Piezoelectric single- and multi-element ultrasonic transducers for medical applications

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Outline

1 Company introduction

2 Ultrasonic imaging

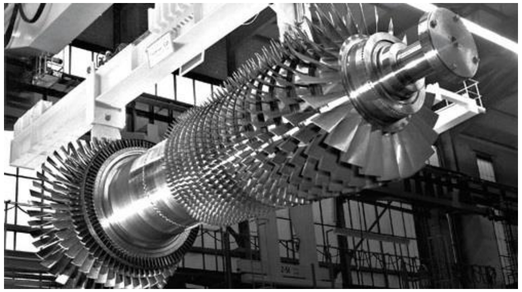
3 Single element transducers

4 Transducer arrays

5 3D imaging

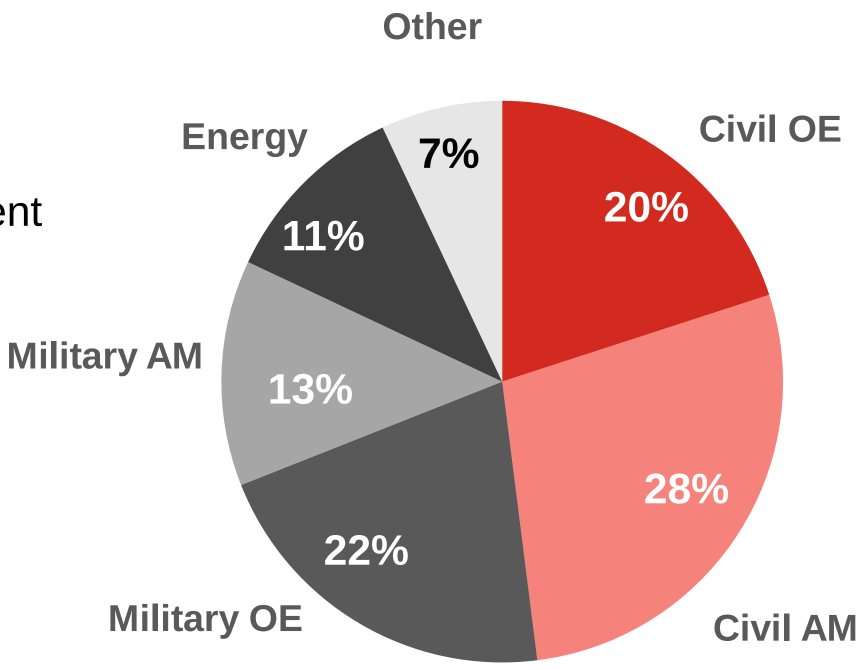
Conclusions

1 Company introduction



Overview

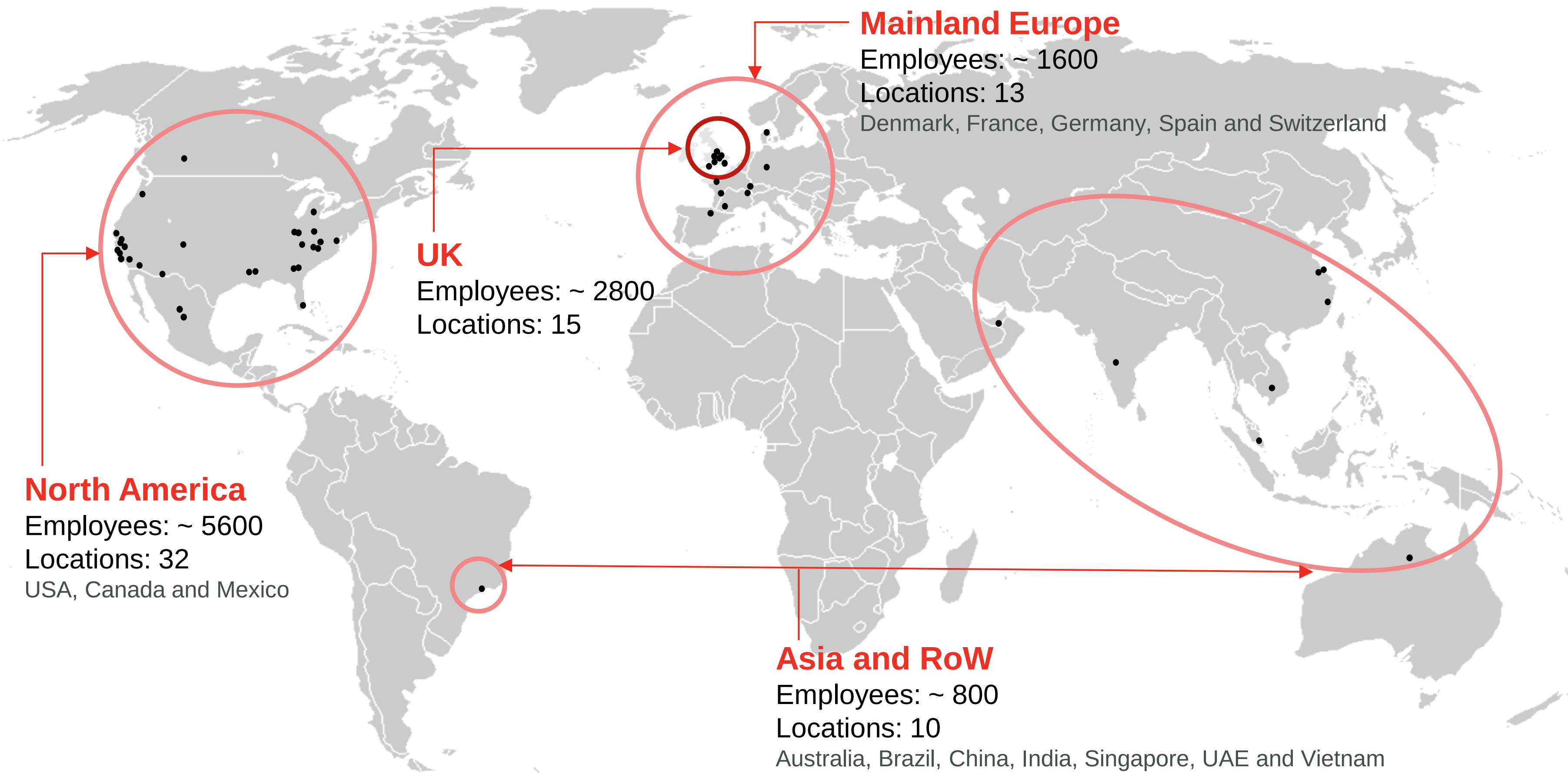
- CTS | Ferroperm is an international global engineering group
  - Extreme environment components and sub-systems for aerospace, defence and energy markets
- Strong expertise in extreme environment engineering
  - High technology products and systems
  - Content on virtually every aircraft – 63,000 installed base
- Well-balanced portfolio
  - Commercial/military/other (48%/34%/18%)
  - Original equipment/aftermarket (41%/59%)
- Global footprint
- Annual sales of £1.554 billion in 2014
- FTSE100 company



Piezoelectric single- and multi-element ultrasonic transducers for medical applications

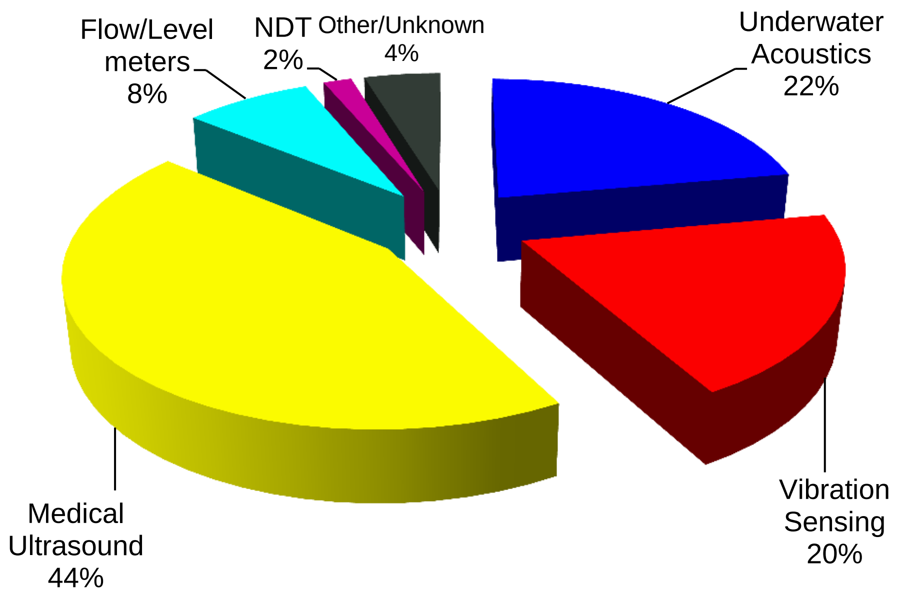
Global presence

~10 800
employees worldwide

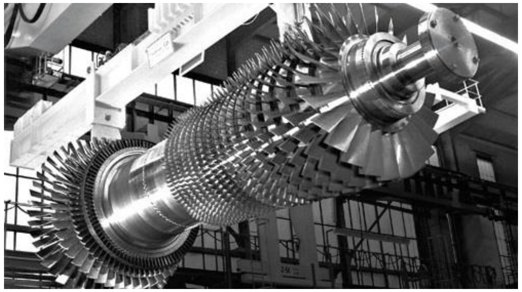


CTS | Ferroperm Denmark

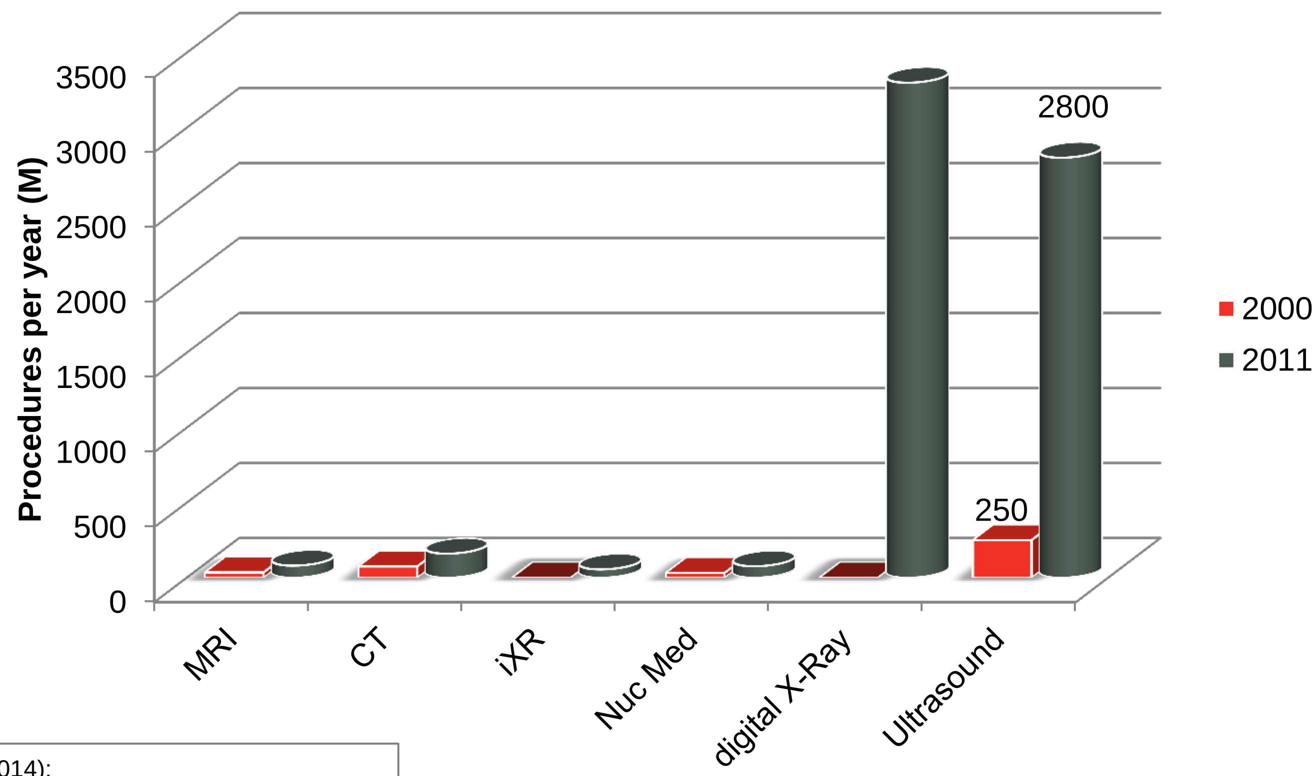
- CTS | Ferroperm is a manufacturer of piezoelectric materials, components, devices of Ferroperm™ Piezoceramics and InSensor™ brands
- 3-4 million units produced annually
- Major markets
  - Medical ultrasound
  - Underwater acoustics
  - Acceleration sensors
  - Flow meters
  - NDT
  - Energy Harvesting



2 | Medical ultrasonic imaging



Global imaging modalities 2011 vs. 2000



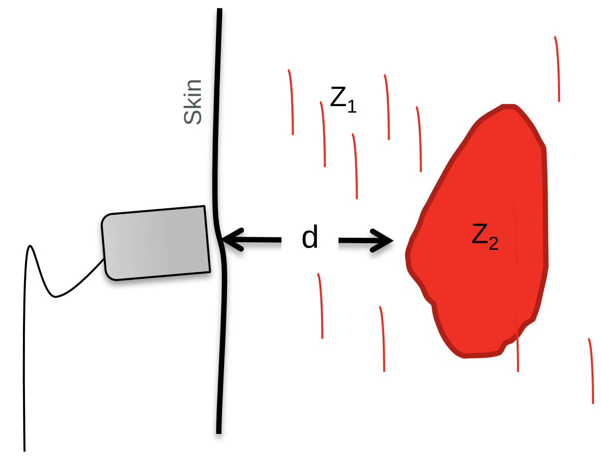
After: T. L. Szabo (2014):
Diagnostic ultrasound imaging: Inside out
Amsterdam, The Netherlands, Elsevier.

