THE OHIO STATE UNIVERSITY

A Multi-Stepped Ultrasonic Horn for Industrial Scale Processes

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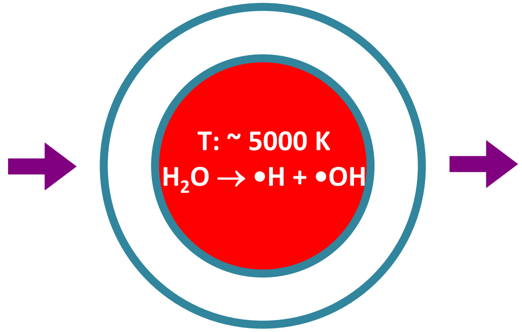
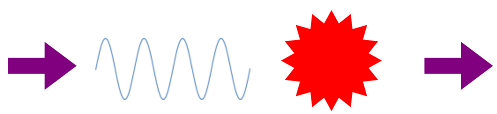
Sonochemistry in Remediation

Cavitation



Transient cavitation bubble

- Oxidation
- Thermolysis



Micro-jet , micro–streaming
pitting, collision

- Desorption
- Accessibility

Scale Up Sonochemical Treatment

- Increase bioavailability, initiate degradation reaction, and enhance reaction rate
- Improve heat and mass transfer
- Designs in both ultrasonic devices and sono-reactors

Typical Ultrasonic Horn

- Shrinking dimension
- Small energy-emitting surface
- Concentrated cavitation volume
- Reduced contaminant removal

- **Low energy efficiency (13.3-28.1%)**
- **Scaling-up is very difficult!**

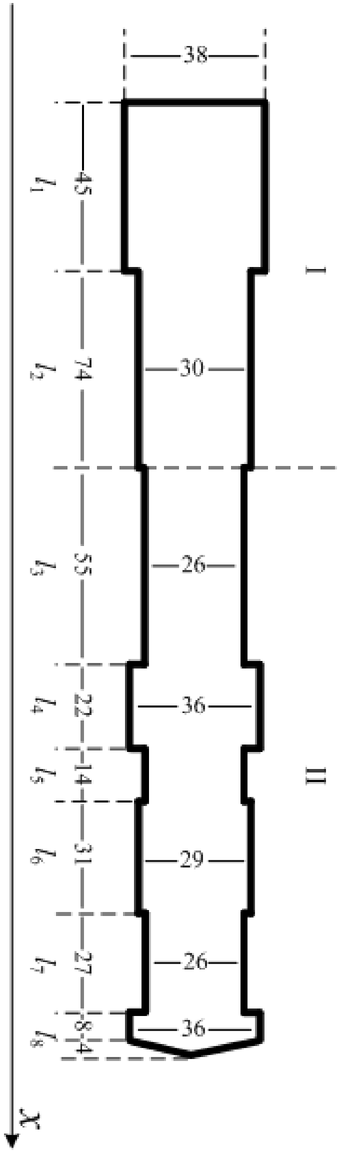
Contamine et al.,1994; Kimura et al., 1996; Weavers et al., 2000; Bhirud et al., 2004; Pee, 2008; Thangavadivel et al., 2009.

Objectives

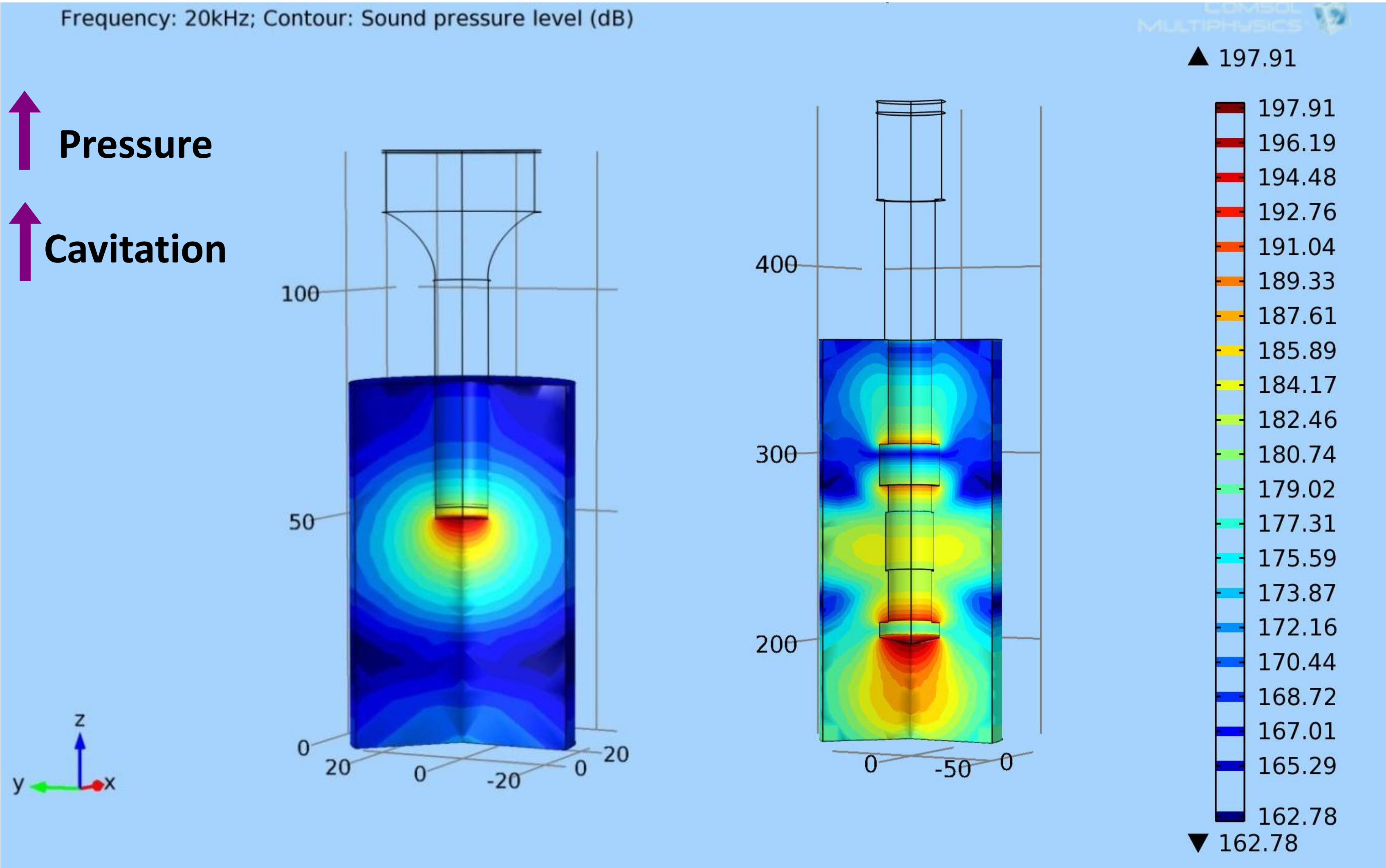
- To design an improved horn configuration
- To characterize the designed horn
  - physical methods
  - chemical methods
- To evaluate large-scale application
  - hydrophone mapping
  - optimal size of sono-reactor

Design Steps

1. General requirements
   – resonance
2. Specific requirements
   – shape
3. Design principles
   – dynamic wave equation
   – equivalent circuit model
4. Verification using simulation
   – finite element analysis (FEA)
   – COMSOL Multiphysics



