International Workshop on LHC, Astrophysics, Medical and Environmental Physics. Shkodra (Albania), 6-8 October 2014

Ultrasound transducers

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CREATIS
Based on the course of Franco Bertora
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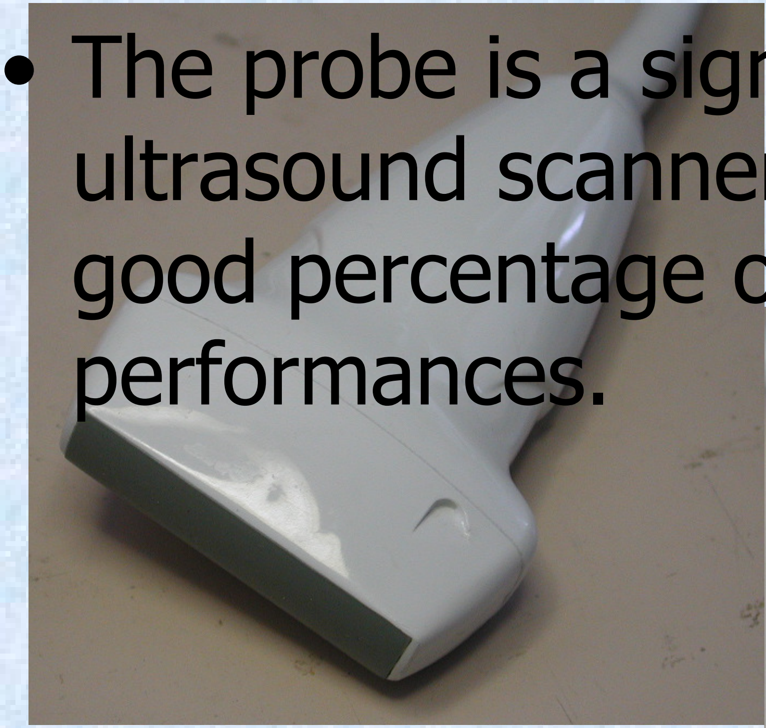
Outline

- Probe types and anatomy
- Transducer models
  - o Structure (finite elements)
  - o Impulse response (acoustics)
  - o Beam profile (aperture)
- Piezoelectricity
- Diffraction and beamforming
- Transducer structure and characterization
- Technological aspects

Probe types and anatomy

- The probe is a significant part of an ultrasound scanner, accounting for a good percentage of its cost and performances.



Probe types and anatomy

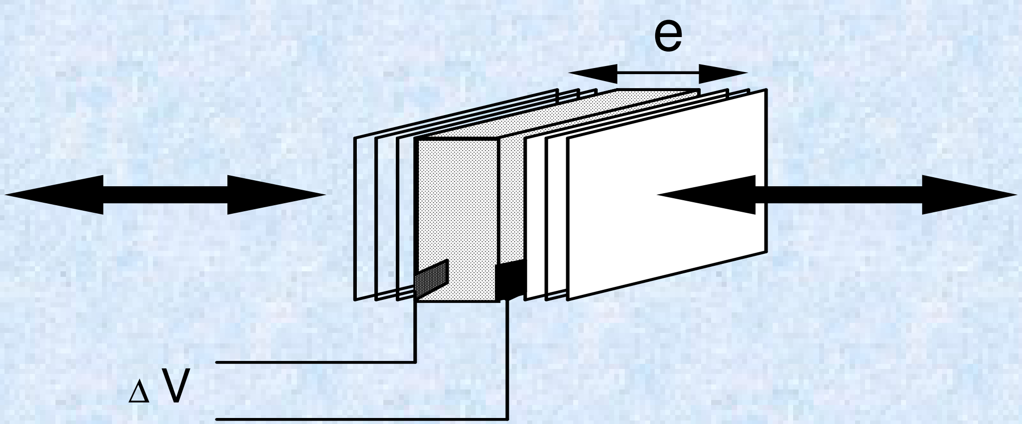
- The main families of probes are:
  - Linear
    - Generally employed for superficial parts at high frequency
  - Convex
    - Generally employed for abdominal scans (low frequency)
  - Phased array
    - Used in cardiac imaging
  - Specialized
    - Endocavitary
      - Transrectal,Transvaginal
      - Transesophageal
    - Surgical

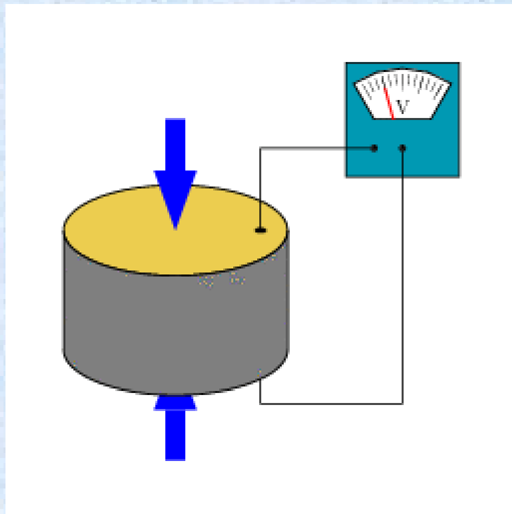
Probe types and anatomy

- There is a multitude of available probes, but they all share some common properties.
- They are made of piezoelectric material
- They comprise many active elements
- Various devices for impedance matching and focalisation are present

Piezoelectricity

– When an electric field is applied it changes dimensions
– When strained an electric field is generated



