Putting Confidence in Ultrasound

In-situ cavitation measurements with a wireless sensor array:

Applications in megasonic photomask cleaning

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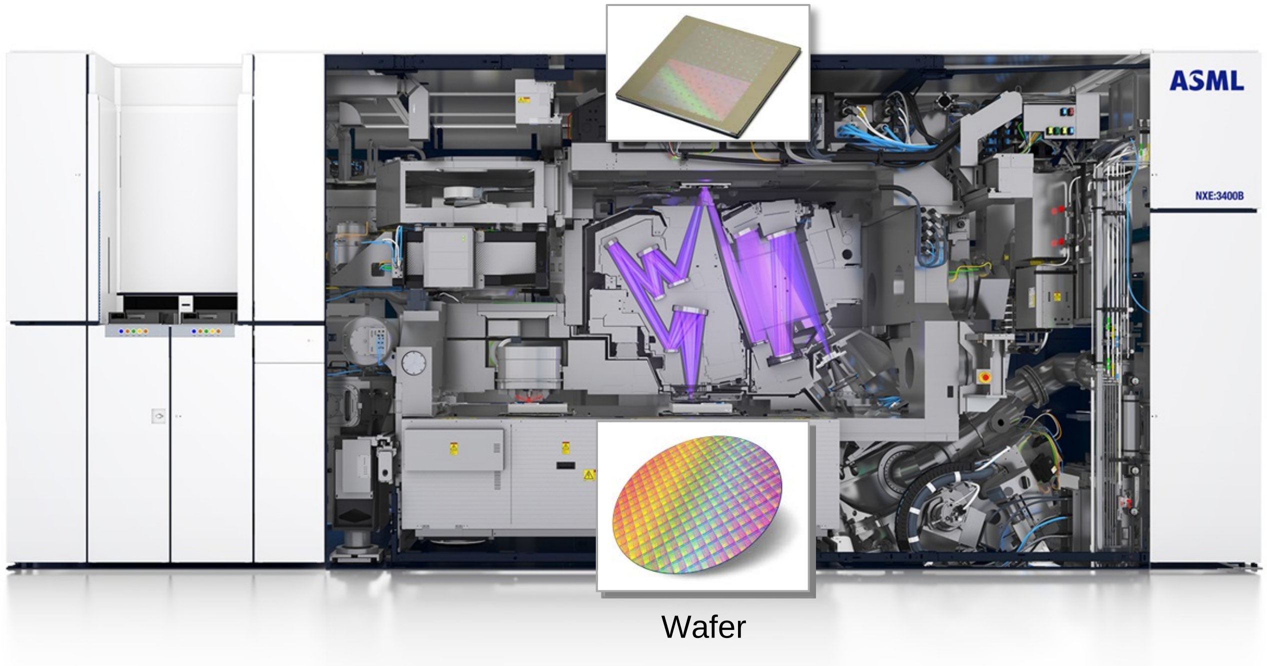
[1] Onda Corporation, [2] Applied Materials

SPIE BACUS (Monterey, CA)

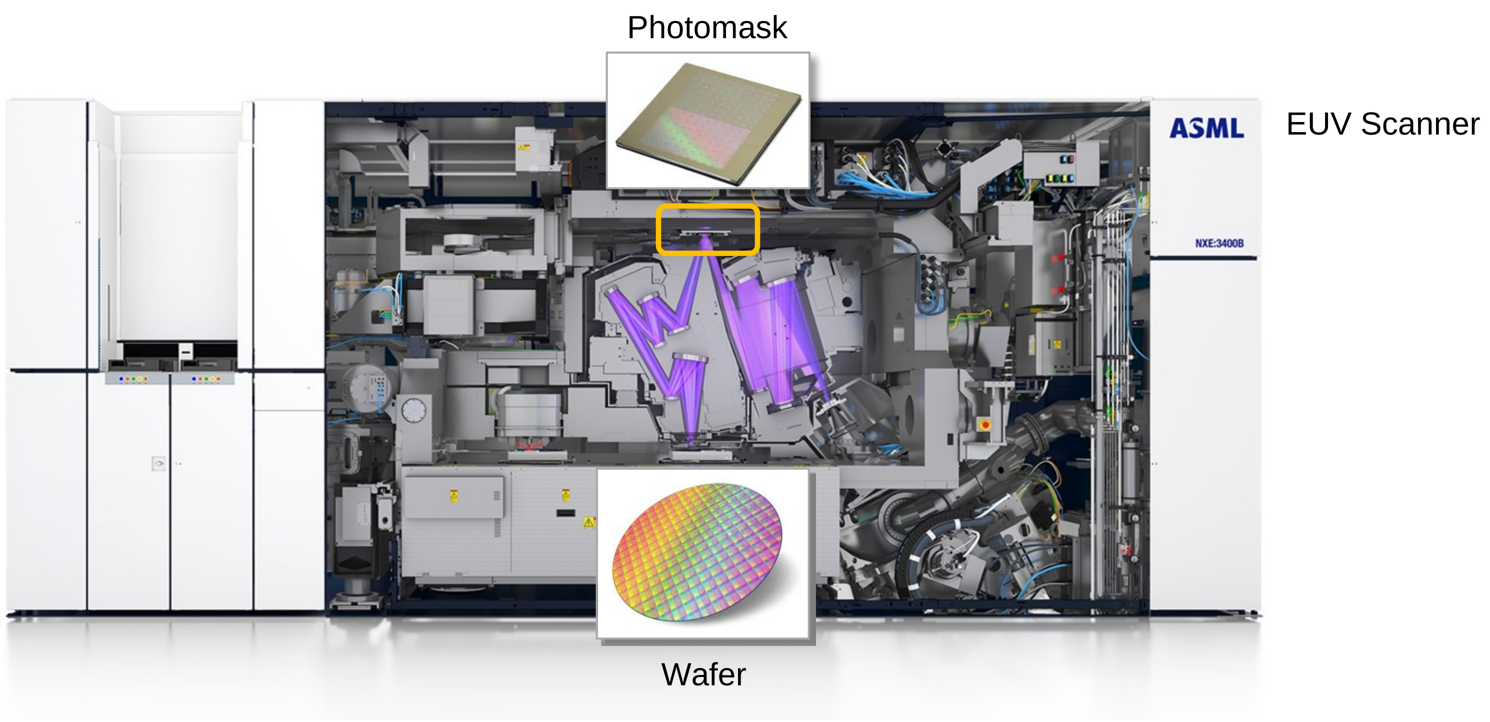
September 26, 2022

Advanced Photolithography



193i and EUV lithography required for shrinking feature dimensions

What needs to be clean?



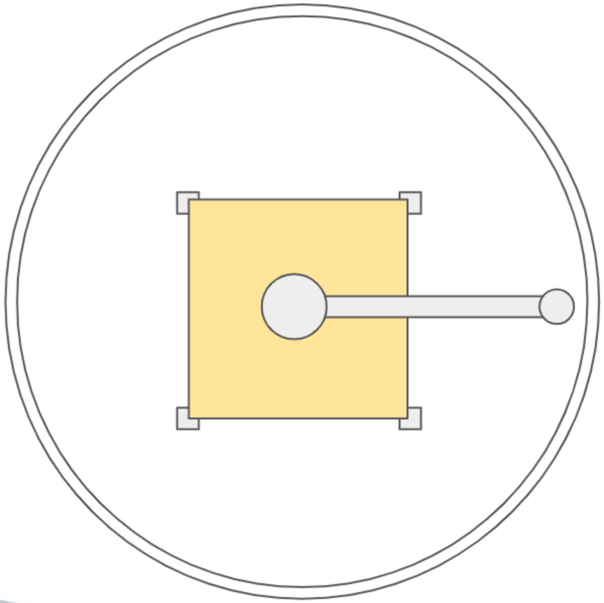
Mask cleaning processes demand zero-defects

How are photomasks cleaned?

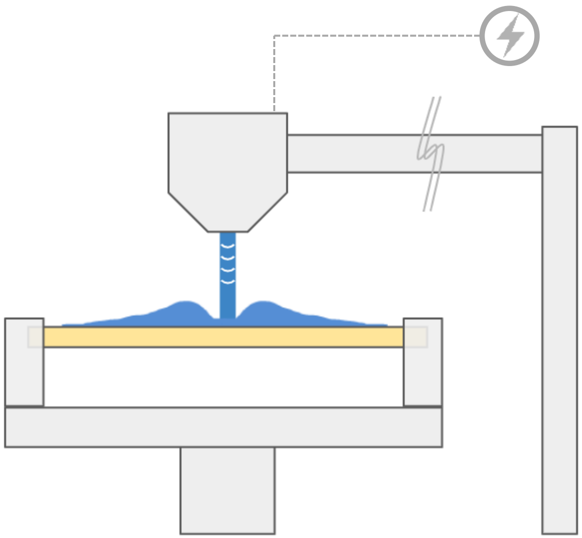
"Megasonics" applied to surface to remove particles; dynamic process to optimize uniformity

How are photomasks cleaned?

TOP VIEW



SIDE VIEW



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How are photomasks cleaned?

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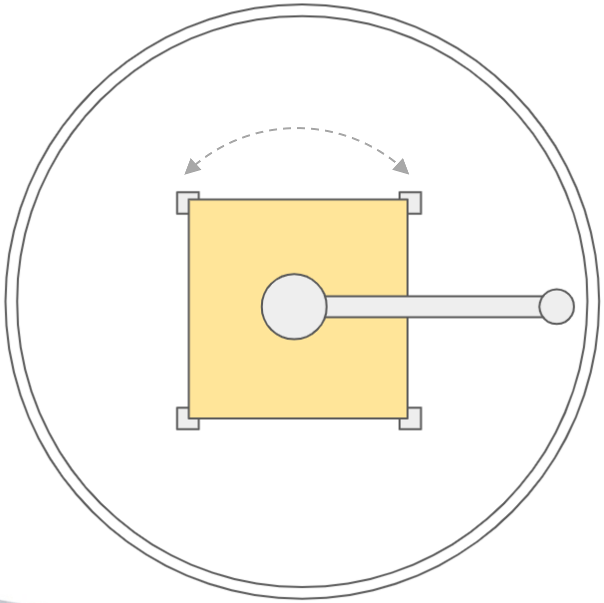
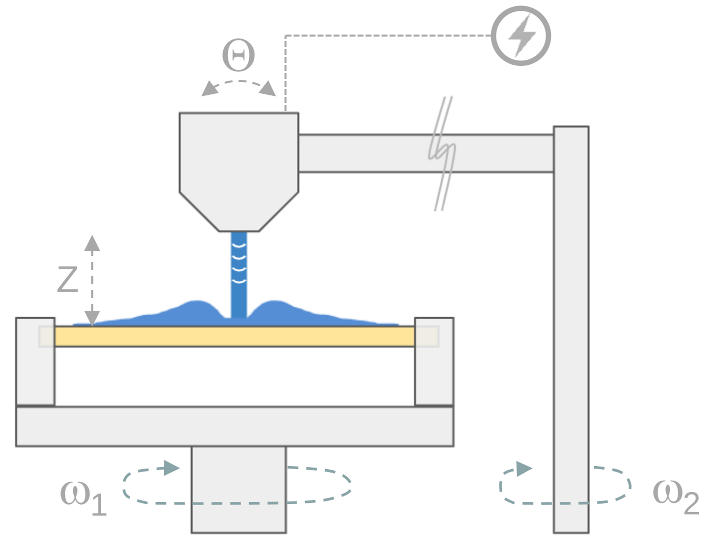


SIDE VIEW



“Megasonics” applied to surface to remove particles; dynamic process to optimize uniformity

