Technologies, conception and caracterisation of transducers used in NDT.

ELyT School
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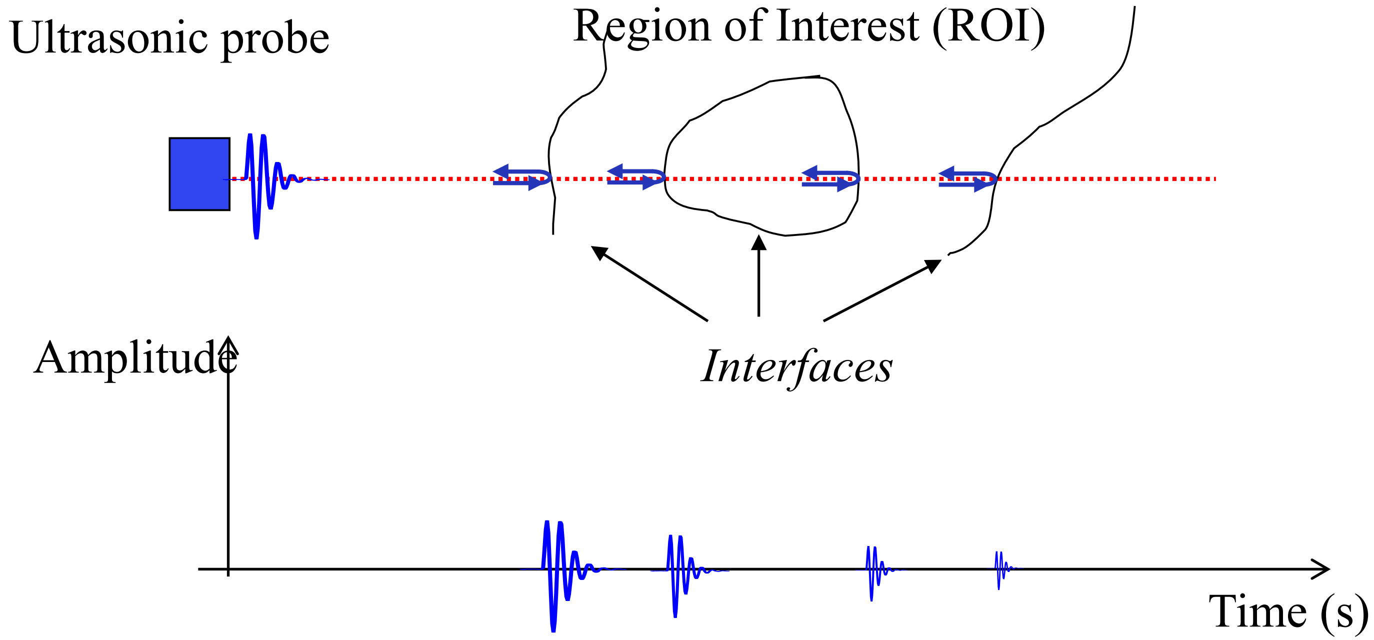
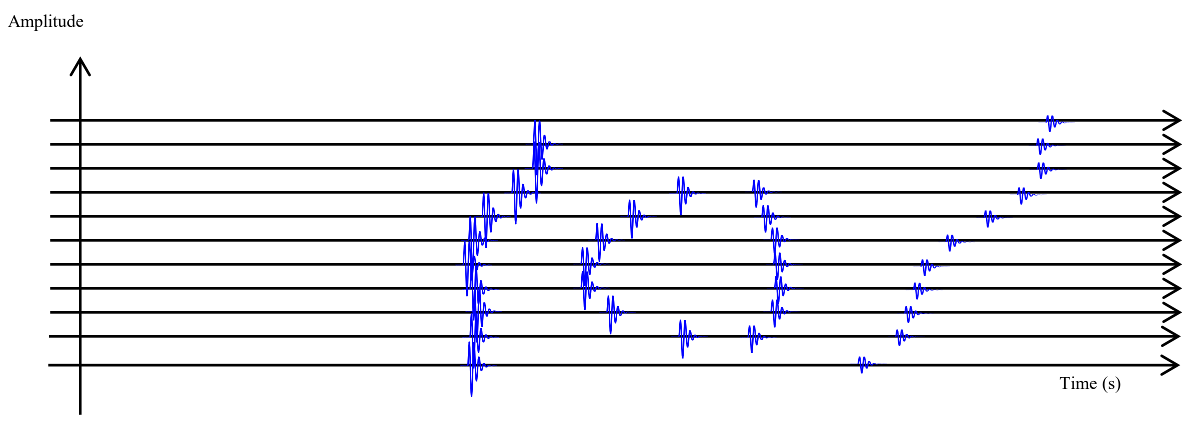
Outline

Ultrasound imaging
Role of the probes
Single element transducer
Characteristics of a transducer
Diffraction approach
multi-element probes
Electroc acoustic characterisation
Conclusion

Ultrasound imaging




Amplitude
Time (s)

Ultrasonic probes

Olympus

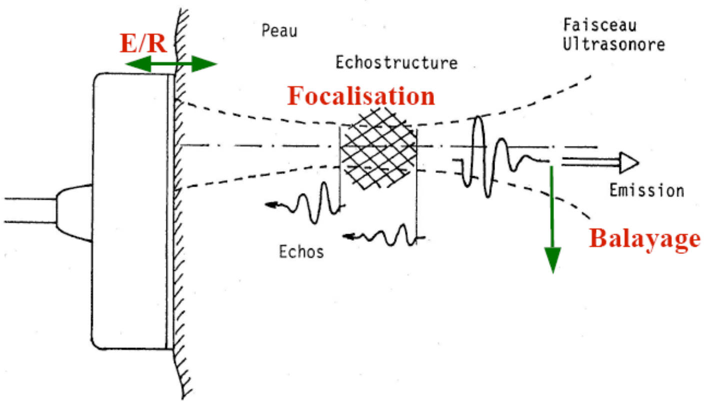
Role

1-Electromechanical transduction

- This is the main function of a probe. The electrical wave is transformed into an acoustic wave on emission (and vice versa on reception).

2-Beam Forming

- a) Focusing
- This can be achieved by shaping the piezoelectri element, or by using a lens glued to the front face using electronic delays.
- b) Beam Scanning
- To obtain an image, the beam direction must be changed. This is done either mechanically (usually by means of a pendulum system) or electronically (by switching specific transducers on and off, or by using electronic delays).



Characteristics of a piezoelectric material

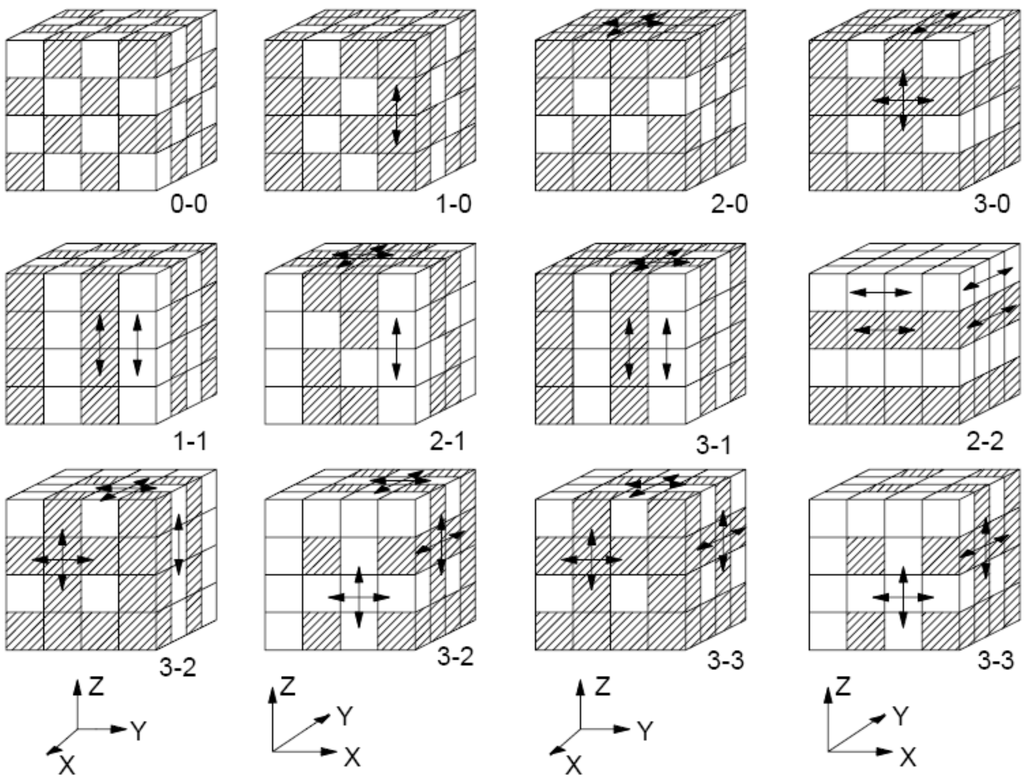
- **k : Coupling Coefficient**
- Defined for each vibration mode. An ideal piezoelectric material has a k equal to 1. typical vvalue 0.5. Its value determines transducer sensitivity and bandwidth.

- **Z (MRayl) : acoustical impedance** ($Z = \rho \cdot c$)
- Typ. value 33 MRayl, Acoustic adaptation is often necessary to transfer ultrasound energy from one to the other.

□ **ε_r: Relative dielectric constant**
- Electrical matching to the device (often 50 ohms).
- Influence the transducer's sensitivity and bandwidth. Its optimum value depends on transducer geometry and size ($Ze \propto 1/\varepsilon$).

Piezo composite ceramics

A composite is made up of ceramic (high kt) and inert resin (light material and therefore low acoustic impedance). The advantage of the composite is the reduction in acoustic impedance (thanks to the lighter resin).



x-y connectivity :

x : number of related directions of the resin

y : number of related directions of the ceramic

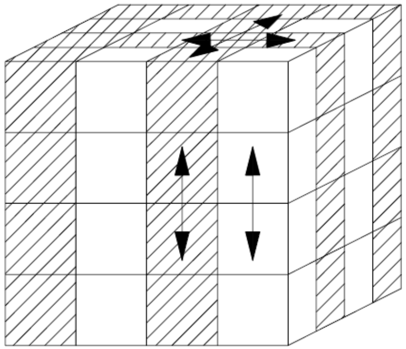
This connectivity can take 4 values:

