Week 07: Acoustic Micromanipulation

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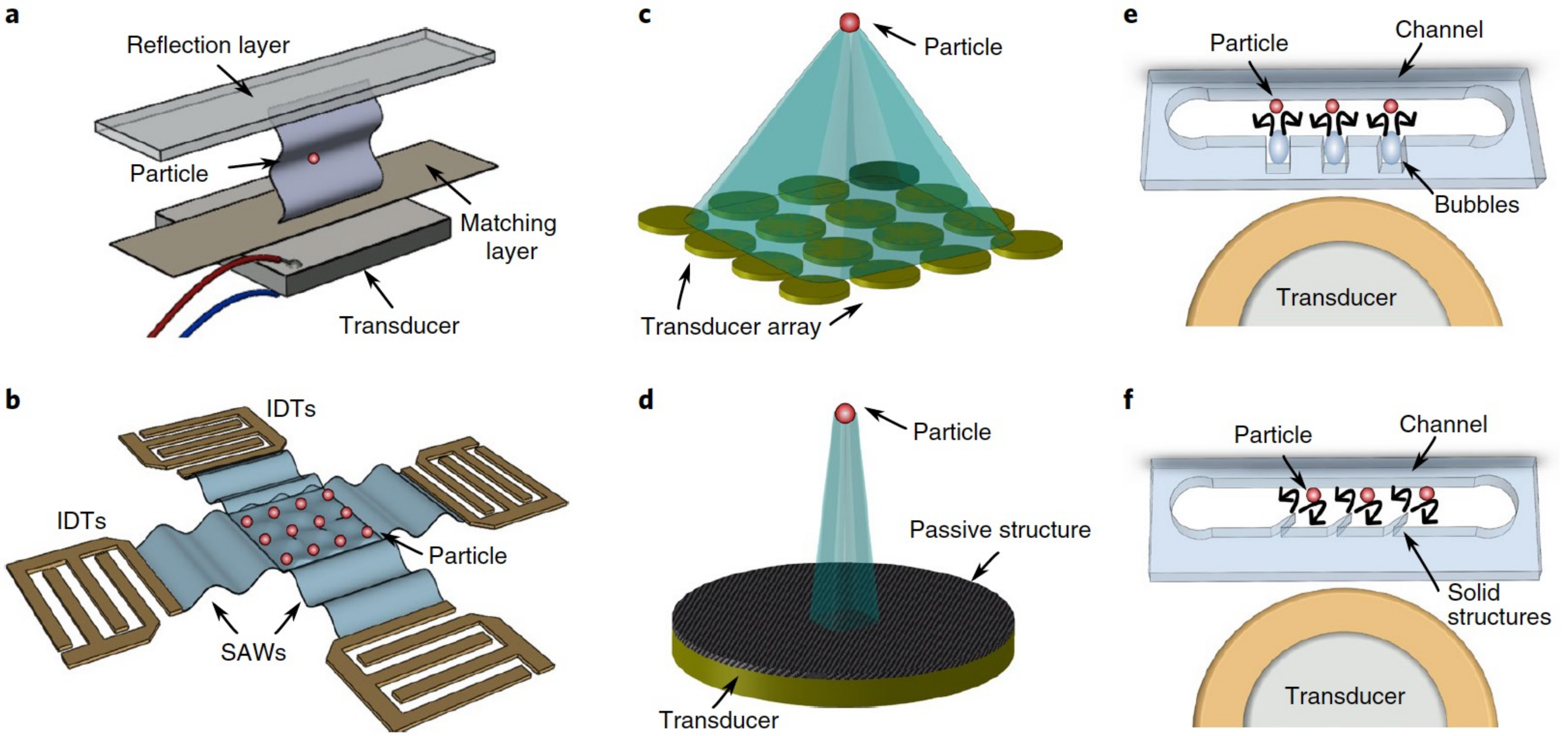
Lecture Overview

- Standing waves
- Traveling waves
- Acoustic streaming and radiation forces

Acoustic radiation pressure

- Summary of acoustic tweezing techniques



Particle Manipulation Overview

- **Optical tweezers**: Very high spatial resolution, force measurement, microparticles (dielectric and optical properties)
  - Plasmonic tweezers: nanoscale particles
  - Thermal management

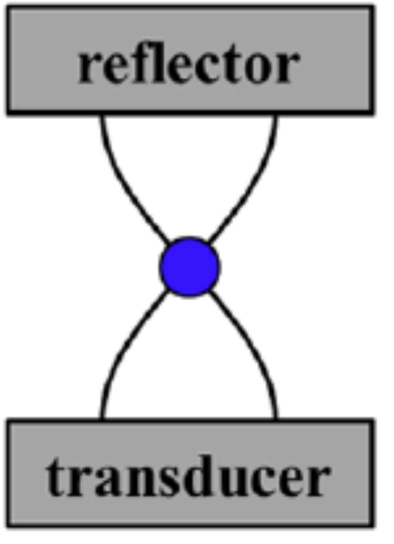
- **Magnetic tweezers**: Larger forces, high spatial resolution, force measurement, magnetic microparticles

- **Acoustic tweezers**: Large length scale (nano- to millimeter), material-independent, interactions with the medium

- Aerodynamic levitation and microfluidic techniques (fluid flow)
- Electrical levitation and electrophroresis

Acoustic Levitation

- Generation of a standing wave between transducer and reflector
- Potential well of the sound field is used to trap small objects including liquid drops, gas bubbles, solid particles
- Spatial variation in the pressure field → the momentum of the fluid impart force on the particle that on average non-zero.
- Objects experience a steady time-averaged acoustic radiation force
- First reported by Kundt et al in 1866



- Resonant vs non-resonant configuration
- **Resonant configuration**: distance between the transducer and the reflector must be a multiple of a half wavelength

Theory

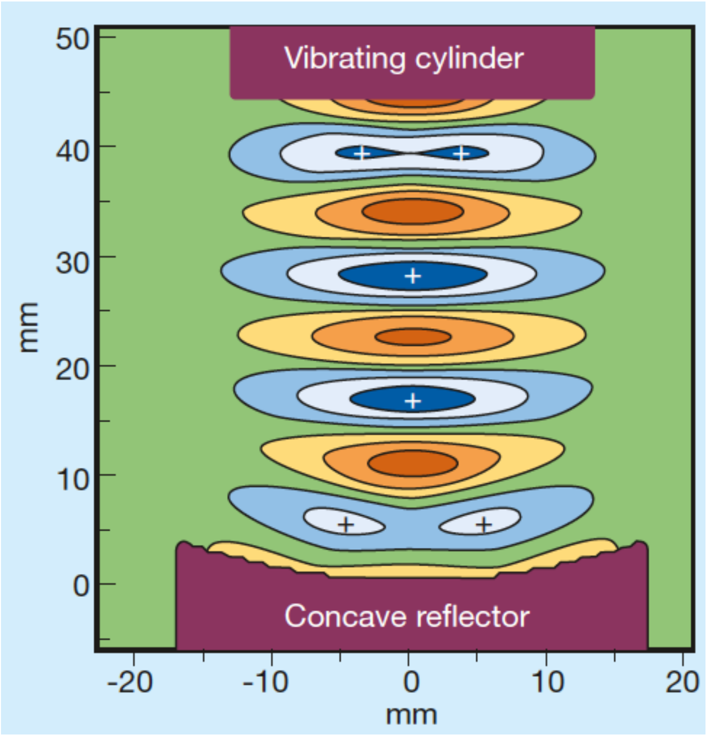
- Gor'kov developed a general theory for incompressible and compressible particles in 1962

$$P_A = \frac{1}{2\rho_0 c_0^2}\langle p^2\rangle - \frac{1}{2}\rho_0\langle v^2\rangle$$

- Angular brackets denote the time average over one period of oscillation
- The integral of the acoustic radiation pressure p_a over the entire surface S of an object give the radiation force
- First term represents a real pressure, whereas second term is the negative Bernoulli pressure that leads to a suction effect

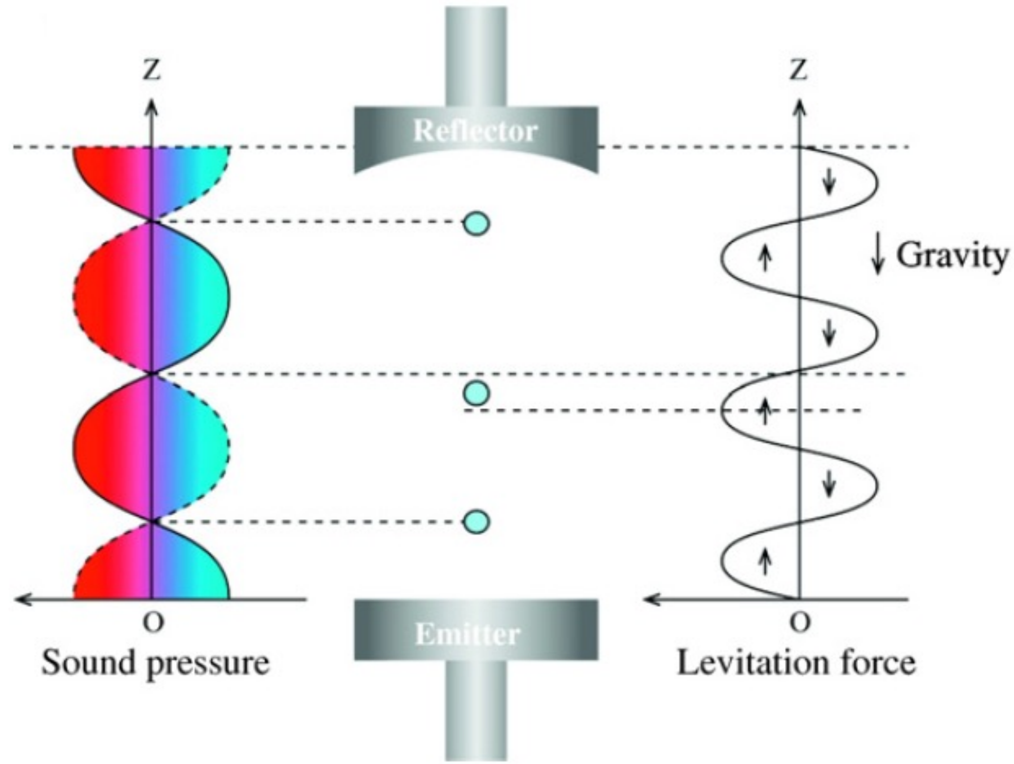
Concept (video)

- Radiation force on a sphere from a traveling sound wave is proportional to the 6th power of the ratio of the sphere radius to the wavelength
- Proportional to the 3rd power in a standing sound wave



Implementation

- Single-axis levitator
- Samples levitated at the pressure nodes (minima)
  - $\lambda/2$
- Object size limit ~ $\lambda/2$
  - Max size of the potential well
  - Typical sample size $\lambda/4$ - $\lambda/3$
- Concave reflector
  - Enhance stability



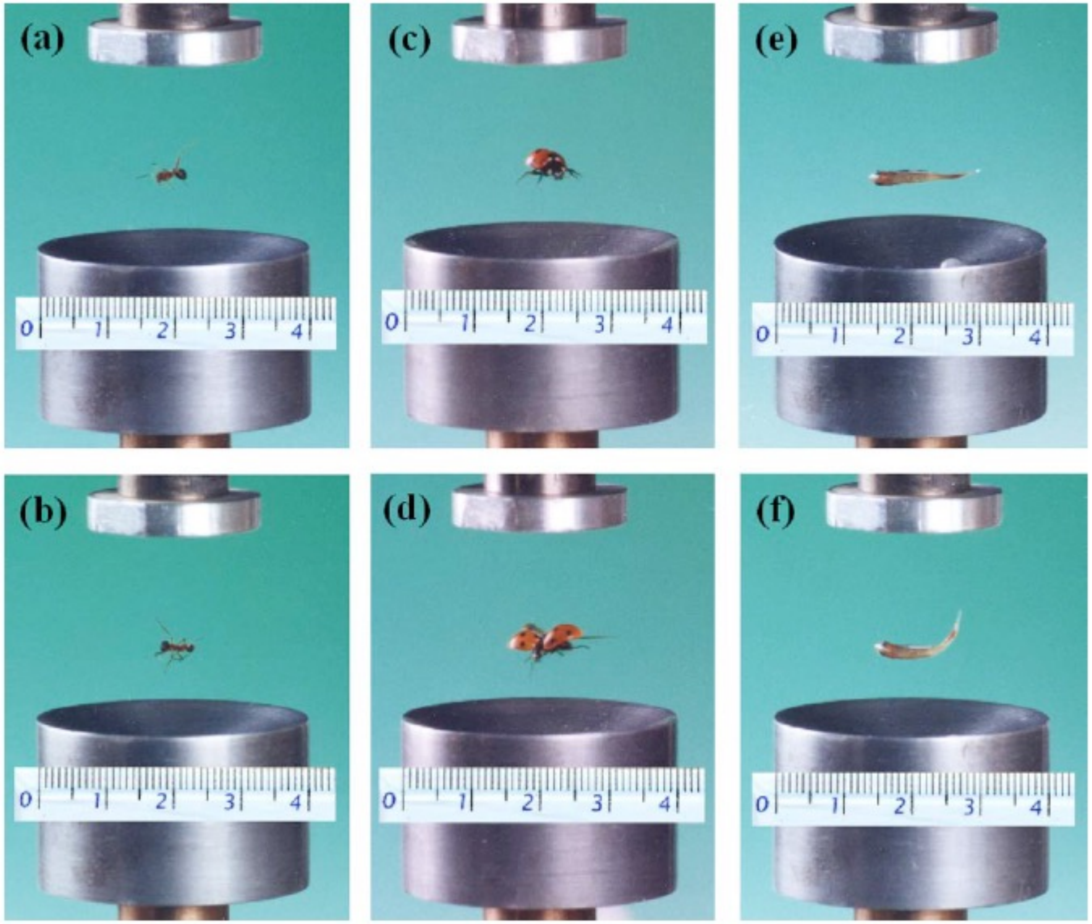
- Different levitation performance at different pressure nodes

Acoustic Levitation in Air

- Single-axis transducer with f=16.7kHz, wavelength=20.3mm

- Distance between emitter and reflector is adjusted to 1.5 λ
- Excites n=3 resonant modes of the standing wave
- Three possible levitation positions along the axis

- Animals survived after 30 minutes of levitation



Acoustic Impedance

- Impedance is given by $z = \rho v$

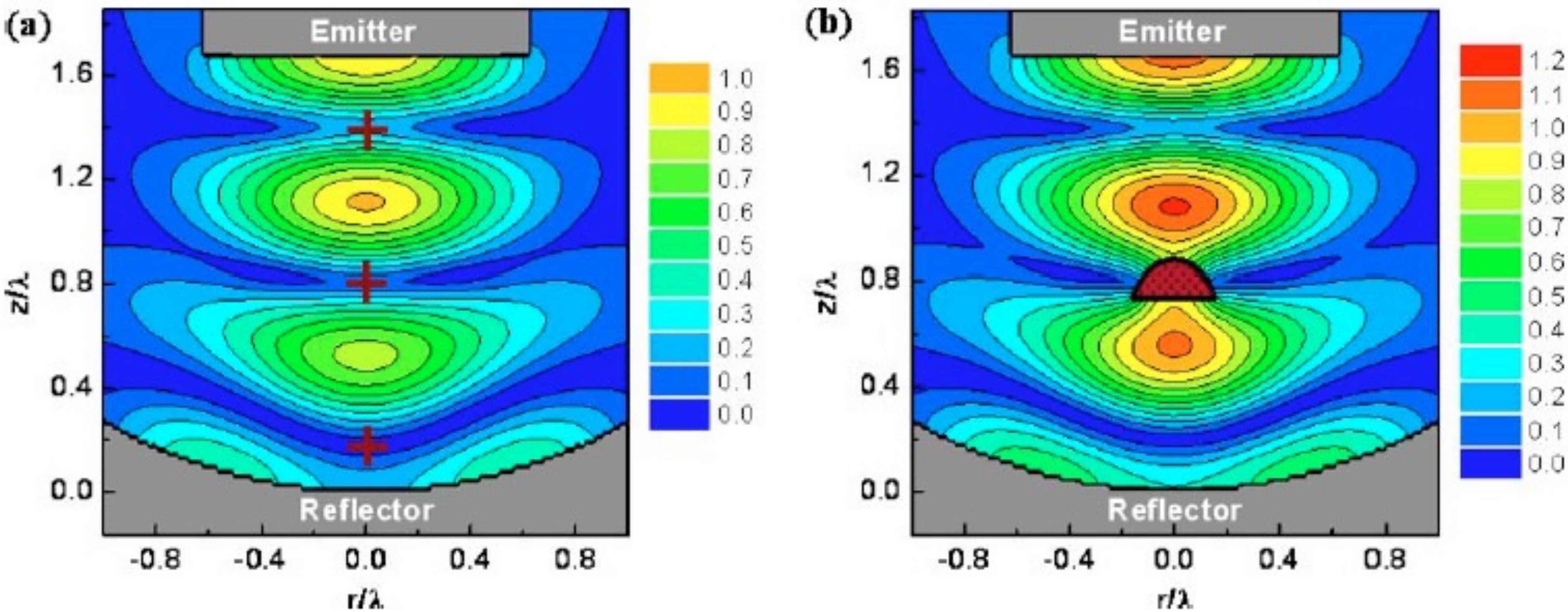
$$Z_{water} = \rho_w c_w = 10^3 \text{kg/m}^3 \times 1450 \text{m/s} \cong 10^6 \text{ kg/m}^2\text{s}$$

$$Z_{air} = \rho_a c_a = 1.2 \text{kg/m}^3 \times 330 \text{m/s} \cong 400 \text{ kg/m}^2\text{s}$$

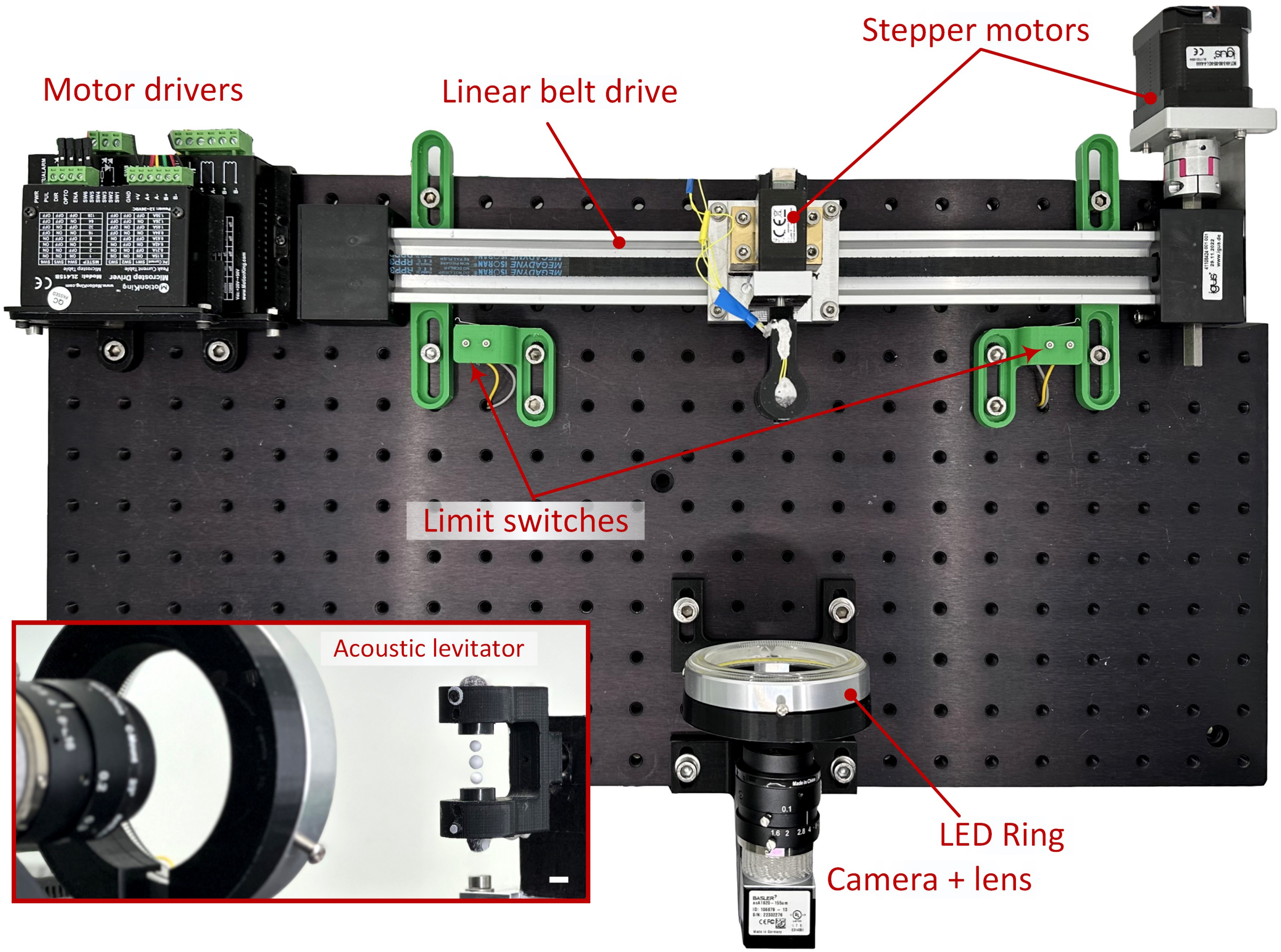
- The interface between the animal and air can be regarded as a rigid boundary
- Scattering of the incident field: strengthening of the two pressure maxima near the object
- Resonance shift effect
- The equilibrium position is determined by comparing the acoustic radiation force and the gravity.

Computational analysis

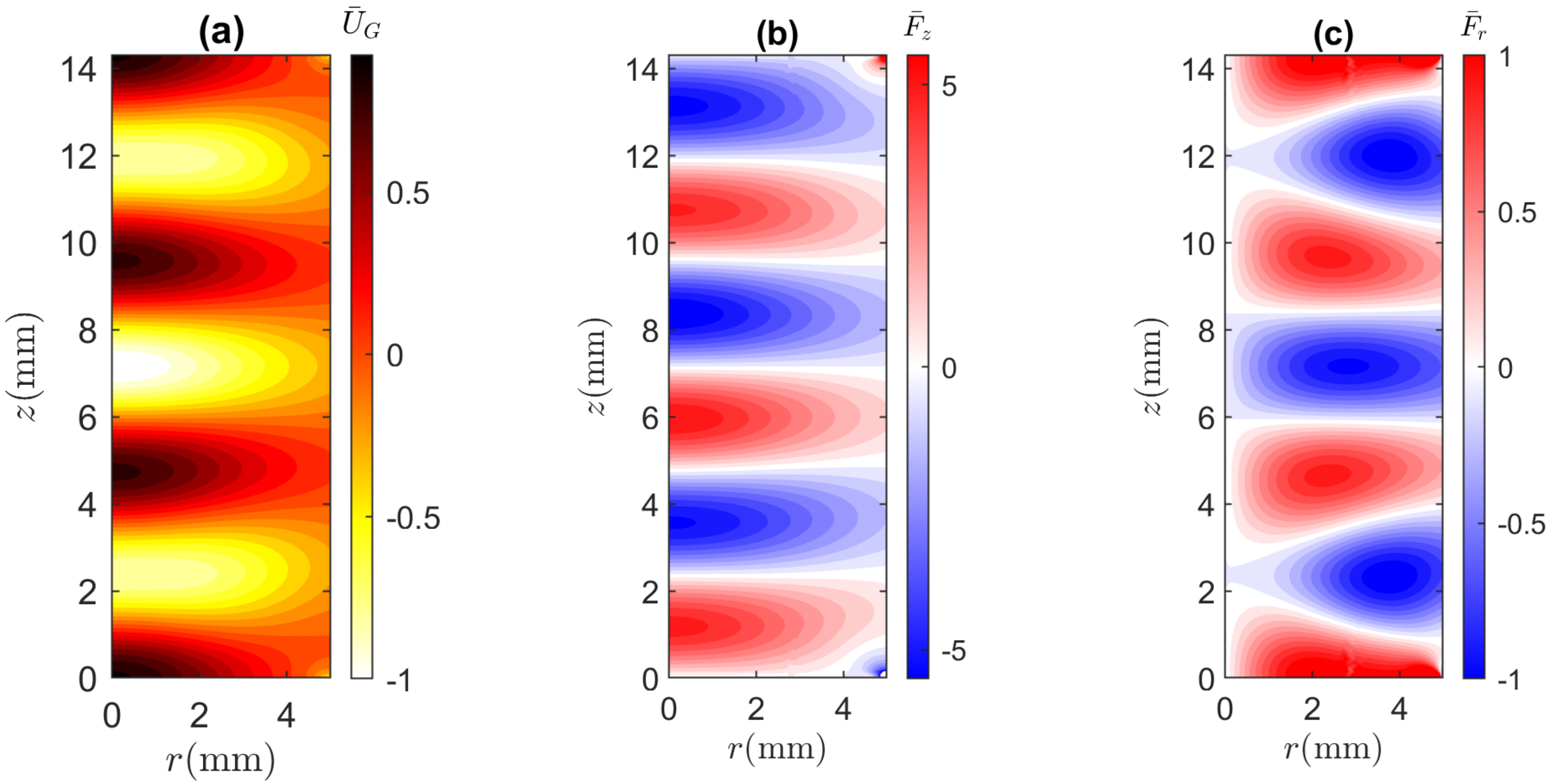
- Velocity potential expressed as the boundary integral equation over the surfaces and numerically solved using boundary element method
- Maximum levitation force: 1.5G
- Equilibrium position at 0.79



