# Transducer for USCT III & USCT 2.5
# Status Update 2016-08-23

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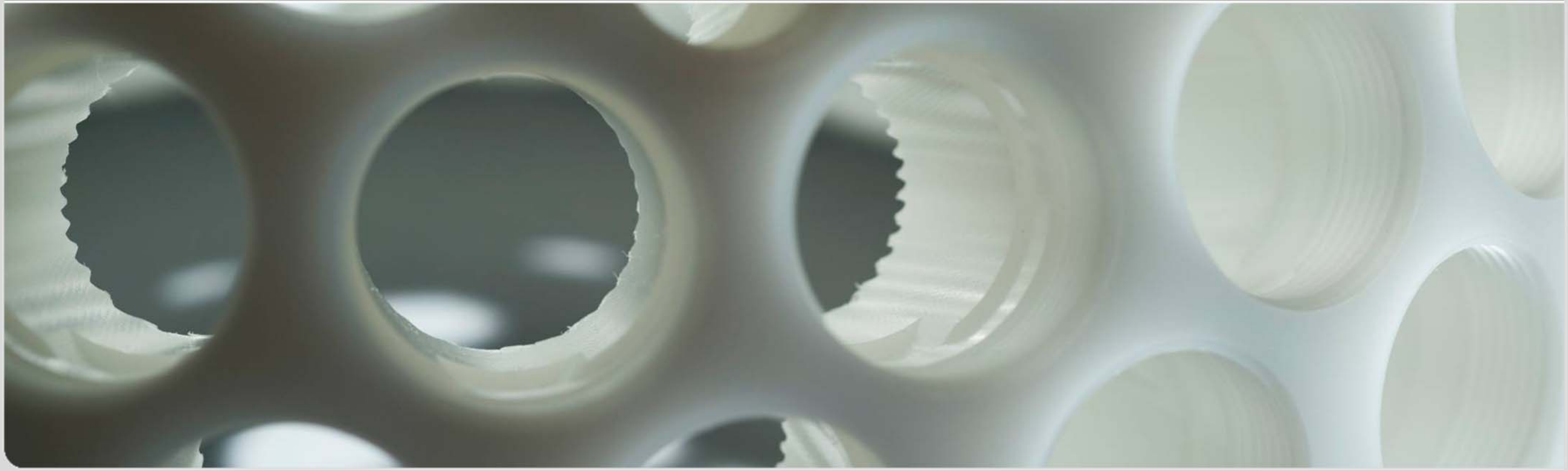
INSTITUTE FOR DATA PROCESSING AND ELECTRONICS



# KIT 3D USCT

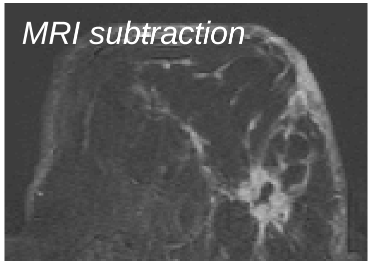
3D Ultrasound Computer Tomography
for early breast cancer diagnosis …

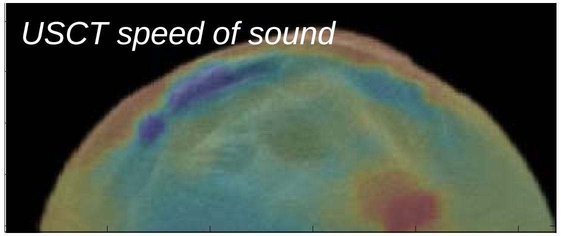
- as harmless as diagnostic ultrasound
- as economical as X-ray mammography
- as sensitive as MRI (long term goal)

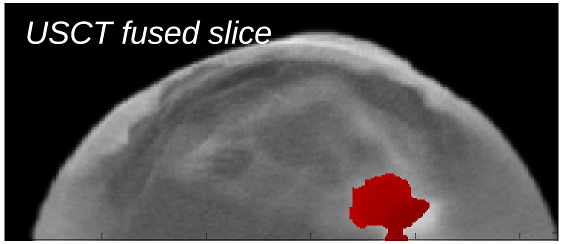
Current stage:

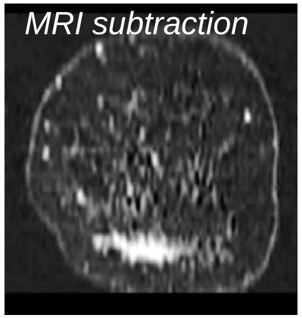
- pilot study 2012-13,
  University Hospital Jena
- study with 200 patients 2015-2016,
  University Hospital Mannheim

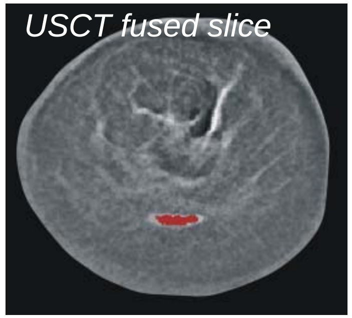
# Clinical Trial  Jena



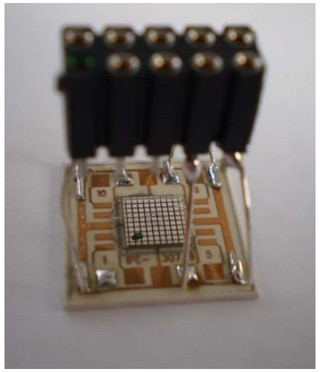
# Motivation / Starting Point

- conclusion from the Jena Study:
  - ROI to small several patient breasts are not well „illuminated“

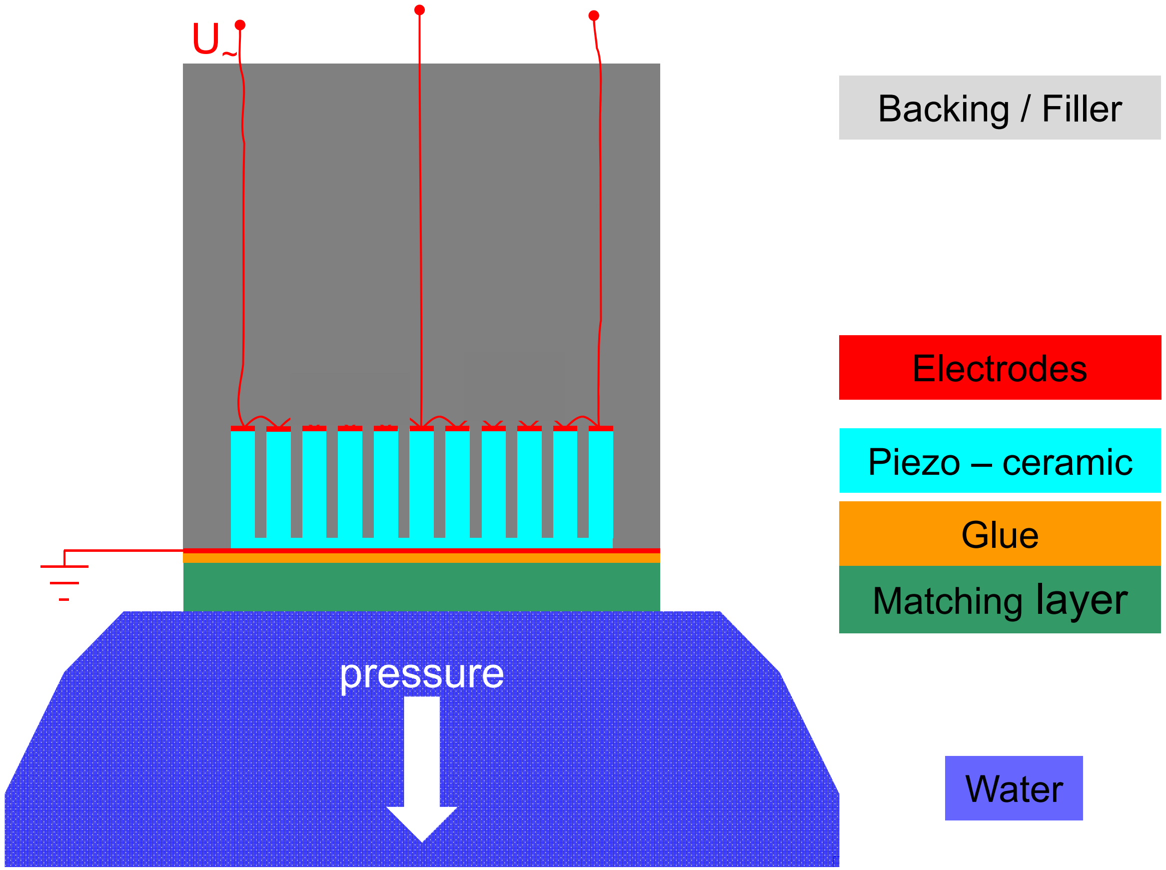
- Solution approaches:
  - Use lower frequencies -> undesirable as SAFT relies on high freq/bandwidth
  - Enlarge the surrounding aperture -> limited by practicability, also increased pressure loss (geometrical damping)
  - Reduce the directivity/increase the opening angle -> was done before USCT I to USCT II migration

# USCT II Transducers

*3D USCT II transducers*



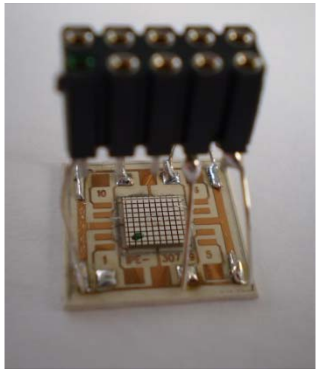
„Raw“ transducer
without Polyurethane




*Scheme: vertical cut*

# USCT II Transducers

*3D USCT II transducers*



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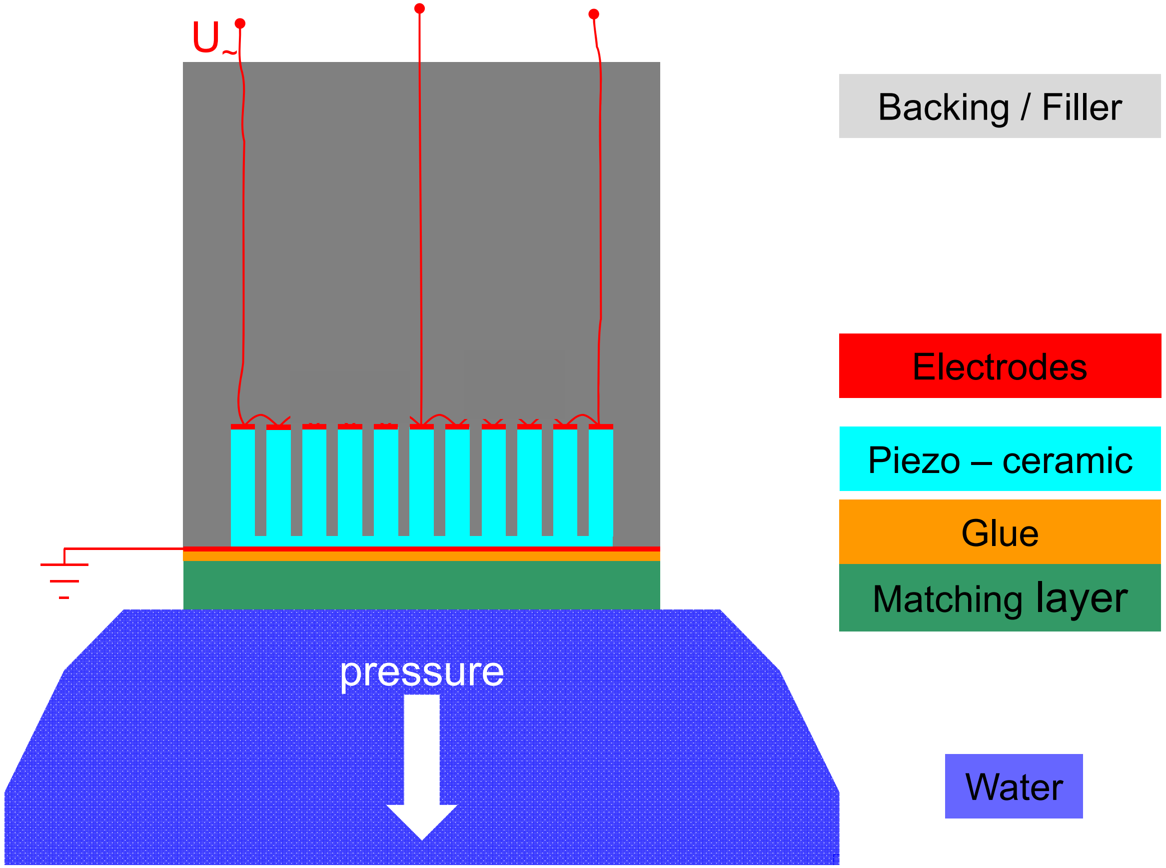


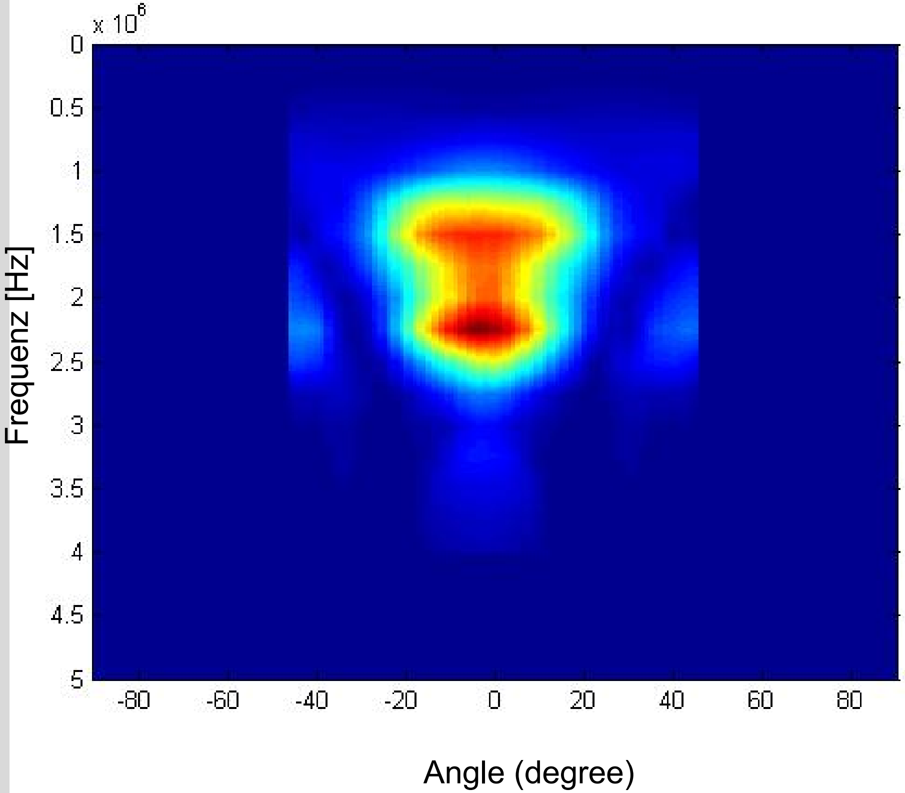

*Scheme: vertical cut*

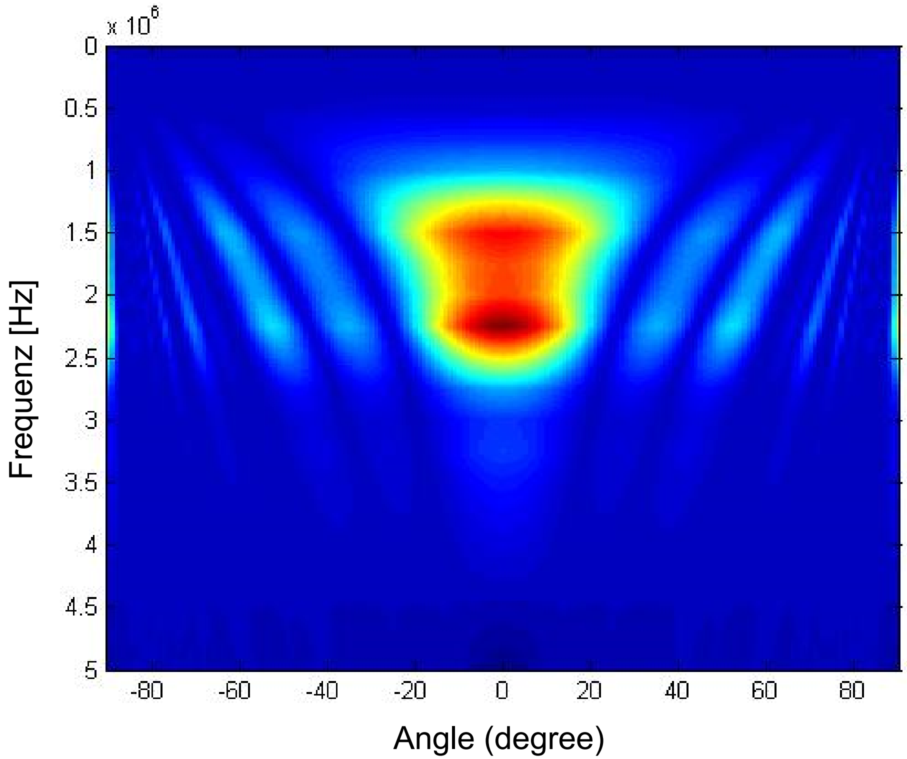
# USCT II transducer setup (current)

- USCT II transducers:
  - PI PIC255 PZT 0.55mm
  - Piezo geometry 0.4mm 0.1mm 0.4mm (Piezo, Gap, Piezo) -> 0.9mm
  - Single Adaption Layer appraoch: TMM4 in front
  - Backing: polyurethane Flexovoss

  - Resulting in
    - ~2.5MHz Center freq., 1MHz Bw (3dB)
    - an directivity/opening angle of 38° (3dB, 2.5MHz)

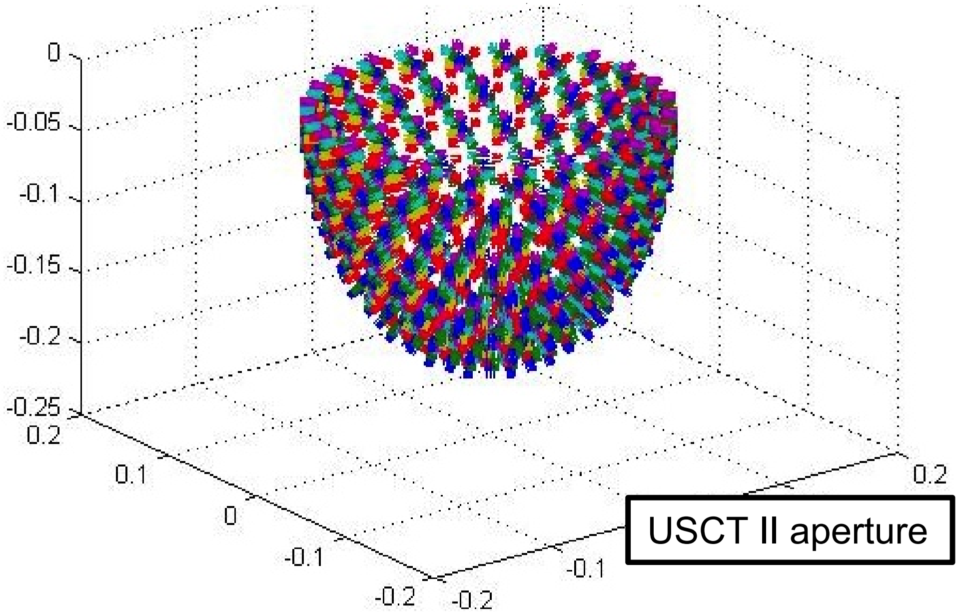
# Status Quo: TAS USCT 2.0

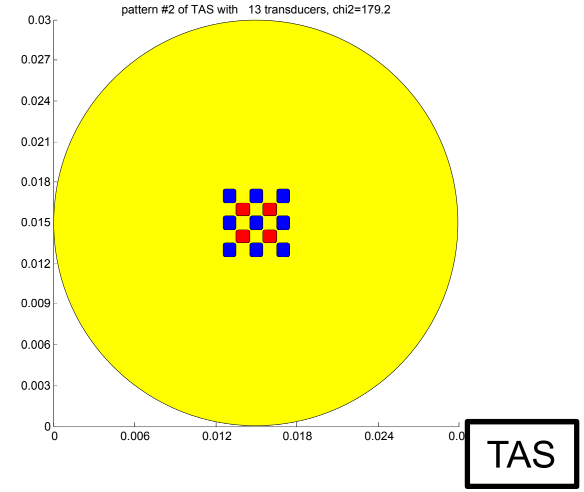



- Very old measurment right (79.4) fraunhofer simulation + measured freq. charactersitic right

# USCT III – Vision: current 3D USCT II aperture



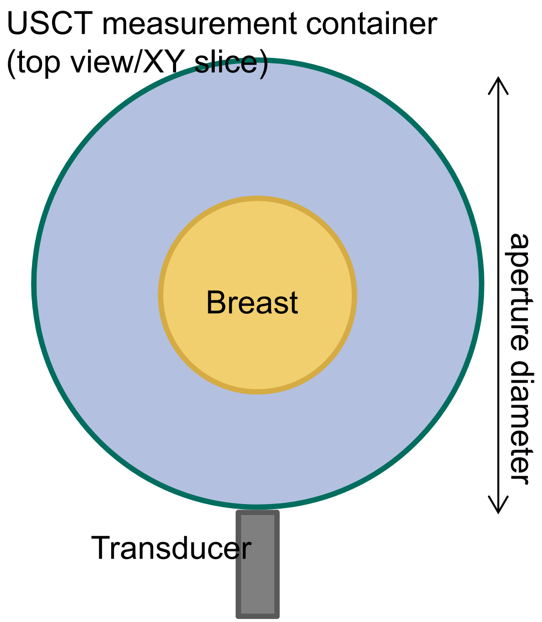




Diameter 26 cm
157 TAS
With 12 movements: 10.7 Mio. A-Scans

TAS diameter 2.3 cm
4 emitters (red)
9 receivers (blue)

- Situation Jena medical trial with 3D USCT II
  - Measurement speed: many slow mechanical aperture re-positioning steps required
  - Still suboptimal imaging characteristics

# USCT III – Design: Relation measured object / aperture size / transducer opening angle



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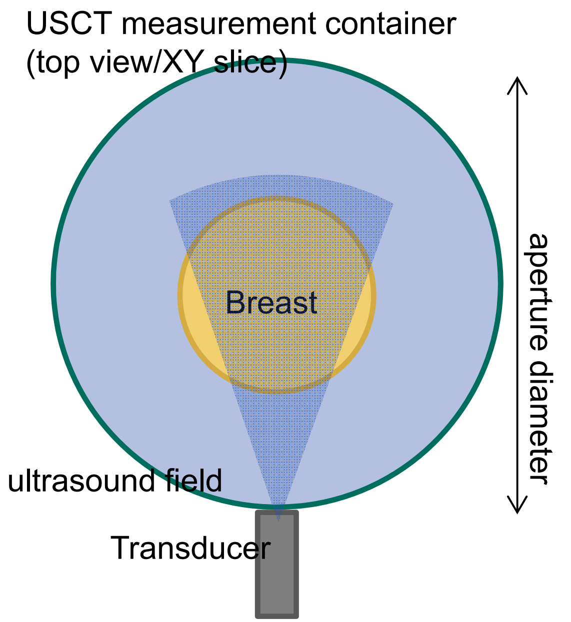

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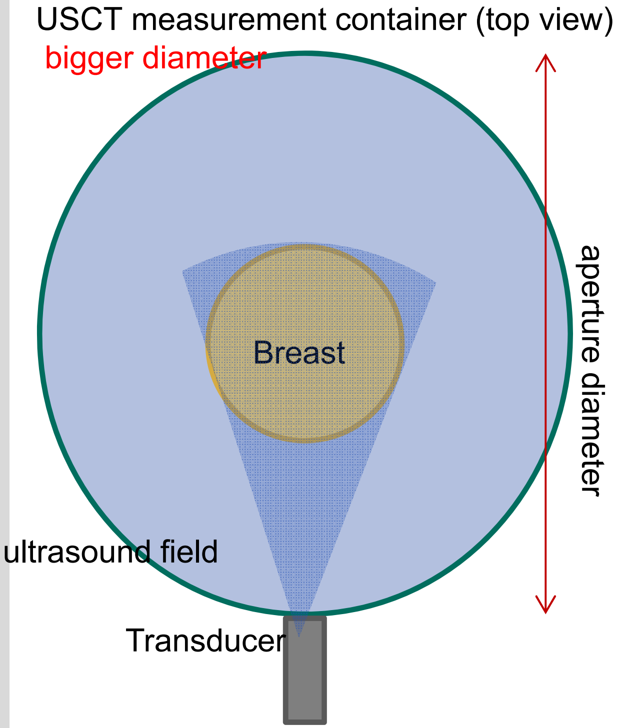
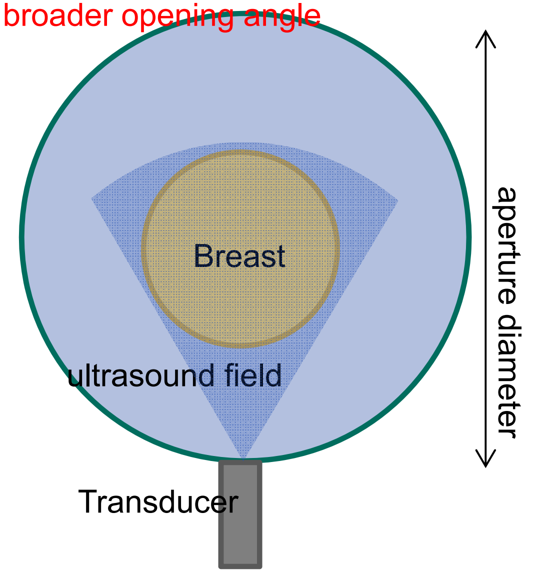


