ECSE-4962
Introduction to Subsurface Sensing and Imaging Systems

Lecture 11: Pulse-Echo Imaging Systems

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Center for Sub-Surface Imaging & Sensing

GE Global Research

Outline of Course Topics

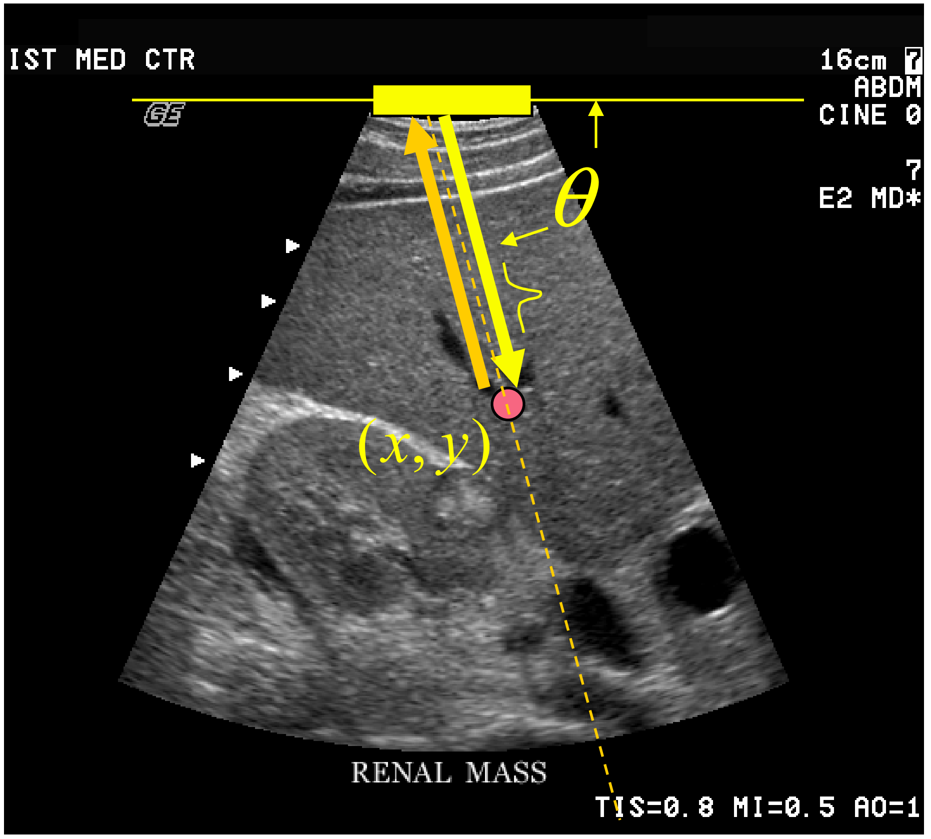
- THE BIG PICTURE
  - What is subsurface sensing & imaging?
  - Why a course on this topic?
- EXAMPLES: THROUGH TRANSMISSION SENSING
  - X-Ray Imaging
  - Computer Tomography
  - Intro into Optical Imaging
- COMMON FUNDAMENTALS
  - propagation of waves, ultrasound
  - interaction of waves with targets of interest
- PULSE ECHO METHODS
  - Examples
- MRI
  - A different sensing modality from the others
  - Basics of MRI
- MOLECULAR IMAGING
  - What is it?
  - PET & Radionuclide Imaging
- IMAGE PROCESSING & CAD

Recap

- Propagation Models
  - Fresnel or near-field
  - Fraunhofer or far field
  - Near to far field transition distance
- Starting w. Rayleigh-Sommerfeld, we derived a simplified CW, far field expression for the probe field.
  - Fourier transform of the aperture
- O'Neil's expression for a circular aperture

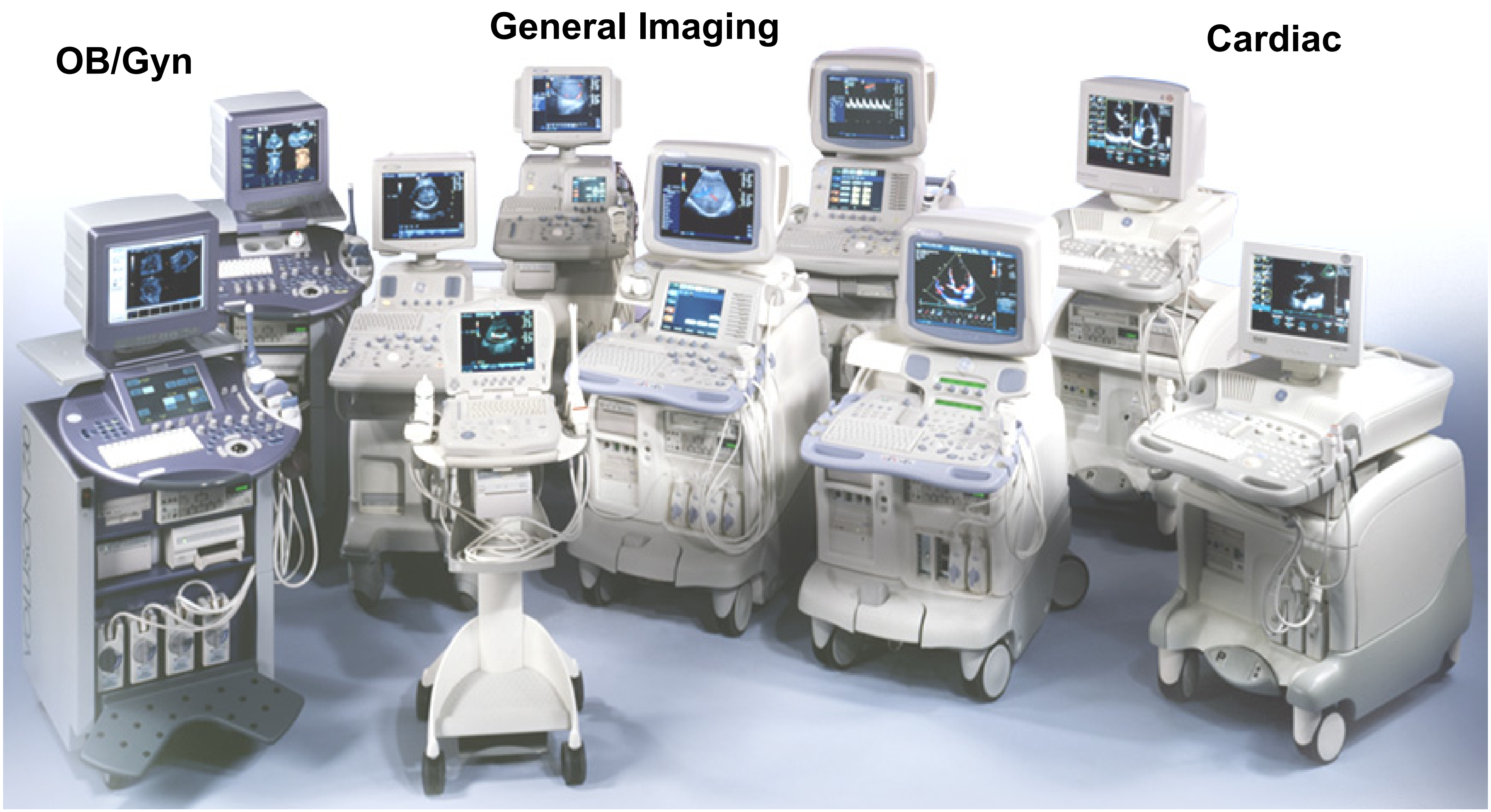
Basic Pulse-Echo Imaging

- Basic Steps
  - Send a pulse of acoustic energy into the patient at a chosen angle θ
  - Record the intensity echoes from patient's body as a function of time along a line at angle θ
  - Using the known speed of sound, and the arrival time of the echo, calculate the location (x, y) of each echo
  - Steer the beam to a new angle, and repeat
  - From the above data, compute and display an image in which the brightness of each pixel is the intensity of the echo at a point in the patient
- This image has the shape of a slice of a pie, i.e., a sector, and is called a "Brightness Scan" or "B-Scan"
  - We can also do linear (parallel) scans, and 3-D scans

