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Vibro-Acoustic Design Principles for High Power Ultrasound

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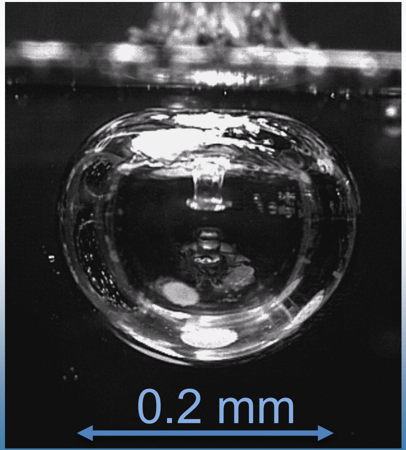

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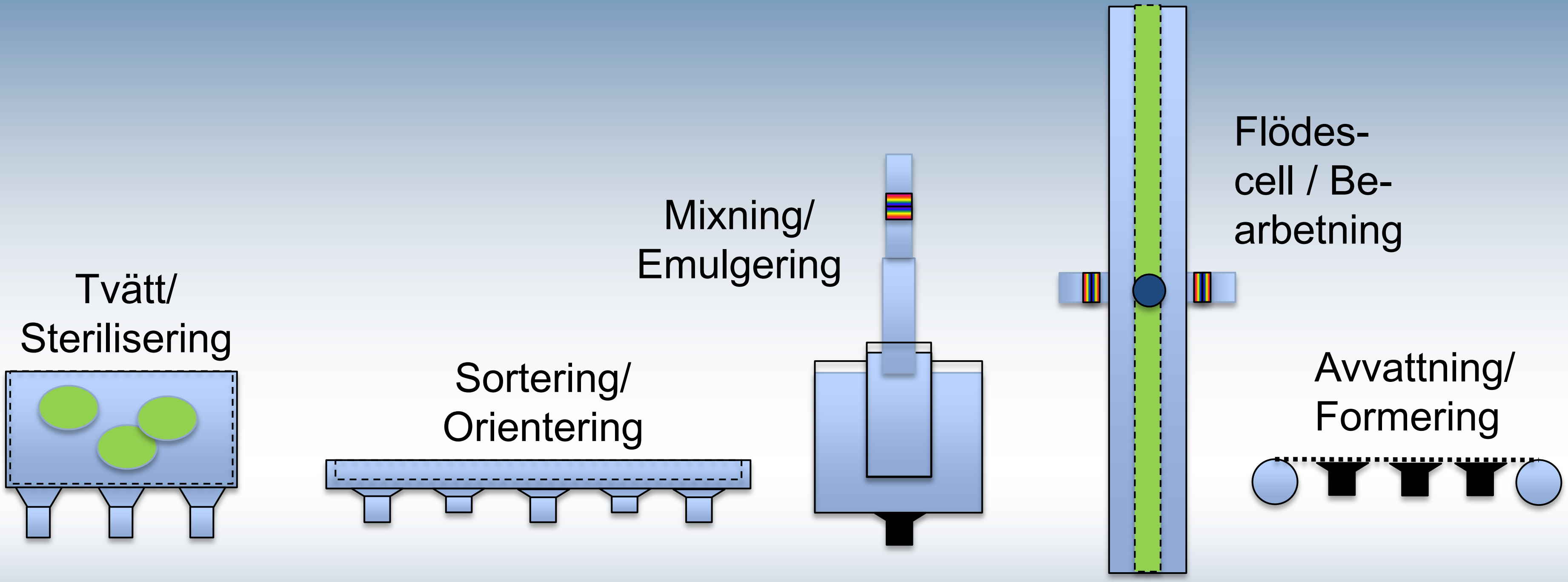
Background – Power Ultrasound



Present projcts and applications

Ultrasound Processing

- Lower process temperatures
- **Better yield and quality**
- **Improve energy efficiency**
- Reduce number of unit operations

– Up-scaling
– Limited process volumes
– Robustness and stabillity
– **Difficult to predict**

Objectives and Goals

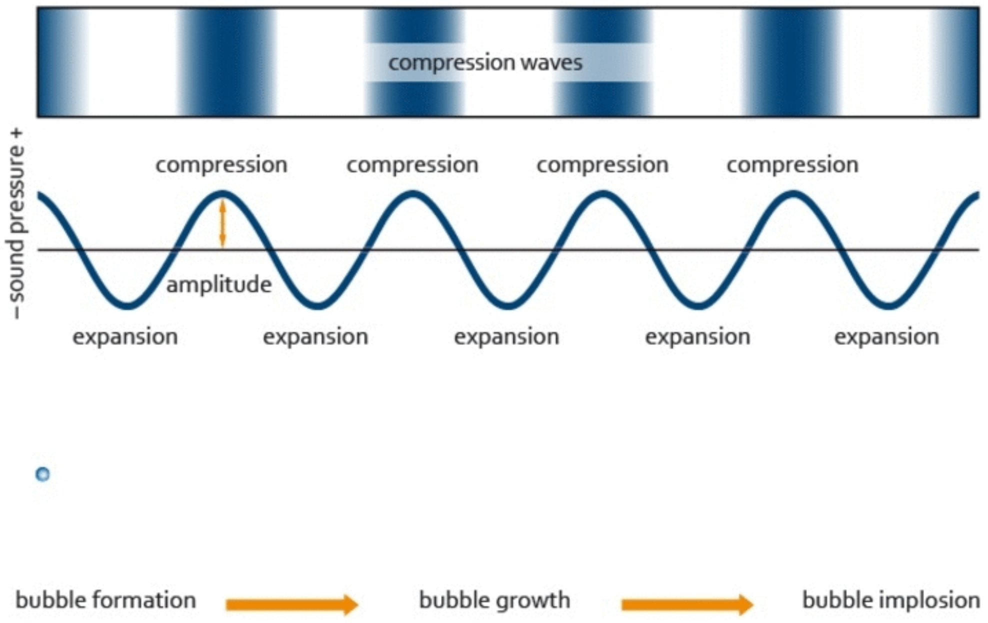
Improve process efficiency and yield based on hydrodynamic and acoustic cavitation

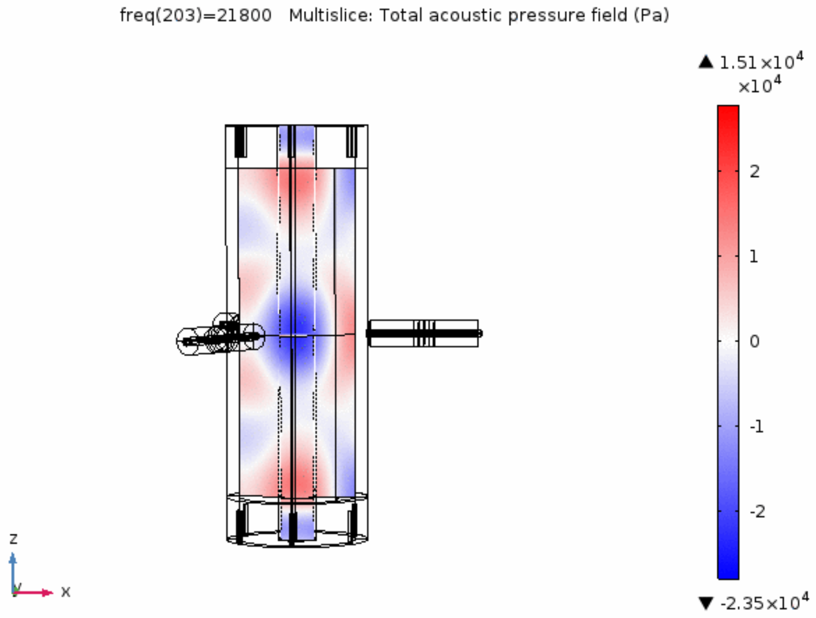
1) Develop a scalable reactor concept for process intensification
2) **Methodology for numerical and experimental optimization**
3) Better energy efficiency compared to traditional unit operations
4) **Improving yield and quality**