Photomask Cleaning Challenges

Skirt-Type
Transducer

Nozzle-Type
Transducer

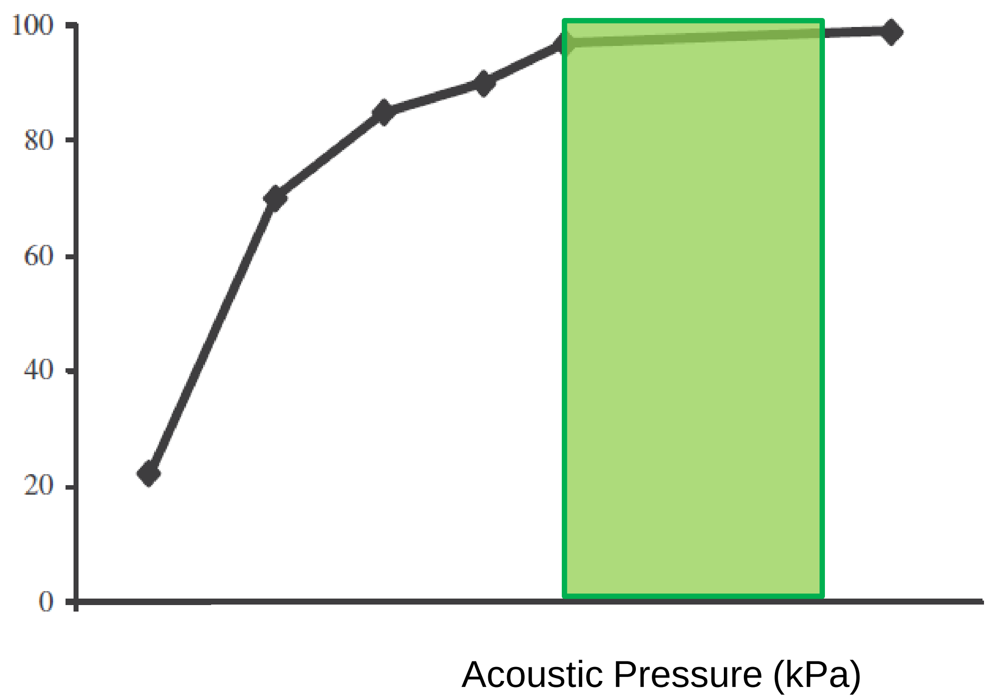
Plate-Type
Transducer

Dynamic Process:

- Acoustic uniformity
- Acoustic cavitation
- Reflections
- Flow rate
- Transducer stability
- Gas concentration
- Mask rotation rate
- Transducer sweep rate
- Transducer orientation
- Temperature
- Chemistry
- Frequency
- Generator power
- Substrate material
- Process time
- And more…

How do we control all these parameters?

How is ultrasound related to cleaning?



Determine Y = F(X) to establish process window

Kim, et al. Seoul National Univ and Samsung

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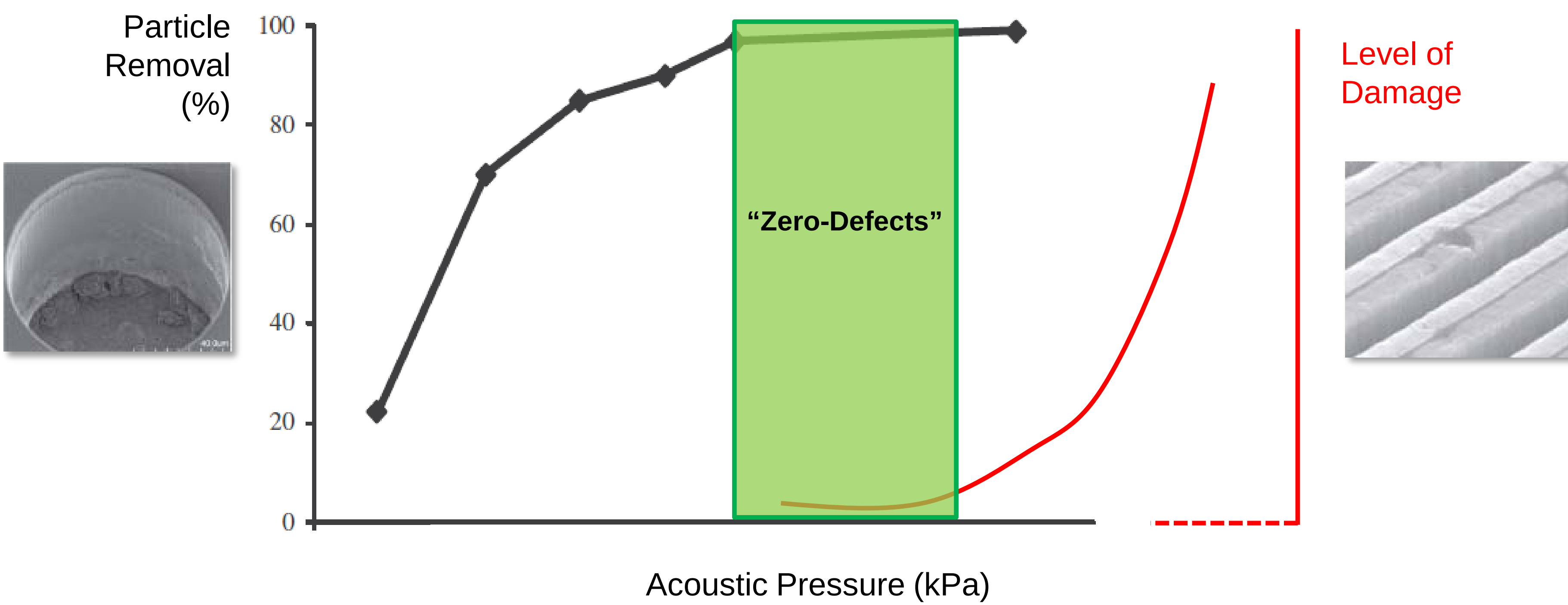
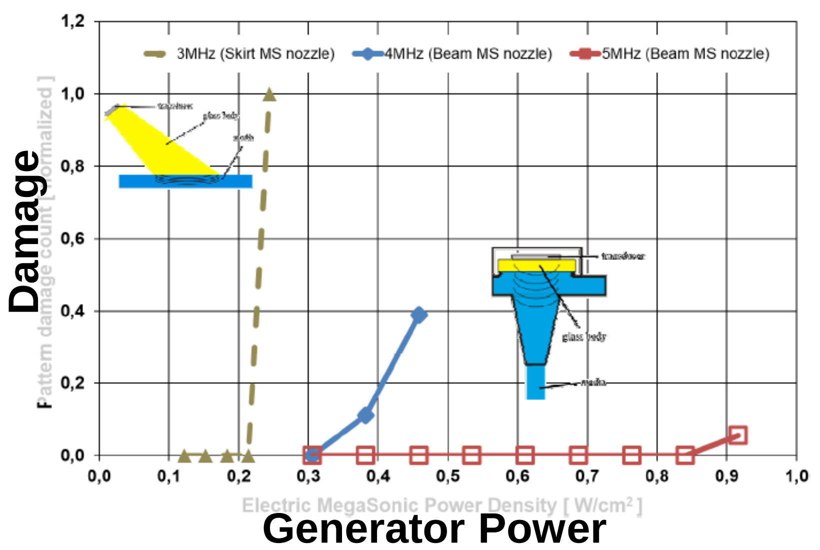
How is ultrasound related to cleaning?



Determine Y = F(X) to establish process window

SUSS & TSMC: Damage Study

Experimental results
Pattern damage control

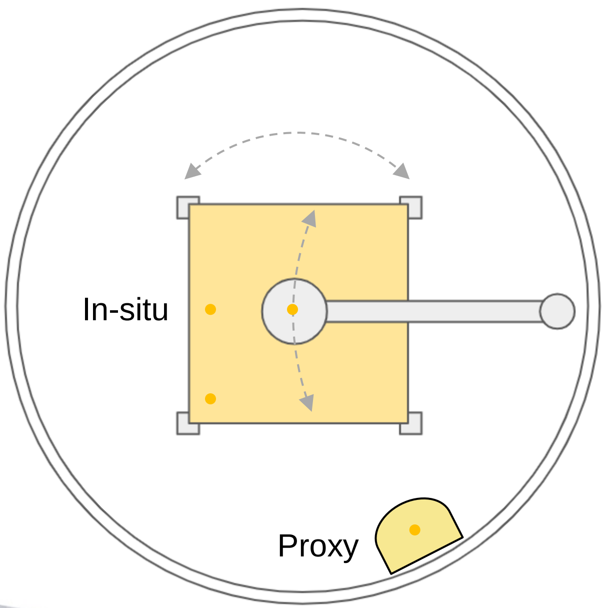


- 4MHz beam nozzle has no process window for 10nm photomask cleaning.
- 5MHz beam nozzle: up to 0.9 W/cm^2.
- 3MHz skirt nozzle: sharply increase pattern damage as power density increase from 0.21 to 0.24W/cm^2.

Electrical Power ≠ Acoustic Power

In-situ Mask Sensor Array & Proxy Sensor

TOP VIEW



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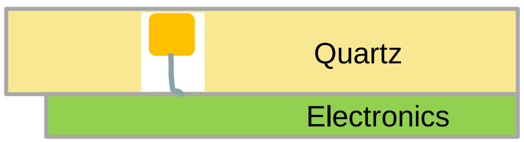


Wireless Mask Sensor provides a means to make in-situ cavitation measurements

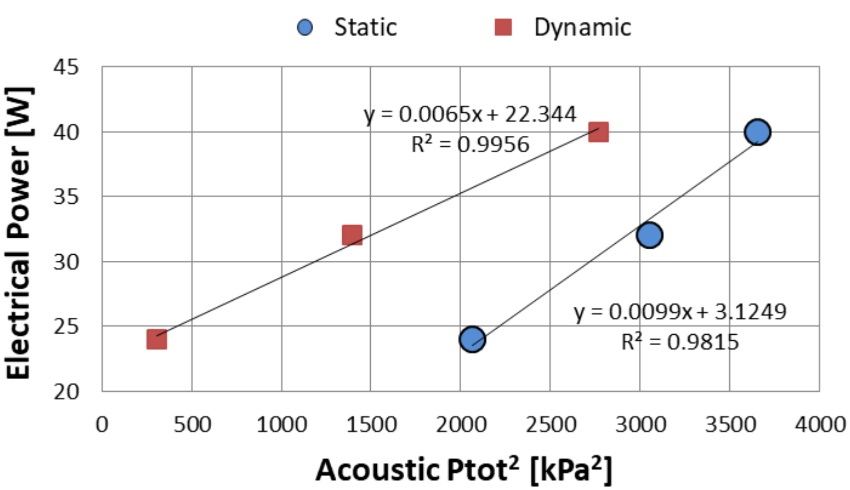
Comparing Static vs. Dynamic
(Wired vs. Wireless Mask Sensor)

2022 SPIE BACUS: Dynamic and Static

$$I_{RMS} = \frac{W}{A} = \frac{P_{RMS}^2}{Z} = 67 \times P_{RMS}^2$$

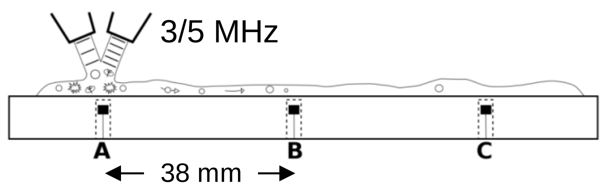
$$Units: \frac{[W]}{[cm^2]} = \frac{[MPa]^2}{[Rayls]} = \frac{[MPa]^2}{[N \cdot s/m^3]}$$

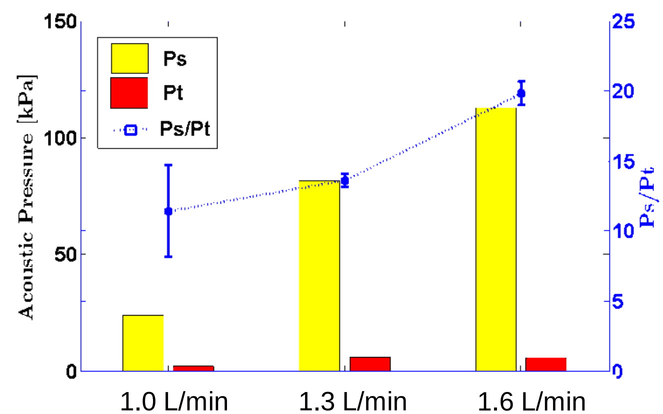
Power $\propto$ Pressure^2



With a 1 MHz nozzle at 2.0 L/min, static and dynamic conditions trend at a different rate with power

2017 SPIE BACUS: Static





Higher flow rates yield higher levels of static cavitation relative to transient cavitation