# USCT III – Design: Relation measured object / aperture size / transducer opening angle

USCT measurement container (top view),
broader opening angle



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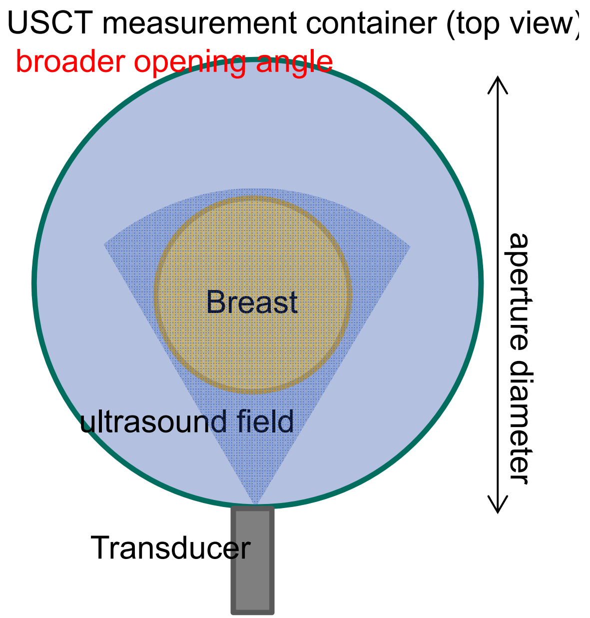


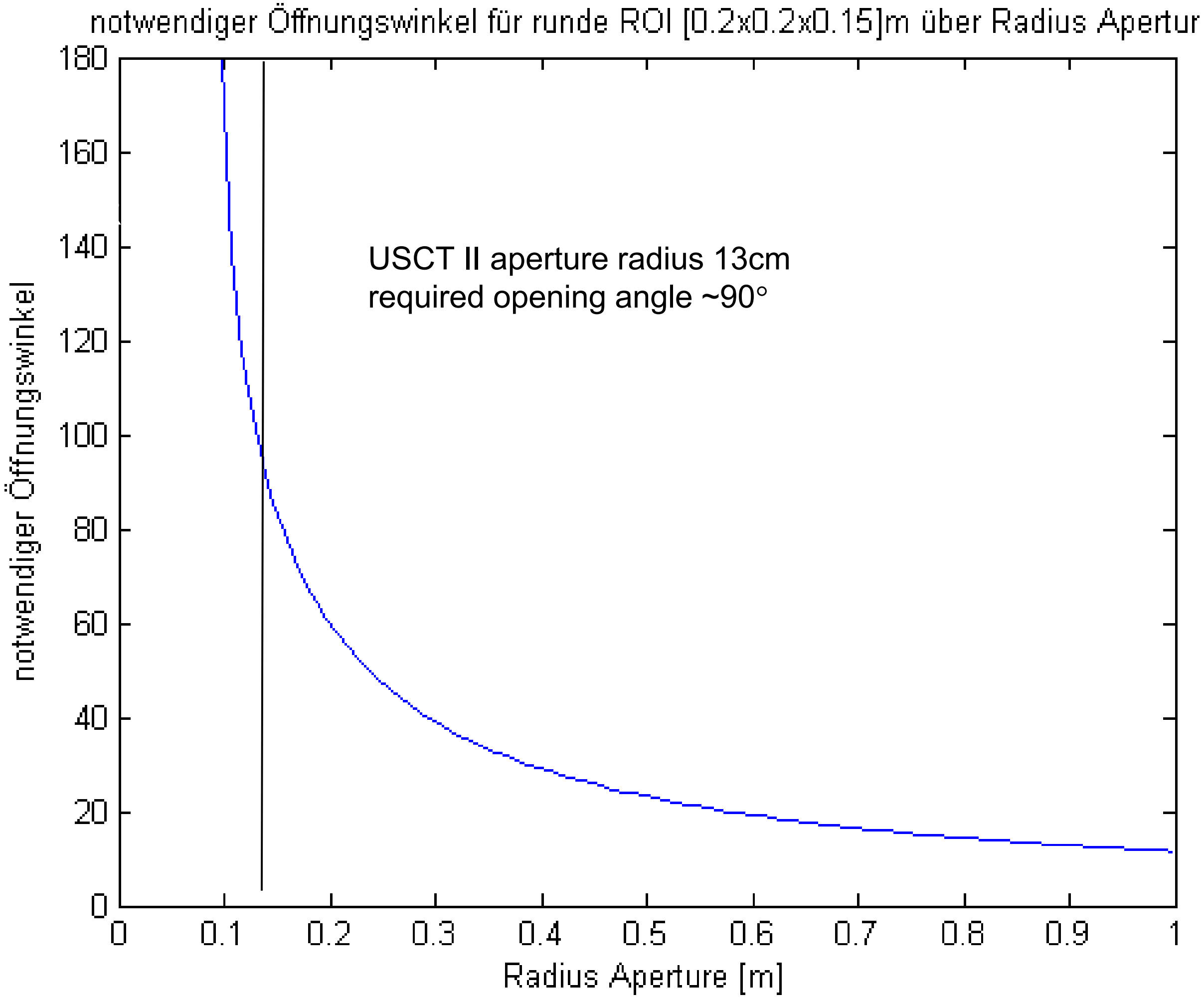

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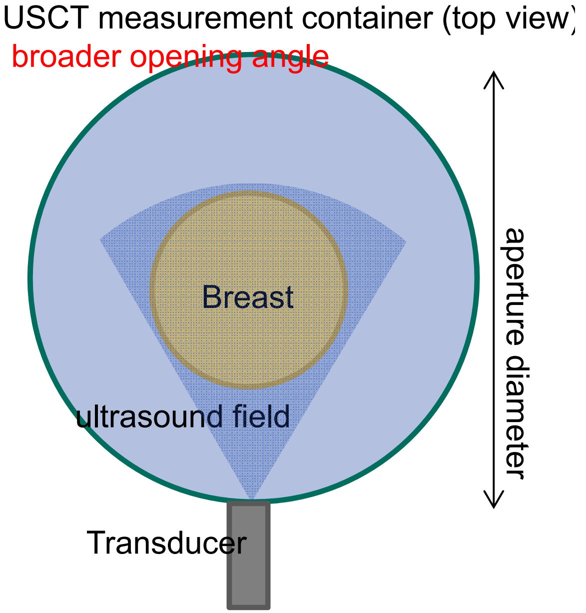


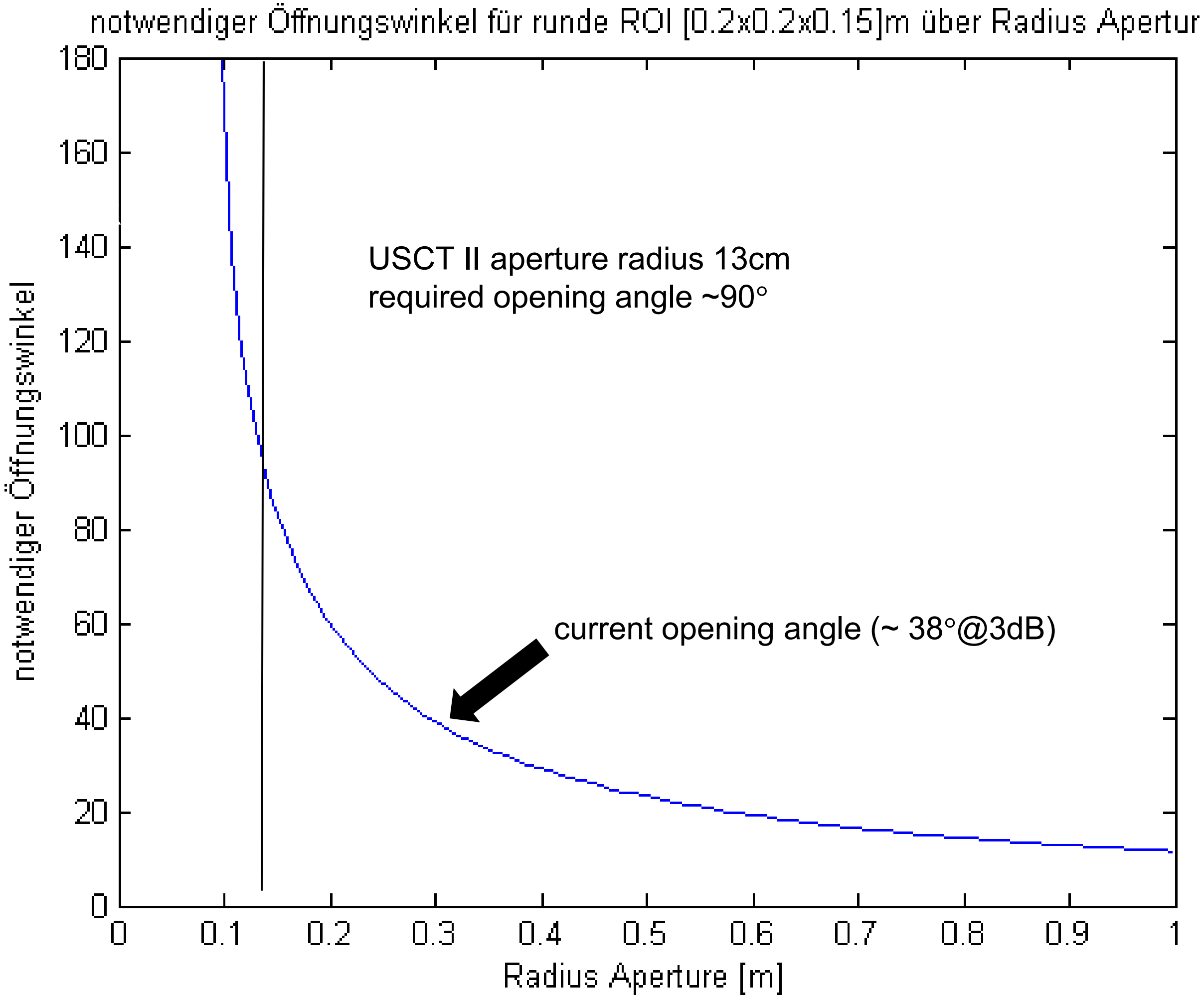

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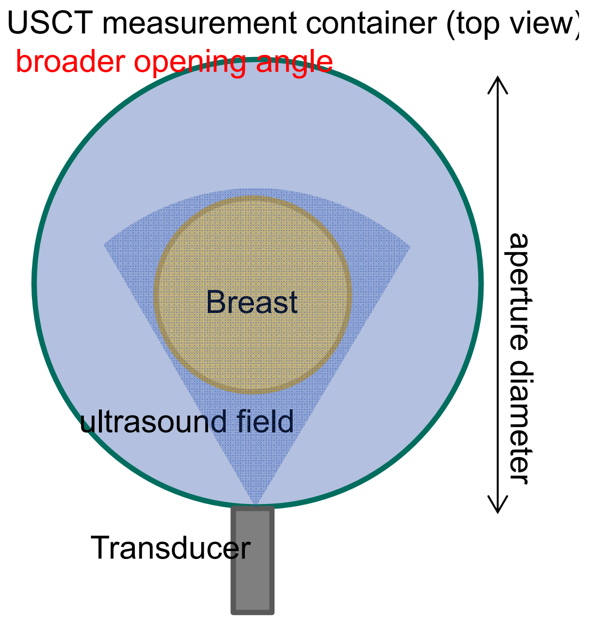


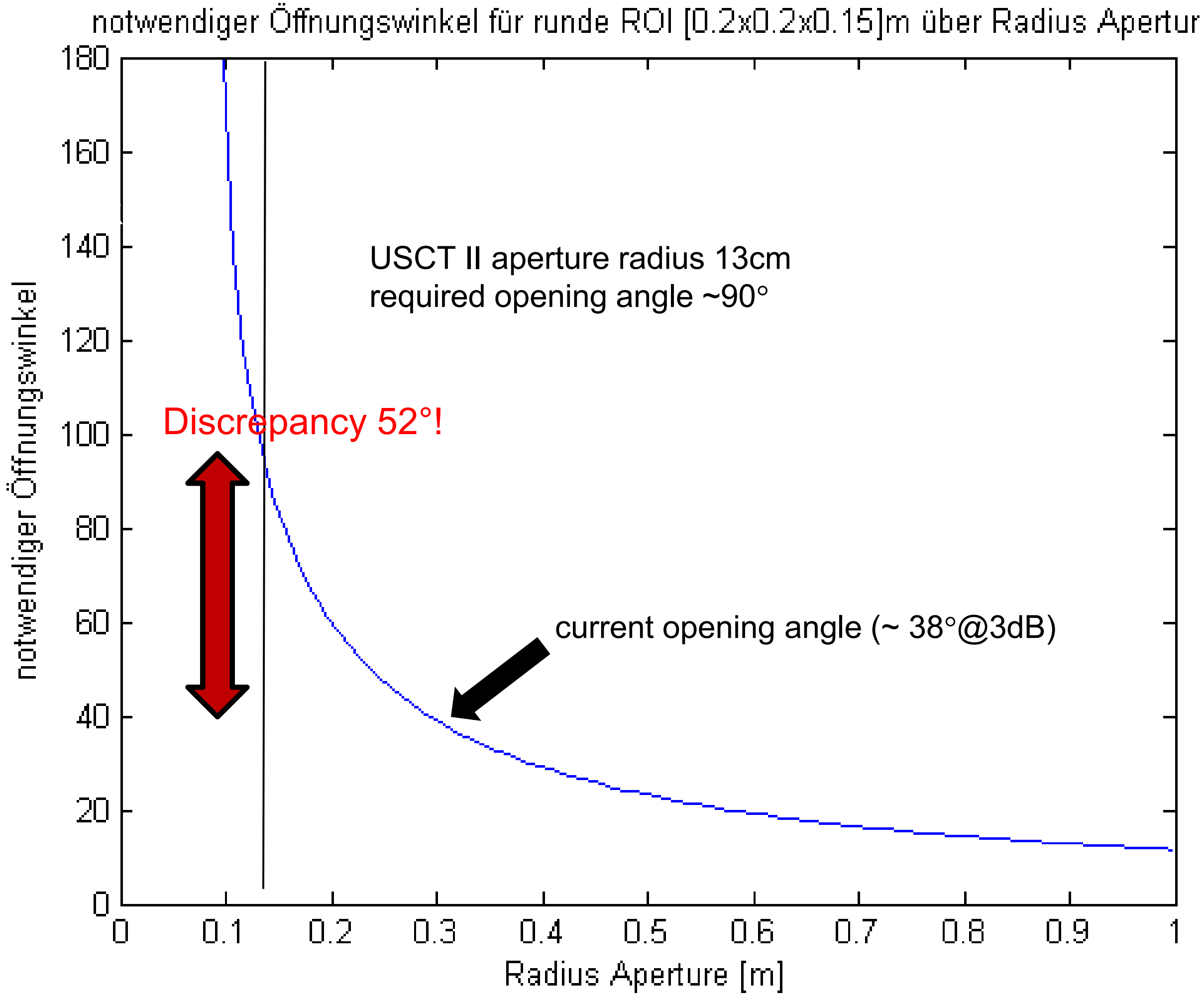

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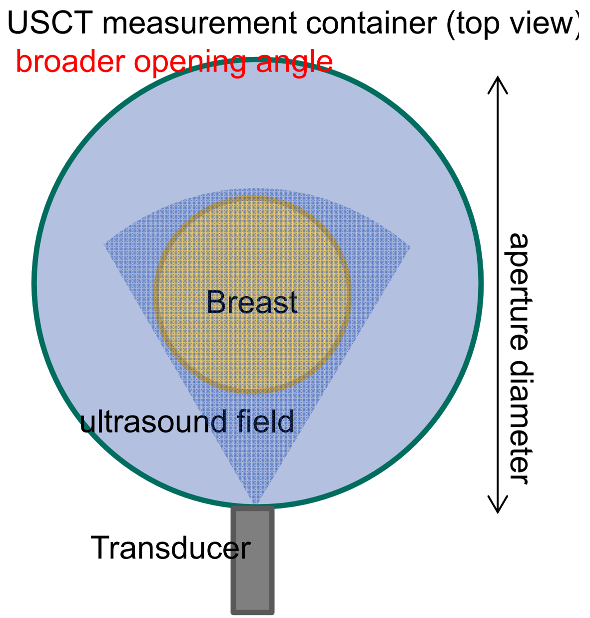


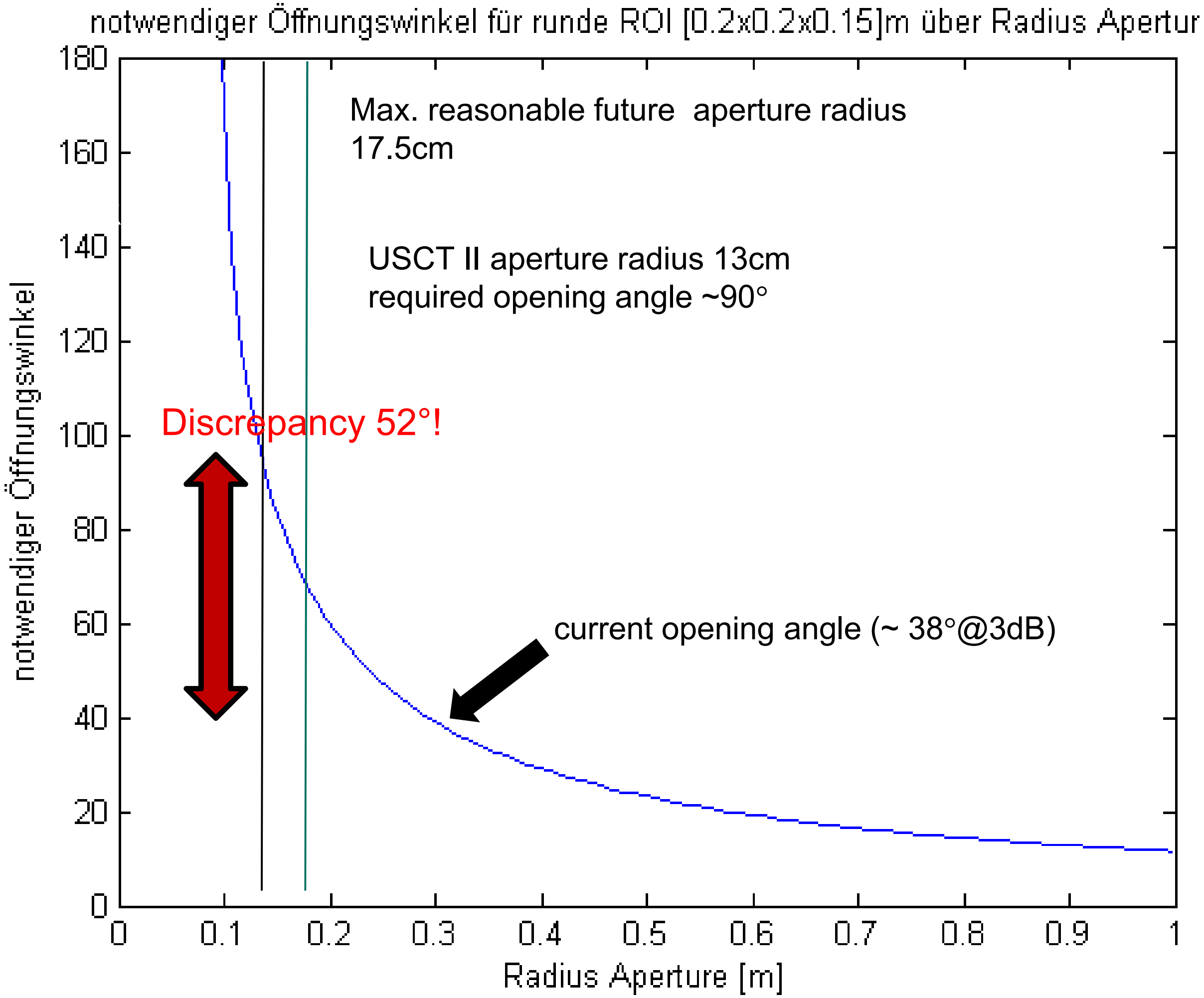

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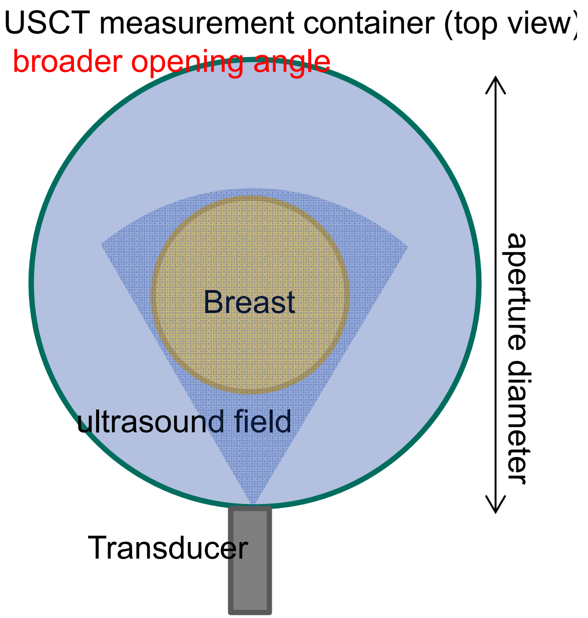


