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Short Courses

2D

Quantitative Acoustic Microscope-Measurement , Analysis, Biological and Material Science Applications

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Part 1

Acoustic Microscopy: Measurements , Analysis, Applications

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Contents

- Basics of acoustic microscopy
- Transducers
- Contrast and resolution
- Types of acoustical microscopes
- Quantitative methods
- Anisotropy measurements
- Non-linear imaging
- From Desktop to Hand-Held: Examples of various advanced approaches & applications

High Resolution Imaging

A picture is worth a thousand words

What is Acoustic Microscope?

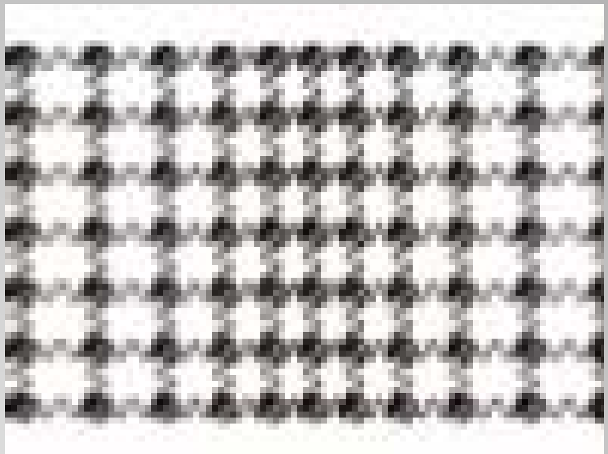
Apparatus for non destructive investigation of internal microstructure of materials of various nature using a high frequency ultrasonic beam emitting into a specimen via an acoustic lens, and detecting acoustic characteristics of the specimen by analysis of a reflected and/or transmitted ultrasonic wave propagating within the specimen.

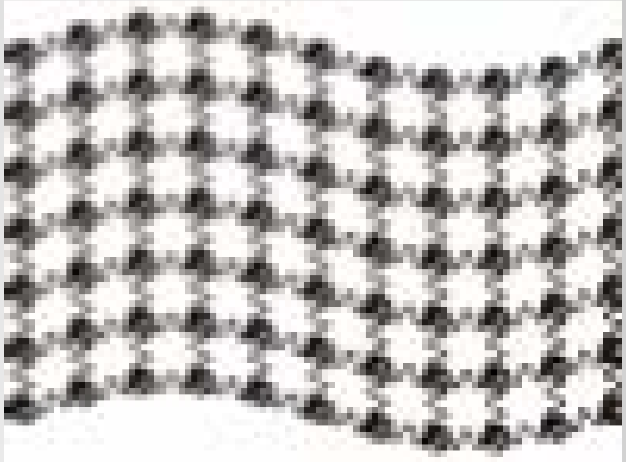
ABC of Acoustic Microscopy

Acoustic waves

Parameters:

- Frequency band
- Amplitude
- Sound velocity
- Acoustic impedance
- Attenuation





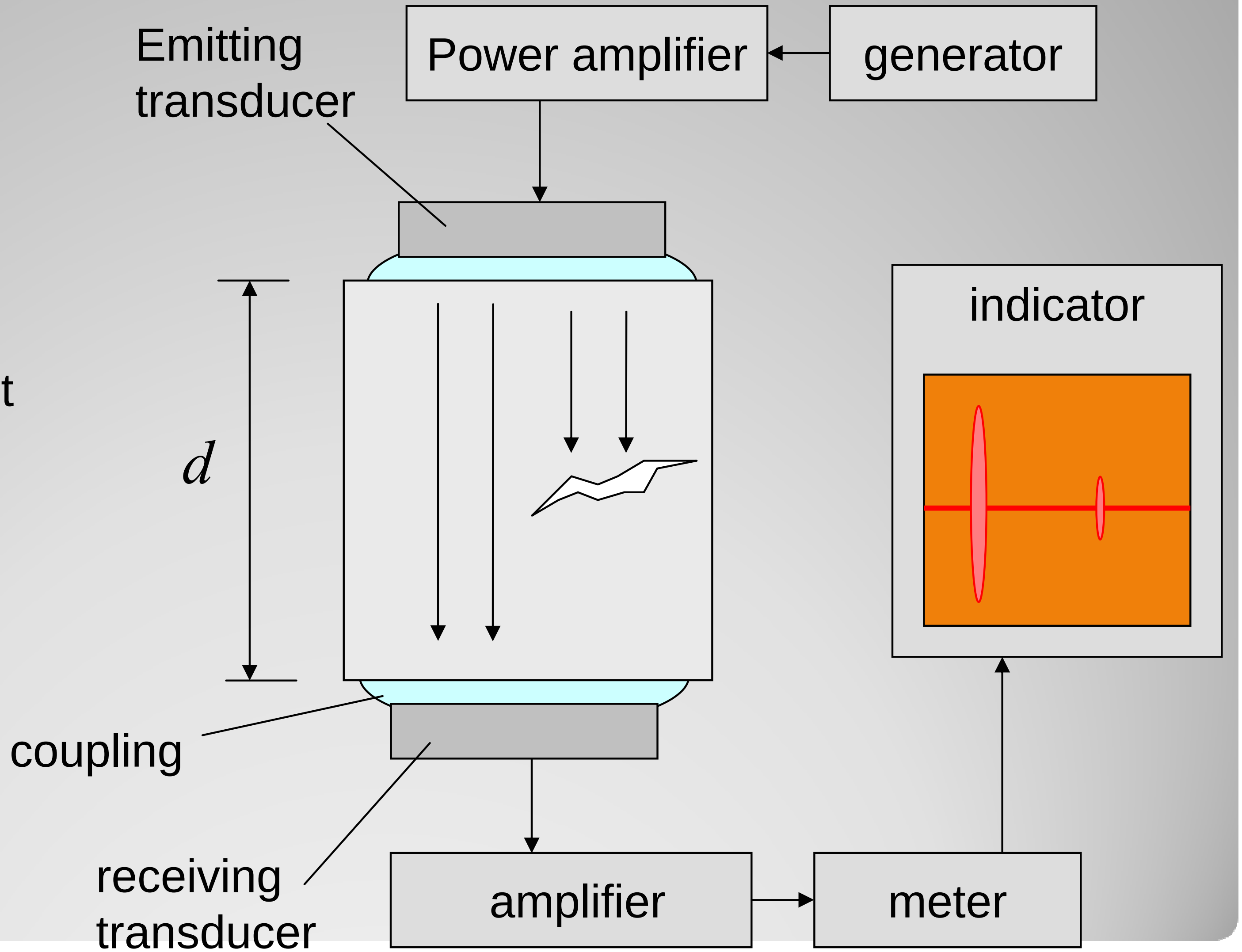
Through-transmission method

Time of flight:

$$t = \frac{d}{V}$$

Attenuation coefficient

$$\alpha = \frac{1}{d} \ln \frac{A_{in}}{A_{out}}$$



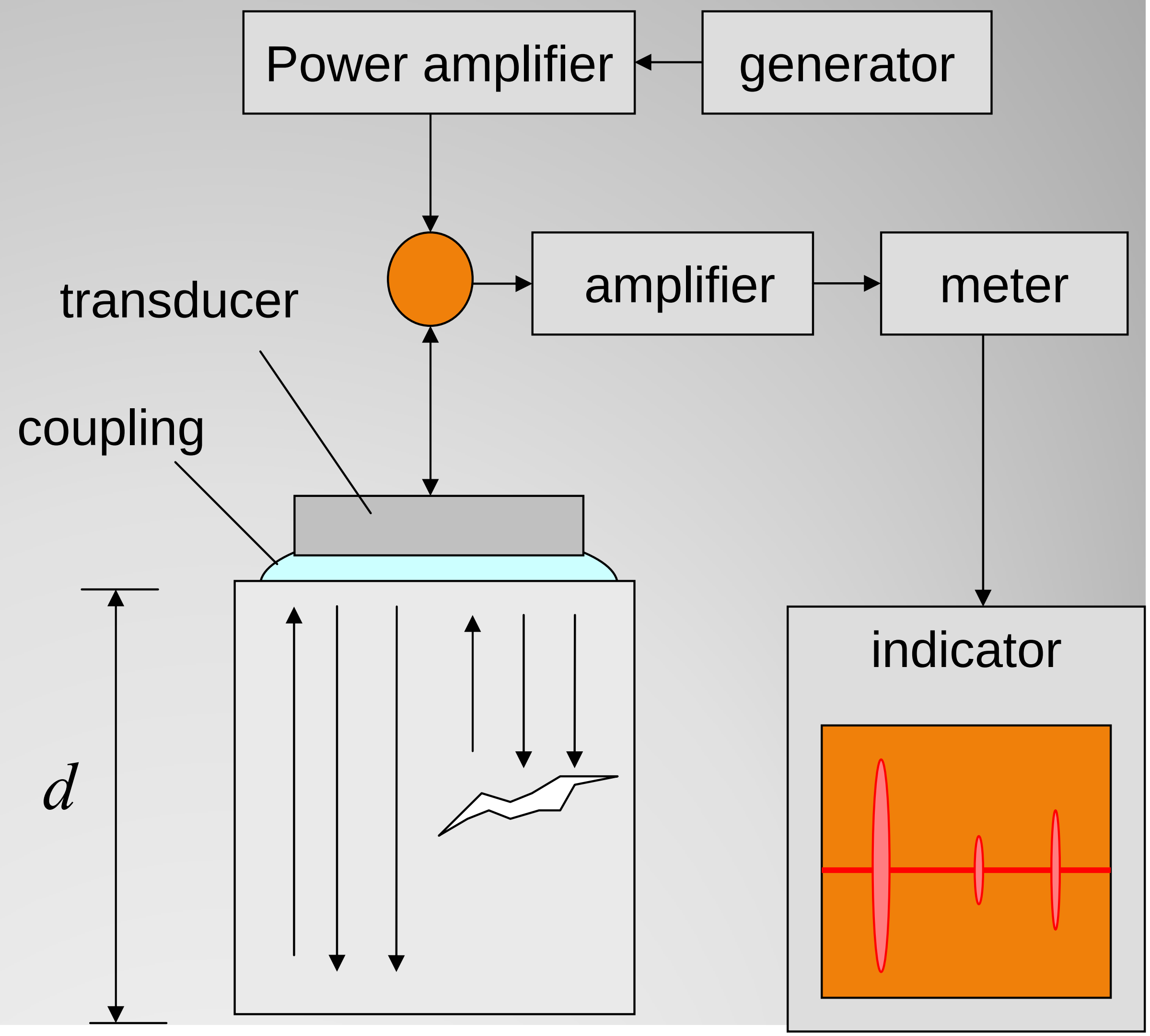
Reflection method

One - side access

Time of flight:

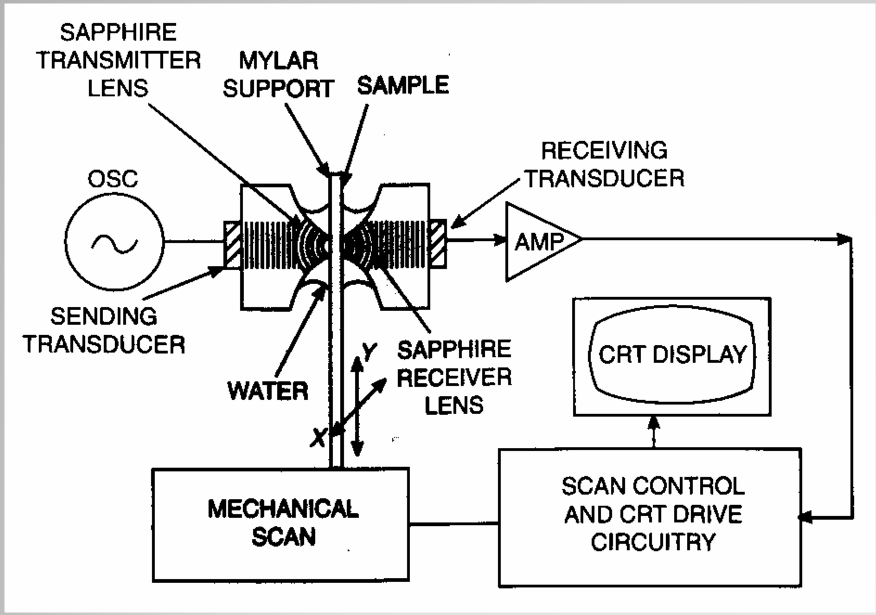
$$t = \frac{2d}{V}$$

Reflection coefficients involved into received amplitude

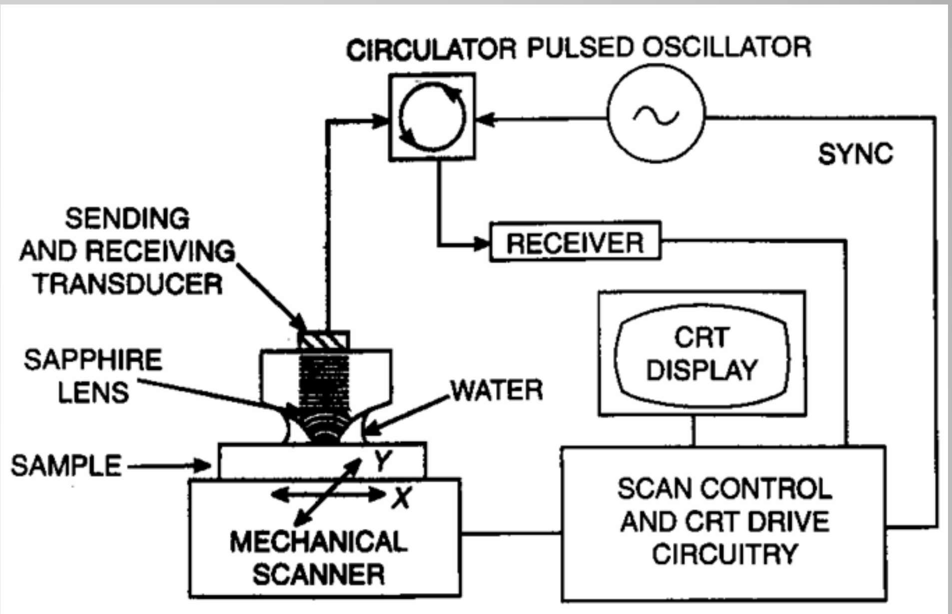


Scanning acoustic microscopy (SAM)

C. Quate and L. Lam, Stanford University, 1973



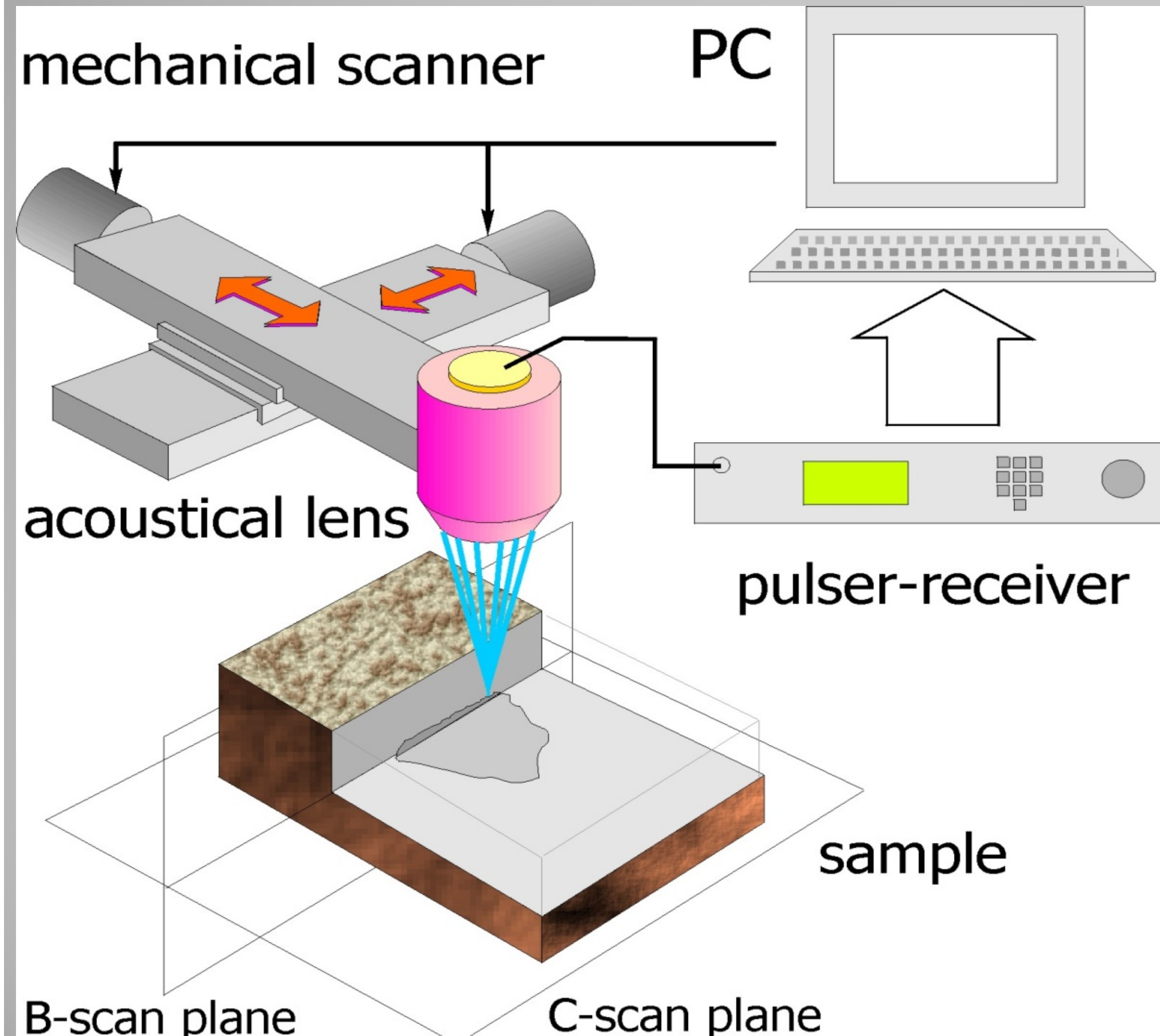
Pulse-transmission setup



Pulse-echo setup

Scanning Acoustical Microscope

Reflection Type



Acoustic lens
Pulser-receiver
Analog-to-digital converter
Mehanical scanner
Computer
Controlling software

Types of Acoustic Images

A-scan:

A plot of signal (amplitude and phase against time that can be related to distance in a specimen).

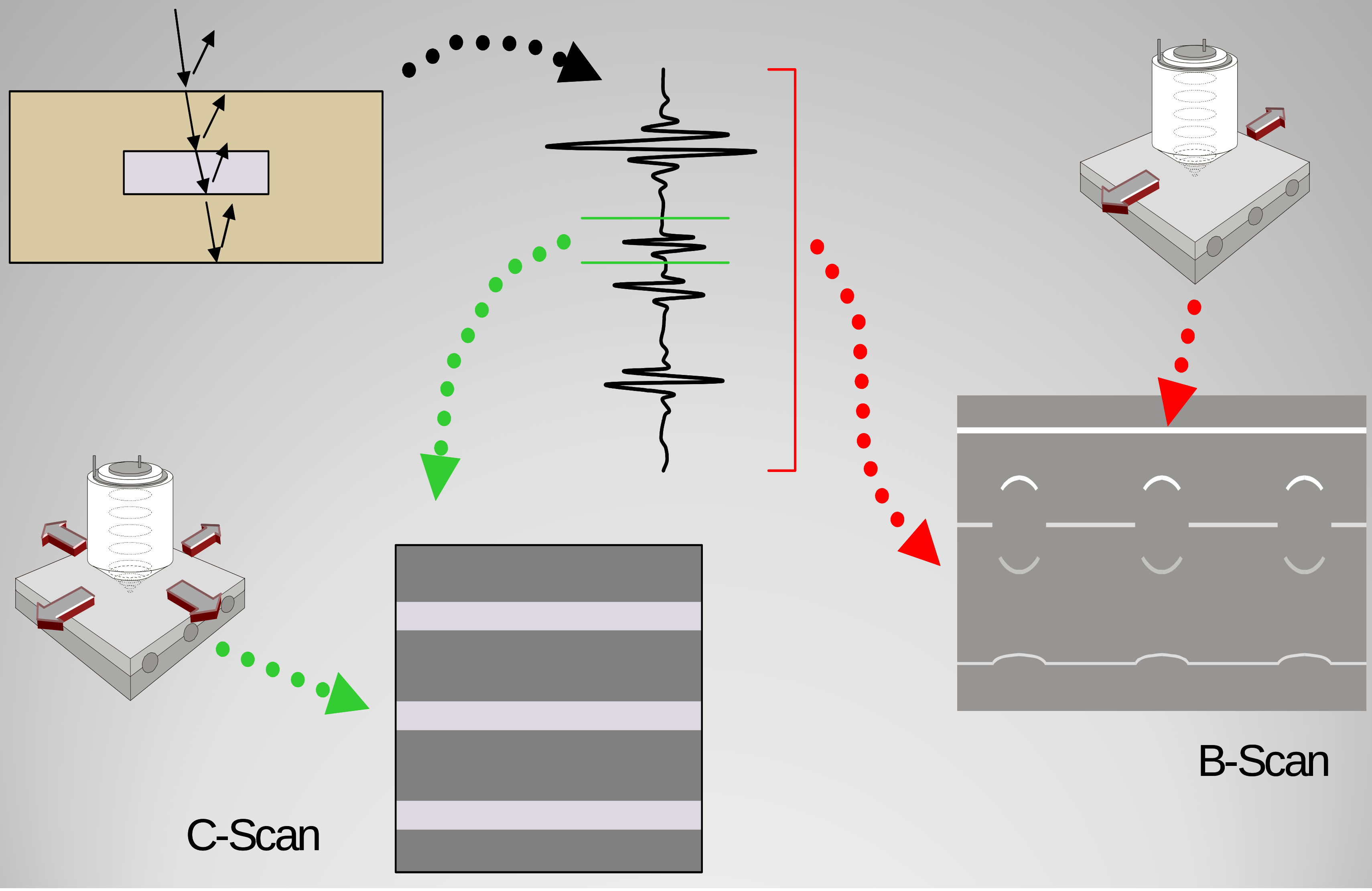
B-scan:

A plot of signal amplitude displaying a cross section of a specimen perpendicular to the upper surface.

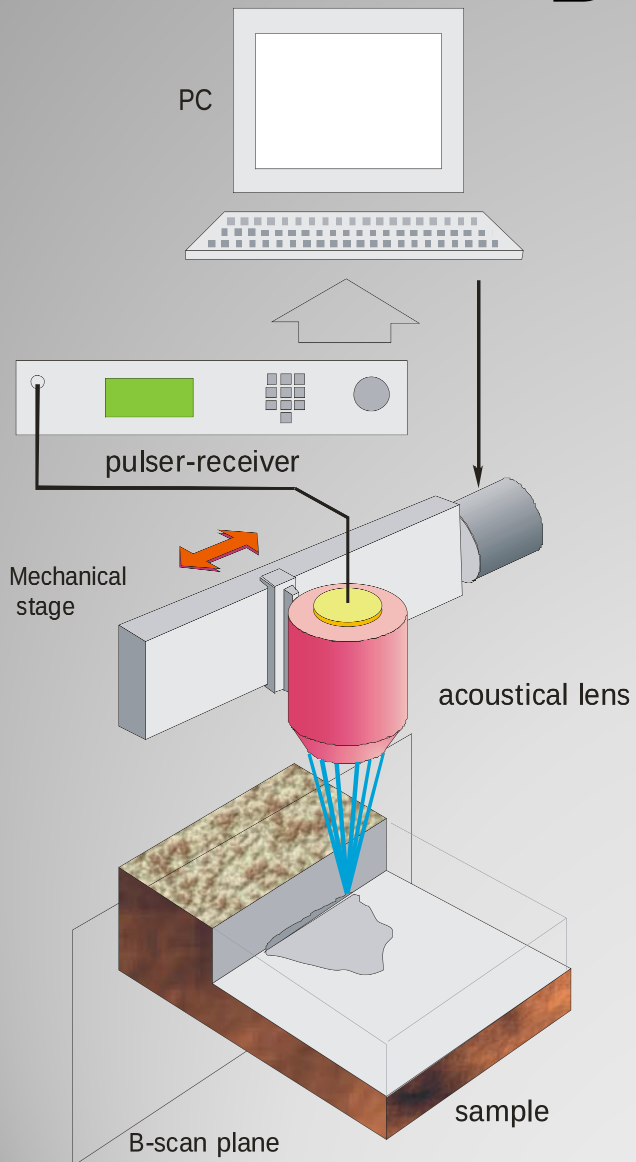
C-scan:

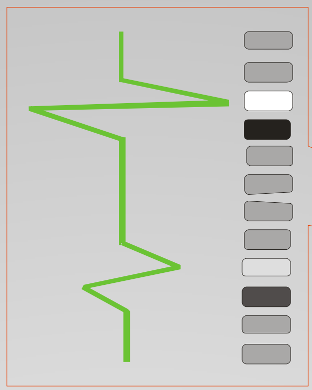
A plot of signal amplitude displaying a cross section of a specimen parallel to the upper surface.