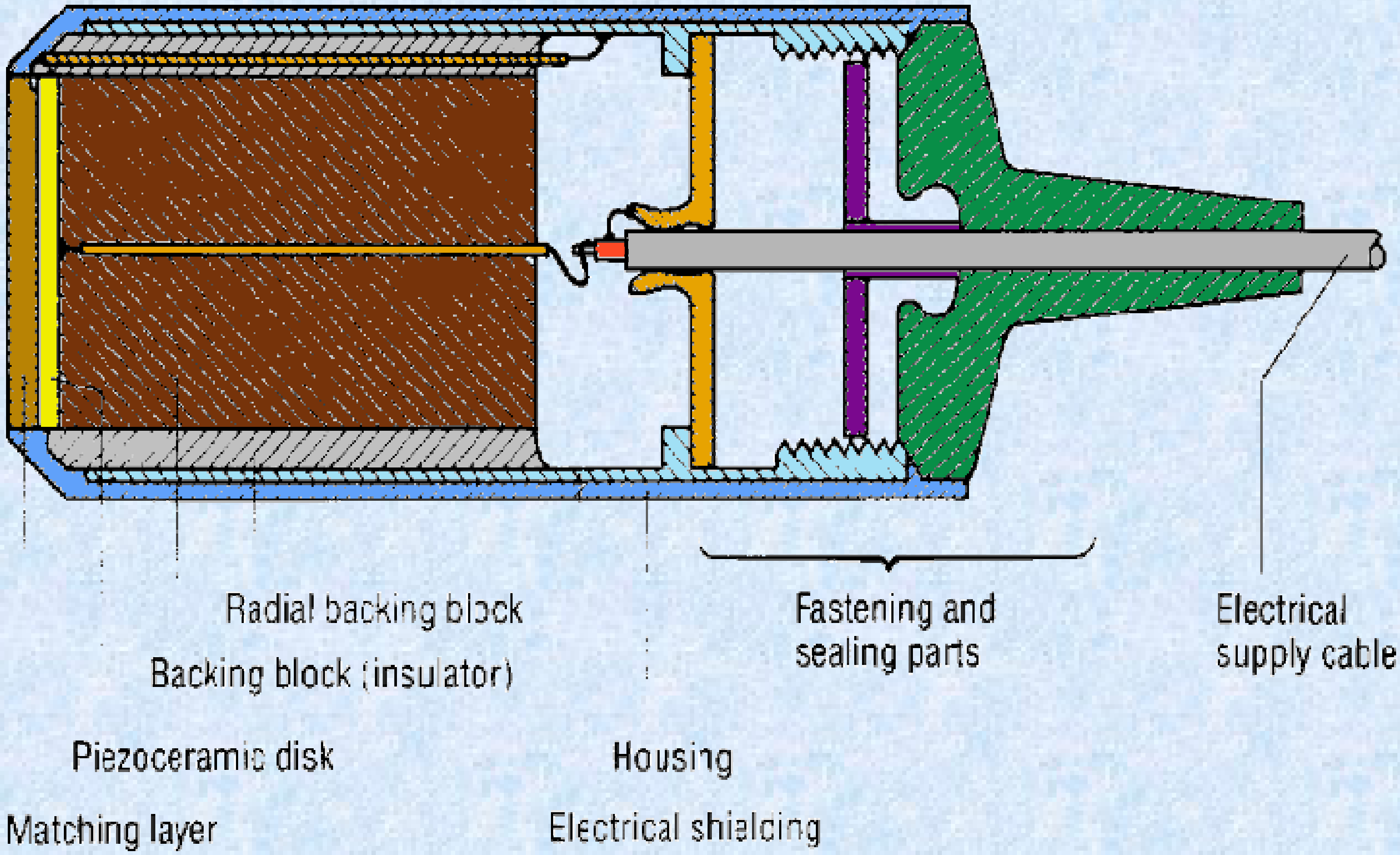


wikipedia

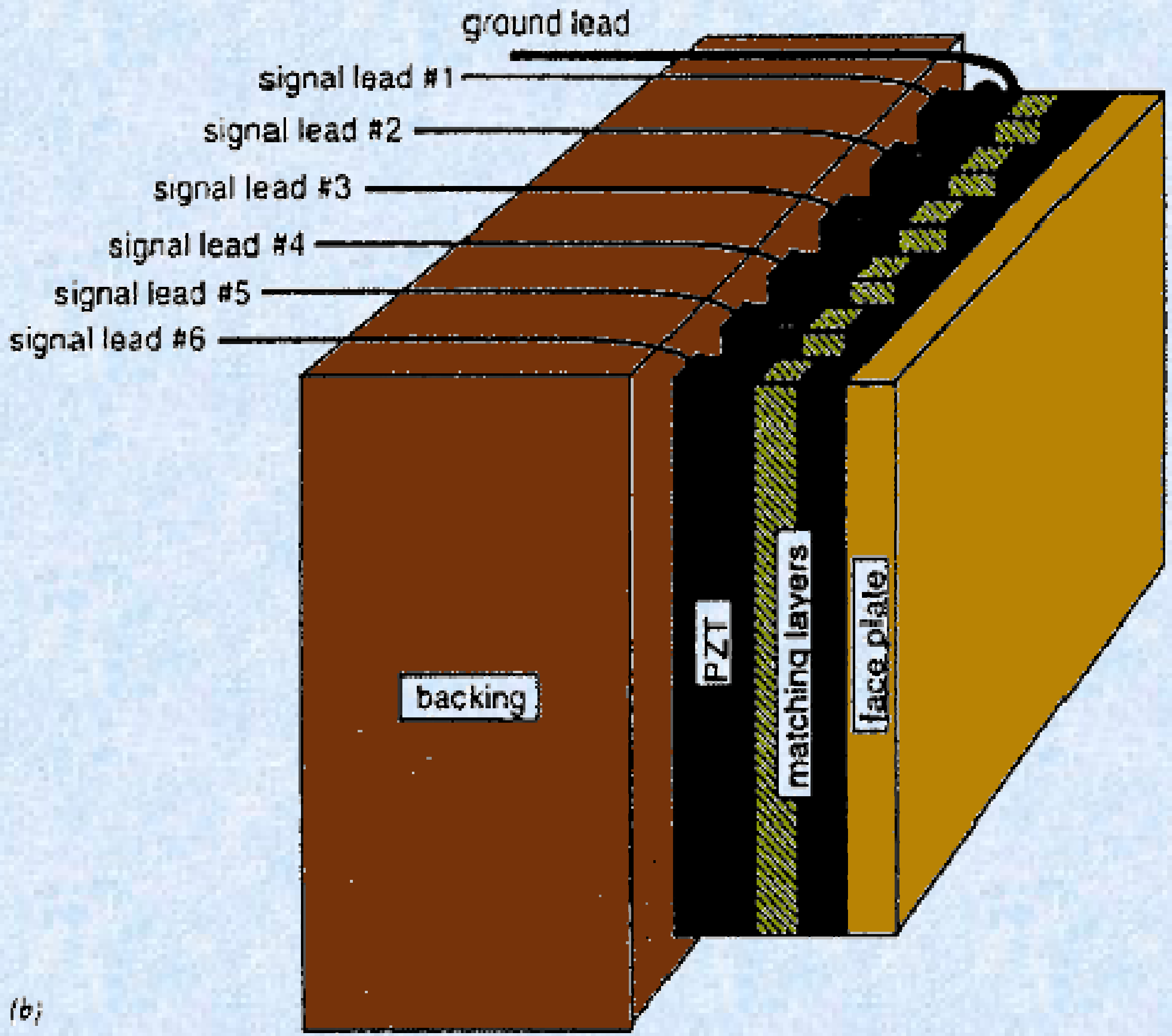
Transducers

- Are made by piezoelectric material elements, often lined up in arrays
- Every element is sandwiched between an absorbing material layer (backing) and an impedence matching layer
- The acoustic impedance of tissues is close to 1.5 MRayl while that of the piezoelectric material is about 20-30 MRayl

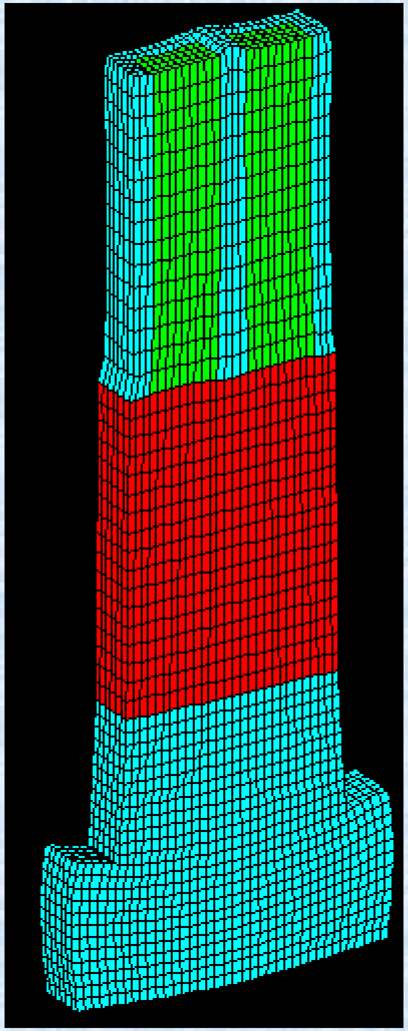
Transducer Structure



Transducer array



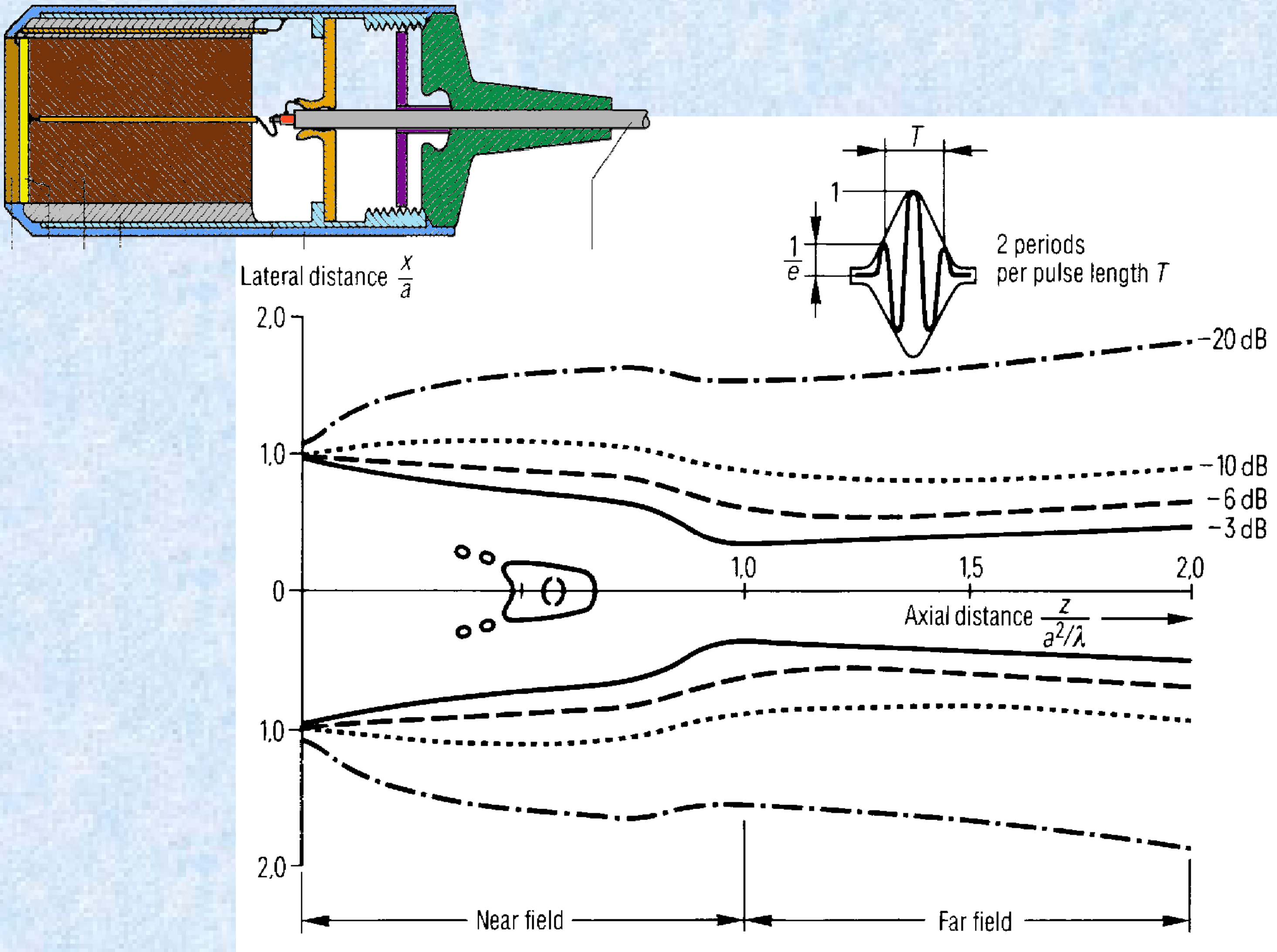
Finite Elements Modeling



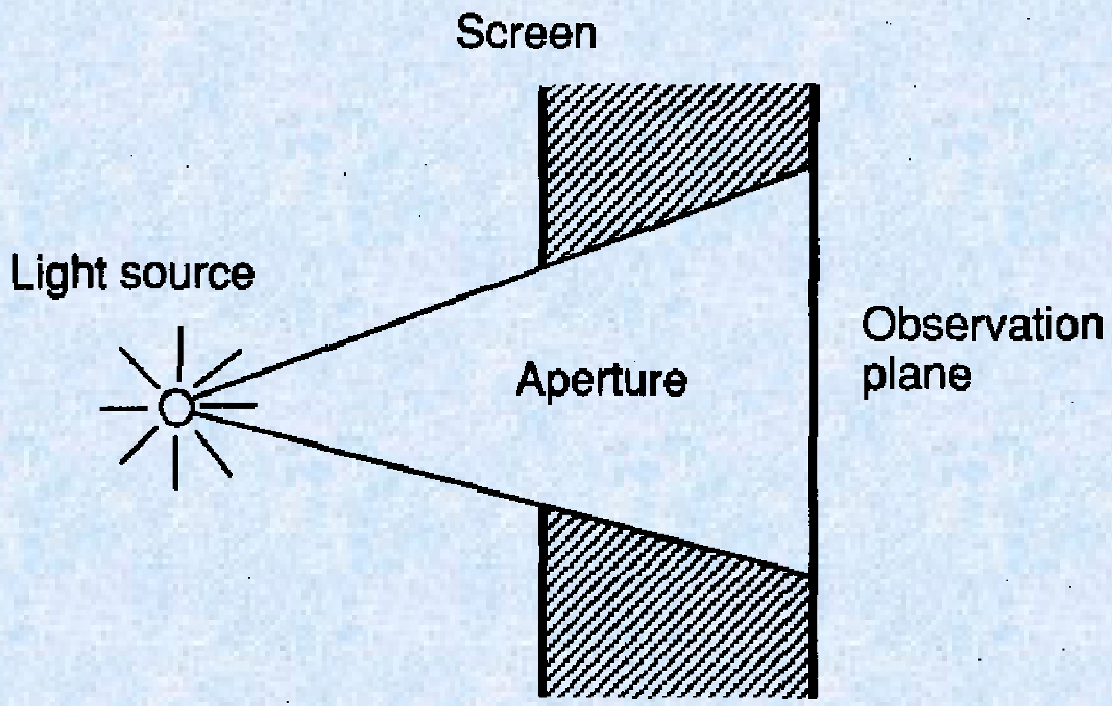
Finite Elements Modeling

- Most diffused commercial packages:
  - PZFlex (Weidlinger Associates Inc.)
    - www.wai.com/AppliedScience/Software/Pzflex/index-pz.html
  - ANSYS (ANSYS Inc.)
    - www.ansys.com
  - ATILA (Cedrat or Magsoft Corp.)
    - www.cedrat-grenoble.fr
    - www.atilafm.com