Fluid dynamics directly affect the acoustic behavior

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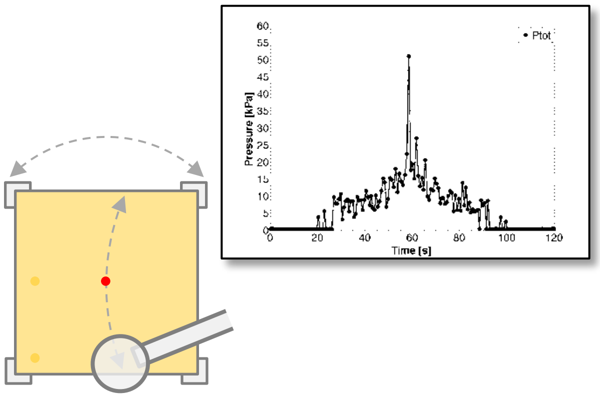
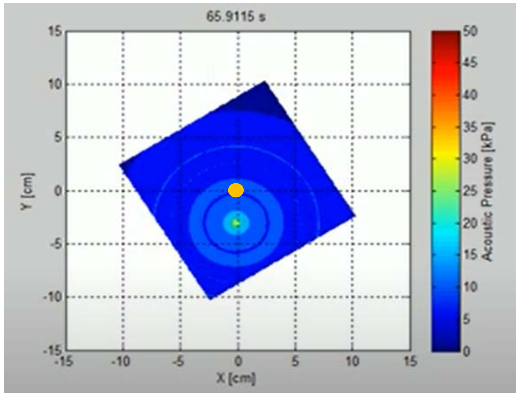
Measurement Method

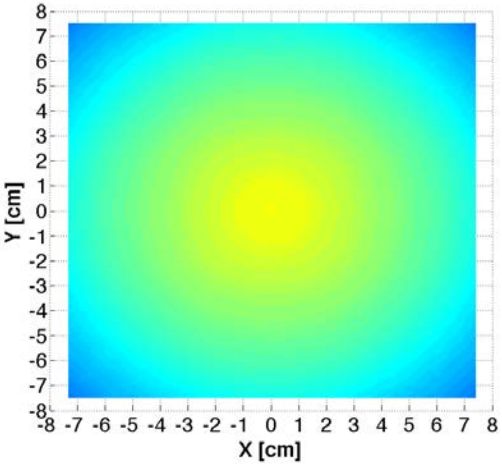
1D Pressure Profile



Integrate

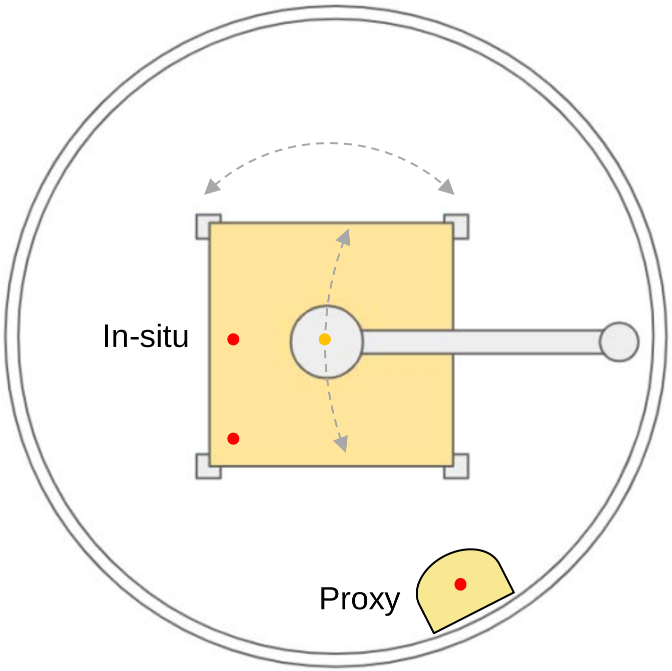


Cumulative Pressure Map



1. Log pressure as transducer sweeps over primary sensor under representative cleaning conditions
2. Determine signature 1D pressure profile
3. Input parameters into model – e.g., transducer sweep speed, sweep range, mask rotation speed, mask size
4. Using the 1D pressure profile, integrate the pressure over space and time
5. Determine 2D cumulative pressure (CP) uniformity; units [kPa-s]

Ways to Verify Method



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   Verified measurement accuracy of data at mask edge is < 10%

2. Proxy sensor

   Verified stability of the acoustic output from transducer is < 5% (1-sigma)

3. Simulation

   Verified correlation between measured and simulated 1D profiles has an $R^2 > 0.85$

4. Cleaning Trials

   Qualitative correlation observed between cumulative pressure and erosion maps

Test Conditions

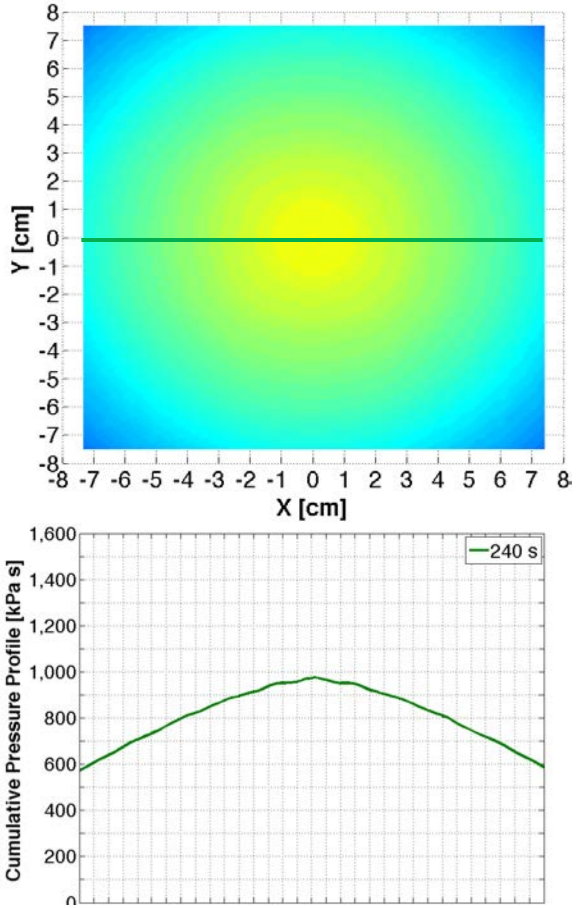
Fixed Parameters

- Frequency: 896 [kHz]
- Rotation speed: 60 [RPM]
- Transducer sweep speed: 3.86 [mm/s]
- Nozzle-mask distance: 10 [mm]
- Medium: water
- Flow rate: 2.0 [LPM]
- Gas conc. : 8.6 [mg/L]
- Temperature: 23.5 C

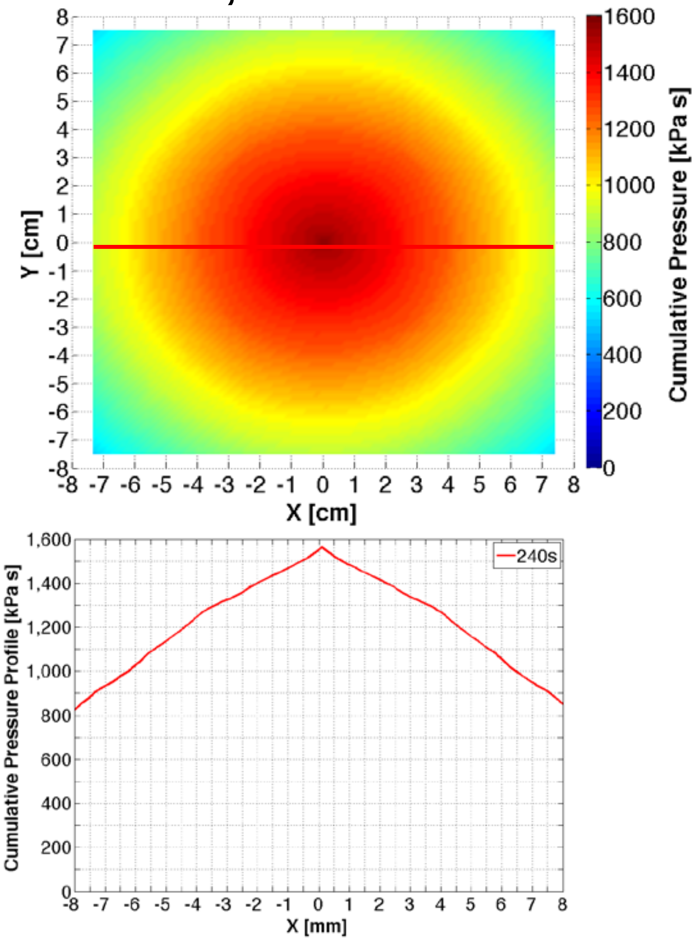
Varied Two Parameters: Generator Power & Exposure Time

Comparing Generator Power
Cumulative Pressure (CP) Plots

24 W, ΔT = 240 sec



40 W, ΔT = 240 sec



Comparing Generator Power

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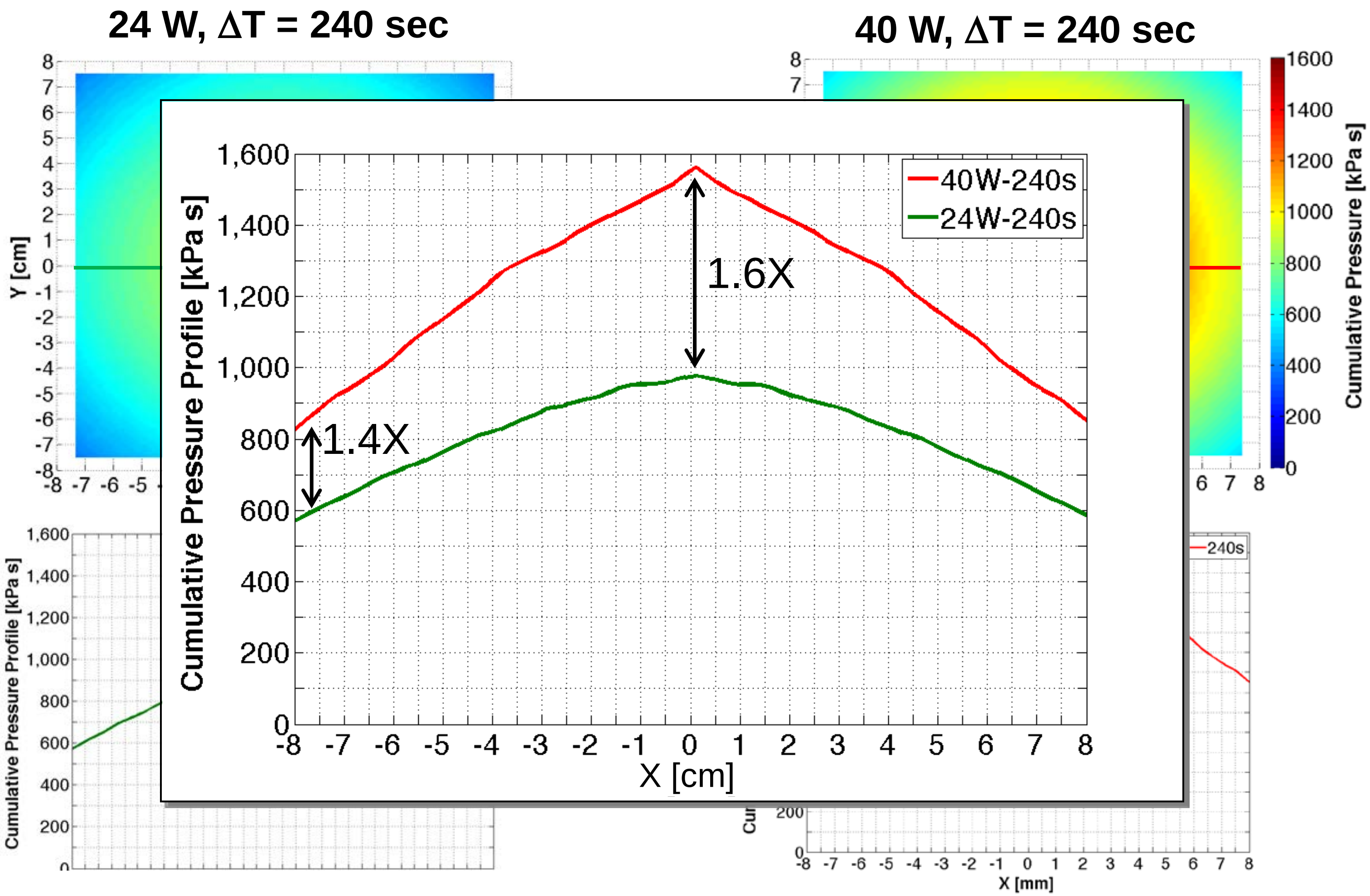
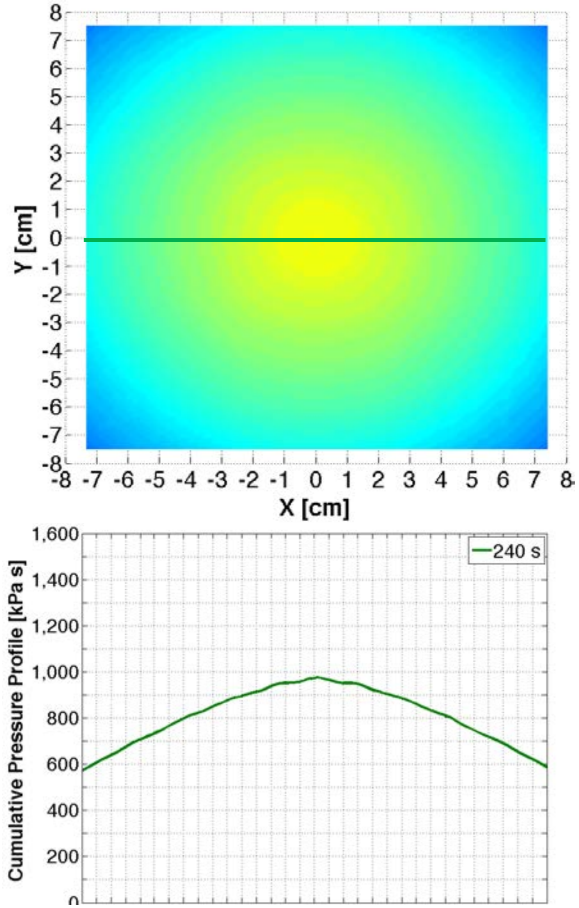


