Ultrasound Pulser ICs for Non-Destructive Testing and Medical Imaging Applications

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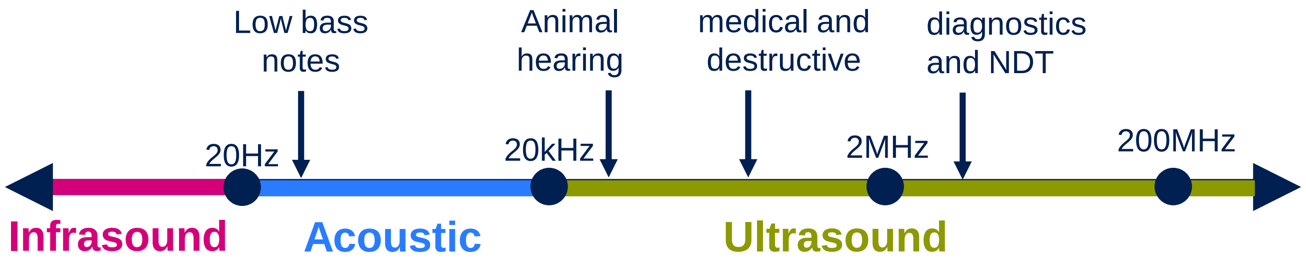
Santa Clara, CA

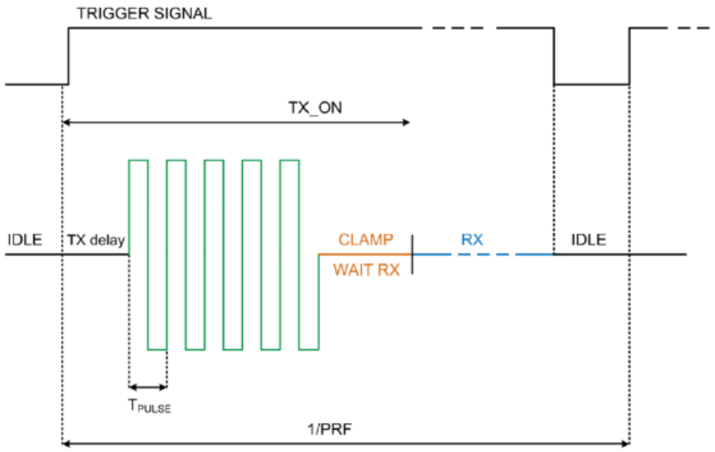
Presentation Outline

- Ultrasound physics:
  - Ultrasound waves
  - Propagation
  - Transducers
  - Beamforming
  - Doppler effect
- Applications:
  - Medical application
  - NDT application
- System and Products:
  - System Architecture
  - ST portfolio

Ultrasound Waves

- Sound is a mechanical wave (acoustic wave) coming from a vibrating object, propagating in an elastic medium (solid, liquid or gas) through particle collision. The pressure of the wave causes the particles of the substance to move.
- Ultrasound is a sound wave with frequency above the audible range limit of human hearing (over 20KHz). Standard application frequencies are 500kHz - 20MHz.
- From the physical point of view, an ultrasound wave is no different from an acoustic wave

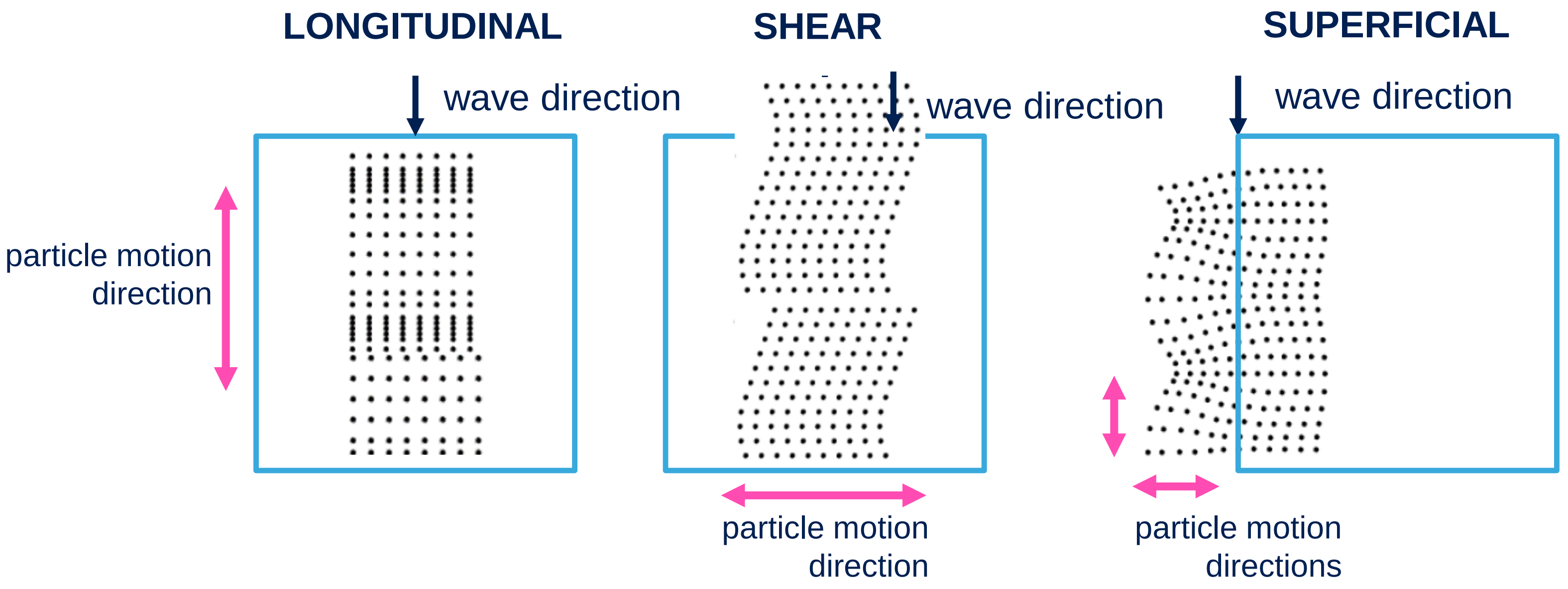




Typical Application

Ultrasound Wave Propagation

- **Longitudinal wave:** expansion and compression, particles moving from rest position in the same direction of wave propagation. It can propagate in solid, liquid or gas.
- **Shear (transverse) wave:** particle vibrations are perpendicular to the wave direction. Speed is lower (about half) than longitudinal wave. It can propagate only in solid mediums.
- **Superficial wave:** the oscillating motion travels along the surface to a depth of one wavelength; the particle movement is a combination of longitudinal and transverse motion, creating an elliptic pattern of motion. Superficial waves follow the surface profile. It can propagate in solid materials.



- In solid materials one form of wave energy can be transformed into another: Longitudinal wave hits interface → creation of shear wave

Main Parameters

- T [s]: time between two maximums of the waveform (Period)
- f [Hz]: Frequency = 1/T
- c [m/s]: propagation speed, it depends on the material properties (elasticity k and density ρ) where $c = \sqrt{k/\rho}$.
- λ [m]: wavelength = c/f
- α: medium attenuation, used to calculate the wave attenuation vs. penetration $A(x) = A_0 e^{-\alpha x}$
  - Absorption is the transformation of Ultrasound energy in thermal energy
  - Diffusion is the beam dispersion, attenuation in the propagation direction
- Z: acoustic impedance, $Z = \rho \cdot c$.
  - It is the resistance to the acoustic particle flow.
  - Ratio of the pressure over an imaginary surface in a sound wave to the rate of particle flow across the surface $Z = p/v$ (Kg/(m2 sec) = Rayl)
  - Characteristic acoustic impedance $Z_0 = \rho \cdot c$
  - Impedance mismatch is the cause of scattering, transmission and reflection

Medium	c [m/s]	ρ [kg/m³]	Z_0 [MRayl]
Air	330	1.2	0.0004
Water	1480	1000	1.48
Aluminum	6320	2700	17.06
Bronze	3530	8860	31.27
Copper	4660	8930	41.60
Iron	5900	7700	45.43
Lead	2160	11400	24.62
Silver	3600	10500	37.80
Titanium	6070	4500	27.31
Blood	1584	1060	1.68
Bone, Cortical	3476	1975	7.38
Cardiac	1576	1060	1.67
Connective Tissue	1613	1120	1.81
Muscle	1547	1050	1.62
Soft tissue	1561	1043	1.63

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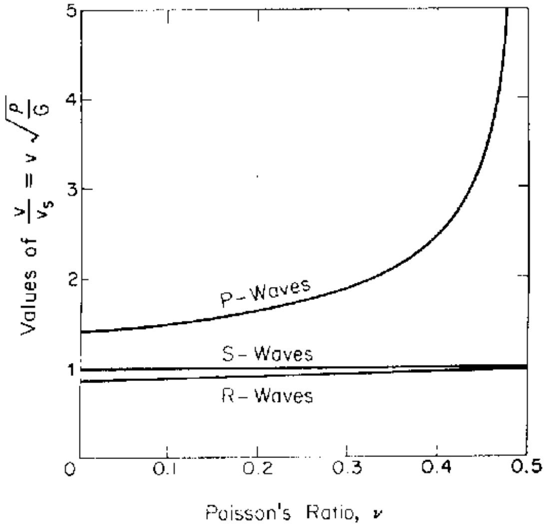
Propagation Speed