COMSOL Simulation

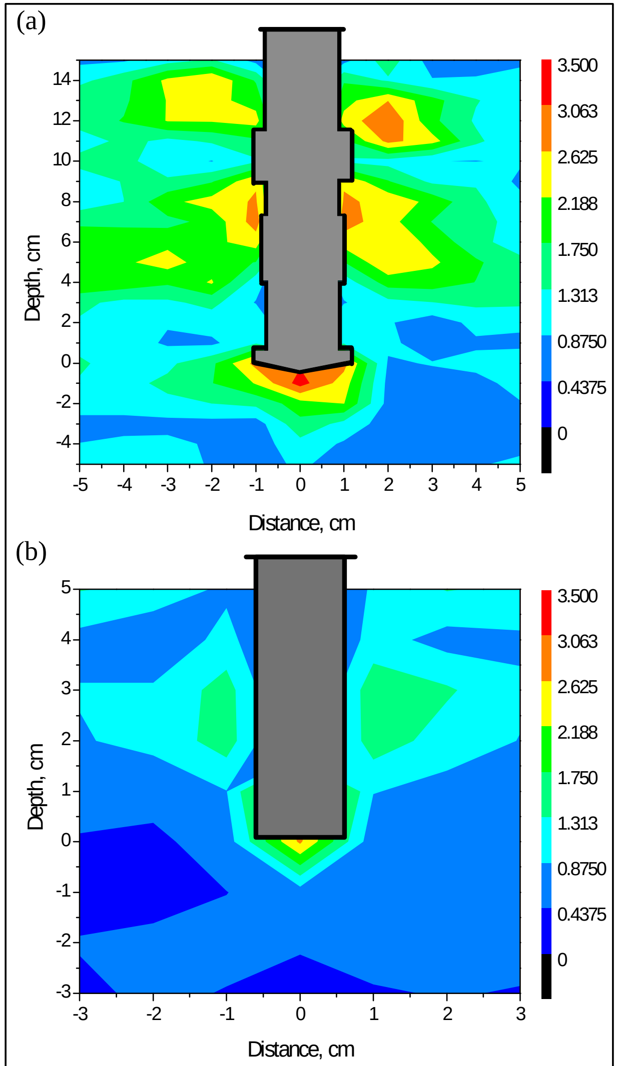


Typical horn **Designed horn**

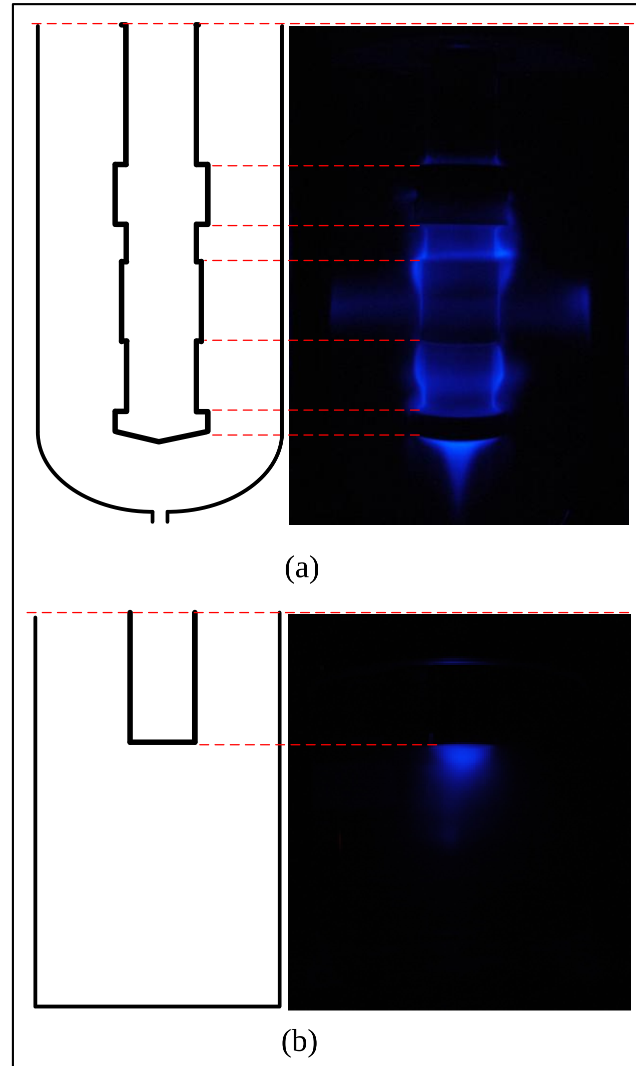
Horn Characterization

Designed horn

Typical horn



Hydrophone Measurements



Sonochemiluminescence (SCL)

Wei et al., Ultrason. Sonochem. (In revision)

Comparison - Energy, Cavitation, and Degradation

Horn	Energy efficiency (%)	[a] Zero-order •OH formation rate constant (μM/min)	[b] First-order degradation rate constants (1/min)
	31.5	0.36	0.022
	13.3	0.09	0.012

[a] Initial concentration of terephthalate acid = 2mM; [b] initial concentration of phenanthrene = 10μM

Wei et al., Ultrason. Sonochem. (In revision)

Energy Cost Estimation

Horn type	Typical	Designed
k, min^{-1}	0.0158	0.0217
t_{90}, min	145.5	106.1
P_{elec}, kW	0.275	1.000
V, L	0.04	1.25
C_0, μM	10.0	10.0
EE/O	1.67×10^4	1.41×10^3
Electricity price, $ kWh^{-1}	0.08	0.08
Cost, $ per 1000L	1,330	113

8.5%

- Phenanthrene (first-order degradation)
- 90% removal
- $0.08/kWh

$$EE/O = \frac{P_{elec} \times t_{90} \times 1000}{V \times 60 \times \log(C_0/C)}$$

