Acoustic Resonance and Atomization for Gas-Liquid Systems in Microreactors

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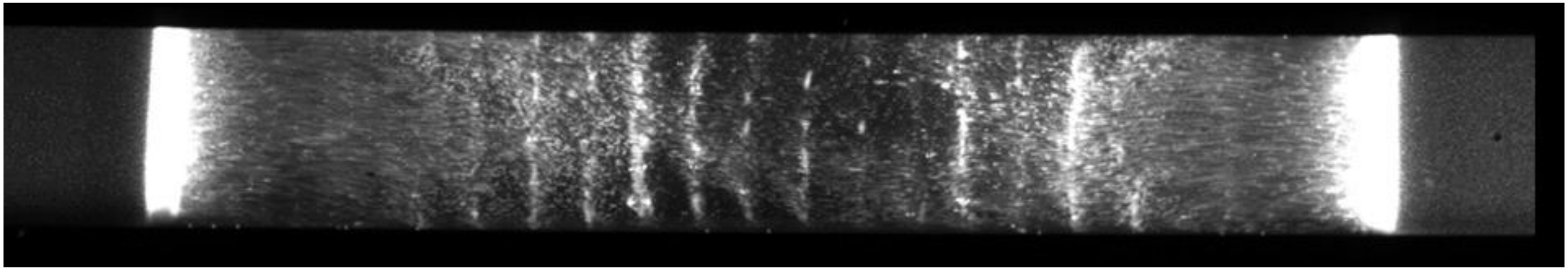


Workshop Kavitation --- Drübeck 30.11.+01.12.2021

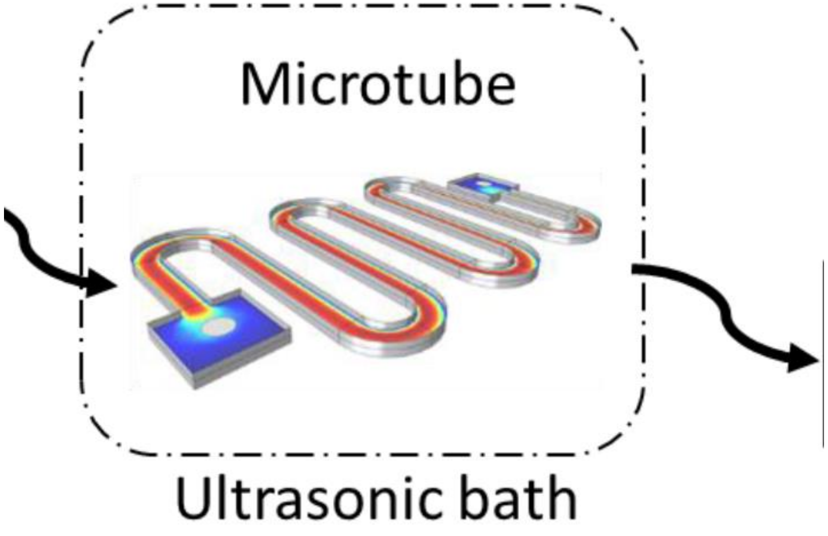
Background

Sonochemistry
is traditionally working in
<u>batch reactors</u>

www.sonomechanics.com

A recent new paradigm:
Process intensification via
<u>sonicated small scale flow reactors</u>

→ better process control
→ use the raw material efficiently and reduce waste
→ improve product quality
→ ease the scale-up



Pradhan et al., Molecules 2019, 24, 331

Sonochemical micro-flow reactors

Several possible geometries to sonicate the small channels:

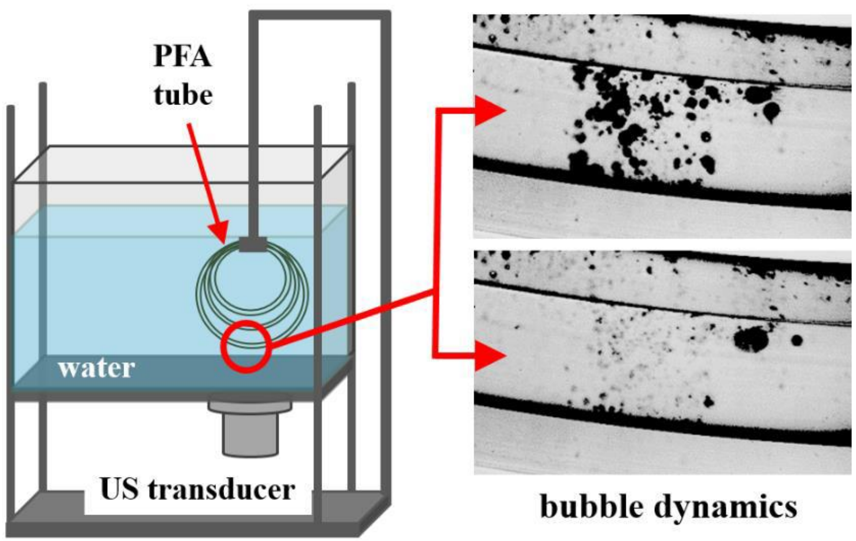
→ submerged tubes in bath (coupling liquid)

→ tubes clamped or glued directly on transducer

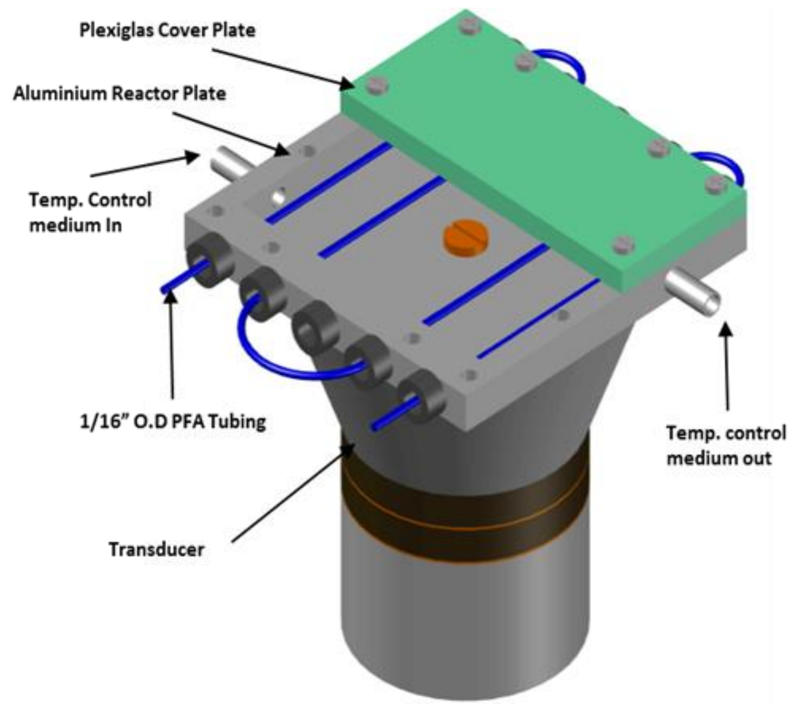
→ machined or etched channels mounted on transducer