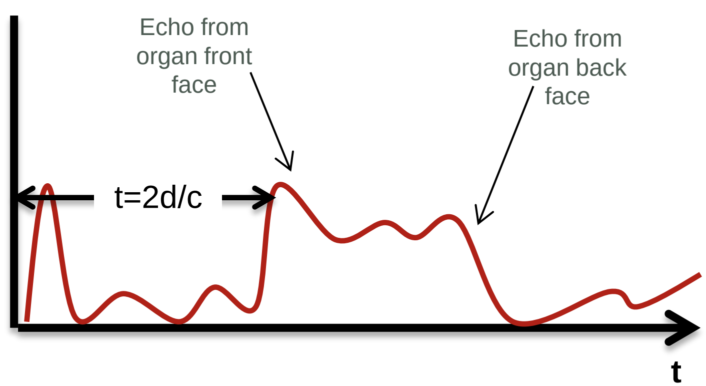
Medical imaging and enabling technologies

	Enabling technology	Ultrasonic imaging
Pre WWII	Piezoelectricity, vacuum tube amp., radar, sonar	Echo ranging, First image of brain, therapy
1950s	Integrated circuits, Phased array antennas	A-mode, Doppler ultrasound, M-mode
1960s	Microprocessors, VLSI	B-mode, Real-time scanner
1970s	RAM, EPROM, ASIC, microcontrollers	Real-time imaging, Gray-scale, arrays
1980s	PC, DSP, CAD of VLSI, SMD	Commercial arrays, Doppler flow imaging, wideband transducers
1990s	Low cost A/D, 3D image processing	Digital US, matrix arrays, commercial 3D systems
2000s	High speed electronics, miniaturization, advanced DSP	Handheld 2D and 3D imaging, elastography, shear wave imaging

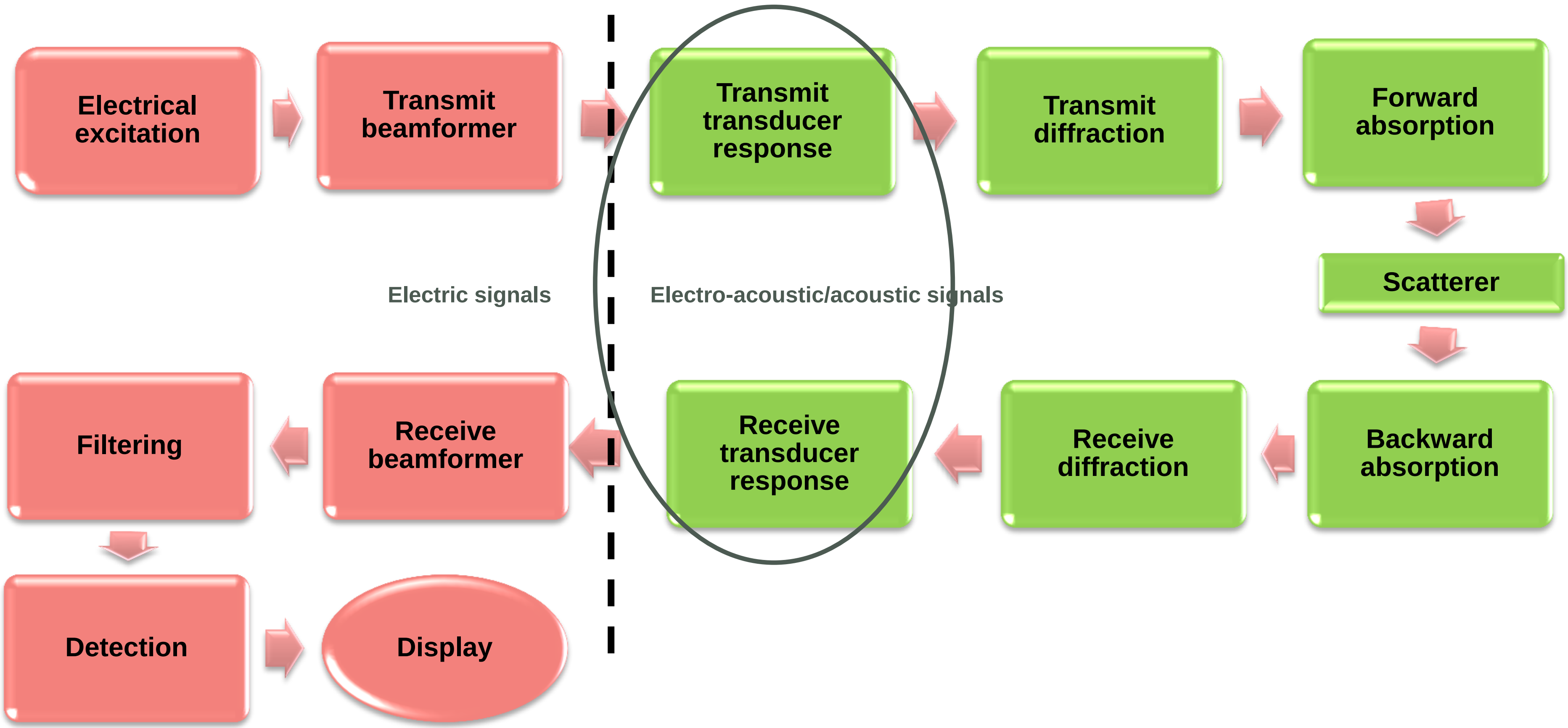
Ultrasonic imaging – basic idea

- Ultrasonic imaging is highly detailed and geometrically correct (average speed of sound in a soft tissue is 1540 m/s and varies only 3%)
- The imaging is enabled by differences of acoustic impedance defined as a product of density and speed of sound ($Z=\rho c$)
- The amplitude reflection factor acoustic plane wave incident at the interface of two tissues (Z_1 and Z_2) is then given by $RF=(Z_1 - Z_2)/(Z_1 + Z_2)$





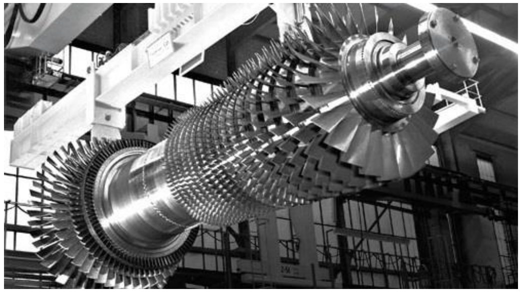
Physical processes in an ultrasonic system



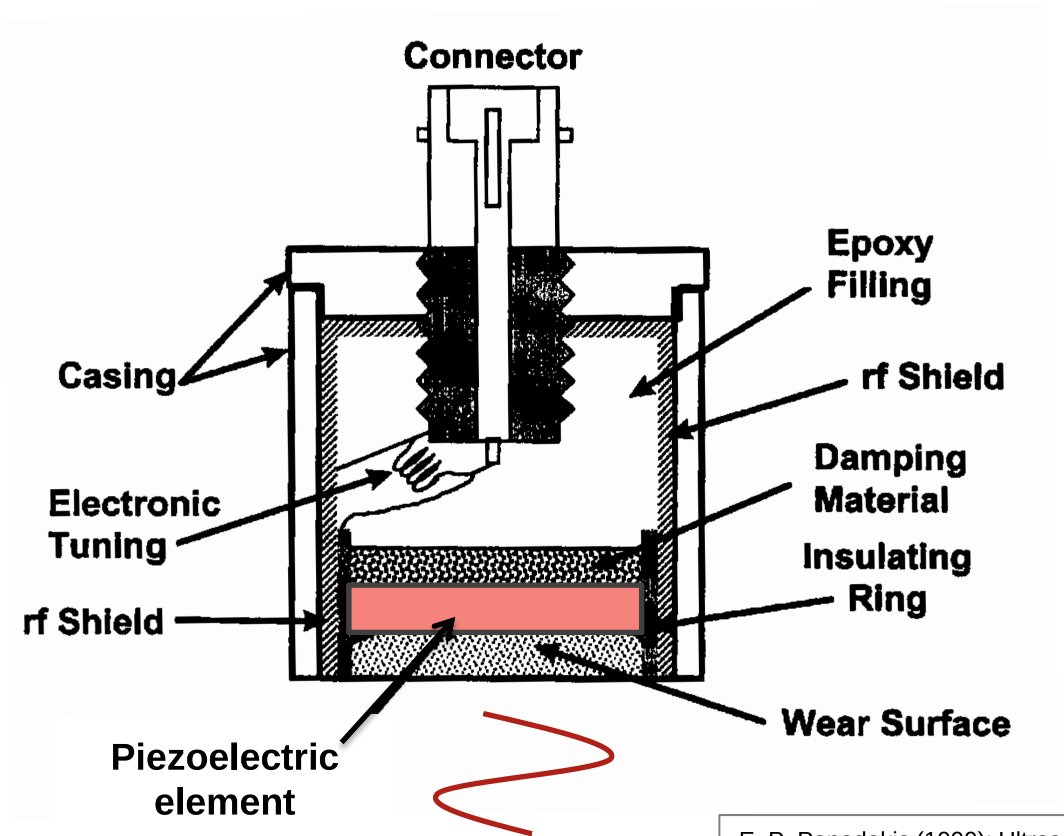
Ultrasonic imaging – basic properties

- Resolution of ultrasound imaging depends on:
  - Aperture size
  - Center frequency
  - Bandwidth
  - Focal depth
- Typical frequencies range from 1-15 MHz, corresponding to lateral resolution of 3 mm to 0.2 mm
- Typically, the best resolution is obtained at the focal depth (due to diffraction)
- Resolution is also affected by attenuation in media, which also depends on frequency (the higher the frequency, the higher the attenuation)

3A | Single element transducers

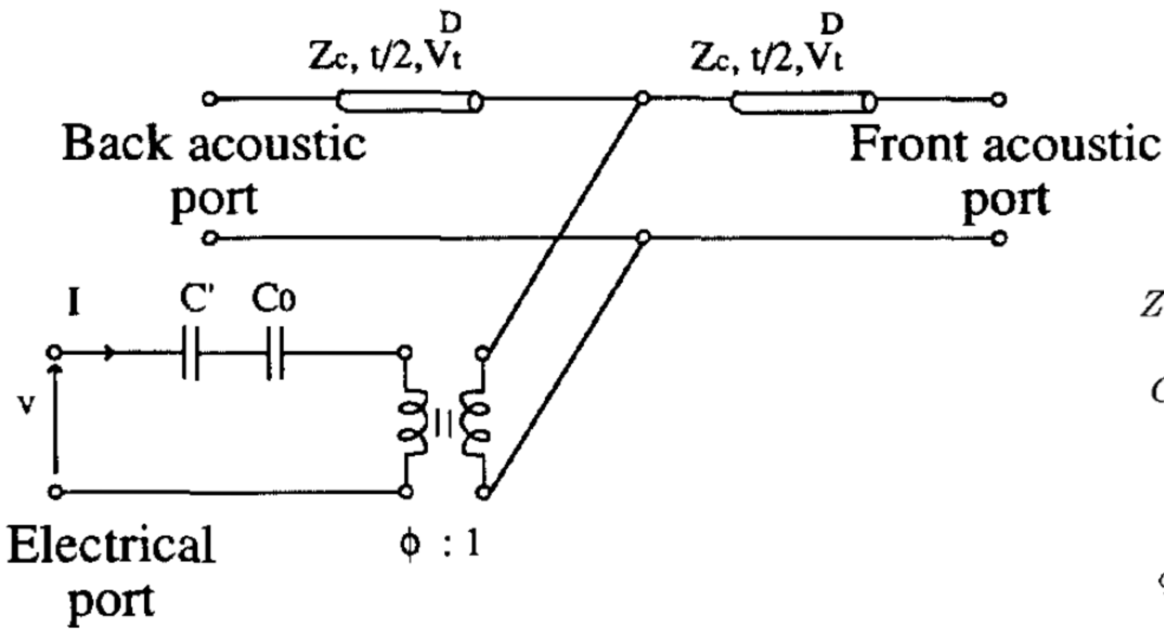


Typical structure



E. P. Papadakis (1999): Ultrasonic Instruments and devices, *San Diego, USA, Academic Press.*

Modelling of a transducer – KLM model



$$Z_c = Z_a l w, \quad C_0 = \frac{\varepsilon_{33}^S l w}{t}$$

$$C = \frac{-C_0}{k_t^2 \operatorname{sinc}\left(\frac{\omega}{\omega_a}\right)}$$

and

$$\phi = k_t \sqrt{\frac{\pi}{\omega_a C_0 Z_c}} \operatorname{sinc}\left(\frac{\omega}{2\omega_a}\right)$$

with

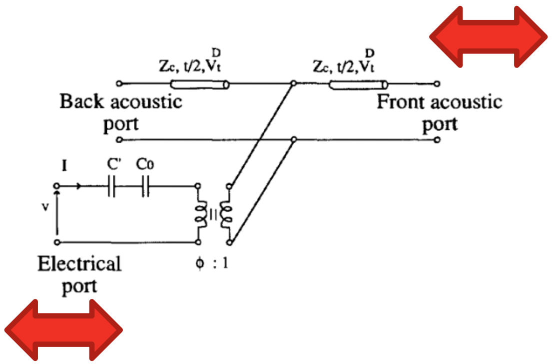
$$\operatorname{sinc}(x) = \frac{\sin(\pi x)}{\pi x}.$$