Large-Scale Reactor Design

- Water tank setup

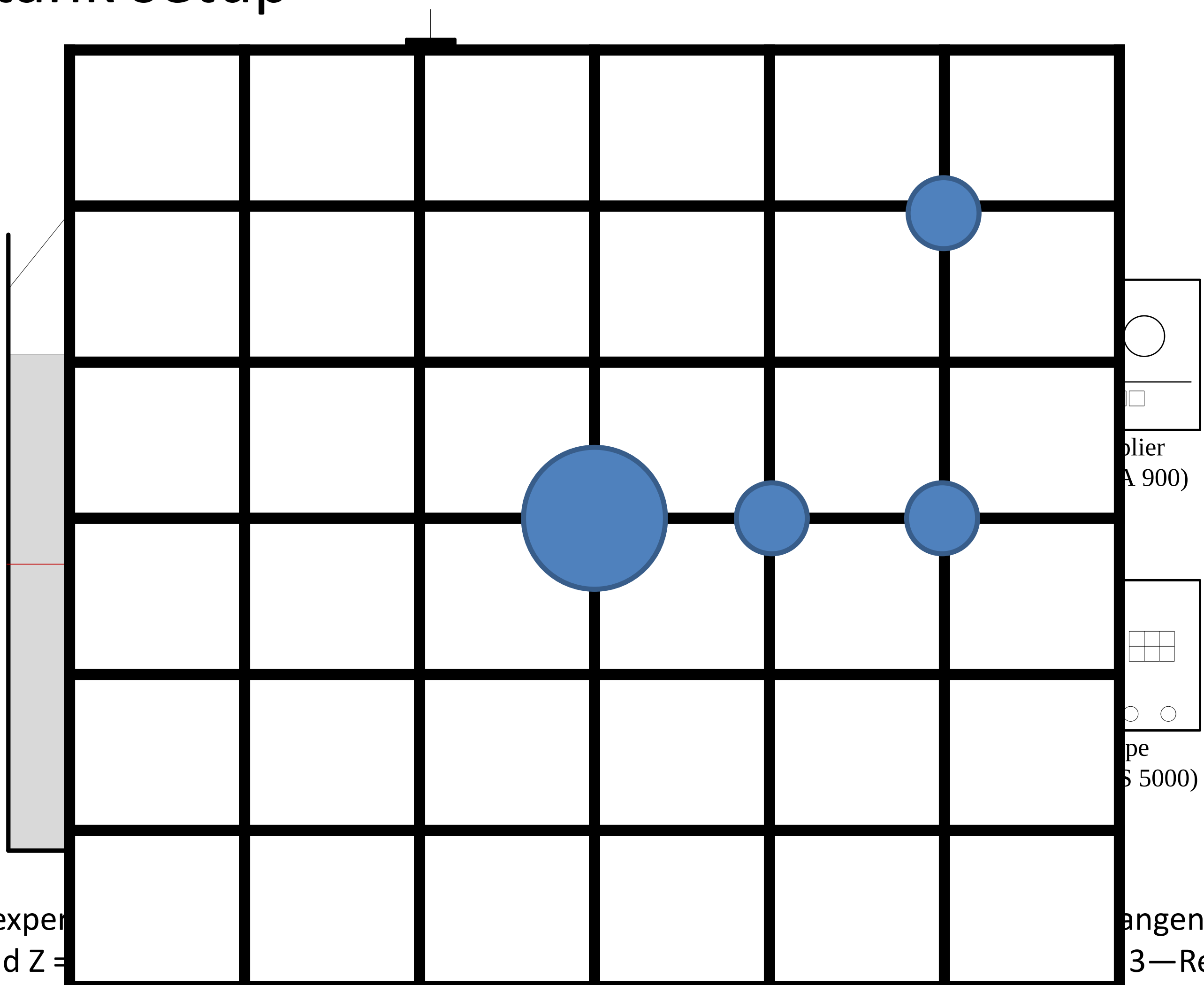
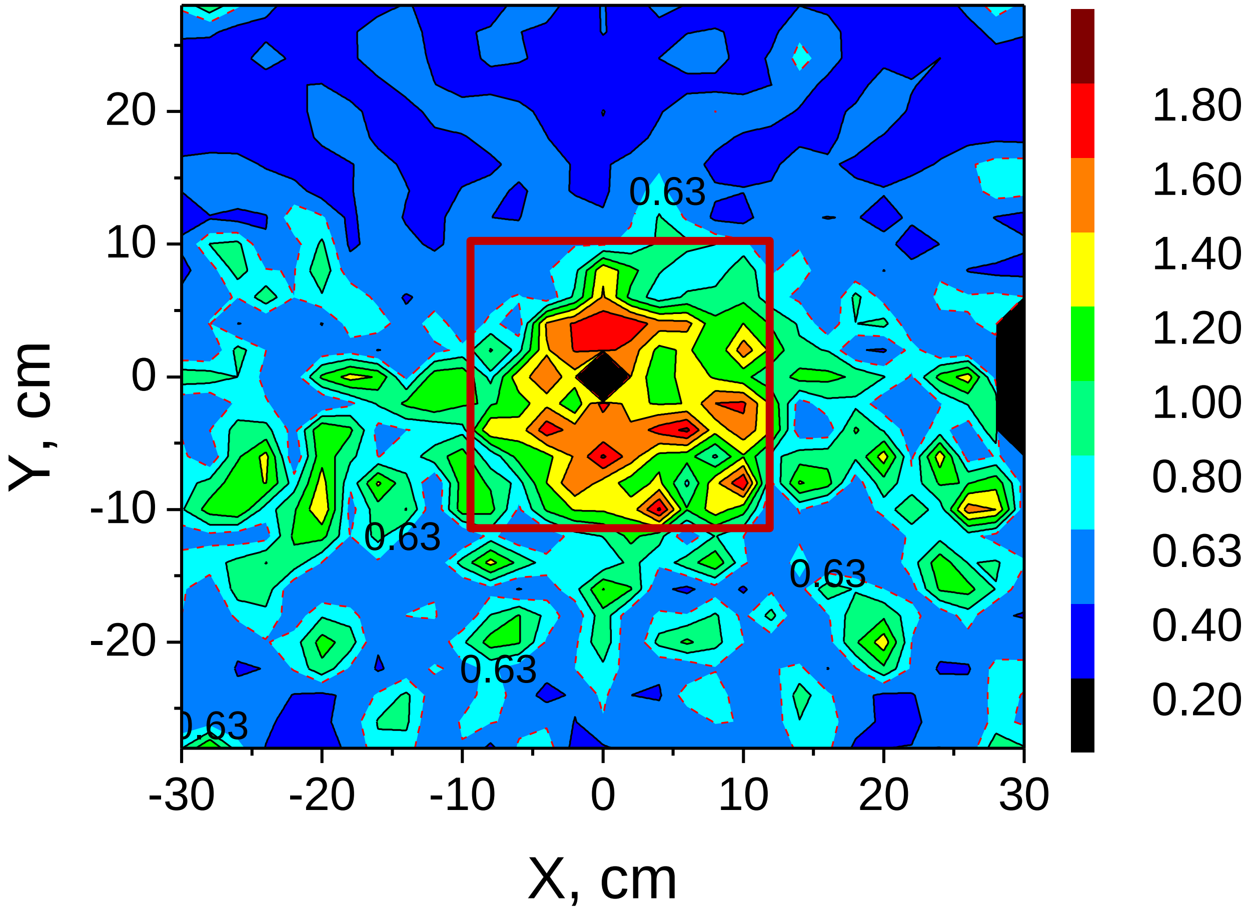


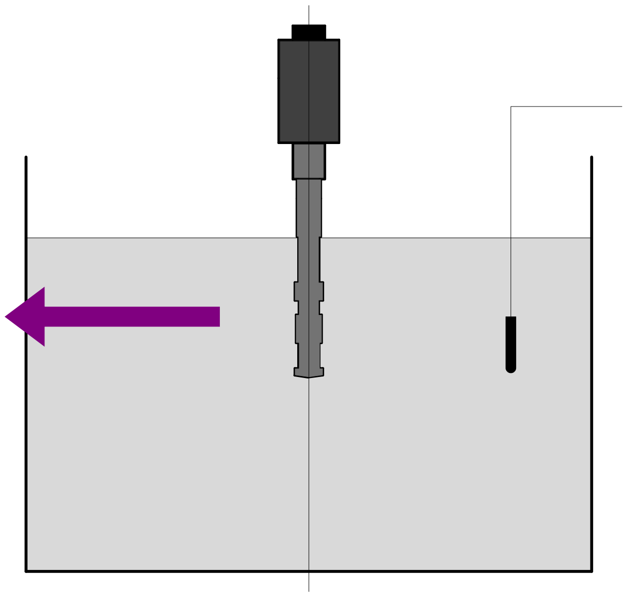
Diagram of exper angential to horn
tip is define d Z = 3—Reson T4013
hydrophone; 4—water; 5—plexiglas box)

Wei et al. (in preparation)

Acoustic Field Mapping (X-Y Plane, Z=+4cm)

- Cavitation threshold (0.63V)
- Effective scale (~10cm)