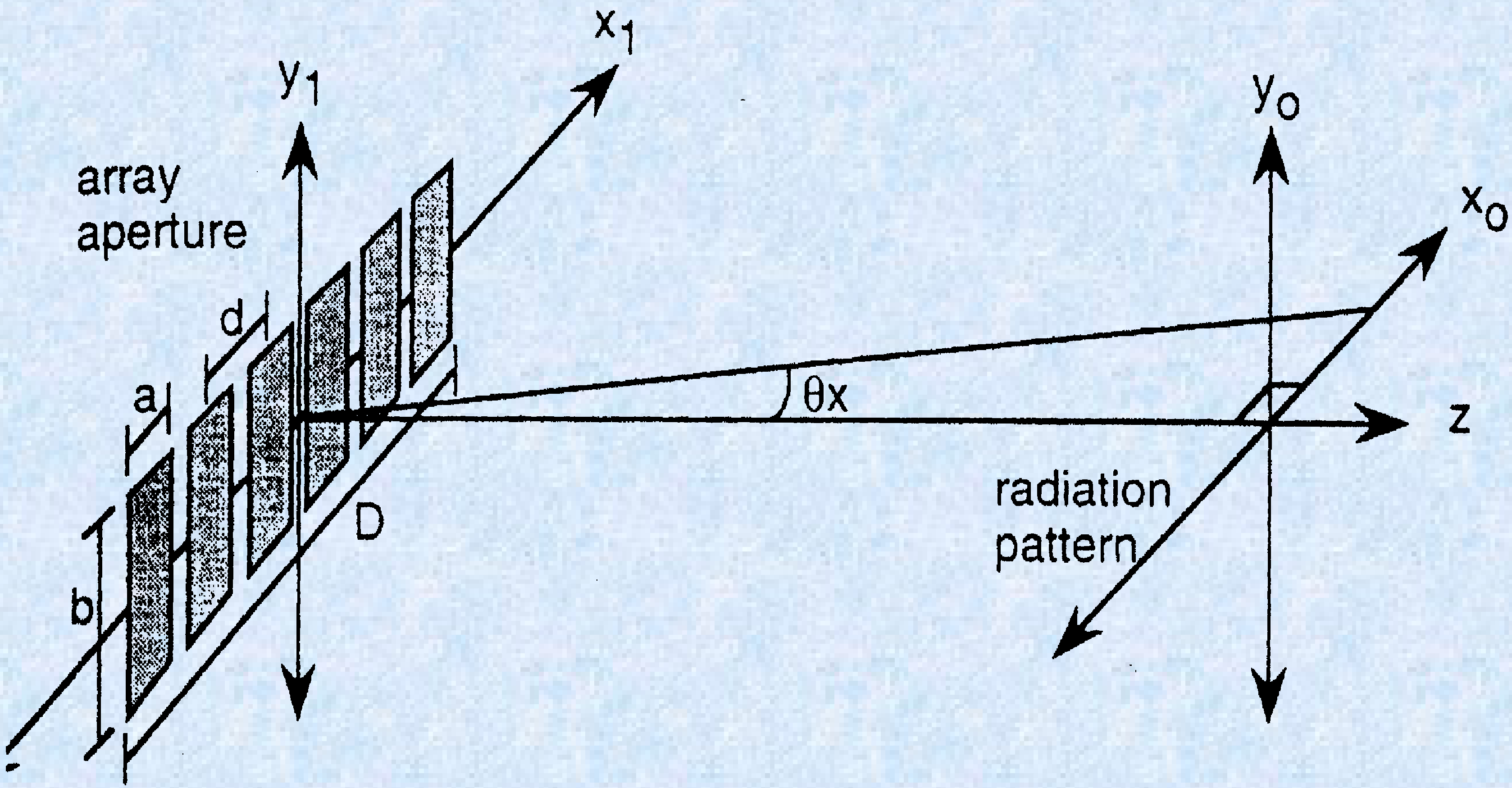
Radiation Diagram



Diffraction

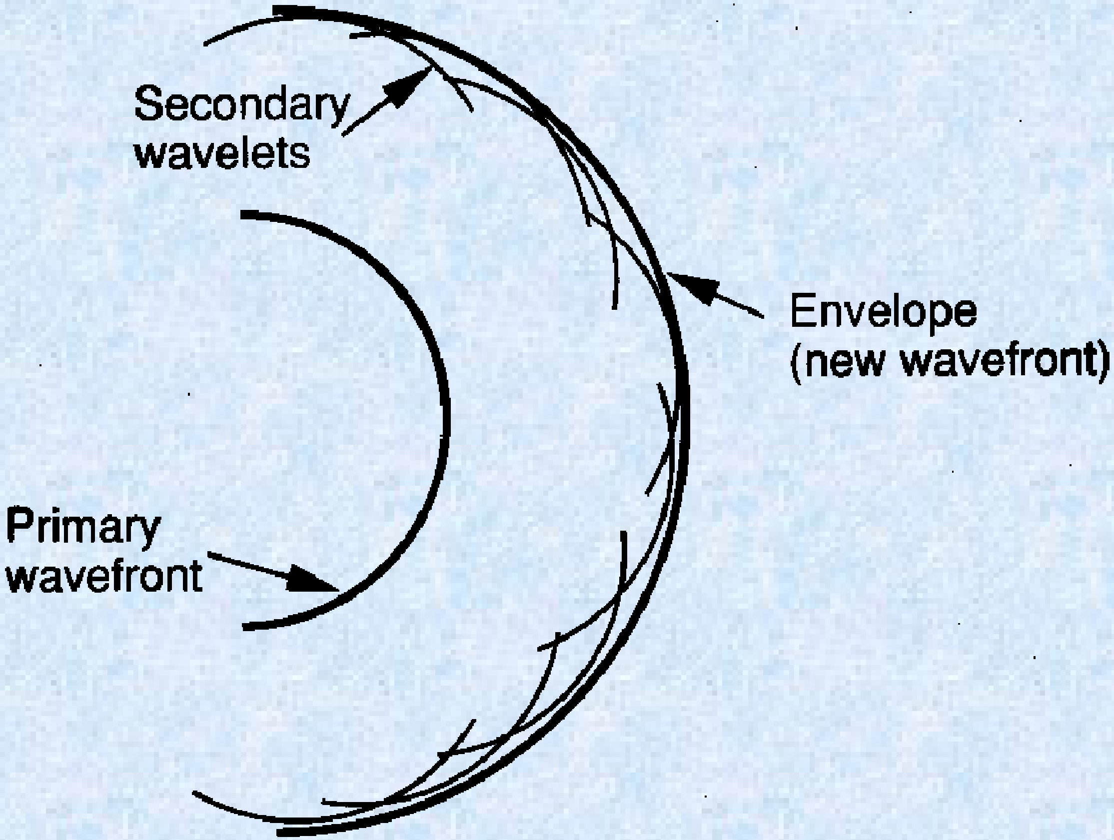


Coordinate system



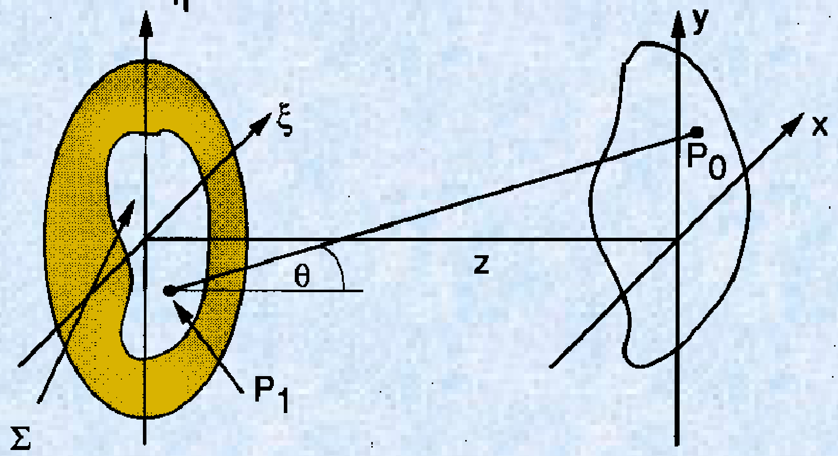
Diffraction

- Huygens principle



Diffraction

- Rayleigh-Sommerfeld formulation



$$U\left(P_0\right)=\frac{1}{j\lambda}\iint_{\Sigma} U\left(P_1\right)\frac{\exp\left(jkr_{01}\right)}{r_{01}}\cos\left(\vartheta\right)ds$$

Diffraction

- In rectangular coordinates $\cos\left(\theta\right)=\dfrac{z}{r_{01}}$ and, as a consequence:

$$U\left(x,y\right)=\frac{1}{j\lambda}\iint_{\Sigma}U\left(\xi,\eta_1\right)\frac{\exp\left(jkr_{01}\right)}{r_{01}^{2}}d\xi d\eta$$

Fresnel approximation

$$r_{01} = \sqrt{z^2 + (x-\xi)^2 + (y-\eta)^2}$$

$$r_{01} \cong z\left[1 + \frac{1}{2}\left(\frac{x-\xi}{z}\right)^2 + \frac{1}{2}\left(\frac{y-\eta}{z}\right)^2\right]$$

$$r_{01} \approx z$$

Propagation as a convolution

$$U(x,y) = \frac{e^{jkz}}{j\lambda z} \iint U(\xi,\eta) \exp\left\{ j\frac{k}{2z}\left[(x-\xi)^2 + (y-\eta)^2 \right] \right\} d\xi d\eta$$

$$U(x,y) = \iint U(\xi,\eta) h(x-\xi, y-\eta) \, d\xi d\eta$$

with:

$$h(x,y) = \frac{e^{jkz}}{j\lambda z} \exp\left[j\frac{k}{2z}\left(x^2+y^2\right) \right]$$

Fresnel diffraction integral

- Factoring the term $e^{\frac{jk}{2z}\left(x^2+y^2\right)}$ outside of the integral we get:

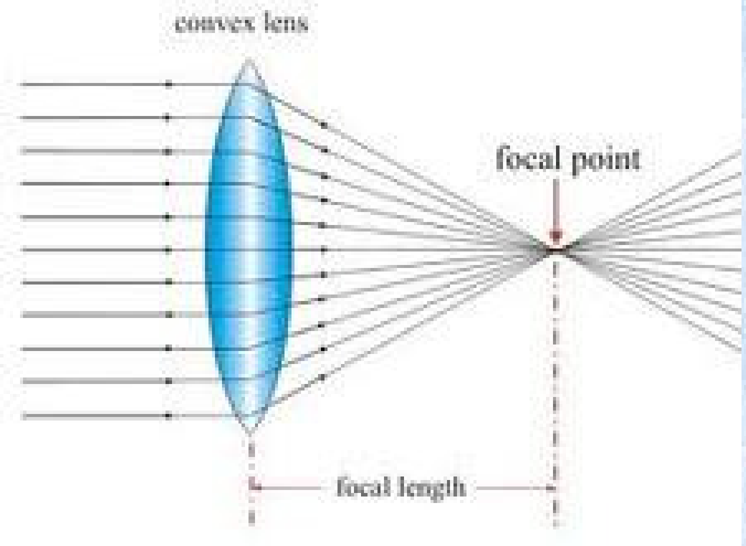
$$U\left(x,y\right)=\frac{e^{jkz}}{j\lambda z}e^{j\frac{k}{2z}\left(x^2+y^2\right)}\iint\left\{U\left(\xi,\eta\right)e^{j\frac{k}{2z}\left(\xi^2+\eta^2\right)}\right\}e^{-j\frac{2\pi}{\lambda z}\left(x\xi+y\eta\right)}d\xi d\eta$$

