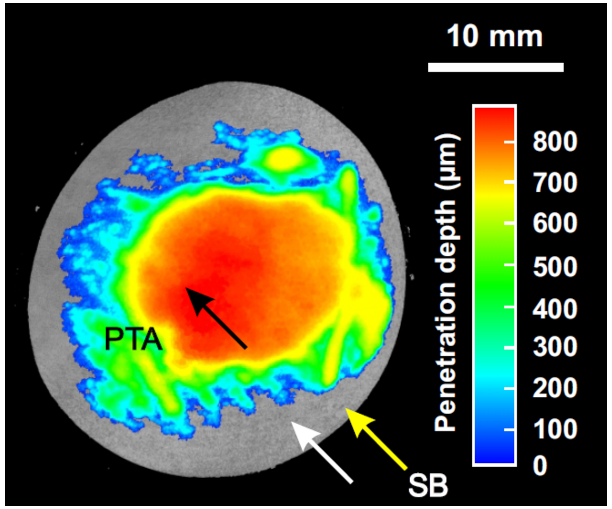
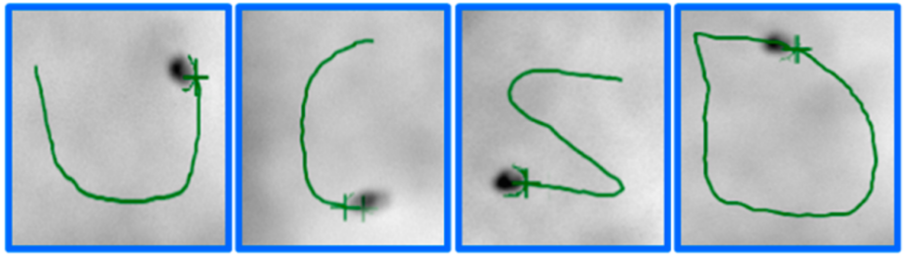
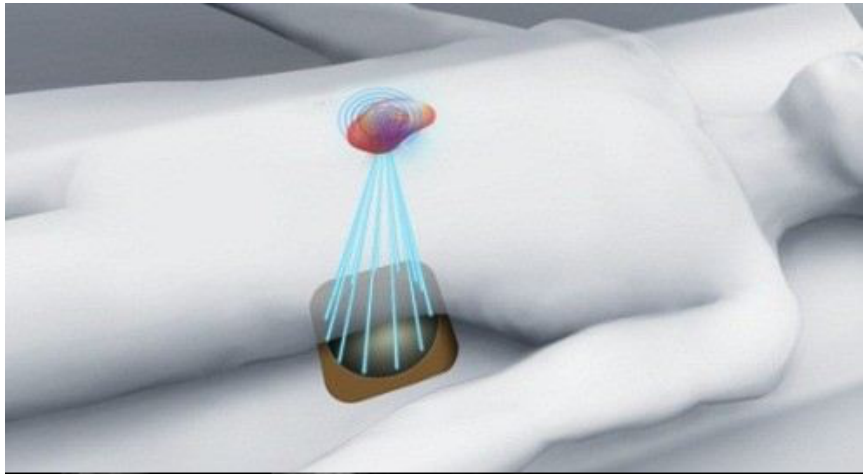
Biomedical Ultrasonics, 5 cr

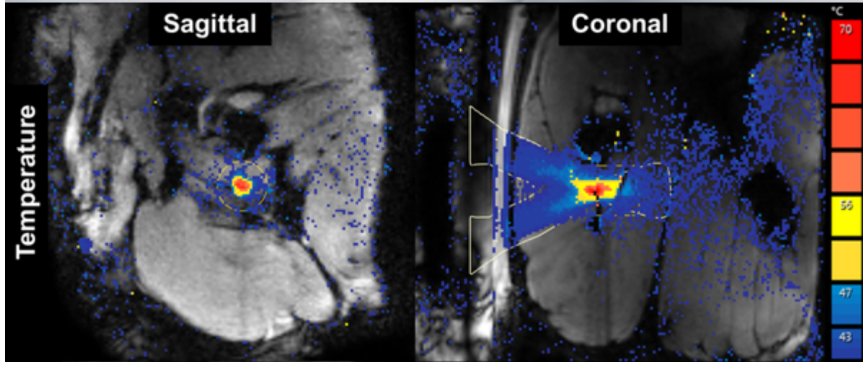
Heikki Nieminen

7.1.-31.5.2019

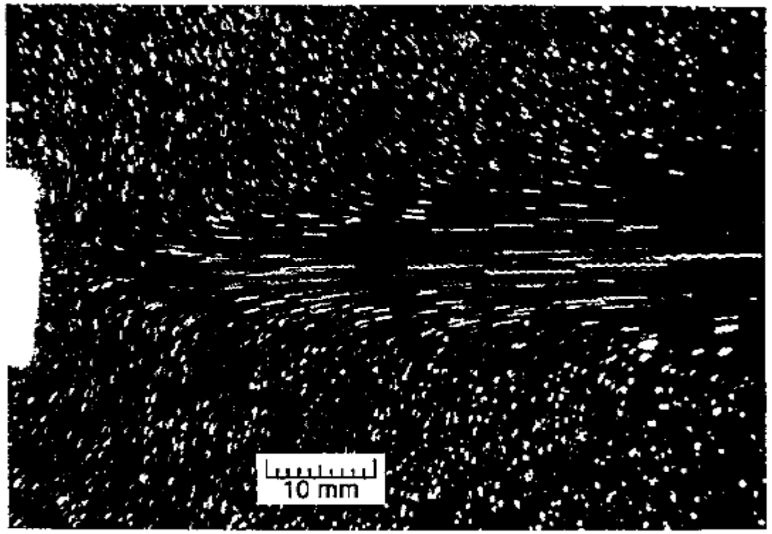






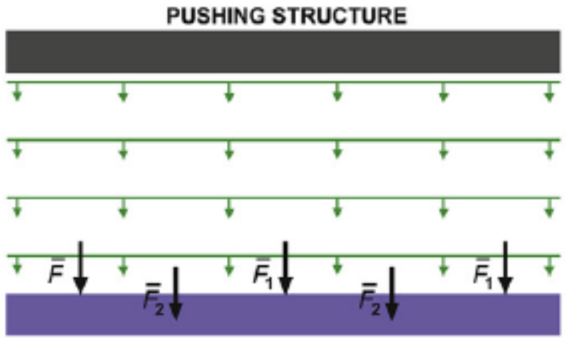


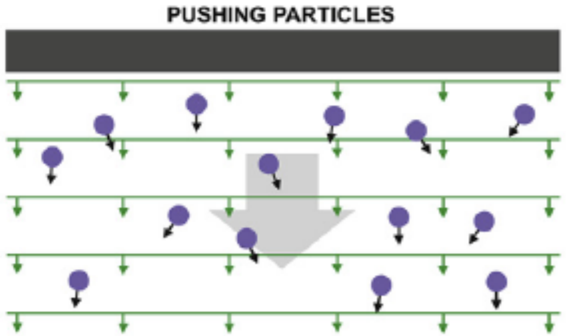
Acoustic streaming

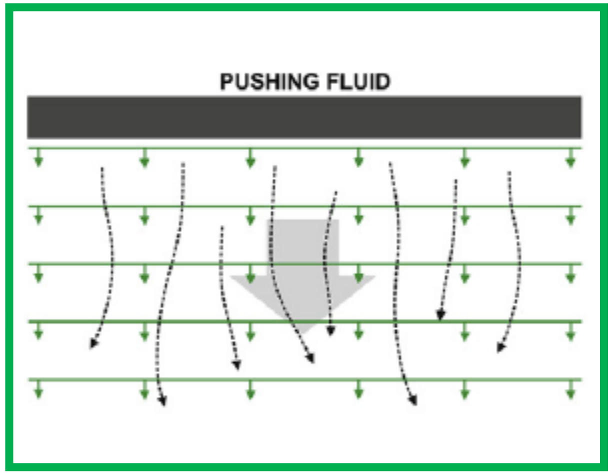


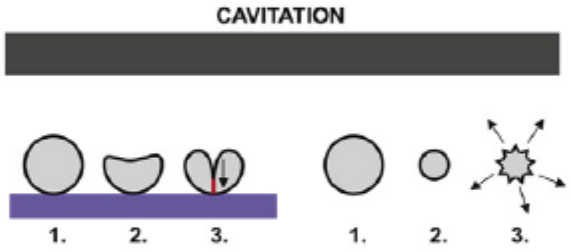
Duck et al 1998.