Demonstration

Ultrasonic Reactor

Cavitation and Acoustic Maximum



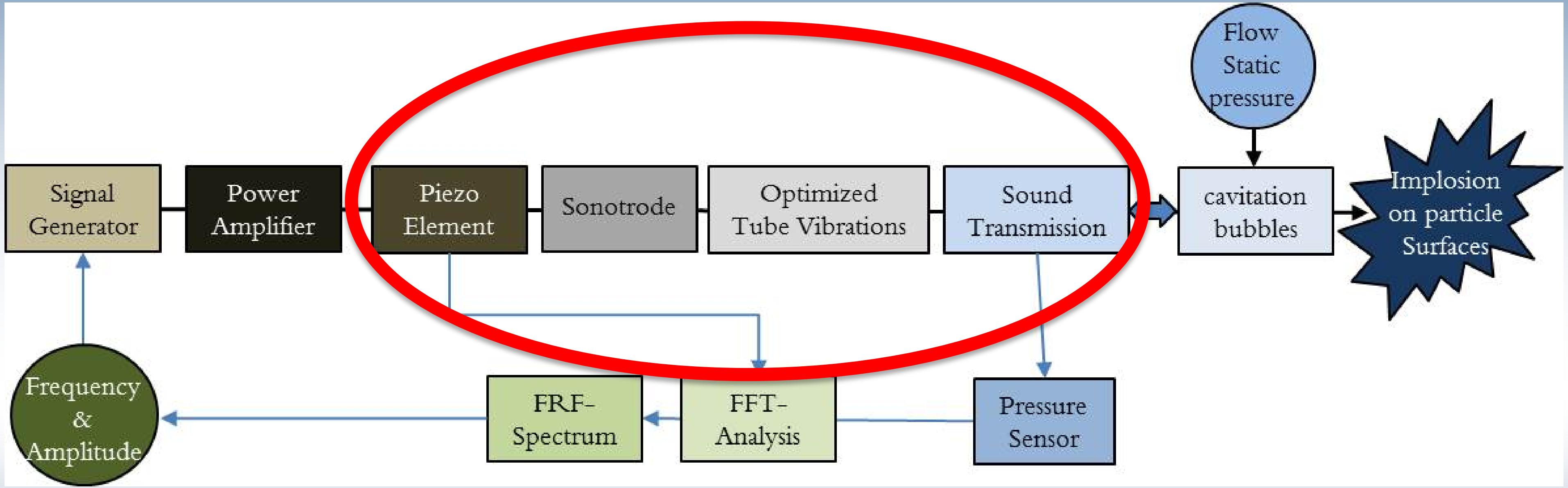


Bubble sizes are frequency dependent!

Why a tube structure?

- **Alows flow**
- Common engineering structure
- *Might be extremely noisy*
- *Shockwaves and extreme vibrations*
- **Natural focusing effect**
- **Difficult to predict sound and vibration**

Coupled and Non-Linear Problem



"Linearized on a saddle point"

Structural acoustic optimization

A stepwise and multivariate approach built upon:

a) Wave speeds in fluids and solid materials

b) Fluid resonances in a cylindrical volume

c) Longitudinal resonances in a shell structure

d) Bending wave resonances in a free cylindrical shell

e) Critical frequency of a bending wave in a cylinder wall

Goal: Combine several resonances at one frequency

a) wave speeds in fluids and solid materials

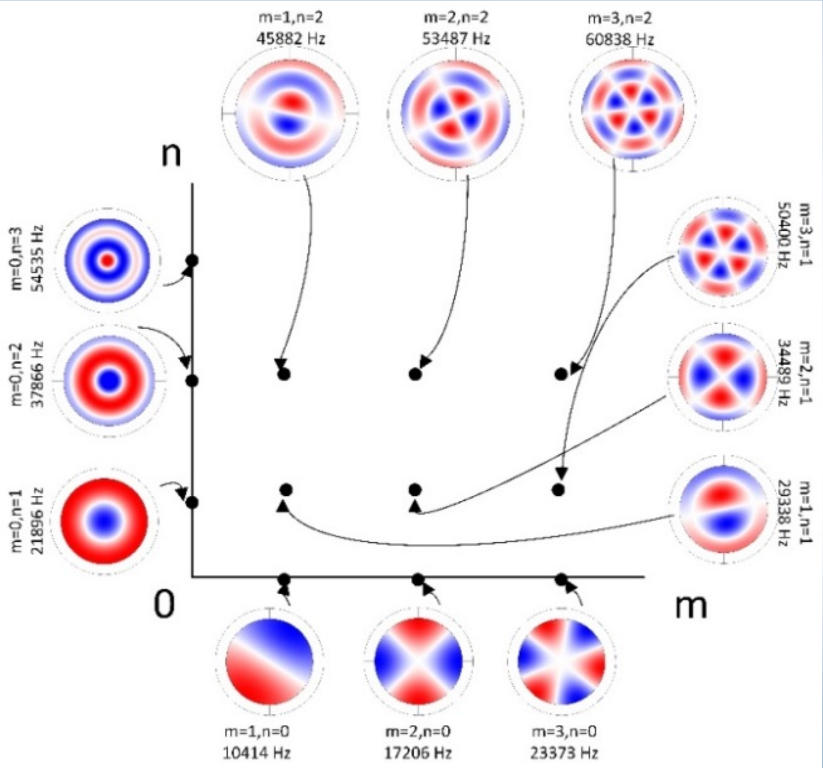
”3D” Solid or fluid	”2D” Plate or Shell	”1D” Beam
$c_L = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}}$	$c_{L''} = \sqrt{\frac{E}{\rho(1-v^2)}}$	$c_{L'} = \sqrt{\frac{E}{\rho}}$

Stainless steel:	**5770 m/s**	**5244m/s**	**5011m/s**
Water (20°C):	**1481 m/s**		

b) Fluid eigenmodes inside a cylinder

- *Cross-sectional eigenmodes*
- *Water filled cylinder*
- *D_i=90mm.*
- *Eigenfrequency:*

$$f_{l,m,n} = \frac{c}{2}\sqrt{\left(\frac{2\beta_{m,n}}{\pi D_i}\right)^2 + \left(\frac{l}{L_f}\right)^2}$$



c) Longitudinal resonances in a shell structure

”Breathing” mode

$$f_1 = \frac{1}{\pi D_M}\sqrt{\frac{E}{\rho(1-v^2)}}$$

”Complex” mode

$$f_{n,l} = \sqrt{\frac{E}{\rho(1-v^2)}\left[\left(\frac{n}{\pi D_M}\right)^2 + \left(\frac{l}{2L}\right)^2\right]}$$

