CMUT application note

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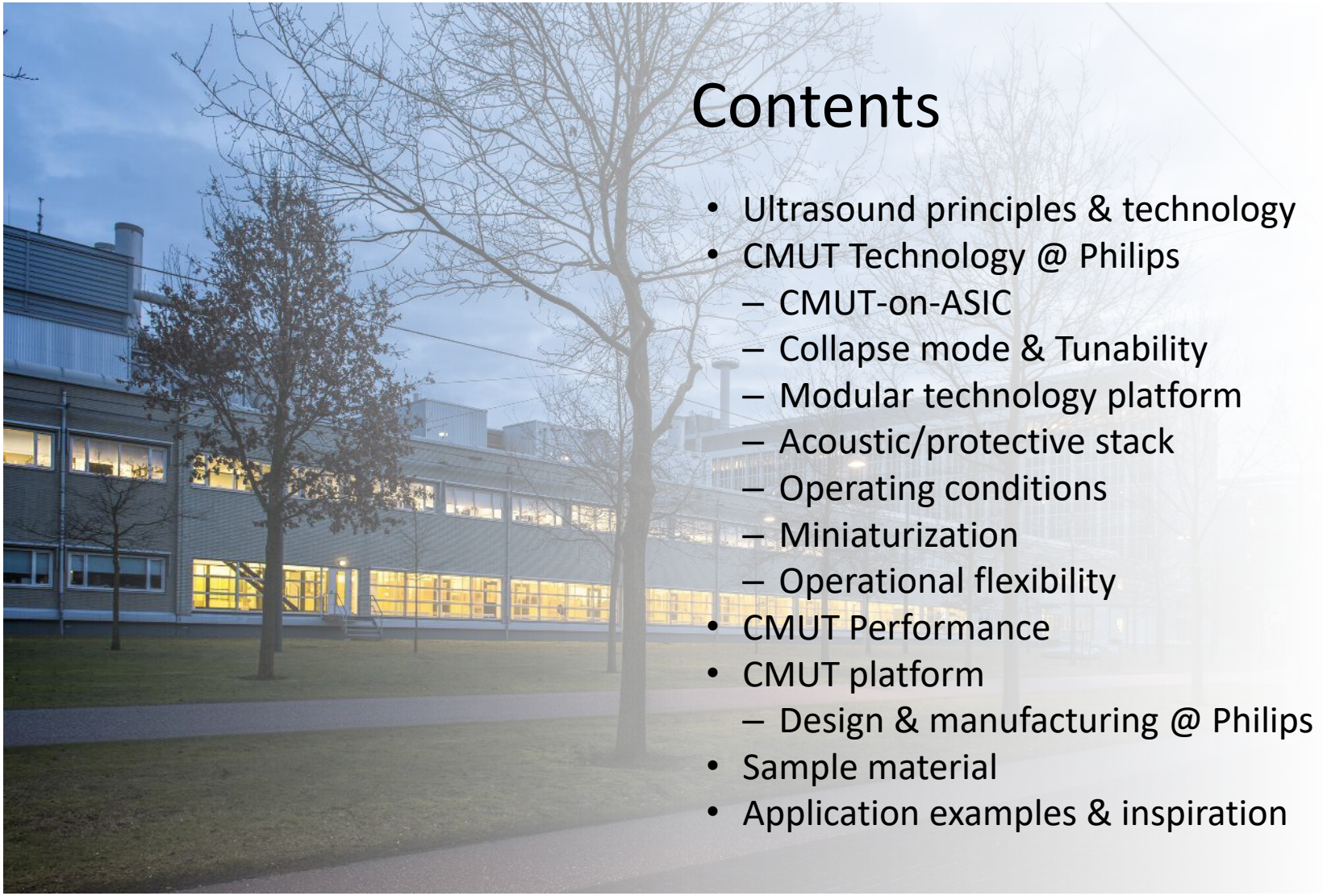
CMUT application note

Goals

- Inform about specs & capabilities of Philips Innovation Services on CMUT technology
- Interest potential customers for design & manufacturing of CMUT devices

Audience

- Technology decision makers and technology scouts.
- Scouting for new sensors or transducers, interested in the possibilities of CMUT technology



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- CMUT Technology @ Philips
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  - Modular technology platform
  - Acoustic/protective stack
  - Operating conditions
  - Miniaturization
  - Operational flexibility
- CMUT Performance
- CMUT platform
  - Design & manufacturing @ Philips
- Sample material
- Application examples & inspiration

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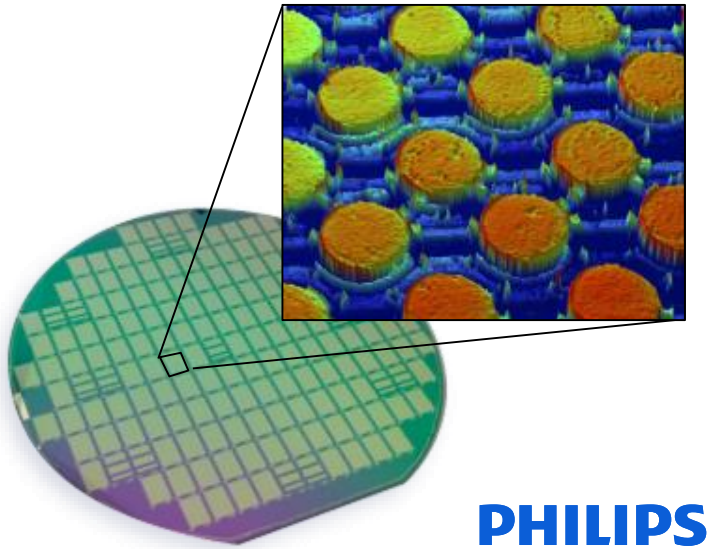
Philips Innovation Services has manufacturing facilities with the capability to develop and produce CMUT devices.

- Capacitive Micromachined Ultrasonic Transducers (CMUT) are micro-structures that can be used to generate and sense acoustic signals in the ultrasonic range
- Highly reliable and miniaturized ultrasound transmitters and receivers have been realized with CMUTs @ Philips
- Fabrication on top of CMOS sets CMUT technology apart from conventional ultrasound devices

- CMUT extends the use of ultrasound to new application areas
- Philips has a leading position in the CMUT development
- We have the infrastructure to manufacture CMUT modules
- We have the interconnect solution to revolutionize manufacturing CMUT devices



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Ultrasound principles

What is measured with ultrasound?

Ultrasound

Pressure wave in MHz frequency range (sub-mm wavelength) of up to a few Mpa

Sensing

- Based on ultrasound reflection and/or transmission
  - Attenuation & scattering of medium
  - Reflection of objects
  - Doppler shift of movements
  - Density (speed of sound)
  - Resonances & shearwaves (changes in frequency)

- Measurement modes
  - Distance (time-of-flight)
    - Possibly combined with attenuation
    - Send & receive on single device or from device to device.
  - Doppler shift
  - Harmonic sensing
    - Detect at a higher frequencies than transmitted
  - Imaging
    - Echography
    - Tomography

Ultrasound principles

What is measured with ultrasound?

Measurements & Applications

- **Particle sizing/monitoring** based on scattering
- **Particle trapping** based acoustic field
- **Moisture content** based on time-of-flight
- **2D/3D imaging** based on echoscopy/tomography
- **Density** based on speed of sound
- **Elasticy** based on harmonic imaging
- **Distance** based on time-of-flight
- **Porosity** based on scattering
- **Induce flow** in e.g. microfluidics
- **Curing/Polymerization** based on local heating
- **Anisotropy in materials** based on attenuation and/or harmonics

Actuation

- Local heating: High Intensty Focused Ultrasound & ablation
- Cavitation: Local induced shearwave by implosions of bubbles
- Acoustic streaming: Flow induced by pressure field

Non-intrusive
Non-destructive
Non-contaminating

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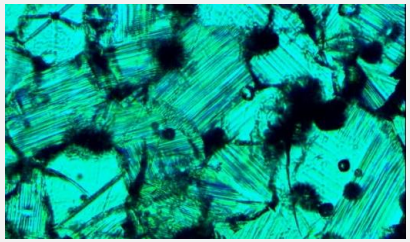
Ultrasound Sensor Technology

Revolution →

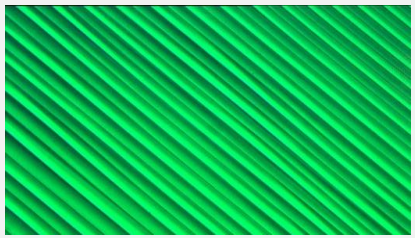
Evolution ↓

PZT ceramic



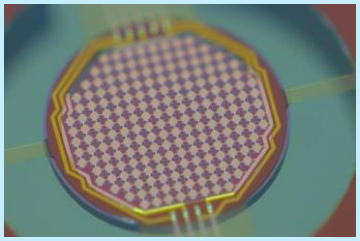
- Inexpensive ceramic piezo-material.
- >40 years in medical ultrasound.
- Good piezoelectric efficiency
- Single element, Phased, Linear & curved linear transducer designs
- Matching layers, backing and lens design has improved acoustic efficiency

SXTL Single Crystal



- Expensive PMN-PT single crystal
- >10 years in medical ultrasound with multiple sources available
- 2nd generation now available
- Superior piezoelectric efficiency
- Single element, Phased, Linear, CLA, Matrix transducer designs
- Matching layers, backing & lens design improved bandwidth

CMUT



- Inexpensive, high volume, wafer level process
- Volume manufacturing ready
- Single element, Phased, Linear, Matrix transducer design capable
- PZT ceramic efficiency, and wideband characteristics shown

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CMUT is fully RoHS compliant

- PZT has been dominating ultrasound applications.
- PZT contains more than 50% lead (Pb), a material that is a regulated substance in accordance with the restriction of hazardous substances (RoHS) guidelines.
- PZT is exempt from RoHS, because there simply were no equivalent substitutes that could rival its piezoelectric performance.

- CMUT is fully RoHS compliant and can, for many applications, compete with PZT.

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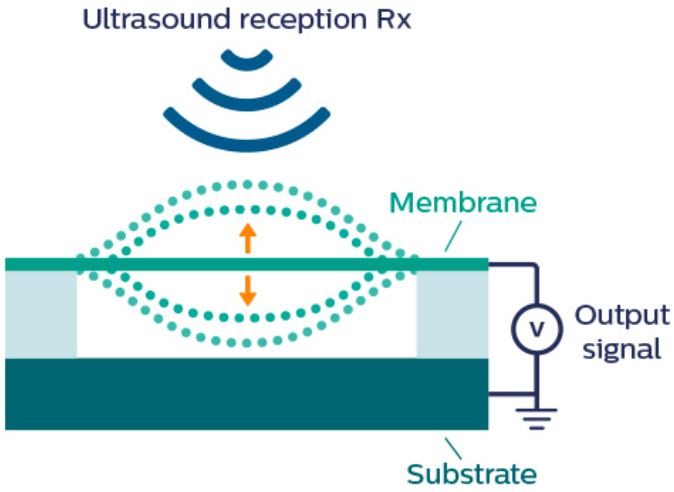
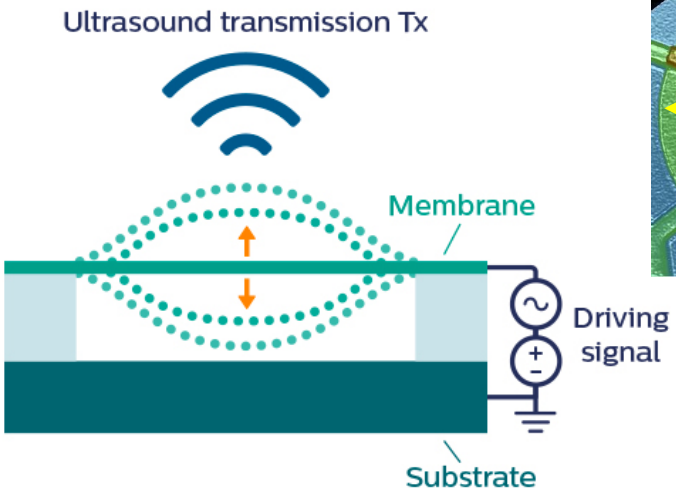
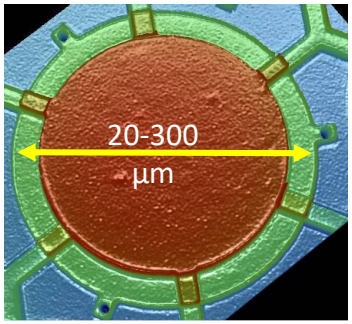
CMUT Principles

Capacitive Micromachined Ultrasonic Transducers (cMUT) are MEMS based structures that can be used to generate and sense acoustic signals in the ultrasonic range. Interest on CMUTs is rising due to the quality of the acoustic signal they provide, ease of integration with CMOS and because their dimensional characteristics enable to broaden the applications of ultrasonics.

