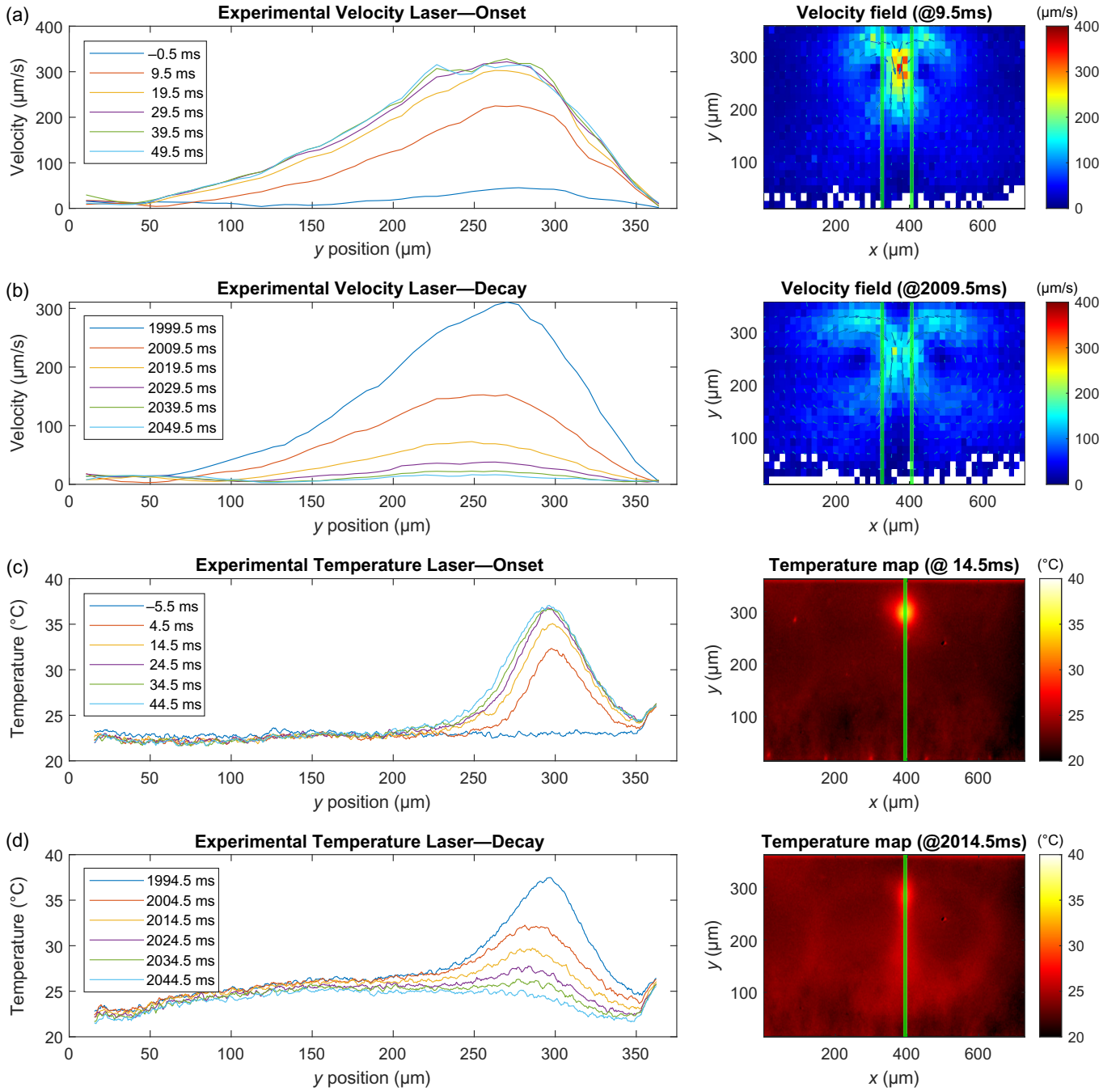


FIG. 9. Plots of measured absolute velocity  $y$ -component along  $y$  for (a) buildup and (b) decay when toggling the laser illumination while having constant sound. Corresponding plots for the measured temperature along  $y$  for (c) the buildup and (d) the decay. To the right of each plot is shown the location of the extracted data overlaid with a corresponding two-dimensional field.