Dynamic Acoustic Levitation

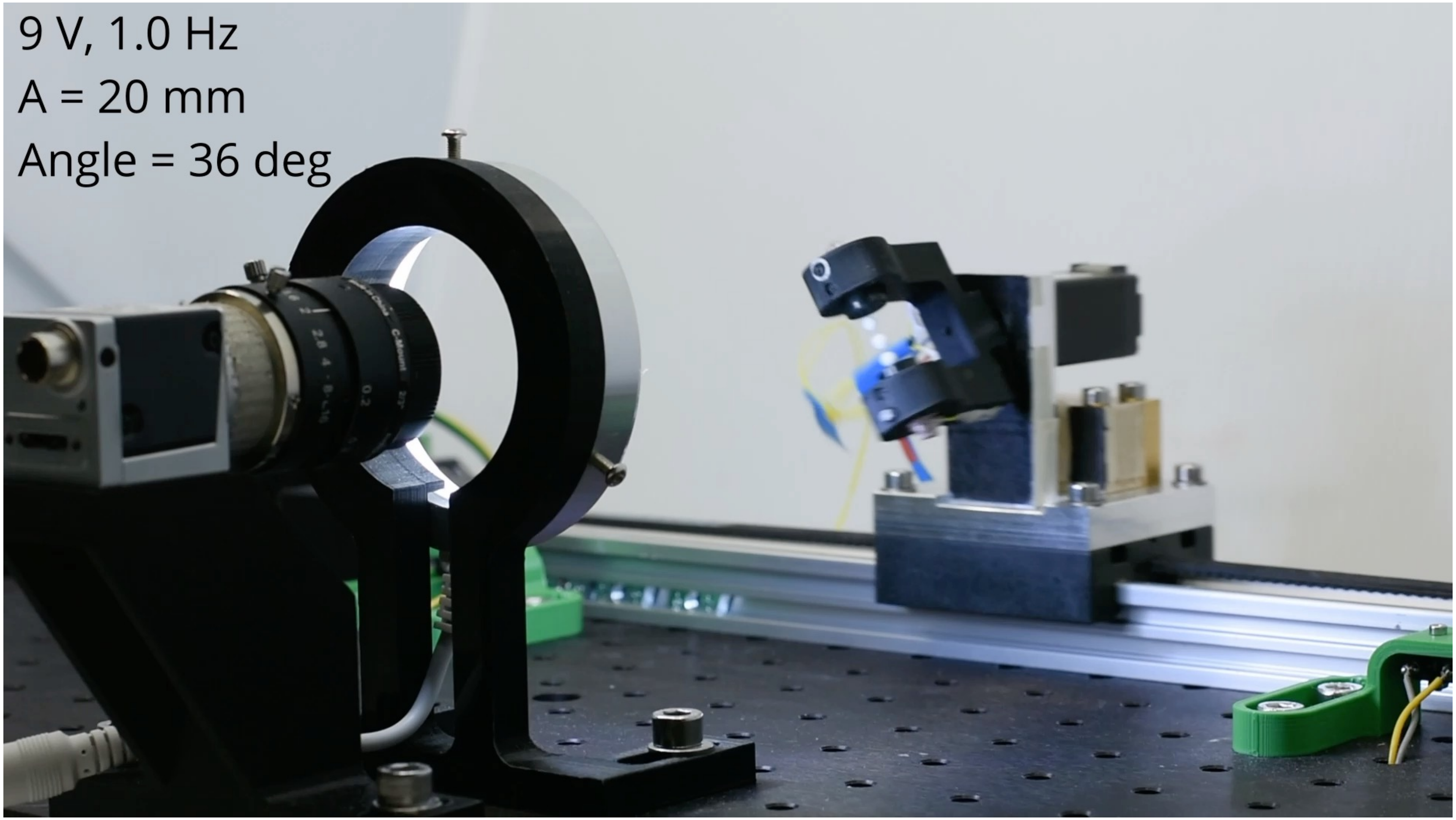


Dynamic Acoustic Levitation

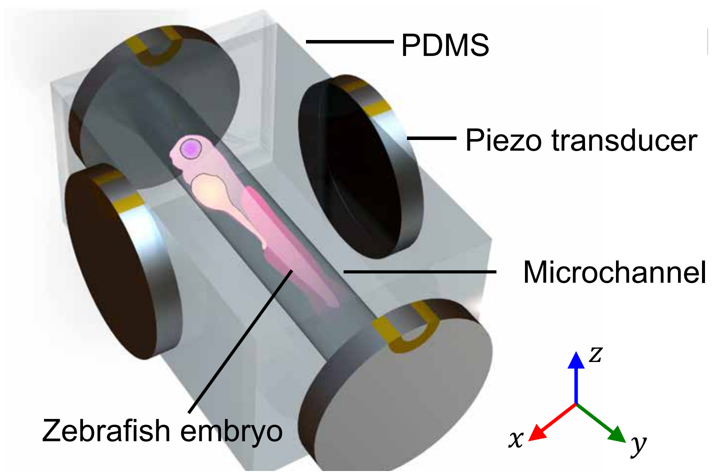


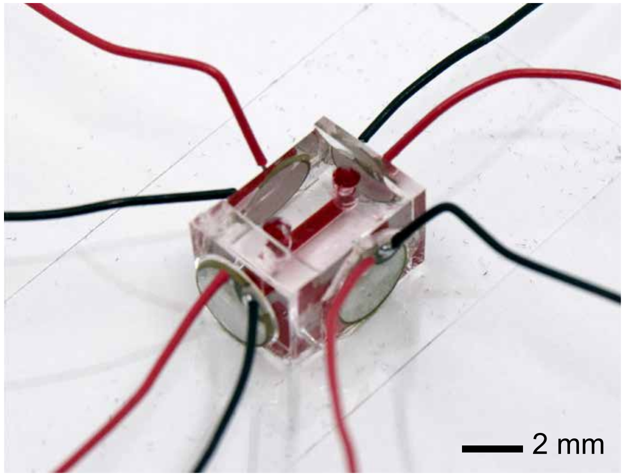
Dynamic Acoustic Levitation

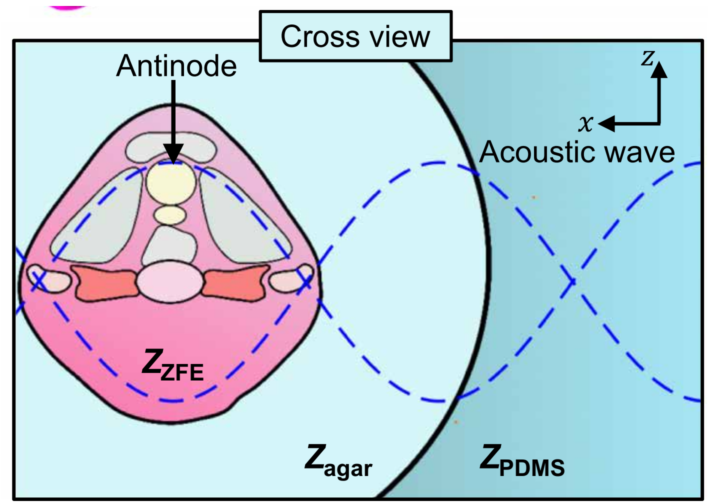
Dynamic Acoustic Levitation



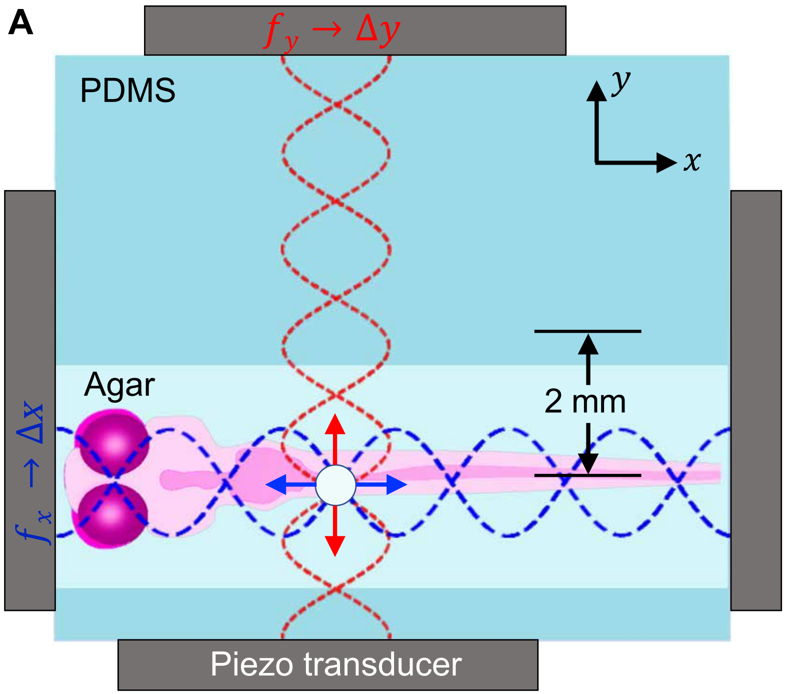
Manipulation of bubbles inside embryos







Manipulation of bubbles inside embryos



Transmission

$$T = 1 - \left[\frac{Z_{ZFE} - Z_{agar}}{Z_{ZFE} + Z_{agar}}\right]^2$$

Primary Radiation Force

$$F_R(x) = 4\pi\phi(\tilde{\kappa},\tilde{\rho})\, k_x a^3 E_a \sin(2 k_x x)$$

Distance between nodes and antinodes

$$d = \frac{c}{4f}$$

Acoustophoretic contrast factor

$$\Phi = \frac{1}{3}\left[\frac{5\tilde{\rho} - 2}{2\tilde{\rho} + 1} - \tilde{\kappa}\right]$$

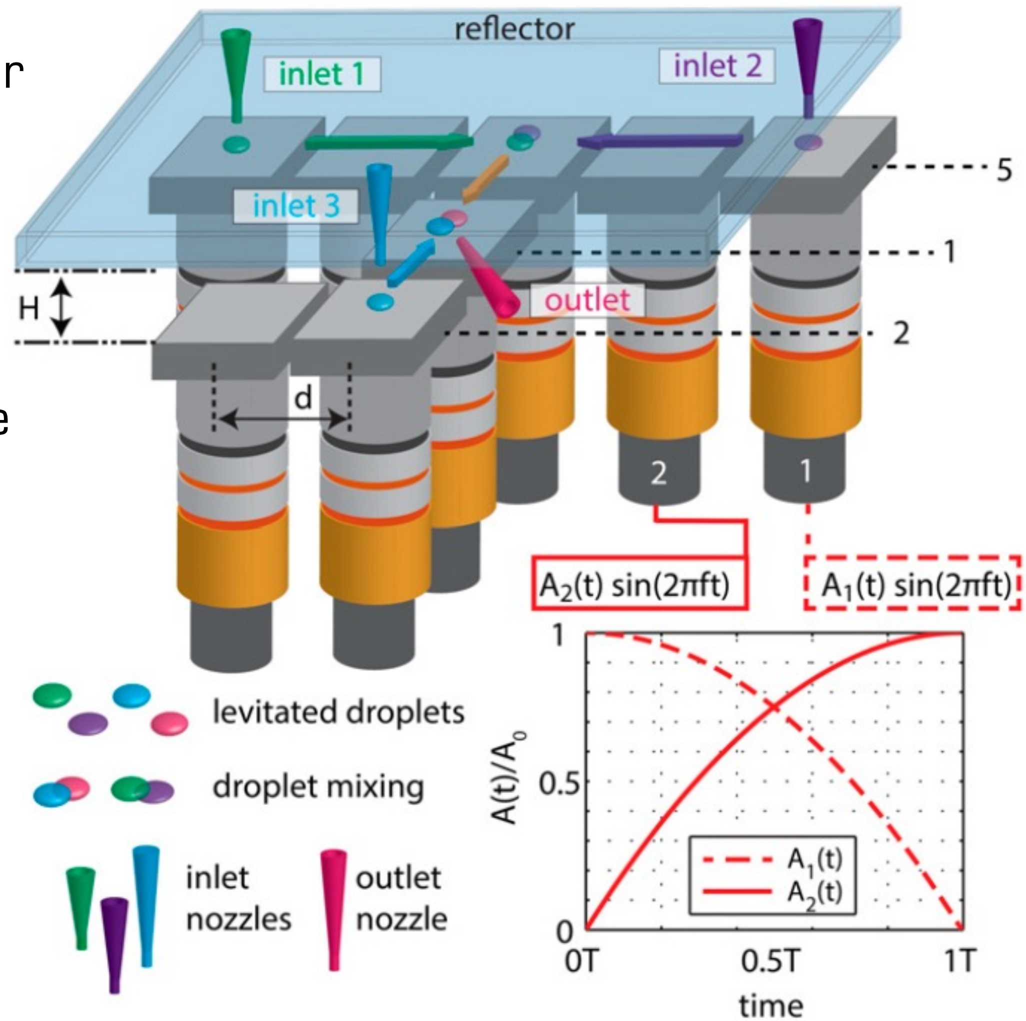
compressibility ratio

density ratio

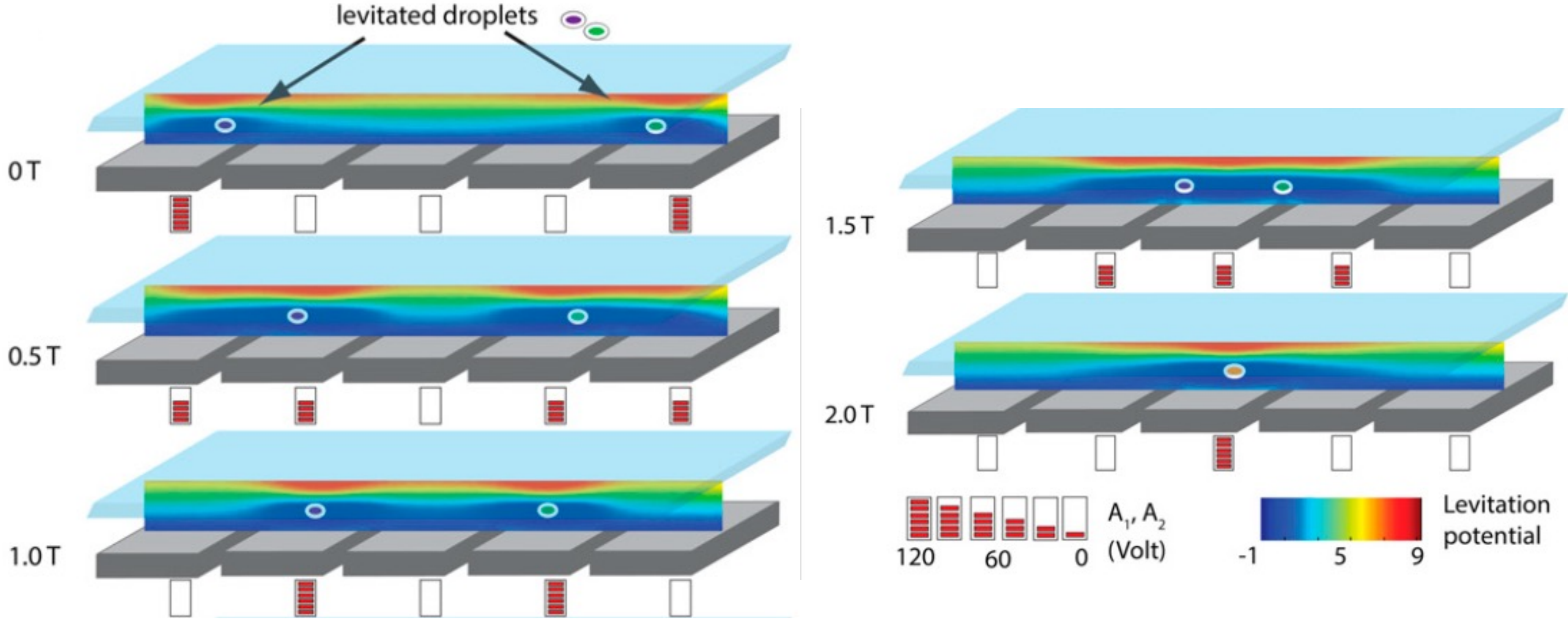
Manipulation of bubbles inside embryos

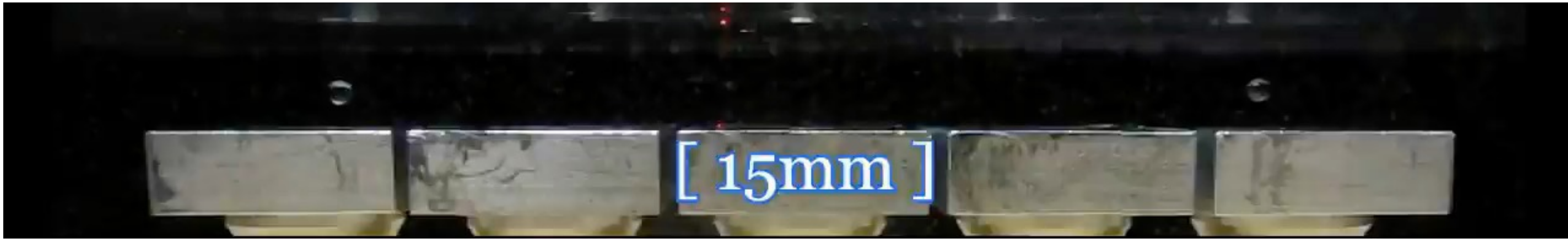
Acoustophoretic handling of droplets

- Discretized planar resonator platform and a single flat reflector
- Langevin piezoelectric transducers excited by a single sinusoidal signal voltage of ultrasound frequency
- Spatiotemporal modulation of the acoustic field
- Millimeter-sized droplets transported at mm/sec speed



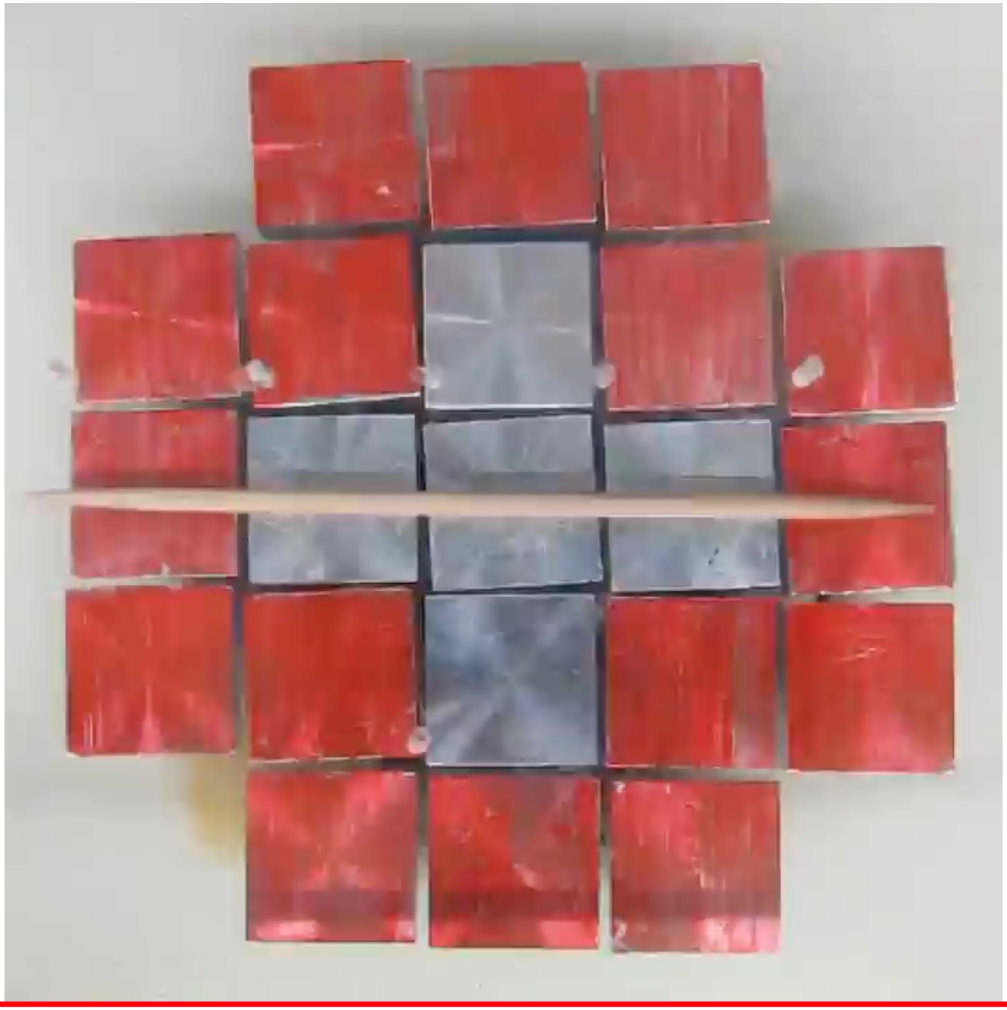
Acoustophoretic handling of droplets





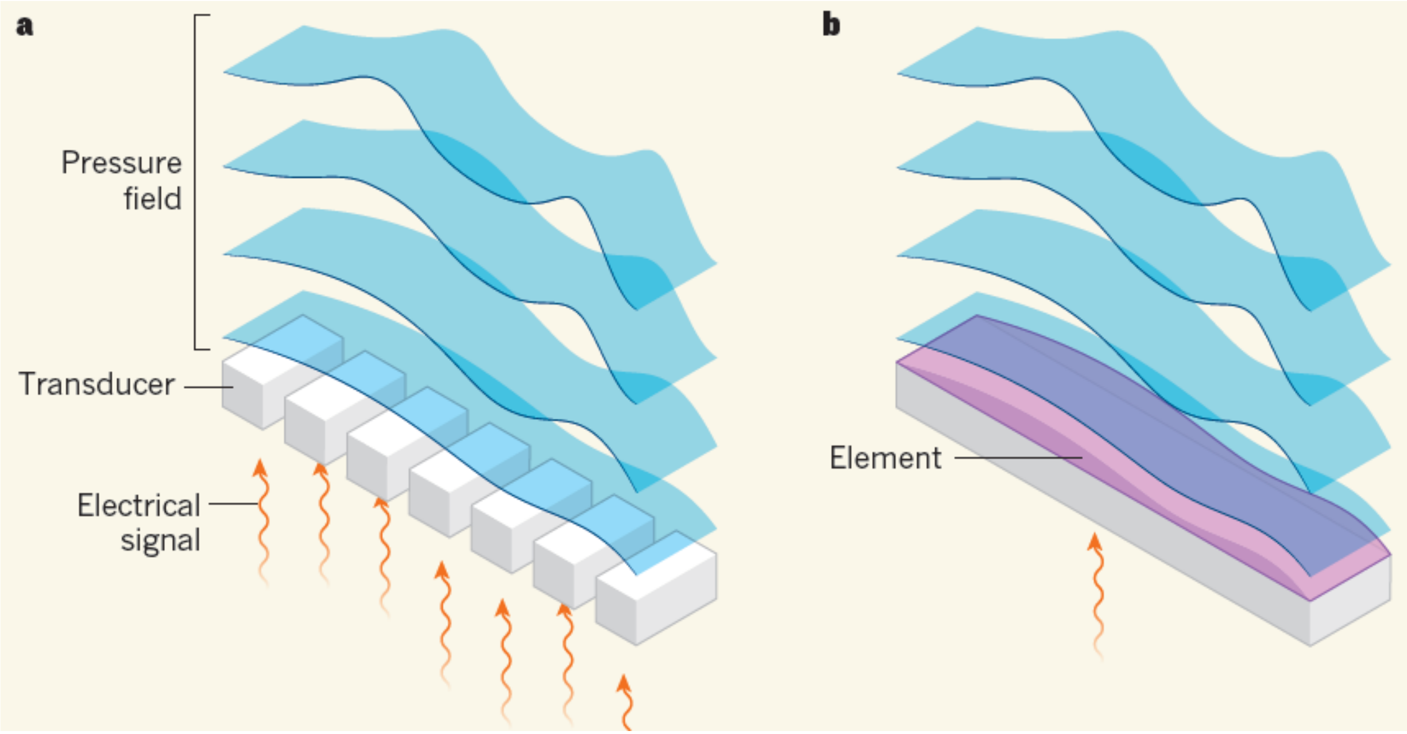
Transport of elongated objects

- Controlled rotation and translation of objects with anisotropic shapes



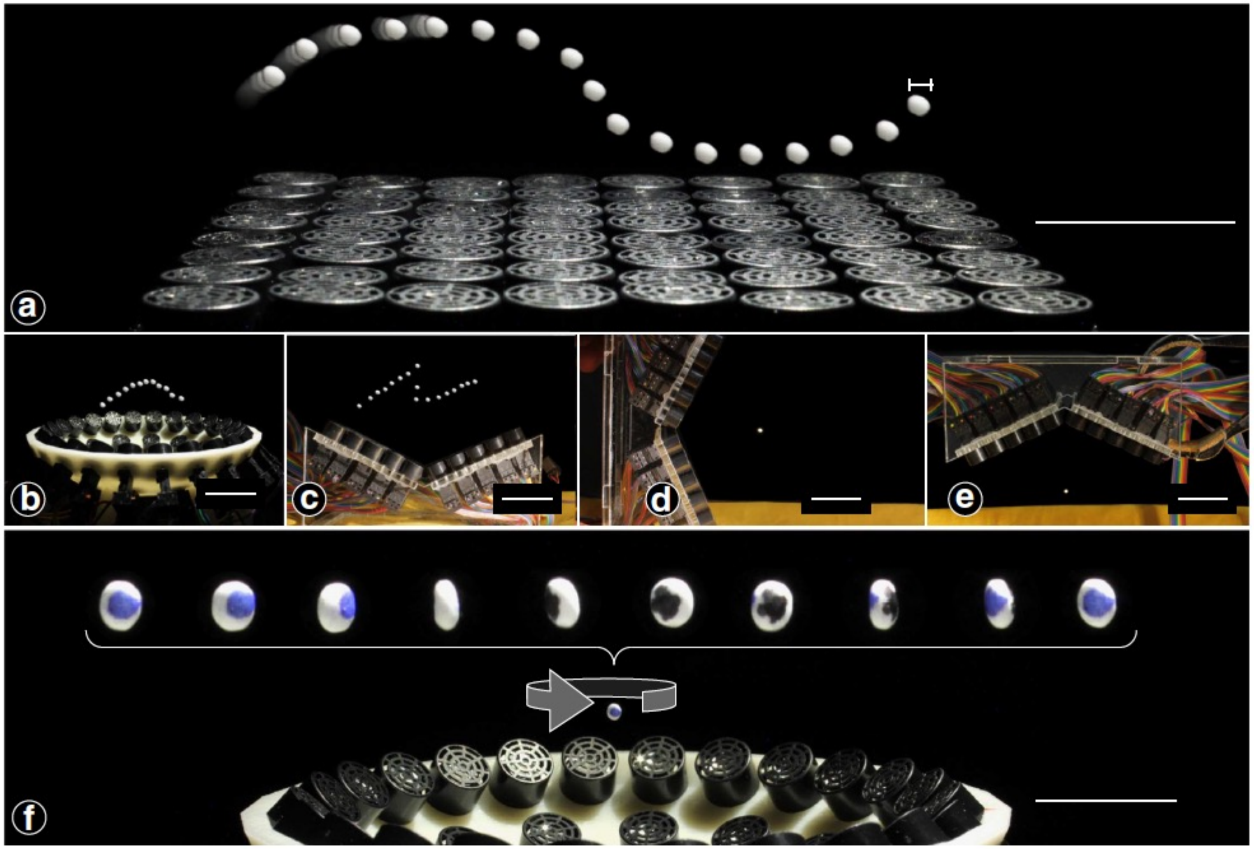
Acoustic Holograms

- Moving particles to predetermined location: spatial and temporal effects
- (a) Arrays of transducers each with a different phase
- (b) 3D printed finely contoured solid plastic block with varying thickness (phase modulation using a monolithic element)