Non-linearity due to fluid dynamics?

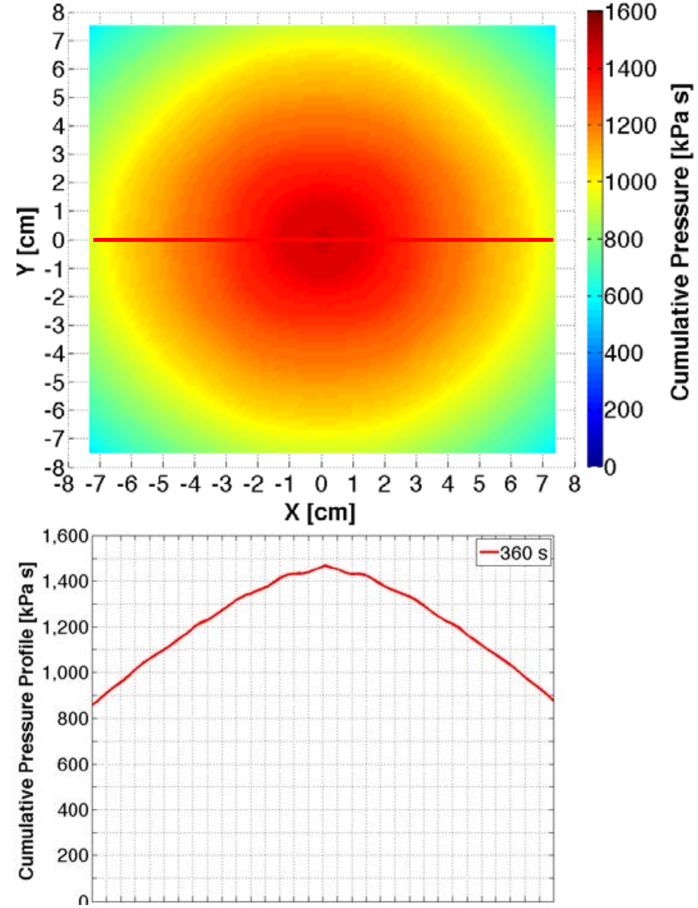
Comparing Exposure Time

Cumulative Pressure (CP) Plots

24 W, ΔT = 240 sec



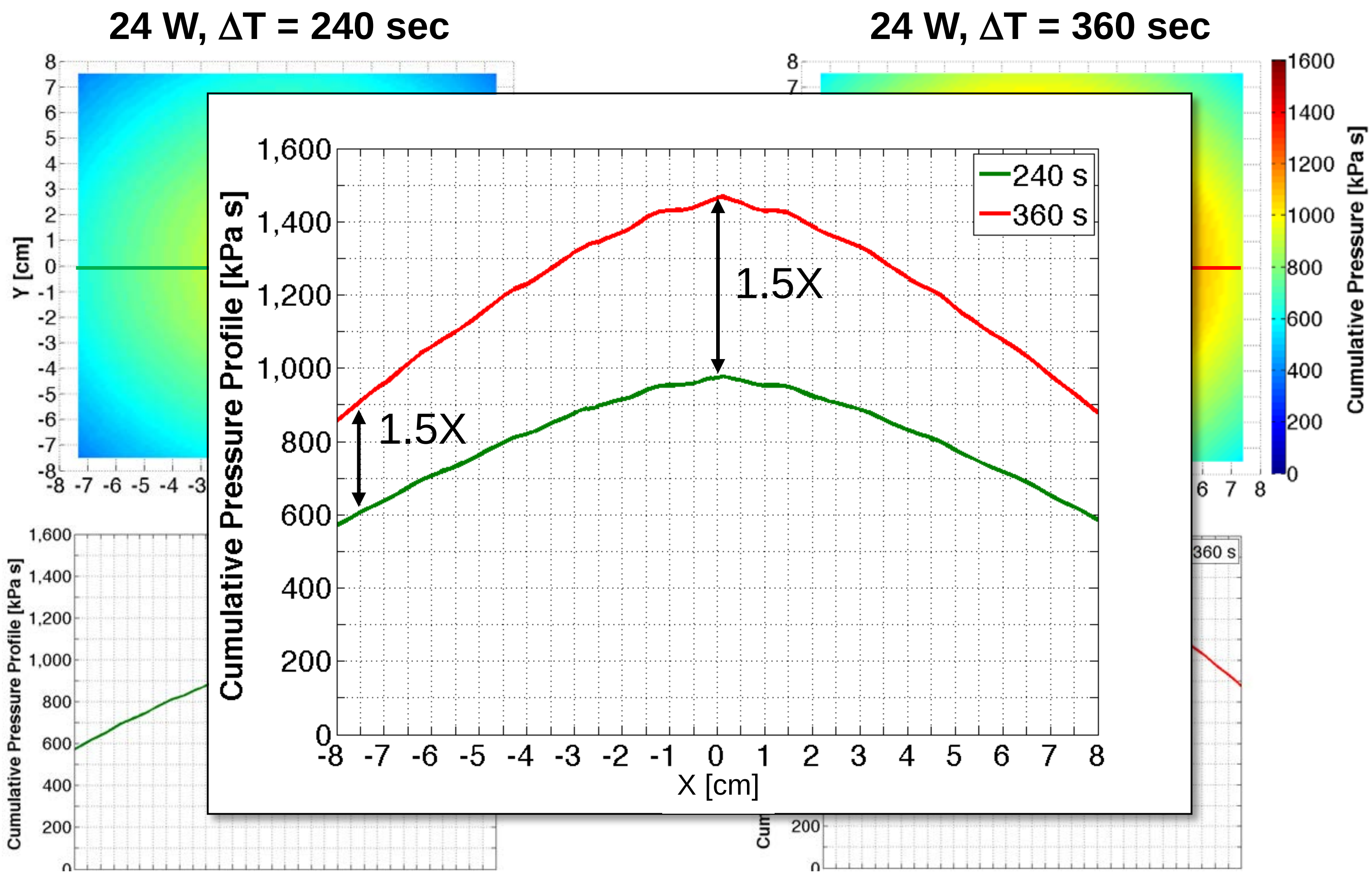
24 W, ΔT = 360 sec



Cumulative Pressure scales with time (as expected)

Comparing Exposure Time

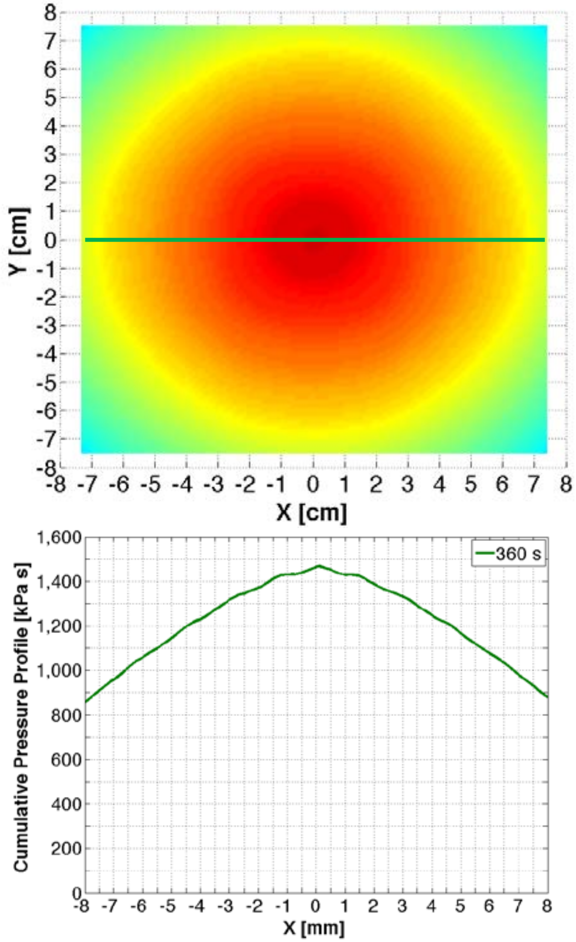
Cumulative Pressure (CP) Plots



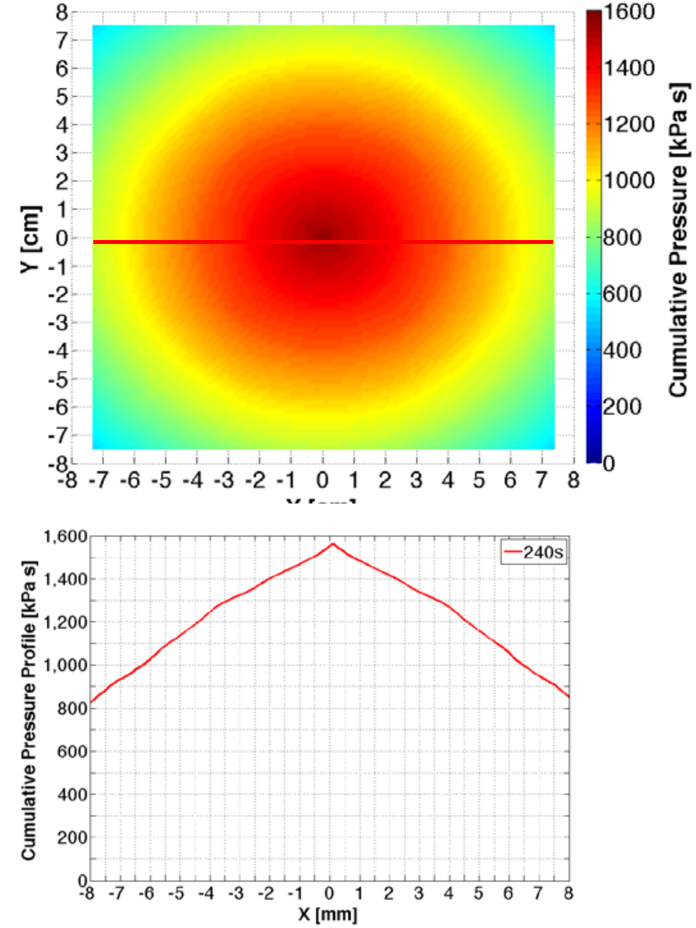
Cumulative Pressure scales with time (as expected)

What if the Cumulative Pressure was similar?