Figure 9 shows experimental data for toggling the laser irradiation during constant sound actuation. Notably, the velocity builds up and decays more slowly than when toggling the sound, which is an effect of the slow buildup of the temperature field, and later the decay follows that trend. Although the experimental data has limited resolution in

time, we can observe that the temperature distribution is somewhat more confined for early buildup times, while the temperature gradient is very similar. This implies that the velocity field generated at early times is confined to a narrow region around the laser's point of incidence. We observe that the velocity maximum moves slightly inwards

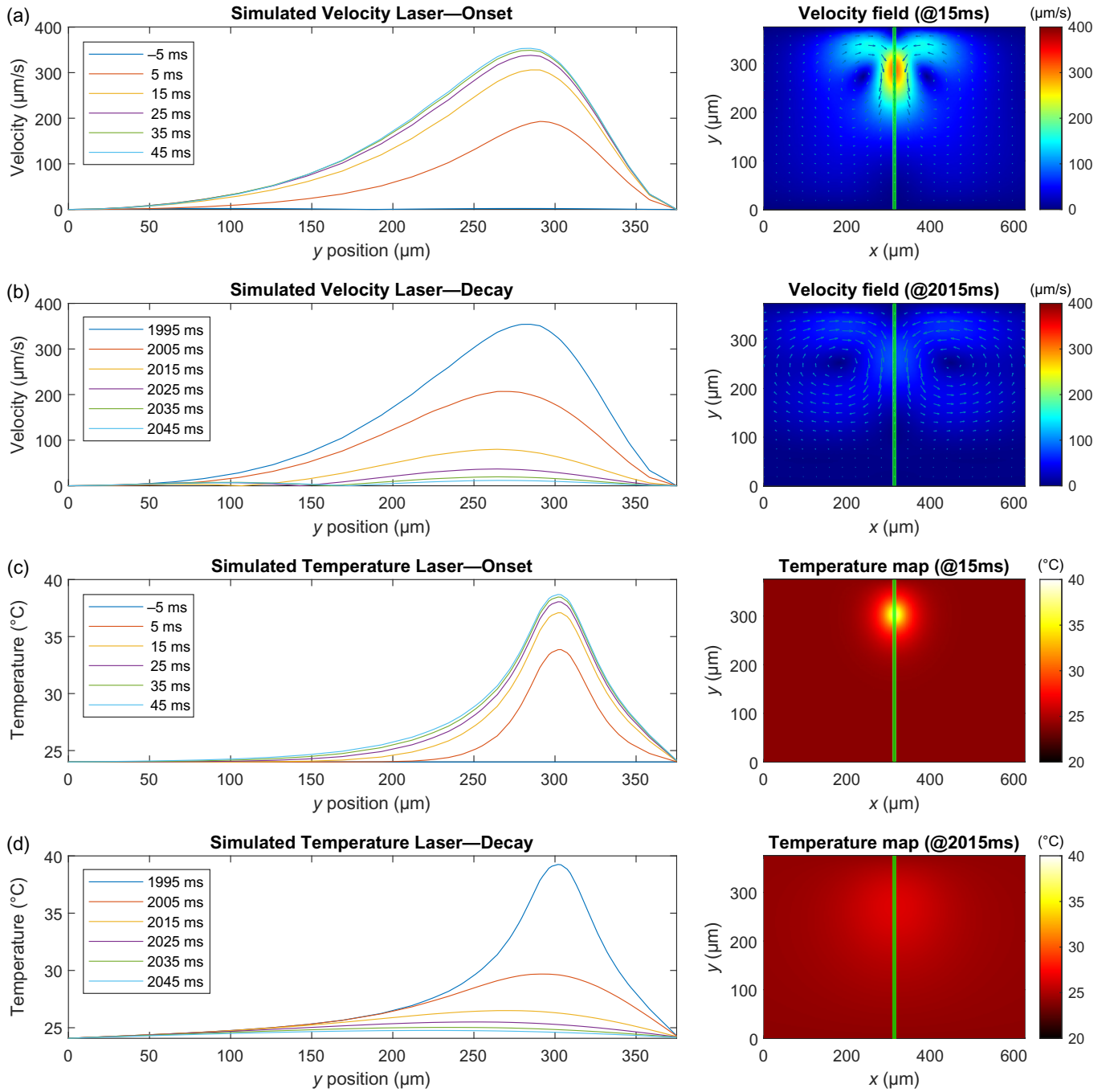


FIG. 10. Plots of simulated velocity  $y$ -component along  $y$  for (a) buildup and (b) decay when toggling the laser irradiation while having constant sound. Corresponding plots for the simulated temperature along  $y$  for (c) the buildup and (d) the decay. To the right of each plot is shown the location of the extracted data overlaid with a corresponding two-dimensional field.

towards the channel center during the buildup and continues outwards during the decay as the temperature gradient flattens after turning the heat source OFF. This trend is even more clear in the simulated buildup and decay plots (Fig. 10).

