Lecture 13 – Ultrasound Instrumentation

This lecture will cover: *(CH4.5-4.7)*

– Ultrasound imaging system

– Ultrasound Transducer/probe

- Piezoelectric material
- Single element transducer
- Transducer array

(*Supplementary reading: The Essential Physics of Medical Imaging CH14.3-14.6*)

Ultrasound imaging system

- Input/output
  - The frequency generator
  - Transmit/receive (Tx/Rx) switch
  - Transducer/probe
- Signal processing
  - Preamplifier
  - ADC
  - Other functions
- Image processing
  - Display
  - Denoise
  - Enhancement
  - Other functions

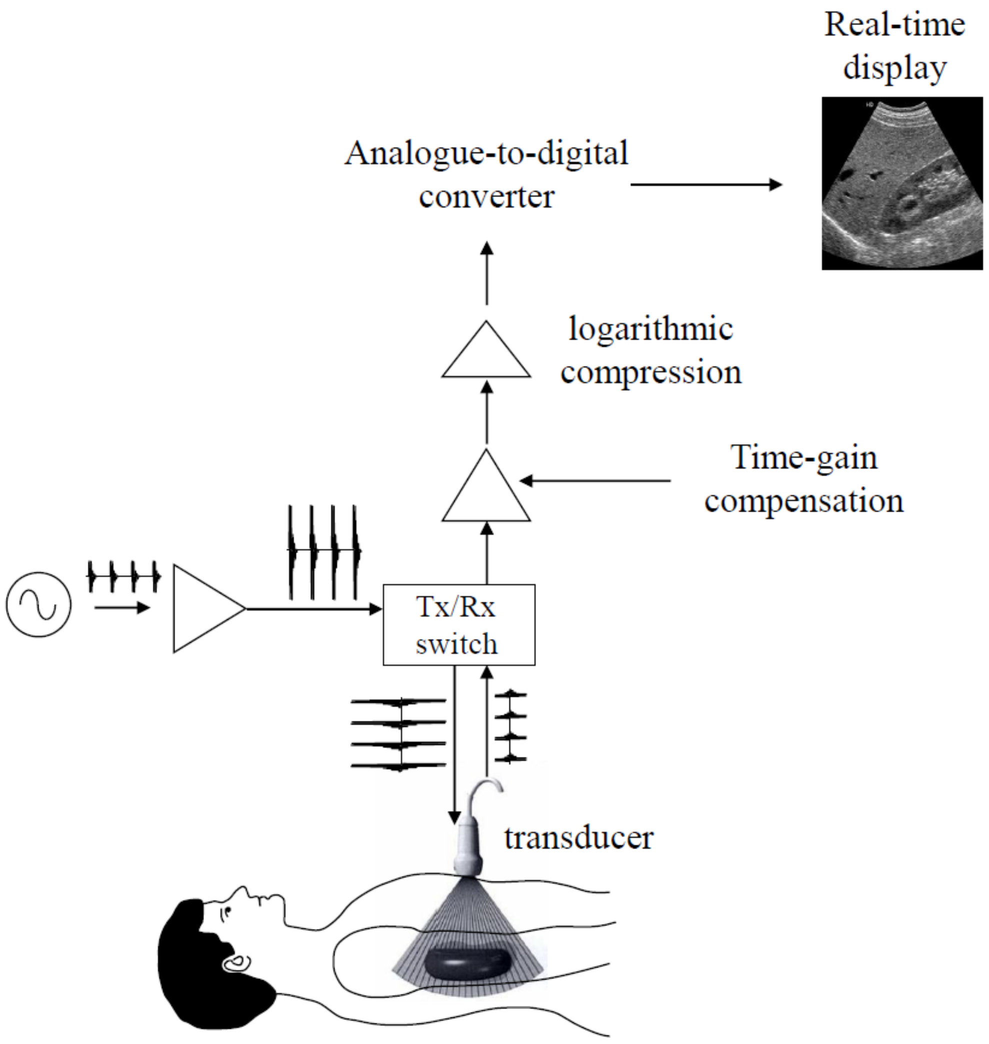


Fig. The major elements of a basic ultrasound imaging system

Piezoelectric material

Piezoelectric material (压电材料)

- ➢ Convert electrical energy into mechanical (sound) energy by physical deformation of the crystal structure and vice versa;
  - External pressure causes an imbalance of charge distribution;
  - External voltage induces the mechanical expansion and contraction of the transducer element;
- ➢ Lead-Zirconate-Titanate (PZT)
  - Exhibited piezoelectric properties after heating to its "Curie temperature" (328-365℃);
  - The structure of molecular dipoles;

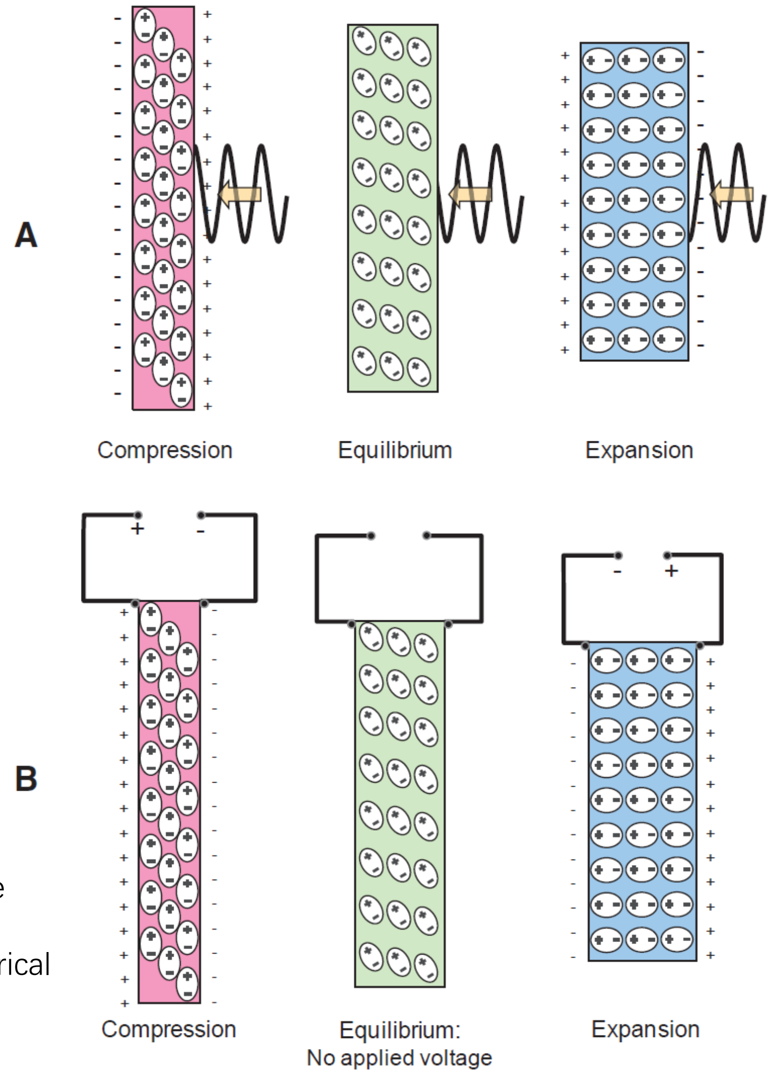


Fig. The piezoelectric element is comprised of aligned molecular dipoles. (A) Under the influence of mechanical pressure from an adjacent medium (e.g., an ultrasound echo), the element thickness contracts (at the peak pressure amplitude), achieves equilibrium (with no pressure), or expands (at the peak rarefactional pressure) causing realignment of the electrical dipoles to produce positive and negative surface charge. Surface electrodes (not shown) measure the charge variation (voltage) as a function of time; (B) An external voltage source applied to the element surfaces causes compression or expansion from equilibrium by realignment of the dipoles in response to the electrical attraction or repulsion force.

Single element transducer

Components:

➢ Piezoelectric element

- Flat shape (unfocused) and hemispherical shape (focused);
- Natural resonant frequency

$$f_0 = \frac{c_{\text{cystal}}}{2t}$$

Where c_{cystal}: velocity of ultrasound wave in PZT crystal (4000m/s)

t: thickness of the element

➢ Coating layers

- Matching layers: $Z_{\text{matching layer}} = \sqrt{Z_{\text{PZT}} Z_{\text{skin}}}$
- Damping layer:
  - ✓ Backing material and epoxy
  - ✓ To achieve short pulse required for good spatial resolution in axial direction;
  - ✓ For large frequency bandwidth.