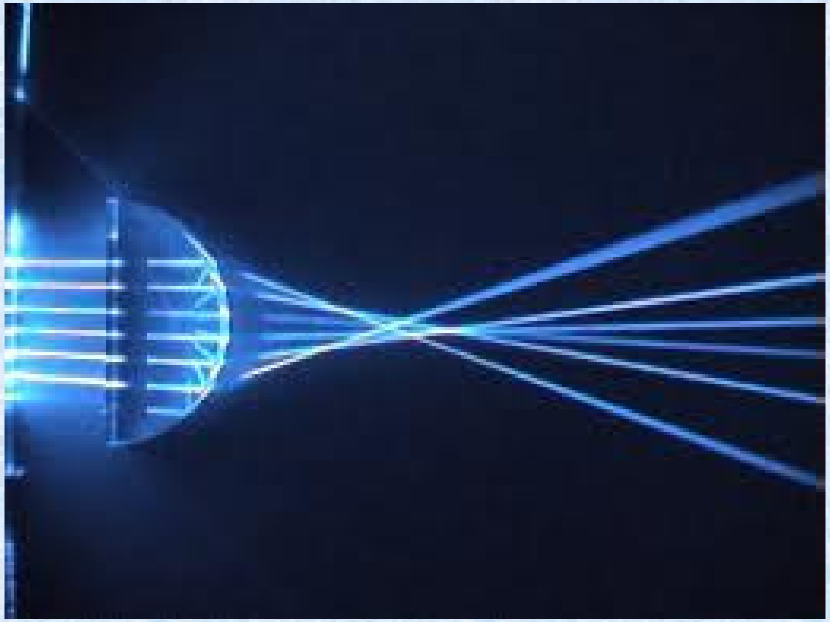
showing the propagation effect as a quadratic factor applied to the Fourier transform of the field at the aperture

Focusing and beamforming

- Diffraction introduces the need for focusing and beamforming in the elevation and lateral directions

Focusing and beamforming





Focusing and beamforming

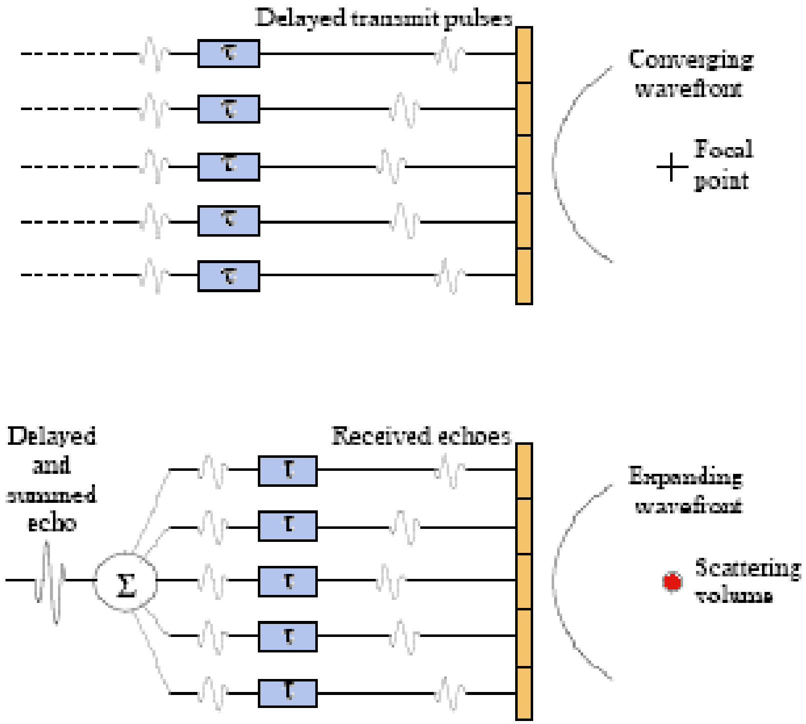
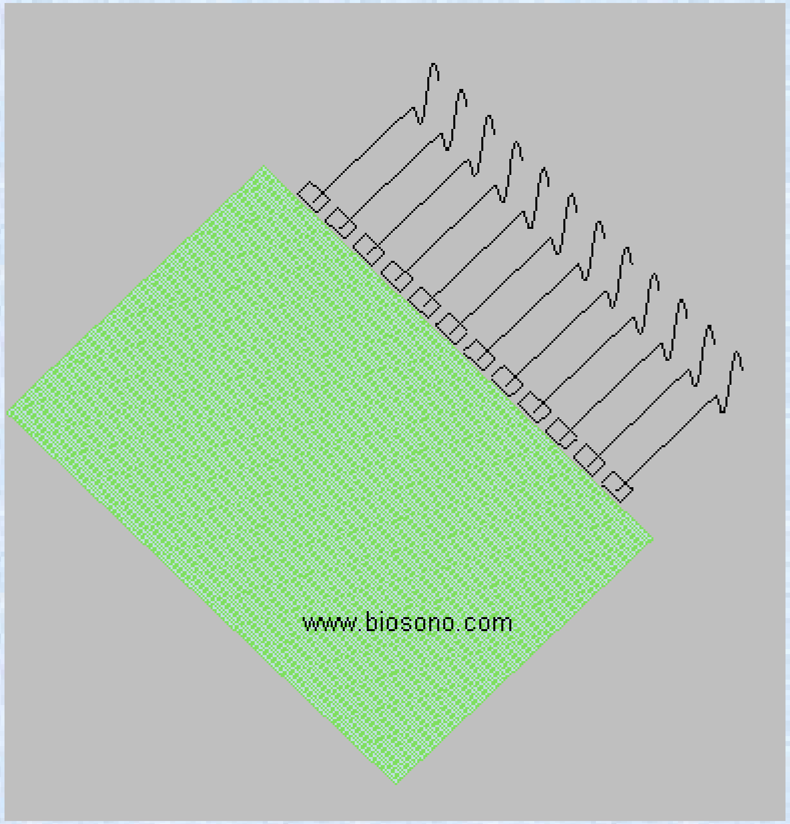
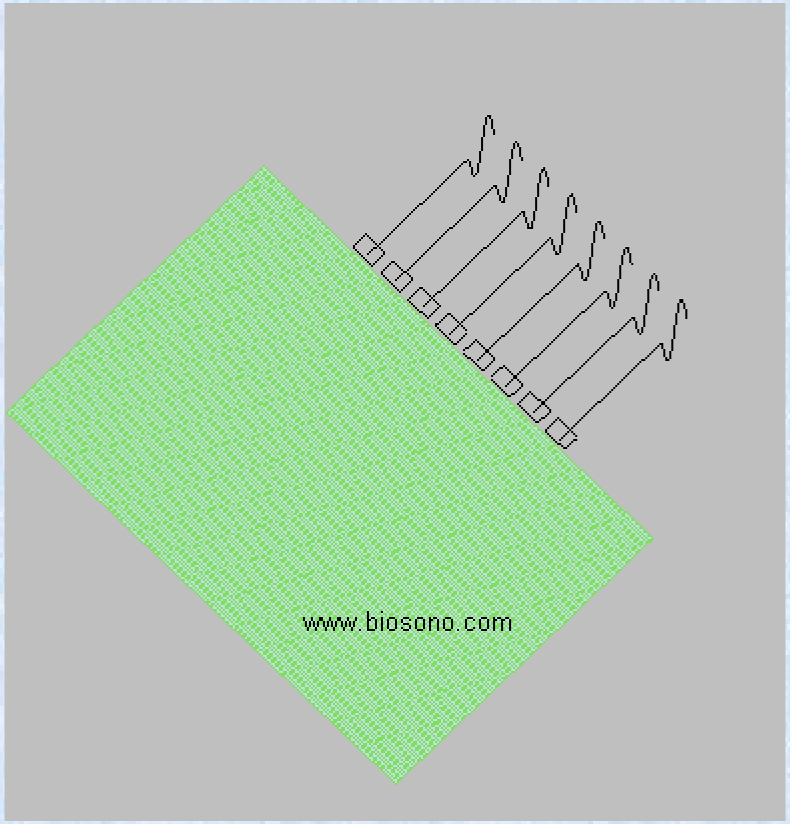


Figure 1.1: A conceptual diagram of phased array beamforming. (Top) Appropriately delayed pulses are transmitted from an array of piezoelectric elements to achieve steering and focusing at the point of interest. (For simplicity, only focusing delays are shown here.) (Bottom) The echoes returning are likewise delayed before they are summed together to form a strong echo signal from the region of interest.