***$f_{1,0}$* = 21000 Hz** (SS; D_M=90mm)

Avoid some length intervals!

d) Bending wave resonances in a cylindrical shell

$$f_{l,m} = \frac{c_B}{2\pi}\sqrt{\left(\frac{l\pi}{L_s}\right)^2 + \left(\frac{m}{a_M}\right)^2}$$

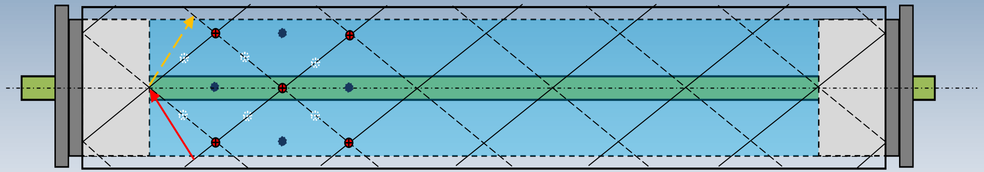
Bending wave speed (c_B) depends on frequency, thickness and material

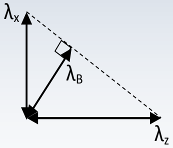
$$c_B^2 = 2\pi f\sqrt{\frac{Eh^2}{12\rho(1-v^2)}}$$

c_B=1550 m/s; L_s=1120 mm; a_M = 50mm; m=3; l=22

***$f_{22,3}$* = 21kHz**

e) Critical frequency - bending wave – “free” cylinder





$$\lambda_B = \frac{\lambda_x \lambda_z}{\sqrt{\lambda_x{}^2 + \lambda_z{}^2}}$$

$$h = \frac{c_B^2}{2\pi f_c}\sqrt{\frac{12\rho(1-v^2)}{E}}$$

$h << \lambda_B$ and $f > f_0$

$c_B \geq c_{fluid}$ or $\lambda_B \geq \lambda_{fluid}$ = 74 mm at 21 kHz give: **h ≥ 12 mm**

Design Methodology

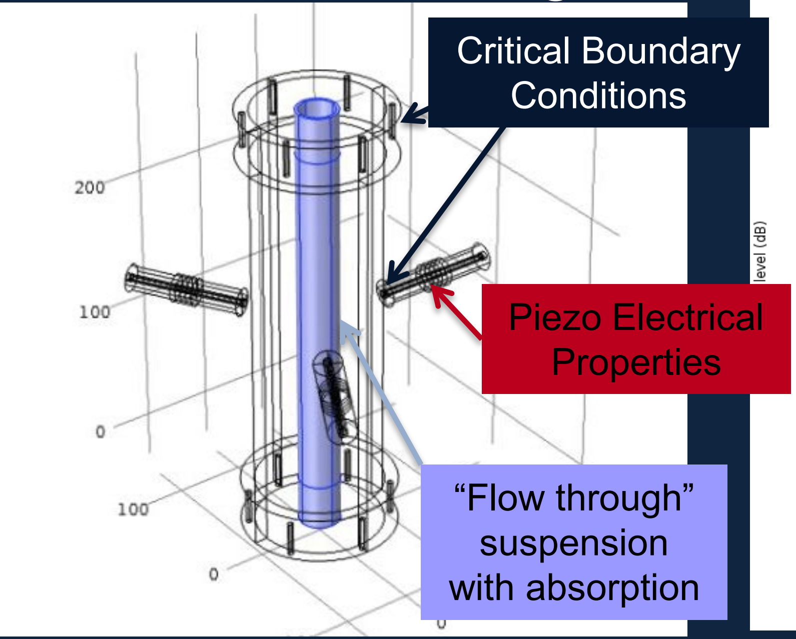
Design parameters:

I. Temperature (T)
II. The diameter of fluid volume(D_i)
III. Length of fluid volume (L_f)
IV. Wall thickness of the surrounding tube (h)
V. Length of the tube (L_s)
VI. Fluid properties of the inner tube *

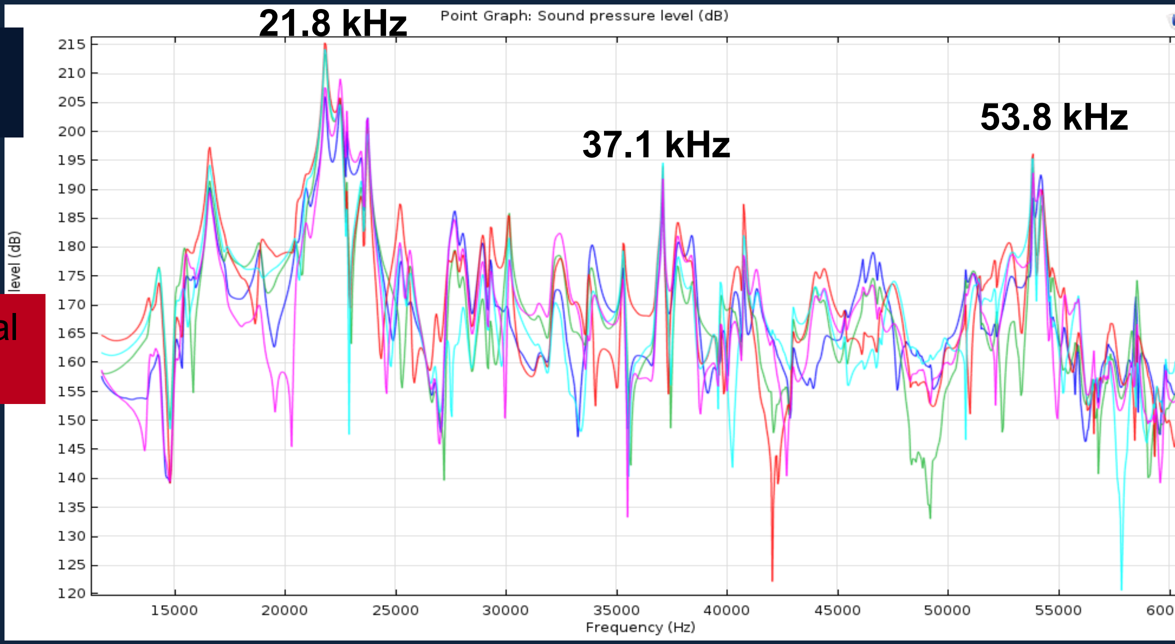
** The design goal is to make the reactor design as robust as possible with respect to losses in the central volume*