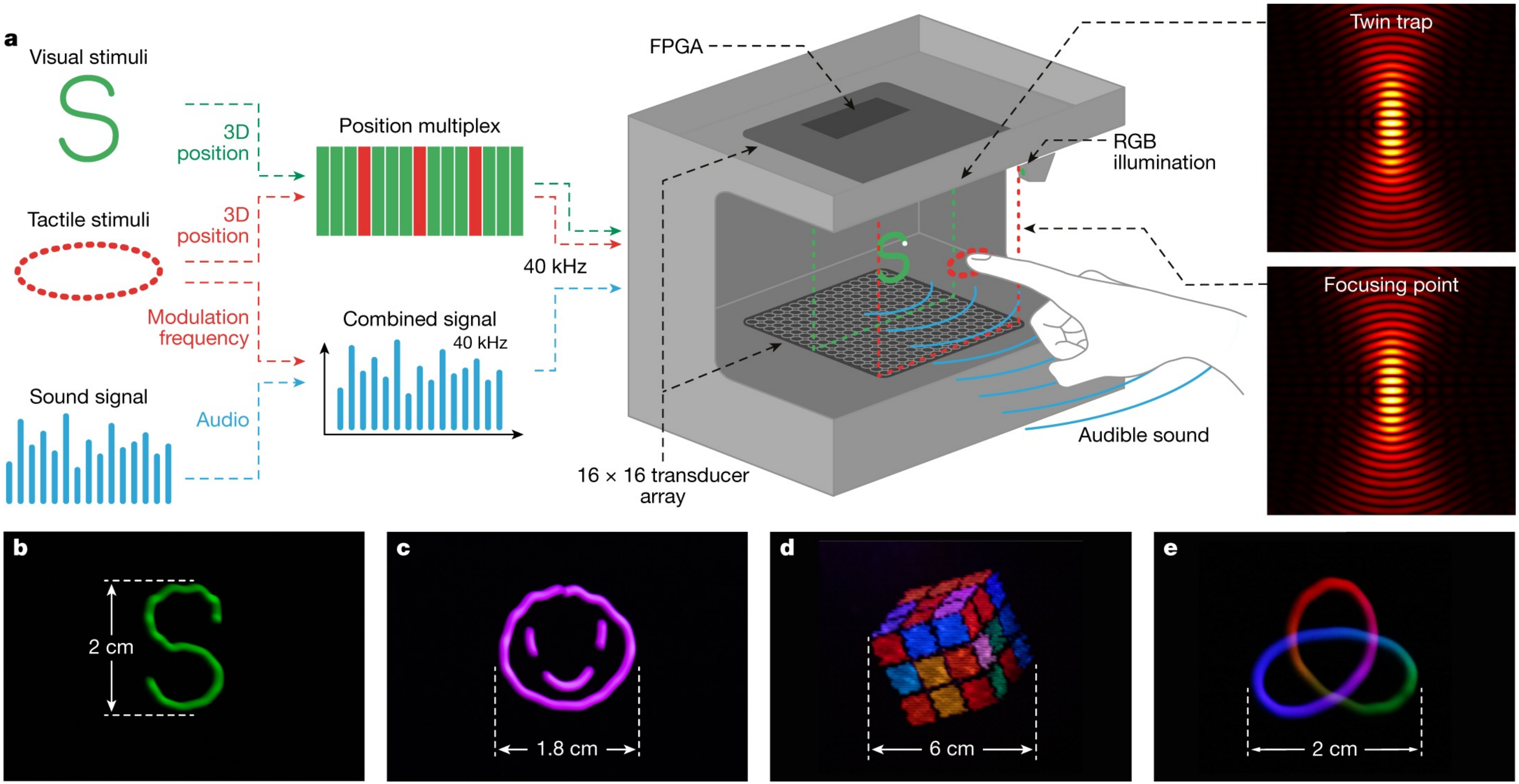


Array of Transducers (movies)

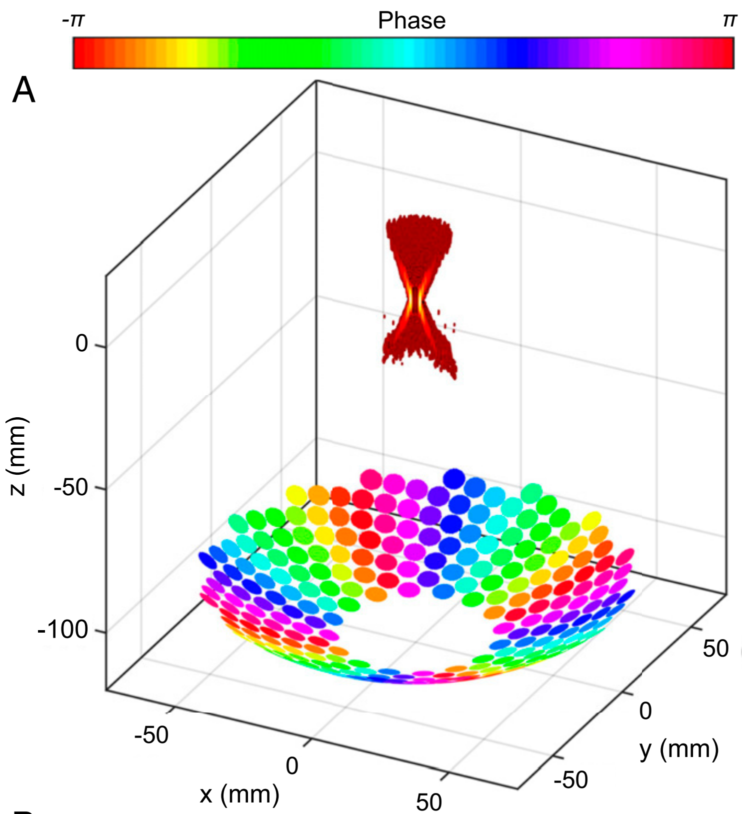
- Controlled 3D trapping, translation and rotation with a single-sided independently driven array of sources operating in air (no reflective surface)
- Optimally adjust the phase delays: formation of acoustic traps

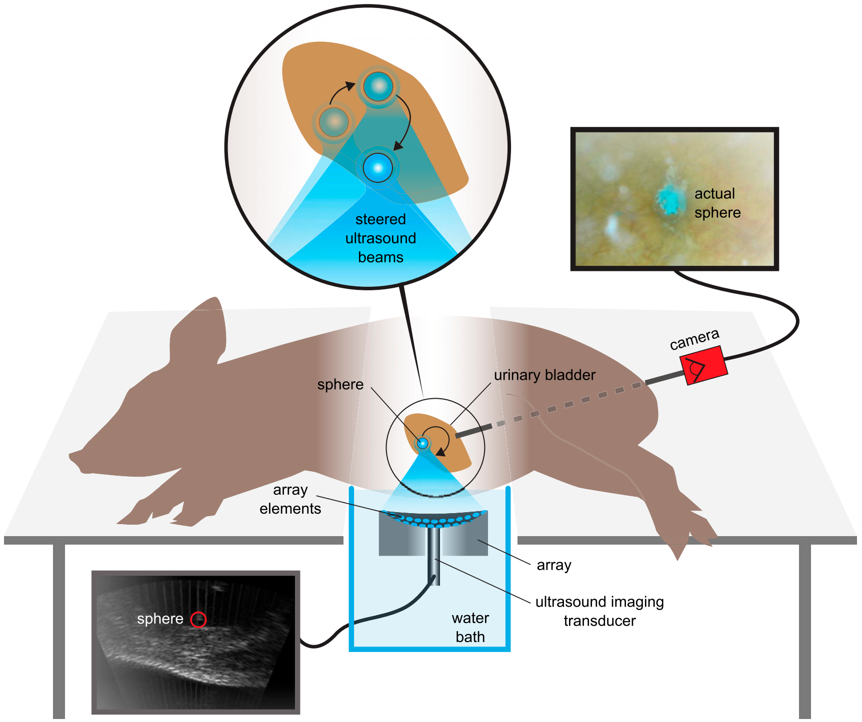


Volumetric Display (movie)



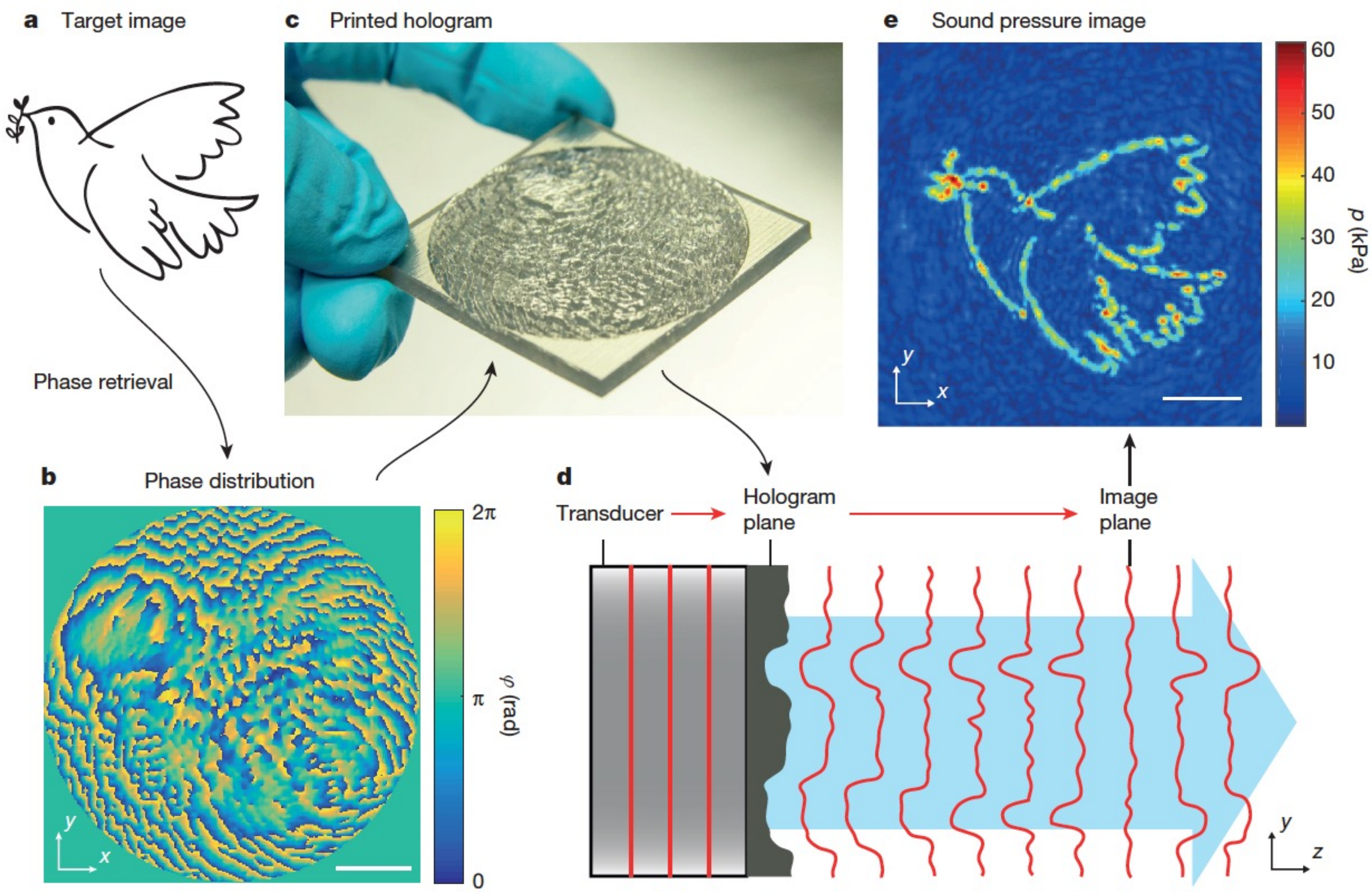
In vivo particle manipulation





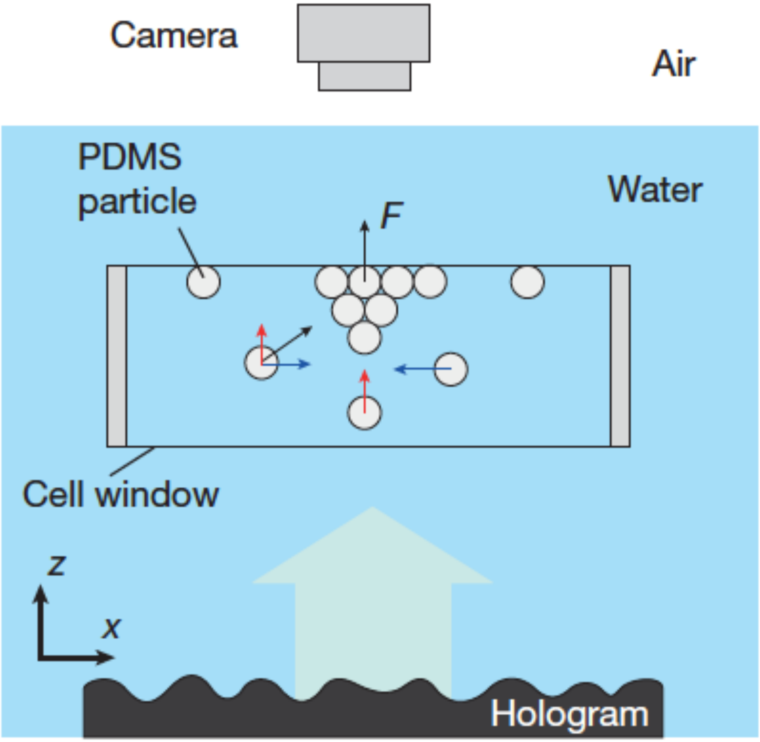
Monolithic Acoustic Holograms

- Complex 3D pressure and phase distribution produced by the hologram

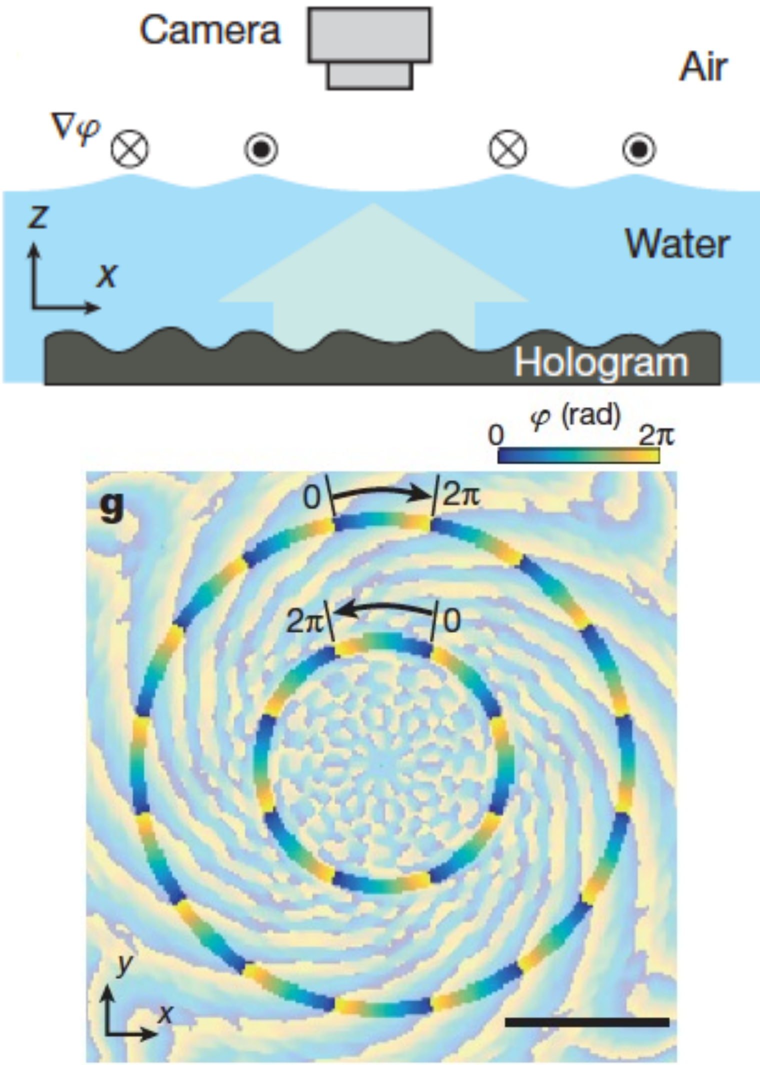


Monolithic Acoustic Holograms

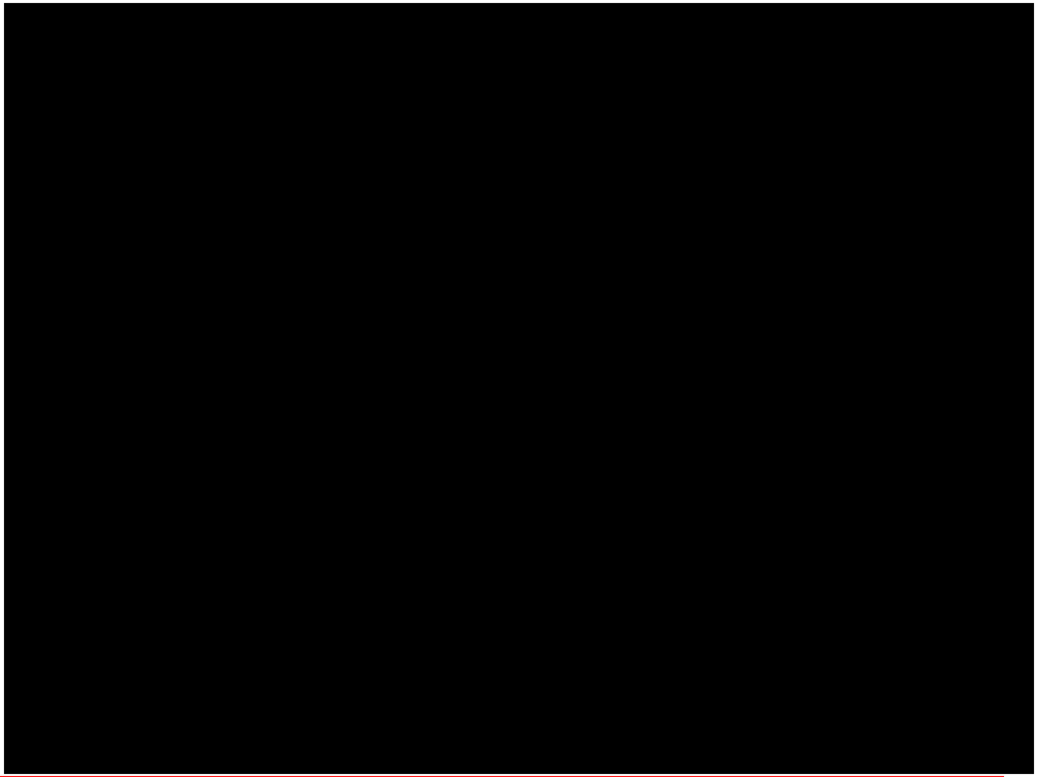
- Top plane of the confinement is coplanar with the reconstruction image plane
- Acoustic radiation force pushes particles up and organize



Monolithic Acoustic Holograms

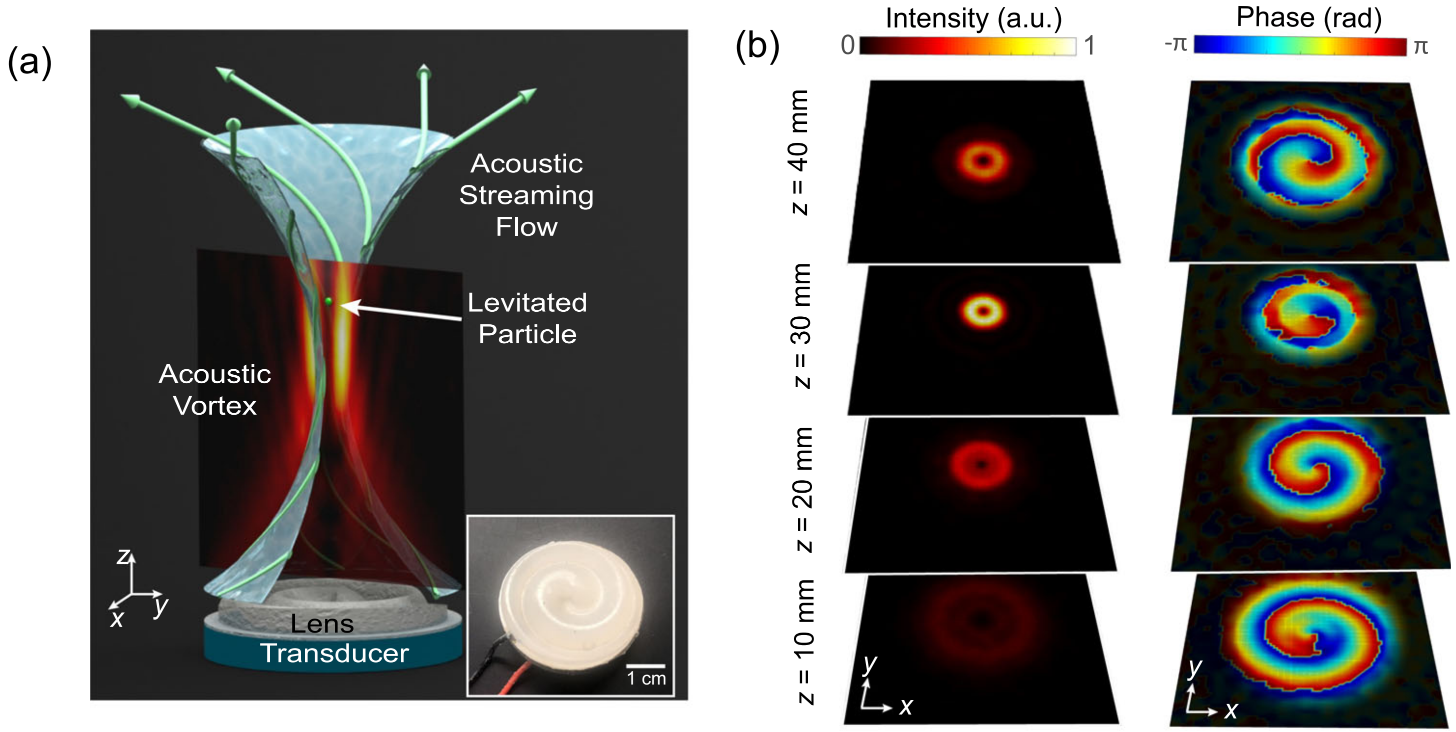


- Focus on the water surface
- Phase gradient provides the driving force to push the particles along the path defined by the pressure

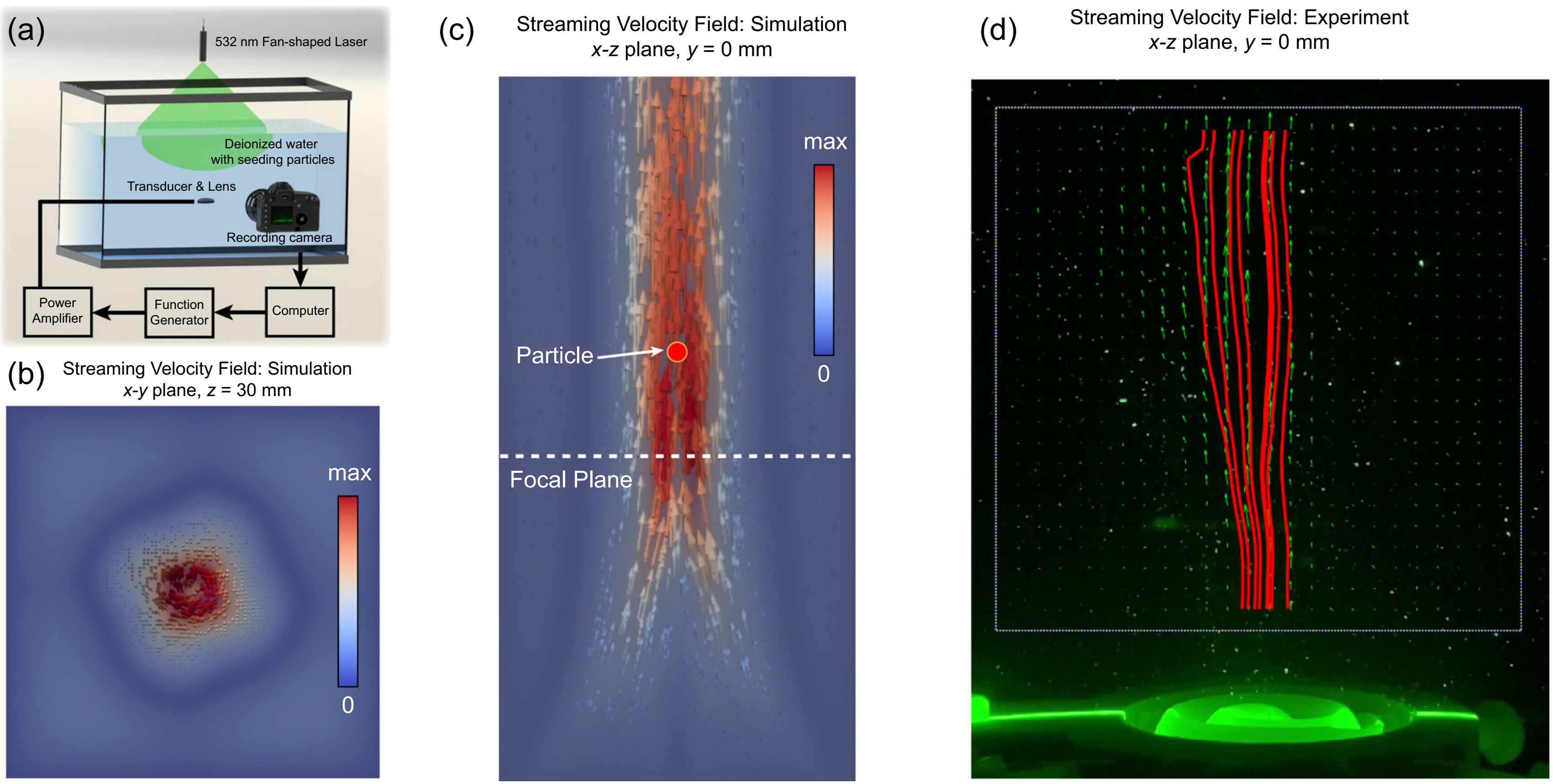


Vortex streaming: miniaturized acoustic tweezers

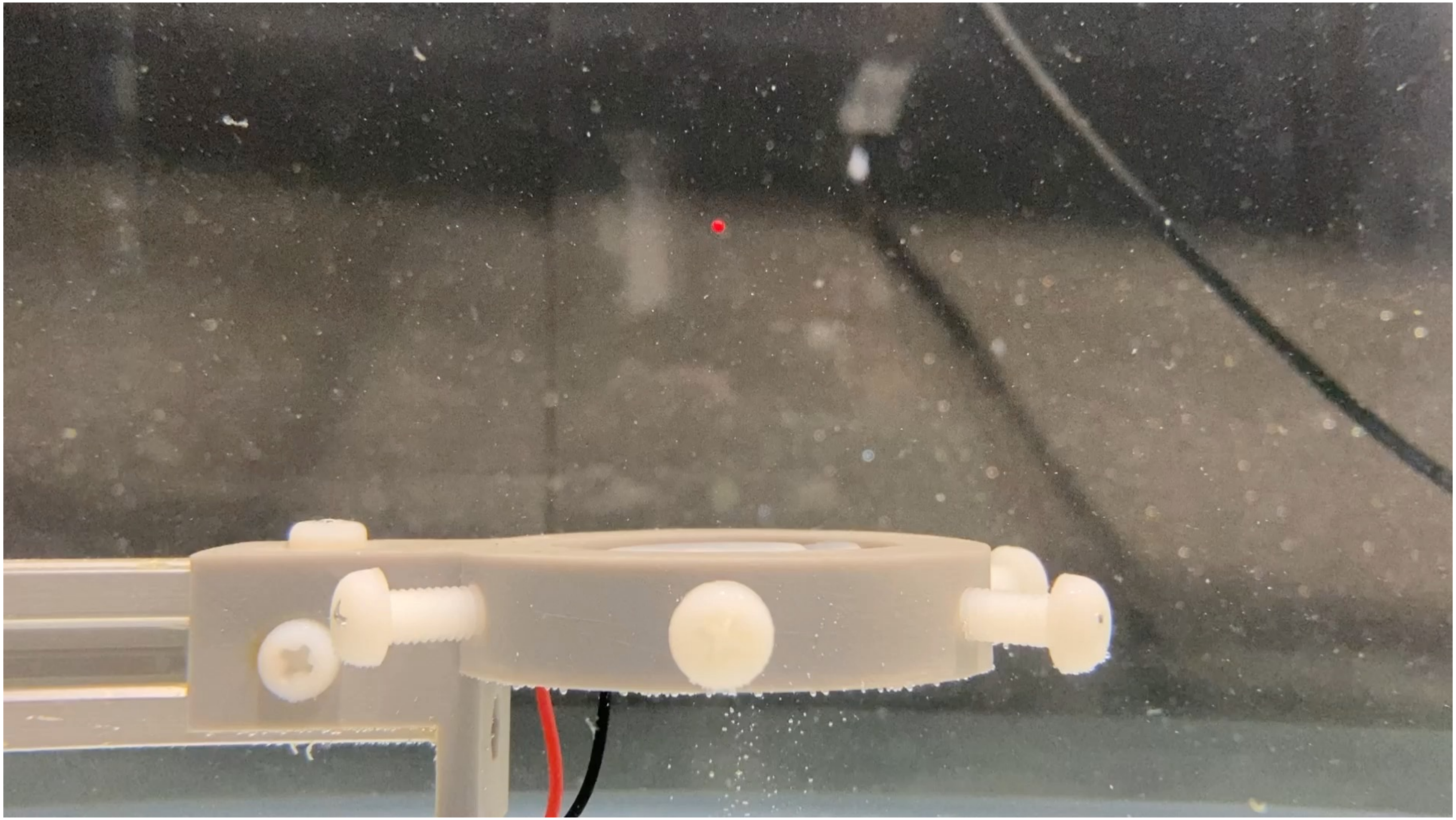
- Combine radiation force with streaming force
- Eckart streaming
- Radiation force scale with volume, drag scales with diameter
- 5 µN levitation force (1.5 mm) where radiation force is 0.02 µN