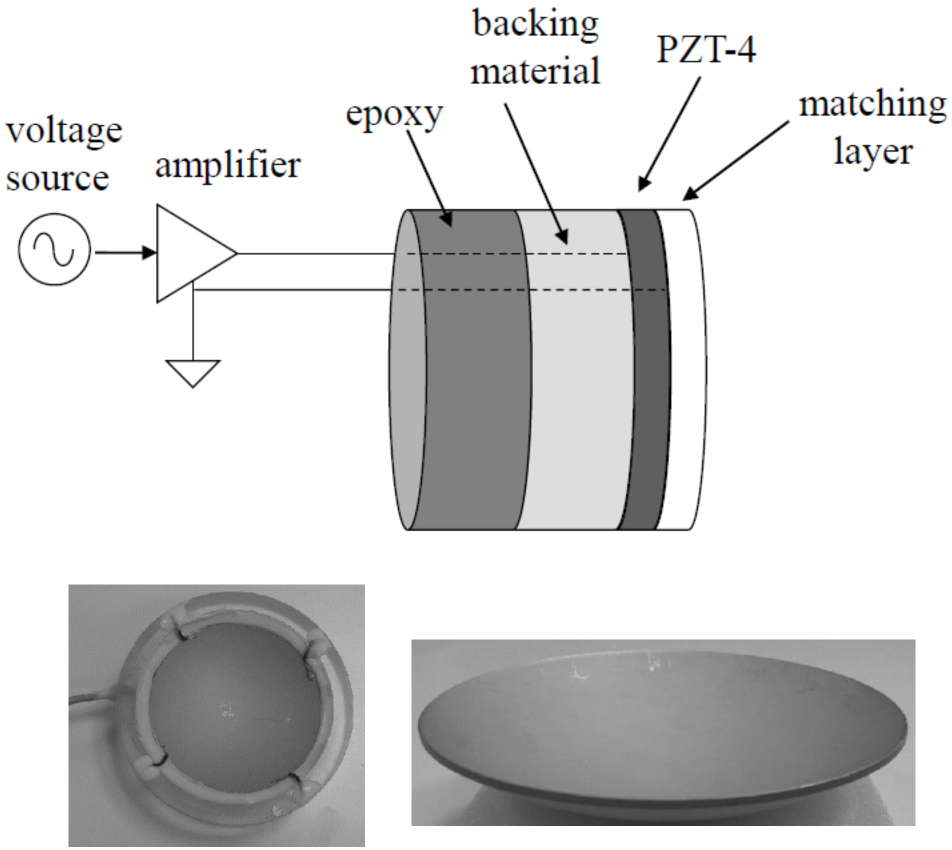


Fig. (Top) A transducer with a flat PZT element. (bottom) Flat and hemispherical PZT elements.

Acoustic properties

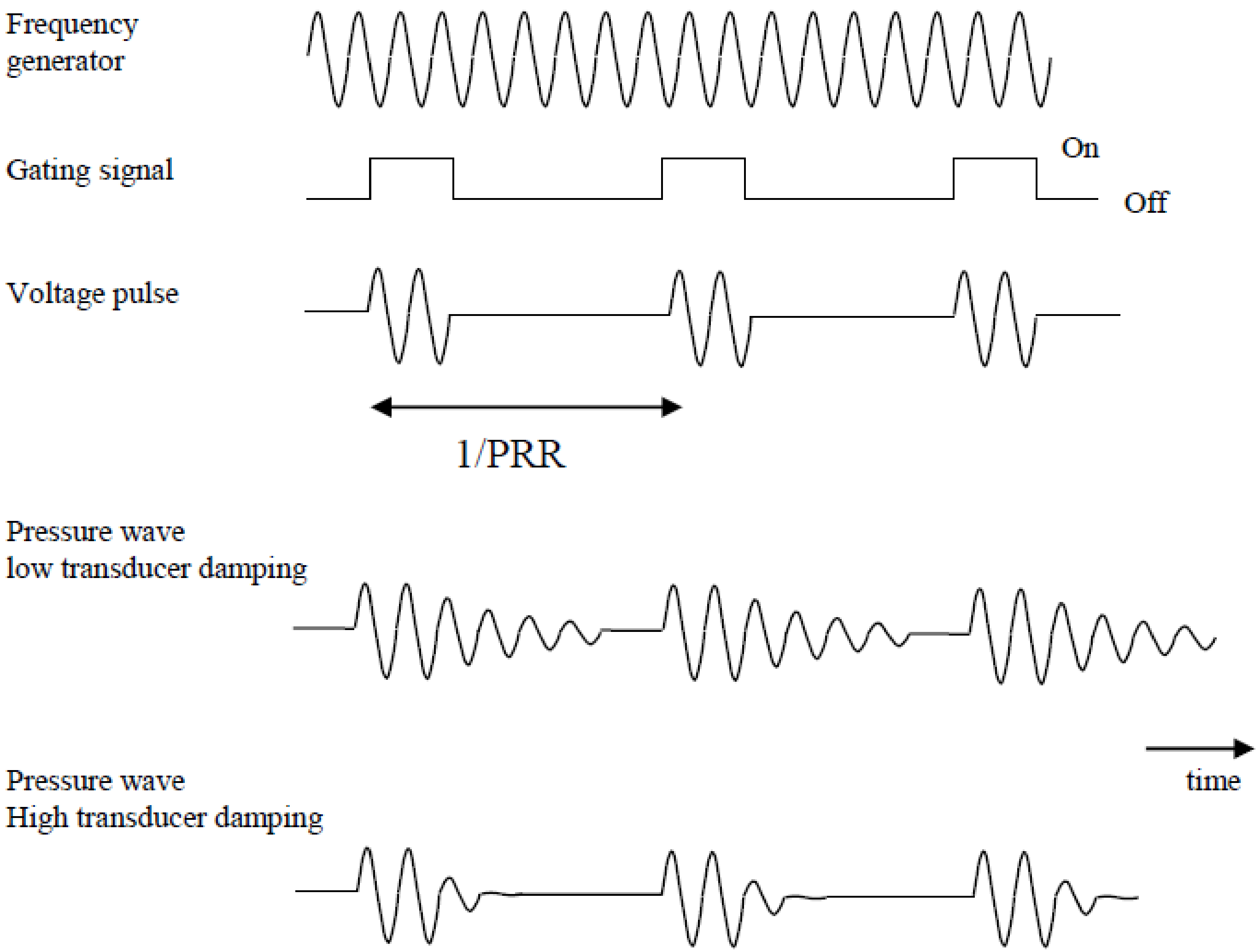


Fig. Voltage pulses are applied to the face of the piezoelectric element by gating the output of a frequency generator. The pulses are produced at a certain rate, termed the pulse repetition rate (PRR). A transducer with low mechanical damping produces a pressure wave which lasts considerably longer than the driving voltage pulse. Increasing the mechanical damping (bottom row) reduces the duration of the pressure wave.

Transducer bandwidth

- The frequency range over which the sensitivity is greater than one-half of the maximum sensitivity (FWHM);
- Center frequency f_0 is in the bandwidth, but not necessary in the middle;
- For both transmission and receiving at wide bandwidth;
- The higher damping, the larger bandwidth;
- Quality factor

$$Q = \frac{f_0}{\text{Bandwidth}}$$

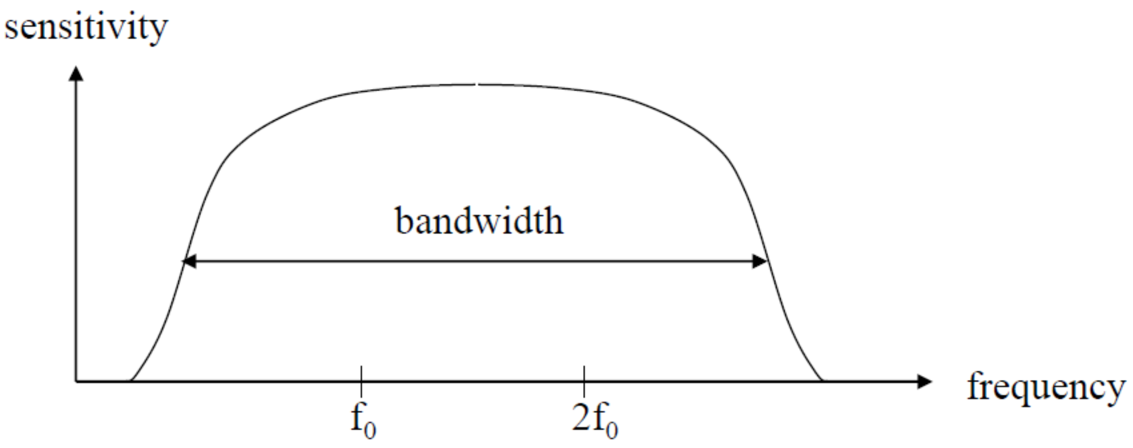


Fig. Sensitivity vs. frequency for a broadband transducer. The bandwidth corresponds to the frequency range over which the sensitivity is greater than one-half of the maximum sensitivity. Note that the bandwidth can be larger than the value of f_0 itself.

