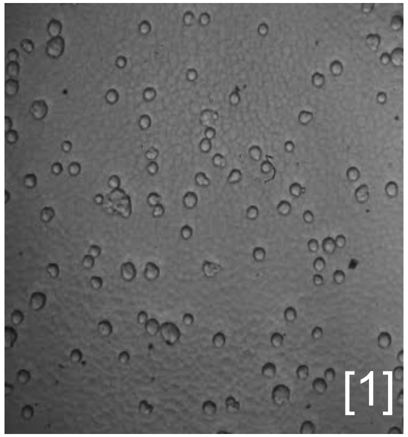
Numerical Modelling of Viscous Damping for Acoustic Resonances of Suspended Microparticles

Thierry Baasch*, Jonas Fankhauser and Jürg Dual
Institute for Mechanical Systems
ETH Zurich
*baasch@imes.mavt.ethz.ch

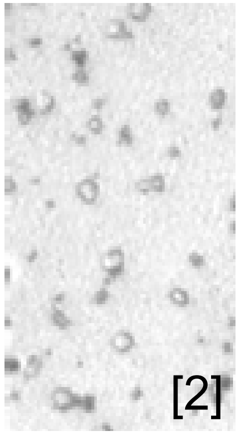
COMSOL CONFERENCE 2018 LAUSANNE

Why acoustics and particles?

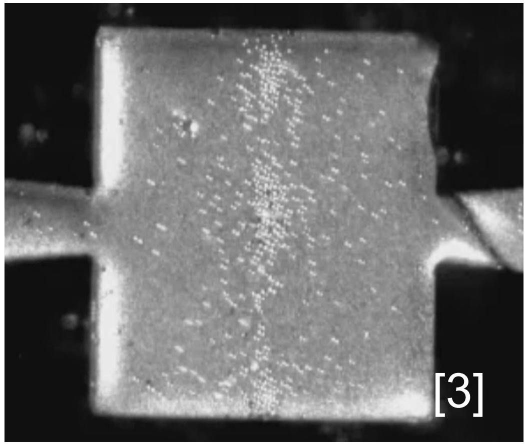
The particle motion can be controlled by acoustic forces.



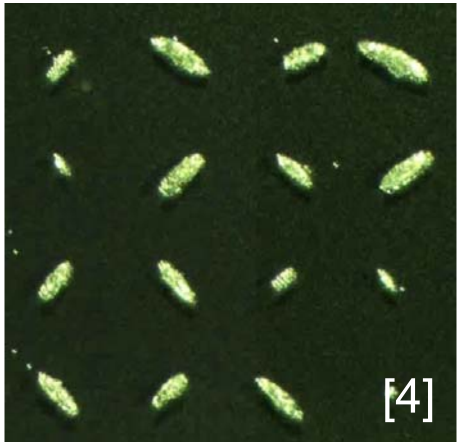
1D focussing of glass particles



focussing of alumina discs



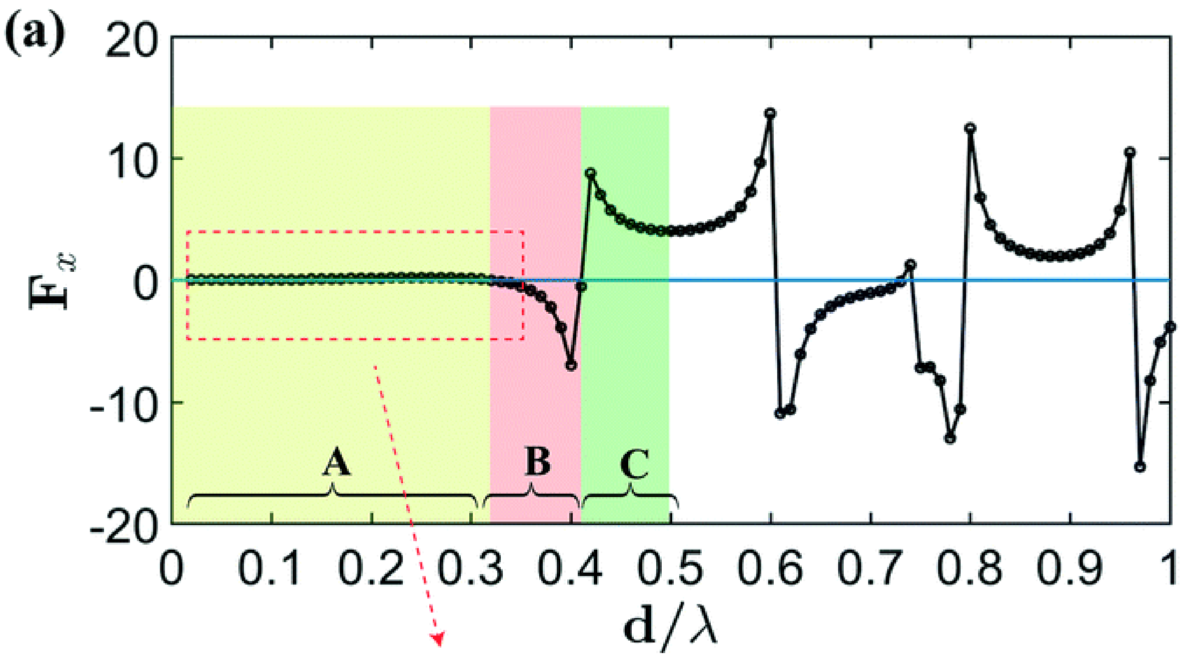
2D focussing



rotation of particle clumps

[1] Baasch, T., Leibacher, I., & Dual, J. (2017) *The Journal of the Acoustical Society of America*, *141*(3), 1664-1674
[2] Courtesy of W. Dietze & I. Leibacher
[3] Garbin, A., Leibacher, I., Hahn, P., Le Ferrand, H., Studart, A., & Dual, J. (2015). *The Journal of the Acoustical Society of America*, *138*(5), 2759-2769.
[4] Schwarz, Thomas. *Rotation of particles by ultrasonic manipulation*. Diss. 2013.

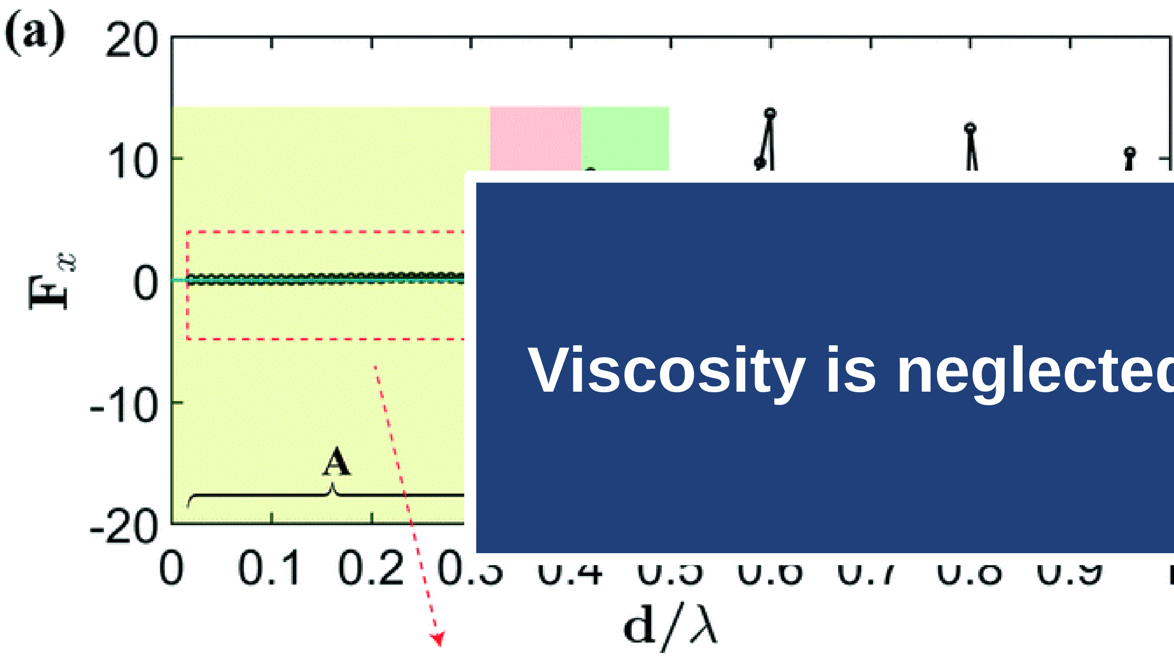
Motivation: At high frequencies particle resonances can be excited



The acoustic radiation force acting on a PMMA particle. Multiple resonances can be observed.