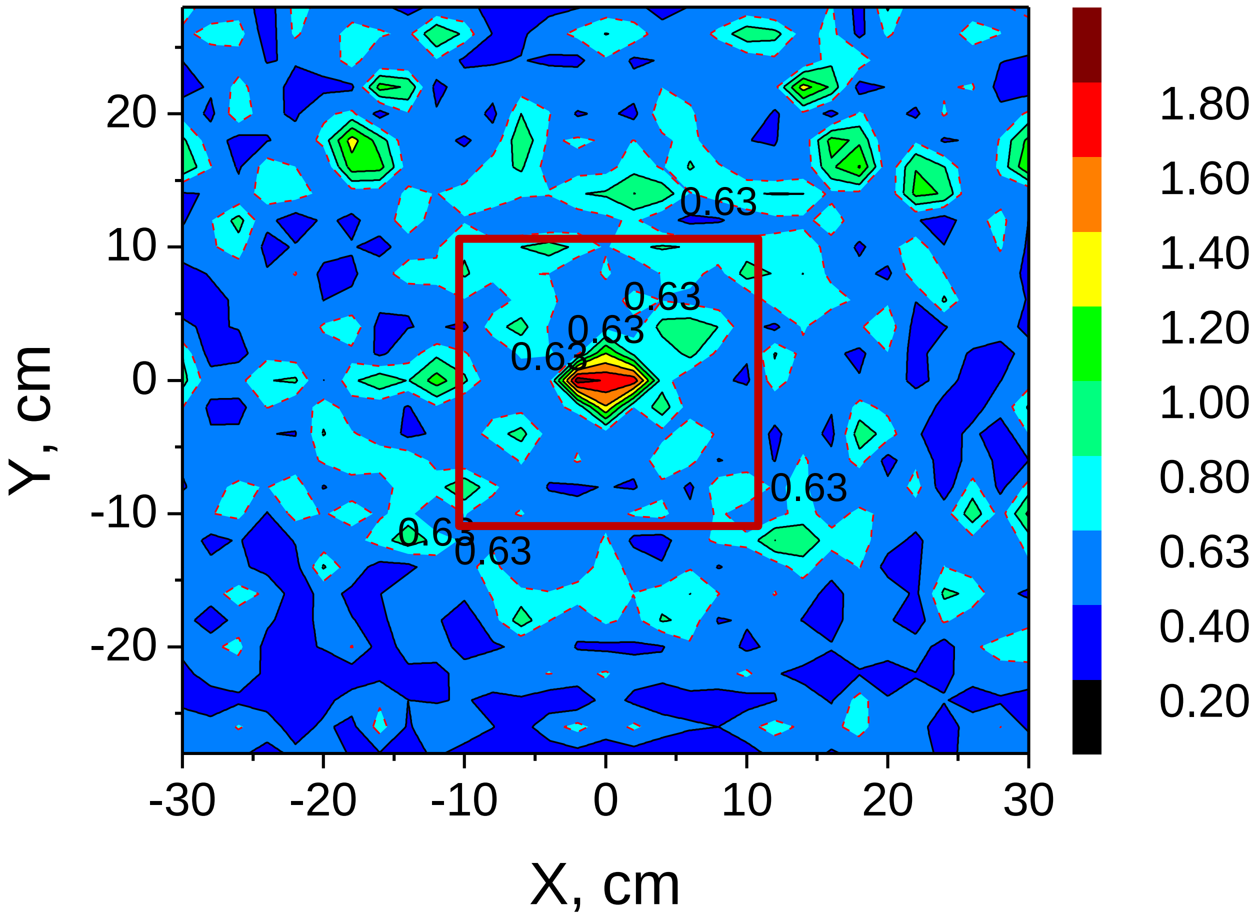


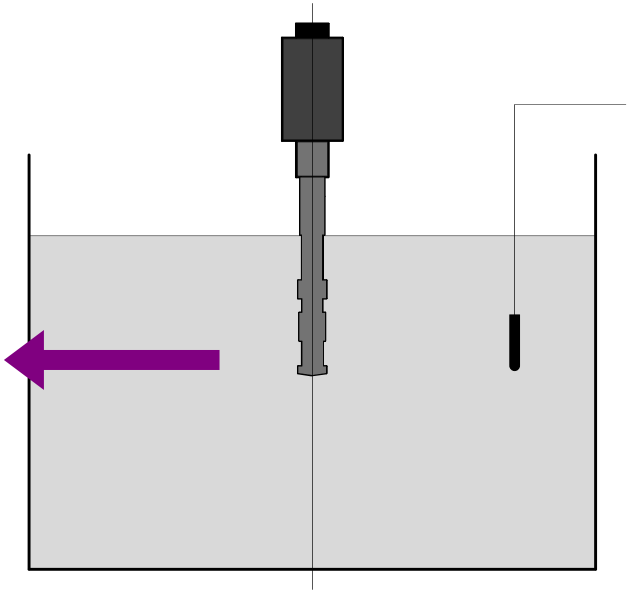


Acoustic Field Mapping (X-Y Plane, Z=0cm)

– Cavitation threshold (0.63V)

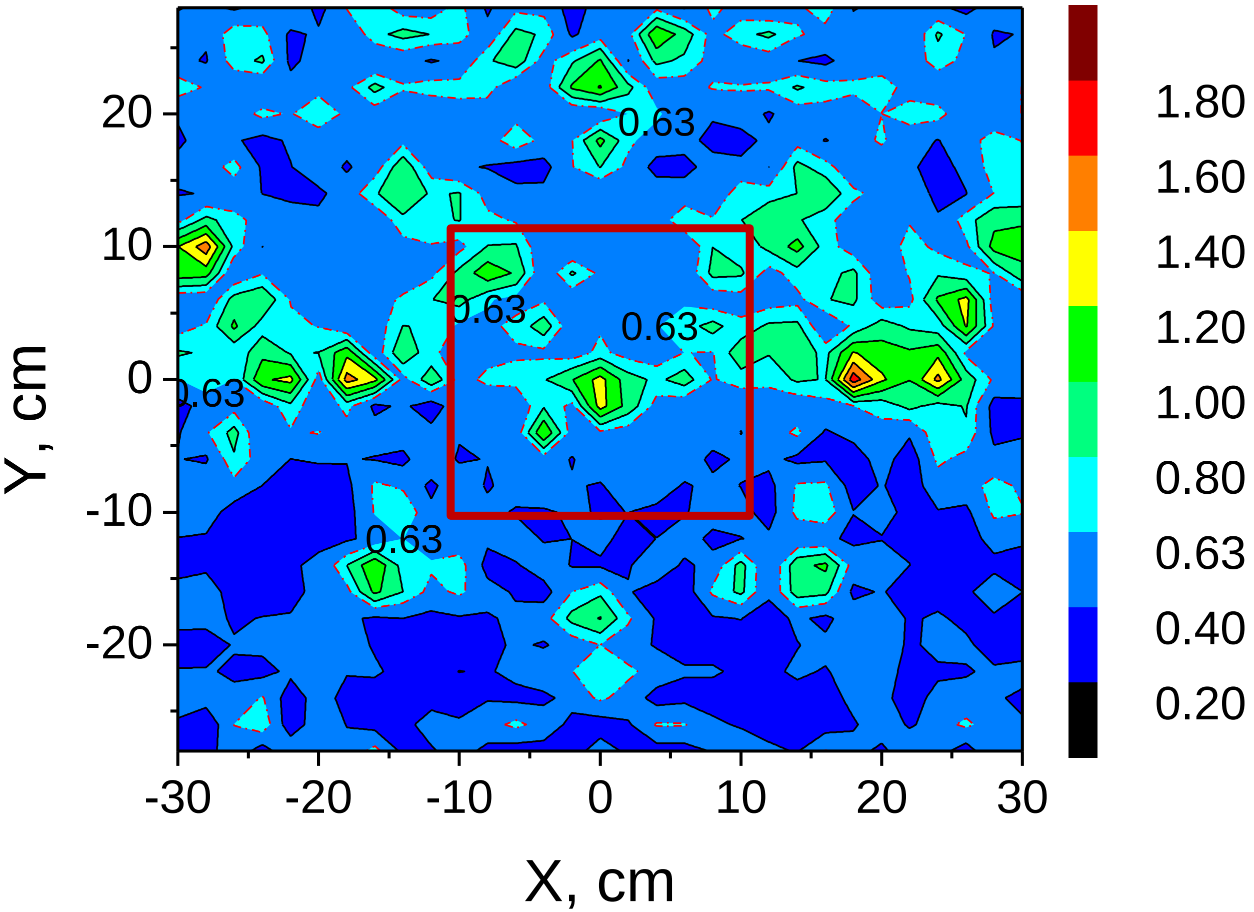
– Effective scale (<10cm)