0 : one grain

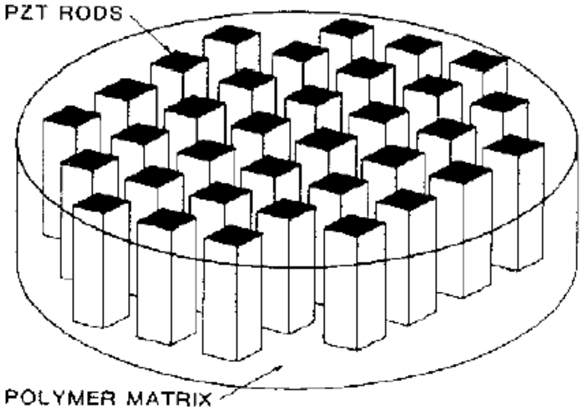
1 : a bar

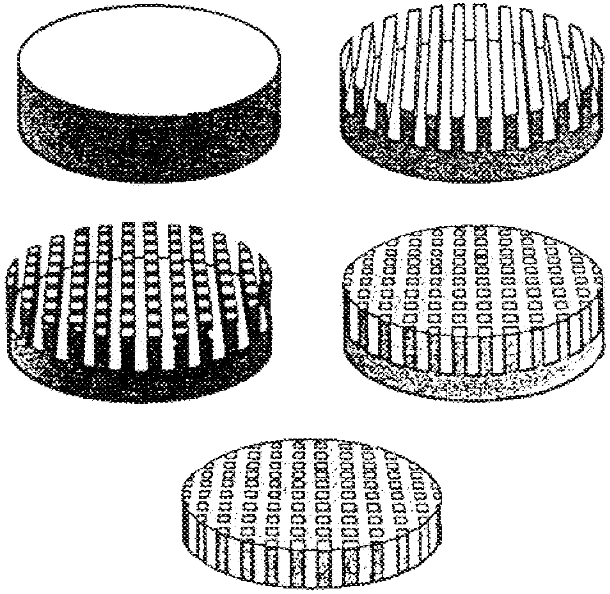
2 : a plate

3 : a solid material



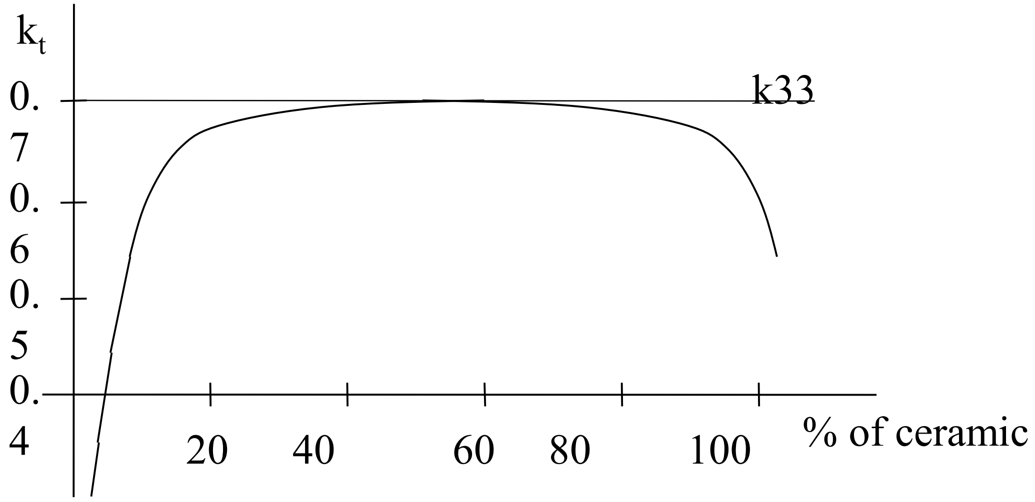
1-3

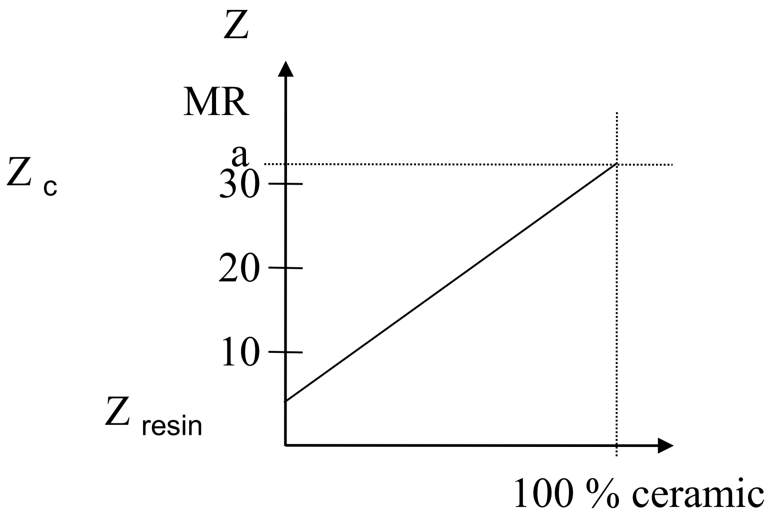


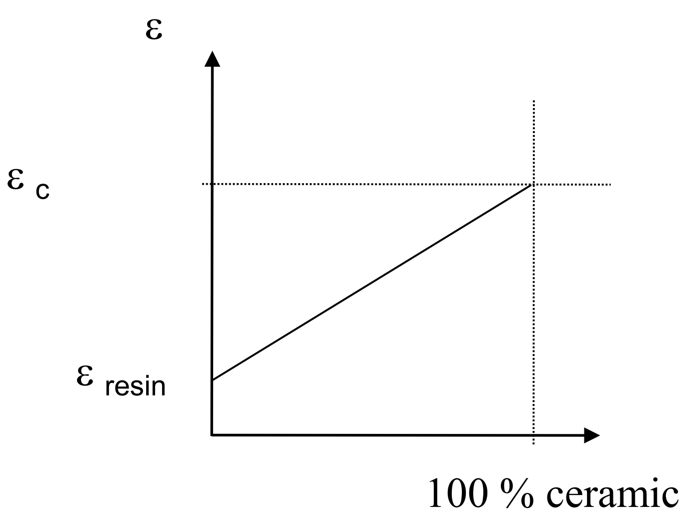


Dice and fill

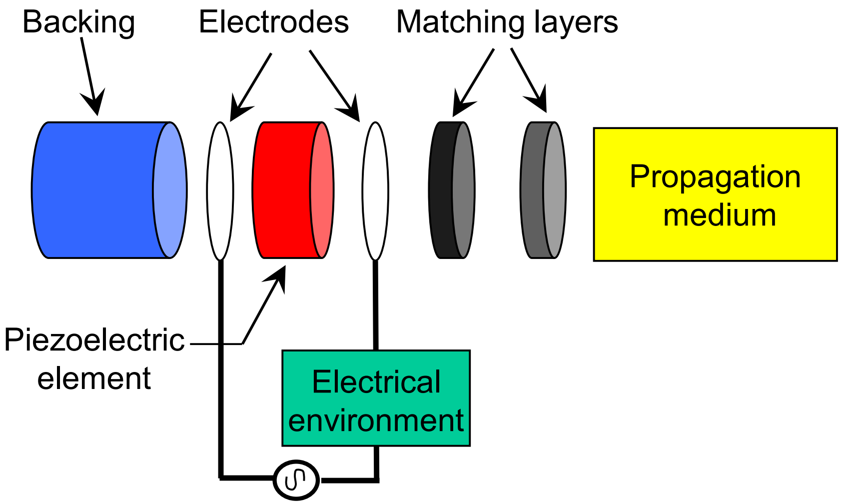
Characteristics of a composite as a function of amount of ceramic

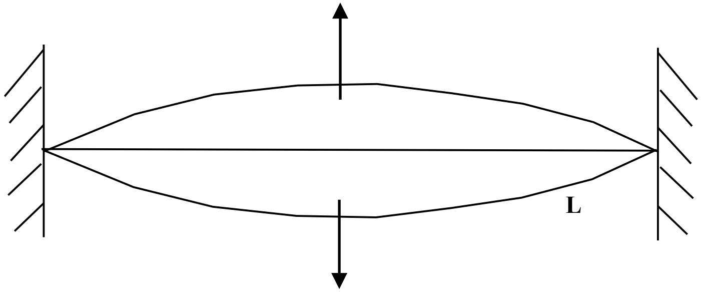






Single-element transducer





Natural frequency of a piezoelectric plate

First mode : $L = \frac{\lambda}{2}$

The center frequency $f_0 = \frac{c}{\lambda} = \frac{c}{2L}$

Ceramic : c =4000 m/s $e = 1\ mm$

$$f_0 = \frac{4000}{0.002} = 2\ MHz$$

Transmission-reflection: importance of acoustic impedance

Calculation of the transmission of the wave from the ceramic in the water on its front face and in the air on its rear face:

In air

Reflexion coefficient: $R = (Z_1 - Z_2) / (Z_1 + Z_2)$

In air

$Z_2 = Z_{air} \approx 0$

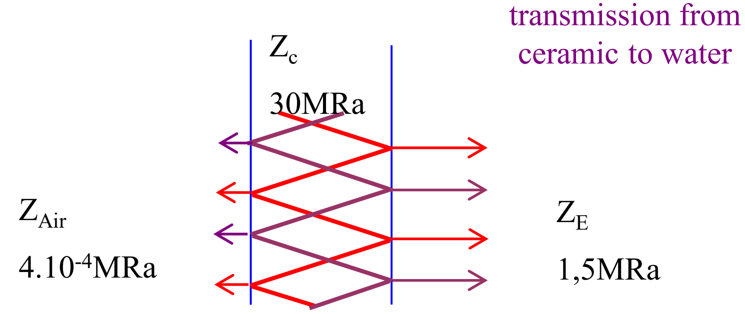
Everything is reflected

In water

$Z_2 = Z_{eau} = 1{,}5$ MRa

R= 0,905 (less than 10%)

Transmission-reflection: importance of acoustic impedance



Transmission of the ultrasonic wave from the ceramic in the water on its front face and in the air on its rear face:

Reflexion coefficient: R = (Z1-Z2) / (Z1+Z2)

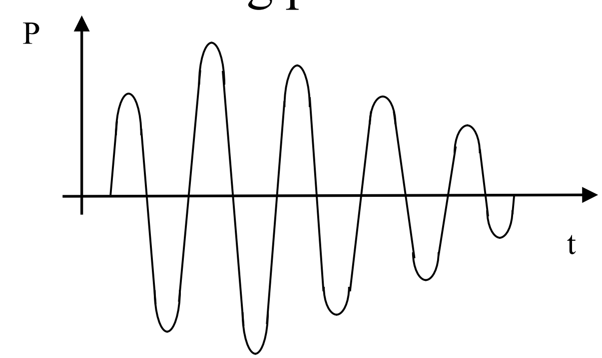
In air Z2 = Zair ≈ 0

Everything is reflected

In water Z2 = Z_E = 1,5 MRa

R= 0,905 (less than 10%)

Long pulse

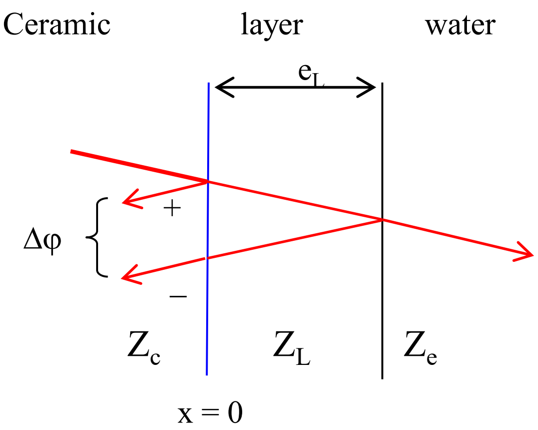


For imaging, a good transducer has a pulse duration of 1 to 3 periods.

two solutions:
- Improve the transmission of ceramics to water
- Absorb the energy emitted in the direction of the rear face

Quarter wavelength matching layer

Its role is to improve the transmission from the ceramic to the water, releasing more than 10% of the energy each time.

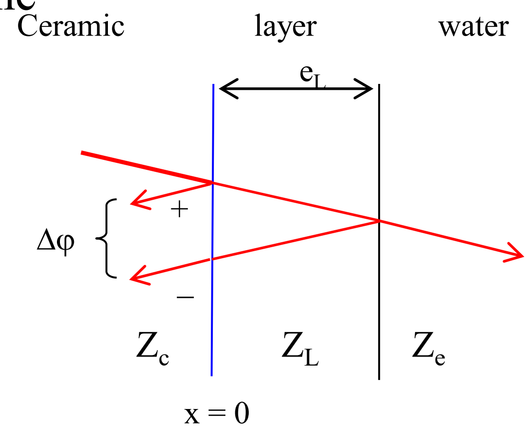


Destructive interference in x =0 . i.e a round trip in the layer must therefore correspond to half a wavelength.

Therefore $2.e_L = \lambda / 2$ thus $\mathbf{e_L = \lambda / 4}$

We are talking about a **quarter wavelength matching layer**.

The acoustic impedance in x==0 depends on the impedance of the matching layer and propagation medium according to



$Z_{x=0} = Z_L \,(Z_e \cos ke + j\, Z_L \sin ke) / (Z_L \cos ke + j\, Z_e \sin ke)$

and k : wave number $(k = 2\pi/\lambda)$

e (mm) : thick of the ceramic

Here because $e = \lambda/4$ then $k.e = \pi / 2$, hence

$Z_{x=0} = Z_L^2 / Z_e$

The optimal value when $Z_{x=0}$ is Z_c the impedance of the ceramic

$Z_{x=0} = Z_c = Z_L^2 / Z_e$

$\mathbf{Z_L = \sqrt{(Z_c.Z_e)}}$ **(for a given frequency)**

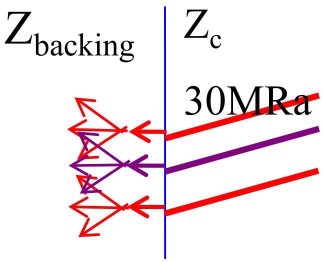
It is an approximate value that works well for a given frequency

Value for Wide Band Operation

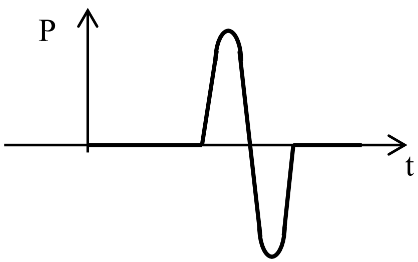
$$Z_L = \sqrt[3]{(Z_c.Z_e^2)}$$

Role of backing

It absorbs and disperses the energy from the rear face of the ceramic (so that there is no return on the ceramic). To do this, it is necessary to put a material with an important acoustic impedance. The extreme case would be to put a backing of the same acoustic impedance as that of the ceramic (30 MRa)



Echo is absorbed in the backing

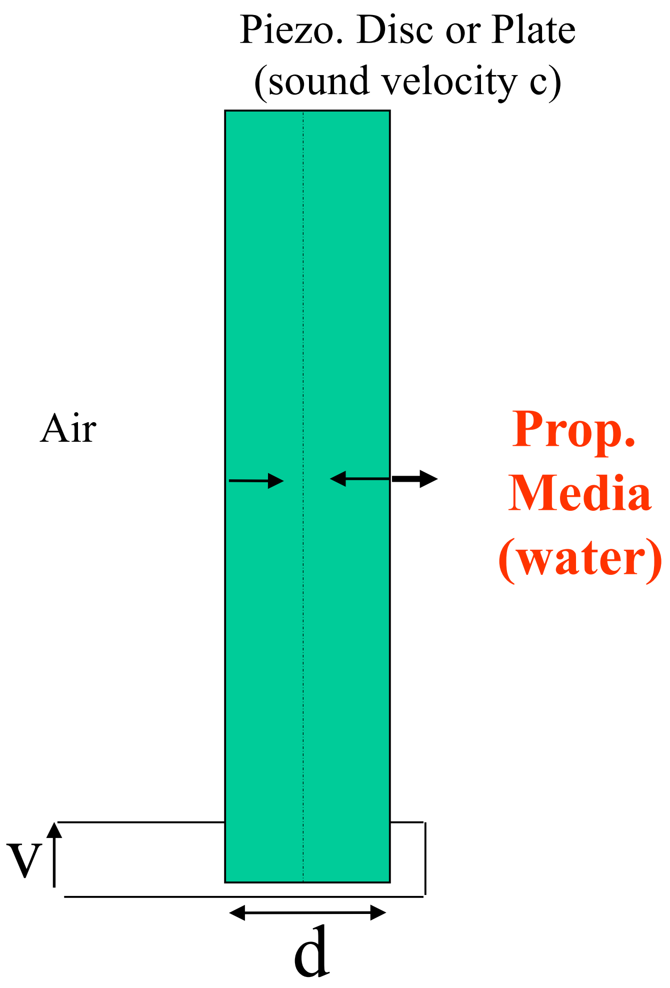


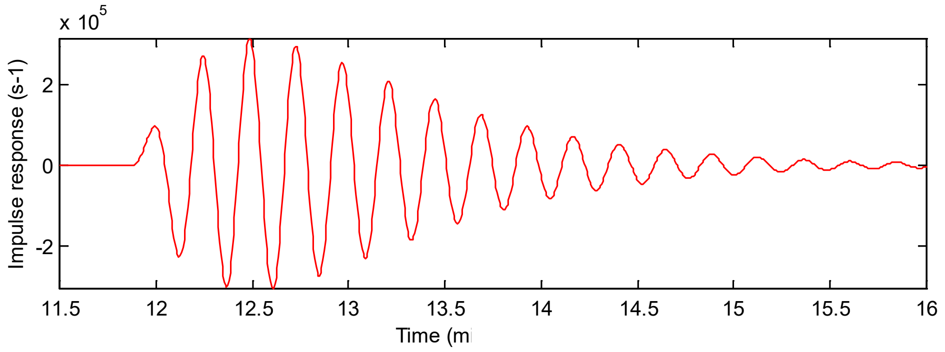
Echo Shape perfect backing

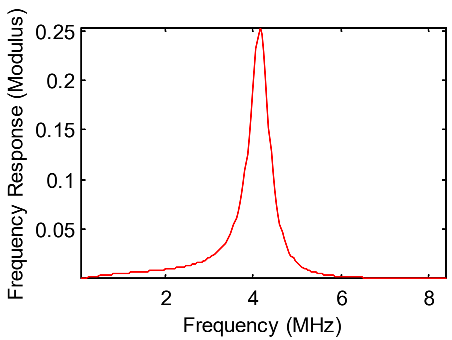
Notes:

- high attenuation and rear face
- non-smooth backing to avoid reflection echo.
- In practice, the impedance used is an intermediate impedance between those of the air and that of the ceramic (typically from 1 to 10 MRa).