Pulse-echo timing

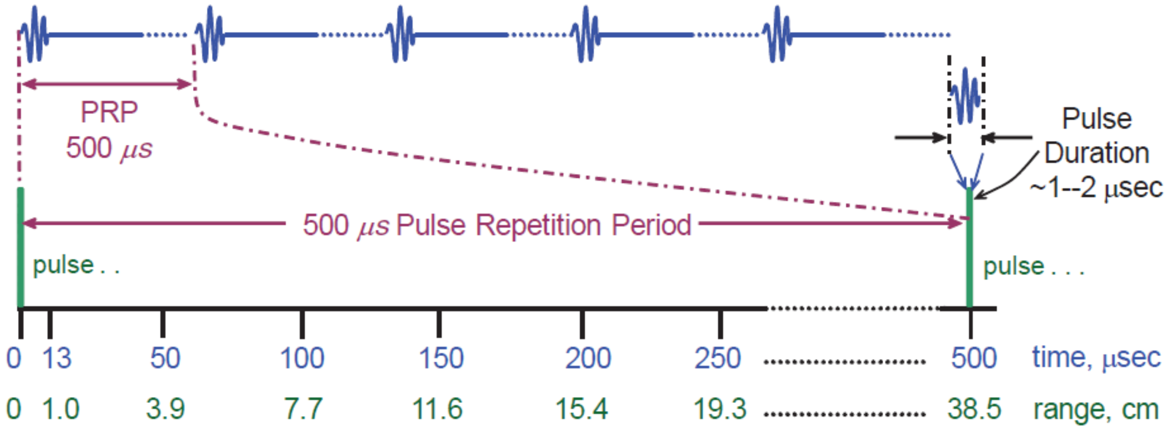
- Pulse duration (脉冲宽度) τ: ~1-2 μs
- Pulse repetition period (PRP, 脉冲重复周期)
- Pulse repetition frequency (PRF, 脉冲重复频率)

$$PRF = \frac{1}{PRP}$$

- Duty cycle (占空比)

$$S = \frac{\tau}{PRP}$$

- Peak power (峰值功率)
- Average power (平均功率): $A \approx P \times S$



$$PRF = \frac{1}{PRP} = \frac{1}{500\,\mu s} = \frac{1}{500 \times 10^{-6}\,s} = \frac{2000}{s} = 2\,\text{kHz}$$

Fig. The pulse-echo timing of data acquisition depicts the initial pulse occurring in a very short time span, the pulse duration = 1 to 2 μs and the time between pulses, the PRP = 500 μs in this example. The number of pulses per second is 2000/s, or 2 kHz. Range (one-half the round-trip distance) is calculated assuming a speed of sound = 1540 m/s.

Beam geometry

- Near field (Fresnel zone): very complicated wave pattern; severe oscillation;
- Far field: wave intensity decays exponentially with distance
- The near-field boundary occurs at the distance

$$Z_{\mathrm{NFB}} \approx \frac{r^2}{\lambda}$$

Where r: radius of the transducer

λ: the wavelength of the ultrasound in tissue

- The angle of deviation (扩散角)

$$\theta = \arcsin\left(\frac{0.61\lambda}{r}\right)$$

- Lateral resolution and side lobes

$$\mathrm{FWHM} = 2.36\sigma$$

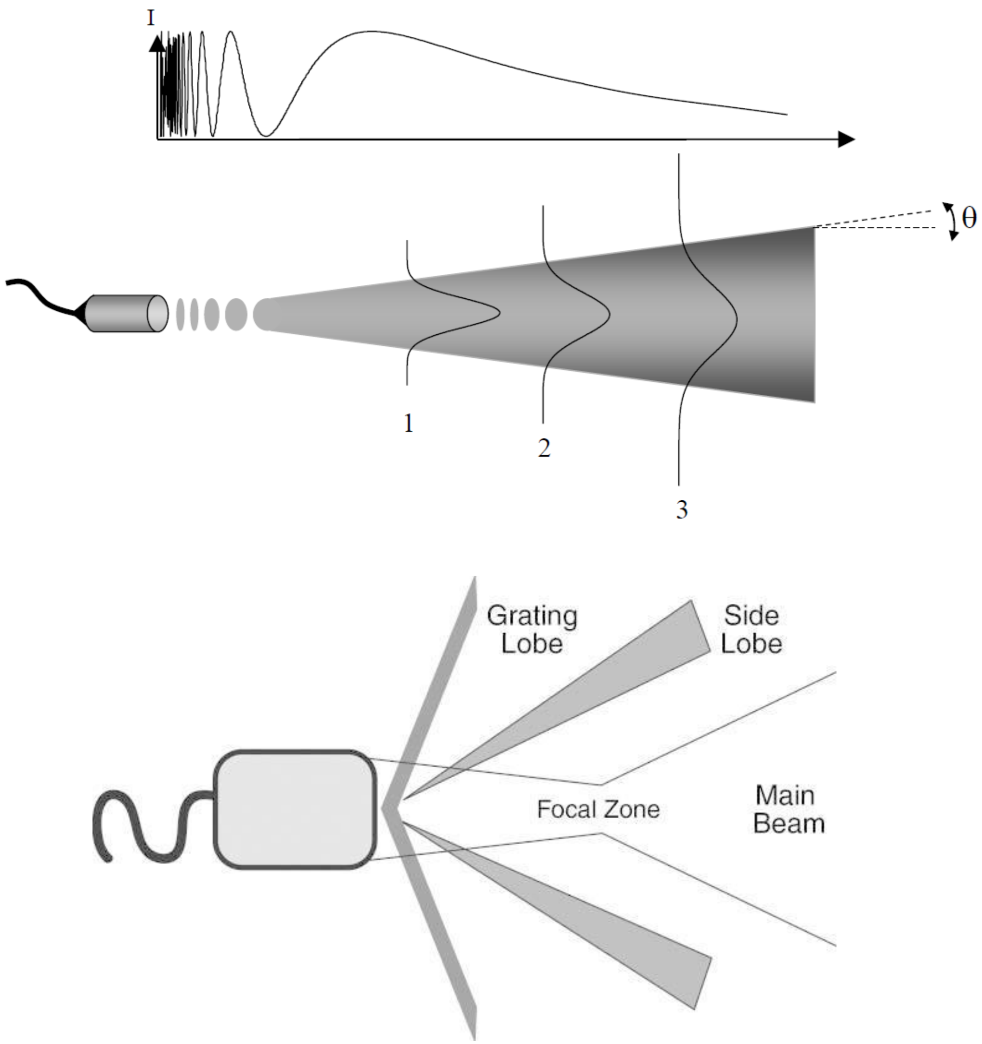


Fig. (Top)Lateral and axial beam patterns from a single element transducer; (bottom) side lobes of the transducer.

Axial resolution

- The closest distance that two boundaries can lie in a direction parallel to the beam propagation and still be resolved as two separate features;
- The value of axial resolution is given by

$$\text{Axial resolution} = \frac{1}{2} p_d c$$

Where p_d: pulse duration

c: velocity of ultrasound

- Attenuation of ultrasound beam increases at higher frequencies, so there is a trade-off between penetration depth and axial resolution.
- Improve axial resolution by increasing damping;
- Wide bandwidth provide both better penetration with low frequency component and high axial resolution with high frequency component;