Coupled FE-Modelleing
Comsol Multiphysics ®

Geometrical Design



Simulated Pressure Response



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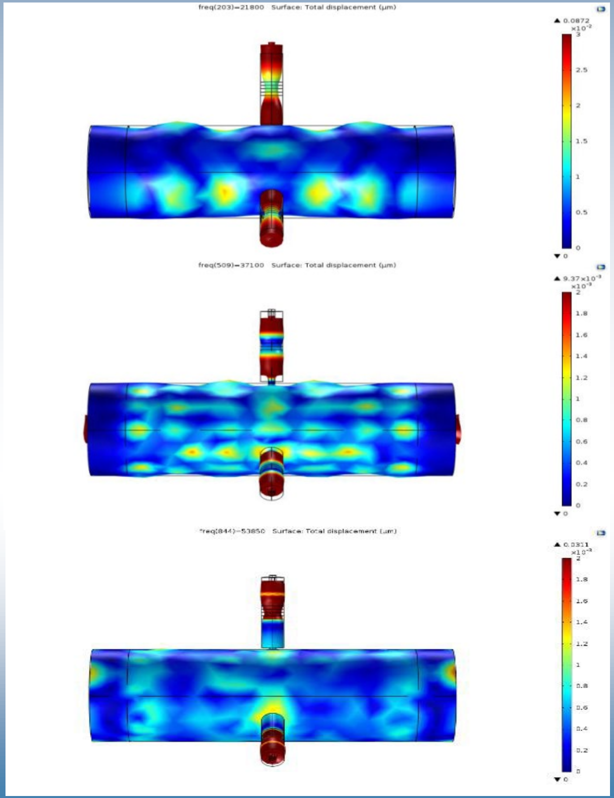
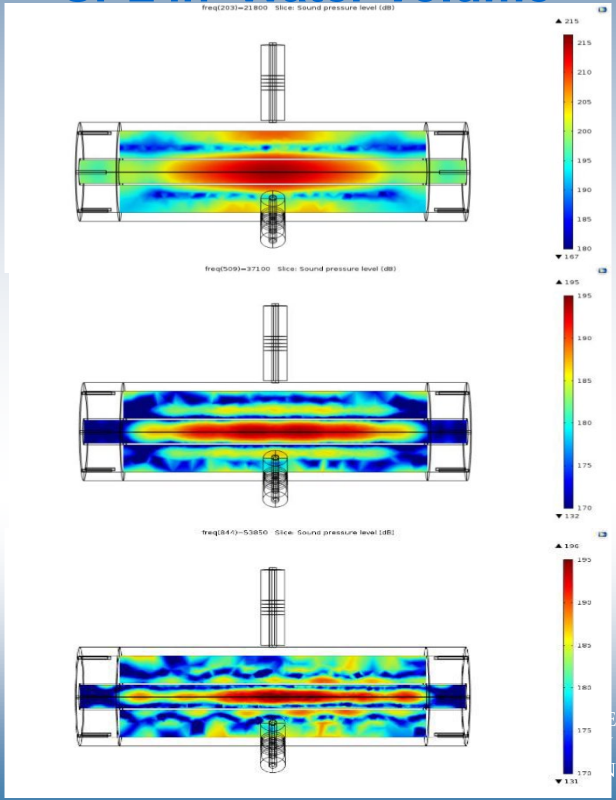
FEM-optimized reactor geometry