Operation of a single-element transducer

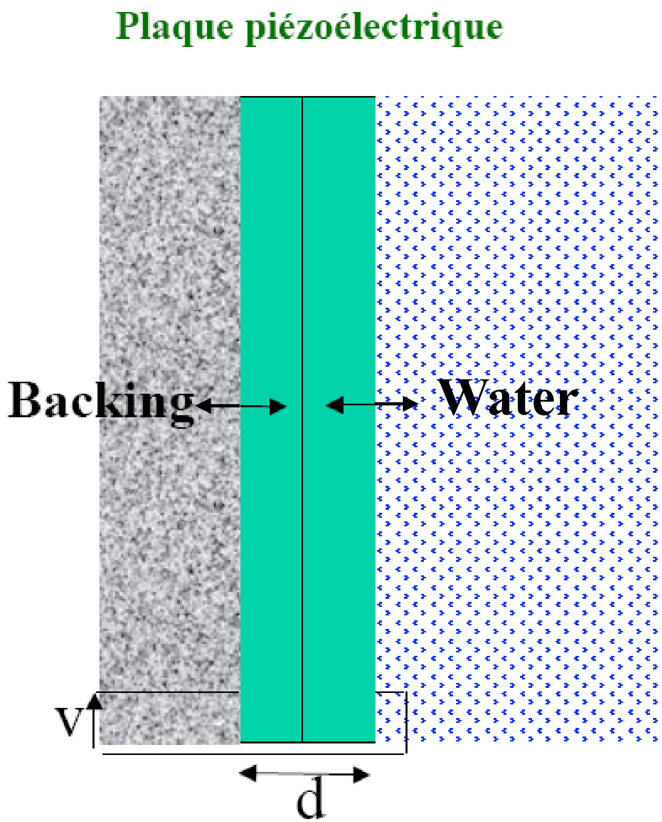


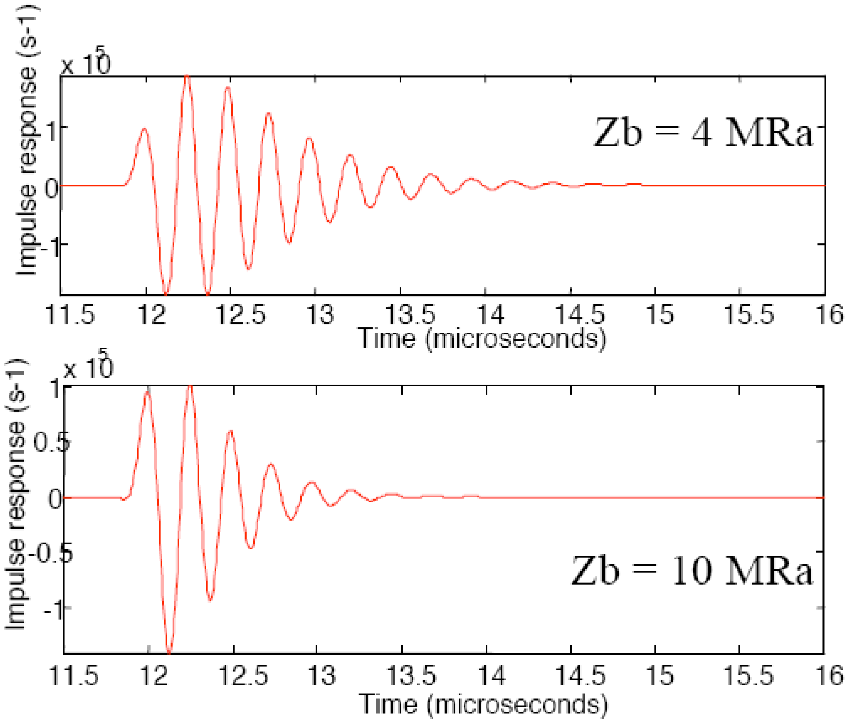




Energy is radiated into water only

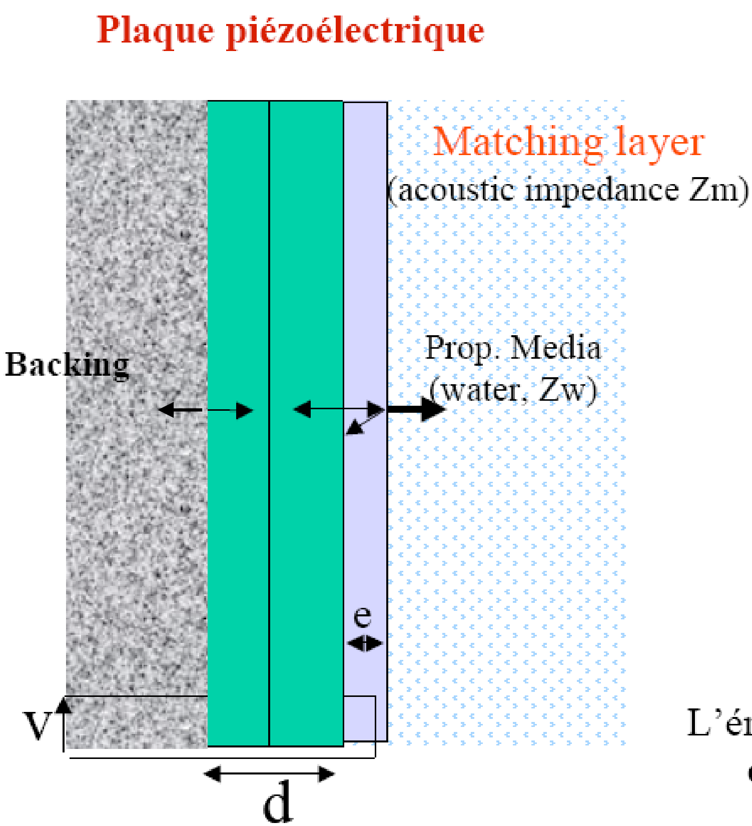
Damping front and rear face

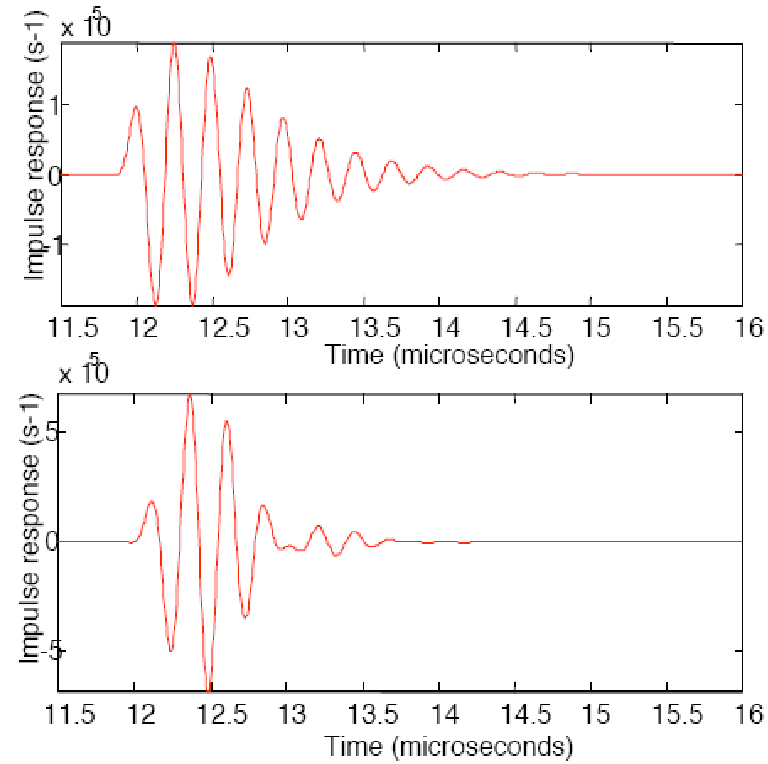




Energy is radiated into backing and water : the duration of resonance is decreased (higher bandwidth) but the sensitivity is reduced

Use of a matching layer





L'énergie transférée dans l'eau est maximum si **e ≈ λ/4** et si Zp < Zm < Zw : sensibilité et bande passante sont augmentée

Conclusion

The QUARTER WAVE LENGTH MATCHING LAYER allows INCREASING SENSITIVITY and INCREASING BANDWIDTH.

BACKING INCREASES THE BANDWIDTH but REDUCES THE SENSITIVITY

(The higher the acoustic impedance of the backing is (the heavier the backing) the less the sensitivity)

The best signal duration that can be obtained corresponds to the signal which has only one period but then a very poor sensitivity.

Characteristic parameters of a transducer

1-Sensitivity

Target (size / position)

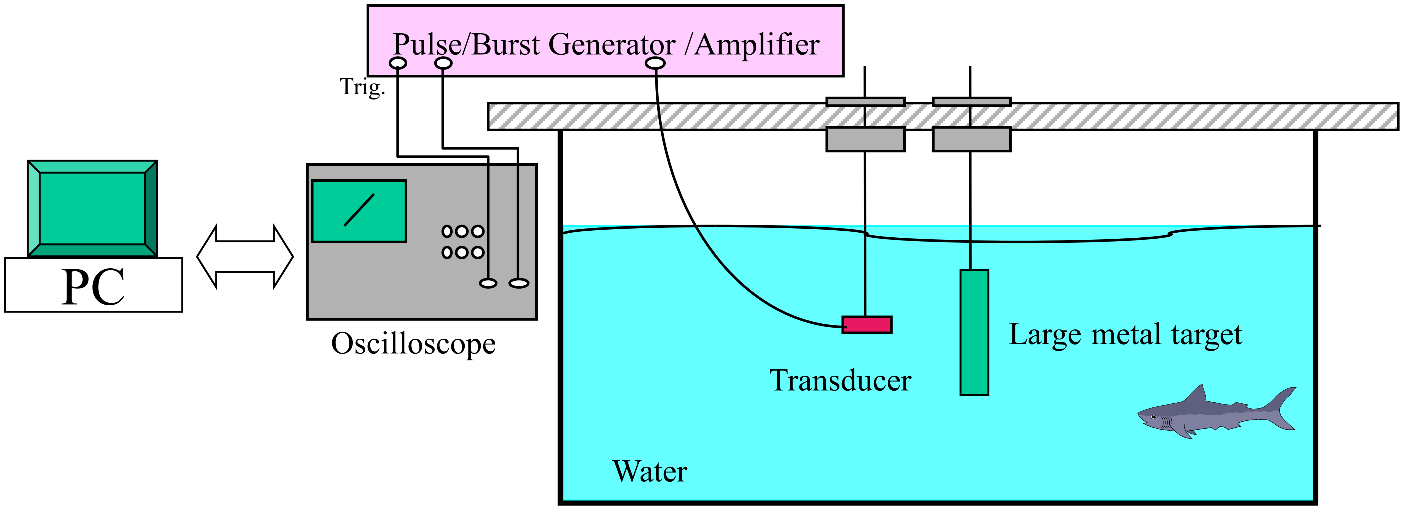
Transducer

A

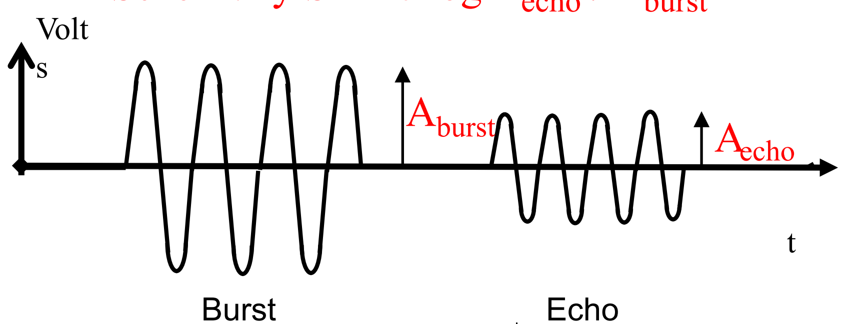
t

Echo on the target:

Higher is the amplitude, higher is the sensitivity. Sensitivity allows to see small structure and to see far away

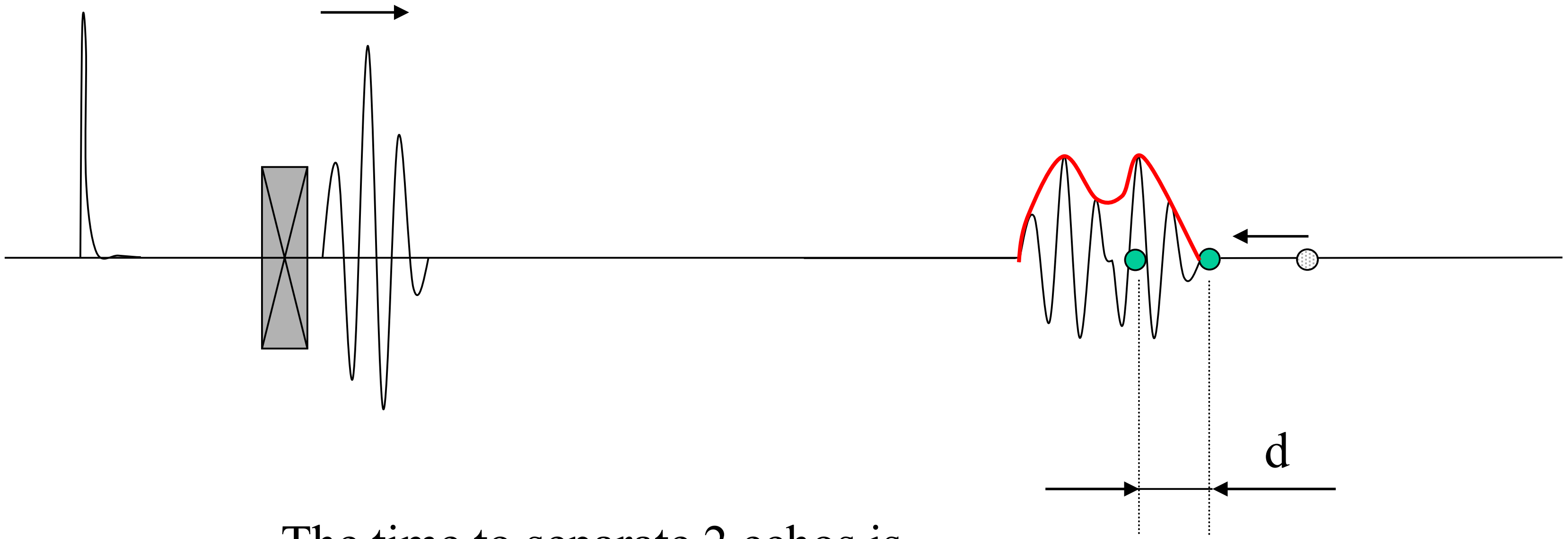


Sensitivity $S = 20 \log A_{echo} / A_{burst}$



Axial Resolution

It characterises the ability to discriminate two targets on the propagation axis.



