TU Clausthal

Influence of bubble size distribution on acoustically cavitating flows

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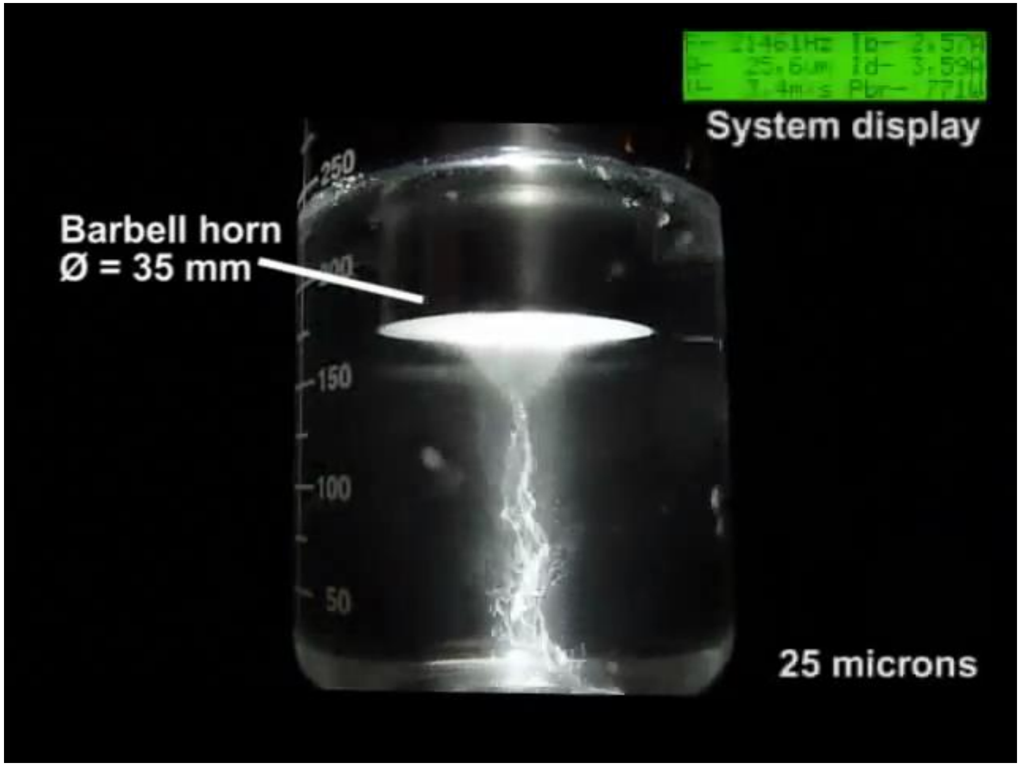
in cooperation with University Göttingen

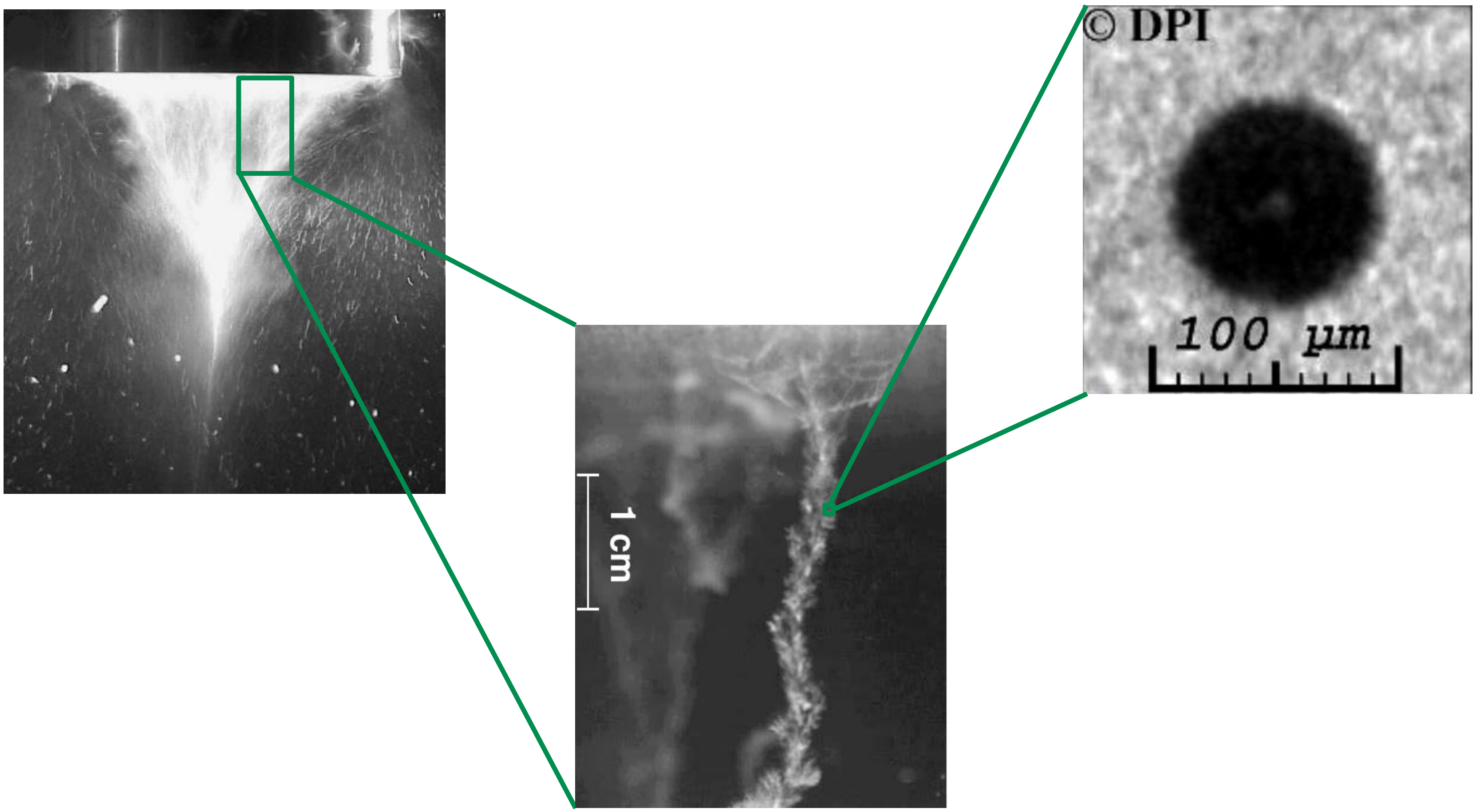
German OpenFoam User meetiNg, Online, 24.03.2021