Habibi, Ruhollah, Citsabehsan Devendran, and Adrian Neild. "Trapping and patterning of large particles and cells in a 1D ultrasonic standing wave." *Lab on a Chip* 17.19 (2017): 3279-3290.

Motivation: At high frequencies particle resonances can be excited

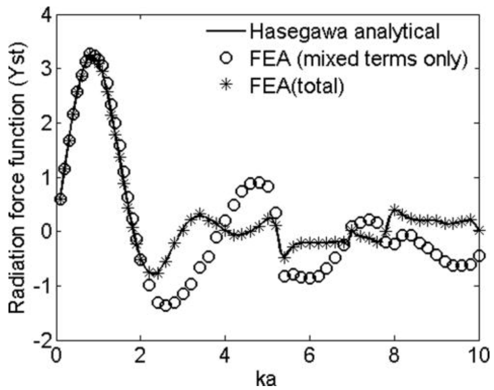


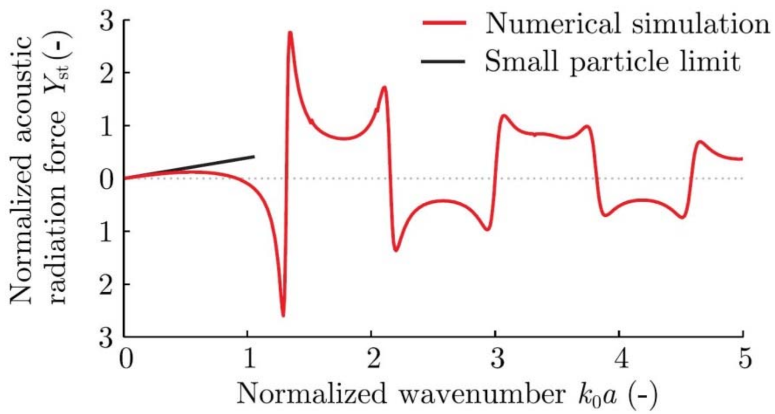
Viscosity is neglected!

Fig. The acoustic radiation force acting … a PMMA particle. …ltiple resonances …n be observed.

Habibi, Ruhollah, Citsabehsan Devendran, and Adrian Neild. "Trapping and patterning of large particles and cells in a 1D ultrasonic standing wave." *Lab on a Chip* 17.19 (2017): 3279-3290.

Former results were obtained without considering the viscous damping!





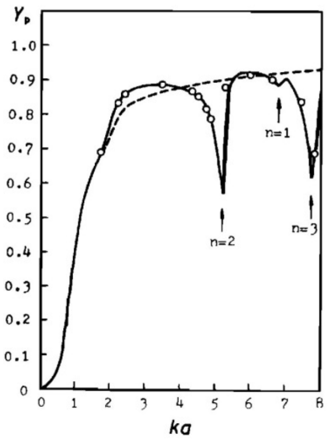
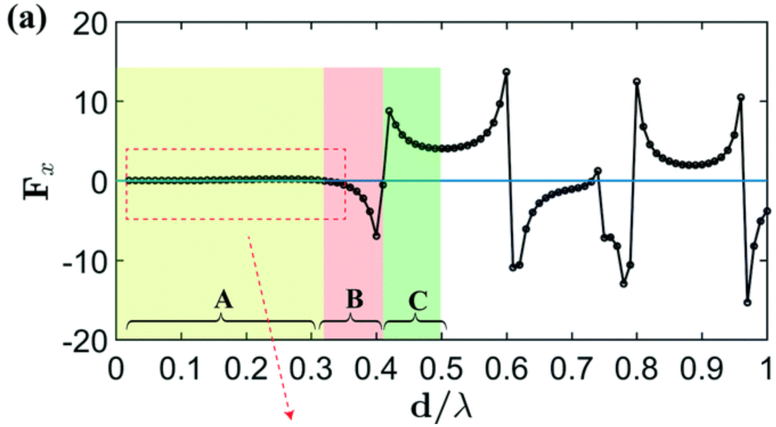
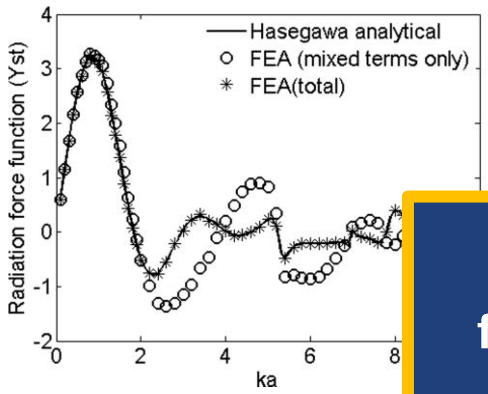
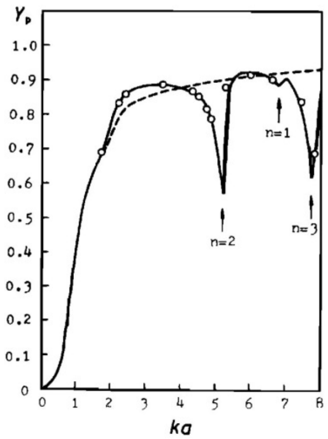


FIG. 4. Y_p vs ka relation for stainless steel spheres in water. Solid curve: calculated by Eq. 29. Broken curve: calculated for rigid stainless steel spheres. ○: measured.

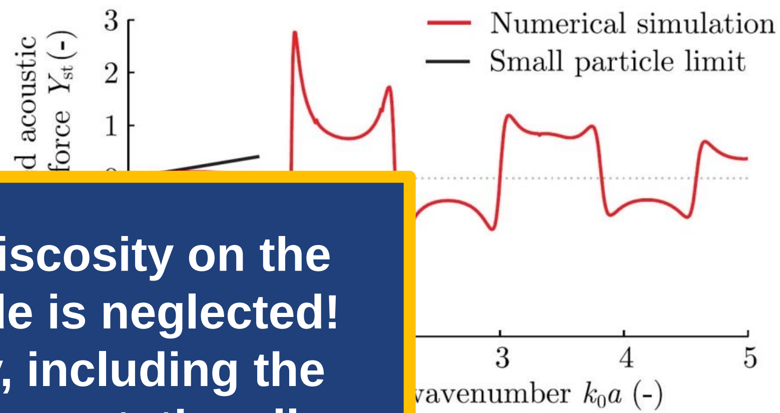


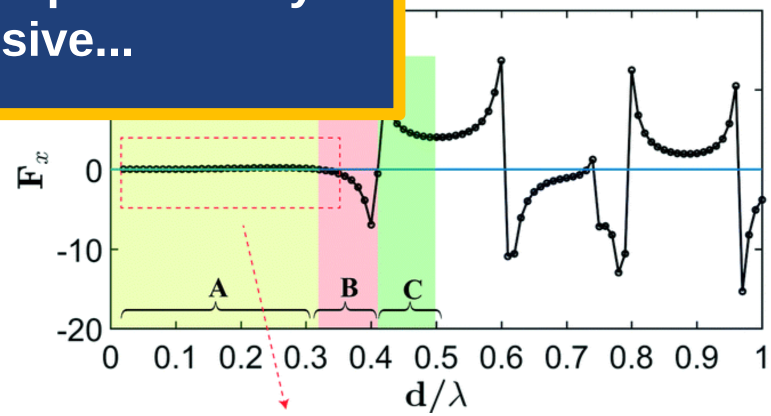
Former results were obtained without considering the viscous damping!





Fi... stainless steel spheres in water. Solid curve: calculated by Eq. 29. Broken curve: calculated for rigid stainless steel spheres. ○: measured.





Influence of viscosity on the force amplitude is neglected! Unfortunately, including the damping is computationally expensive...