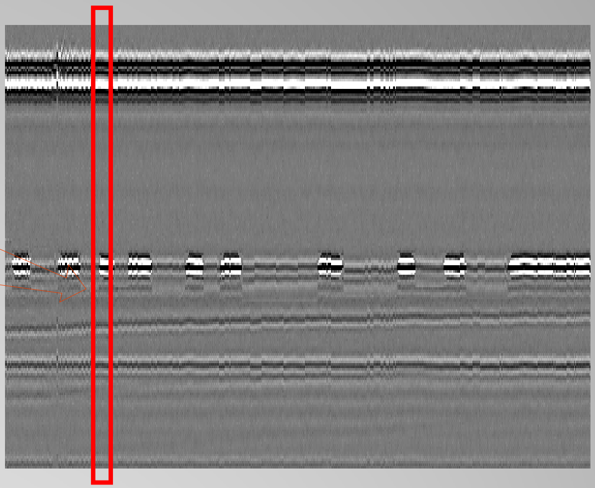
Various Imaging Modes



B-scan obtaining

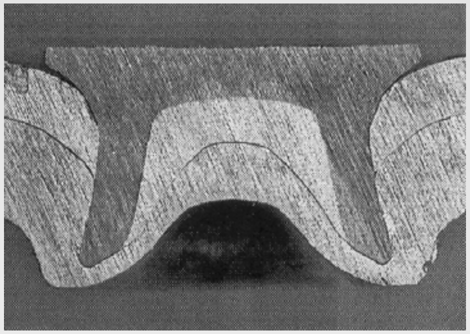




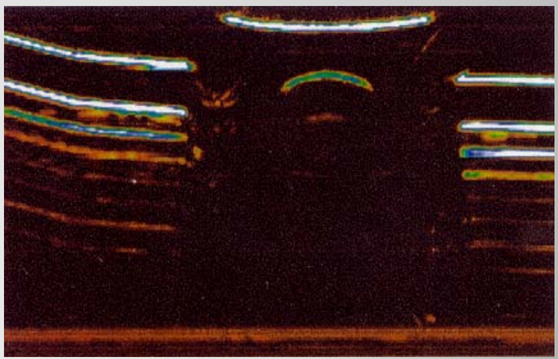


Inspection of rivets quality

Optical image after cross section

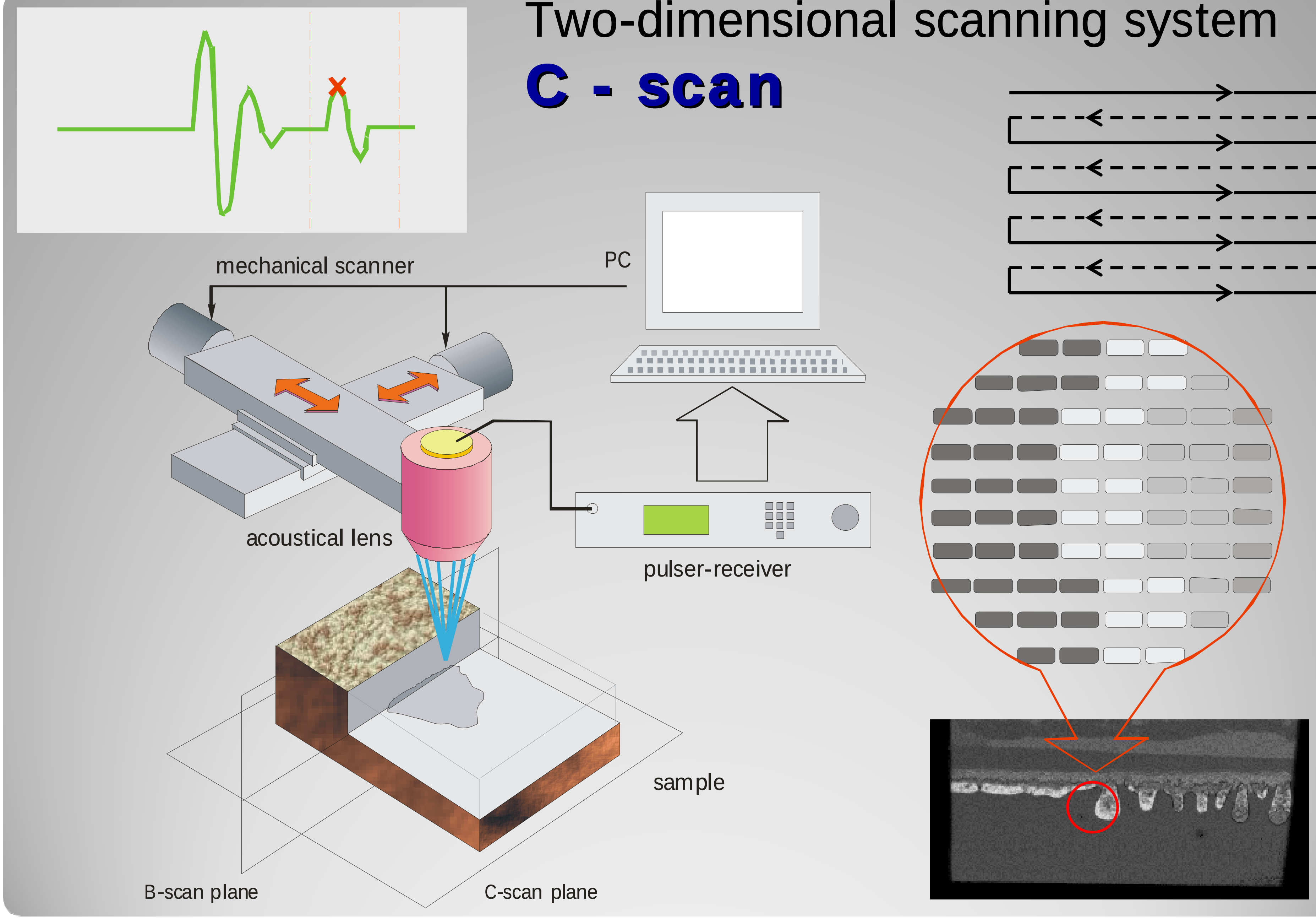


B-scan (in quasicolors)

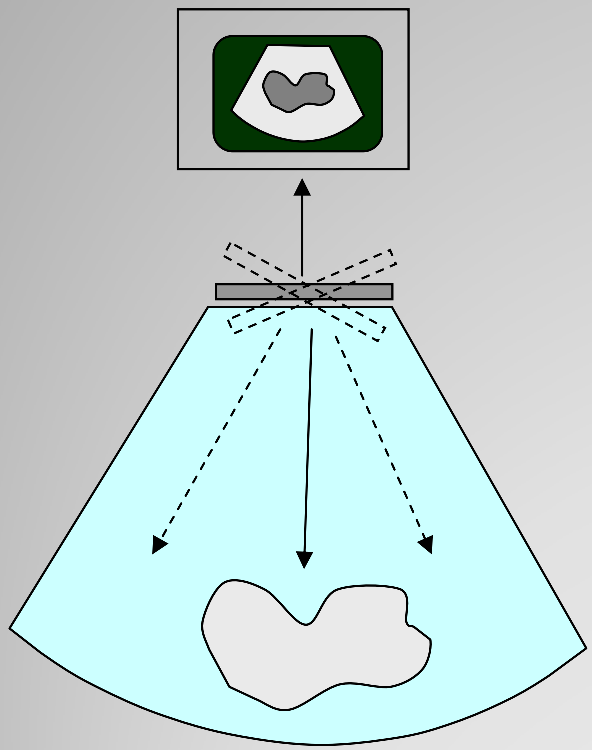


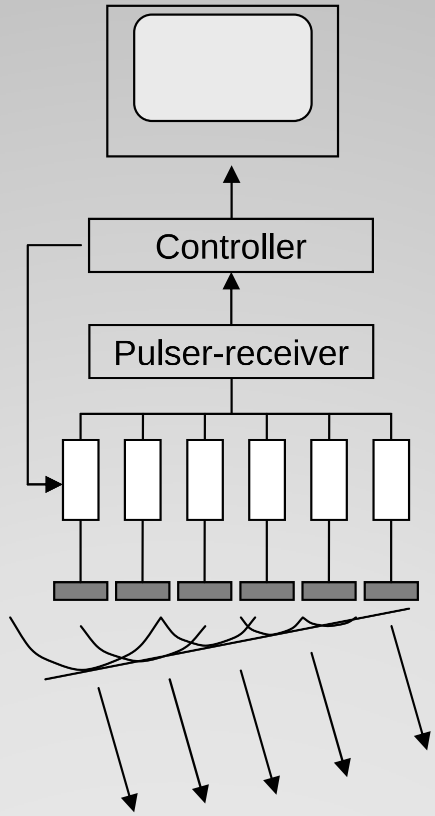
Two-dimensional scanning system

C - scan

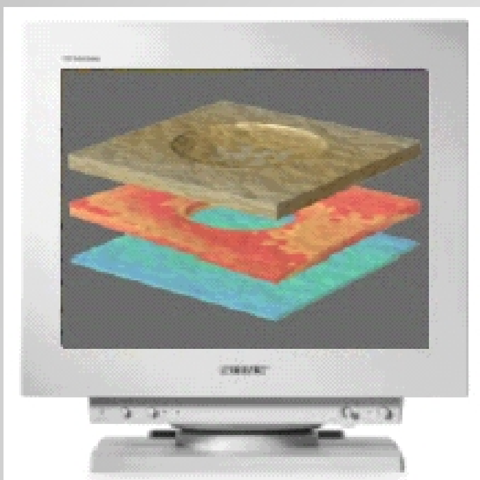


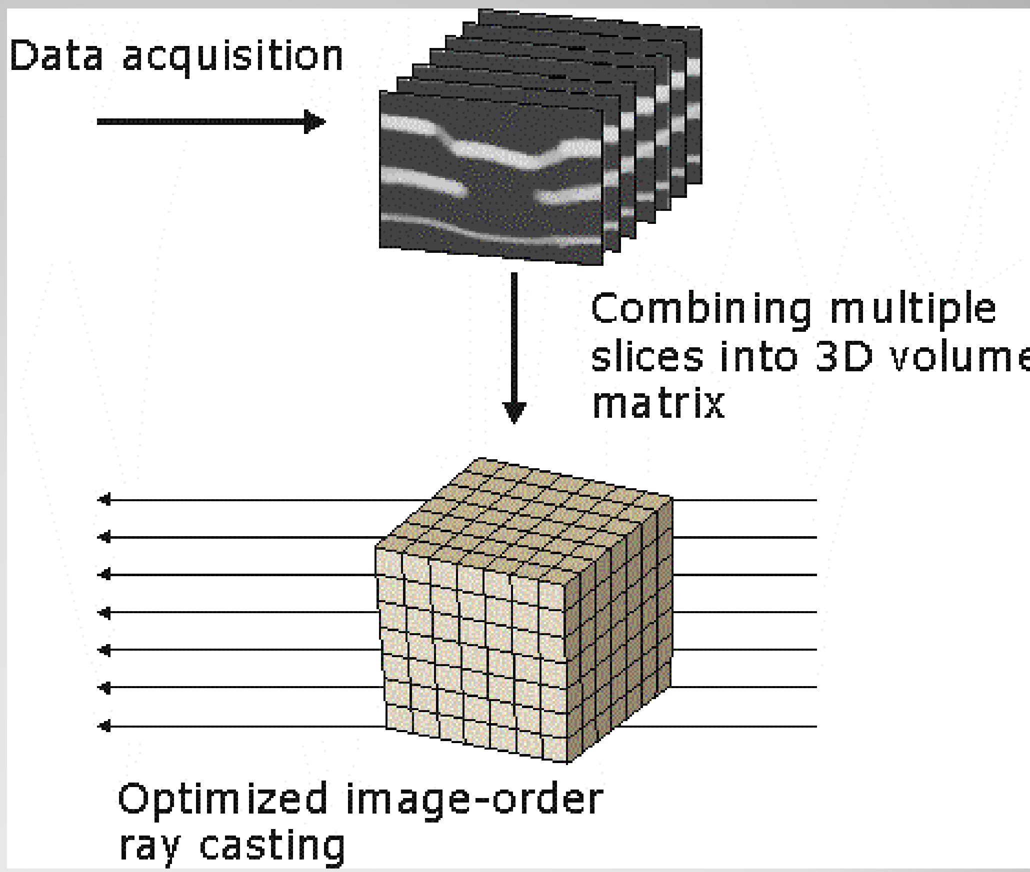
Sector scanners





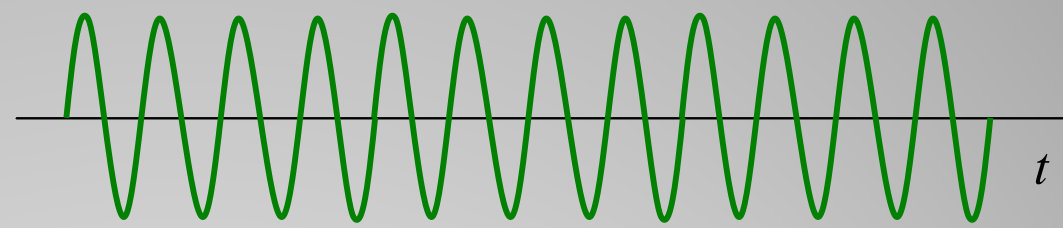
Direct Volume Rendering



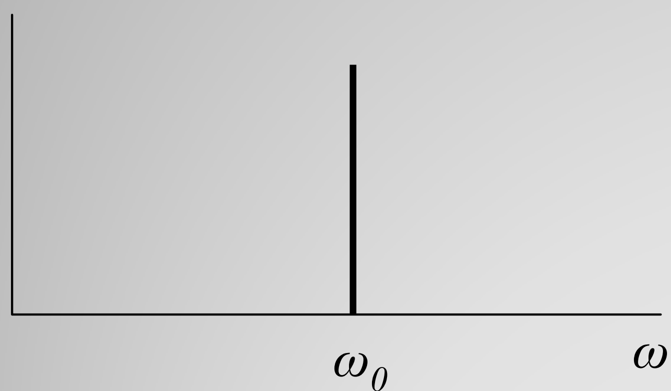


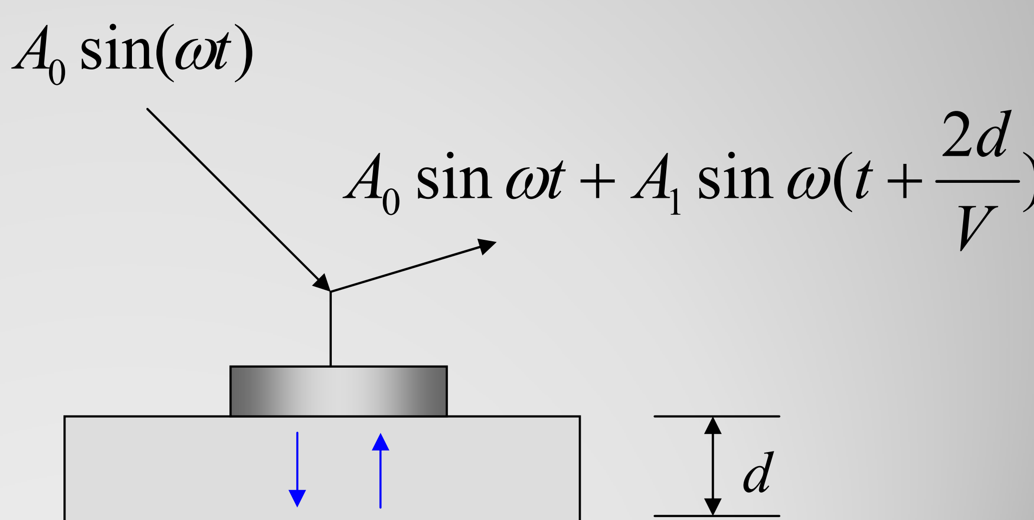
Excitation signals

Continuous wave



Parameters: frequency ω_0, amplitude A_0, phase φ



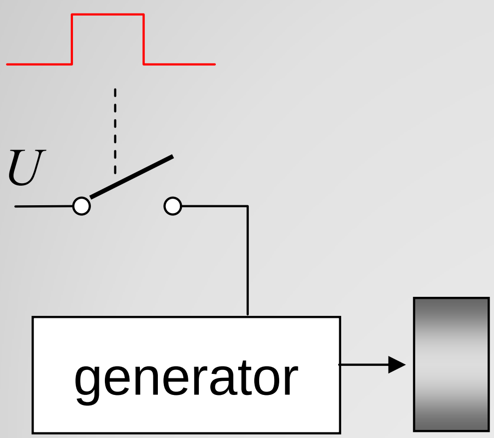


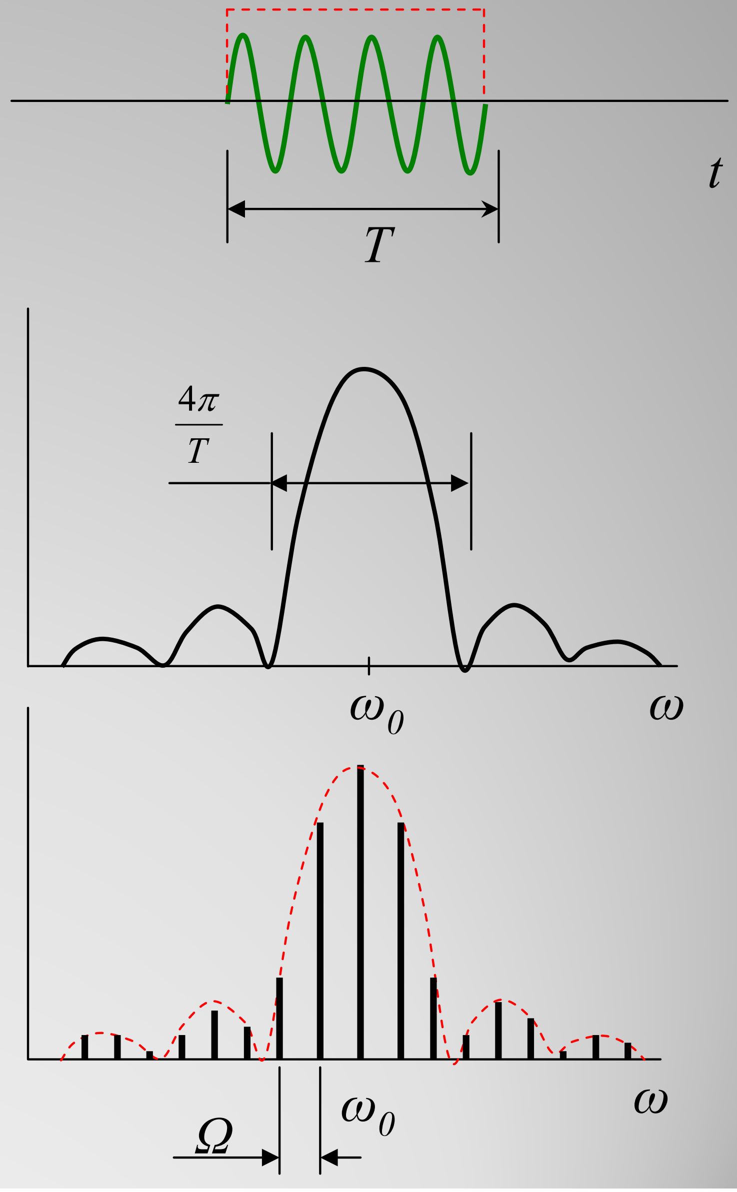
Applications: beam evaluation, phase measurements

Toneburst

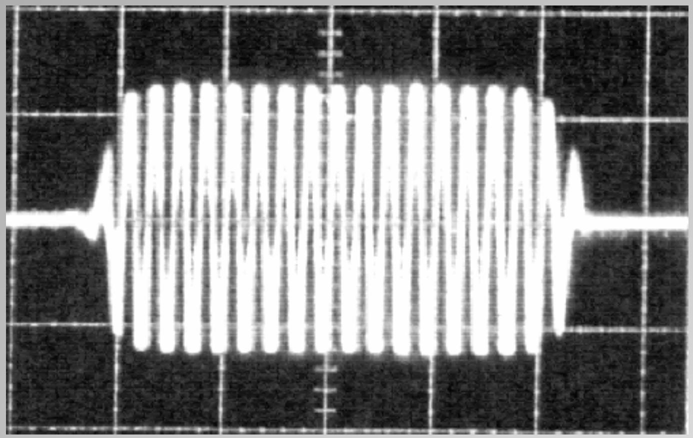
Parameters:

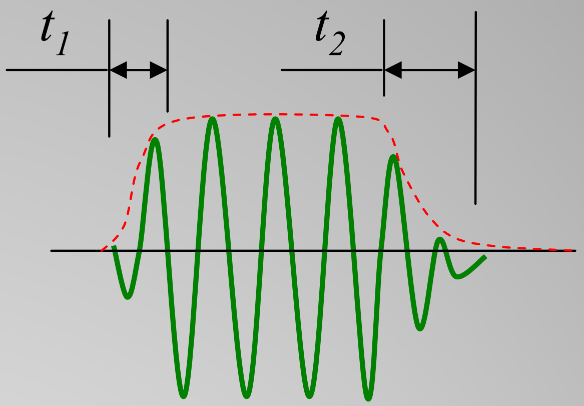
- frequency ω_0,
- amplitude A_0,
- phase φ,
- duration T,
- repetition frequency Ω



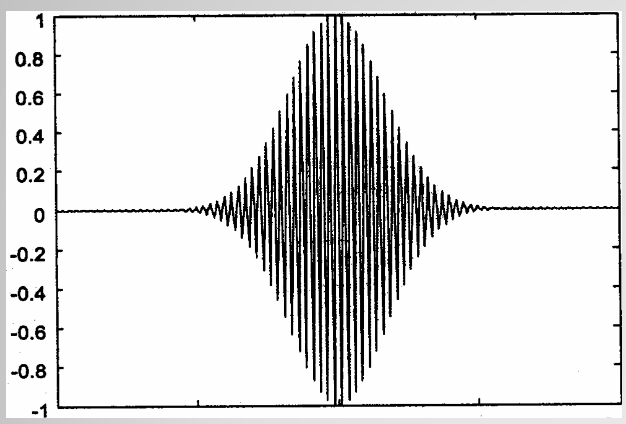


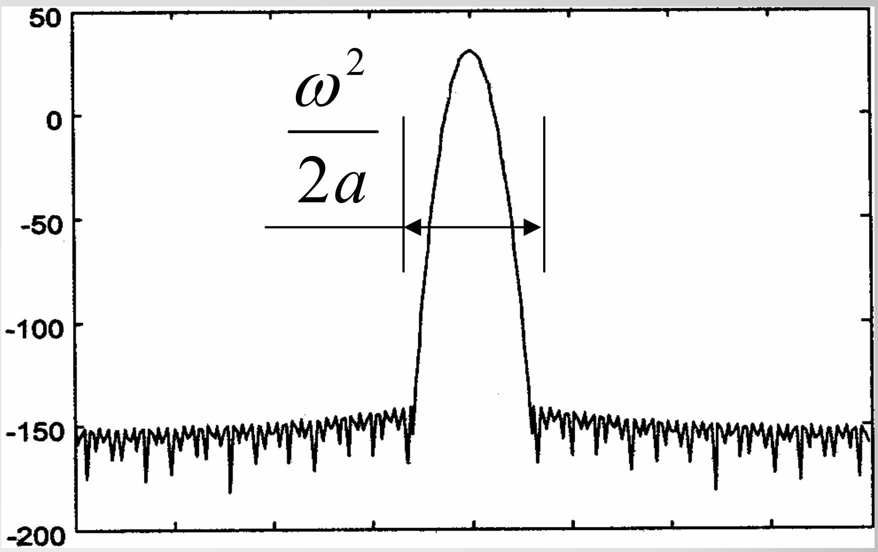
Toneburst





Gaussian modulation

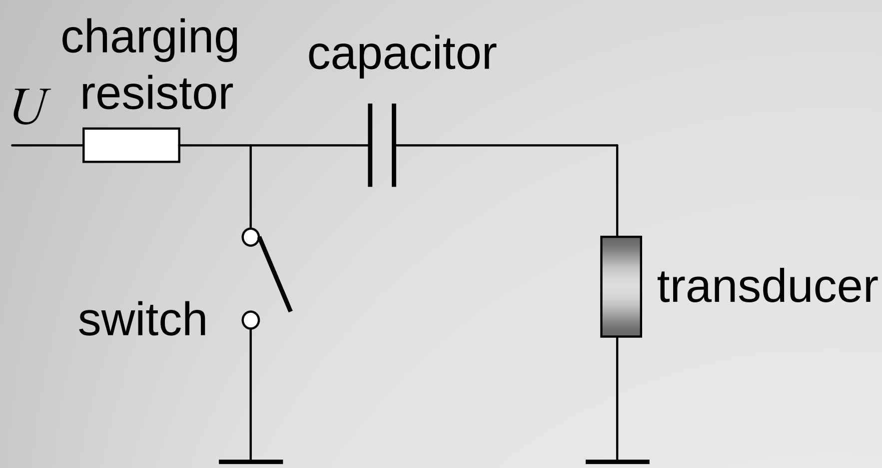


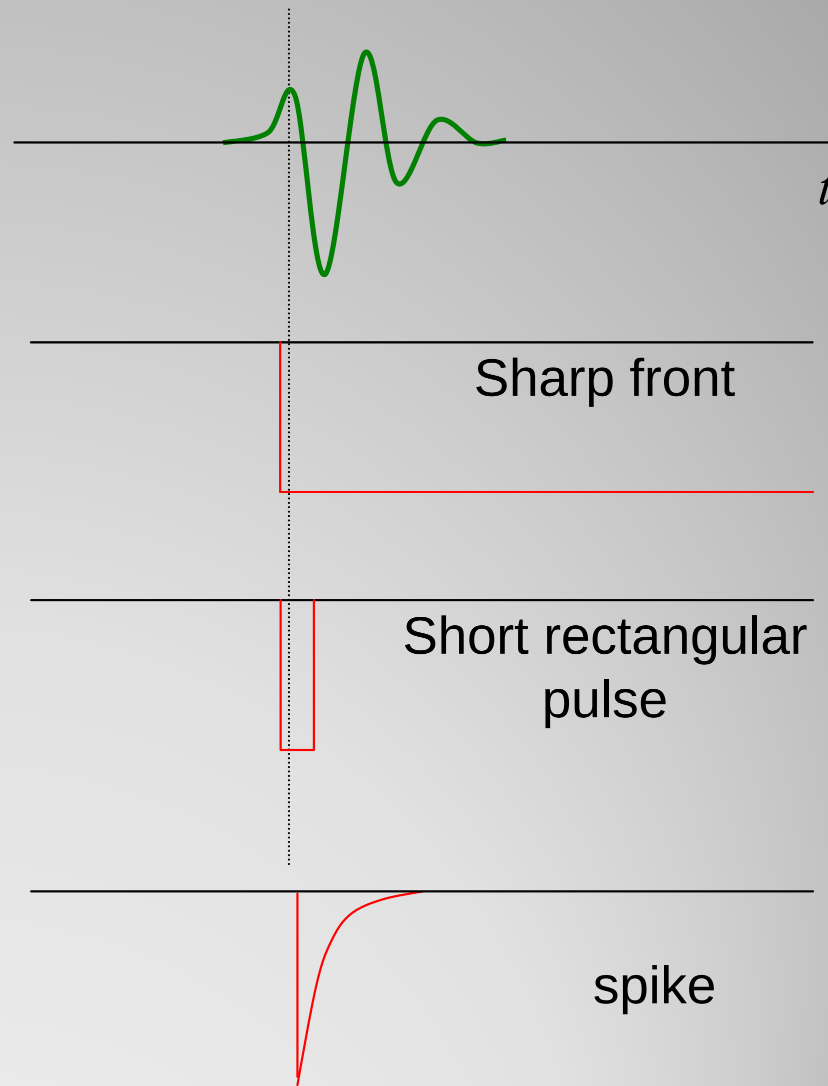


$$u = A\exp(-a(t-t_0)^2)\sin(\omega t)$$

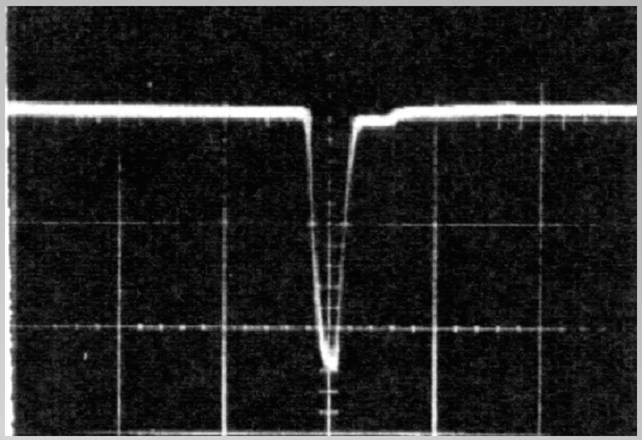
Short pulse

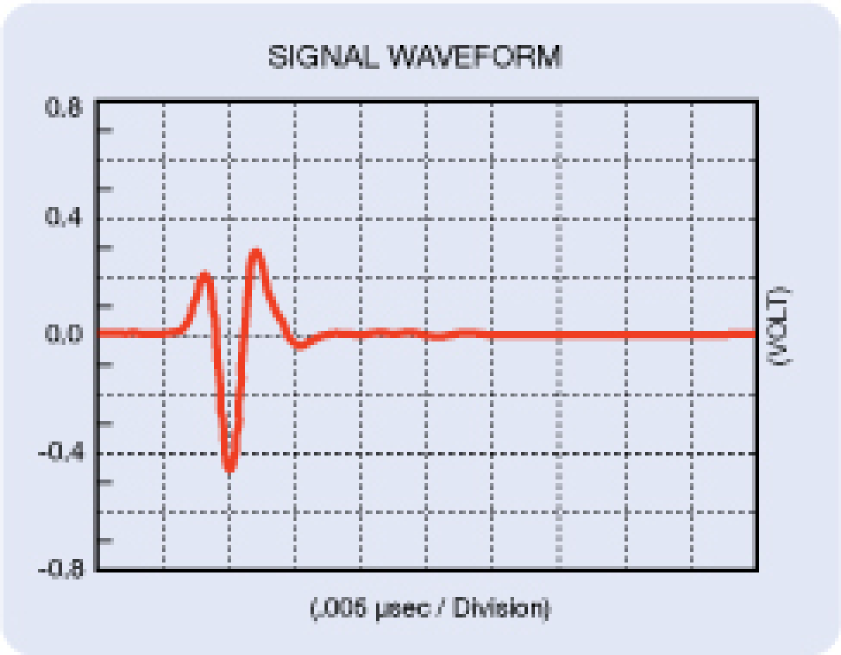
Excitation: one short pulse.
Parameters completely determined by transducer properties