Axial resolution

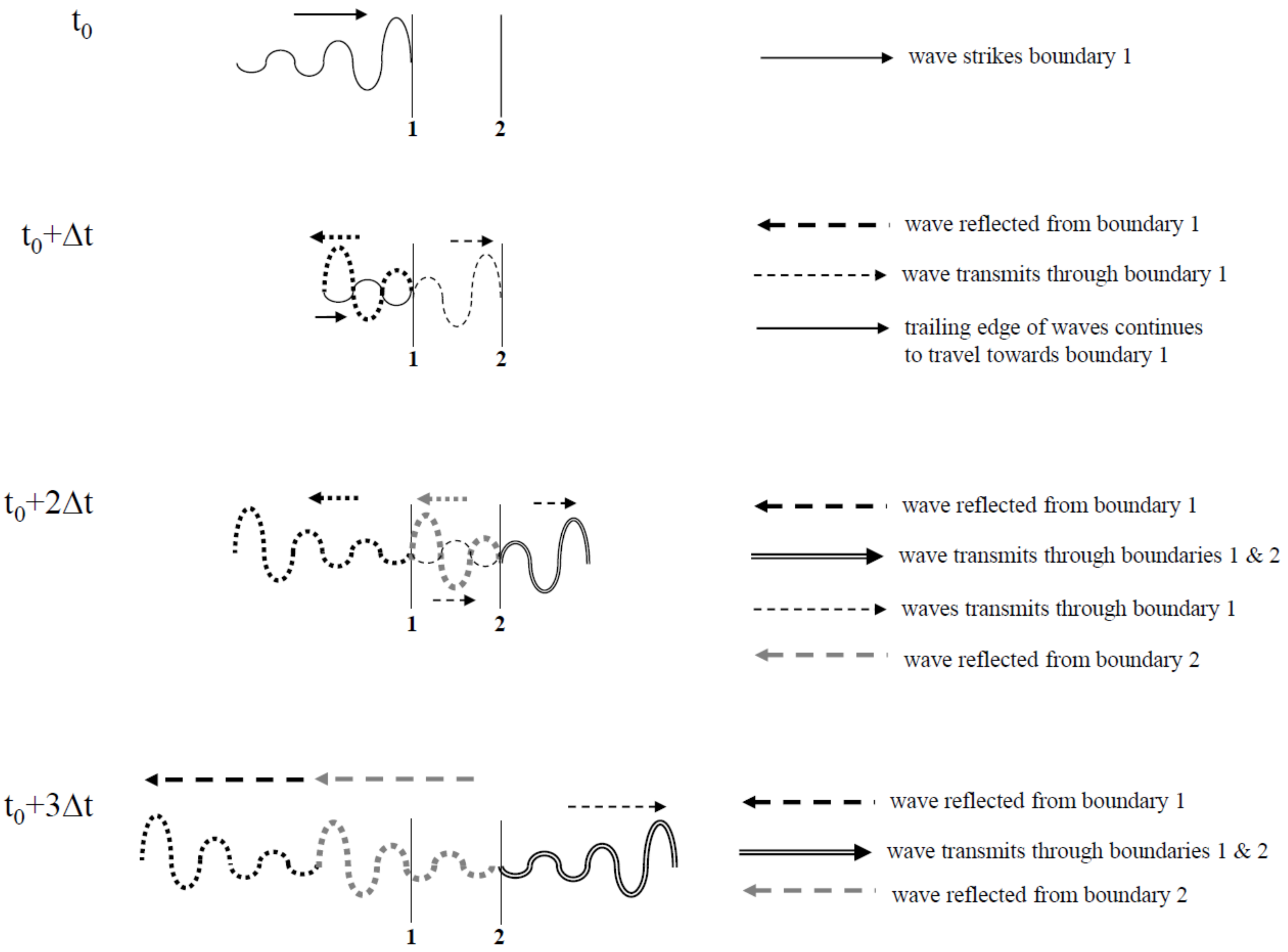


Fig. Two boundaries (1 and 2) are separated by one-half of the length of a pulse of ultrasound transmitted into the body from a transducer. The echoes from the two boundaries (bottom diagram) are just distinguishable, since they do not overlap in time. If the two boundaries were separated by a smaller distance, then the two returning echoes could not be resolved and the two boundaries would be represented by one very thick feature.

Transducer focusing

- To produce a "tighter" ultrasound beam;
- Two methods:
  - Concave lens placed in front of the piezoelectric element;
  - Curved surface for element;
- The lateral beam width is most narrow at focal point (focal distance/length, F);
- The lateral resolution is $\lambda F/D$.

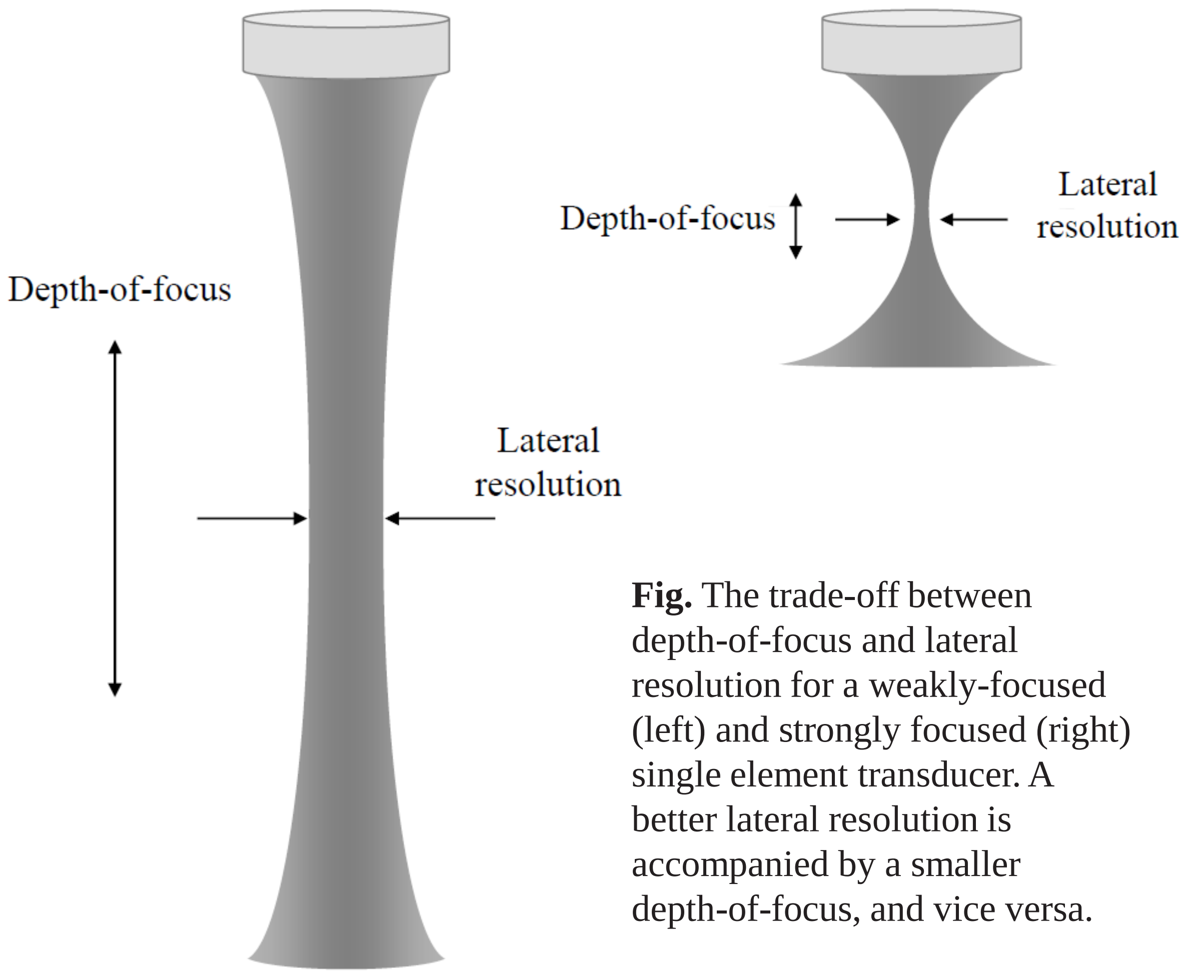


Fig. The trade-off between depth-of-focus and lateral resolution for a weakly-focused (left) and strongly focused (right) single element transducer. A better lateral resolution is accompanied by a smaller depth-of-focus, and vice versa.