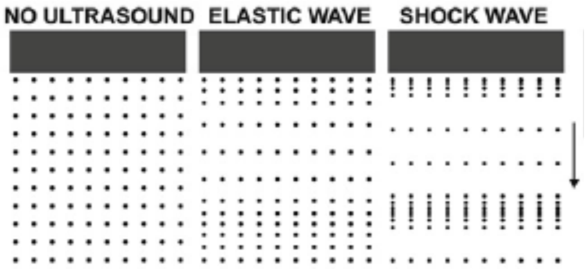
Non-linear ultrasonics

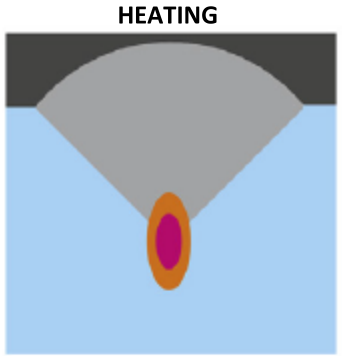

PUSHING STRUCTURE


PUSHING PARTICLES


PUSHING FLUID


CAVITATION




HEATING

Questions

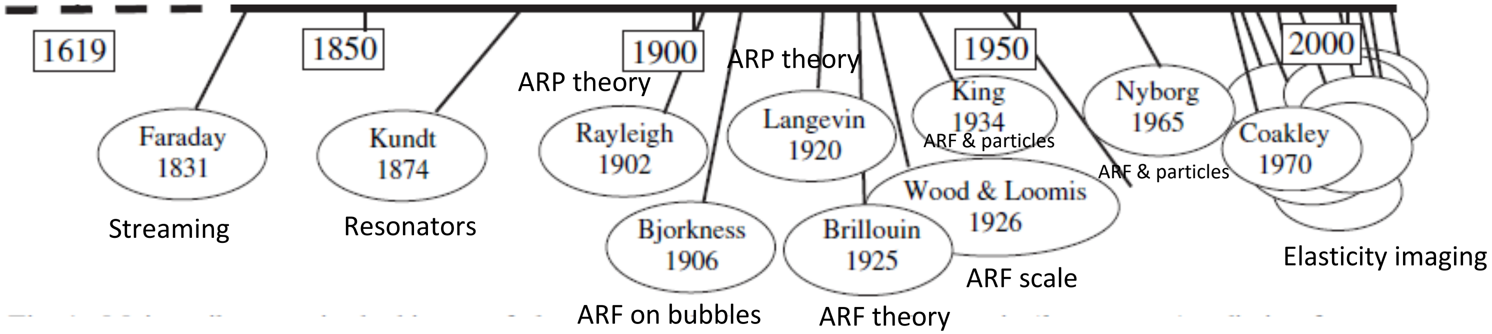
- What is needed to generate radiation force in tissue?
- What actually happens in the tissue when a constant radiation force is applied?
- What happens when the radiation force is applied on a fluid volume?

Acoustic streaming

- Acoustic streaming was originally discovered by Faraday in 1831
- Faraday observed that very light powder moved near a sound source

Michael Faraday
1791-1867

Major milestones of acoustic radiation force



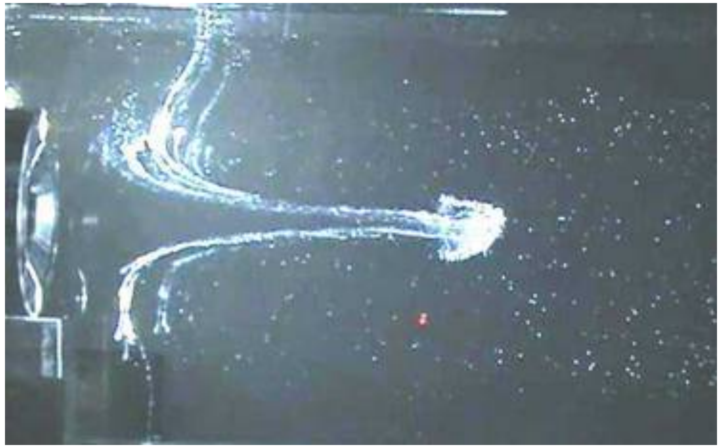
Reading:

Sarvazyan et al. 2010: http://www.sciencedirect.com/science/article/pii/S0301562910002450 (not accessible inside Uni. Helsinki)

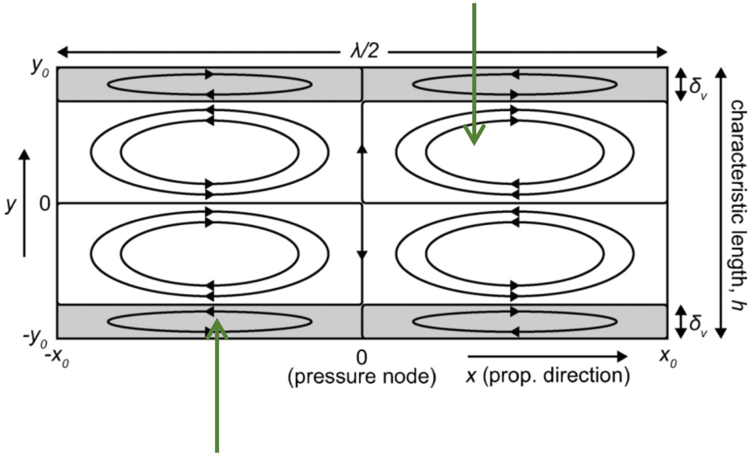
Acoustic streaming

- In the following, we deal with three forms of acoustic streaming:
  - Eckart streaming
  - Rayleigh streaming
  - Schlichting streaming

Eckart streaming

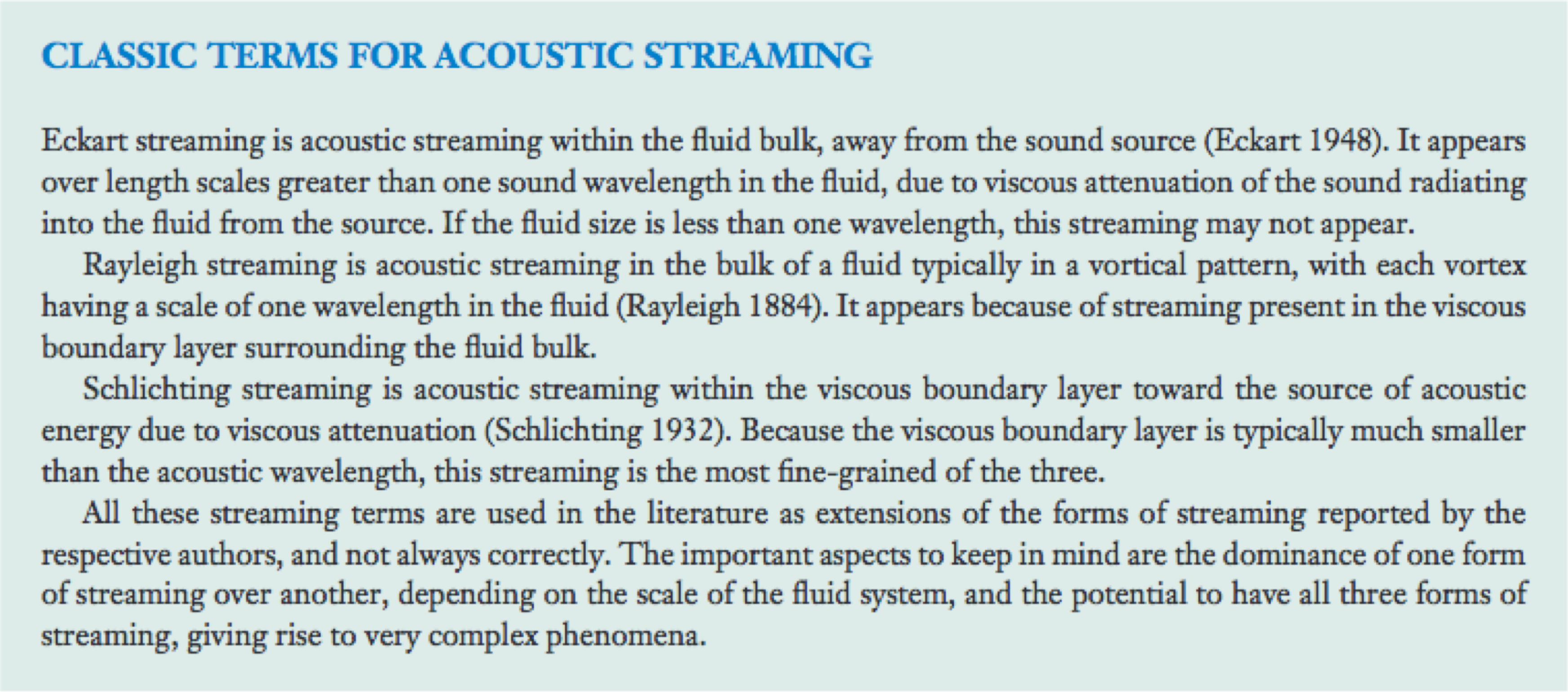


Rayleigh streaming



Schlichting streaming

Different forms of acoustic streaming



CLASSIC TERMS FOR ACOUSTIC STREAMING

Eckart streaming is acoustic streaming within the fluid bulk, away from the sound source (Eckart 1948). It appears over length scales greater than one sound wavelength in the fluid, due to viscous attenuation of the sound radiating into the fluid from the source. If the fluid size is less than one wavelength, this streaming may not appear.

Rayleigh streaming is acoustic streaming in the bulk of a fluid typically in a vortical pattern, with each vortex having a scale of one wavelength in the fluid (Rayleigh 1884). It appears because of streaming present in the viscous boundary layer surrounding the fluid bulk.

Schlichting streaming is acoustic streaming within the viscous boundary layer toward the source of acoustic energy due to viscous attenuation (Schlichting 1932). Because the viscous boundary layer is typically much smaller than the acoustic wavelength, this streaming is the most fine-grained of the three.