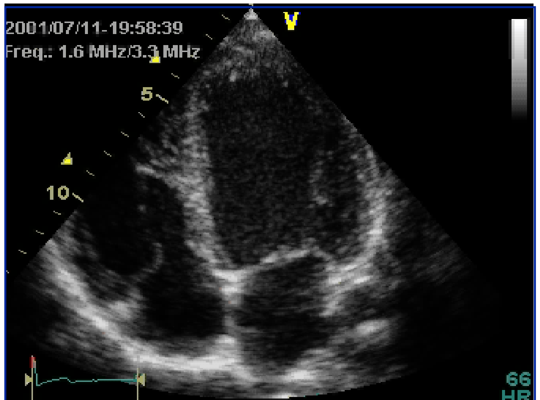


Ultrasound Scanners

- Most often prescribed modality
  - –Instrument sales: $4B every year



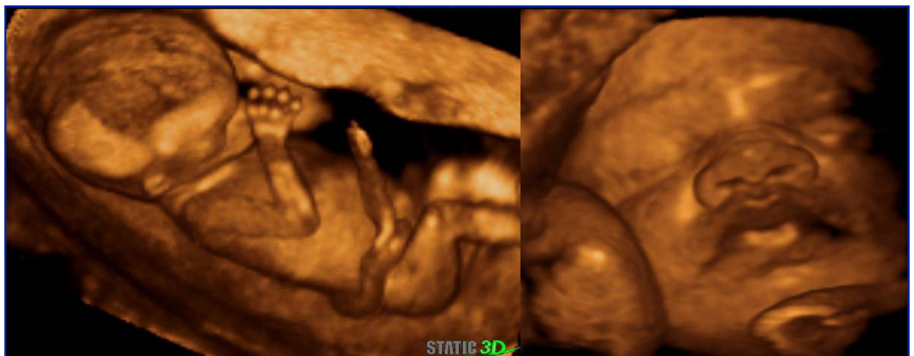
Variety of Applications



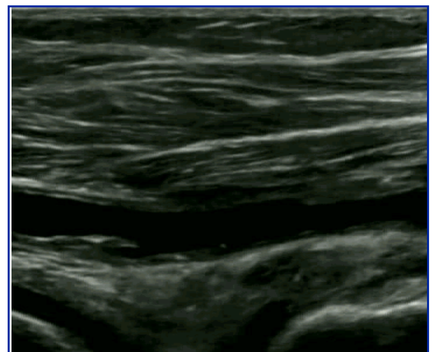
Cardiac

Kidney

Liver



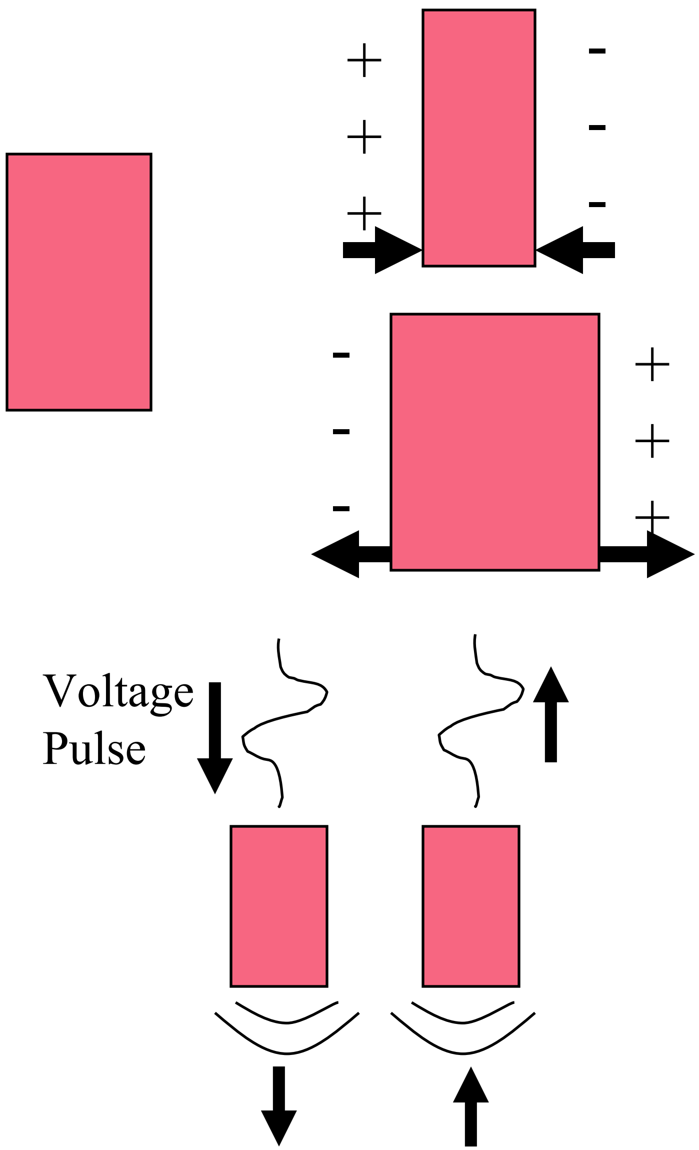
Obstetrics



Vascular

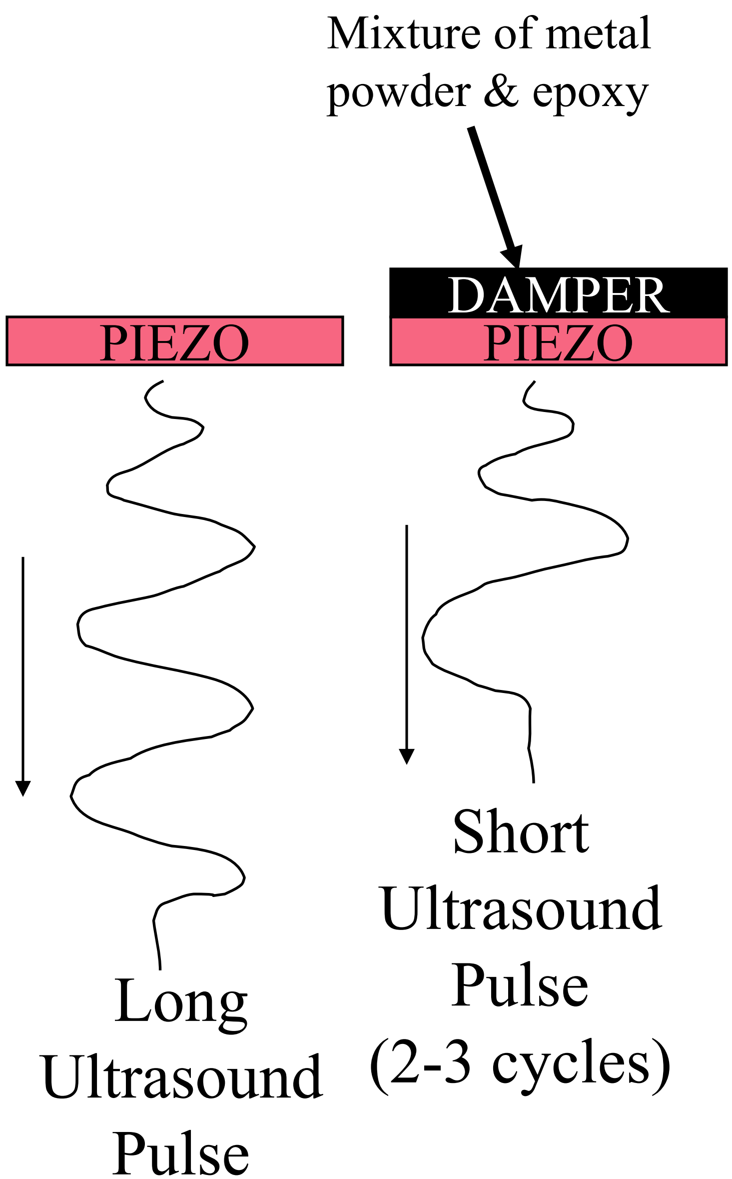
- Portable
- Low-Cost
- Safe
- Real-Time

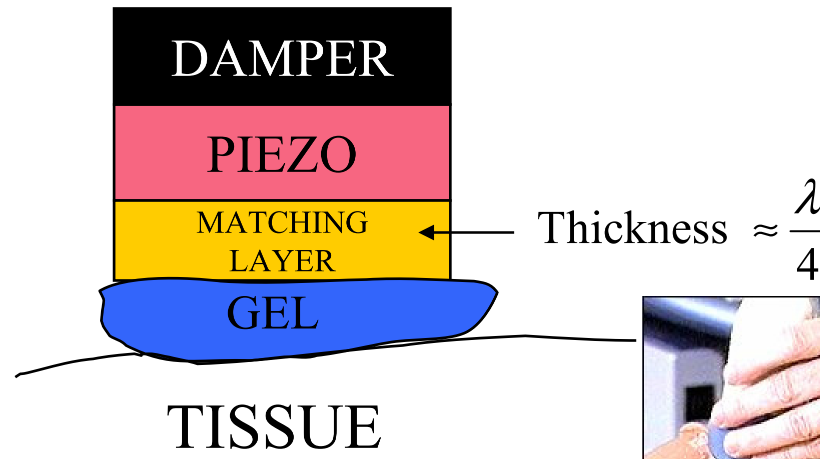
Ultrasonic Transducers



- Rely on the piezo-electric effect
  - "piezo" means to press in Greek
  - Lead Zirconate Titanate (PZT) a common piezo-electrical ceramic material
  - Material compresses or expands depends on polarity of voltage
  - **Works in reverse as well – compressing/expanding the material produces a voltage**
    - Can transmit and receive using the same device!
  - An array of piezo elements (crystals) provide an array of acoustic sources
    - Each element is roughly 0.2 – 1 mm thick
    - Smaller elements have higher resonance frequencies

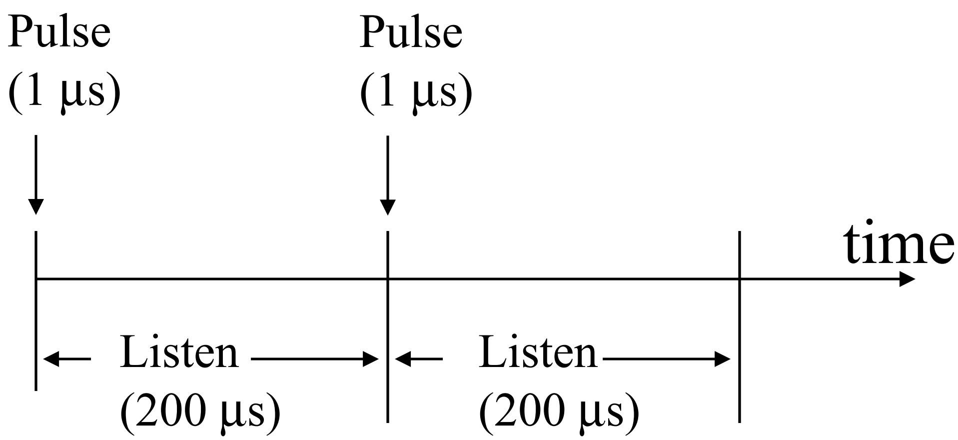
Damping & Coupling Materials





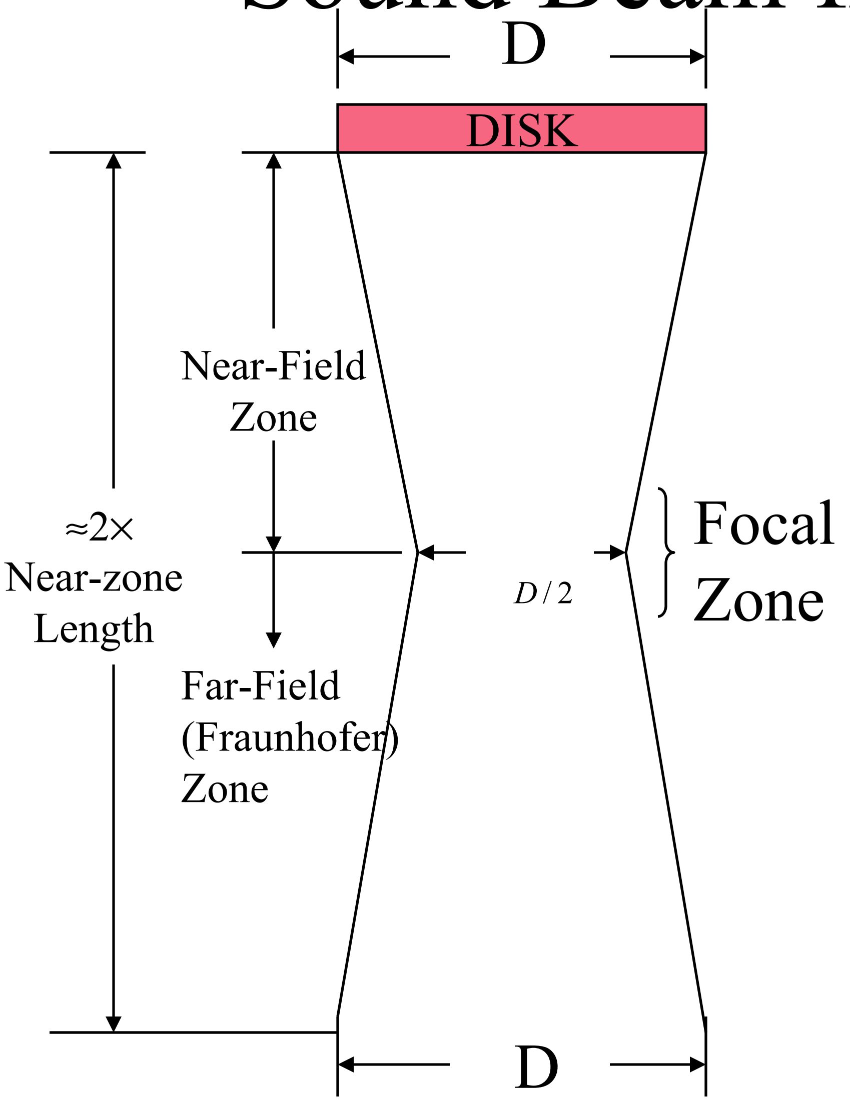
- The impedance of the solid transducer is 20 times that of tissue $\Rightarrow$ 90% reflection at surface
- The matching layer(s) and the gel are of intermediate impedance and they bridge the impedance gap
  - Better coupling