Structural vibrations



SPL in Water Volume

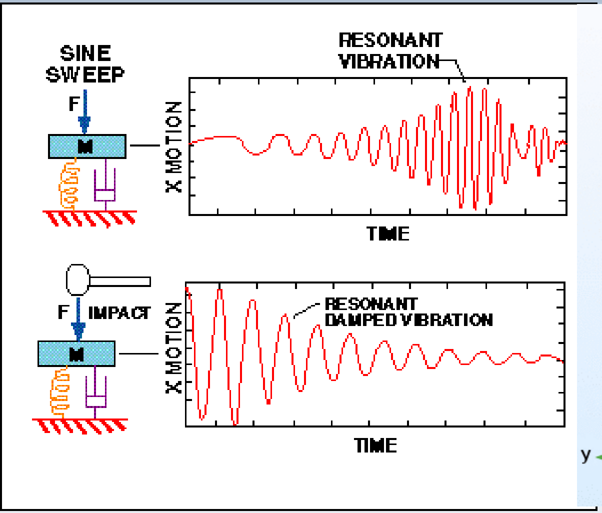


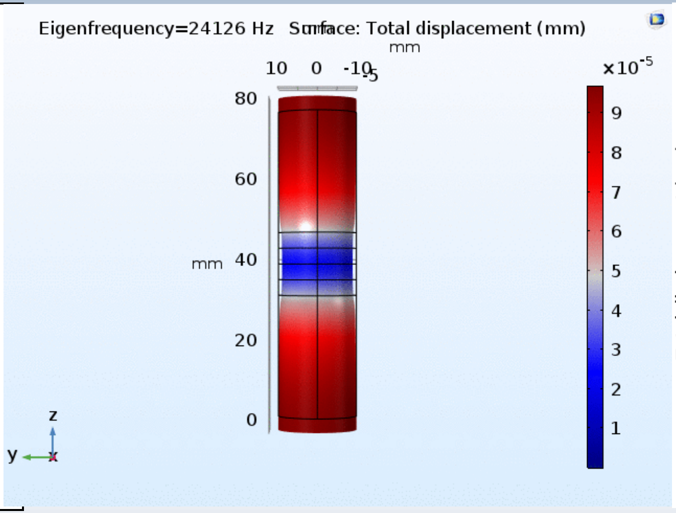
21.8 kHz

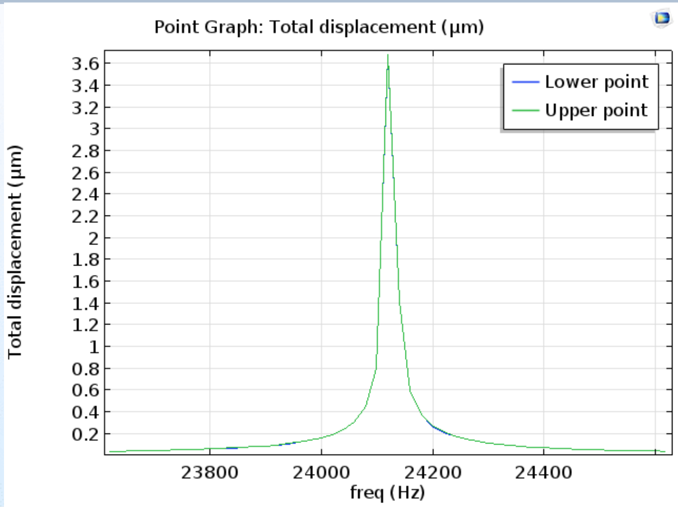
37.1 kHz

53.8 kHz

Excitation by Sonotrodes





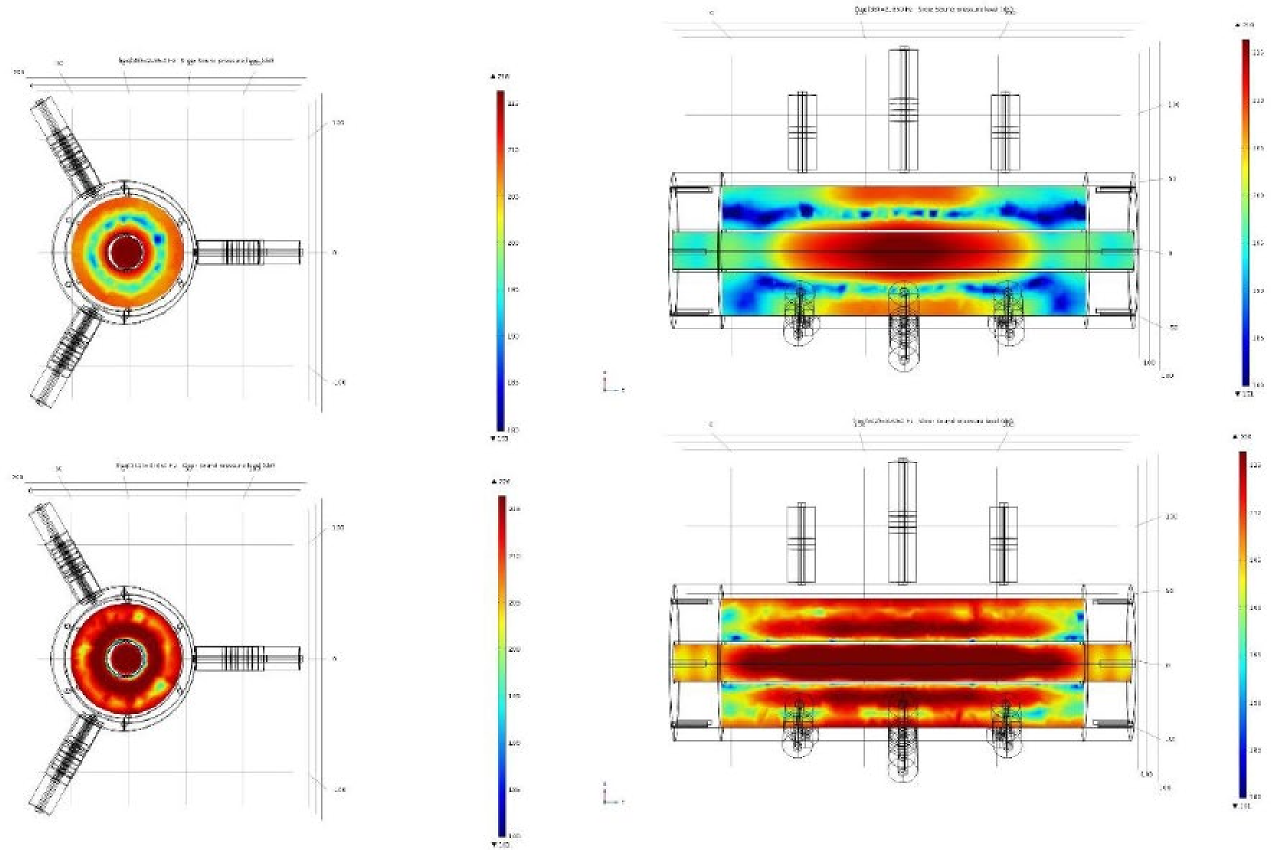


3.6 µm at 24 kHz give acc ≈ 8000g

9 Sonotrodes & 2 Frequencies

3 x 22 kHz

6 x 37kHz



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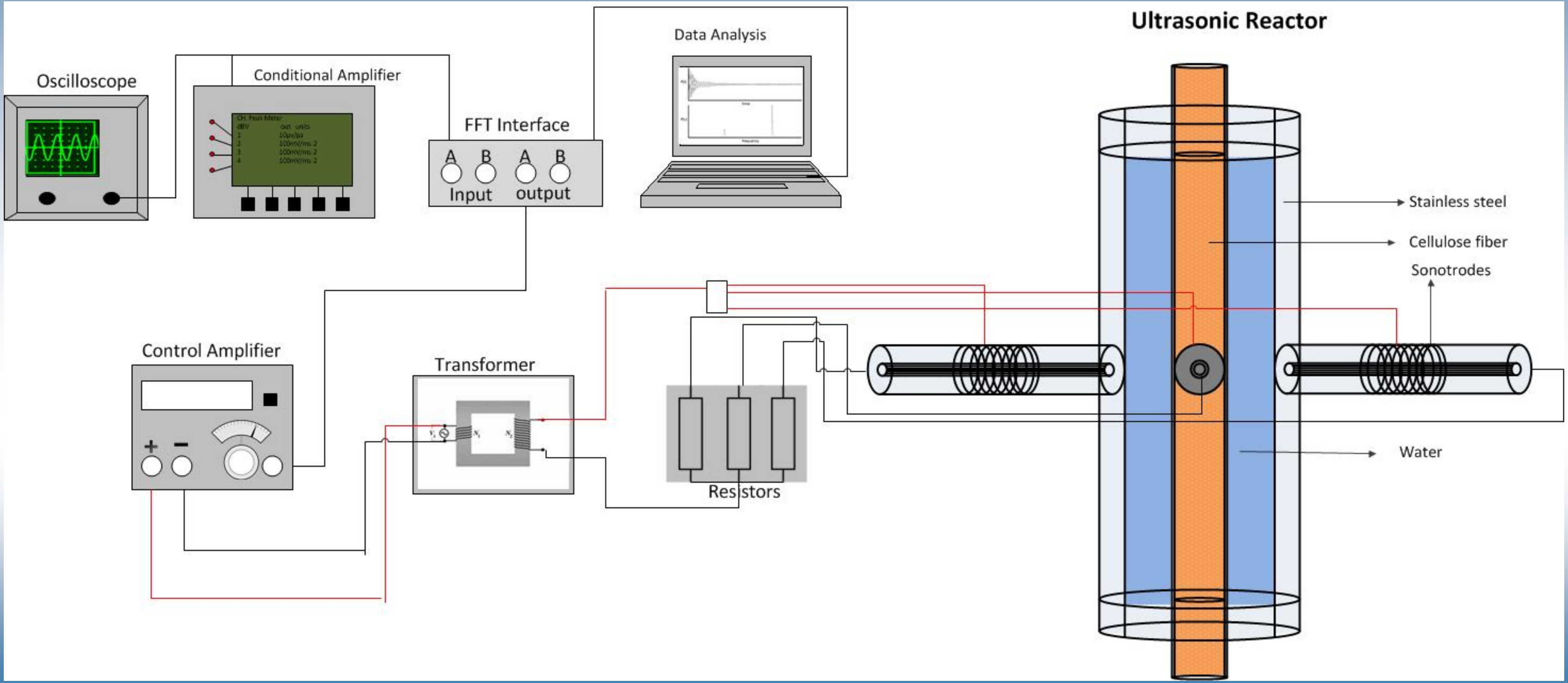
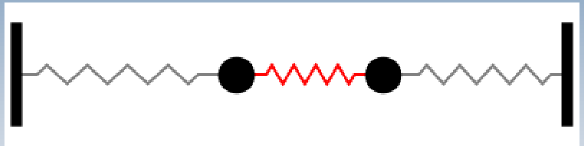
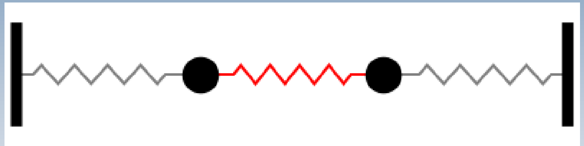
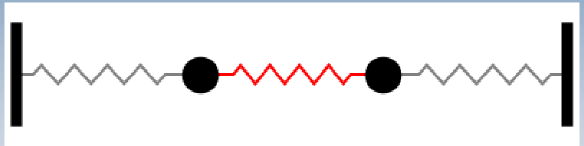
Experimental verification