Acoustic cavitation



Source: Industrial Sonomechanics, LLC

Acoustic cavitation: multiscale problem



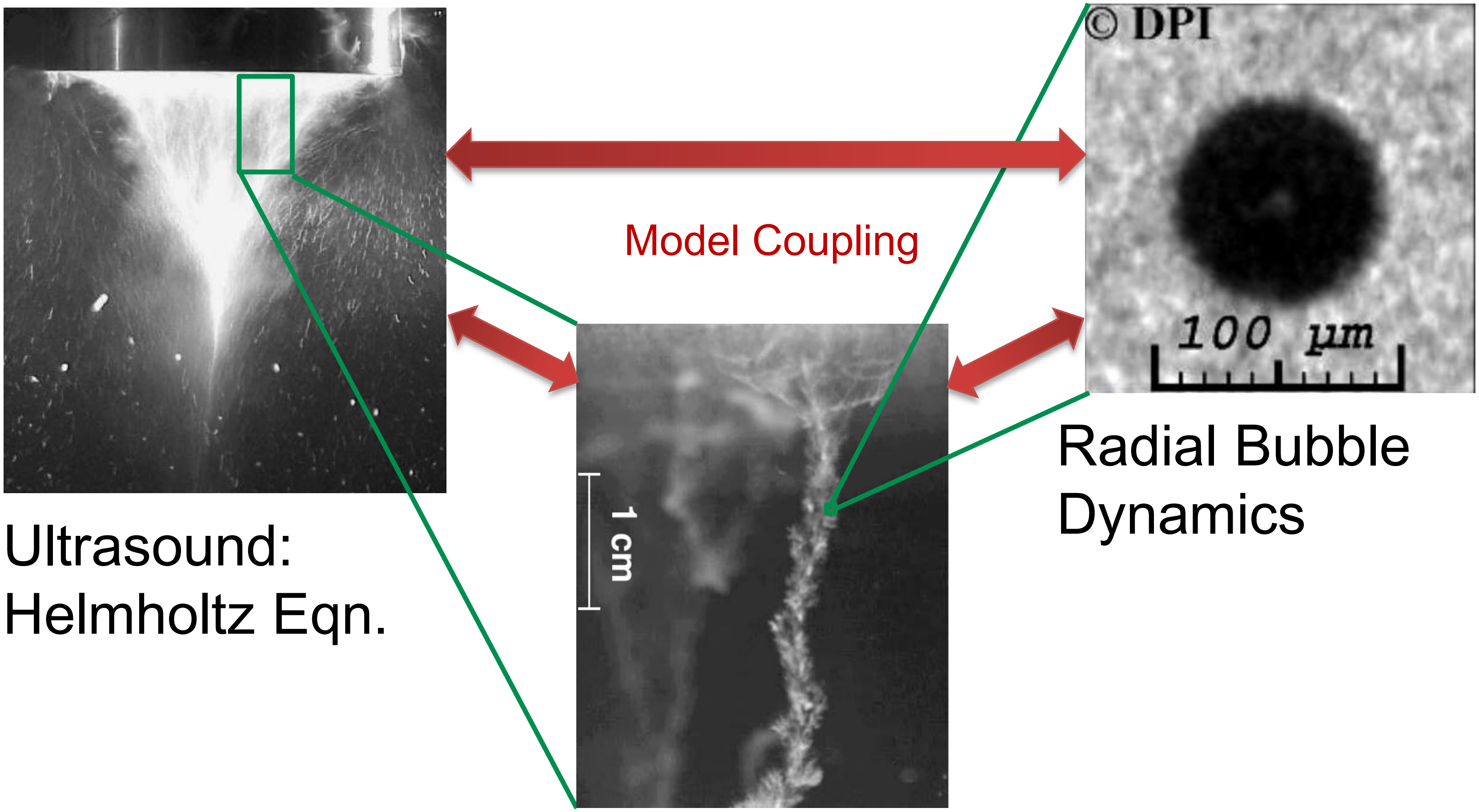
Source of figures: University of Göttingen, Drittes Physikalisches Institut

Motivation

- State of the art
  - fundamental physics of microscopic phenomena well understood
  - macroscopic computations: only linear bubble oscillations with homogeneous distribution
- Goals
  - relatively large geometries (~1-10dm³)
  - spatially inhomogeneous polydisperse bubble distribution
  - predict flow and bubble motion
  - current study: sensitivity to
    - void fraction
    - bubble population