Pulse Timing Sequence



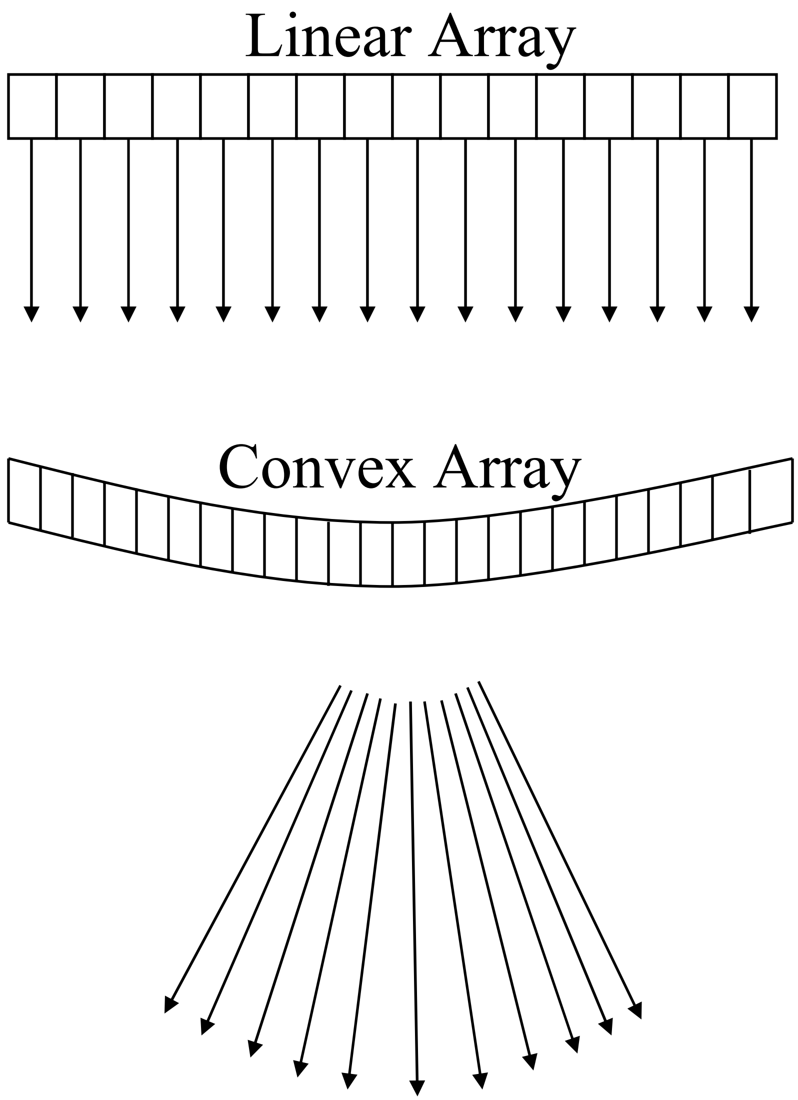
- Pulse repetition frequency (PRF)
  - Number of pulses sent to transducer per second
  - Ranges from 4-15kHz
- Listening time must be long enough to receive all echoes from the most recently sent pulse
  - Need to minimize "old echoes"
  - Deeper imaging requires lower PRF

Sound Beam from a Transducer



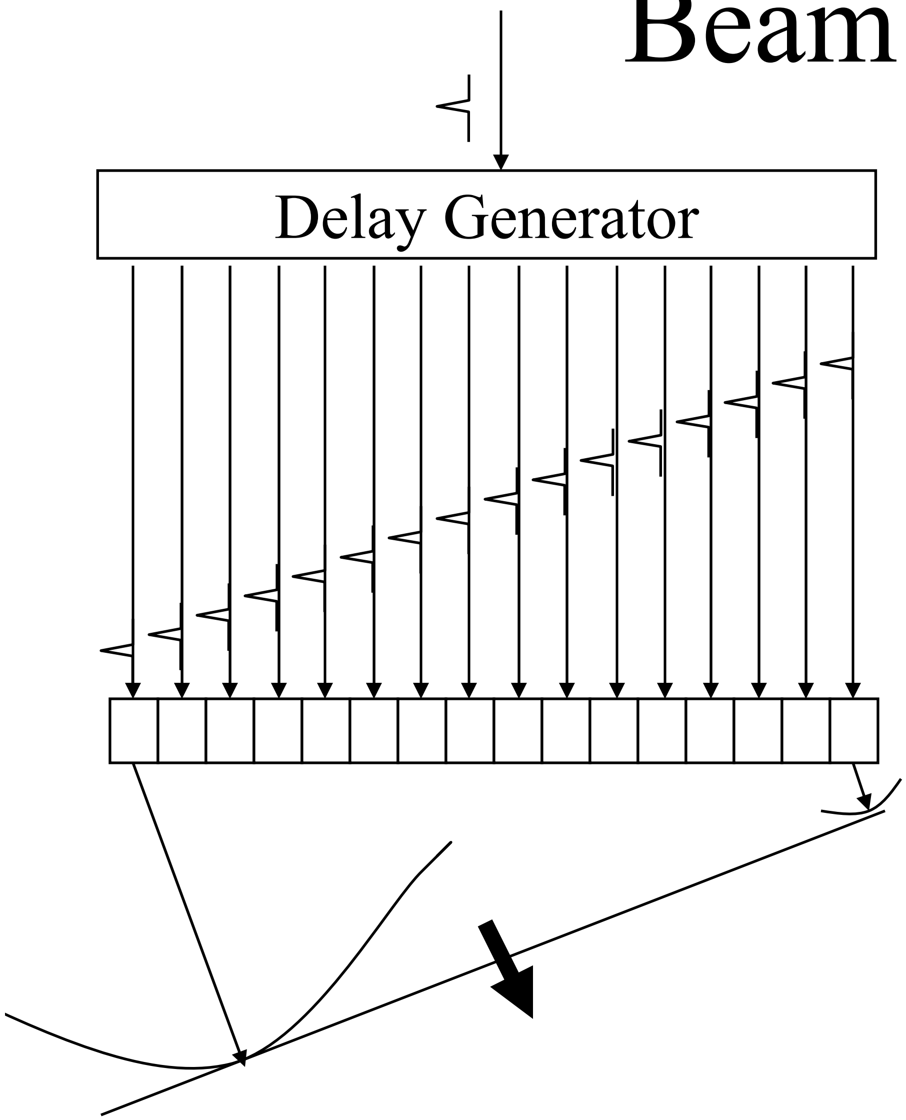
Frequency (MHz)	Width (mm)	Near-Zone length (cm)
2.0	19	12
3.5	13	10
3.5	19	20
5.0	6	3
5.0	10	8
5.0	13	14
7.5	6	4
10.0	6	6

Arrays of Transducers



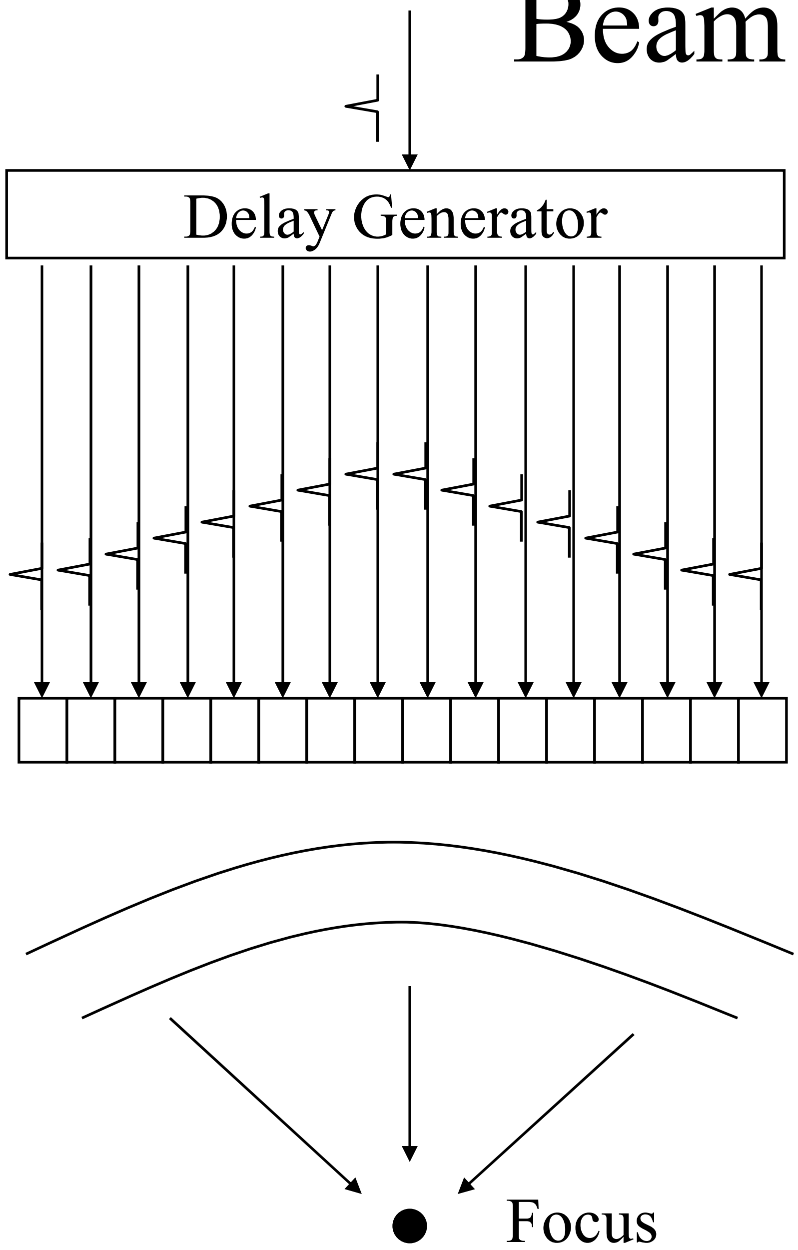
- Arrays are a recurring theme in imaging systems
- By timing the operation of array elements, we can achieve a large number of useful effects