All these streaming terms are used in the literature as extensions of the forms of streaming reported by the respective authors, and not always correctly. The important aspects to keep in mind are the dominance of one form of streaming over another, depending on the scale of the fluid system, and the potential to have all three forms of streaming, giving rise to very complex phenomena.

http://www.annualreviews.org/doi/pdf/10.1146/annurev-fluid-010313-141418

Acoustic radiation force in fluids = **acoustic streaming**

- *Acoustic streaming a.k.a quartz wind*
- Radiation force in absorbing medium **(solid or fluid)**: $F_{abs} = 2\alpha\, I_{\mathrm{ta}} / c$

Unit: N/m^3 or Pa/m

Unit for α: Np/m

- The interpretation of this equation is that it actually is the *force excerted per volume unit* or *Pascals per length unit*
- By applying radiation force on absorbing fluid one can generate flow of fluid that is generated along the axis of sound propagation

Acoustic streaming

Particle transport

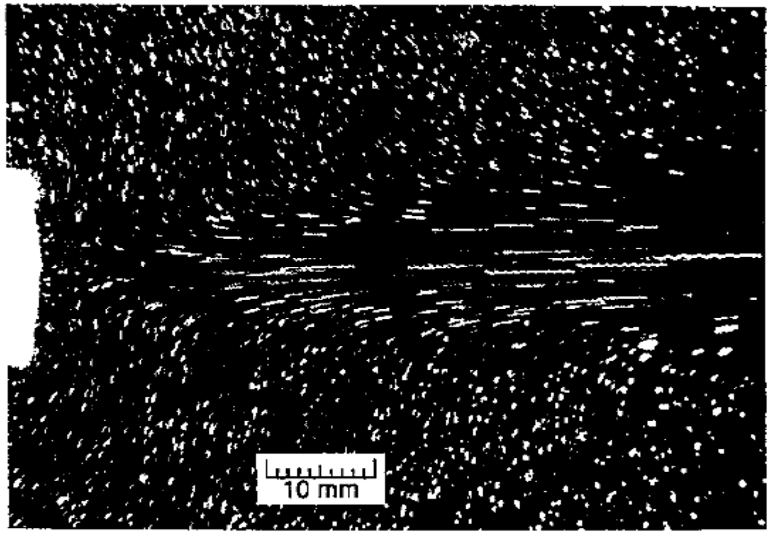


Figure 3.2. *Photograph of streaming motion induced in water by a weakly focused 1 MHz transducer. The radiation pressure field is shown in figure 3.1. Exposure time 1 s.*

Contrast agent transport

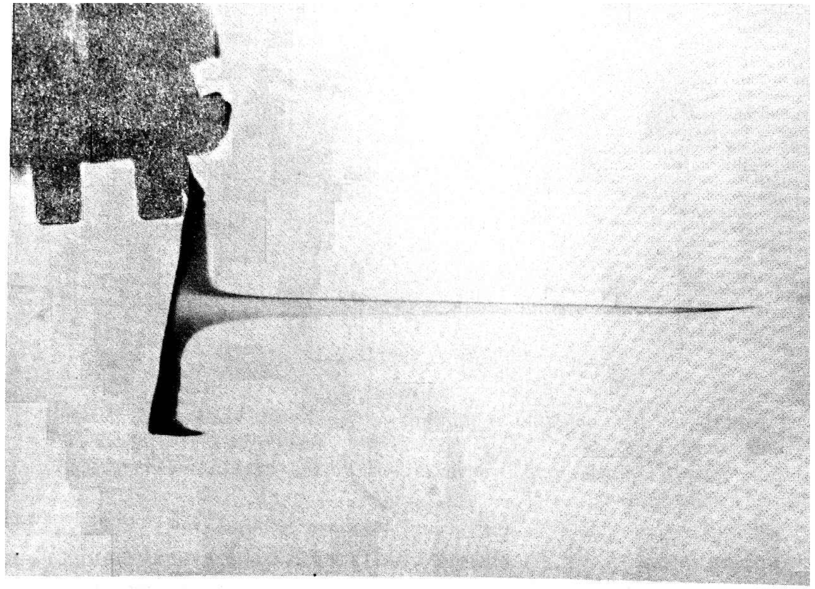


Figure 3.5. *Acoustic streaming demonstrated using thymol blue for a 3 MHz pulsed beam. (From* Starritt et al *(1991), with permission.)*

Radiation pressure example

- Describe how the axial and radial radiation pressures affect streaming:

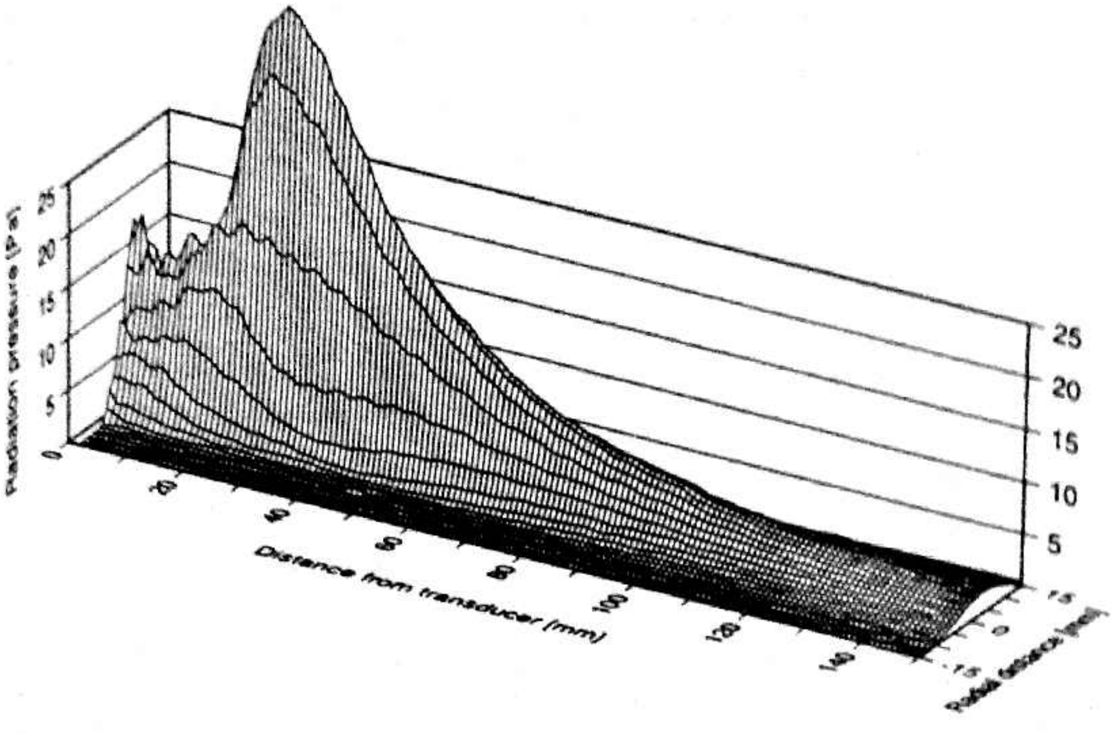


Figure 3.1. *Measured radiation pressure field from a weakly focused 1 MHz transducer. (From Hertz (1993) with permission.)*

Acoustic streaming video

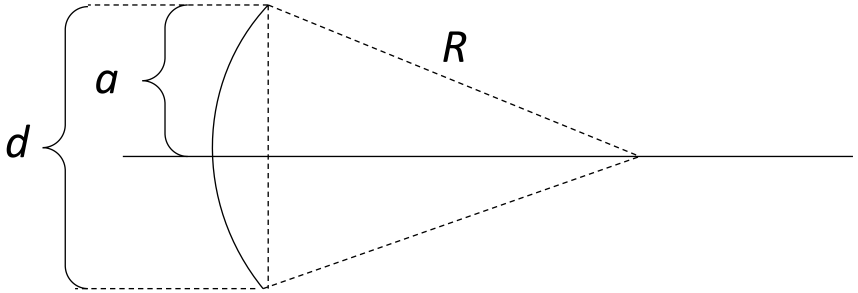
http://www.youtube.com/embed/ArpclLD4yP8

Streaming velocity

- Streaming velocity v in the focus of a focused beam can be approximated as follows:

$$v = \left(\frac{2\alpha I_{\mathrm{ta}}}{c\nu}\right) d^2 G$$

$\nu = \eta/\rho =$ kinematic viscocity
$\eta =$ shear viscocity

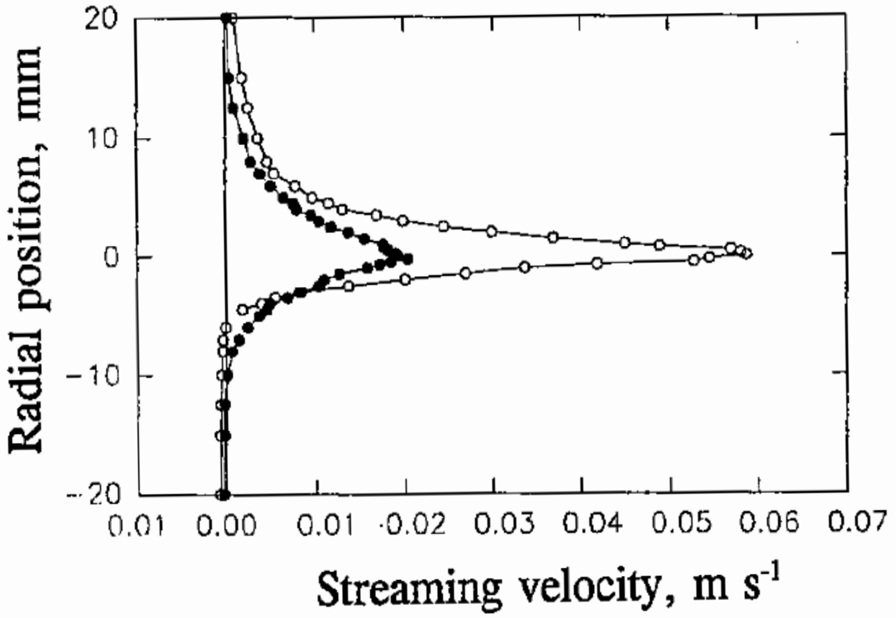


$G = \frac{\pi a^2}{\lambda R}$ is the geometric factor

Weak focus: $0 < G <= 2$
Medium focus: $2 < G <= 2\pi$
Strong focus $G < 2\pi$

- This streaming, *i.e.* Eckart streaming, is different to Rayleigh streaming, because there is net mass transfer
- Any absorption mechanism can contribute to the absorbtion term ”α” (shear viscosity, kinematic viscocity, ”excess absorption due to non-linearity etc.”)