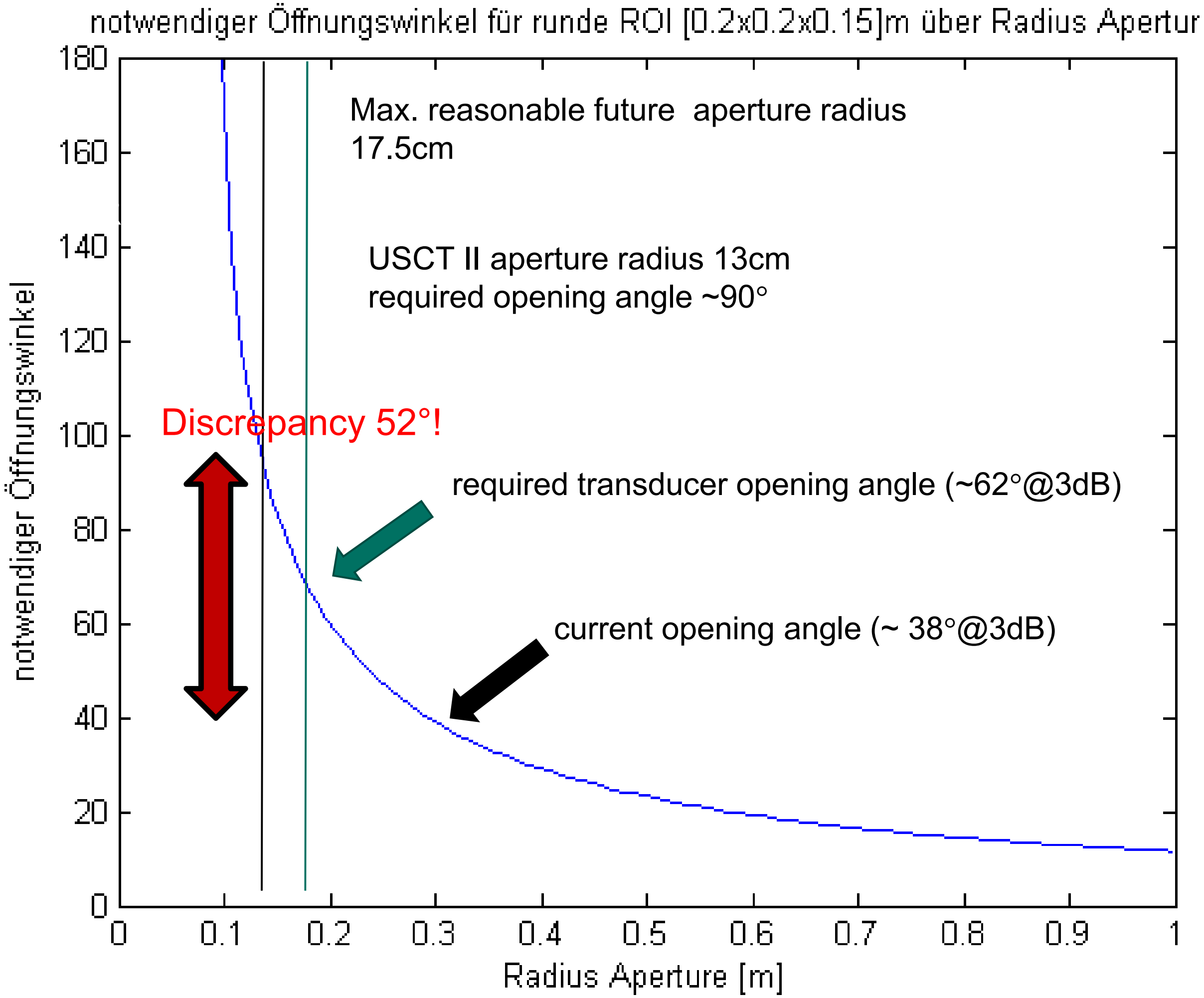

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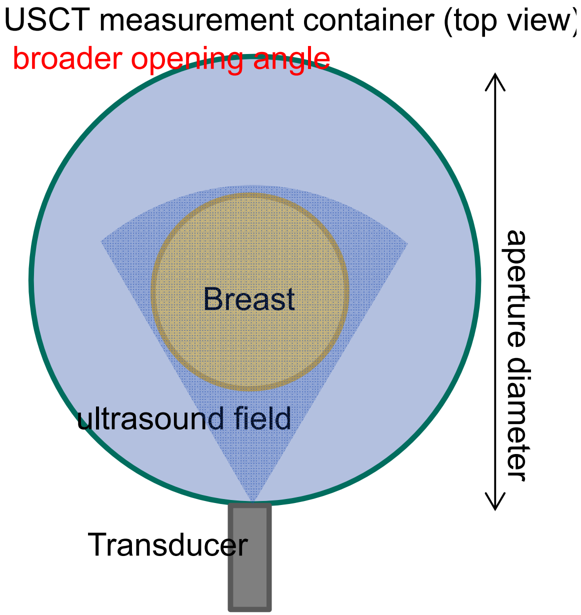
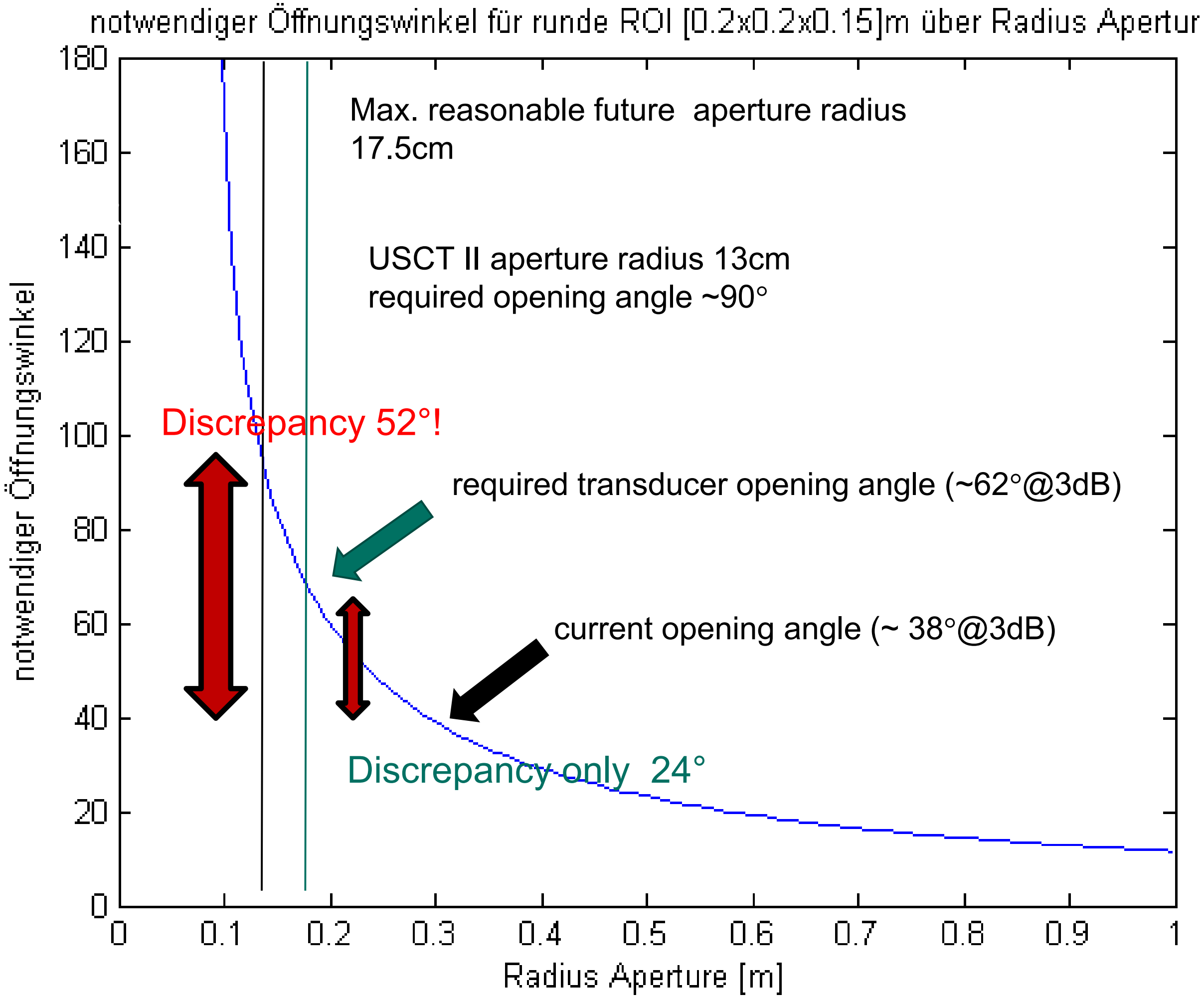
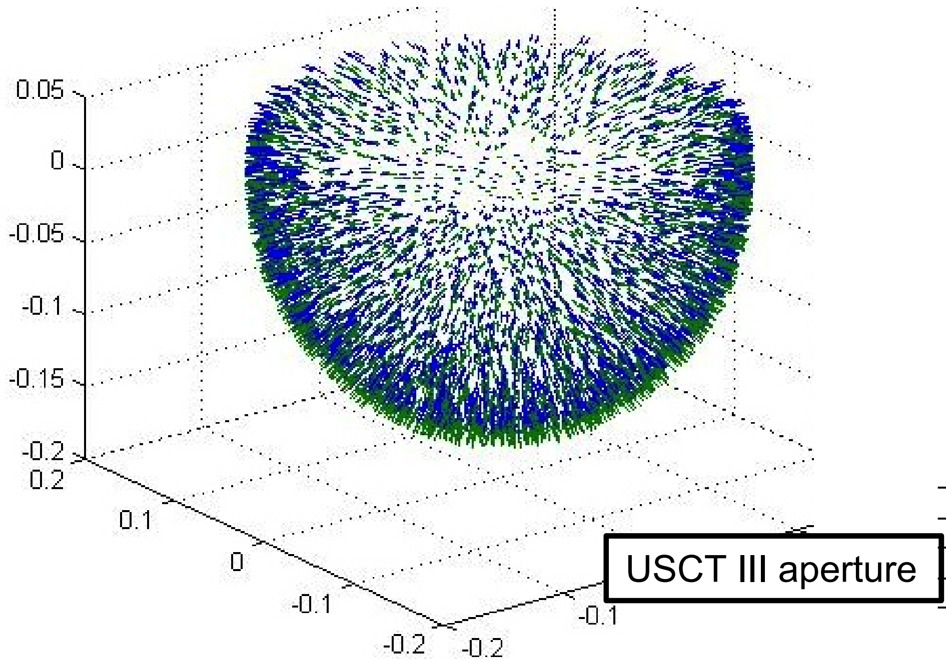
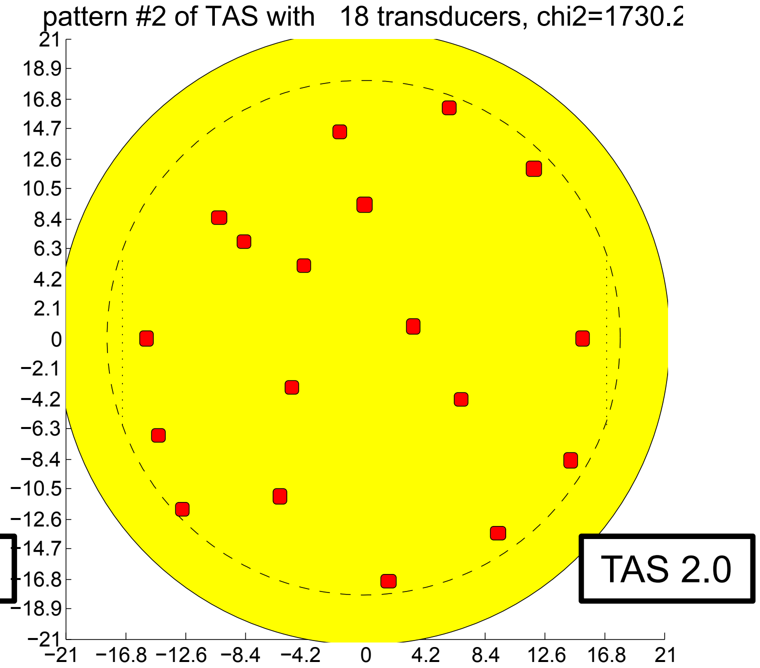



- Better imaging: increased opening angle required additional to increased aperture radius

# USCT III – Vision: bigger and denser aperture



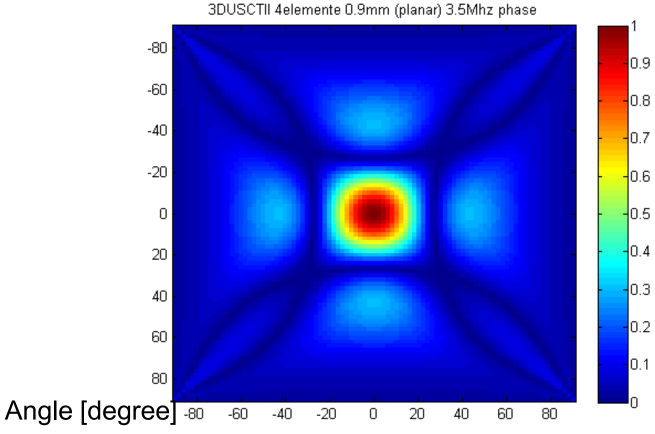

Diameter **35 cm**
128 TAS
with 2 movements: ~10 Mio. A-Scans

TAS diameter **4.15 cm**
~**18** transducers (pink)
both emitter and receiver

- Faster: More transducers, less slower aperture re-positioning required
- Better imaging: Bigger diameter leads to more homogenous imaging characteristics

# Design: Opening angle increase

- Reduced transducer surface for a ROI of 20x20x15cm³
  - Plus additional advantages




Transducer rectangular (0.9mm x 0.9mm) 100% soundpressure

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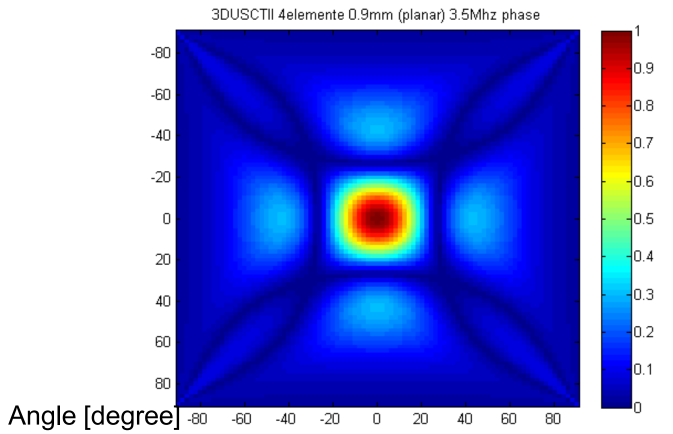


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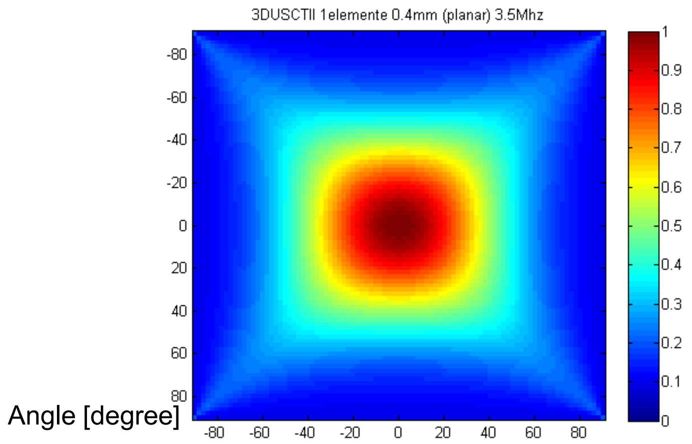


Transducer rectangular (0.4mm x 0.4mm) 25% soundpressure

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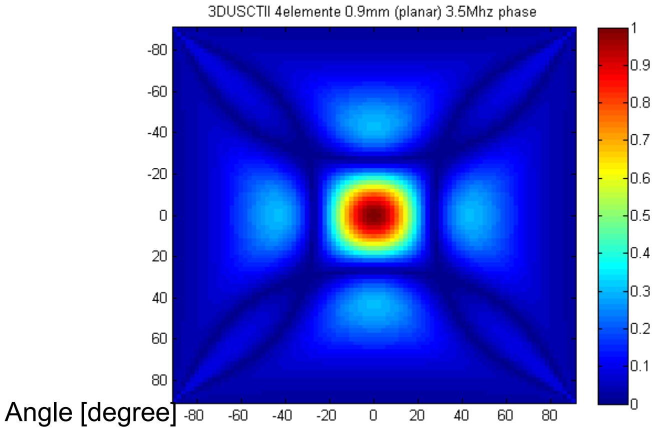
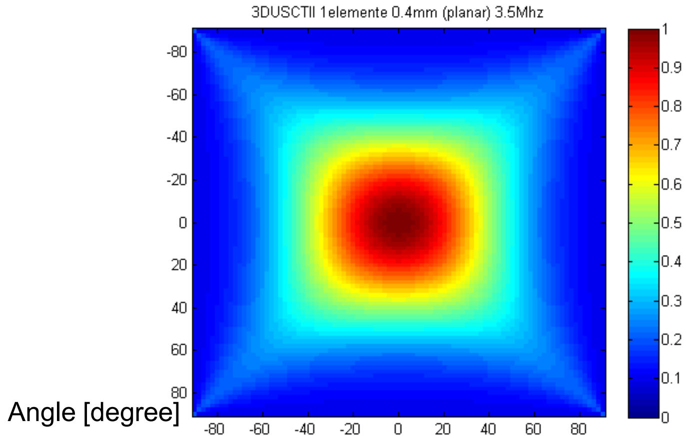
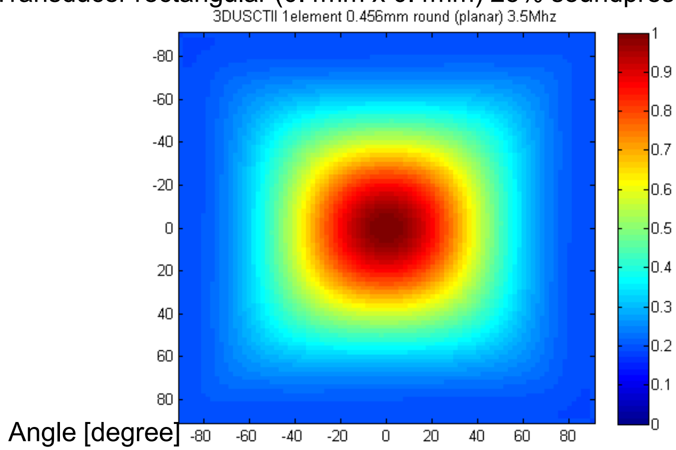



Transducer rectangular (0.9mm x 0.9mm) 100% soundpressure




Transducer rectangular (0.4mm x 0.4mm) 25% soundpressure




Transducer round (diameter 0.456mm) 25% sound pressure

# Design: Opening angle increase

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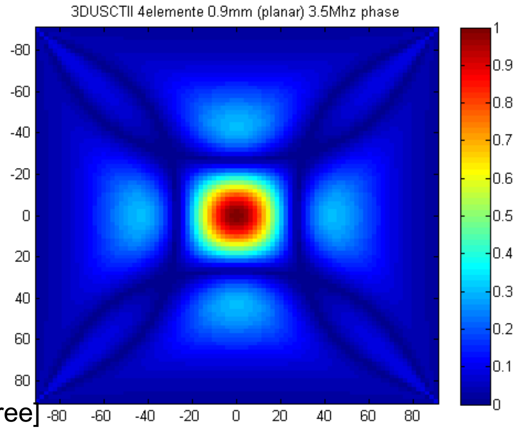
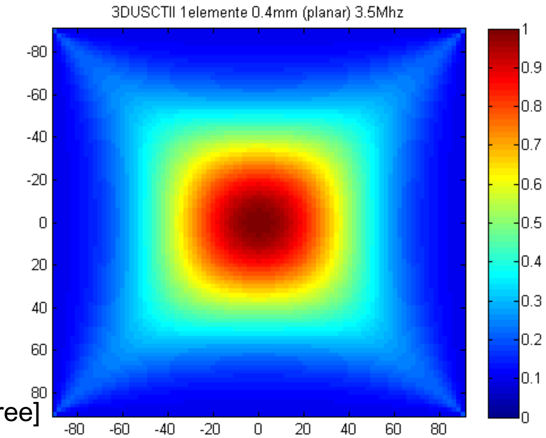
  - Plus additional advantages



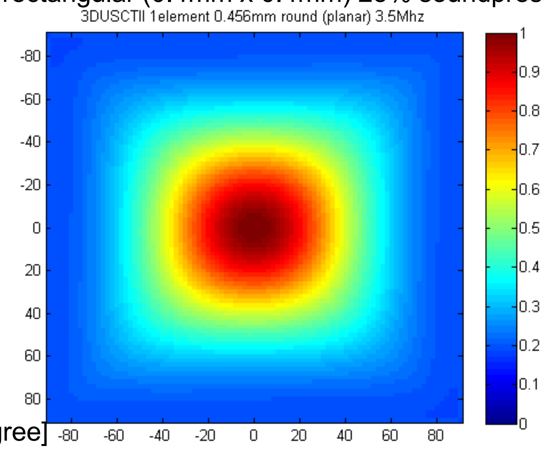

Angle [degree]

Transducer rectangular (0.9mm x 0.9mm) 100% soundpressure




Angle [degree]

Transducer rectangular (0.4mm x 0.4mm) 25% soundpressure



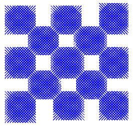

Angle [degree]

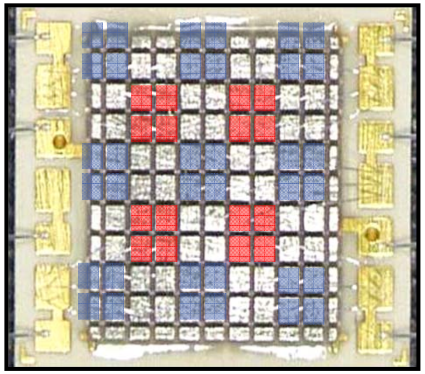
Transducer round (diameter 0.456mm) 25% sound pressure

| **Opening angle for $f_{max}$ (3.5MHz) receiver*emitter** | **20%drop** | **50%drop** | **Sound pressure** |
|---|---|---|---|
| **3DUSCTII Transducer (0.9mm, rect)** | **14°** | **22°** | **100%** |
| **Transducer 0.902mm round** | **16°** | **28°** | **100%** |
| **Transducer 0.4mm rect** | **30°** | **54°** | **25%** |
| **Transducer 0.4561mm round** | **33°** | **58°** | **25%** |

# Vision next generation USCT III transducers

TAS 1.0





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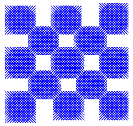
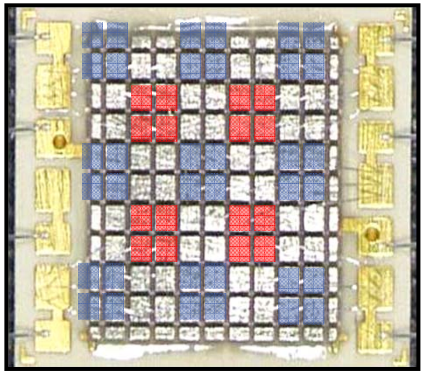
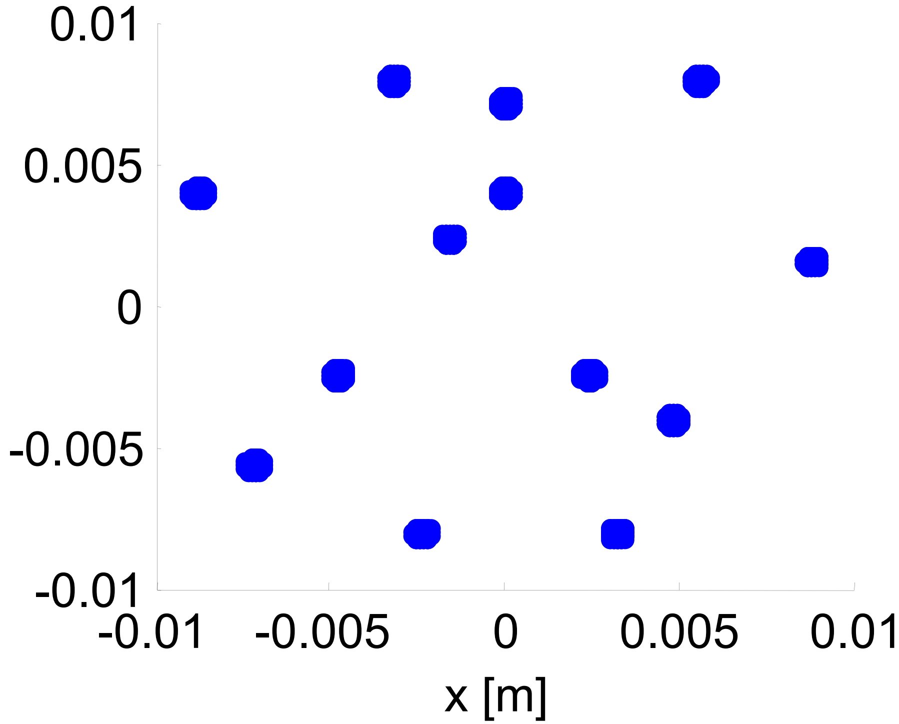




TAS 1.5 13 oktagonale Elemente



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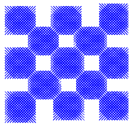
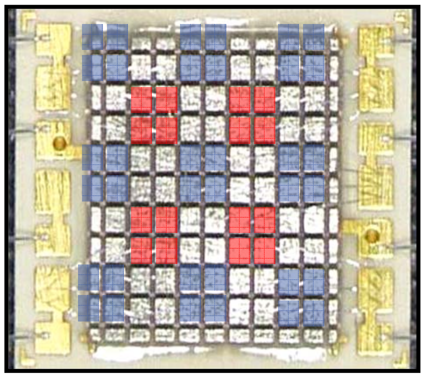
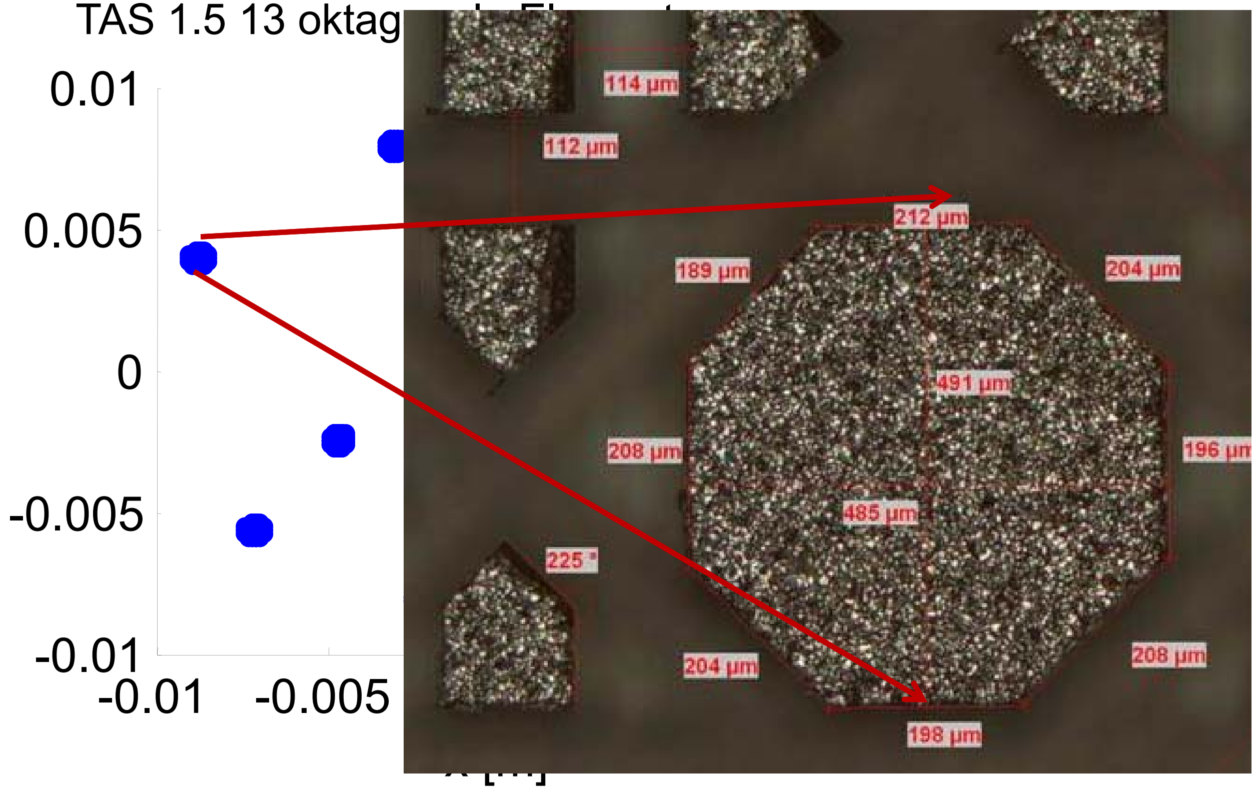




TAS 1.5 13 oktag



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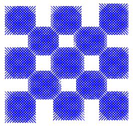