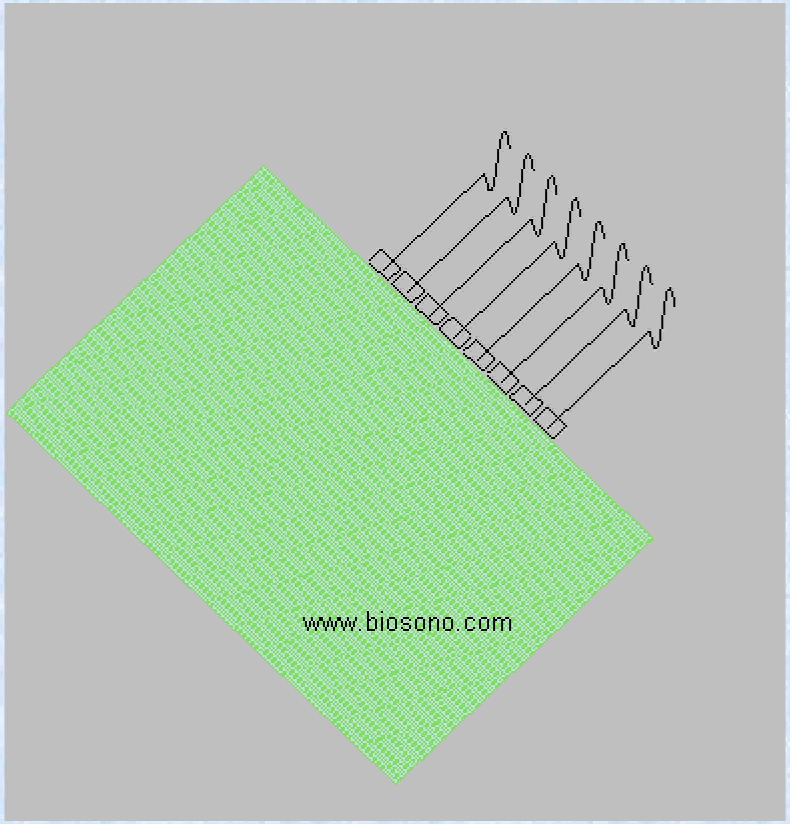
Focusing



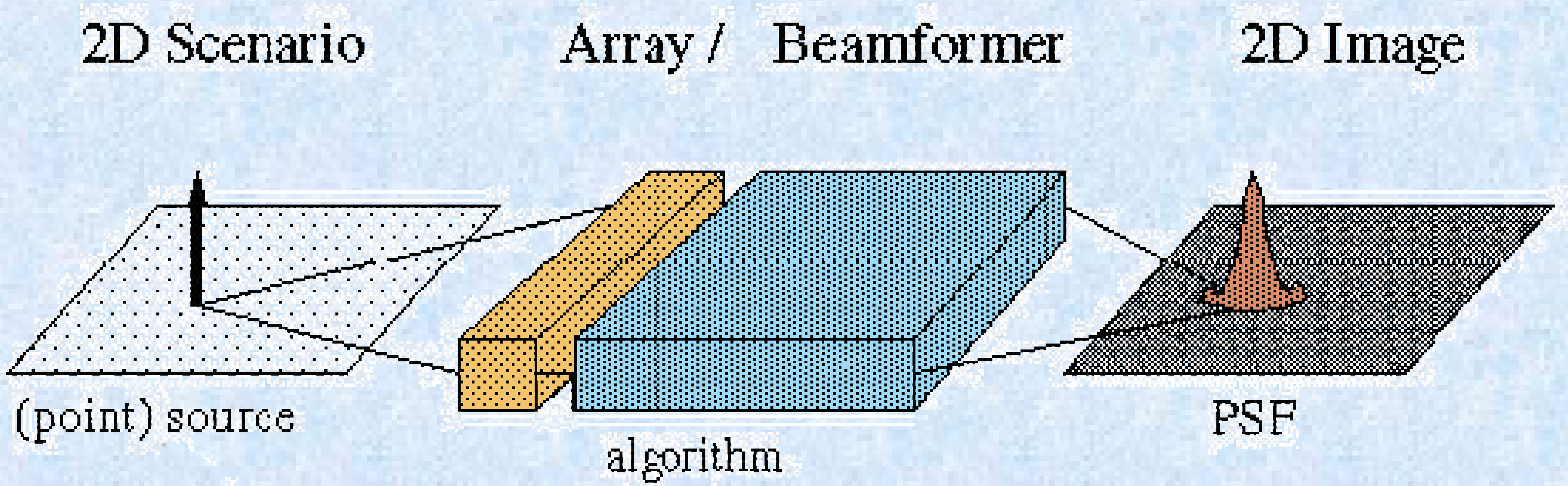
Steering



Steering and focusing



PSF



2D Scenario
Array / Beamformer
2D Image
(point) source
algorithm
PSF

Focusing and beamforming

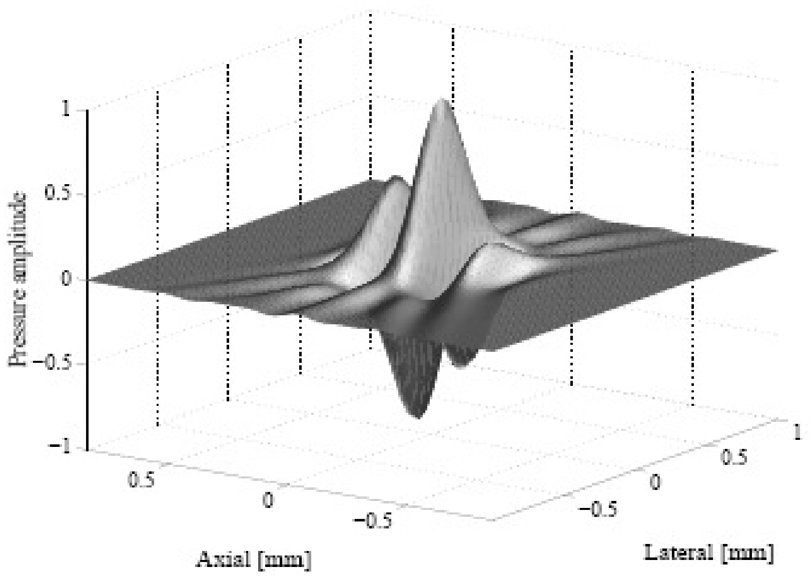
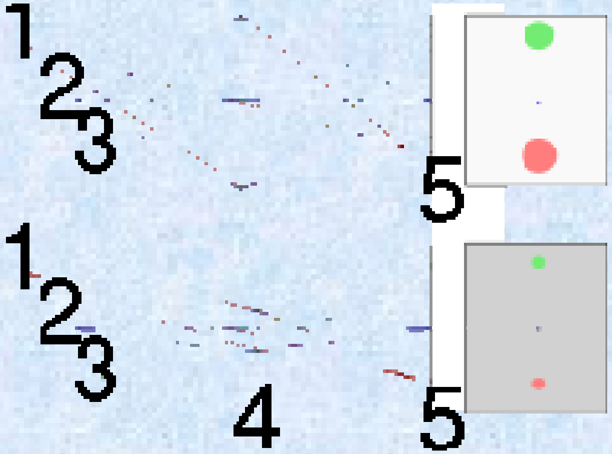


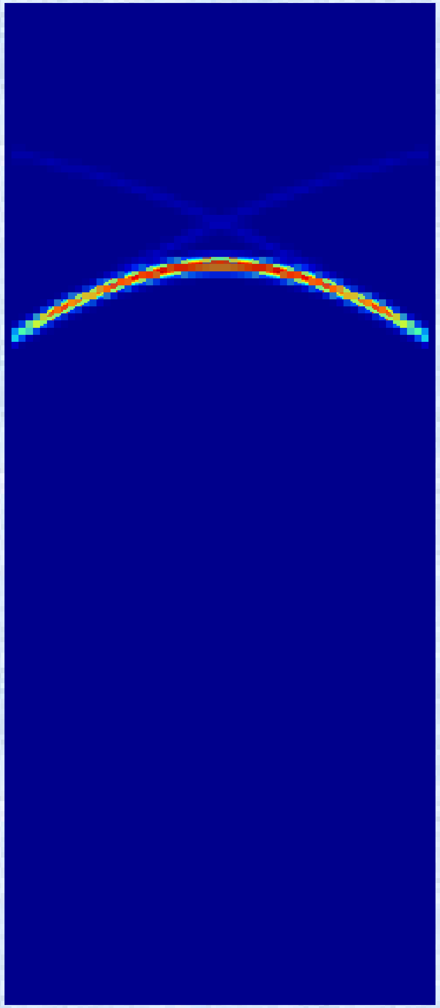
Figure 1.3: The acoustic pulse from a typical array (7.5 MHz, 60% bandwidth, 128 elements of width equal to the wavelength), shown at the acoustic focus. The pulse is displayed as a map of pressure amplitude and is traveling in the positive direction along axial dimension.

Baemforming - f-number



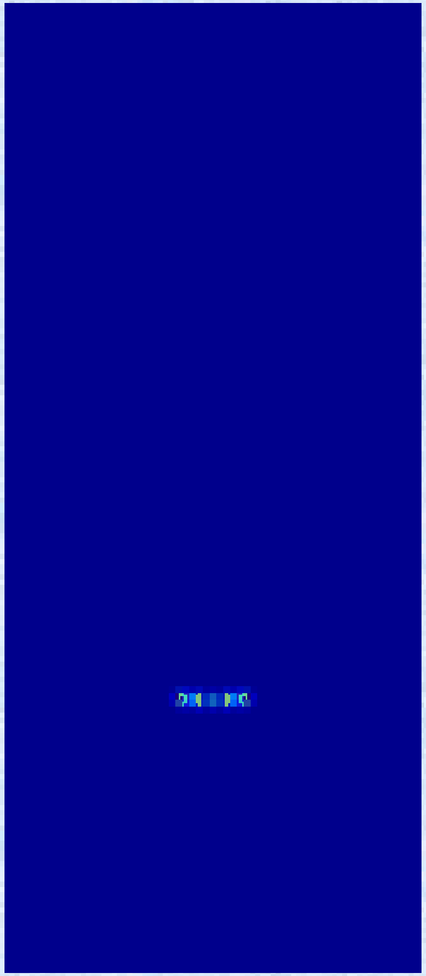
Beamforming - low f-number

- a low f/ number gives a great sharpness but a limited depth of field
- good for receiving but not to illuminate the scene



Beamforming - high f-number

- a high f/ number gives a good depth of field at the sacrifice of sharpness
- good for transmitting



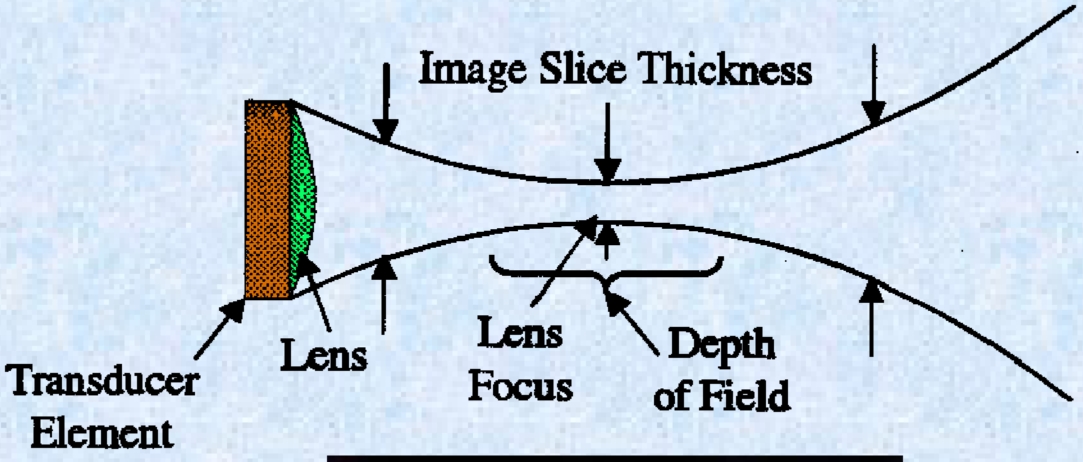
Dynamic focus

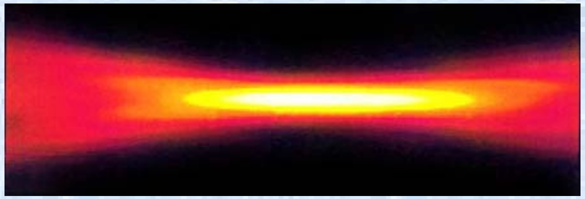
Dynamic focus

- The ideal solution is to employ a moderate f/ number in transmit and to receive dynamically changing a low f/ number focus, tracking the region where the echo might come from
- If frame rate is not an issue multi-zone focusing can be used

Elevation beamforming

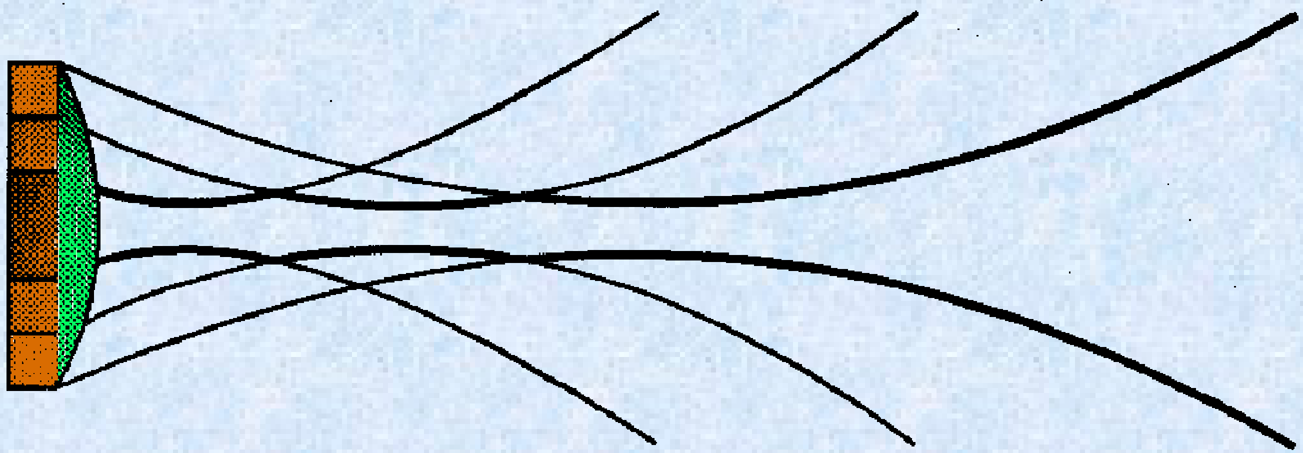
- Elevation focusing is generally done by means of a fixed focus mechanical lens