- Depends on material properties, different elastic constants are used:
  - Bulk modulus, **K**: a measure of the incompressibility of a body subjected to hydrostatic pressure. Describes response to uniform compression. Air → 100kPa, Rubber → 1.5 GPa, Water → 2.2 GPa, Steel → 160 GPa
  - Young's Modulus, **E**: stiffness, a proportionality constant between uniaxial stress and strain. Describes response to linear stress. Measures deformation in the direction of stress. Rubber → 0.1 GPa, Steel → 200 GPa, Diamond → 1.1TPa
  - Poisson's Ratio, **ν**: the ratio of radial strain to axial strain. Describes response to linear stress. Measures deformation in the directions perpendicular to the direction of stress. Rubber → 0.5, Steel 0.3, Cork → 0.0
  - Shear Modulus, **G**: also called rigidity, a measure of a substance's resistance to shear. Describes response to shear. Rubber → 0.6 MPa, Titanium → 41.4 GPa, Steel → 79.3 GPa, Diamond 478 GPa
  - Longitudinal Modulus **M**: = K+4G/3
- Longitudinal wave in gas/fluid: $c = \sqrt{K/\rho}.$
- Longitudinal wave in solids: $c = \sqrt{(K + 4/3G)/\rho}.$
- Shear wave in solids: $c = \sqrt{G/\rho}.$



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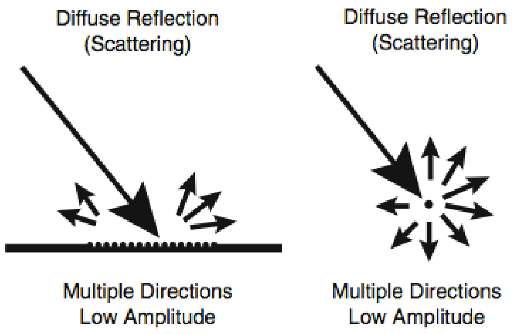
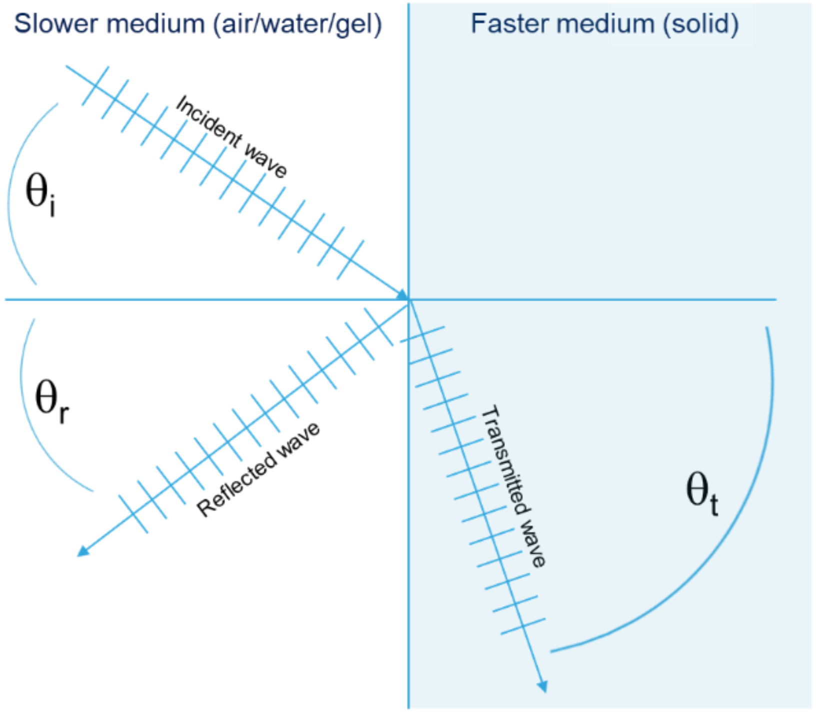
Scattering, Reflection & Transmission

At the boundary between materials with different acoustic impedance and different acoustic velocity

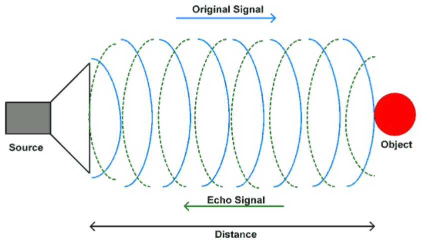
- Scattering: the energy lost when the wave propagates onto a medium interface whose irregularities are comparable with λ (the two mediums must have different acoustic impedance)



- Reflection/Transmission: when an incident wave propagates onto an interface larger than λ, the "ray approximation" can be used.



- The reflected wave is the *echo*



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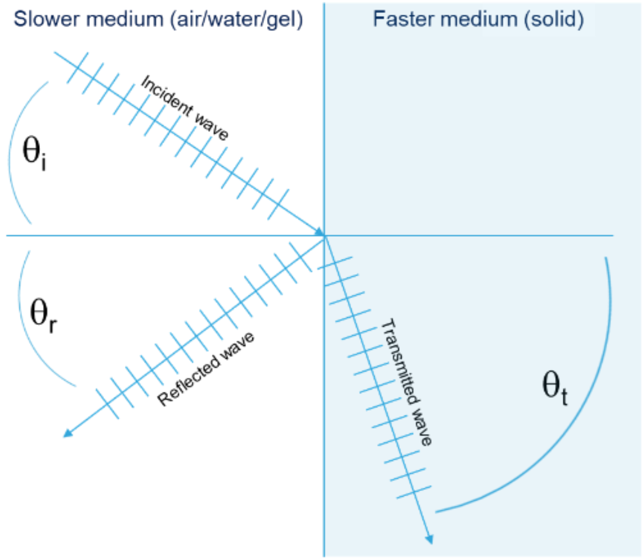
Transmission and Reflection

- Angle of refraction is defined by Snell's law:

$$\frac{\sin\theta_I}{\sin\theta_T} = \frac{c_1}{c_2}$$

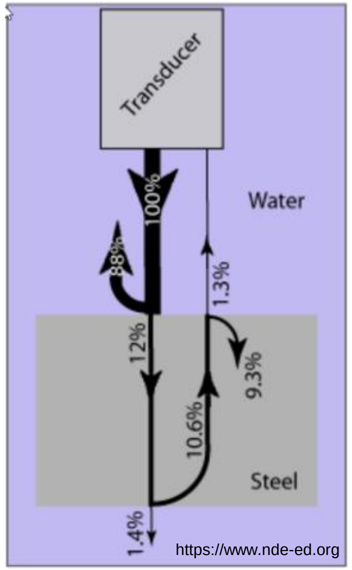


- The angle of reflection is equal to the incident angle
- The fraction of transmitted and reflected energy depends on the acoustic impedance (Z) and incidence angle (θ). The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and another

$$R = \frac{(Z_2 \cos\theta_i - Z_1 \cos\theta_t)^2}{(Z_1 \cos\theta_t + Z_2 \cos\theta_i)^2}$$

$$T = 1 - R = \frac{(4 Z_1 Z_2 \cos\theta_i \cos\theta_t)^2}{(Z_1 \cos\theta_t + Z_2 \cos\theta_i)^2}$$

- Couplant: material facilitating transmission of ultrasonic energy from transducer to material.
  - Couplant (usually liquid) displaces air between transducer and material, reducing the acoustic impedance mismatch and therefore reflected energy