Project goals

Understanding the influence of the viscosity on:

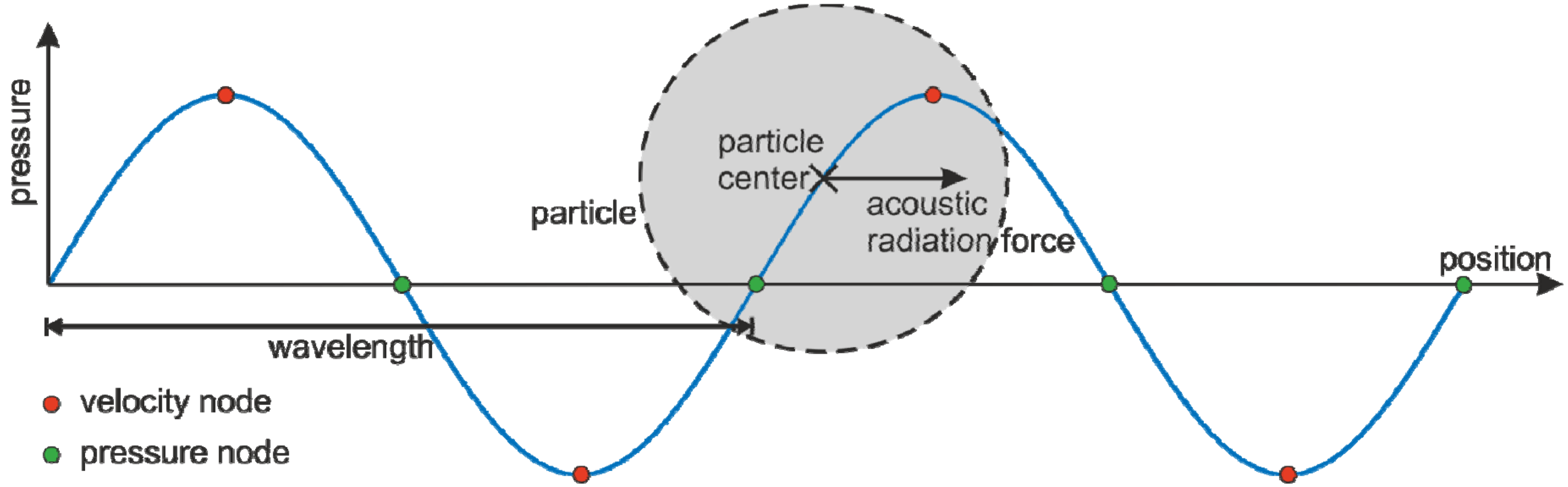
- The stored energy,
- the acoustic radiation force,

for an acoustically excited particle close to resonance.

Three different FEM (Comsol) models are used:

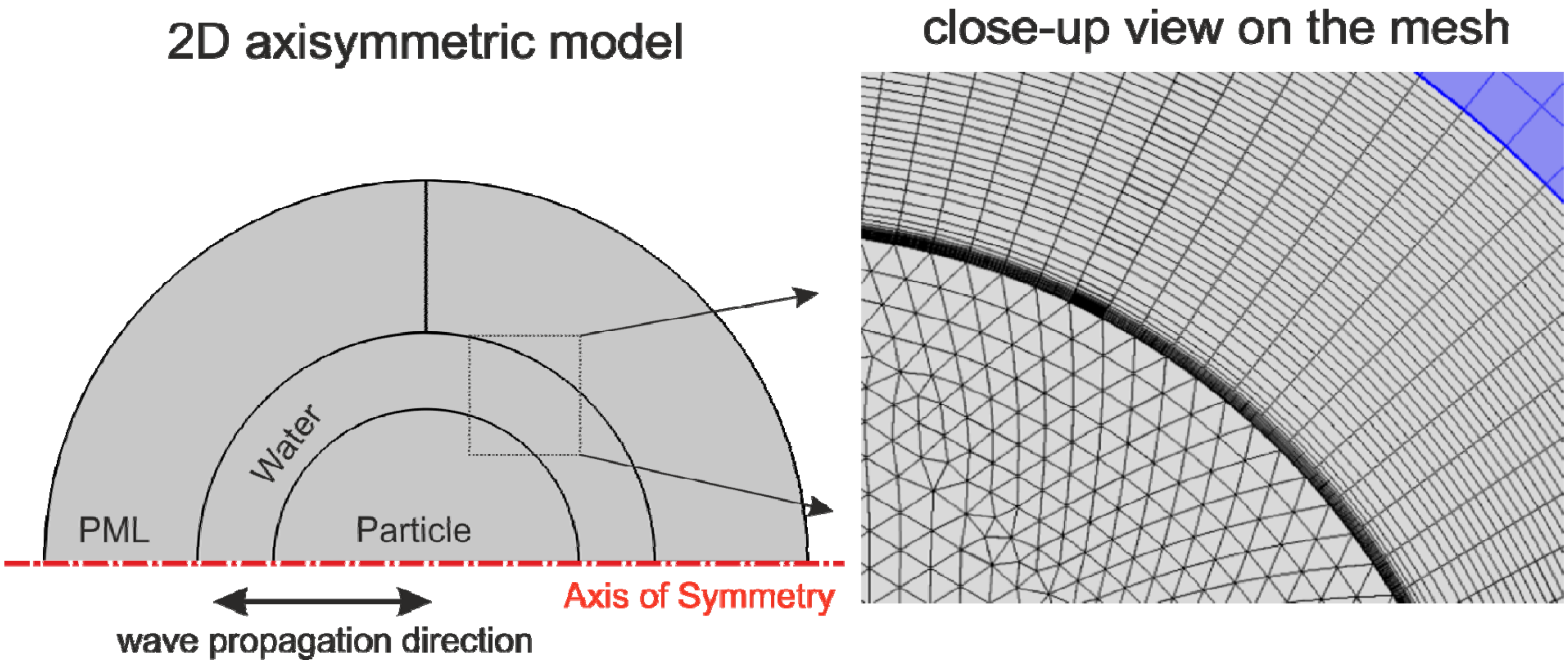
Inviscid Model:	Radiation losses, computationally cheap
Viscous Model:	Radiation & viscous losses, computationally expensive
Loss Factor Model:	Radiation & viscous losses, computationally cheap

Setup: Particle placed in standing wave



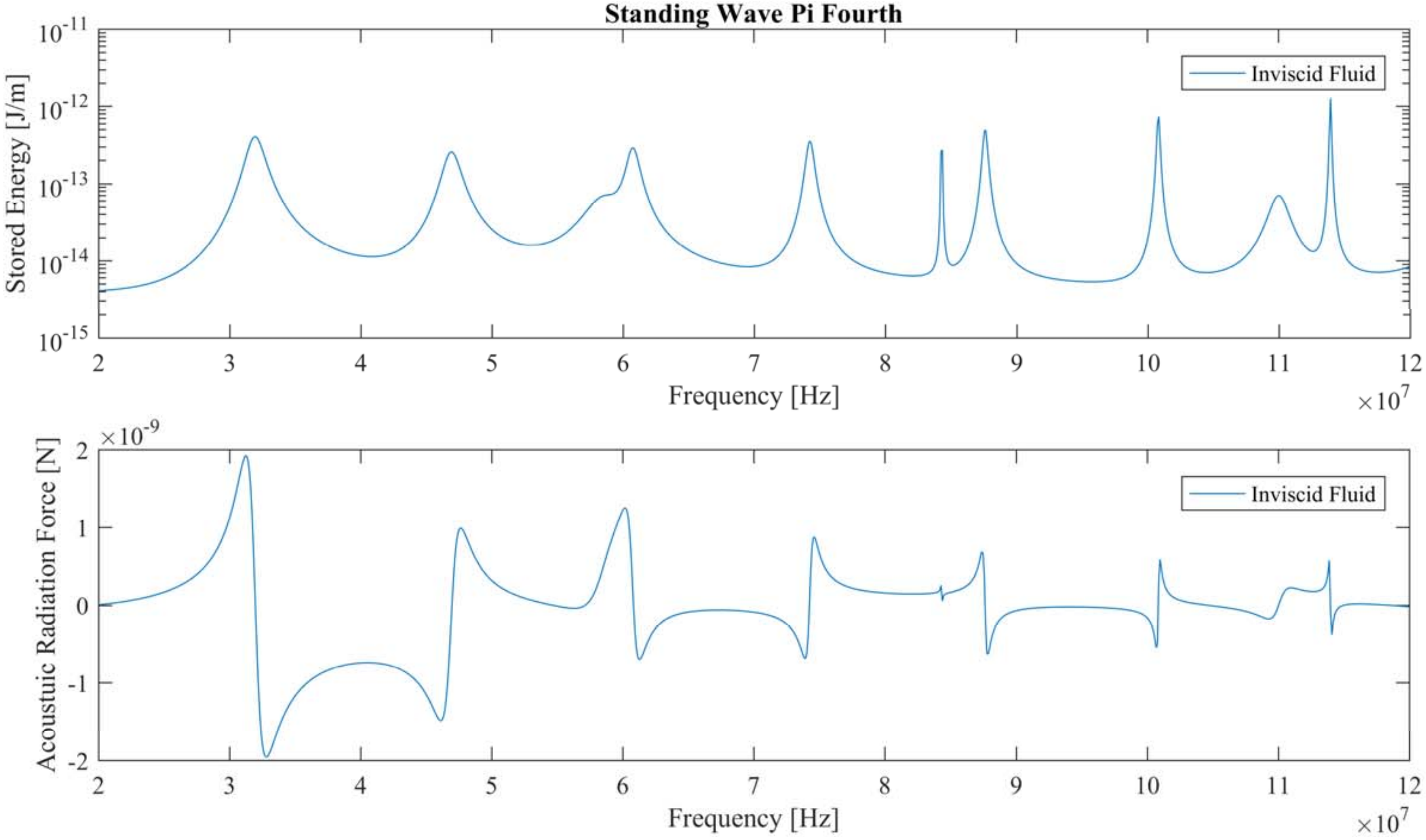
- 10 µm radius polystyrene particle
- One-dimensional standing wave.
- Placed between pressure and velocity node.