#### APPENDIX D: SIMULATED TRANSIENT DEVELOPMENT WITHIN THE REGION OF INTEREST

The transient development of the simulated thermoacoustic streaming within the ROI is shown in Fig. 11.

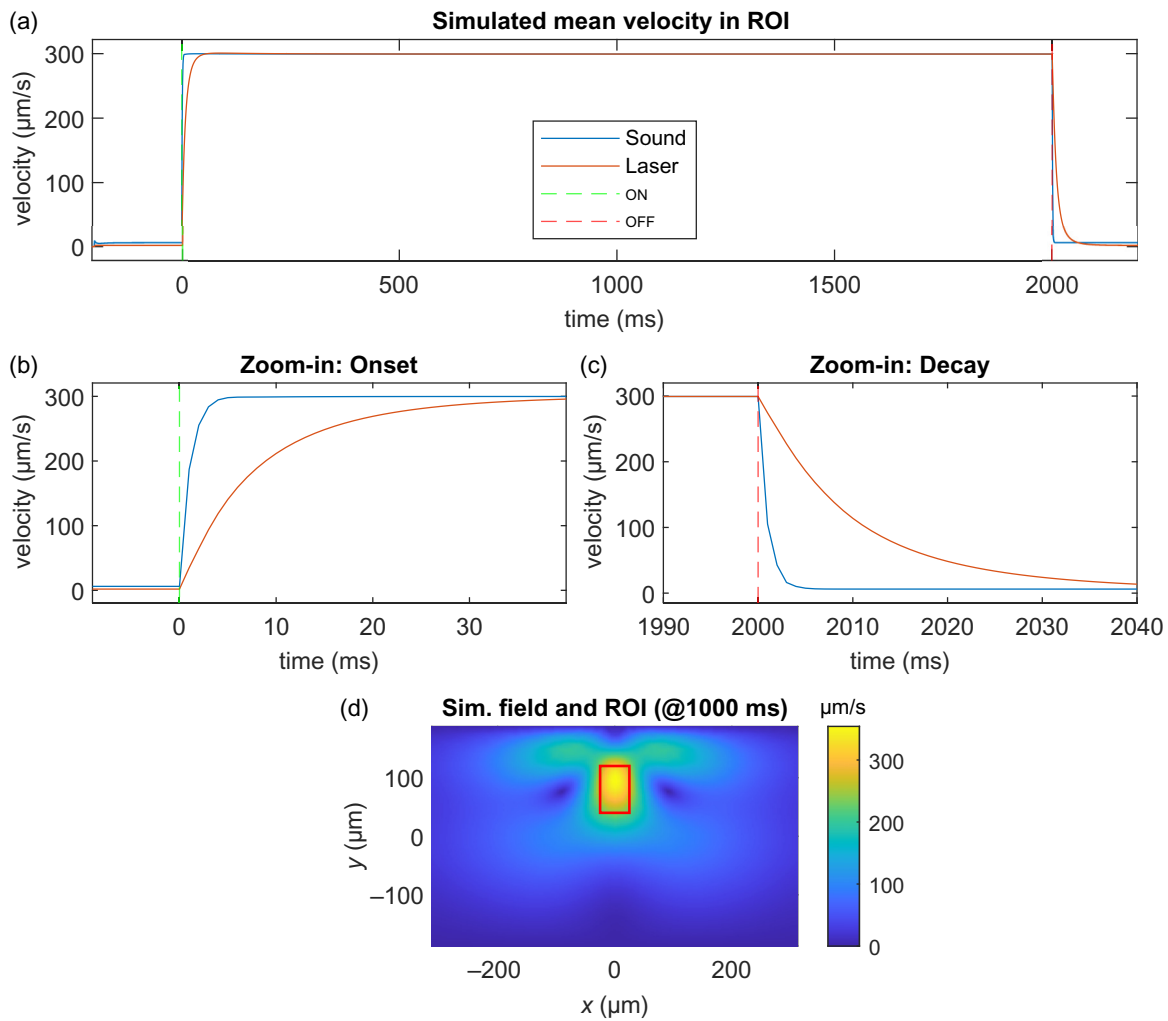


FIG. 11. Simulated thermoacoustic streaming velocity buildup and decay for toggling the sound and laser, respectively, showing (a) the full time sequence, (b) the details of the buildup, and (c) the decay. (d) The simulated velocity field at  $t = 1000$  ms indicating the ROI.

The velocity rise time (10–90% of maximum) for turning the sound ON is 2 ms, while the rise time for turning the laser ON is 19 ms. The fall times are 2 ms and 25 ms, respectively. Nonzero velocities before the trigger are the constant fields from natural convection or boundary-driven Rayleigh-type acoustic streaming.

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