R. Krimholtz, D. A. Leedhom, and G. L. Matthaei (1970): New equivalent circuits for elementary piezoelectric transducers, *Electron. Lett., vol. 6, no. 13, pp. 389-399*

Matching – optimizing energy transfer

- The transducer has maximum broadband sensitivity only when properly matched to the driving circuit (electrical matching) and the patient (acoustical matching)
- Typically a passive circuit network is used for electrical matching (targeting 50 Ohm matching)
- Acoustic matching is typically obtained by using additional matching layers on the front of the transducer
- Typically λ/4 layers are used with acoustic impedance between the Z_t = 34 MRayls (typical PZT) and 1.5 MRayls (human body)

Acoustic matching

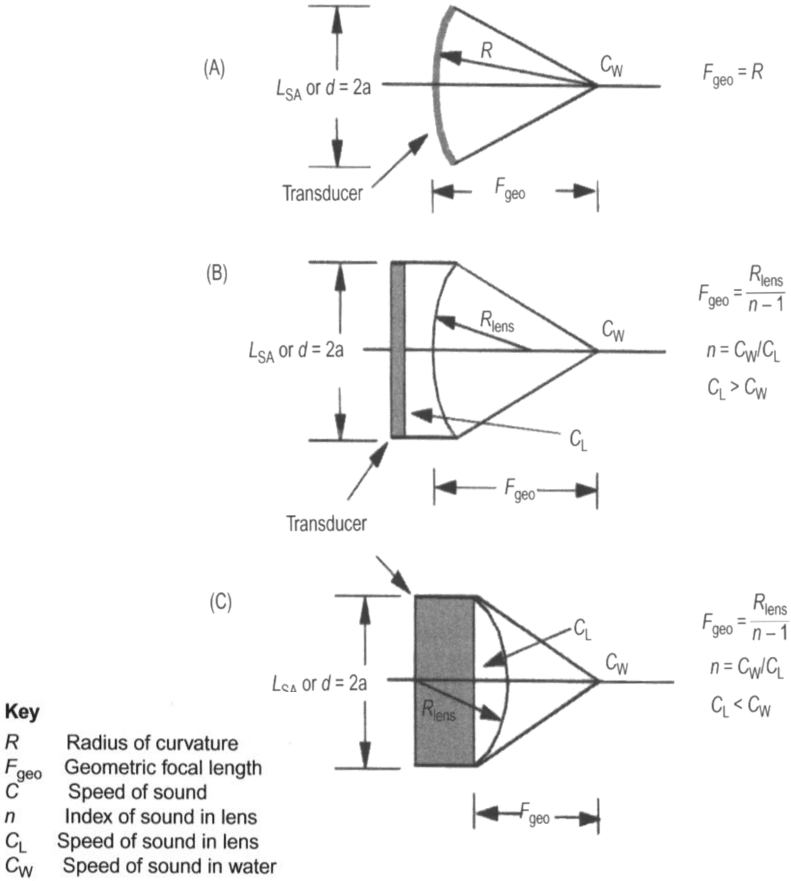


Electrical matching

Focusing

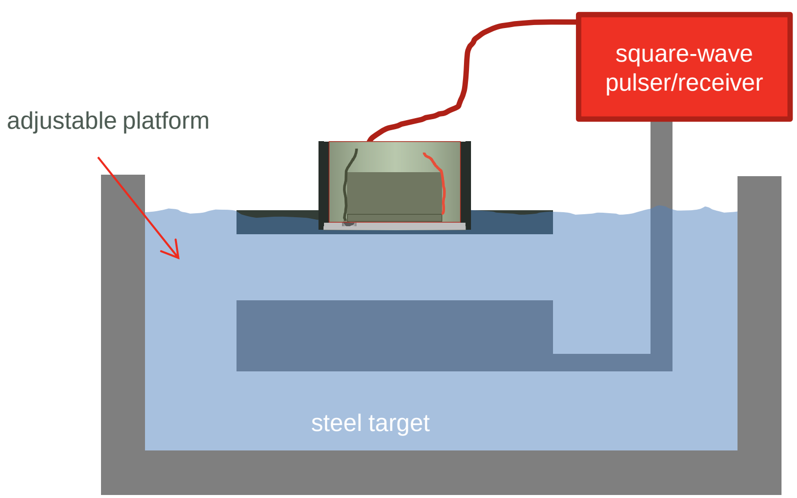
After: T. L. Szabo (2014):
Diagnostic ultrasound imaging: Inside out
Amsterdam, The Netherlands, Elsevier.

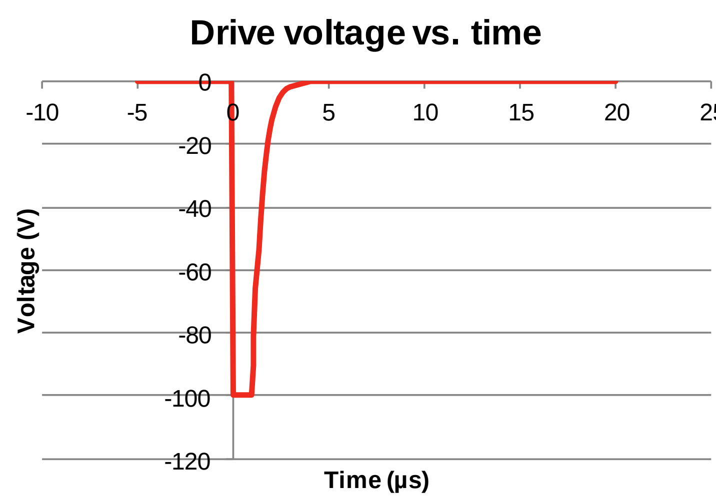
- Focusing is used to increase the spatial resolution in a selected region
- There are similarities between optics and acoustics, e.g. focal region, focal length
- However, apertures do not have to be circularly symmetric, lenses can be made out of materials having equivalent refraction index less than one
- Acoustic focusing can also be achieved by electronic means



Pulse-echo test set-up (round-trip testing)

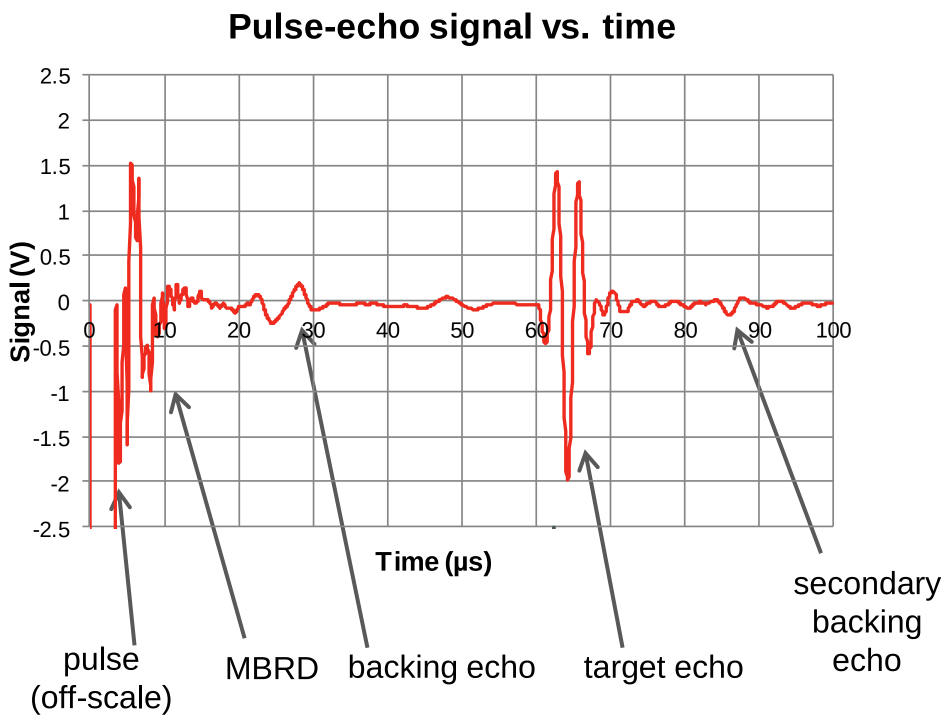
- A pulse-echo transducer uses the same element to send out the signal and monitor the returning sound echoes
- The transducer rests on a platform with adjustable angle with respect to the target surface (in order to make the face of the transducer parallel to the face of the steel target)
- Typically a signal amplitude of 100 V was used, and the period of the pulse was varied to maximise the return signal (~ pulse period corresponding to one half the period of the transducer's resonance frequency)



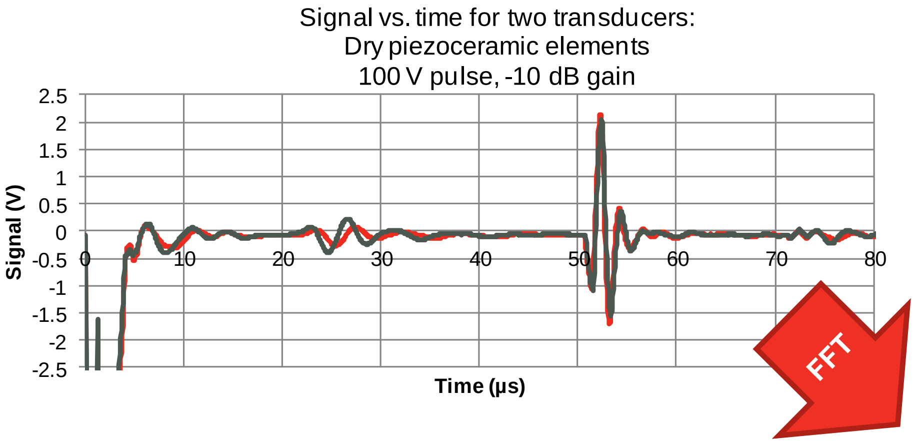


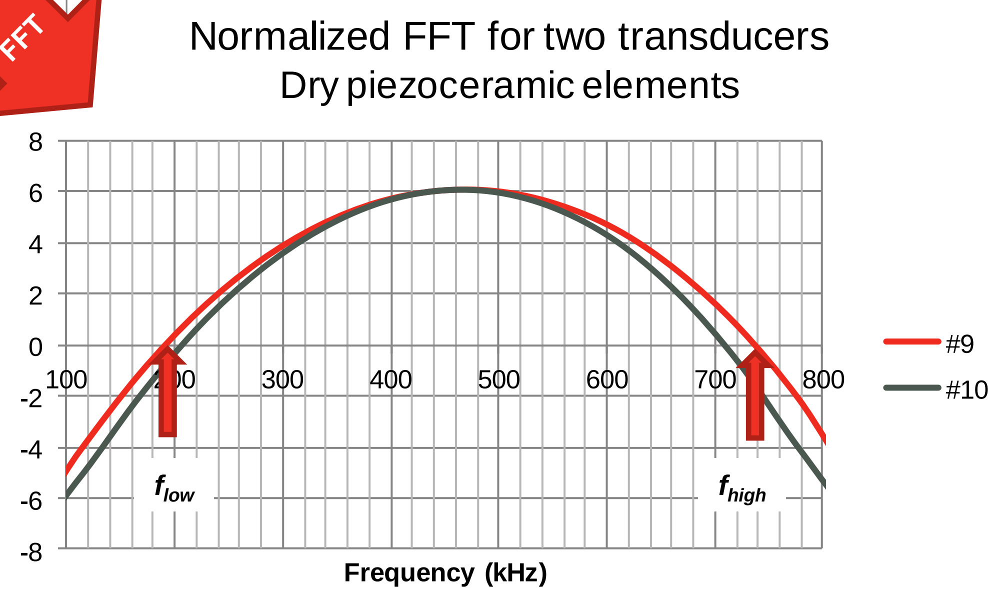
Characteristics of a pulse-echo signal (example)