FEM Setup

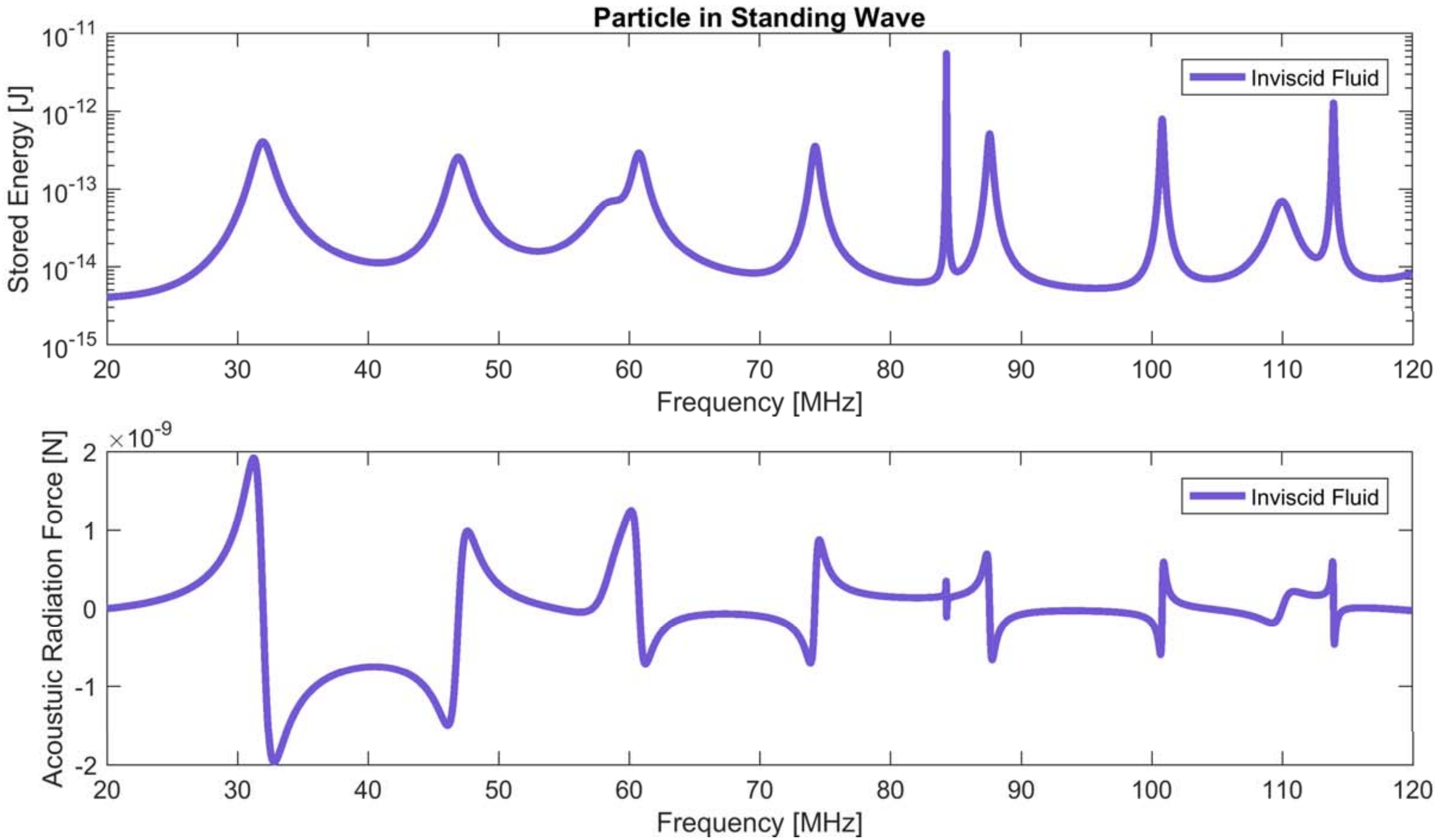


- Simple symmetrical setup
- Viscous boundary layer requires many mesh elements

Particle vibrations for the inviscid fluid

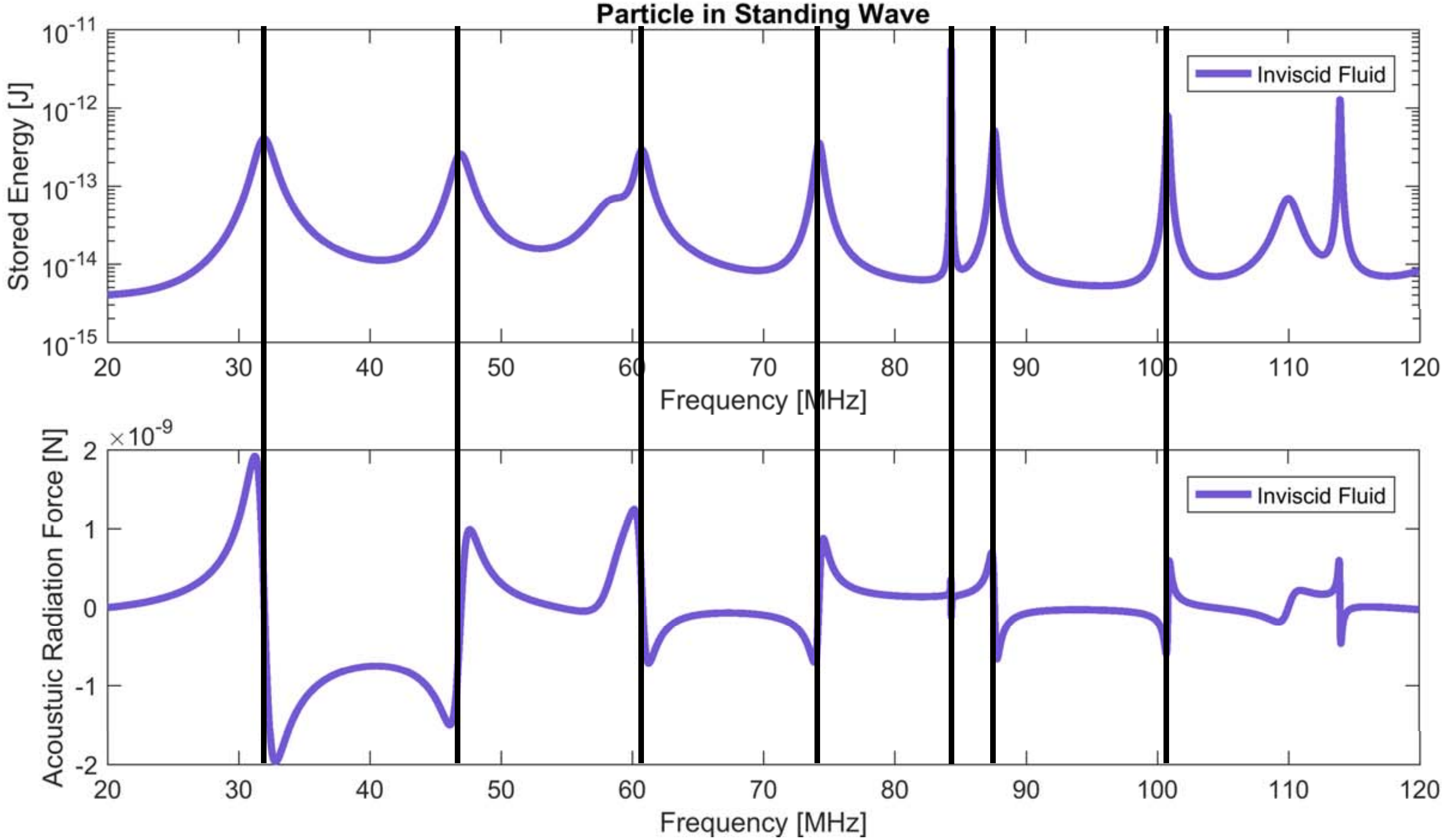


Particle vibrations for the inviscid fluid

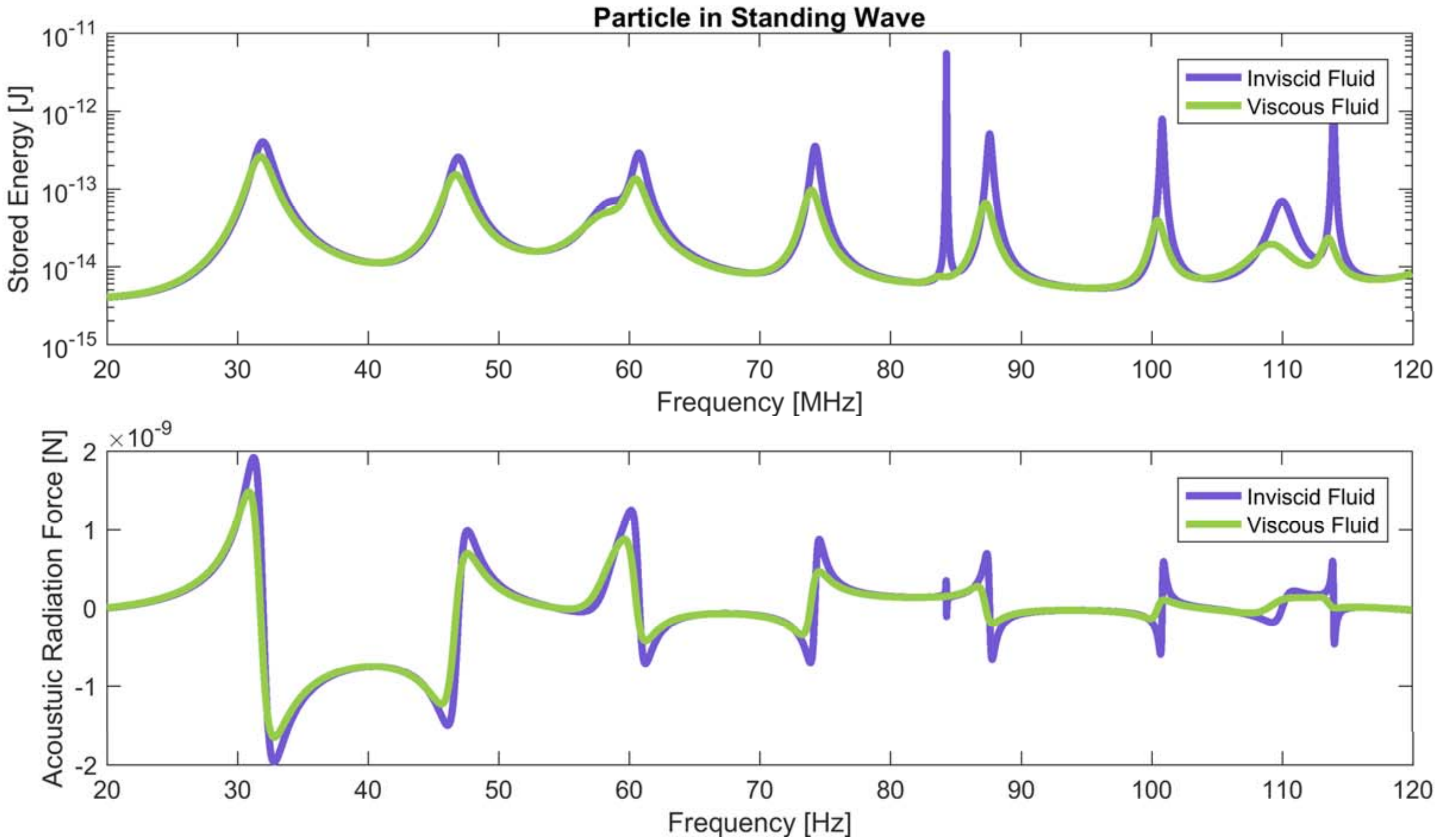


ETH zürich

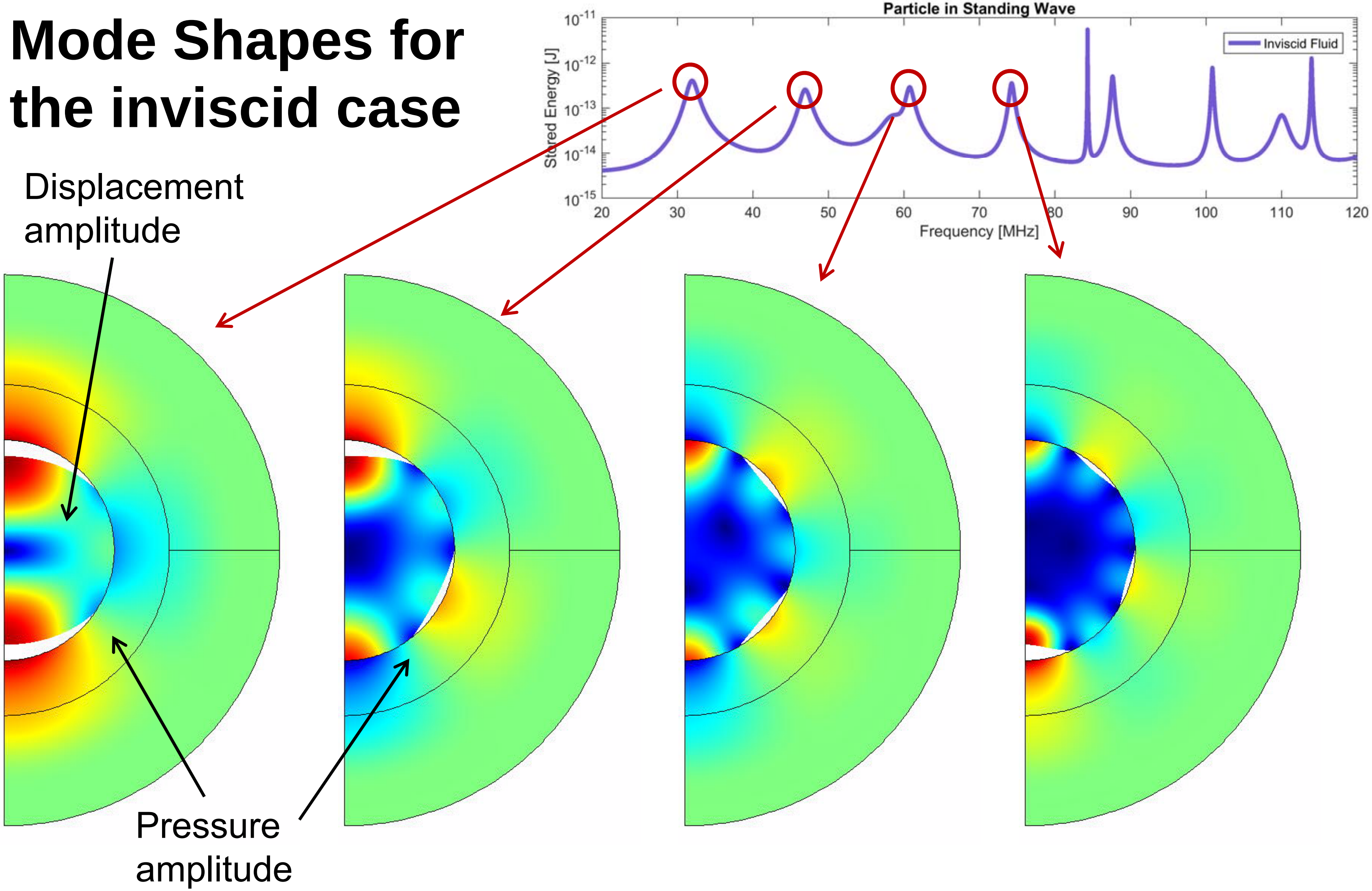
Multiple resonances can be observed



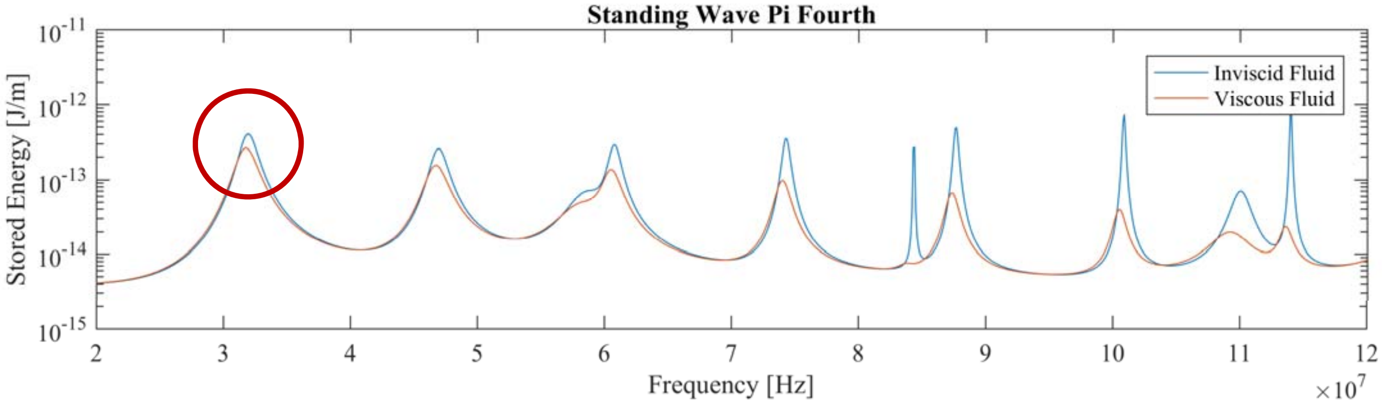
Viscosity adds damping and mass to the vibration mode