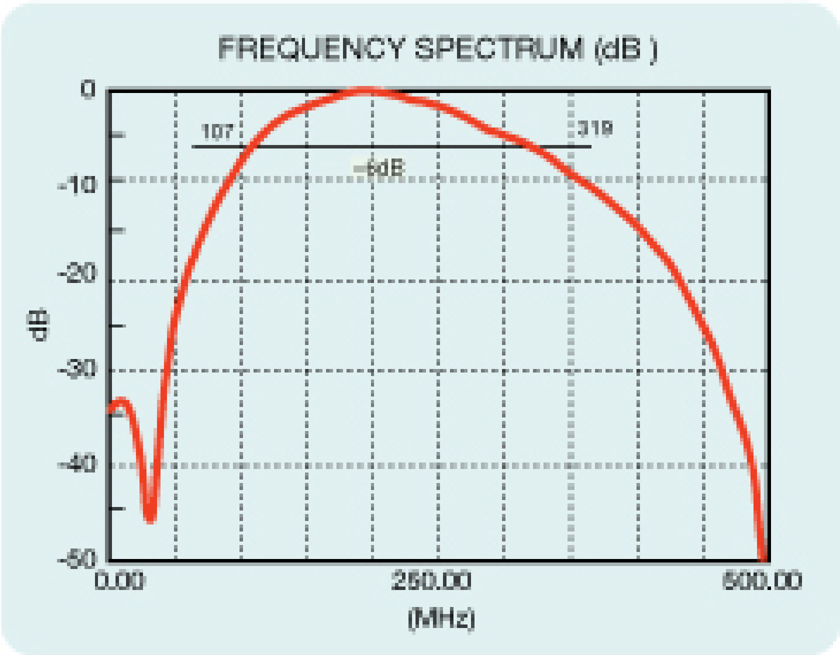


Short pulse





SIGNAL WAVEFORM
0.8
0.4
0.0
-0.4
-0.8
(VOLT)
(.005 µsec / Division)

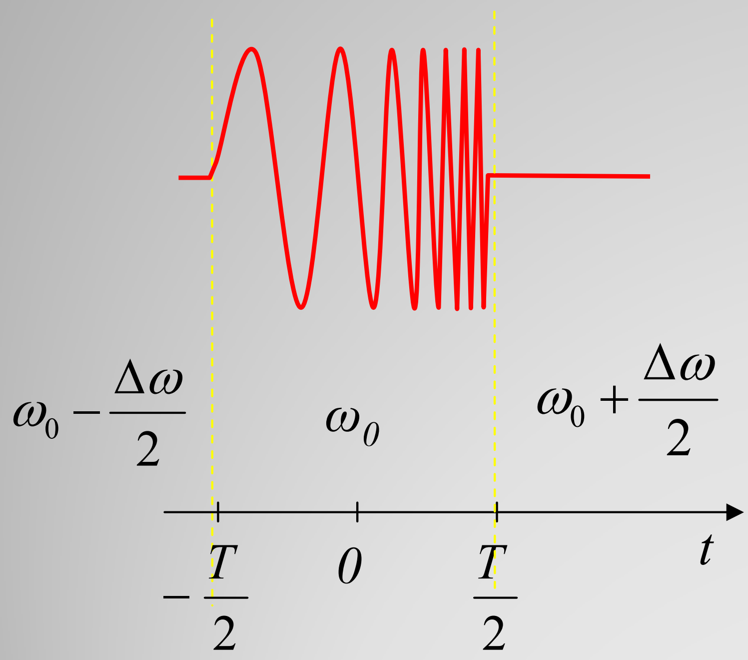


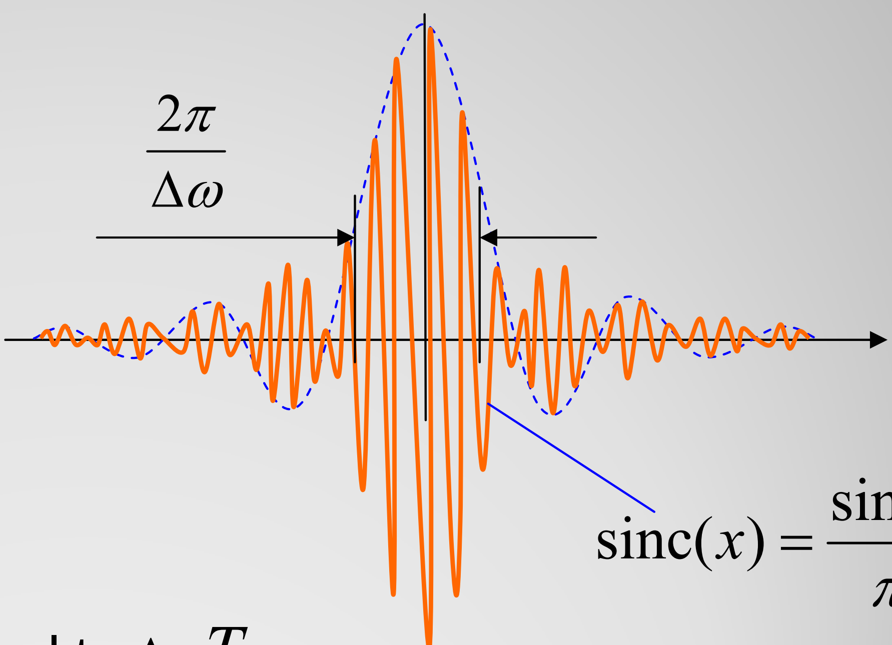
FREQUENCY SPECTRUM (dB)
0
-10
-20
-30
-40
-50
dB
107
319
-6dB
0.00
250.00
500.00
(MHz)

Pulse compression

Linear frequency modulation:

$$f_t(t) = \begin{cases} A\exp(jt(\omega_0 + \Delta\omega \frac{t}{T}), & \text{if } -\frac{T}{2} \le t \le \frac{T}{2} \\ 0, & \text{else} \end{cases}$$



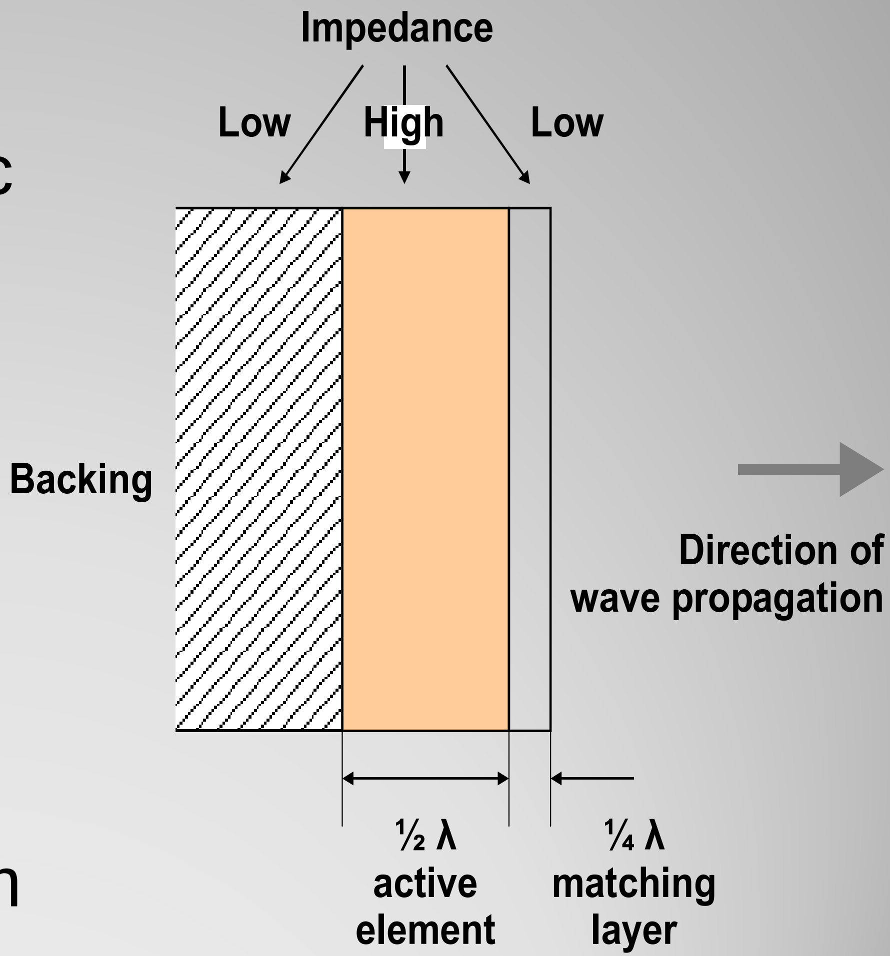


Amplitude of $f_{cc}(t)$ is proportional to $\Delta\omega T$

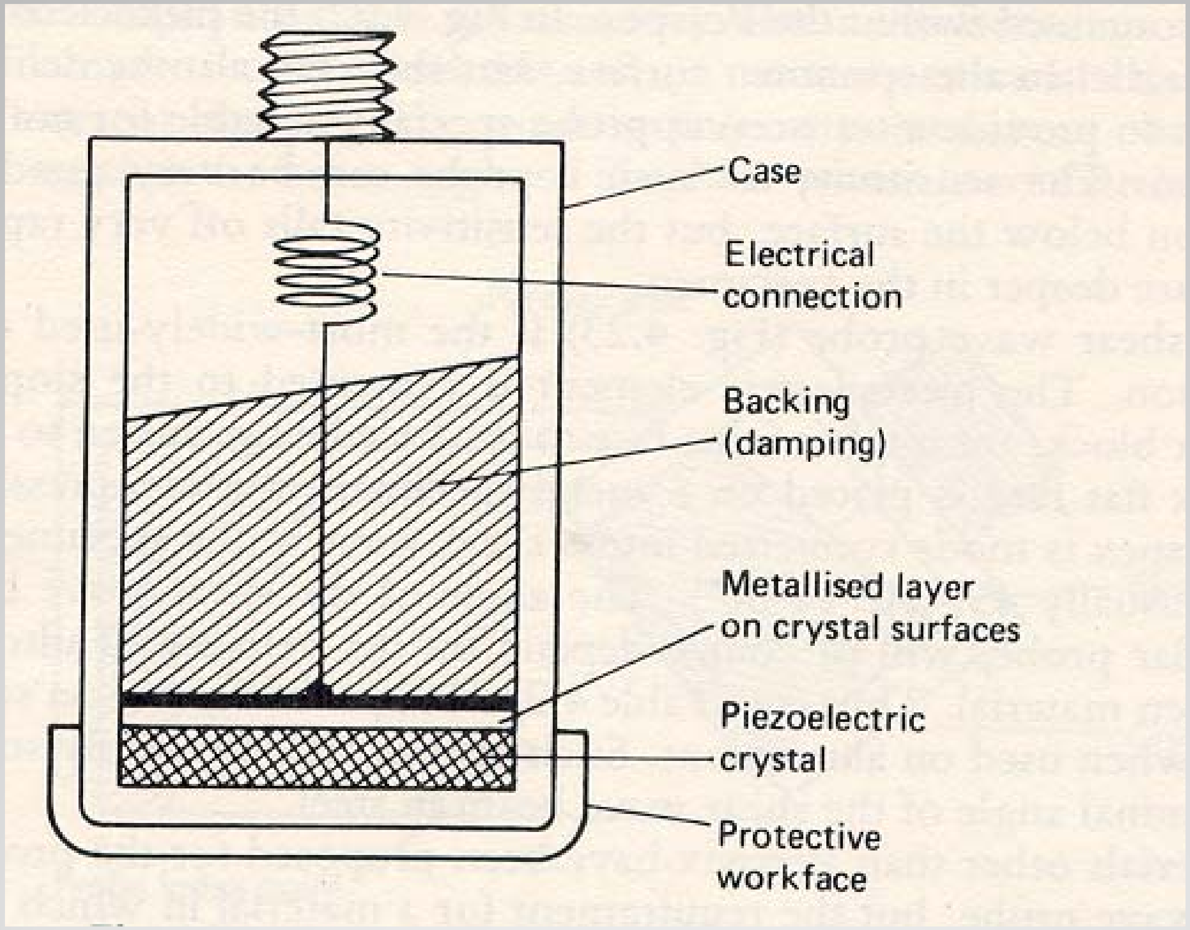
Transducers

Transducer Design

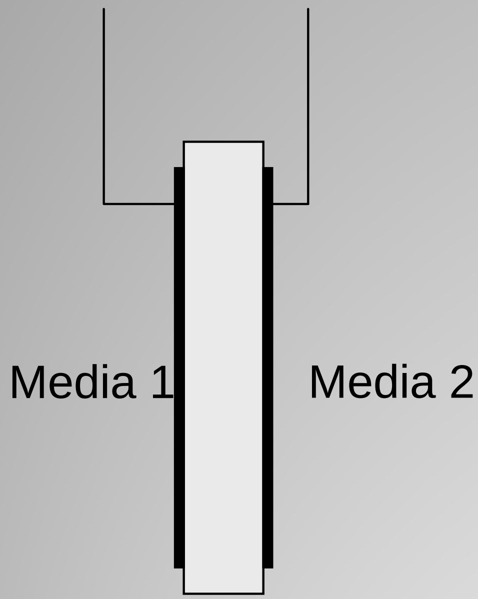
- Natural wavelength is twice the thickness of piezoceramic wafer
- Optimal impedance matching is achieved by a matching layer with thickness ¼ wavelength
- Commonly used materials include lithium niobate, barium or zirconate titanate, etc.



Longitudinal Wave Probe



Loaded transducer

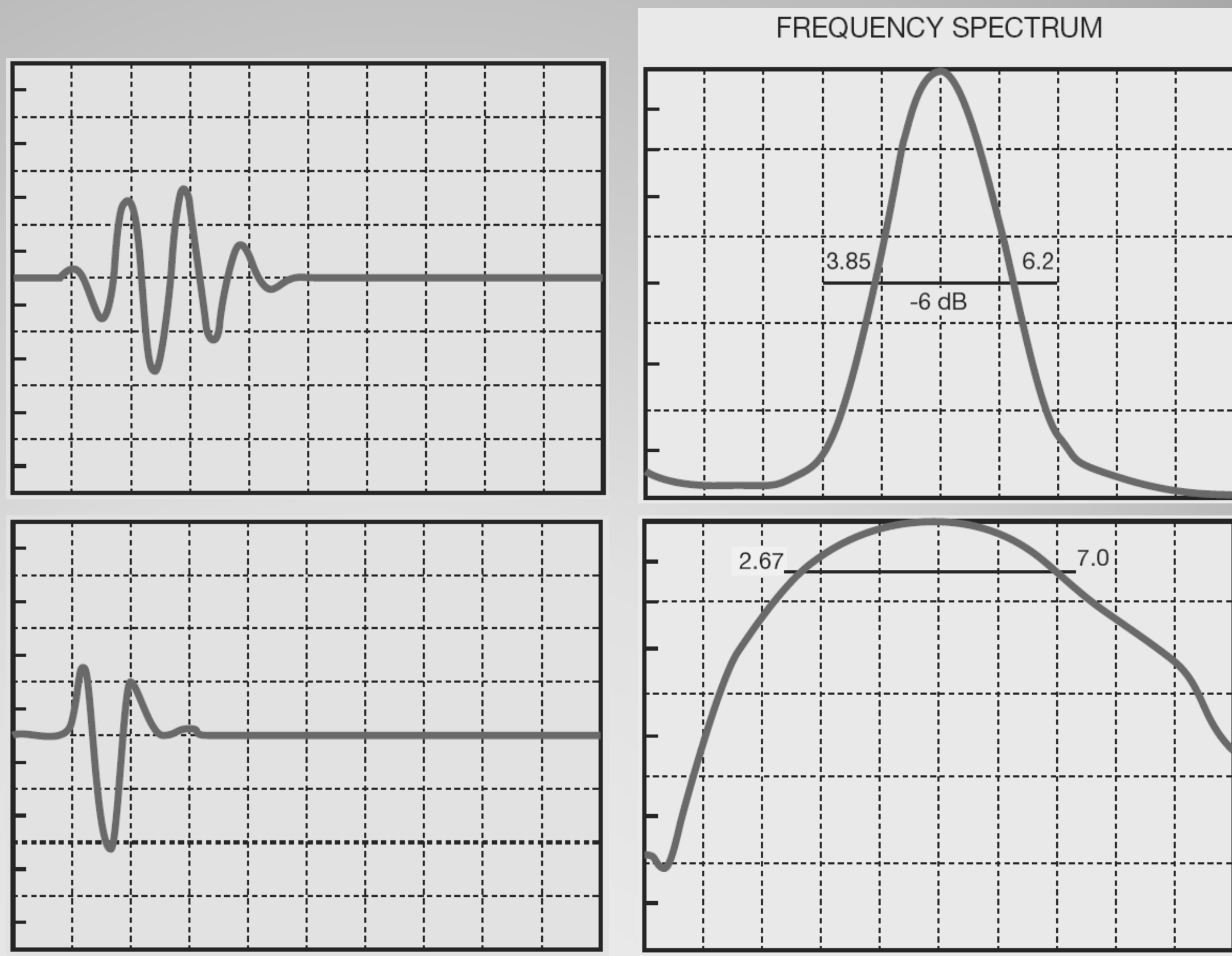


Well matched transducer

$$Z_1 = Z_2 = Z_C$$

or

$$Z_1 = 0;\ Z_2 = 2Z_C$$



Piezoelectric materials

Crystals: **Quartz** (SiO_2) 32º X-cut $k_t = 0.093$

Lithium niobate ($LiNbO_3$) 36º Y-cut $k_t = 0.49$; 163º Y-cut $k_t = 0.3$

ZnO Z-cut $k_t = 0.28$; X-cut $k_t = 0.32$

Ceramics: $BaTiO_3$ $k_t = 0.28 - 0.42$

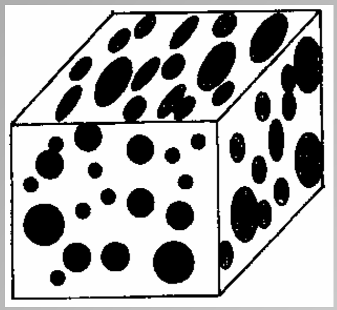
Lead metaniobate ($Pb[Zr_xTi_{1-x}]O_3$ $0<x<1$) K-83 $k_t = 0.51$

Lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$ $0<x<1$) PZT-4 $k_t = 0.51$

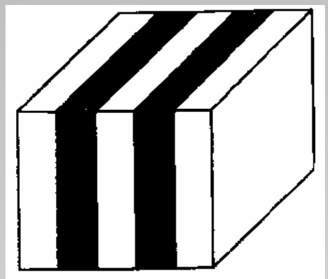
Polymers: **Polyvinylidene fluoride (PVDF)** $k_t = 0.1 \sim 0.2$