CMUT:	Capacitive Micromachined Ultrasound transducer
Principle:	Parallel plate capacitor. A RadioFrequency (RF) Voltage applied to electrodes in the capacitor plates makes the top plate (membrane) vibrate and an ultrasound signal is produced.
Performance:	Transmits/receives ultrasound from **~500kHz to >40 MHz** in a wide band characteristic (>100% in immersion). Center frequency can be tuned by adapting the CMUT dimensions
Technology:	IC – technology, Low temperature, "CMUT-on-CMOS" compatible







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CMUT technology @ Philips

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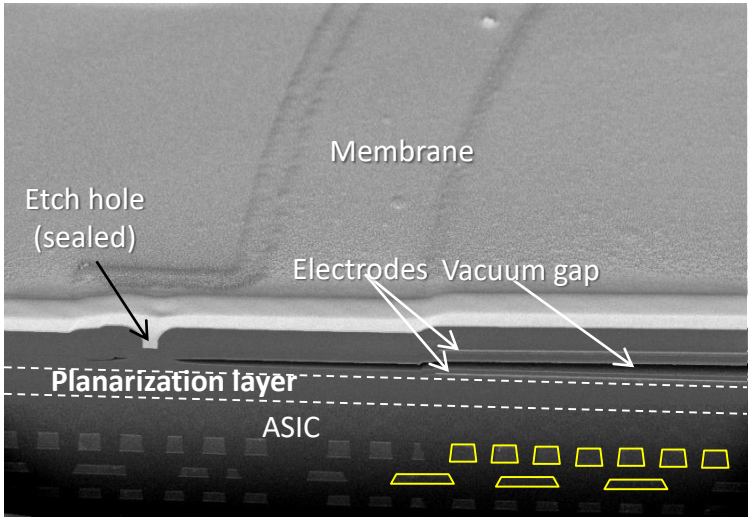
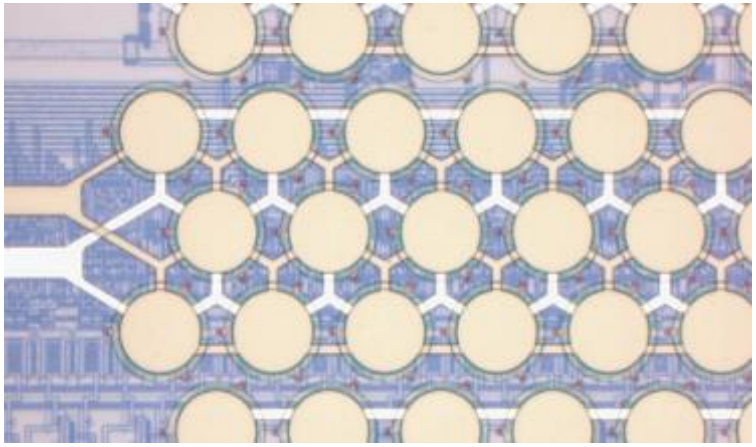
CMUT known issues solved @ Philips

Issue	Cause	Solution
Lifetime	High electric fields causes structure breakdown	Dielectric optimized
Charging	Electric field causes charges to be trapped at material interfaces	Thin film process optimization
Efficiency	Mismatch acoustic and electric impedance	Acoustic window and design optimization
Limited pressure output	Thin film processing limitations	Novel thin film deposition techniques
Crosstalk	Closely packed ultrasound elements	Acoustic isolation with the use of trenches

CMUT-on-CMOS





CMUT technology enables high volume ultrasound transducer manufacturing and **high levels of integration** at lower cost.

CMUT on a substrate wafer with CMOS-processed dedicated ASIC has been realized.

Philips has broad experience with:

- Ultrasound application-specific IC design, including specification, design and test of proofs-of-concept ASICs and industrialization support. CMUT-specific ASIC's have been realized.
- Ultrasound transducer design and characterization, including the design of the full acoustic stack with backing and lens materials and electrical, acoustical and mechanical testing.
- Ultrasound imaging, which includes knowhow of the entire imaging chain.

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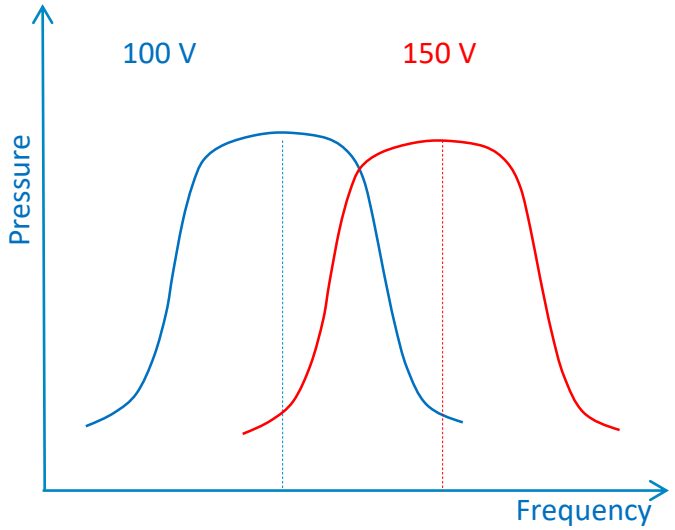
Collapse mode & Tunability

Our cMUT is typically (but not necessarily) operated in a so-called **collapse mode**. When the bias voltage exceeds the collapse voltage, the membrane is partly collapsed to the bottom of the cavity. Only the central part of the membrane is in contact with the bottom, but the rim is 'free'. Advantage: **large output pressure**.

As the bias is further increased, the collapse radius increases as well. The amount is determined by the cMUT parameters such as membrane thickness (stiffness) and dielectric materials. A consequence of collapse mode is that the frequency increases with bias. This feature is called **frequency tunability** and can be exploited in applications.



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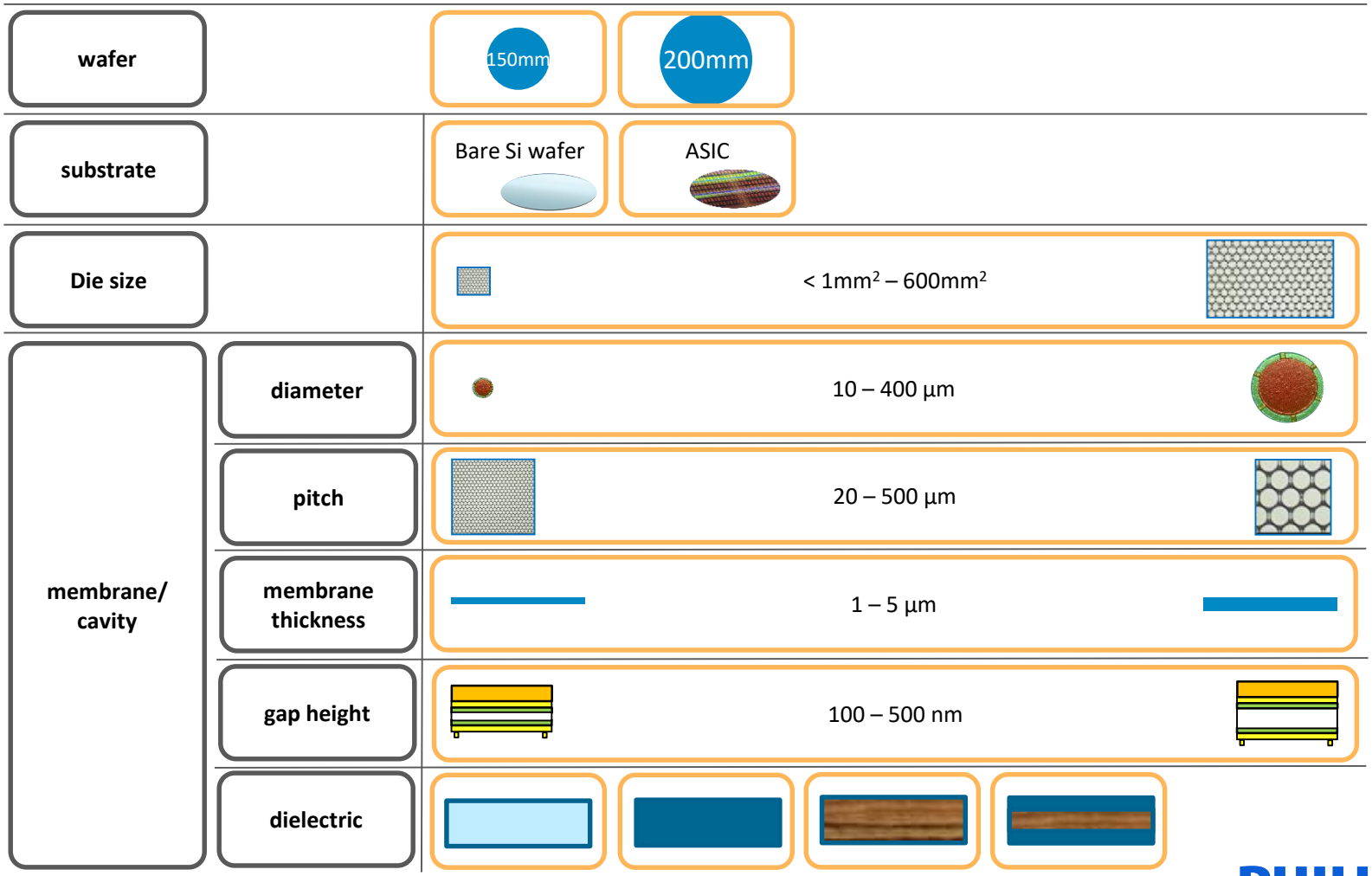
Modular technology platform

Processing knowledge includes key know-how/trade secrets for the optimization of the cMUT technology to specific application requirements. cMUT in general offers a lot of **design freedom**.