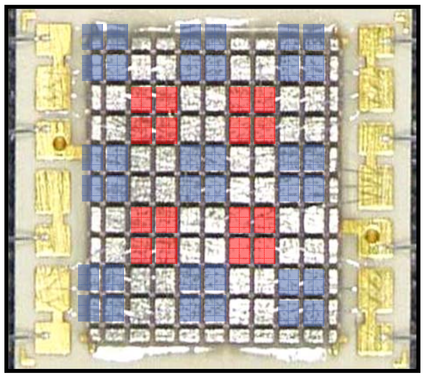

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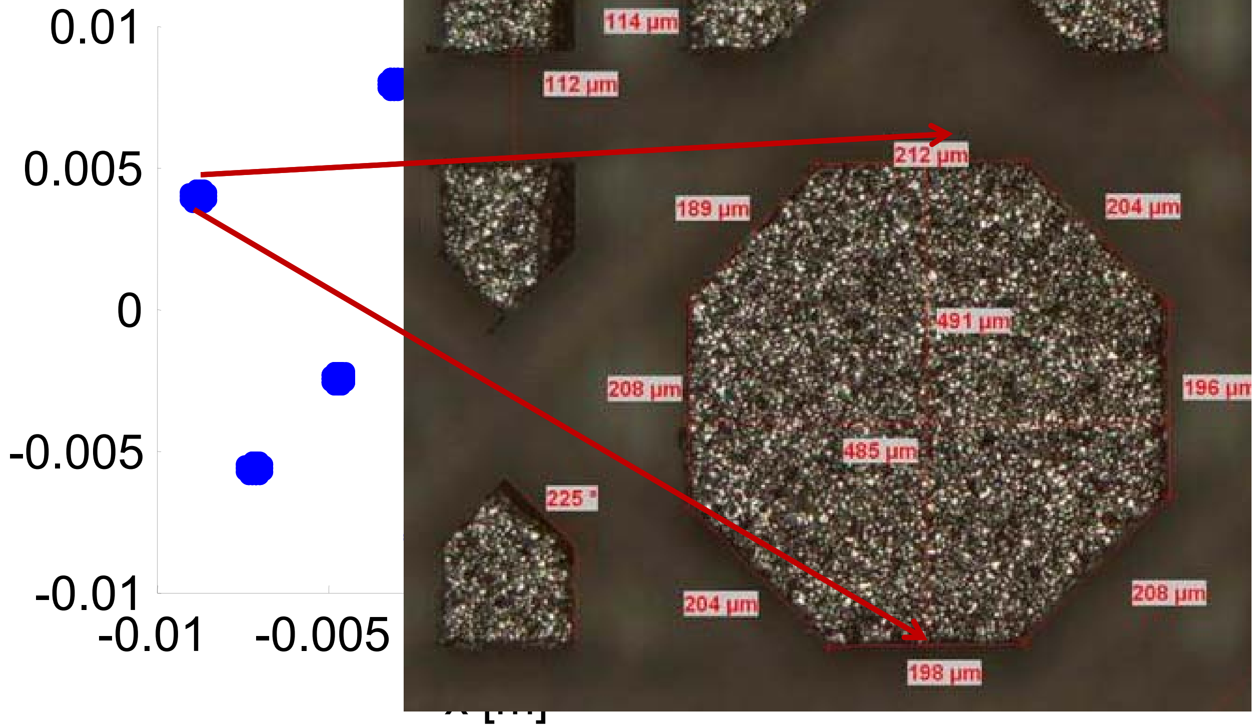


- Challenges

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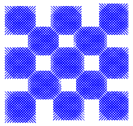

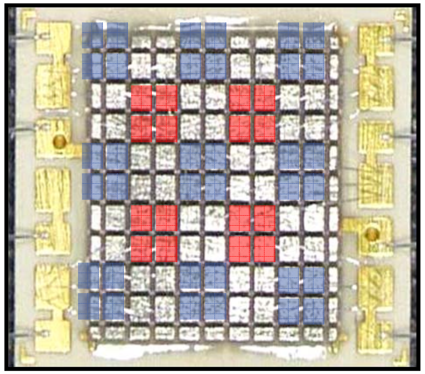

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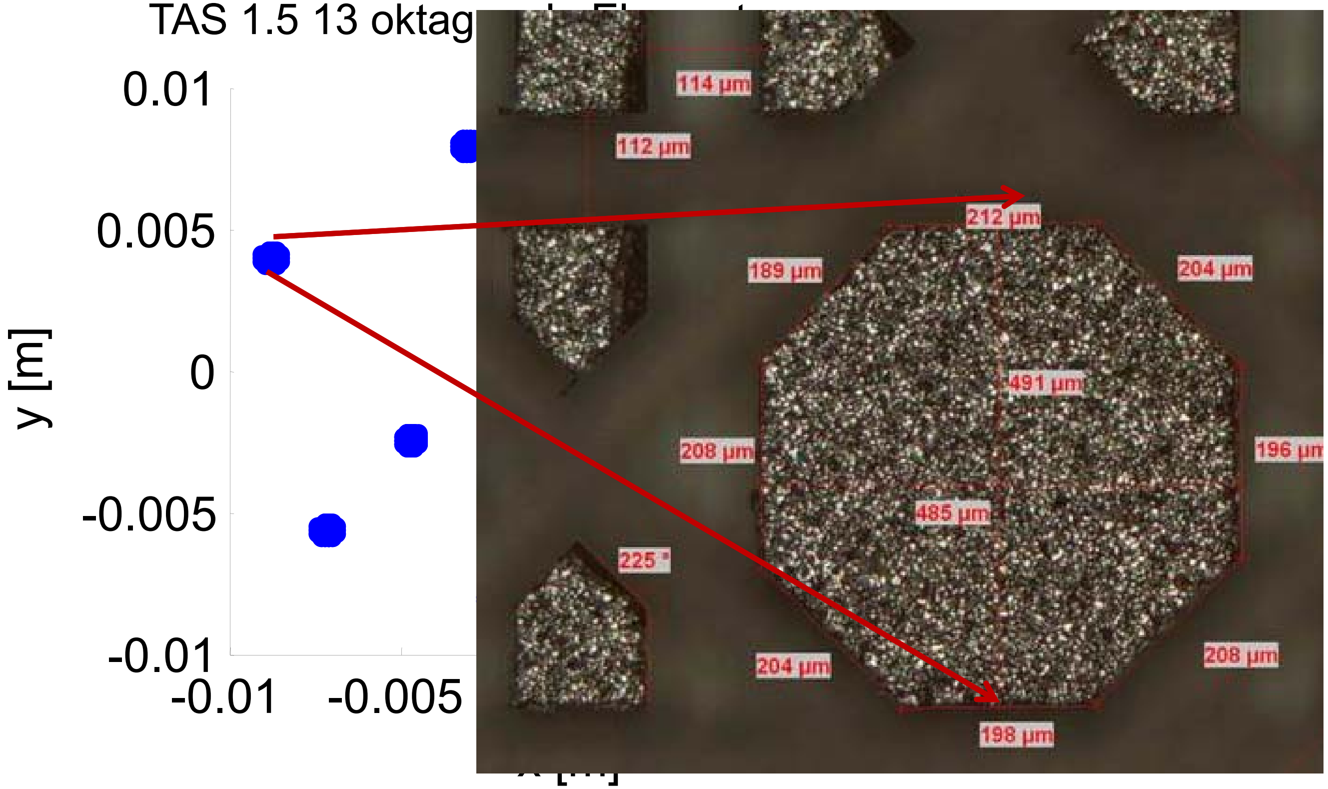


- Challenges
  - New process: Adaption of the saw and fill process,

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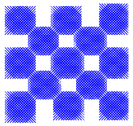

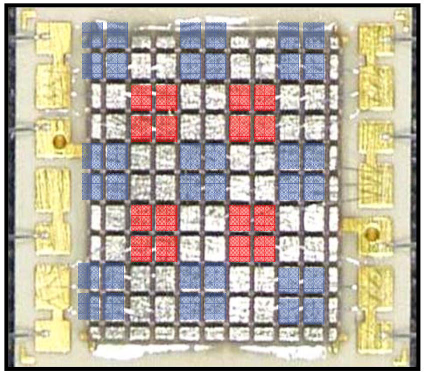

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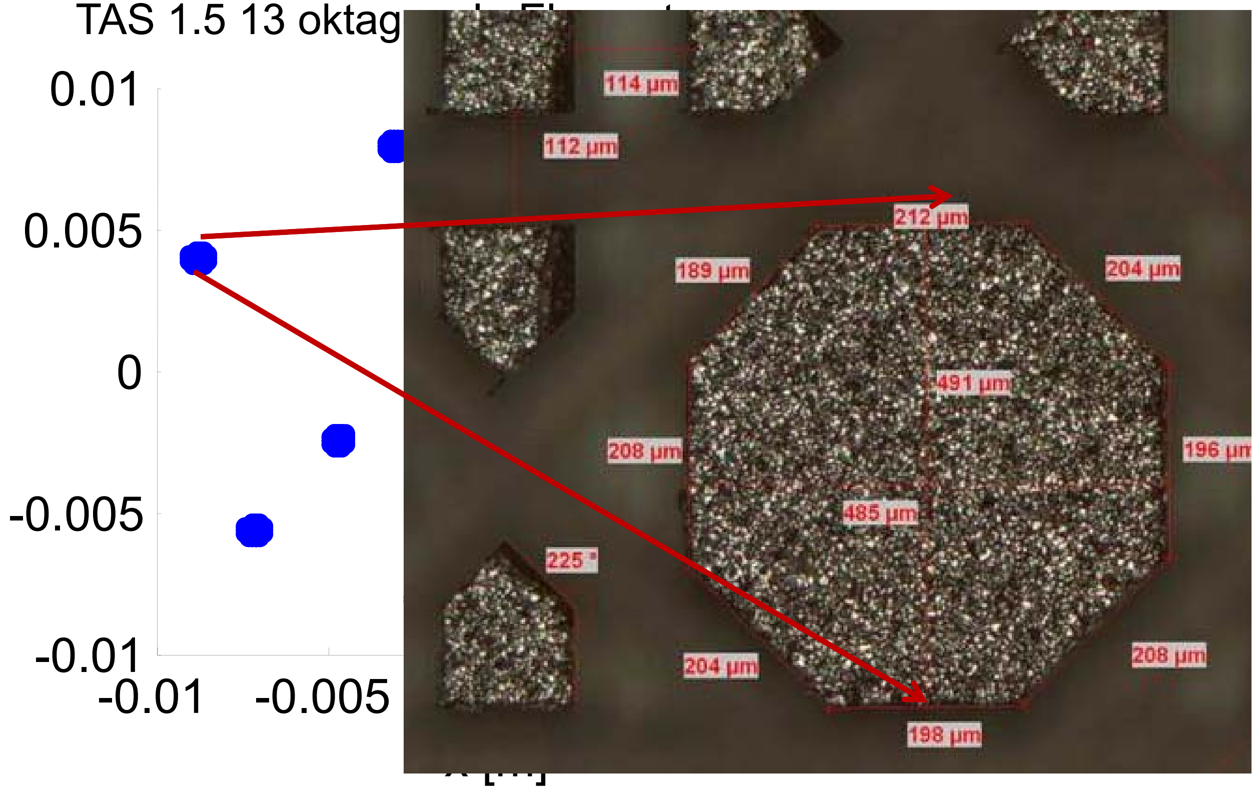


- Challenges
  - New process: Adaption of the saw and fill process,
  - 75% soundpressure loss compensation ?

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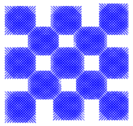

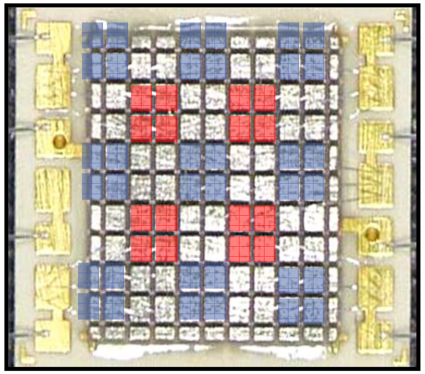

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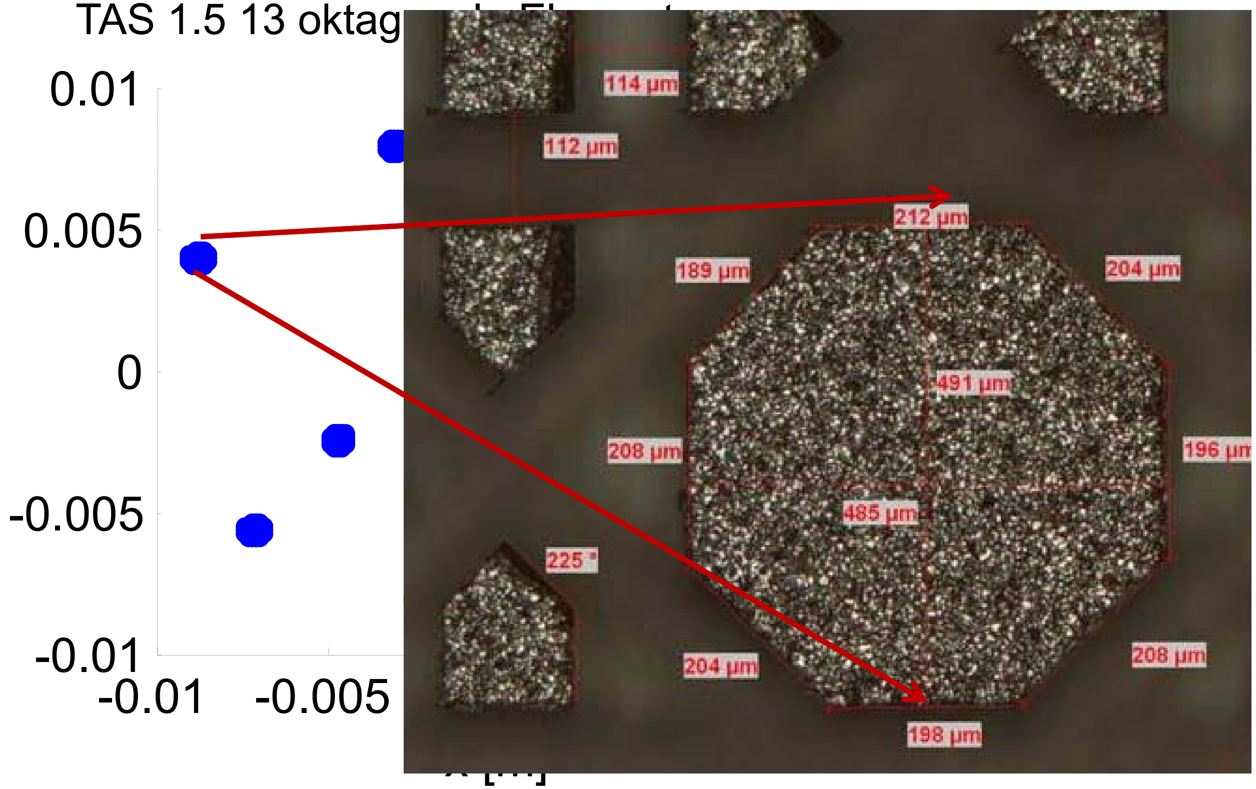
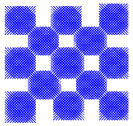
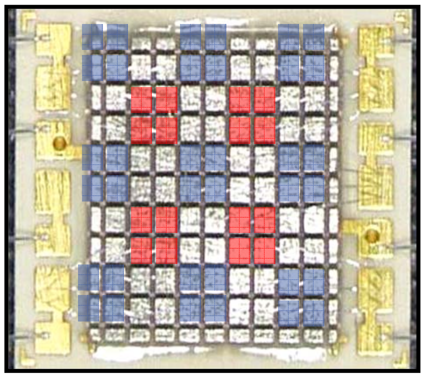



- Challenges
  - New process: Adaption of the saw and fill process,
  - 75% soundpressure loss compensation ?
  - Get rid of bonding ?

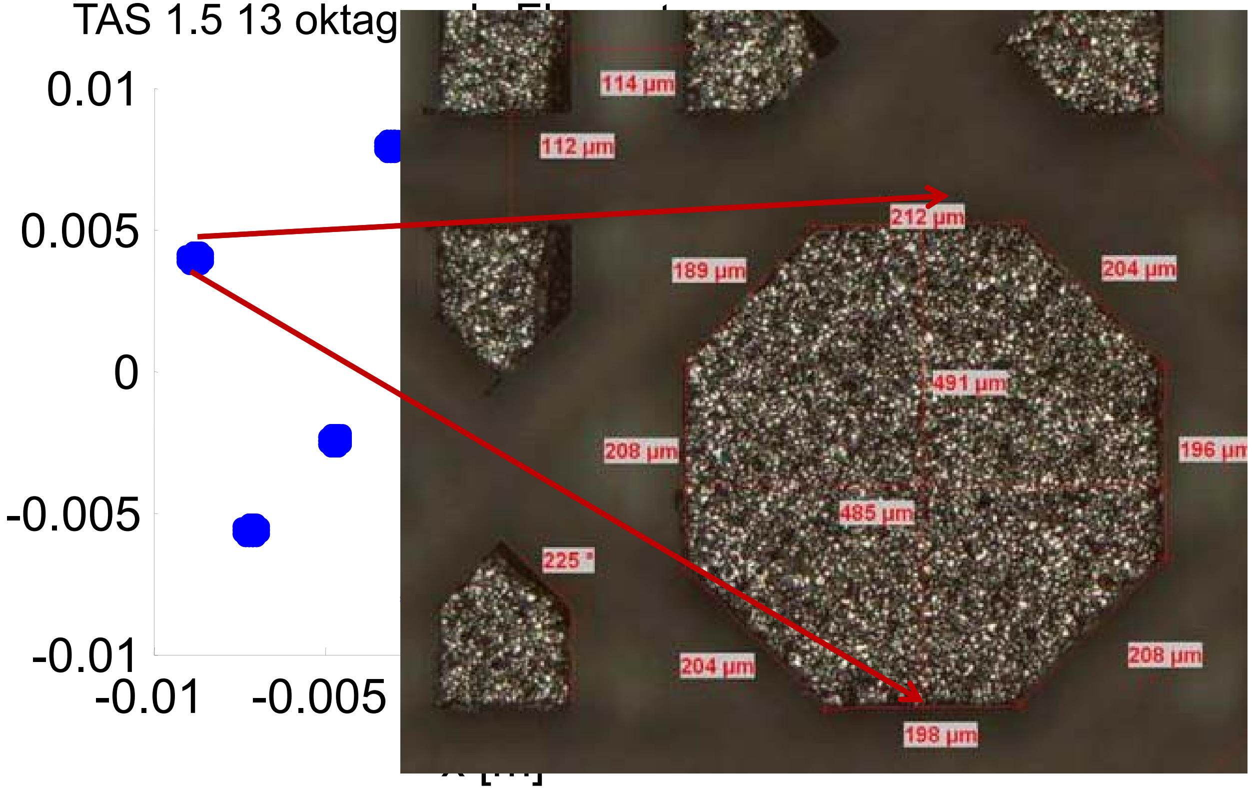
# Vision next generation USCT III transducers

TAS 1.0



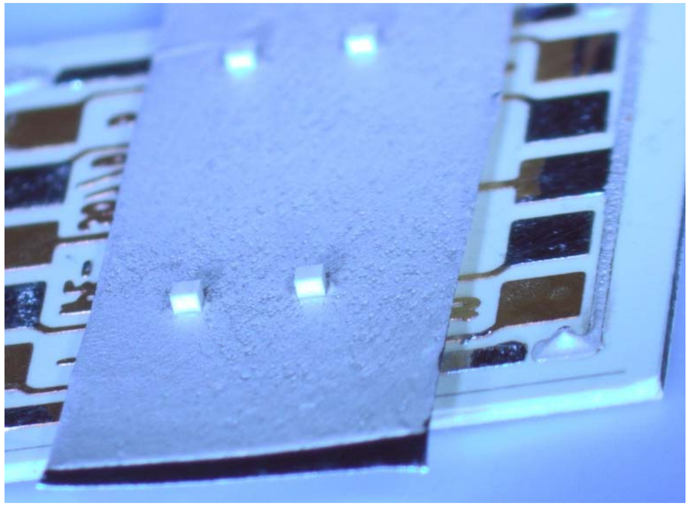


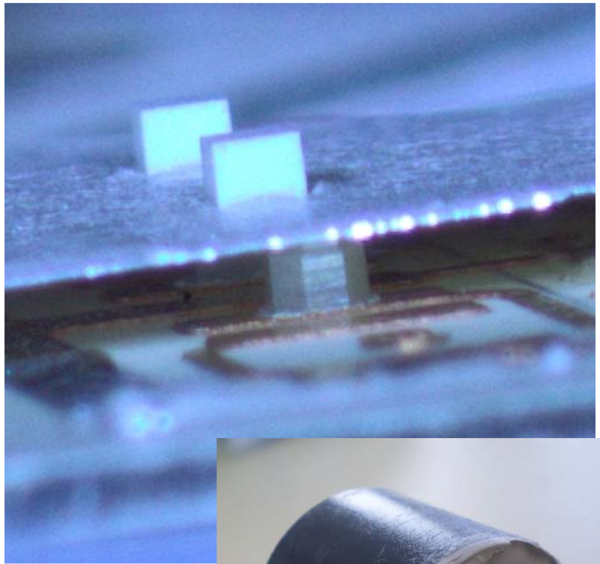
TAS 1.5 13 oktag

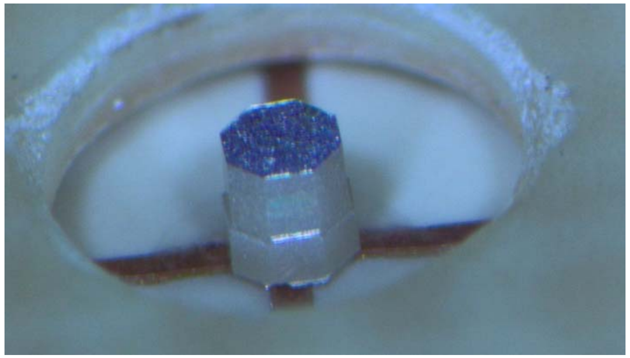



- Challenges
  - New process: Adaption of the saw and fill process,
  - 75% soundpressure loss compensation ?
  - Get rid of bonding ?
  - Substitute the acrylic glue against conductive glue / soldering material?

# Karlsruher Transducer Prototyp #27

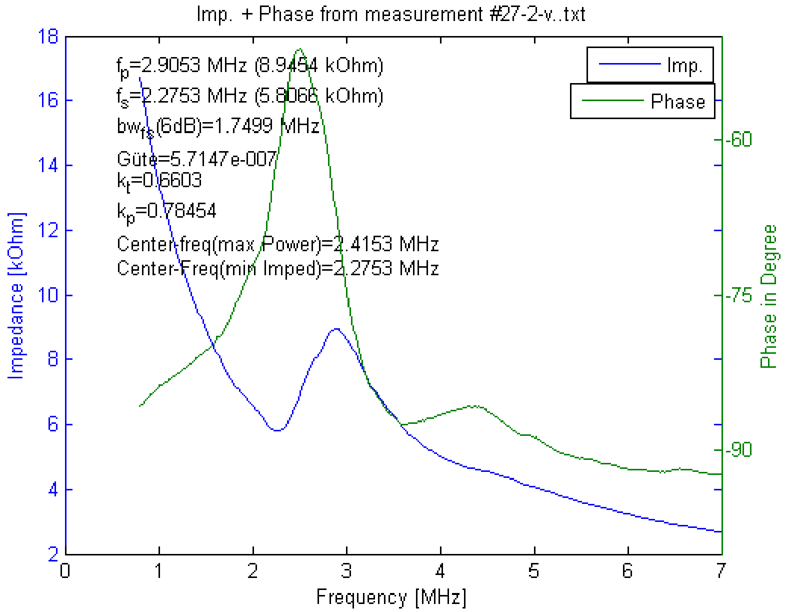


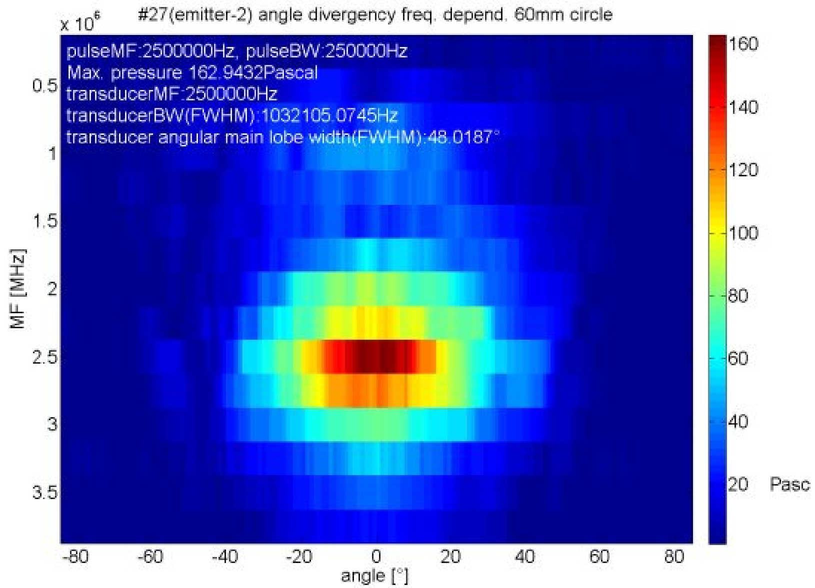


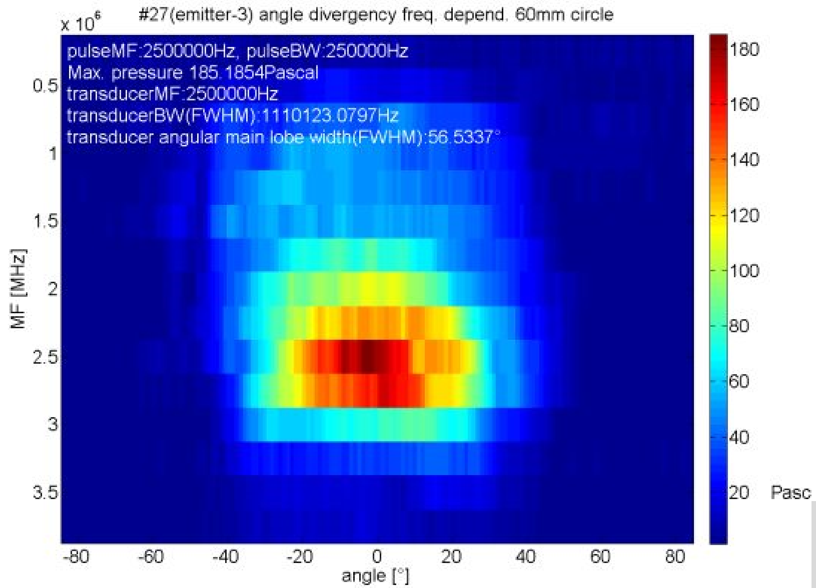


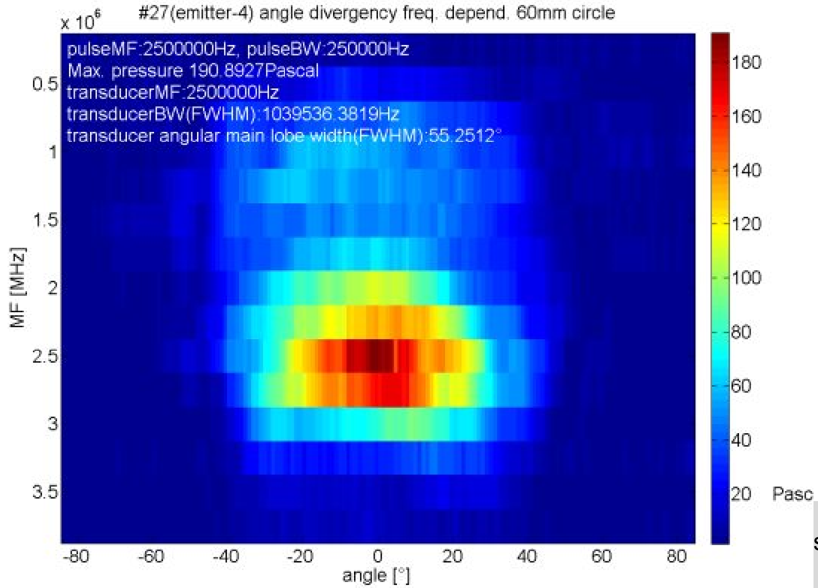
- Neuer Aufbau „vorwärts“: Piezos in Wasserrichtung, non-conductive Matchinglayer TMM4 strukturiert, Piezo Oktagon, Backing TMM4 + PU