k_t – piezoelectric coupling constant

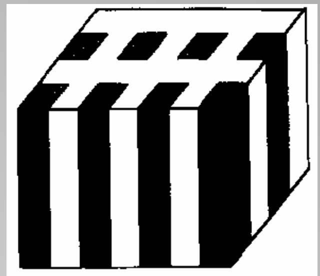
Piezocomposite materials



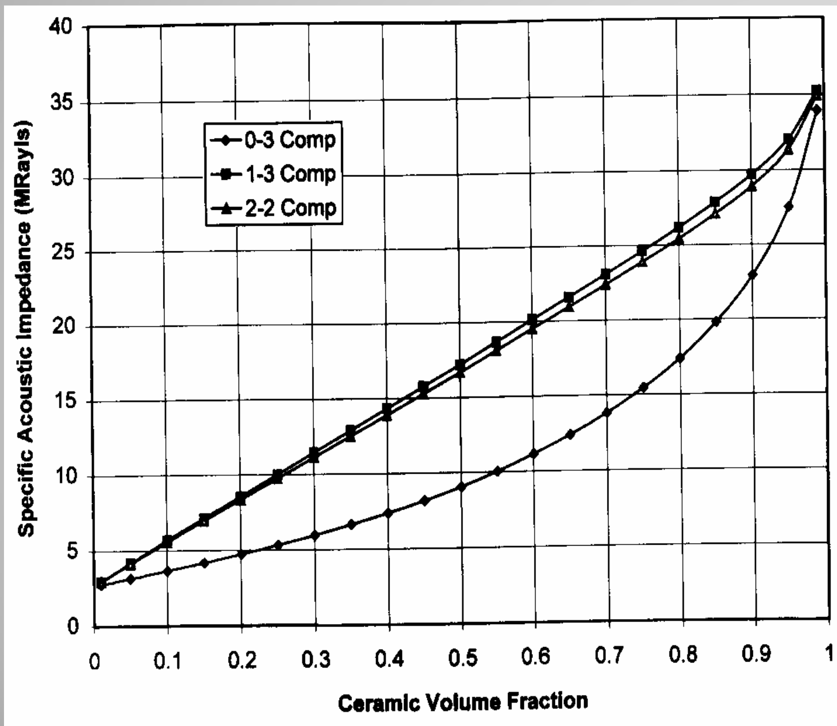
0-3 composite

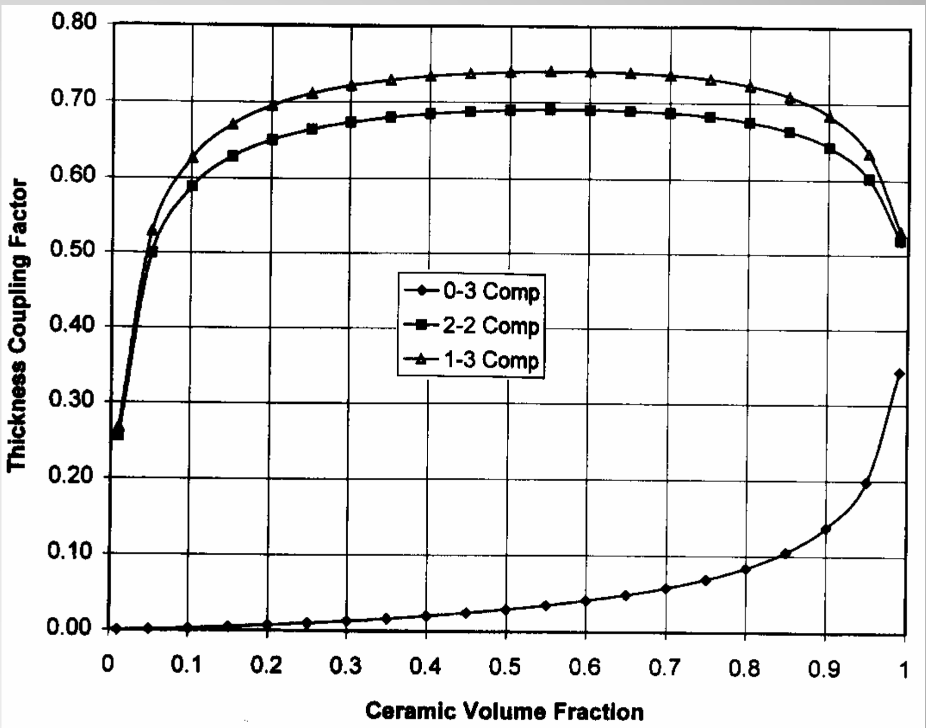


2-2 composite



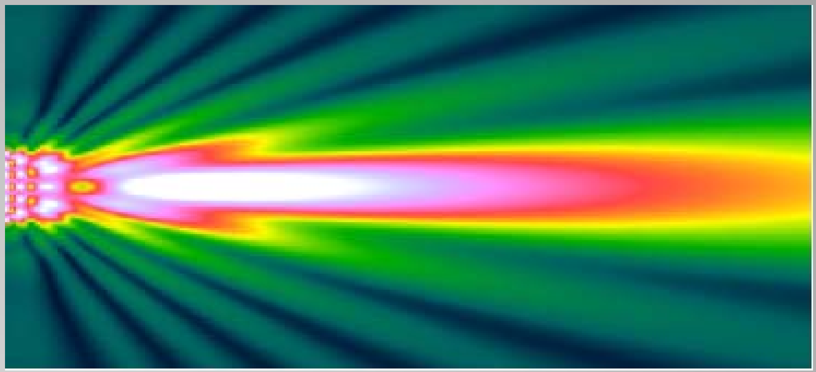
1-3 composite





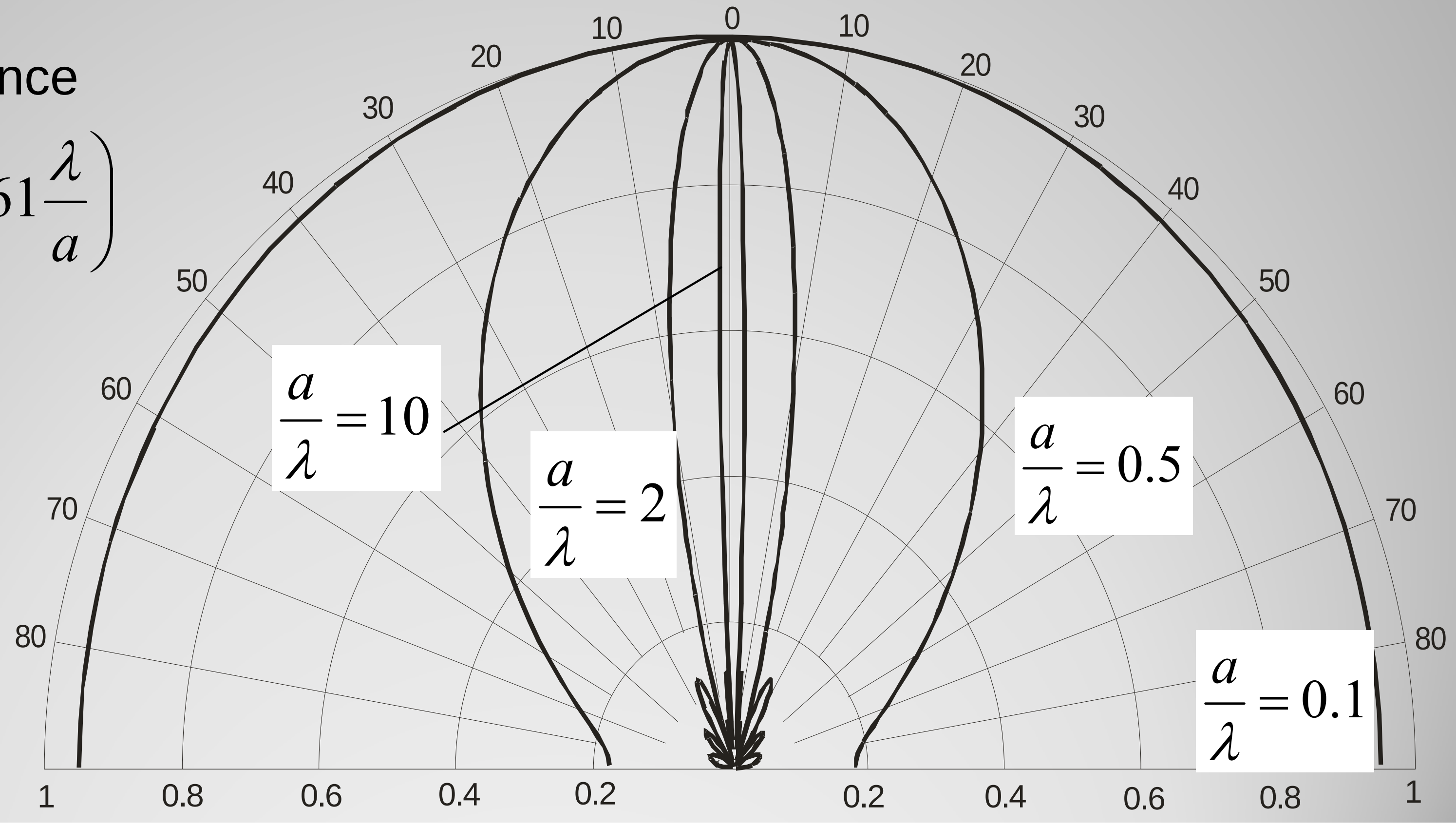
Directivity function

$$A(\theta) = A_o \frac{2J_1(ka\sin\theta)}{ka\sin\theta}$$

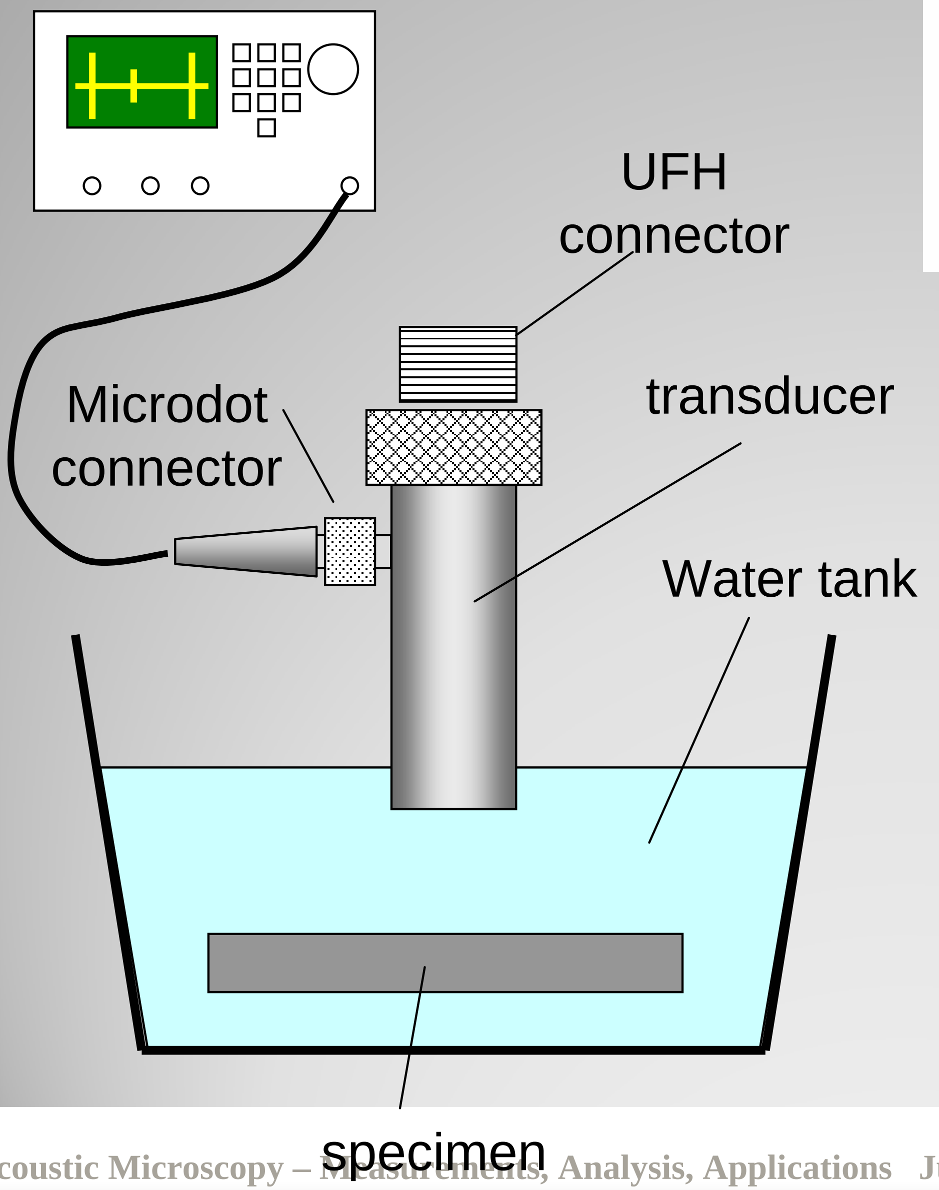


Beam divergence

$$\varphi = \arcsin\left(0.61\frac{\lambda}{a}\right)$$



Immersion ultrasonic testing

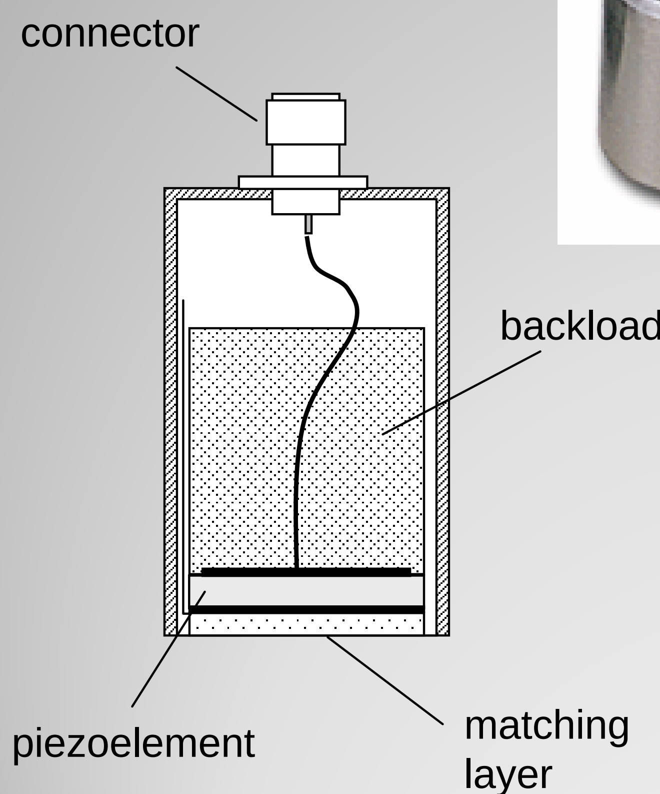


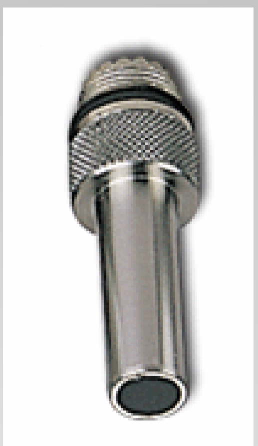
Automated scanning
On-line thickness gaging
High speed flaw detection
Time-of-flight and amplitude based imaging
Through transmission testing
Material analysis and velocity measurements

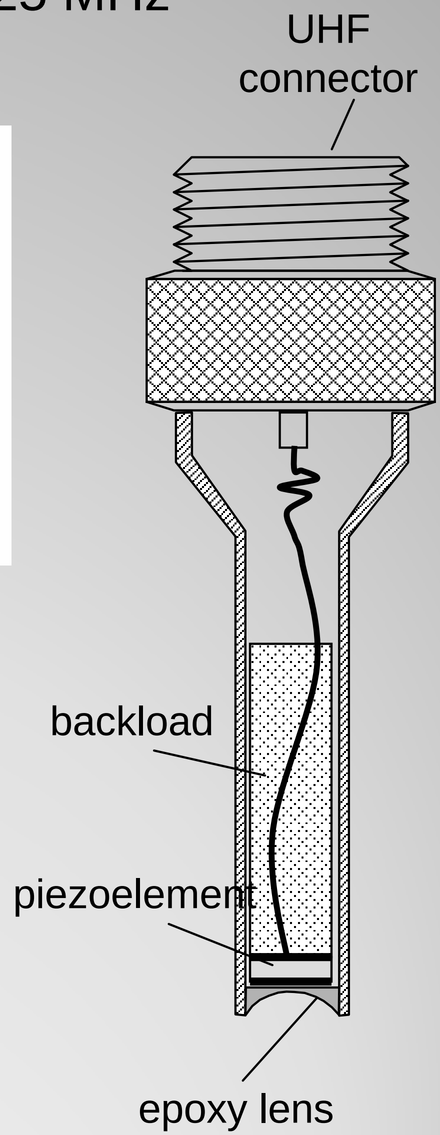
Acoustical transducers

5-25 MHz

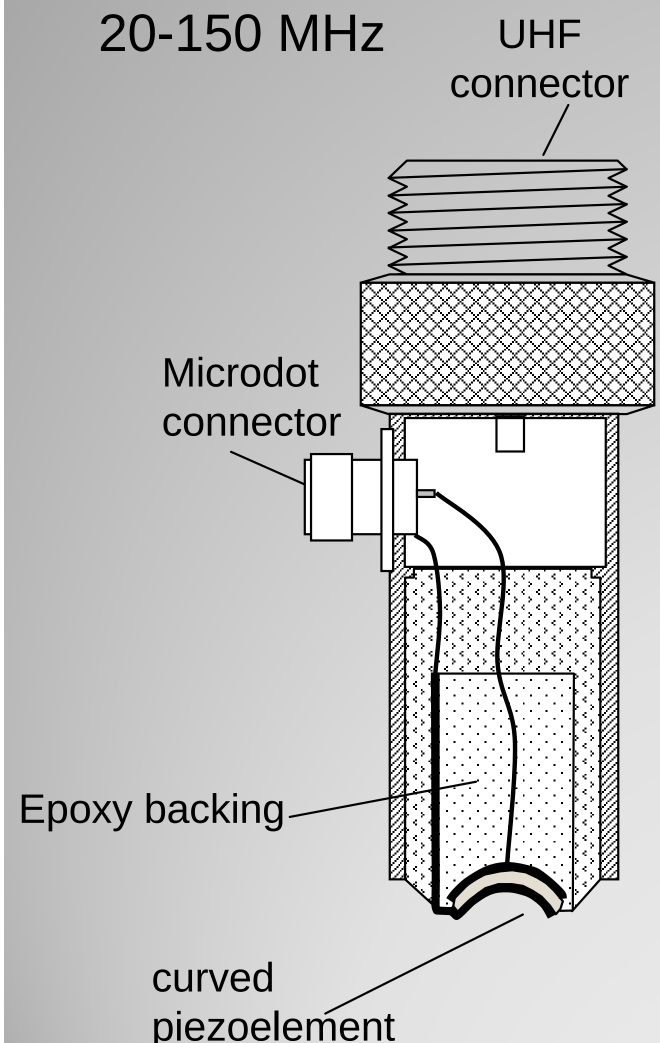
0,5-25 MHz

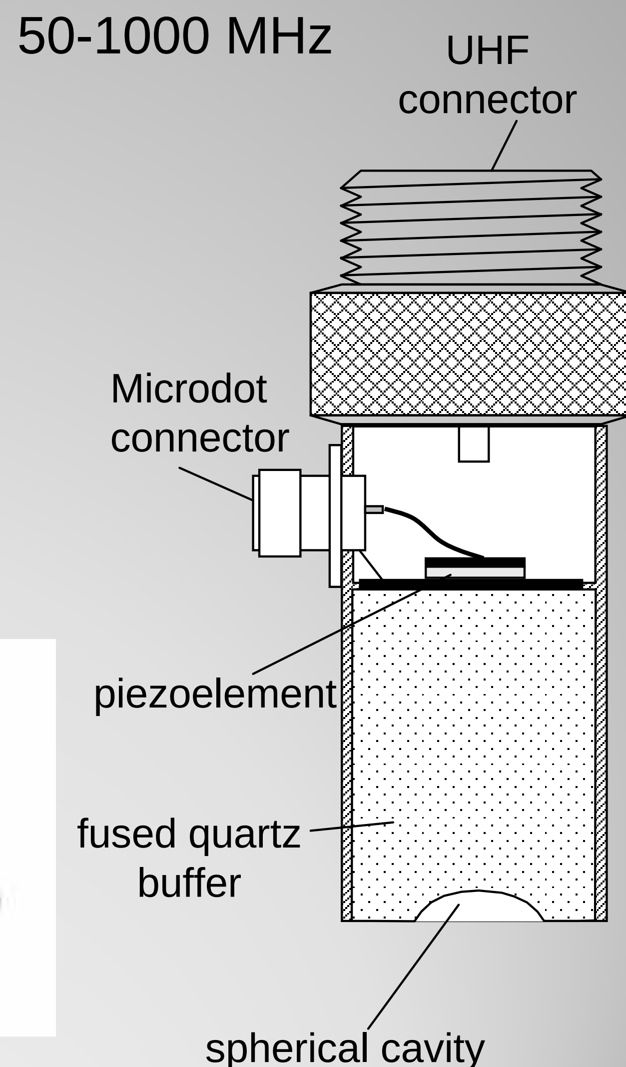






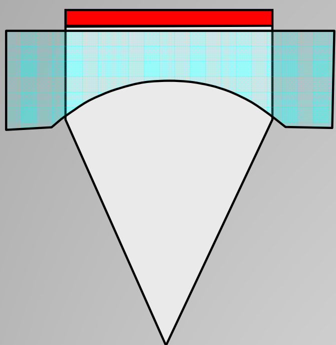
High frequency acoustical lenses

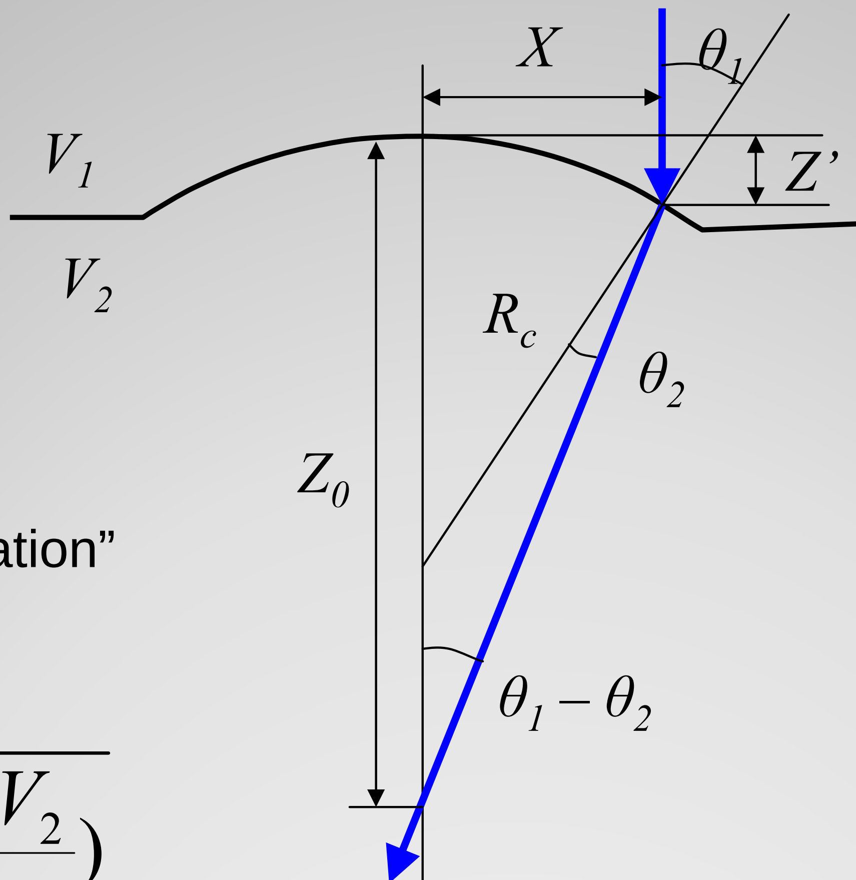




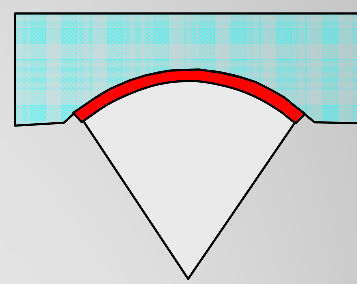
Focusing of acoustic beams

Focusing lens





Curved piezoelectric element



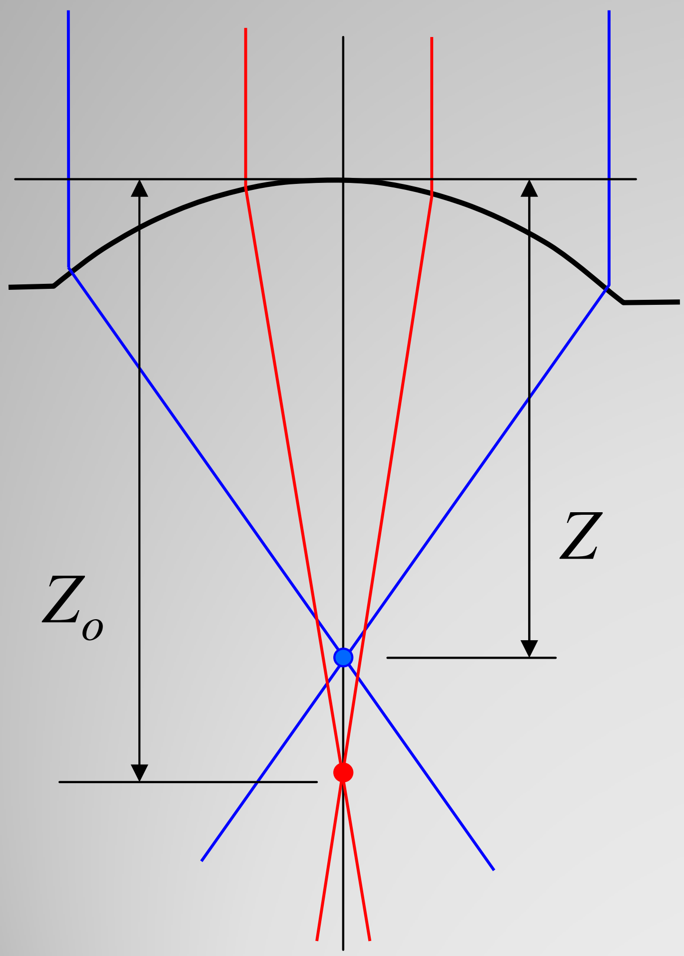
"Lens maker equation"