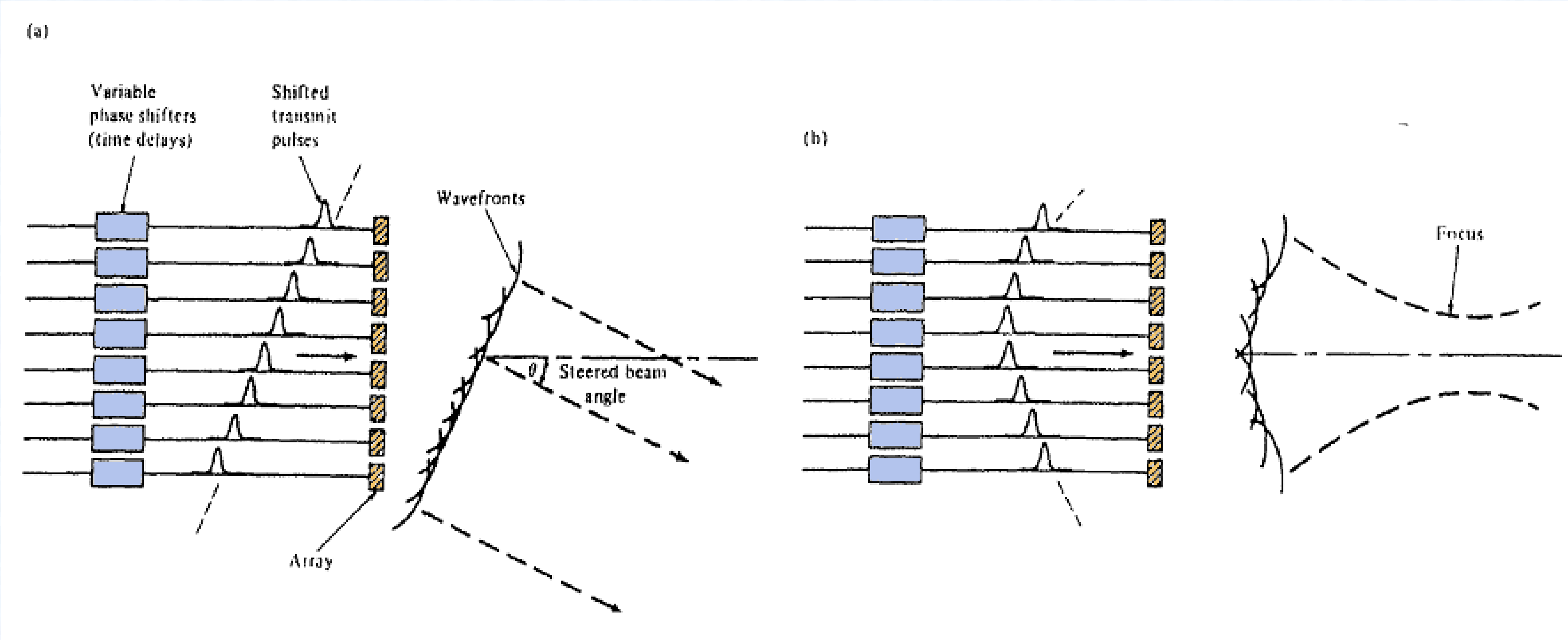


Elevation beamforming

- But can also be done electronically to get a better depth of field

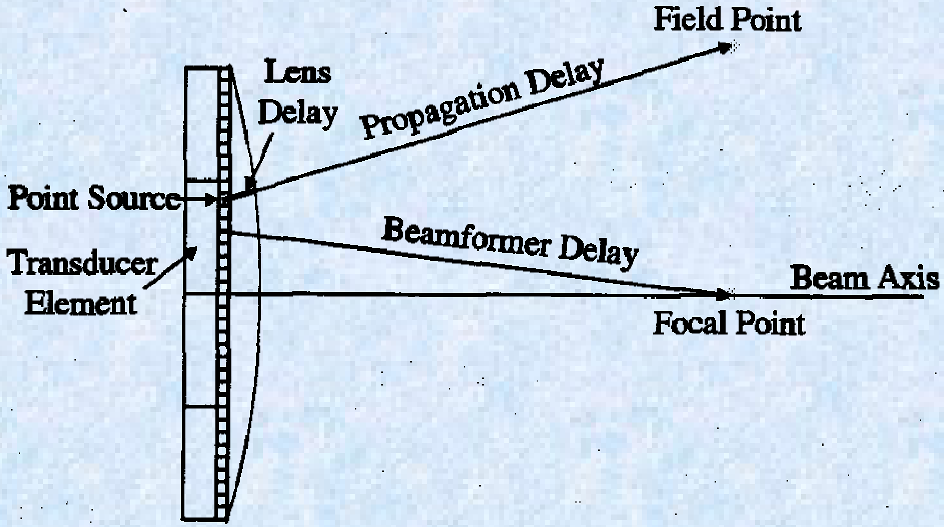


Beamforming



Beamforming

Acoustic Field Model

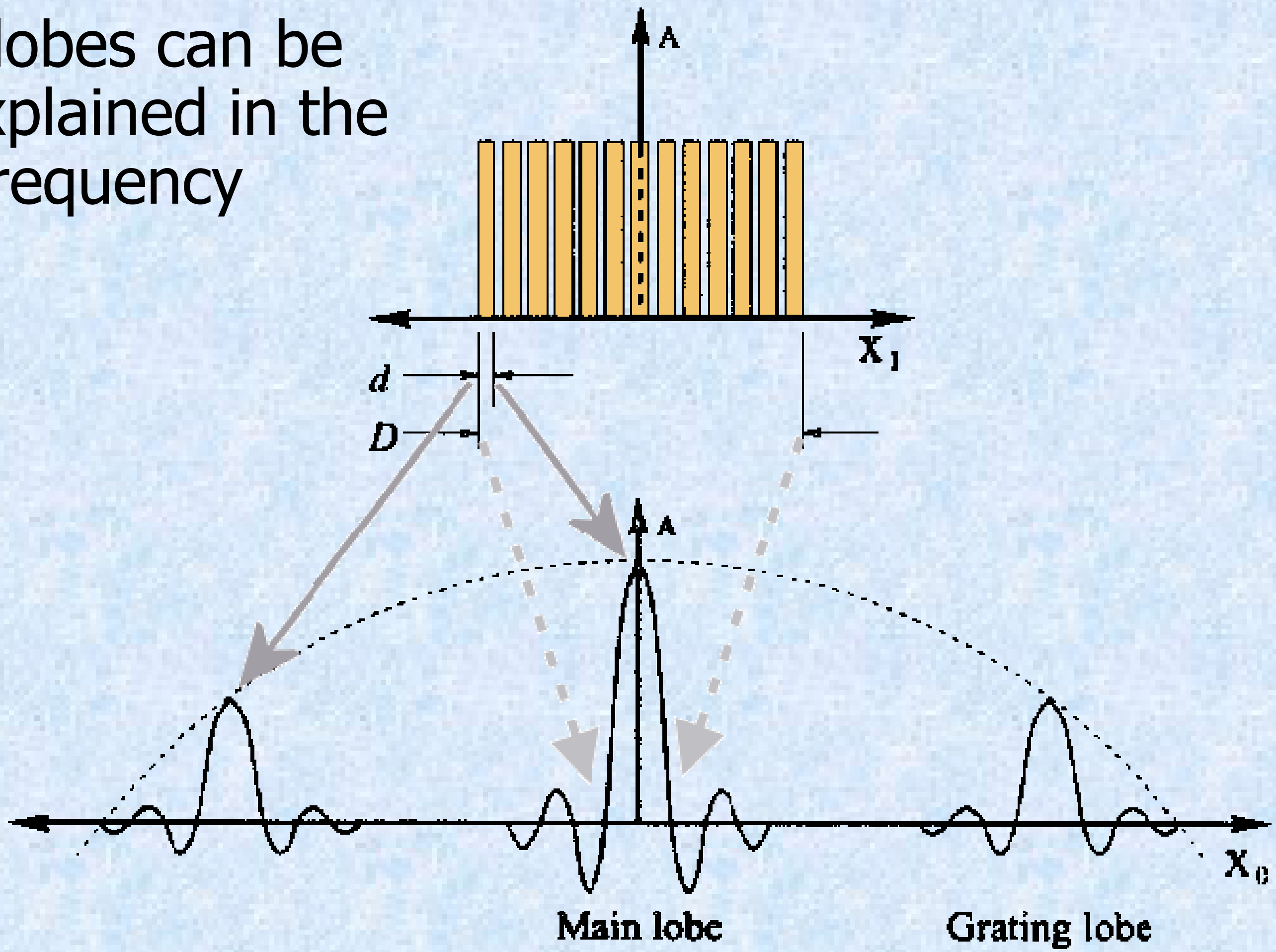


Field II: http://eswww.it.dtu.dk/~jaj/field/

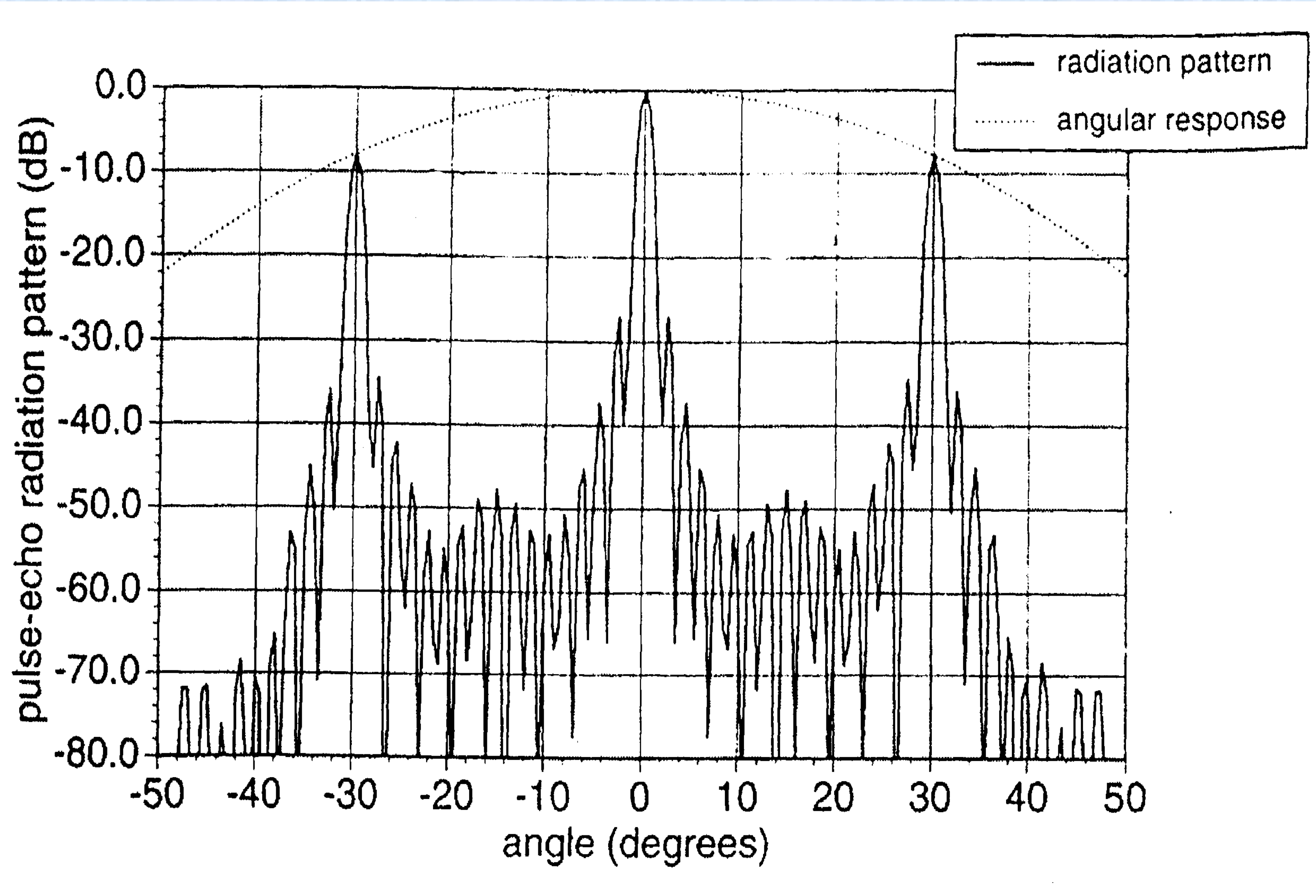
J.A. Jensen and N. B. Svendsen, "Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers," IEEE Trans. Ultrason., Ferroelec., Freq. Contr., 39, pp. 262-267, 1992.

Grating Lobes

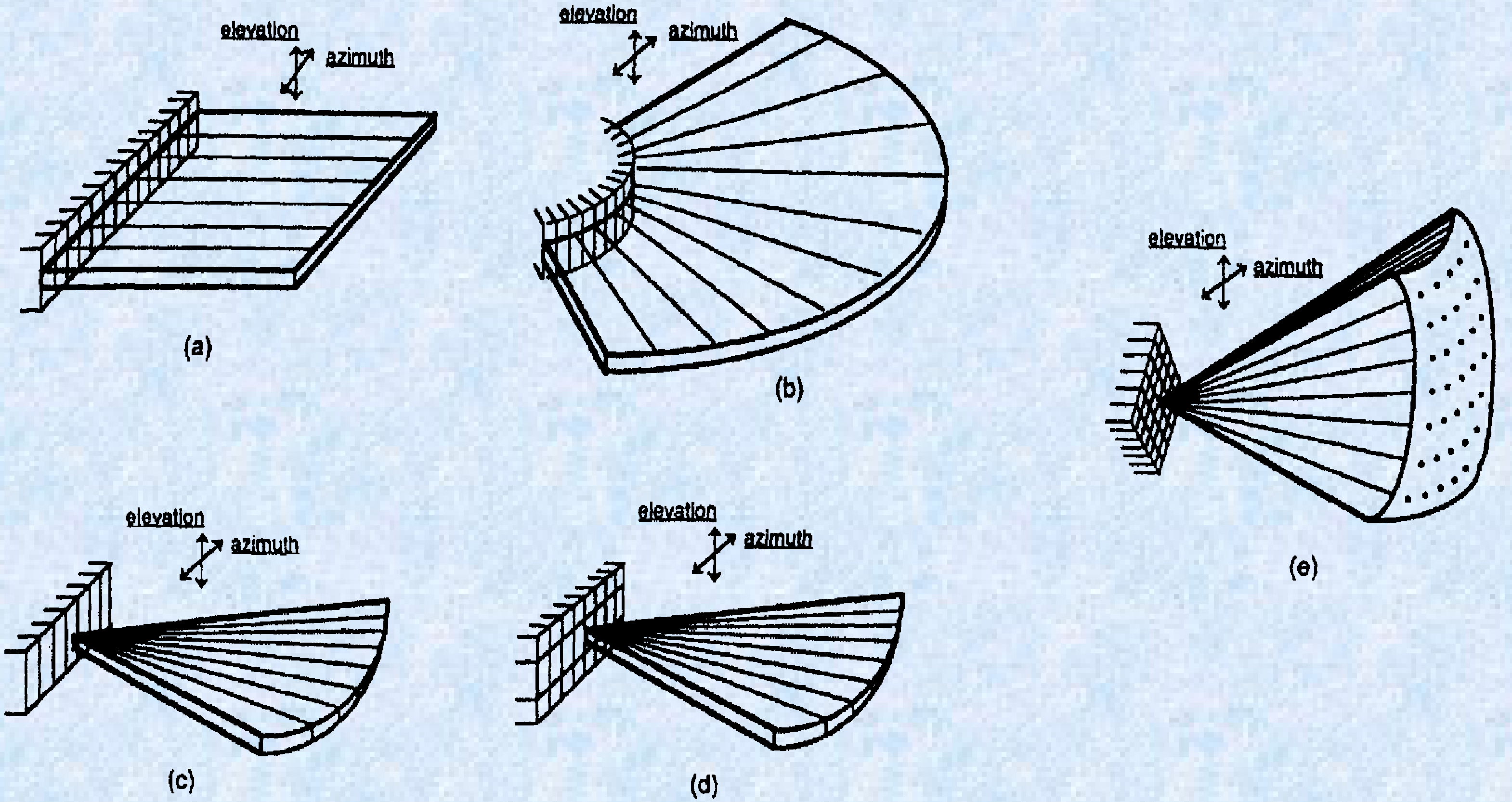
Grating lobes can be easily explained in the spatial frequency domain



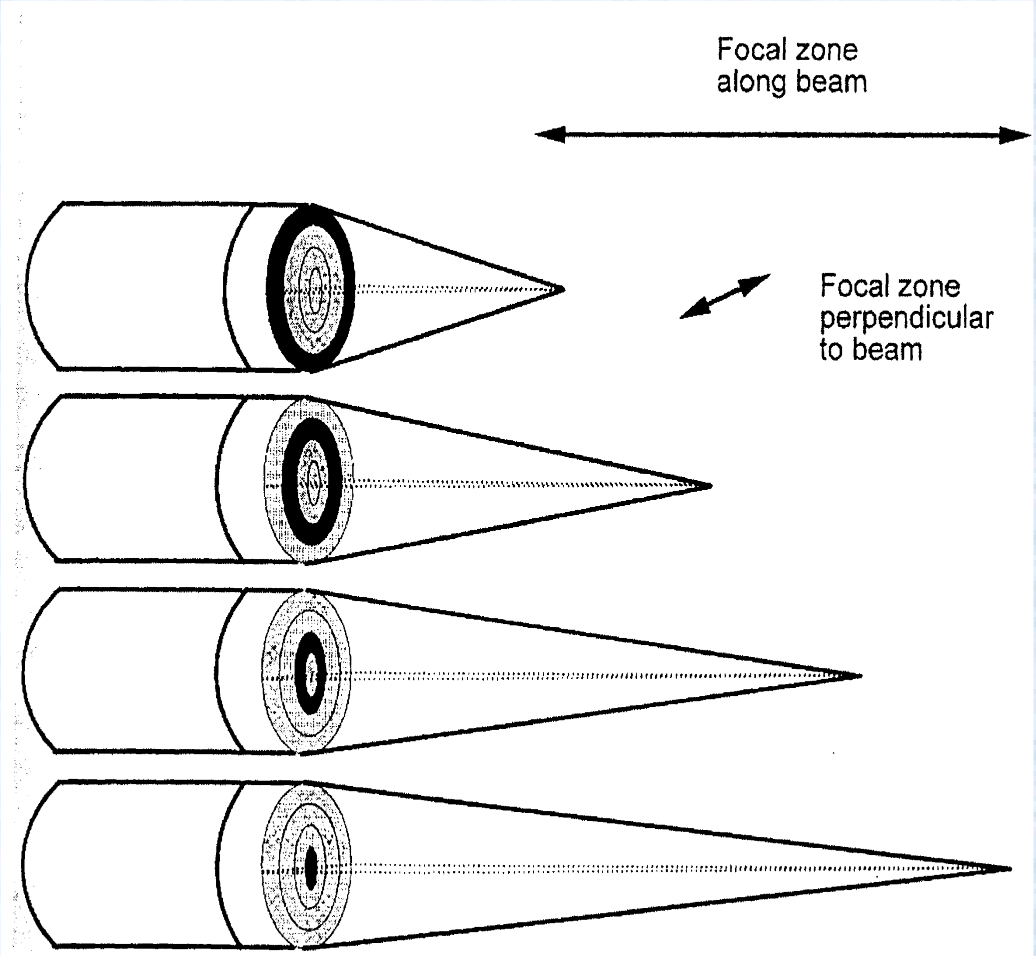
Radiation Diagram



Array types


elevation
azimuth
(a)
elevation
azimuth
(b)
elevation
azimuth
(e)
elevation
azimuth
(c)
elevation
azimuth
(d)

Annular array



Array Types

- To each application its own specialized transducer:
- Abdominal
- Cardiac
- Vascular
- Small parts
- Endocavitary

Abdominal

- Requisites:
  - Deep penetration
  - Wide field of view
  - Moderate footprint
- Solution:
  - Low frequency
  - Convex probe

Cardiac

- Requisites:
  - Good penetration
  - Wide field of view
  - Very small footprint
- Solution:
  - Low frequency
  - Phased array probe

Vascular

- Requisites:
  - Good resolution
  - Moderate penetration
  - Doppler flow imaging
- Solution:
  - Medium frequency
  - Linear probe