Model

Source of figures: University of Göttingen, Drittes Physikalisches Institut



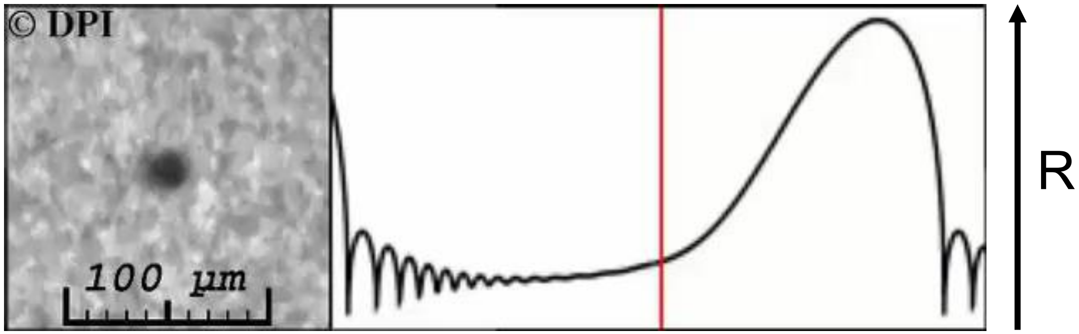
Ultrasound:
Helmholtz Eqn.

Bubble Motion

Radial Bubble
Dynamics

Radial bubble dynamics (RBD)

Time period
$T = 50\mu s$
$(f = 20 kHz)$



Source: University of Göttingen, Drittes Physikalisches Institut

- Toegel model: 3 ODEs
  - Keller-Miksis eqn. (R – bubble radius)

$$\left(1-\frac{\dot{R}}{c}\right)R\ddot{R}+\left(1-\frac{\dot{R}}{3c}\right)\frac{3}{2}\dot{R}^2=\frac{1}{\rho}\left[\left(1+\frac{\dot{R}}{c}\right)\left(p_{\mathrm{g}}-|P_{\mathrm{ac}}|\sin(\omega t)-p_0\right)+\frac{R\dot{p}_{\mathrm{g}}}{c}-\frac{4\mu\dot{R}}{R}-\frac{2\sigma}{R}\right]$$

  - energy transfer (θ – temperature)
  - mass (vapor) transfer (n – amount of substance)
- Stiff system
- Solution as pre-processing step in python
- Usage in solver as interpolation 2D table ($f(R_0, P_{ac})$)

Helmholtz equation (HE)

- Wave equation in frequency domain
  - P_{ac} - complex sound pressure amplitude
  - k_{m} - complex wave number of the gas-liquid **m**ixture
- Solution in foam-extend
  - block-coupled solver
  - direct linear solver (MUMPS)
  - Newton-Raphson method for coupling to non-linear bubble dynamics

$$\nabla^2 P_{\mathrm{ac}} + k_{\mathrm{m}}^2 P_{\mathrm{ac}} = 0$$

$$k_m^2 = \int_T f(R, T, n, t, \ldots) dt$$

Bubble motion

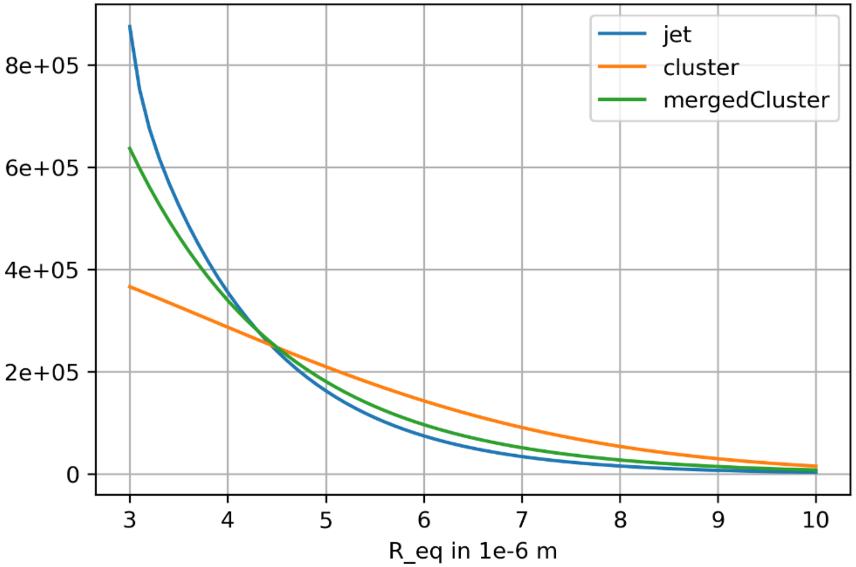
- Lagrangian
- Force balance

$$m_{\mathrm{b}} \frac{\mathrm{d}U_{\mathrm{b}}}{\mathrm{d}t} = F_{\mathrm{G}} + F_{\mathrm{Am}} + F_{\mathrm{D}} + F_{\mathrm{Bj}}$$

- $m_{\mathrm{b}}, U_{\mathrm{b}}$- bubble mass and velocity
- Forces:
  - F_{G} - gravitation
  - F_{Am} - added mass
  - F_{D} - drag
  - F_{Bj} - Bjerknes, due to interaction of non-linear oscillation and acoustic pressure gradient $F_{\mathrm{Bj}} = \langle V_{\mathrm{b}} \rangle_T \nabla P_{\mathrm{ac}}$

Bubble populations

- Source: F. Reuter, S. Lesnik, K. Ayaz-Bustami, G. Brenner, R. Mettin, Bubble size measurements in different acoustic cavitation structures: Filaments, clusters, and the acoustically cavitated jet, Ultrason. Sonochem. 55 (2019) 383–394.