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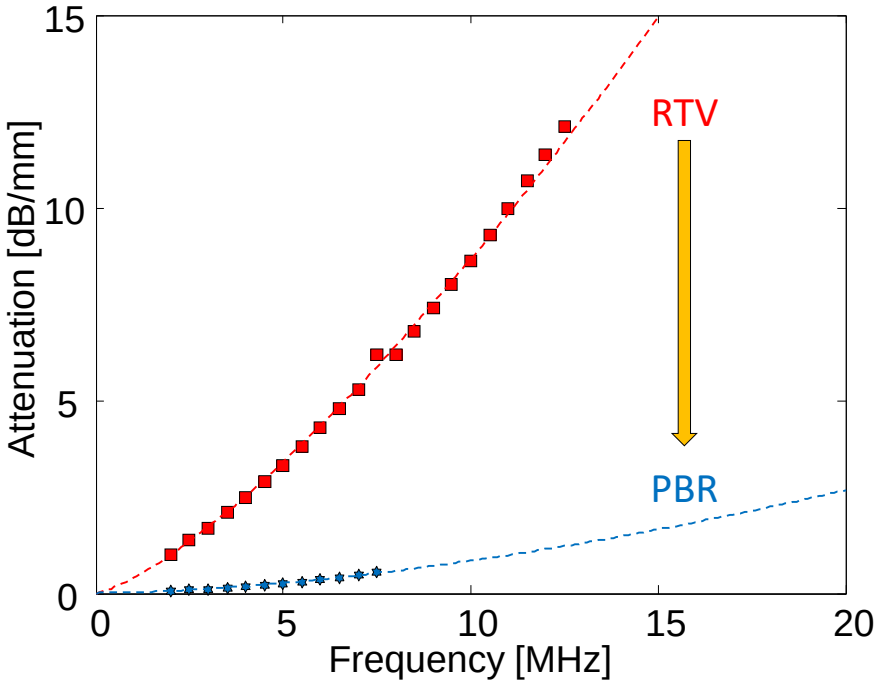
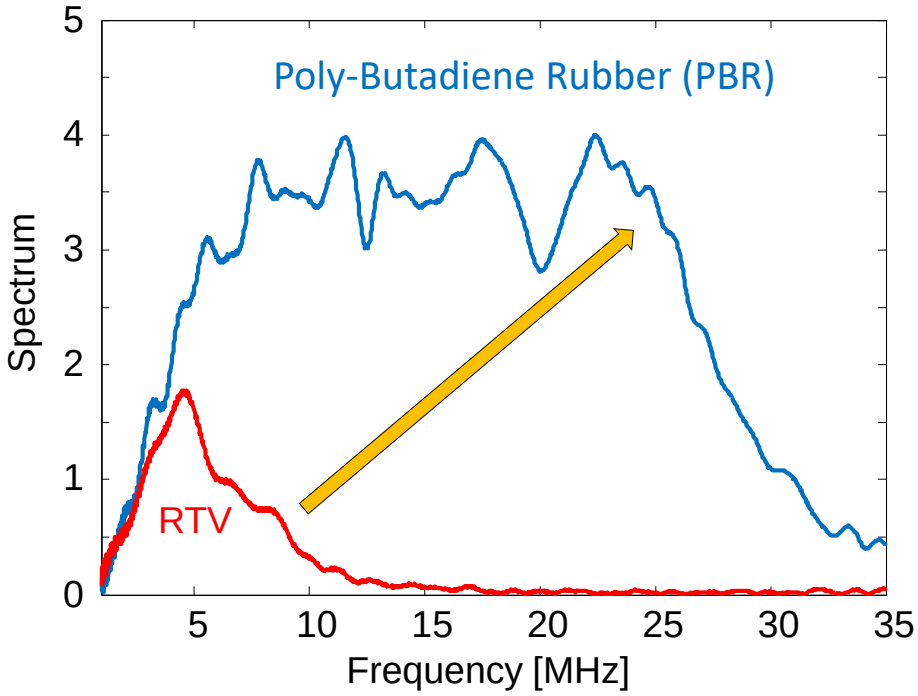
Acoustic & protective interface

Key to output characteristic: pressure and bandwidth





- CMUT requires a dedicated window, optimized for its application.
- FEM - optimization on attenuation, impedance and mechanical properties.
- Physical processes involved: attenuation, reflection and resonance
- Currently, a range of protective layer materials (predominantly polymers) has been qualified
- With further testing and development, the properties of the acoustic/protective stack can be improved

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Operating conditions

Operating conditions of CMUT strongly depends on design parameters and material choices of:

1. The CMUT transducer
2. Substrate and (if applicable) ASIC design
3. Acoustic/protective stack (window/lens material)
4. Additional packaging

The expertise of Philips on CMUT design allows for adaption to demanding operating conditions like Bio-compatibility, harsh Oil&Gas environments (High Temp, High Pressure).

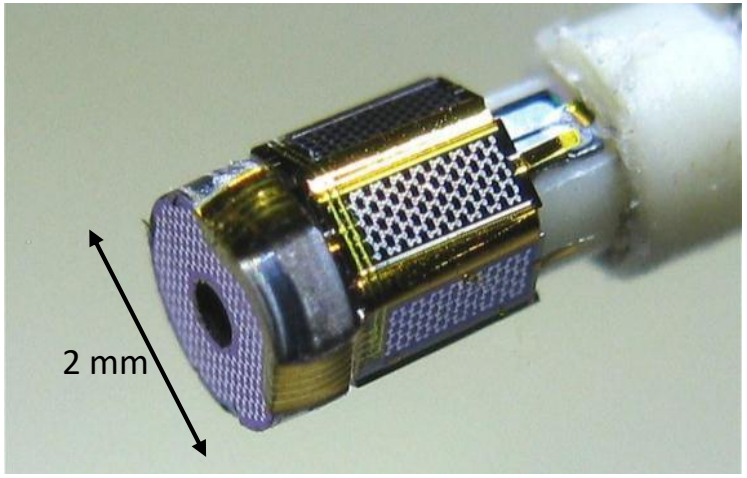
Operating conditions

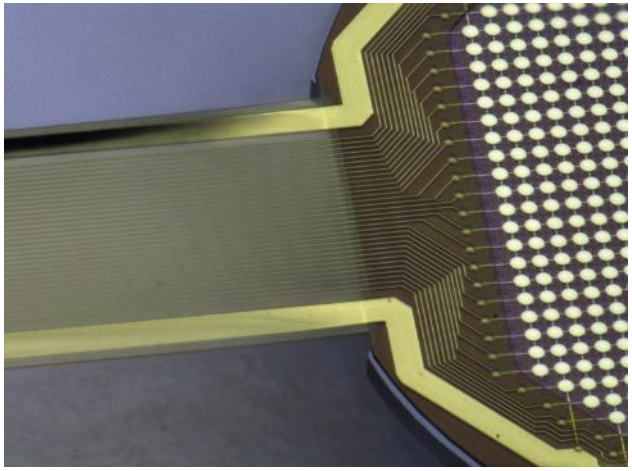
• Temperature:	up to 400°C (up to 250°C with ASIC substrate)
• Pressure:	current design up to 10 bar, packaging & redesign to withstand higher pressures
• Abrasion resistance	protective stack very abrasion resistant, material specs on request
• Chemical robustness:	current acoustic/protective stack resistant against for example: sulfuric acid (98%), ammonia water, sodium hydroxide, sodium oxalate, acetone, ethanol.

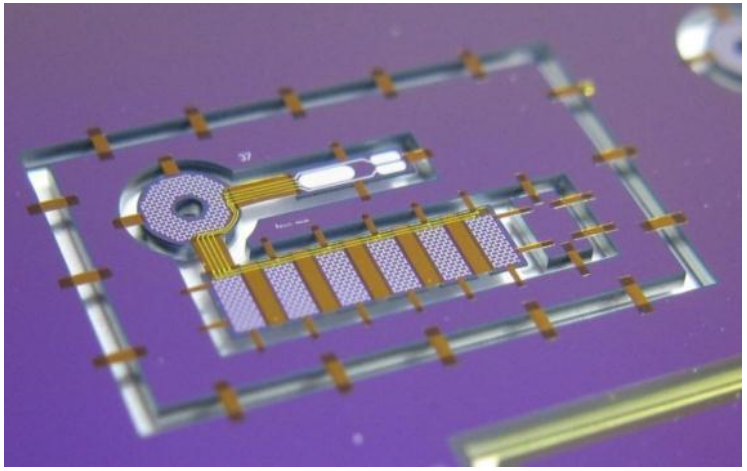
Miniaturization

Si-wafer processing also allows for the integration and miniaturization of an interconnected CMUT module via the proprietary **Flex-to-Rigid** technology. This can reduce assembly cost considerably.

The frequency and miniaturization capabilities demonstrate that the CMUT technology is very good candidate to meet form-factors and performance requirements for miniaturized applications.







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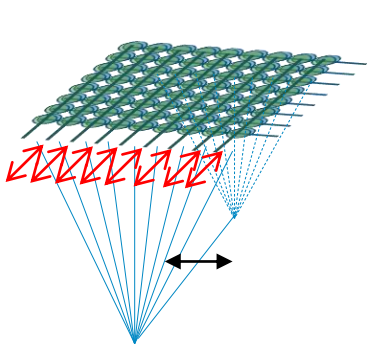
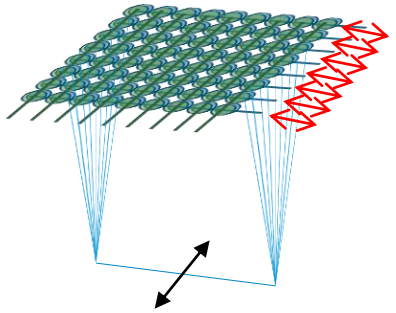
Operational flexibility

CMUT offers the benefit to addressing areas of the transducer array. Clever design allows for directional measurement, bi-plane operation, focusing (aperture changing) and even send/receive from one end of the array to another.

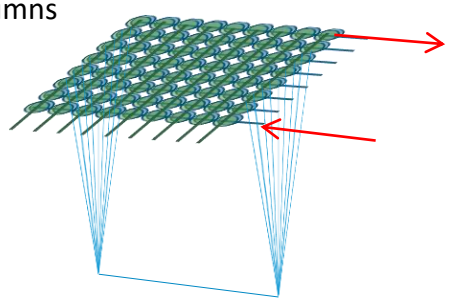
With extensive CMUT redesign and dedicated electronics, maximum flexibility can be achieved.