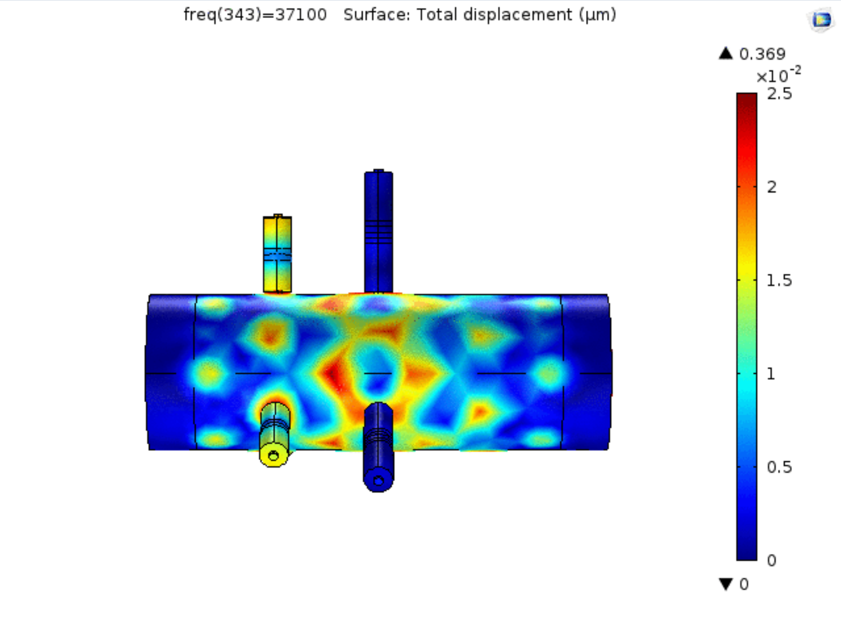


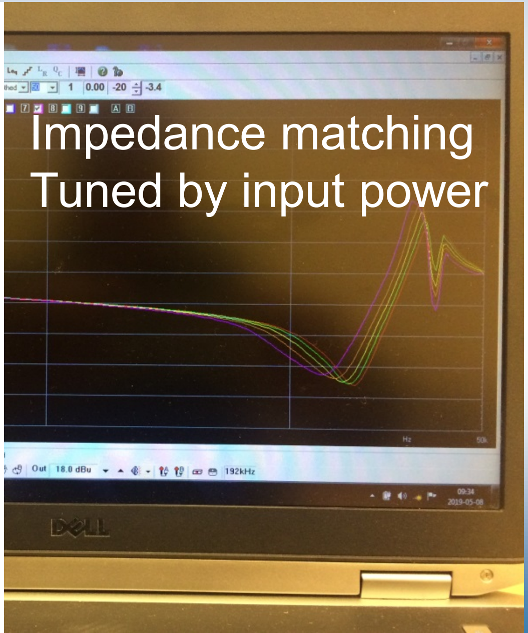
Mission Impossible?