CW LIUS vs. shocked pulsed beam



Total acoustic power was 150 mW in both cases. ● continuous wave, low amplitude beam; ○ strongly shocked pulsed beam, 1.4 μs pulse length, 10.1 kHz prf, 1.20 W cm^{-2} time-average intensity. The beam width at the focus was 2.5 mm.

The average intensitites are the same

Why do the streaming profiles differ?

Radiation pressure gradient in different tissues/media

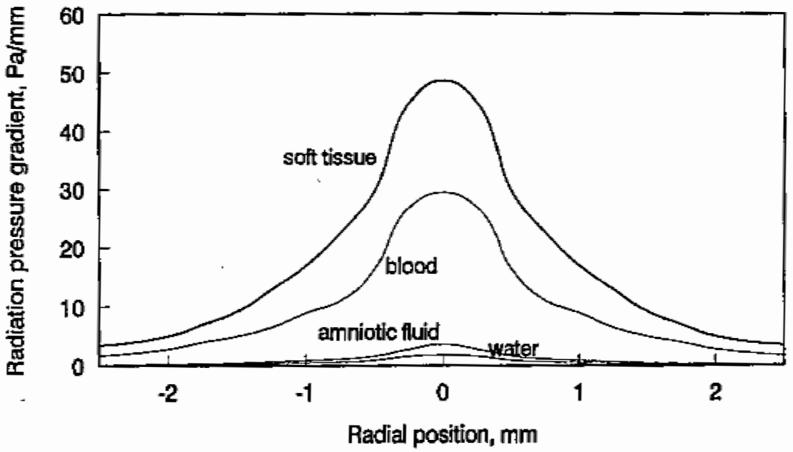


Figure 3.3. *Radial profiles of radiation pressure gradients calculated from measured pulse intensities at the focus of a shocked, weakly focused beam in water. Frequency 3 MHz; pulse-average intensity 118 W cm^{-2}.*

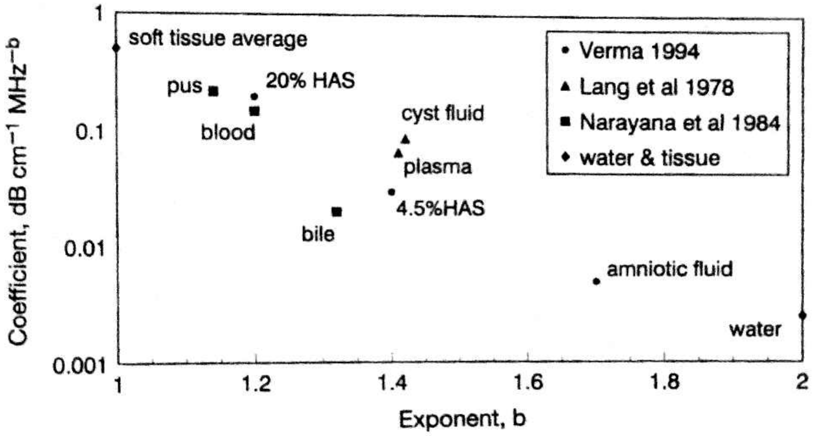


Figure 3.4. *Attenuation coefficient, α, for several biological liquids, expressed as $\alpha = af^b$ in dB cm^{-1} MHz^{-b}. The graph demonstrates the decrease of exponent from 2 (for water) to 1 (for soft tissue) as the attenuation at 1 MHz increases.*

Note the effect of attenuation coefficient, beam profile and the radiation pressure

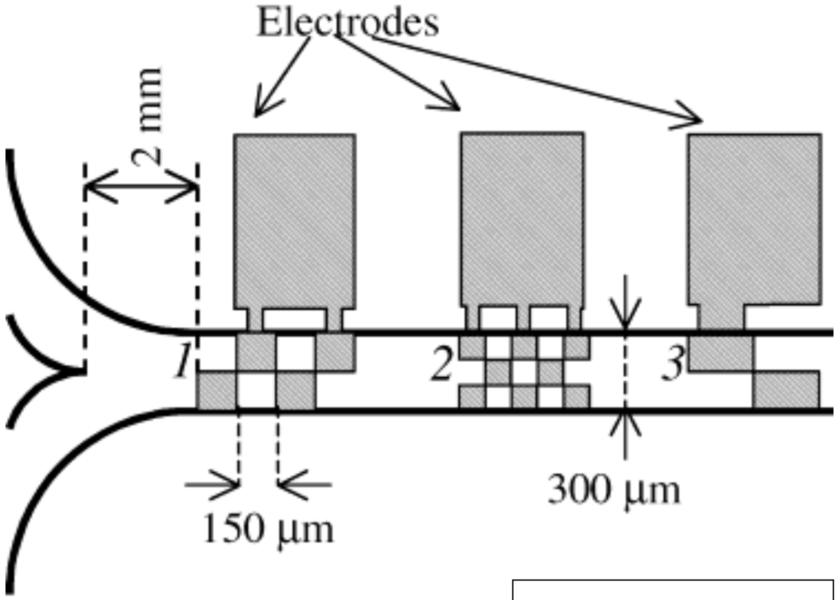
Acoustic streaming *in vivo*

- Acoustic streaming is relatively commonly observed in the clinical context during imaging, but poorly documented
- Examples of streaming in vivo:
    - Cyst fluid in breast, ovary and testicle
    - Ventricular hemorrhage
    - Liquified vitreous humour