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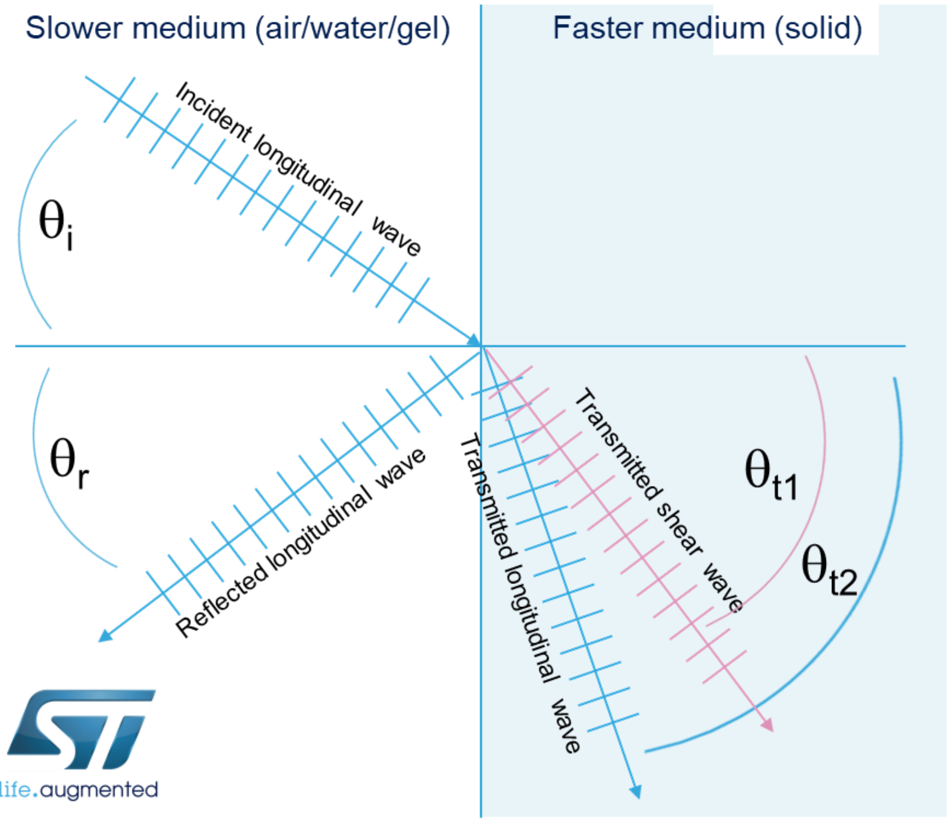
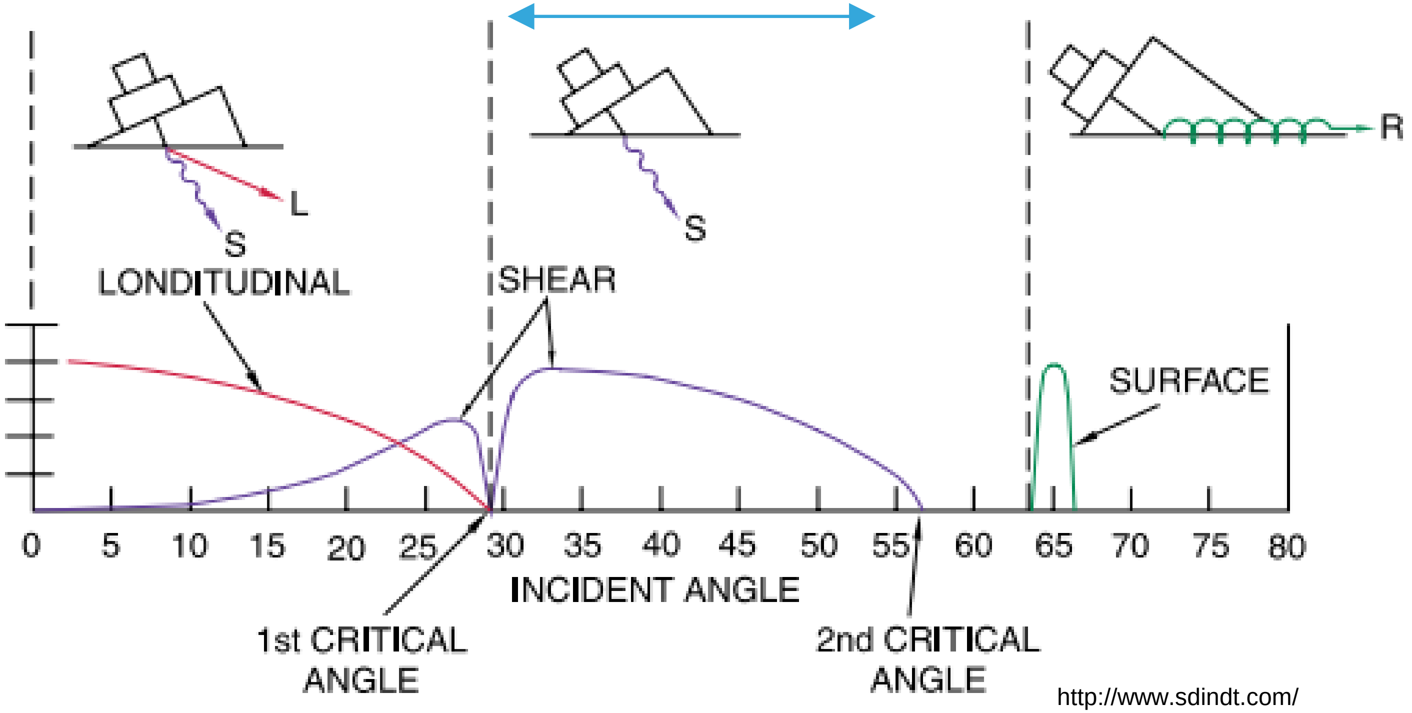
Critical Angle Incidence

- At the interface between slow and fast medium, part of the incoming longitudinal wave energy is reflected, part is refracted as longitudinal wave, part is refracted as shear wave
- 1st critical angle: incident angle that makes the angle of refraction of the longitudinal wave exactly 90°
- 2nd critical angle: incident angle that makes the angle of refraction of the shear wave exactly 90°



Preferred condition in NDT: only shear wave into material, avoids multiple echoes from same irregularity



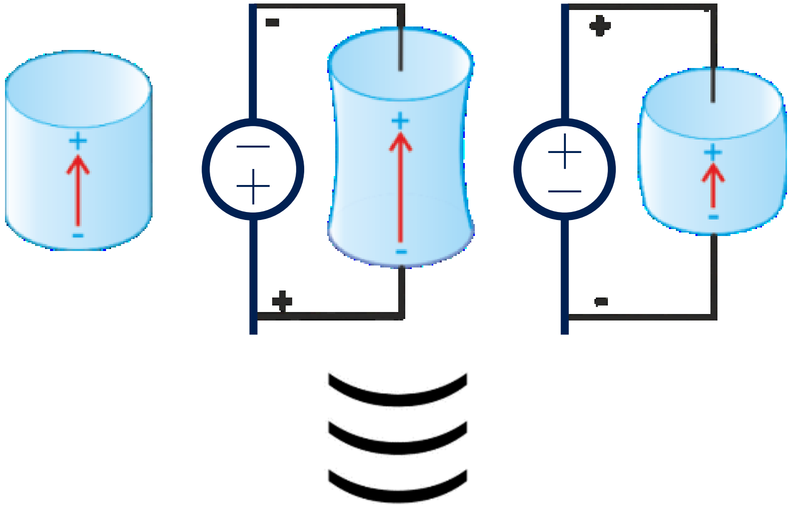
http://www.sdindt.com/

Transducer

- converts electrical signals into mechanical vibrations (transmit mode) and mechanical vibrations into electrical signals (receive mode)

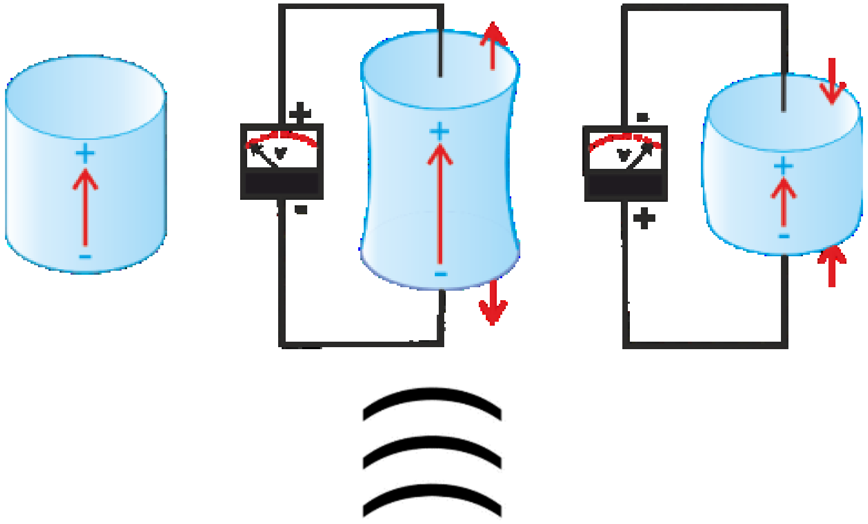
Transmission (TX) mode

E.g. Forcing a voltage on a piezoelectric material, it contracts or expands proportionally to the applied voltage



Receiving (RX) mode

E.g. Forcing a mechanical stress on a piezoelectric material, it generates an electric field



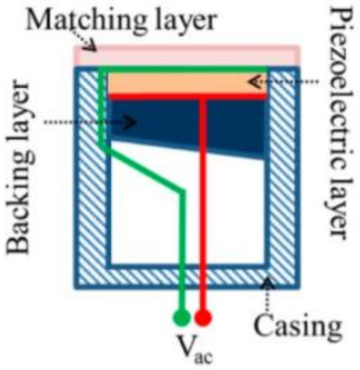
Transducer Types

- An Ultrasound transducer is a material able to convert electrical energy into mechanical vibrations (ultrasound waves) and vice versa.