The time to separate 2 echos is

$$\Delta T = 2d / c$$

or

$$d = c/2 \; . \; \Delta T$$

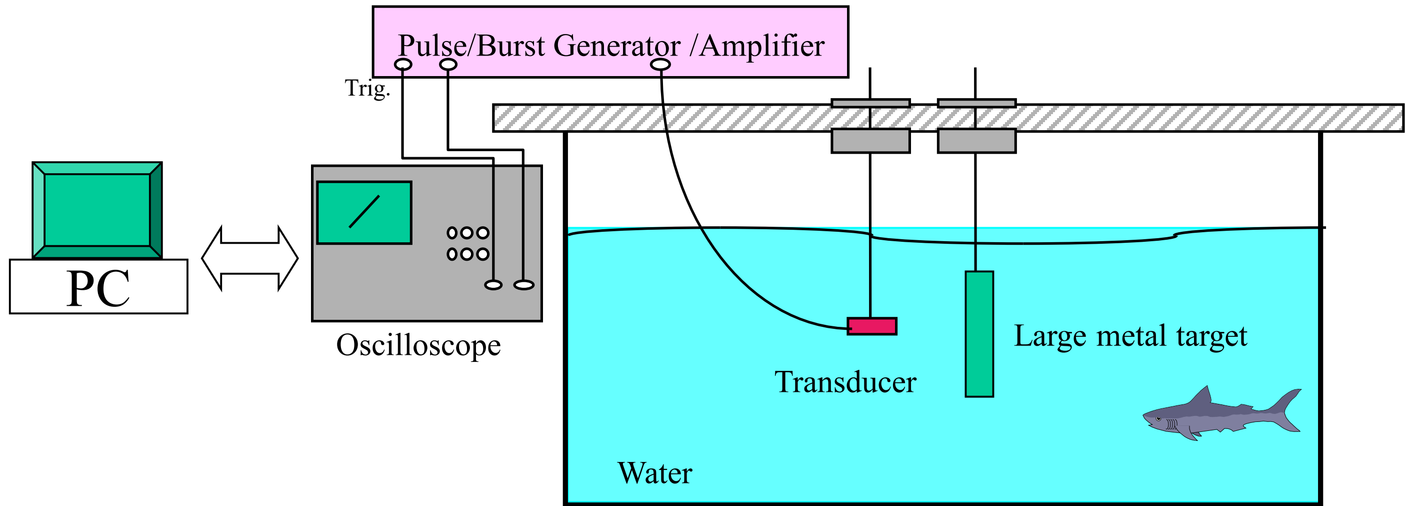
The axial resolution is

The 2 echoes are mixed: the apparatus only see one echo sctruture instead of two :

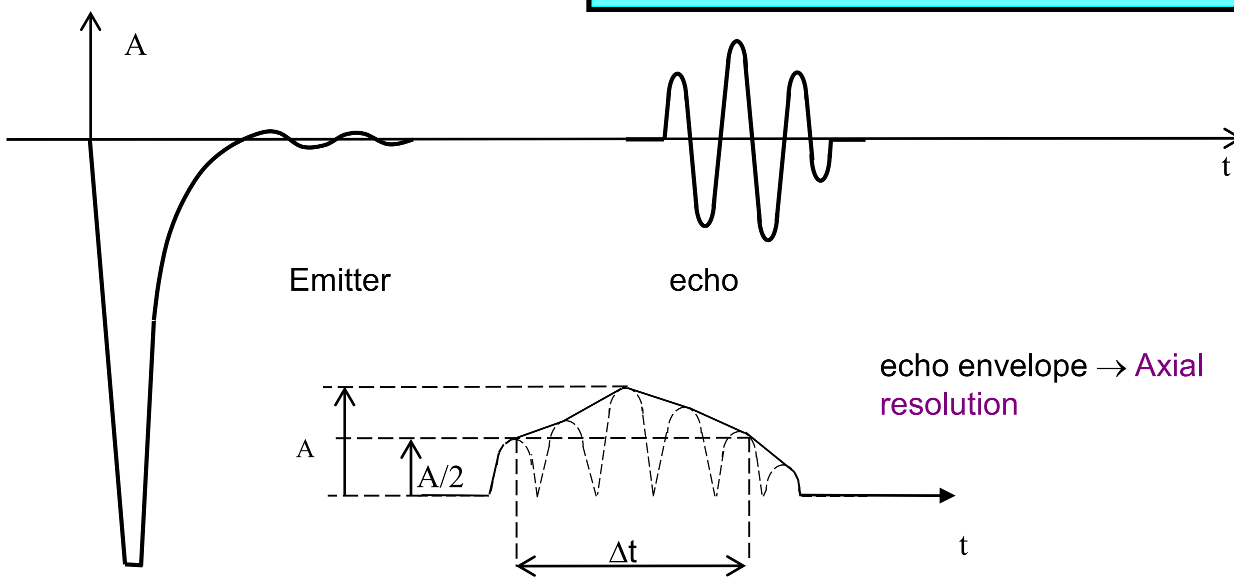
d= c.ΔT/2 the axial resolution is = c x echo duration/2

The echo duration is detemined from de half duration of the envelope. It is inversely proportional to the bandwidth (gaussian shape)

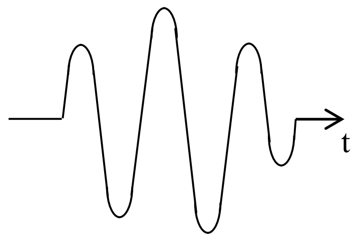
Axial resolution Mesurement method

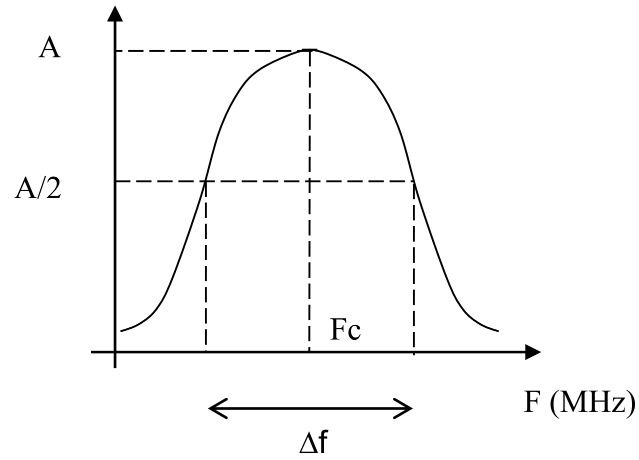


Oscilloscope trace



Band width





The bandwith is obtained by taking the fourier transform of the echo.

Δf (-6dB) : bandwidth (@ –20 dB, à – 30dB…)

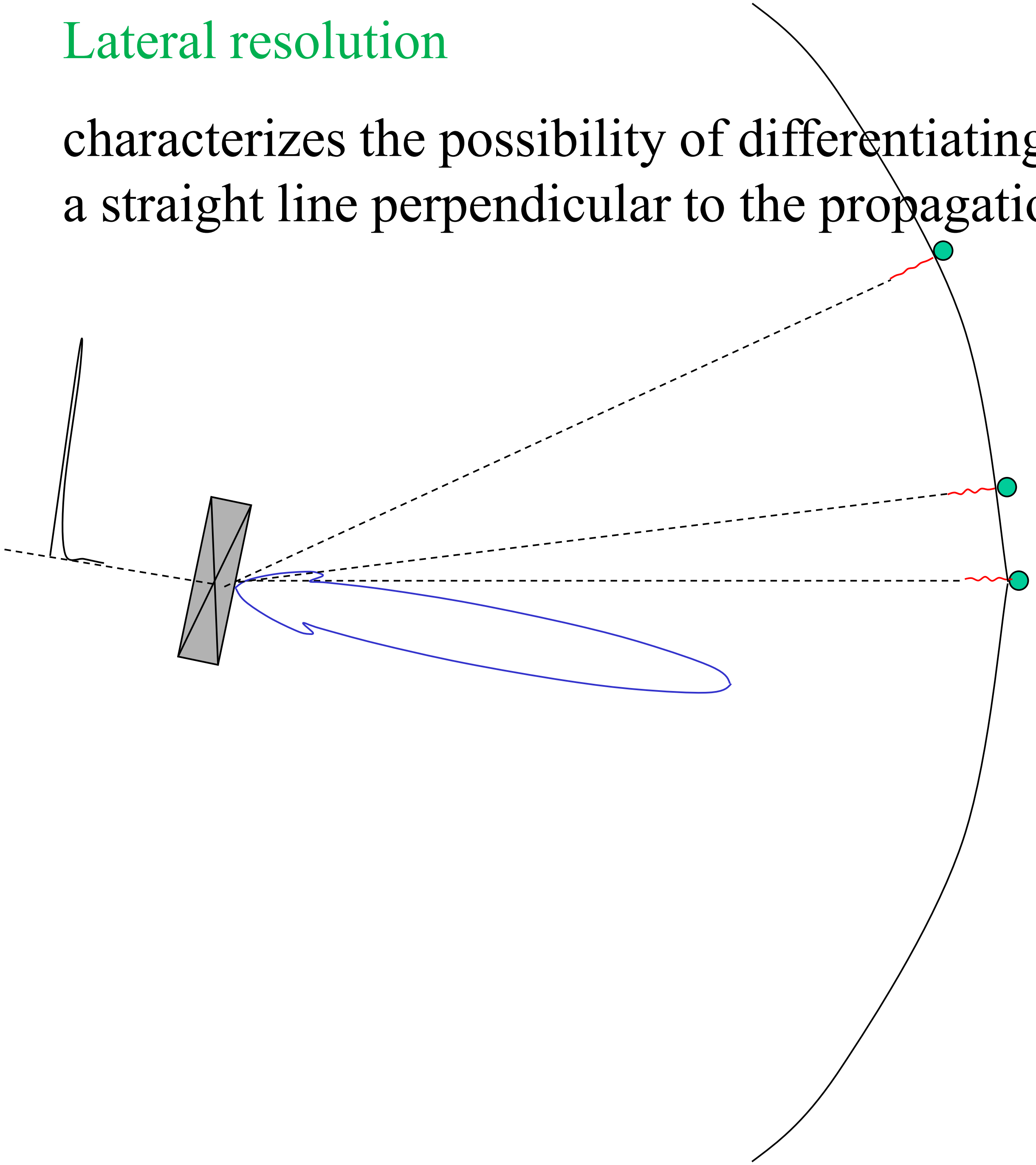
relative bandwidth : bandwidth divided by the center frequency % .

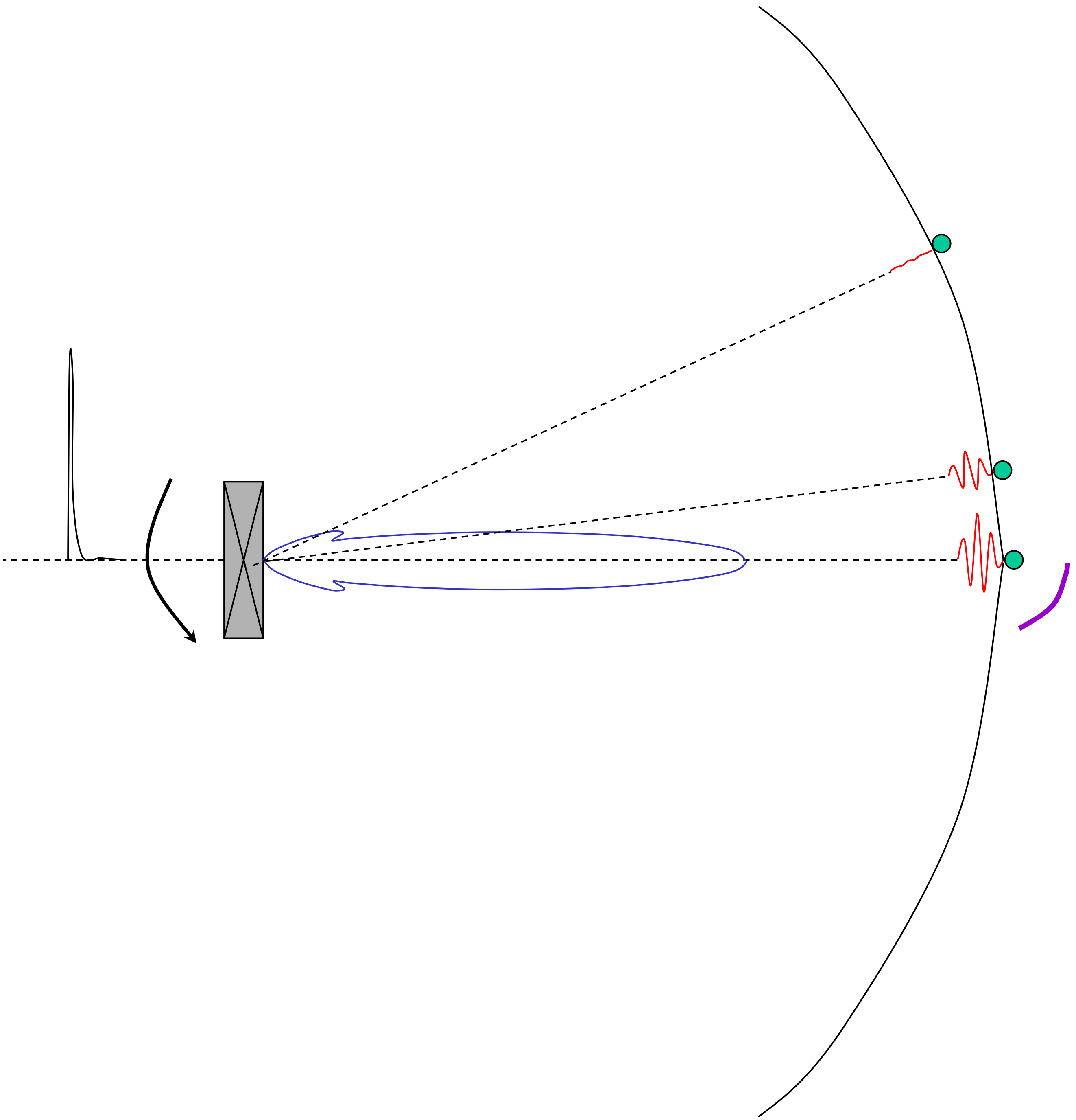
More Δt is short, more Δf is large.