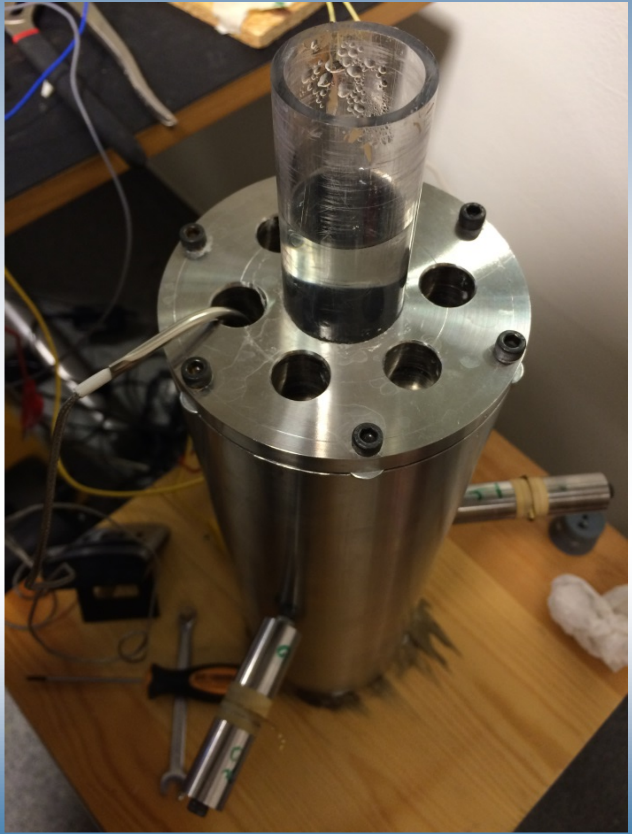


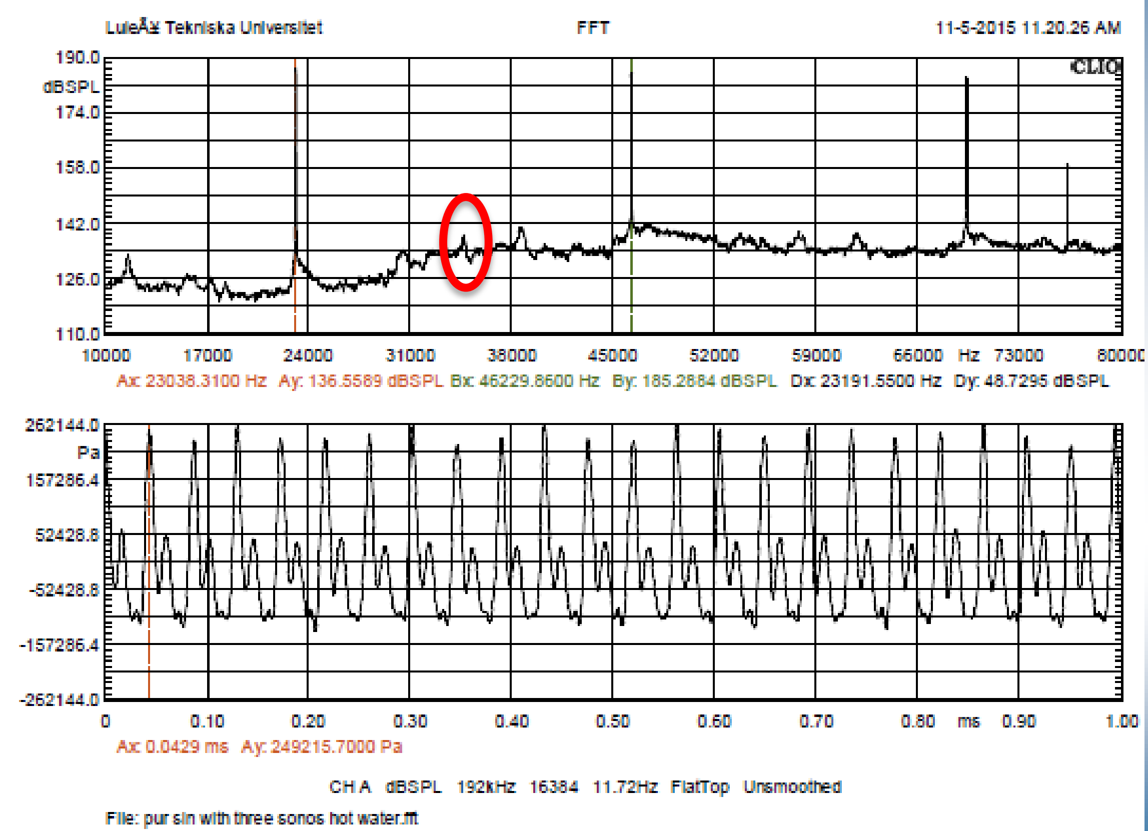




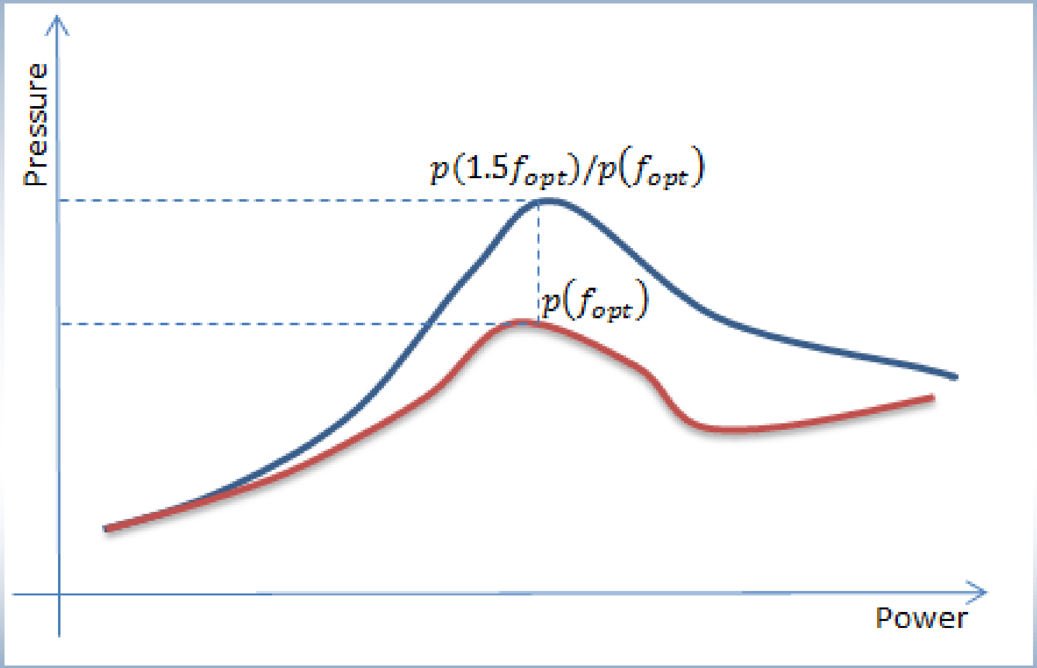


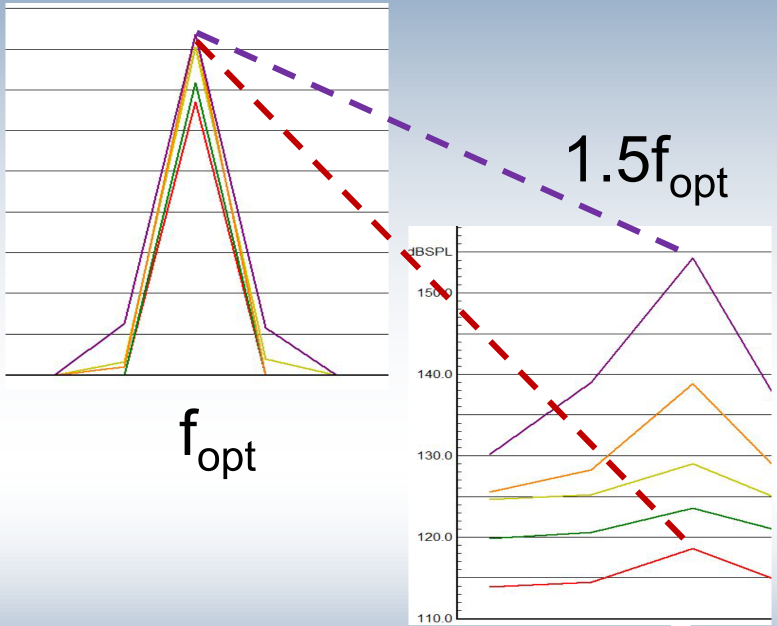
Verification measurements





Optimum cavitation intensity?





”Listening” for control

Parameters Influencing Quality

1. **Excitation frequency** (multiple)
2. **Flow characteristics** (initiate bubbles and mixing)
3. **Process temperature** (typically lower)
4. **Static pressure** (increase cavitation intensity)
5. **Signal characteristics** (patented signal)
6. **Cavitation intensity** (optimized by electrical power)
7. **Pulp characteristics** (concentration and size distribution)
8. **Lossfactors** (amplification)

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20190416
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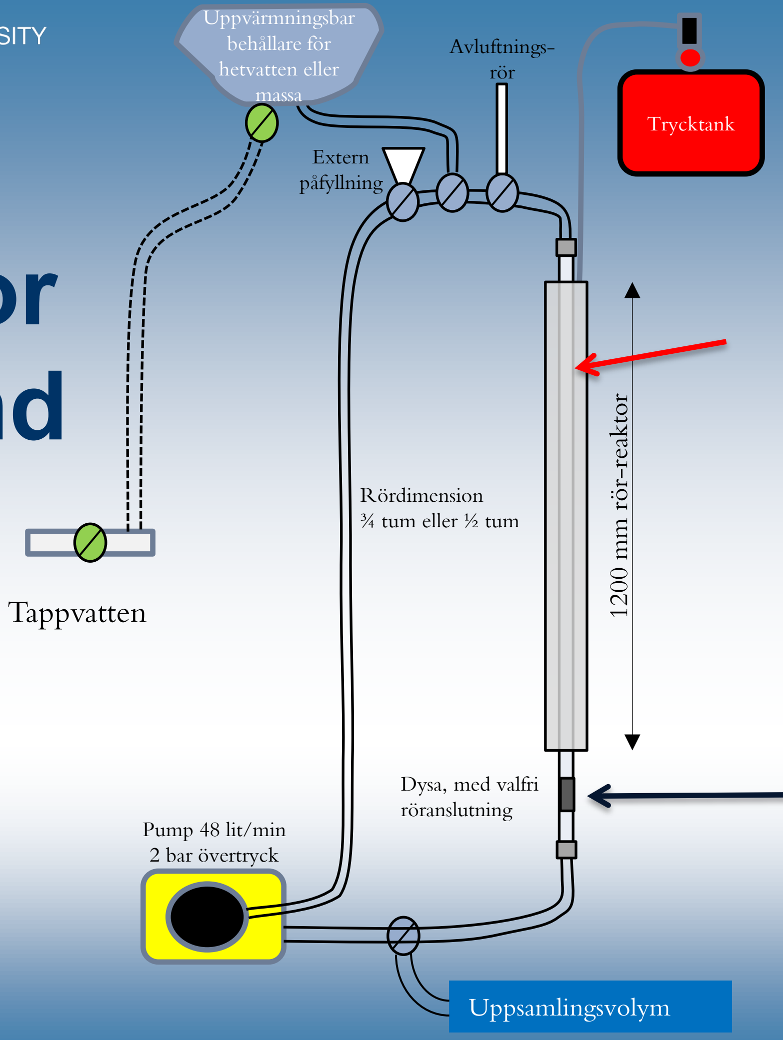
System for Ultrasound treatment of liquid solvents