# Karlsruher Transducer #27 II

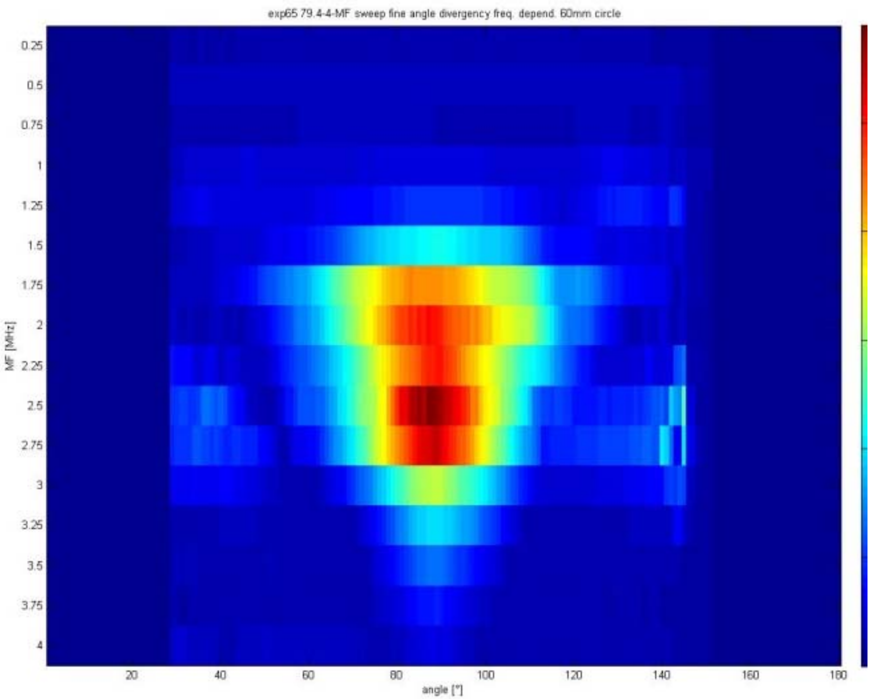


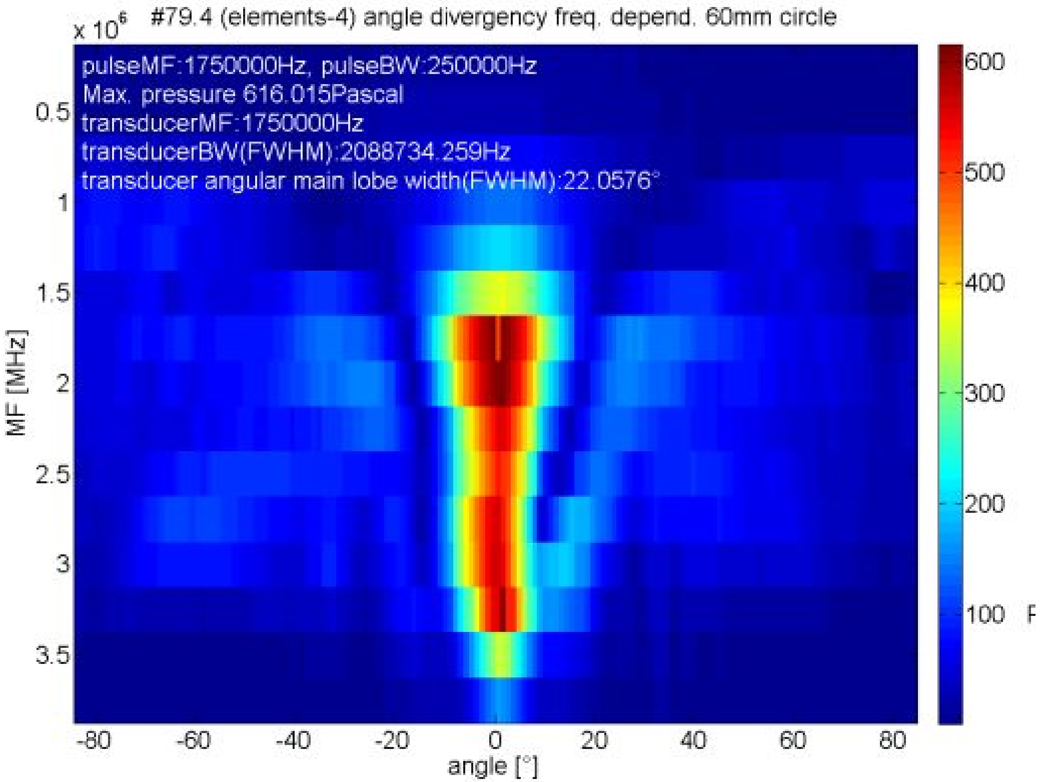



# Current Transducers: USCT II




- Filling hardening?
- More advanced simulation required to explain opening angle -> PZ Flex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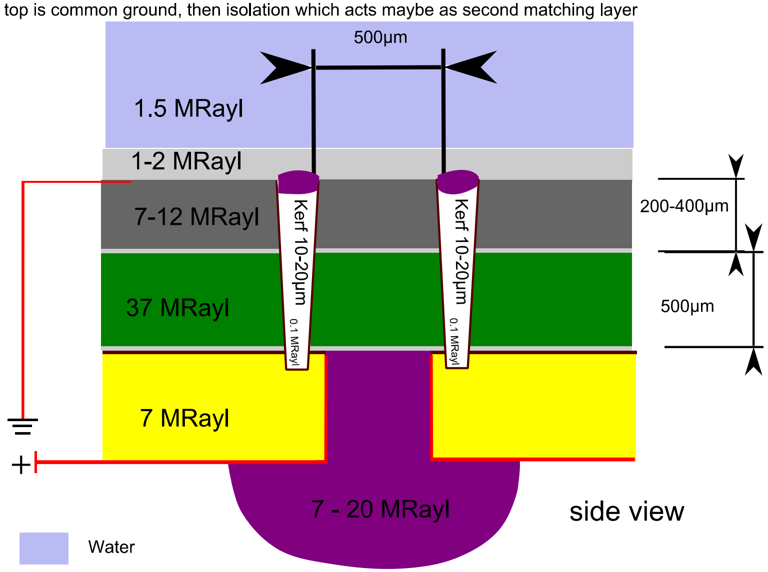
# USCT III Transducer Design KIT Delft (rev.1)

## Base design1 : laser+PCB with vias

PZT plate glued together with conductive matching layer;
- glued with low accurarcy demands (50µm) on PCB with Vias
- lateral positioning of transducer perfect due to laser-cutting in 1 step, catching markers on chassis
- vias in the PCB (drilled) gives electrical connection per transducer element
- filling is air for maximum lateral crosstalk separation / good emission pattern
- top is common ground, then isolation which acts maybe as second matching layer
-




- Water
- Isolation / Water protection: Parylen-Coating (40µm) or (filled) Silicon (etc SilGel)
- PCB (e.g. TMM4) with Vias
- conductive Matching layer (e.g. silver filled epoxy glue)
- PZT (e.g. Pic255)
- conductive glue (e.g. eccobond 56C)
- nonconductive glue
- circuit pathes (Copper, alu, gold etc)

## Base design 2: sawing+pcb with vias

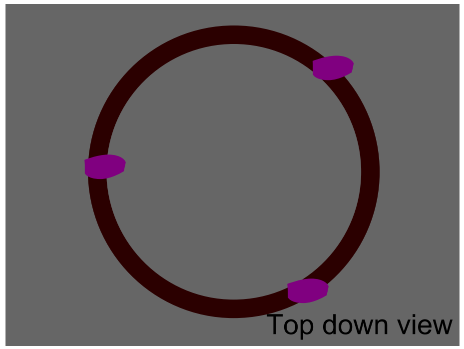
- instead of lasering sawing: kerf 20-100µm instead of 10µm,
- as kerf is to wide for dropplet, filling with PU foam with small bubbles or foil
- Sputtering common ground, parylination possible

Advantage: mechnical stability

## Top variante 1: droplets

dispensed droplet (conductive glue) for ground connection
- size of dropplets minimized to keep lateral crosstalk / influence on emission pattern minimal
- "Filling volume" kept filled with air
- silicon on top gives mechanical stability

- downside: no parylenation, significant thicker silicon layer with unknown influenceon emission pattern




## Top variant 2: sputtering

- "Filling volume" laser kerf filled with PU foam / silicon
- sputtering copper / cold
- parylenation on top

## Base design3: capton

- iinstead of PCB -> capton foil
- rest see other designs

Advantage: direct glueing on foil, no conductive mushroom req.
Disadvantage: worse mechnical stability



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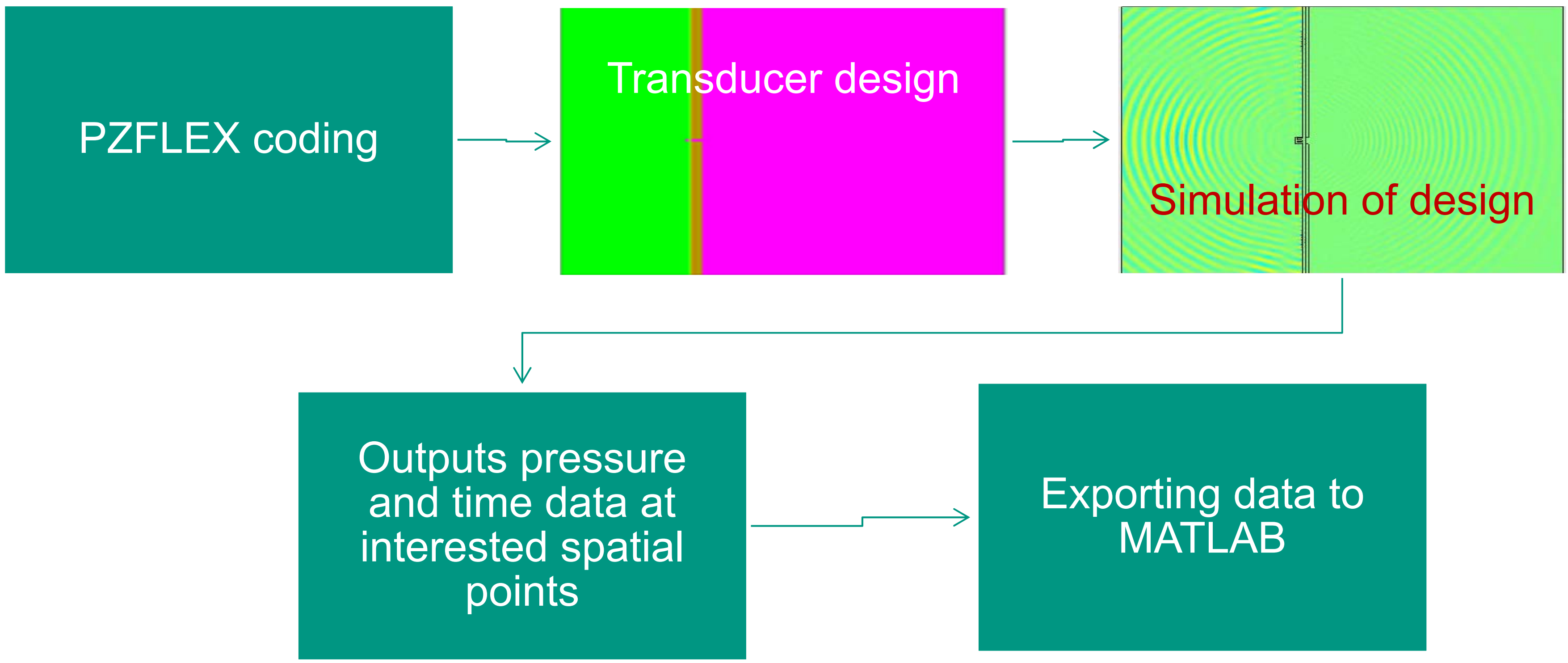
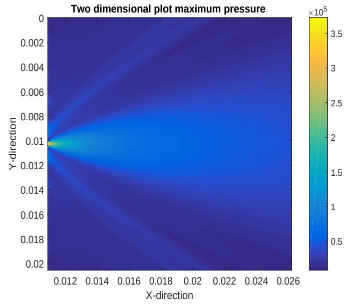
# PZFLEX: enhanced simulation



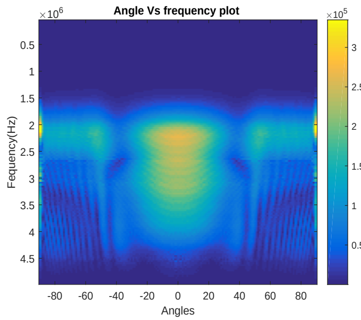
# Export data from PZFLEX to MATLAB

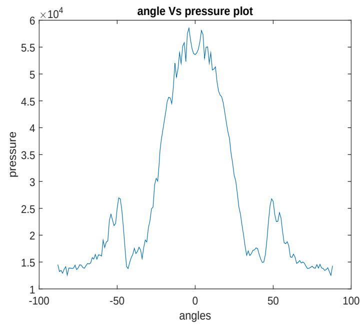
PZFLEX → MATLAB → Maximum pressure plot (2D)

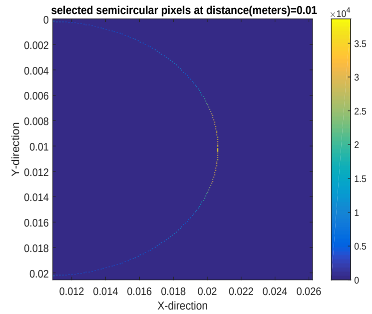
.flxhst file with the pressure and time data



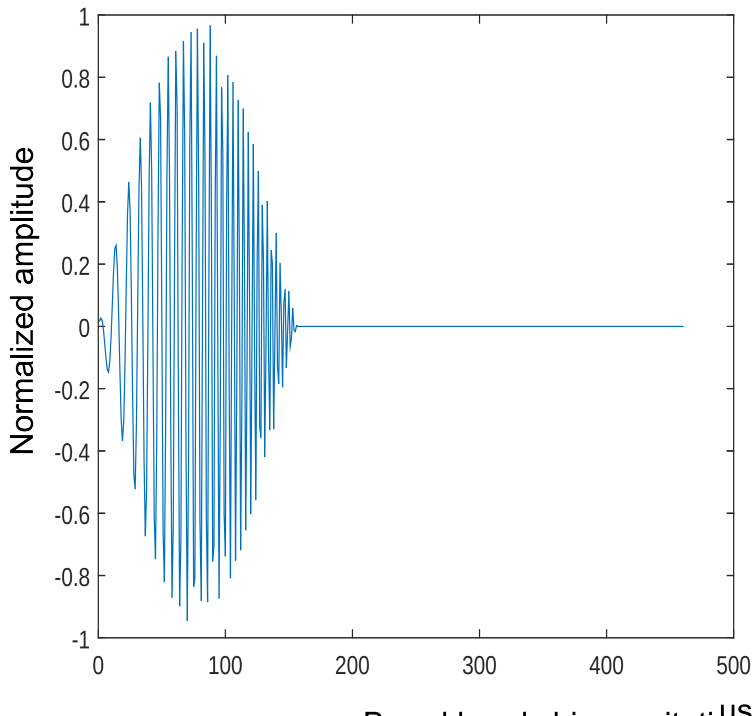

Select semicircular points → Pressure over angles at the selected semicircular pixels → Angle Vs Pressure plot at selected semicircular points



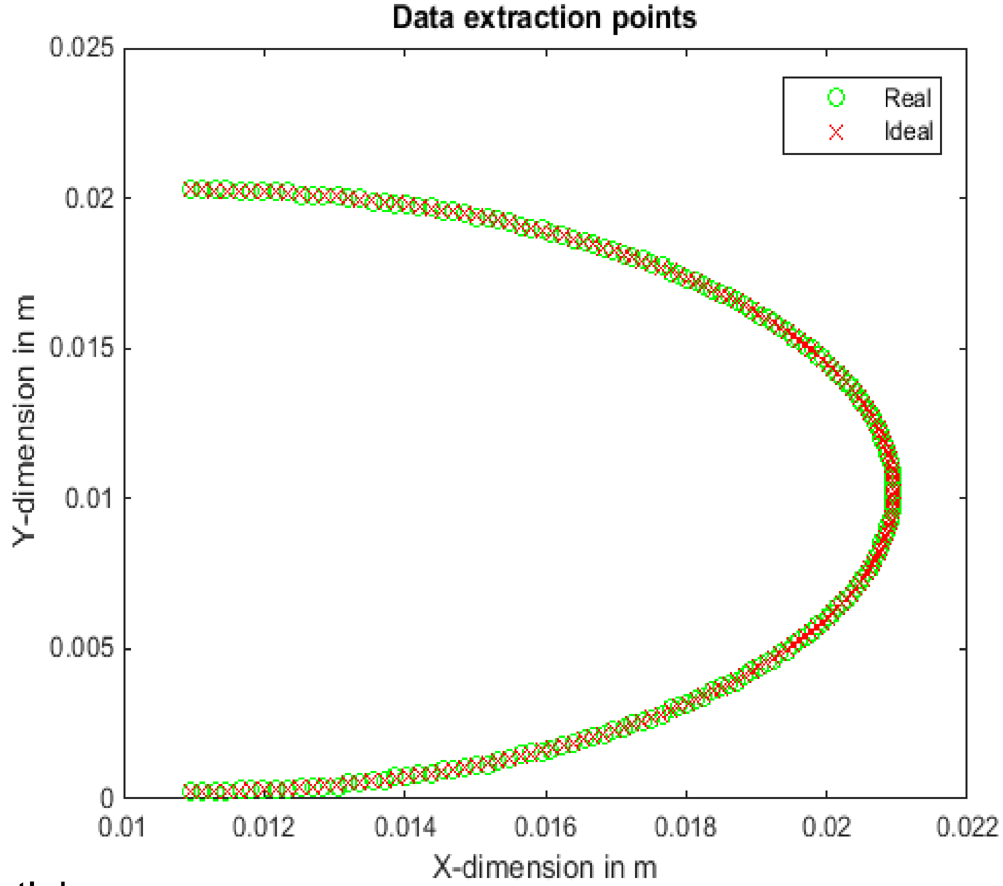



# Simulation setup: Analysis

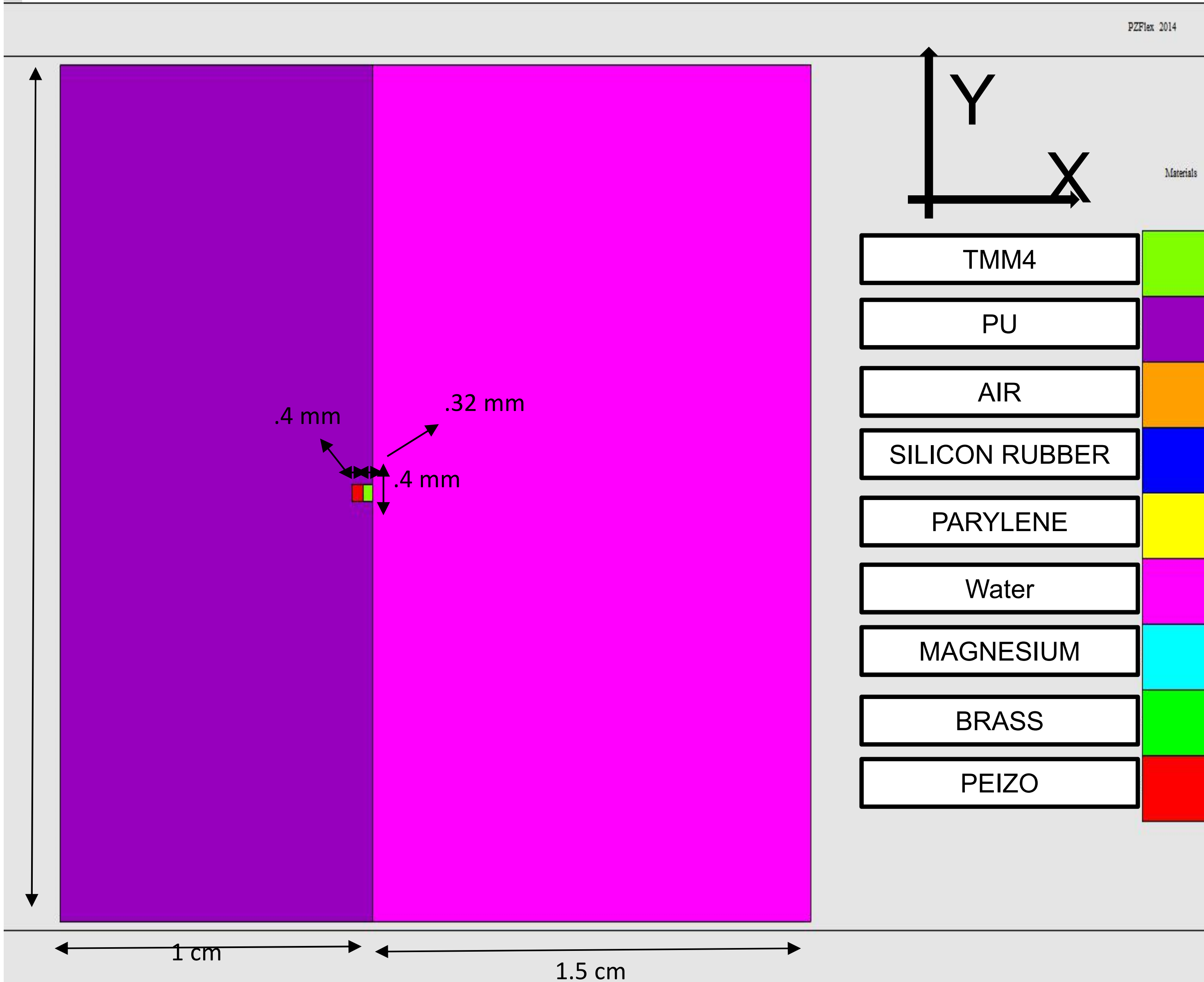



Broad band chirp excitation




- water sample points exported to Matlab
- Extraction of semicircle of 1cm for angular & frequency characterisation (downsampled inside nyquist)
- Compensated match filtering has been performed to achieve a flat spectrum response