Transducer array

- Linear array
- Phased array
  - Pulse transmission – dynamic focusing
  - Beam-forming and steering
    - ✓ Beam-forming and steering transmission
    - ✓ Analogue and digital receiver beam-forming
    - ✓ Time gain compensation
- Multi-dimensional arrays
- Annular arrays

Linear array

- Typically consist of 128-512 rectangularly shaped piezoelectric elements;
- **kerf**-the space between elements; filled with acoustic isolating material;
- **Pitch**- the distance between the element centers; the size ranges from $\lambda/2$ to $3\lambda/2$, where λ is the ultrasound wavelength in tissue;

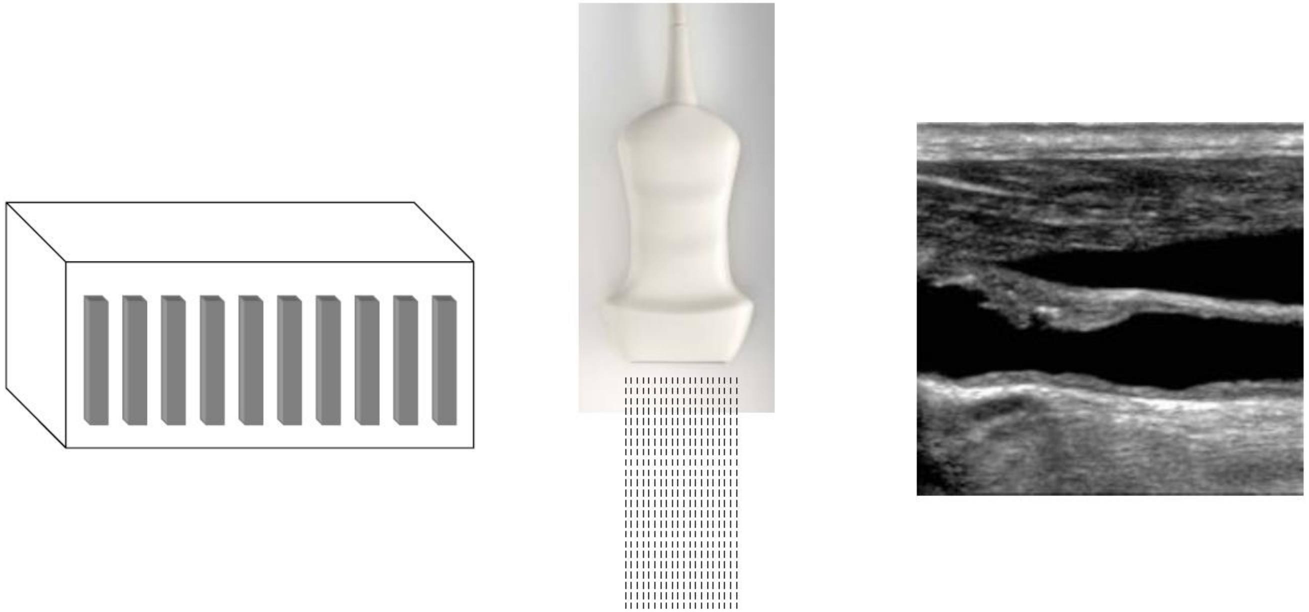
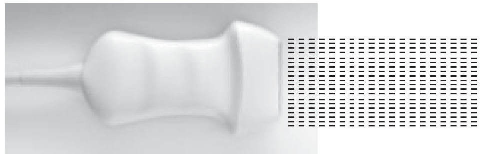
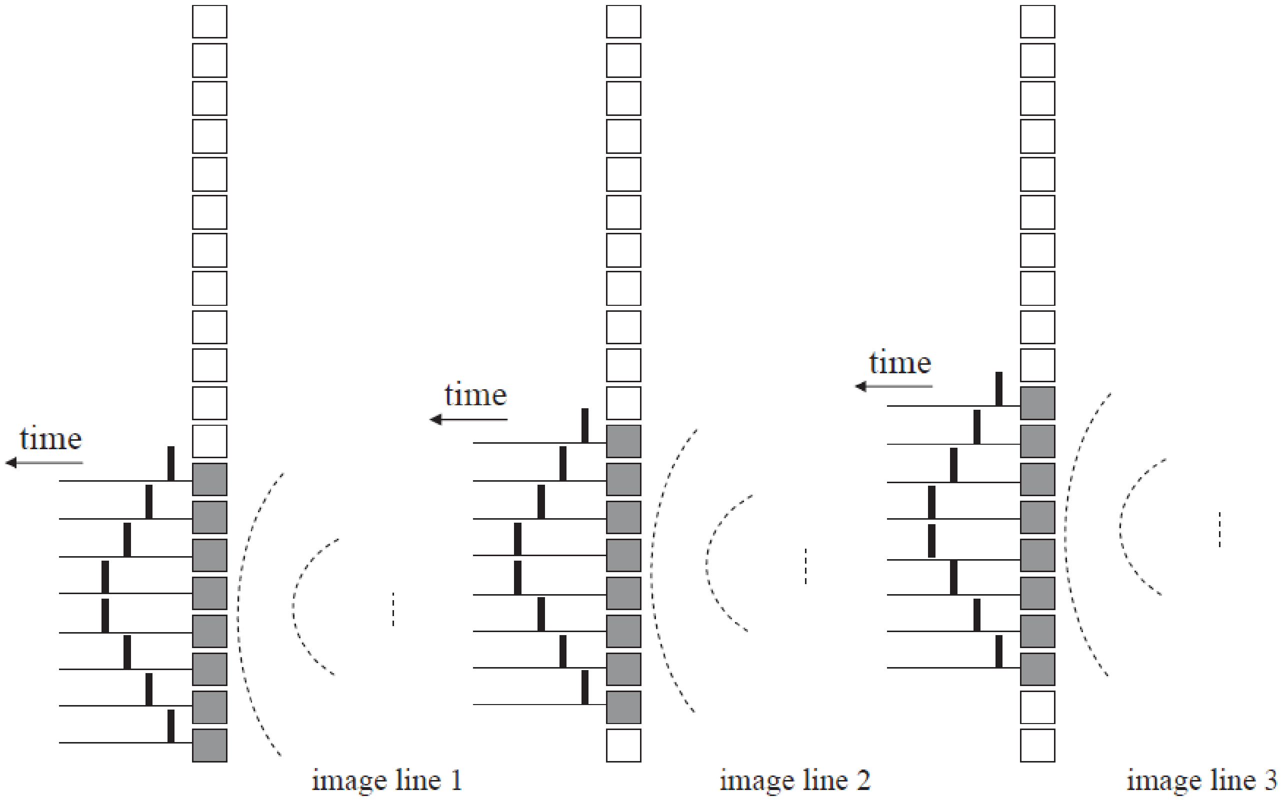


Fig. Design and operation of a linear array. (left) A large number of rectangular piezoelectric elements form a one-dimensional array. Each element is connected by a small coaxial cable to the voltage source. (center) A commercial linear array, with the dashed lines showing the ultrasound beams that are sent out sequentially from left-to-right. (right) A two-dimensional ultrasound image acquired using a linear array.

Linear array





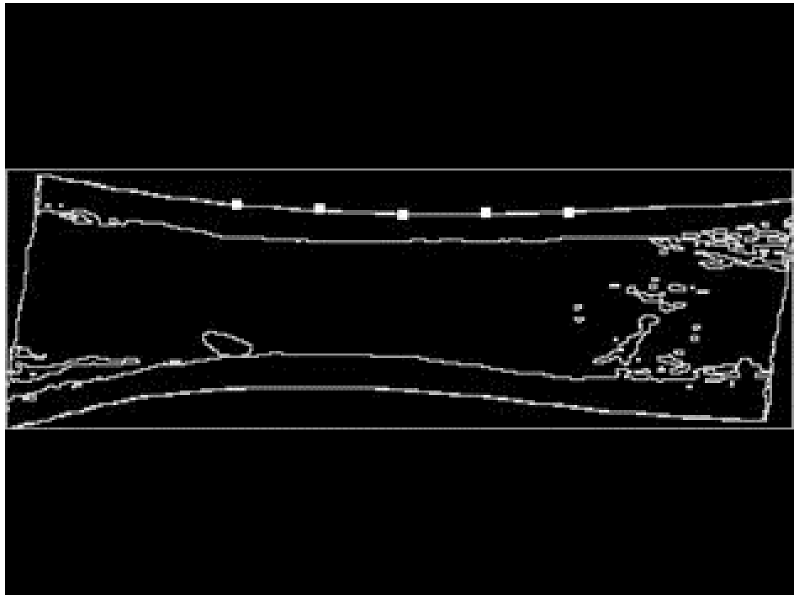


Fig. Operation of a linear array. Sequential excitation of a small subgroup of the elements is used to produce a series of ultrasound lines which lie parallel to one another, and thus the image is built-up sequentially. Application of voltage pulses which are slightly delayed in time with respect to one another produces an effective focused beam for each line.