Beam Steering



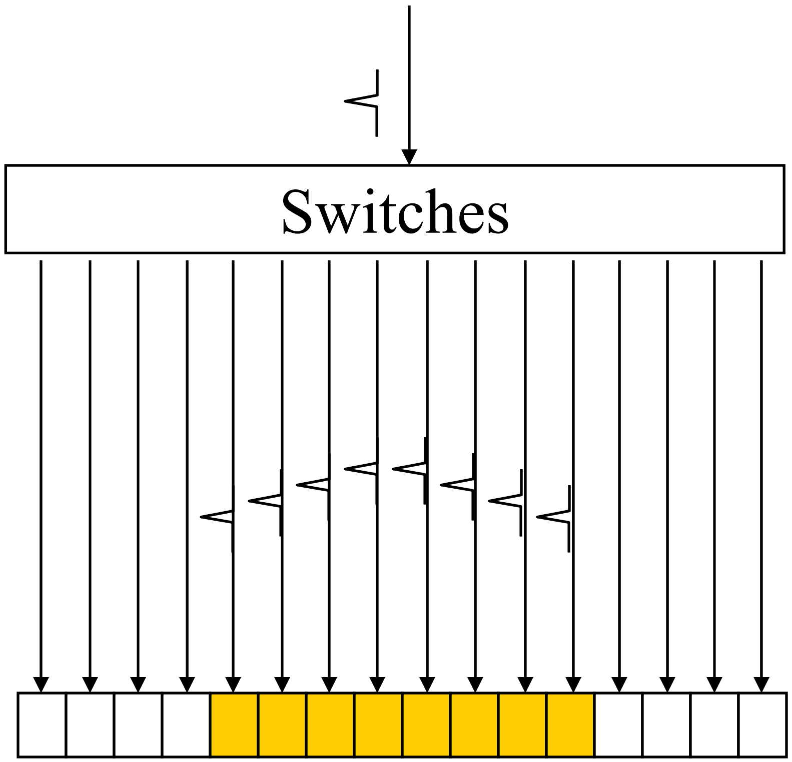
- Pulses are applied in rapid succession to adjacent transducers
- The sum of the waves generated by the transducers is a big wavefront
- The direction of the wavefront can be pointed at any desired angle

Beam Focusing



- Pulses to the center elements are send ahead of the peripheral transducers
- The sum of the waves generated by the transducers is a curved wavefront with a focus
- The focal length can be adjusted dynamically by varying the pulse timing

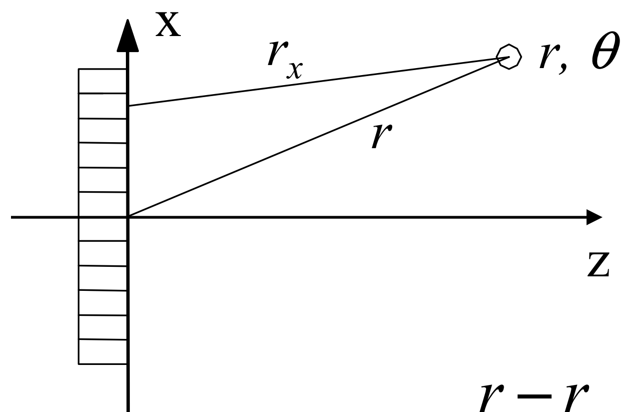
Variable Aperture



- We can choose to activate any subset of transducers
  - Small subset ⇒ low aperture
  - Big subset ⇒ large aperture
- Used to maintain comparable focal beam width at different depths
  - Low aperture at low depths
  - High aperture at high depths

Geometry for Beam Calculations

- Delay determination:
  - simple path length difference
  - reference point: phase center
  - apply Law of Cosines
  - approximate for ASIC implementation
- To combine steering & focusing, we can split delay into 2 parts:
  - beam steering
  - dynamic focusing