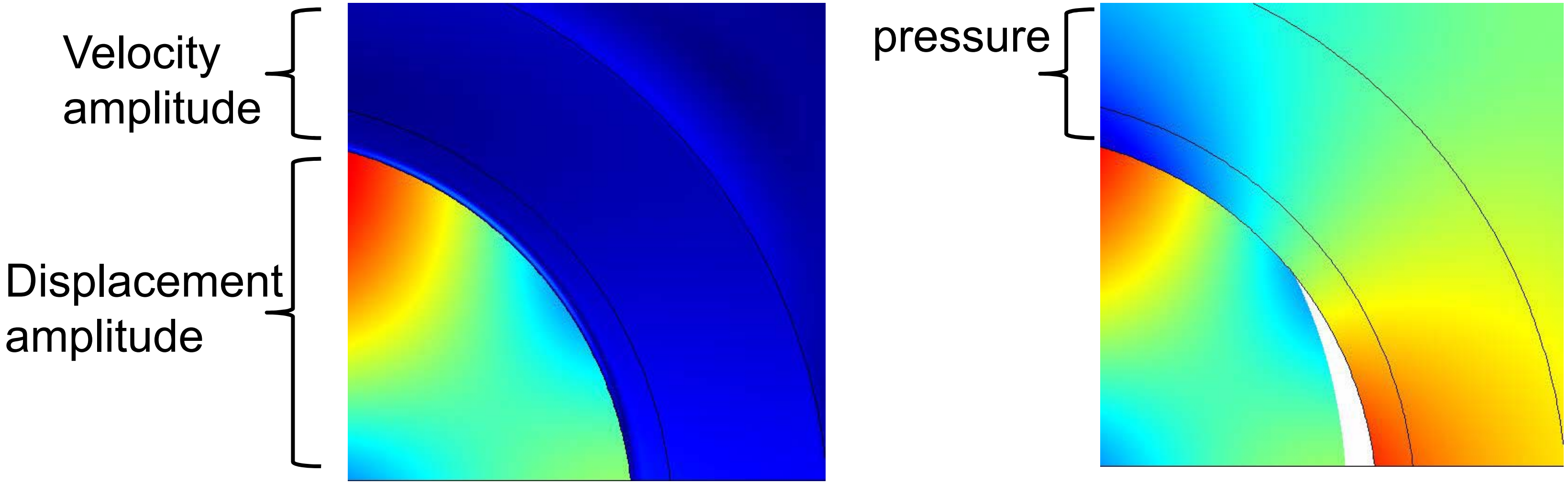


Mode Shapes for the inviscid case



Viscous boundary layer





The viscous boundary layer (BL)

Adds **mass** and **damping** to the vibration.

The added **mass** and **damping** can be approximated analytically if:

- BL thickness smaller than wavelength, δ << λ.
- BL thickness smaller than body curvature, δ << r.

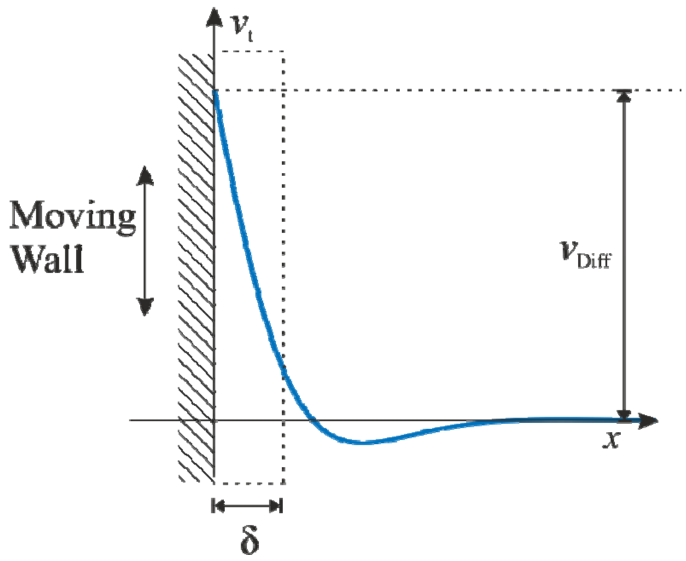


Fig. The tangential velocity profile in the viscous boundary layer for a moving wall and resting external fluid.