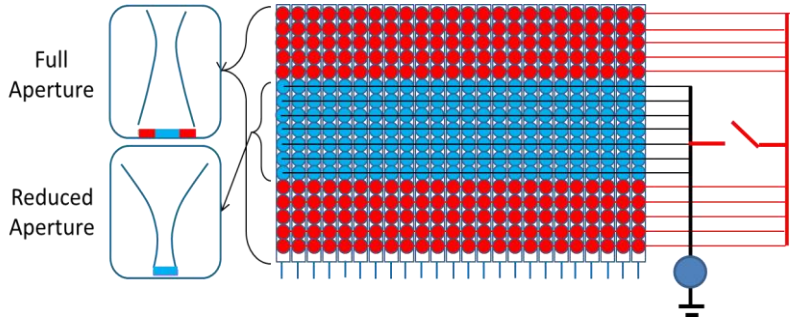
Drive & receive from columns



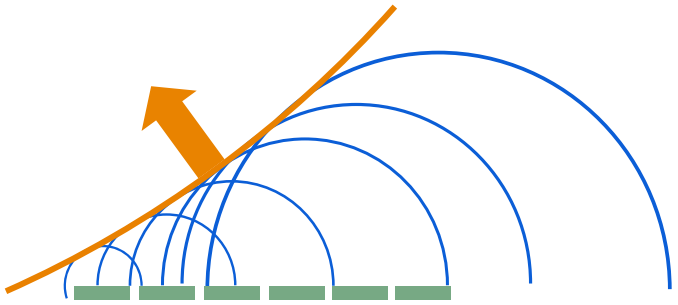
Drive & receive from rows



Drive from 1 column/row, receive from another



Addressing areas with switching bias voltage



Phased array beam steering & forming

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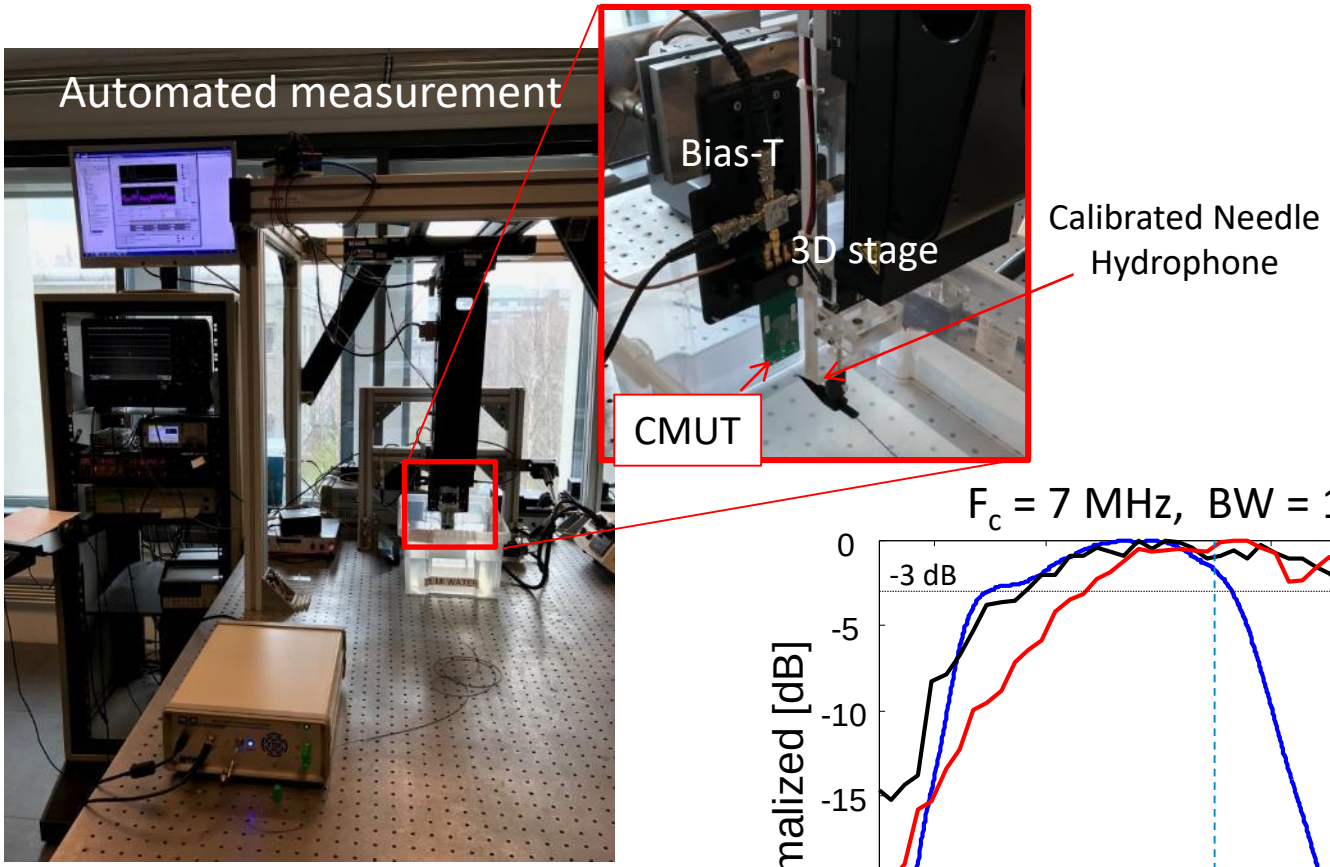
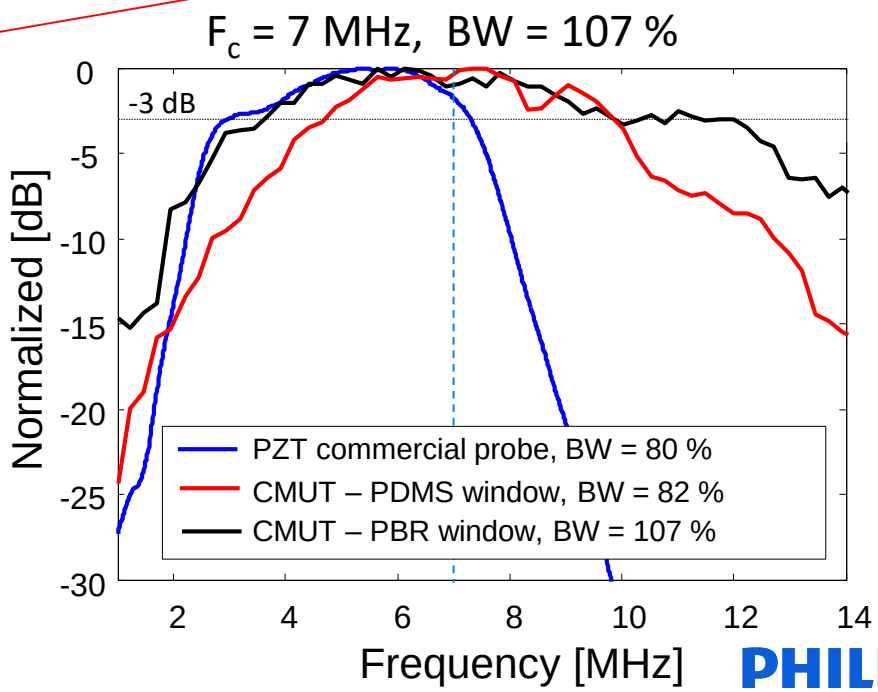
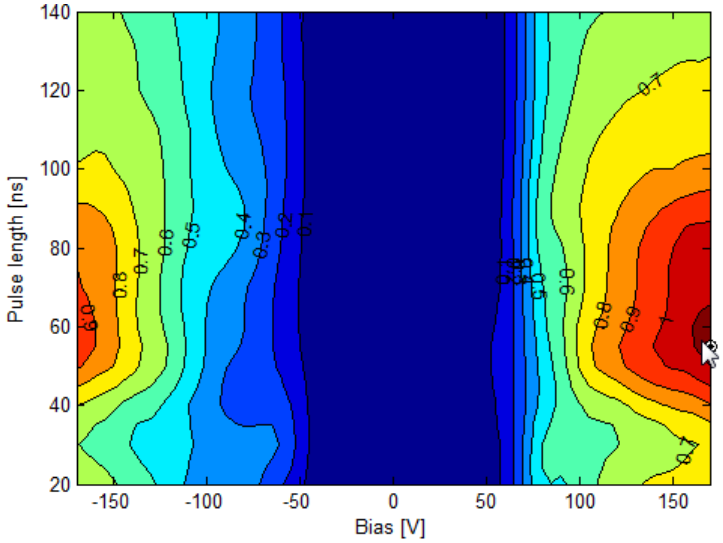
CMUT Performance

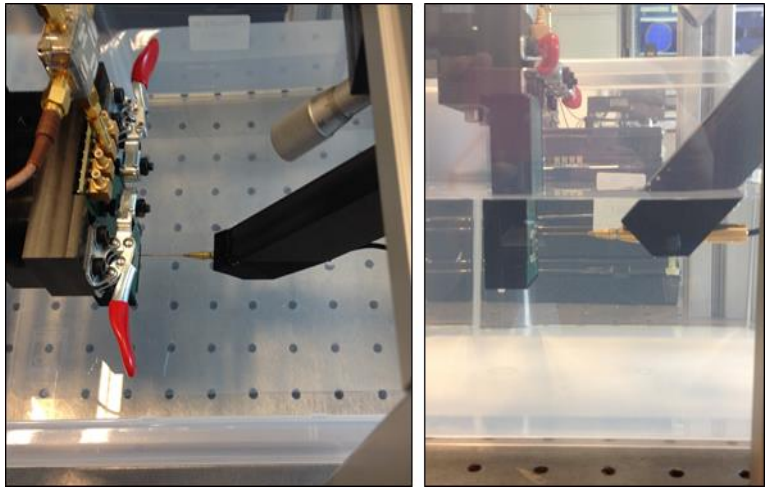
Acoustic Characterization

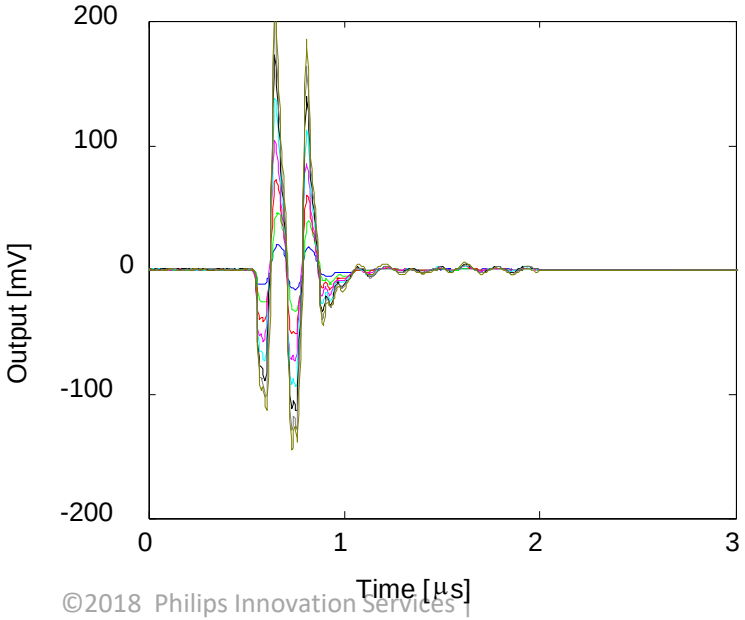


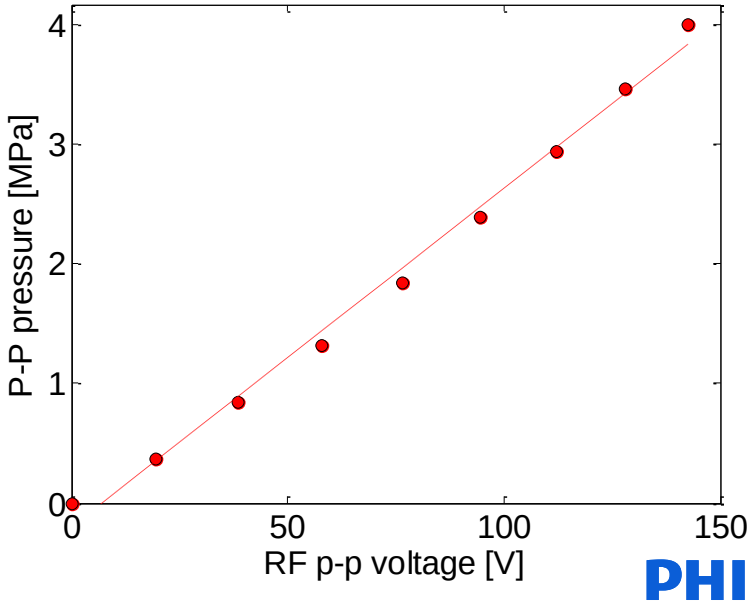


Acoustic characterization: pressure map



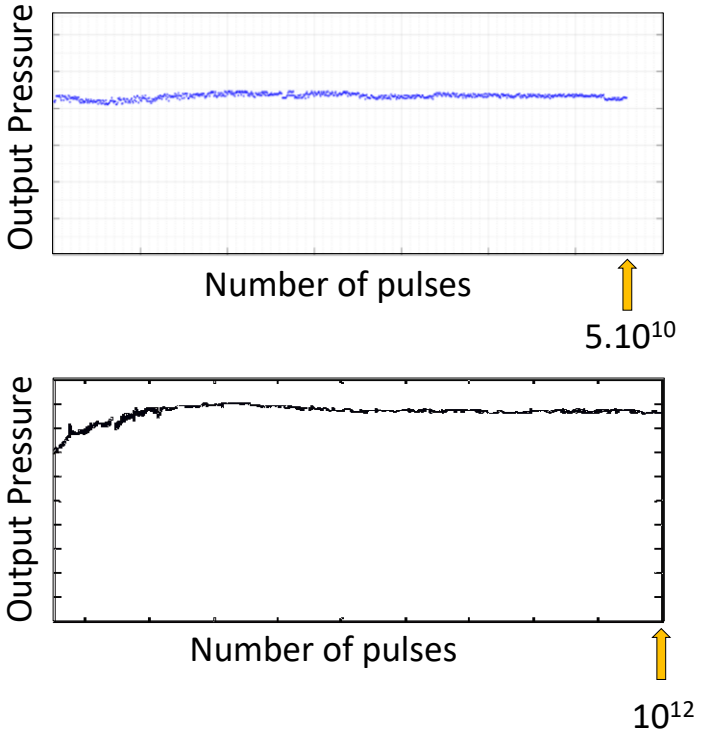






Lifetime for collapse mode CMUT

Acoustic Accelerated lifetime test: standard operating conditions, very high repetition rate, hence acceleration factor



High frequency (30 MHz) transducer

- Requirement < 24 hr
- Test duration > 60 hours
- $5x10^{10}$ pulses ↔ > 6000 hours

Low frequency (6 MHz) transducer

- Requirement 5-10 years
- Test duration > 4 month
- $>10^{12}$ pulses ↔ 10 year

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CMUT compared to PZT

CMUT opens up new application spaces for ultrasound

- **Production volumes**
  - Advantage at high volumes (>1000 wafers/yr): lowering costs.
  - Matrix array solutions at low cost levels.