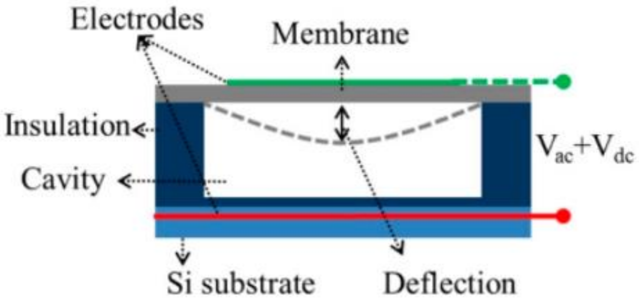
- Mainstream industrial solutions:
  - Piezoceramic (PZT, lead zirconate titanate) → most common

  Advanced emerging technologies:
  - CMUT (Capacitive Micro machined Ultrasound Transducer)
  - PMUT (Piezoelectric Micro machined Ultrasonic Transducers)

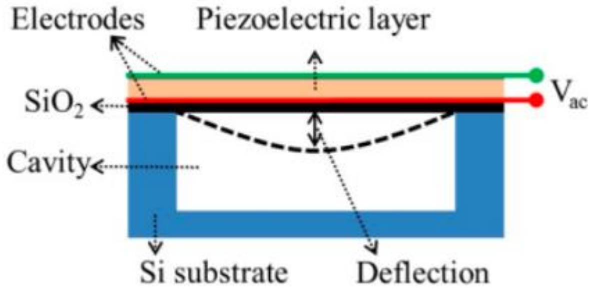
Parameters	PIEZOCERAMIC	CMUT	PMUT
Bandwidth	narrow	**wide**	**wide**
Linearity	**high**	low	low
Sensitivity	**high**	medium	low
Cost	high	**low**	**Medium/ low**
Dimension	large	**small**	**small**
HV bias in RX	**no**	yes	no
Other		**Compatible with semicon mfg process**	



Piezoceramic

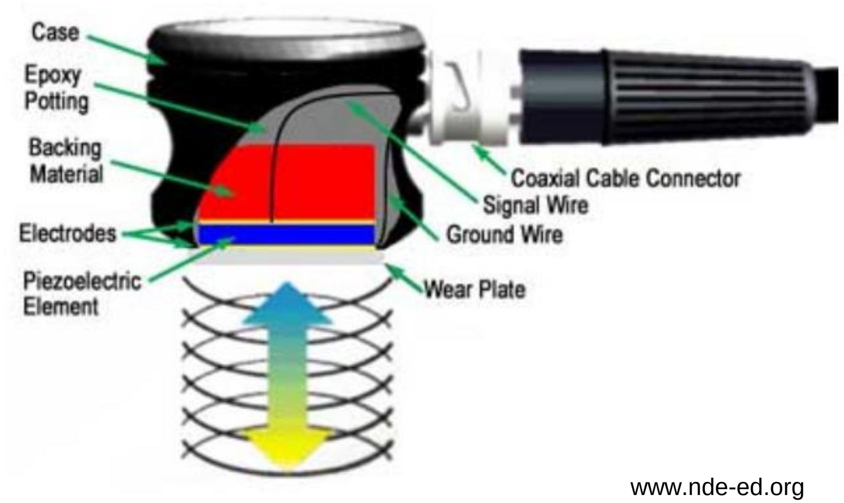


CMUT

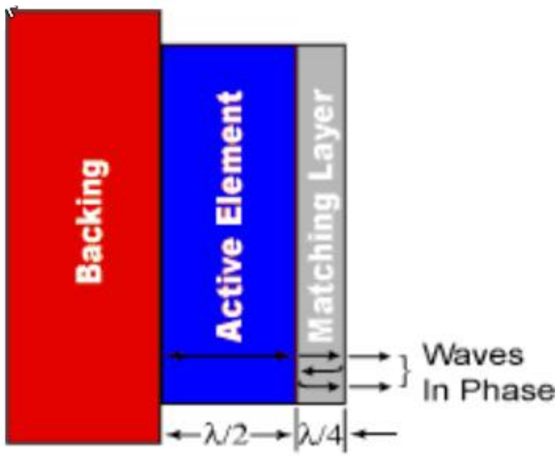


PMUT

Physical Structure of Piezo Transducers



www.nde-ed.org



Active element: Piezoelectric material, cut to 1/2 the desired wavelength

Matching Layer: improve the coupling between active element and the medium, optimal impedance matching with a thickness of 1/4 of the desired wavelength

Backing material: structural support, absorbing material influencing the damping characteristics of transducer, therefore influencing the resonant frequency

Transducer main characteristics:

- Physical dimensions
- Resonant frequency:
  - low frequency → lower resolution / higher penetration;
  - high frequency → higher resolution / lower penetration

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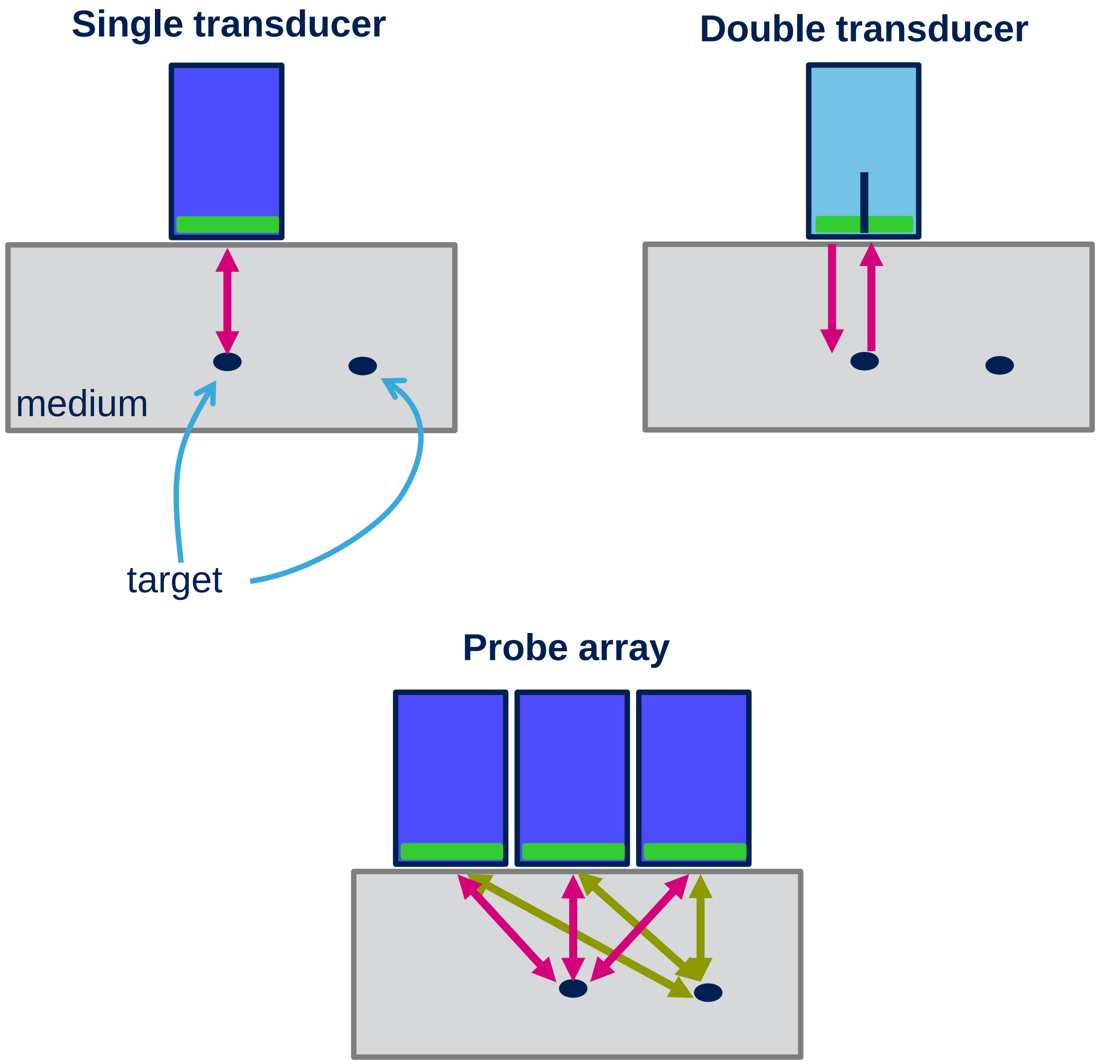
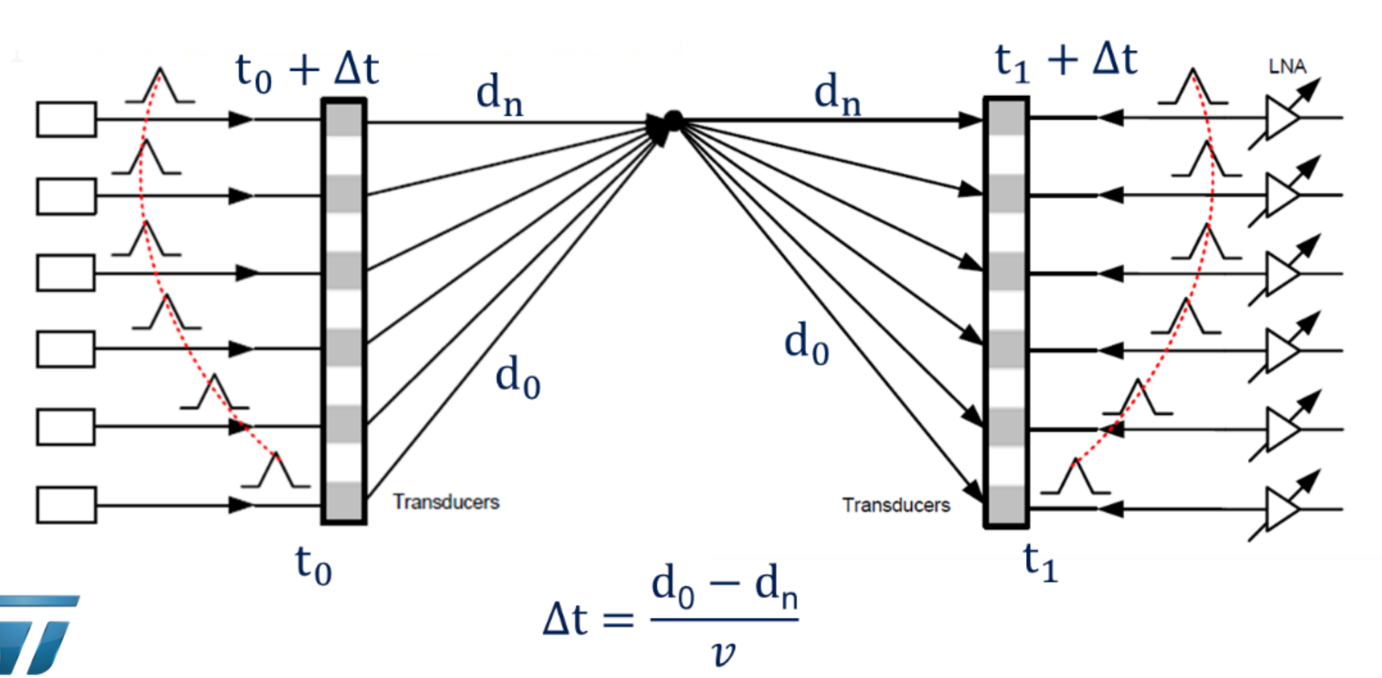
Transducer Arrangements