→ combinations

→ …



Sarac et.al. Chem. Eng. Process. Process Intensif ***150*** *(2020)*



John. et.al. Chem. Eng. Process. Process Intensif. ***102*** *(2016)*

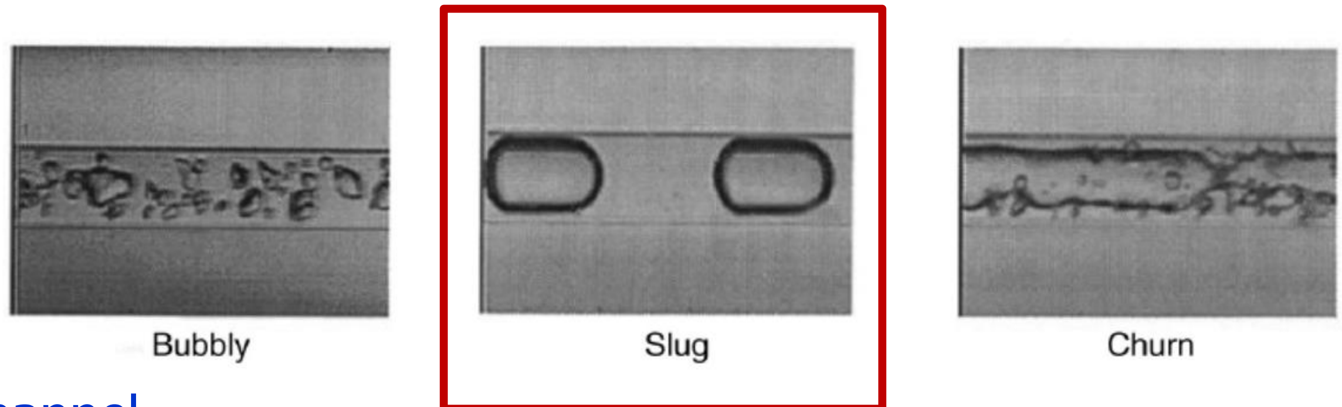
How to initiate cavitation?

In any case cavitation in small enviroment:

→ milli- and micro-channels

→ small liquid volumes, clean walls, no air contact

→ cavitation bubble **nucleation** can be a problem!



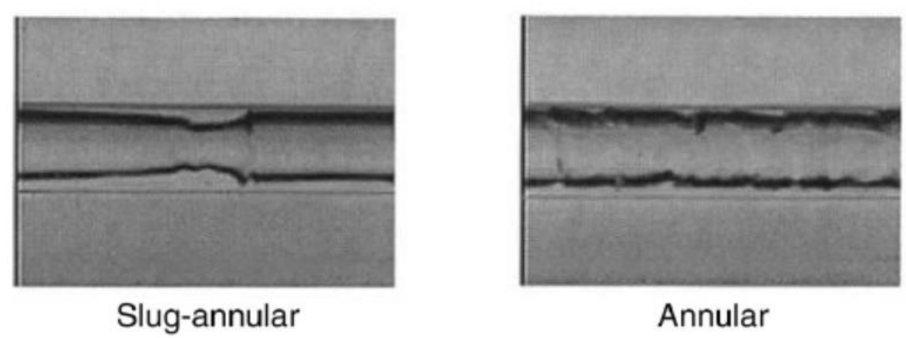
One approach:

gas phase in the channel

→ **"Taylor flow"**

= gas/liquid slug flow

→ "free" boundaries

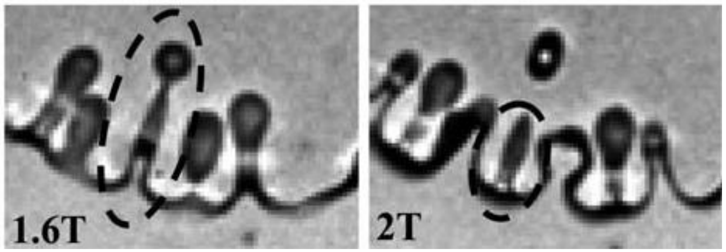


Gupta et al. 2010, after Triplett et al. 1999

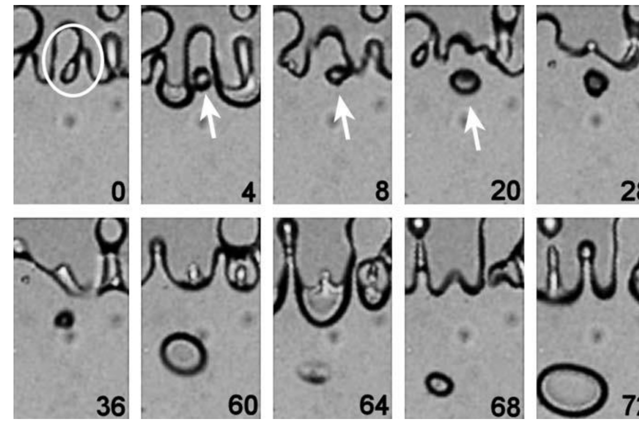
Nucleation at liquid / gas phase boundary

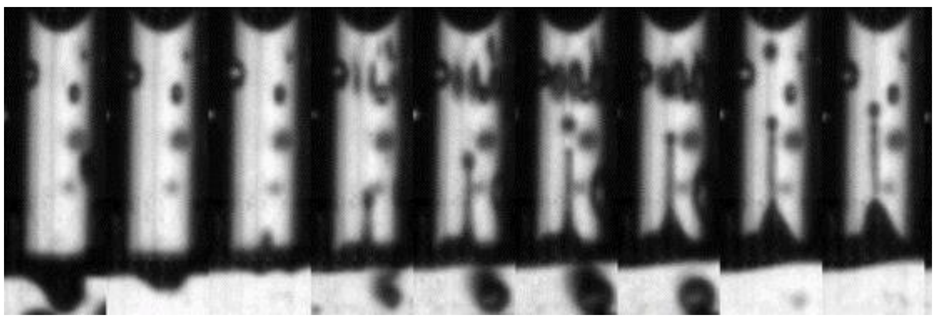
Capillary waves → bubble seeding (gas into liquid)

→ droplet ejection (liquid into gas)