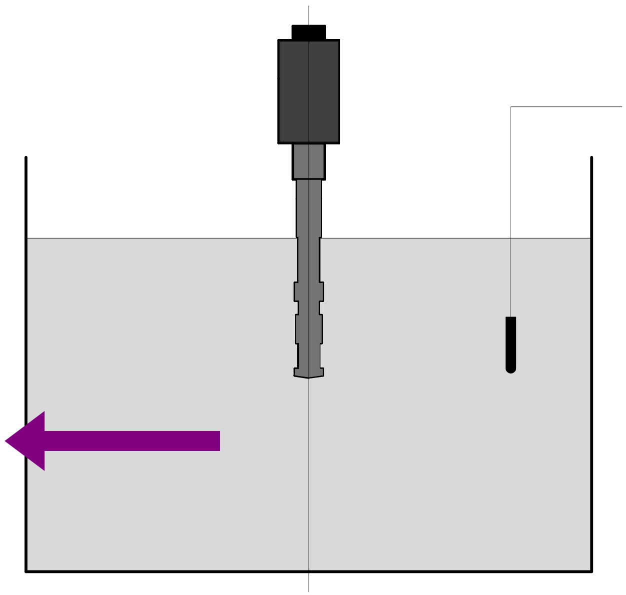




Acoustic Field Mapping (X-Y Plane, Z=-4cm)

- Cavitation threshold (0.63V)
- Effective scale (<10cm)

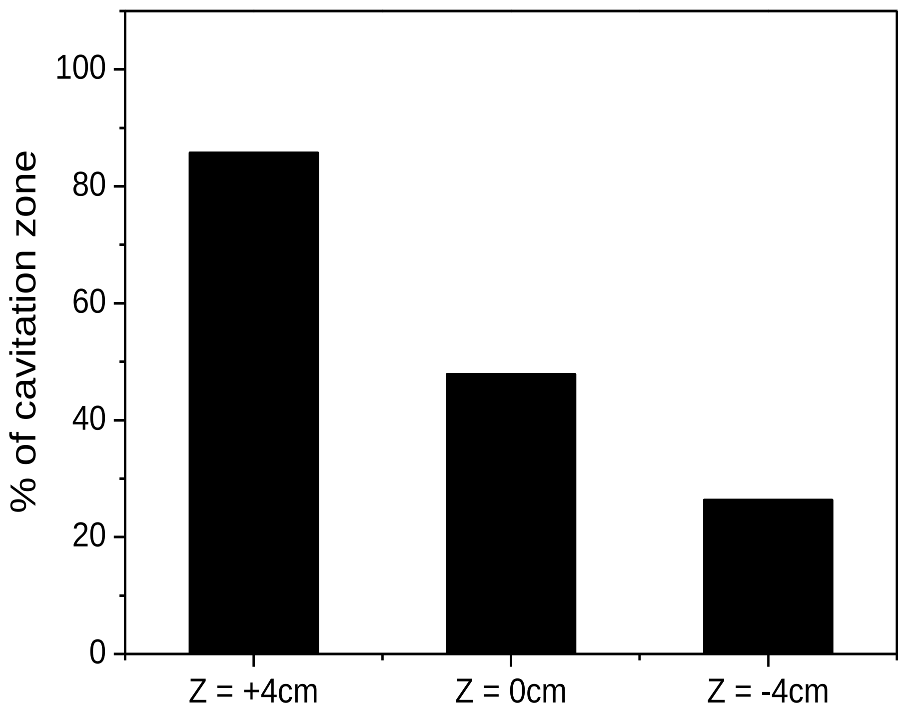


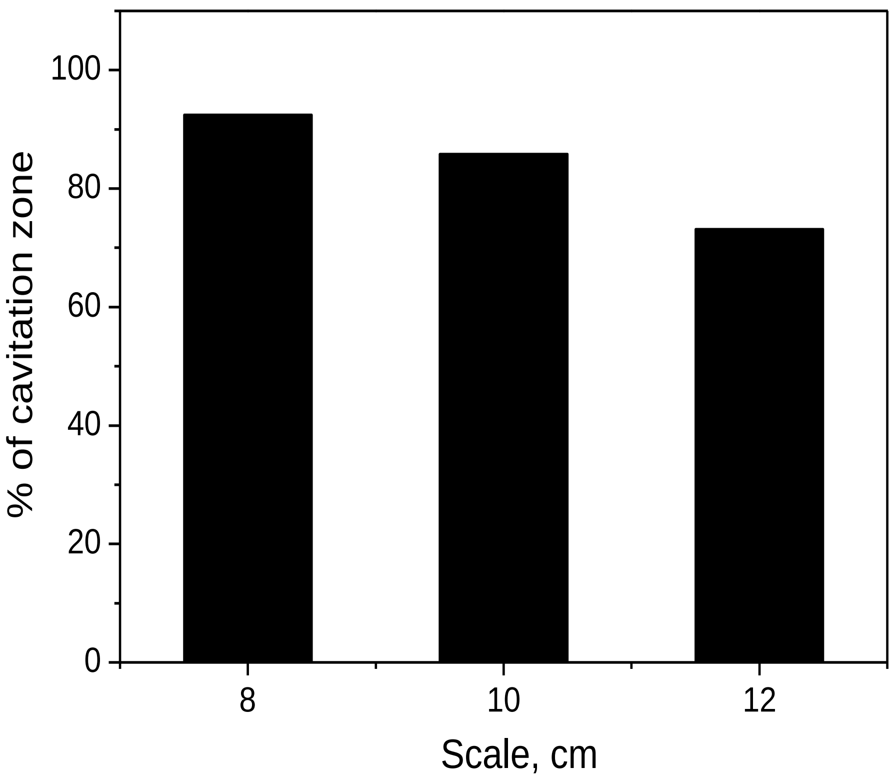


Percentage of Cavitation Zone in X-Y Plane

– Cavitation threshold (0.63V)

– Effective scale (~10cm)