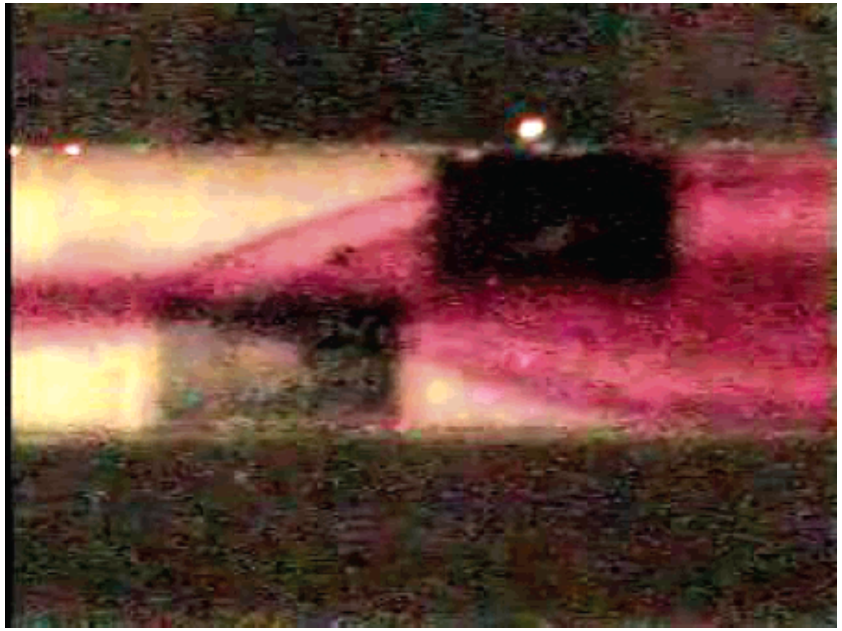
Acoustic streaming examples

Ultrasound-induced streaming turbulence

- **Acoustic streaming**
- Micro-fluidic mixer

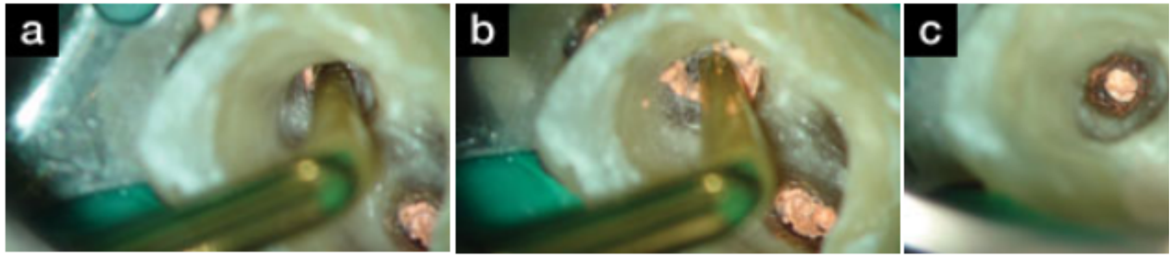


p_0 = 816 kPa
f = 450 MHz

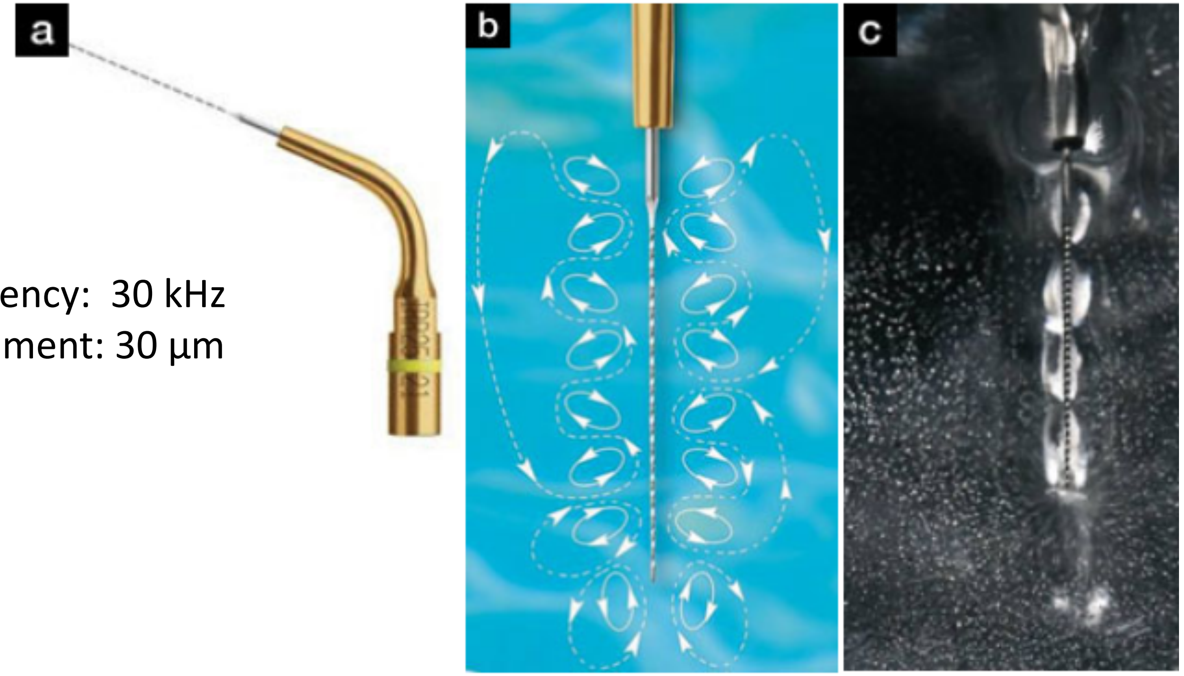


Yaralioglu *et al. Anal. Chem. (*2004);76:3694-3698.

Dental irrigation



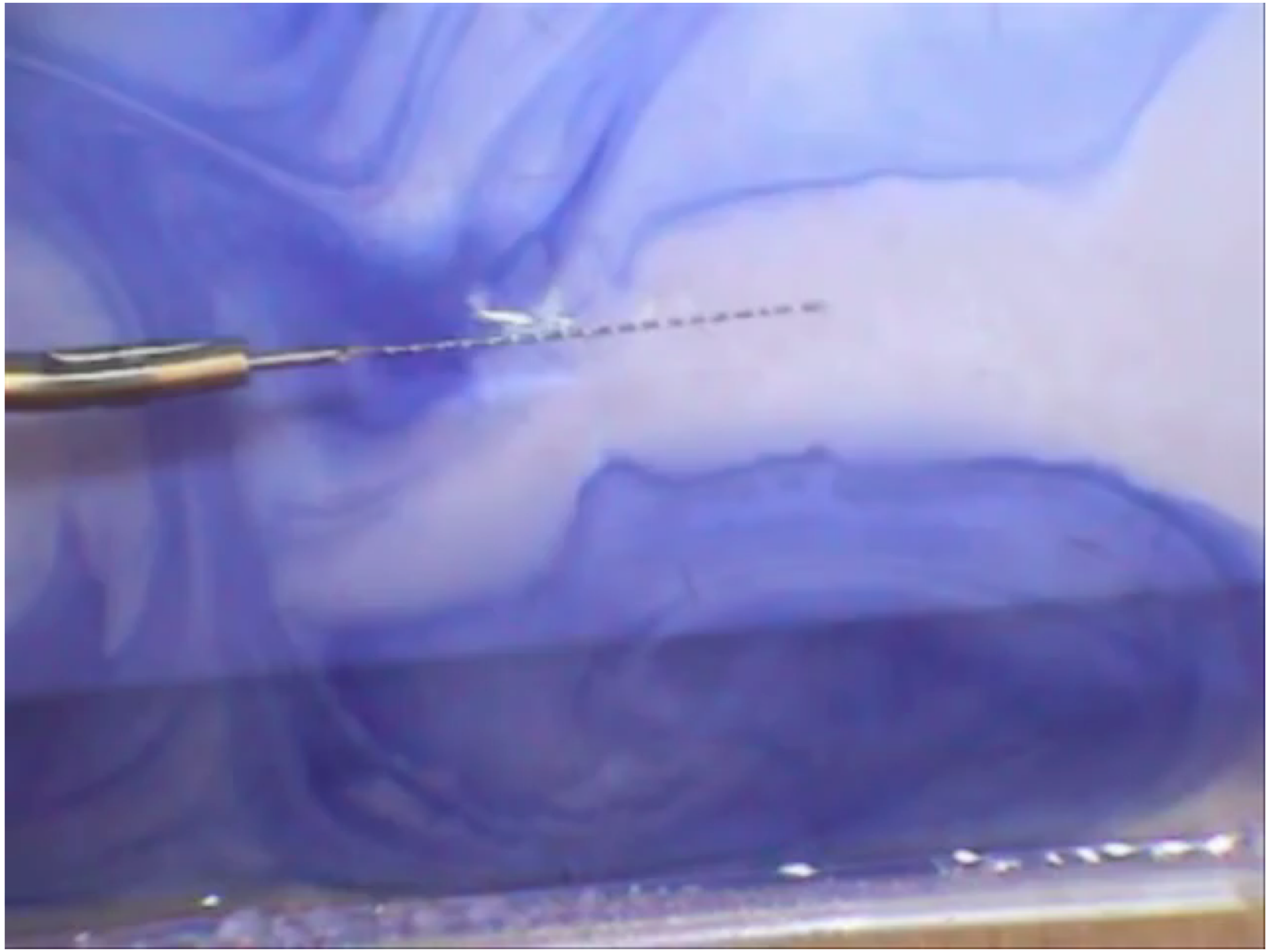
Figures 13a to 13c. BL-5 tips used deeper in the canal. (Courtesy of Dr. Yoshi Terauchi, Japan)



Operating frequency: 30 kHz
Surface displacement: 30 µm

http://www.dentistrytoday.com/endodontics/6067-ultrasonics-in-endodontics-luxury-or-necessity

Acteon IrriSafe



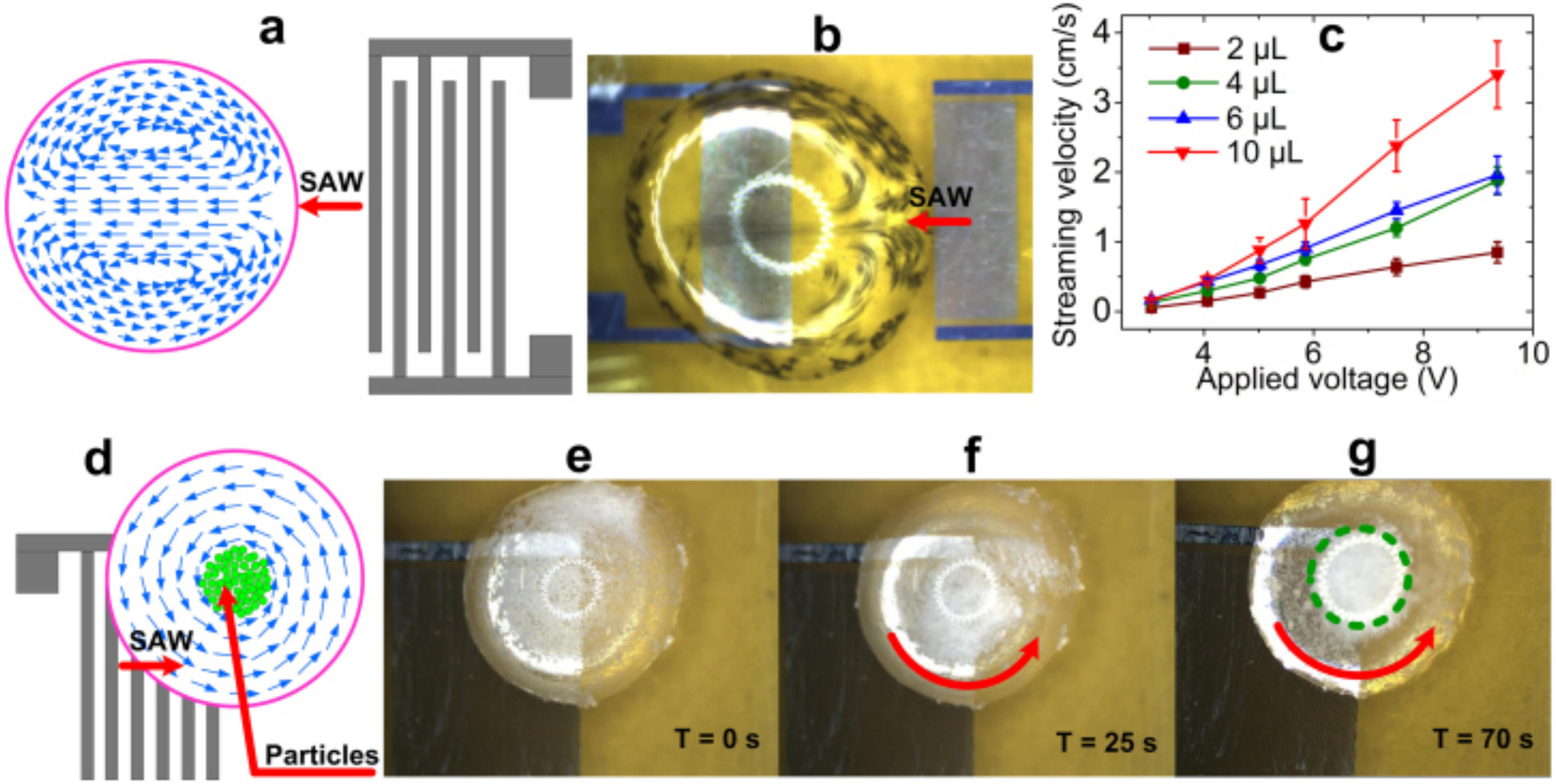
https://www.youtube.com/watch?v=3jaTPpEthTs