- **Form factor**
  - CMUT-on-ASIC results in a highly integrated solution.
  - High flexibility in transducer dimensions, array sizes, array shapes, actuation/sensing shaping etc.
  - Environmentally robust at low cost levels (no need for special piezo materials)
  - RoHS compatible

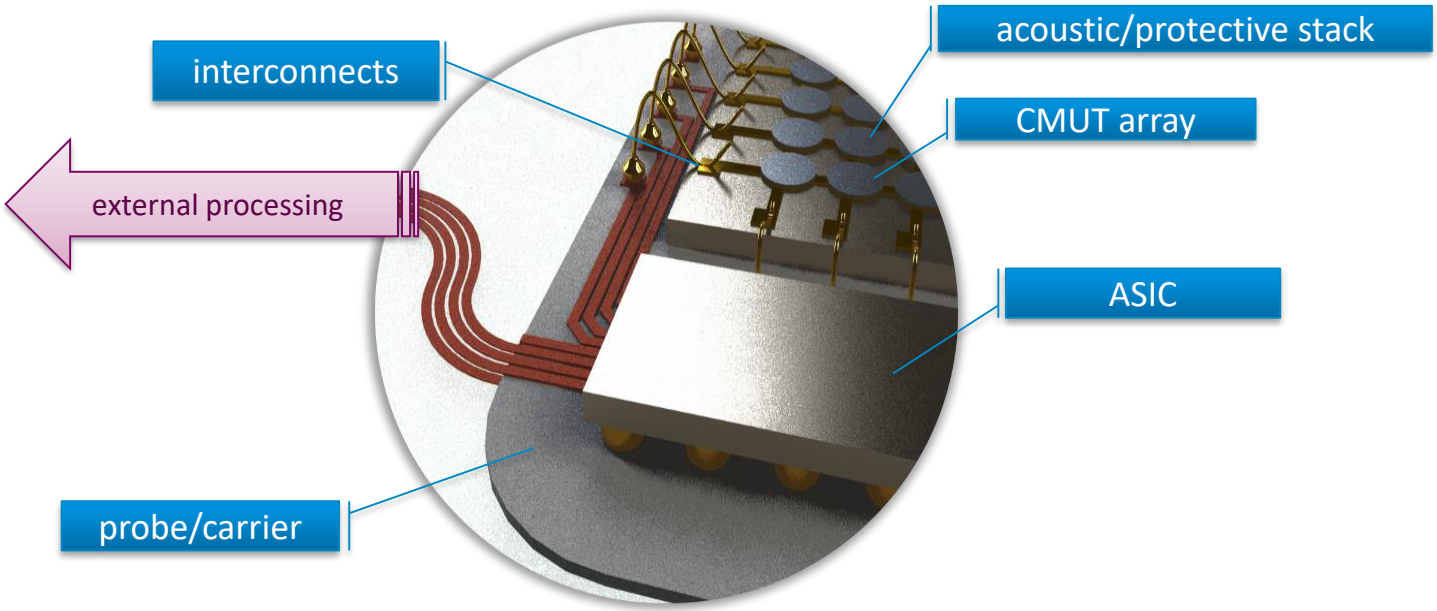
- **Non-traditional diagnostic ultrasound space**
  - Potential for disposable solutions where miniaturization, manufacturing cost and optimized functionality are important differentiators.
  - Wearable, ”one-chip”, ultrasound where BOM costs and freedom of placement & ease of use are key.
  - Ultrasound application for high-frequency (> 15 MHz) solutions.

CMUT Platform

CMUT Platform

design & manufacturing under one roof

Philips MEMS Foundry & Micro Assembly provides the complete CMUT assembly and builds upon the experience of Philips Research



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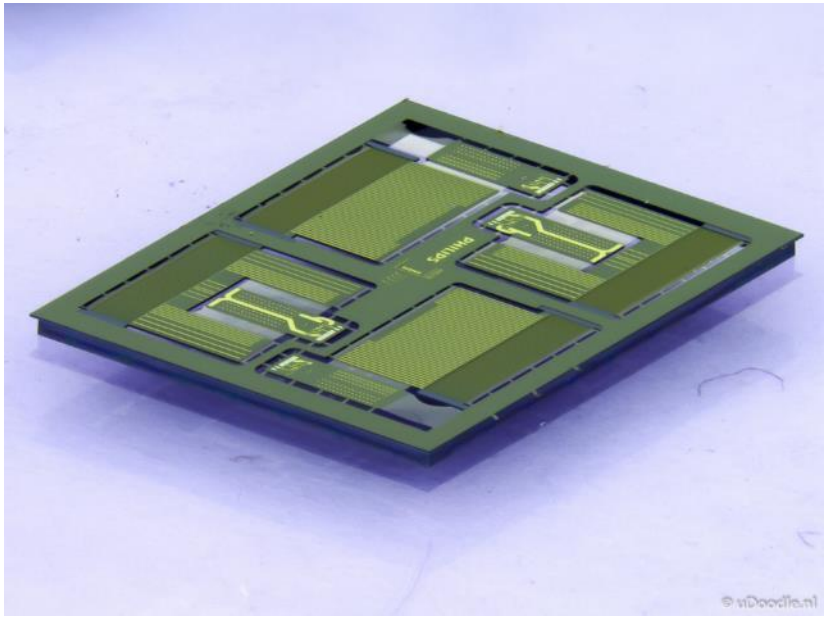
CMUT design choices

Design choices for both the electrical and acoustical domains, based on >10 years of CMUT design experience, results in short Time to Market.

- Dedicated electronics (CMUT-on-ASIC or not)
- Custom design for application
- Characterization & testing know-how



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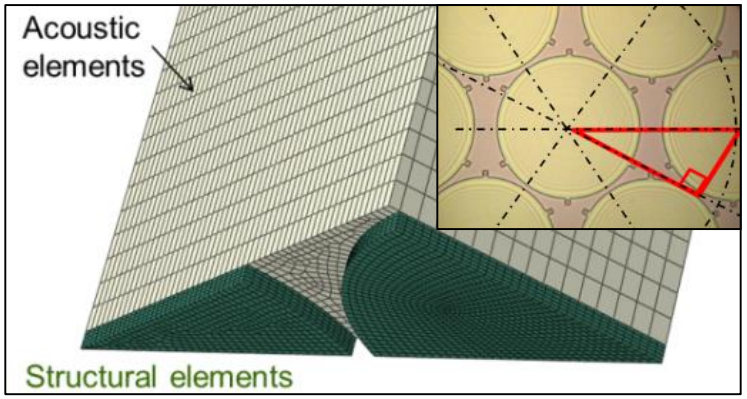
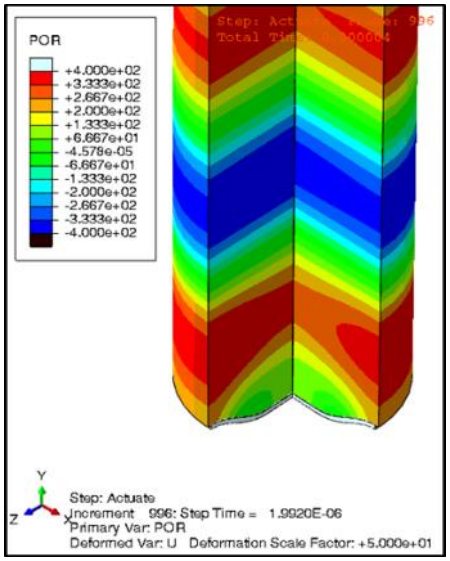
Finite Element Modeling





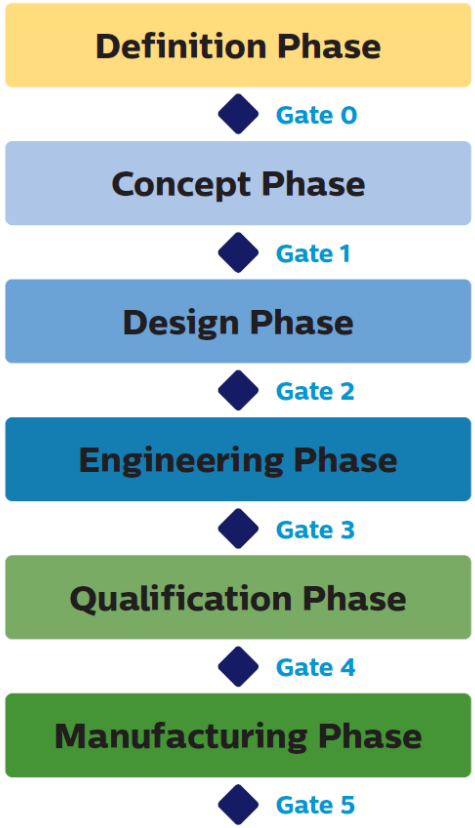
In Philips, CMUT behavior can be fully modeled. We can accurately predict (within 10 % of experiment) efficiency, electrical behavior, frequency and performance before actually manufacturing a design. This enables first time right designs addressing application requirements from the start.

Input: voltage V(t) and structural information

Output: time depended membrane shape, acoustic pressure wave, electrical impedance parameters

Phase-gated approach

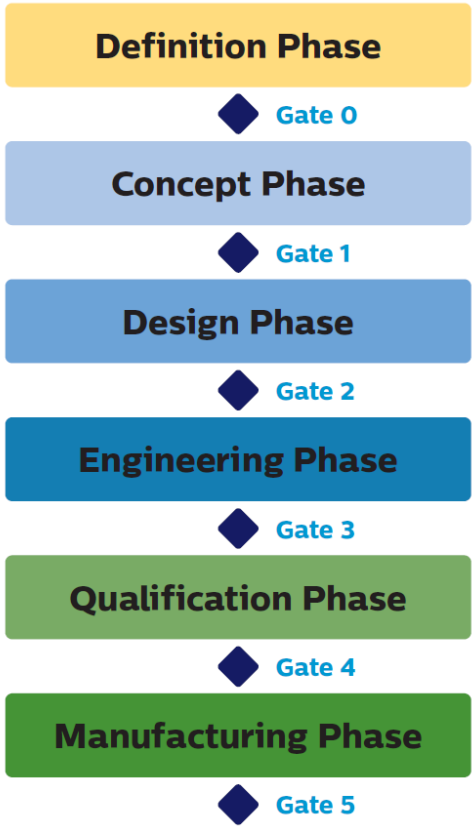
Philips makes use of a phase-gated approach, which ensures a structured way of working to go in a controlled (gated) manner from idea ➔ concept ➔ development ➔ production.



← Status of CM12 CMUT baseline transducers

Custom CMUT transducer development

You benefit from our key know-how/trade secrets for the optimization of the CMUT technology to specific application requirements.
When you opt for a custom device, our experience ensures a speedy **Time to Market.**



← Starting point custom CMUT transducer

← First fabrication runs of custom CMUT transducer. First prototypes.

← Design freeze. Tailoring process on basis of results of first prototypes.

← Finalizing proces.

← Production qualified material. Statistics to verify volume manufacturing.

← Volume manufacturing.