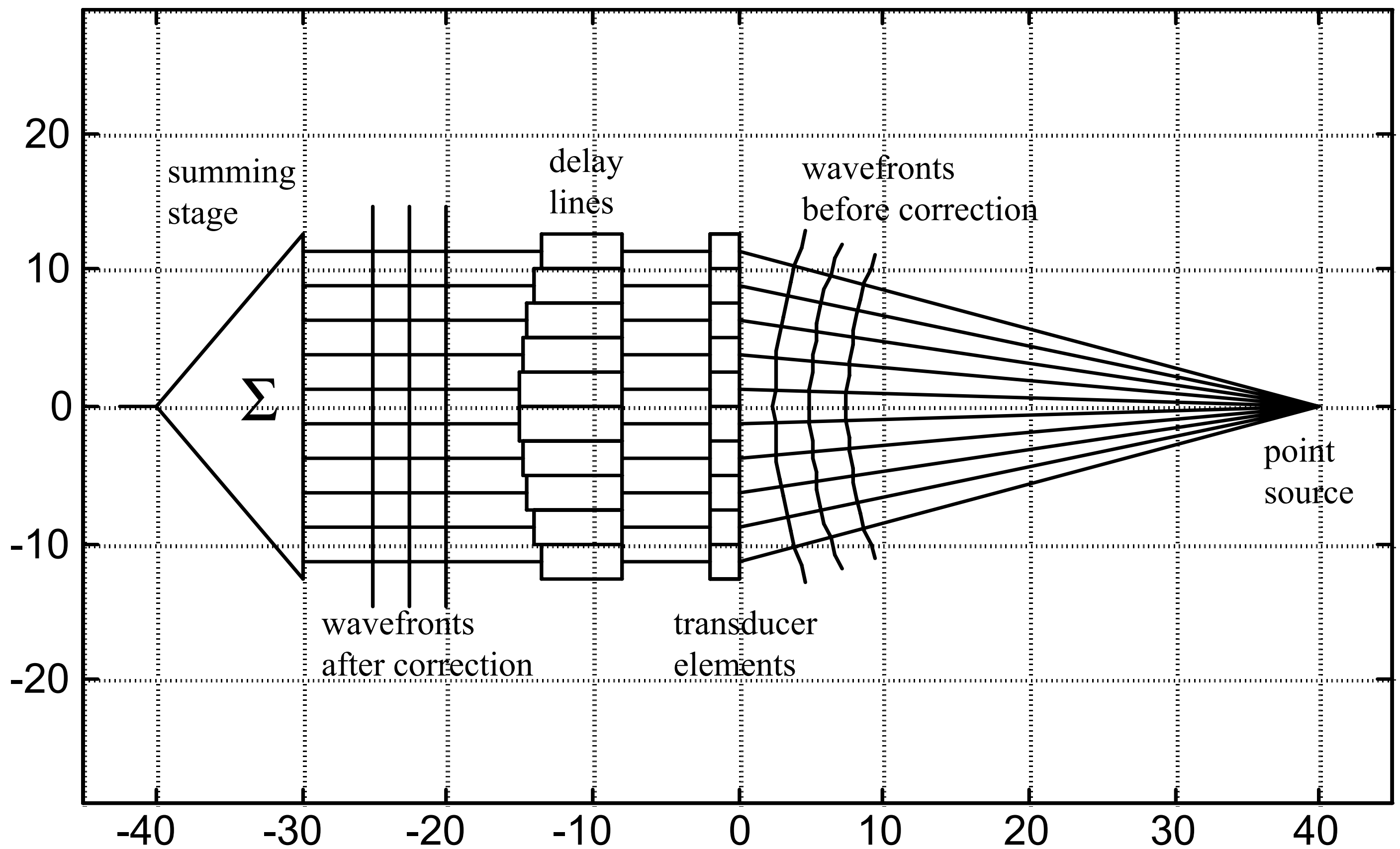


$$\tau = \frac{r - r_x}{c}$$

$$\tau = \frac{1}{c}\left[\sqrt{x^2 - 2rx\sin(\theta) + r^2} - r\right]$$

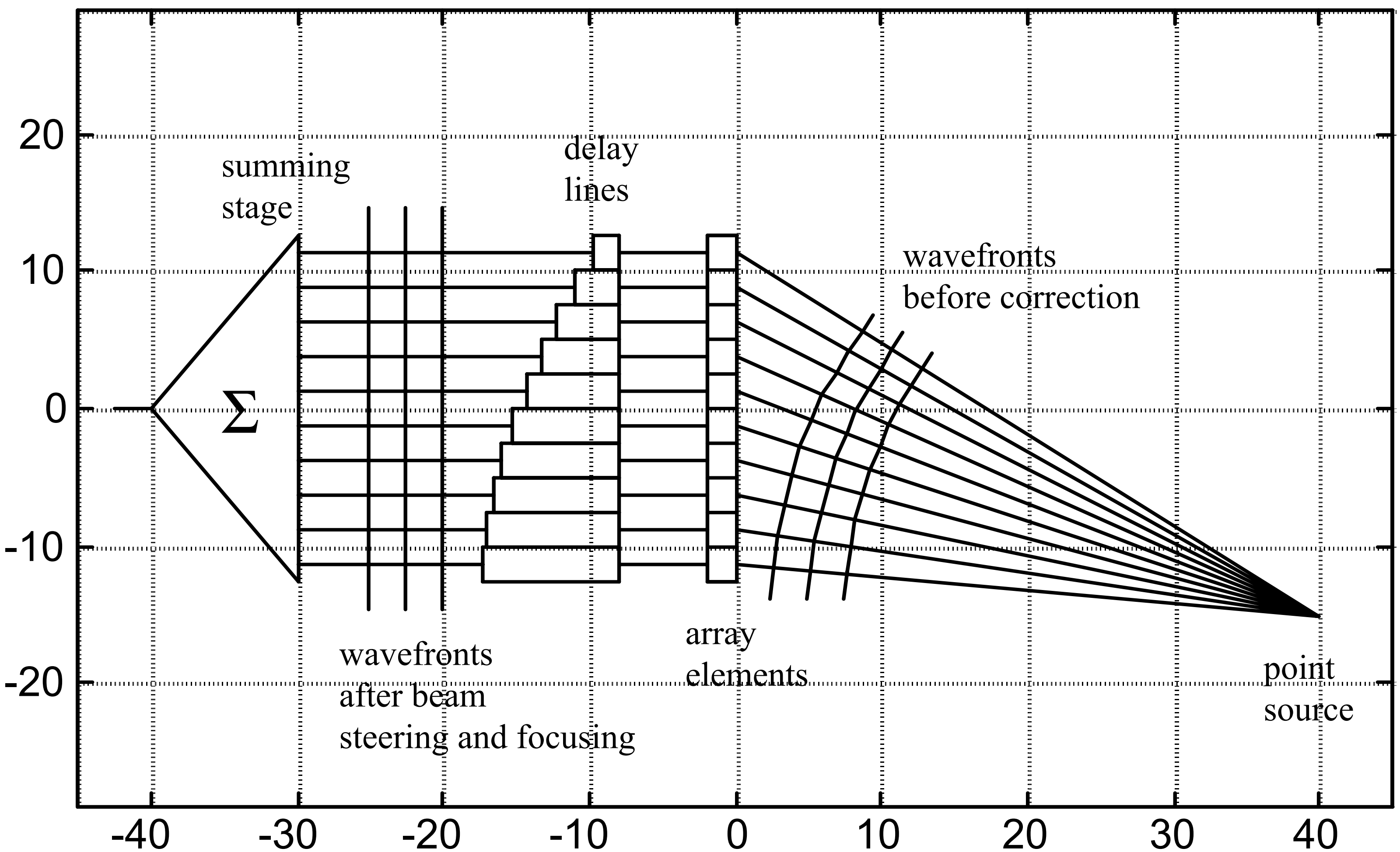
$$\tau = \tau_s + \tau_f$$

Reception Focusing

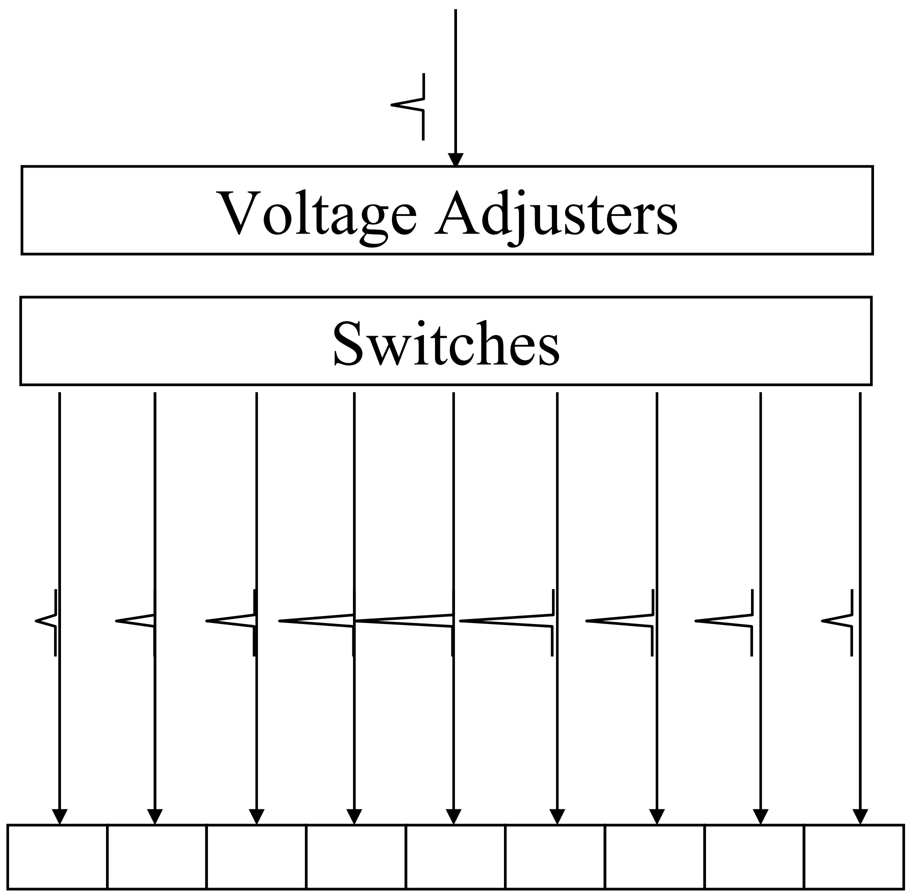


We can “listen” in a focused manner

Reception Focusing & Beam steering



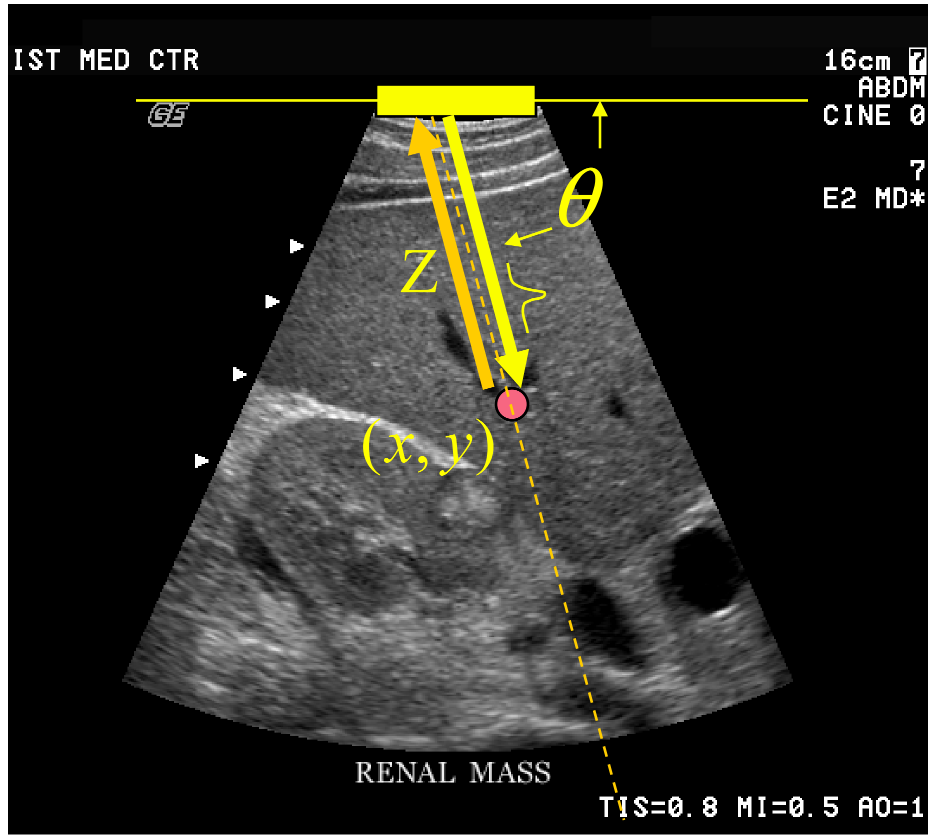
Apodization



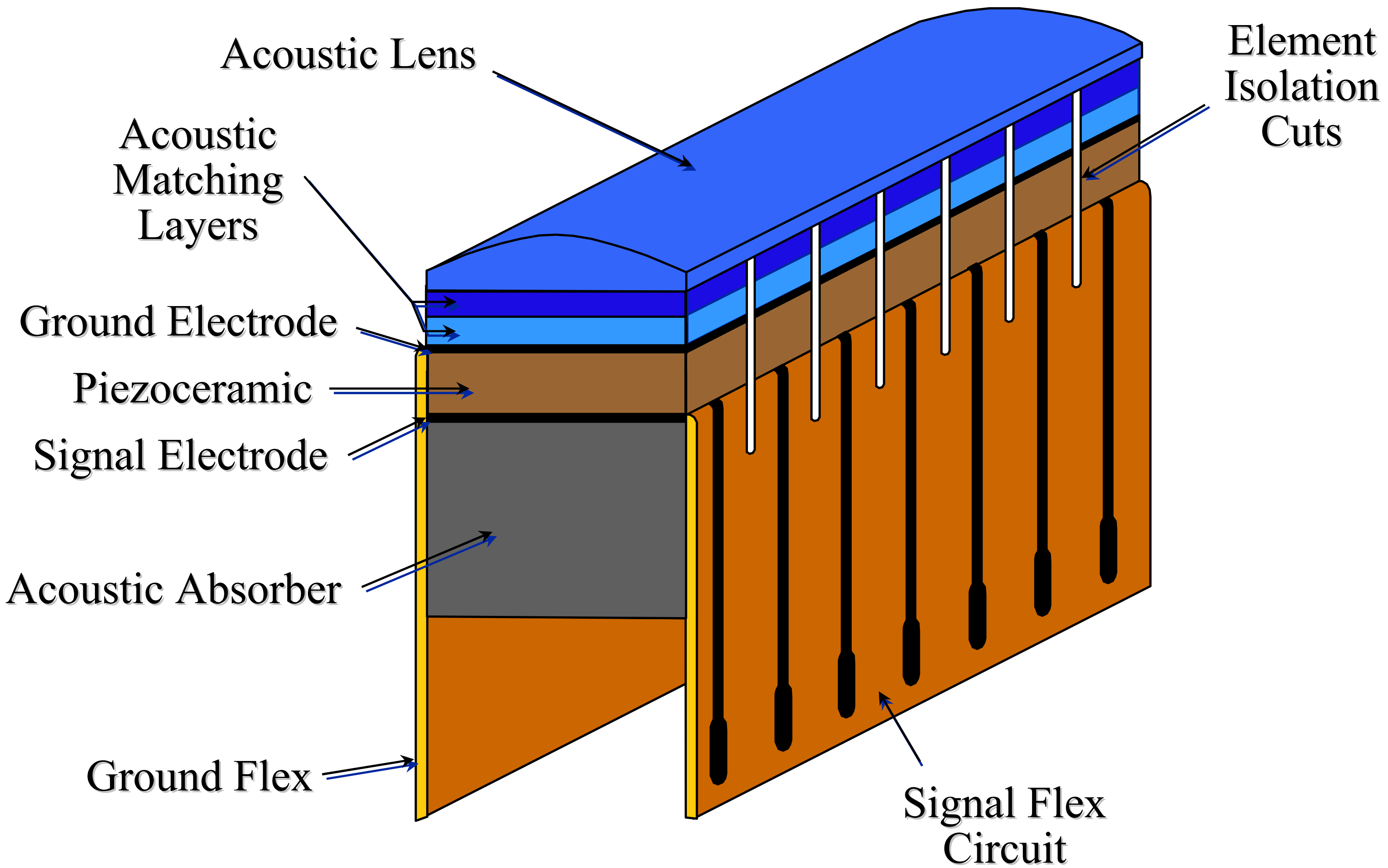
- We can choose to apply different voltages to transducers across the array
- Used to minimize sidelobes in the beam pattern
  - Higher voltages in the middle
  - Set according to a mathematical window pattern (e.g., Hamming Window)

Improved Pulse-Echo Imaging

- Focus the beam at a specific distance Z along the line
  - While listening, reject all echoes outside the focal zone
- Takes longer, but produces better images by rejecting clutter
- This is a recurrent idea in imaging systems
  - We'll see a similar idea in 3-D confocal optical microscopy!