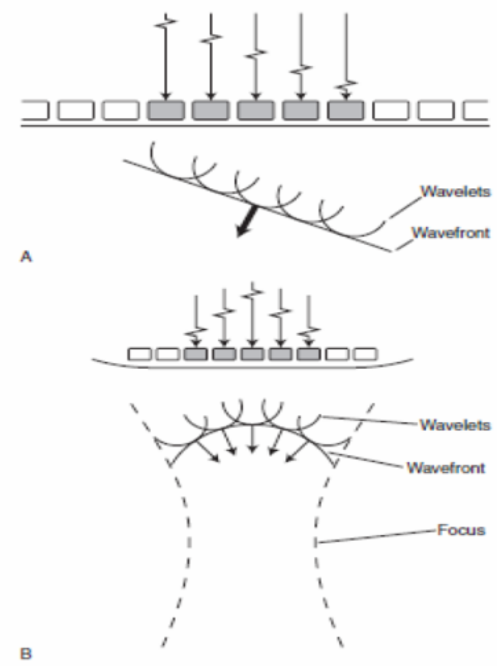
- Single transducer
  - Used for both RX and TX
  - Alternate phases (TX, wait, RX)
- Double transducer
  - Dedicated transducer for TX
  - Dedicated transducer for RX
  - Continuous analysis
- Probe array
  - More elements side-by-side
  - Dynamic focusing (beamforming)



Beamforming

- In a probe array application, the generated ultrasound intensity is affected by constructive and destructive wave interference
- Beamforming uses a delay profile and the resulting interference to steer the ultrasonic beam in a certain direction or focus the energy in a particular area
- The delay is important also in RX to realign the echo and improve SNR





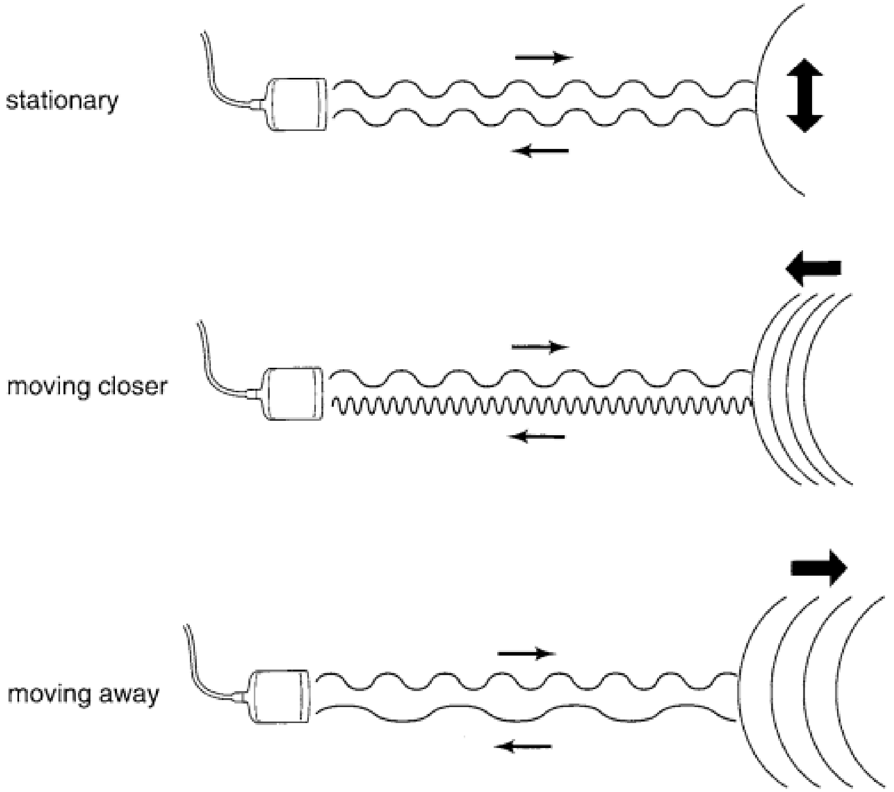
Beam steering

Beam focusing

The reflected wave from a moving obstacle shows a frequency shift proportional to the obstacle speed

$$\Delta f = 2\,\frac{v\,cos\theta}{c}\,f_0$$

$v\cos\theta$: target speed component in the wave propagation direction
c: wave speed
f_0: wave frequency



- The frequency shift is due to the Doppler effect
- Positive or negative depending on the direction of motion
- Doppler mode has no imaging capability
- E.g. used to accurately measure blood velocity and detect heart disease

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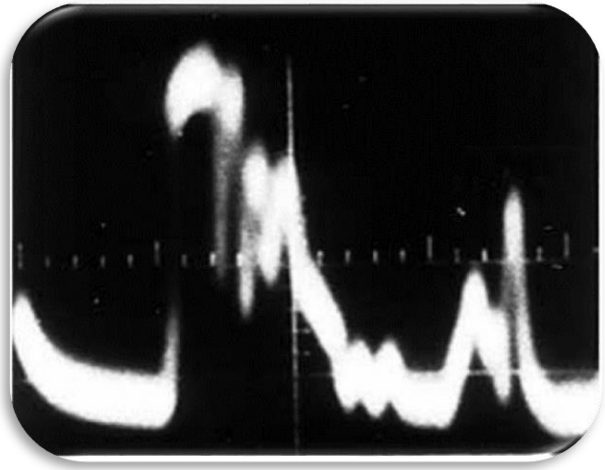
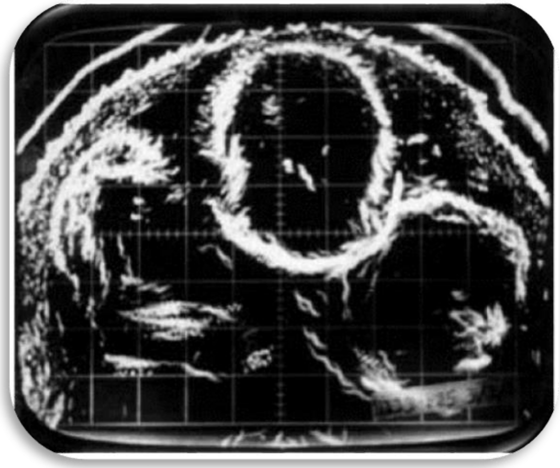
Ultrasound and Medical Imaging



Early ’50: A-mode (amplitude) image



Late ’50: B-mode (brightness) static image

’60: real time B-mode imaging

2000: 3D ultrasound imaging (static)

2010: real time 4D ultrasound imaging

Ultrasound NDT application

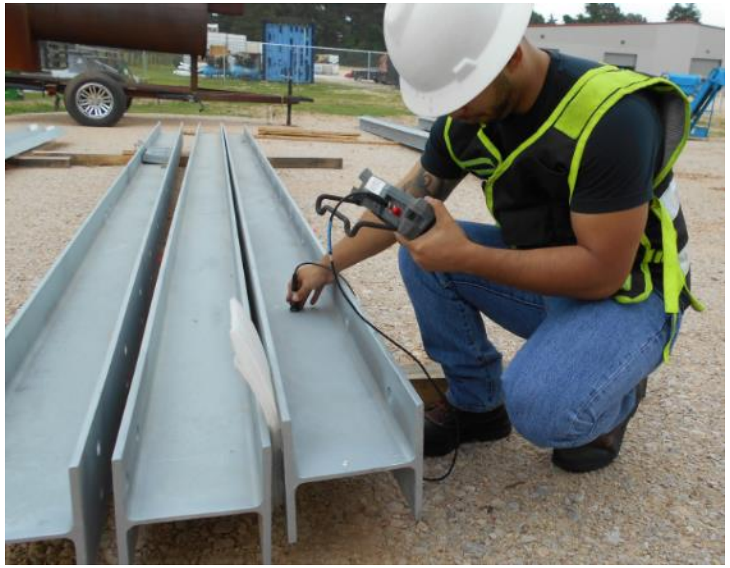
Non-Destructive Testing (NDT) is a technology used to detect defects in materials and structures, either during manufacturing or while in service (cracks, slag, porosity, stringers, …).