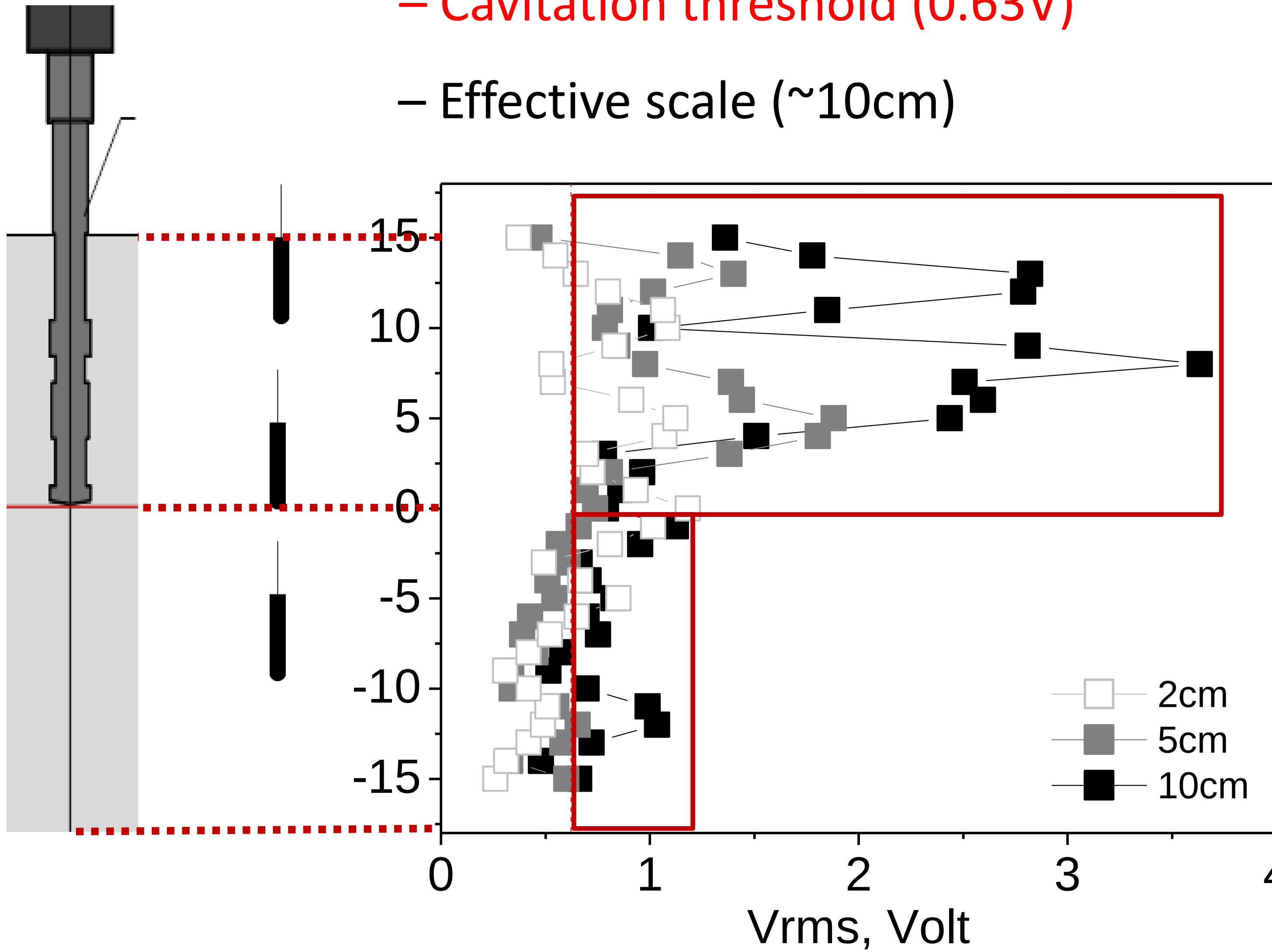




Acoustic Field Mapping (Z-Direction)

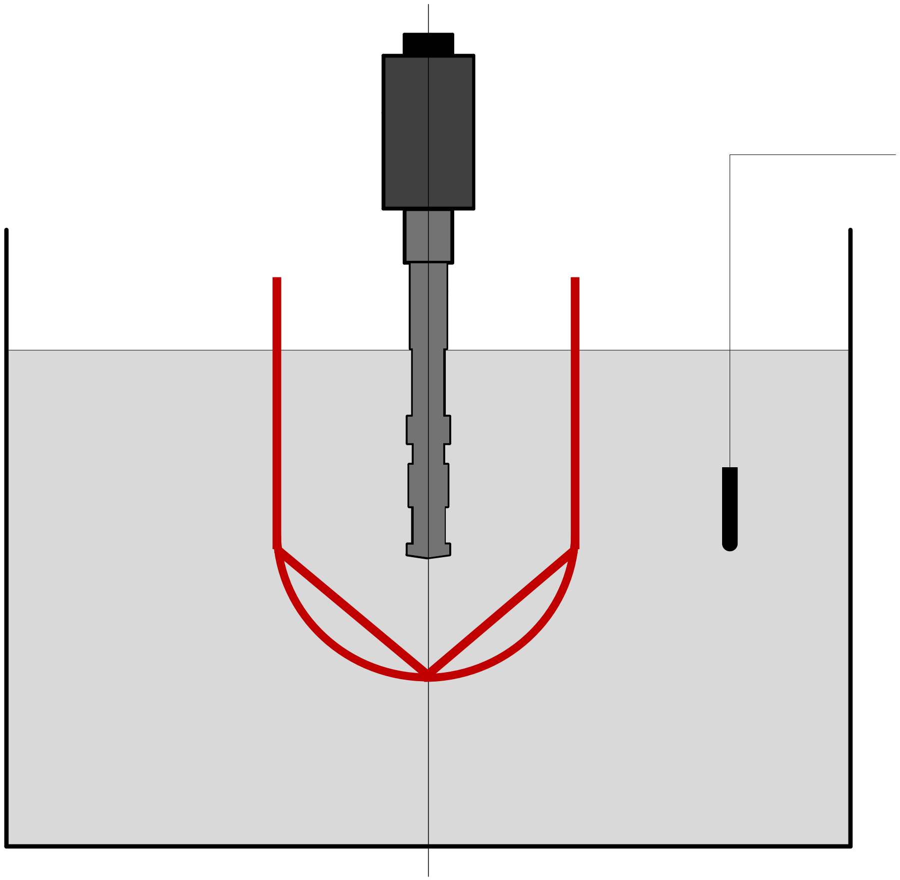
– Cavitation threshold (0.63V)

– Effective scale (~10cm)



Wei et al. (in preparation)

Reactor Configuration



– Effective scale (10cm)

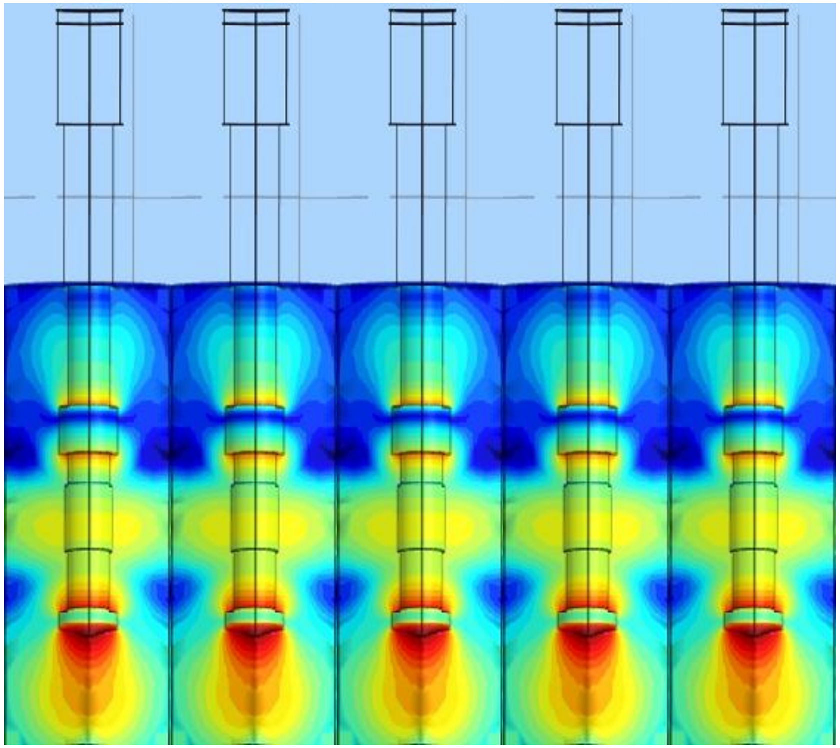
– Increase percentage of cavitation volume