Vortex streaming: miniaturized acoustic tweezers

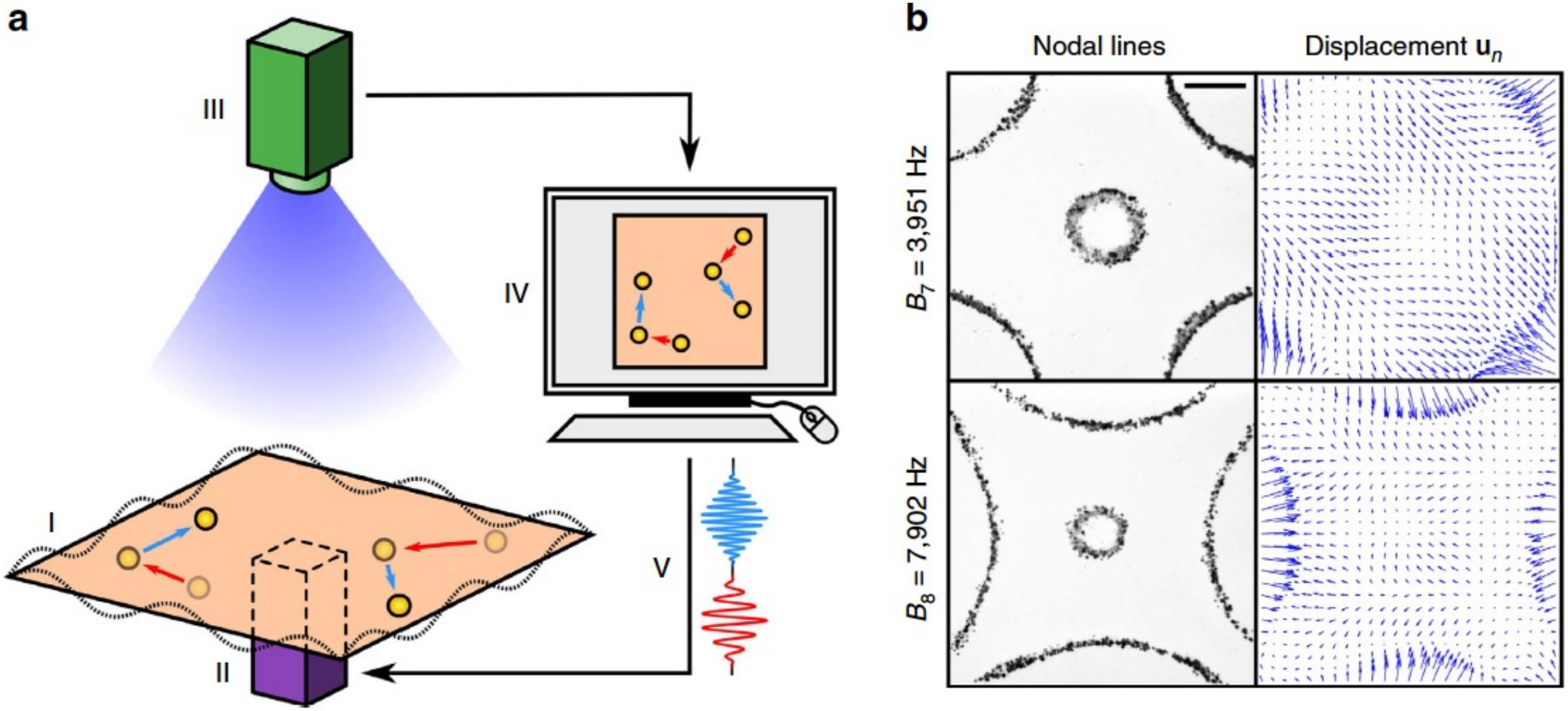


Vortex streaming: miniaturized acoustic tweezers



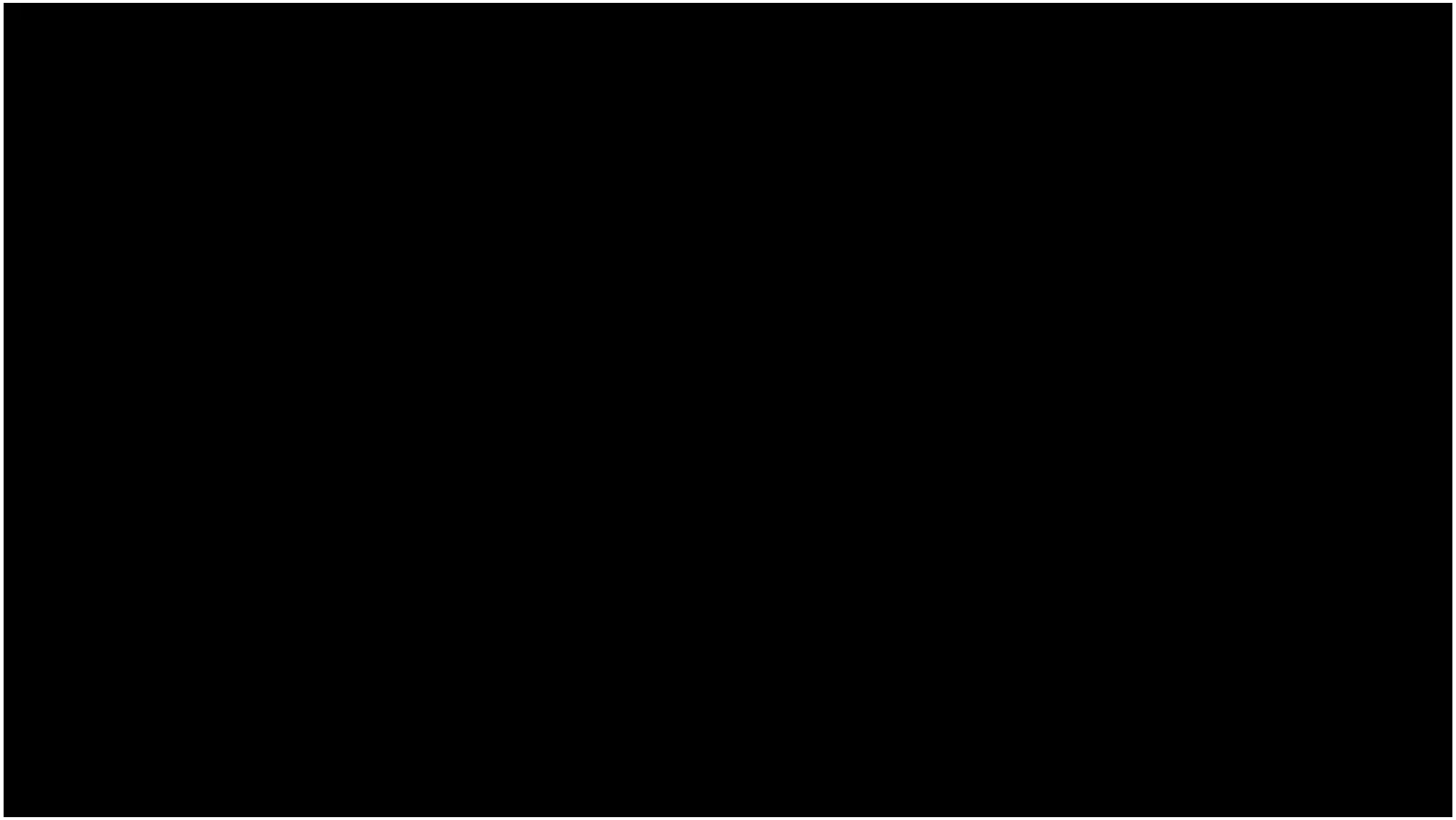
Chladni Plate (movie)

- Moving objects on a vibrating plate
- Ernst Chladni in 1787: Aggregation of sand onto nodal lines
- By playing carefully selected musical notes, one can control the position of multiple objects simultaneously and independently



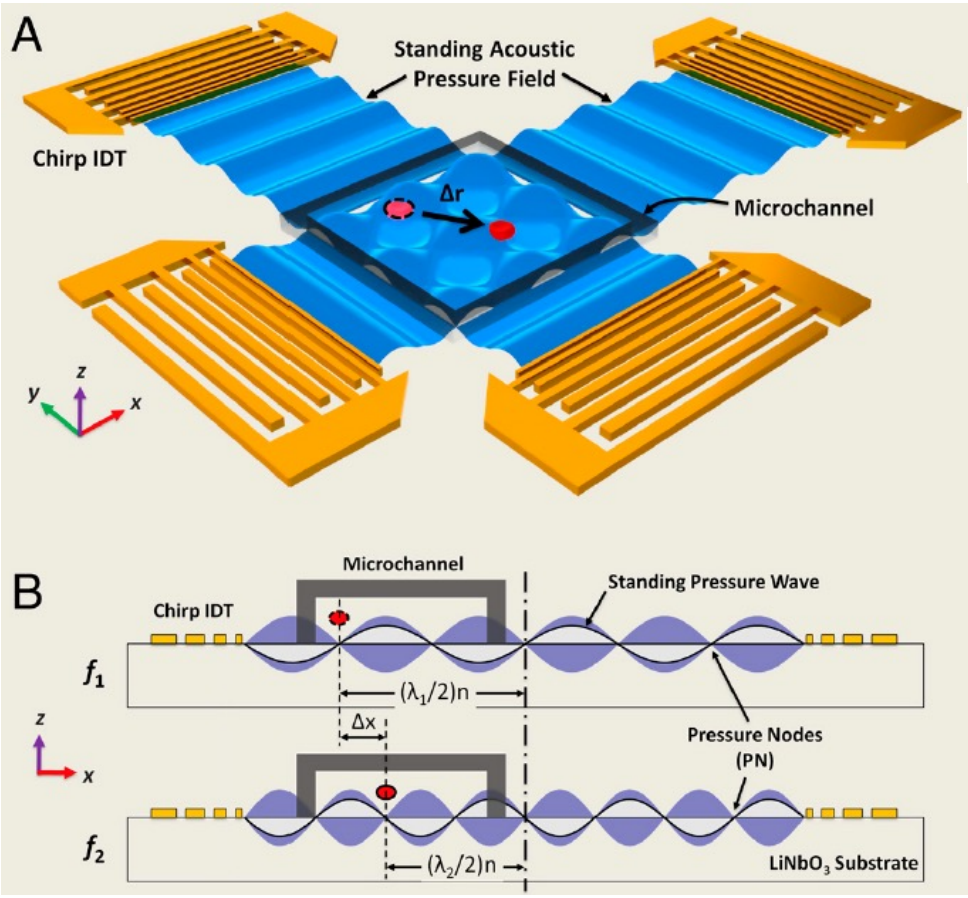
Chladni Plate

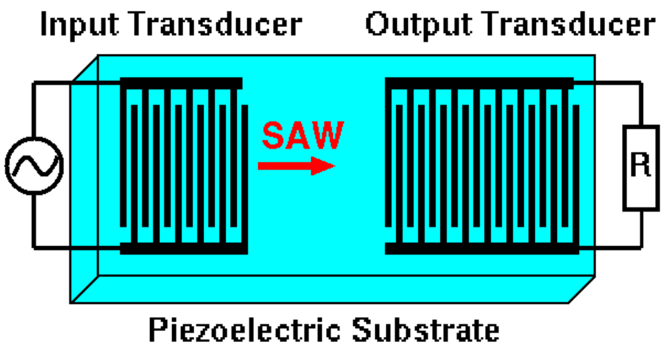
- Position error: 120um (600 um object)
- Duration, amplitude, and frequency of different tones

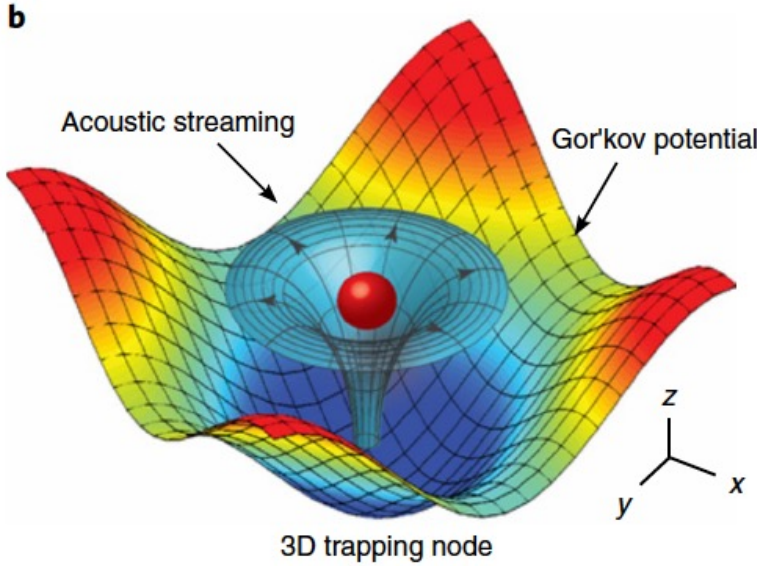


Interdigital Transducers (IDTs)

- Pairs of electrodes with a linear gradient in their finger period patterned on a piezoelectric substrate (lithium niobate, $LiNbO_3$)







Interdigital Transducers (IDTs)

- Absolute node location: $x_n = n\lambda/2$ for nth order pressure node
- Move higher-order nodes (n > 0) by altering the applied signal frequency
- Node displacement (18.5 to 37 MHz corresponds to $\lambda \sim$100-200 um)

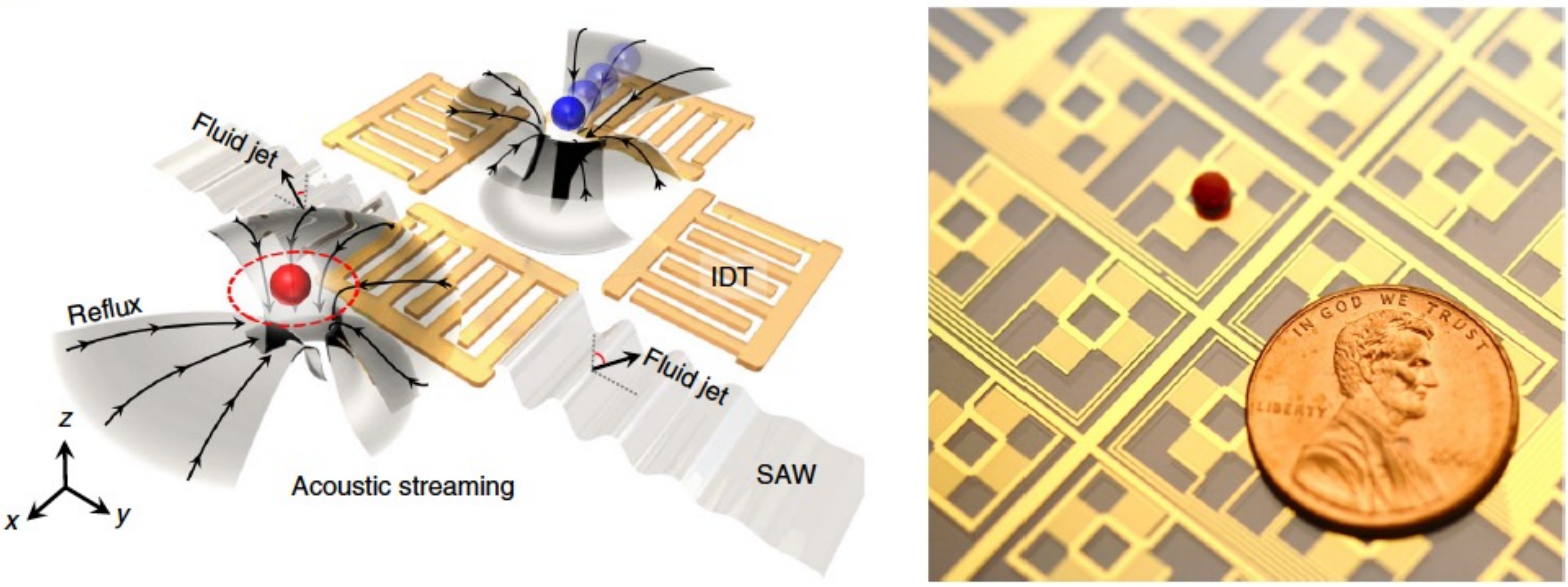
$$\Delta x_n = \frac{n(\lambda_1 - \lambda_2)}{2} = n\left(\frac{c}{f_1} - \frac{c}{f_2}\right)/2$$

10-um bead moves with 30 um/s

Digital acoustofluidics

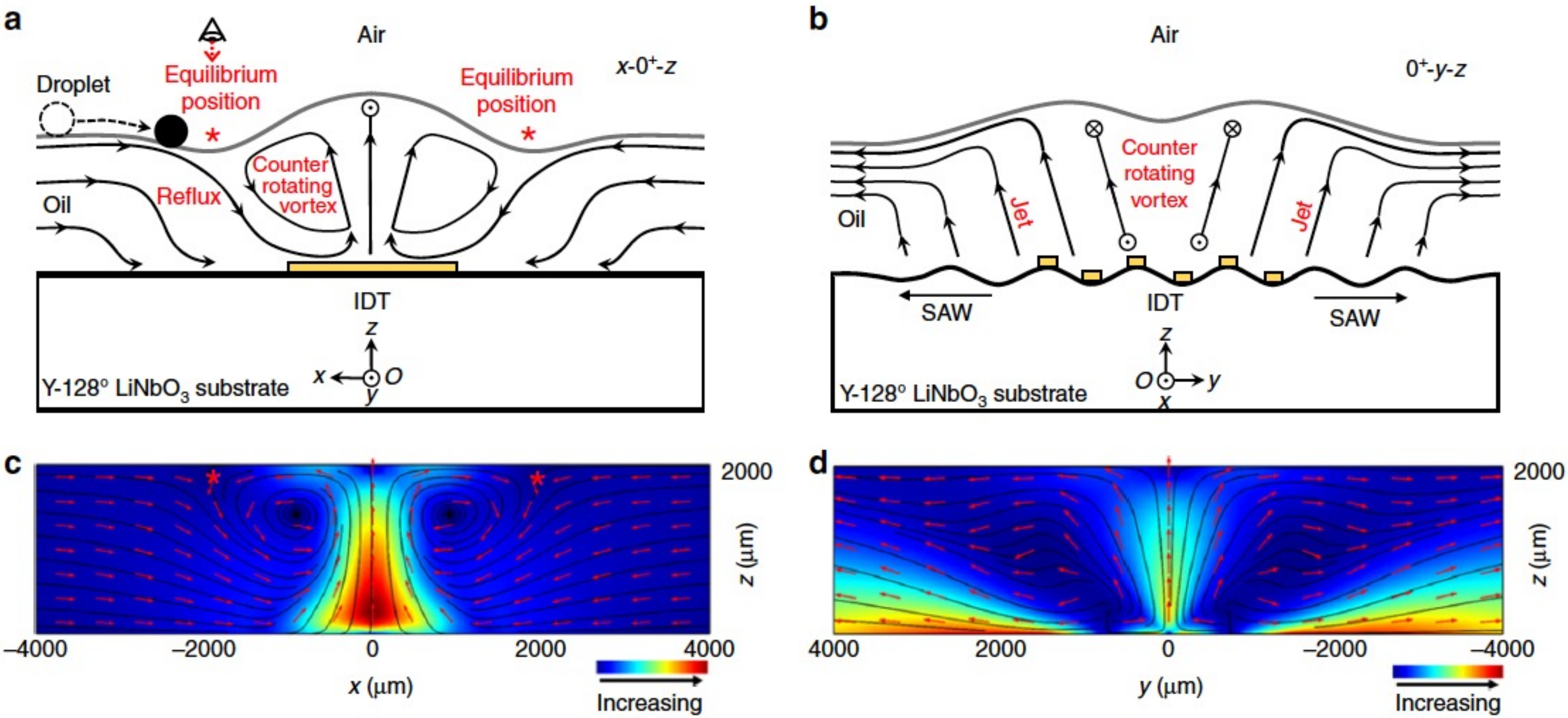
- Fluidic manipulation between potential wells
- A dense carrier layer of fluorinated oil on $LiNbO_3$ substrate
- Bulk waves and leaky surface acoustic waves: two symmetric fluid jets