Air or cracks represent a reflector with different acoustic impedance

- By analyzing these reflections it is possible to measure the thickness of a test piece, or find the location of internal flaws.
- Amplitude, frequency and delay of echoes are related to position, speed, material composition and geometry of the target

Ultrasound NDT works with a large number of materials:

- Metals, plastics, ceramics, biological tissue… It doesn't work well in wood

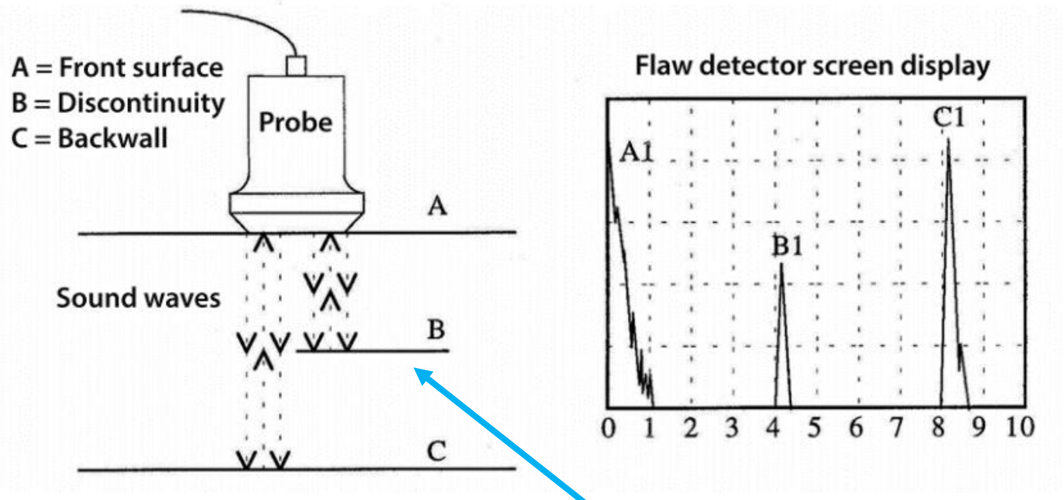


Application Examples:

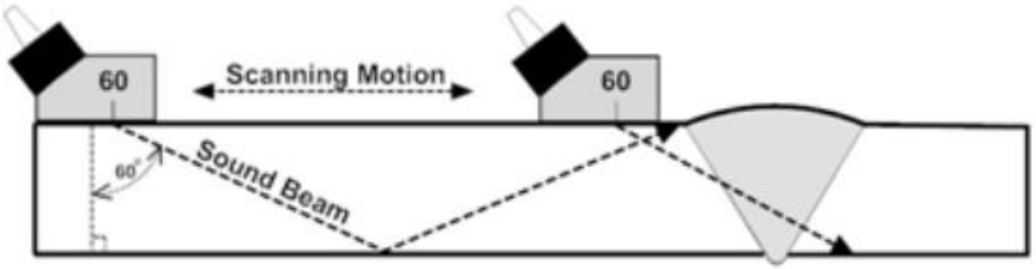
- Analyzing quality of steel beams, structural integrity of airplane wings/fuselage, wall thickness of corroded pipes, welded areas
- Flow meters (Doppler)

Inspection Methodologies

- Normal beam inspection:
  - Longitudinal wave
  - Perpendicular to surface
  - Not useful on welded areas
- Angle beam inspection:
  - Refracted shear wave (high incident angle to remove longitudinal wave)
  - Variable angle between transducer and surface → depending on material
  - Works on area with irregular surface (welded areas)

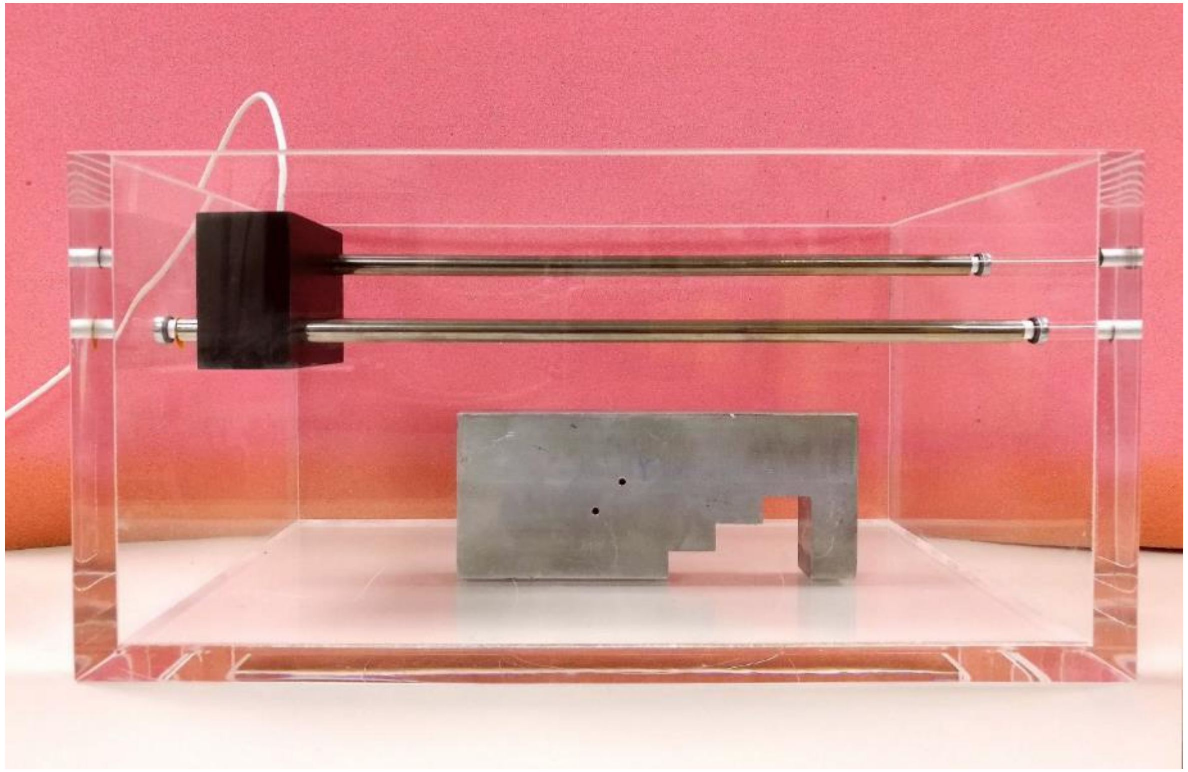


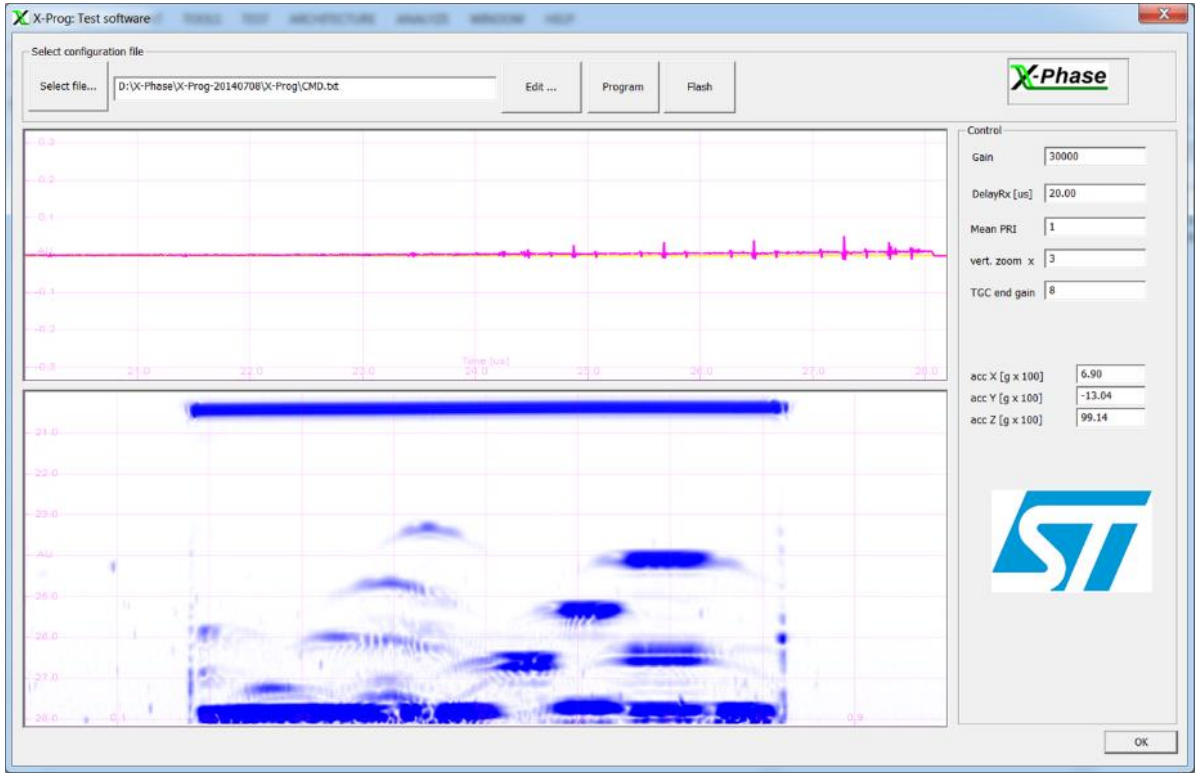
Not able to see under first flaw

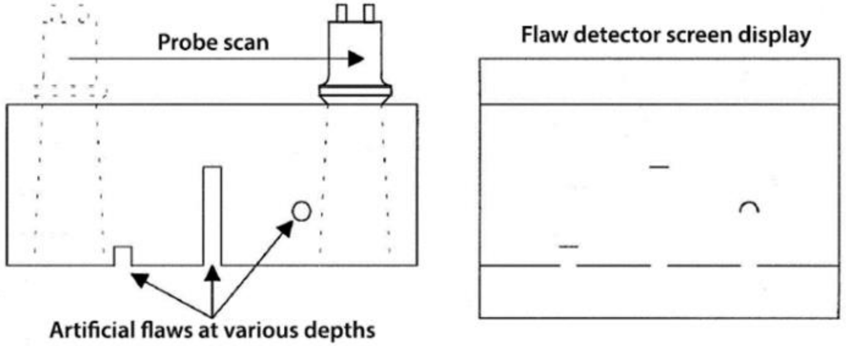


Angle Beam Testing

Ultrasound NDT Demo







- STHV800, 1 TX channel active, 80Vpp, 5MHz PZT
- Test setup submerged in water as couplant
- Red signal on top shows actual echo over time
- Bottom image created from measured distances
- Array of transducer could cancel spurious reflections (due to beam spreading) → sharper image