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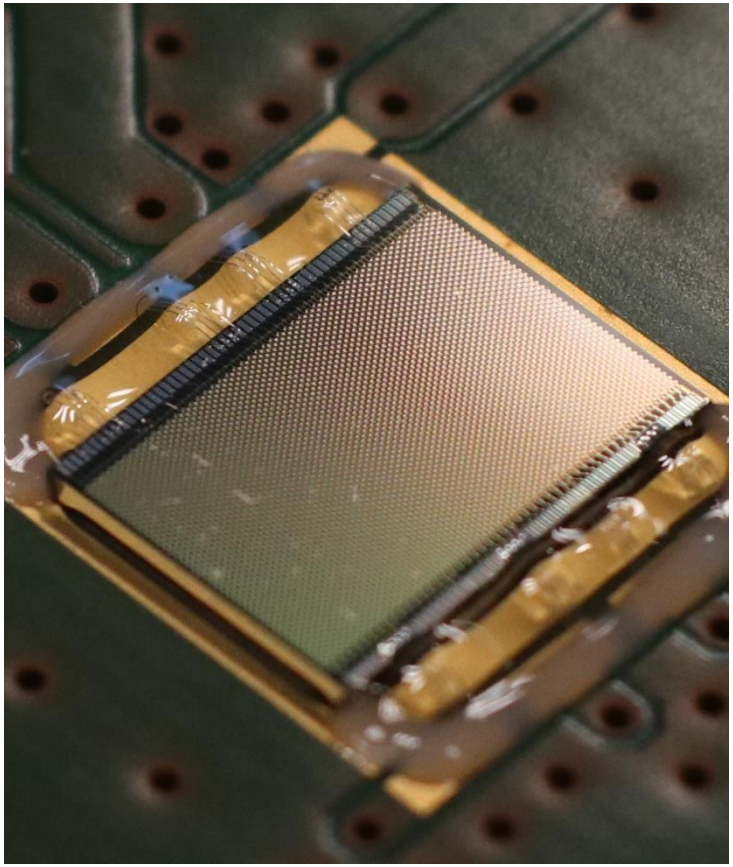
Sample material available

CM12 1D imaging transducer



CM12 1D CMUT imaging transducer

- Process flow frozen
- Key performance parameters:
  - Center frequency: 8.5MHz
  - Bandwidth: 80%
  - Maximum pressure output: 3.5MPa
  - Collapse voltage: 50V
- 96 lines with 42 drums per line
- Available as bare (unassembled) chip, assembled imaging flex and in Evaluation kit module.

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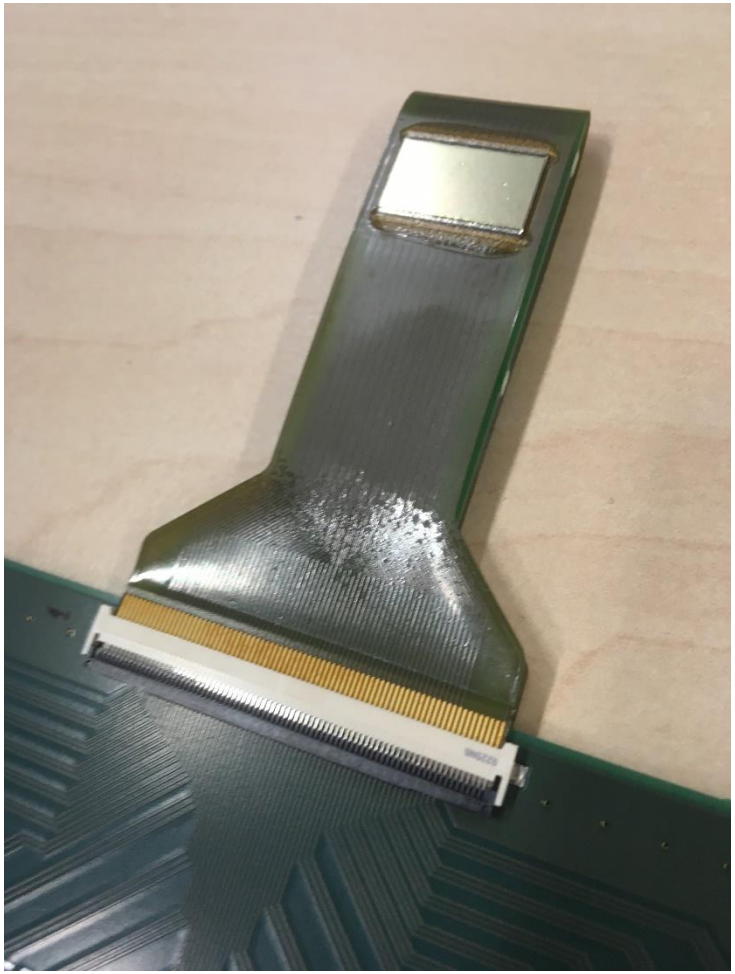
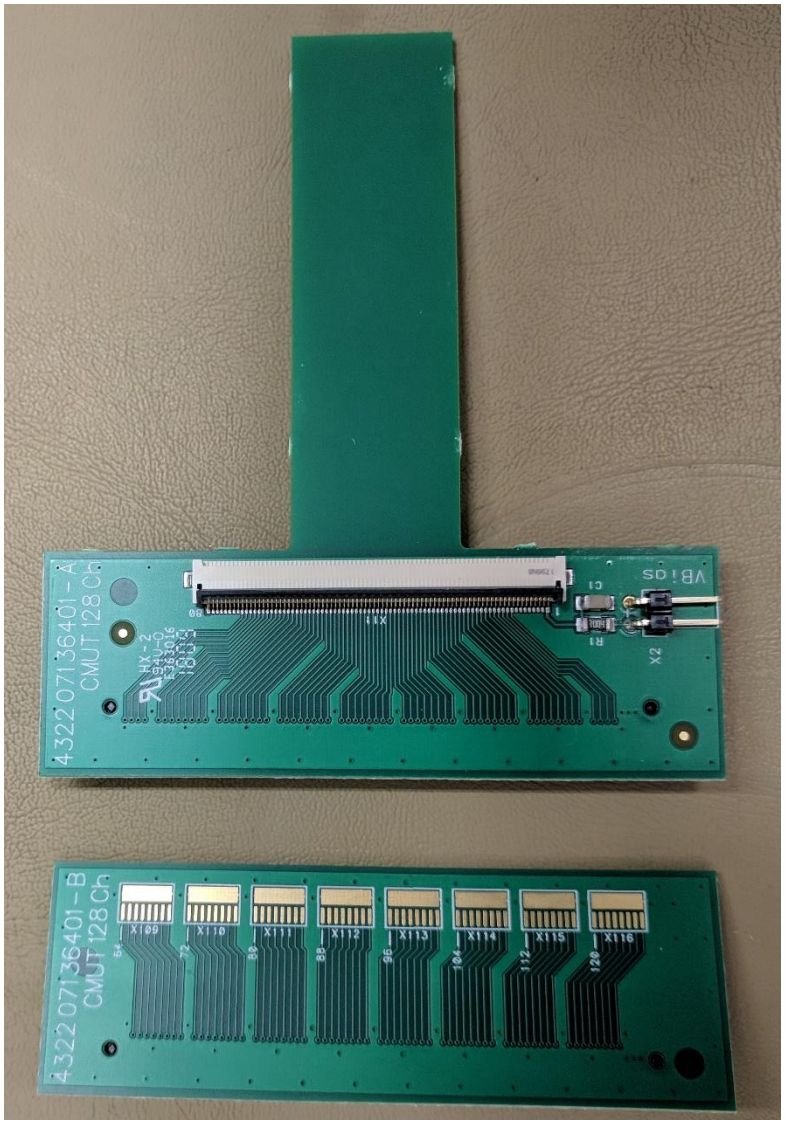
Imaging flex



Flex with CM12 1D CMUT imaging transducer

- All 96 lines connected
- Connects on both front- and backside of available connector PCB

Imaging flex connector PCB



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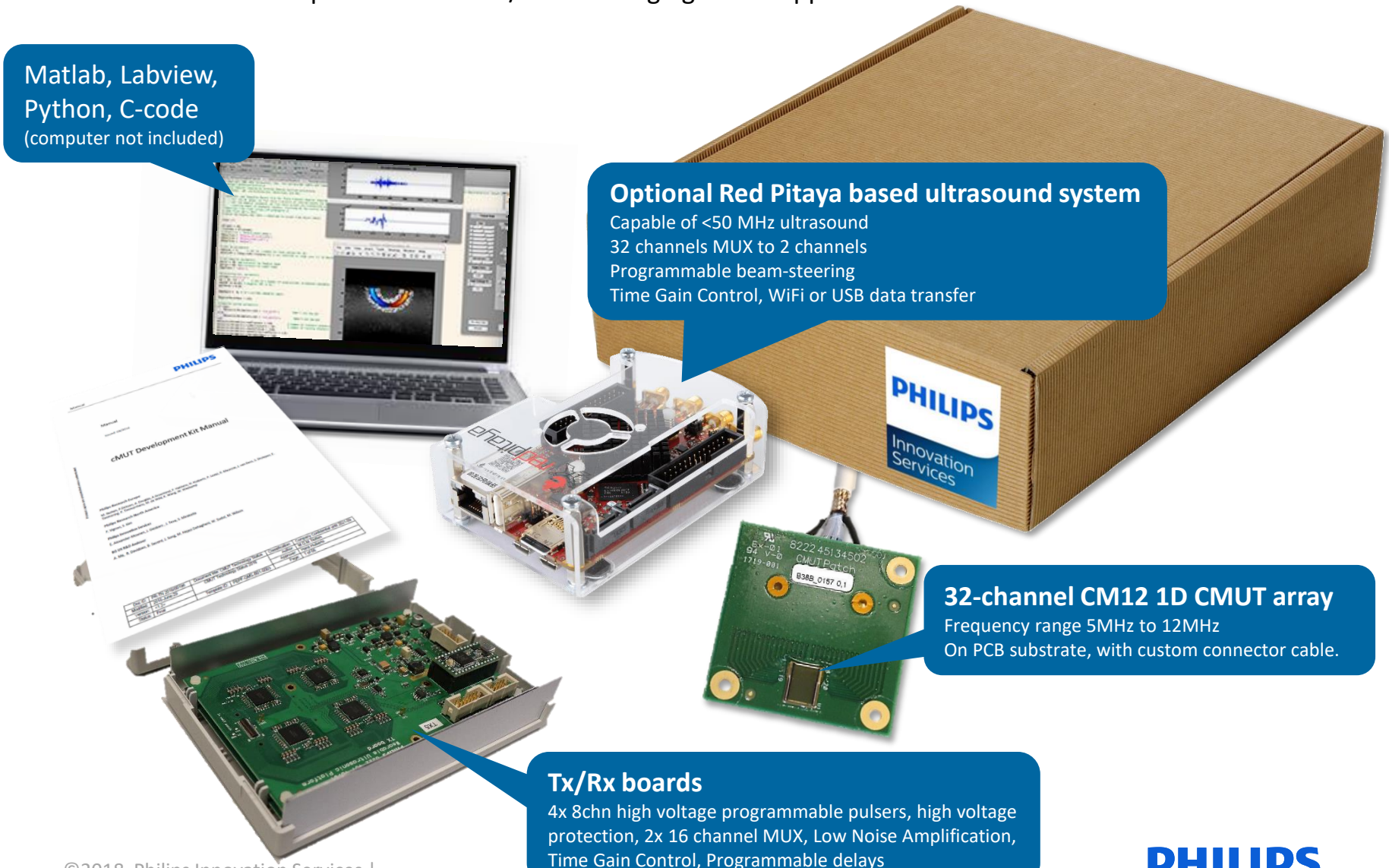
Evaluation kit

For evaluation of CMUT performance and/or non-imaging CMUT applications



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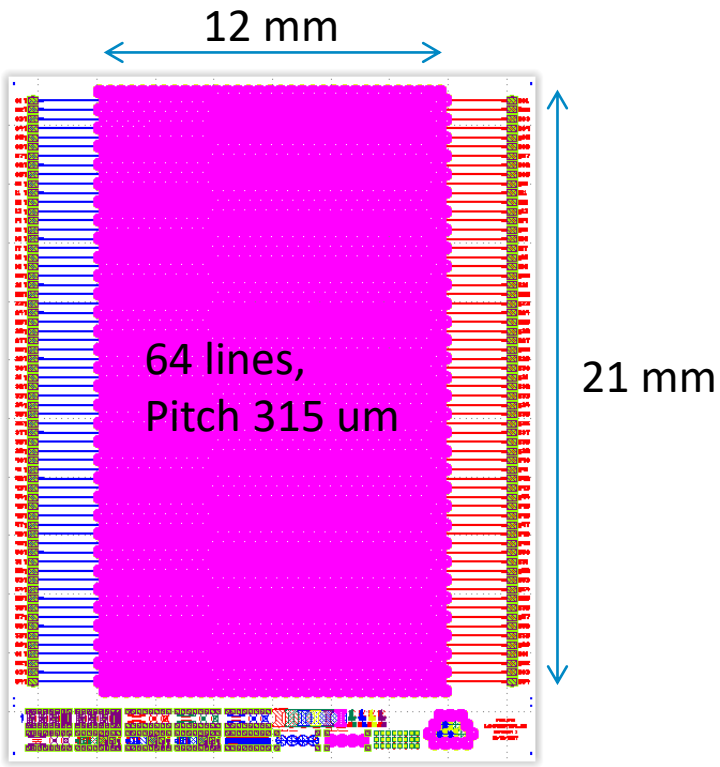
CM5-1 – Soon available