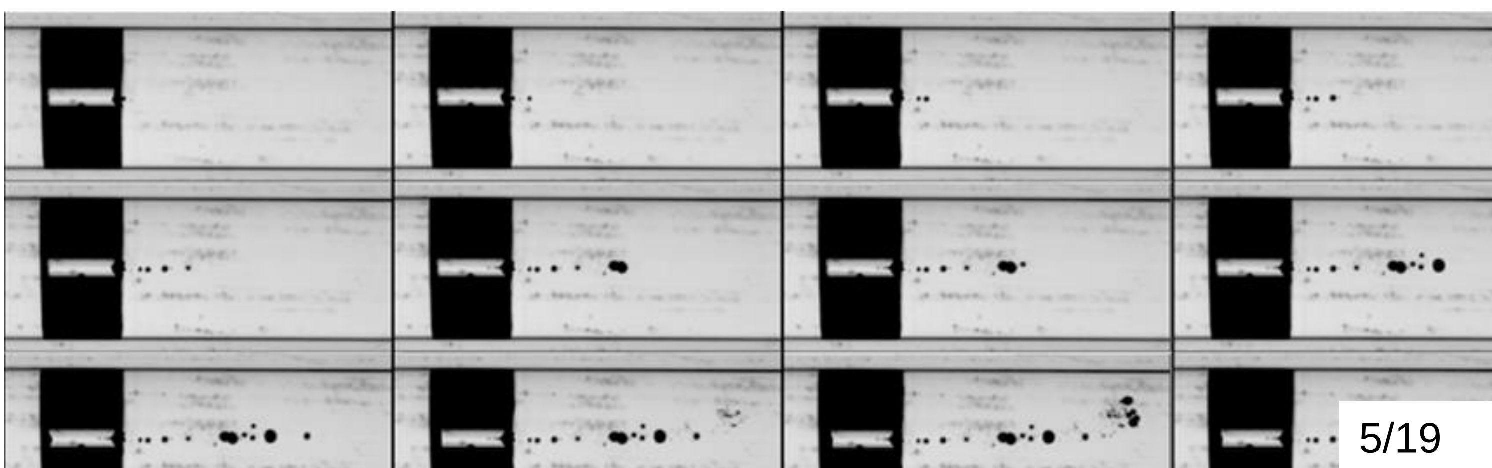


Tandiono et al. Lab Chip 10 (2010)
100 kHz





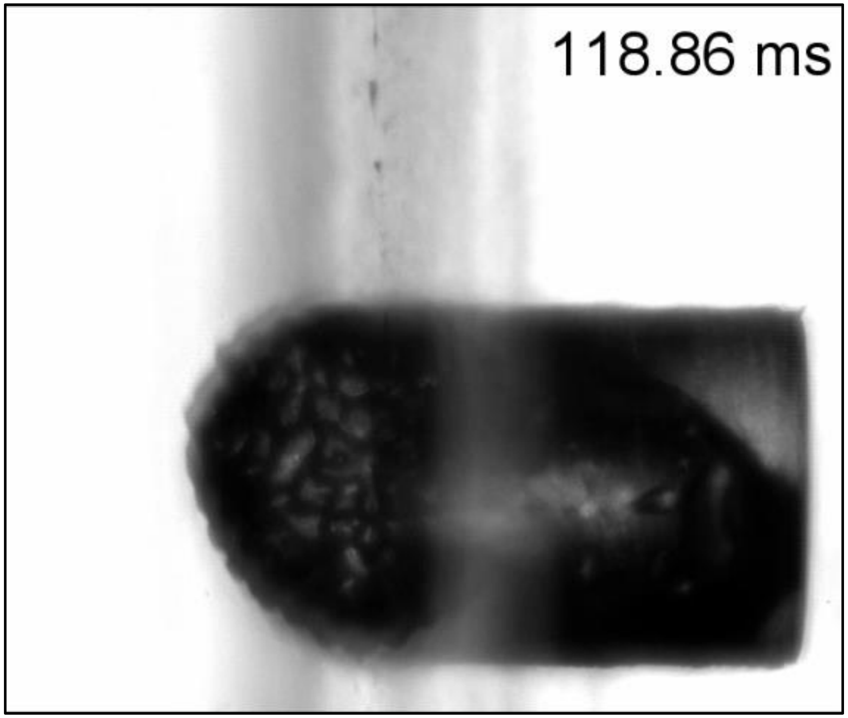
Sarac et.al., Chem. Eng. Process. Process Intensif ***150*** *(2020)*
25 kHz



Reminder: Ultrasonic wetting of holes

(last Workshop Drübeck 2019)

Let‵s focus on the drops now!



