Introduction to Ultrasound Medical Imaging

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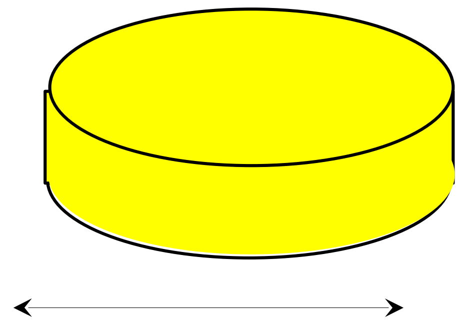
Overview of talk

- Introduction to medical ultrasound.
- Fourier analysis of ultrasonic imaging.
- A model for ultrasound backscatter.
- Our high-resolution imaging algorithm (HD scanning).

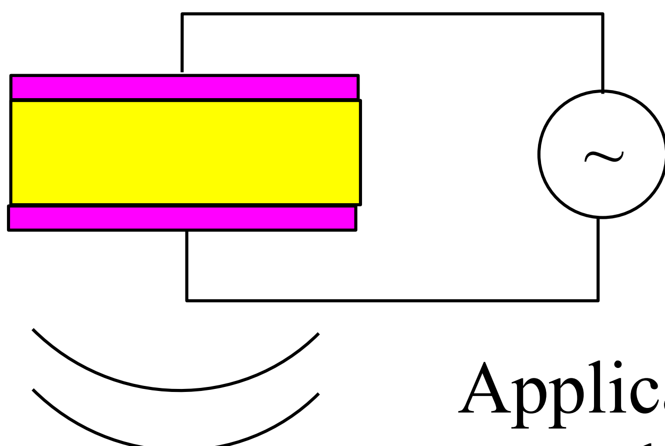
Definition of Ultrasound

- Sound consists of traveling (spatio-temporal) pressure waves.
- Frequency range: 2 MHz < f < 10 MHz
- Ultrasound is produced using piezo-electric transducers
- Applications of Medical Ultrasound
  - Imaging
  - Measurement of Blood Flow (Doppler and transit-time flowmeters)

Transducer Properties

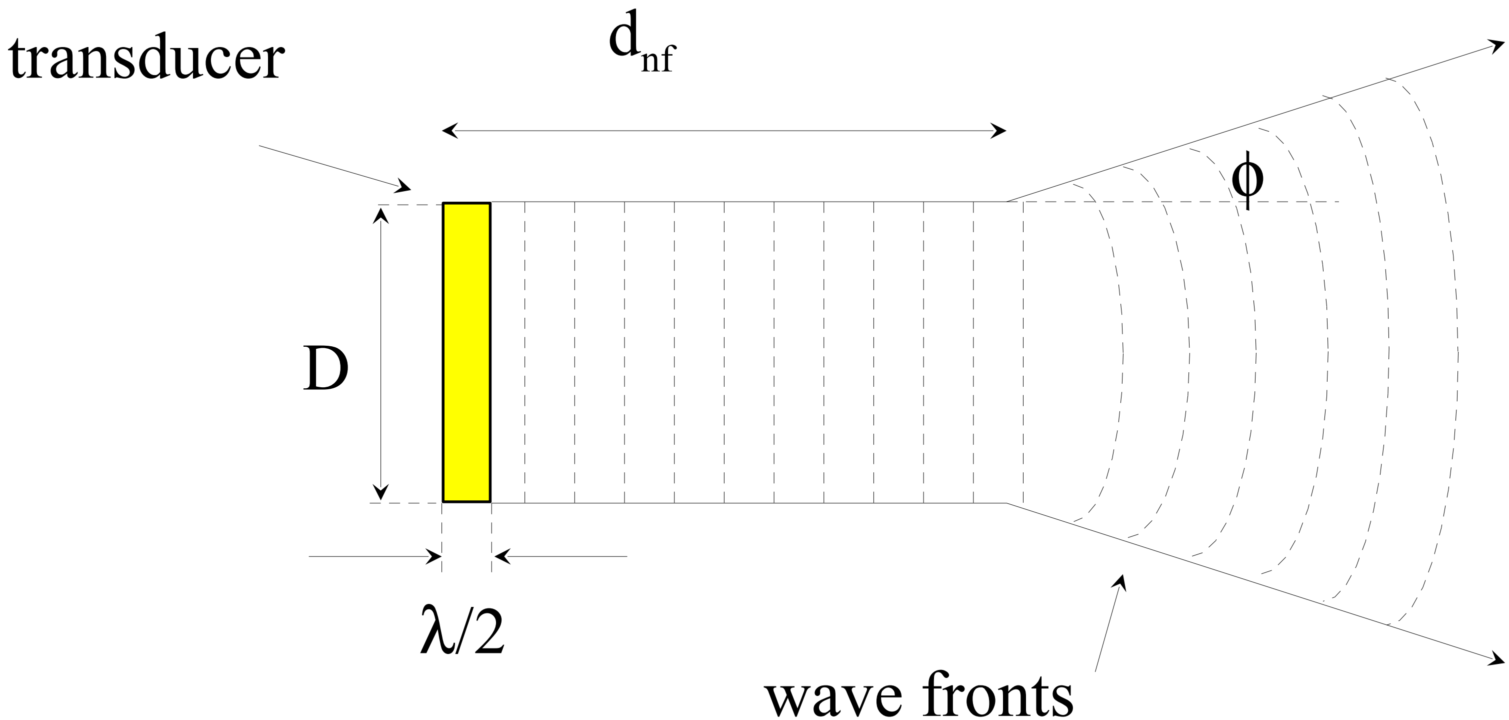


D = transducer diameter



Application of a voltage causes crystal to vibrate at 2-10 MHz.

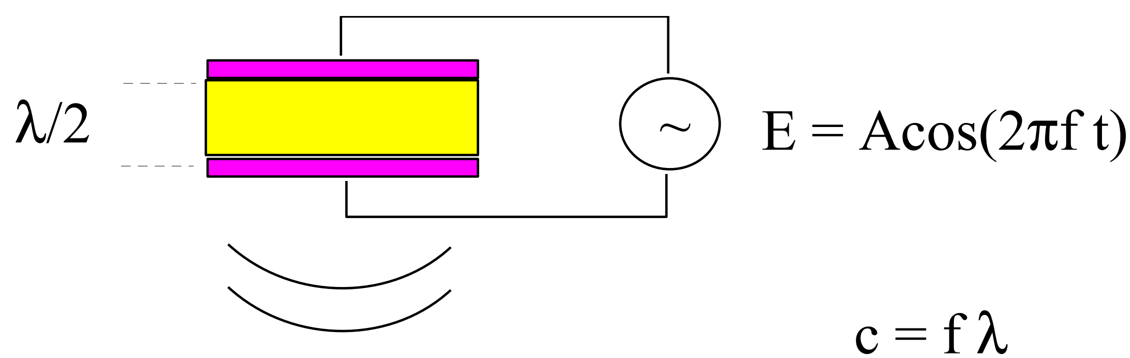
Near/Far Fields



$$d_{nf} = \text{near-field distance} = \frac{D^2}{4\lambda}$$

$$\phi = \text{divergence angle:} \quad \sin\phi = 1.2\lambda/D$$

- crystal will vibrate at same frequency, f, as that of the applied voltage.
- c: speed of sound in tissue, about 1500 m/s
- λ: wavelength of sound