Small parts

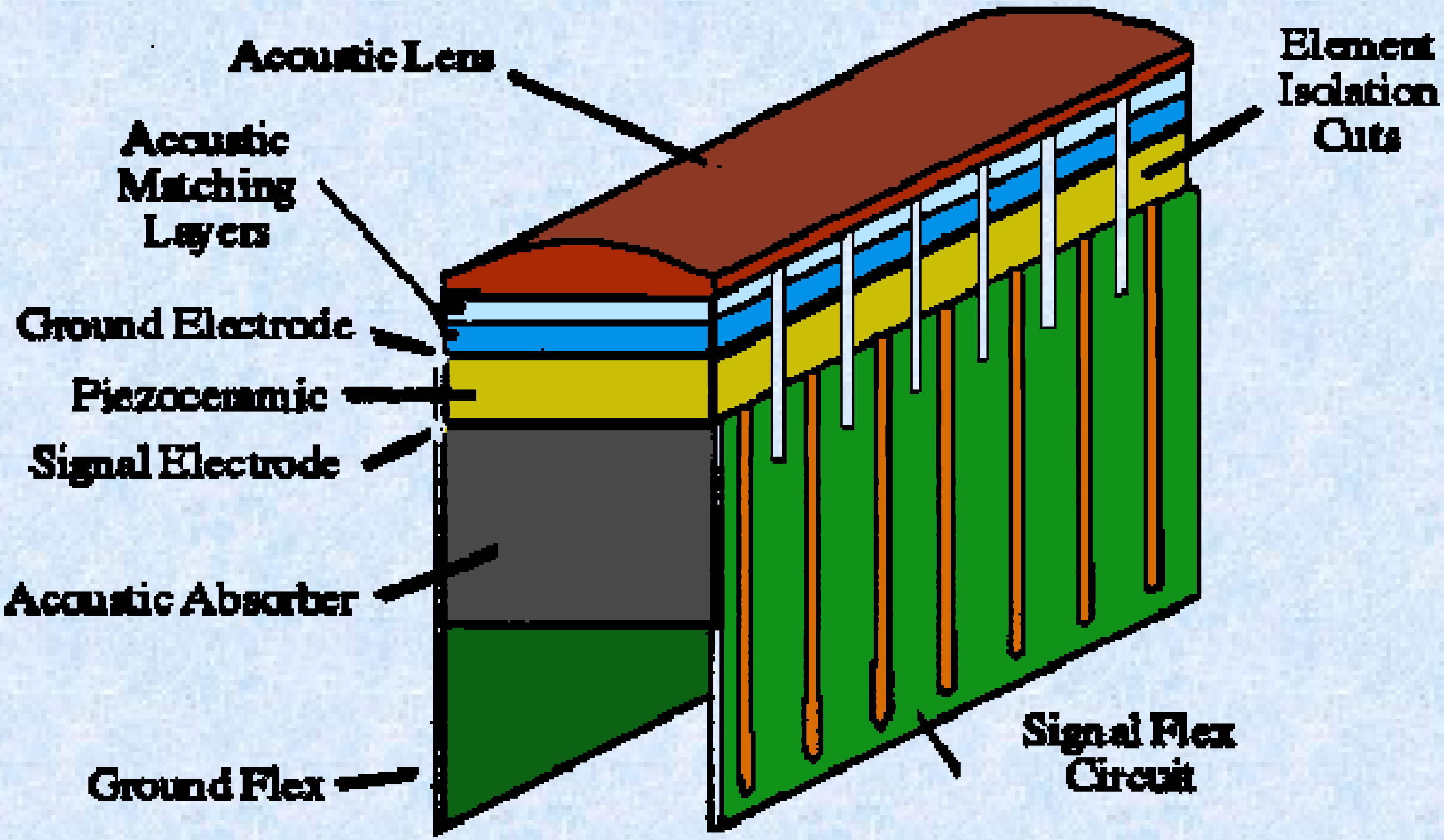
- Requisites:
  - Very Good resolution
  - Moderate penetration

- Solution:
  - High frequency
  - Linear probe

Technological aspects

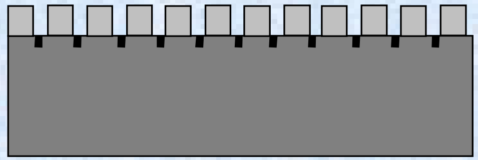
- Safety and ergonomic aspects regulate the physical characteristics of the probe:
  - Waterproof
  - Appropriate materials (sterilization, cleaning)
  - Electrical safety
  - Weight
  - Cable compliance
  - Footprint

Typical array construction

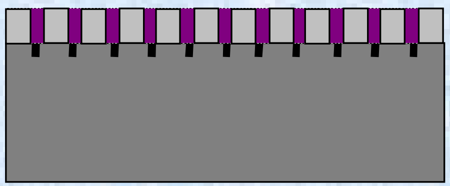


Fabrication process

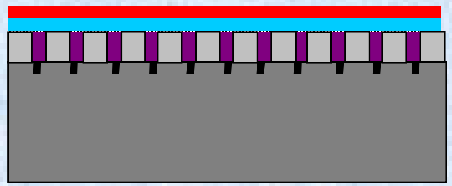
ceramic glued to backing



cut

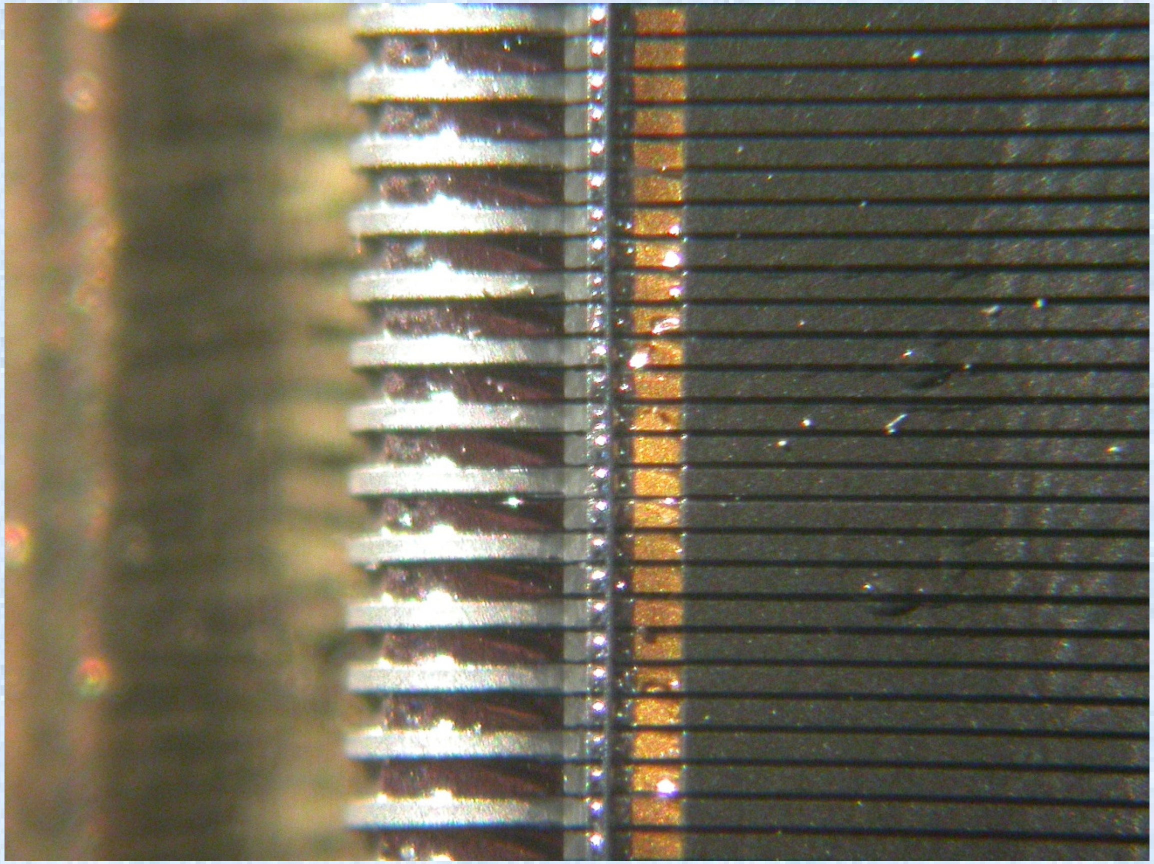


Kerf filled

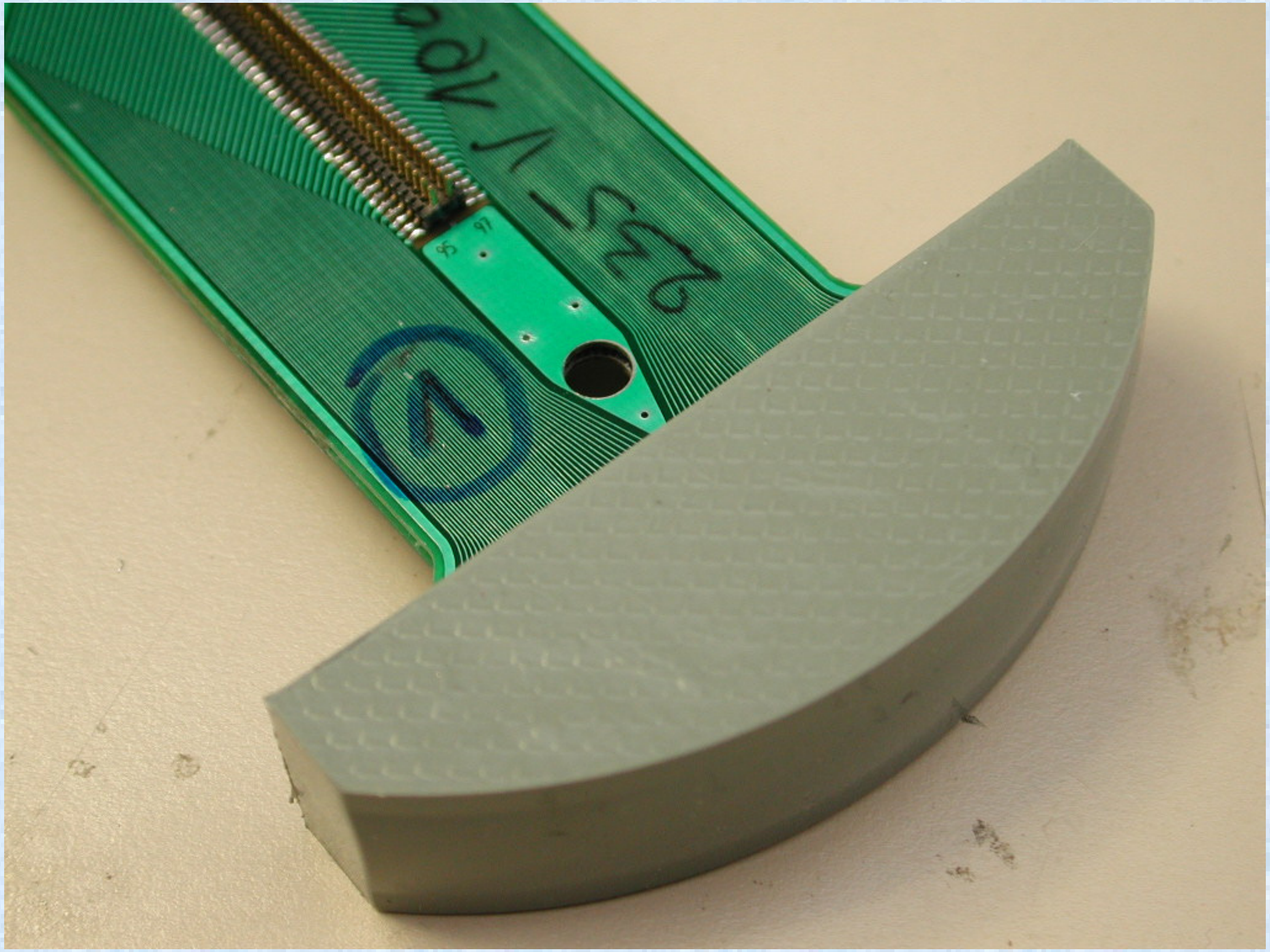


Matching layers applied

Fabrication process



Fabrication process



Fabrication process