M. Kauer et al., Ultrasonics Sonochemistry, 48 (2018)

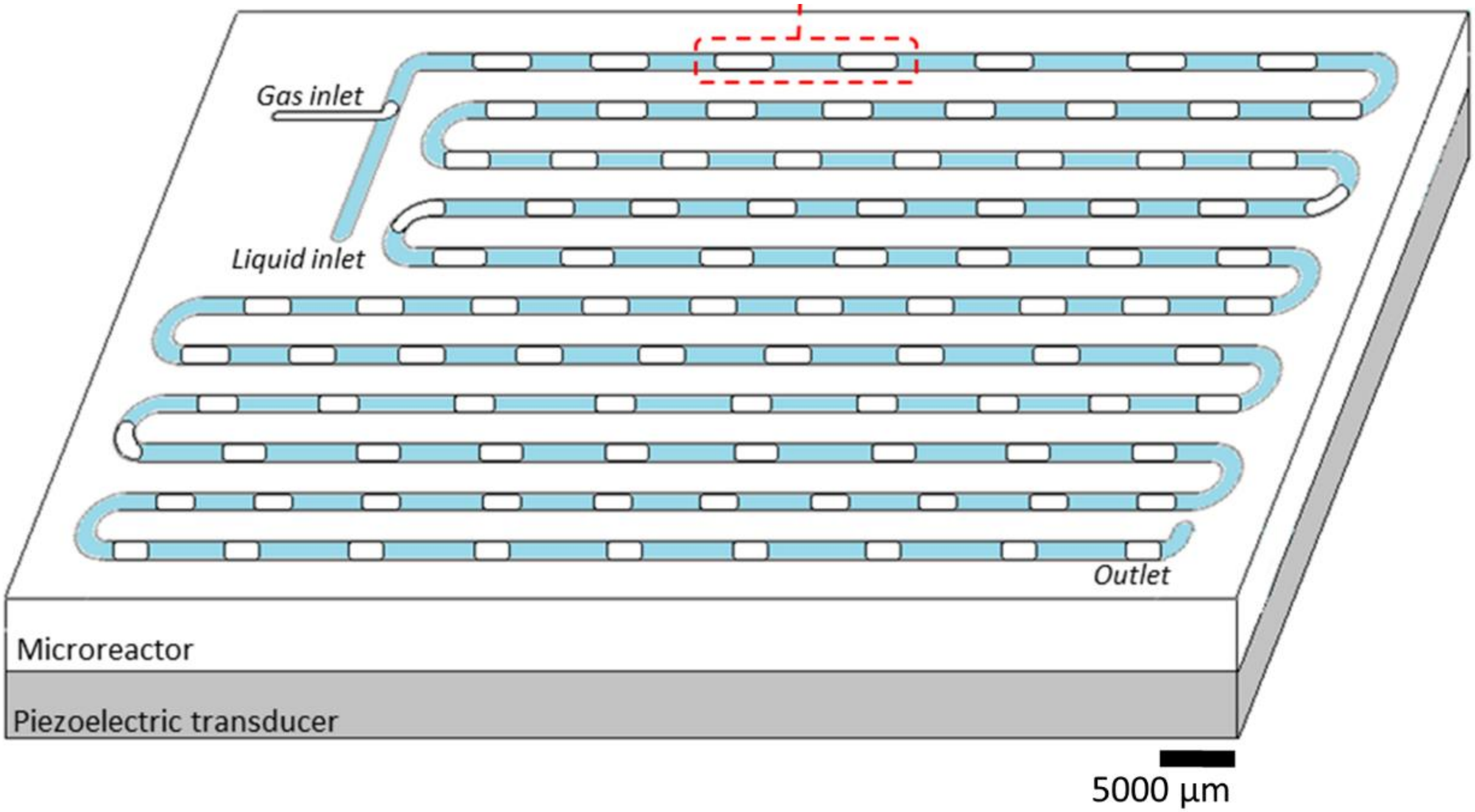
1 mm blind hole, length : 1.2 mm

At high amplitude capillary waves inject droplets to gas phase

→ “internal atomization“

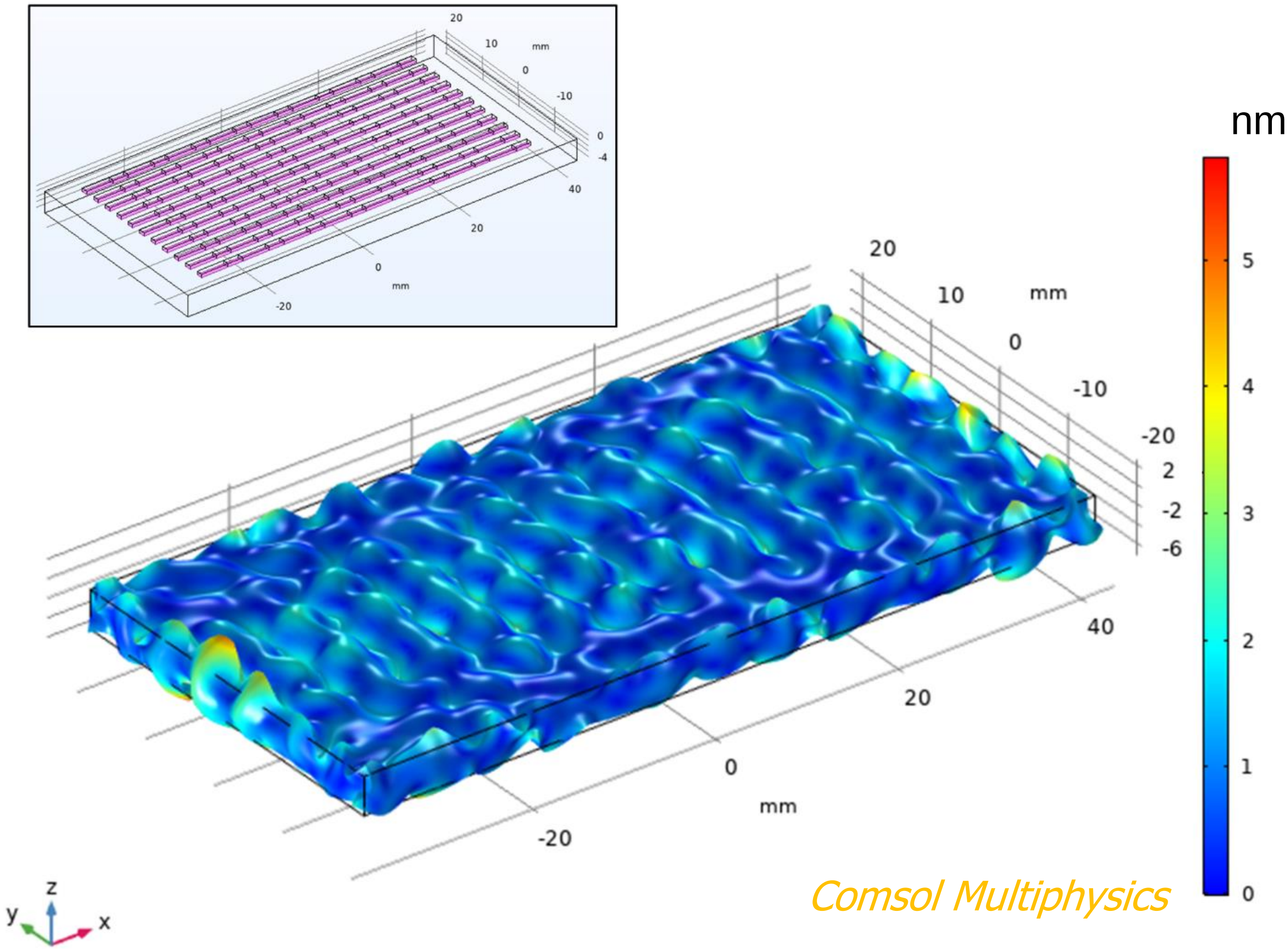
Microreactor system

→ meandering channel etched in silicon, glued on piezo plate transducer
→ channel dimensions 1.2 mm x 0.6 mm, length 740 mm
→ Liquid/gas **Taylor flow** (slug flow) of water and CO_2



Simulated transducer oscillation (411 kHz)