a b



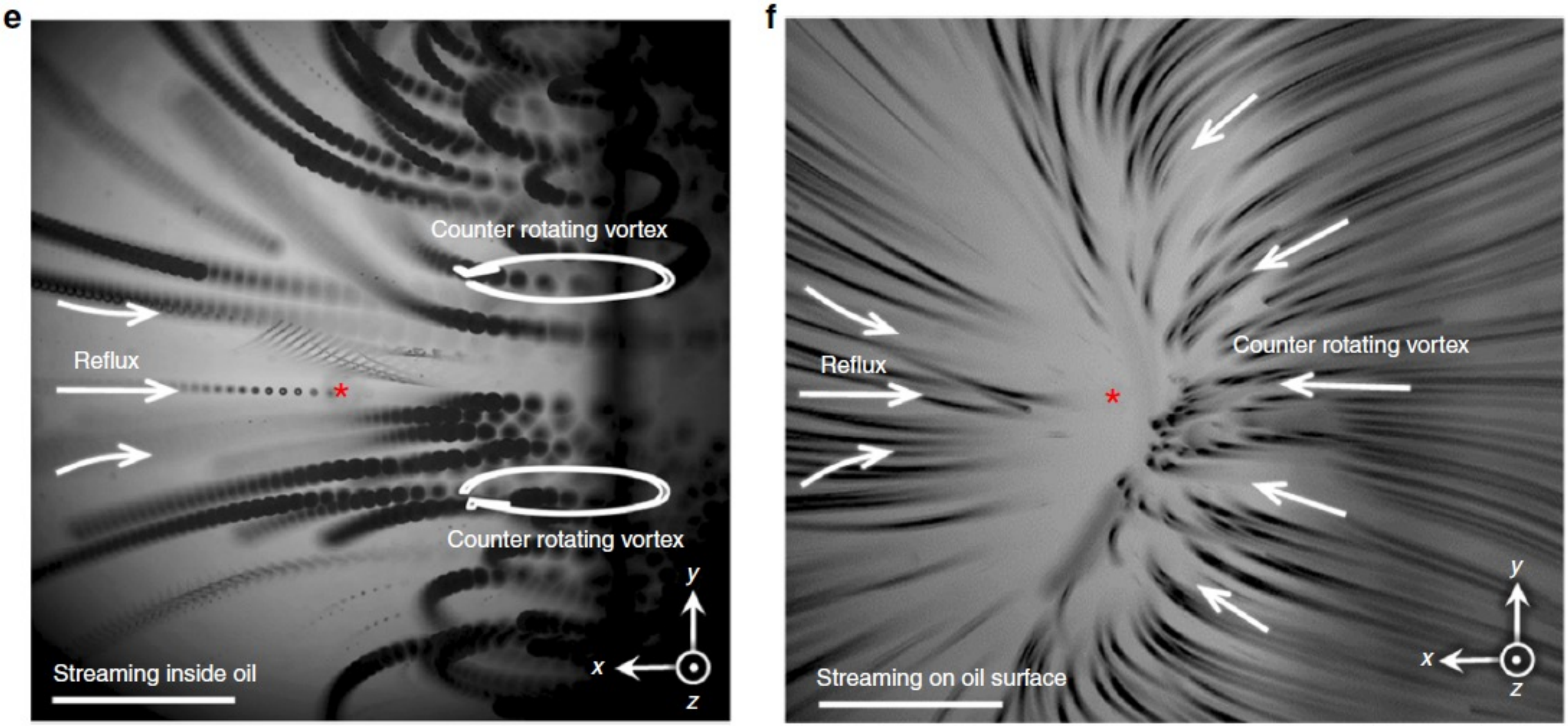
Digital acoustofluidics: Mechanism

- Simulation results

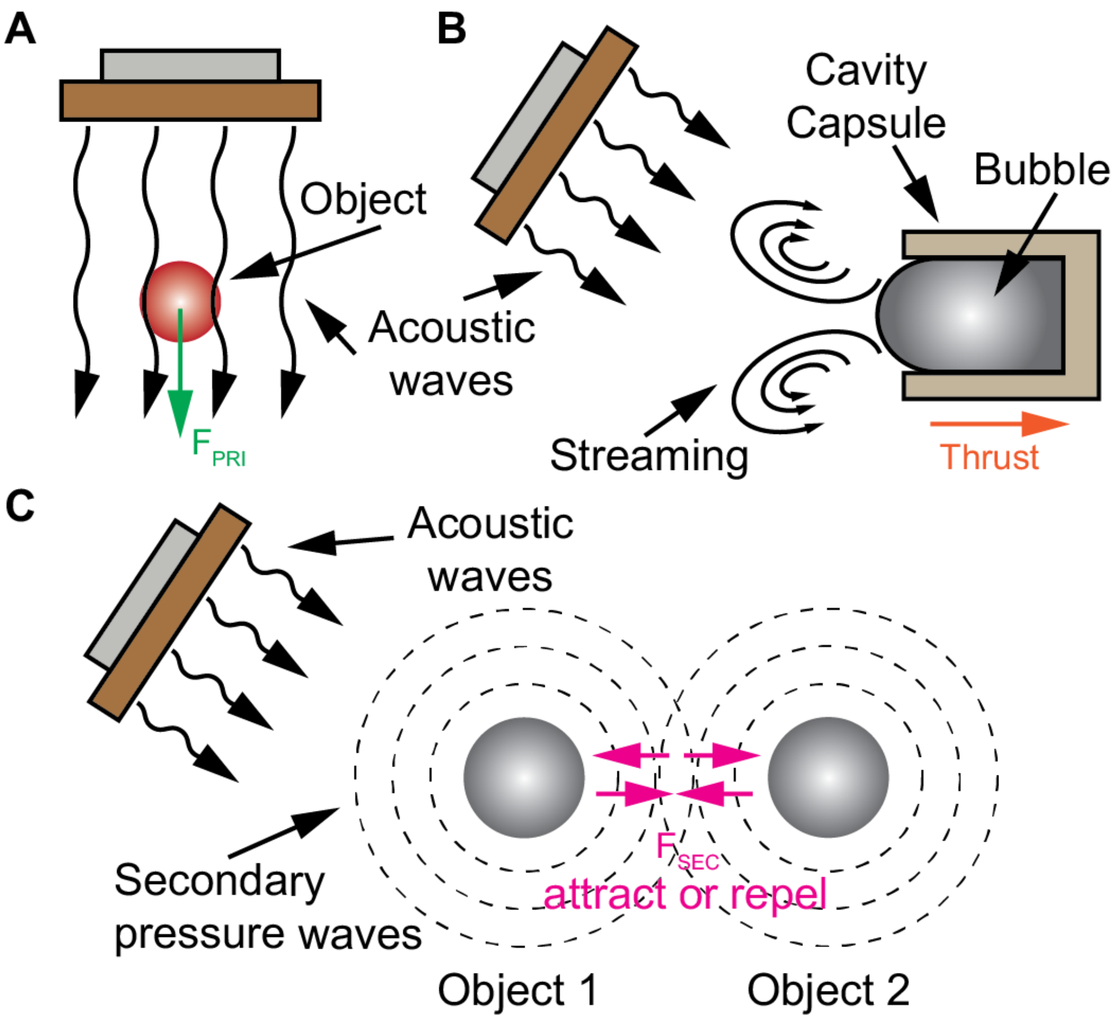


Digital acoustofluidics

- Streamlines

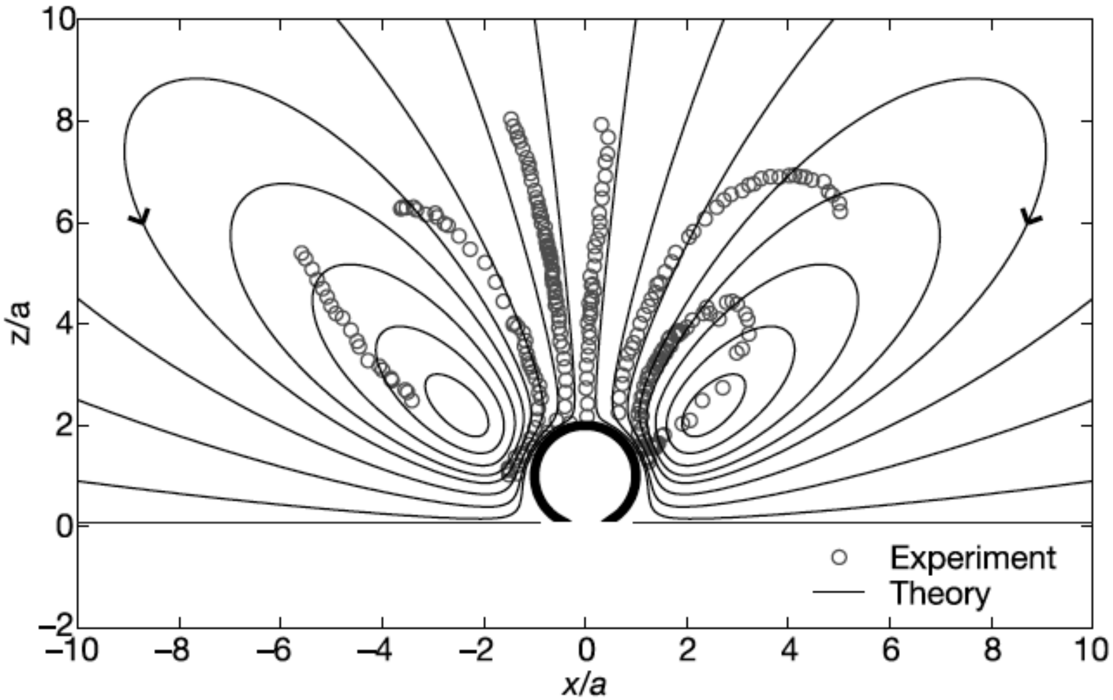


Acoustic forces acting on microscale objects



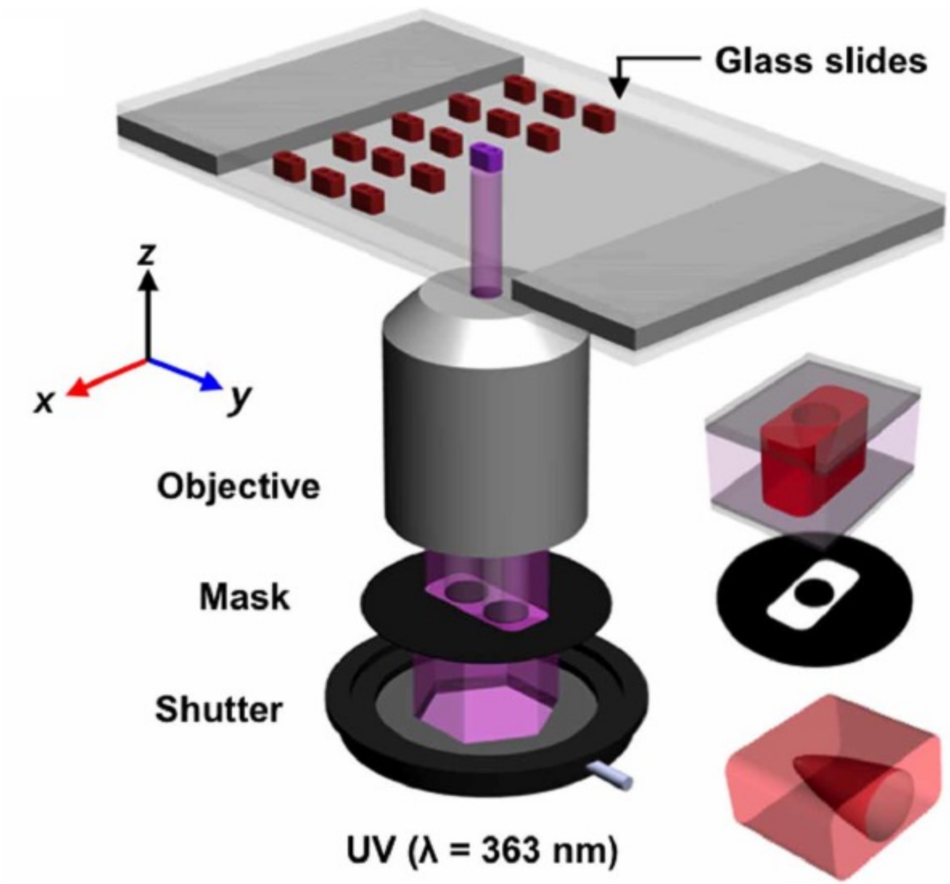
Oscillating bubbles

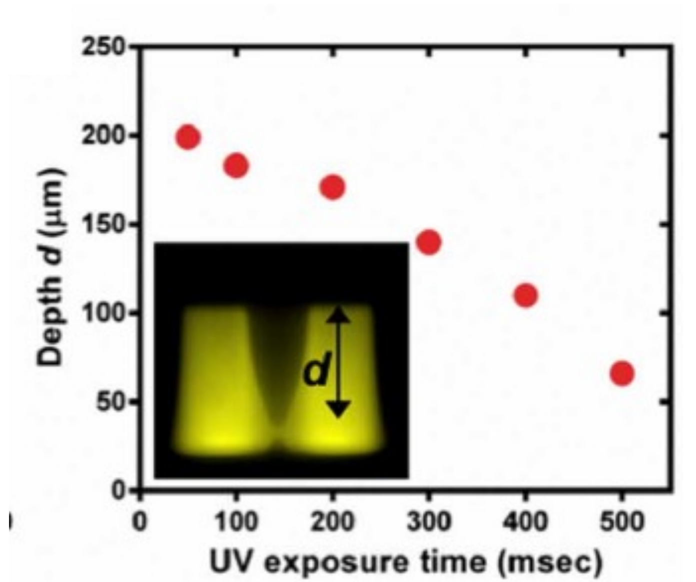
- Ultrasound-driven microbubbles as contrast agents for imaging
- Cavitation: Collapse of bubbles for opening pores in biological membranes
- Acoustic streaming around an oscillating bubble

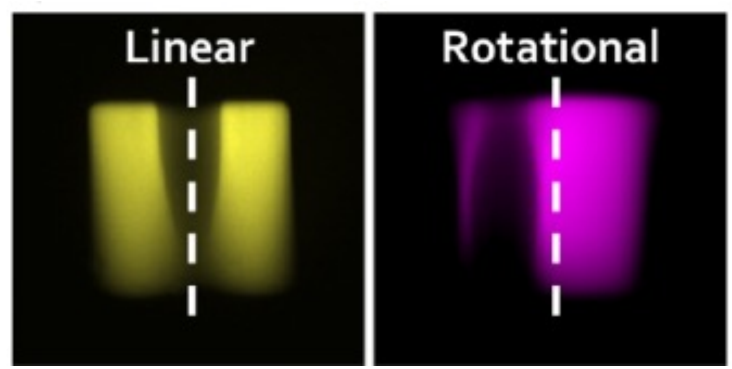


Bubble as a propeller

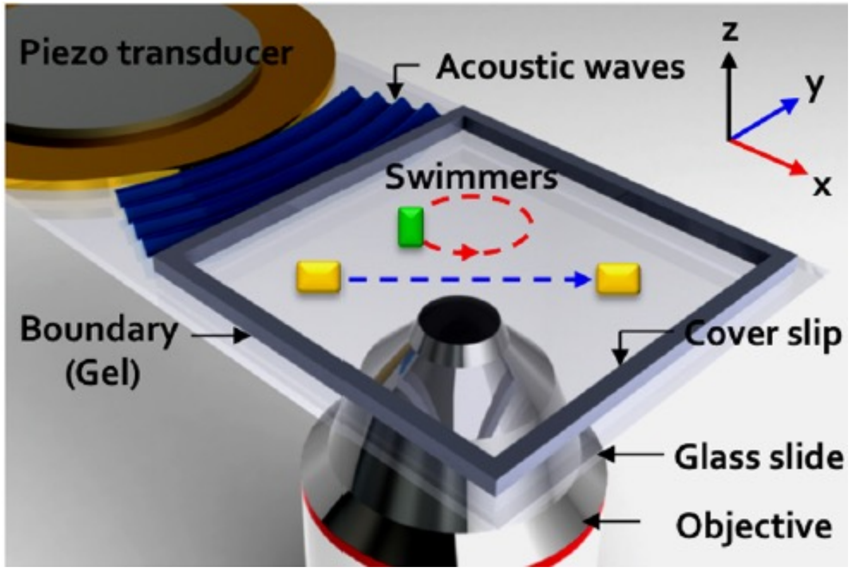
- Trapping bubbles inside hydrogel microstructures

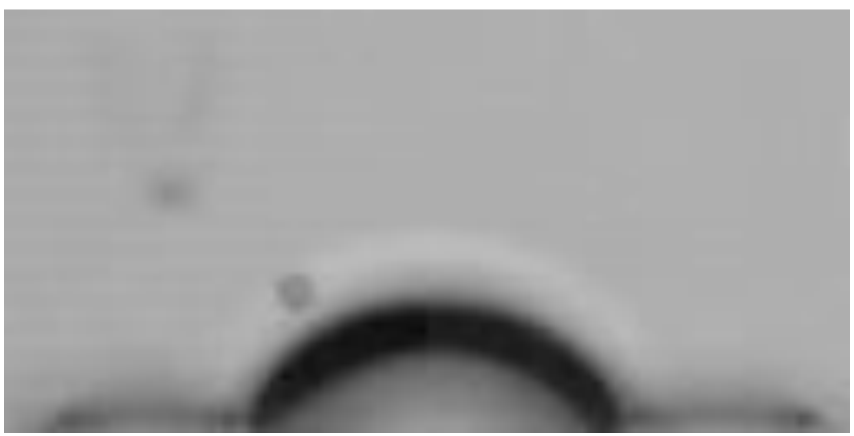




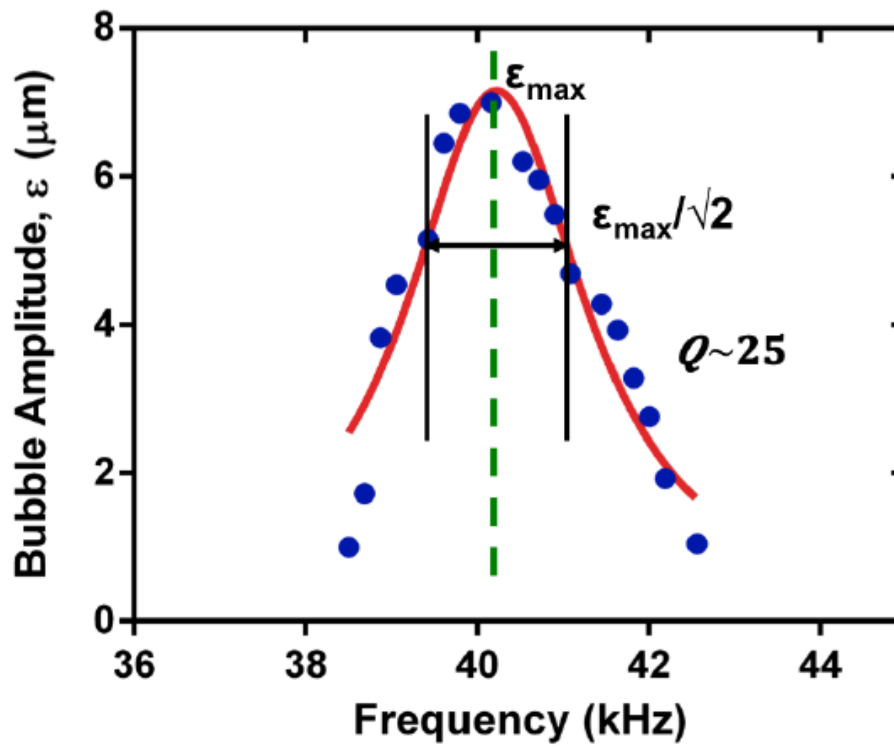


Bubble as a propeller

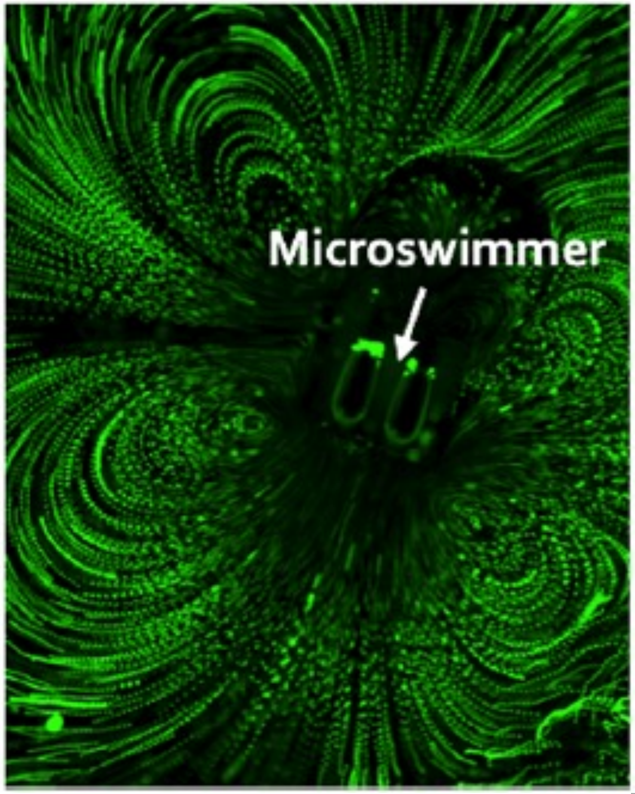


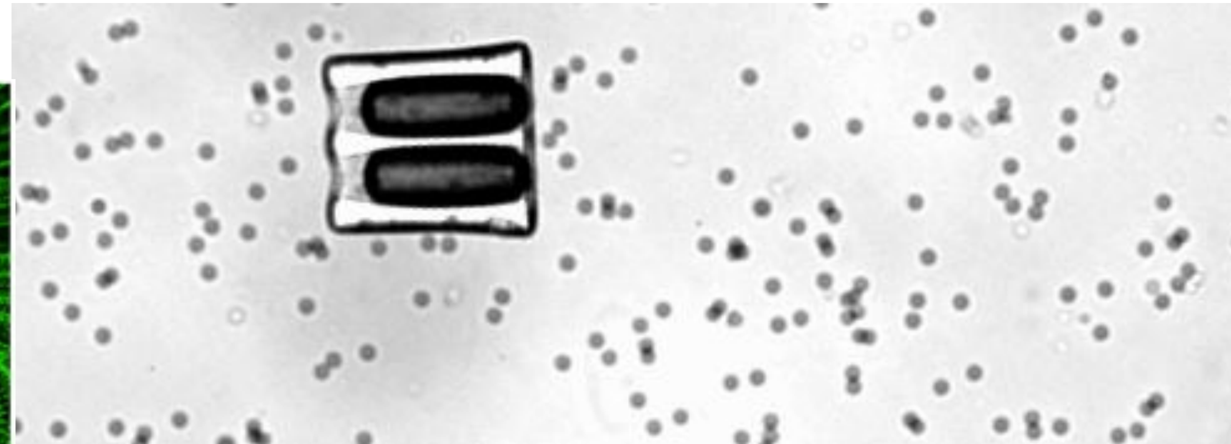


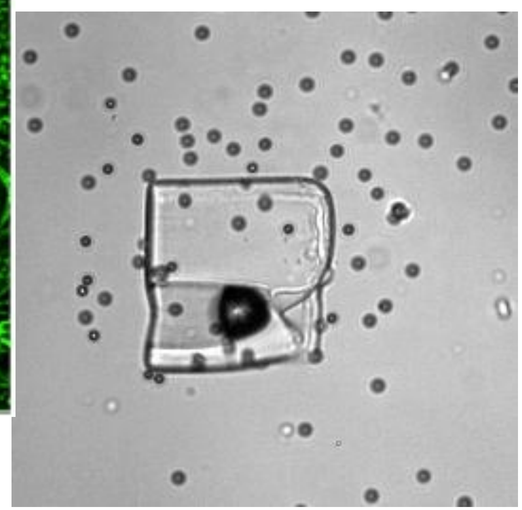
- Bubble size: 45 um
- Oscillation amplitude is largest when the driving field is resonant with natural frequency of the bubble

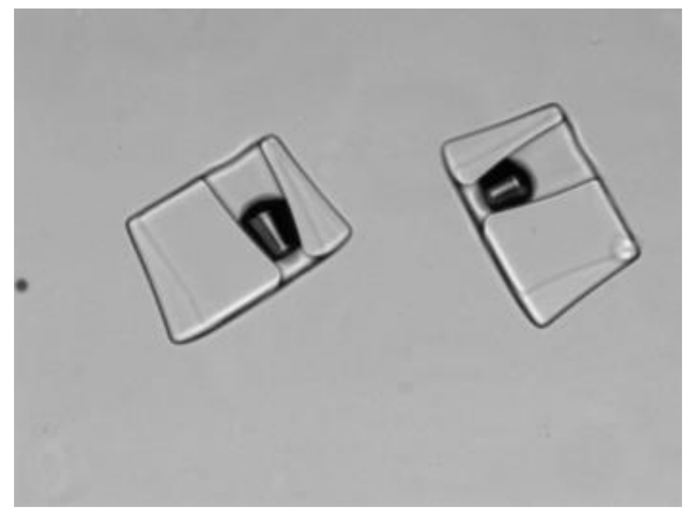


Bubble as a propeller









Bubble as a propeller

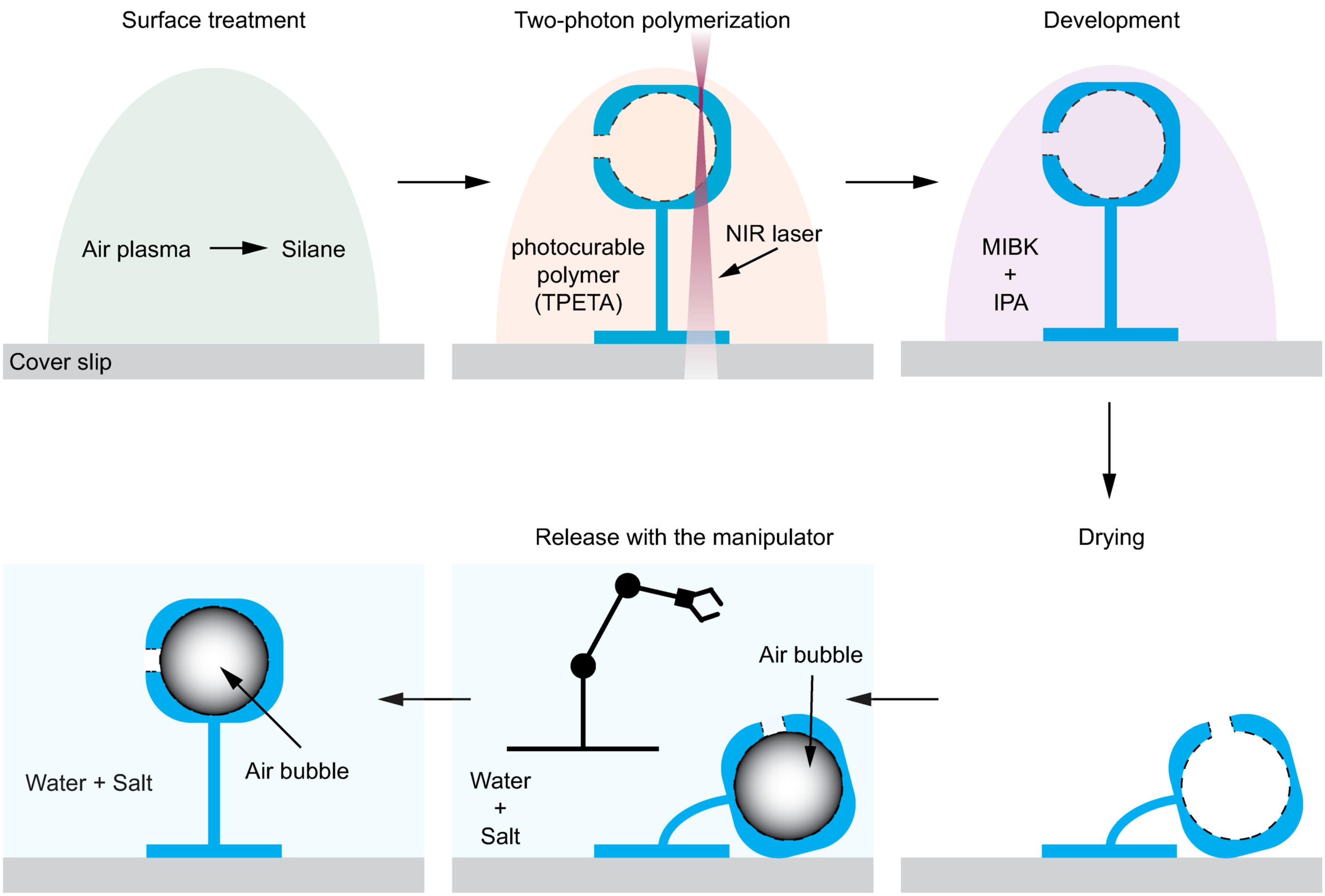
- Selective actuation
- Quality factor is around 25
- A small difference in diameter yields a robust separation in frequency
- Two swimmers with bubbles of different radii
- 74 kHz vs 91 kHz