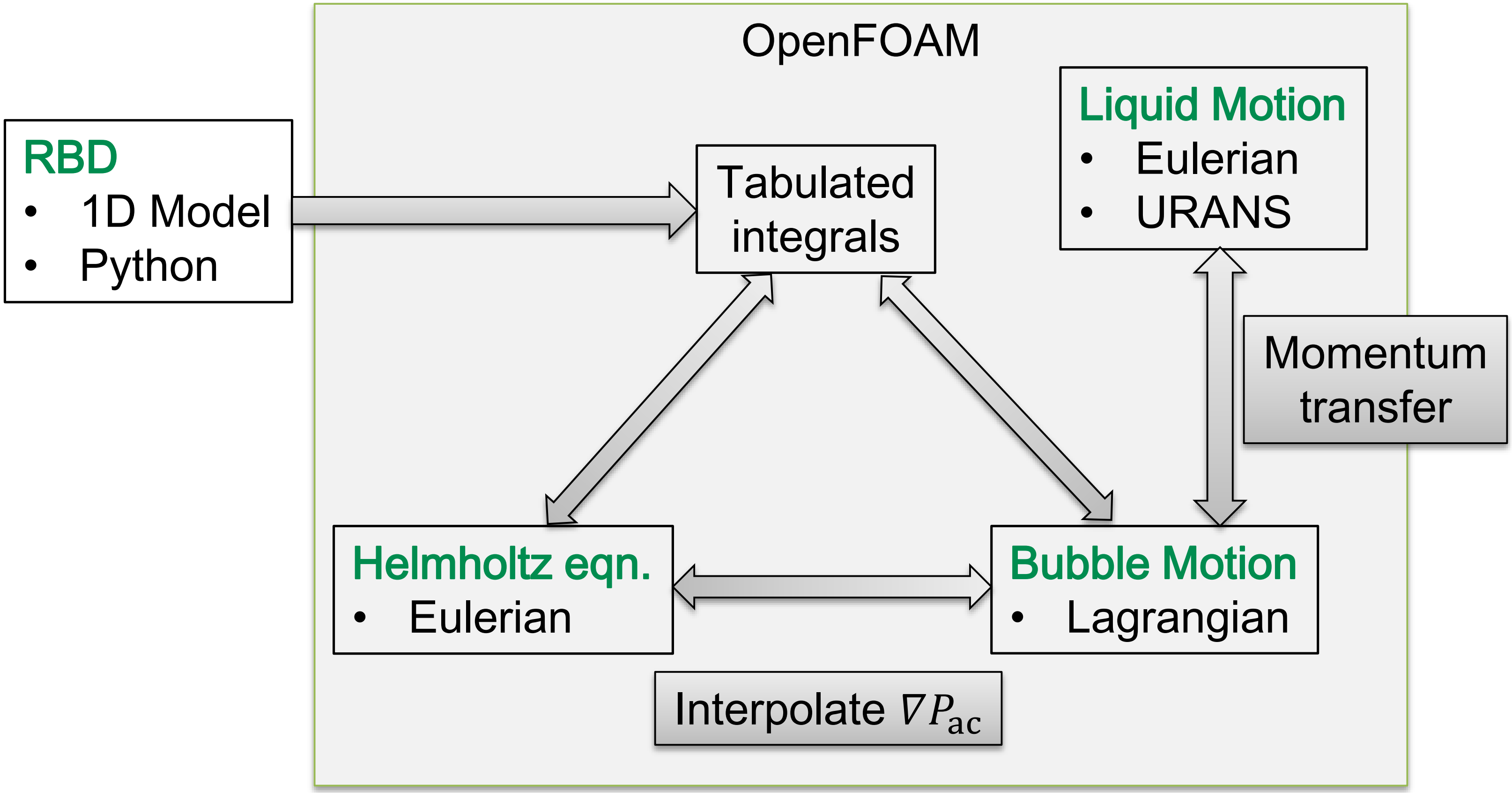


Bubble populations implementation

- Assumptions:
  - void fraction at walls is kept above a threshold (injection)
  - bubbles jet when touching walls (escape condition)
  - initial homogeneous void fraction

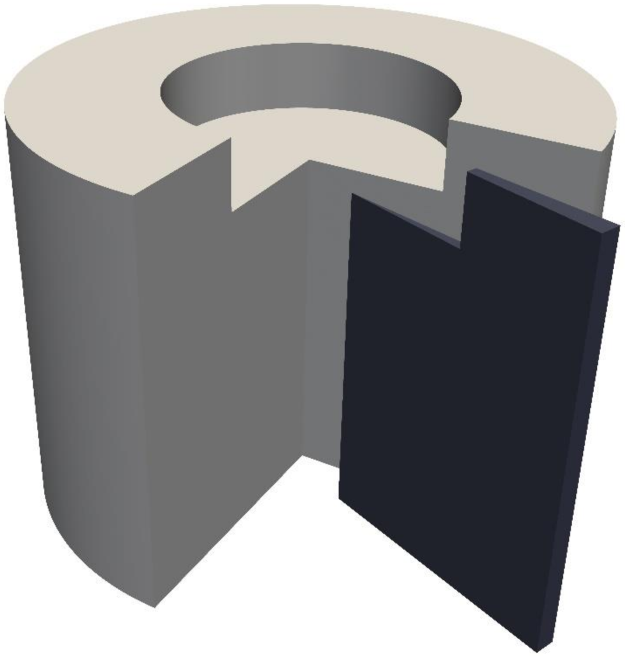
- Dynamic Load Balancing (foam-extend)
  - $\beta = 10^{-5}$ => 1 to 100 Mio bubbles (β – void fraction / bubble density)
  - due to cavitation forces bubbles may accumulate at stagnation points -> performance issues in parallel runs
  - rebalance mesh if imbalance is high such that every processor has similar number of bubbles