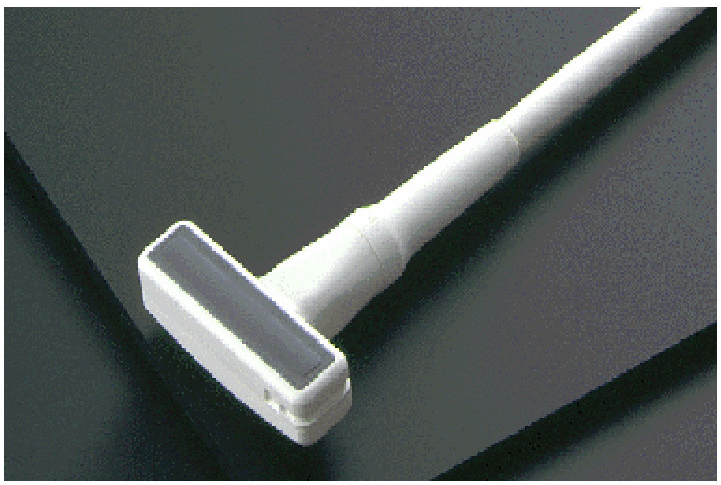
Ultrasound Transducer Array



Ultrasound Probes

Linear

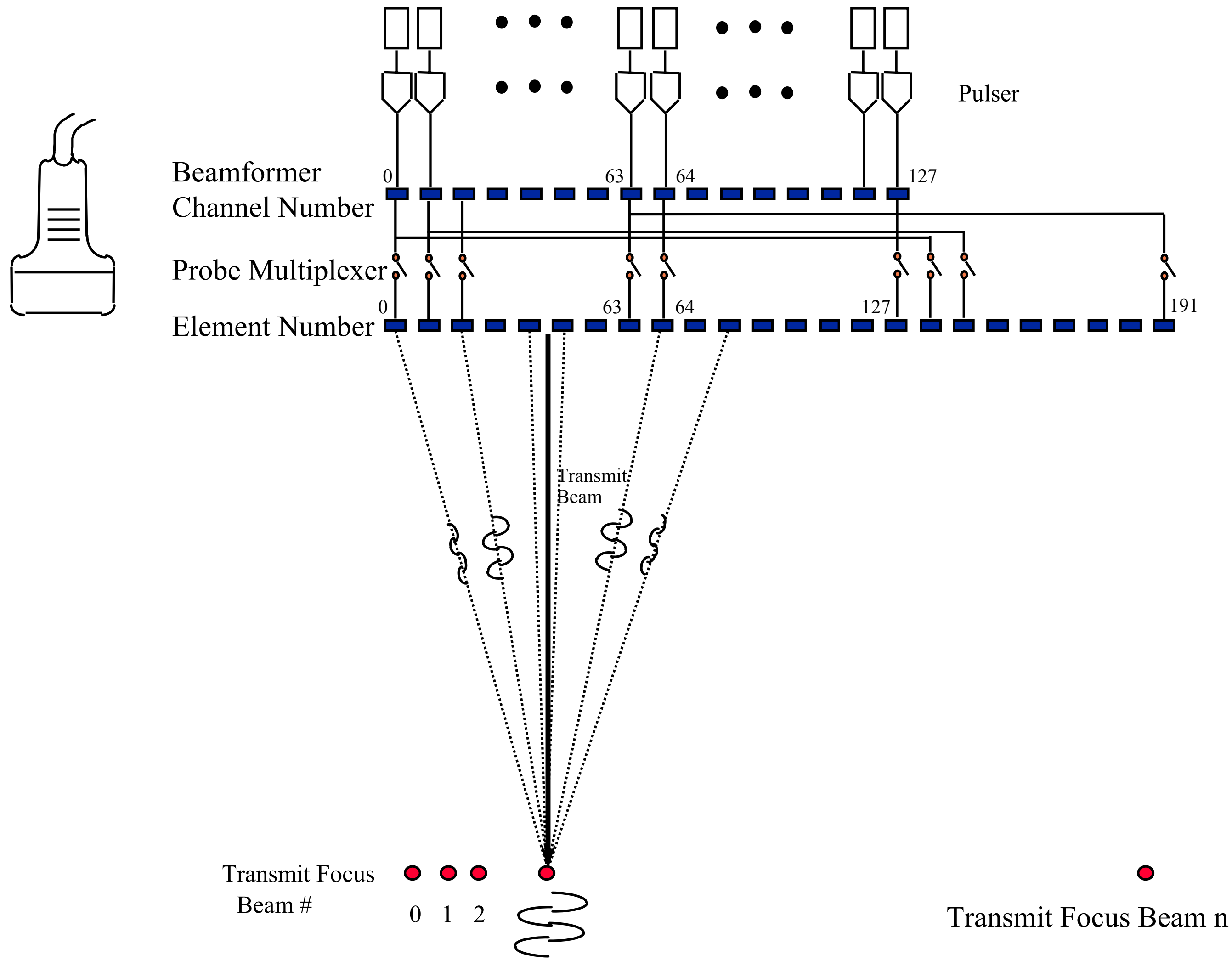
Convex

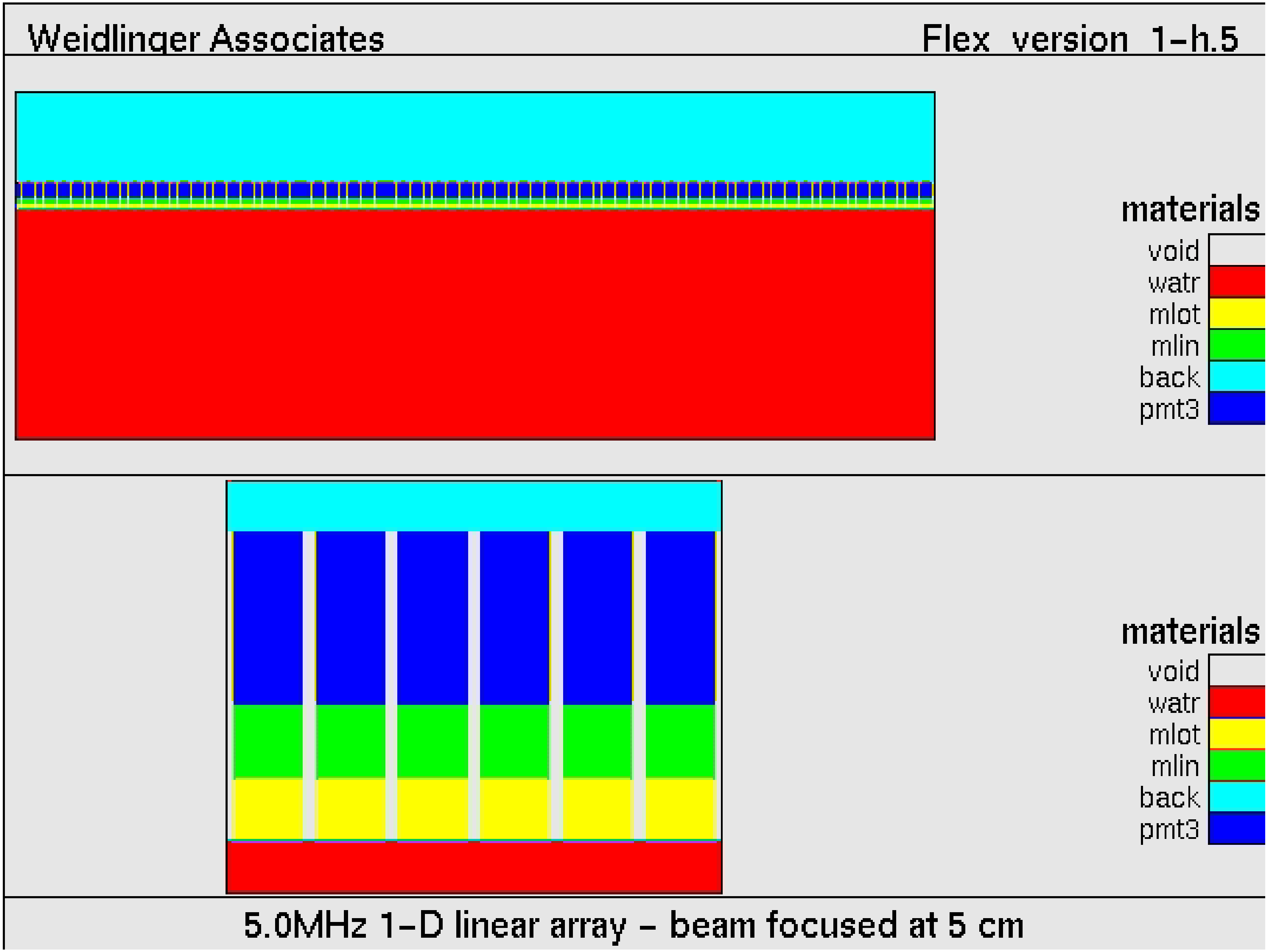


Intraoperative

Vaginal / Rectal

Linear Scan - Transmit Beamforming




Weidlinger Associates
Flex version 1-h.5
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void
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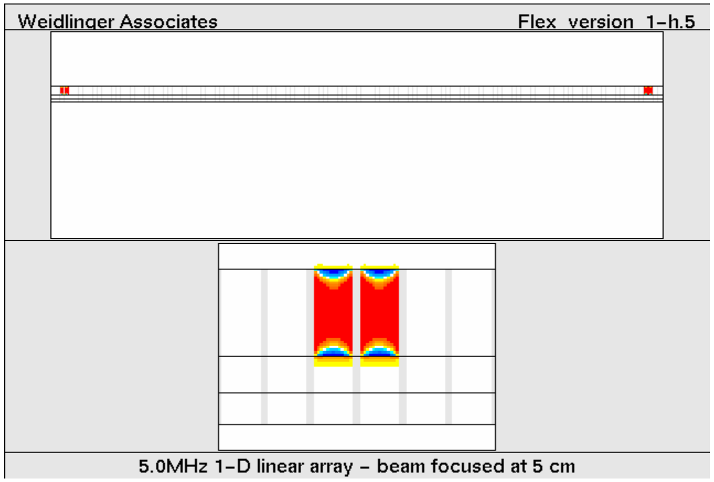
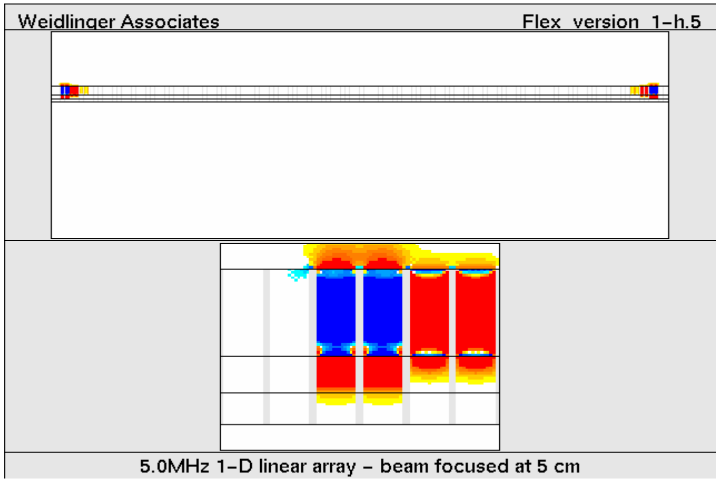
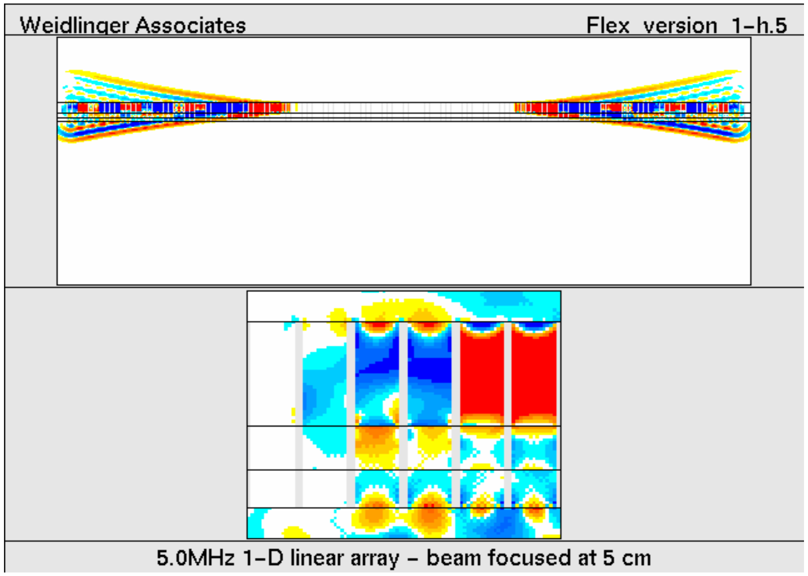
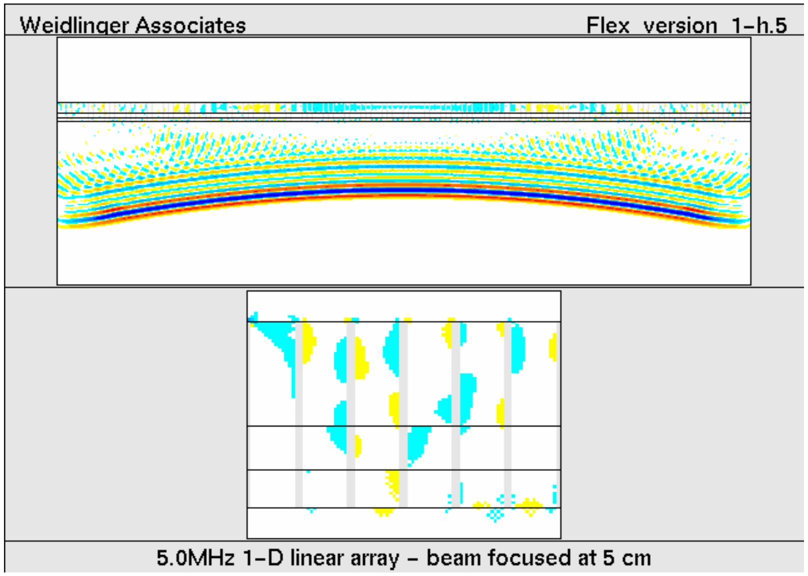
5.0MHz 1-D linear array - beam focused at 5 cm