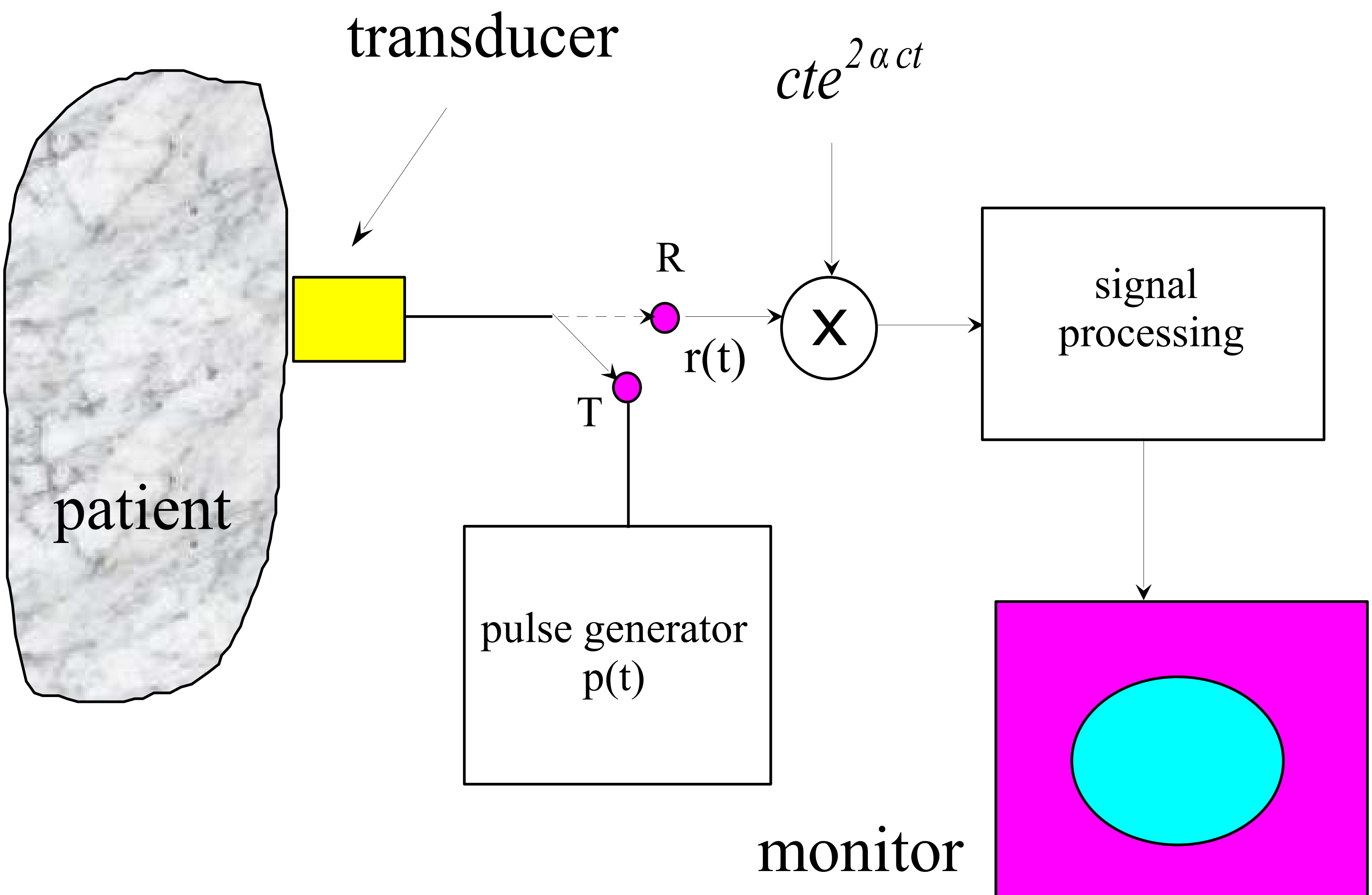
Transducer Materials

$S =$ change in crystal thickness/original crystal thickness is proportional to the applied electric field.

$$S = gE$$

Material	*g (m/V)x10^{-12}*
quartz	2.3
barium titanate	60-190
lead zirconate titanate (PET-4)	290
lead zirconate titanate (PET-5)	370

Basic Ultrasonic Imaging Configuration



Acoustic Impedance and Pressure

- Acoustic impedance

$$Z = \rho c$$

  - ρ: density of the medium through which the sound is travelling
  - c: speed of sound in the medium