Acoustic streaming (SAW)

Micro-centrifuging by breaking the symmetry

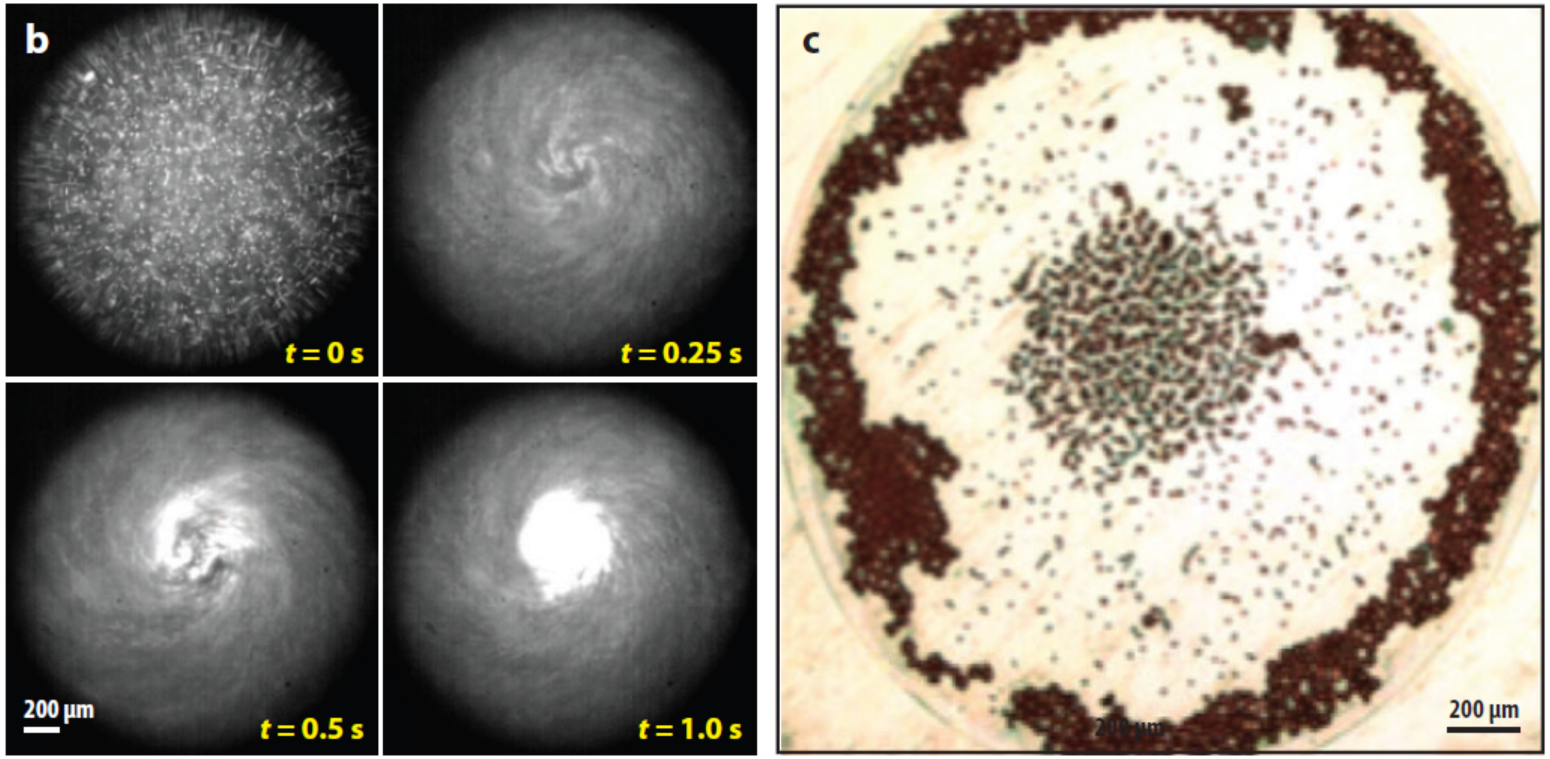
Leslie et al 2013: http://www.annualreviews.org/doi/pdf/10.1146/annurev-fluid-010313-141418

Micro-centrifuging in small droplet



Jin et al 2013: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3701897/

Micro-centrifuging in micro-droplet

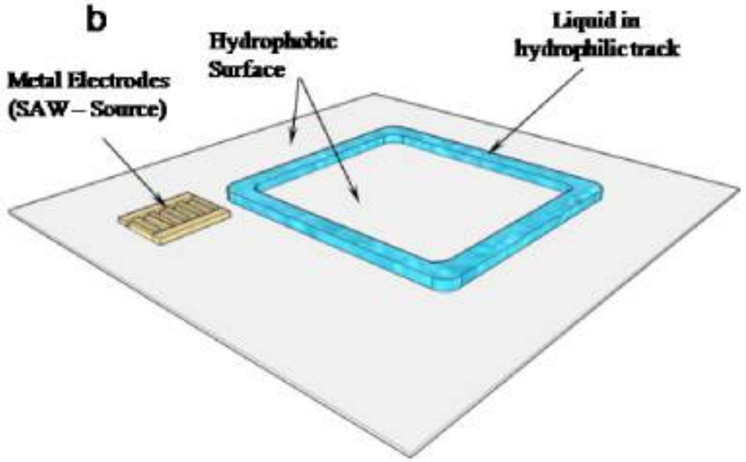


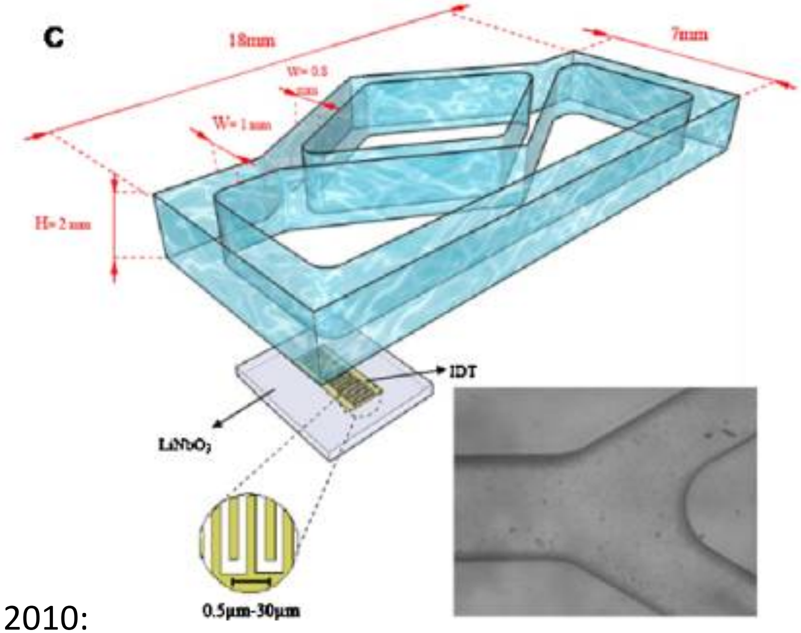
Note the very short time scale!

Leslie et al 2013:
http://www.annualreviews.org/doi/pdf/10.1146/annurev-fluid-010313-141418

How could this be used for drive-in?