Acoustic streaming and magnetic steering

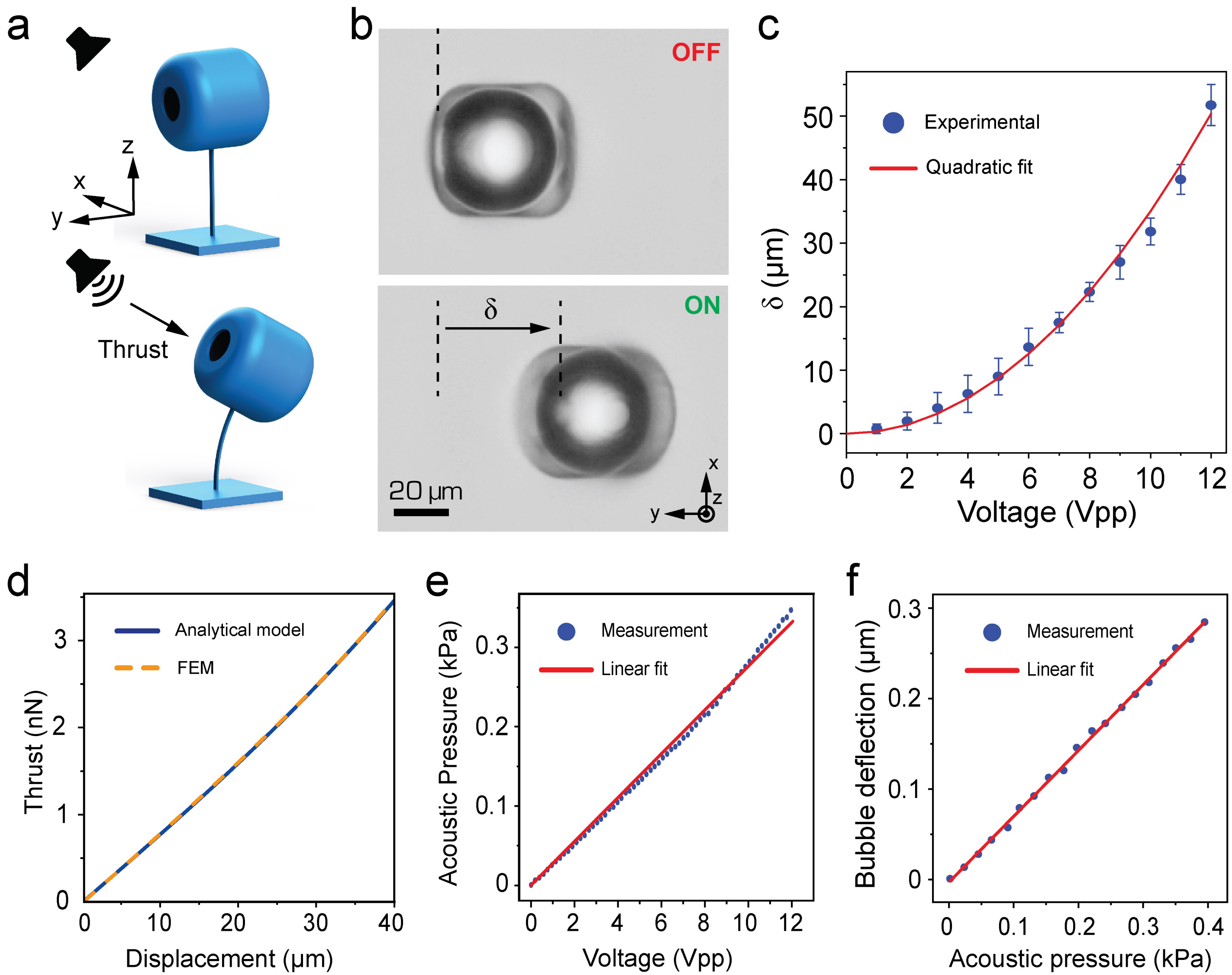
Supplementary Movie S9

Magnetic control of the acoustic microrobots

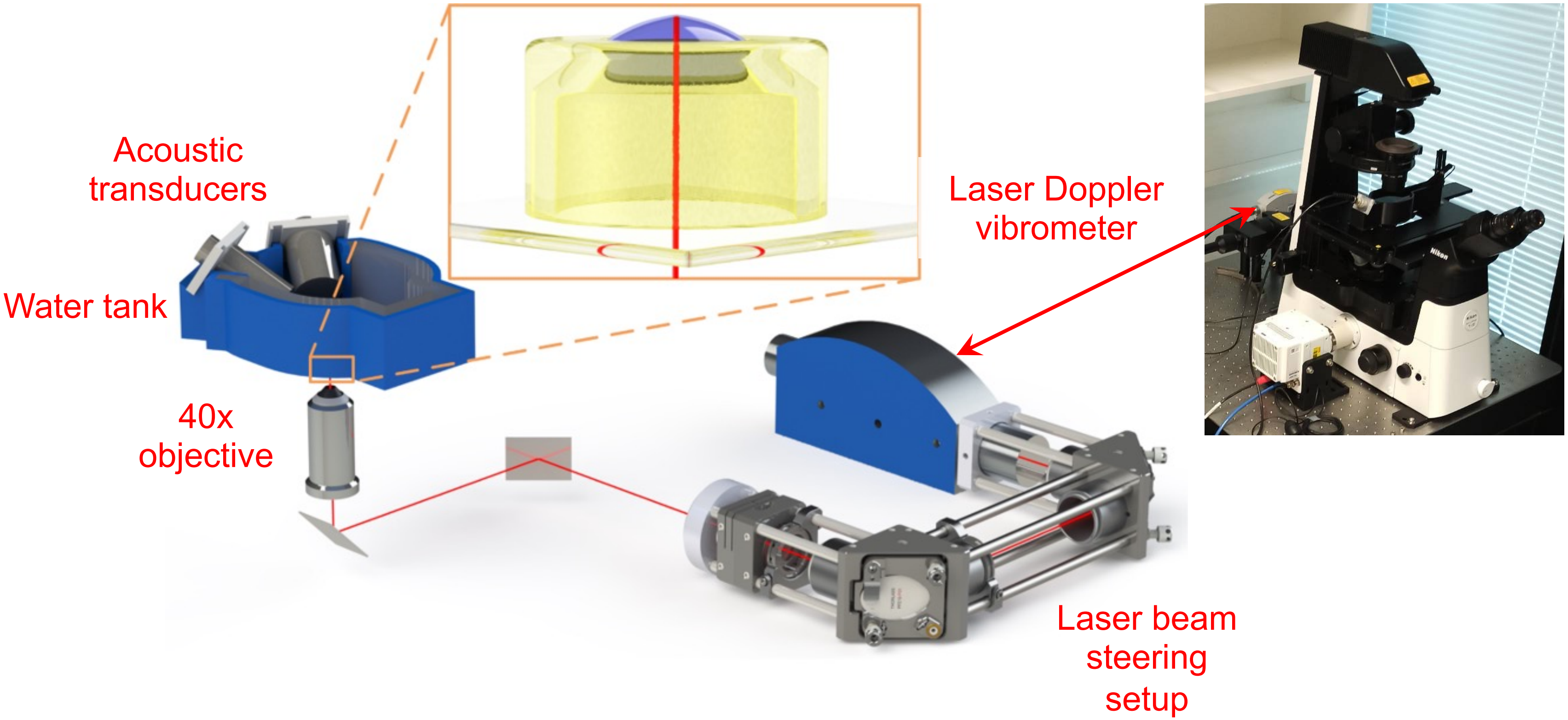
Bubble microactuators



Acoustic streaming force

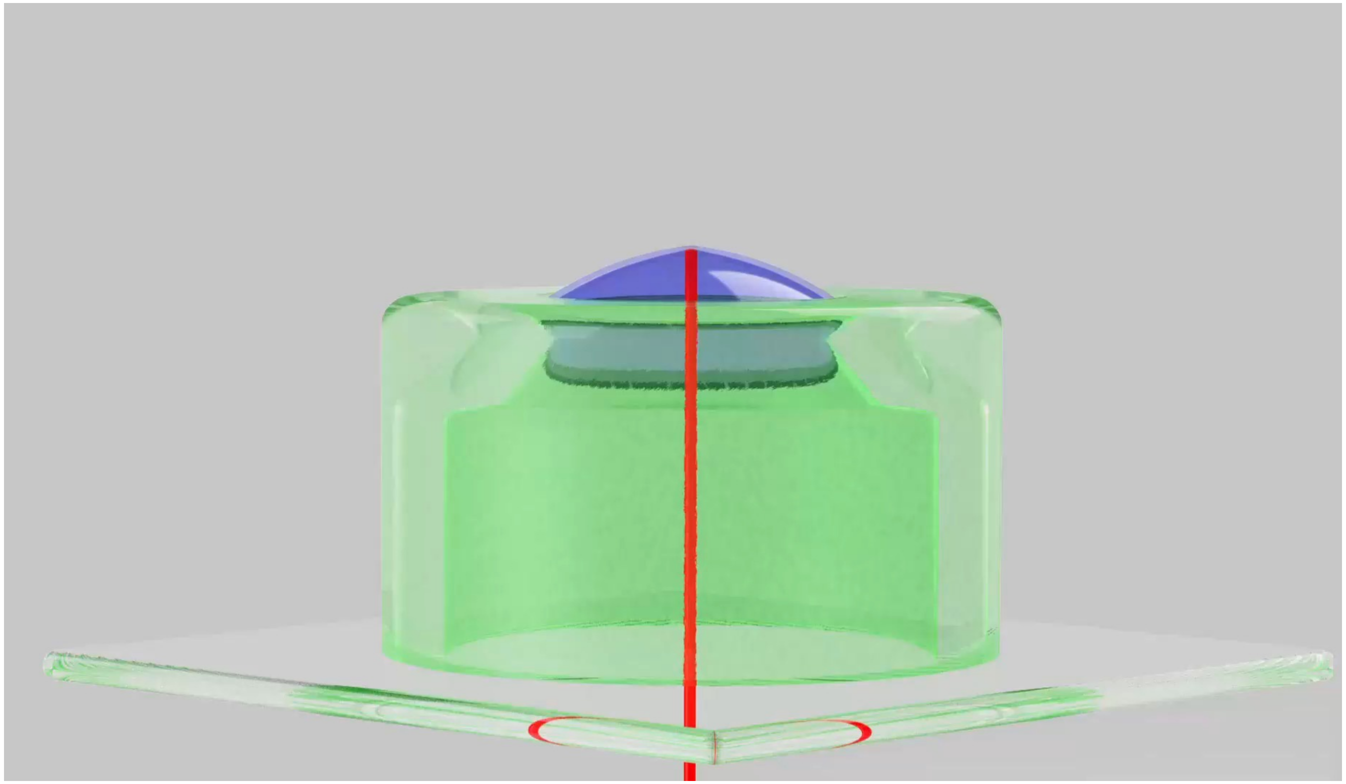


Measurement of water-air interface



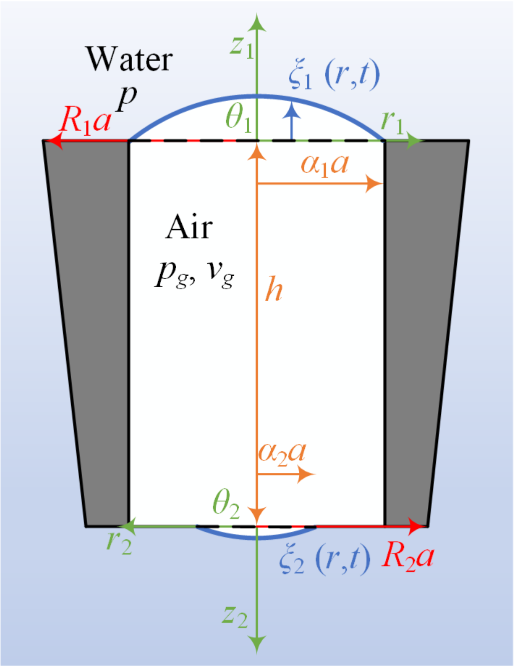
Secondary acoustic radiation force

Reference signal
Laser signal



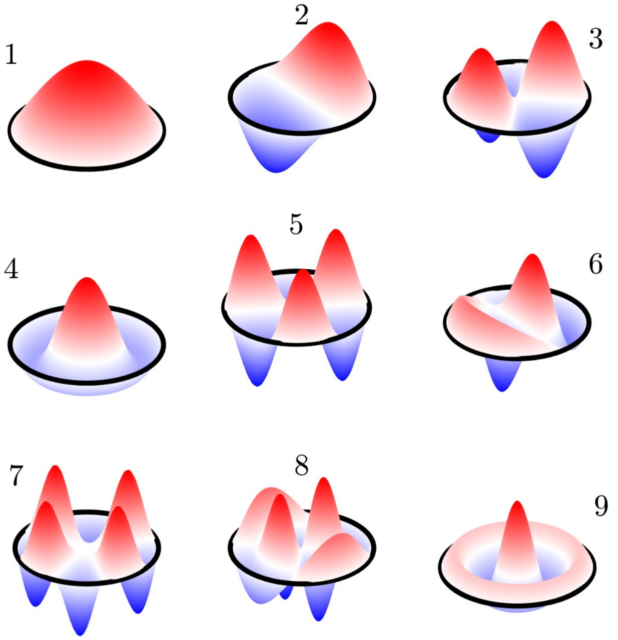
Analytical model

- **Natural frequencies** → max forces
- Natural frequencies & vibration modes
- FSI problem



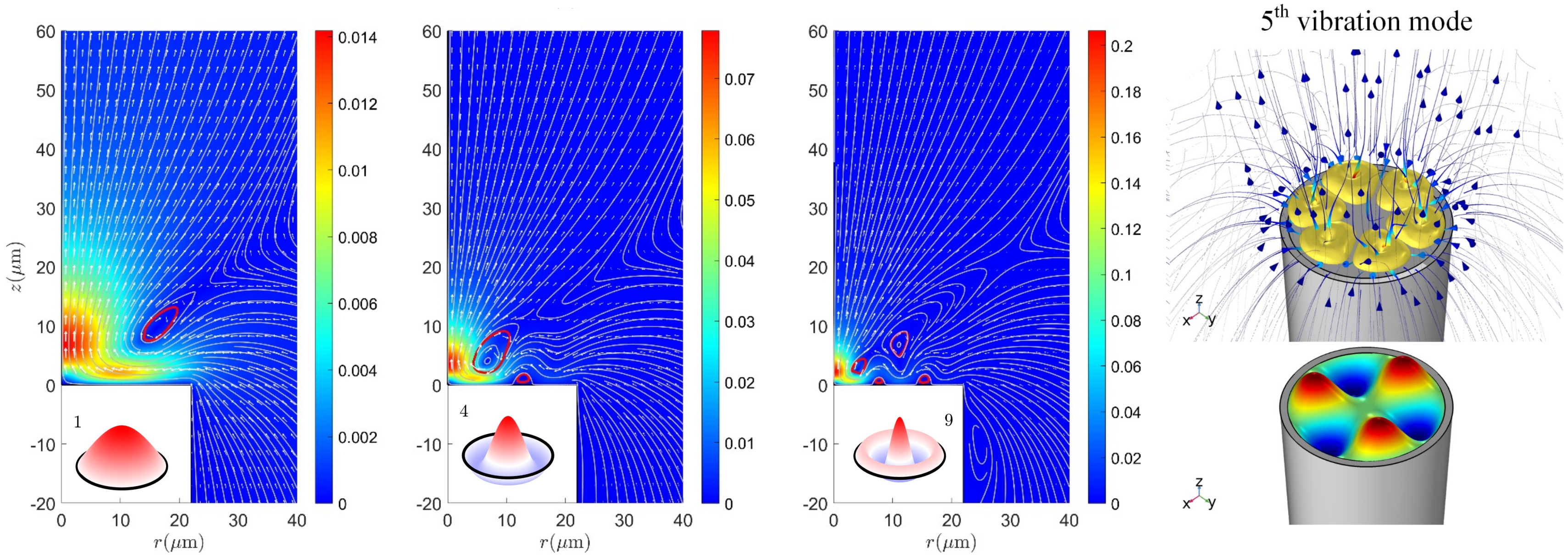
Numerical simulations

- **Natural frequencies** → max forces
- Natural frequencies & vibration modes

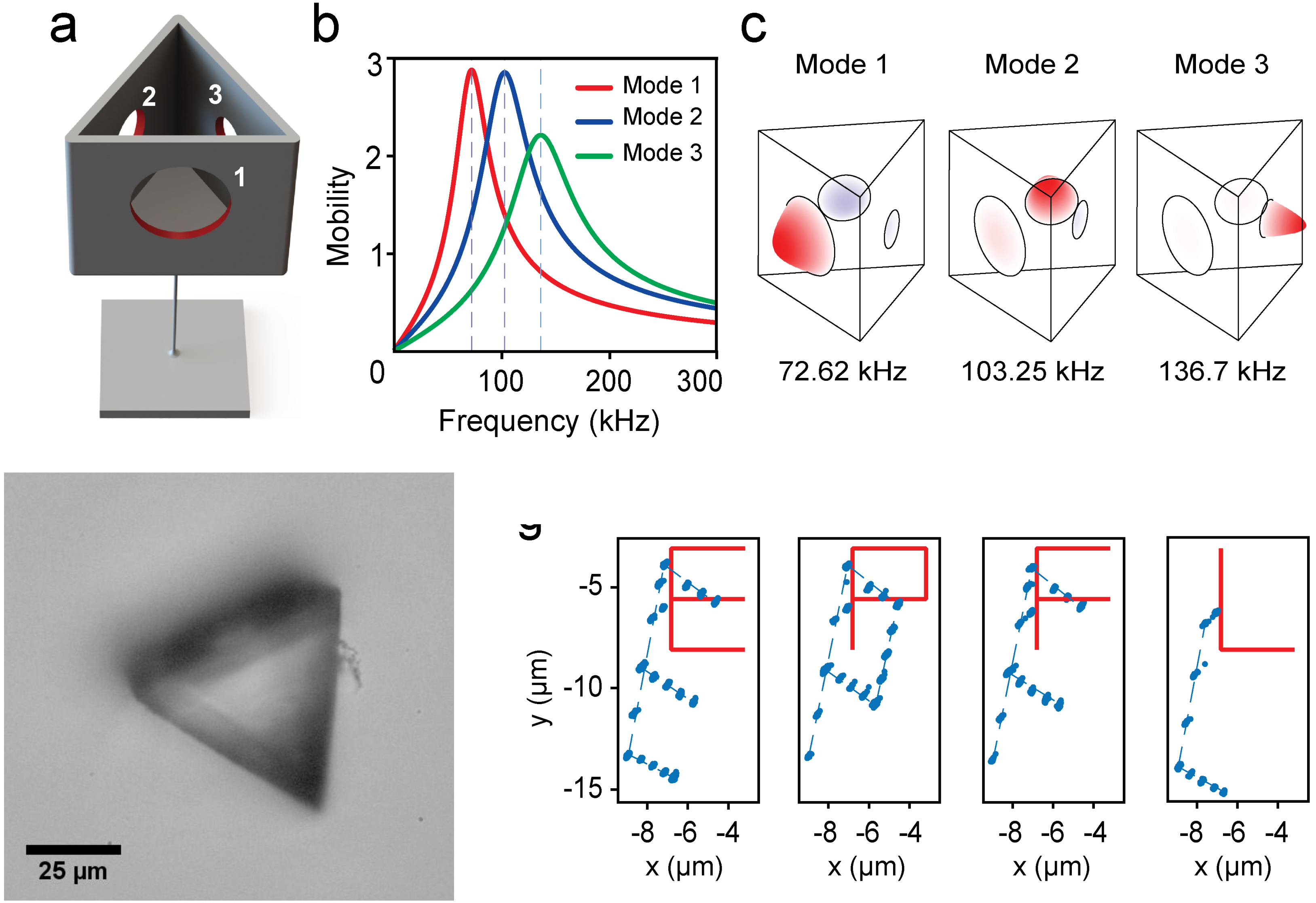


Finite element analysis

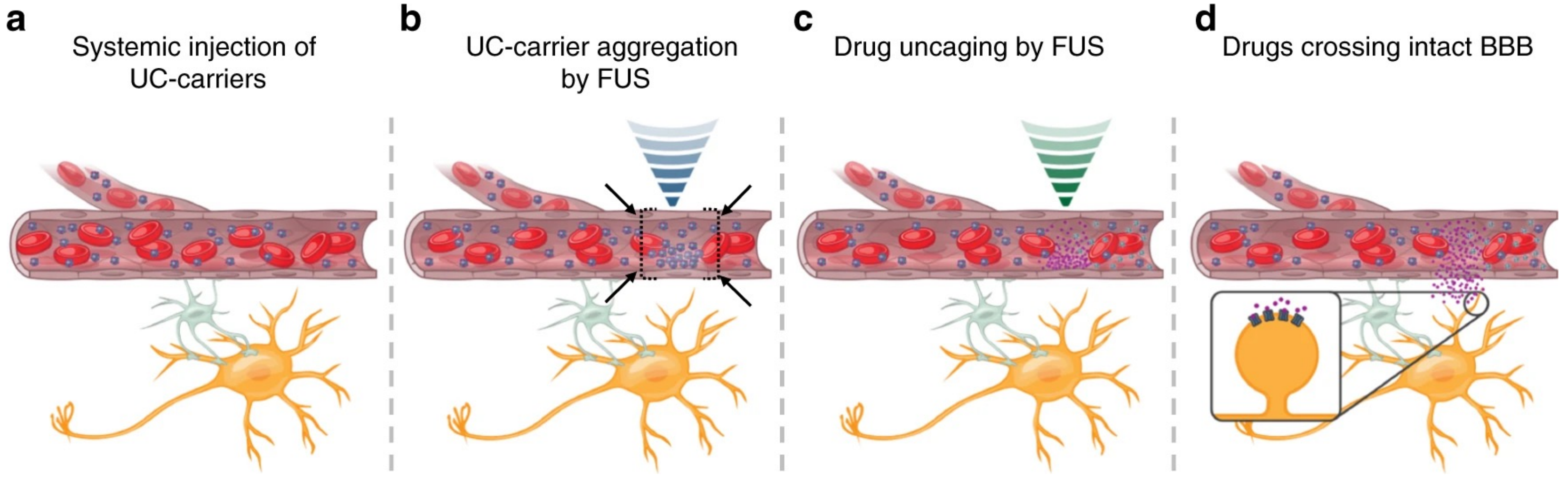
- Estimate the streaming patterns

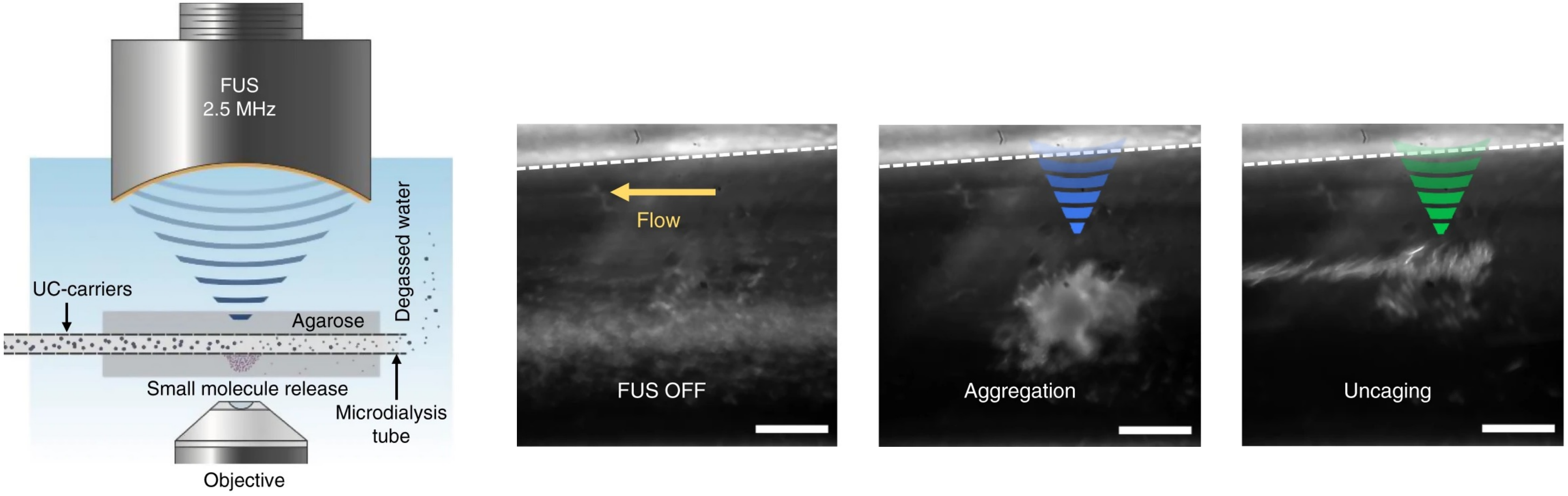


Multi-DOF actuation



Manipulation of bubbles inside cerebral arteries





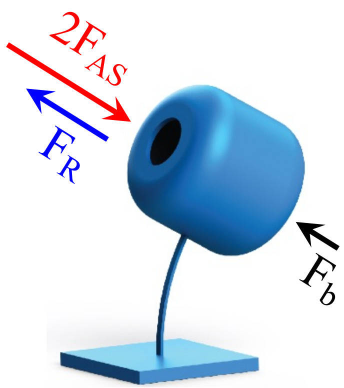
Manipulation of bubbles inside cerebral arteries