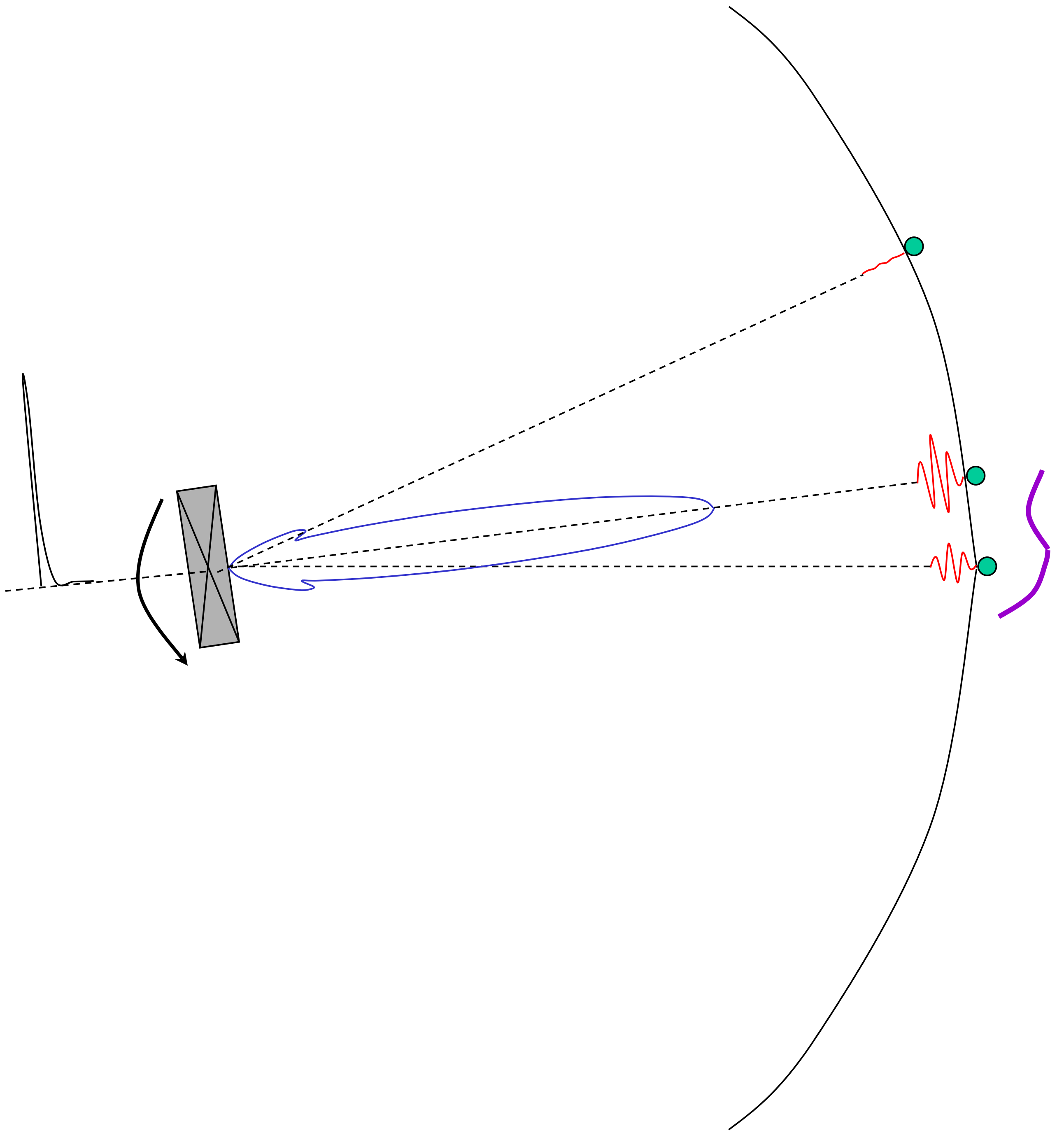
High resolution = large bandwidth

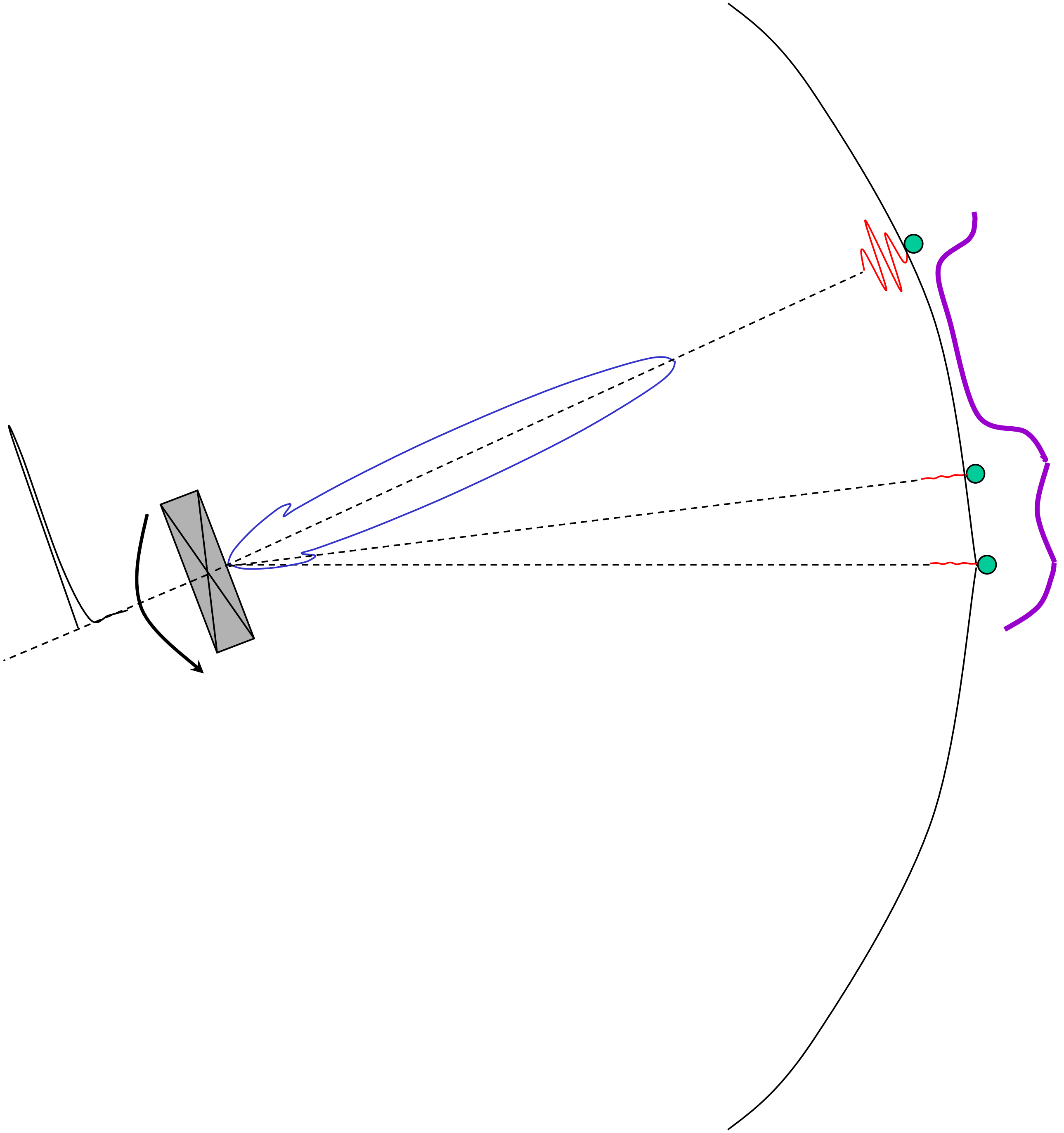
Lateral resolution

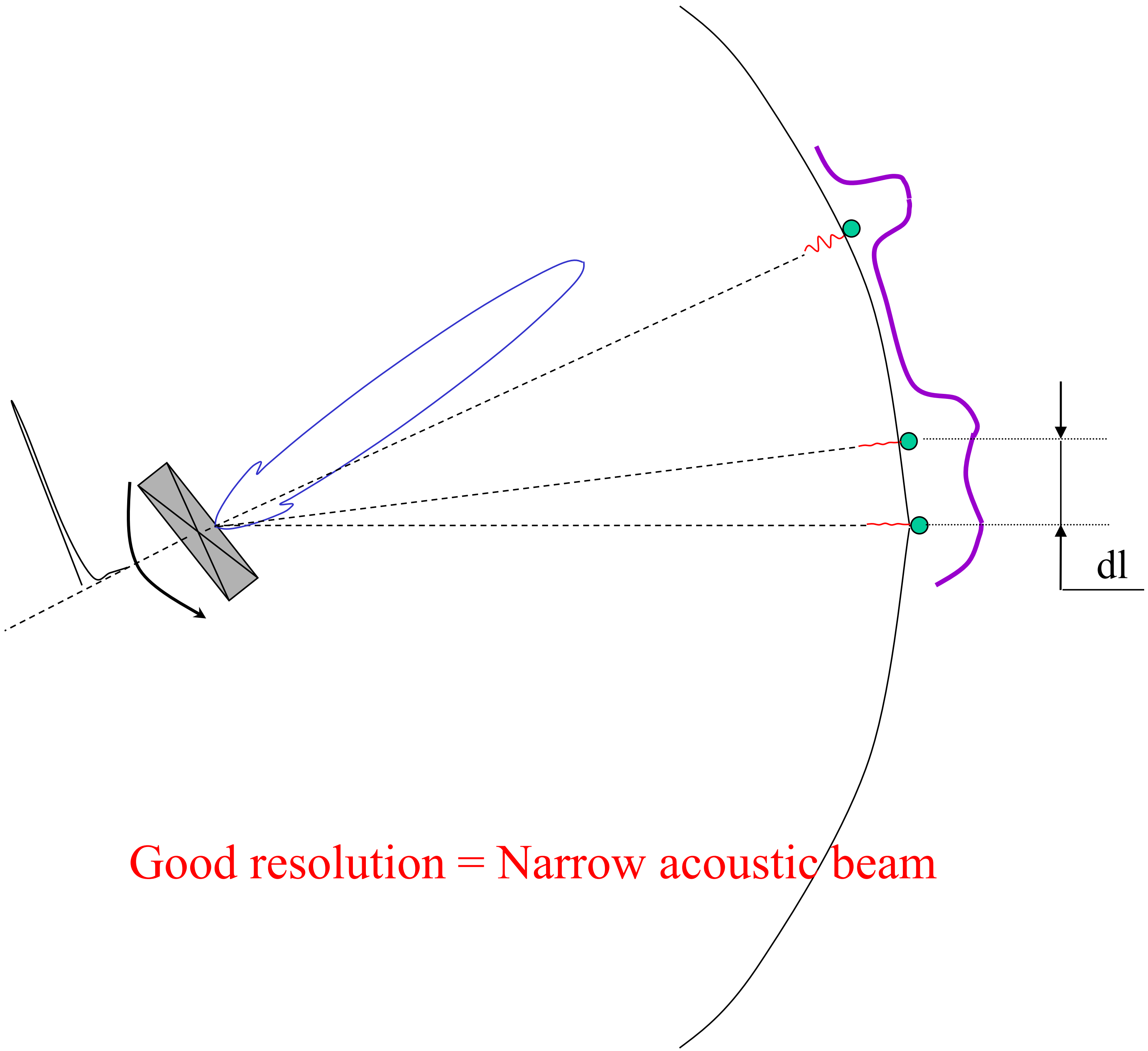
characterizes the possibility of differentiating two points on a straight line perpendicular to the propagation axis.La