Overview

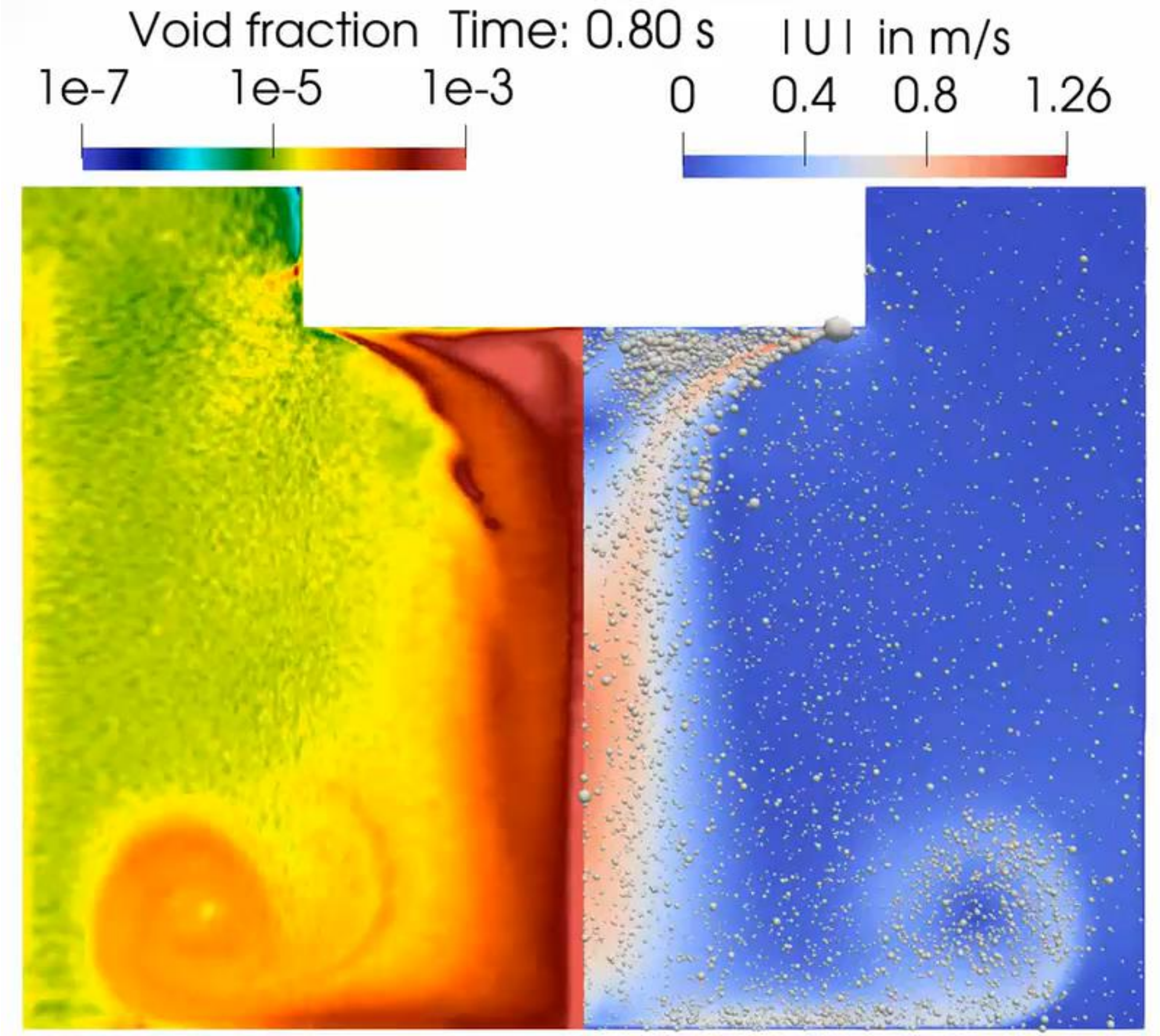

OpenFOAM
RBD
• 1D Model
• Python
Tabulated integrals
Liquid Motion
• Eulerian
• URANS
Momentum transfer
Helmholtz eqn.
• Eulerian
Bubble Motion
• Lagrangian
Interpolate ∇P_{ac}

Geometry

- Sonotrode immersed in a cylindrical geometry
  - typical setup also for large scale reactors
  - axisymmetric
  - tank
    - 18cm tall
    - 24cm diameter
  - sonotrode
    - 3cm beneath water surface
    - 12cm diameter