24 W, ΔT = 360 sec



40 W, ΔT = 240 sec



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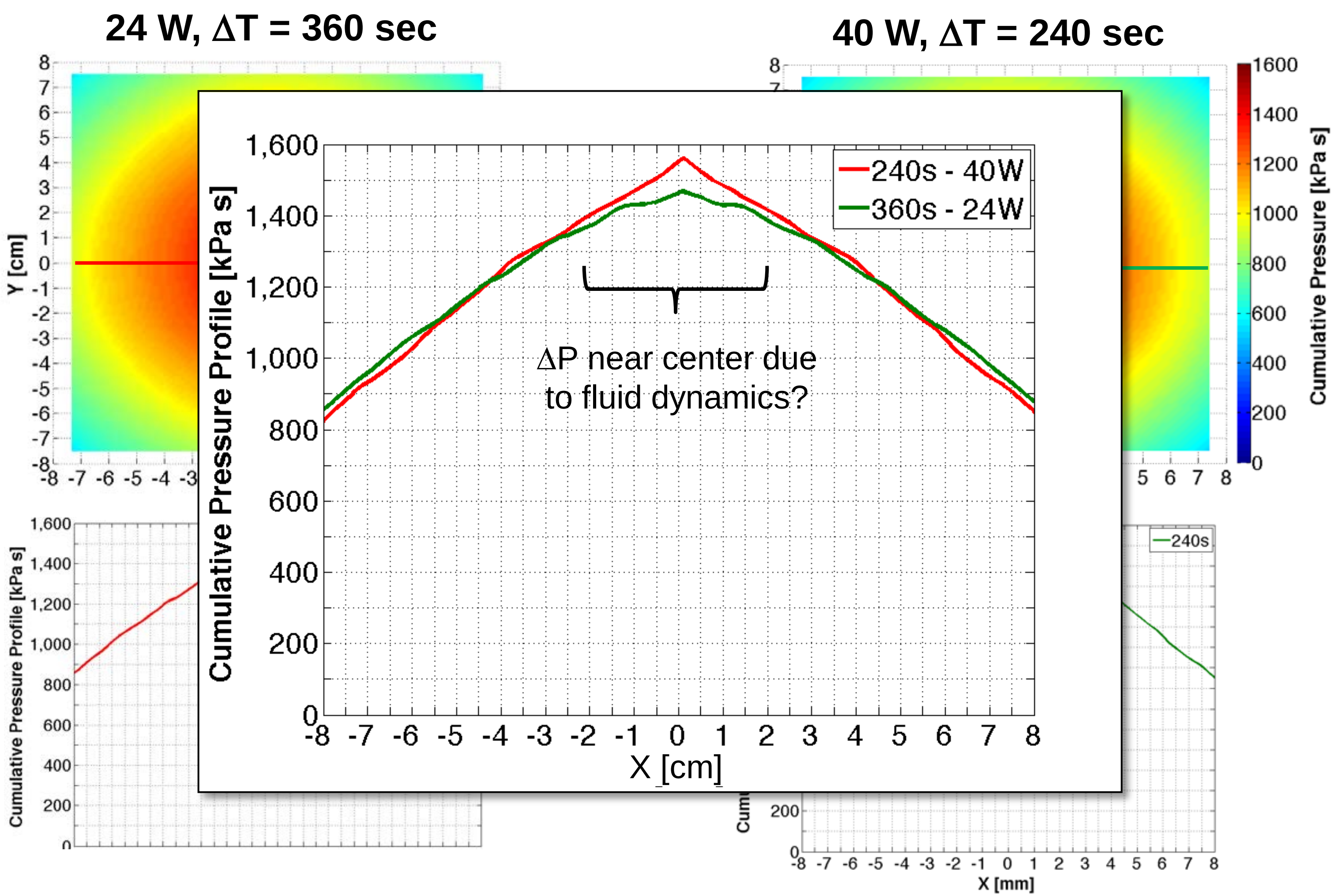

What matters more: Time or Instantaneous Pressure?

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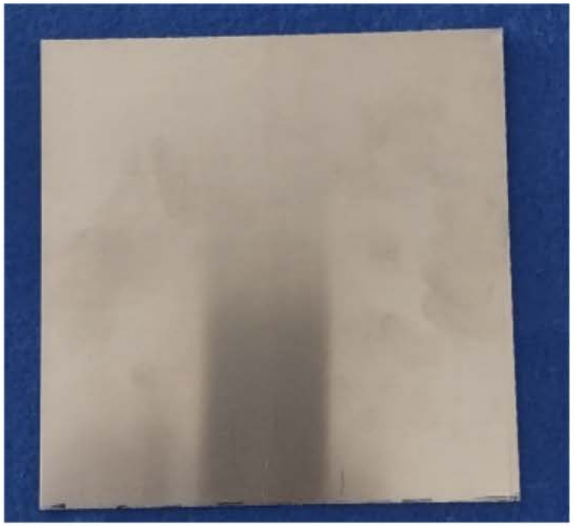
Cleaning Trials

Aluminum sheet
150X150 mm



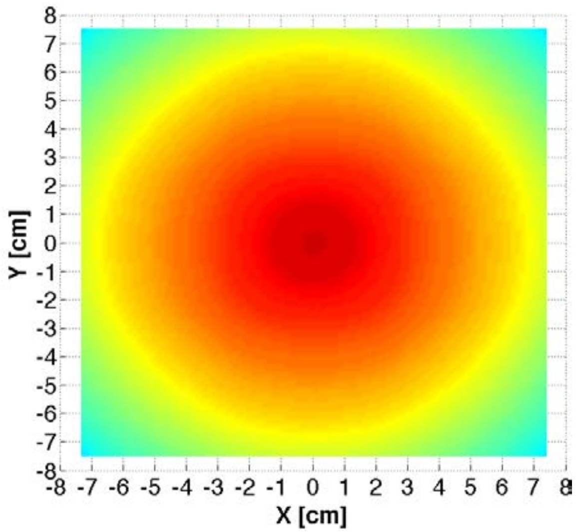
Paint

Painted aluminum sheet

Similar Cumulative Pressure

Acoustics

24 W, ΔT = 360 sec



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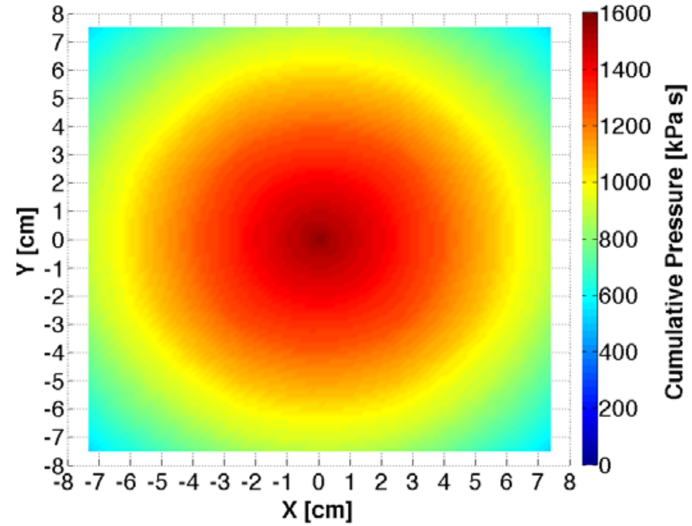
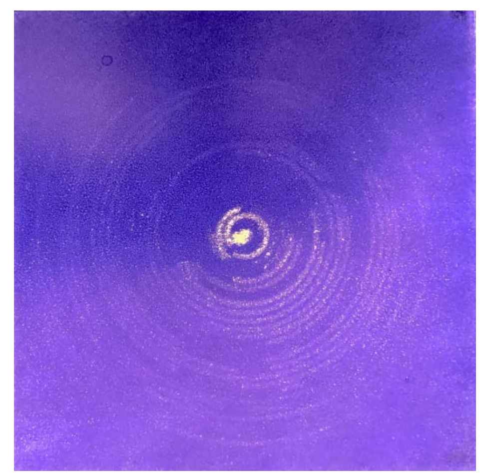
40 W, ΔT = 240 sec



Cleaning

≠



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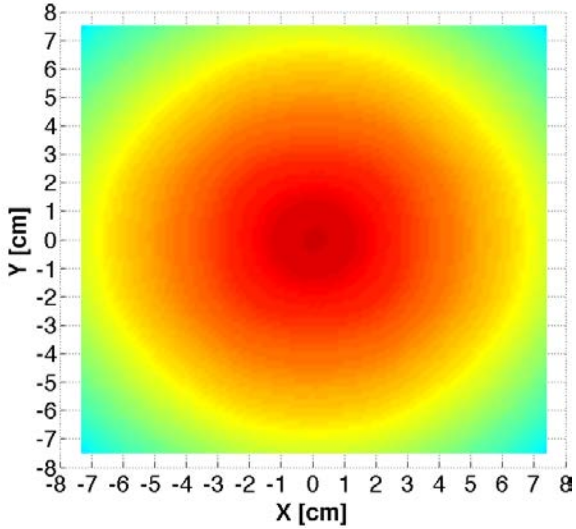
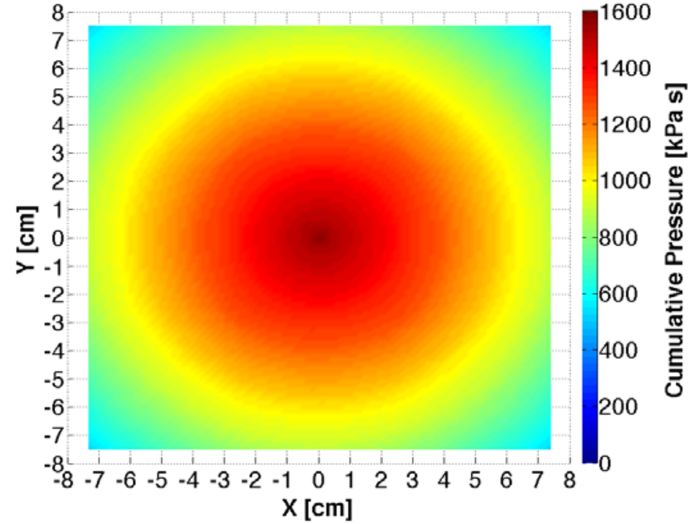


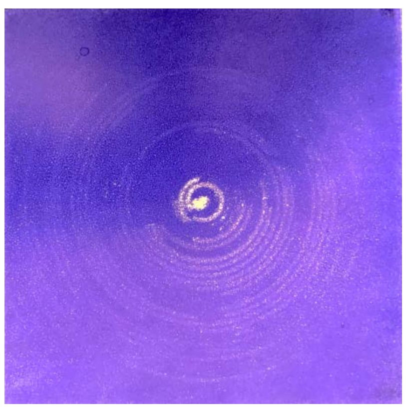
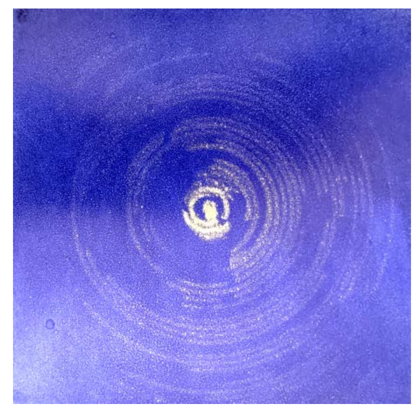
40 W, ΔT = 240 sec



Cleaning

Cleaning only effective beyond a pressure threshold?