$$Z_0 = R_c \frac{1}{(1 - \frac{V_2}{V_1})}$$

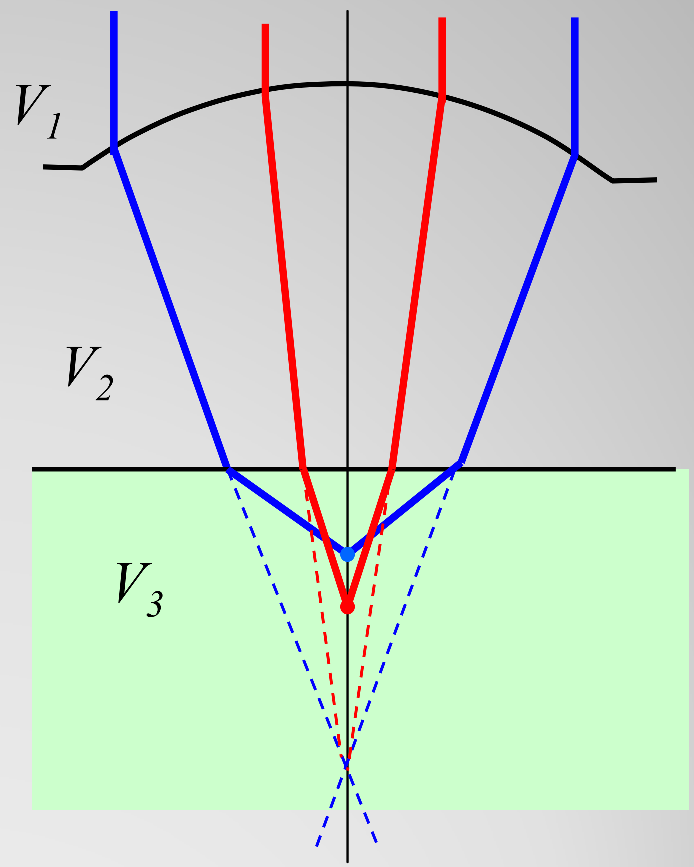
$$Z_0 = R_c$$

Aberration

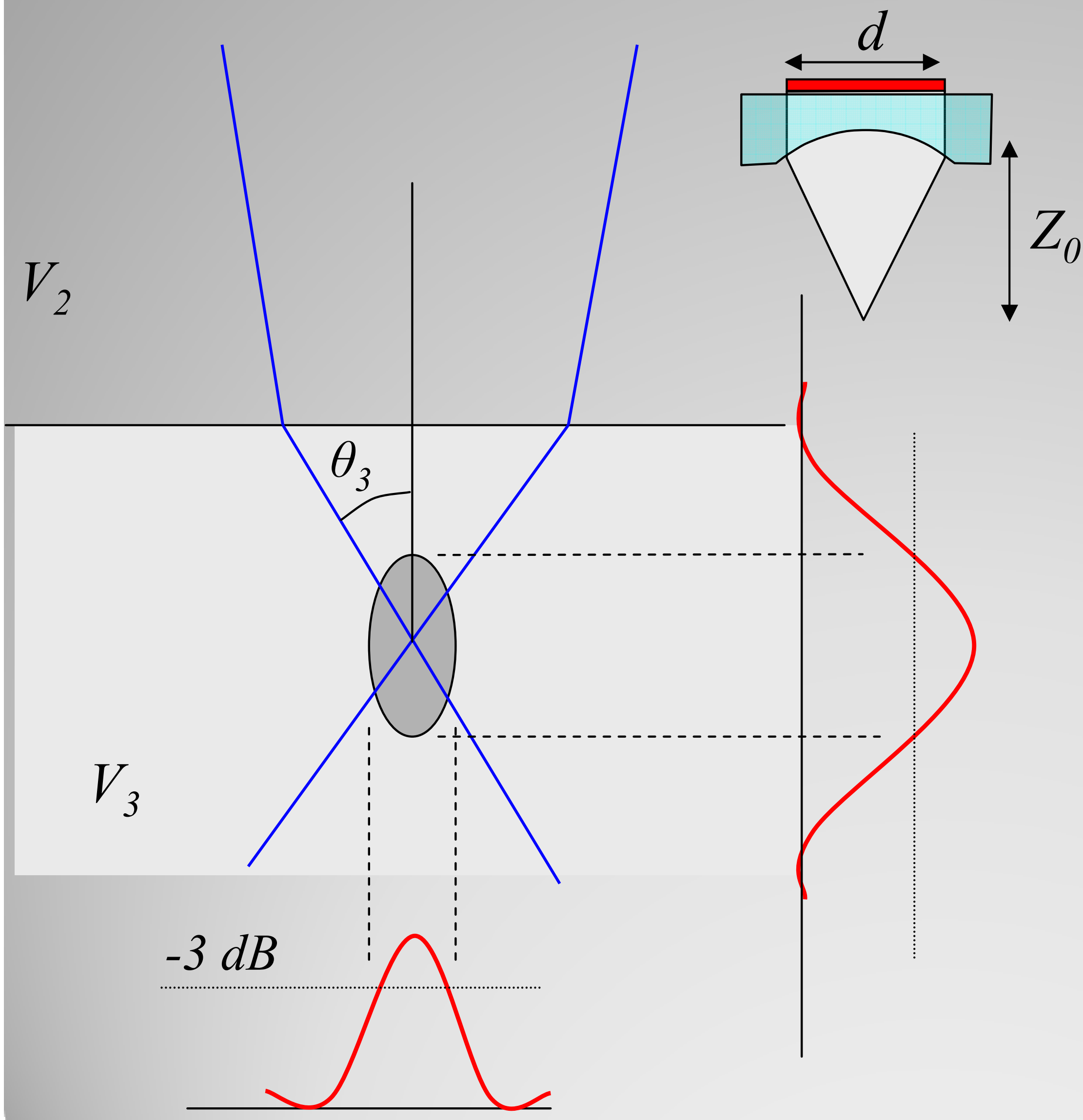
Spherical aberration



Material-induced aberration



Diffraction-limited spot size



Beam profile

$$P(r) = \frac{2J_1(0.5kd(r/Z_0))}{0.5kd(r/Z_0)}$$

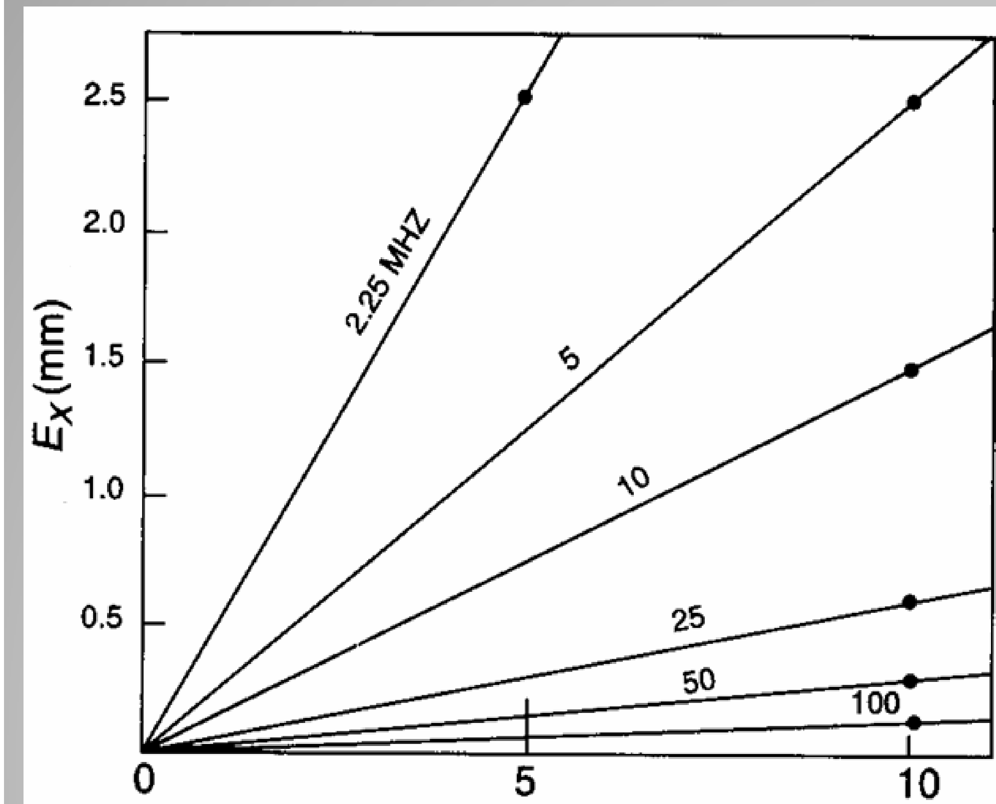
The beam diameter on -3 dB level

$$E_X = 1.03\lambda_2 \frac{Z_0}{d}$$

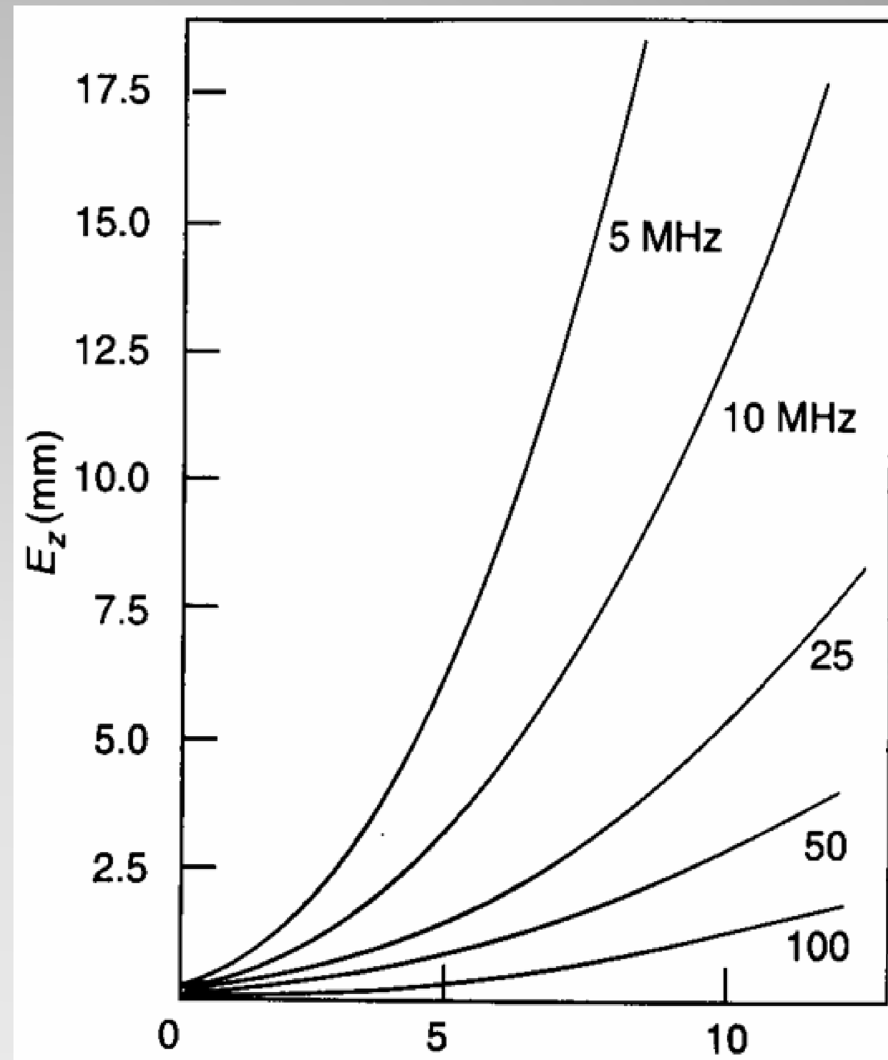
Focus depth on -3 dB level

$$E_Z = 3.6\lambda_2 \left(\frac{Z_0}{d}\right)^2 \frac{V_2}{V_3}$$

Focal spot size

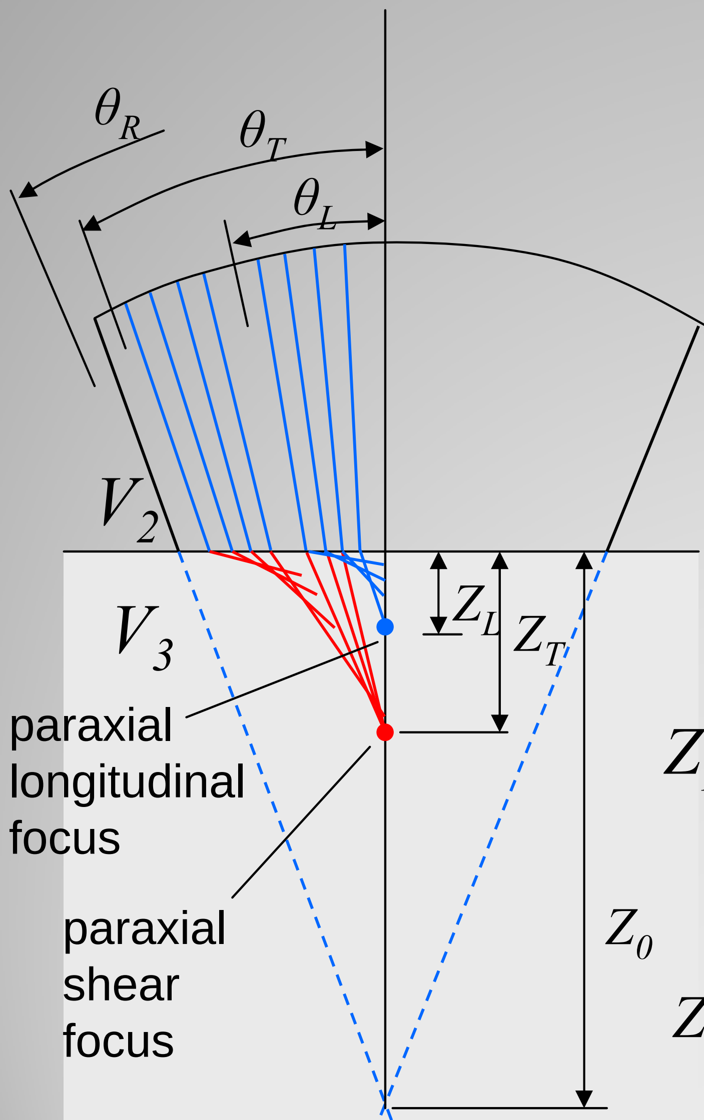


Focal spot diameter



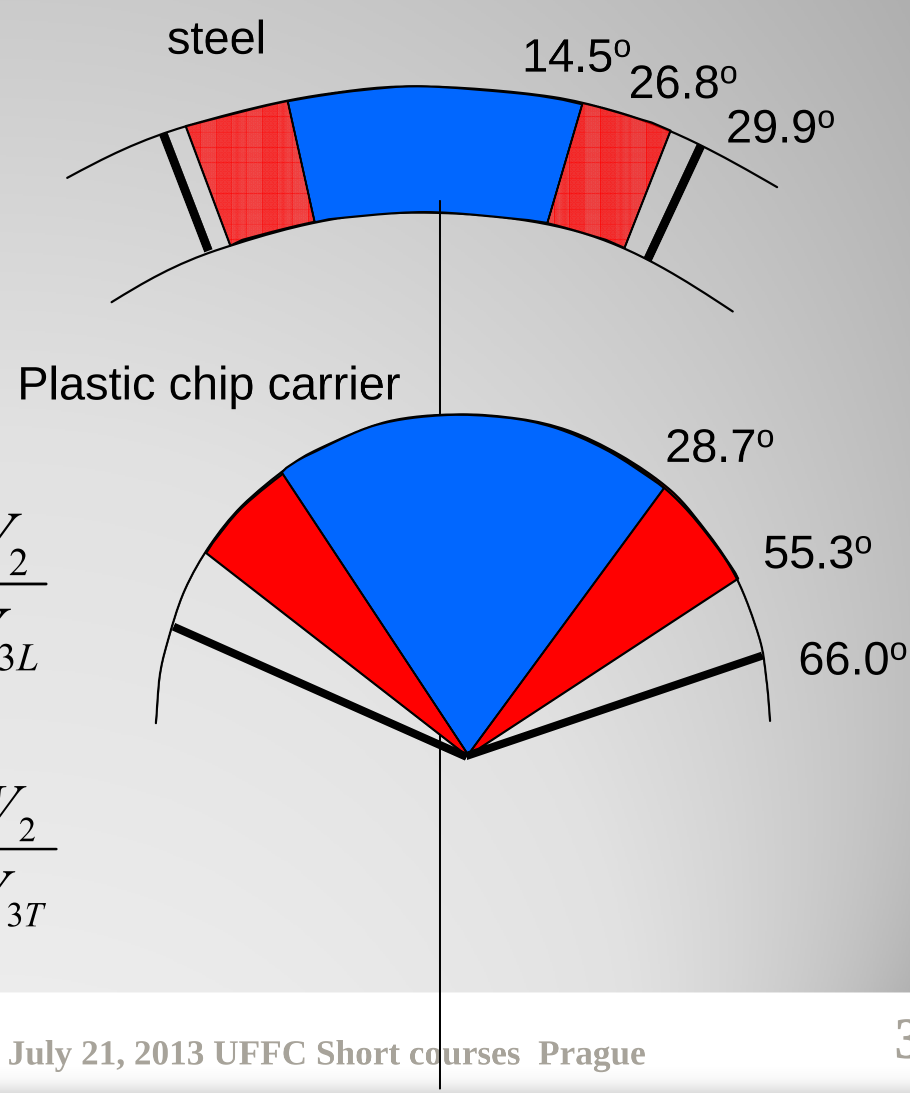
Depth of focus

Angular spectrum



$$Z_L = Z_0 \frac{V_2}{V_{3L}}$$

$$Z_T = Z_0 \frac{V_2}{V_{3T}}$$

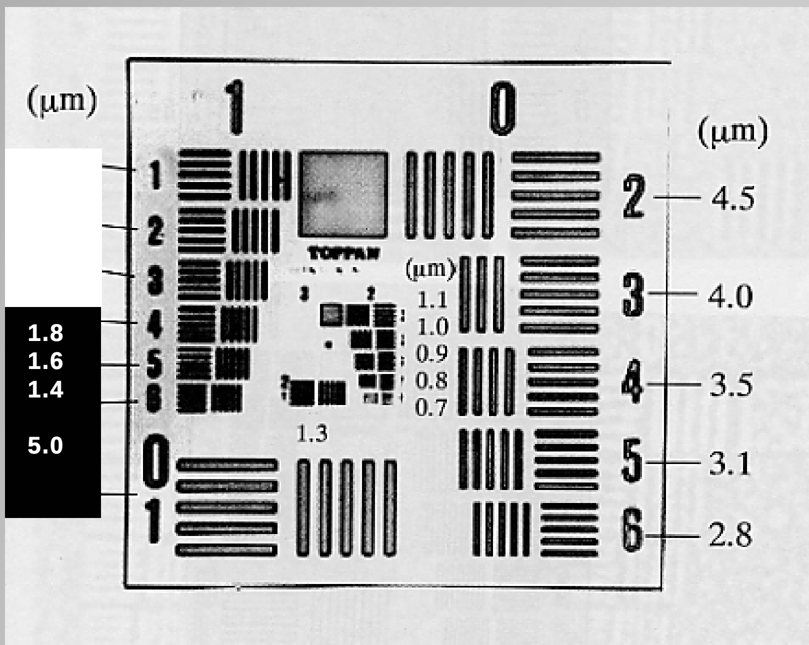


Surface and Sub-Surface Resolution of Scanning Acoustic Microscope

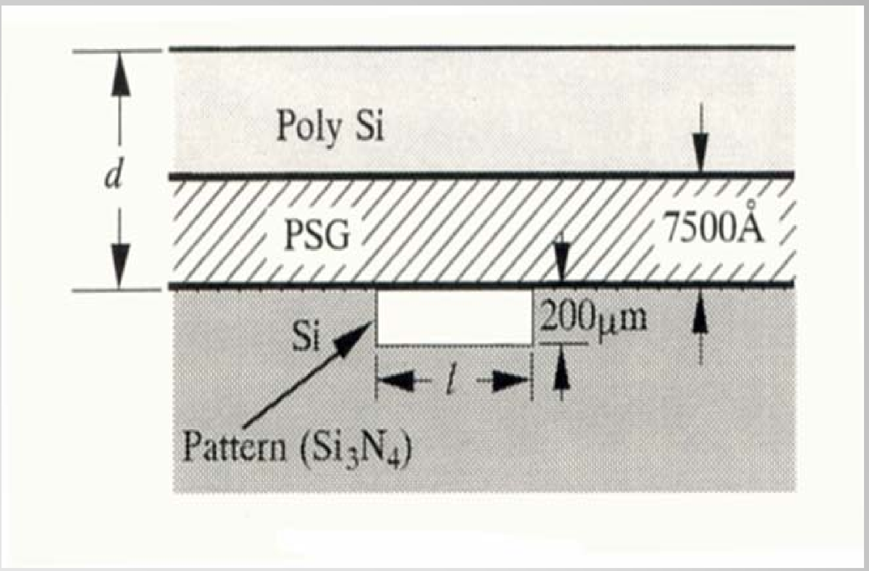
Resolution: Definition (I)

The resolution of the scanning acoustic microscope is defined to be the minimum distance between two points closely situated on an acoustic image plane (either a surface or interior plane) formed by the scanning acoustic microscope, wherein the minimum distance is defined by Rayleigh's criterion.

Resolution Charts

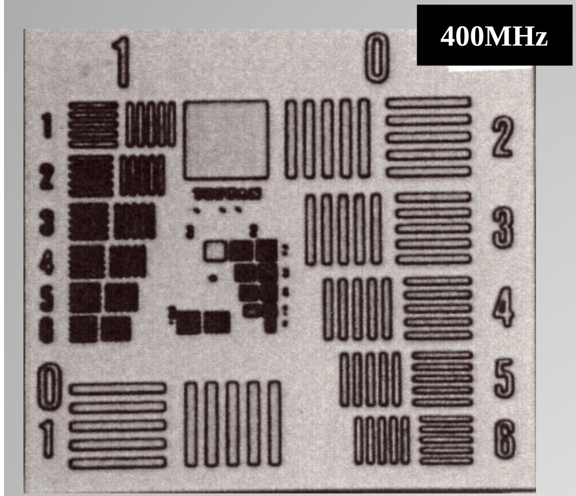


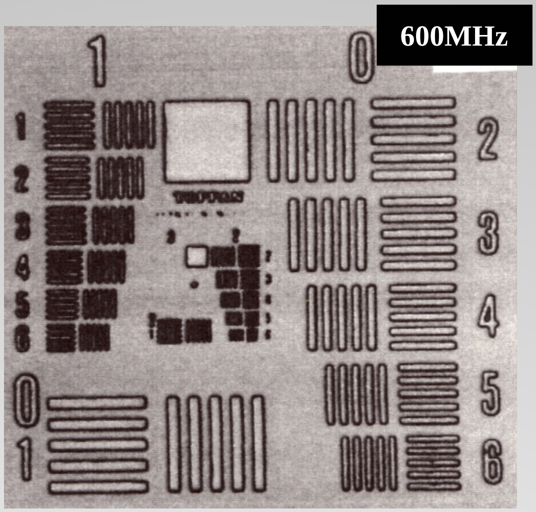
Resolution Chart (Optical Image) to measure subsurface resolution

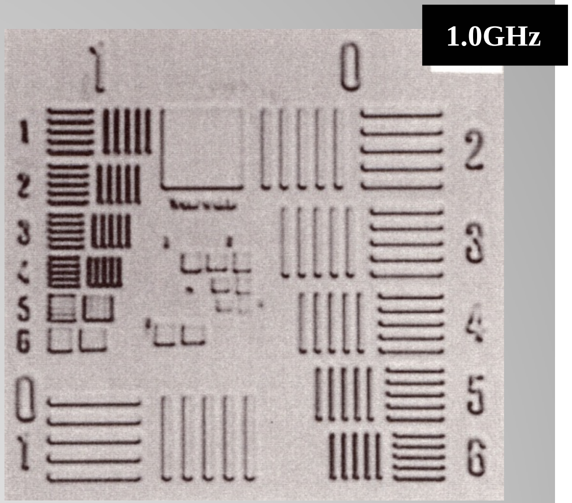


A vertical cross-sectional view of a resolution chart to measure subsurface resolution, wherein d is the thickness of the coating indicating the penetration depth of SAM, and l is the internal lateral resolution of the SAM.

Surface Lateral Resolution Chart with SAM



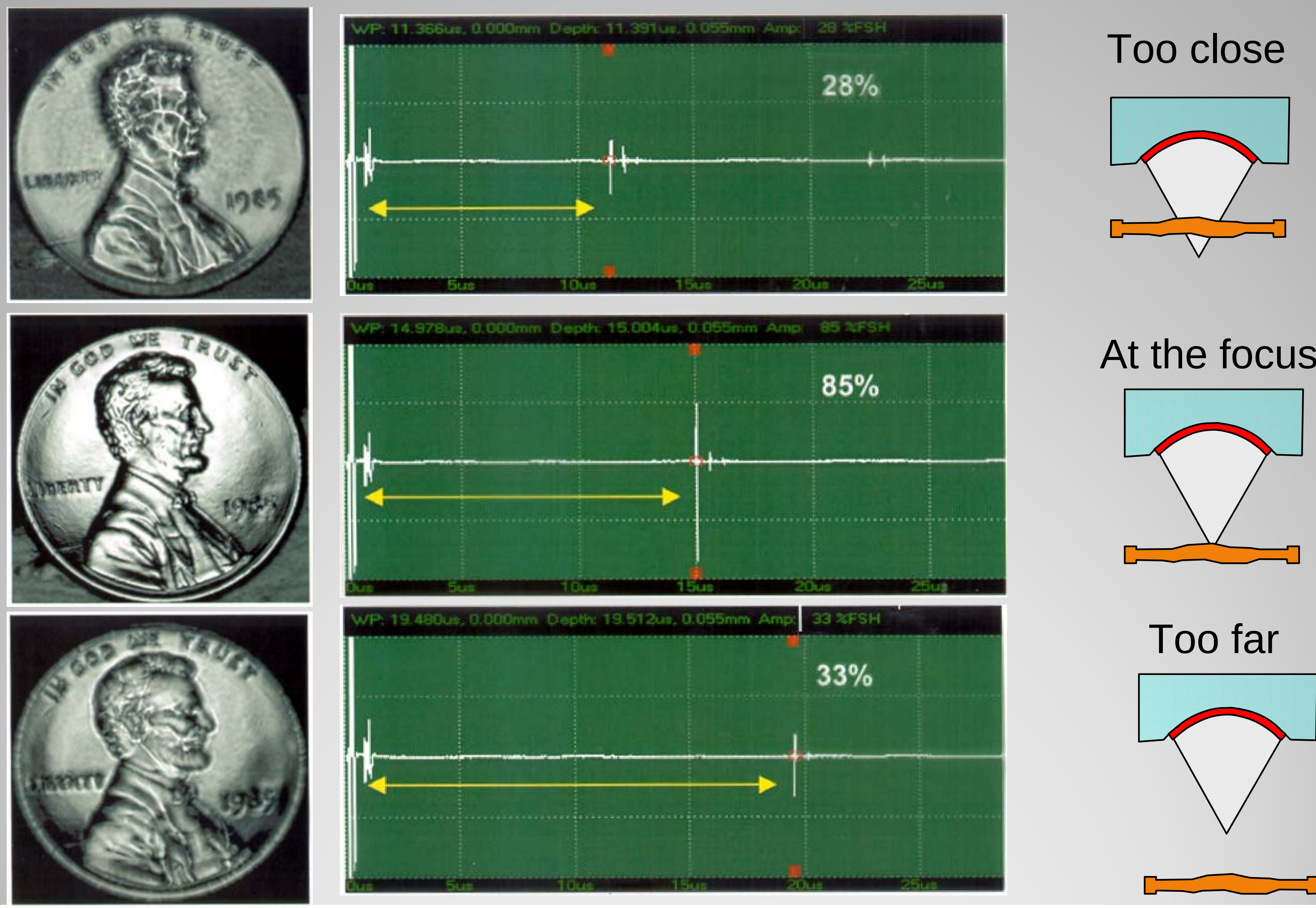




Surface resolutions measured from acoustic images are as follows:

Δr=1.8μm　　**Δr=1.4μm**　　**Δr=0.7μm**

Focusing the Transducer



Courtesy Sonix Inc.

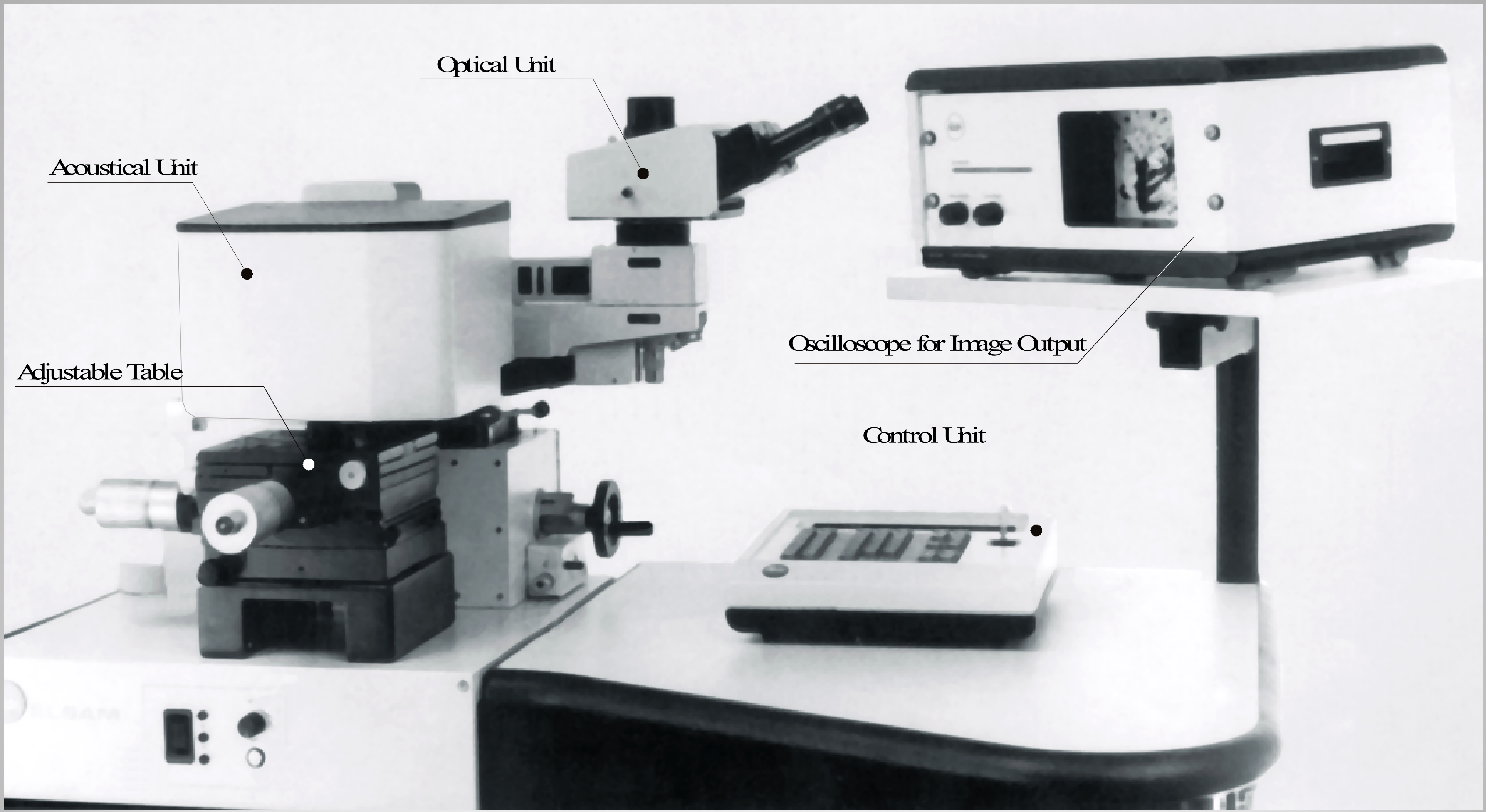
Types of Scanning Acoustic Microscopes

Characteristics of SAM

- Apparatus for evaluating both surface and inside of the specimen.
- High Resolution
- High Contrast
- Quantitative Data Acquisition