– Treatment volume (~5.0L)

50 mL

Summary and Future Work

- Multi-stepped shape – more energy-emitting surfaces
- Hydrophone – design large sono-reactors
- Large-volume reactor
- Array of designed horns
- Synergistic effect



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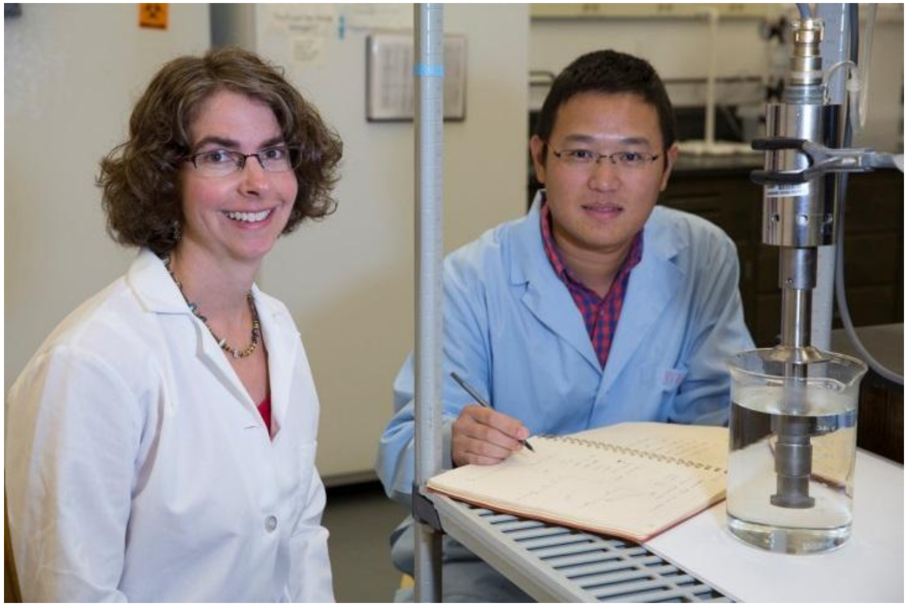
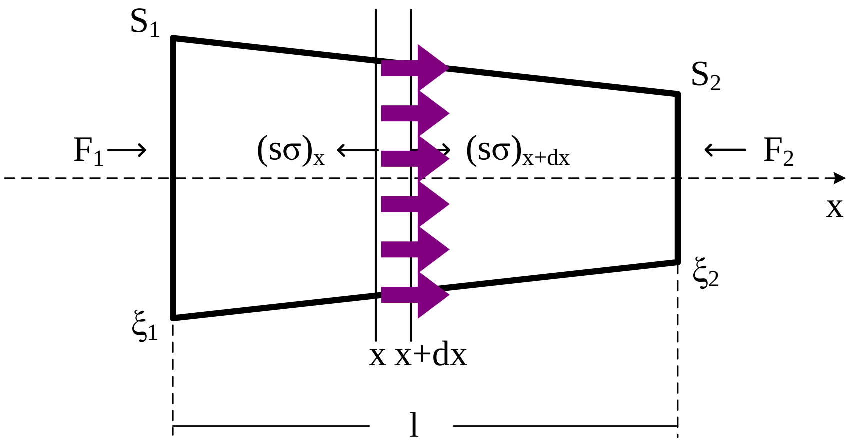


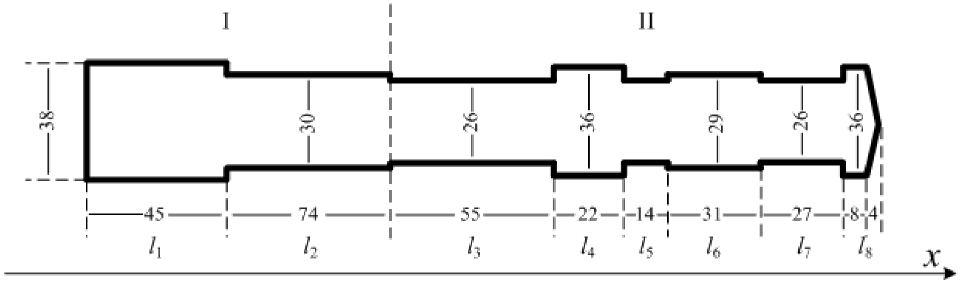
Thank You !

Backup Slides

Horn design requirements

- Resonance
  - *half-wave length*
  - *L=x·(λ/2)=280mm*
- Planar Homogeneous
  - *D<(λ/4)=70mm*
- No concentrated energy
  - *Mp=2.0*
- Multi-stepped shape
  - *"edges"*



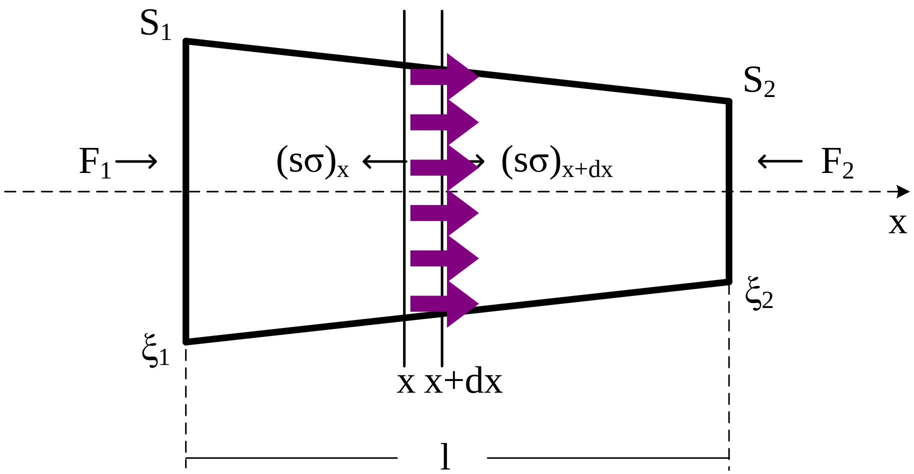


Design Principles

- Dynamic wave equation

$$\frac{\partial(S\cdot\sigma)}{\partial x}dx = S\cdot\rho\frac{\partial^2\xi}{\partial^2 t}dx$$

$$F = ma$$



- For a cylindrical horn in a steady-state mode

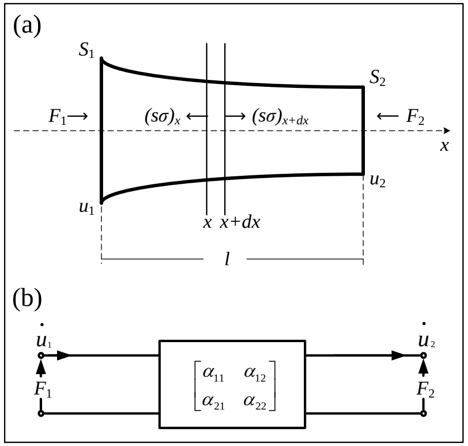
$$\frac{\partial^2\xi}{\partial^2 x} + k^2\xi = 0$$