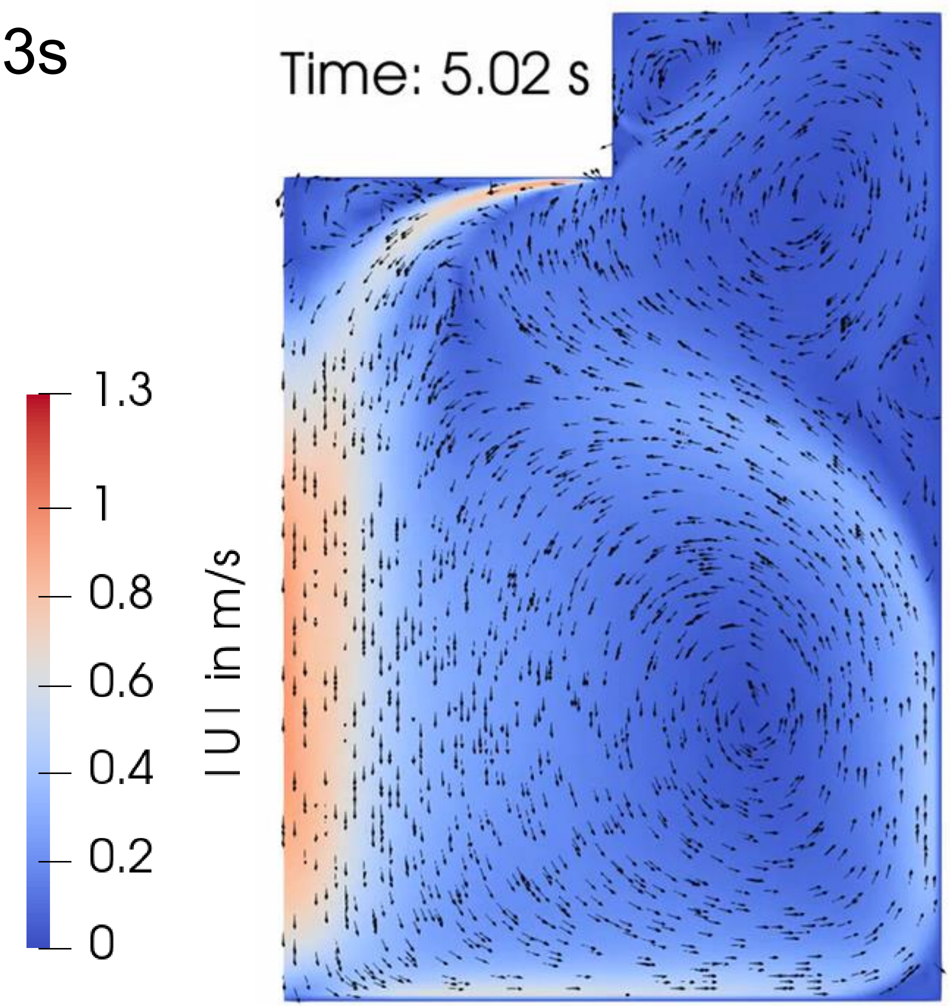


Cylindrical tank



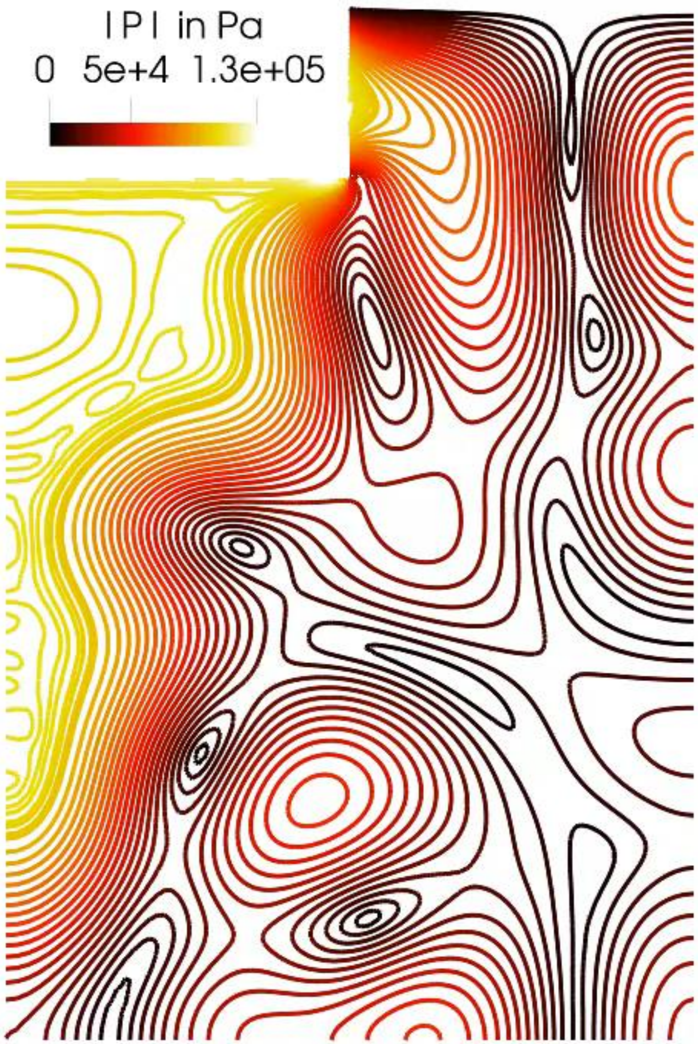
Velocity with glyphs

- Quasi-stationary after 3s
- Periodic fluctuations
- Velocity magnitude fits experimental results