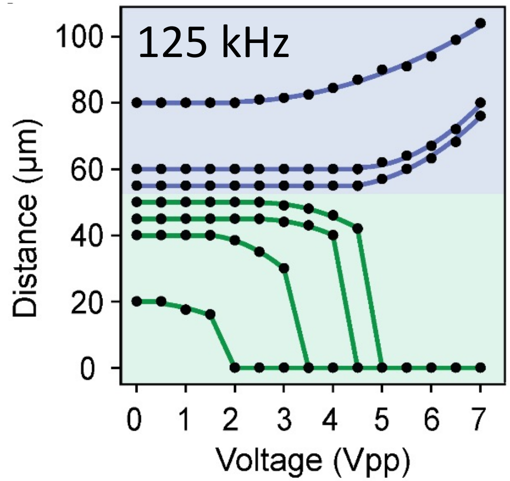
Bubble-bubble interactions

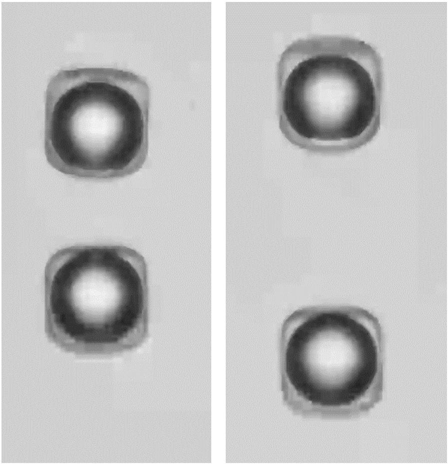
$$F_b = F_R + F_{AS} + F_d$$

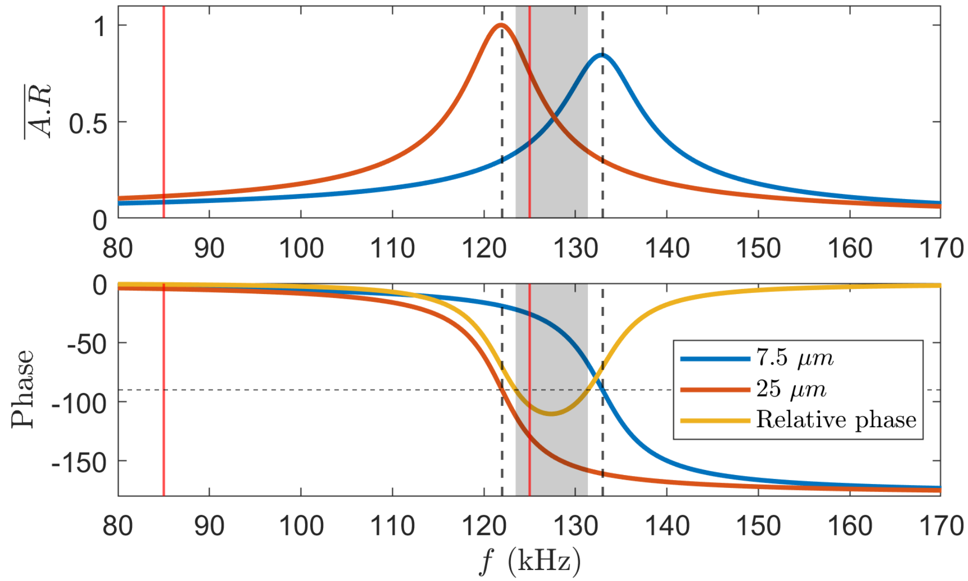
$$F_b = F_R + 2F_{AS}$$

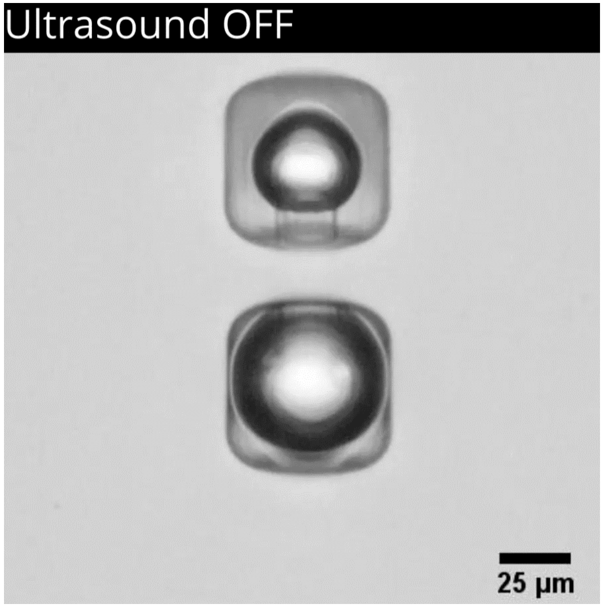
$$F_R \propto d^{-2}$$



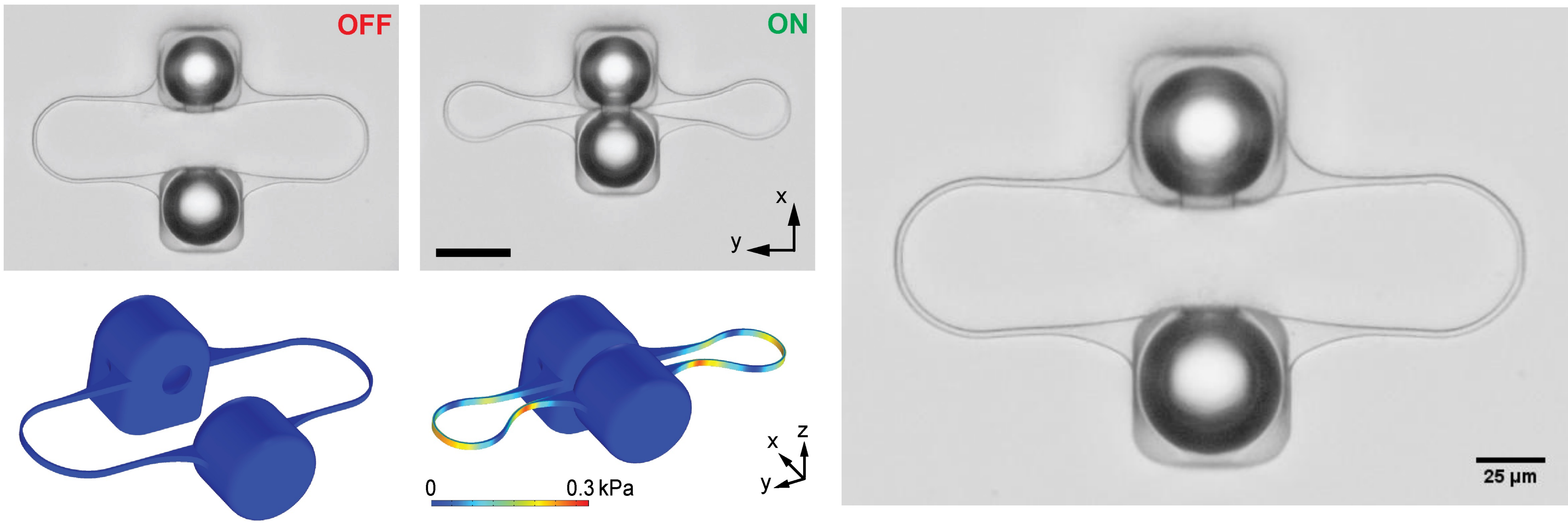


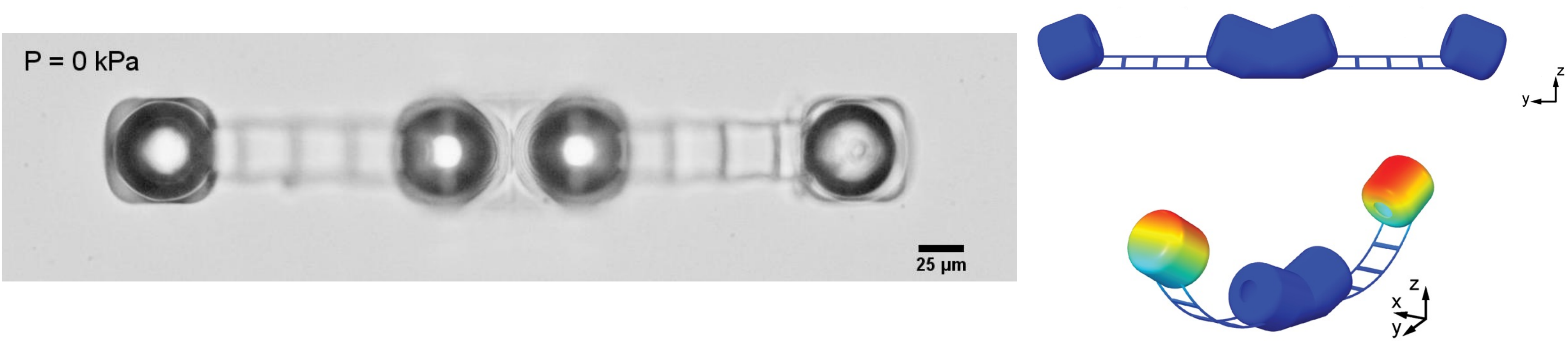






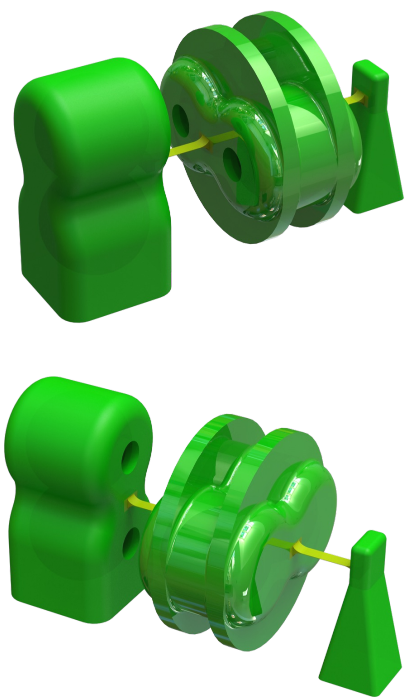
Linear and bending actuators

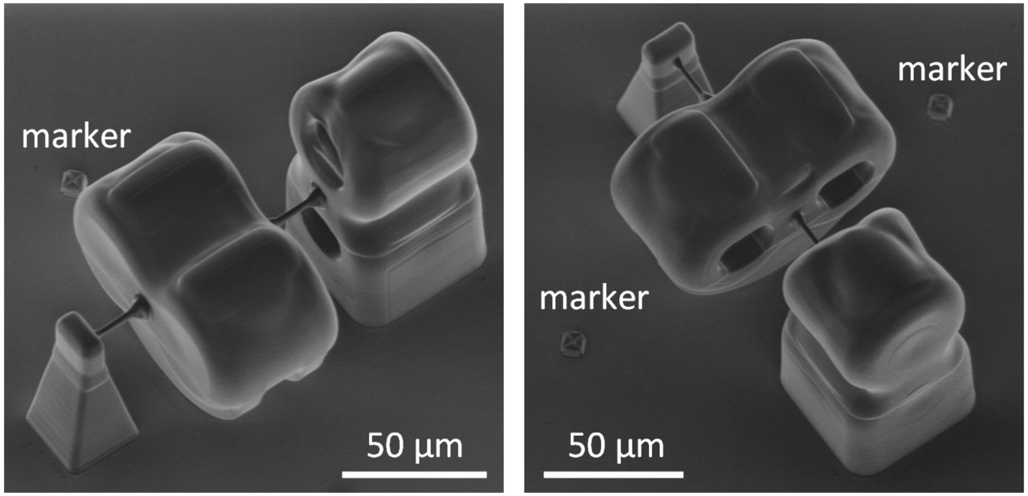




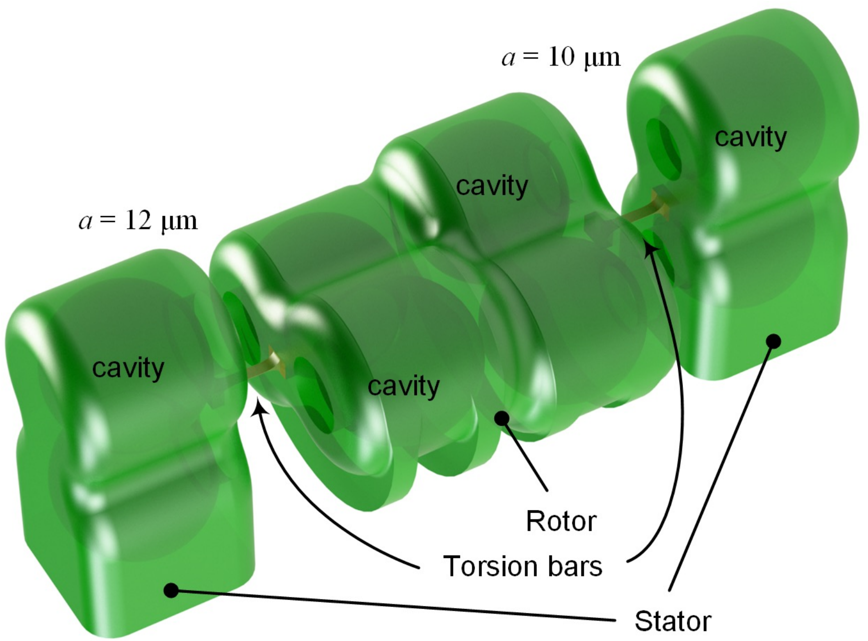
Rotary actuation

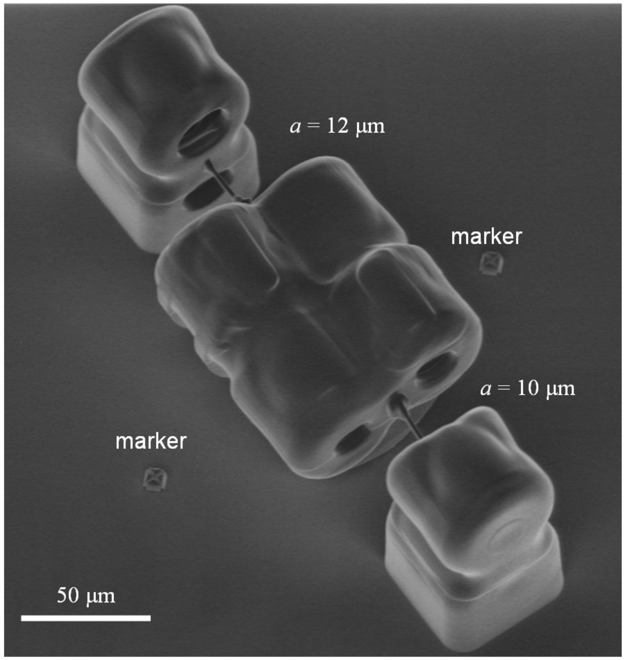
- Multi material two-photon printing (TPETA + PETA)
  - PETA, $E \approx 3$ GPA
  - TPETA, $E \approx 12.7$ MPA





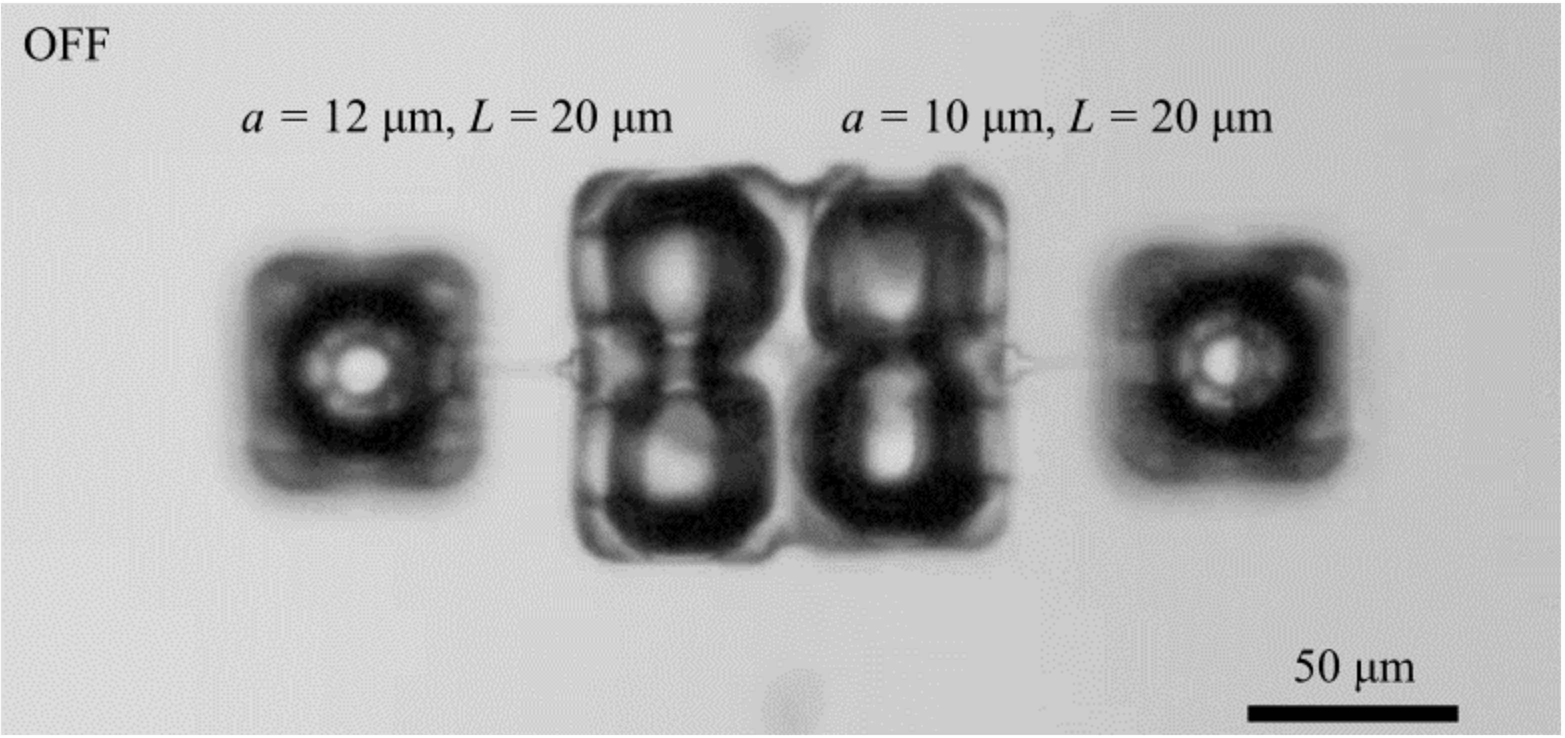
Bidirectional torsional microactuator





Manipulation of bubbles inside cerebral arteries

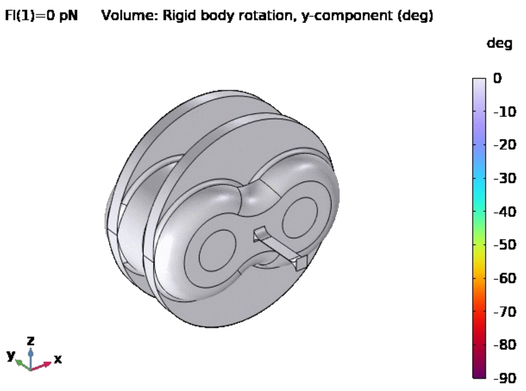
- Characterization – Frequency sweep → 82.5 kHz, 222 kHz



Calculation of forces via FEM

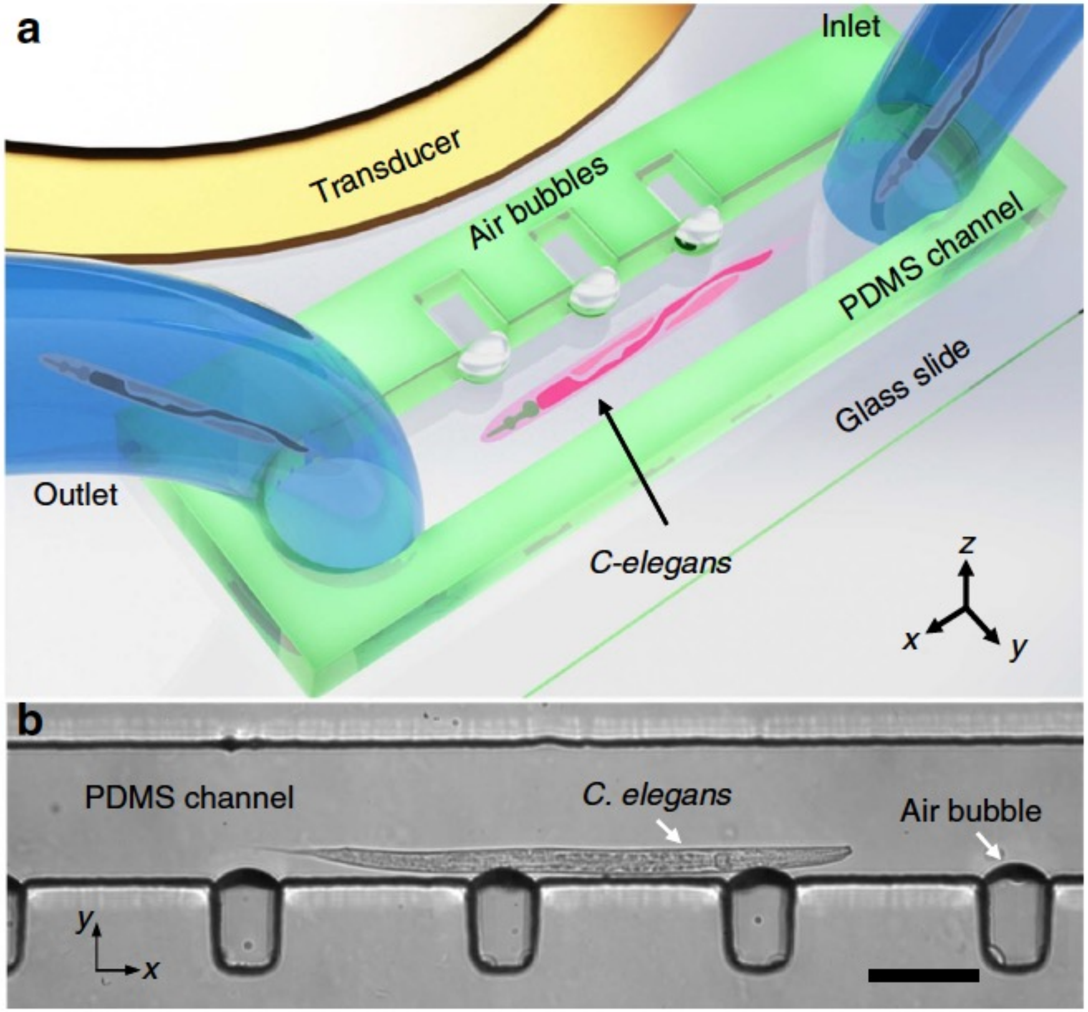
- Calibration
  - Run the actuator at different frequency and pressure
  - Pressure vs angular displacement curve
- Analytical model to calculate forces and torques
  - Estimate bar stiffness from finite element simulations
  - Fit experimental data to calculate beta

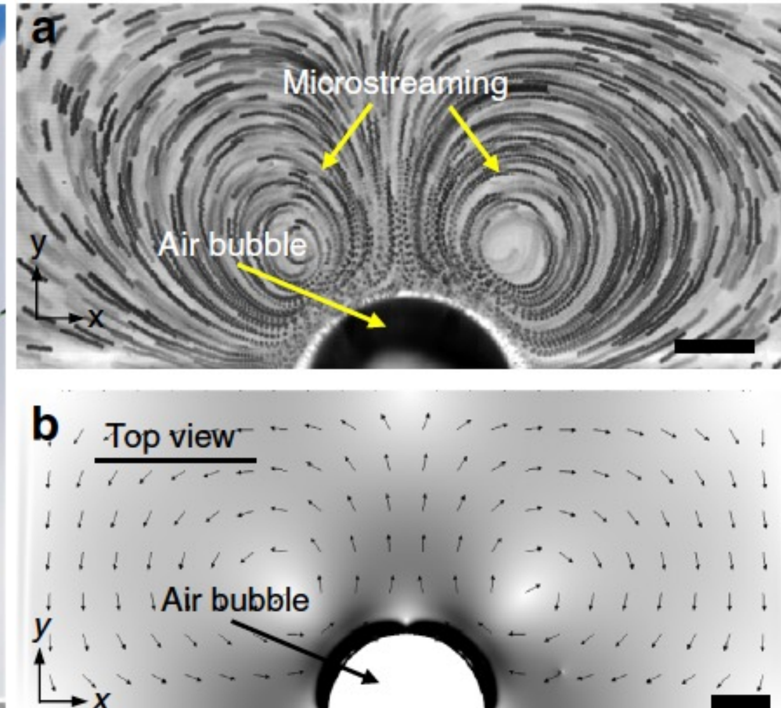
$$\mathbf{F}_{\mathbf{R}} = \beta \rho \omega^2 \frac{a^4 p^2}{d_{ij}^2} \hat{\mathbf{d}}_{ij}$$



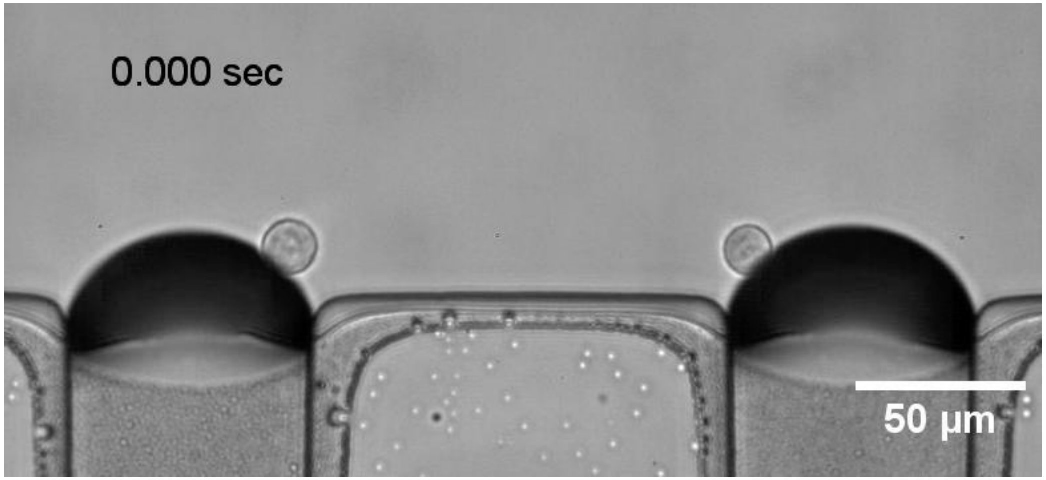
Rotational manipulation using acoustic waves

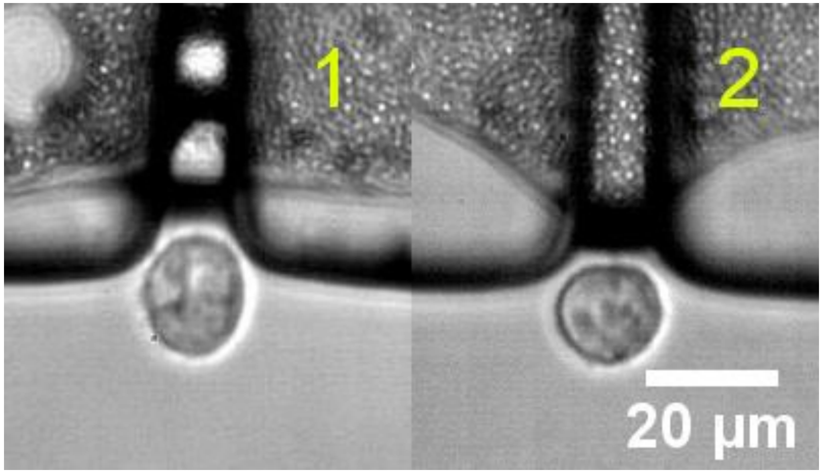
- Experimental observations

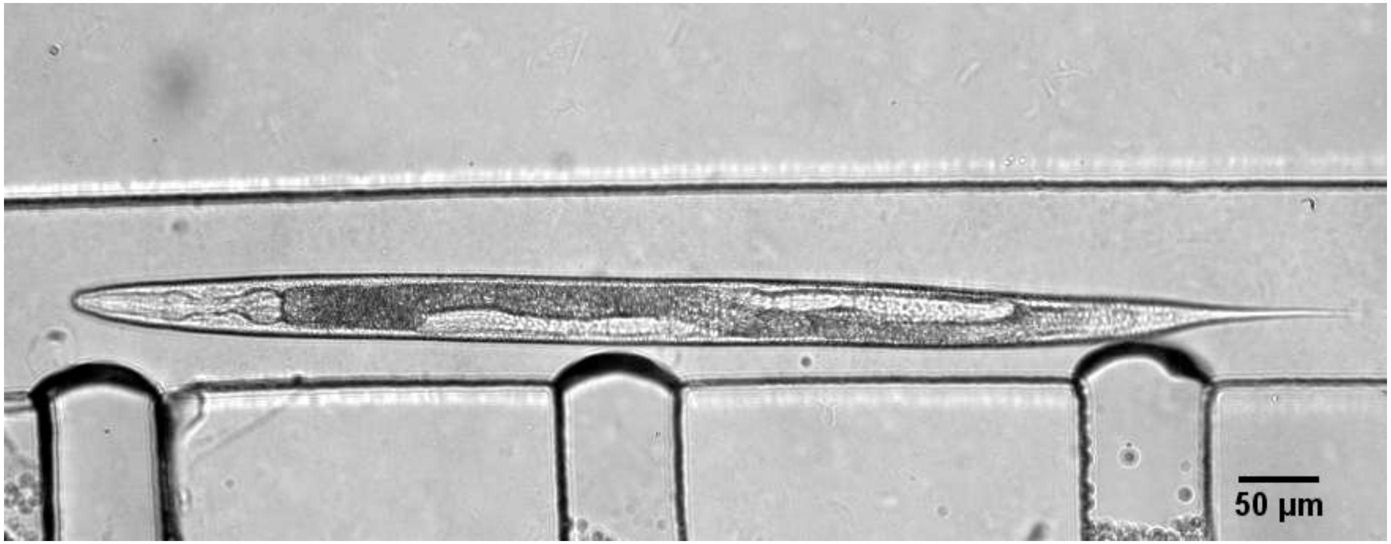




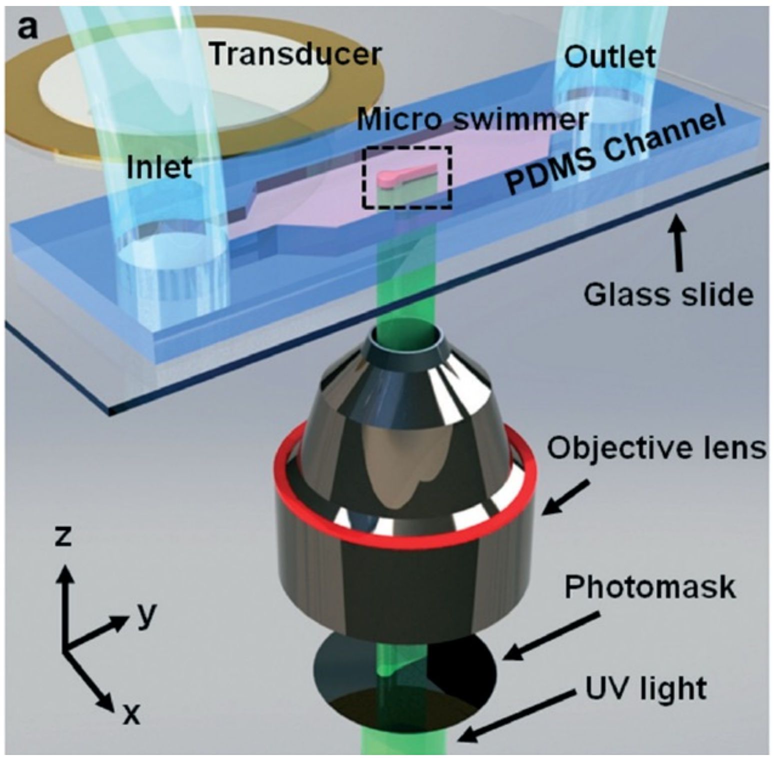
Rotational manipulation using acoustic waves