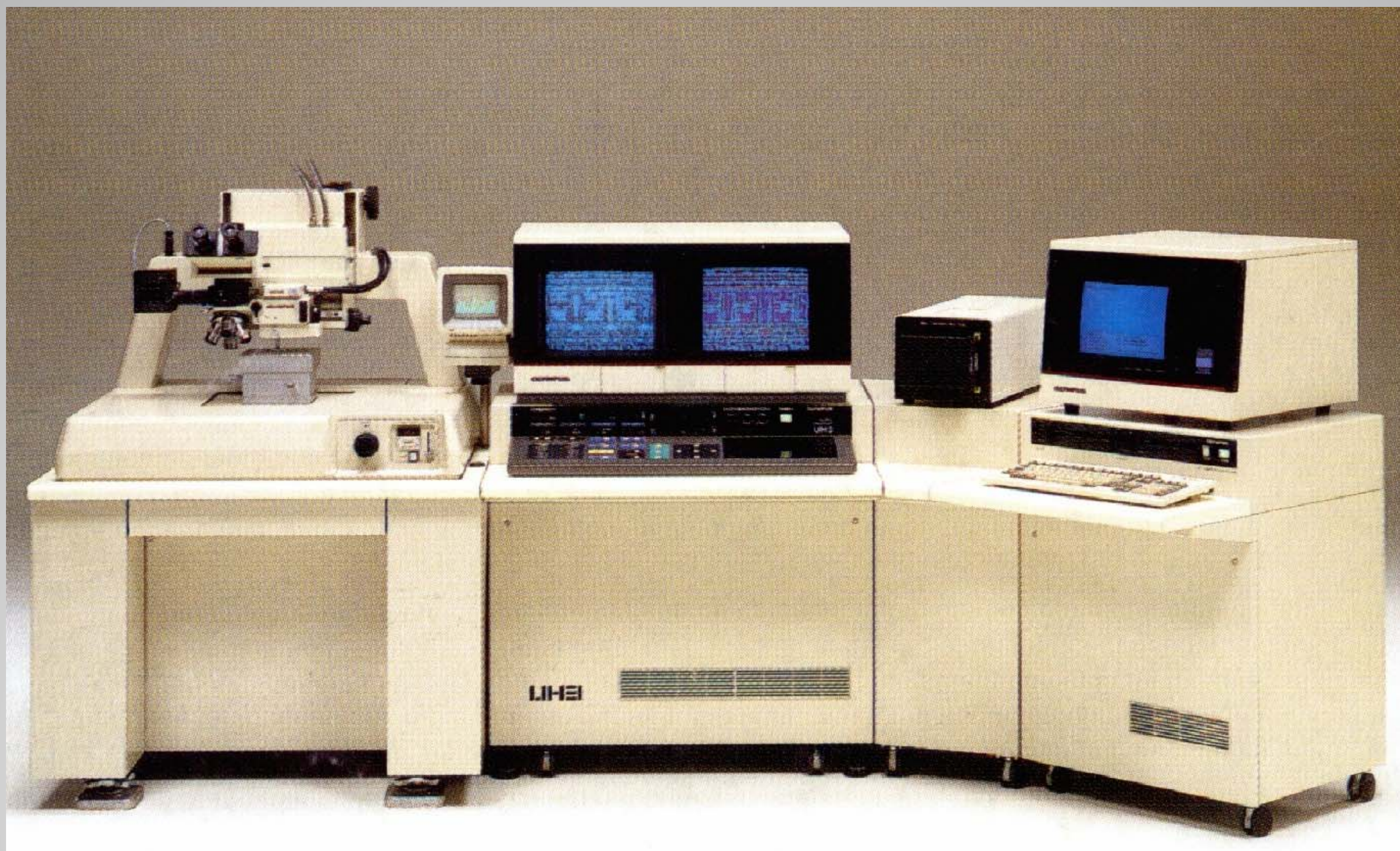
ELSAM (SAM 2000)

100 - 2000 MHz



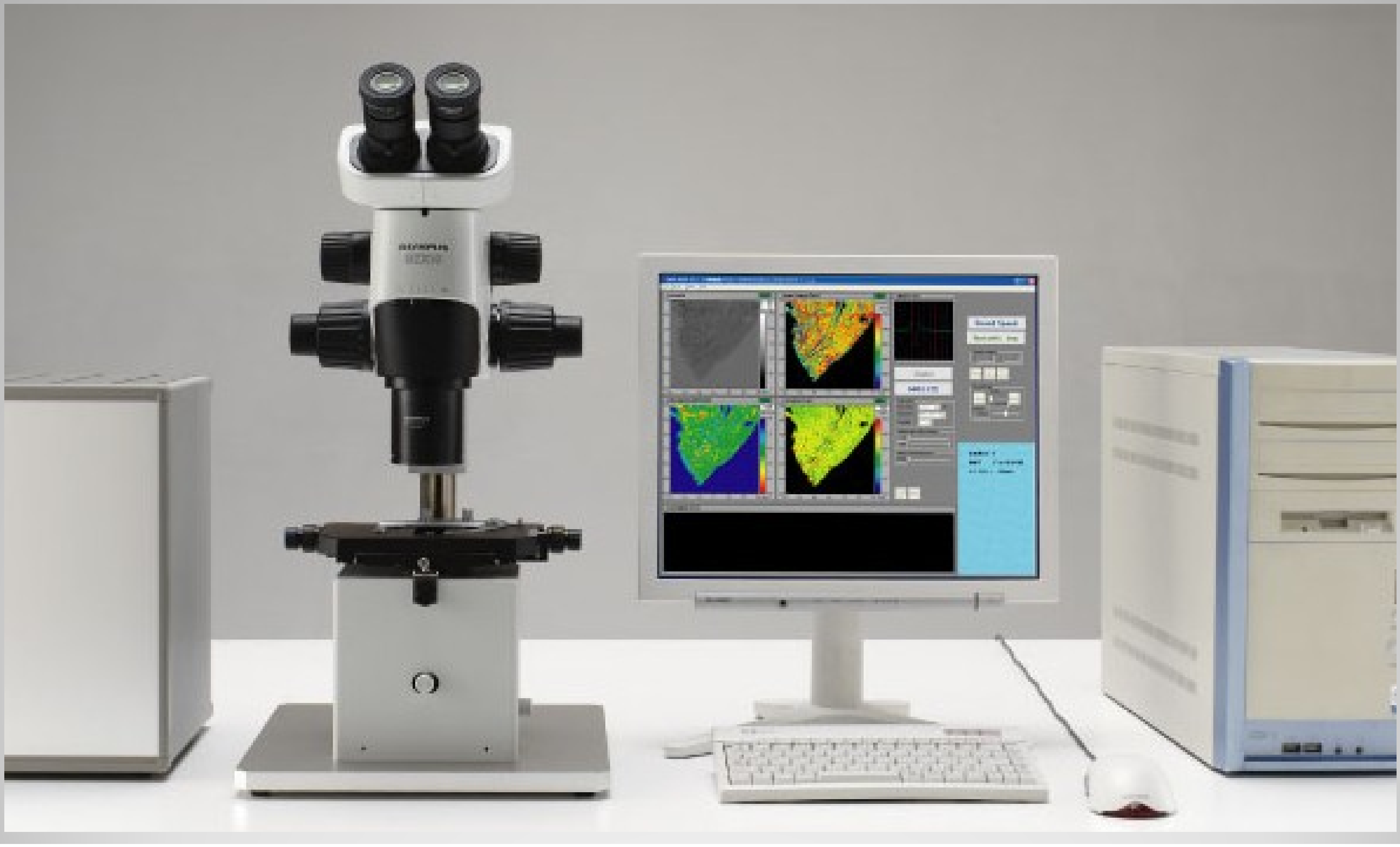
Olympus Mechanical Scanning Acoustic Reflection Microscope

100 - 2000 MHz



AMS-50SI (Honda Electronics)

50 - 400 MHz

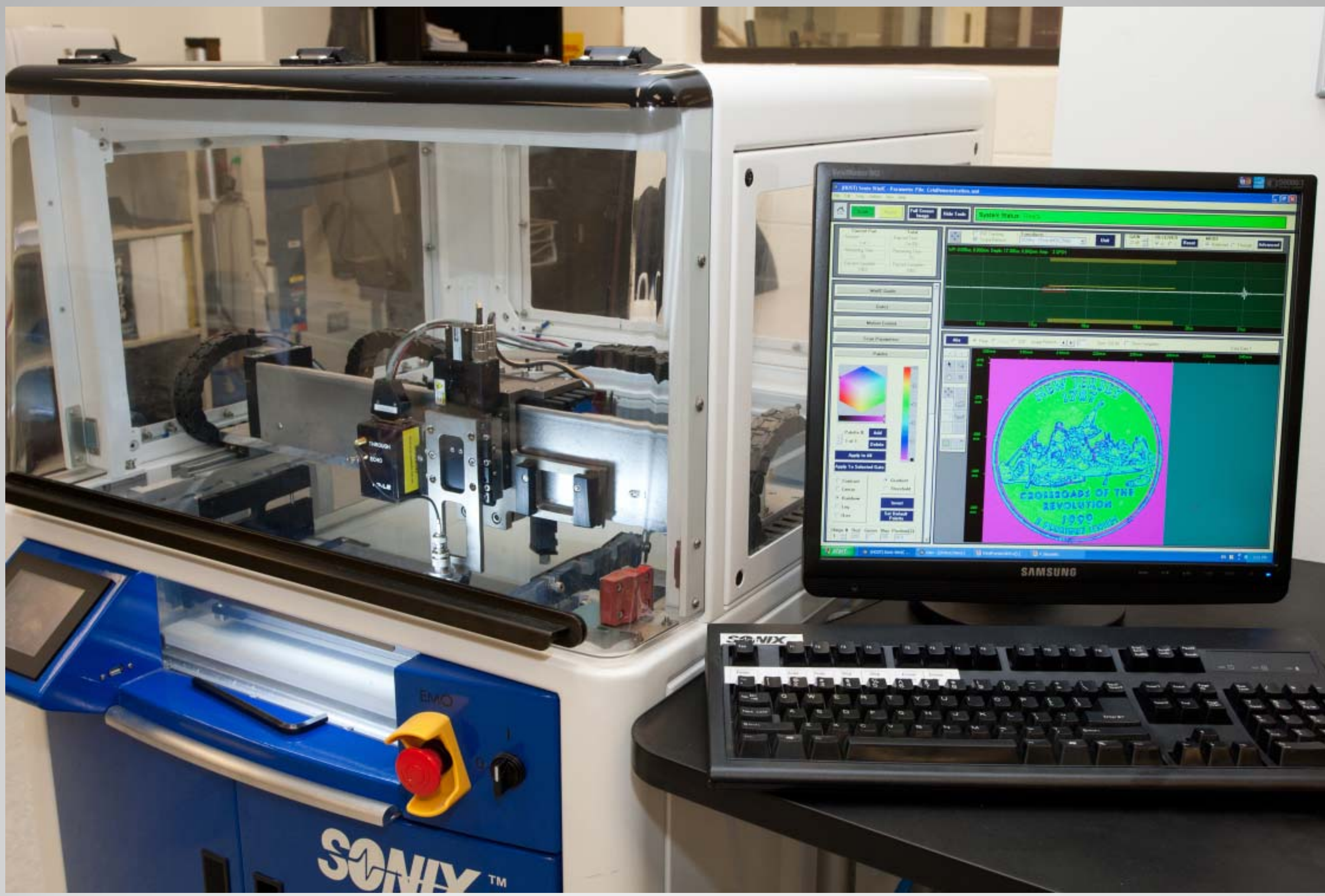


Tessonics Comprehensive Acoustic Microscope

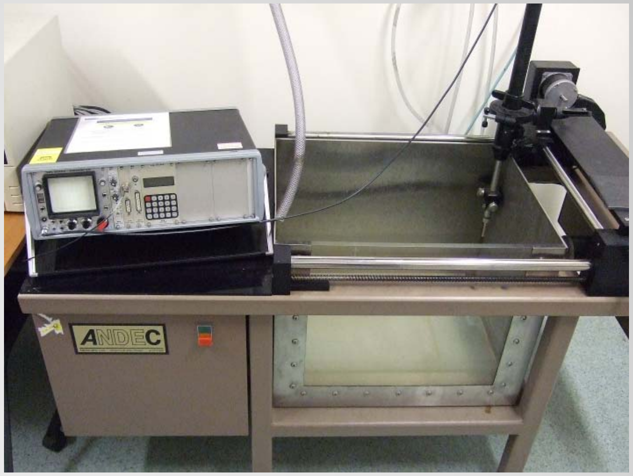
5 - 400 MHz

SONIX (Sonoscan) scanning system

10 - 250 MHz

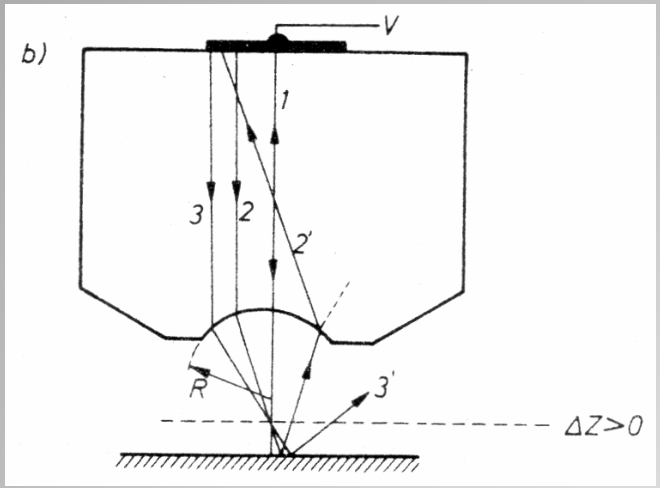


Various Ultrasonic Imaging Systems

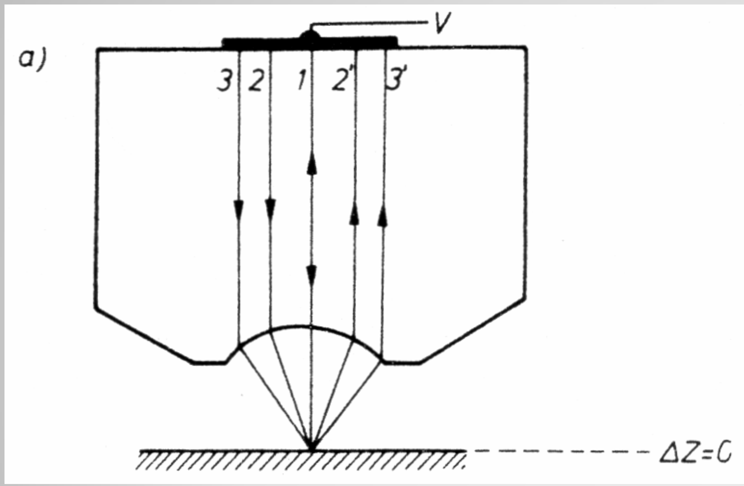


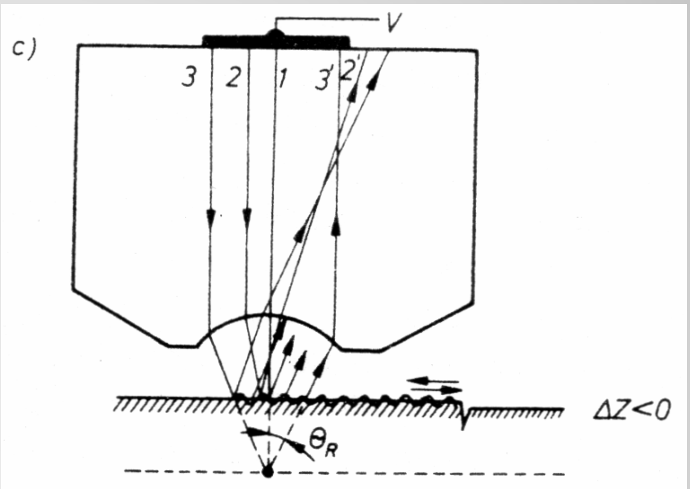
Quantitative Methods

V(z) Method

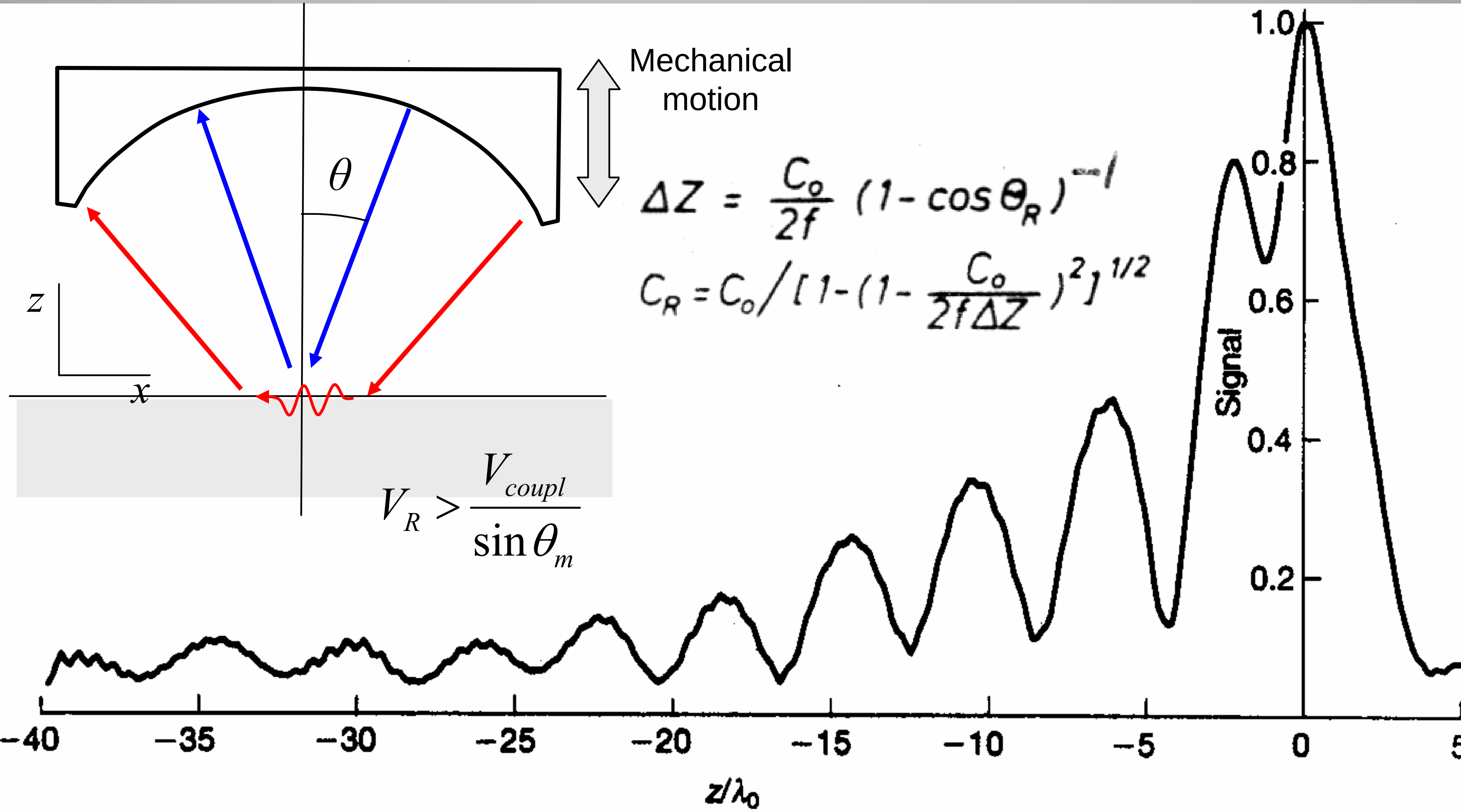


Formation of output signal in a reflection SAM. z– the focal length of a lens. In case: a) $\Delta z = 0$ – output signal is formed by the integrity of all the refracted rays, b) $\Delta z > 0$ – only paraxial beams contribute to output signal, c) $\Delta z < 0$ – the output signal emerges as the superposition of the signal produced by a mirro–reflection of paraxial rays and of the signal due to the leaky surface Rayleigh wave





V(z) method

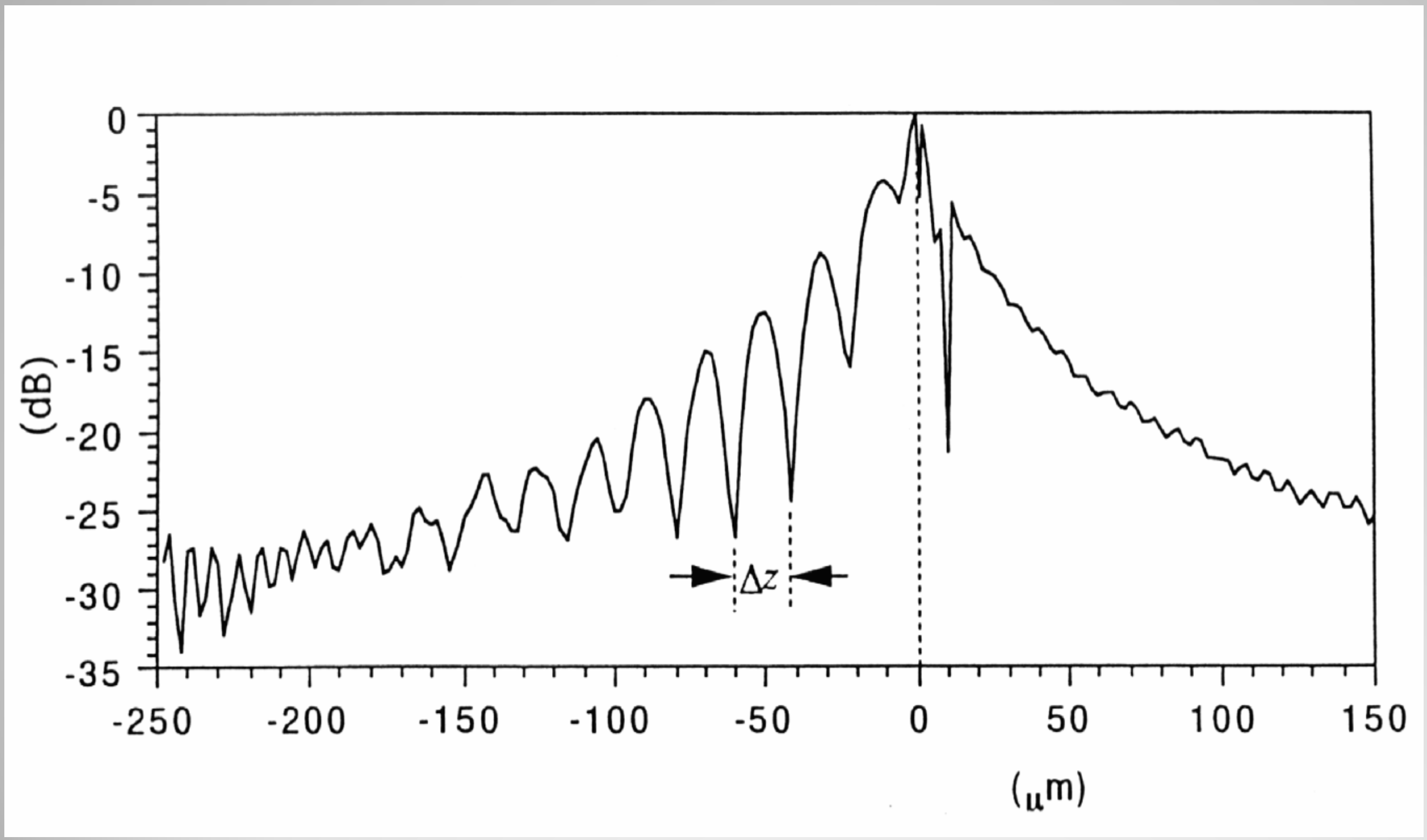


$V(z)$ curve for a glass specimen; $f = 300$ MHz, $T = 70$°C, $\lambda_0 = 5.2\ \mu$m.

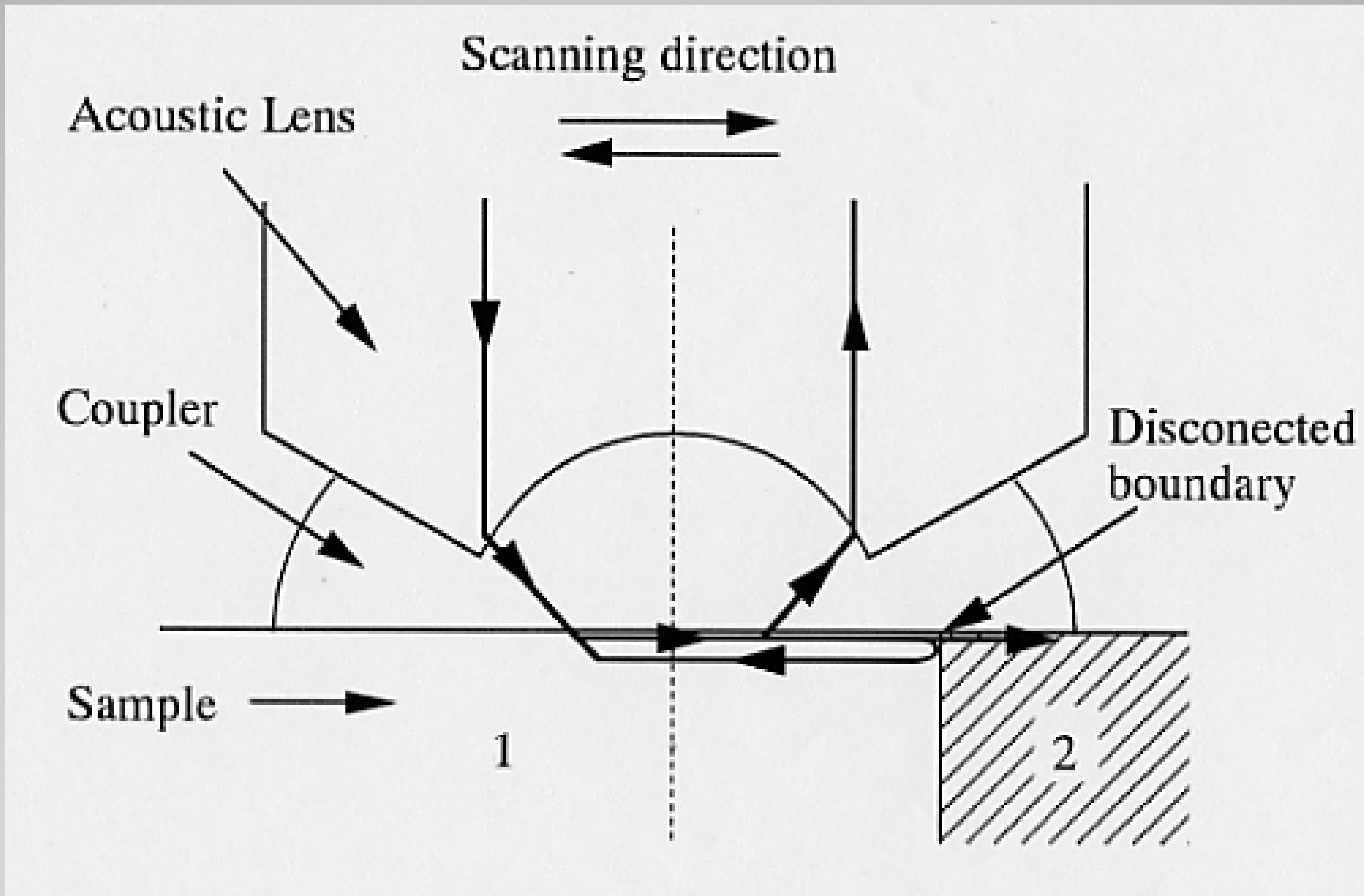
V(z) - Curve

$$\Delta z = \frac{\lambda_W}{2\left(1-\cos\theta_R\right)}$$

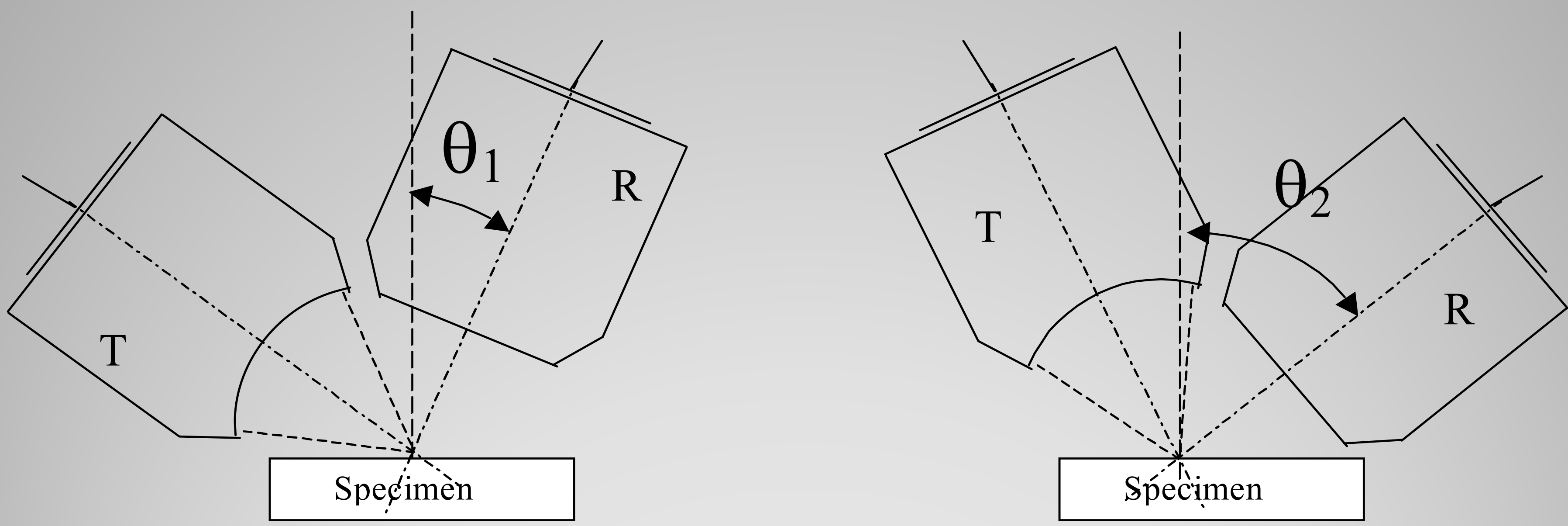
Specimen: Fused Quartz
Coupling medium: Distilled Water
Temperature: 22.3°C (change less than 0.1°C).
Frequency: 400MHz,
Aperture angle: 120°, and
Working distance: 310 μm.