Layout, pitch diameter

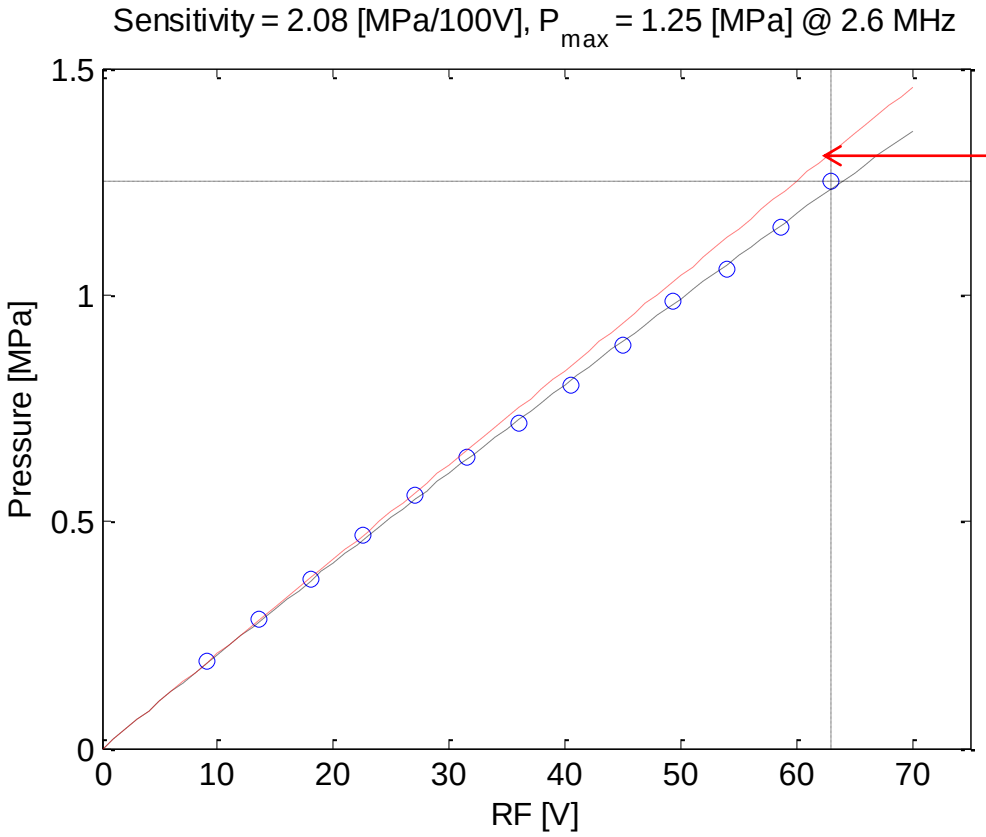
overview



- Active Aperture 21 x 12 mm
- Pitch 315 micron
- 64 elements

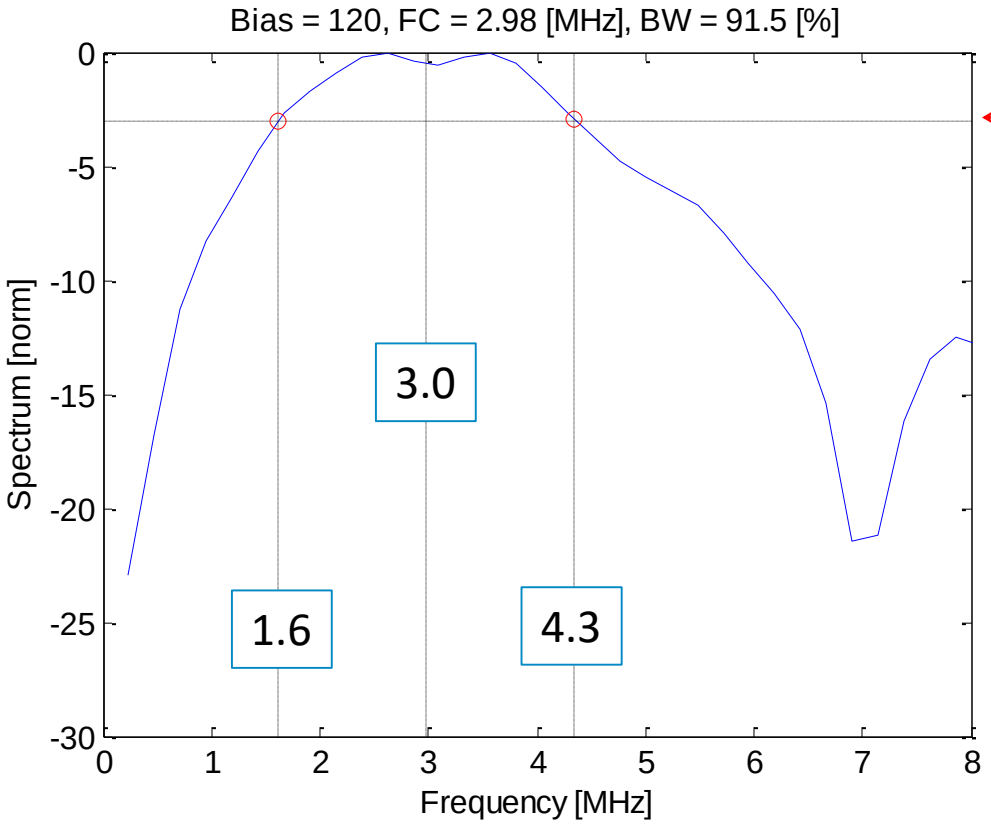
Pressure output linearity

2-Pulse at 2.6 MHz



- Sensitivity 2.08 MPa/100 V
- Max pressure 1.25 MPa at 2.6 MHz
- Collapse voltage 70 Volt
- Nominal Bias 120 Volt
- RF voltage ≤ 60 Volt

Spectrum

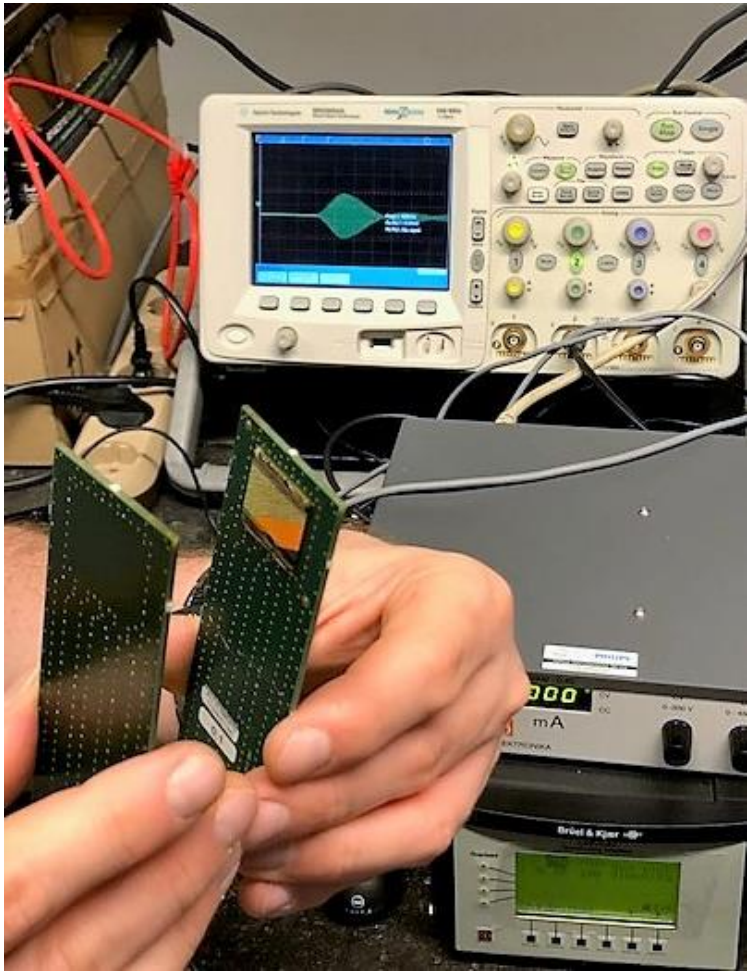


One-way Tx, -3 dB

- Center frequency 3.0 MHz
- Left corner 1.6 MHz
- Right corner 4.3 MHz
- Bandwidth > 90%
- PDMS window

- Optimized window will extend bandwidth to calculated:
  - Left corner 1.2 MHz
  - Right corner 4.6 MHz
  - Bandwidth > 100%

Air coupling experiments

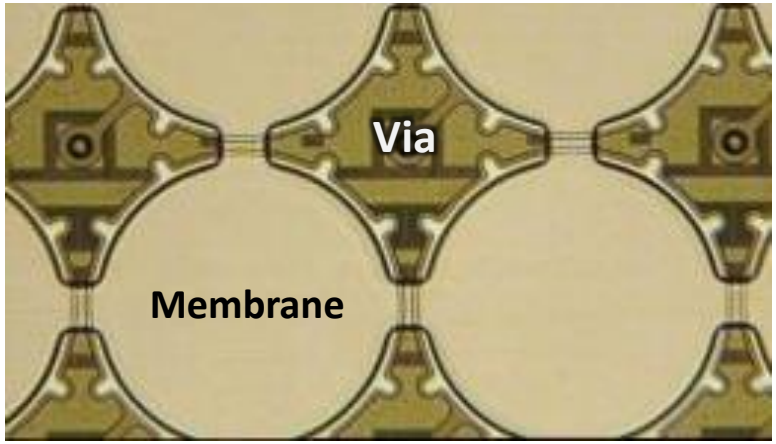


- First crude experimentation done
- Achievable air-coupling frequency: ~850kHz
- Beam steering and focusing functional
- Application-specific investigation needed
- Custom air-coupled CMUT will improve performance