Still images from sequence

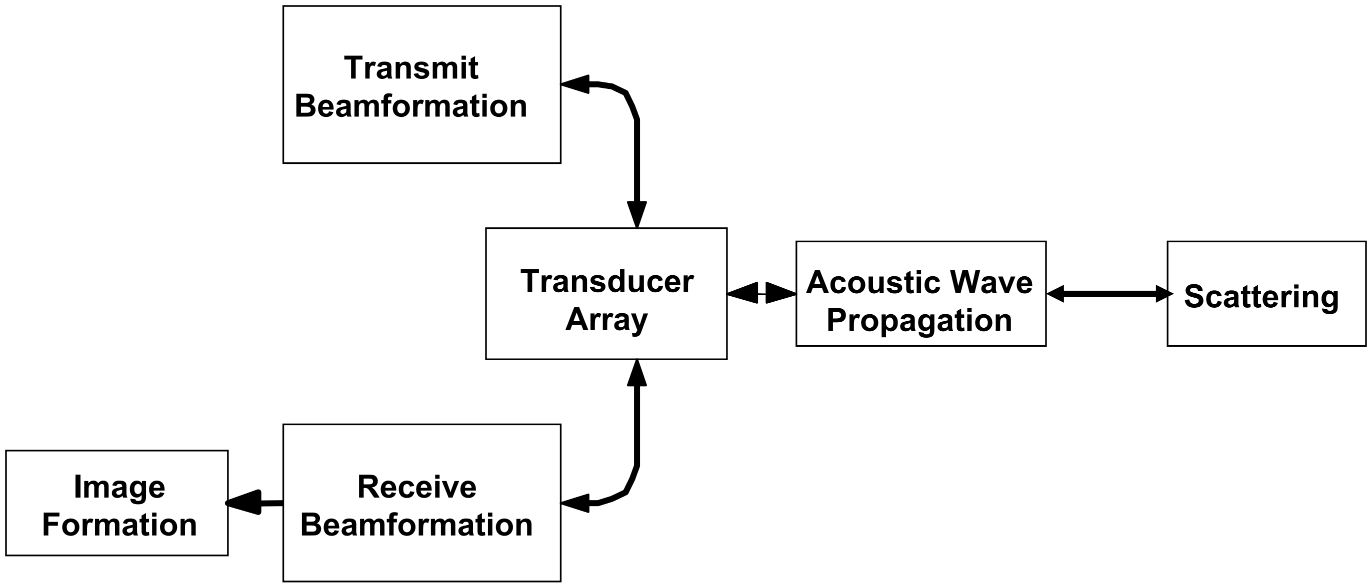






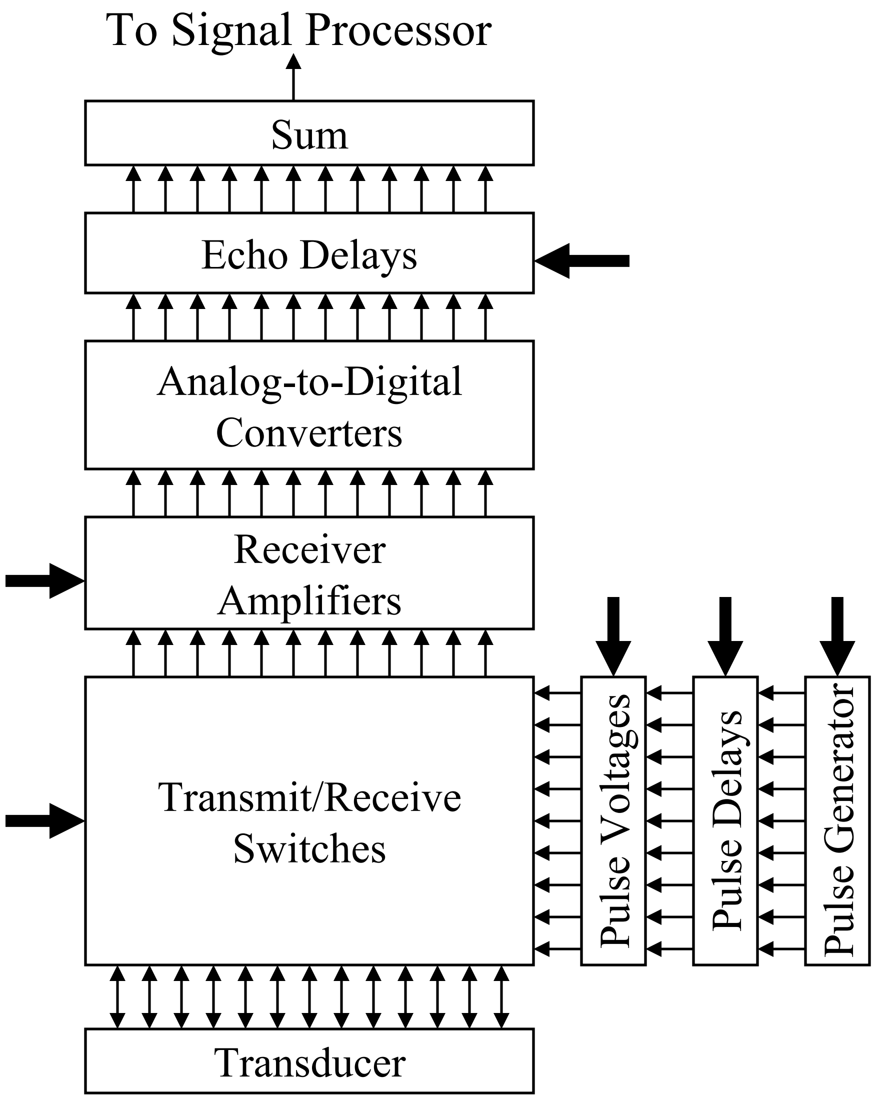


Overall Block Diagram of an Ultrasound Scanner



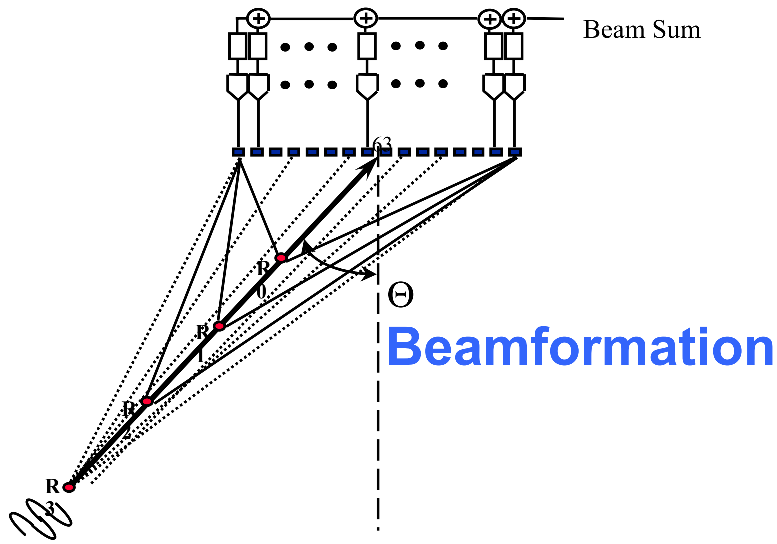
- Beamformation: generation of coordinated timing signals for transmit and delays for receive processes.
  - Probably the most expensive building block.
- Transducers: usually multi-element arrays or piezoceramic elements.
- Image formation: conversion to video raster, image processing.