The added mass and loss factor

<u>Added Mass</u>:

The particle density ρ_p is changed to

$$\rho^* = \rho_p\left(1 + \phi_\rho\right) \text{ with}$$

$$\phi_\rho = \frac{\delta\rho_f}{4E_{\text{kin}}}\int_S < v_{\text{Diff}}^2 > dS.$$

<u>Loss factor</u> [1]:

The damping is included in the complex youngs modulus E^*:

$$E^* = E_p(1 + i\phi_\nu) \text{ with}$$

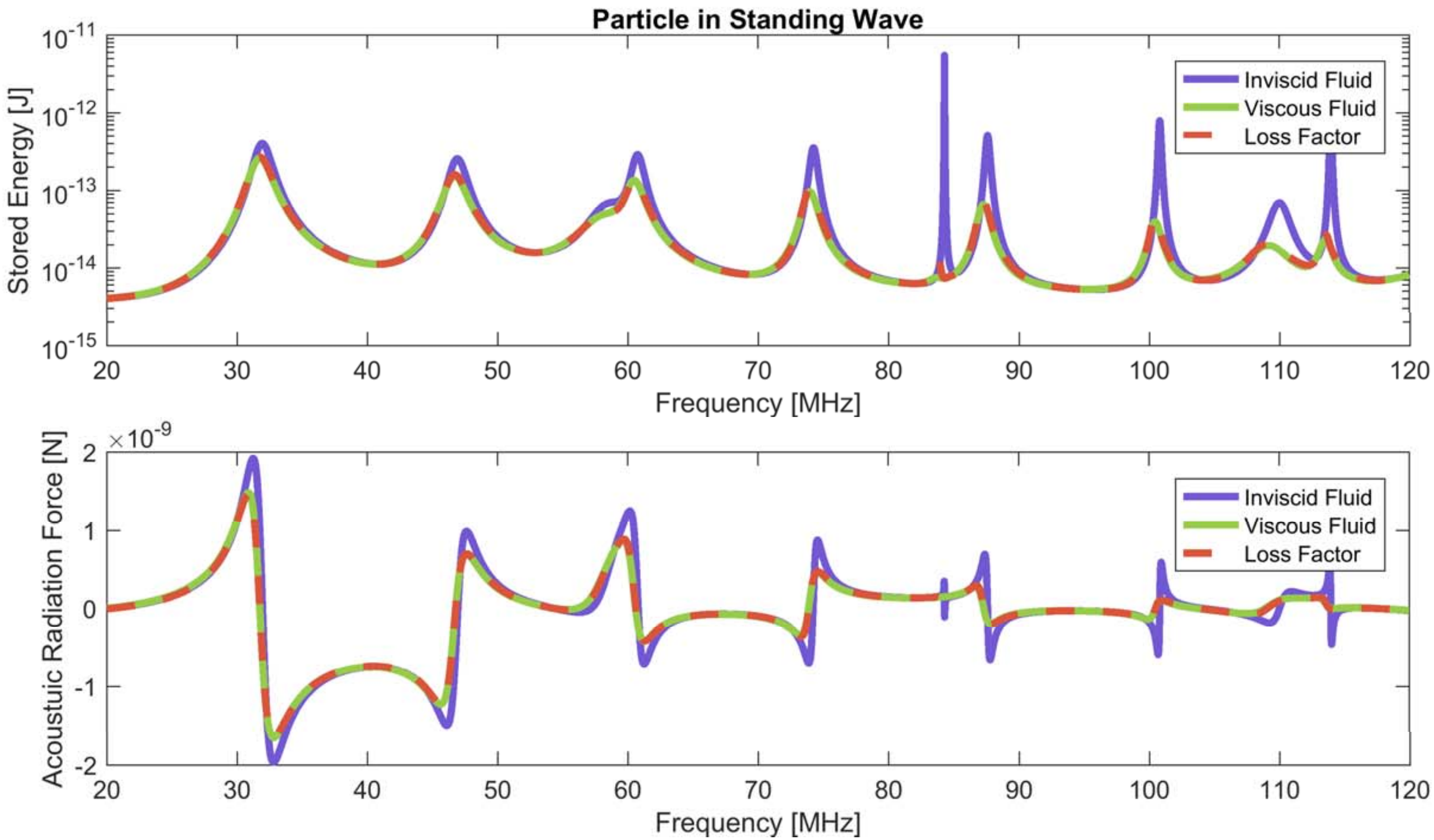
$$\phi_\nu = \frac{\delta\rho_f}{4E_{\text{strain}}}\int_S < v_{\text{Diff}}^2 > dS.$$