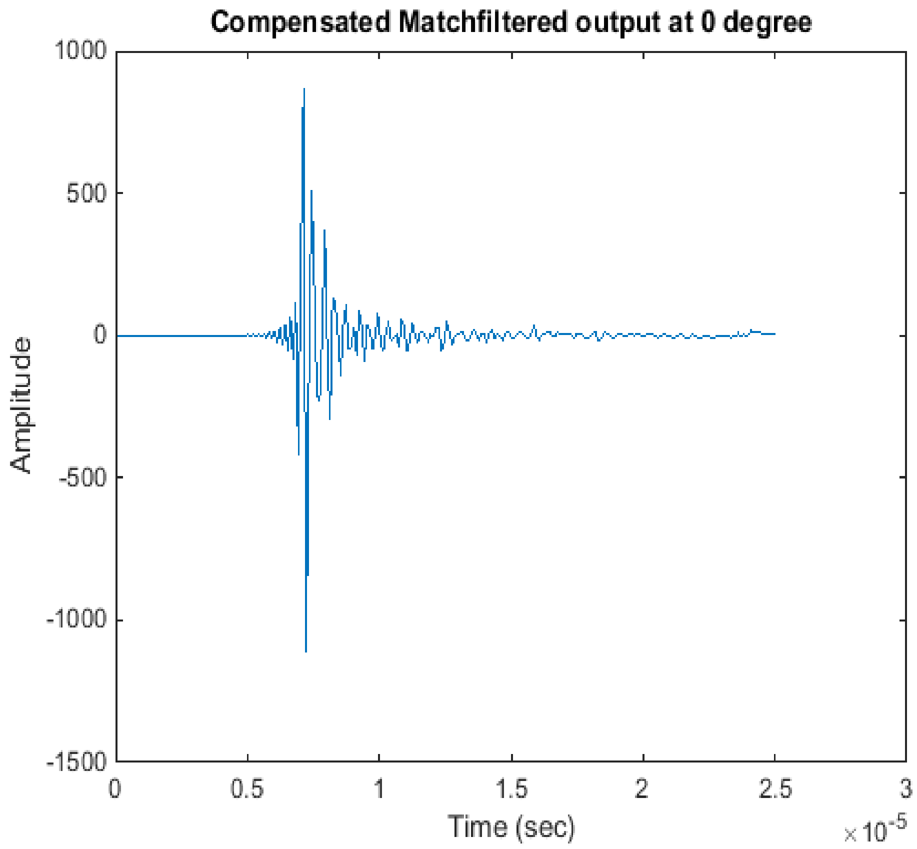
# USCT Base Model: rectangular 0.4mm

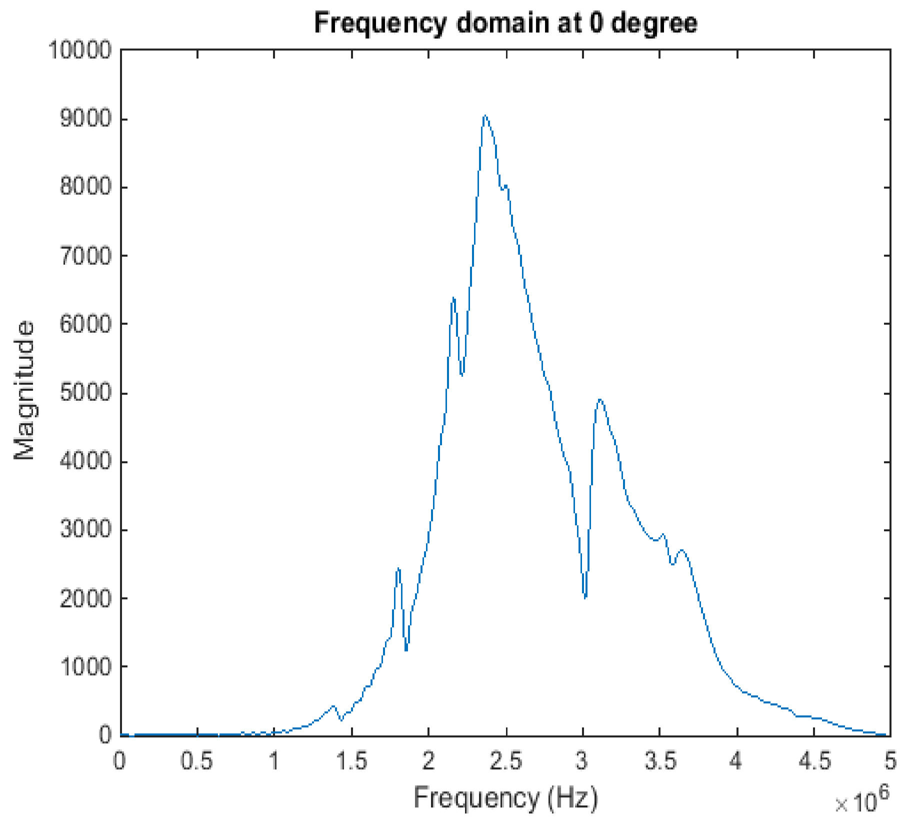



| Material | Spatial sampling |
|---|---|
| Brass | .574e-4 m |
| Magnesium | .25e-2 m |
| Water | .1315e-4 |
| Piezo | .50e-4 m |

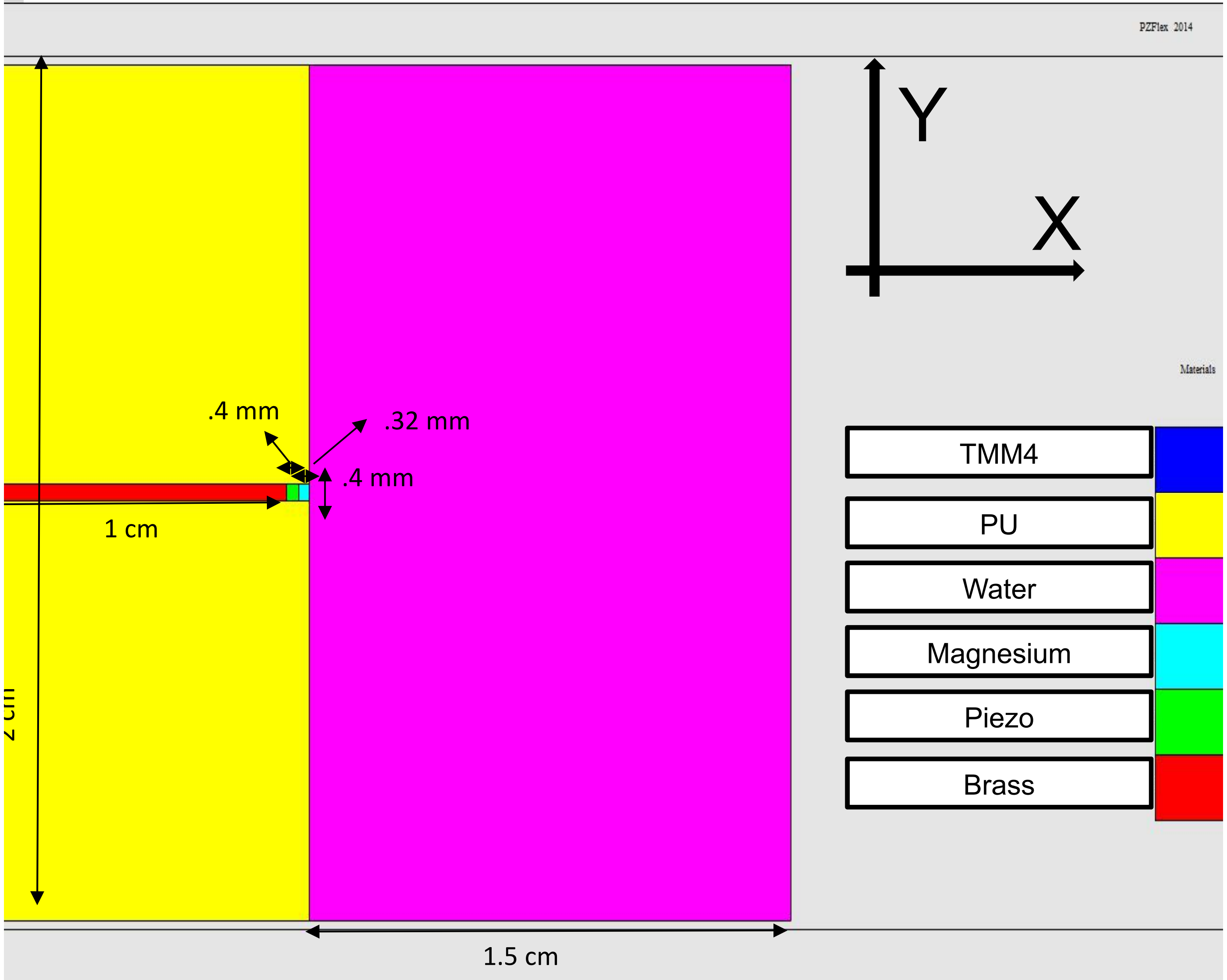
| Material | Velocity (m/sec) | Density (kg/m3) |
|---|---|---|
| PU | 2150 | 1585.4 |
| TMM4 | 3097.9 | 2065.86 |
| Brass | 4321 | 8292 |
| Magn. | 5770 | 1740 |
| PIC255 | 3846.9 | 7480 |

# USCT Base Model: Results



# USCT 2.5 II: aggressive bandwidth optimized

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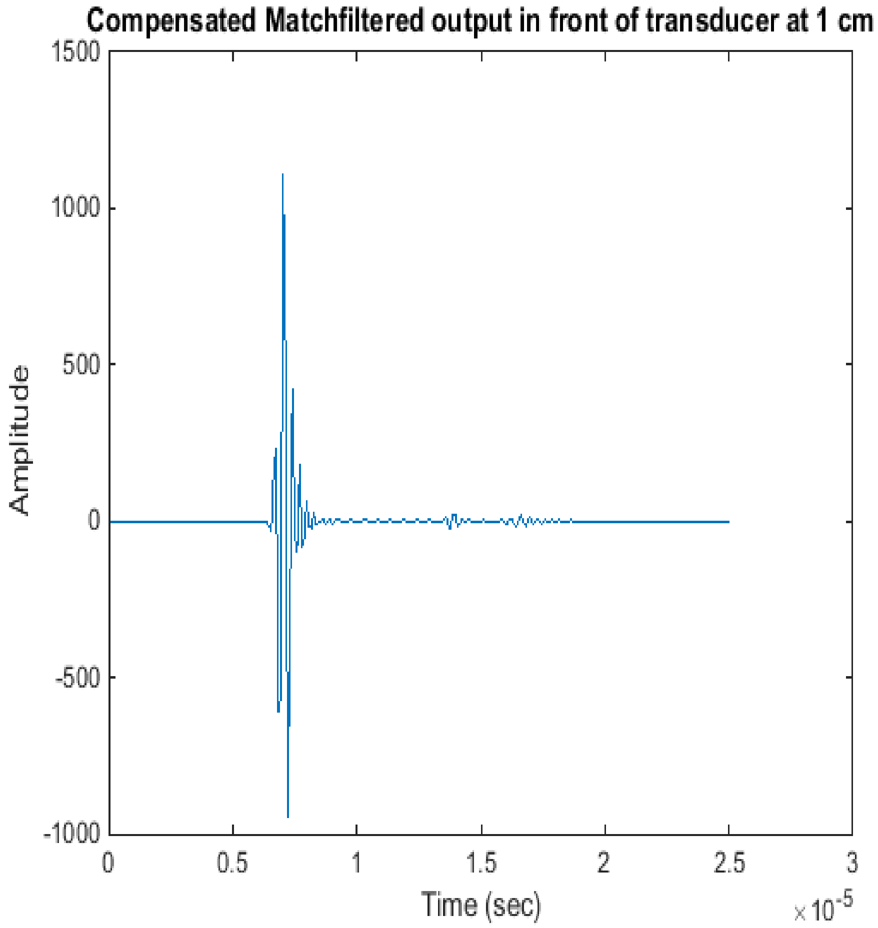
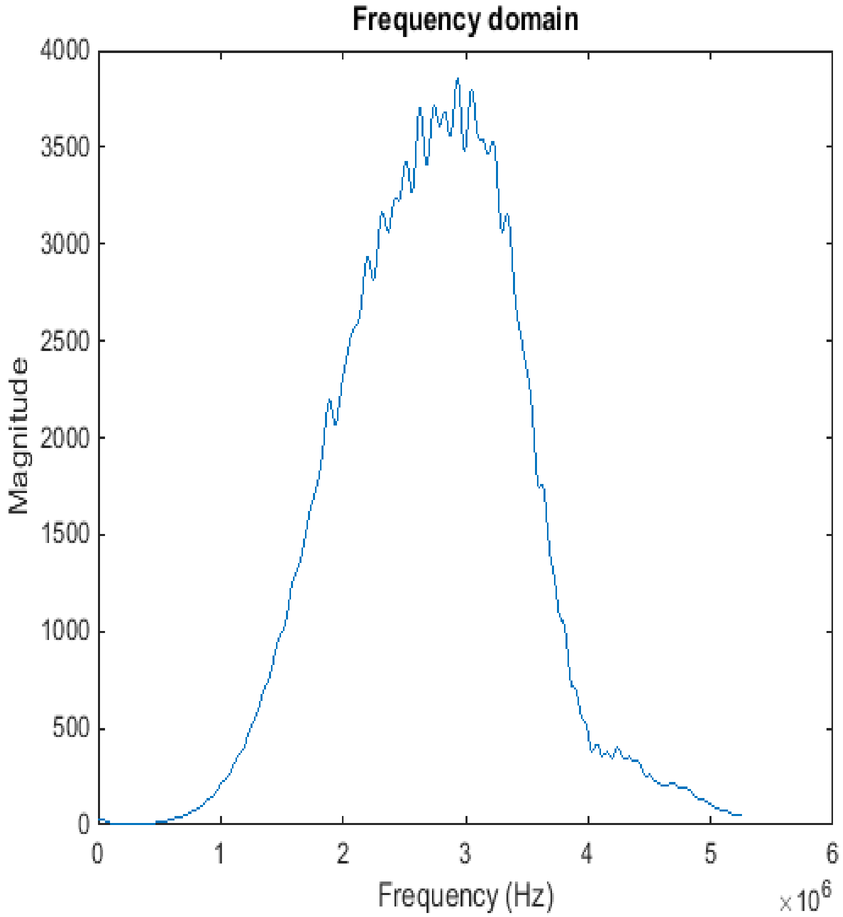
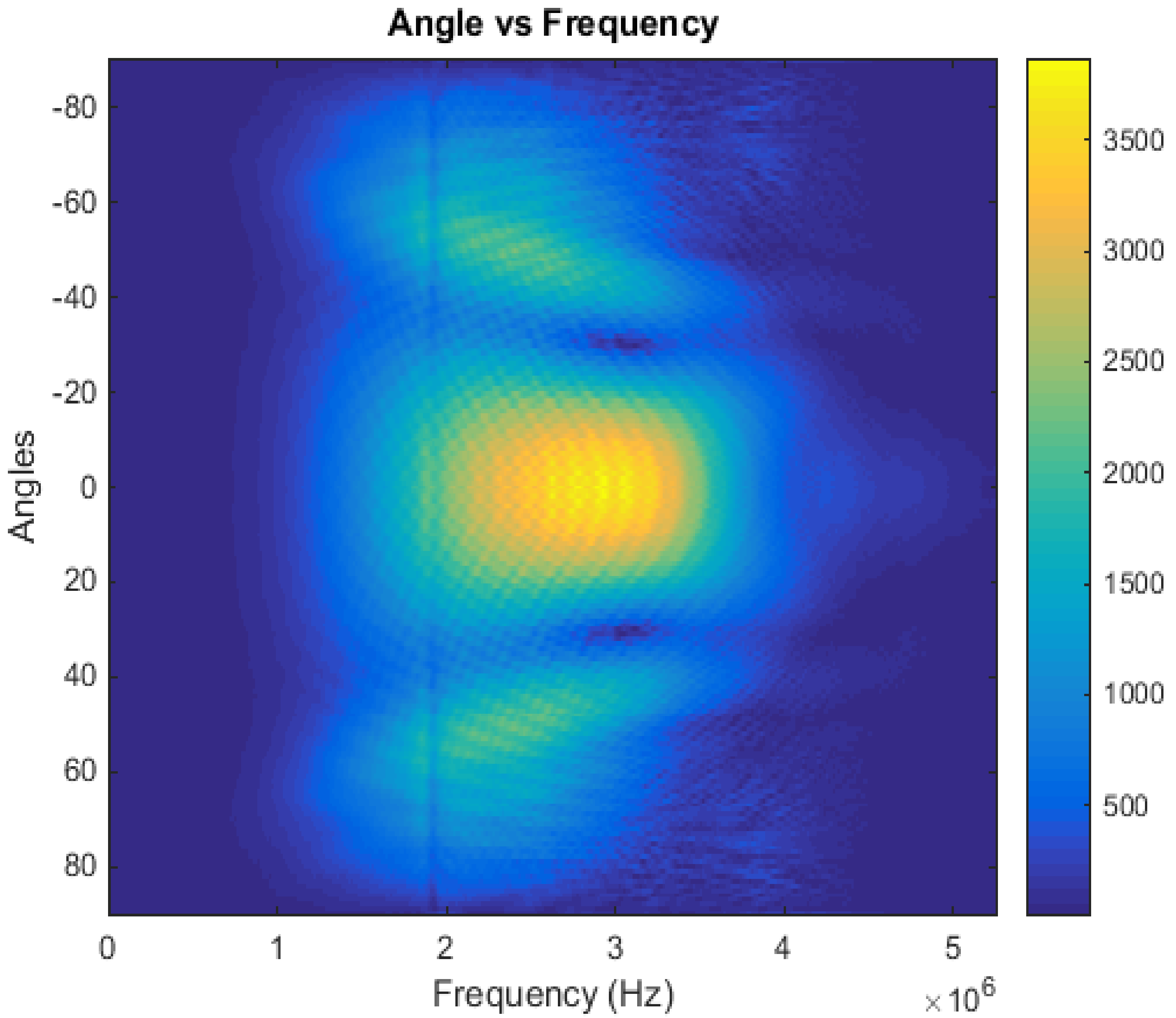
# USCT 2.5 II: aggressive bandwidth optimized Results