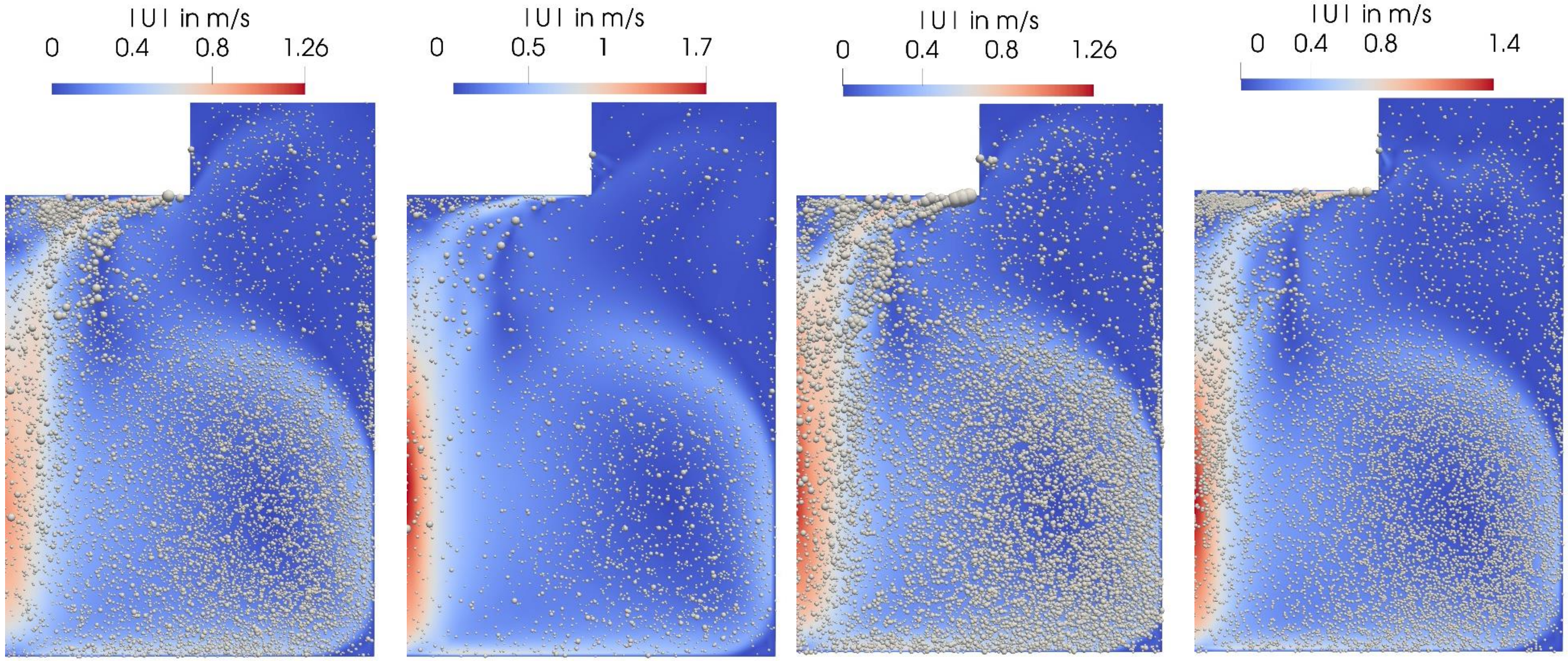


Acoustic pressure contours

- In the area of the cone structure |P| is fluctuating
- Bubbles are driven by ∇P
- Thus, bubbles form clusters and disturb the flow, which leads to fluctuations



Fluid velocity



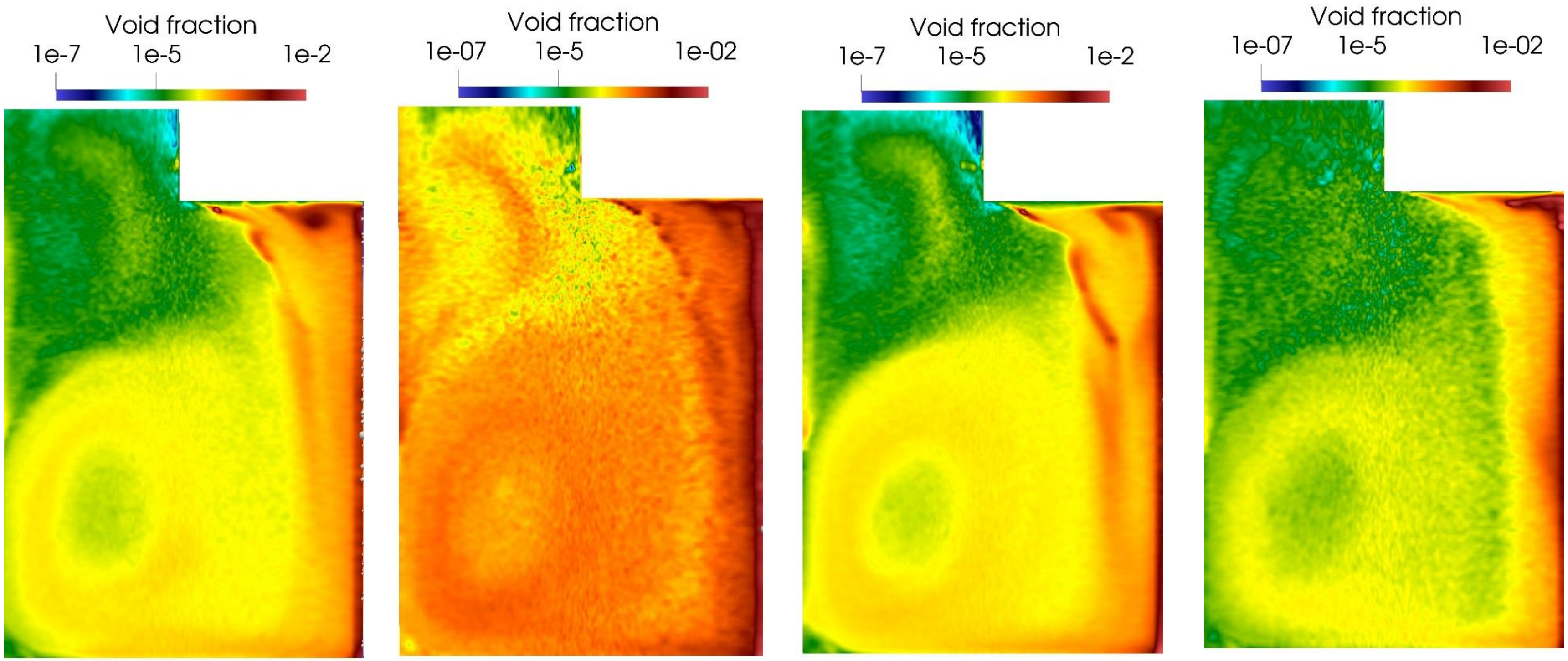
Reference
$\beta = 1.2 \cdot 10^{-5}$,
R_0 Jet distribution