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Ultrasound vs. Other NDT Technologies

Parameters	Visual	X-ray	Eddy current	Magnetic particle	Liquid penetrant	Infrared thermography	Ultrasonic
Testing cost	low	high	low/medium	medium	low	high	very low
Time consuming	short delay	delayed	immediate	short delay	short delay	short delay	immediate
Possible to automate	no	fair	good	fair	fair	good	good
Portability	high	low	high/medium	high/medium	high	low	high
Type of defect	External	all	external	external	Surface breaking	internal	internal
Thickness gauging	no	yes	yes	no	no	yes	yes
Effect of surface geometry	Negligible	significant	significant	negligible	negligible	negligible	significant

- Many advantages of Ultrasound have been made possible by recent miniaturization of pulsers
- Products like STHV1600 with high level of integration enable miniaturization and therefore portable, relatively low cost and high performance ultrasound NDT systems

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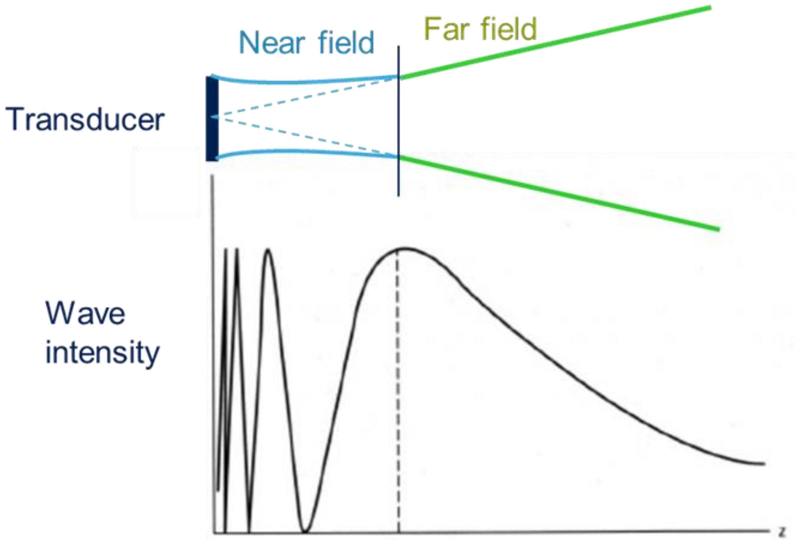
Quality Parameters

- **Sensitivity** is the ability of a system to detect reflectors at a given depth. The greater the signal that is received from these reflectors, the more sensitive the transducer system.

- **Resolution** is the ability of a system to detect separate echoes from reflectors placed near to each other.
  - **Axial resolution:** Smallest detail that can be seen in the direction of propagation, it is equal to λ so it depends on frequency (higher frequency, higher resolution) (+/-1um @ 1MHz)
  - **Lateral resolution:** Smallest detail that can be seen in the direction perpendicular to the propagation axis. It depends on frequency, transducer width, focusing capability.
  - **Near surface resolution** is the ability of the ultrasonic system to detect reflectors located close to the surface



	High frequency signal (15-25 MHz)	Low frequency signal (0.5-2.25 MHz)
Attenuation	HIGH	LOW
Penetration	LOW	HIGH
Resolution	HIGH	LOW

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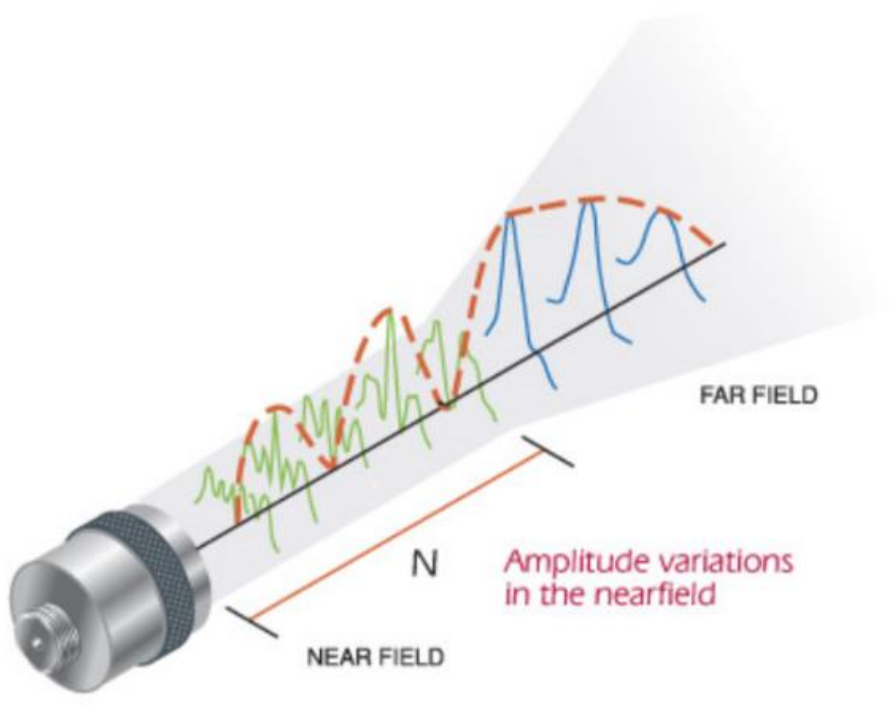
Near Field and Far Field



www.olympus-ims.com

Ultrasound wave intensity along the beam is not constant because of transducer finite dimension

- Near field: zone close to active element.
  - Extensive fluctuations in the sound intensity due to interference patterns
  - Difficult evaluate flaws in this zone
- Far field: zone far to active element.
  - Beam is more uniform
  - Beam spreads out
  - Good detection
- Natural focus: point between the far field and near filed.
  - Distance from the transducer where sound waves have the maximum strength

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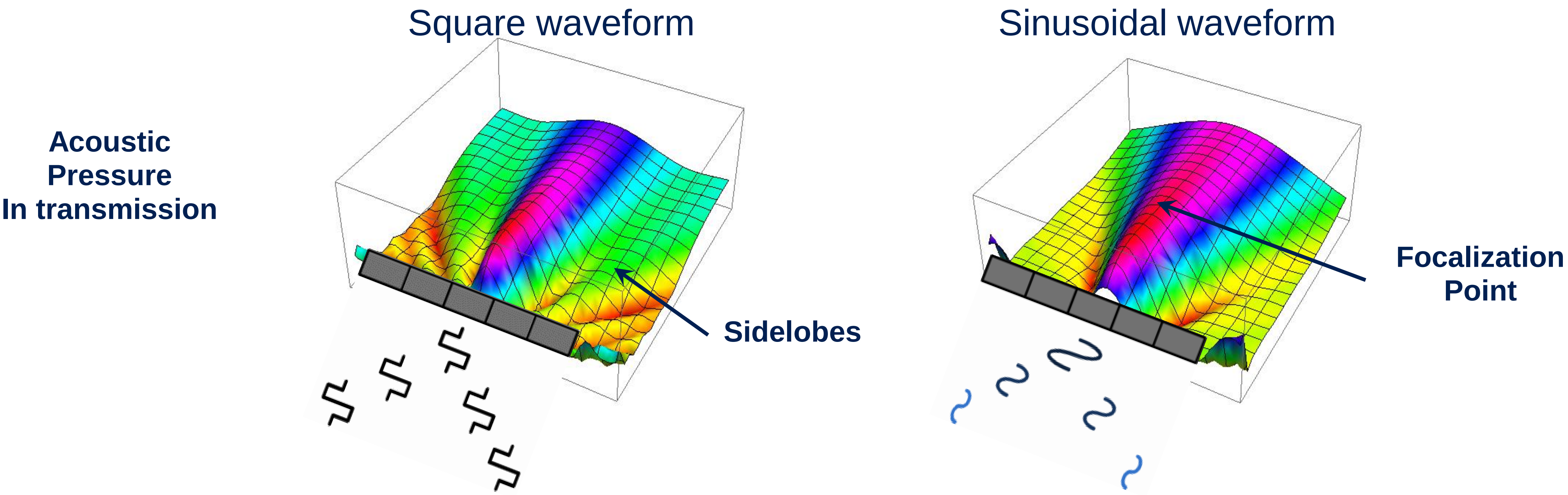
Far Field Wave Front