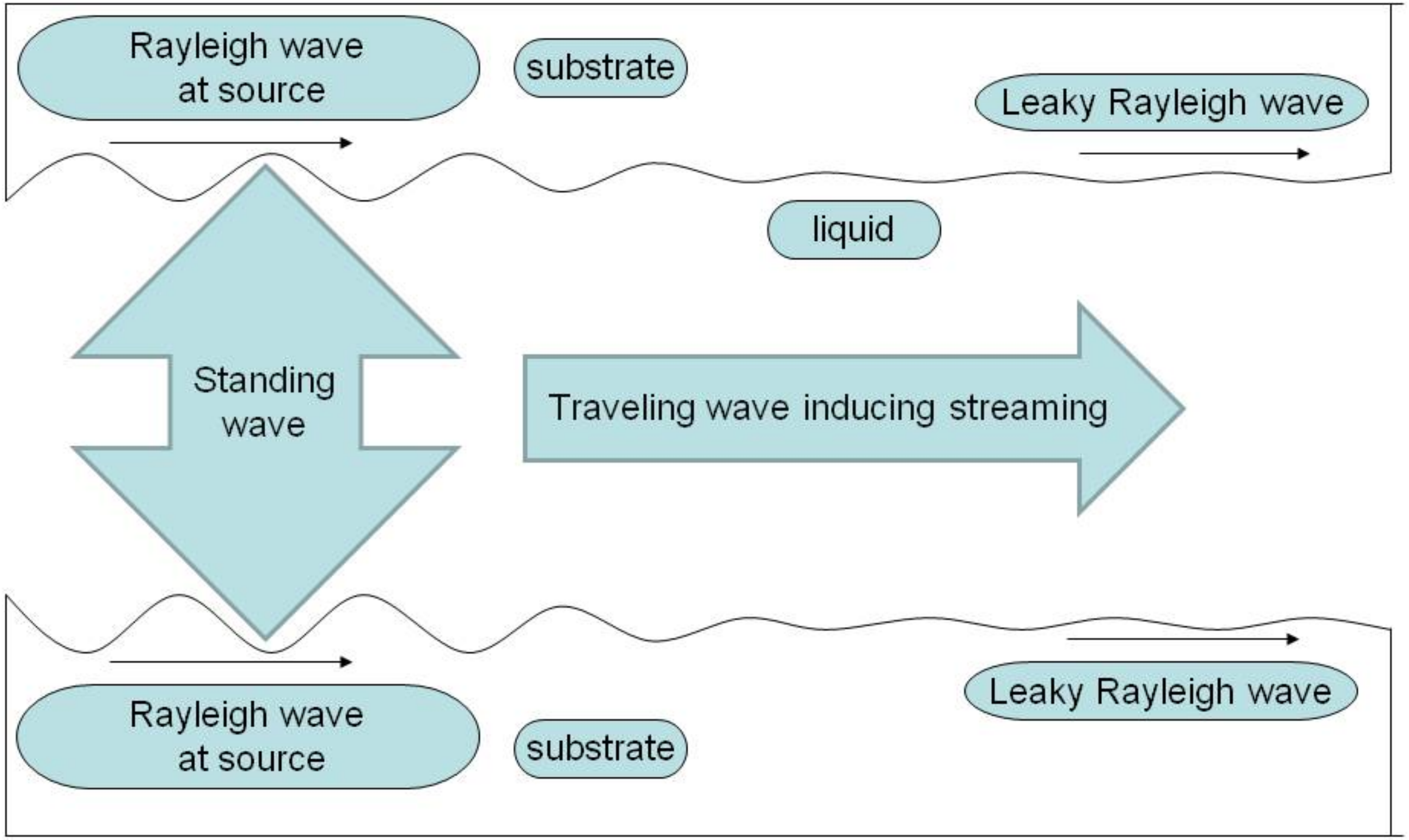
Functionalized micro-fluidic channel to study cell adhesion





Fallah et al. 2010:
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2917880/

Micro-pump


Rayleigh wave at source
substrate
Leaky Rayleigh wave
liquid
Standing wave
Traveling wave inducing streaming
Rayleigh wave at source
substrate
Leaky Rayleigh wave

SAW mixer

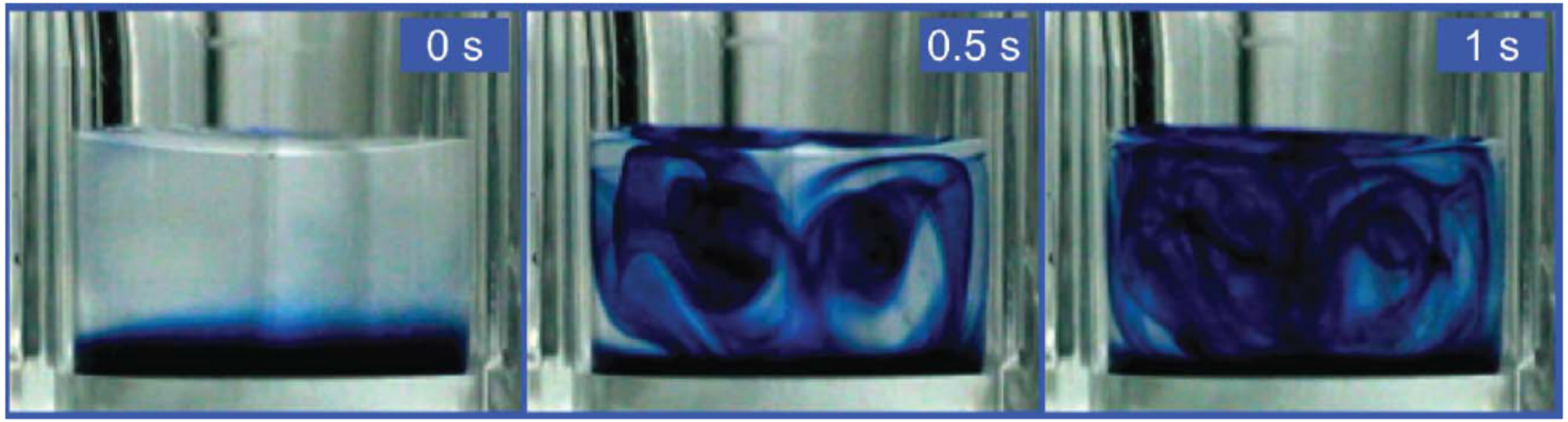


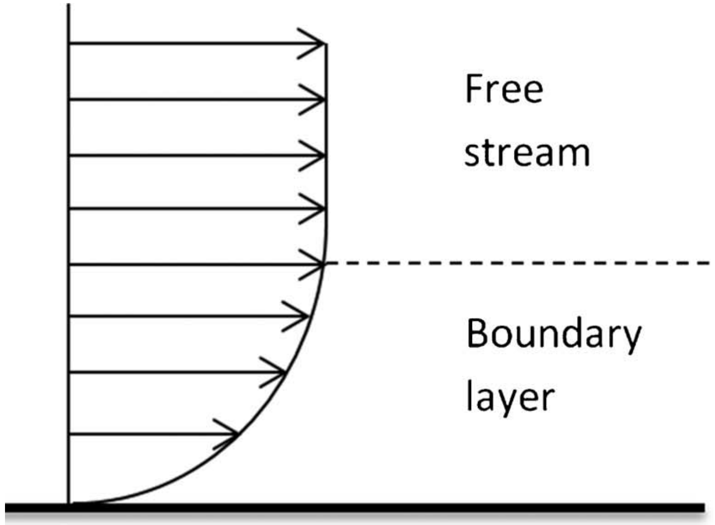
Fig. 14 Surface acoustic wave (SAW) induced mixing in one well in a 96-well plate. The well diameter is approx. 6 mm. Figure taken from Wixforth.[73]

Wiklund et al. 2012: http://pubs.rsc.org/en/content/articlepdf/2012/lc/c2lc40203c

Rayleigh and Schlichting streaming

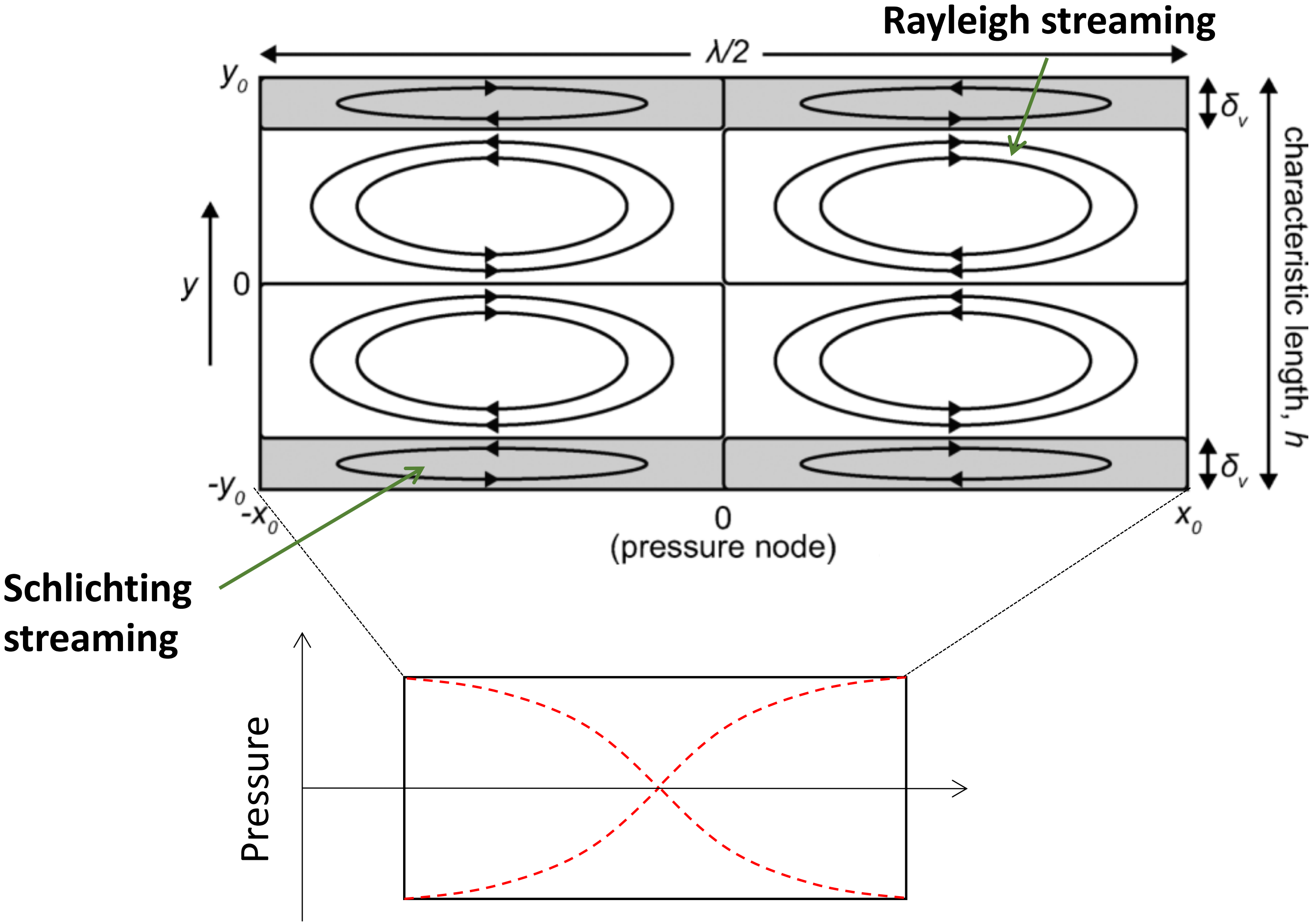
Schlichting streaming

- We have learned that absorption of sound energy is converted to streaming
- Dissipation is amplified at boundaries due to viscosity
- Boundary layer:



Wiklund et al 2012: https://www.aphys.kth.se/polopoly_fs/1.489548!/Wiklund%20Lab%20Chip%202012_2.pdf

Rayleigh streaming in a closed λ/2 resonator

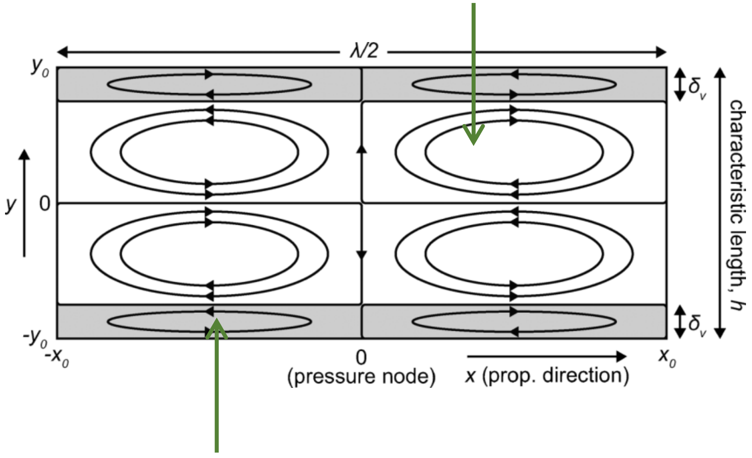


Rayleigh streaming

Schlichting streaming

Agglomeration of 10μm polymer beads

Rayleigh streaming



Schlichting streaming

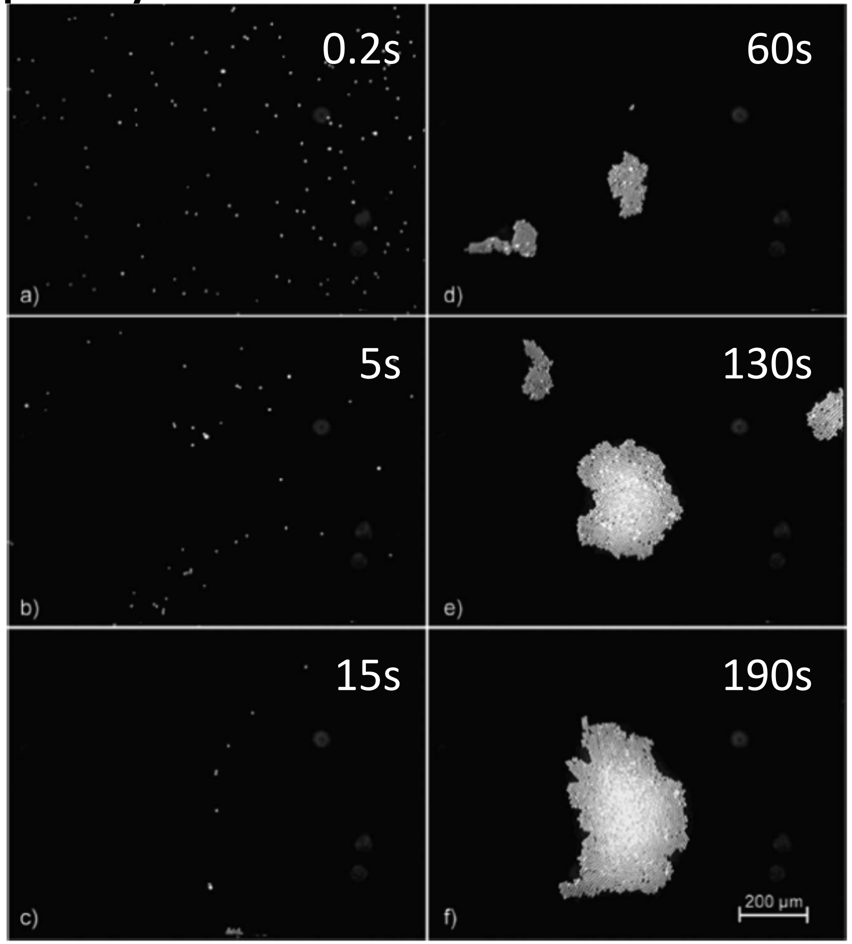
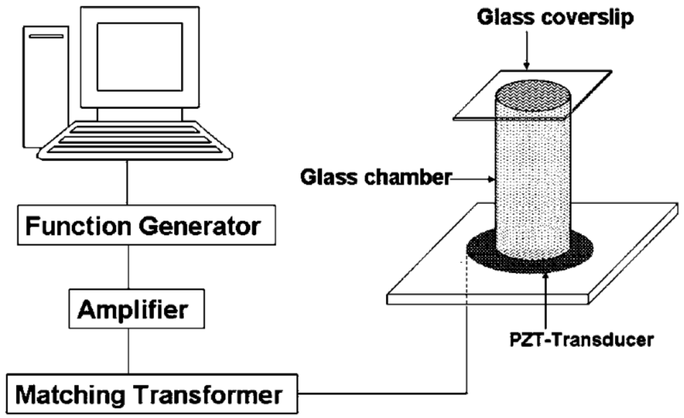
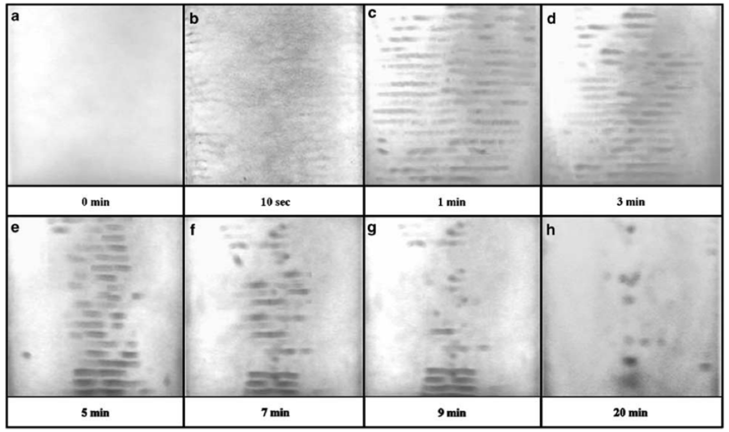


Fig. 6 In-plane development of an aggregate of 10 μm polymer beads at times (a) 0.2 s, (b) 5 s, (c) 15 s, (d) 60 s, (e) 130 s, and (f) 190 s. Once driven to the pressure nodal plane, the beads initially move away from the center of the field of view due to Rayleigh streaming (a–c). They interact off camera and return as compact mini-aggregates (d–e). The packing of the growing central aggregate adjusts to incorporate these merging mini-aggregates (f). The figure is taken from Spengler and Coakley.[29]

http://pubs.rsc.org/en/content/articlepdf/2012/lc/c2lc40203c

Enhanced gene delivery with combination of radiation force and streaming





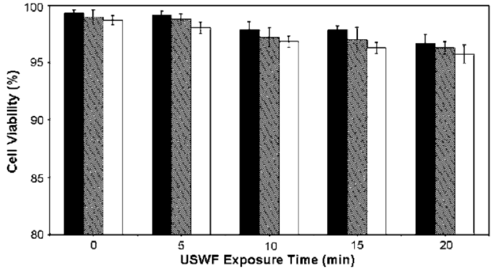
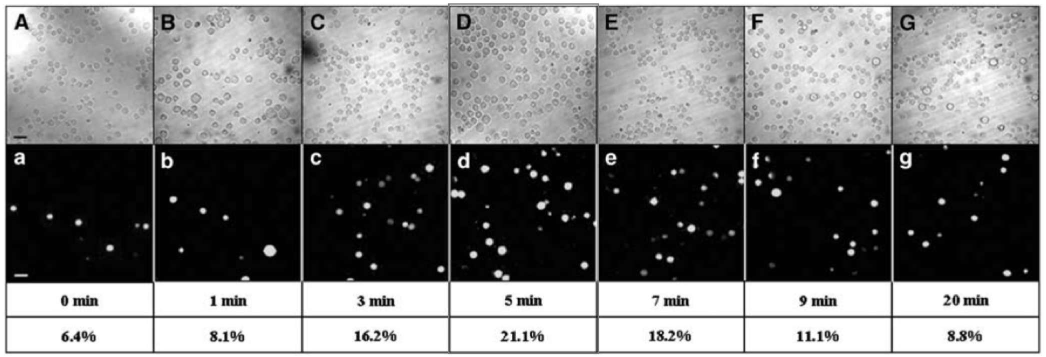


Figure 3 Viability of K562 cells after exposure to USWF for various times. Followed by USWF exposure for 0, 5, 10, 15, and 20 min, cell viabilities of K562 cells were determined right away (■), after 24-h (▨), and after 48-h incubation (□), using a hemocytometer with the trypan-blue exclusion method. Each bar represents the mean of three independent experiments. Error bars are standard error of the mean cell viability ($P < 0.05$).



Percentage of K562 cells with eGFP expression at various USWF exposure times.

What is the radiation force of retroviruses (100 nm size) vs.
Radiation force on K562 leukemia cells (um range)?

Lee et al 2005: http://www.nature.com/gt/journal/v12/n7/abs/3302444a.html