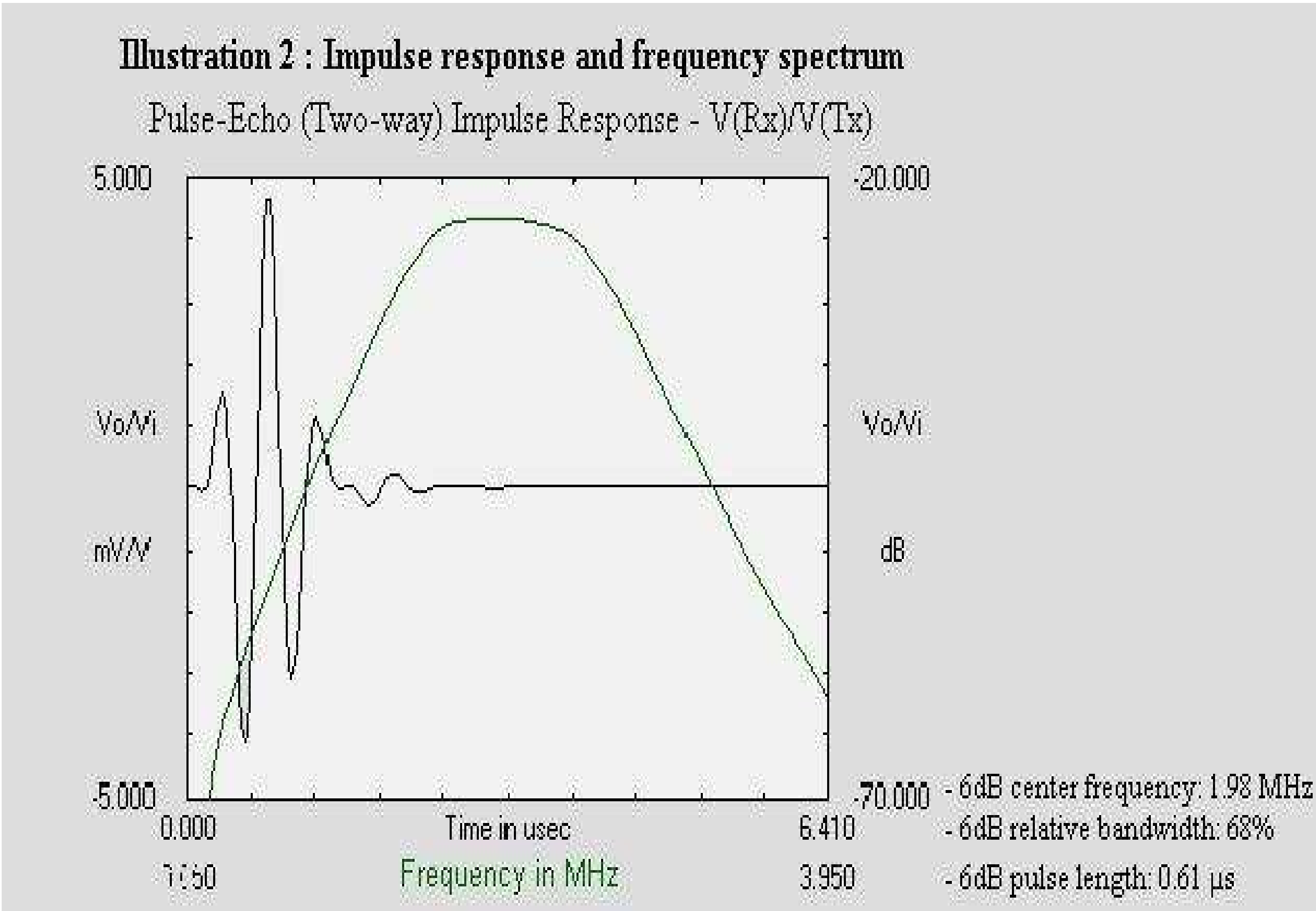
- Acoustic Pressure

$$P = Zu$$

u: particle velocity in the medium

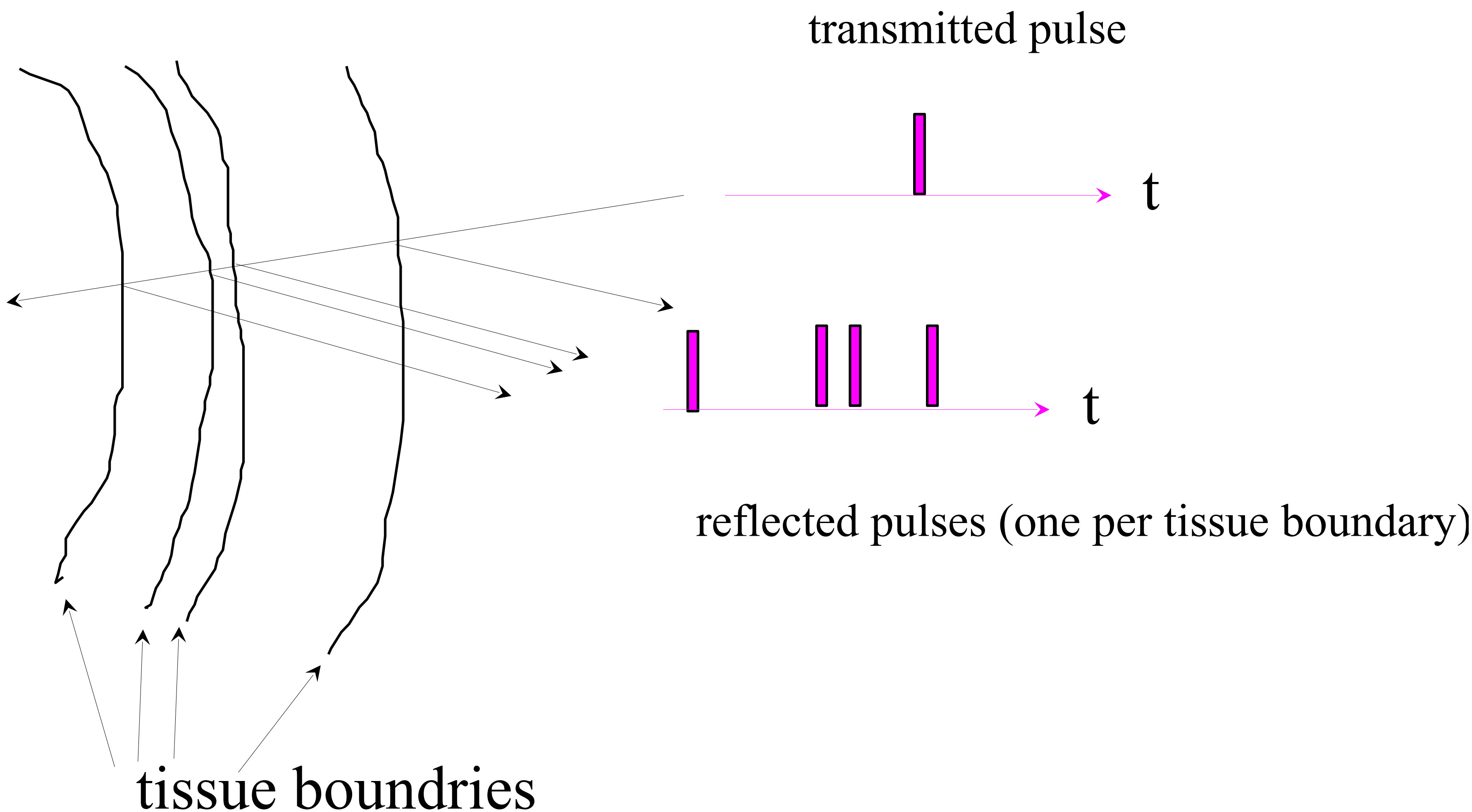
- Transducer is pulsed and transmits a short burst of ultrasound.
- Transmitted ultrasound propagates through the tissue.
- Acoustical scatterers within the tissue produce backscatter.
- Backscattered ultrasound is then detected by the transducer (now in receive mode).
- Derived image depends on the distribution of backscatterers along the ultrasound path.