Beam Former

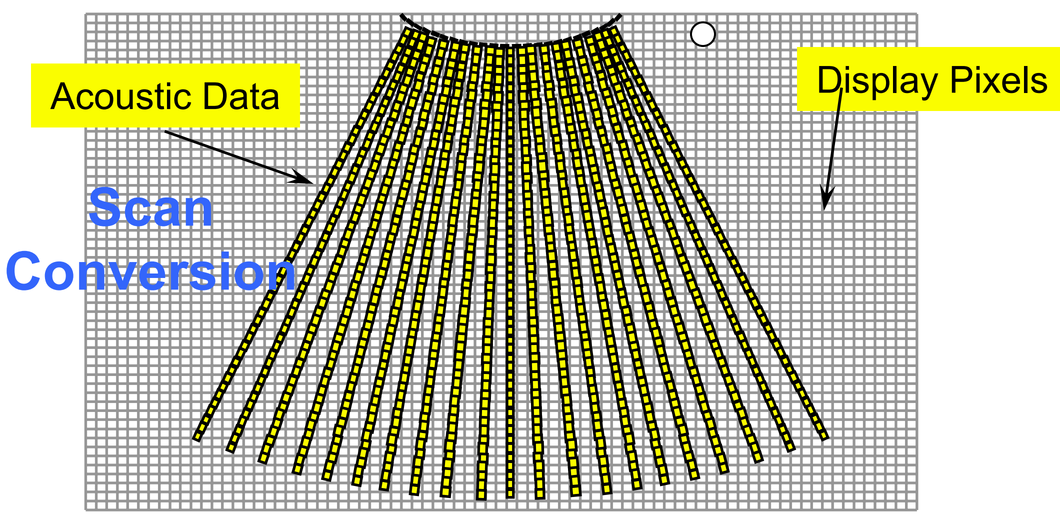


- The heart of the machine
- Lots of functions
  - Generate voltages to drive transducers
  - Determine PRF, frequency, intensity, etc.
  - Steer, scan, focus & apodize the transmitted beam
  - Amplify received echo voltages
    - Adjust gain to correct for depth-dependent attenuation
  - Digitize echo voltages
  - Direct, focus, and apodize the reception beam

Scan Conversion

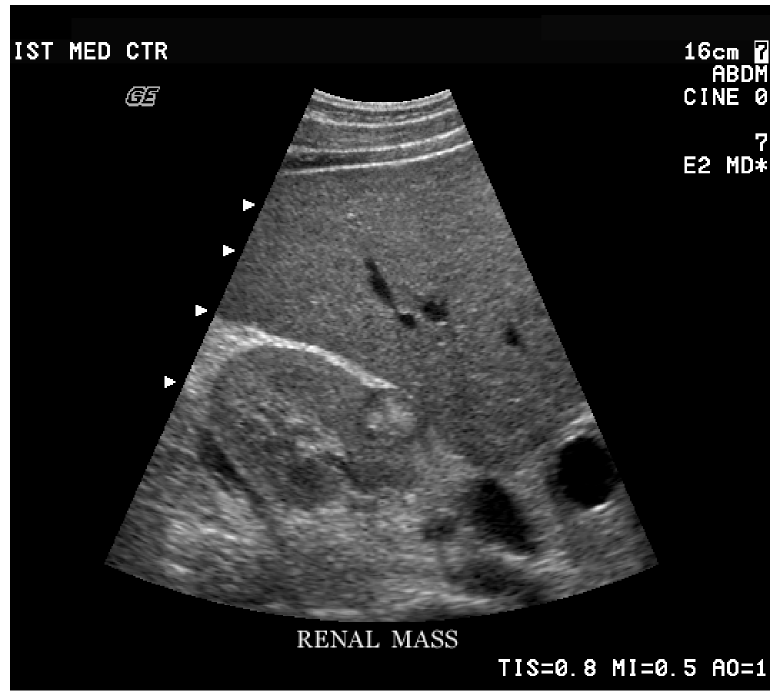


- Vectors from acoustic space must be scan converted to display pixels (rasterized)
  (nominal 400 x 400 pixels)
  - (R, Θ) to (X,Y)
  - (X,Y) to (X,Y)



Sequence of Events in Scanning

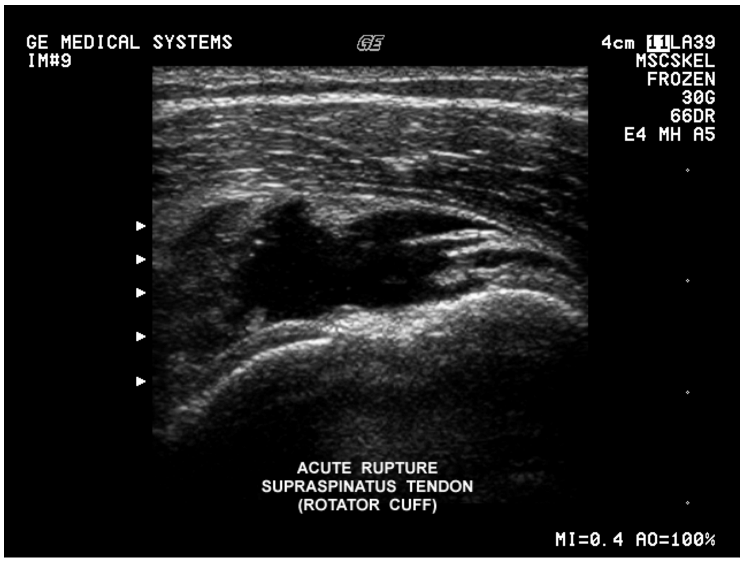
- System processor initiates a scan
  - Beamformer set to appropriate:
    - Scan angle
    - Transmit focal location
  - Pulsing voltage applied to array elements in timed sequence.
  - Sound emitted from elements
  - Pre-amplifiers initiate reception of echoes
  - Receive beamformer applies needed delays to optimize energy from desired focus and look angle.
  - Data stored, scan conversion to video raster begins
- Process repeats itself.



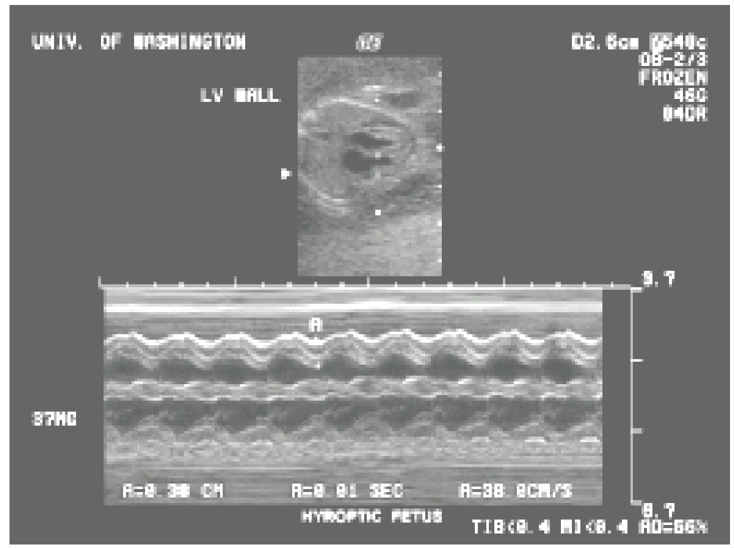
Time-Lapse Imaging

- The entire sequence of events we just discussed can be completed surprisingly fast (<< 1 sec)
- Once we start to approach 15 – 30 frames/sec for the entire scan, the system is considered “real time”

Scanning Modes



B-Scan Real Time

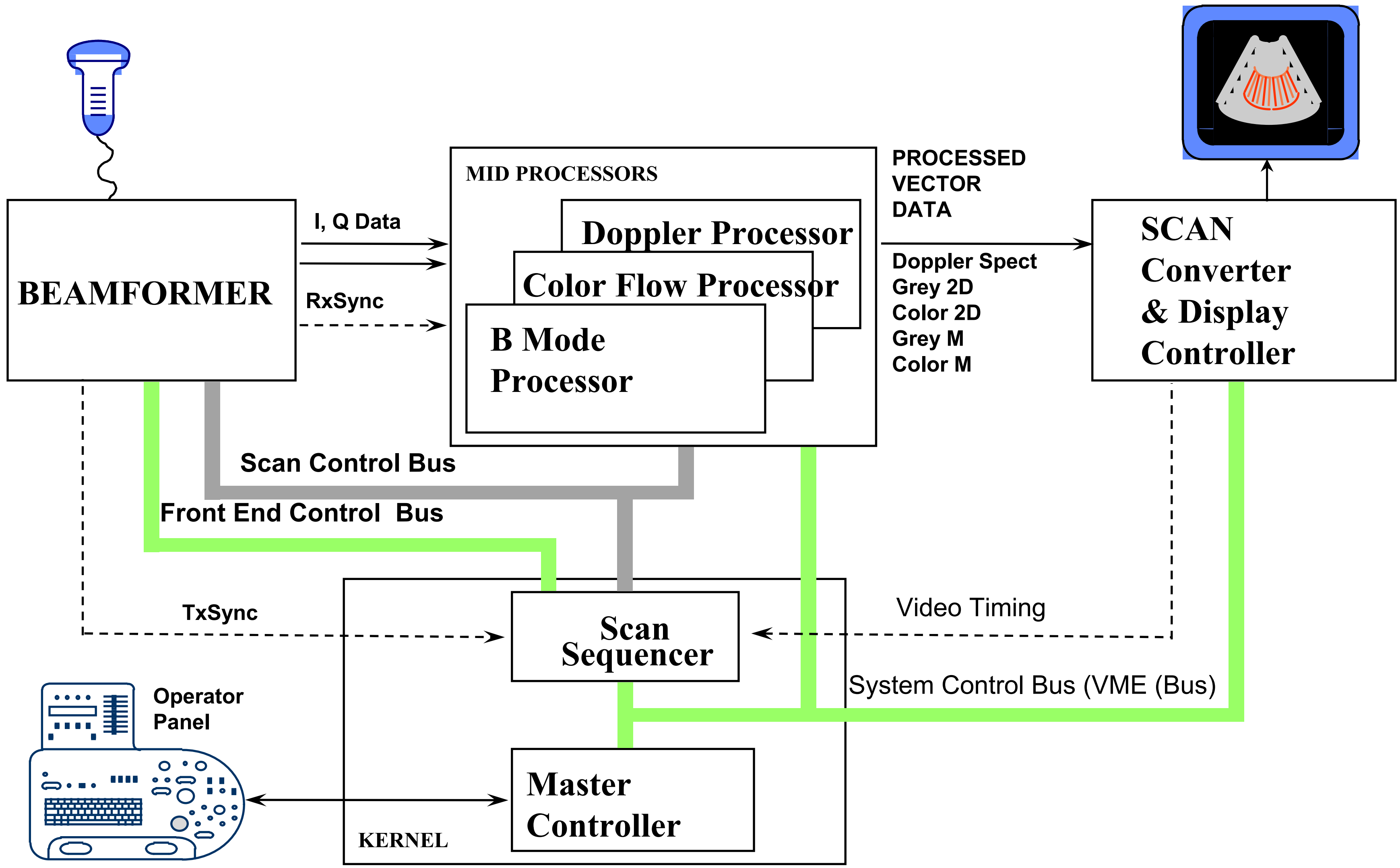


time

M-Mode

There are several additional modes, mainly involving Doppler. These will be covered in later lectures.

Typical Commercial Ultrasound System



Homework

1. For a 10-mm disk transducer, what are the beam widths at the near-zone length and at 2 times the near-zone length?
2. Download & install **Field II** and the **User's Guide** to your computer.
    1. http://www.es.oersted.dtu.dk/staff/jaj/field/index.html
3. Execute the first example from http://www.es.oersted.dtu.dk/staff/jaj/field/examples.html, the point spread function logo case.
    - You should get a strange looking impulse response.
    - Don't forget to initialize Field with field_init command!
4. Change the number of transmitted cycles to one cycle, three cycles. How does the point spread function change?
5. Hand in your graphical MATLAB results.

Summary

- We have reviewed the major building blocks of an ultrasound scanner:
  - Transduction
  - Beamformation
  - Steering, Focusing, Apodization
  - Scan conversion
- Next Class:
  - We'll learn about the Field II MATLAB simulation program.