Dynamic focusing

- Used to optimize the lateral resolution over the entire depth of tissue being images;
- The focal depth (distance) changes with the number of excited elements:
  - Small number --- small focal point close to the transducer surface;
  - Large number --- large depth
- Disadvantages:
  - Multiple scans are required to build up a single scan line;
  - Frame rate is reduced

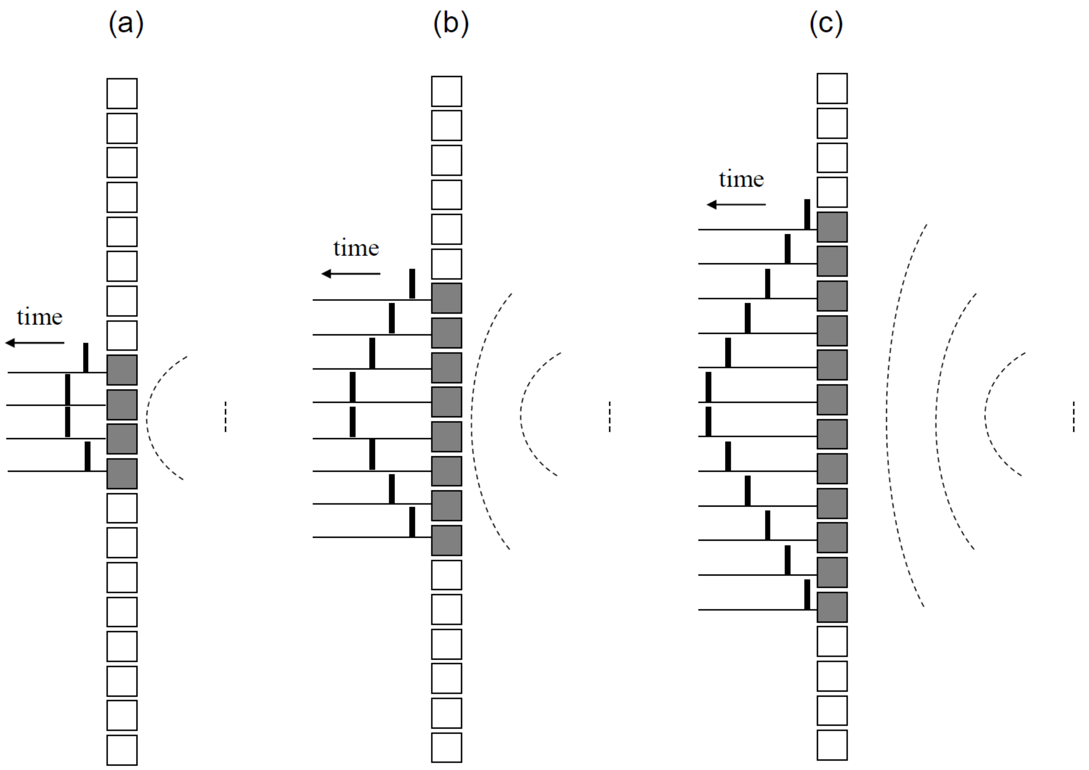


Fig. The process of dynamic focusing involves exciting an increasing number of elements in order to dynamically focus at different depths within the tissue. First, a small number of elements are used to acquire signals from very close to the transducer surface. The time required to acquire the backscattered echoes from such a shallow depth is very short, and so subsequent excitations using a larger number of elements for focusing at points deeper within tissue can be executed rapidly.

Beam forming

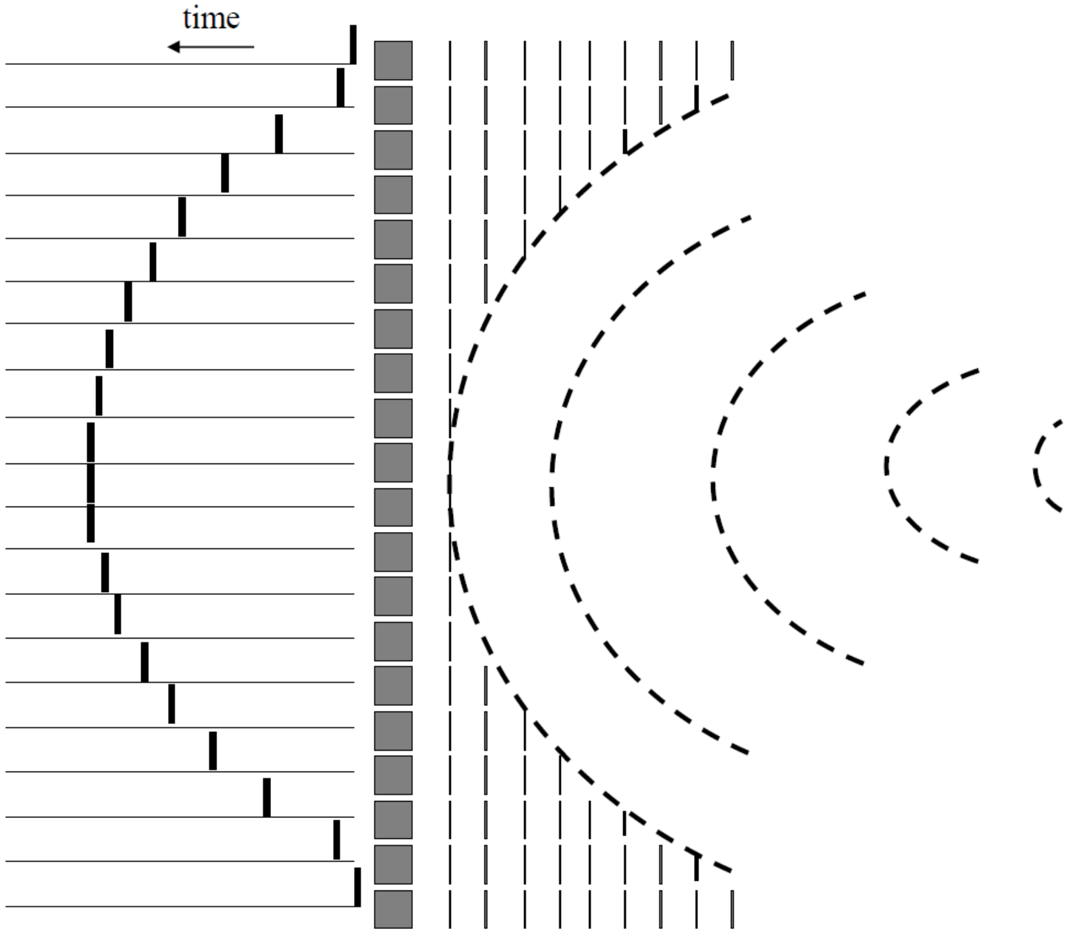


Fig. Beam-forming during ultrasound transmission. Applying voltage pulses to each individual element of the array at different times produces a composite wavefront. Applying the voltages symmetrically with respect to the centre elements, with the top and bottom elements excited first, causes the beam to focus at a point which is half-way along the array.

Beam steering

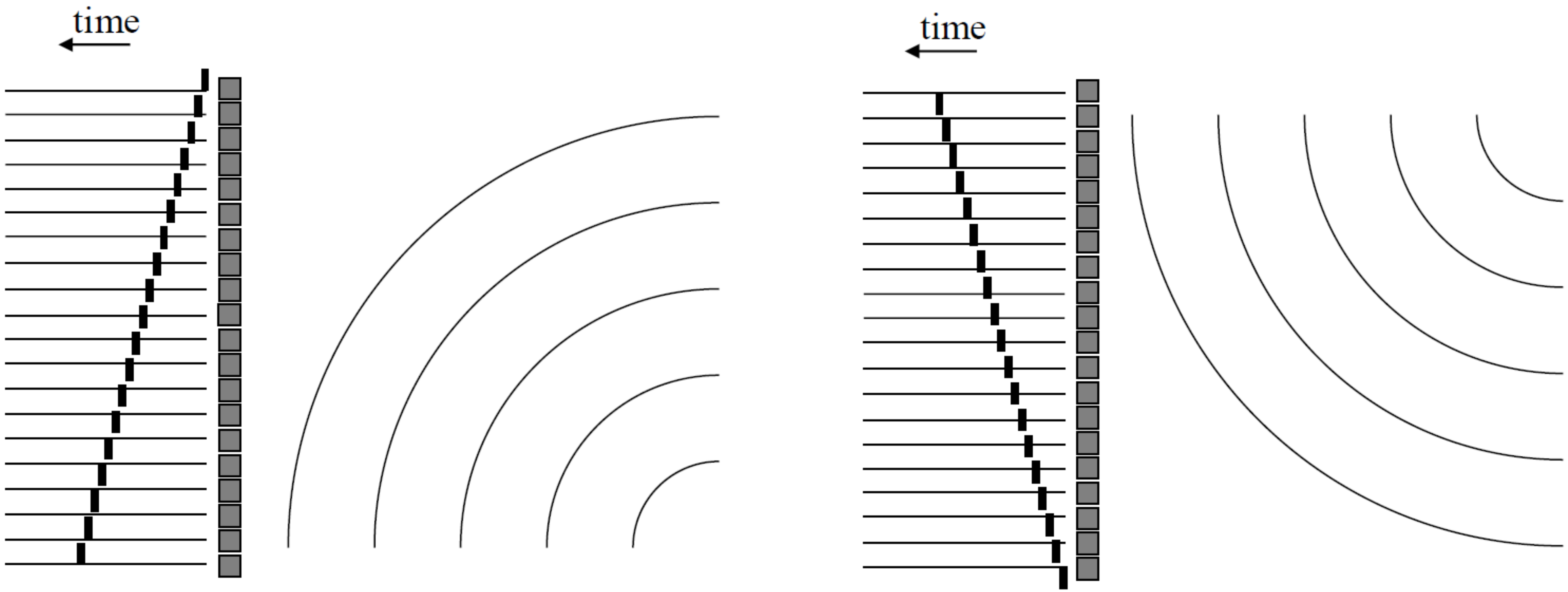


Fig. Beam steering using phased arrays. By changing the pattern of excitation of all the elements, the beam can be steered to a point below (left) and above (right) the centre of the array.