Vertical crack detection method

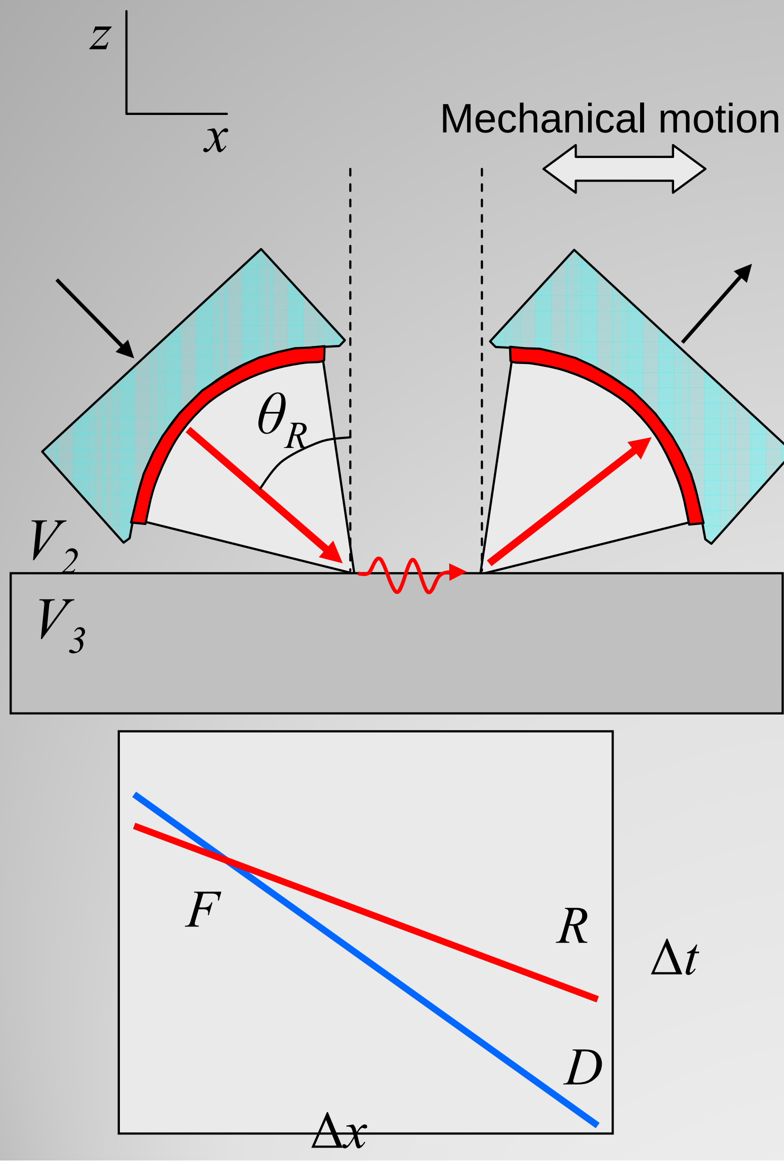


Ultrasonic Micro-Spectrometer

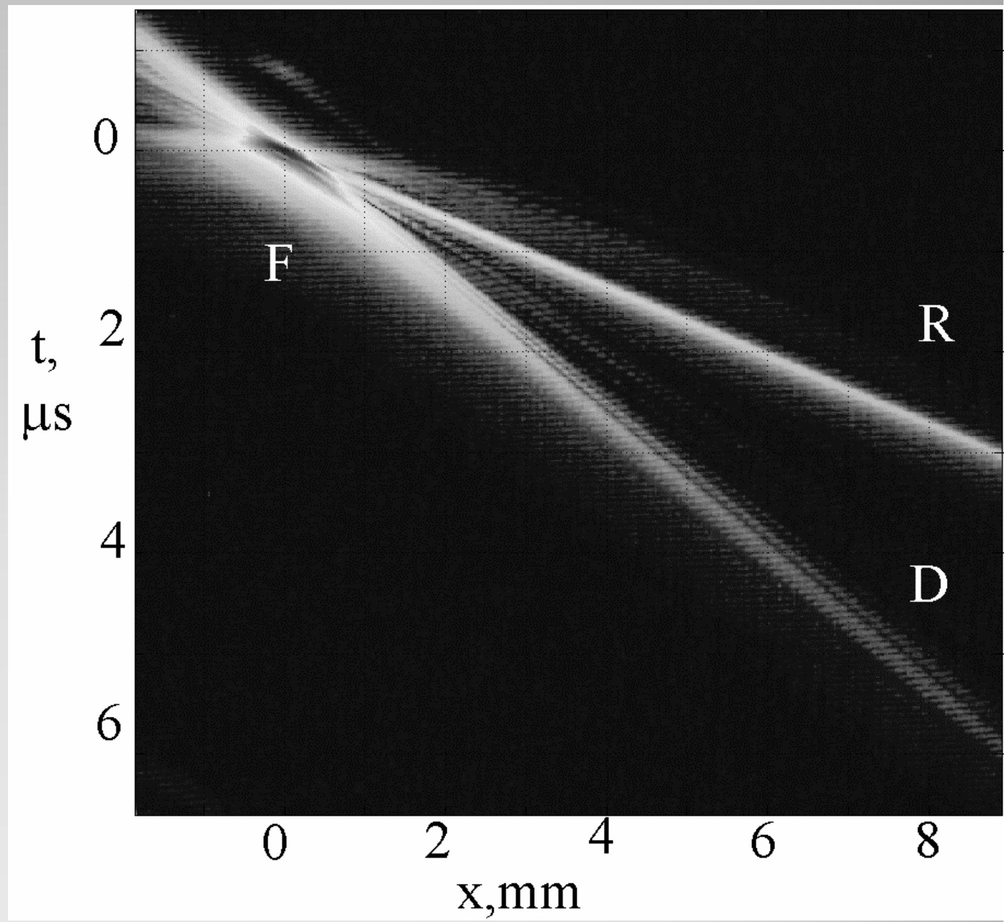


Spherical-Planar-Pair lenses (SSP); Incident angle $\theta_1 < \theta < \theta_2$

V(x) method

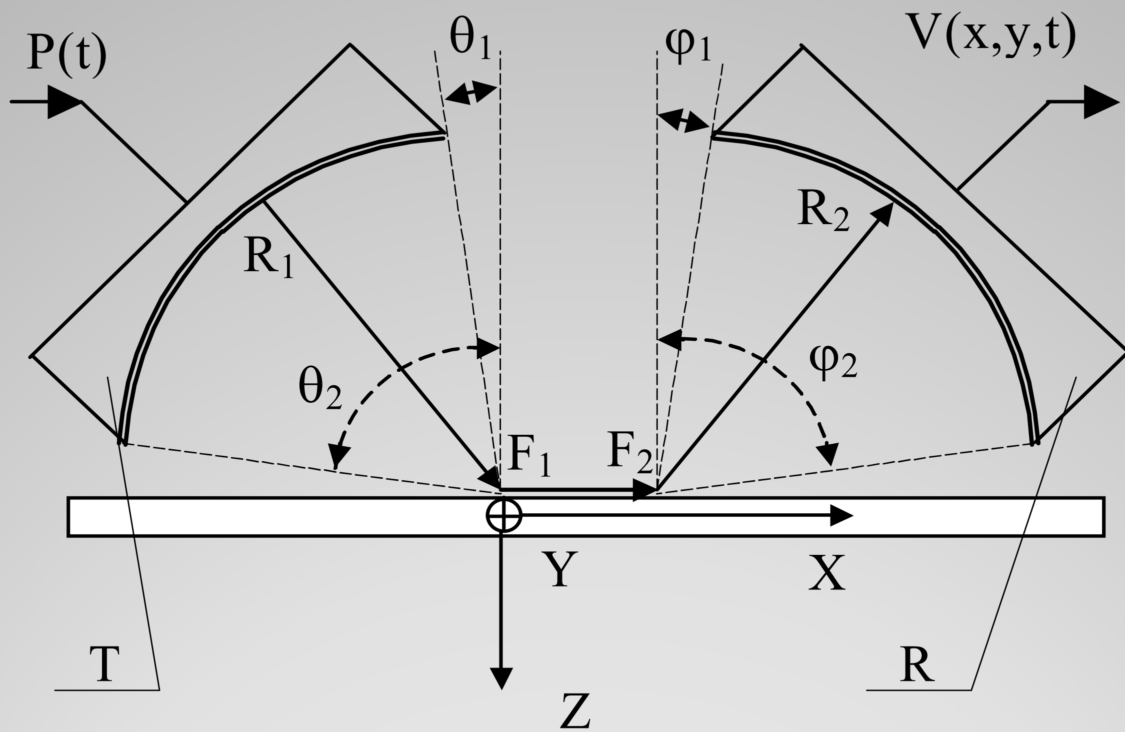


V(x) waveform



$$V_R = \frac{\Delta x}{\Delta t}$$

V(x,t) method



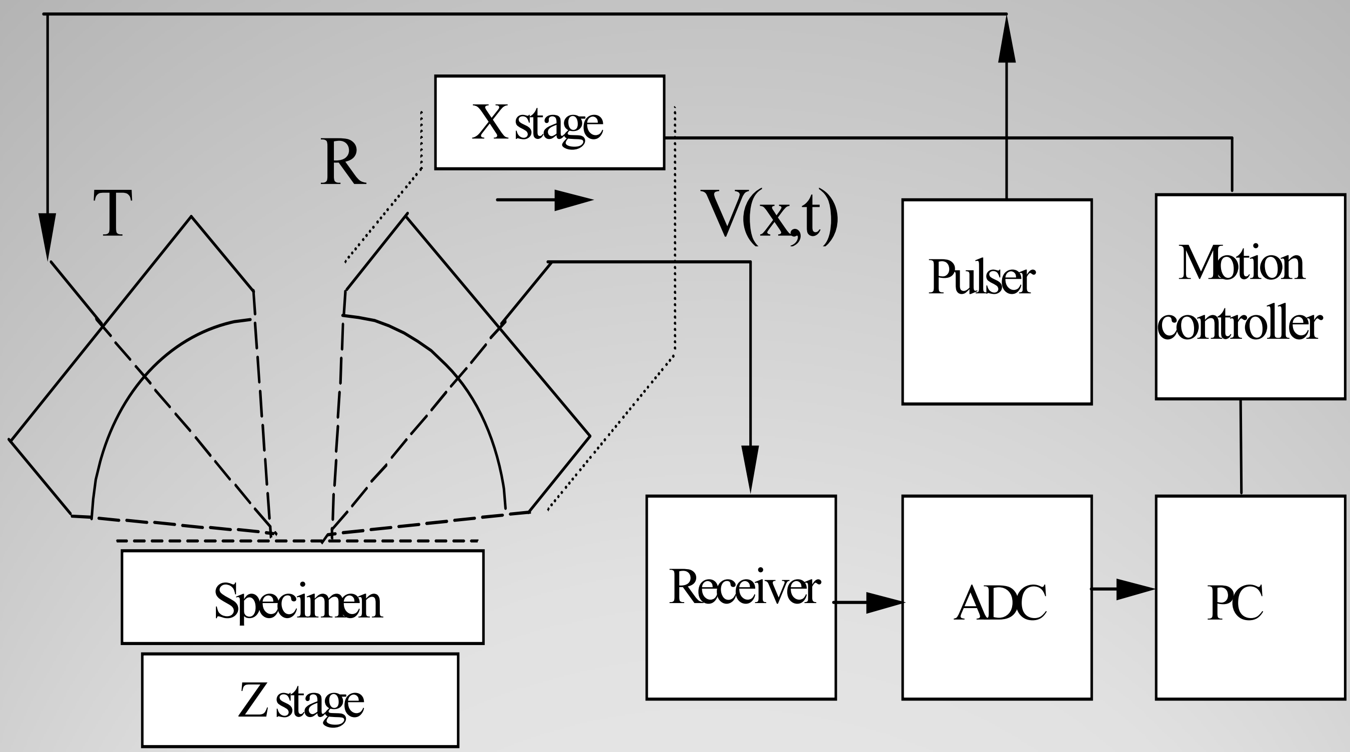
From ray model: C_R the velocity of the leaky surface wave :

$$C_R = \Delta d / \Delta t ,$$

Δd - is travel distance F_1F_2 of the leaky wave along the surface

Δt - is the corresponding time of flight.

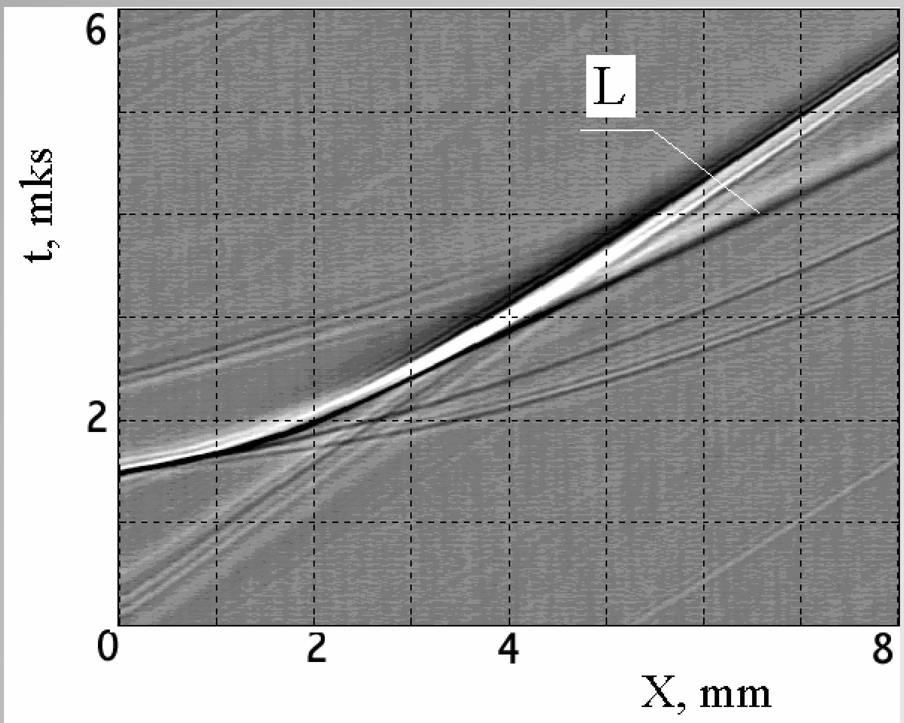
V(x,t) method – Experimental Setup



PVDF line-focus lens-less transducers
Focal distance R1=R2=9 mm, length 12 mm
Aperture angels:
- transmitting transducer - 50°±40°;
- receiving transducer - 45°±35°

Central frequency 12 MHz
Negative spike pulse - 150 V, 30 ns
Receiver bandwidth 1-30 MHz, SNR >40 dB
ADC 8 bits; sampling rate 200 MHz

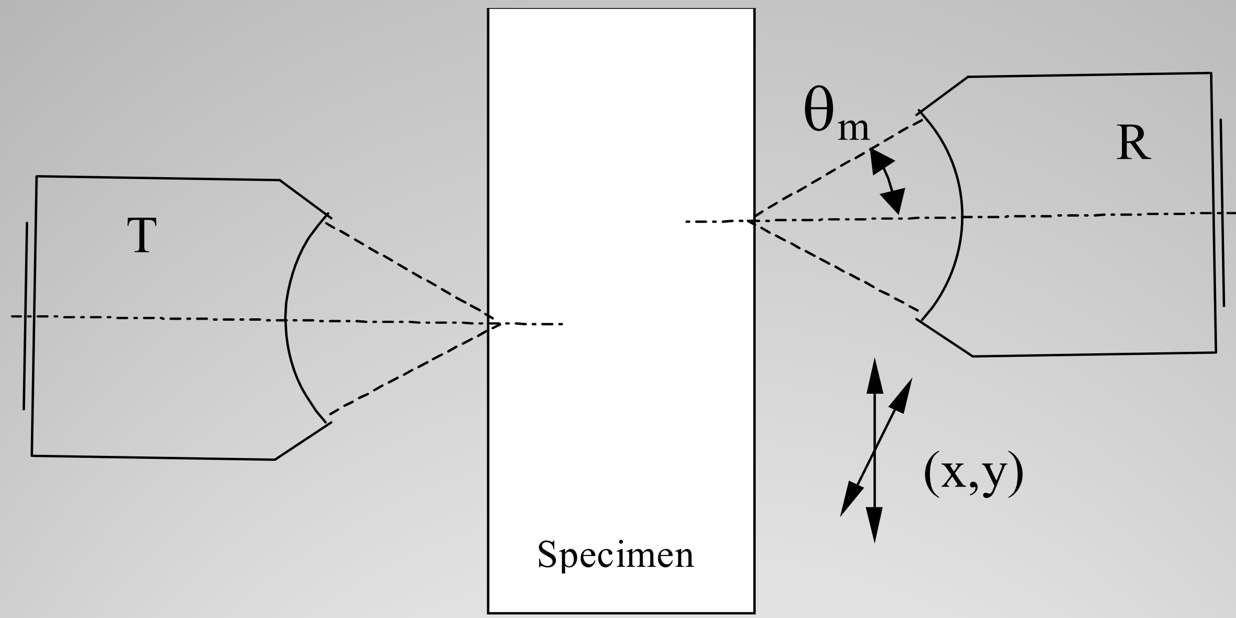
V(x,t) method – Experimental Results



V(x,t) waveform measured for polystyrene;
L - leaky longitudinal wave

Material	Measured leaky wave velocity, m/s	Known value, [1]
Fused quartz	3398	3410 (R)
Steel	3027	2996 (R)
Aluminum	2941	2906 (R)
Copper	2184	2171 (R)
Plexiglas	2683	2750 (L)
Polystyrene	2358	2400 (L)

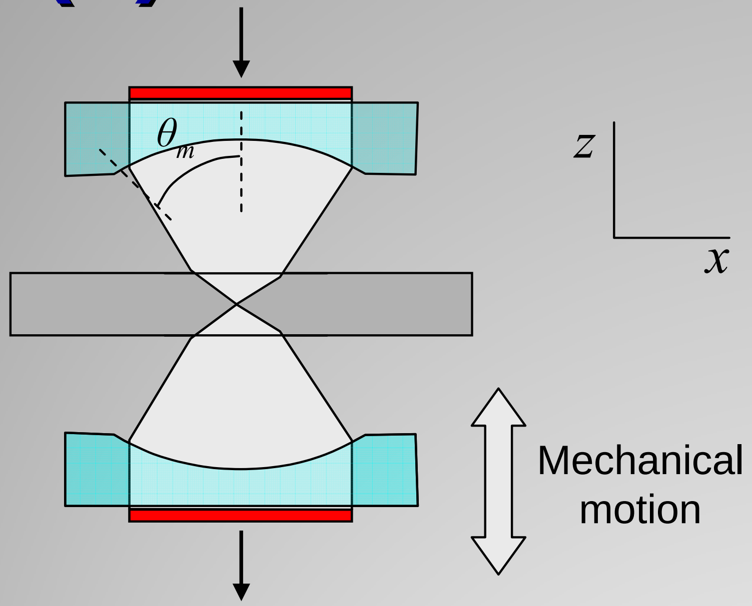
Through Transmission Mode

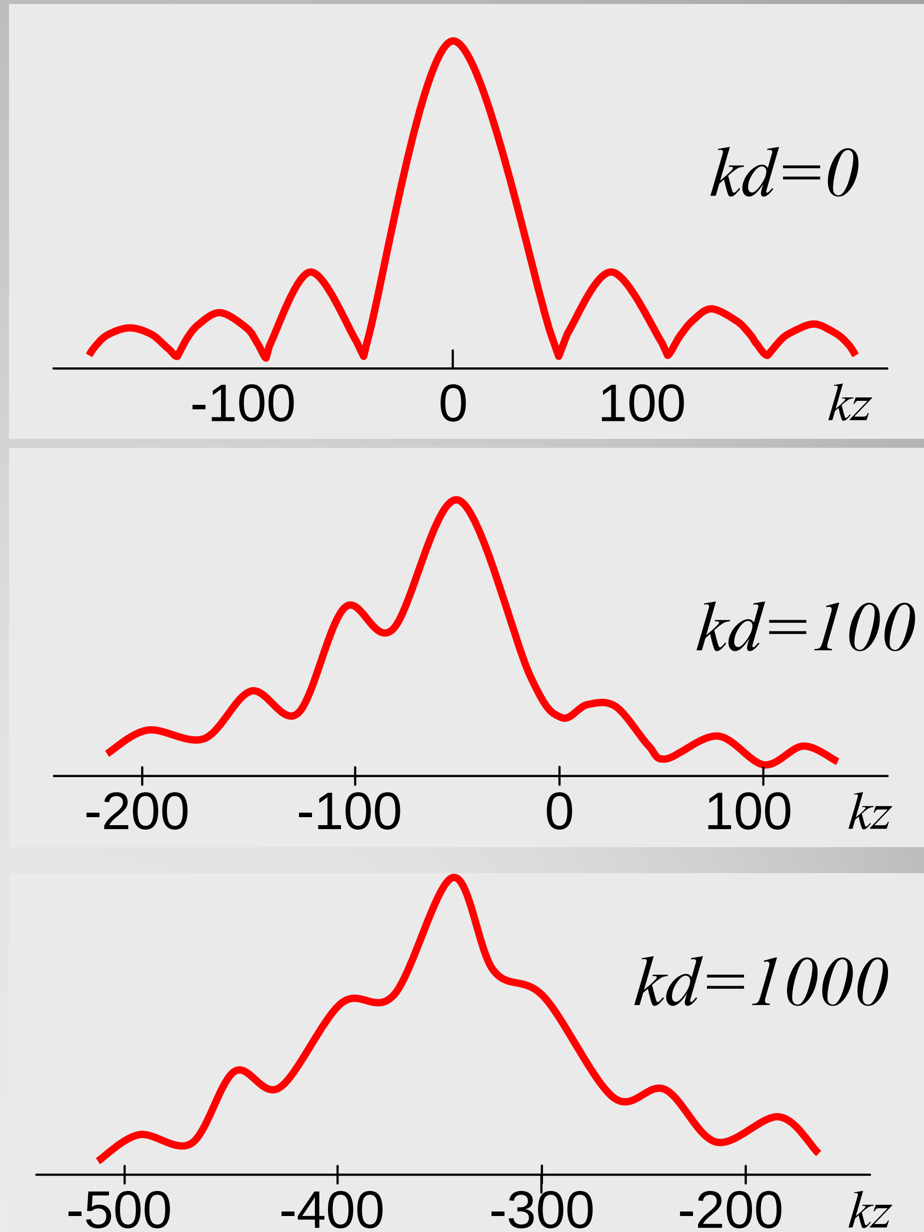


Incident angle $\theta < \theta_m$

The angular resolution of the methods are determined by the spatial resolution of the receiver and the distance between scan plan and focus

A(z) method



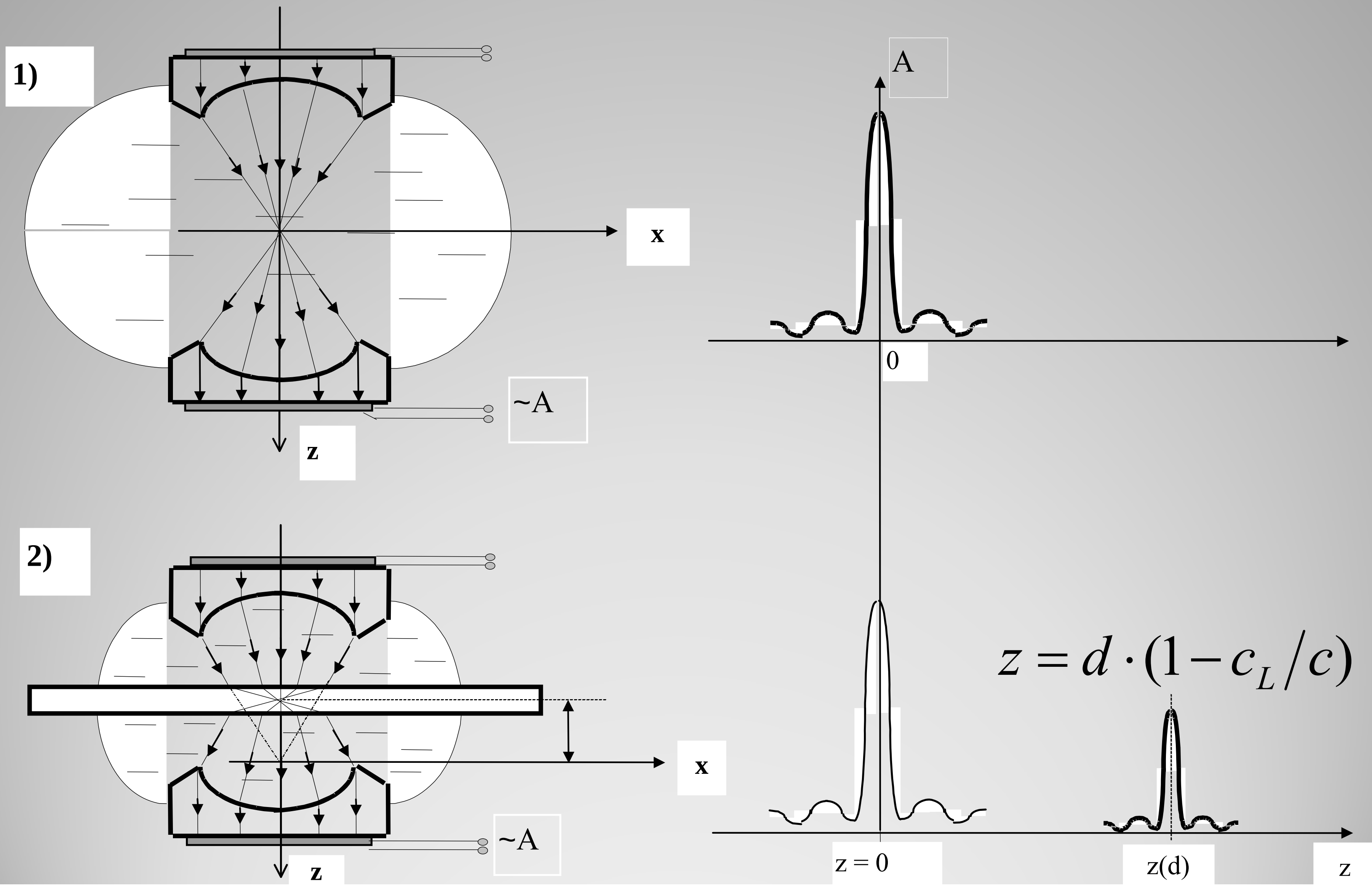


For thin samples

$$A(z) = A_0 x_m \frac{\sin(\pi x_m \frac{d}{\lambda}(1 - \frac{V_L}{V} - \frac{z}{d}))}{\pi x_m \frac{d}{\lambda}(1 - \frac{V_L}{V} - \frac{z}{d})}$$