- The *pulse* is a high-voltage drive; amplification of the actual signal is turned on after the pulse event is completed
- The *main-bang ringdown* (MBRD) is a period where high acoustic energy reverberates in the piezo-element
- The signal has a *backing echo* starting at about 20 µs and a secondary one at about 85 µs
- The actual *target echo* arrives at about 60 µs



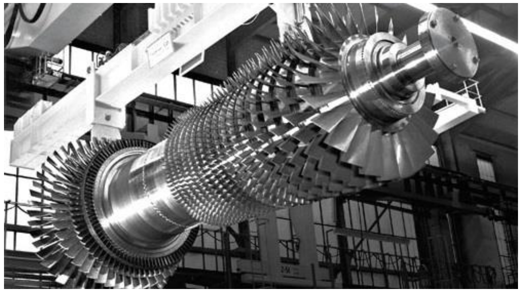
Frequency domain pulse echo properties





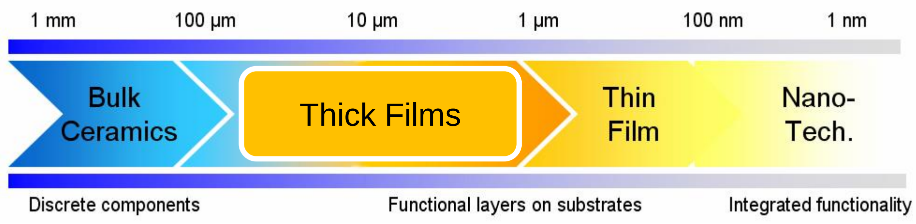
- » Center freq. (f_c) = (f_{high}+f_{low})/2
- » Bandwidth (BW) = f_{high}-f_{low}
- » Fractional bandwidth (fBW) = BW/f_c

3B PZT Thick film imaging transducers



PZT thick films – InSensor™

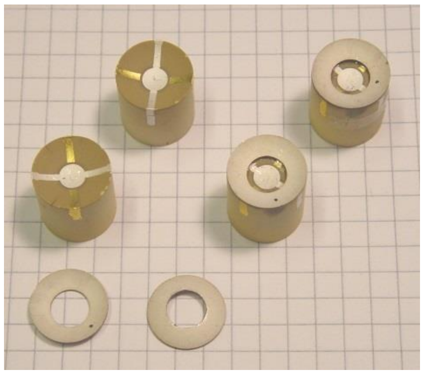
» Technology of piezoelectric thick films – enabling deposition and integration of piezoelectric layers (10 µm to 100 µm in thickness) with high lateral resolution (100 µm x 100 µm)



» Key features of InSensor™ technology
- Capable of manufacturing miniaturized devices
- Low prototyping costs
- High volume production
- High lateral resolution
- High frequency
- High response
- Piezoelectric material can be deposited on a number of different substrates (compatible with MEMS)

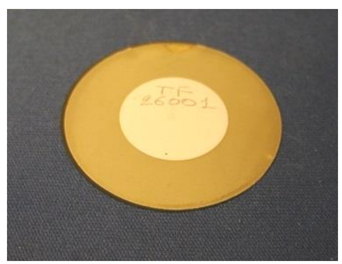
PZT thick film compatibility

SUBSTRATES

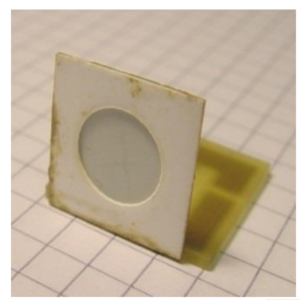


Ceramics

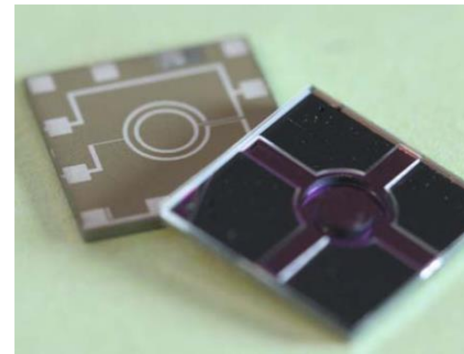
A.Guiroy, A.-P. Abellard, E. Ringgaard, R. Lou-Moeller, T. Zawada, A. Novell, J.M. Gregoire, A. Bouakaz & F. Levassort (2013): Dual-frequency transducer for nonlinear contrast agent imaging. *IEEE Trans. UFFC*, **60** [12] 2634-2644.



Stainless steel



LTCC

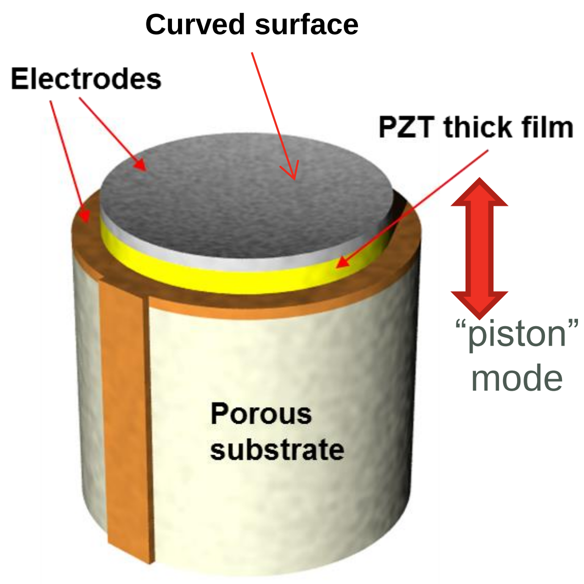


Silicon

T. Zawada, K. Hansen, R. Lou-Møller, D. Jurkow, E. Ringgaard, L. Golonka (2009): LTCC Electromechanical Devices Based on PZT Thick Film Technology, *Proc of CICMT 2009*

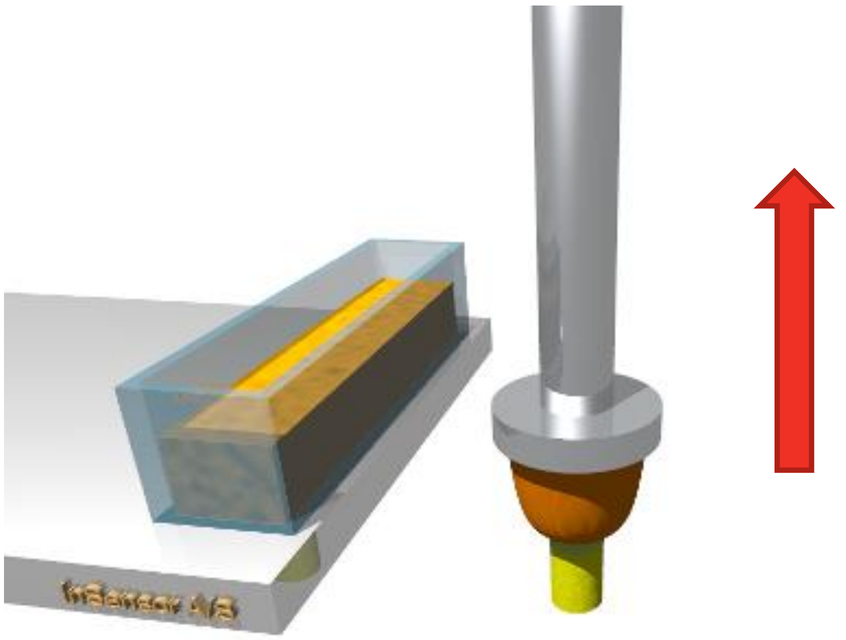
Thick-film ultrasonic transducers - concept

- The characteristics of the printed thick film make it a perfect candidate for medical imaging due to the following:
  - More than 20 % porosity
  - Low acoustic impedance
  - Low permittivity
  - High frequency (more than 20 MHz) easily obtained without machining
- When the thick film is combined with the optimised substrate, a fractional bandwidth above 100 % is measured

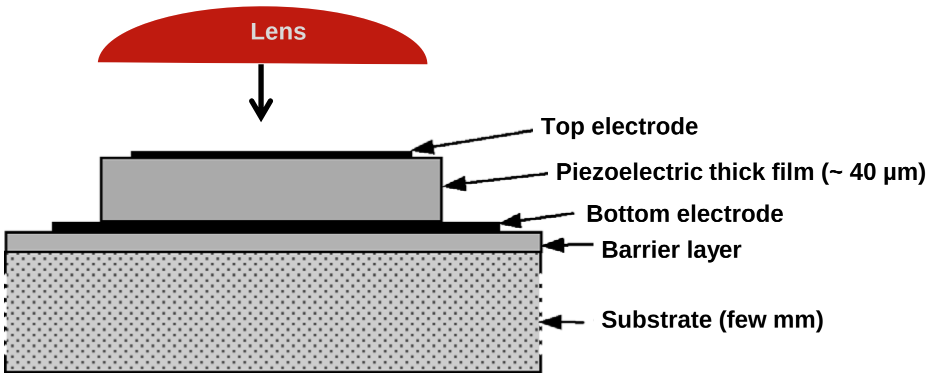


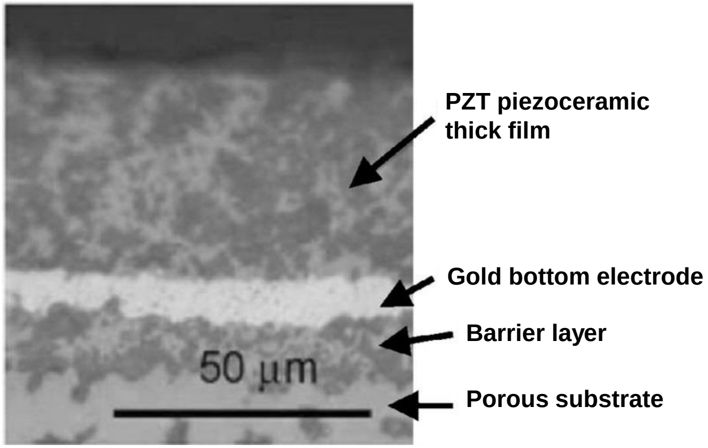
Typical structure of a high-frequency acoustic transducer based on thick film

Fabrication method – pad printing



High frequency imaging transducer

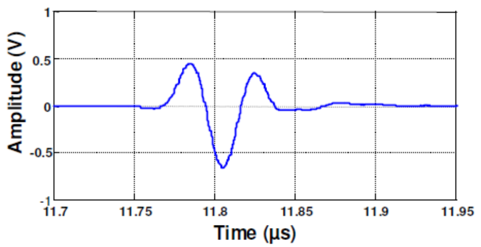


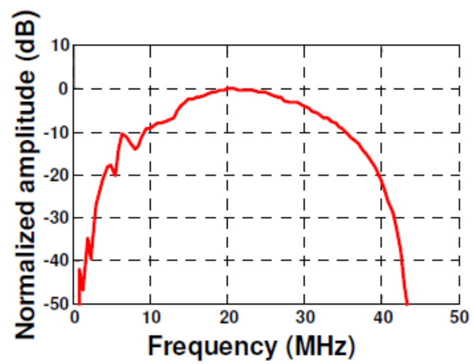


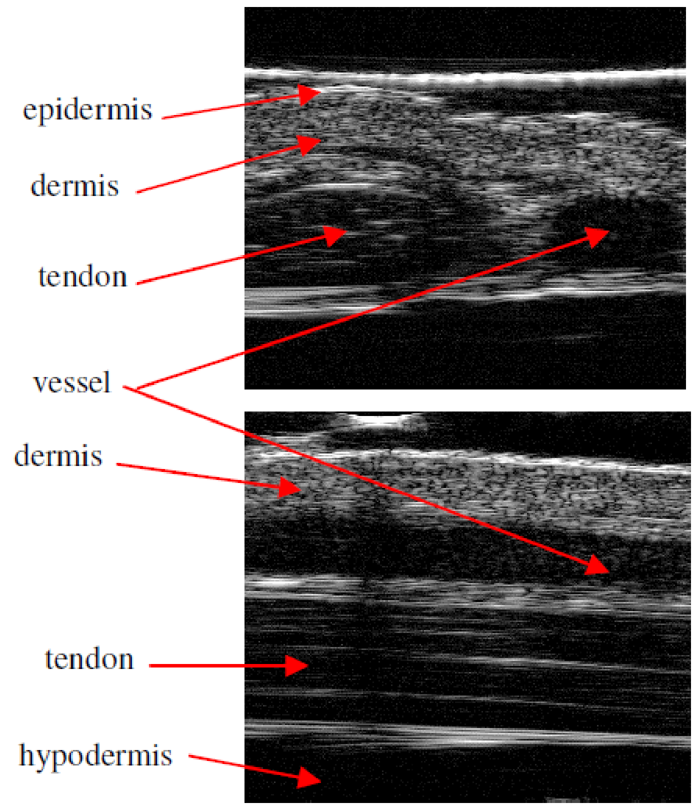
P. Maréchal, F. Levassort, J. Holc, L.-P. Tran-Huu-Hue, M. Kosec & M. Lethiecq (2006): High-frequency transducers based on integrated piezoelectric thick films for medical imaging. *IEEE Trans. UFFC*, **53** [8].

cf. F. Levassort, L. P. Tran-Huu-Hue, J. Holc, T. Bove, M. Kosec & M. Lethiecq (2001): High-performance piezoceramic films on substrates for high-frequency imaging. *In* Proc. IEEE Ultrason. Symp. 2011, 1035-1038.