→ High order mode(s) excited: “nodes“ and “antinodes“

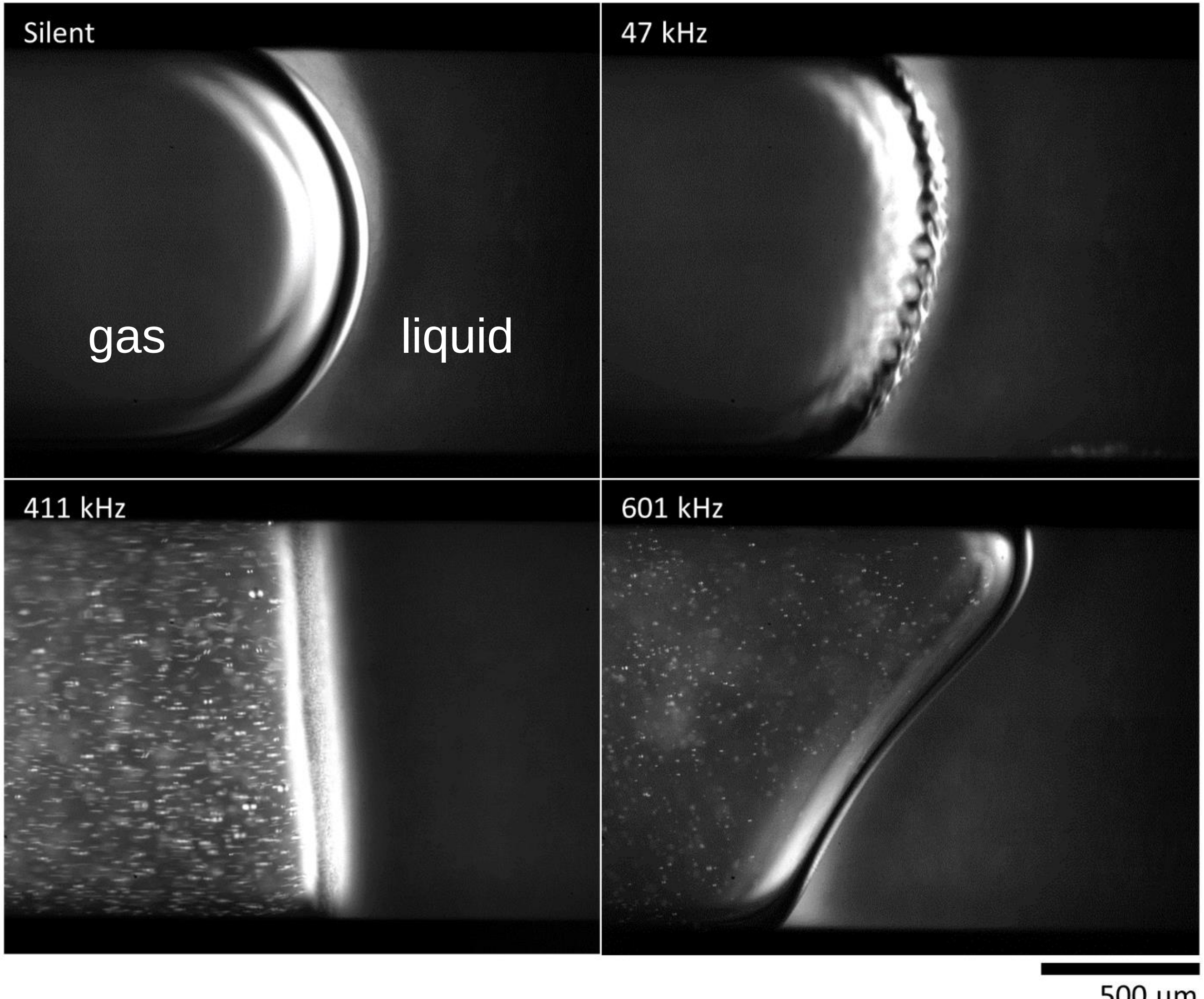


Atomization at phase boundaries

→ Surface waves and droplets

silent

47 kHz

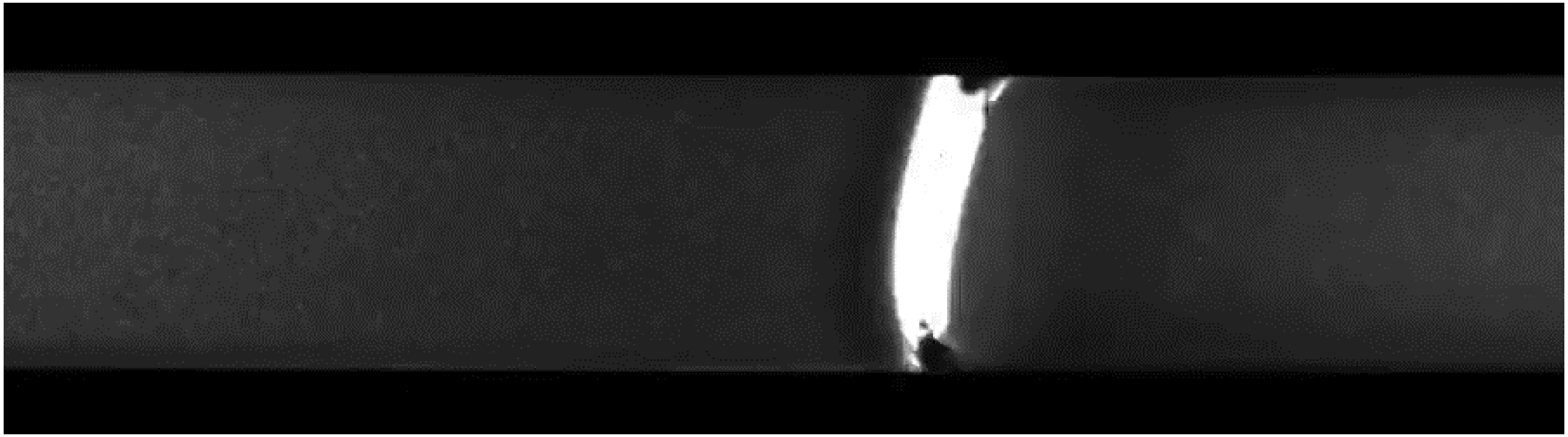


411 kHz

601 kHz

Atomization at phase boundaries

movie at 411 kHz driving



→ sometimes violent drop ejection, sometimes none!

Since always imaged at the same position:

→ no antinode ("hot spot") effect

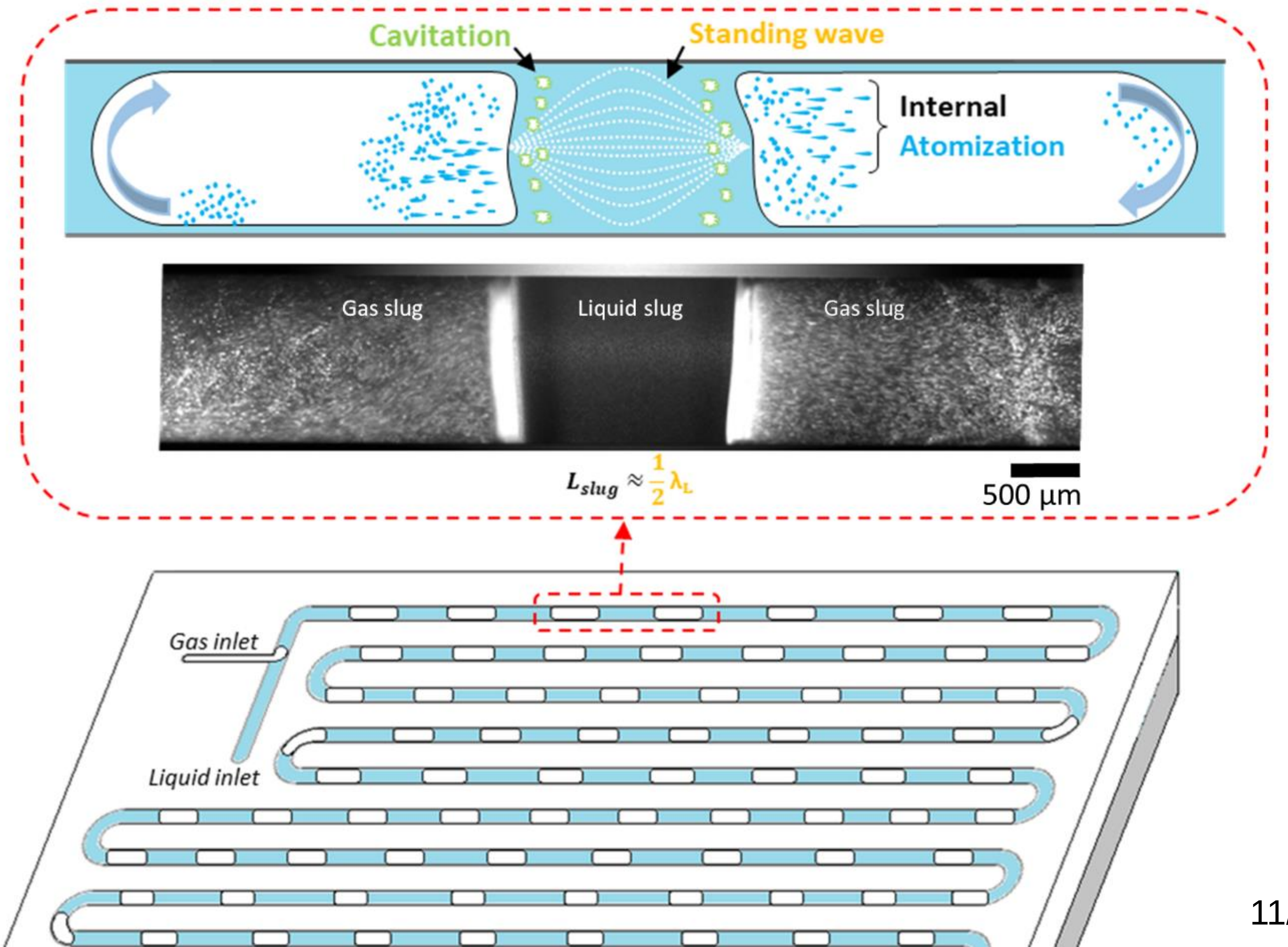
Resonant internal atomization

→ conjecture: acoustic resonance in liquid slug amplifies sound field

a)

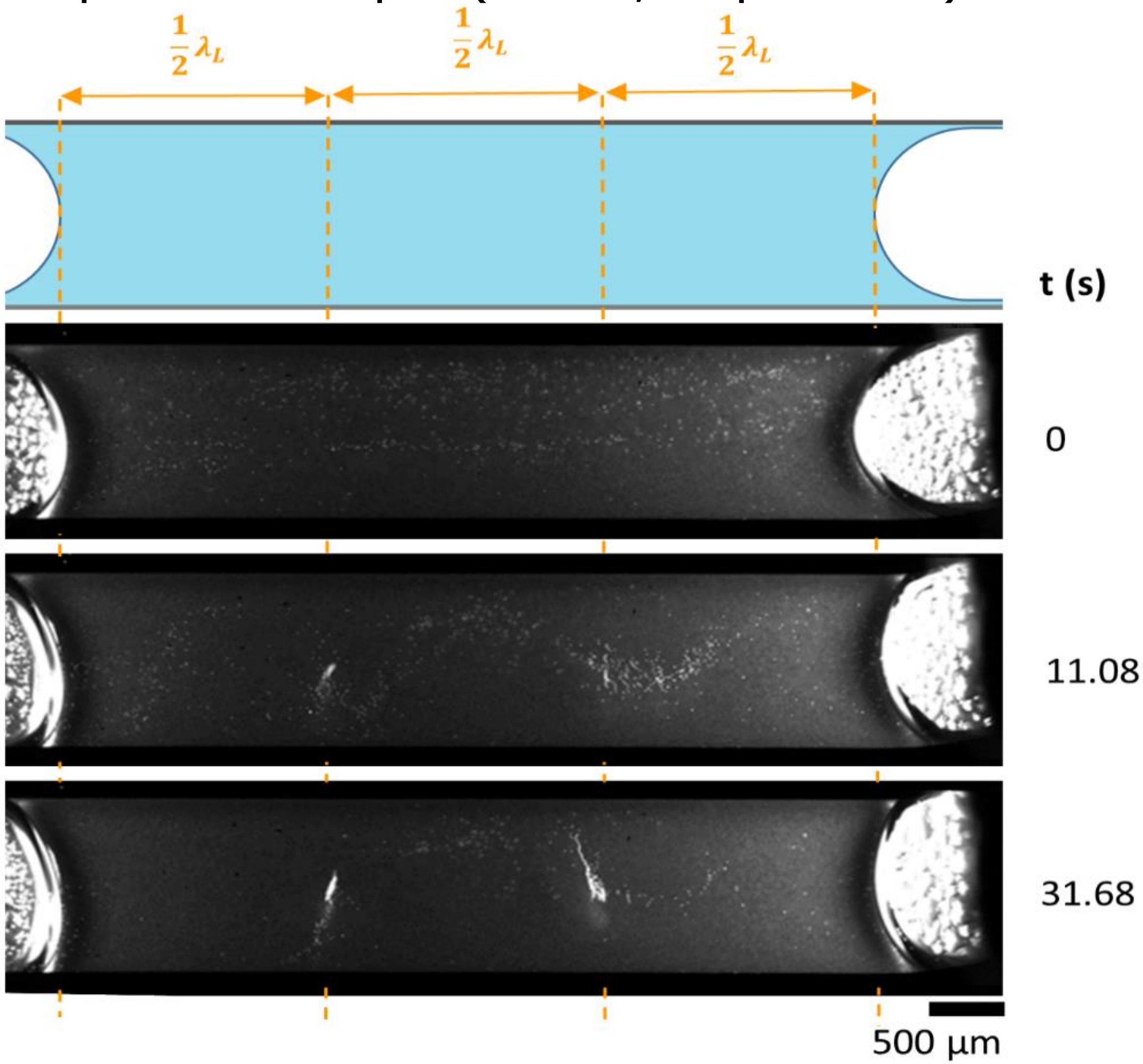
b)

c)



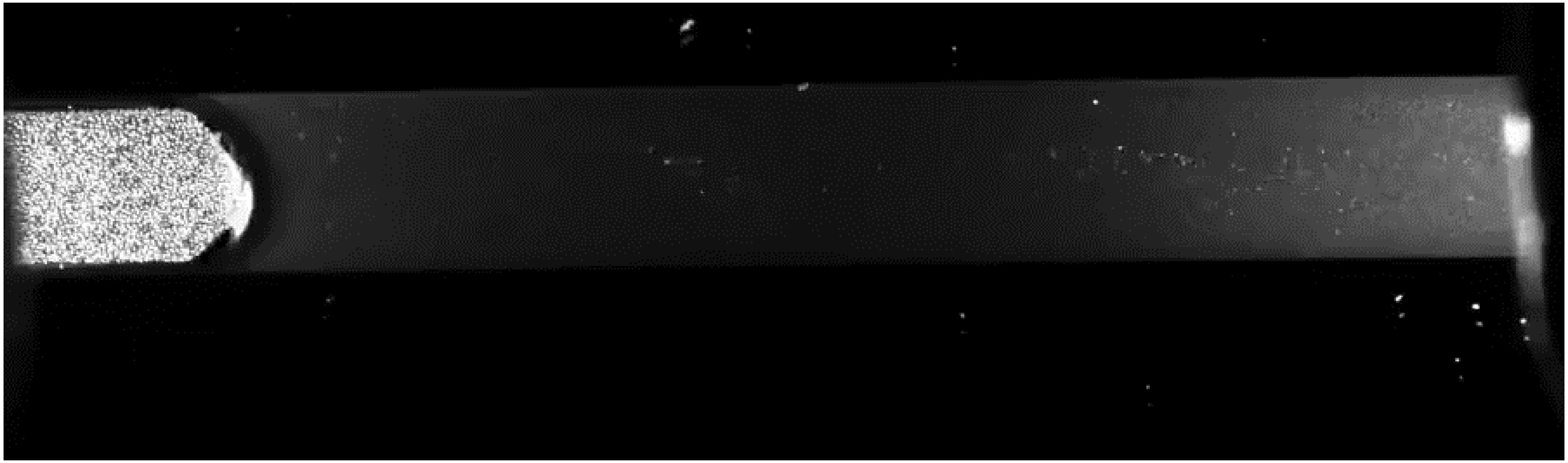
Resonance confirmed by particles gathering at nodes