Analogue and digital receiver beam-forming

- The returned echo from each element is incrementally delayed to receive the effective signal being in focus;
- Receiver beam forming can be done by analogue circuitry and digital equivalent components;
- Post-processing on the stored data after ADC;

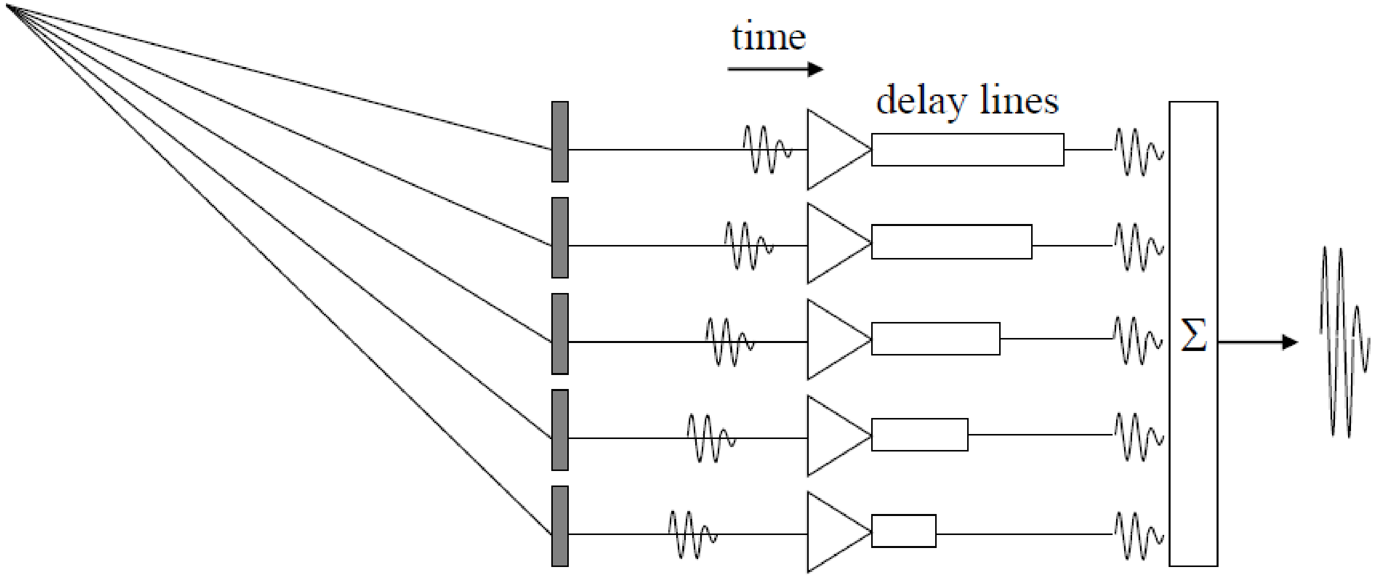


Fig. The process of receiver beam-forming. Individual echoes from the focal point reach each element in the array at slightly different times. Summation of the signals at this point would result in partially destructive interference and signal loss. After amplification, each signal is delayed by a time specified by the path length from the focal point to the transducer. After passing through the various delay lines, the signals are now in-phase and so are co-added to produce the maximum signal.

Time gain compensation (TGC)

- Total range of signal amplitudes may be as high as a factor of 100dB;
- TGC is amplifying the signals with the factor increased as a function of traveling time (depth) of ultrasound wave;
- To compress the dynamic range of echoes into the range of linear gain in ADC;

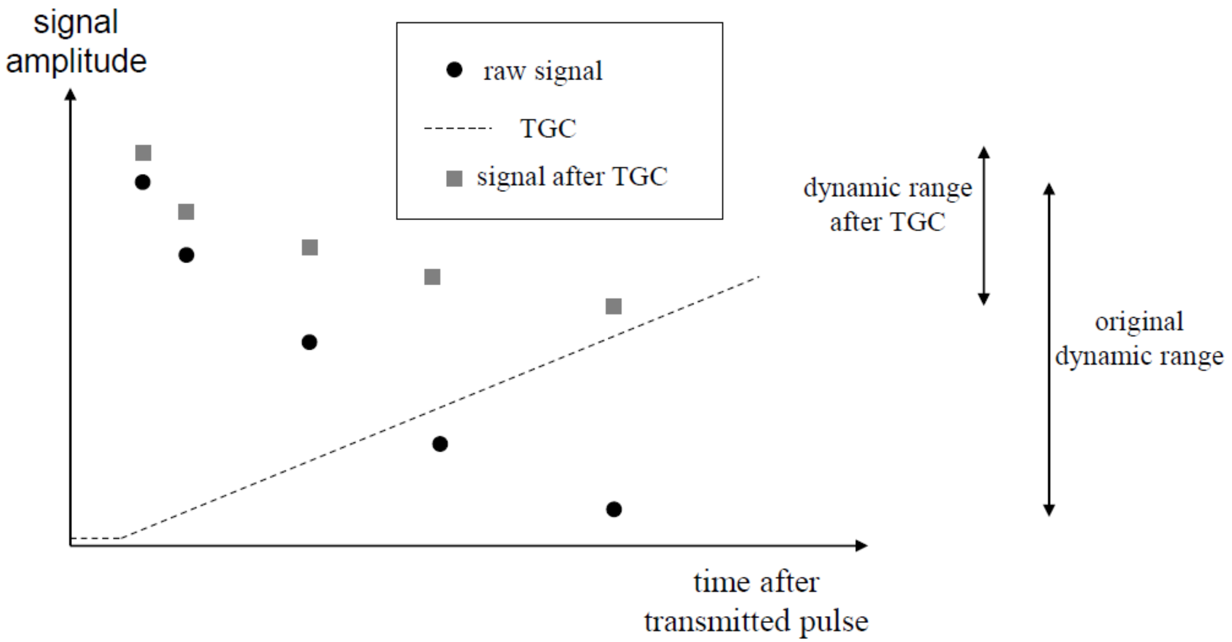
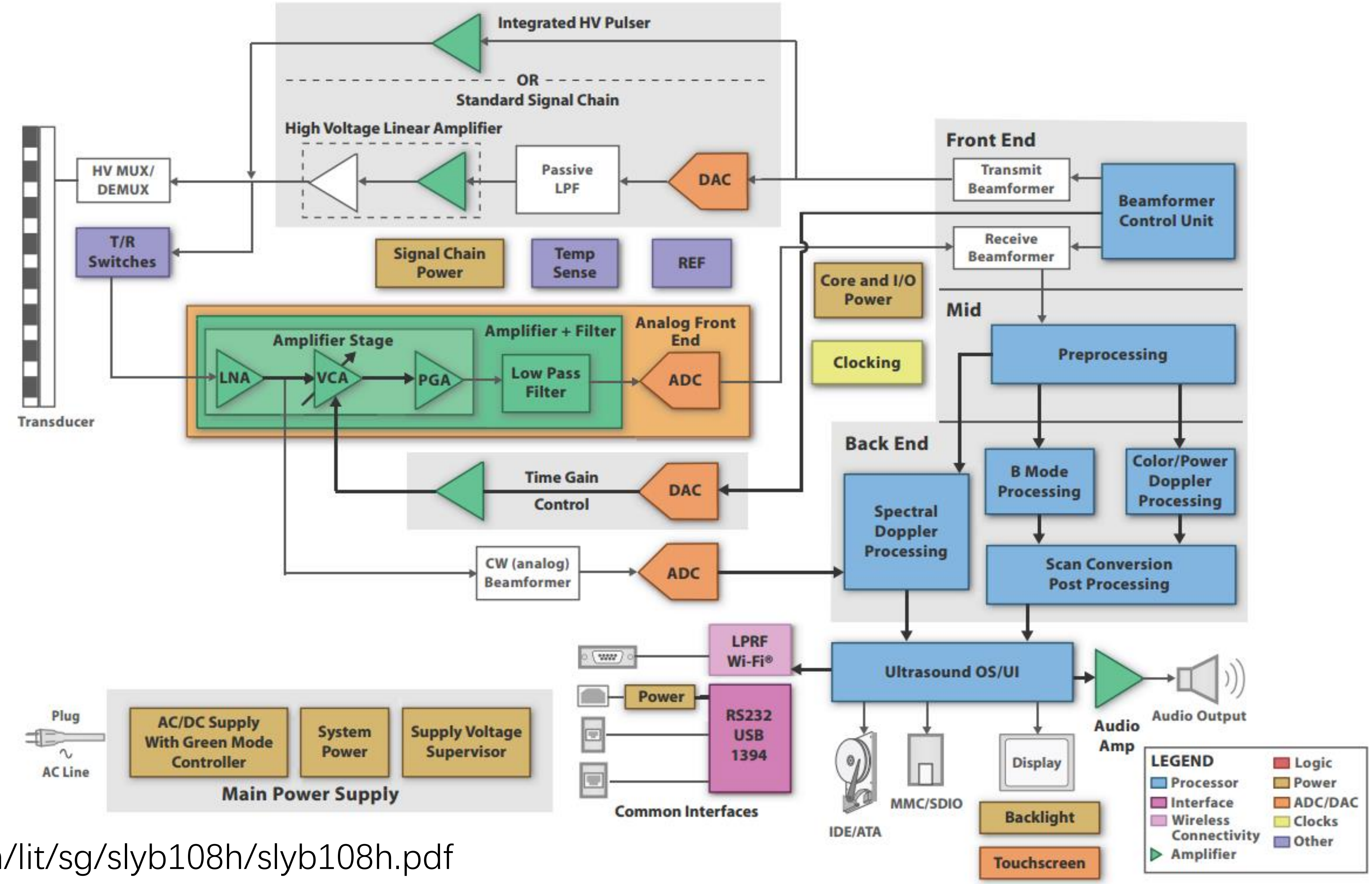