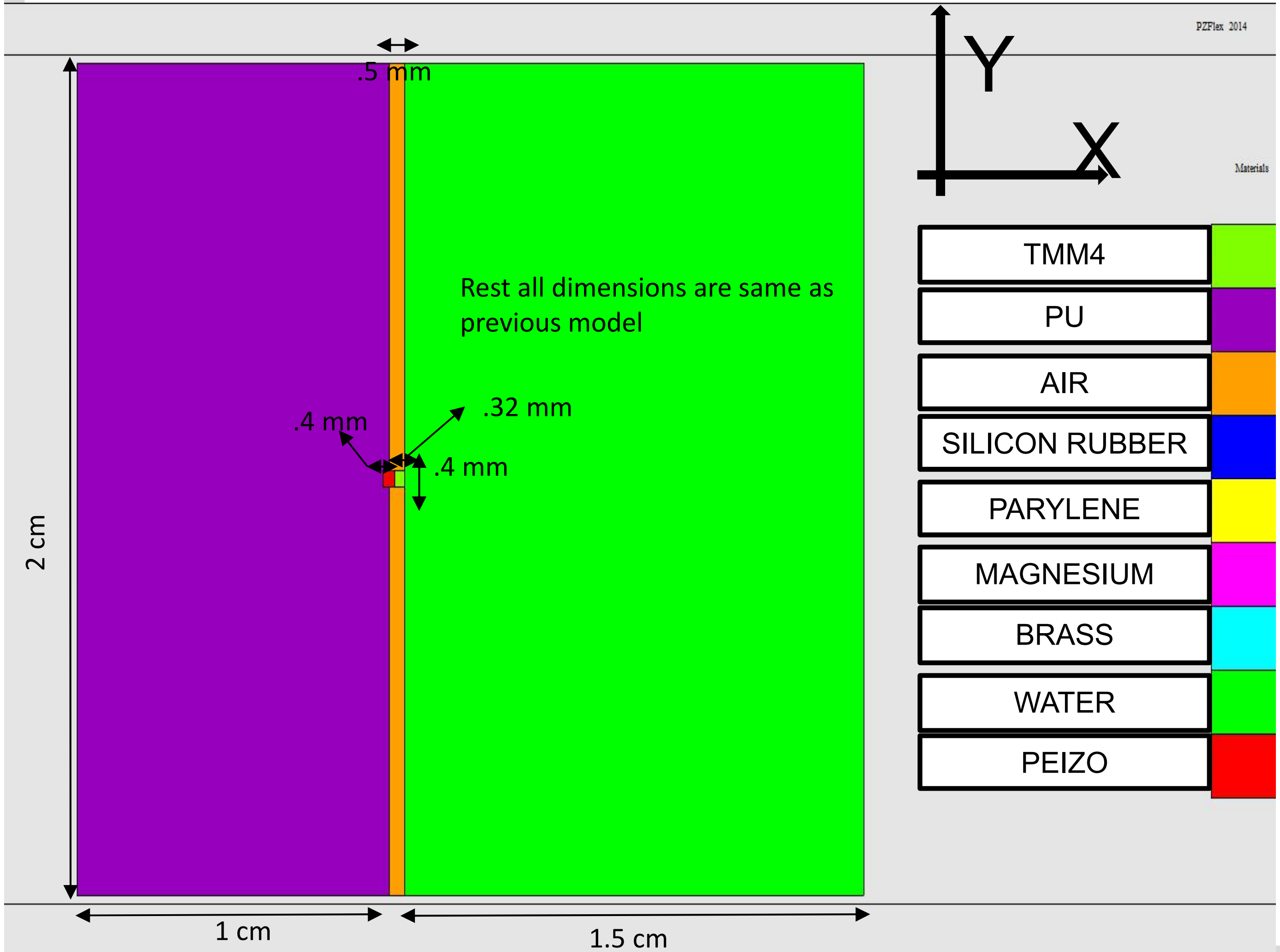


# USCT 2.5 II: aggressive bandwidth optimized opening angle



# USCT 2.5 model: full air filling




| Material | Velocity (m/sec) | Density (kg/m3) |
|---|---|---|
| PU | 2150 | 1585.4 |
| TMM 4 | 3097.9 | 2065.86 |
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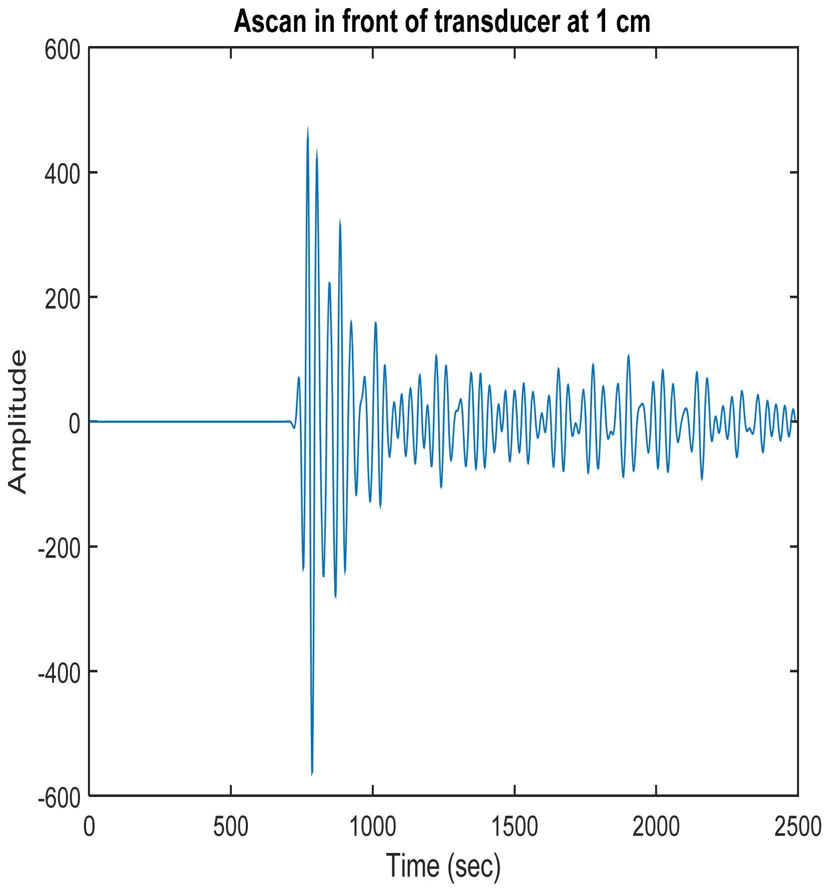
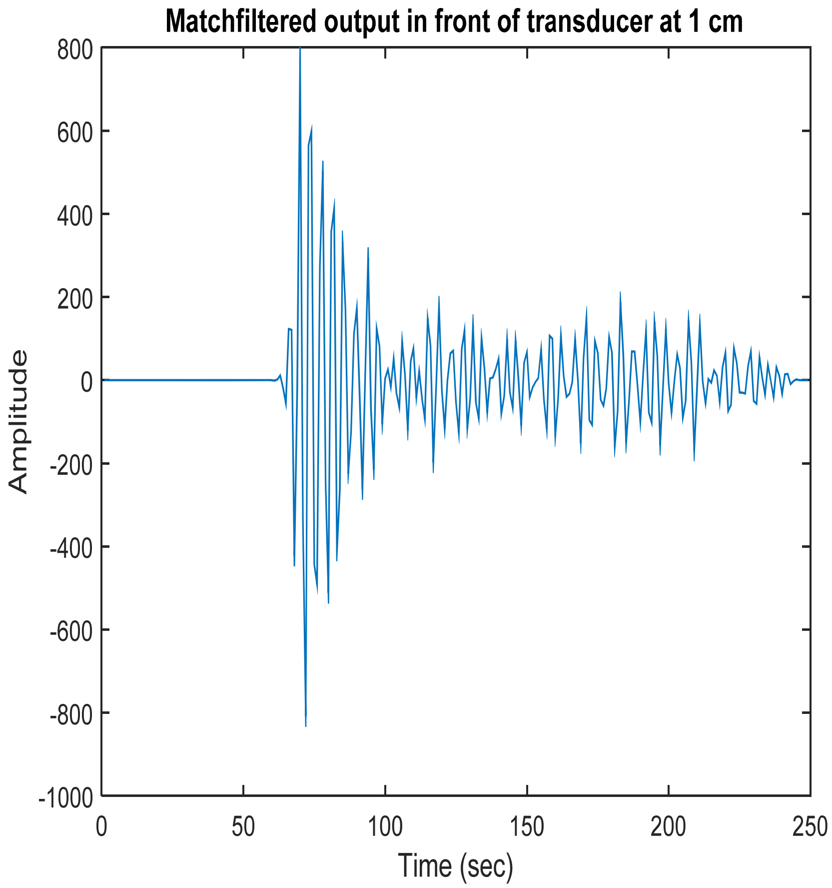
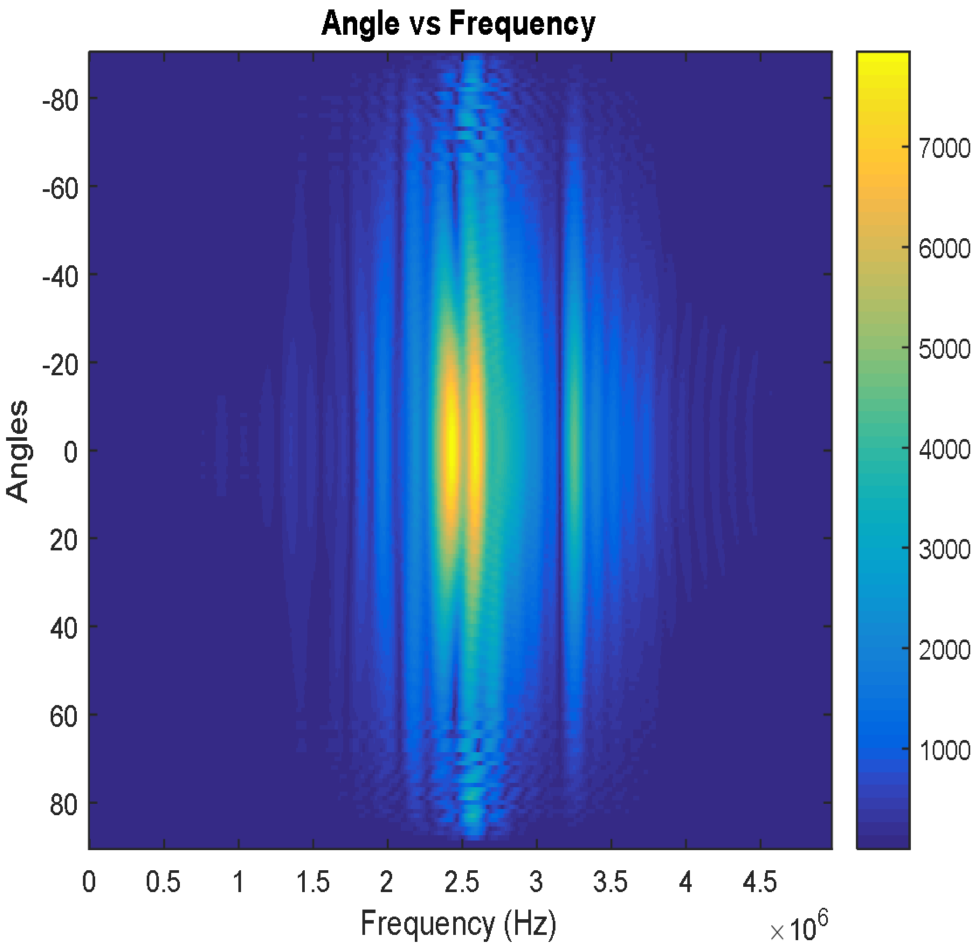
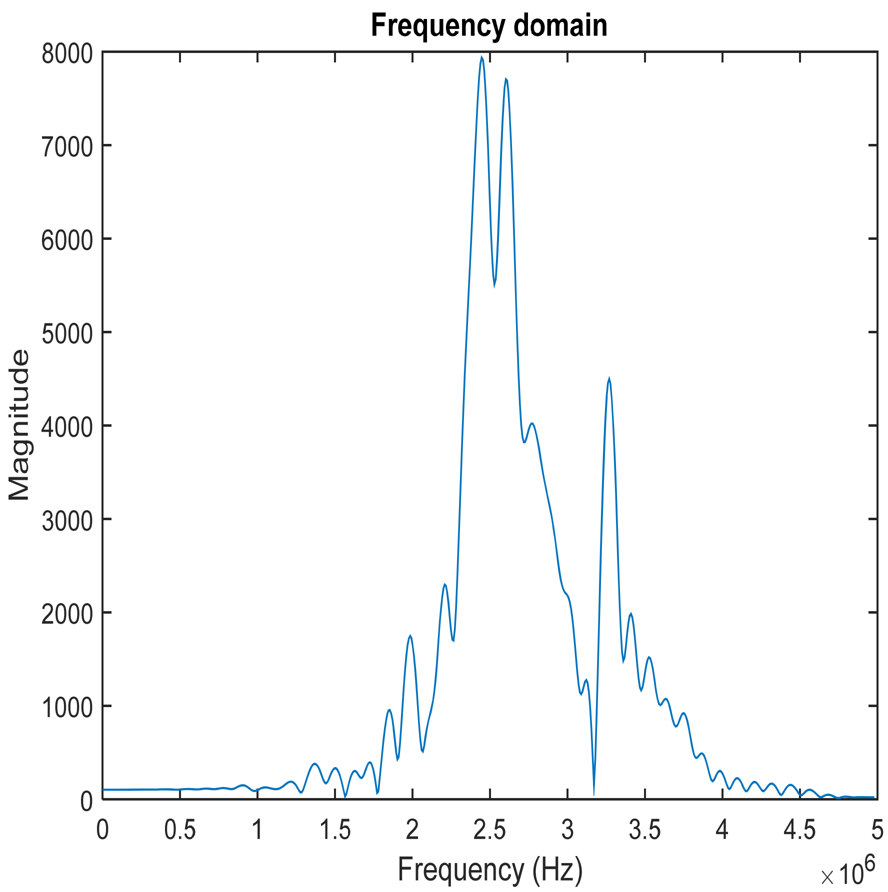
# USCT 2.5 model: full air filling Results



# USCT 2.5 model: full air fillling opening angle and bandwidth



# Intermediate status

- Insufficiant opening angle
- Unsatisfying bandwidth

- **Ideas:**
  - Improved **matching in backing** for improved bandwidth and reduced reflection ?
  - Instead of insulation of filling, a **matching filling** to get the lateral waves out (damping) to reduce ringing ?
  - Additional **front insulation layer** to suppress surface waves and leaking out lateral waves which ?
  - **Sub-structuring** for supressing lateral waves?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# Idea: Composite Materials

- Impedance of water: $Z_1 = 1.5$ MRayl
- Impedance of Piezo: $Z_2 = 35$ MRayl
- Optimal matching layer: $\sqrt{Z_1 Z_2} \sim 6.7$ MRayl
- Sound speed of homogeneous composite of n materials:
  - $c = \frac{1}{\frac{v_1}{c_1}+\frac{v_2}{c_2}+\cdots+\frac{v_n}{c_n}}$
- Density of composite of n materials:
  - $\rho = v_1\rho_1 + v_2\rho_2 + \cdots + v_n\rho_n$
- For n matching layers, for the j-th layer:
  - $Z_j = \sqrt[n+1]{{Z_2}^{n-j+1} \times {Z_1}^{j}}$


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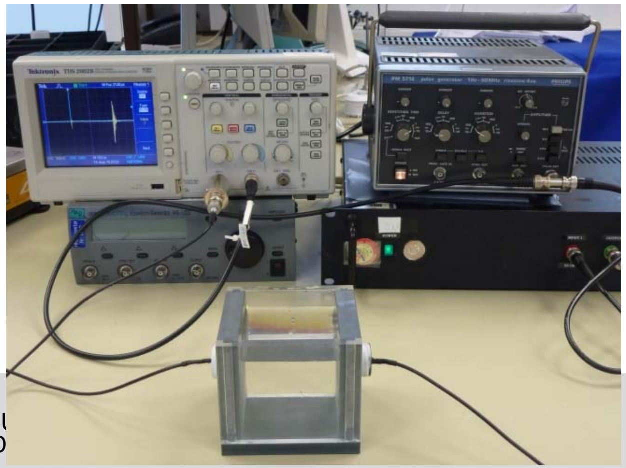
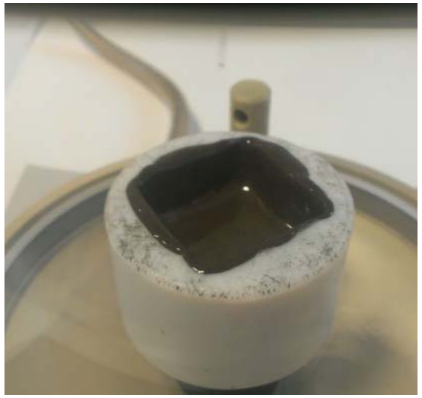
# Improvements: Composite Materials

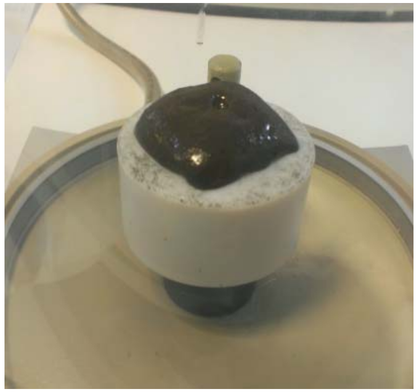
- Syntactic Foams / microbubbles: **insulation material**
- Test: Wacker SilGel 612 A&B + 3M iM30K Glass Bubbles
  - Non-conductive, bubble size < lambda/2
  - Possible damping layer for lateral oscillations
  - Tunable viscosity, absorption, tackiness, elasticity
  - Good adhesion properties: tested
  - Attenuation > PU achievable
  - Challenges: viscosity increase, mixability
  - Outlook: bubbles+PU?

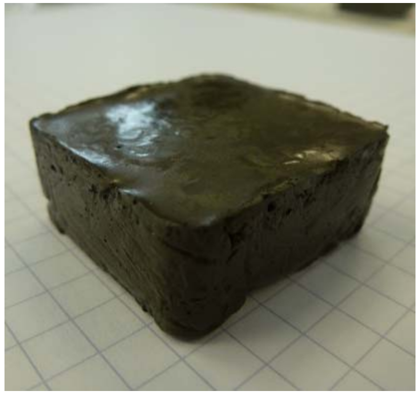



# Improvements: Composite Materials

- Filled Polymer composits as **matchinglayer**
  - Possible application as conductive/nonconductive matching layer to water and matching layer to backing
  - Polymer + one or two metal powders
  - Tunable impedance, conductivity, attenuation, density
  - Challenges: mixability, high viscosity
  - outlook
    - further improve mixability to achieve conductivity
    - find optimal matching to backing to reduce reflections





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# Composite Materials: Results

- Araldit D + TiN + Cu
  - Z = 5.8MRayl; $c_m$ = 2613 m/s; $c_{theo}$ = 2872 m/s
- Araldit CY221 + Graphit + Cu
  - Z = 5.8MRayl; $c_m$ = 2220 m/s; $c_{theo}$ = 2483 m/s
- Araldit CY221+ TiN + Alu
  - Z = 5.7MRayl; $c_m$ = 2587 m/s; $c_{theo}$ = 2893 m/s
- PU + Tungsten (not degassed)
  - Z = 4.6MRayl; $c_m$ = 1609 m/s; $c_{theo}$ = 2254 m/s
- Conclusions
  - Challenging step: degassing
  - After degassing reproducable deviation from expected values
  - Correlates to ~ 5% of residual gas left
  - Residual gas explains deviations in sound speed


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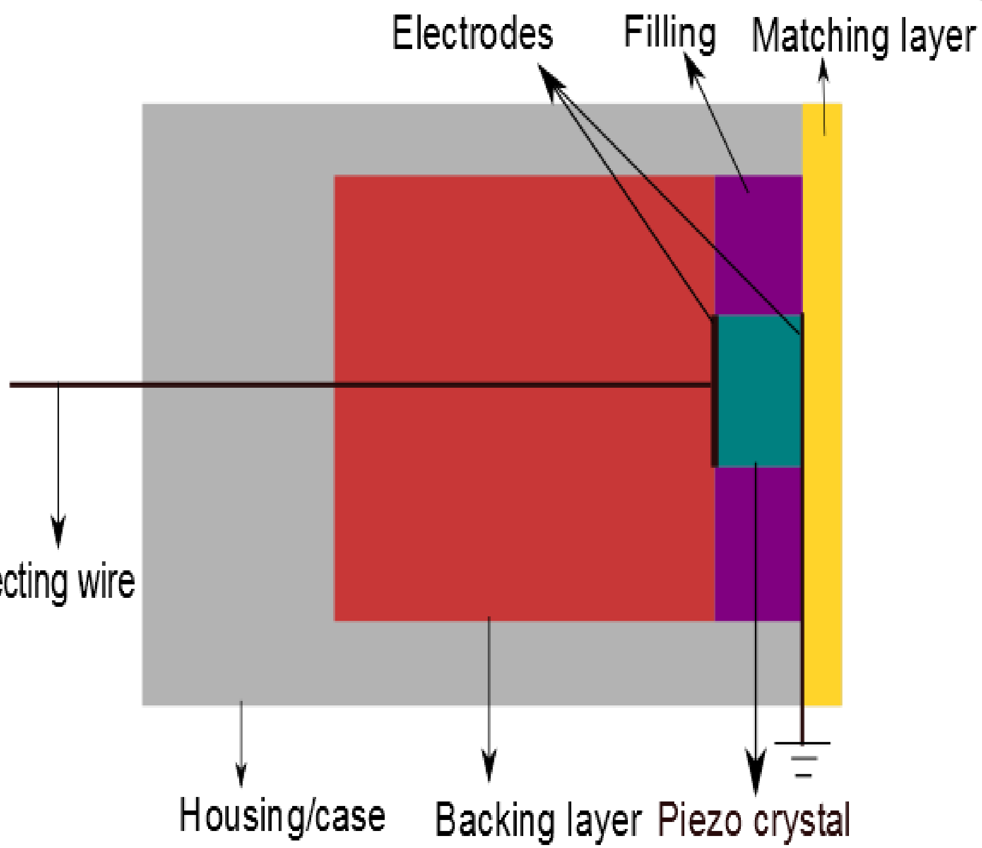
# Evaluation of improved materials, substructuring, insulation, damping etc

- Backing layer
  - Comparable acoustic impedance for better damping
  - Improved Bandwidth
  - Polyurethane (3.4 MRayl)
  - Epoxy (2.8 MRayl)
  - Polyurethane and tungsten composite(12.49 MRayl)
- Matching layer
  - Match the impedances of piezo element (30 MRayl) and water(1.5 MRayl)
  - Epoxy and silver composite with 12.9 Mrayl
- Filling Material
  - Damp the lateral oscillation modes of Piezo element



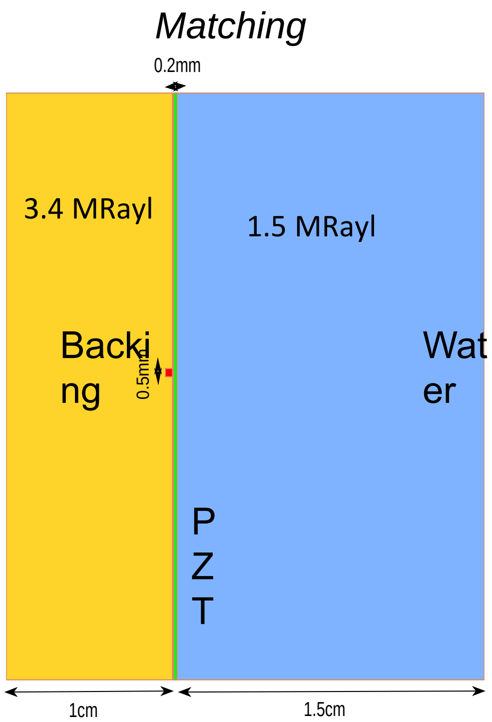
# Experimental and simulation setup

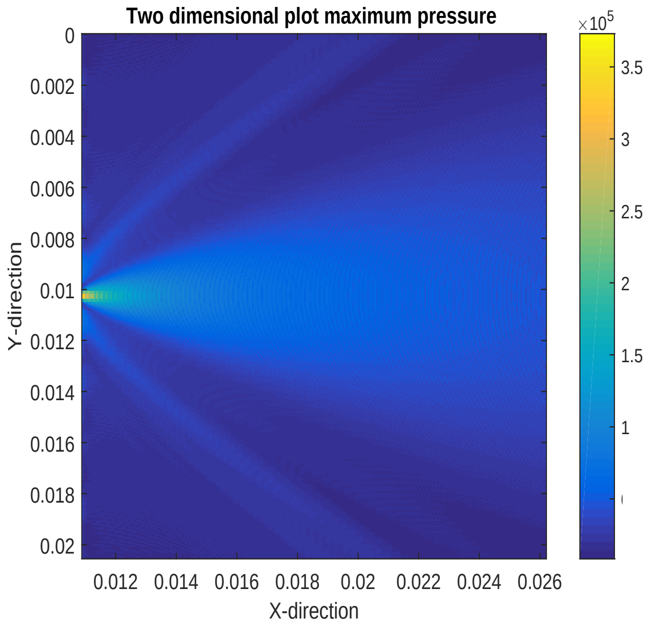
- ***PZFLEX***
  - Input chirp signal of length 10µsec with 5MHz bandwidth and amplitude 1V.
  - Spatial resuloution of PZFlex model - 2e-5m in both X,Y directions.
  - Spatial resultion of the exported data (to MATLAB) – 6e-5m in both X,Y directions.
  - The data exported to MATLAB
  - 1) Excitation signal
  - 2) pressure at spatial points
  - 3) complete simulation time data with a time step of 6.40e-08

- ***MATLAB***
- Interested parameters analyzed
  - Opening angle
  - Bandwidth
  - Sound pressure

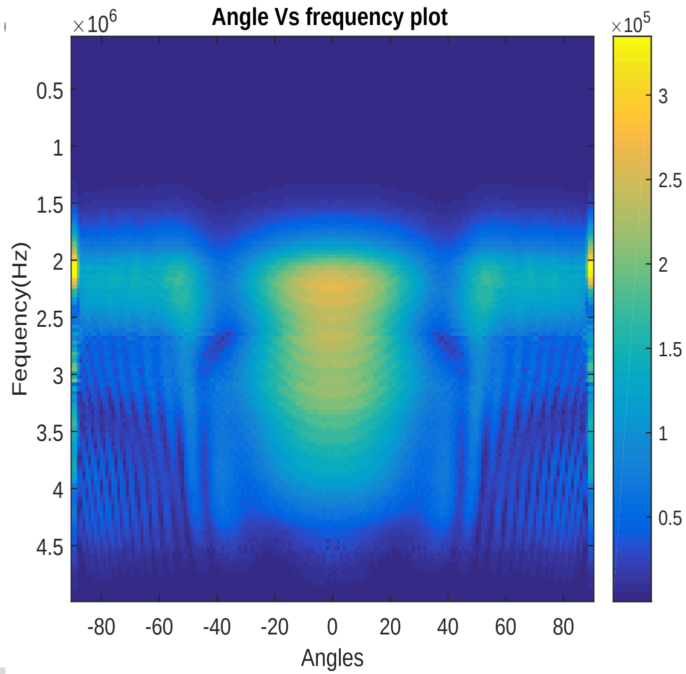
# *Transducer model: no substructuring*

- *No slit in piezo element*
- PU backing and filling
- Epoxy and silver composite in matching

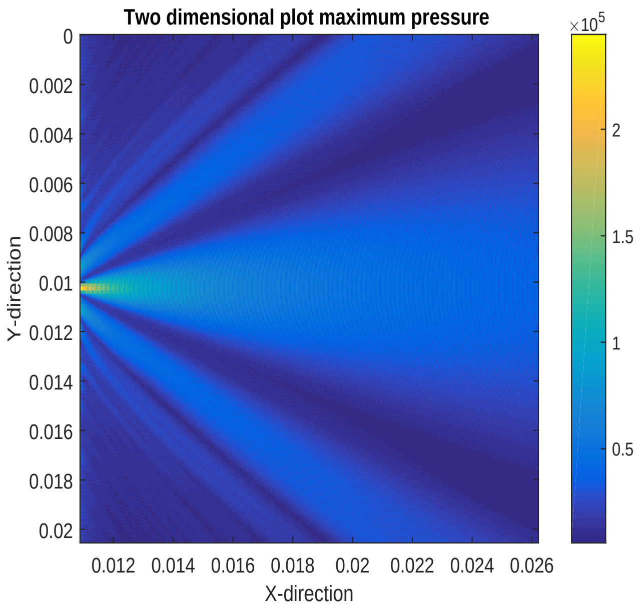


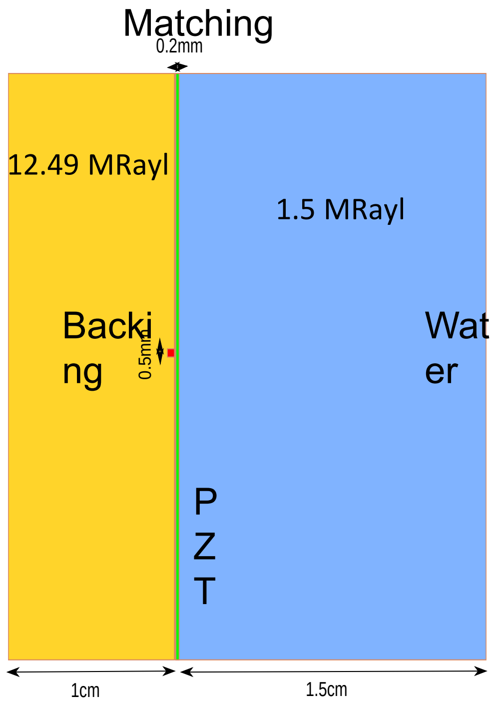

Opening angle = 46°
Bandwidth (3db) = 1.8 MHz
Bandwidth (6db) = 2.49 MHz



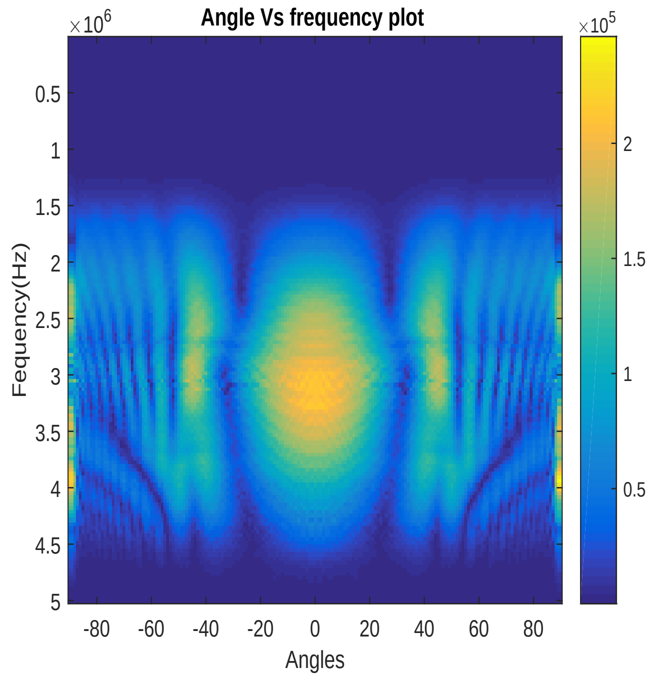
- *No slit in piezo element*
- PU and tungsten composite backing and filling
- Epoxy and silver composite in matching



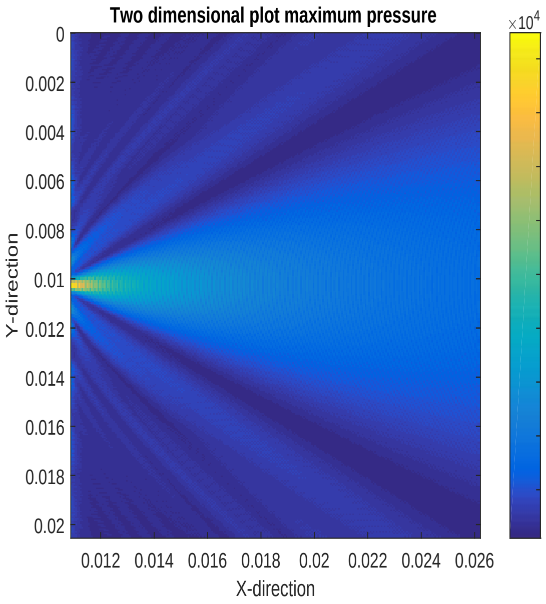

Opening angle(3db) = 38°
Bandwidth (3db) = 1.9 MHz
Bandwidth (6db) = 2.85 MHz



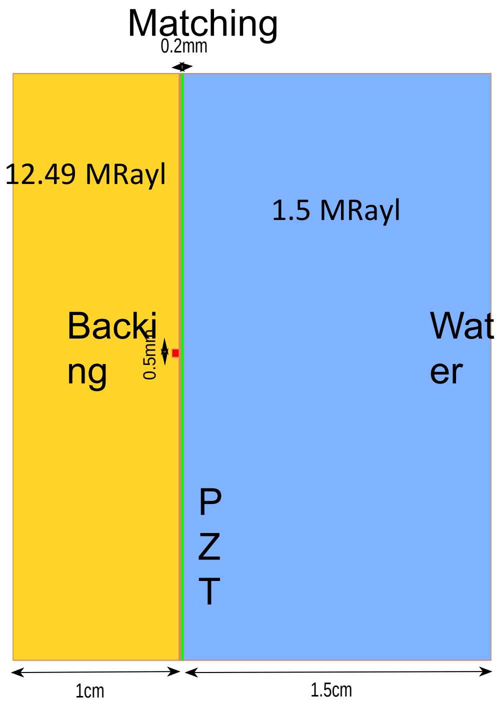

Expectation:
Improved bandwidth



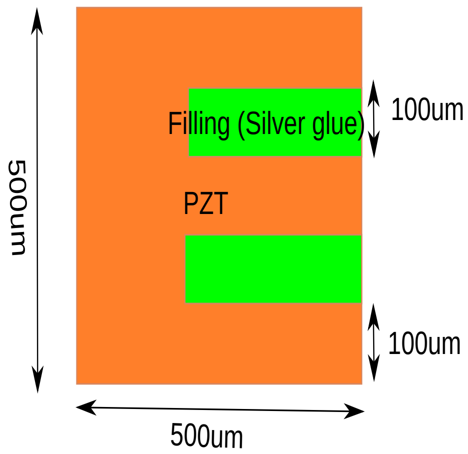
- *2 slit in piezo element*
- PU and tungsten composite backing and filling
- Epoxy and silver composite in matching