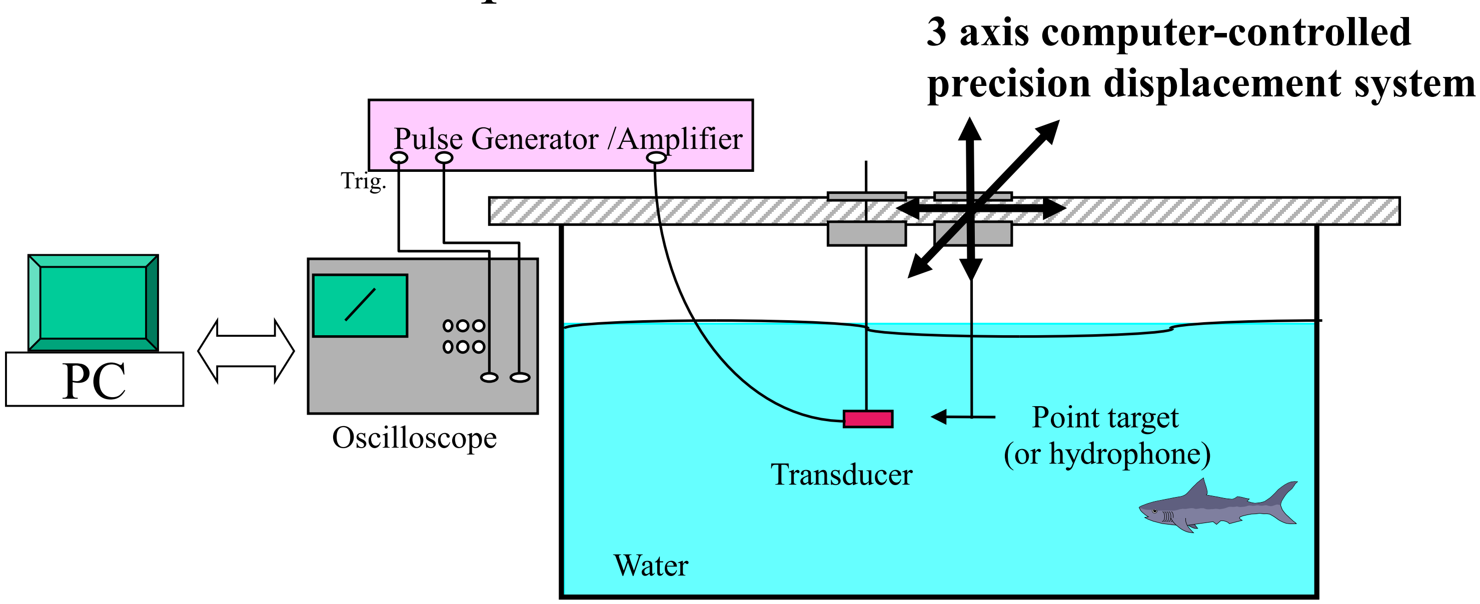


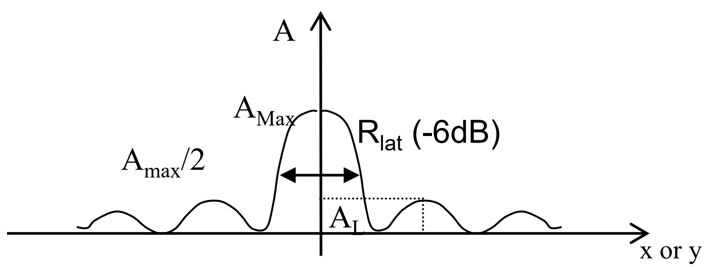


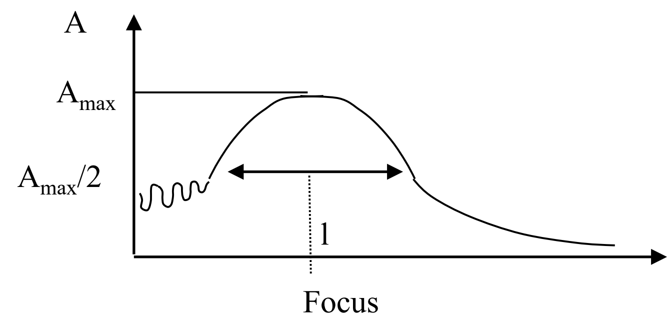


Good resolution = Narrow acoustic beam

Measurement set-up



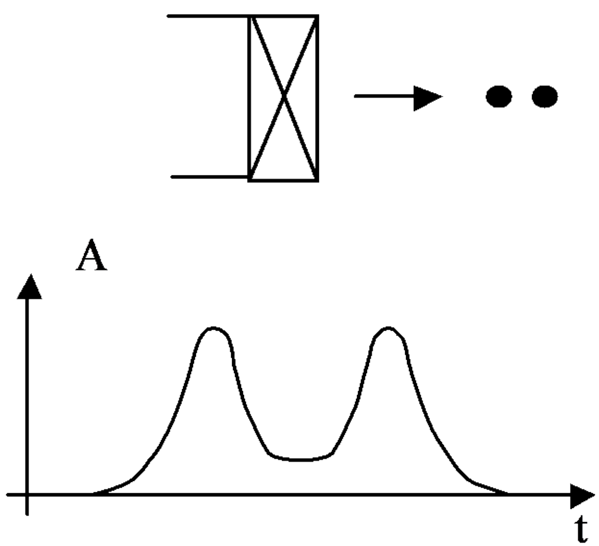


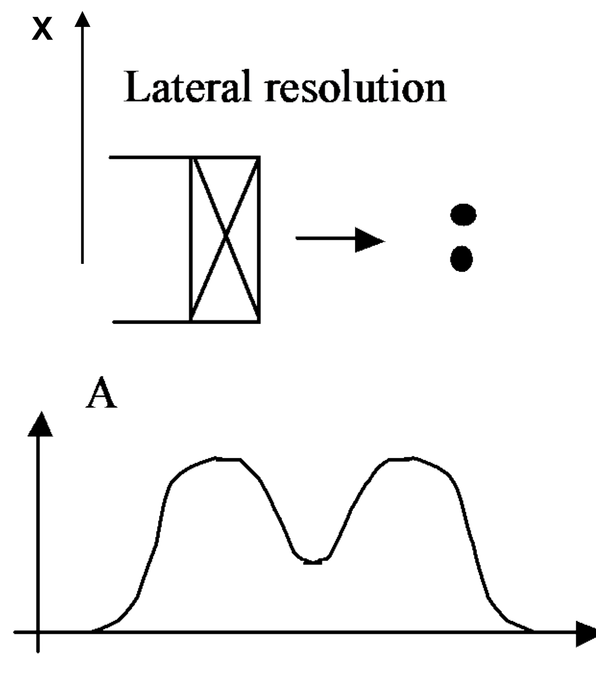


4-Results

TO DETECT A SMALL STRUCTURE: SENSITIVITY
TO DIFFERENTIATE TWO NEARBY STRUCTURES: RESOLUTION

Axial resolution





5-Typical values

Sensitivity (in relation to the ideal transducer): -4 to -12 dB

Axial resolution: -6dB: 1 to 3 wavelengths

For example at 3.5 MHz, $2\lambda = 0.43mm = R_{axial}$ -6dB

($\lambda = c / f$)

Lateral resolution: -6dB: 2 to 5 wavelengths at focal point

Degradation of lateral resolution when moving away from the focal point.

Lateral resolution is more often used than axial resolution.

Diffraction approach

1-General considerations

Diagramme de rayonnement

M δ

Φ

O

θ

lobe principal

lobes secondaires

θ

Justification of the zero points: the wave coming from the center O is in phase opposition with the wave coming from the edge M.

For this, the distance between the zero point and M must be one half wavelength more than that between the point zero and O.

$\delta = \lambda / 2 = (\Phi / 2) \sin \theta$

If the angle is small $\sin \theta \approx \theta$ and $\theta = \lambda / \Phi$

The far field radiation pattern is equal to the Fourier transform of the aperture function: rectangle --- sinc.

Beam spreading

θ

O $\Phi^2 / 4\lambda$

Φ x

Zone de Fresnel Zone de Fraunhoffer

The divergence of the beam is inversely proportional to the number of wavelengths contained in the aperture.

The Fresnel zone corresponds to an irregular field.

Fresnel zone $\leq \phi^2 / 4\lambda$

Beyond the Fresnel zone, in far field, the larger the transducer, the narrower the beam and the smaller the transducer the wider the beam.

Mechanical focusing

This focusing can be obtained either by shaping the ceramic or by adding a lens.

Calculation of the radius of curvature of a lens

a) focus at an abscissa point F in advance. Curve shape ceramic

C_2

y δ F

F

Distance : $F^2+y^2=(F+\delta)^2 \approx F^2+2F\delta$

$\Rightarrow$ the path difference is $\delta = y^2/(2F)$

$\Rightarrow$ the time difference is $\tau = \delta / C_2 = y^2/(2FC_2)$

b) Advance achieved by a spherical lens (concave if C1> C2 or convex if C2 <C1)

y e R

Φ

F

c_2

c_1

Advance of the lens: $\tau' = e/C_2 - e/C_1$

We have $e \approx y^2/(2R)$ thus $\tau' = y^2(1/C_2 - 1/C_1)/(2R)$

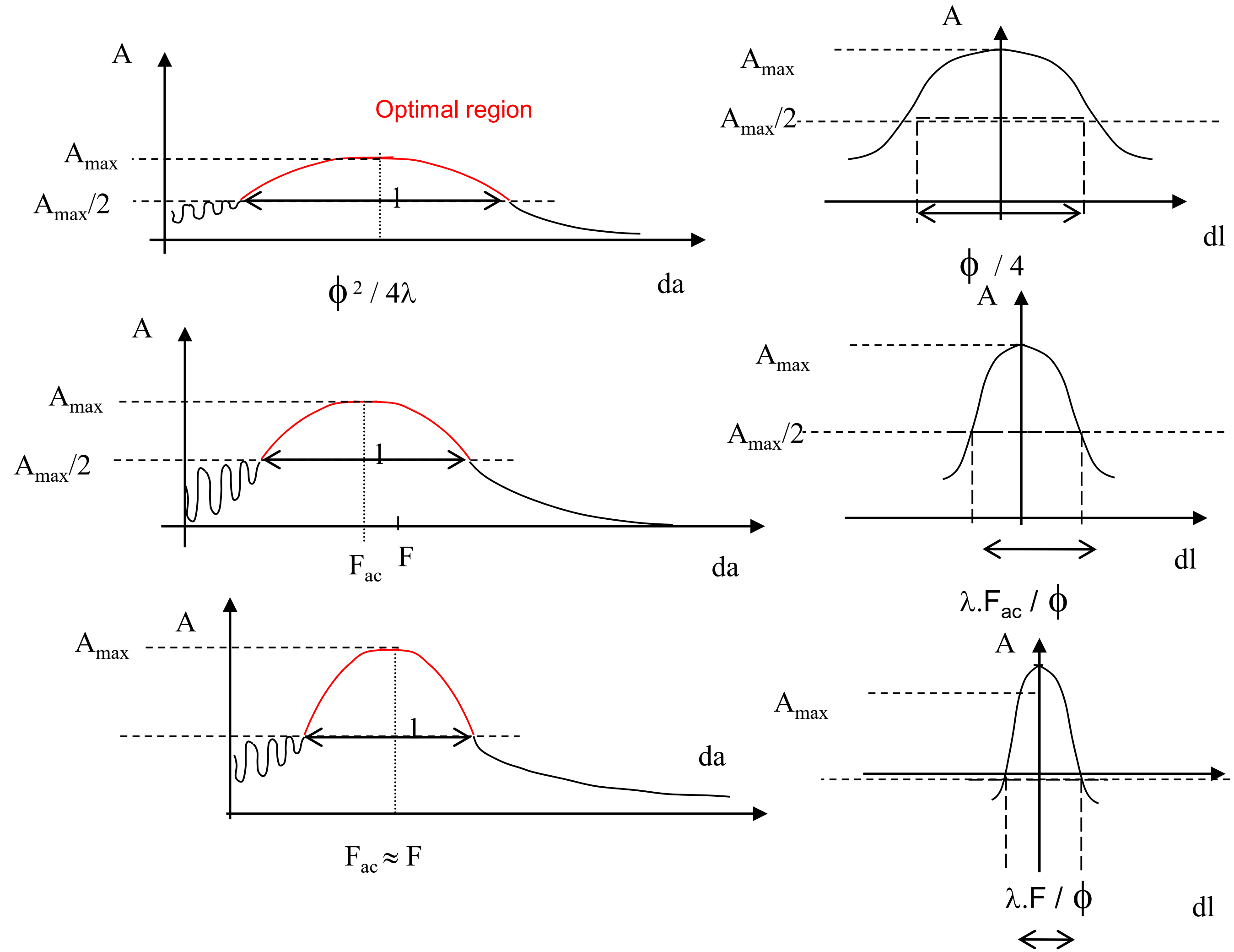
We want $\tau = \tau' \Rightarrow$ $R = F\, c_2.(1/c_2 - 1/c_1)$

$R = F(1 - c_2 / c_1)$

Non focused

Low focusing

High focusing



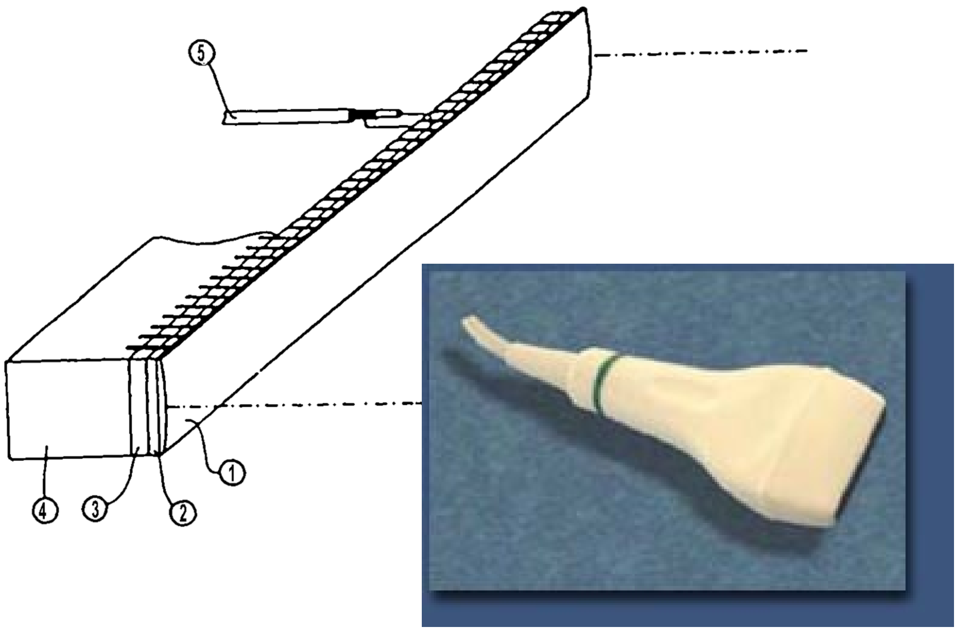
Lateral resolution is given by $R_{lat} \approx \lambda.F_{ac}/\phi$

Without focusing, $F \rightarrow \infty$, $F_{ac} = \phi^2 / 4\lambda$ et $R_{lat} = \phi / 4$)

Depth of field dis given by $l \approx 7\lambda (F_{ac} / \phi)^2$

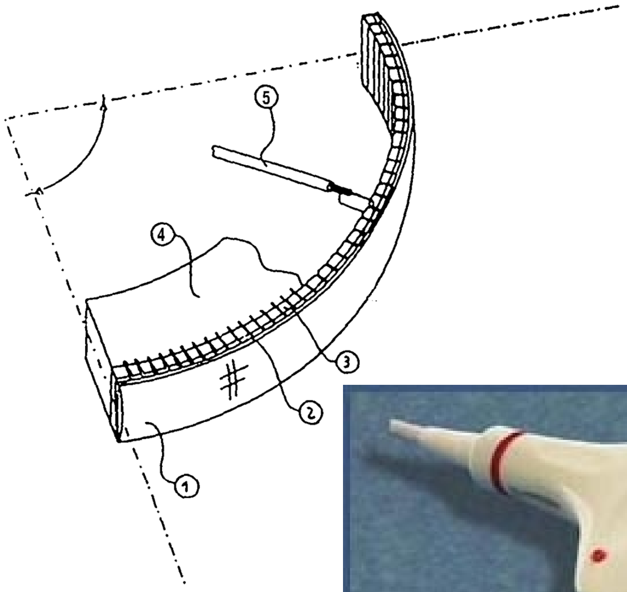
3-Linear array

plane



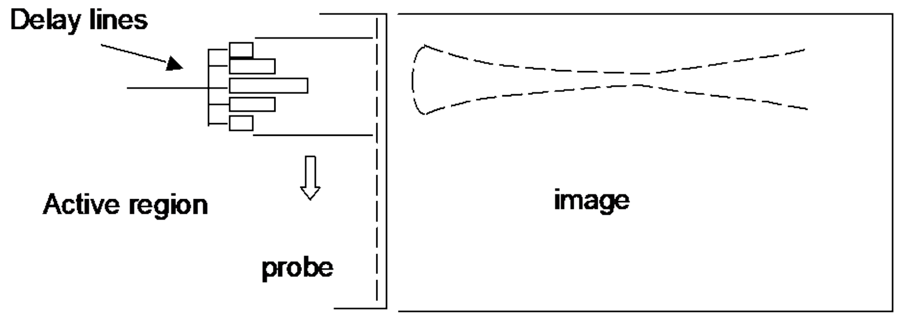
vermon.com

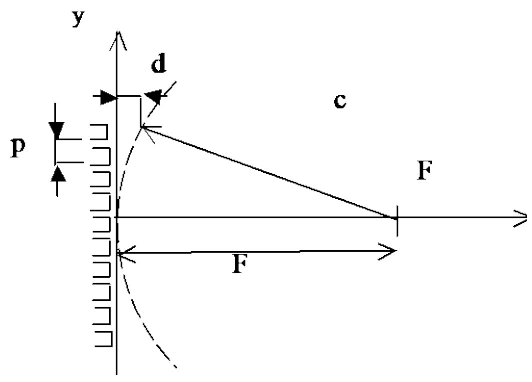
curve



1 acoustic lens
2 matching layer
3 piezo-electric ceramic
4 backing
5 coaxial line

The scanning is done by moving the group of active elements. There is also a delay line focusing.





$d = y^2 / 2F$

$\tau = d / c$

$\tau = y^2 / 2FC$

$y = n.p$

$$\tau = n^2.p^2 / 2Fc$$

n: # transducer from the center

p (mm) : ptch of the array

F (mm) : focal distance

C (m/s) : speed of sound in the propagation medium

numerical application: $p = 1mm$, $F = 60mm$, $c = 1500m / s$

$\tau = 5.5$ n2 ns

Durind the emmission, the focal length is defined for each shot (several shots per depth range but slowing down due to the frame rate).

At the reception there is possibility of modifying the delays so that the focal length is always optimal.

4-Radiation of a linear array

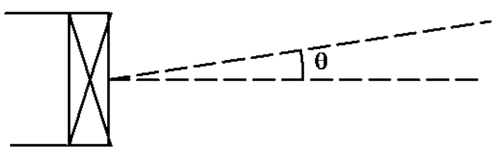
When using a transducer in the far field transducer, the Fourier transform can be applied to the aperture function.