→ polystyrene particles in liquid (1 wt%, 10 μm diam.)



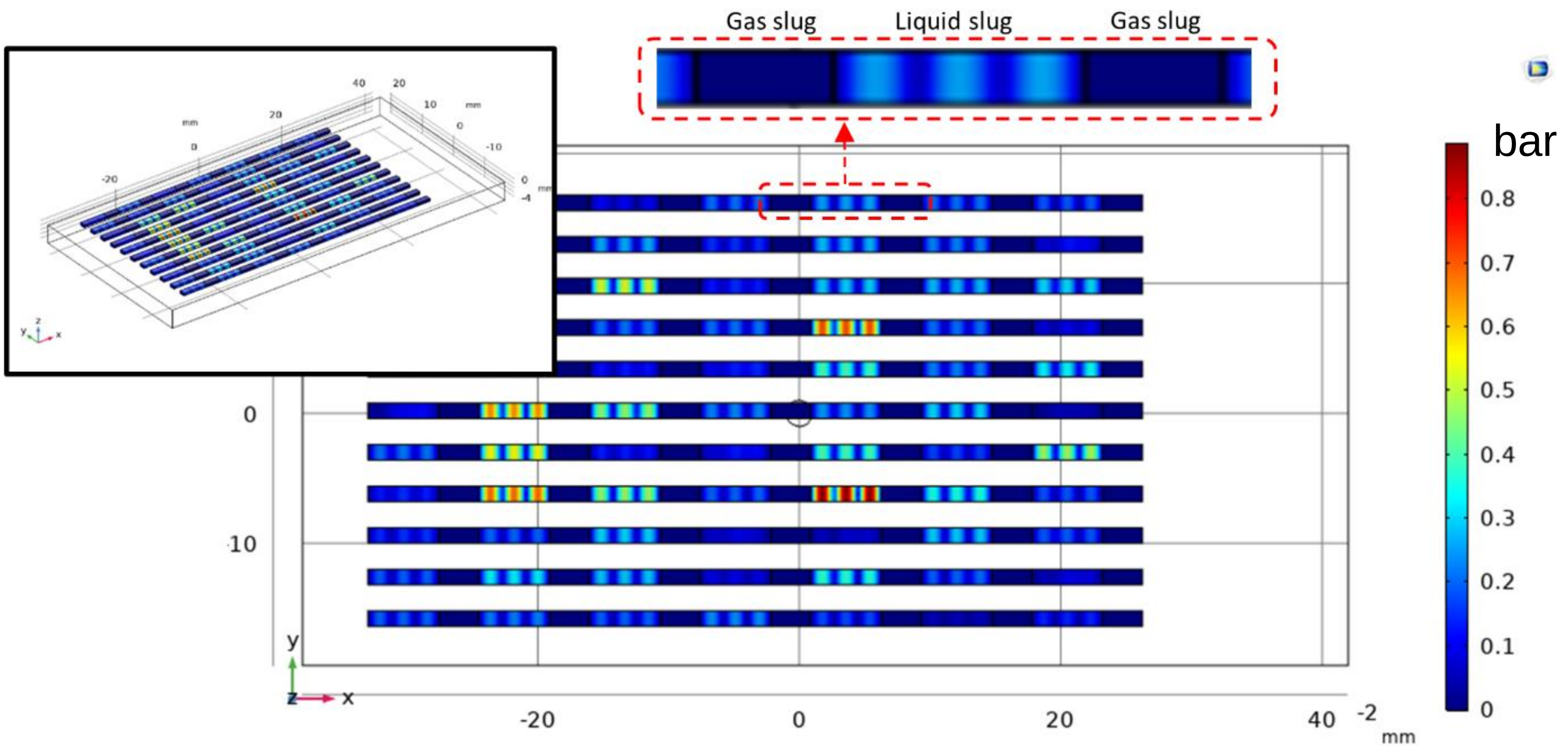
Resonance confirmed by particles gathering at nodes

→ particles in resonating slugs are transported by flow (again: no "hot spots")