<u>Algorithm</u>

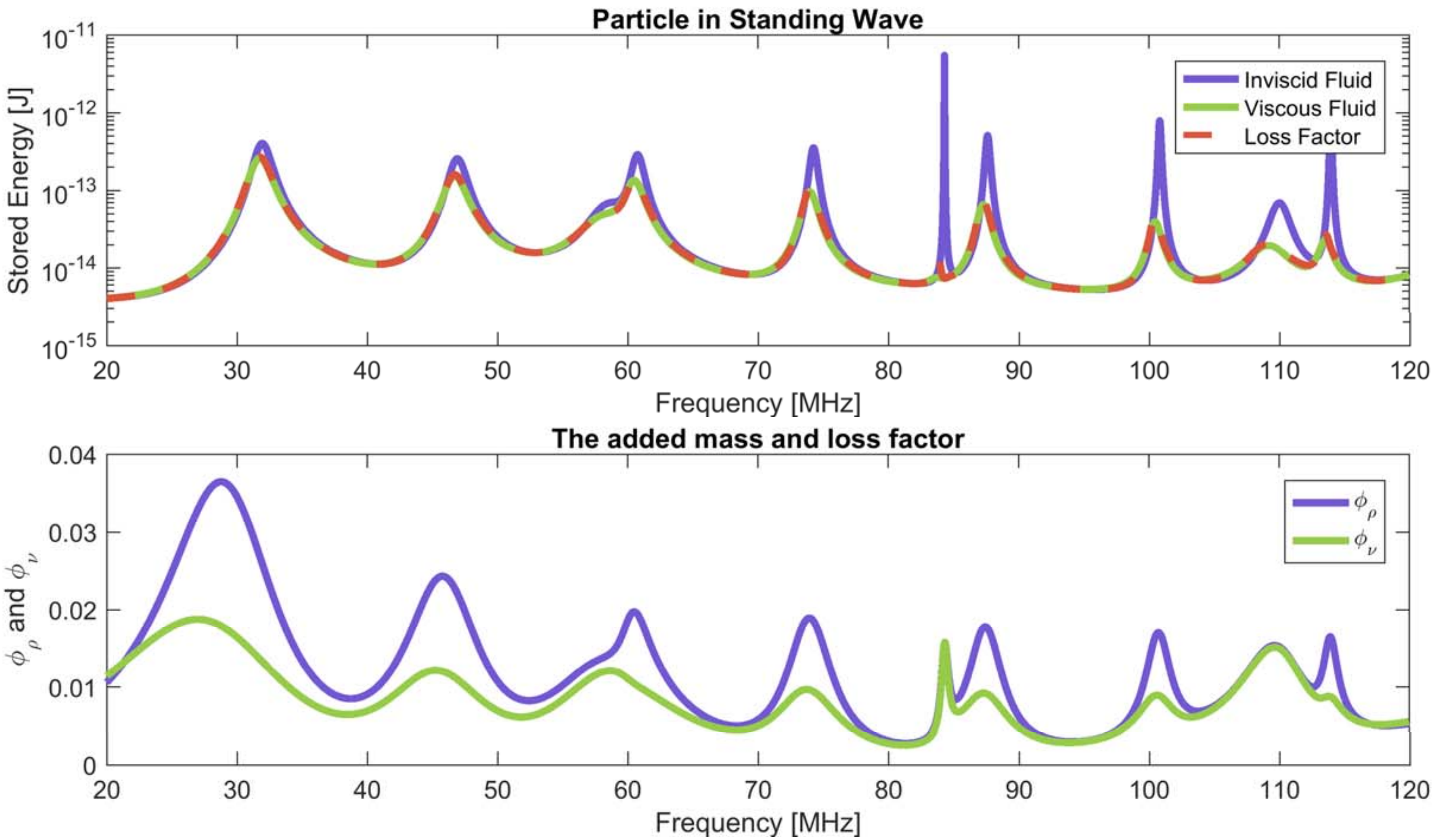
1. Inviscid simulation.
2. Acquire v_{Diff}^2, T_{kin} and E_{st}.
3. Calculate ϕ_ρ and ϕ_ν.
3. Simulate again with **added mass** and **loss factor**.

[1] Hahn, Philipp, and Jurg Dual. "A numerically efficient damping model for acoustic resonances in microfluidic cavities." *Physics of Fluids* 27.6 (2015): 062005.