High frequency transducer manufacturing





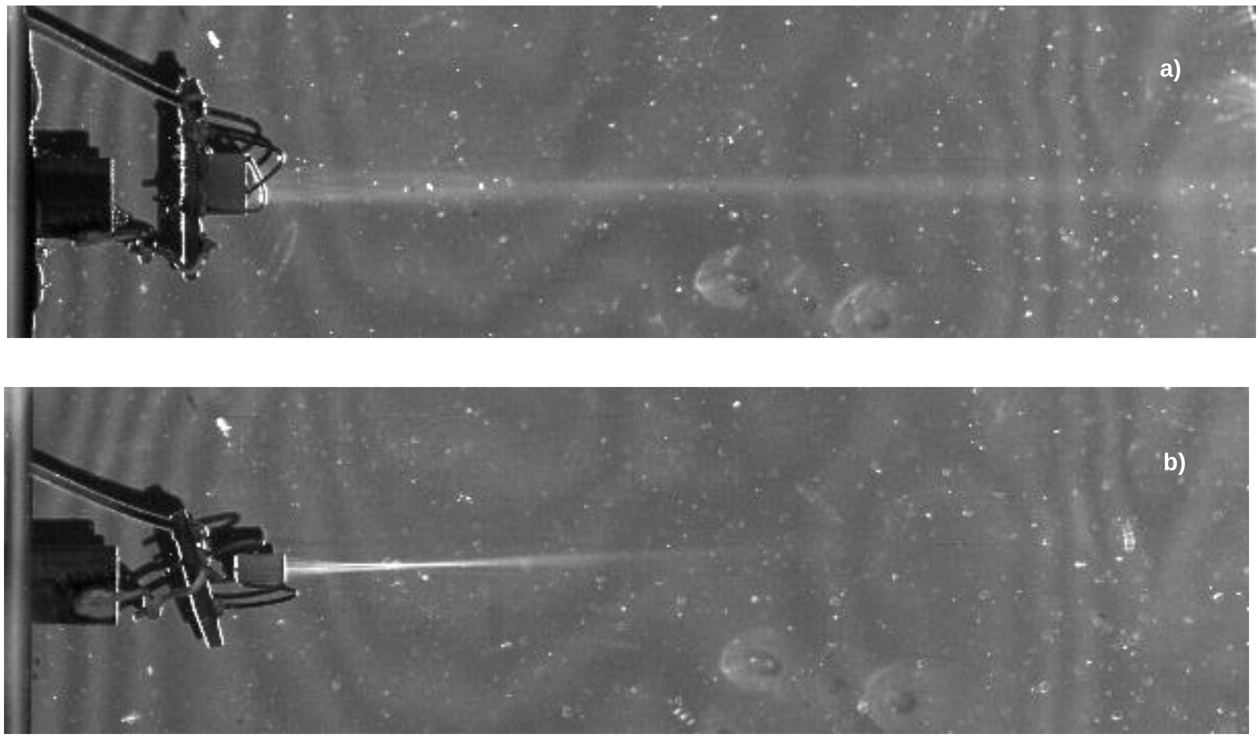


Piezoelectric material	Process	F (mm)	DOF_6 (mm)	Δz_6 (µm)	BW_6 (%)	BW_{20} (%)
PZT	Pad-printing	8.7	2.7	41	82	150

[1] F: measured focal distance; DOF_6: depth of field at –6 dB; Δz_6: axial resolution, BW_6: relative bandwidth at –6dB, BW_{20}: relative bandwidth at –20 dB.

F. Levassort, E. Filoux, M. Lethiecq, R. Lou-Møller, E. Ringgaard & A. Nowicki (2006):
Curved piezoelectric thick films for high-resolution medical imaging.
In Proc. IEEE Ultrason. Symp. 2006, 2397- 2400.

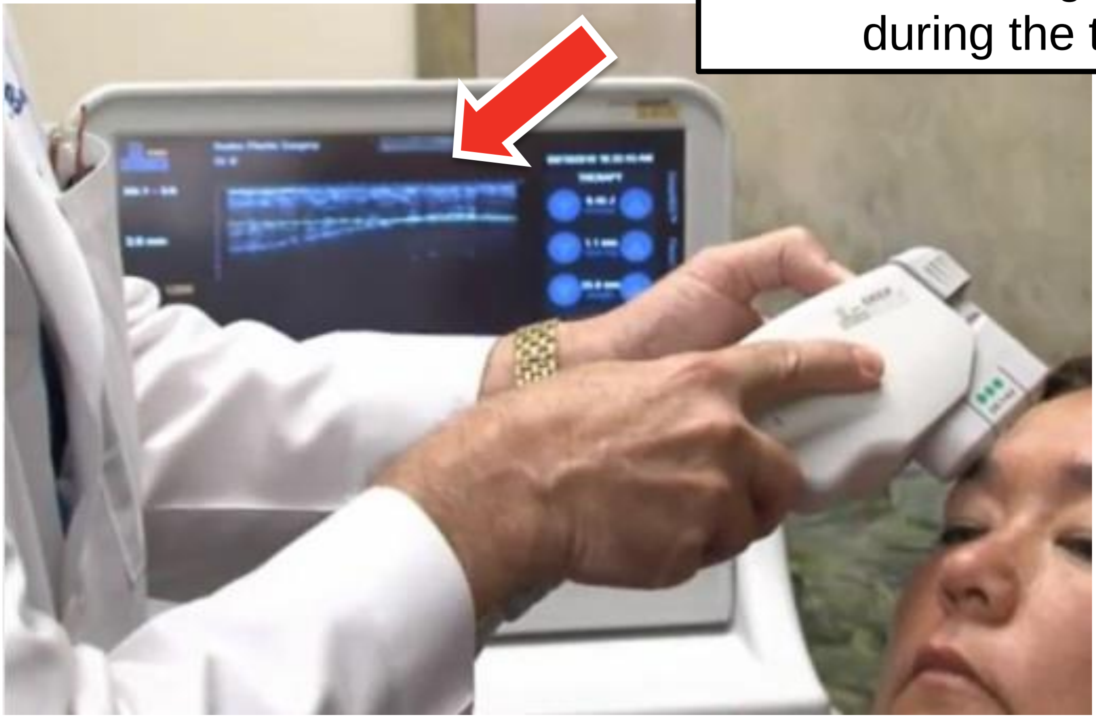
High-frequency ultrasonic transducers – acoustic field



Acoustic field of thick film transducers measured by means of Schlieren setup,
a) flat transducer, b) focused transducer (in collab. with A. Nowicki, IPPT).

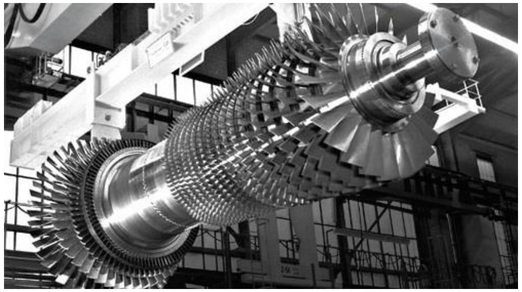
High-frequency ultrasonic transducers – medical imaging

Real-time image of soft tissue during the treatment



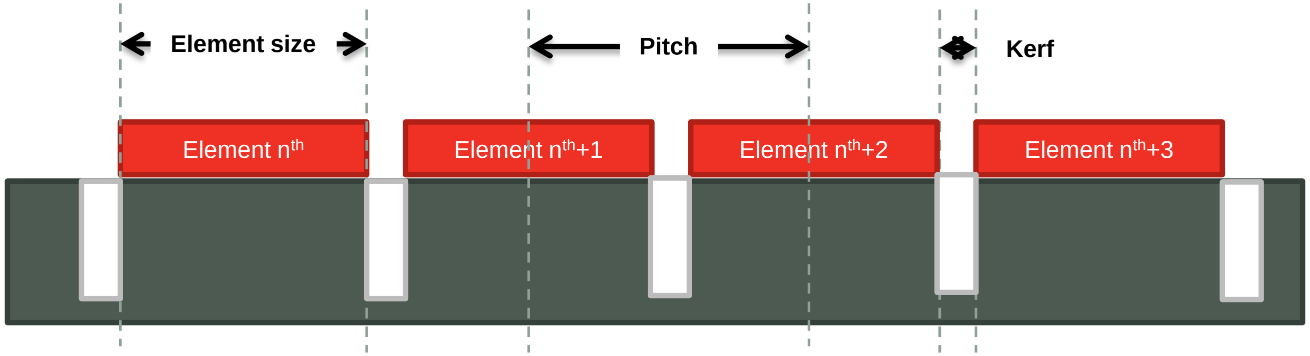
Source: Ulthera video http://www.youtube.com/watch?v=XhafnO0uB_k

4A | Multi-element transducers



Why arrays?

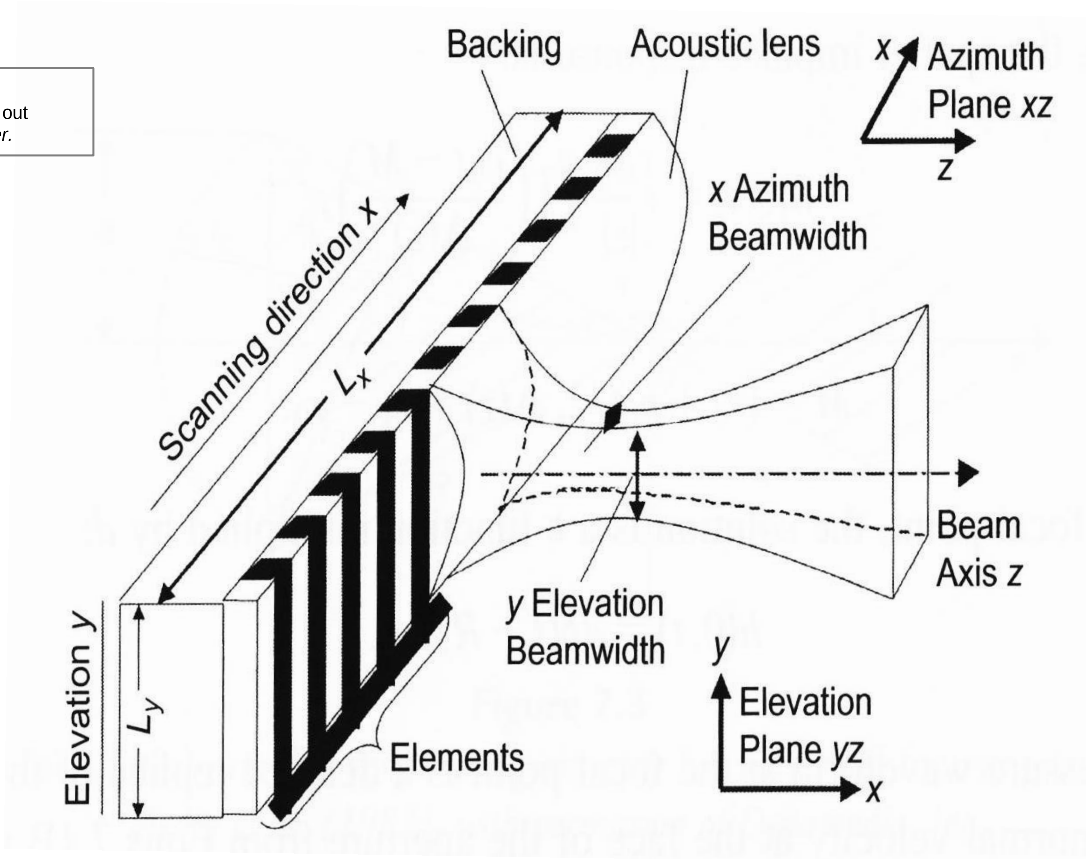
- No moving parts, no mechanical scanning
- Arrays:
  - Enable electronically controlled beam steering
  - Enable dynamic focusing on receive
  - Improve lateral resolution by adjustment of the length as well as apodization (compensation for finite size of an element)
- Enable flow imaging