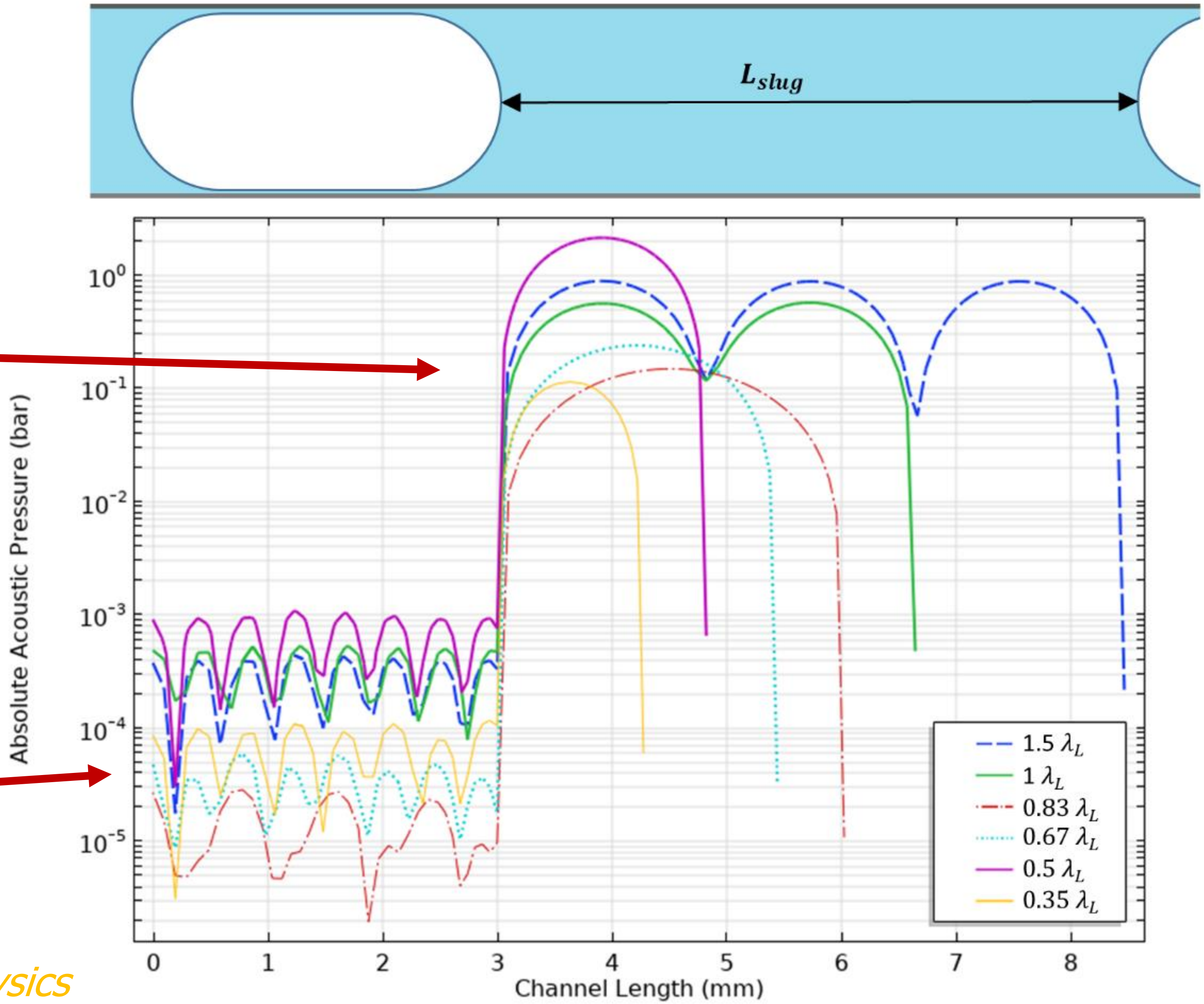
Simulated slug resonance

→ sound field indeed amplifies in resonant slugs
(here superimposed by modal oscillation of plate transducer)



Comsol Multiphysics

Simulated slug resonance



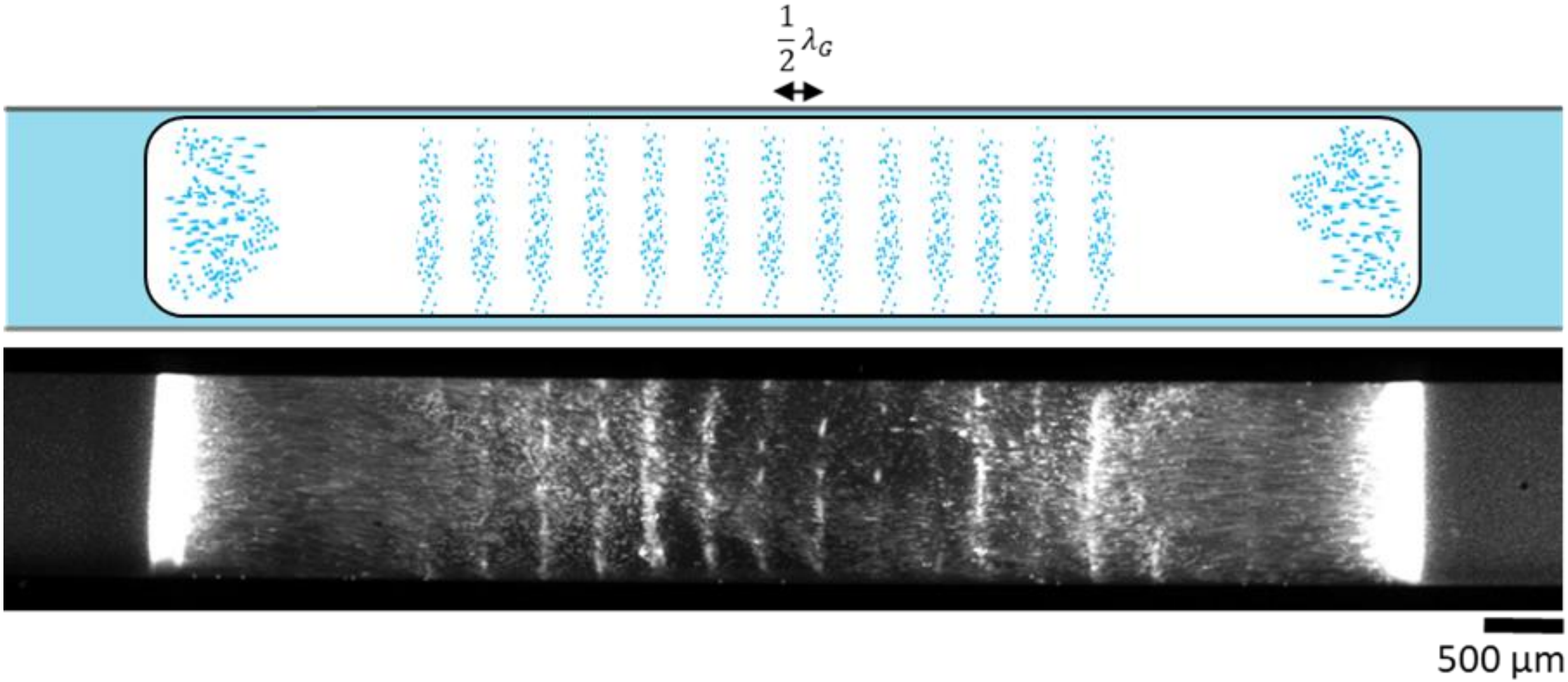
→ resonance depends on slug length

→ also resonances in gas phase possible

Comsol Multiphysics

Resonance in gas volume

→ Droplets show "Kundt's tube" behavior



Conclusion

→ peculiar phenomenon of **massive droplet ejection** (atomization) in micro-channels

→ mechanism relies on **acoustic resonance** in liquid slugs

→ numerical **simulations capture essentials** of this resonance effect

→ considerable **amplification of acoustic pressure** within slugs, also facilitating cavitation

→ acoustic **resonance in gas bubbles** can also partly be observed

→ **atomization mechanism** (at least partly) based on
capillary waves and cavitation / entrained bubbles at interface
possibly more details to explore…

Outlook

→ further analysis of **physical mechanisms** (e.g. details of atomization, flattening of slug wall: radiation pressure?,…)

→ application: increase of gas/liquid interfacial area and **increase of mass transfer** in microreactors

→ resonance within microchannels might **increase efficiency of ultrasound** used for clogging prevention, emulsification or particle size reduction in microreactors

Publication:
K. Mc Carogher, Z. Dong, D.S. Stephens, M.E. Leblebici, R. Mettin & S. Kuhn: *Acoustic Resonance and Atomization for Gas-Liquid Systems in Microreactors*, Ultrasonics Sonochemistry, 105611 (2021)

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Thank you for your attention and enjoy the discussions !!!