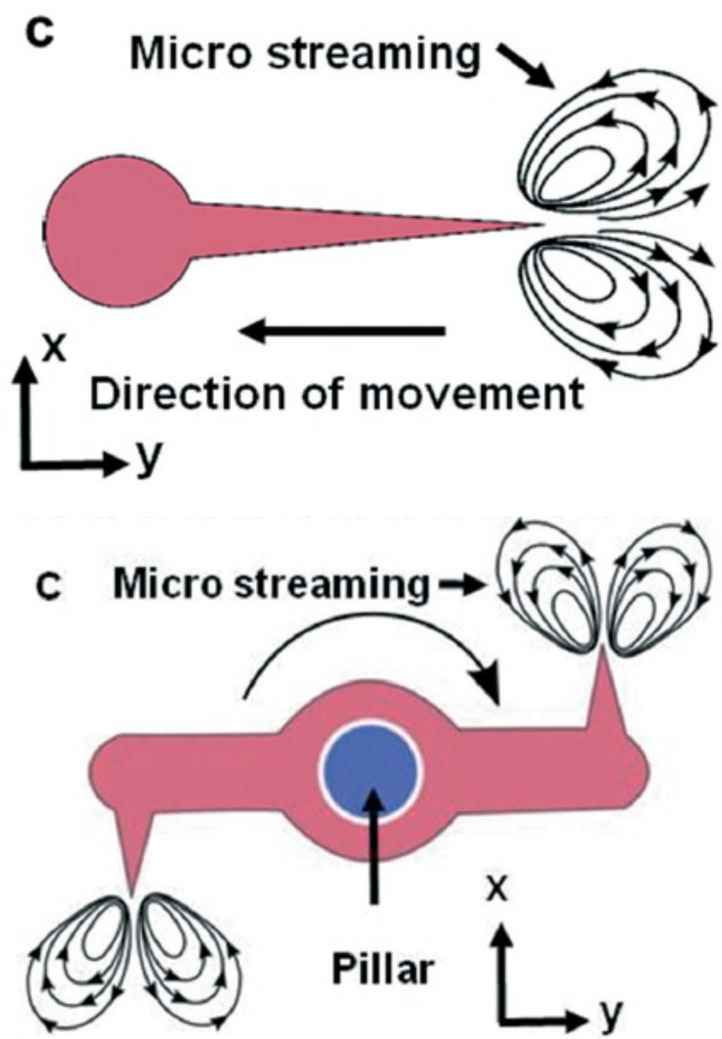




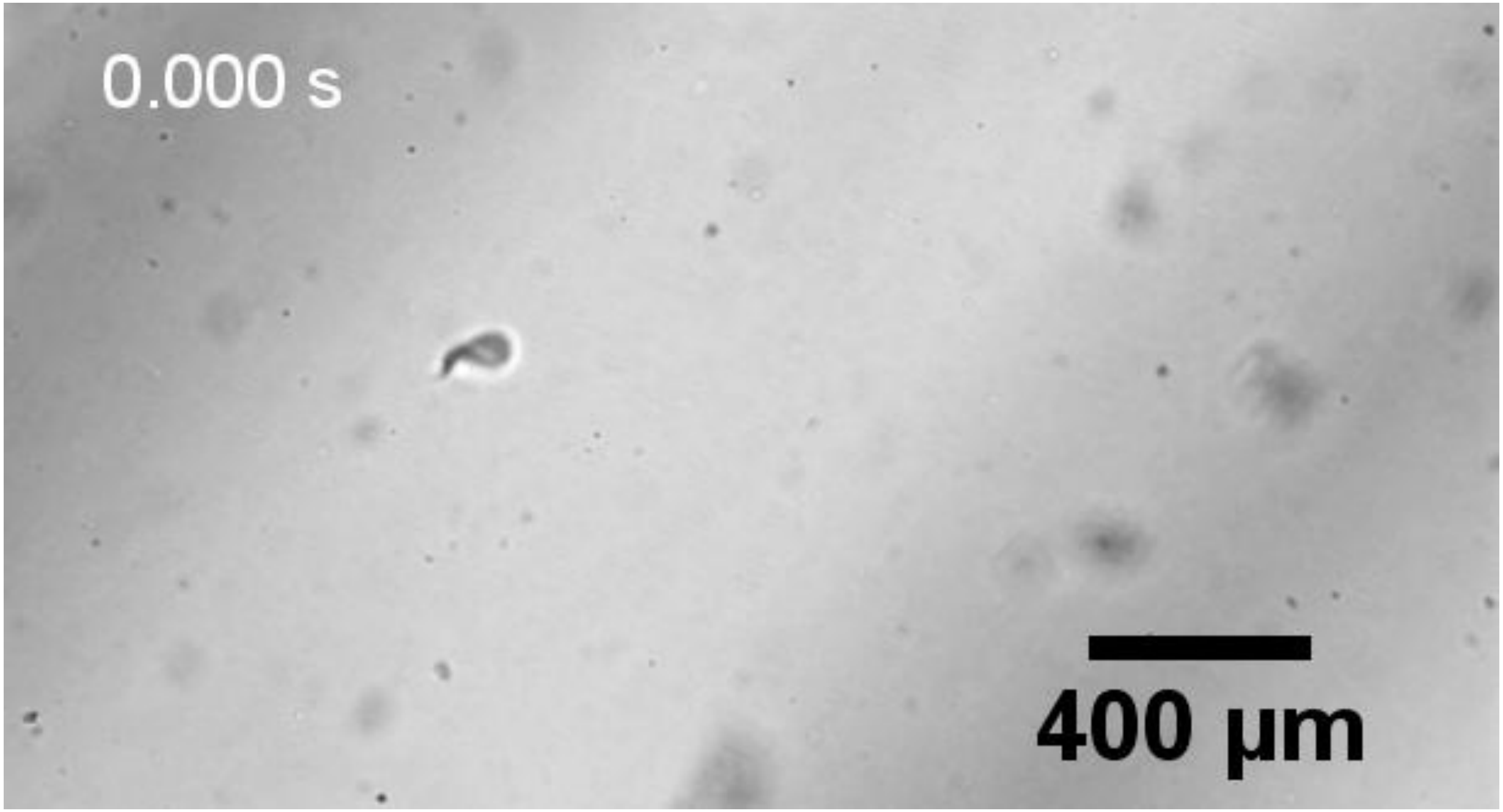


Acoustic Streaming: Oscillating solid structures

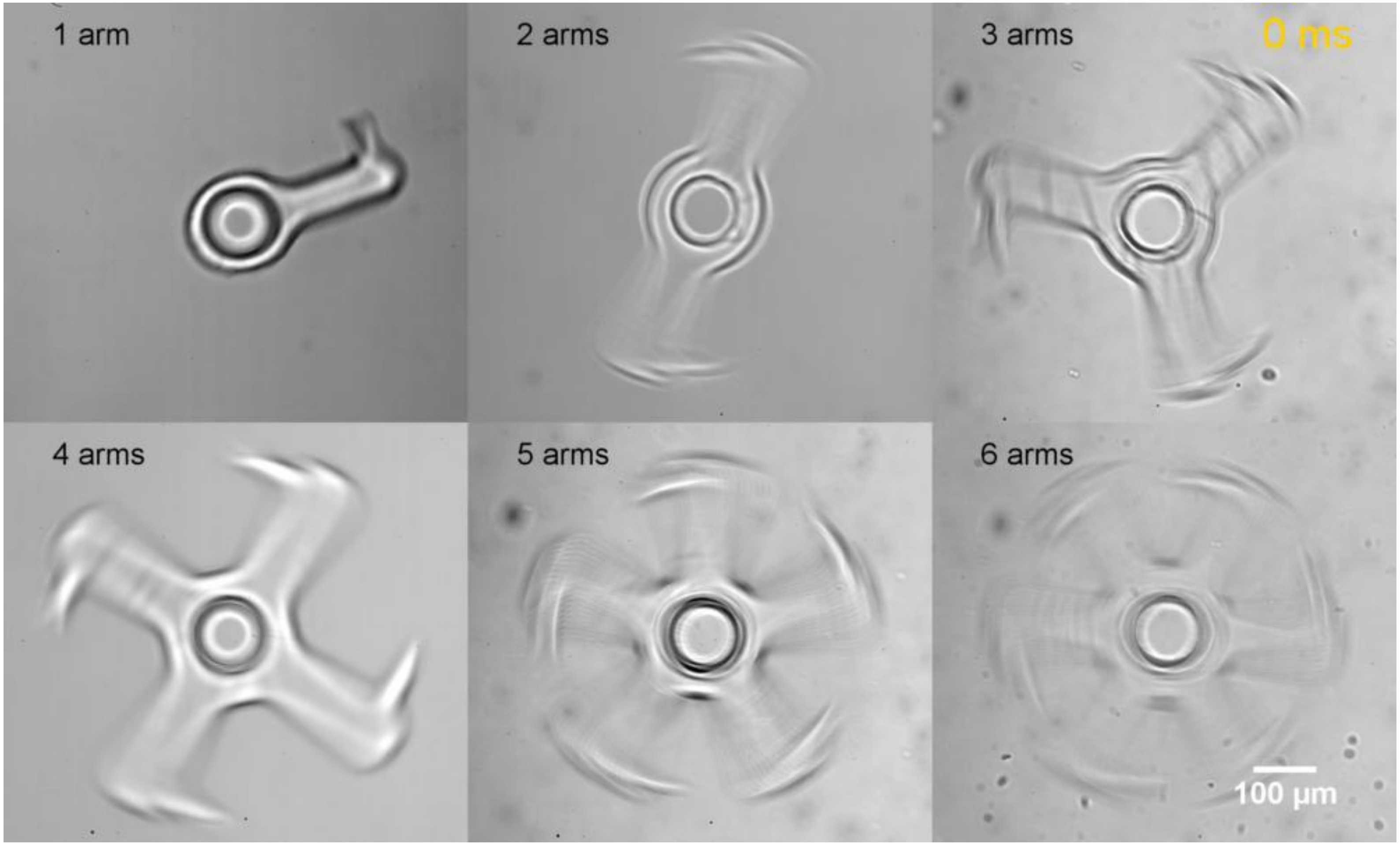




Acoustic Streaming: Oscillating solid structures

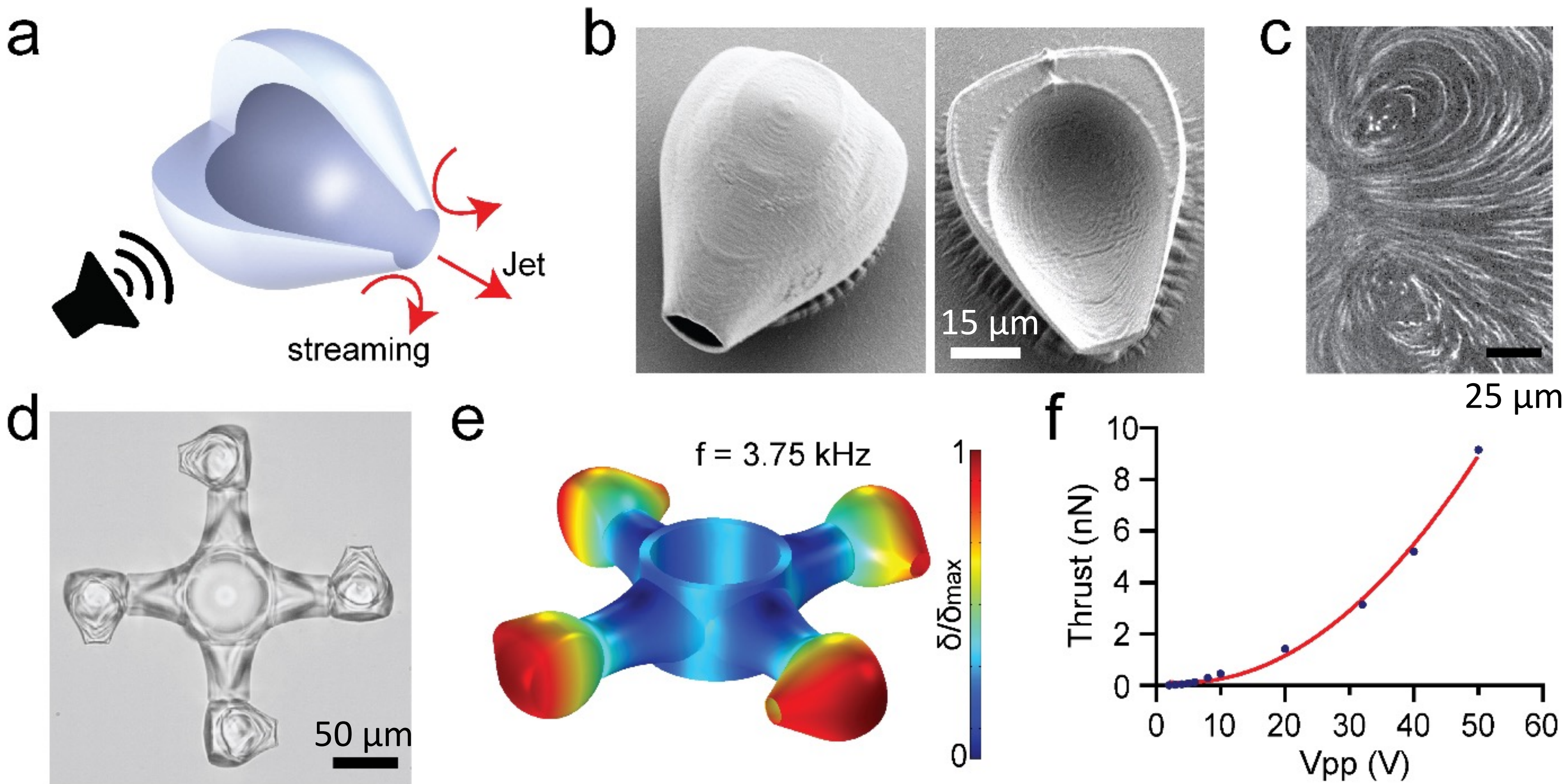


Acoustic Streaming: Oscillating solid structures

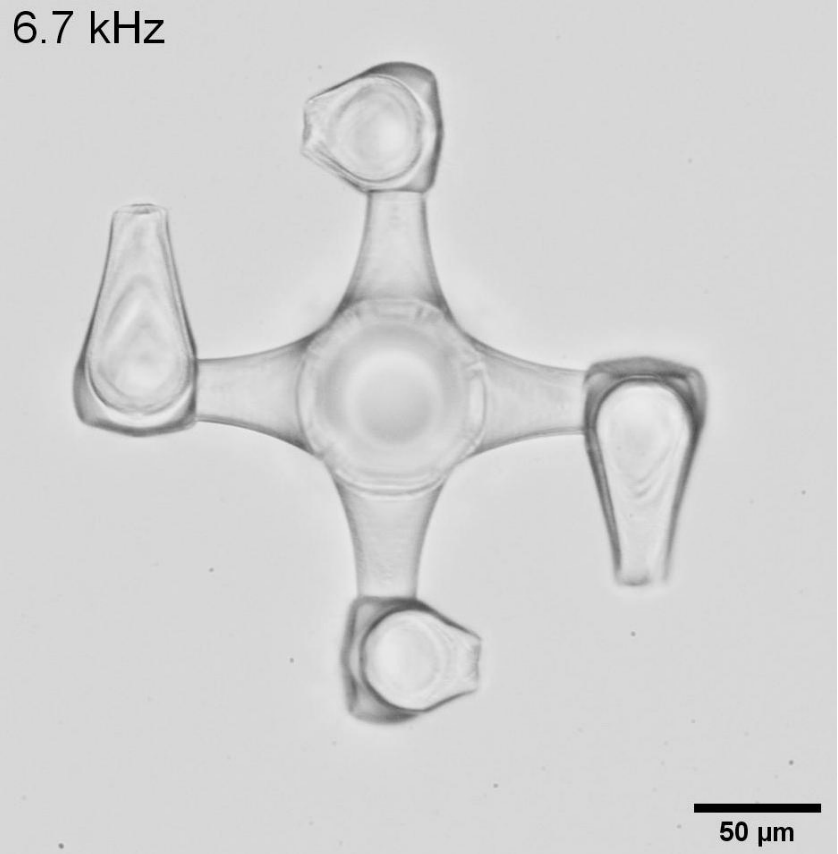


3D printed micro-thrusters

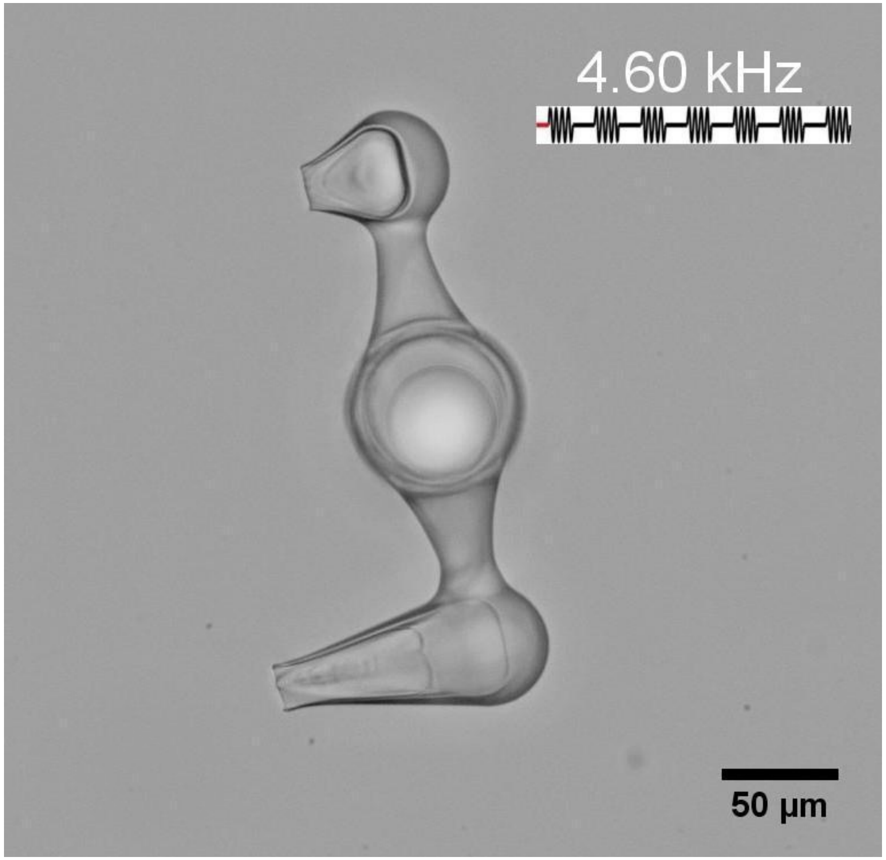
- Boundary (Rayleigh) streaming with sharp-edged structures



Acoustic control of motion



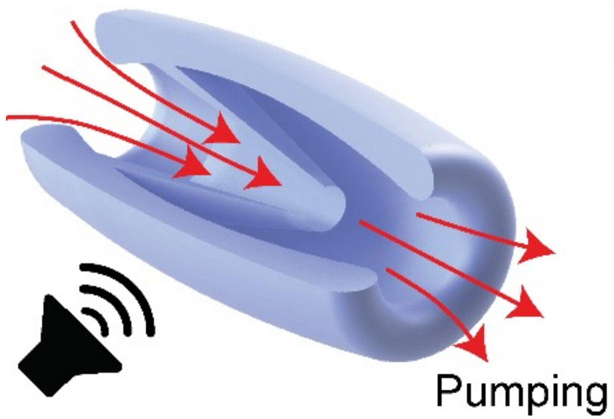
Frequency selective activation

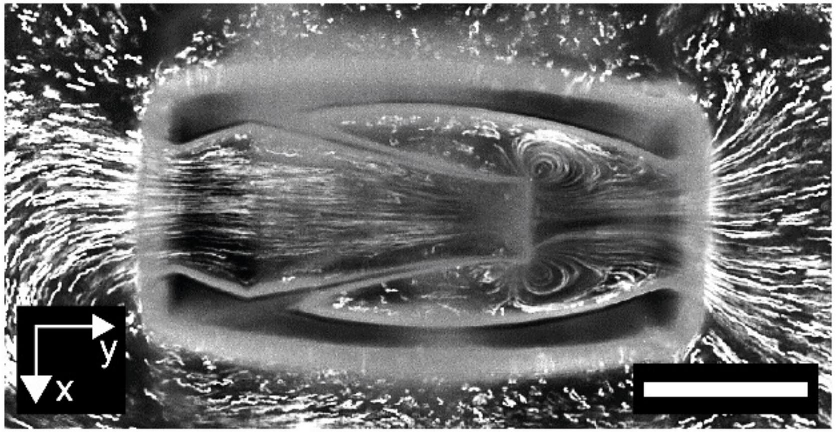


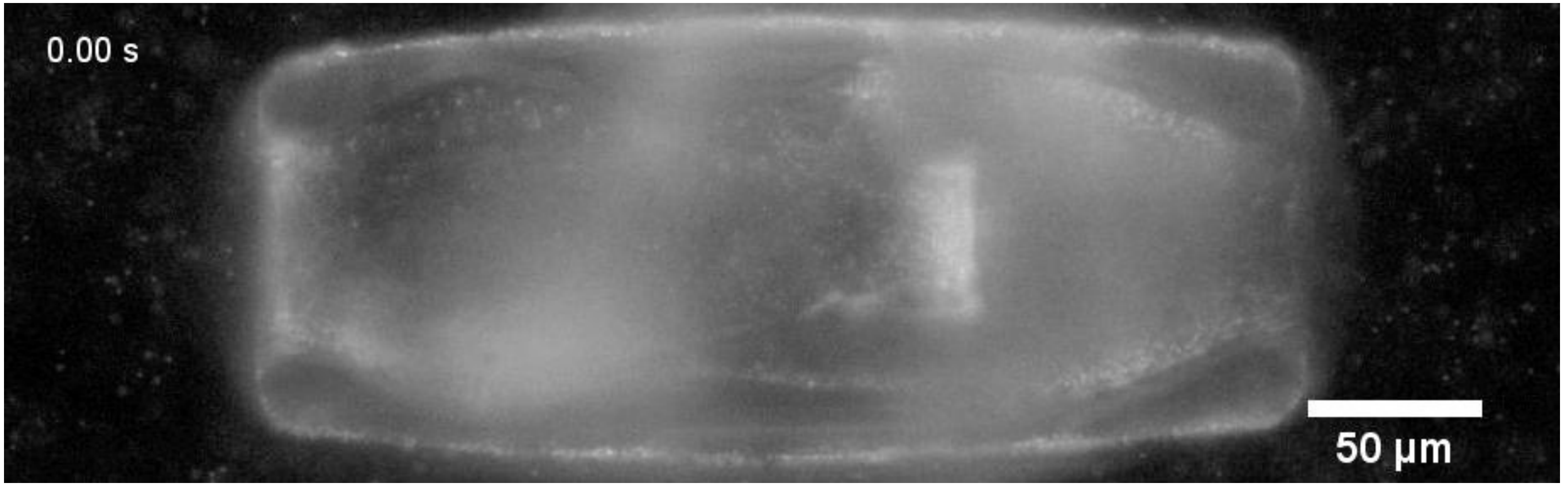
Pulse width modulation

3D printed untethered microfluidic pumps

- Cylindrical casing for channeling flow

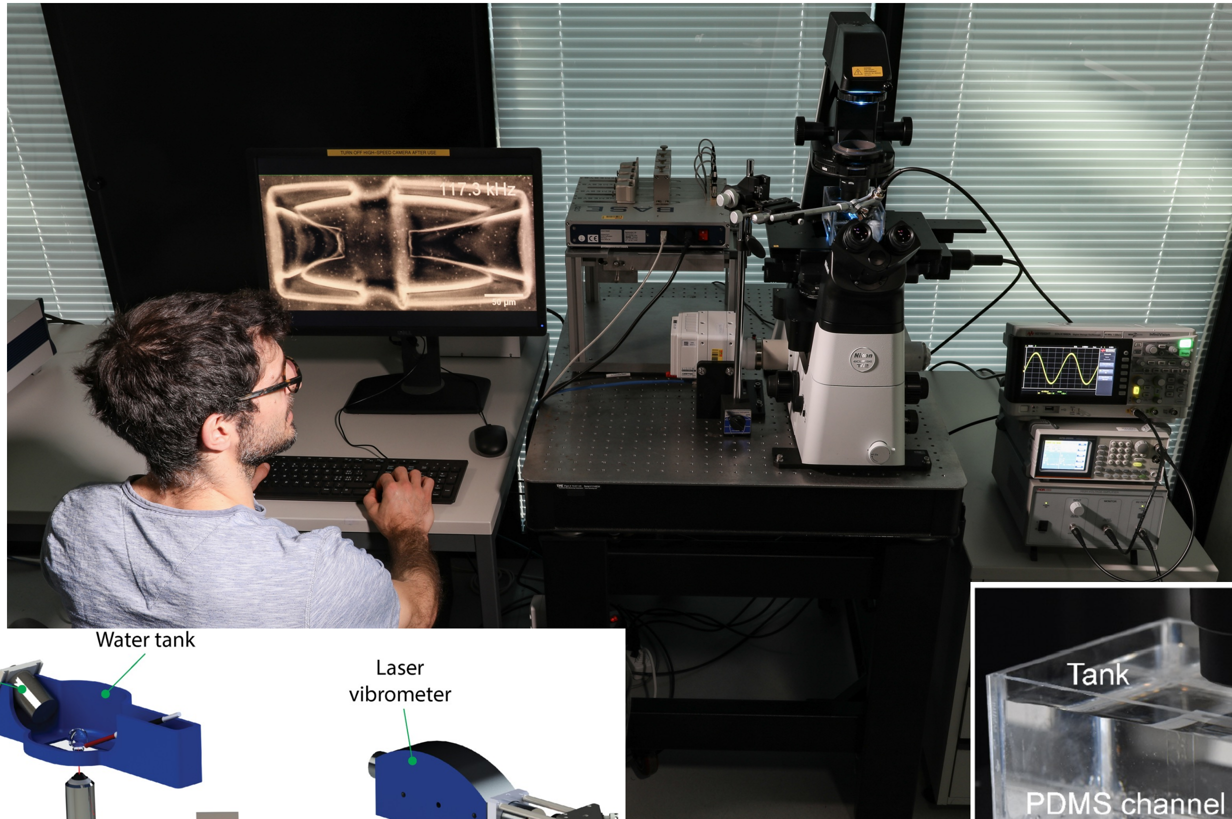


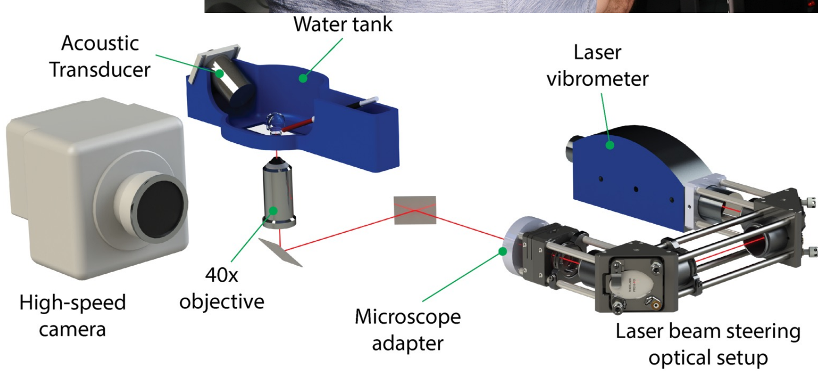


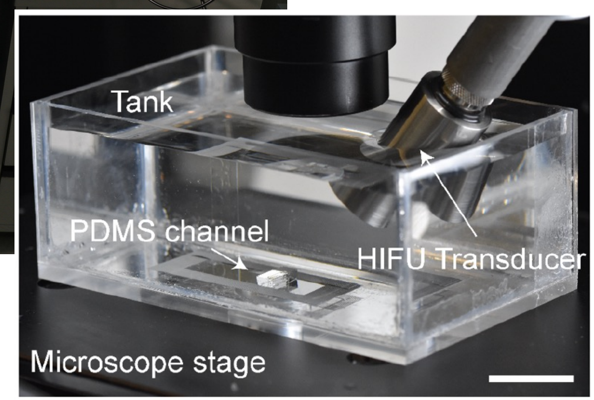


Experimental platform

- Clinically-relevant (focused) ultrasound powering
- High-speed imaging, flow visualization, laser vibrometer, hydrophones







Comparison Table

Type	Subtype	Advantages	Disadvantages	Applications
Standing-wave tweezers	Surface acoustic waves[40]	Precision (for example, the ability to manipulate nanoparticles);simple, compact, inexpensive devices and accessories	Low throughput (<1 mL/min); limited acoustic-field pattern	Nanoparticle manipulation, cell separation, cell patterning, cell concentration, 3D translation and rotation
	Bulk acoustic waves[71]	High throughput (e.g., 10 mL/min)	Limited precision; excessive heat generated due to high power	Cell separation, sample preparation, levitation of cells and small organisms
Traveling-wave tweezers	Active[43]	Flexibility (i.e., the ability to rewrite the acoustic field in real time)	Typically multiple transducers needed; multiplexed transmission system needed	Cell sorting, real-time cell patterning for bioprinting and tissue engineering, 3D translation and rotation of cells and droplets
	Passive[46]	Simple, easily fabricated structures;simple electronic control scheme	Generation of only a few acoustic-field patterns with one structure; complex simulation and calculations needed	Cell patterning, levitation of droplets, high-resolution ultrasonic imaging
Acoustic-streaming tweezers	Bubble based[36,52,72]	Selective frequency actuation	Unstable bubble size; limited reproducibility	Fluid mixing and pumping, 3D rotation of cells and small organisms, neural stimulation
	Solid structure based[53,54]	Stability and reproducibility; ability to handle highly viscous fluids (for example, blood and sputum)	Limited vibration patterns	Fluid mixing and pumping, 3D rotation of cells and small organisms