Typical Transducer Characteristics

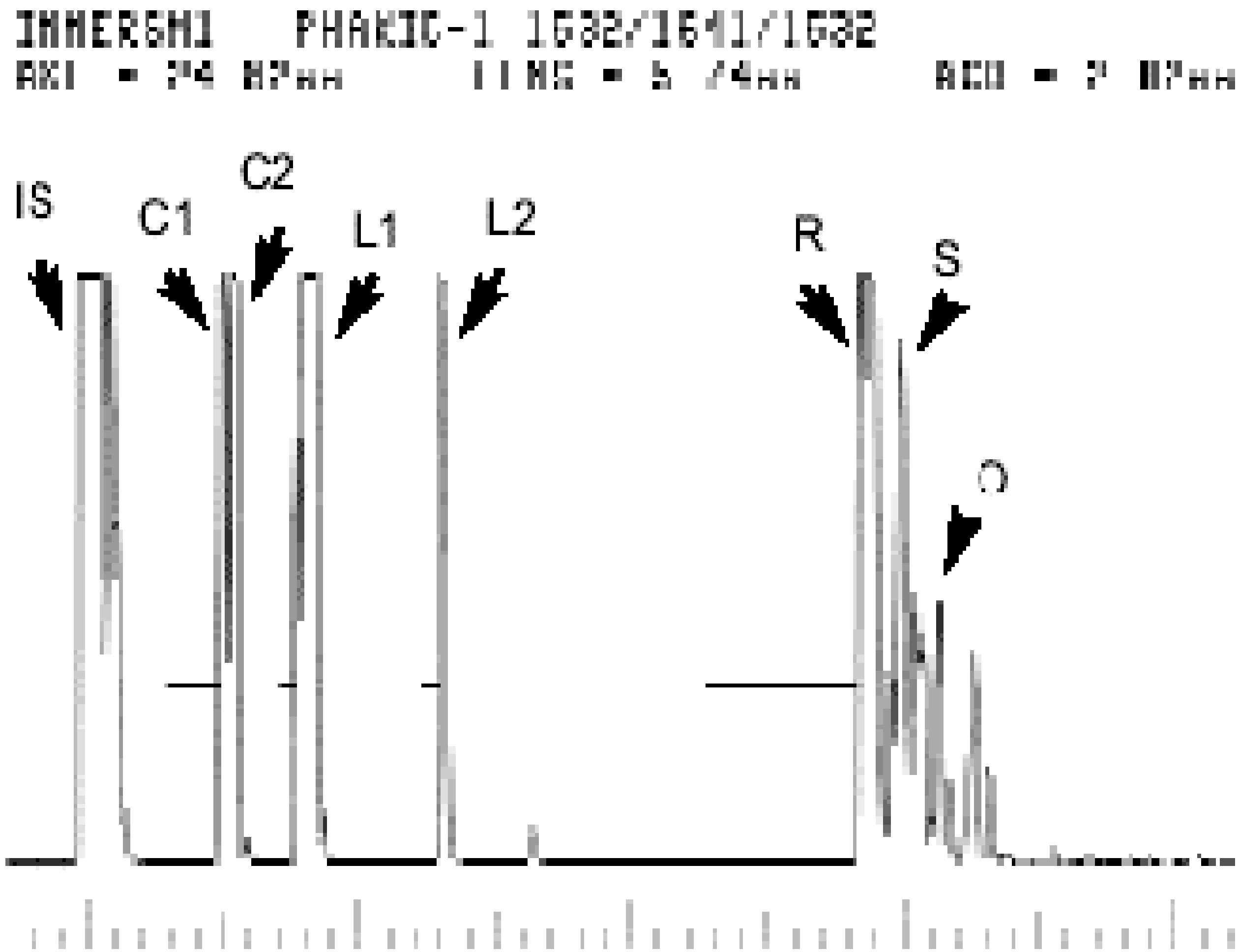


A-Mode Scans

One-dimensional scans, (typical in ophthalmology):