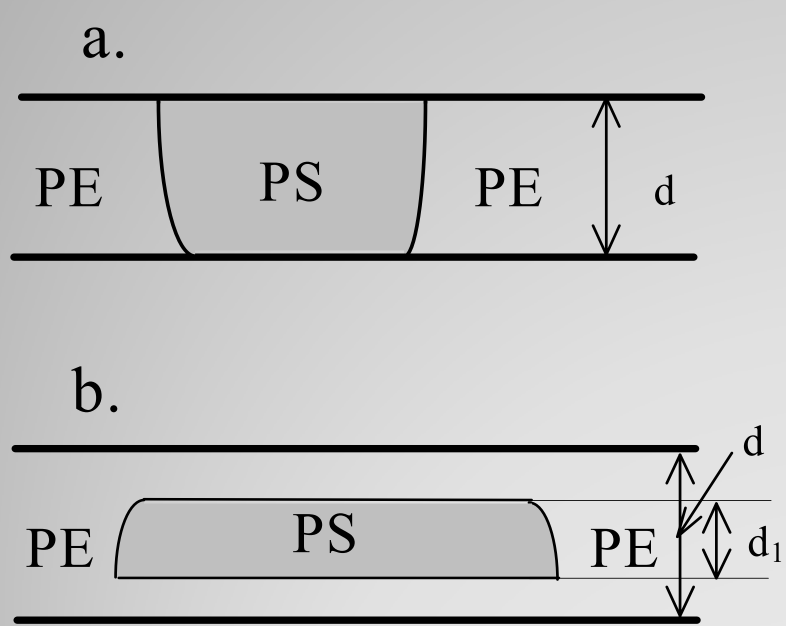
here $x_m = 1 - \cos\theta_m$

A(z) Method of Quantitative Measurements



$$z = d \cdot (1 - c_L / c)$$

Application of A(z) Method for Polymer Studies



Substance	**PE**	**PS**
density ρ, g/cm^3	0.920	1.050
sound velocity c_L, km/s	1.95	2.40
velocity ratio c/c_L	1.304	1.605
impedance $\rho\, c_L$	1.794	2.520
impedance ratio $\rho_1 c_L/\rho\, c$	1.20	1.69
attenuation: m, dB/cm·MHz b, dB/cm γ, cm^{-1} *(f = 450 MHz)*	 5.25 -1.72 272	 2.16 -0.27 112

Anisotropy Measurements

Elastic Anisotropy

Application Areas

–NDE

–Biomedical

–Seismic and Geophysical

Materials

–Crystals

–Stressed Materials

–Oriented cracks, pores, or inclusions

–Textured metals with oriented grains

–Thinly layered laminates

–Lamellar or fibrous composites

Characterization Techniques

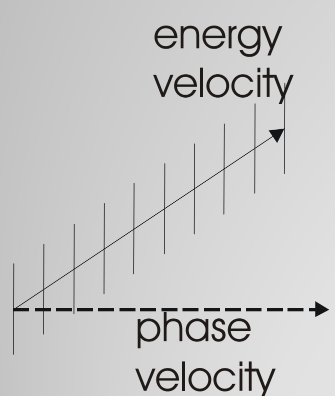
–Bulk methods (through transmission, point source)

–Surface waves, reflection coefficients (line focused system)

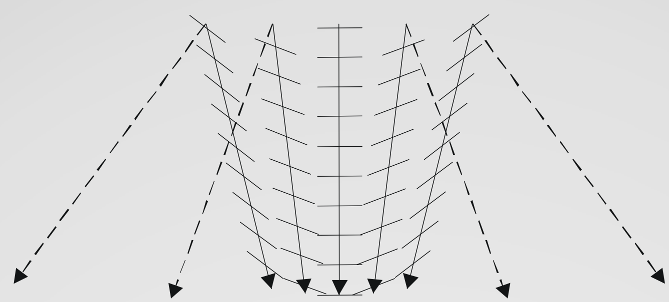
–Resonance, diffraction and other techniques

Effects of Anisotropy: Obstacles and Opportunities

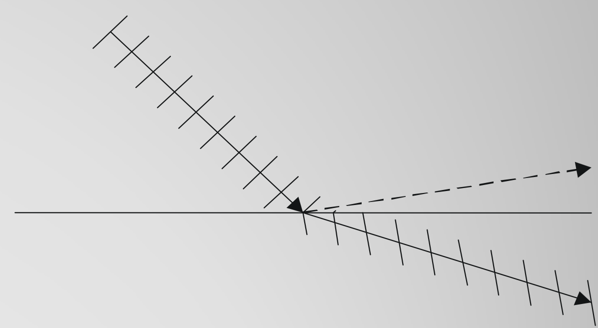
The anisotropy of a material gives rise to three major effects. These are a consequence of the fact that, in anisotropic materials, the energy does not travel perpendicular to the wave front (energy velocity and phase velocity are in different directions). The link between them is established in theory through the slowness (inverse phase velocity) surface.



beam steering

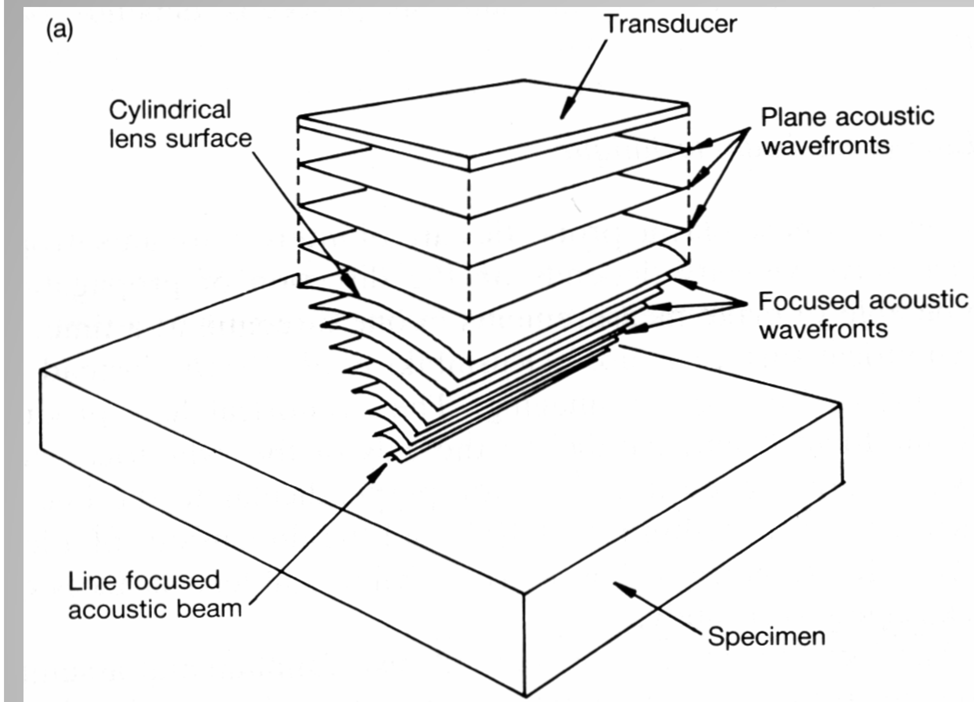


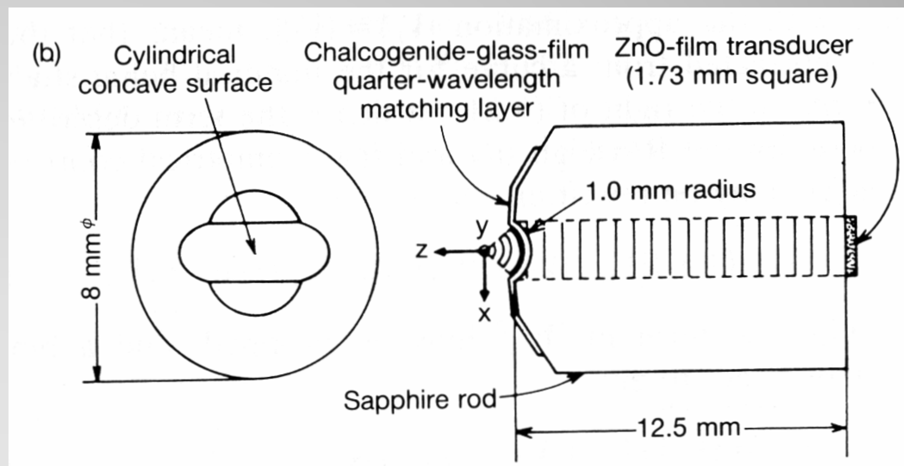
self focussing
(defocussing)



reflection &
critical angles

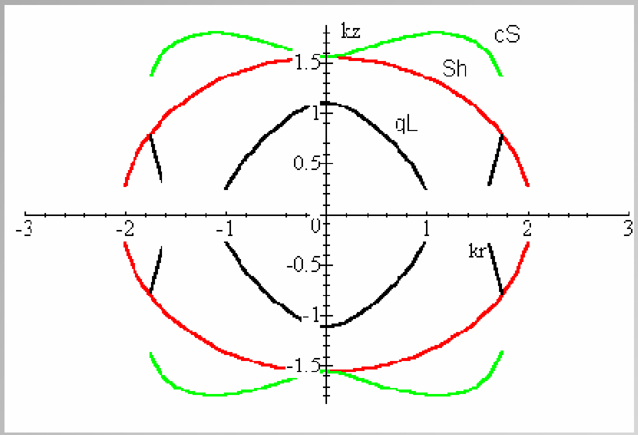
Cylindrical Lens for Anisotropic Measurements



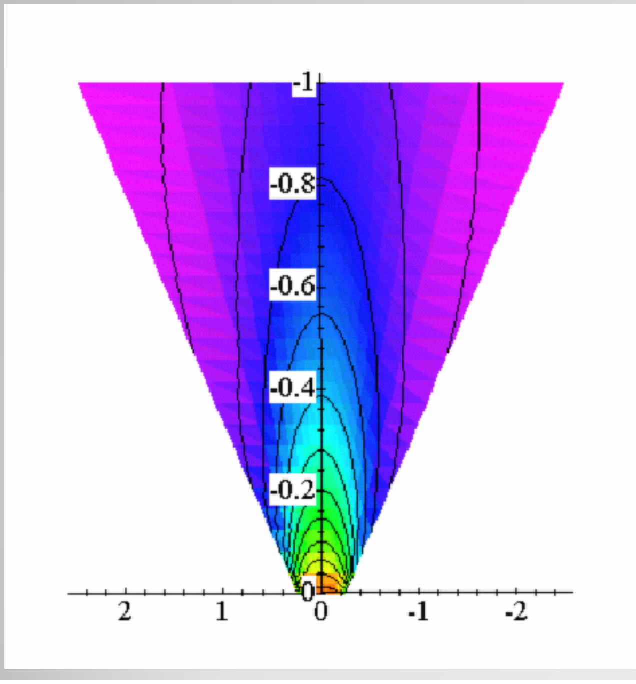


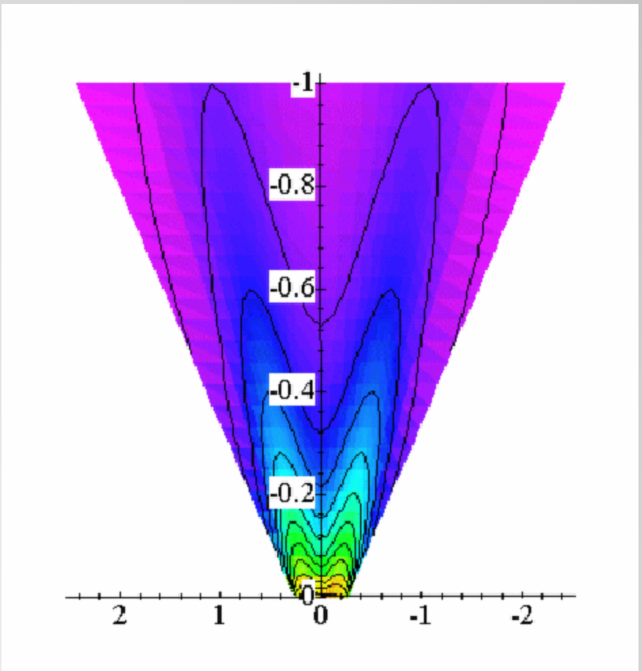
(a) Wavefronts in a line-focus-beam microscope; (b) structure of a line-focus-beam lens with dimensions for 225 MHz (Kushibiki and Chubachi 1985).

Example: Austenitic Weld Metal



(left) Slowness surfaces for a transversely isotropic austenitic stainless steel weld metal. (below) A theoretical comparison of (quasi)longitudinal beam profiles for isotropic parent and anisotropic weld metals.

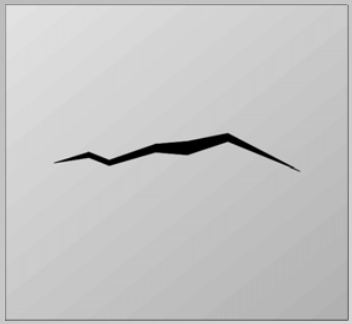




Non-Linear Imaging

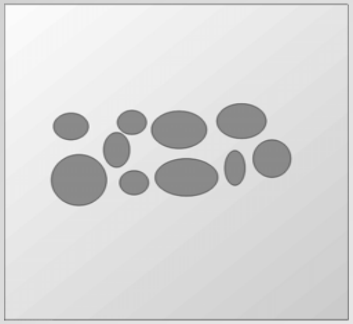
Non-Linear Acoustical Methods

Some special cases of defects, invisible by usual acoustic methods

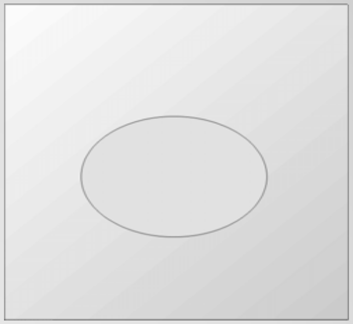


Thin cracks or other discontinuity

Glue layers

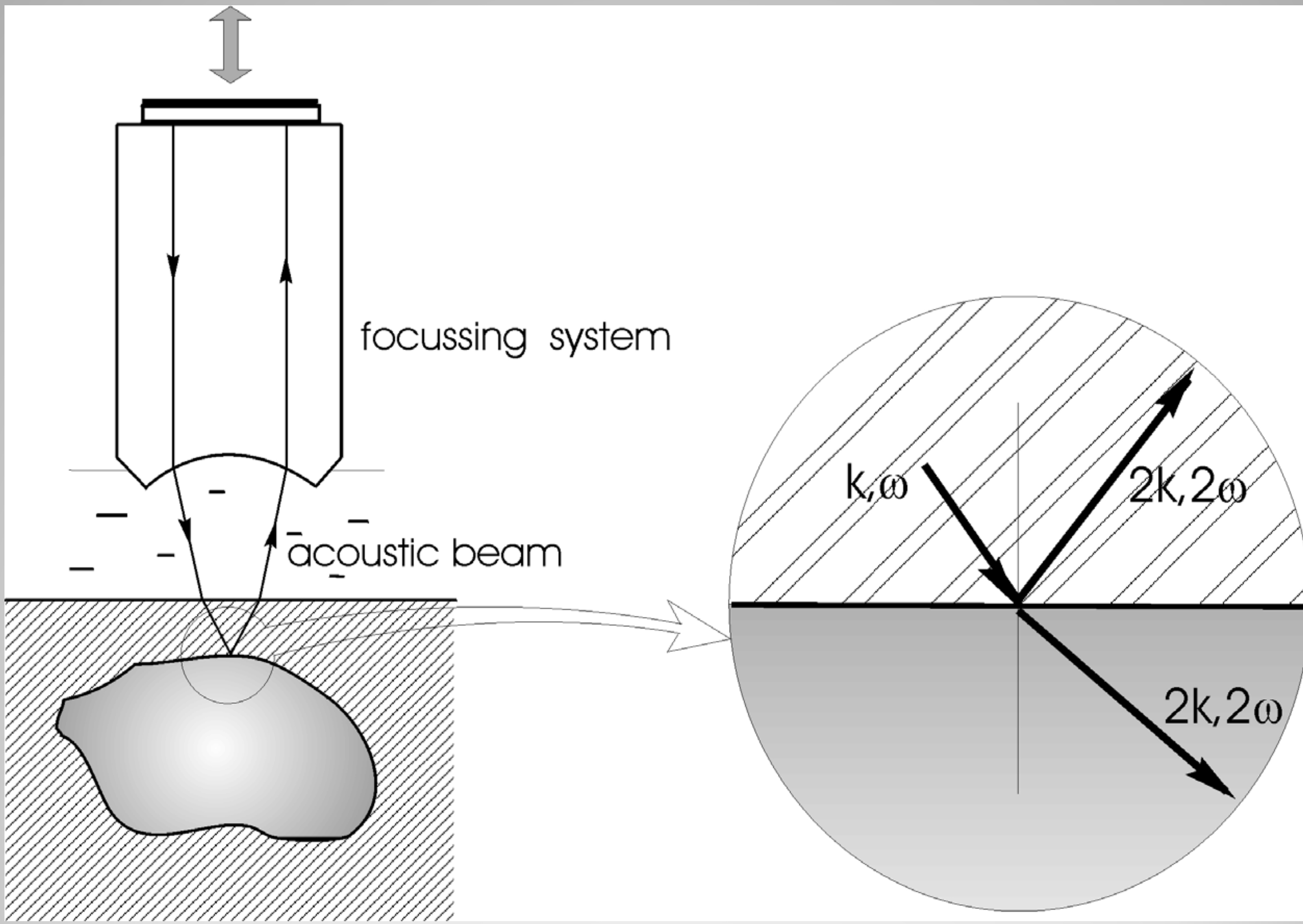


Small-grain structure (grain dimension less then wavelength)

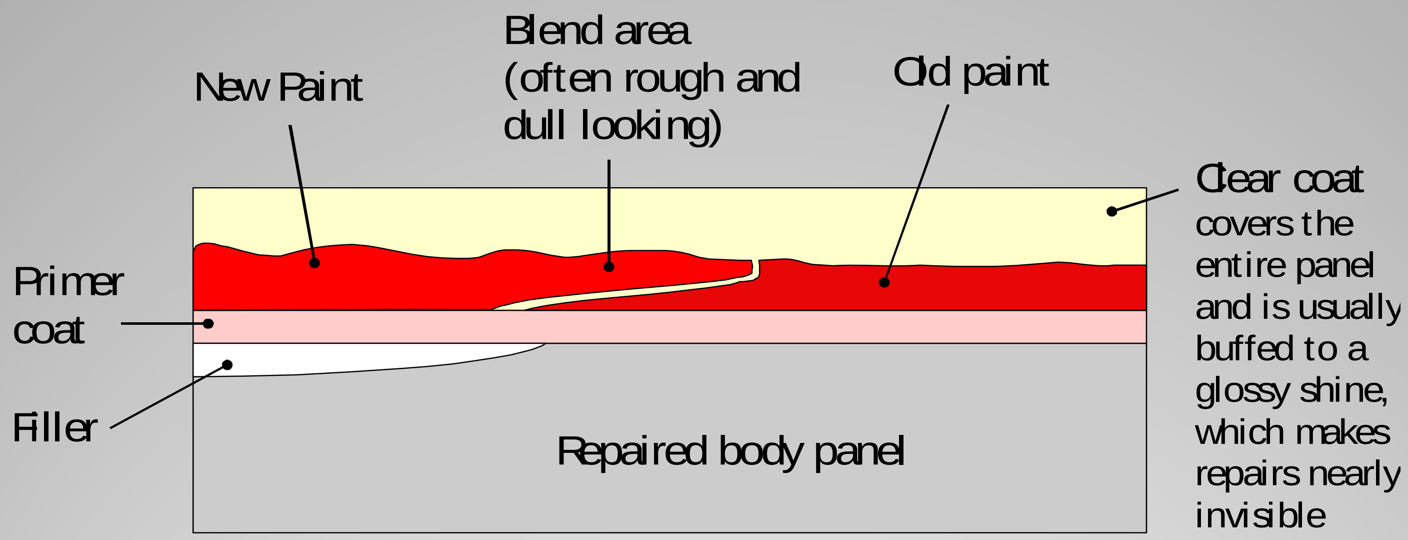


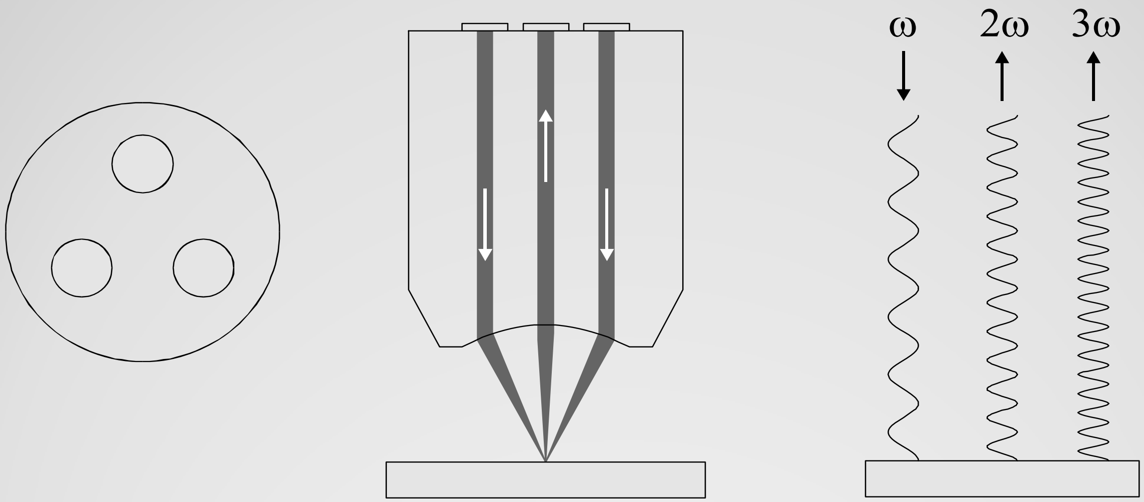
Inclusions of materials with similar acoustical parameters

Non-Linear Methods

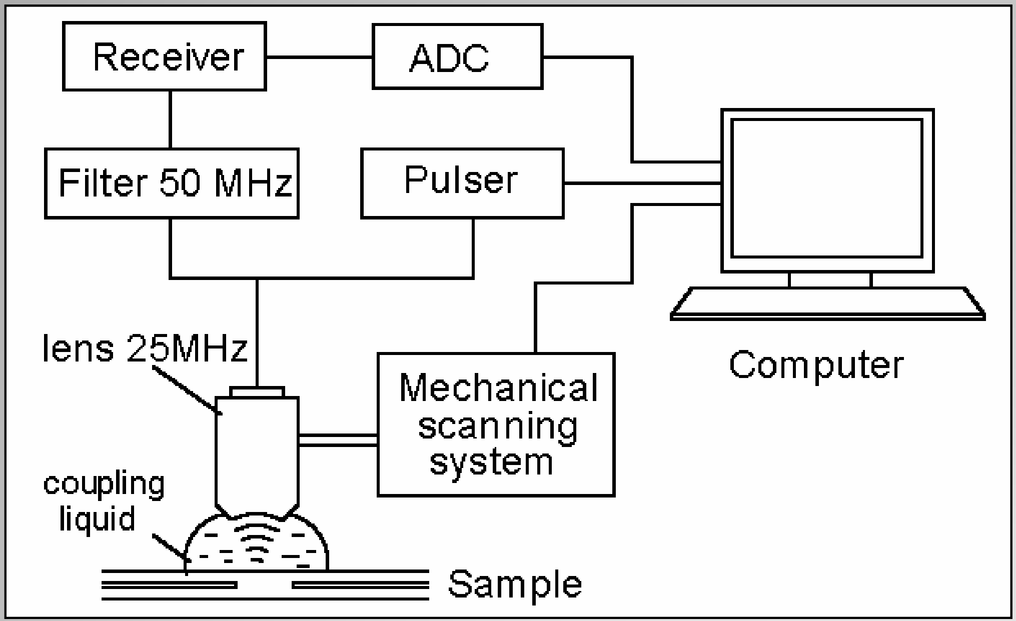


Non-Linear Methods



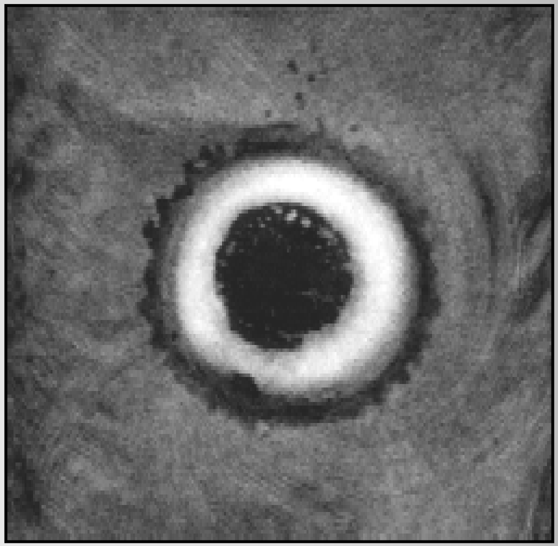


Non-Linear Imaging Methods



L

NL



Samples: two steel 2-mm sheets, joined by resistive weld and polished to exclude surface effects

Non-Linear Imaging Methods