II. Acoustic controlled cavitation

I. Hydrodynamic initiation of cavitation bubbles

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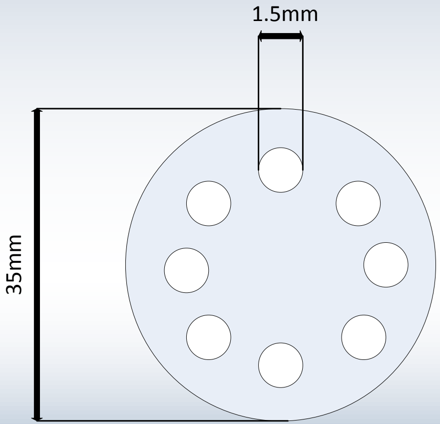
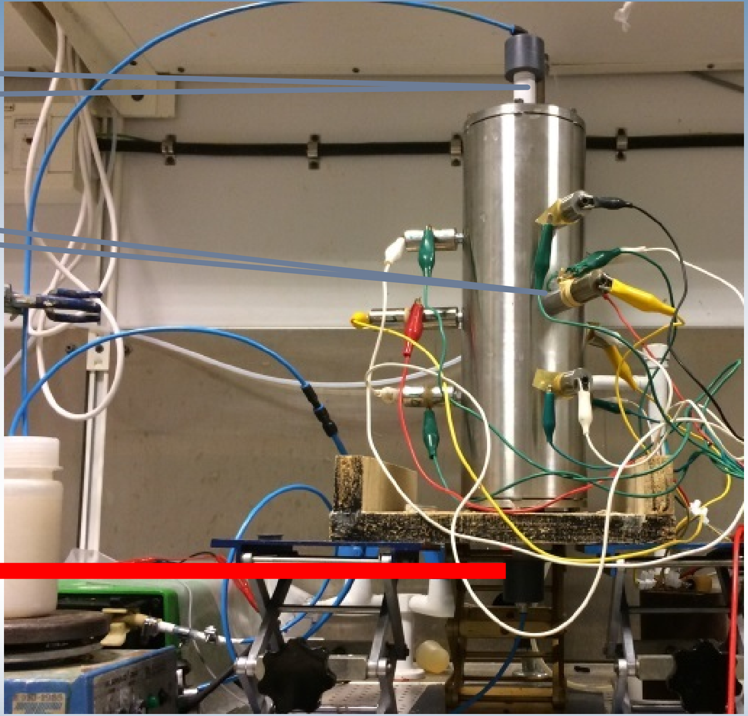
Experimental set-up for metal extraction

PVC pipe

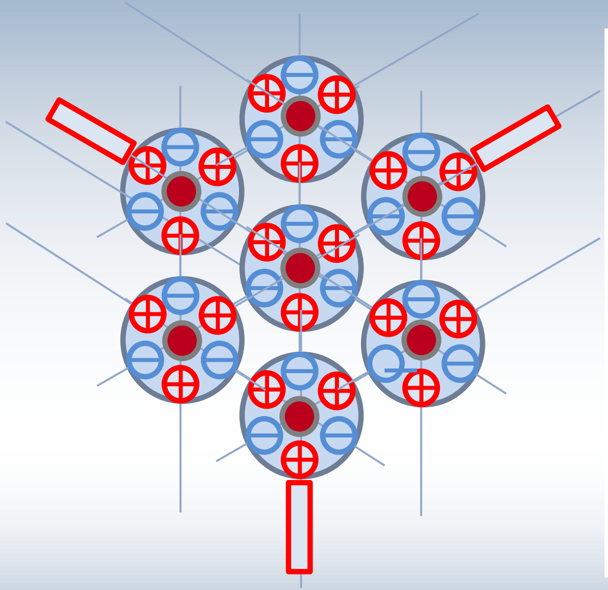
Sonotrodes

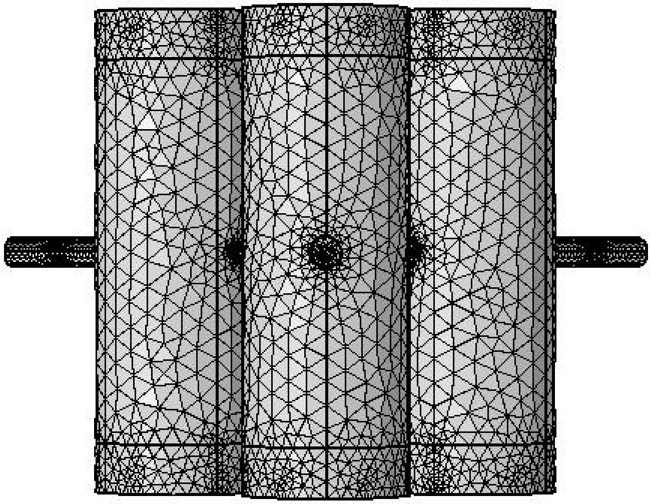
ORIFICE PLATE

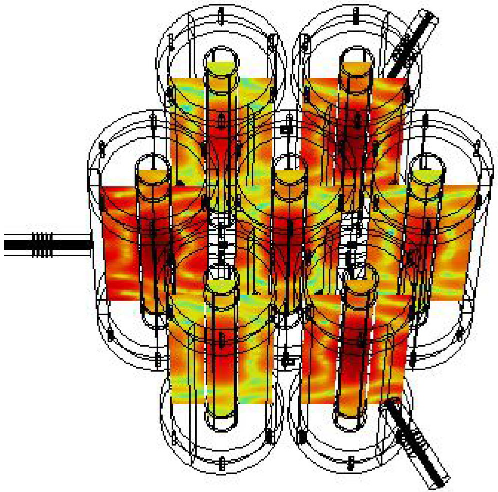




Scaleable Reactor Concept







Conclusions

I. The reactor concept is developed by an **iterative procedure** combining **multi-physic simulation** and experimental **optimization**

II. The reactor **vibration response** gives pressure maximum and transient cavitation in the **flow through zone**

III. The reactor concept is **scalable** and **adaptable** to various process industry applications