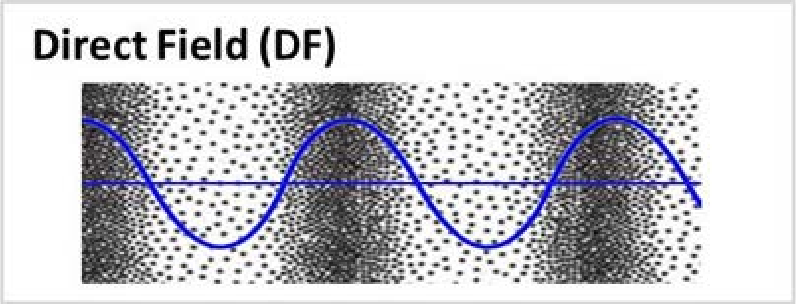
Cleaning is a function of both Time and Power

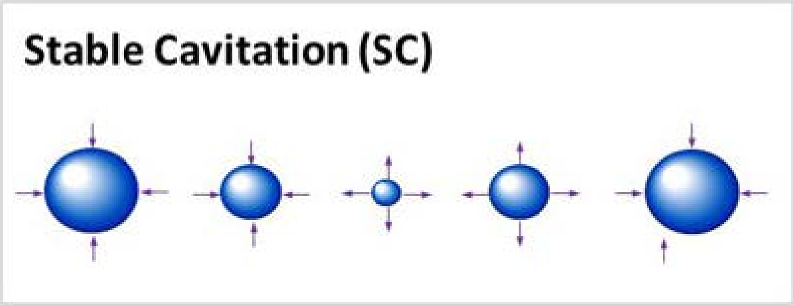
	ΔT = 240 sec	ΔT = 360 sec
24 W		
40 W		

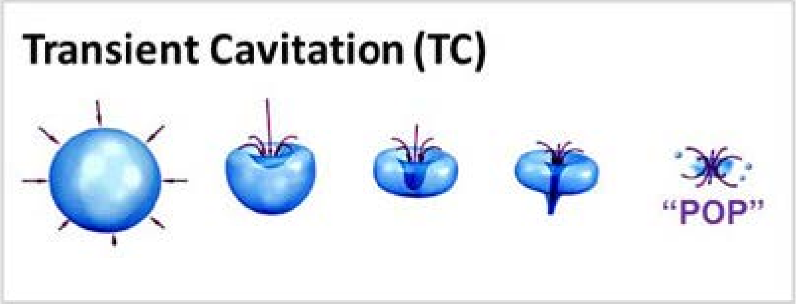
Threshold between 24 and 40 W?

To understand this, let's dig deeper

1. Sound wave
2. Bubble oscillation
3. Bubble implosions

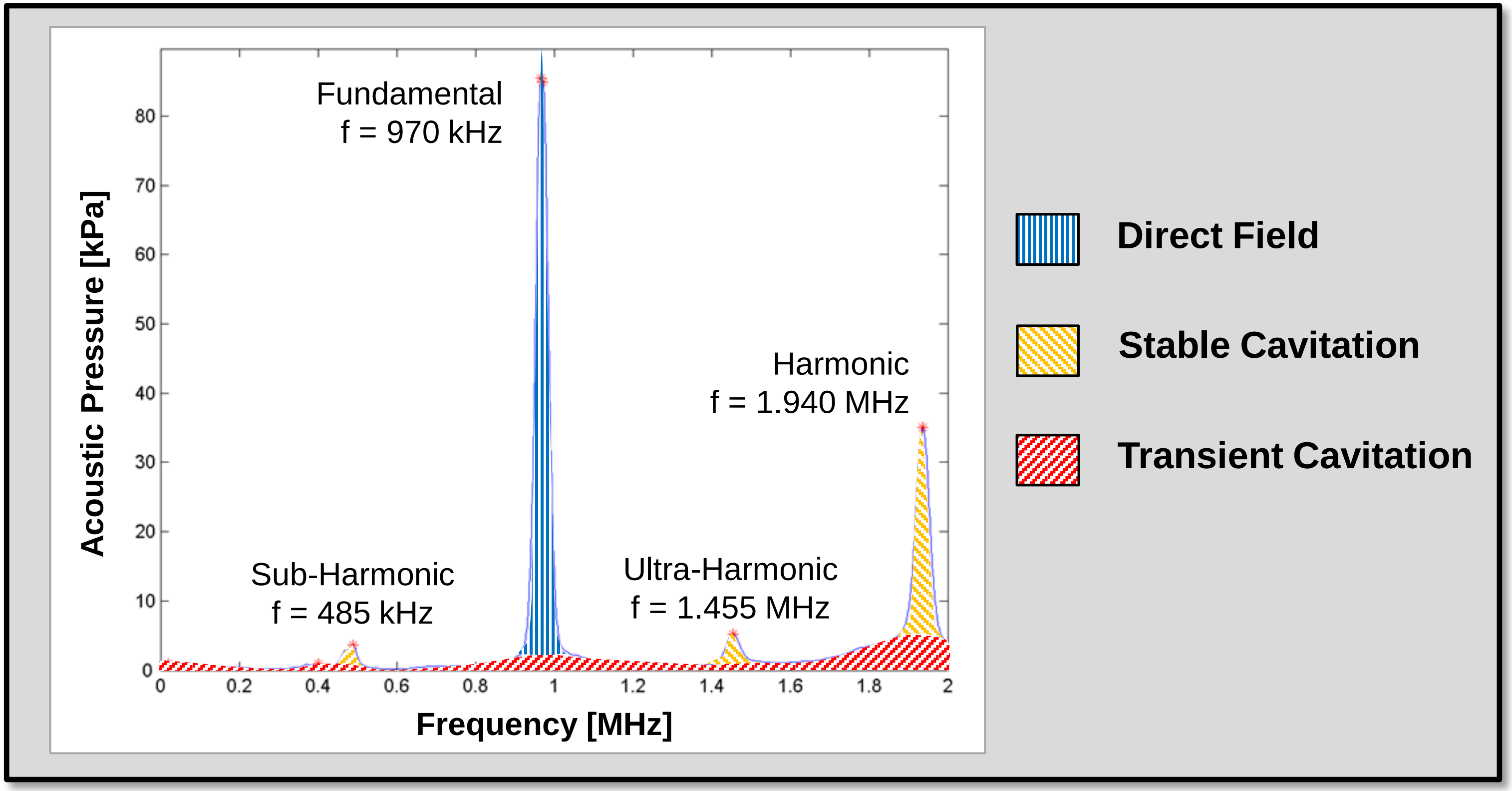






Anatomy of Acoustic Spectrum

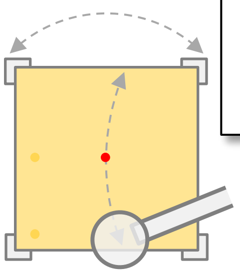
$$Ptot = \sqrt{P0^2 + Ps^2 + Pt^2}$$

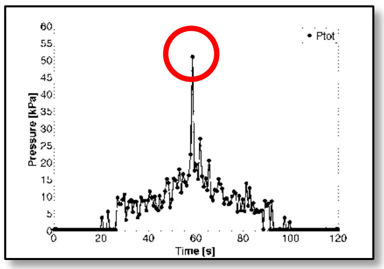


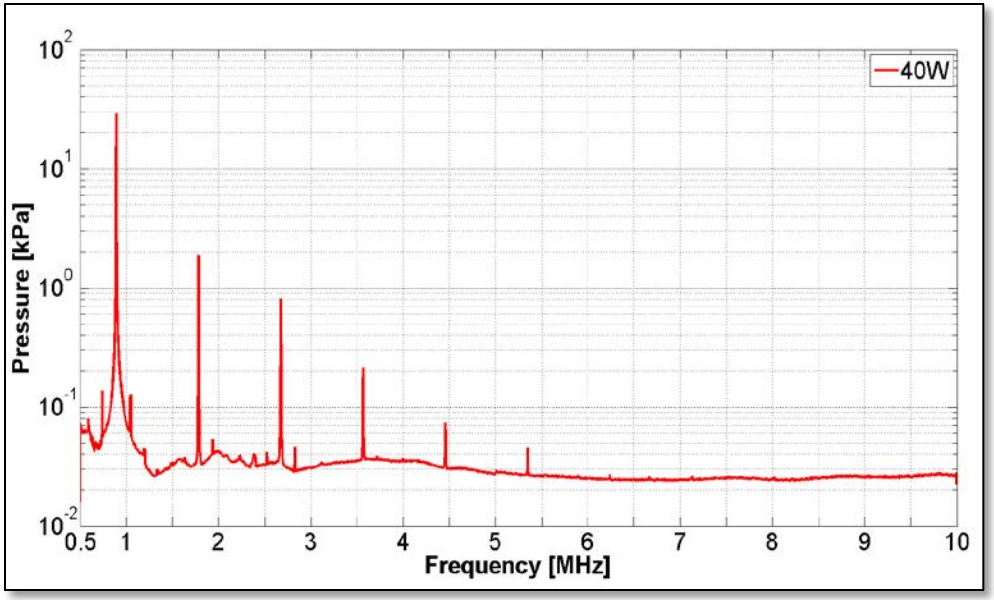
MCT-2000

Spectral analysis to separate the direct field and cavitation pressure

Cumulative Pressure for the Direct Field, Stable and Transient Cavitation







Will the lower level information provide more insight?

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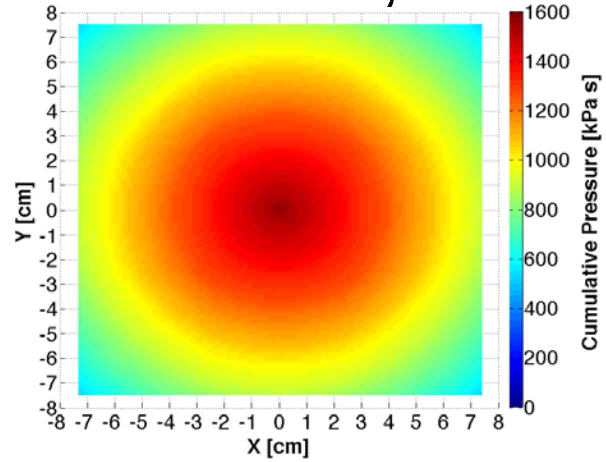
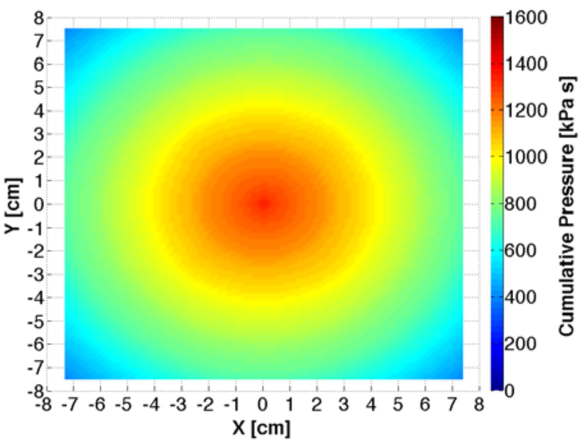
Cumulative Pressure Distribution

Ptot vs P0, Ps, Pt (40W, 240sec)