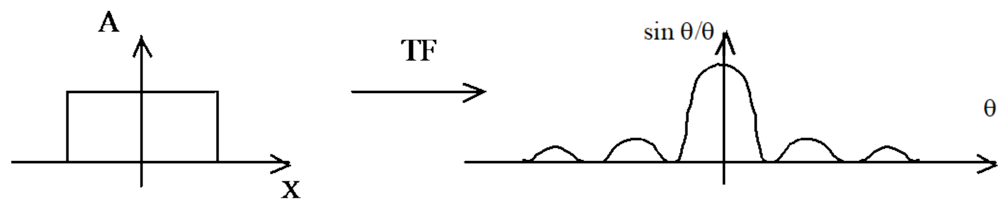
remind : × multiplication et $\ast$ convolution

$$A \times B \xrightarrow{TF} TF(A) \ast TF(B)$$

$$A \ast B \xrightarrow{TF} TF(A) \times TF(B)$$

Single element

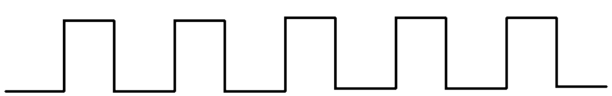




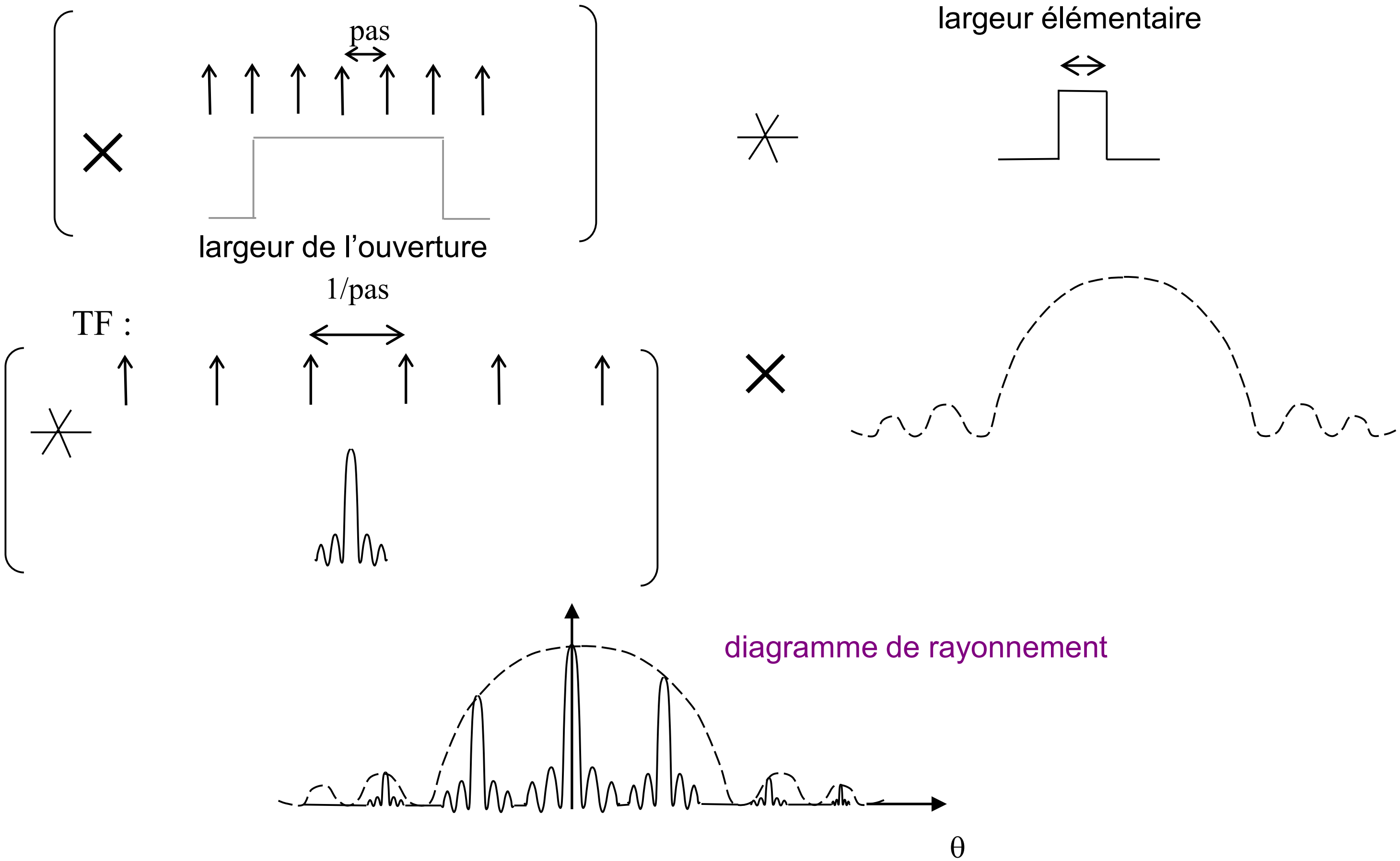
Aperture function

Radiation pattern

Array
Many transducers

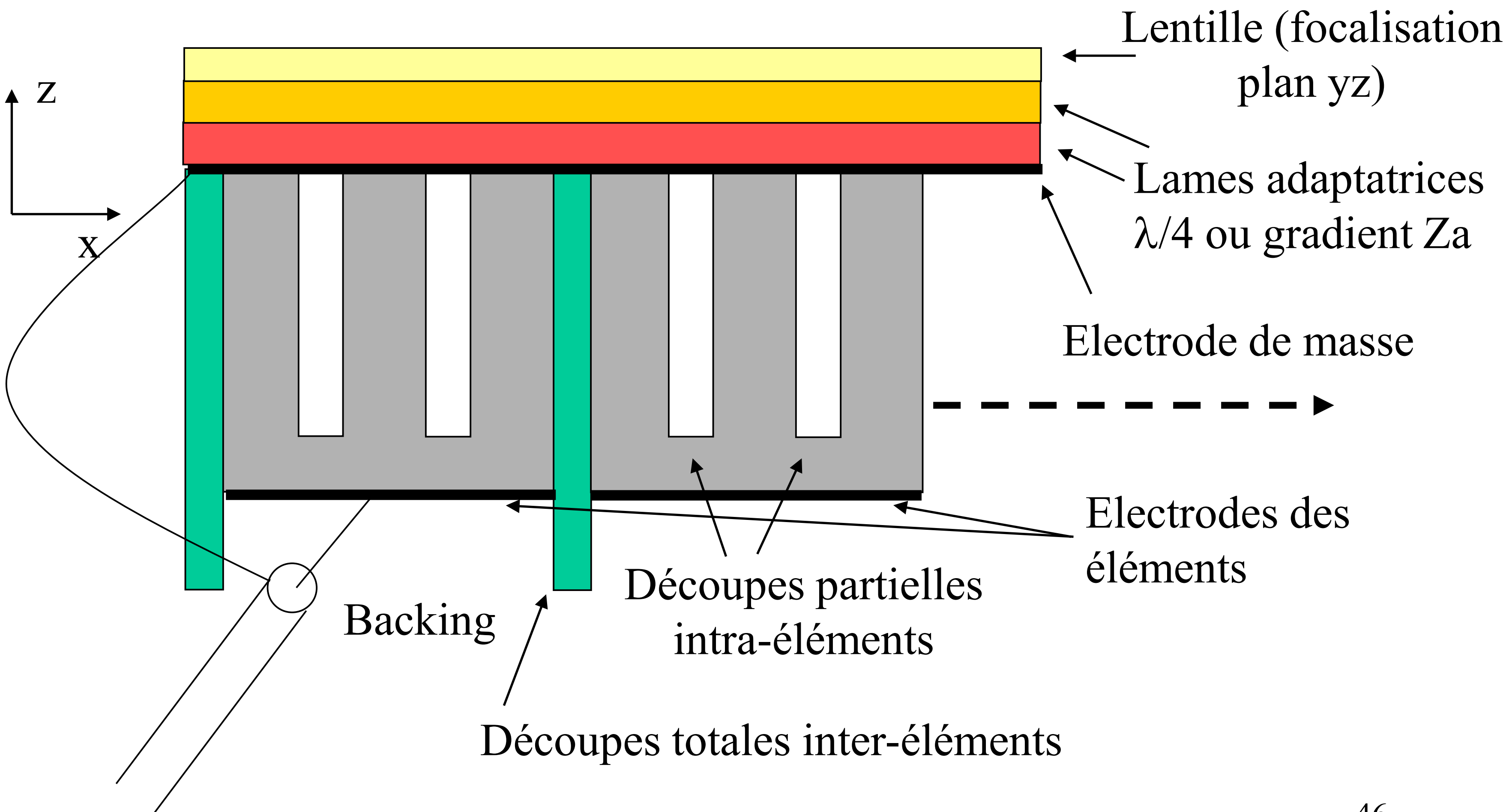


Apperture function



Note that there are additional lobes in the radiation pattern. They are embarrassing for imaging. They must therefore disappear. For this we can push them back to 90°.
In practice, the pitch is reduced to a value around λ.

1D array probe Technology (2-2 piezocomposite)

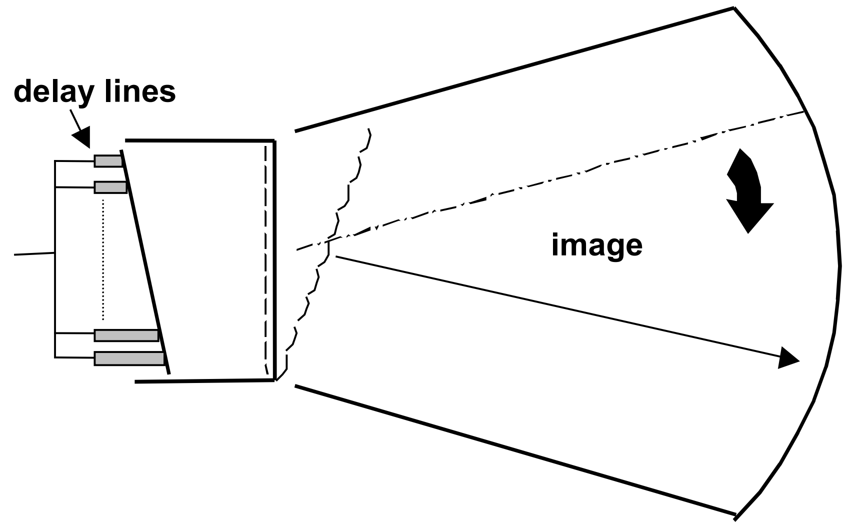


Exemple of design and conception of a classical linear array 3 MHz

- Width « l » of one element = 1,5 λwater (low deflexion) = 0,75 mm
  - Thickness of the ceramic= 0,5 λcer = 0,75 mm
  - width= thickness : many vibration modes (non-piston)
  - Criteria to be respected (according ceramic) : $l < 0,4e$ ($l < 0,3$ mm)
  - Sub dicing of each element in 3 (de 0,25 mm)
- Dicing between elements
  - ceramic
  - Rear electrode
  - Begining of backing
- Typically : 192 elements, height= several 10 λwater

« Phased-arrays » : electronic deflexion (and focalisation) – requires a very small elements (wide angular aperture)

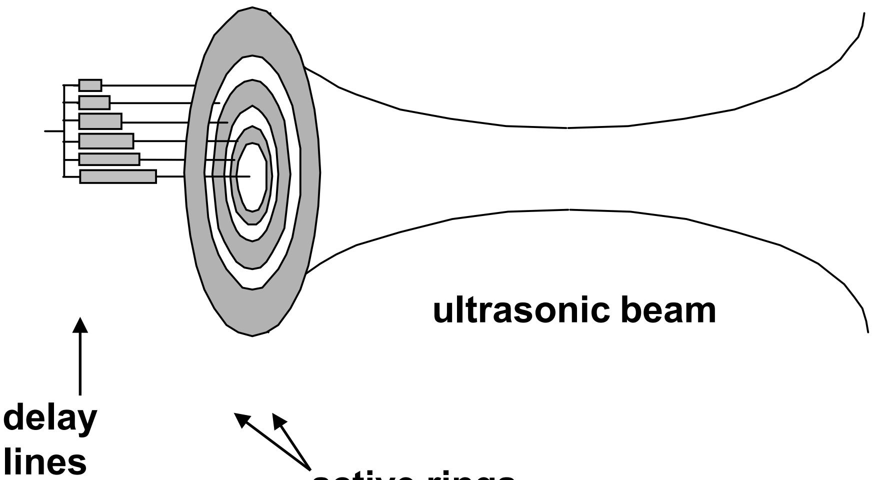
Olympus



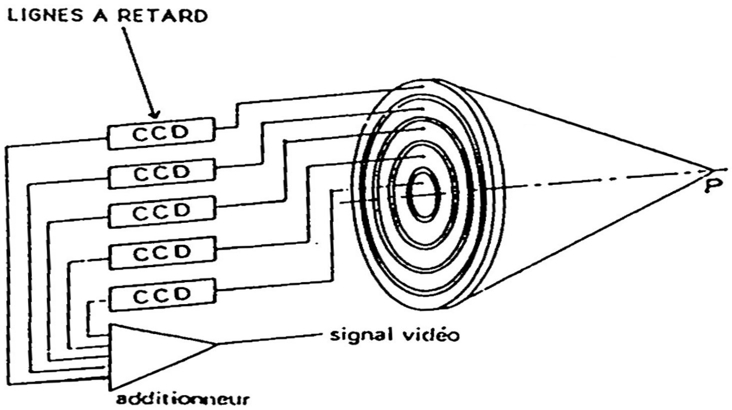
Electronic focusing and steering

In the case of using a phased array, delays are used to deflect and delays to focus. deflection: modification of the direction of the ultrasonic beam.