The results for the approximate model



The results for the approximate model



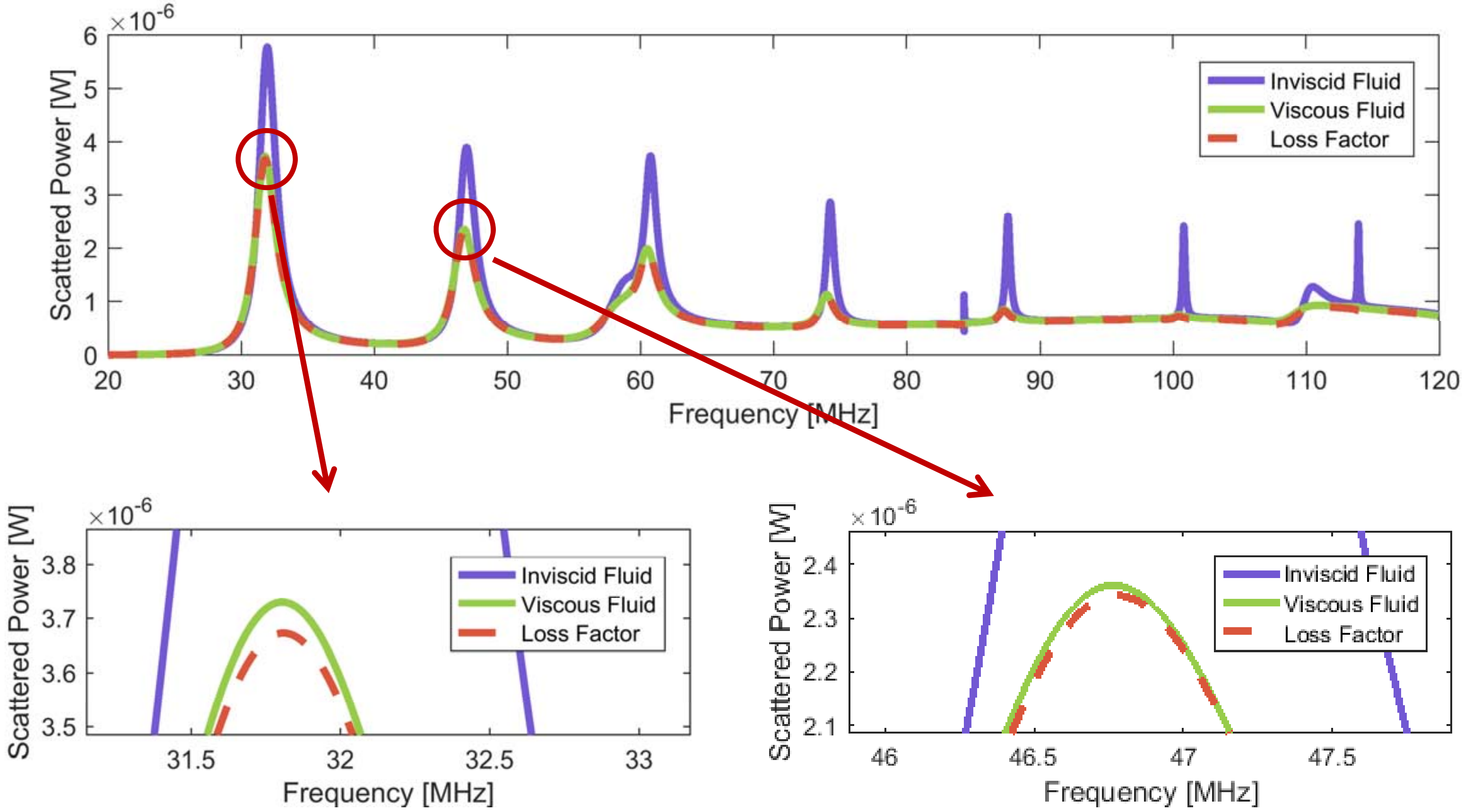
Outlook

- Investigate **thermal losses**.
- Calculate the acoustic radiation force **between multiple particles**.
- Incorporate acoustic streaming.

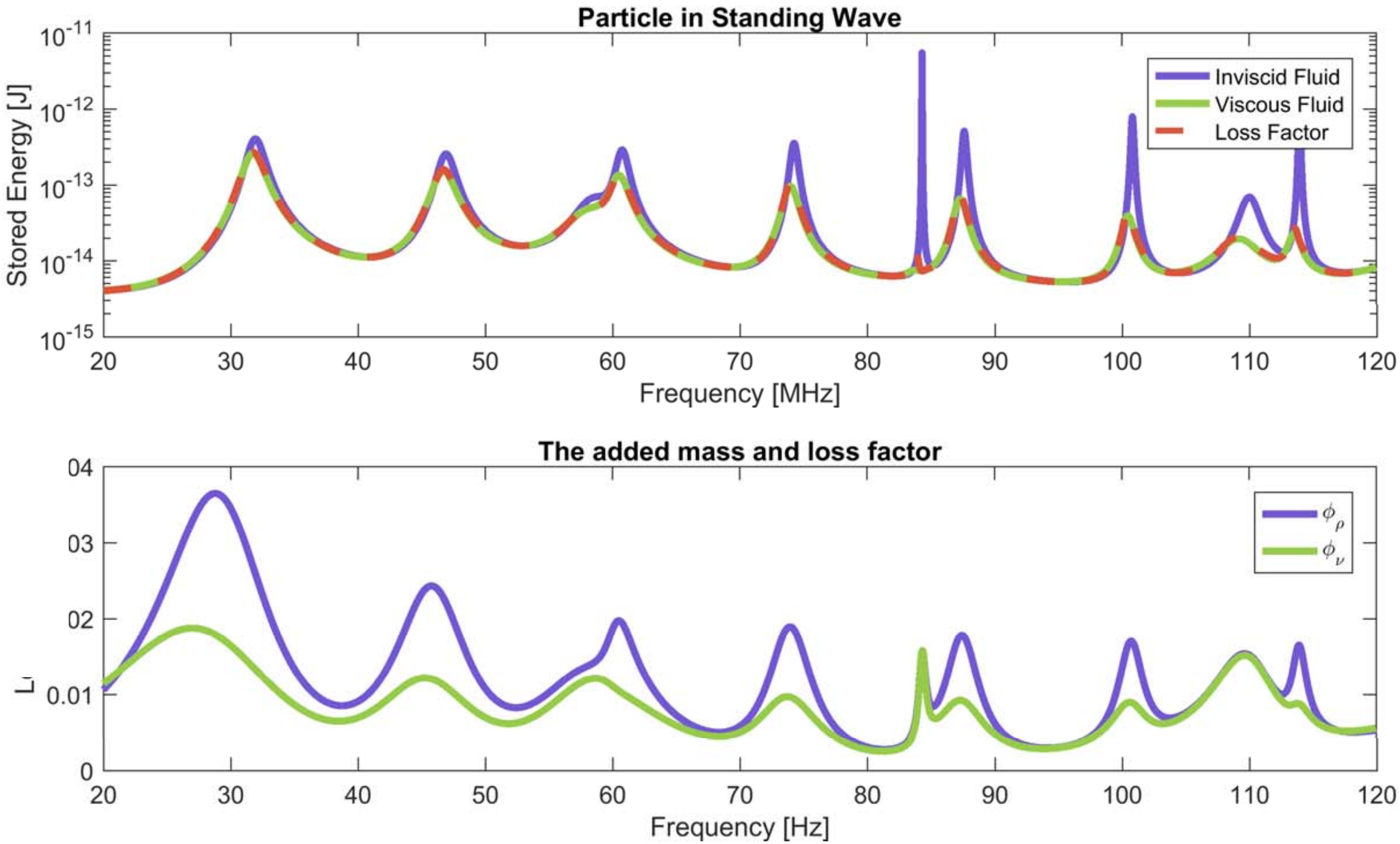
ETH zürich

Thank you!

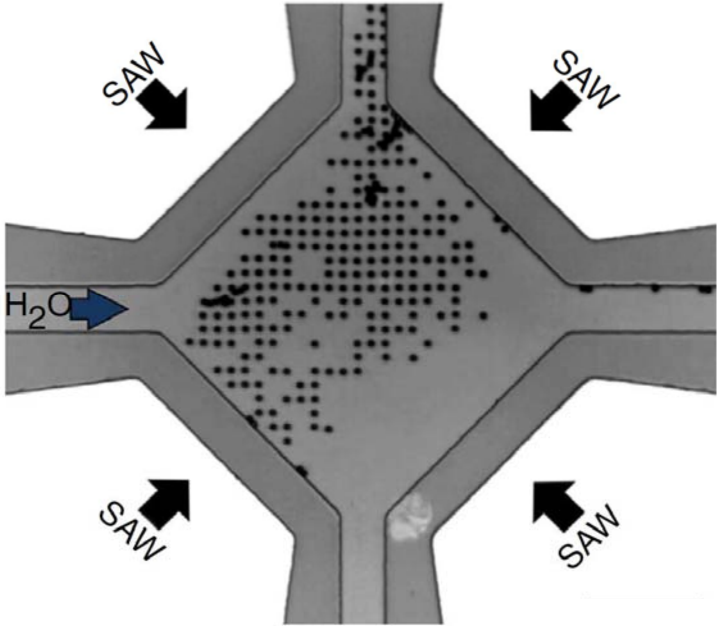
Scattered power



Loss Factors

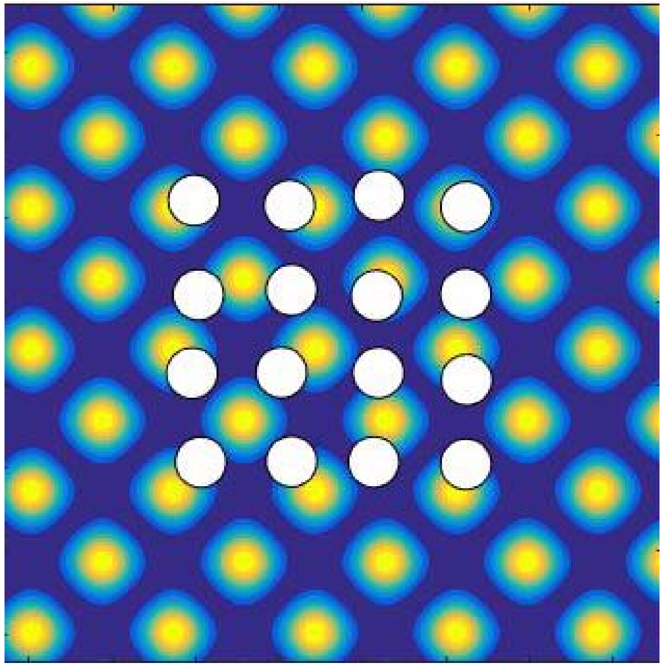


Motivation: Calculating the particle trajectories at high frequencies



One-cell-per-(acoustic)-well

[1] Collins, D. J., Morahan, B., Garcia-Bustos, J., Doerig, C., Plebanski, M., & Neild, A. (2015). *Nature communications*, *6*.



[2] Baasch, T., and Jürg Dual.
The Journal of the Acoustical Society of America 143.1 (2018): 509-519.