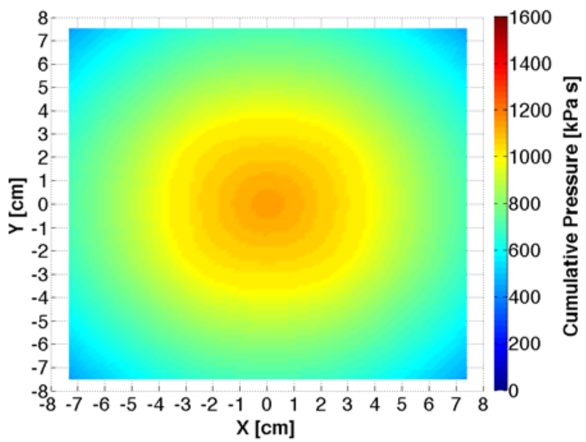
Total Pressure, Ptot



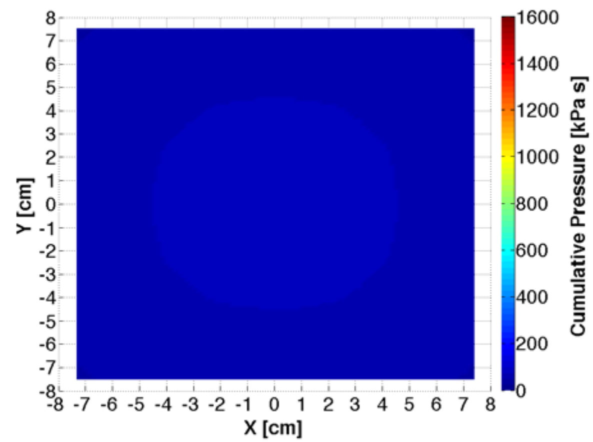
Direct Field, P0



Stable Cavitation, Ps



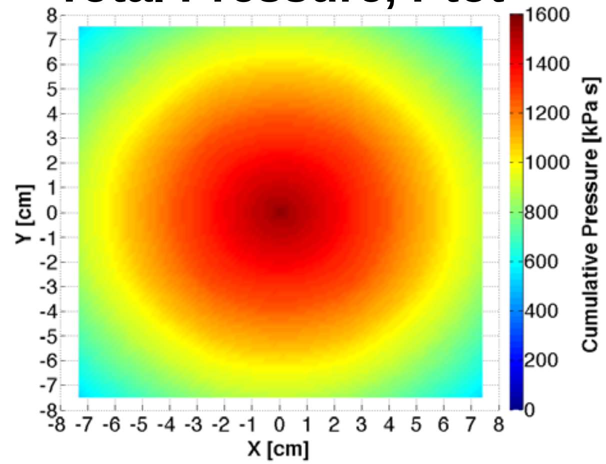
Transient Cavitation, Pt



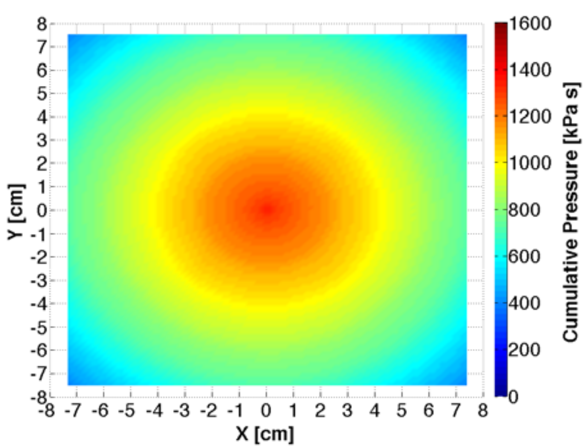
Cumulative Pressure Distribution

Ptot vs P0, Ps, Pt (40W, 240sec)

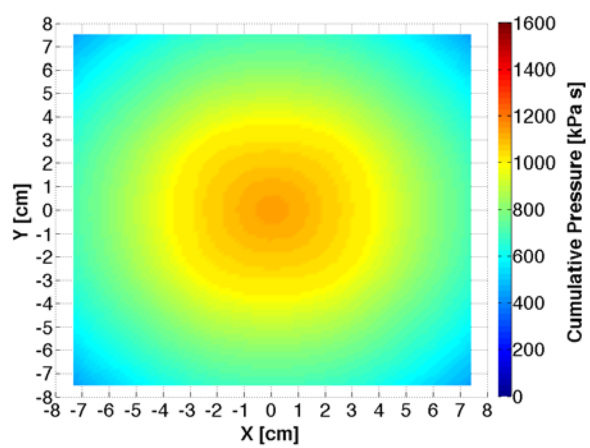
Total Pressure, Ptot



Direct Field, P0



Stable Cavitation, Ps



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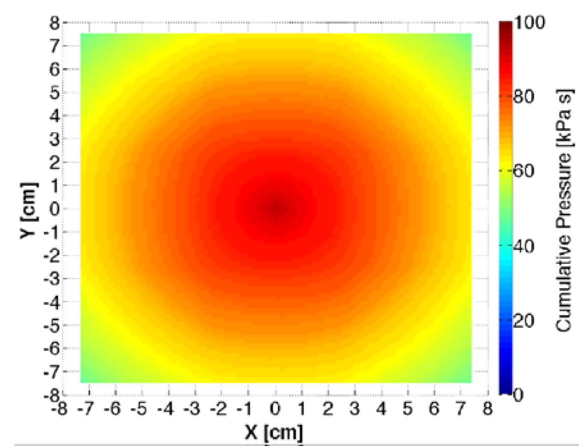
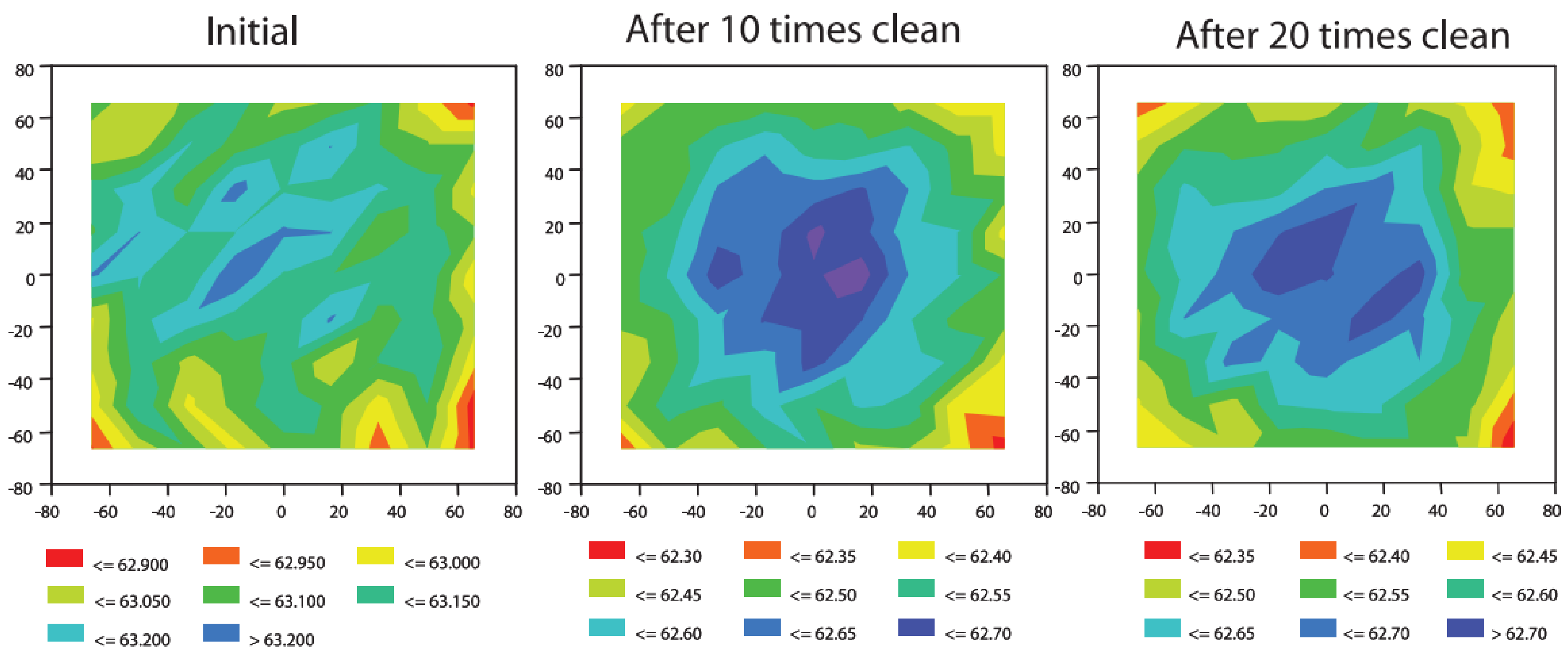


Ultimately, what matters?



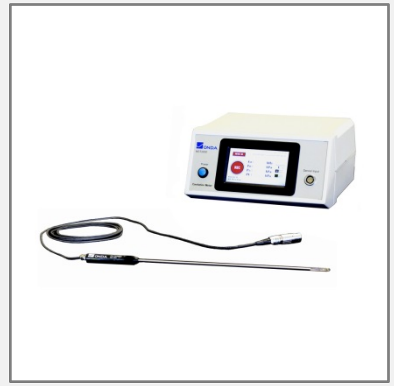
Ru cap EUV reflectivity damage

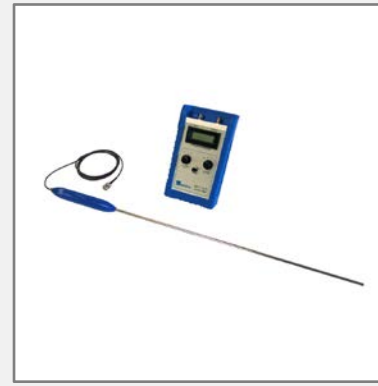
Naoya Hayashi, et al, Dai Nippon Printing Co., Ltd., BACUS News Vol 27, Issue 7

Future work: investigate how in-situ acoustic measurements correlate with precision cleaning

Ultrasound Measurement Solutions

Hydrophones
Meters
Arrays
Scanners





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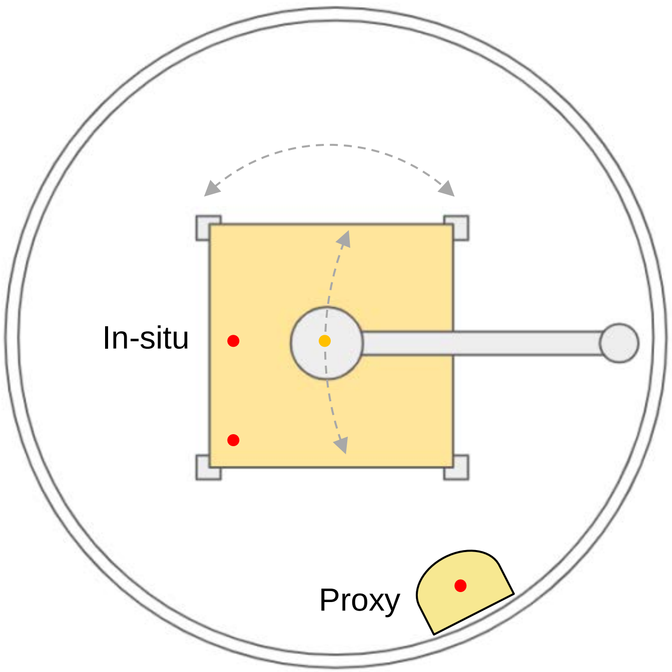
Ways to Verify Feasibility



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3. Simulation

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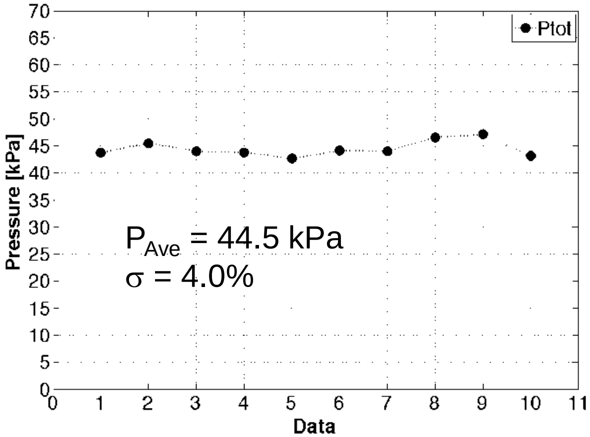
   Qualitative correlation observed between cumulative pressure and erosion maps

Ways to Verify Feasibility

24 W, Repeatability (10X)



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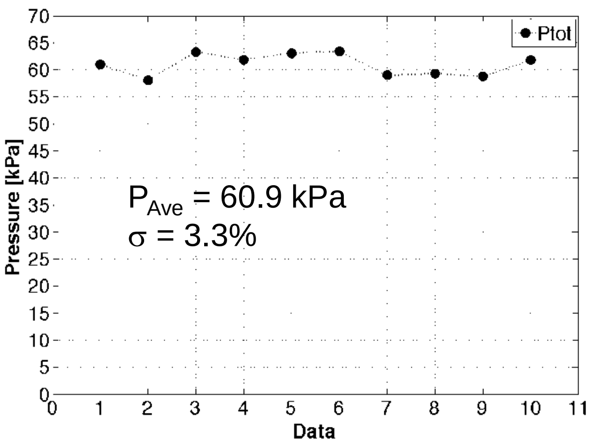