Annular arrays: electronic focusing (piezocomposite)



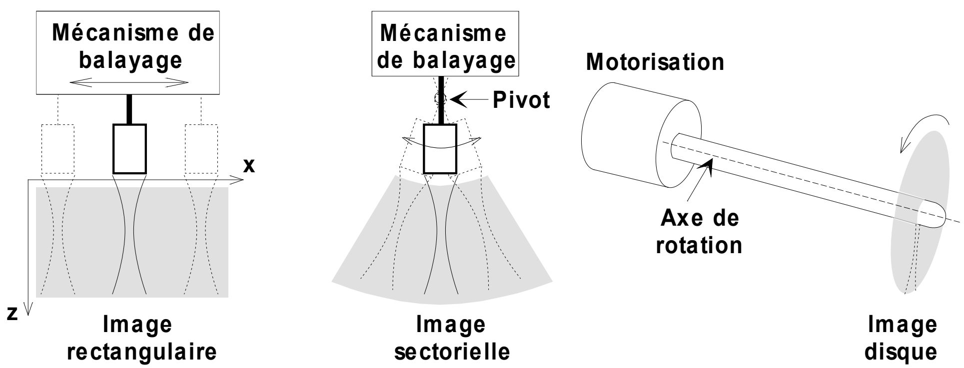
toraytechno.ab.psiweb.com



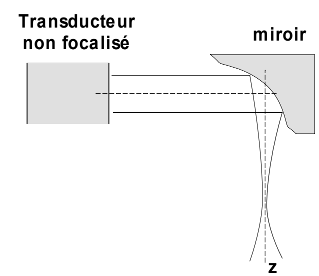
Mechanical scanning

Electronic scanning is generally preferred over mechanical scanning which remains used for particular probes:

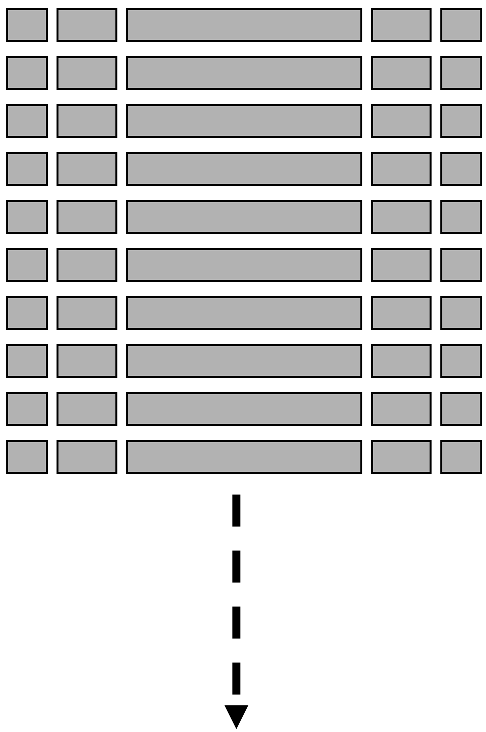
- **high-resolution probes (frequency> 20 MHz arrays difficult to realize)**
- **catheter probes for vascular exploration (miniaturization)**



a b c



Multi rows arrays

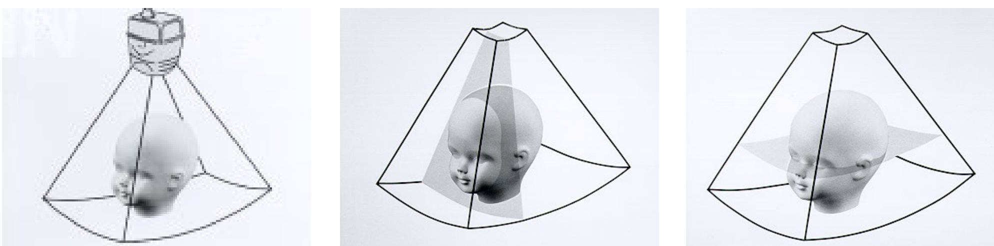


- Operation 1.25 D: the number of rows is set / depth

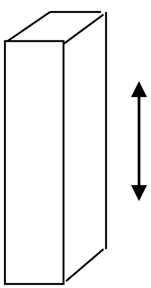
- Operation 1. 5 D: Delays are applied between internal and external rows

- Operation 1. 75 D: delays may occur be adjusted independently for each element

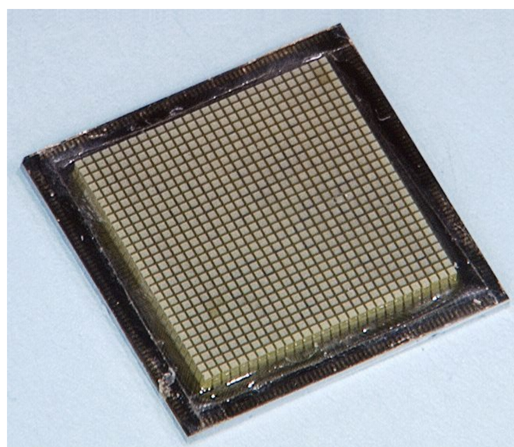
Matric arrays(2D) : double deflexion of the beam allows 3D



33 Vibration mode 33



Polarisation
And
vibration
Along axe 3



Marconi Electronic Systems- GIP Ultrasons :

Medicalphilips.com

Technical Issues and solutions matrix arrays

- Number of elements = several 1000, typ. 64x64
  - Control electronics (only cost Pb)
  - Connectivity and cables (miniaturization, ergonomics)
  - Small size of elements (miniaturization, high impedance)
  - Proximity of elements (coupling)
- Operating modes
  - Sparse arrays or fully connected
  - Transmitter and / or receiver elements
  - Simultaneous management of multiple beams (speed)
- Integration of electronics in the probe, multilayer, MEMS technologies.

Electroacoustic modelling

- Equivalent electrical circuits:
  Mason, KLM, ... (single mode)

- Finite element codes: ATILA,
  PZ FLEX, ANSYS, ...

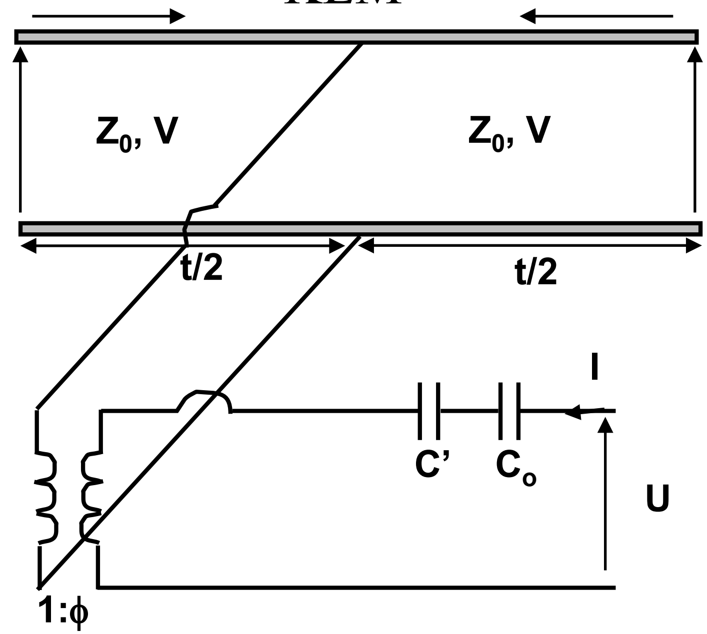
- Calculation of:

Input impedance

Impulse response E, R, E / R

with consideration of the environment
acoustic and electric transducer

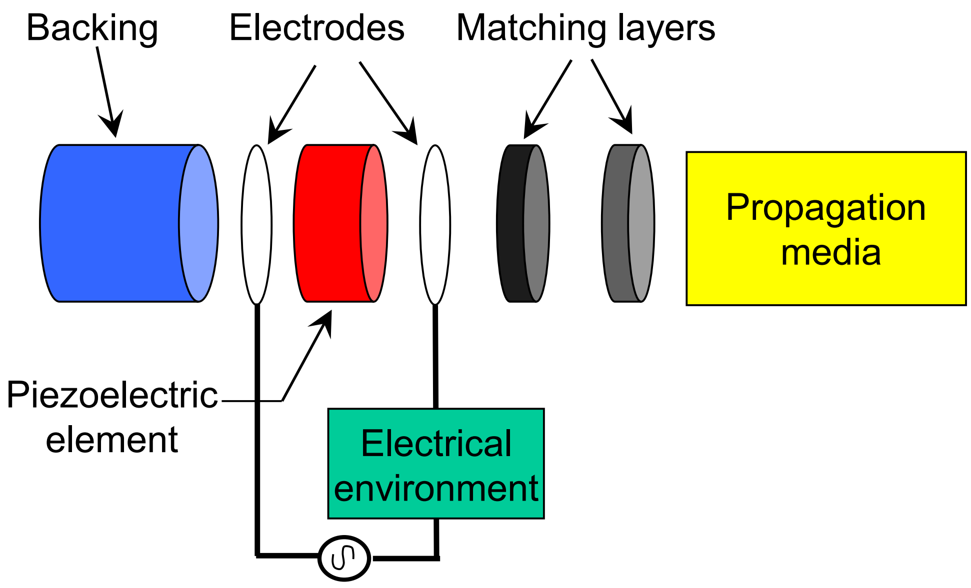
KLM



A : *area*; t : *thickness*; e : *piezoelectric coefficient*

$$C_0 = \frac{\varepsilon^S A}{t};\ C' = \frac{-C_0}{k_t^2 \sin c(kt)};\ \phi = \frac{2e\sin\left(\frac{kt}{2}\right)}{A\varepsilon^S Z_0 \omega}$$

Transducer simulation method

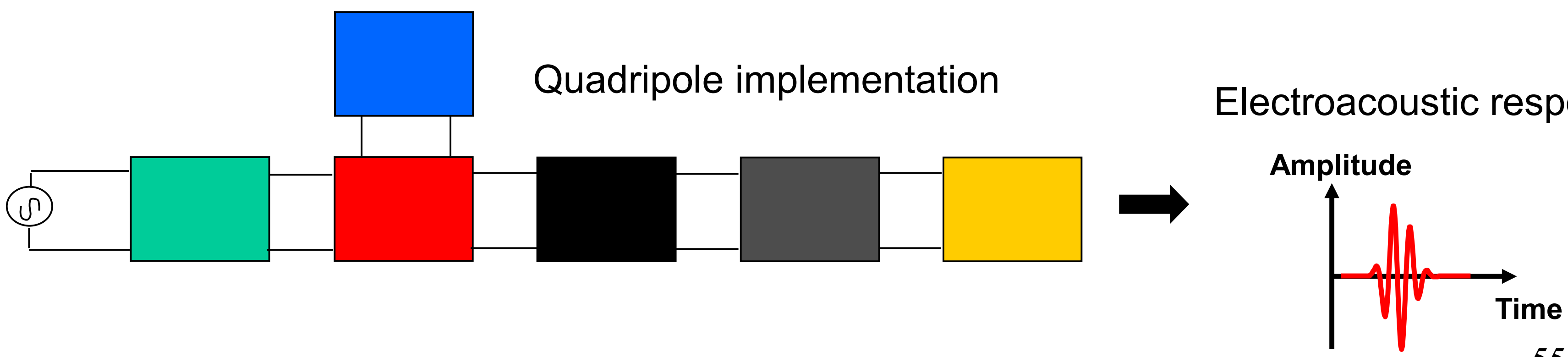


1D Model
Electrical equivalent scheme

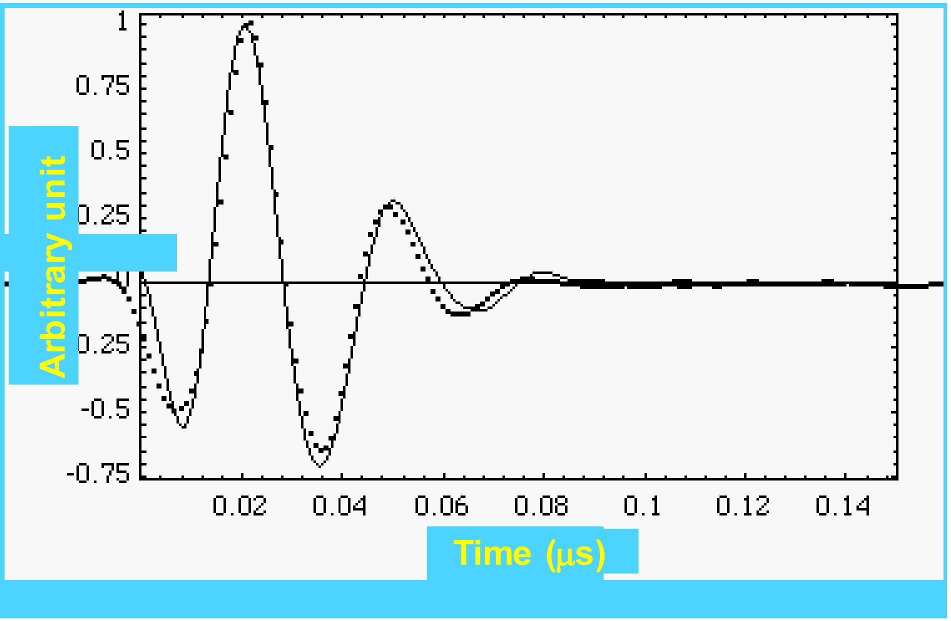
KLM Model is chosen

Quadripole implementation

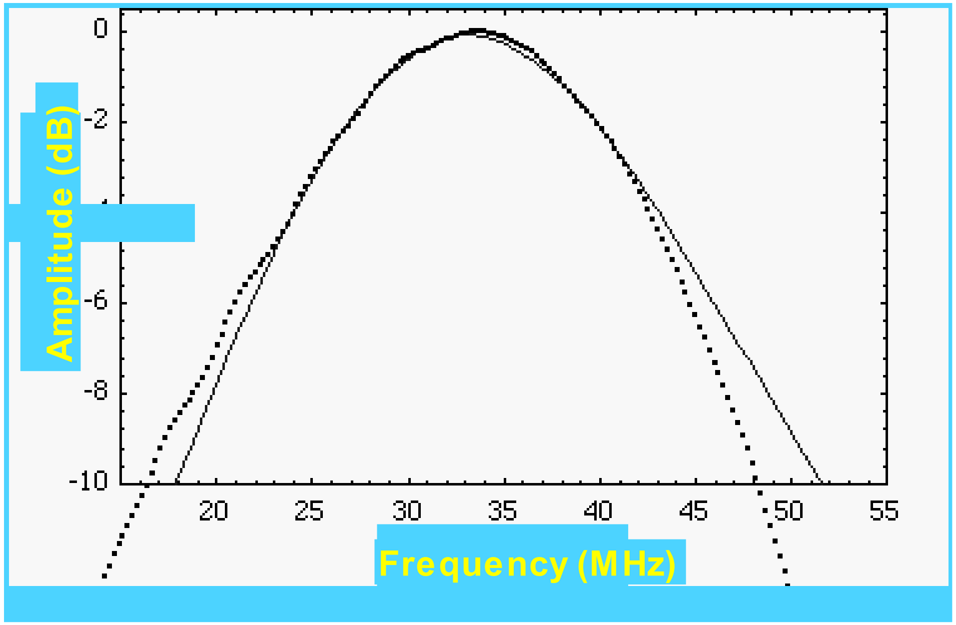
Electroacoustic response



Pulse echo response E/R



Frequency response (FFT)



KLM: solid, Measurement: points

Modelling of the acoustic field

- Huygens' theorem (spatial sampling of each element in point sources $d < \lambda / 10$)
- Pulse Diffraction Methods
- Determination of:
  - Latteral resolutions
  - lobes / noise levels
  - depth of field

Conclusions

- The technology and therefore the design of an ultrasound probe is very complex because it has to optimize 2 essential functions: transduction and beam formation.
- It is therefore necessary to optimize the quality of the piezoelectric material, but also the configuration of the damping and adaptation materials to improve the compromise between sensitivity and bandwidth

- It is also necessary to optimize the geometry of the multi-element sensors in order to ensure good beam formation (focusing + scanning): 1D, 1.5D, 2D