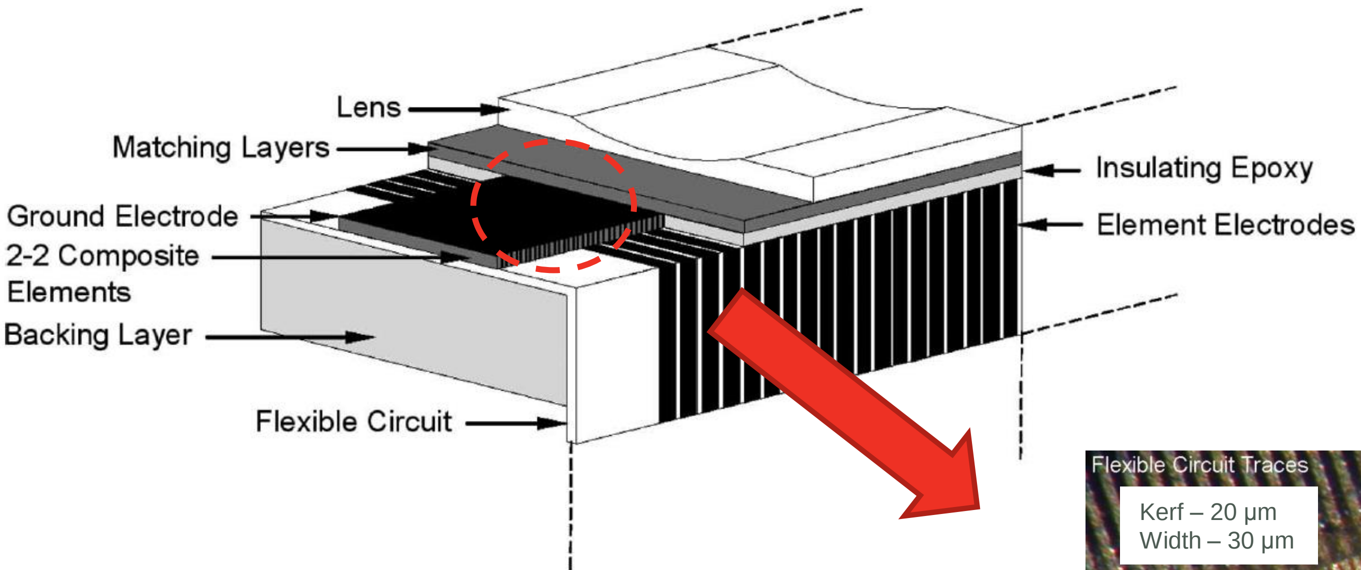
Basic terminology

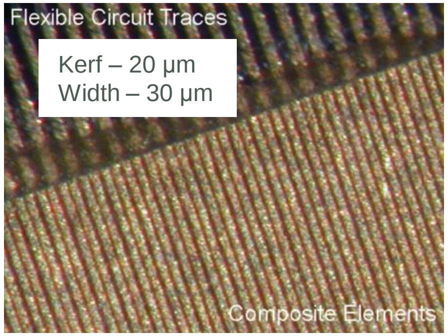
1D array orientation

After: T. L. Szabo (2014):
Diagnostic ultrasound imaging: Inside out
Amsterdam, The Netherlands, Elsevier.



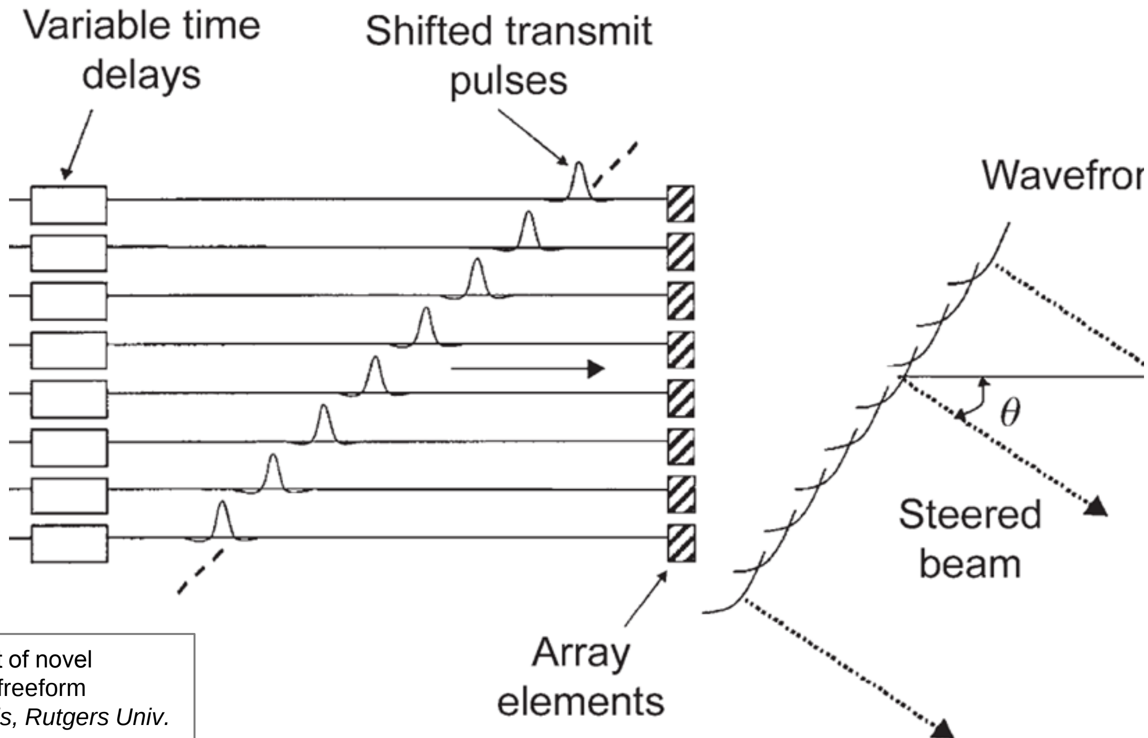
30 MHz 1D array - an example





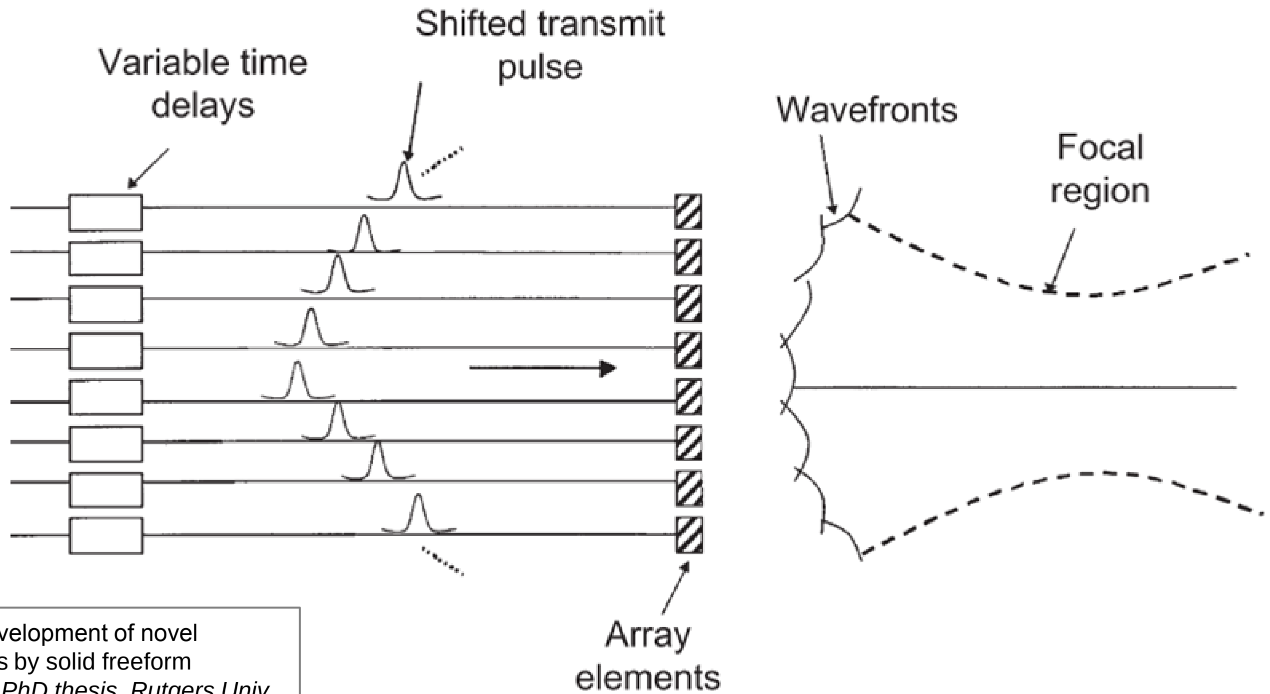
J. M. Cannata, J. A. Williams, L. Zhang, C.-H. Hu and K. K. Shung, (2011): A High-Frequency Linear Ultrasonic Array Utilizing an Interdigitally Bonded 2-2 Piezo-Composite, *IEEE trans. UFFC, vol. 58, no. 10, 2202-2212*

Beam steering



R. K. Panda (1998) “Development of novel piezoelectric composites by solid freeform fabrication techniques”. *PhD thesis, Rutgers Univ. New Brunswick, NJ*

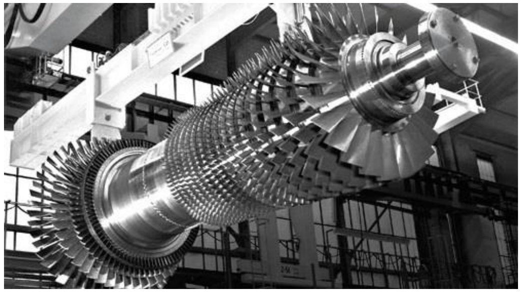
Beam focusing



R. K. Panda (1998) “Development of novel piezoelectric composites by solid freeform fabrication techniques”. *PhD thesis, Rutgers Univ. New Brunswick, NJ*

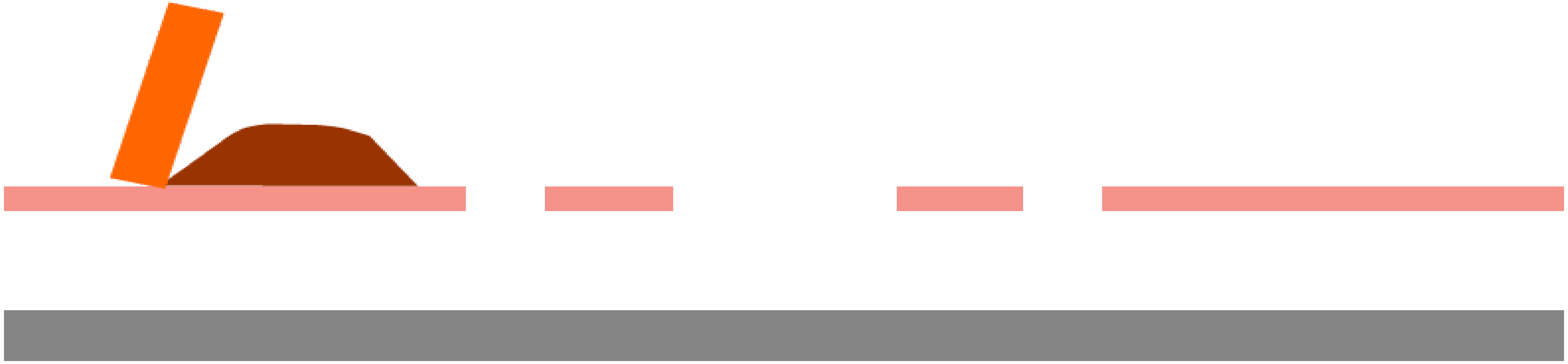
4B

Thick film arrays for medical imaging



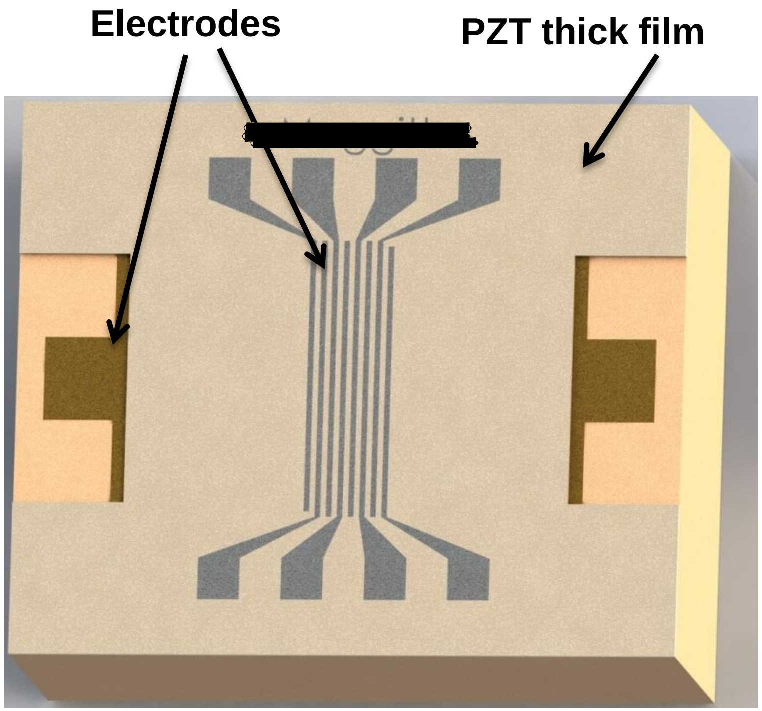
Deposition – screen printing

Paste: PZT powder dispersed
in an organic vehicle



Concept of thick film based array

- Fabrication be means of screen printing
- Special characteristics of PZT thick films open for
  - High frequency > 10 MHz
  - An integrated backing layer
  - Large bandwidth
- Fully printed design
  - Huge implication for cost reduction
  - Arbitrary patterning possible