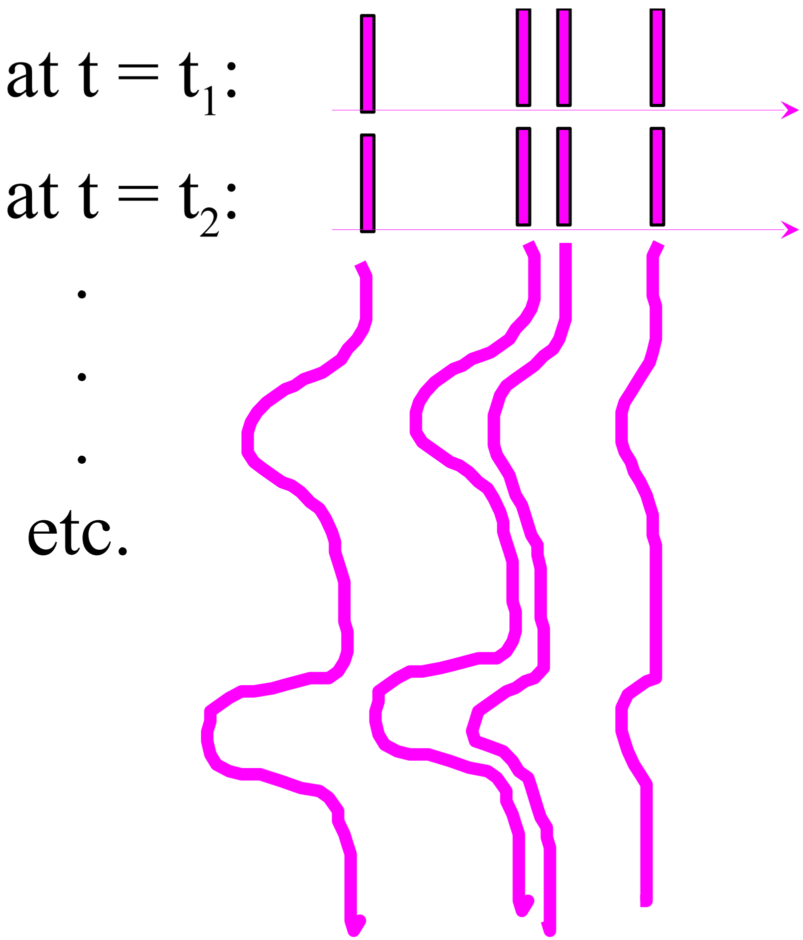


A-Mode Scan of the Eye



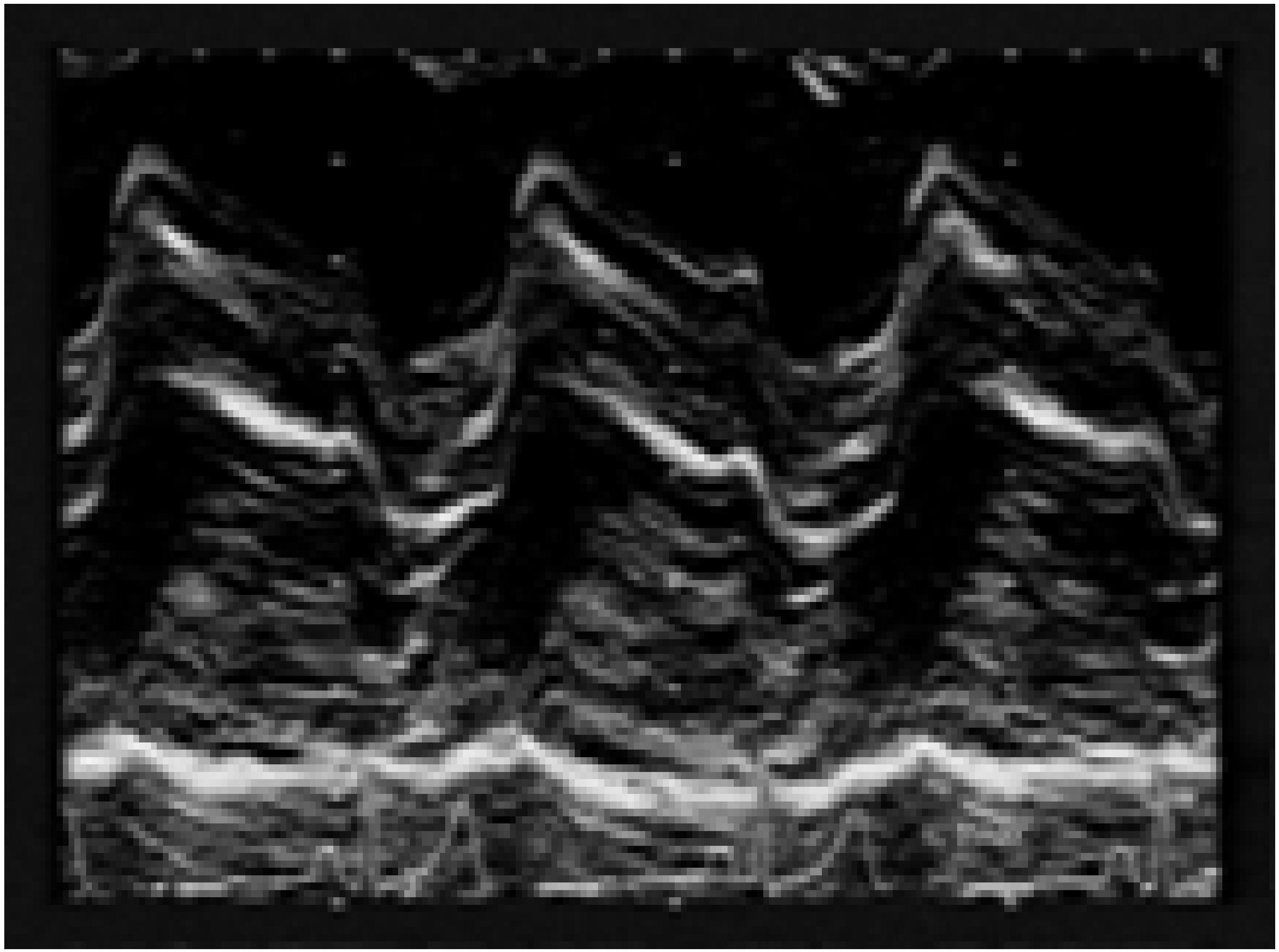
M-Scans

A-mode scans are plotted vs. time (echocardiogram)

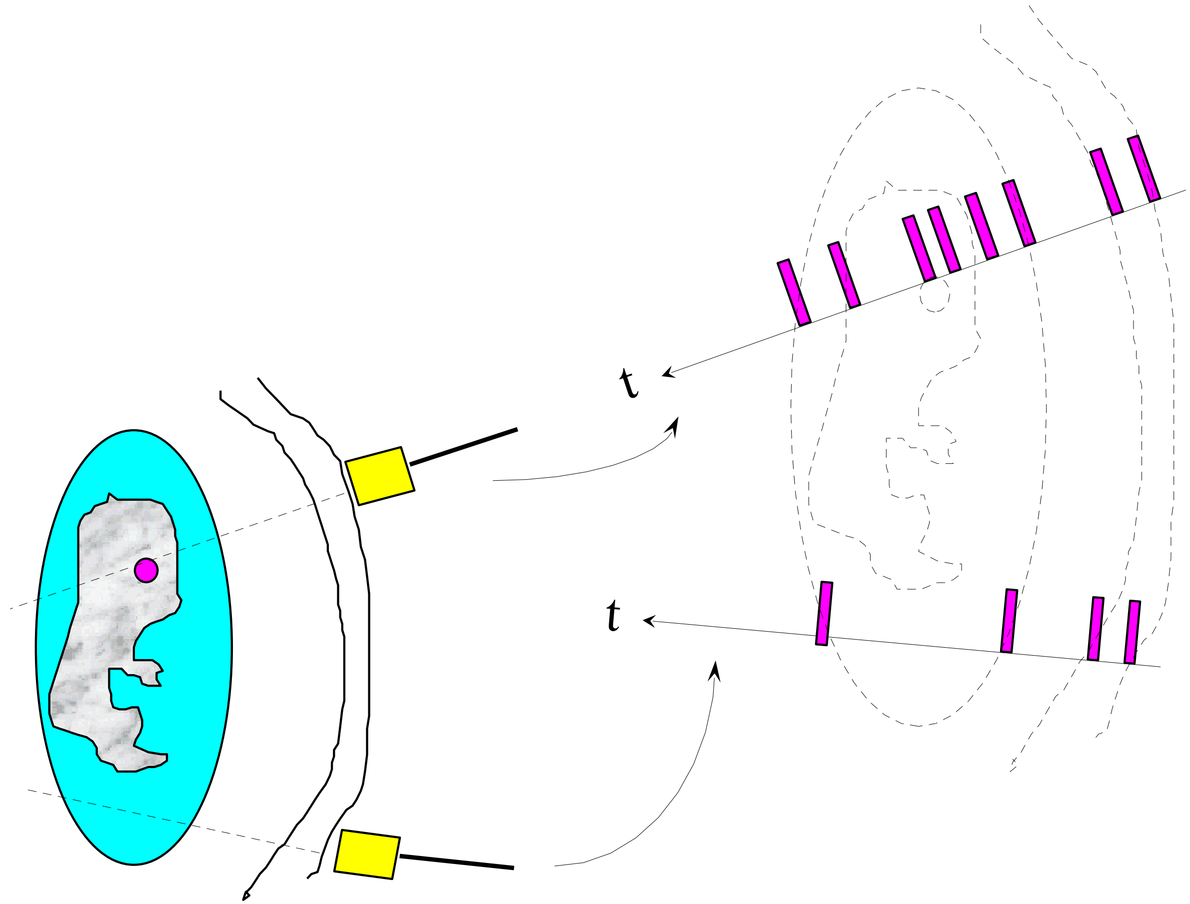


Can image moving tissue boundaries by stacking A-mode scans obtained at different times on top of each other. Used to image heart valves. Trandsucer is stationary.

M-Mode Scan of Mitral Valve



B-Mode Scans



B-Mode Scan of a Fetus

Pros and Cons of Medical Ultrasound

Pros:

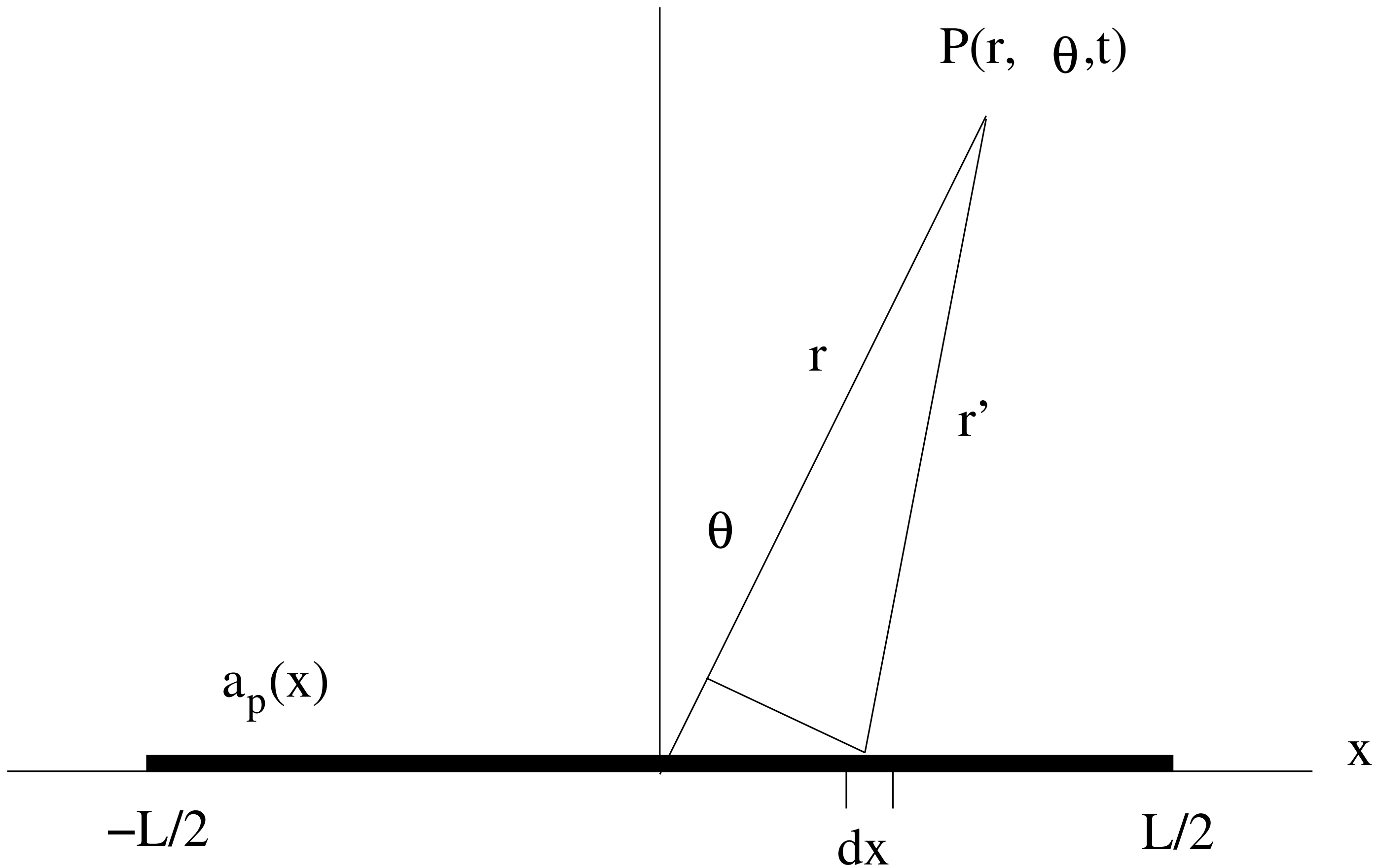
- Low cost.
- Doesnt use ionizing radiation, is safe and painless.
- Relatively easy to use.
- Gives “real-time" images.

Cons:

- Resolution can be low.
- Difficult to interpret.
- Diagnostic value is limited in some cases (e.g. breast cancer detection).

Fourier Analysis of Ultrasound

Geometry of a line apperture



Far-Field Approximation

$$P(r,\theta) \approx P_{ax}(r)H(\theta)$$

$$P_{ax}(r) = \frac{\rho c U_o k L}{4\pi r}$$

$$H(\theta) = \frac{1}{L}\int_{-\infty}^{+\infty} a_p(x) e^{jkx\sin\theta} dx$$

When

$$a_p(x) = \begin{cases} 1, & |x| \leq L/2 \\ 0, & \text{otherwise} \end{cases}$$

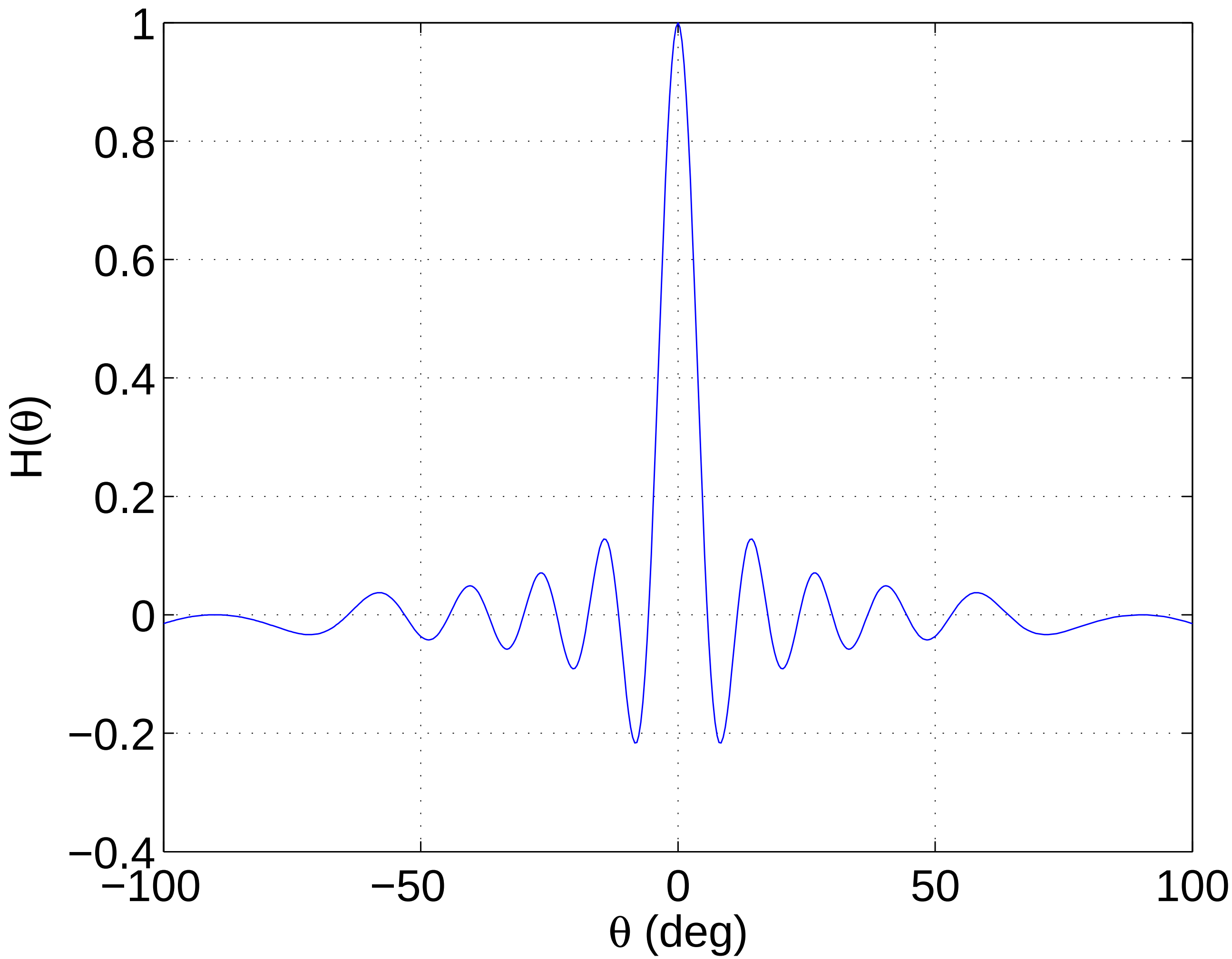
Then

$$H(\theta) = \frac{\sin(\pi L f \frac{\sin\theta}{c})}{\pi L f \frac{\sin\theta}{c}} = \frac{\sin(\frac{k}{2} L \sin\theta)}{\frac{k}{2}\sin\theta}$$