Fig. The effects of time-gain compensation in reducing the dynamic range of the signals received from close to the transducer surface and deep in tissue.

Phased array system block diagram



http://www.ti.com/lit/sg/slyb108h/slyb108h.pdf

Multi-dimensional arrays

- Multiple rows of elements;
  - 1.5D array: typically 3-10 rows;
  - 2D array; a large number of rows, even equal to the number of elements in each row;
- Beam forming and steering in both direction (elevation and lateral);
- More complex for the transducer;
- Used for 3D data acquisition;

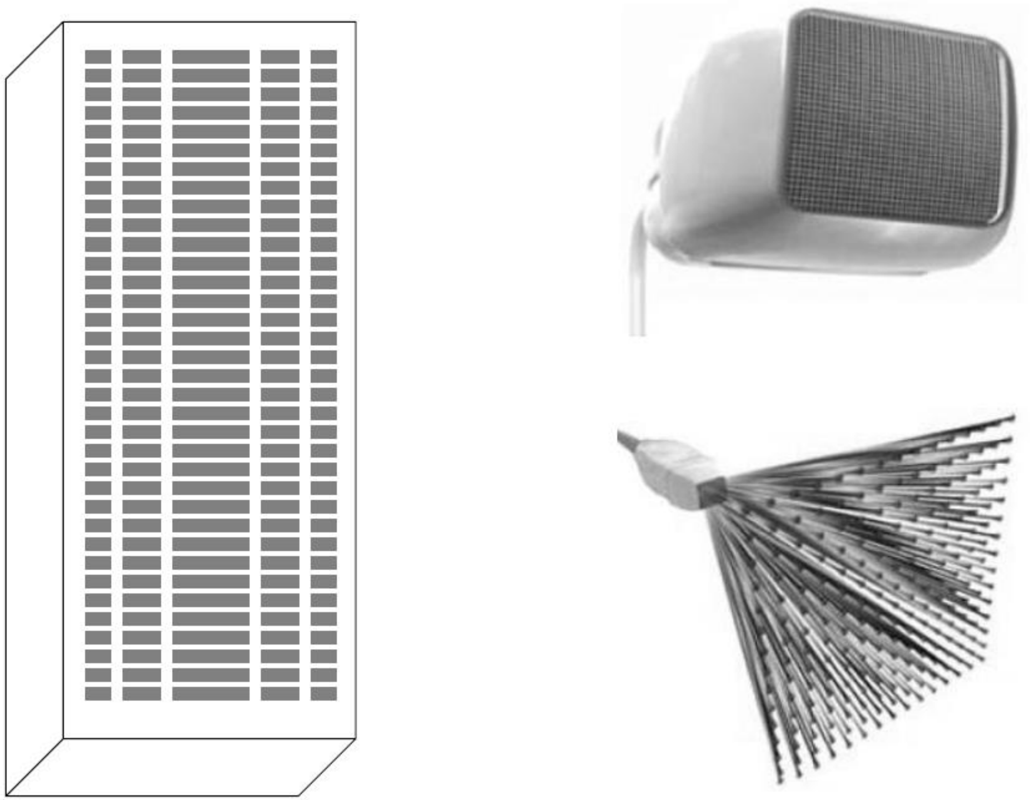


Fig. Multi-dimensional array transducers. (left) A 1.5-dimensional array, with five elements in the elevation direction which can be used to focus the beam in this dimension. (upper right) A 50*50 twodimensional array transducer, which can be used for beam-forming and beam steering in two dimensions (below right).

Annular arrays

- For high frequency transducer (>20MHz);
- 5-10 ring elements;
- Beam forming in both transmit and receive modes;
- Mechanical motion is needed to form an image.

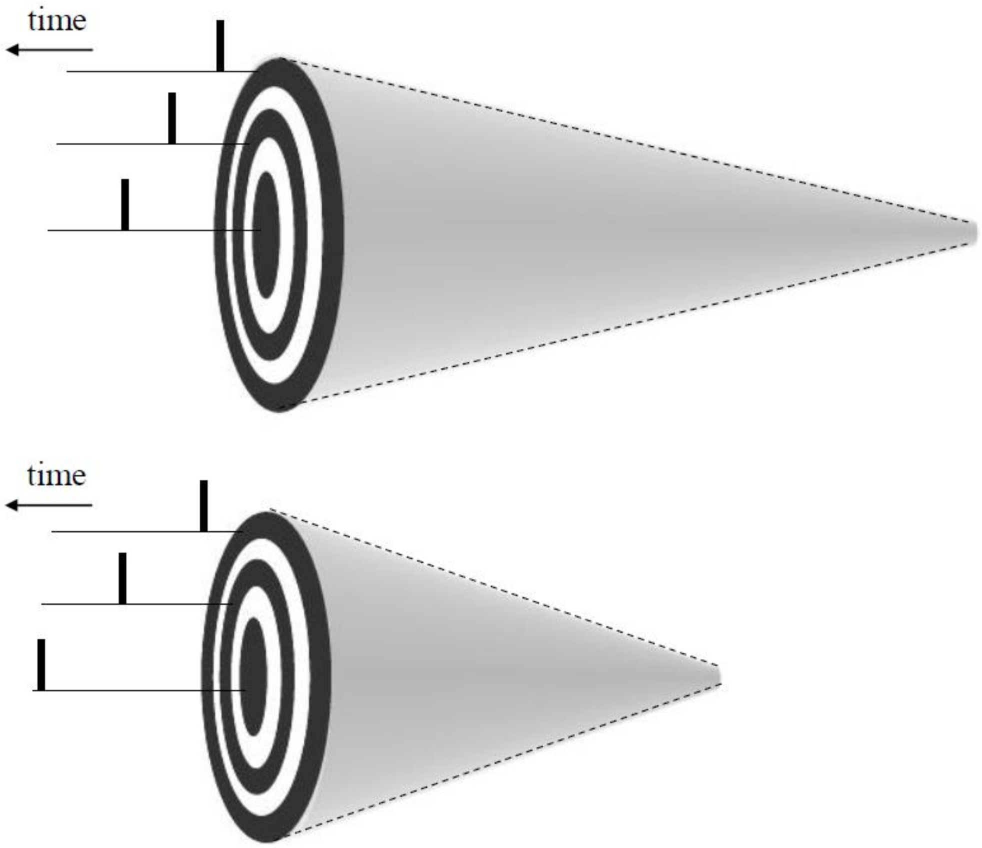


Fig. Mode of operation of an annular array. Dynamic focusing can be performed in two-dimensions simultaneously by varying the time at which each element of the array is excited. Rings of piezoelectric material (shown in black) are separated from each other by acoustic isolation material.