$\beta = \mathbf{10^{-4}}$,
R_0 Jet distribution

$\beta = 1.2 \cdot 10^{-5}$,
R_0 **Cluster** distribution

$\beta = 1.2 \cdot 10^{-5}$,
$R_0 = 2\mu m$, **monodisperse**

Void fraction



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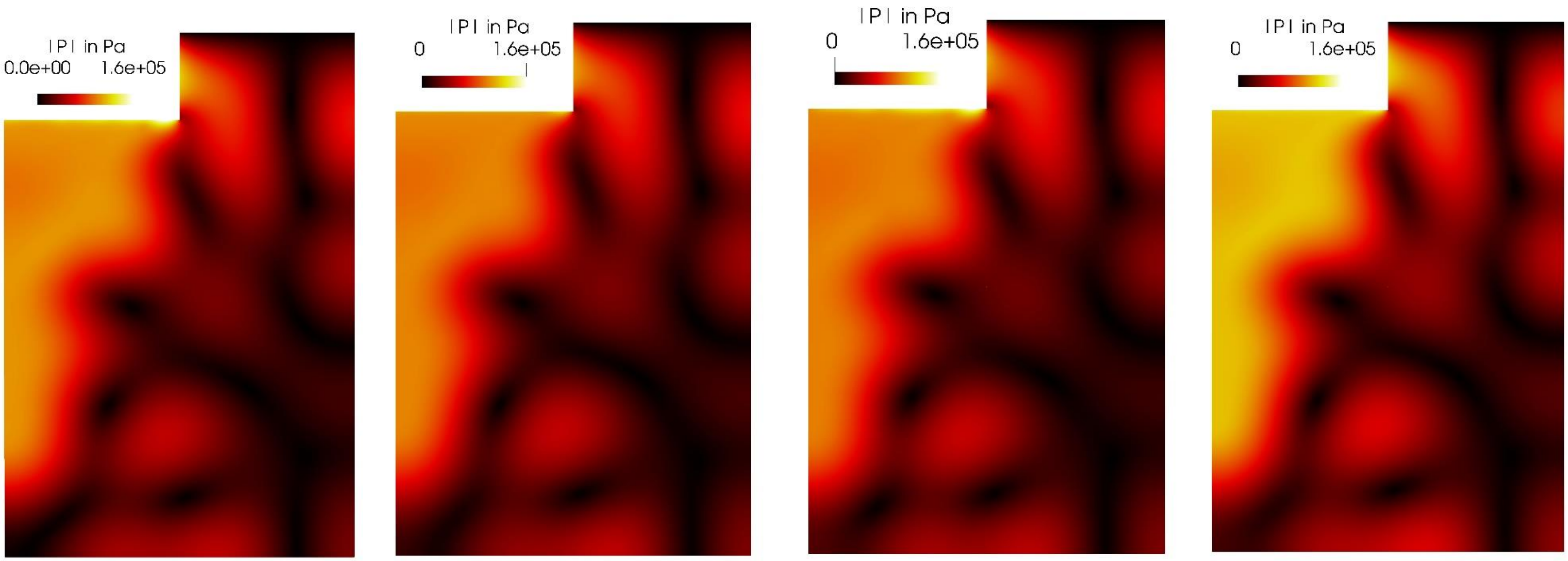
Acoustic pressure



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Summary

- Computation of cavitation flows in large scale reactors
  - solution agrees qualitatively with experiments
- Fluctuation of the flow, which is also seen in experiments, is explained by interaction between bubbles and acoustic pressure
- Bubble populations
  - generally: the flow and acoustic pressure structure show low sensitivity due to the population type
  - flow velocity may alter by up to 50%

Source code for Helmholtz solver (MUMPS interface):

https://github.com/technoC0re

Questions?

Deutsche Forschungsgemeinschaft

ALLIANZ INDUSTRIE FORSCHUNG

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