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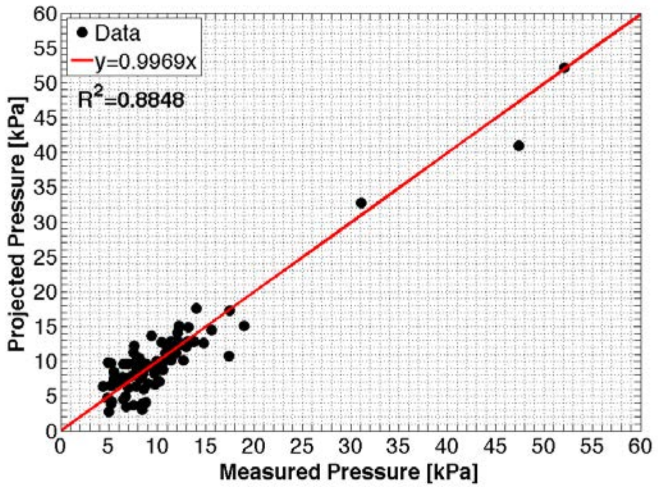

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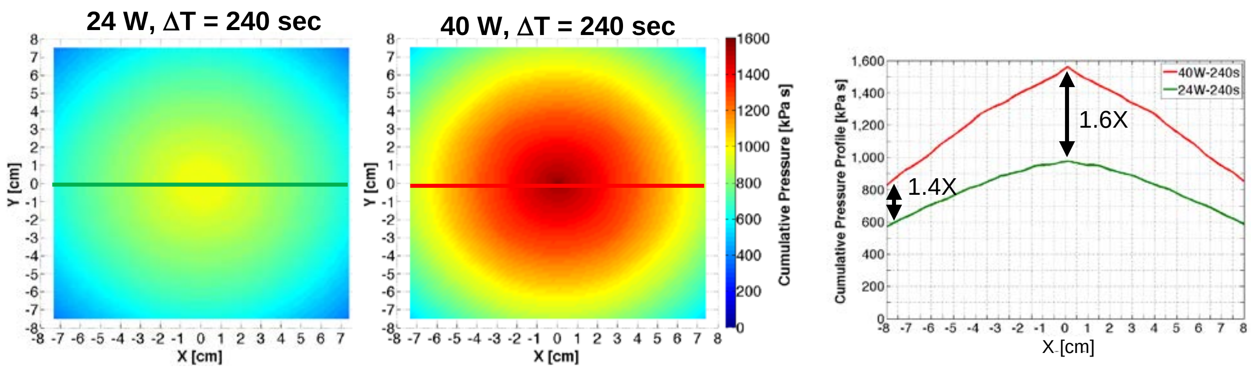
Comparing Exposure Time and Power

Cumulative Pressure (CP) Plots

Change in power

24 vs 40 W

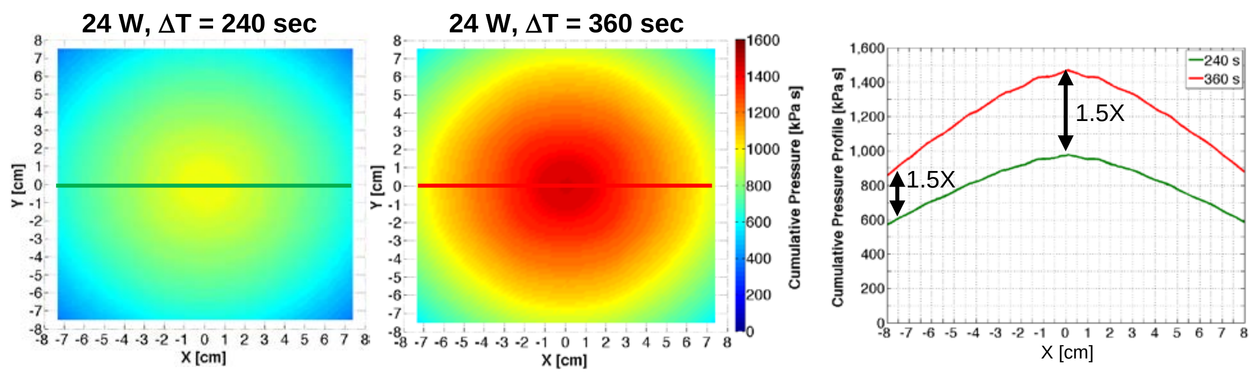
240 sec



Change in time

24 W

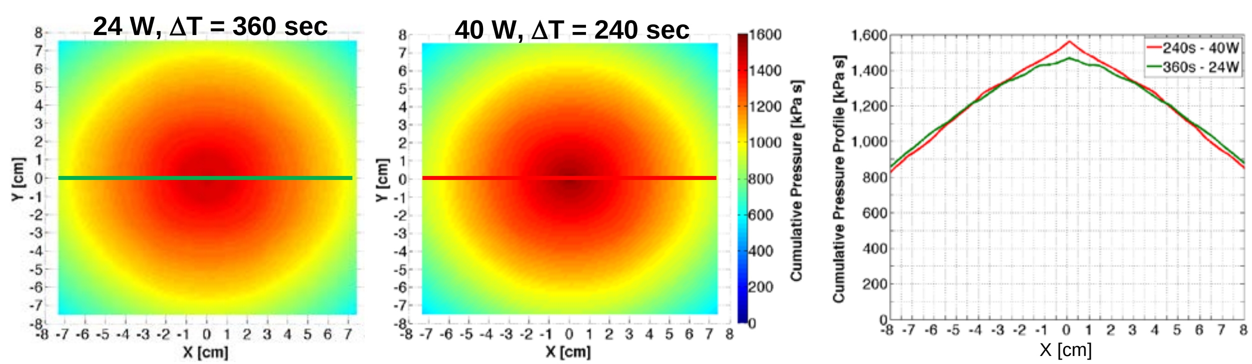
240 vs 360 sec



Change in both power and time

24 vs 40 W

240 vs 360 sec



ONDA

Method to Measure Cavitation

Reference: IEC/TS 63001:2019

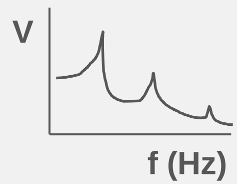
Measurement of cavitation noise in ultrasonic baths and ultrasonic reactors

Acquire data with Hydrophone

Voltage vs Time

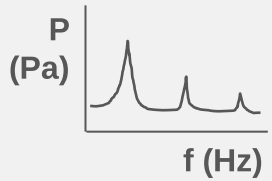
Fourier Transform

Voltage vs Frequency



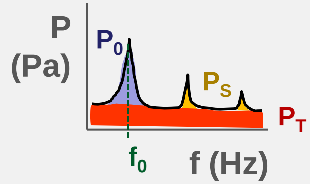
Apply Calibration

Pressure vs Frequency

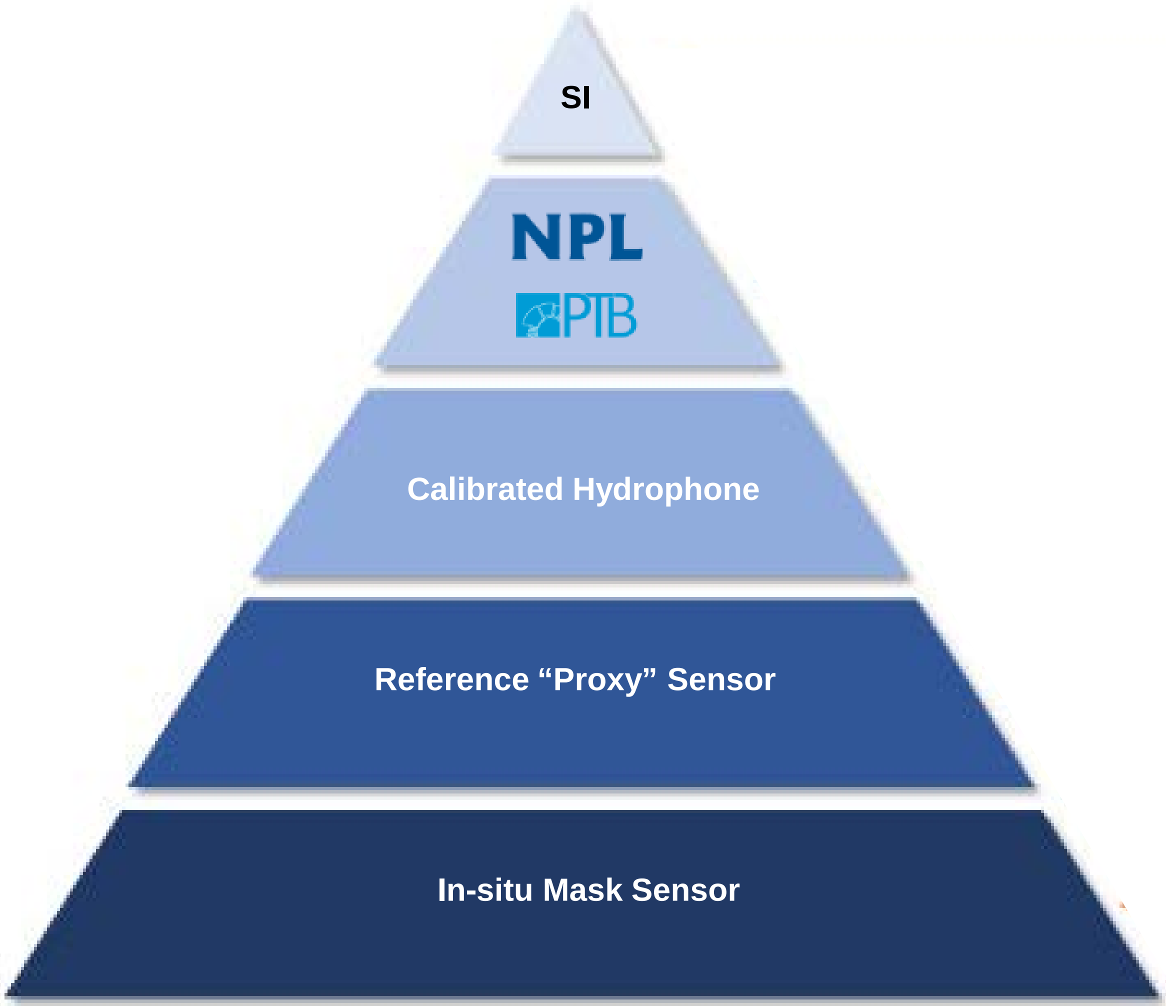


Apply MCT-2000 Algorithms

Calculation of P_0, P_S, P_T, f_0



Measurement Traceability



Calibration Method

<u>Stepped Single Frequency Comparison Technique</u>:

Step 0 *: Calibrate Reference Hydrophone per IEC 62127-2

Step 1: Measure with Reference Hydrophone in *Cavitation Vessel*

Step 2: Measure with Test Hydrophone in *Cavitation Vessel*

Step 3: Determine Gain at each frequency in *Cavitation Vessel*

Step 4: Apply Gain to determine sensitivity of Test Hydrophone

* Reference: http://www.ondacorp.com/images/brochures/Onda_HydroCalMethod.pdf

Control Your Process with a Combined Solution



MCT-2000		MCT-1200
R&D, Absolute Reference	APPLICATION	Process Monitoring
Cavitation Pressure & Frequency (P0, Ps, Pt, F0)	PARAMETERS	Total Pressure & Frequency (Ptot, F0)
Conforms with IEC/TS 63001:2019	METHOD	--
External-calibration to achieve traceability and matching	CALIBRATION	Self-calibration to achieve matching
Data saved to local memory	AUTOMATION	Real-time data transfer for continuous monitoring
Higher Performance	VALUE	Lower Cost

Resources: Talks and Publications

- Mask Sensor Arrays (wired) installed in Taiwan, Japan, USA, Germany
- Studies done to acoustically characterize the effect of:
  - Drive frequency, generator power, acoustic uniformity, nozzle distance, flow rate, sensor position, transducer orientation, etc.
- Presentations
  - Cavitation Study for a 3/5 MHz Dual Nozzle Transducer
  - Acoustic Comparison of a 3 MHz Nozzle and Skirt Transducer
  - Acoustic Characterization of a 1 MHz Skirt Transducer
  - Schlieren Video of the wave propagation from a 1 MHz Skirt Transducer