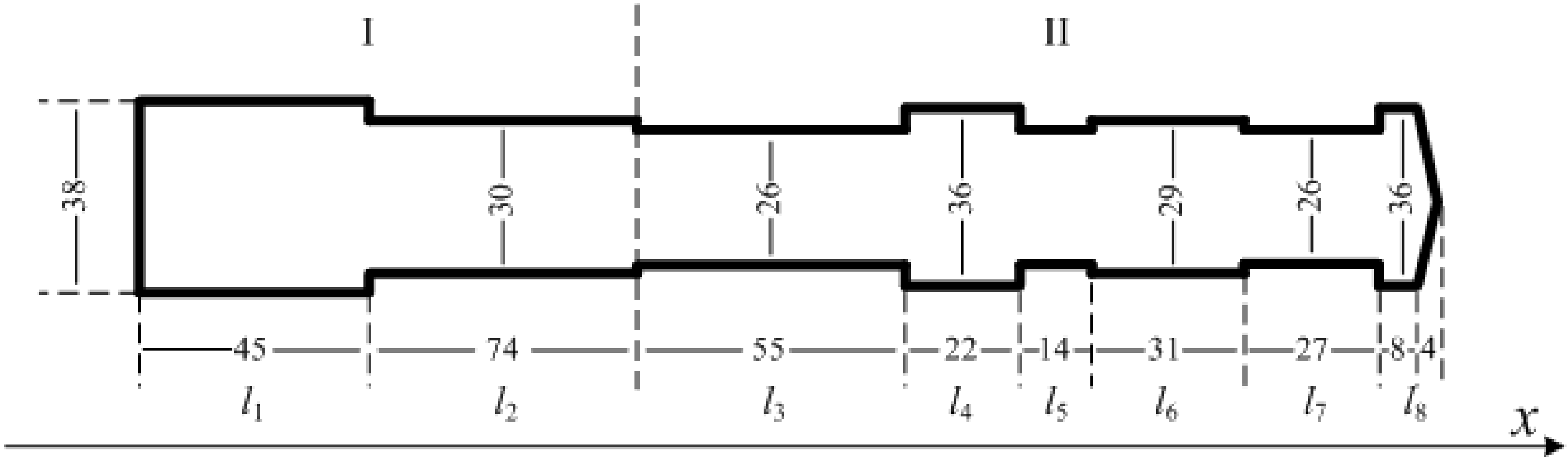
Design Principles

- Equivalent Circuit Model

$$\begin{bmatrix} \dot{u}_2 \\ F_2 \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \begin{bmatrix} \dot{u}_1 \\ F_1 \end{bmatrix}$$

$$A = \begin{bmatrix} (\cos kl_8) & \dfrac{-j(\sin kl_8)}{\rho c S i} \\ -j\rho c S i(\sin kl_8) & (\cos kl_8) \end{bmatrix} \cdots \begin{bmatrix} (\cos kl_1) & \dfrac{-j(\sin kl_1)}{\rho c S i} \\ -j\rho c S i(\sin kl_1) & (\cos kl_1) \end{bmatrix}$$



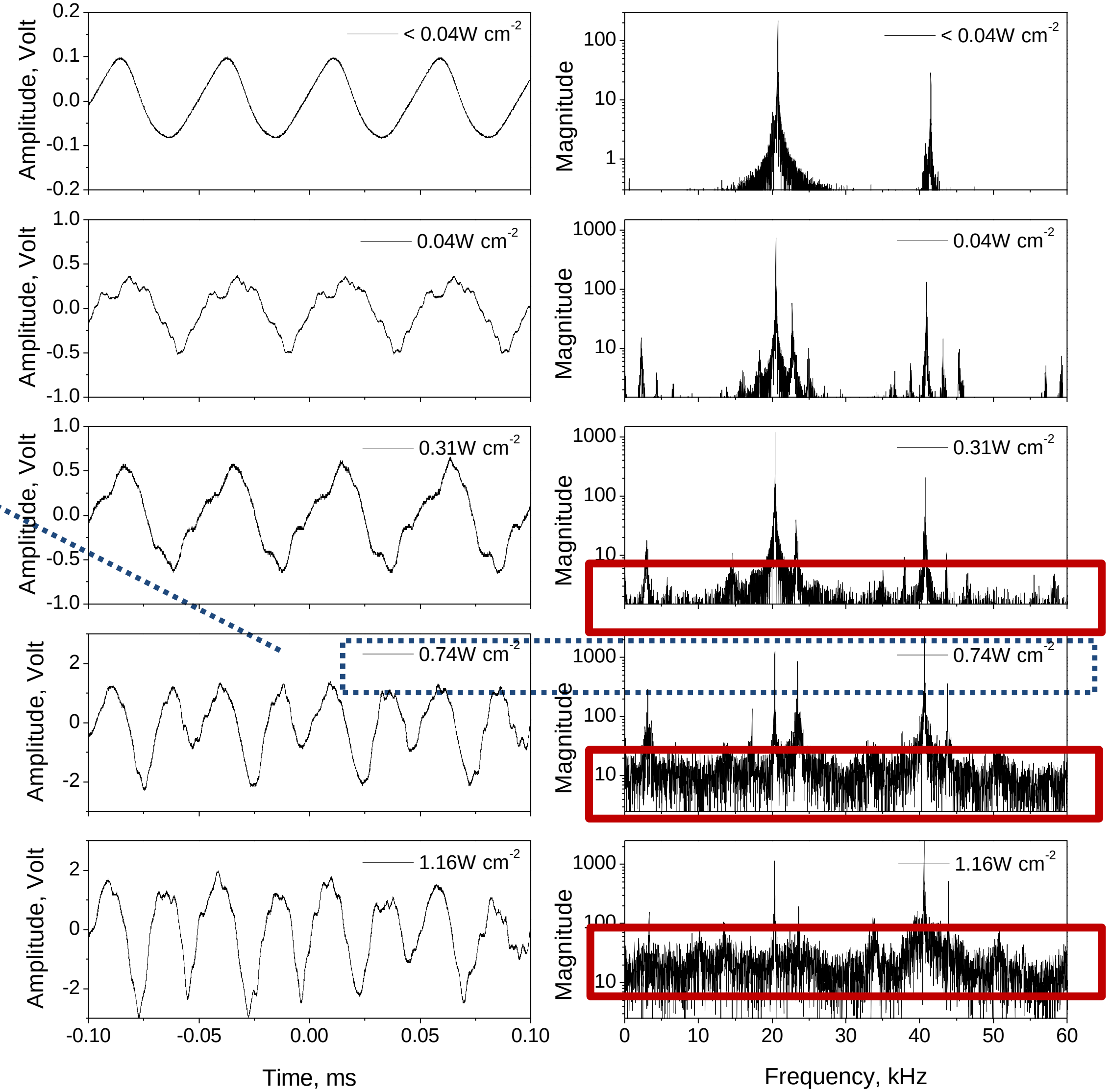


Wei et al., Ultrason. Sonochem. (In revision)

Cavitation Threshold in Water

Threshold for bubble collapse!

0.63 Volt



Stable oscillation

Broadband Transient cavitation

Broadband Transient cavitation

Ultrasound waveforms and frequency spectrum observed from water at different power intensities

Wei et al., in preparation