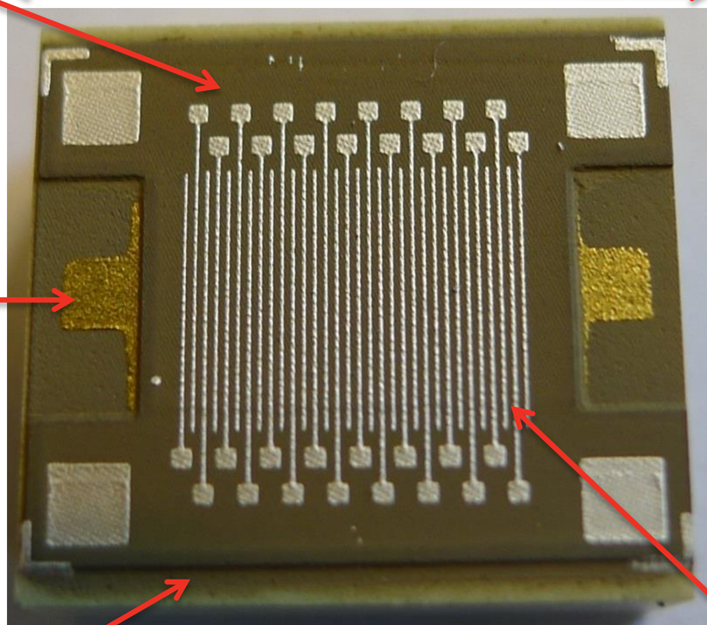


32 element kerfless thick film ultrasonic array – fully printed

TF2100, PZT thick film

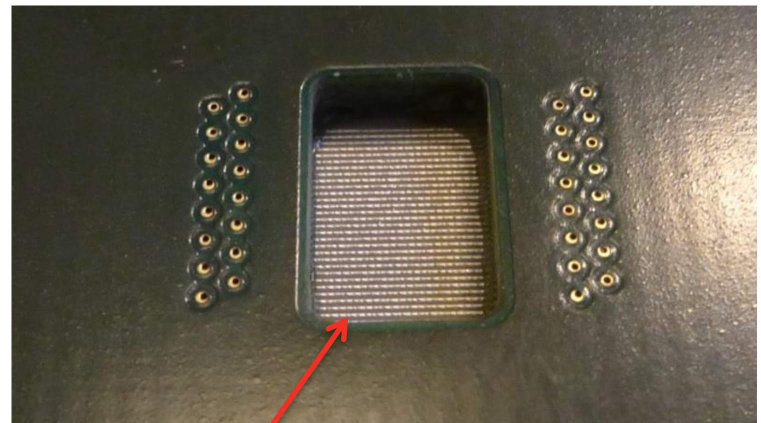
11 mm

Ground electrode, gold



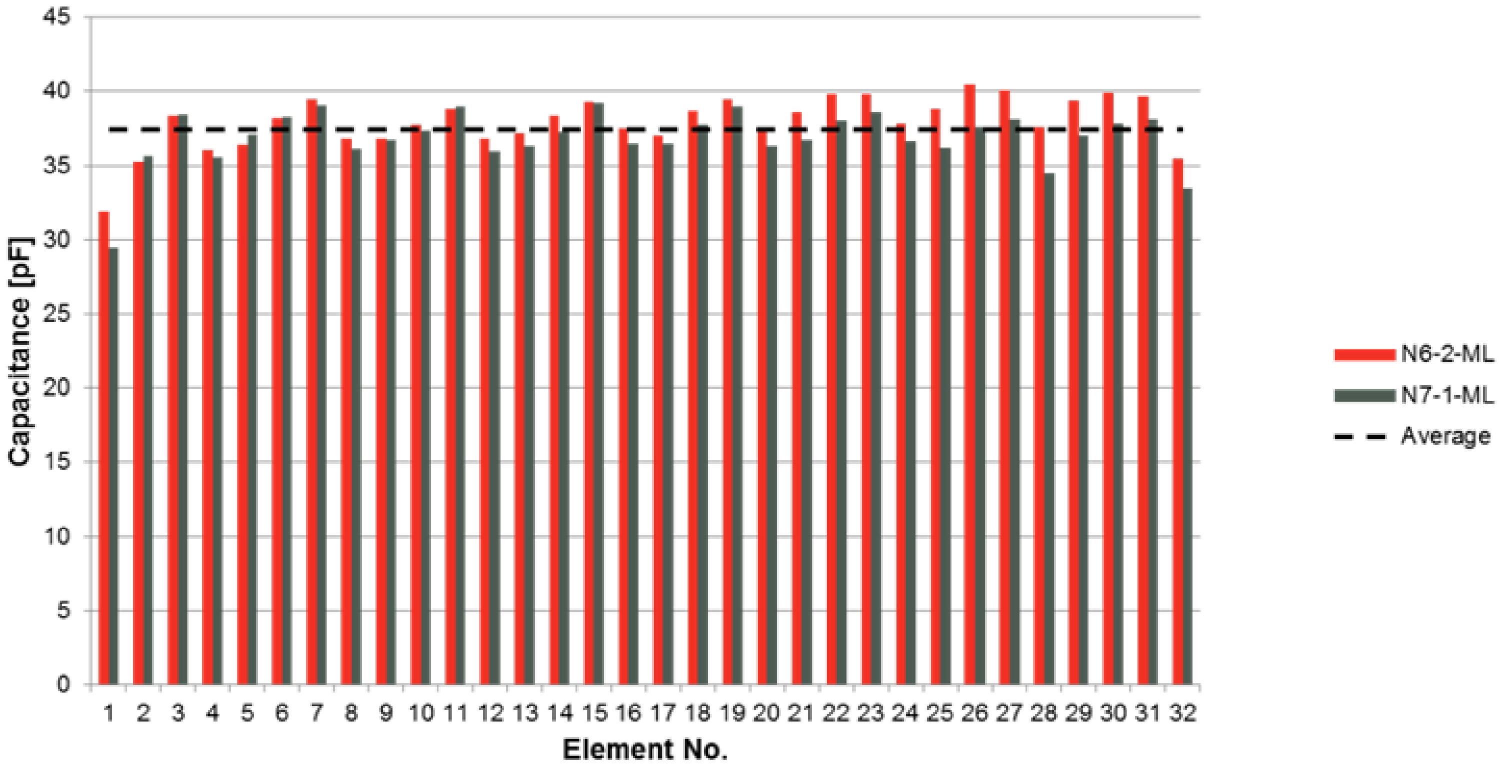
Ceramic integrated backing layer

Array connected to a PCB

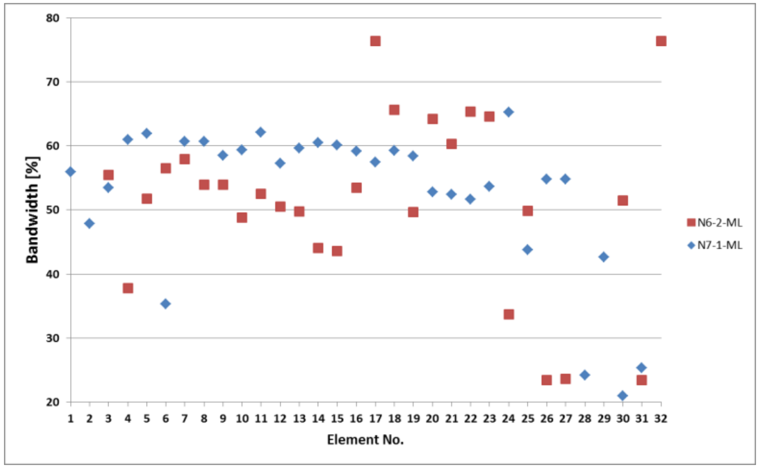


Top electrode, silver

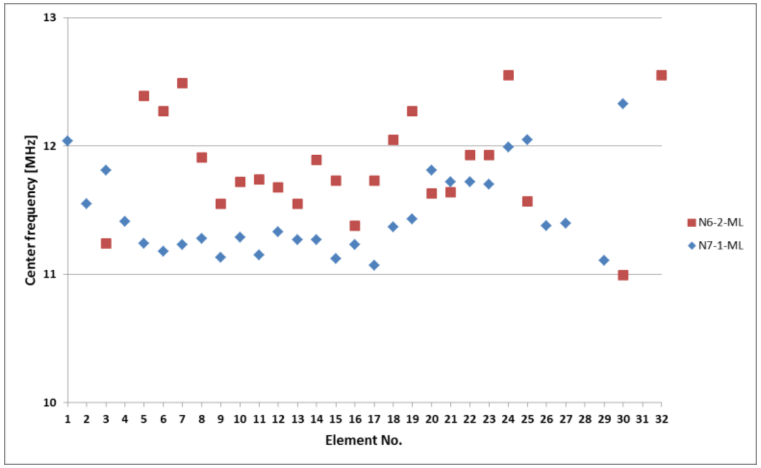
Very good distribution of capacitane over the elements



Pulse-echo measurements continued



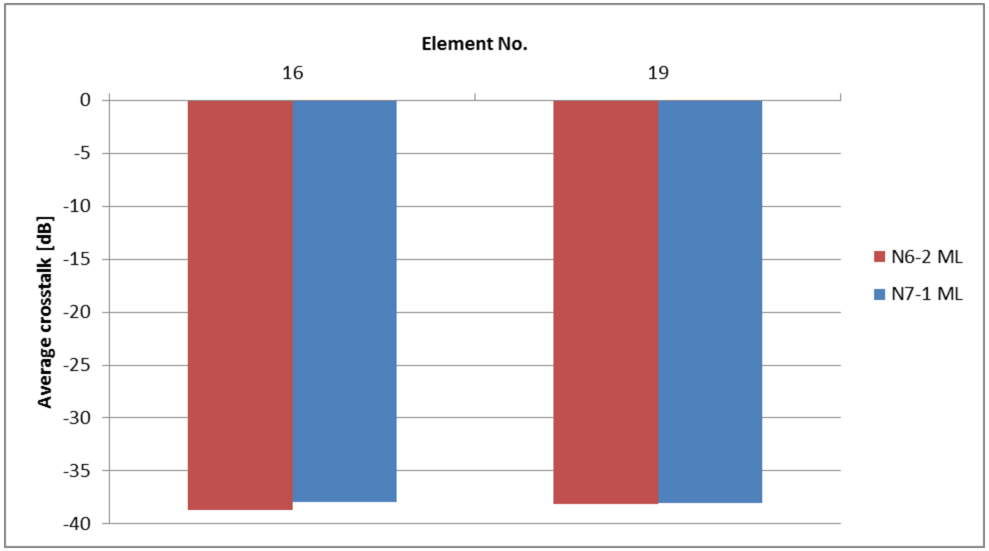
Bandwidth of each element for two 32-element thick film ultrasonic transducers



Center frequency of each element for two 32-element thick film ultrasonic transducers

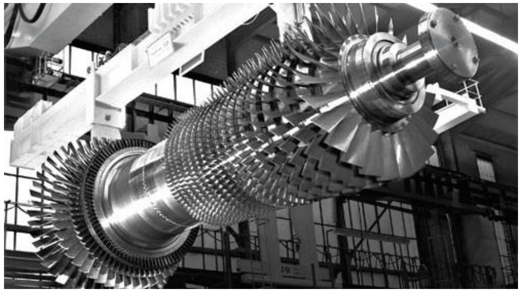
- Thick film ultrasonic arrays offer a unique combination of high frequency, good sensitivity and a bandwidth comparable to conventional bulk transducers
- 32-element transducers generally show acceptable uniformity