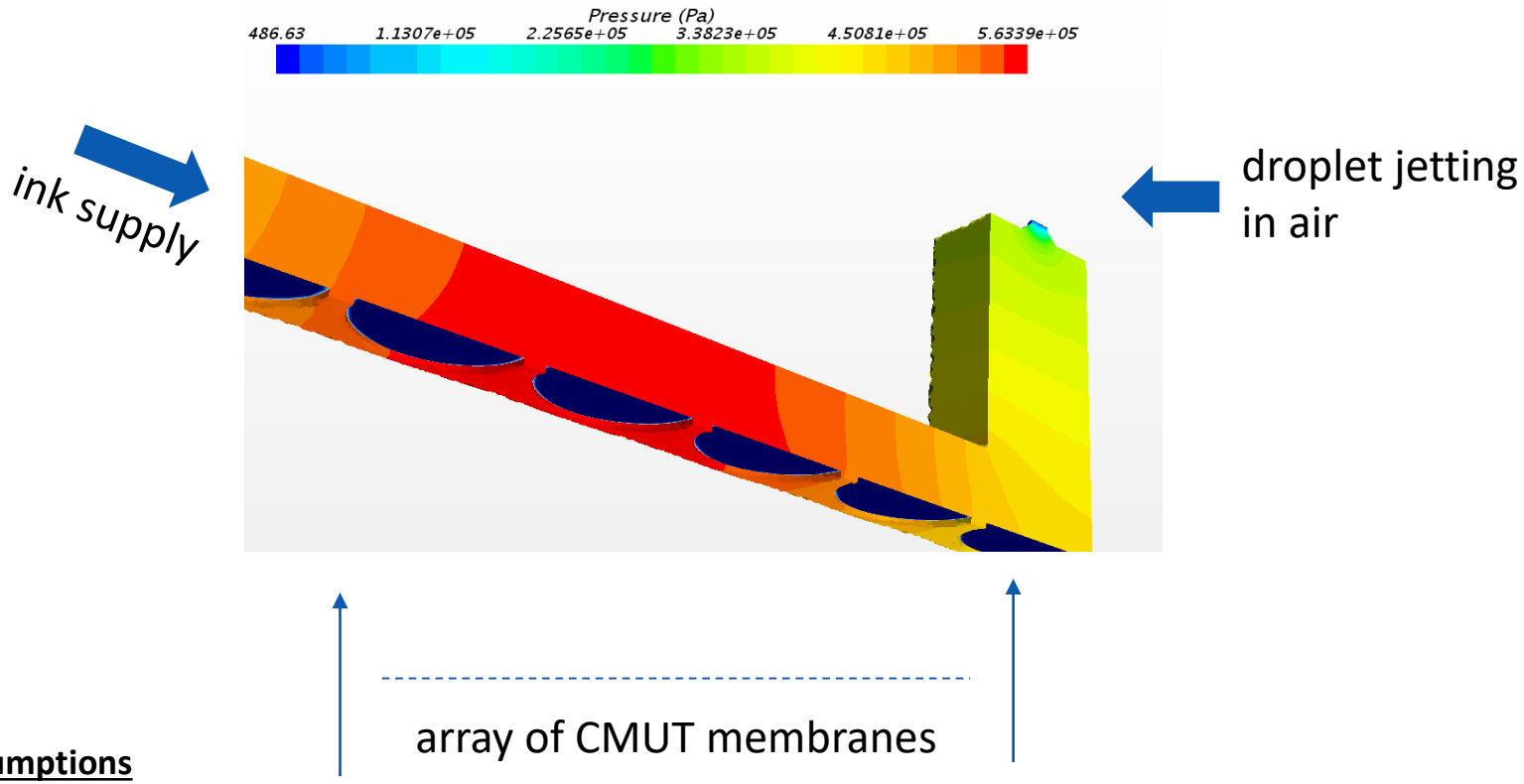
Application examples

Live 3D ultrasound image

- Monolithic integrated CMUT–on-ASIC
- Test array 6×6 mm with 2000 individual elements
- Each element ⇔ one membrane and has it's own transmit and receive circuit



CMUT for inkjet: Pressure



Model assumptions

Properties of ink:

ρ = 1100 kg/m3

μ = 0.01 Pa·s

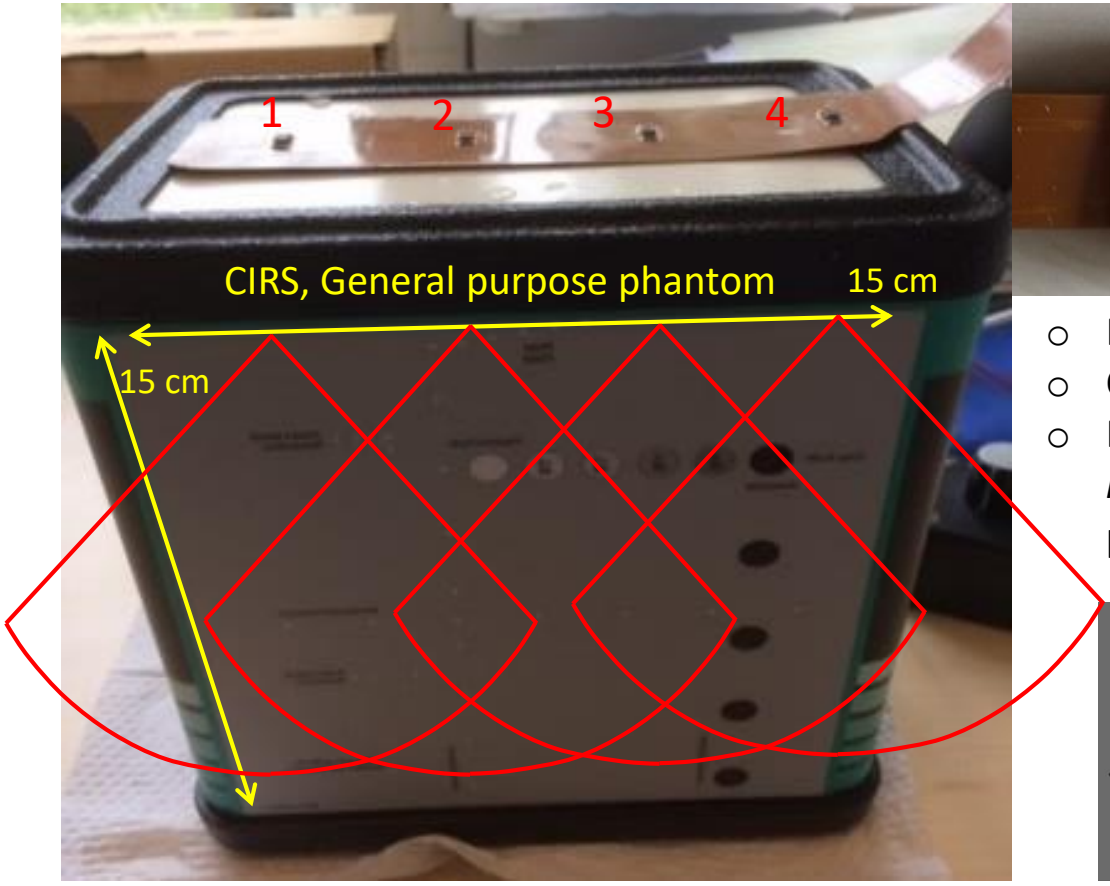
σ = 0.035 N/m

Simple compressibility – linear elastic analogy

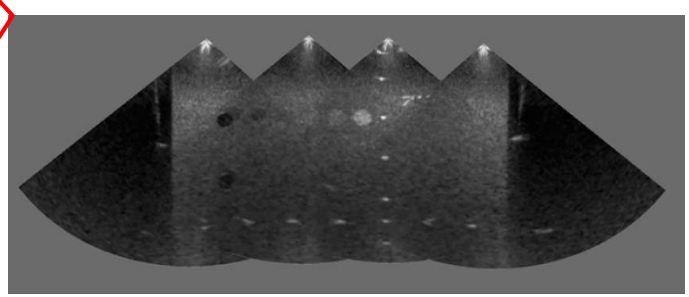
CMUT imaging flex prototypes

Large Field of View Demonstrator

4 CMUT imaging arrays, connected to a commercial USB probe



- Four CMUT array's, well separated
- Cycle through views by switching bias
- Four images are combined into a single *large field of view*, equal to the phantom size



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Catheter-based concepts

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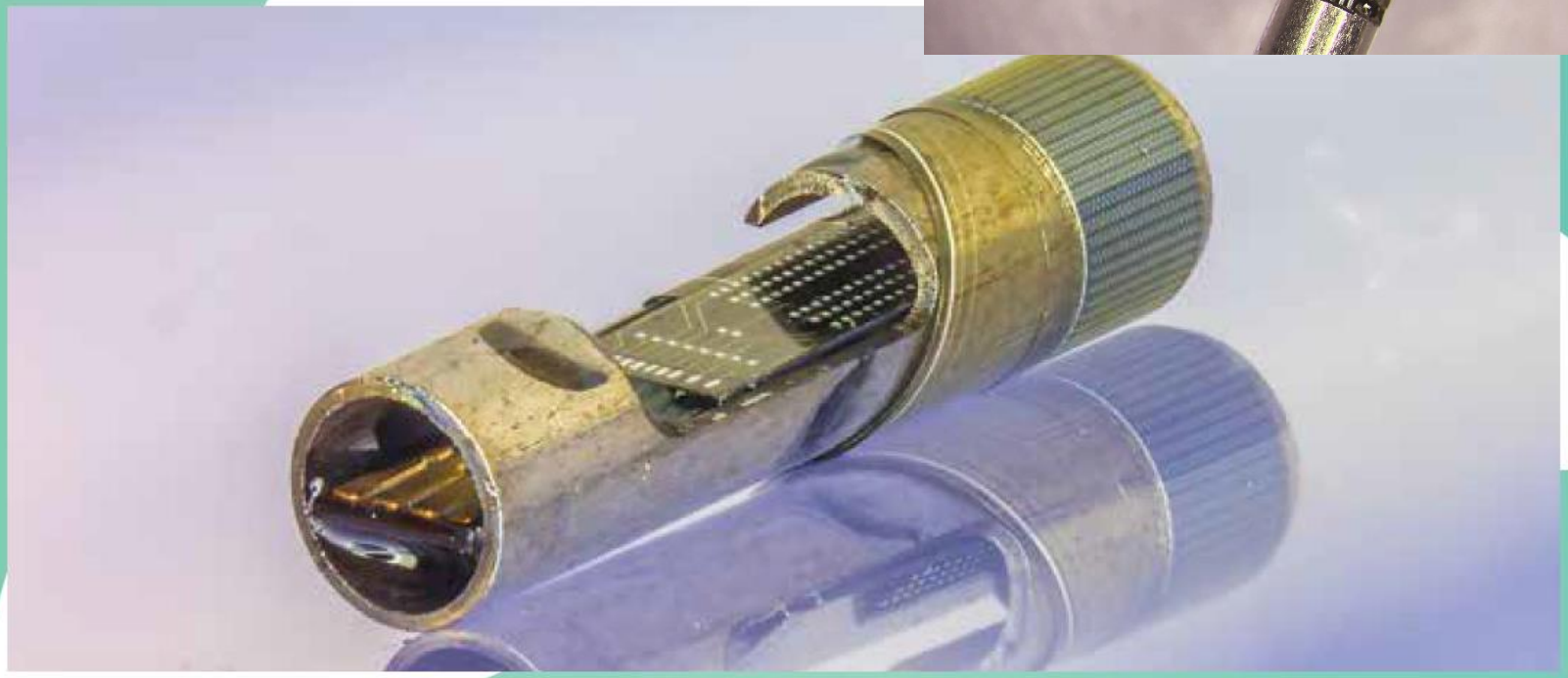
Catheter-based concepts

1 mm diameter intravascular ultrasound transducer comprising 48 individual silicon islands in a circular array



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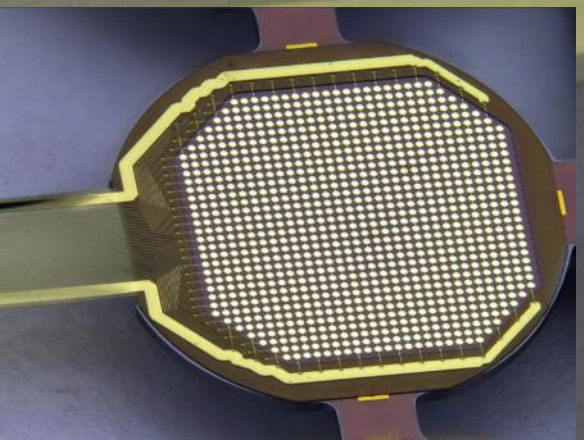
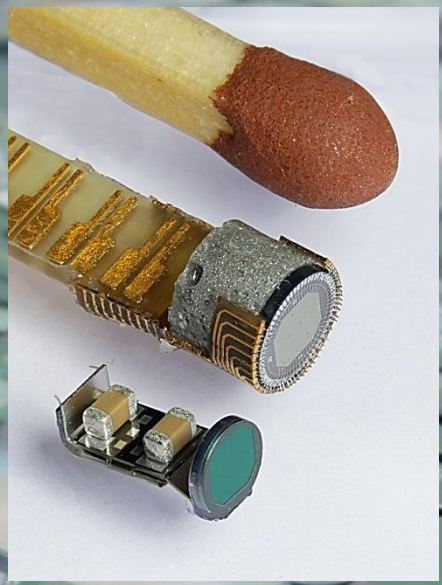
Integrated flexible electrical connections



Wafer based flex-to-rigid platform



Flex-to rigid manufacturing based on standard IC processing

- Integrating rigid silicon components and flexible polyimide interconnect

✓ Arbitrarily shaped circuits
✓ Highly flexible
✓ Further miniaturization
✓ Low cost integration

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