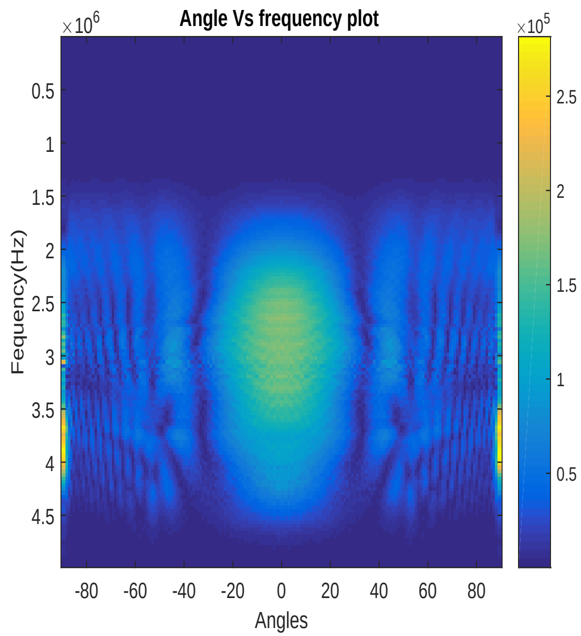



Opening angle = 46°
Bandwidth (3db) = 2.2 MHz
Bandwidth (6db) = 3.54 MHz

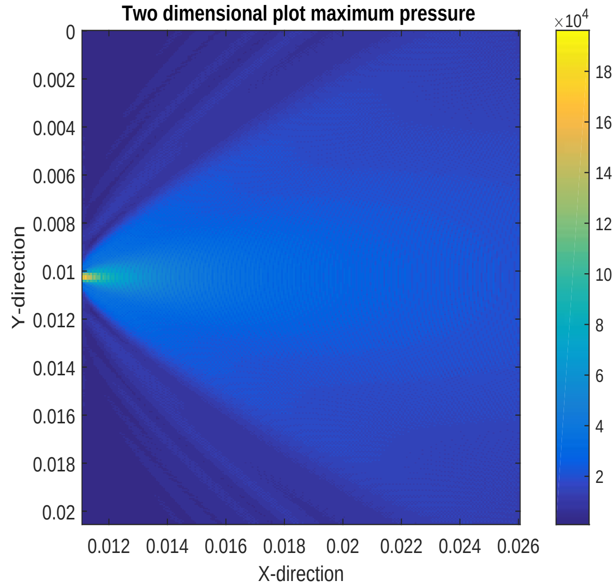



Expectation:
Improved opening angle

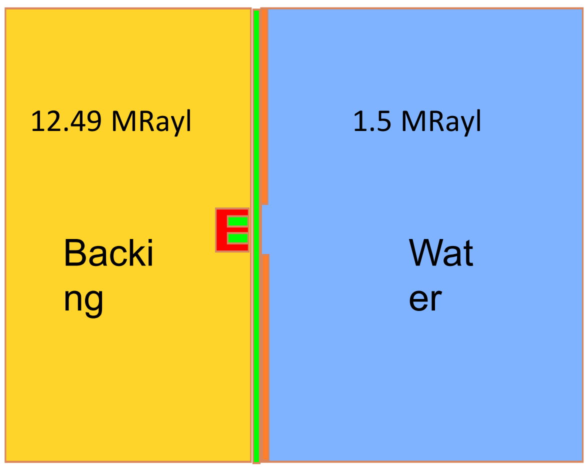


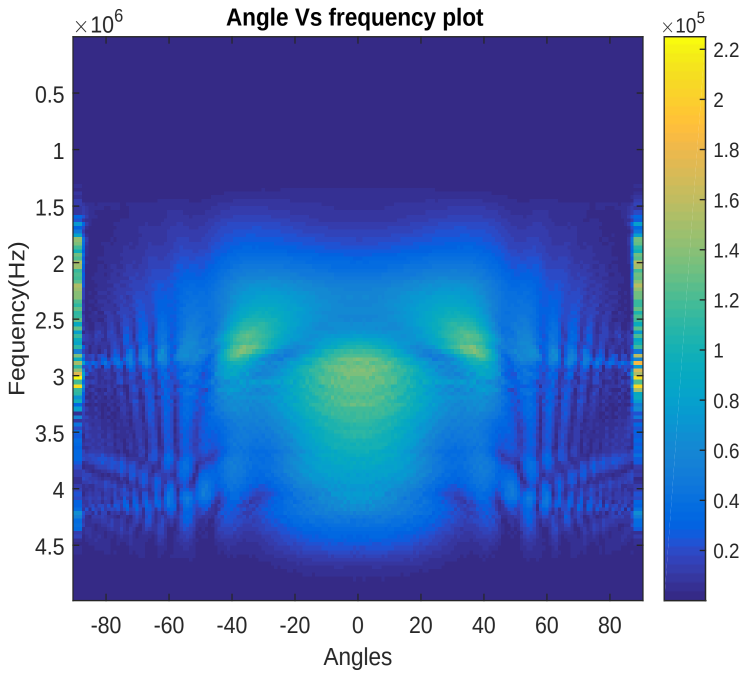
- *2 slit in piezo element with insulation layer*
- PU and tungsten composite backing and filling
- Epoxy and silver composite in matching
- Silicon and im30k glass bubble composite




Opening angle = 86°
Bandwidth (3db) = 1.54 MHz
Bandwidth (6db) = 2.45 MHz




Expectation:
Improved opening angle



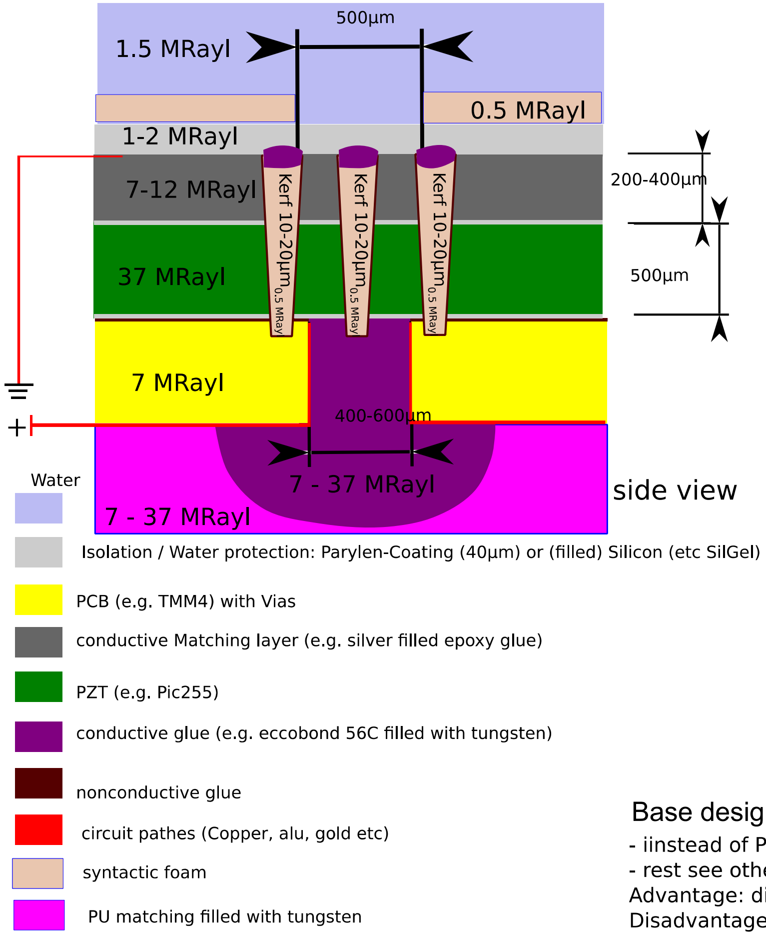
# Improved model

## 2016-08-23 USCT III Transducer Meeting (update2)

Koen van Dongen, Emile Noothout, Patrick Pfistner, Nivedita Mylapalli, michael Zapf

### Base design1 : laser+PCB with vias

PZT plate glued together with conductive matching layer (e.g. eccobond 56c)
- glued with low accurarcy demands (50µm) on PCB with Vias
- lateral positioning of transducer perfect due to laser-cutting in 1 step, catching markers on chassis
- vias in the PCB (drilled) gives electrical connection per transducer element
- filling is air for maximum lateral crosstalk separation / good emission pattern




### Base design 2: sawing+pcb with vias

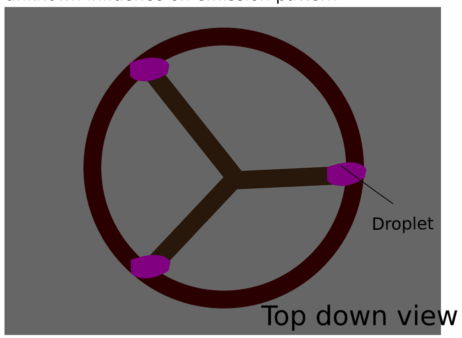
- instead of lasering sawing: kerf 20-100µm instead of 10µm,
- as kerf is to wide for dropplet, filling with PU foam with small bubbles o
- Sputtering common ground, parylination possible

Advantage: mechnical stability

### Top variante 1: droplets

dispensed droplet (conductive glue) for ground connection
- size of dropplets minimized to keep lateral crosstalk / influence on emission pattern minimal
- "Filling volume" kept filled with air
- silicon on top gives mechanical stability

- downside: no parylenation, significant thicker siliconelayer with unknown influence on emission pattern




### Top variant 2: sputtering

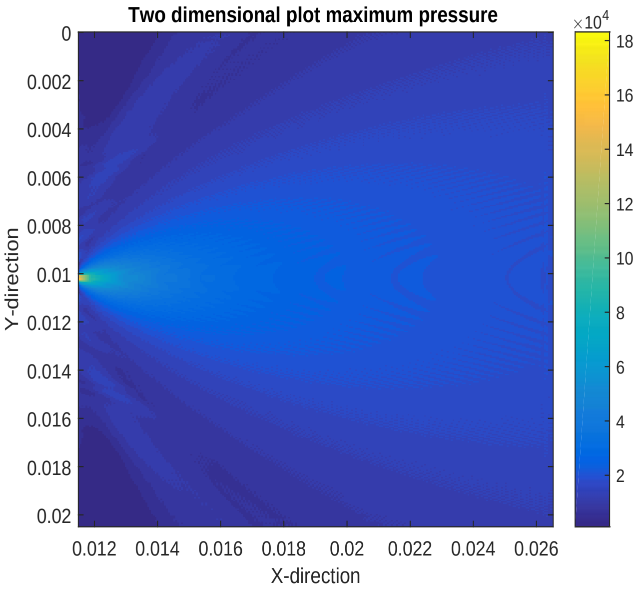
- "Filling volume" laser kerf filled with PU foam / silicon
- sputtering copper / cold
- parylenation on top

### Base design3: capton

- iinstead of PCB -> capton foil
- rest see other designs

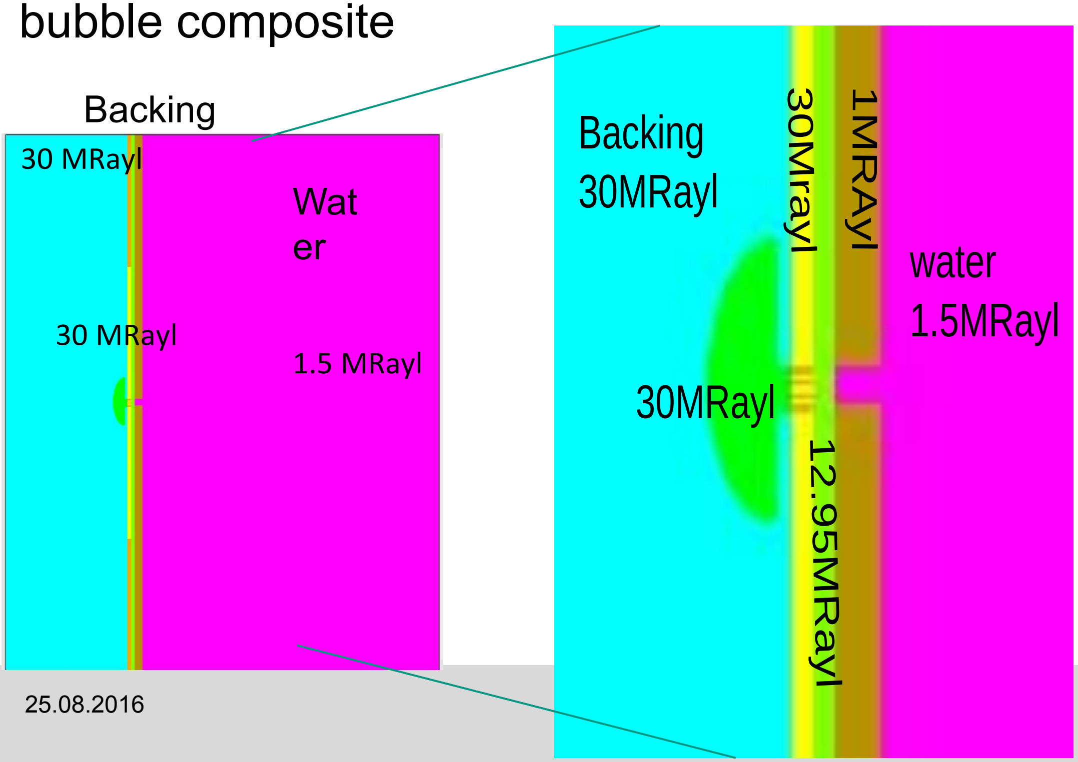
Advantage: direct glueing on foil, no conductive mushroom req.
Disadvantage: worse mechnical stability

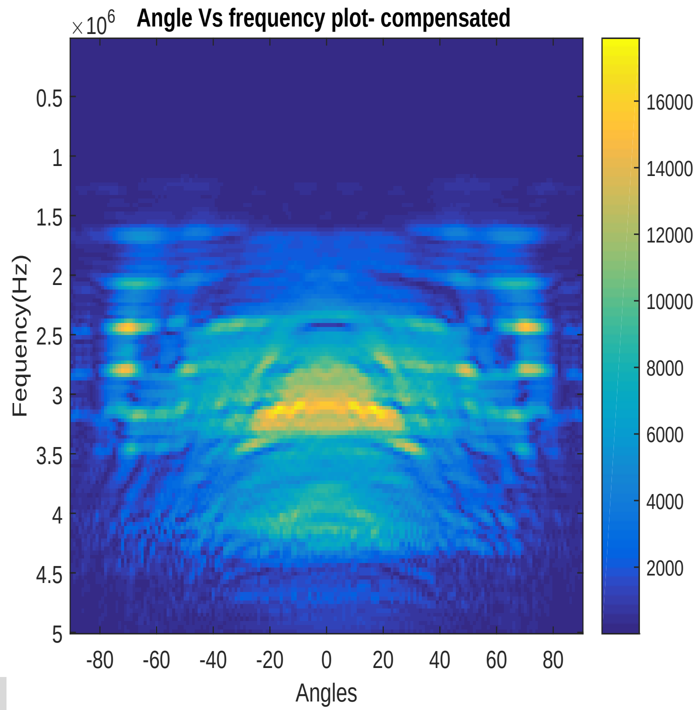
- *2 slit in piezo element (delft model)*
- PU and tungsten composite backing and filling
- Epoxy and silver composite in matching
- Silver glue and tungsten composite in bubble
- Silicon and im30k glass bubble composite




Opening angle = 80°
Bandwidth (3db) = 0.8 MHz
Bandwidth (6db) = 1.80 MHz

Expectation:
Improved opening angle



# Further improved model after further discussions

2016-08-23 USCT III Transducer Meeting (update3)

Koen van Dongen, Emile Noothout, Patrick Pfistner, Nivedita Mylapalli,
michael Zapf

## Base design1 : laser+PCB with vias

PZT plate glued together with conductive matching layer (e.g. eccobond 56c)
- glued with low accurarcy demands (50µm) on PCB with Vias
- lateral positioning of transducer perfect due to laser-cutting in 1 step, catching markers on chassis
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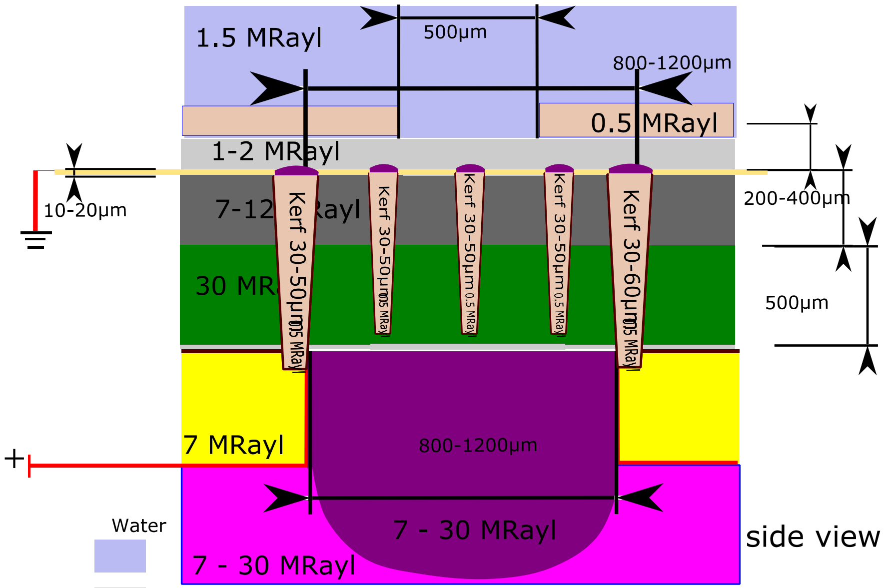
- filling is air for maximum lateral crosstalk separation / good emission pattern




Water

Isolation / Water protection: Parylen-Coating (40µm) or (filled) Silicon (etc SilGel)

PCB (e.g. TMM4) with vias

Matching layer (e.g. silver filled epoxy glue)

PZT (e.g. Pic255)

conductive glue (e.g. eccobond 56C filled with tungsten)

nonconductive glue

Alu foil

circuit pathes (Copper, alu, gold etc)

syntactic foam

## Base design 2: sawing+pcb with vias

- instead of lasering sawing: kerf 20-100µm instead of 10µm,
- as kerf is to wide for droplet, filling with PU foam with small bubbles (
- Sputtering common ground, parylination possible

Advantage: mechnical stability

## Top variante 1: droplets

dispensed droplet (conductive glue) for ground connection
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- silicon on top gives mechanical stability

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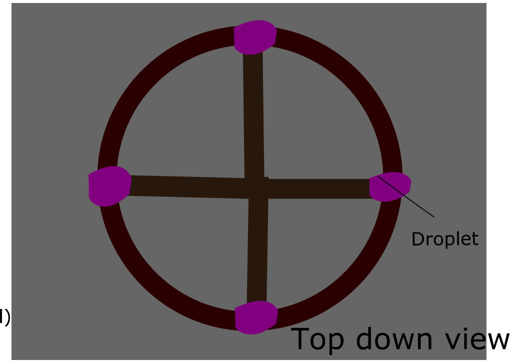



## Top variant 2: sputtering

- "Filling volume" laser kerf filled with PU foam / silicon
- sputtering copper / cold
- parylenation on top

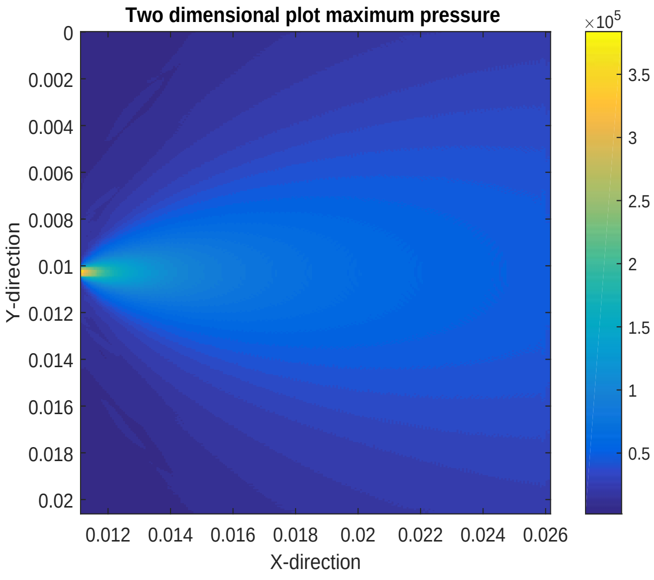
## Base design3: capton

- iinstead of PCB -> capton foil
- rest see other designs

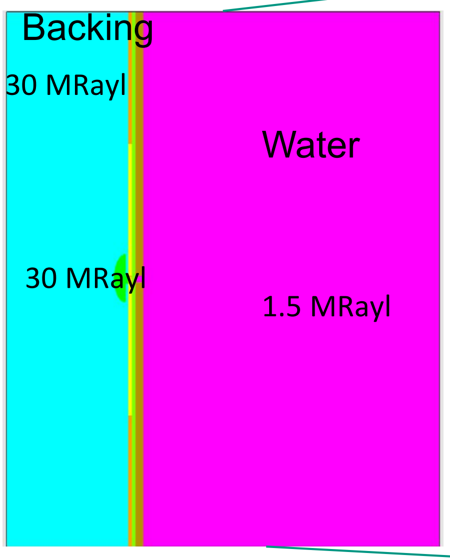
Advantage: direct glueing on foil, no conductive mushroom req

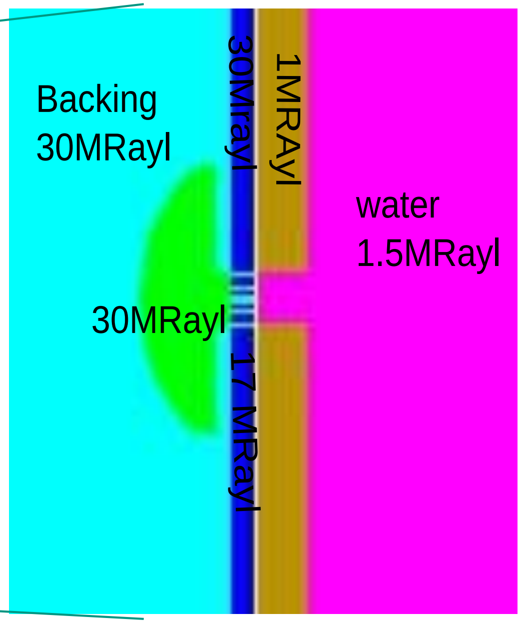

M. Zapf - 3D USCT II

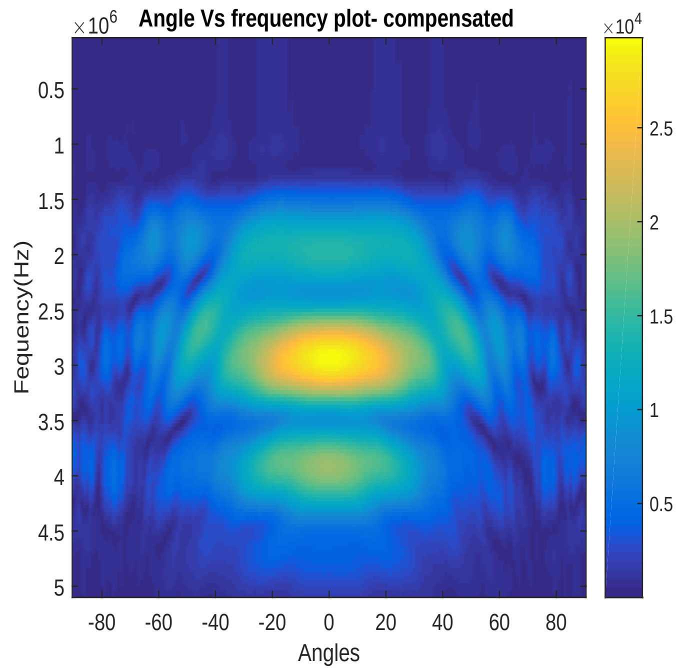
- *3 slit in 1mm piezo element (delft model)*
- PU and tungsten composite backing and filling
- Aluminium foil in matching
- Silver glue and tungsten composite in bubble, pu-tungsten kerf filling
- Silicon and im30k glass bubble composite




Opening angle = 80°
Bandwidth (3db) = 0.5 MHz
Bandwidth (6db) = 1.20 MHz



# Conclusion and discussion

- Substructuring alone currently not sufficient for supressing lateral waves which detoriates the opening angle
- Decoupling of lateral waves vs coupling: currently coupled design
- The insulation layer with a low density syntactic foam suggests suitable performance
- „Ripples“ in bandwidth need to be analyzed (artifacts, ringing?)
- Producibility tests of some elements missing
- Inproved homogeneity of electrical field by using wider piezo and blocking outer parts by syntactic foam
- Optimized matching to backing to reduce ringing


M. Zapf - 3D USCT II

# Next steps for final USCT III transducer design

- Laser cutter: Testing of possible maximum cutting depths and aspect ratios
- Kerf filling: Testing of possible kerf fillings material for expected kerf (viscosity)
- Conductive foil influence simulation
- Optimal substructing cutting numbers (-> Shreyas and Maysam paper)

- Checking theoretical open angle in dependency on individual element aperture size
- PZT matrix 3x3 subgroup 5mhz, cross check theory
- 30µm kerf for 5MHz simulation
- PI PZT samples for laser cutting
- building up samples , work´distribution


M. Zapf - 3D USCT II

# Appendix


M. Zapf - 3D USCT II