since $k = \frac{2\pi f}{c} = \frac{2\pi}{\lambda}$

Fourier Analysis of Ultrasound

Beam pattern of line apperture



First zero occurs at

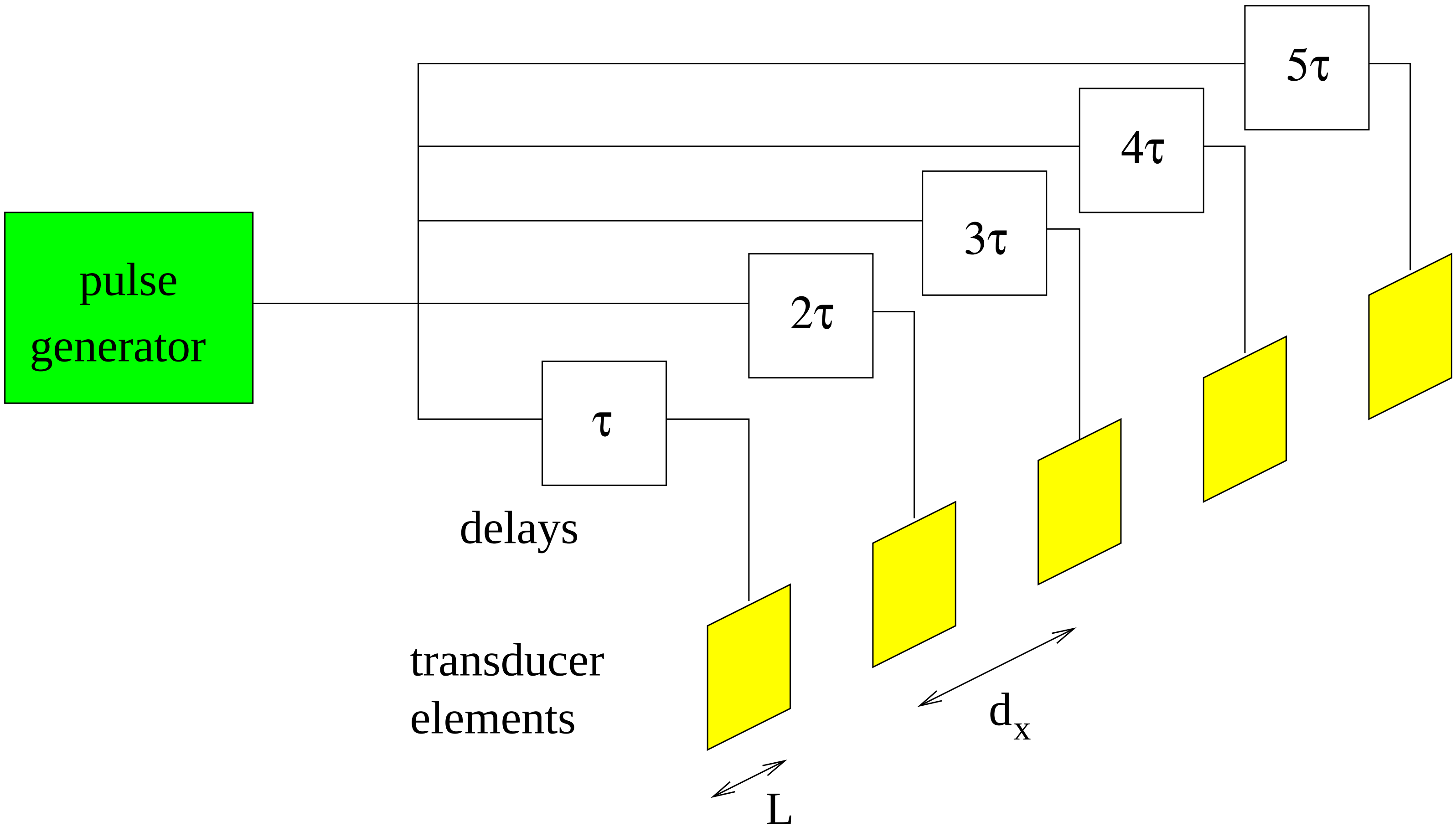
$$\sin\theta = \frac{c}{Lf} = \frac{\lambda}{L}$$

Main lobe width depends on:

- The frequency of the transducer, higher f means narrower lobe.
- The size of the array L.

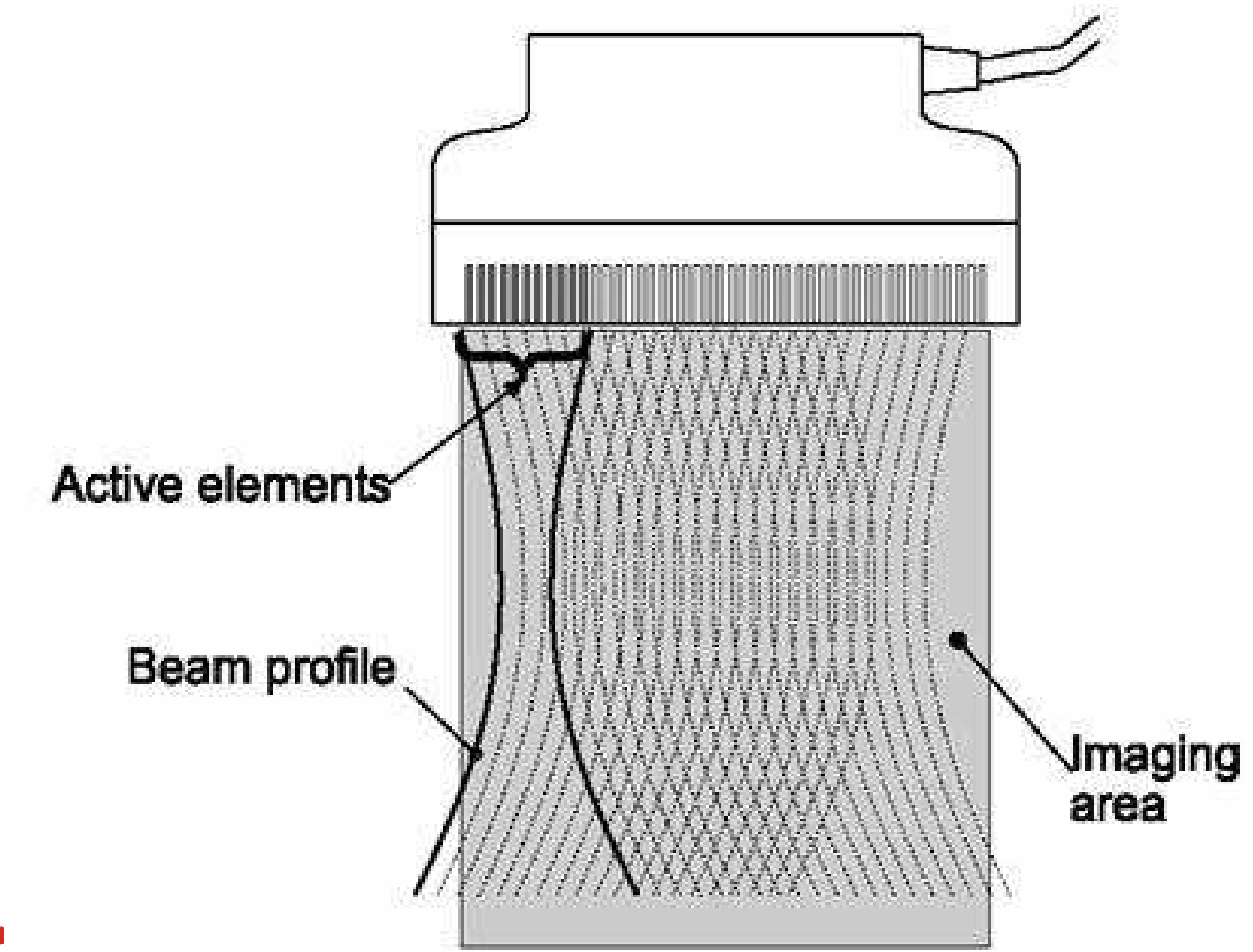
The narrower the main lobe, the better the lateral resolution of the scan.