Pulse-echo measurements - Crosstalk



- Crosstalk is measured at time zero by comparing the voltage amplitude for the four elements closest to the exited element
- The average crosstalk is found to be approx. -38 dB
  - An acceptable level for an ultrasonic transducer

5 | 3D ultrasonic imaging

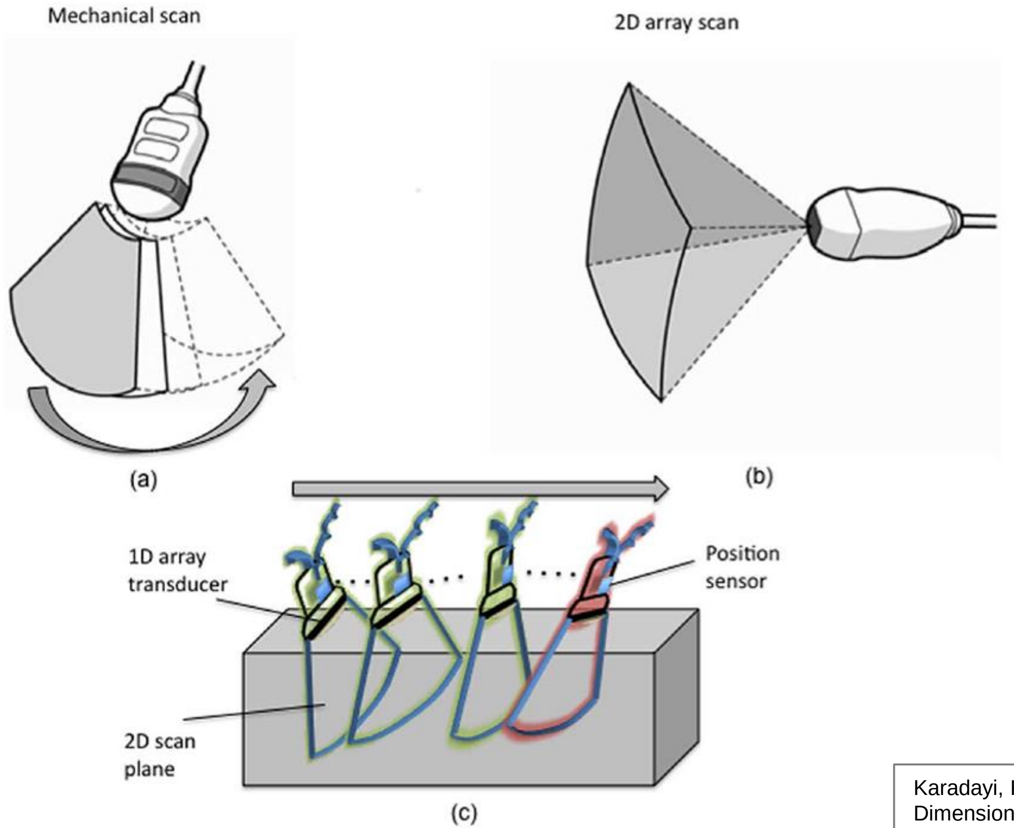


3D ultrasonic imaging

Fetus 34 weeks old with bilateral cleft lip visualized using (a) conventional 2-D US imaging and (b) 3-D US volume rendering

Karadayi, K., R. Managuli, and Y. Kim (2009) “Three-Dimensional Ultrasound: From Acquisition to Visualization and From Algorithms to Systems”. *IEEE Trans. UFFC, vol. 56, no. 4, April 2009*

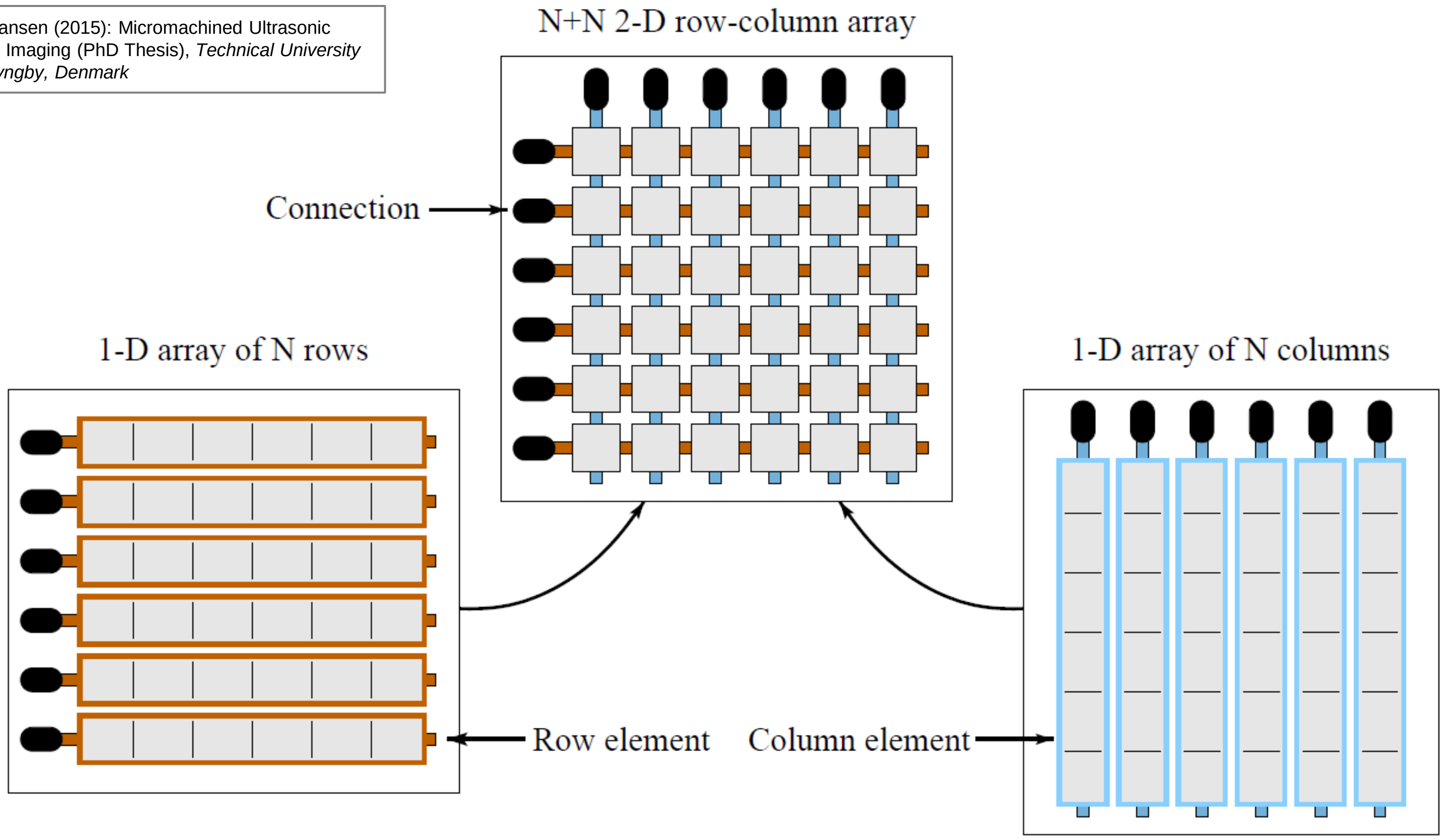
3D ultrasonic imaging – scanning strategies



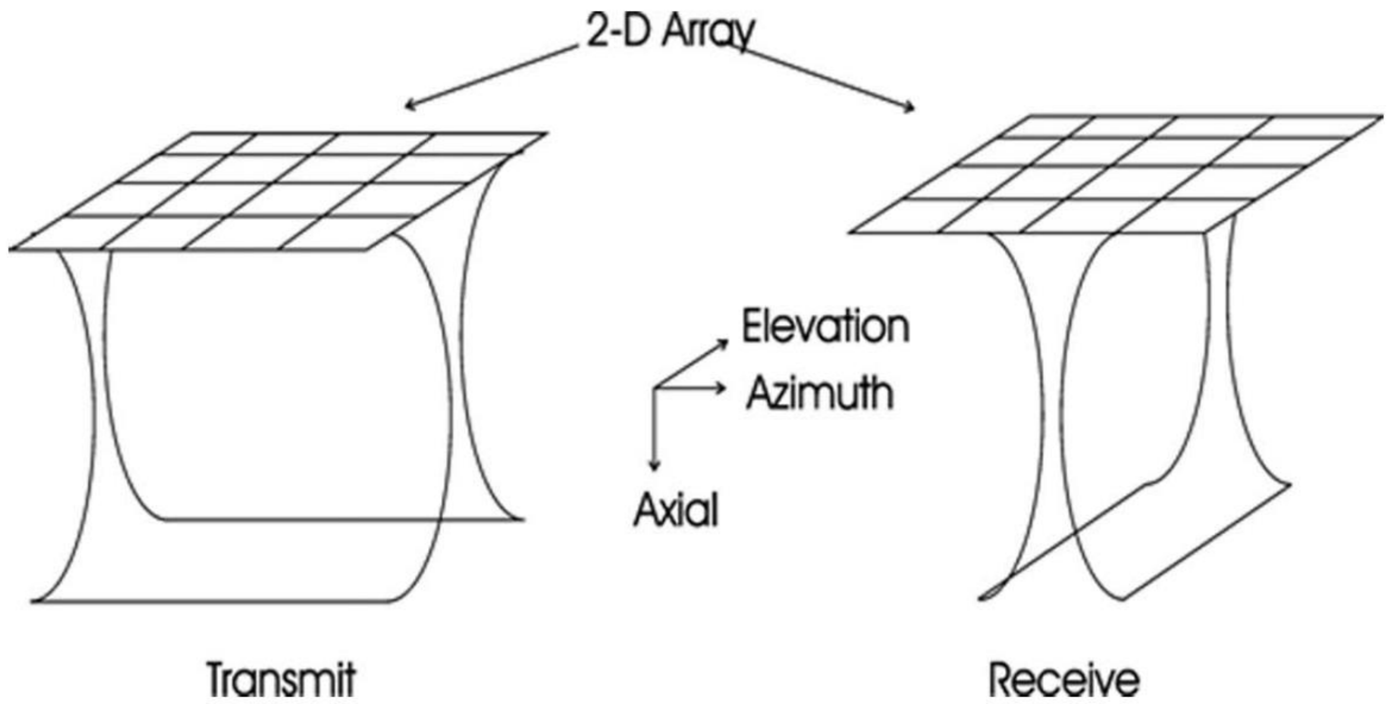
Karadayi, K., R. Managuli, and Y. Kim (2009) “Three-Dimensional Ultrasound: From Acquisition to Visualization and From Algorithms to Systems”. *IEEE Trans. UFFC, vol. 56, no. 4, April 2009*

Row-column concept

T. Lehrmann Christiansen (2015): Micromachined Ultrasonic Transducers for 3-D Imaging (PhD Thesis), *Technical University of Denmark, Kgs. Lyngby, Denmark*

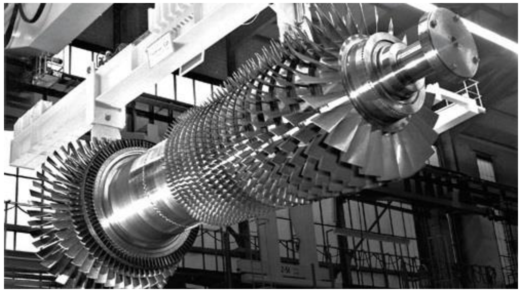


Acoustic field at transmission and reception



Karadayi, K., R. Managuli, and Y. Kim (2009) "Three-Dimensional Ultrasound: From Acquisition to Visualization and From Algorithms to Systems". *IEEE Trans. UFFC, vol. 56, no. 4, April 2009*

Conclusions



Conclusions

- Ultrasonic imaging is a versatile, non-invasive and low cost alternative to other diagnostic methods
- Ultrasound is used mostly for imaging of soft tissue
- Image quality (resolution, contrast, etc.) strongly depends on properties of the ultrasonic transducers
- Historically, mechanically scanned single element transducers have been used, but these are now being replaced by multi-element array systems
- The current development of ultrasonic transducers is aiming at:
  - Higher quality imaging at lower cost
  - High frequency imaging with deeper penetration
  - Integrated probes reducing the impact of expensive and heavy cabling
  - New modalities, e.g. elastography (measurement of elastic properties of tissue)
  - New technologies, e.g. cMUT (capacitive micromachined ultrasonic transducer)
- The thick film process allows for cost-effective manufacturing of linear arrays, and the performance of each element is comparable to the single-element thick films

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Thank you