Phased Array

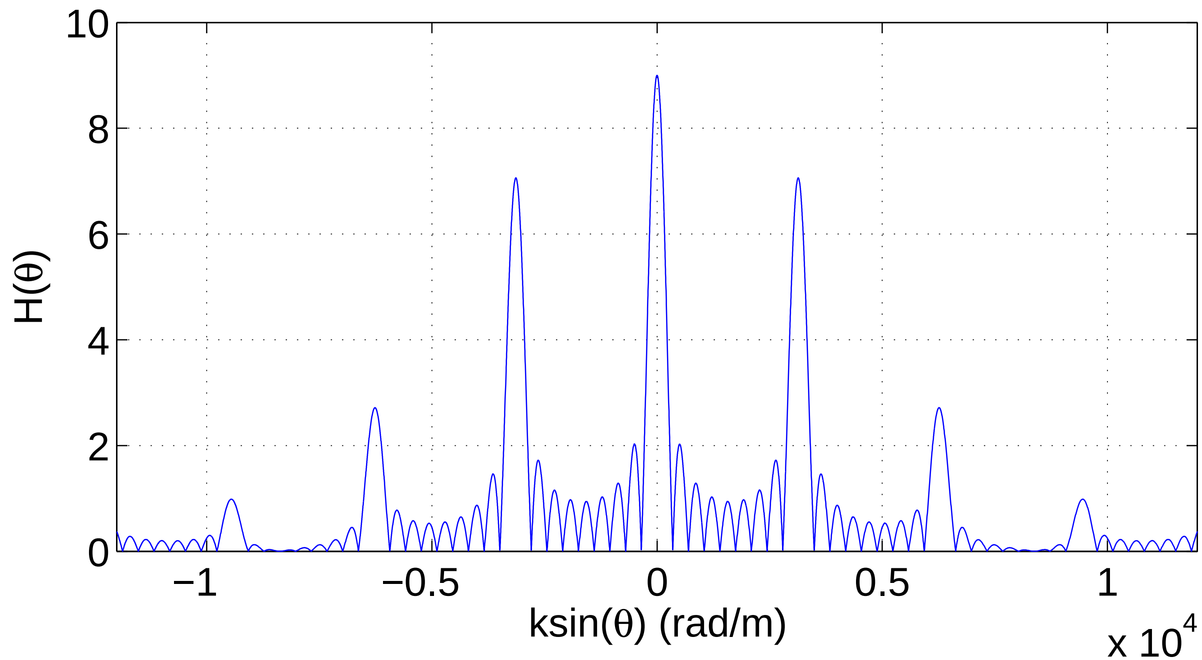


Array can focus and steer the beam over a 2-D region..

B-Mode Scanning



Phased Array Beam Pattern

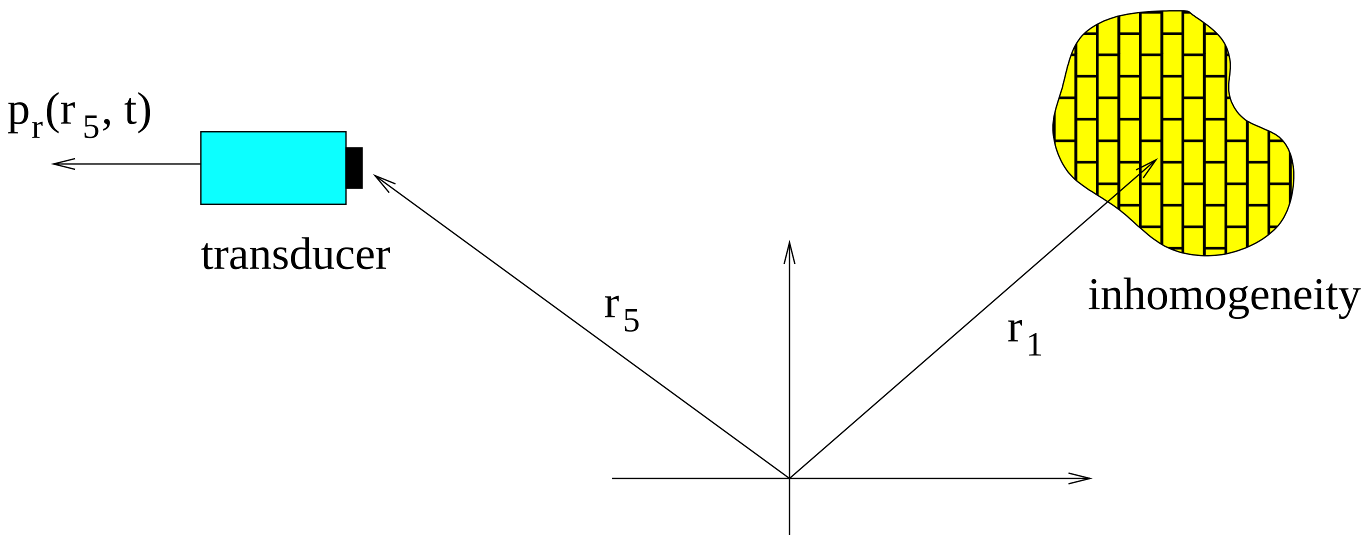


Main lobe width here inversly proportional to N and d_x:

- $d_x = 2$ mm
- $L = 0.75$ mm
- $N = 8$

Jensen's Backscattering Model

Geometry:



received signal:

$$p_r(r_5, t) = v_{pe}(t) \underset{t}{*} f_m(r_1) \underset{r}{*} h_{pe}(r_1, r_5, t)$$

Received Signal

$$p_r(r_5, t) = v_{pe}(t) \underset{t}{*} f_m(r_1) \underset{r}{*} h_{pe}(r_1, r_5, t)$$

- $v_{pe}(t)$: pulse-echo wavelet, includes transducer excitation, and its electromechanical impulse response during transmission and reception.
- $f_m(r_1)$: represents inhomogeneities in the tissue due to density and propagation velocity perturbations. This is the “desired" signal.
- $h_{pe}(r_1, r_5, t)$: pulse-echo spatial impulse response, a smoothing operator.