- Far field: no uniform wave front either → beam spread and side lobes
- Maximum sound pressure always along the center line of transducer → max sensitivity
- Side lobe reduction:
  - Multi-level stimulation → apodization
  - Sinusoidal stimulation → superior images but higher power dissipation → linear pulsers in medical

ST Ultrasound Pulsers

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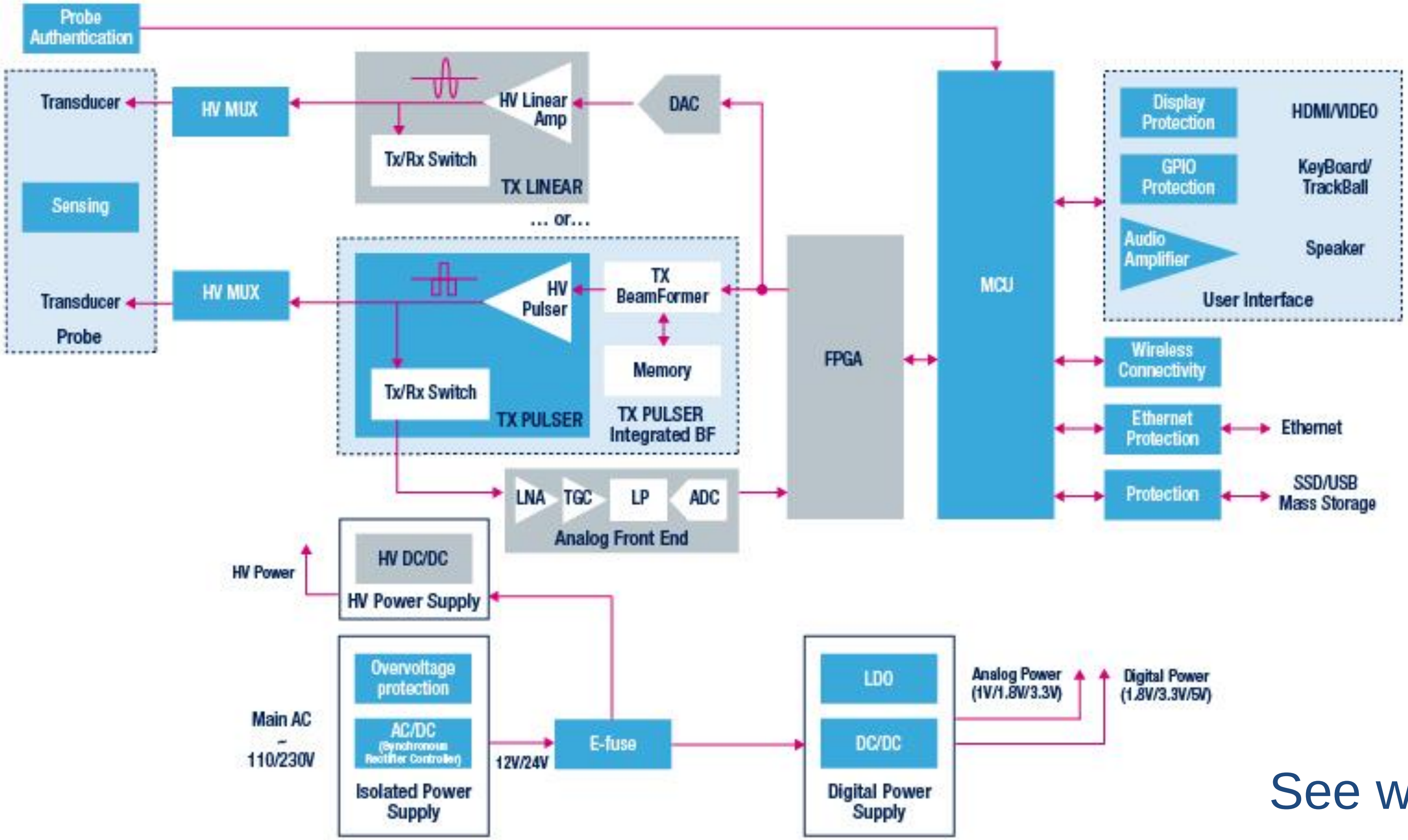
Medical Ultrasound

ST technologies for Ultrasound: from Standard Products to Application Specific ICs



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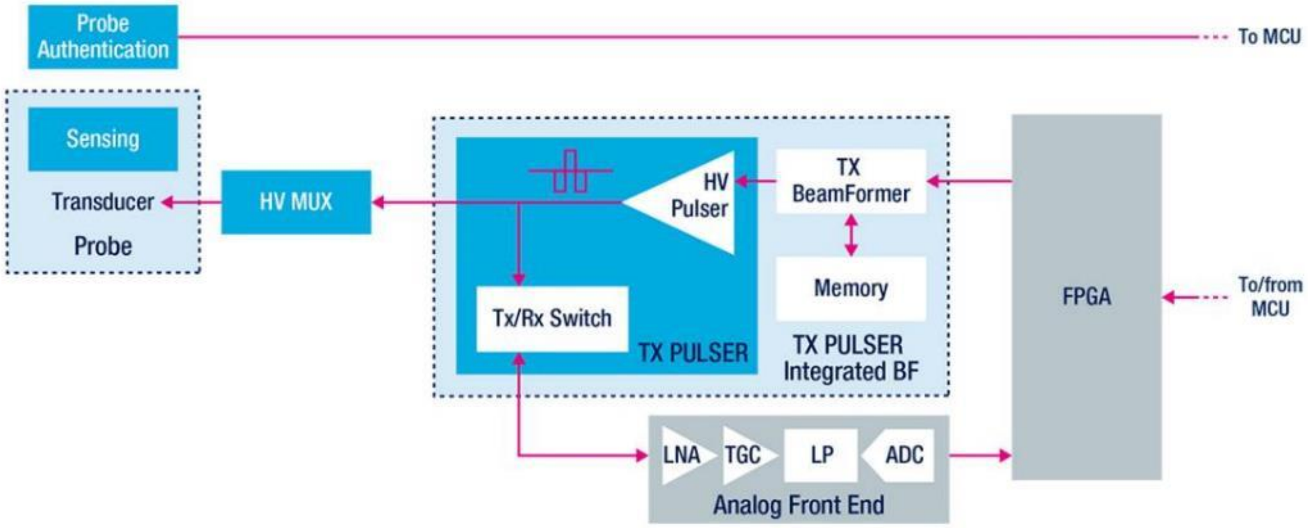
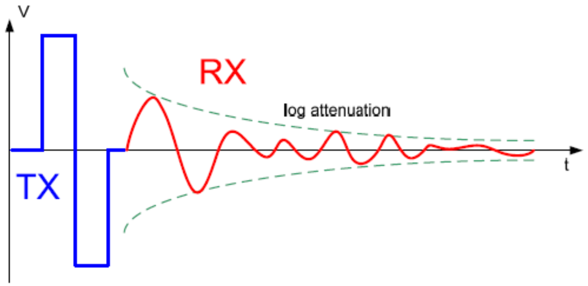
Medical Ultrasound Partitioning

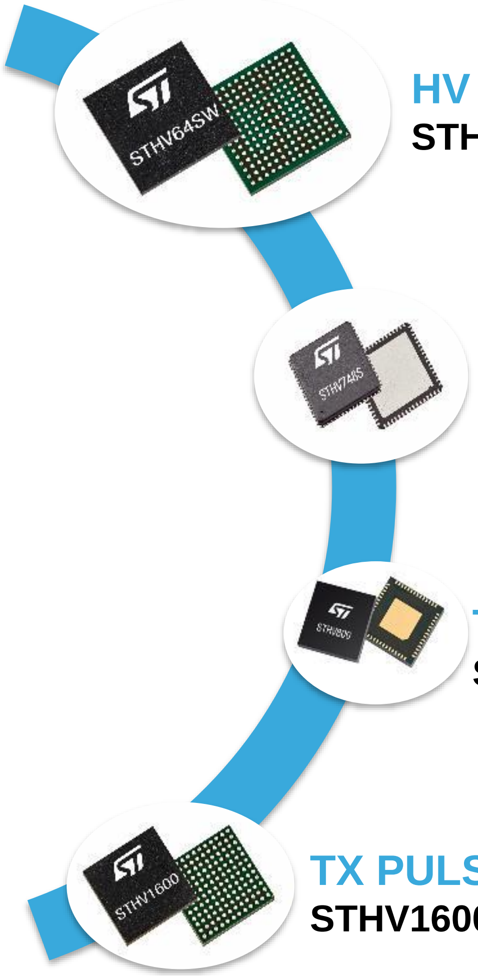
High Voltage Stage and Smart Probe



- Integrated T/R switch in all ST pulsers → isolate receiving path (low noise AFE, 5V max) during transmission phase (pulses of 2A, 200Vpp)

Electrical signals in transmission and receiving





HV MUX
STHV64SW (64 HV analog switches)

TX PULSER
STHV748S (4-channels)

TX PULSER
STHV800 (8-channels)

TX PULSER with Integrated Beamforming
STHV1600 (16-channels)

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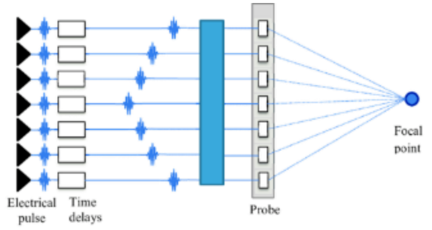
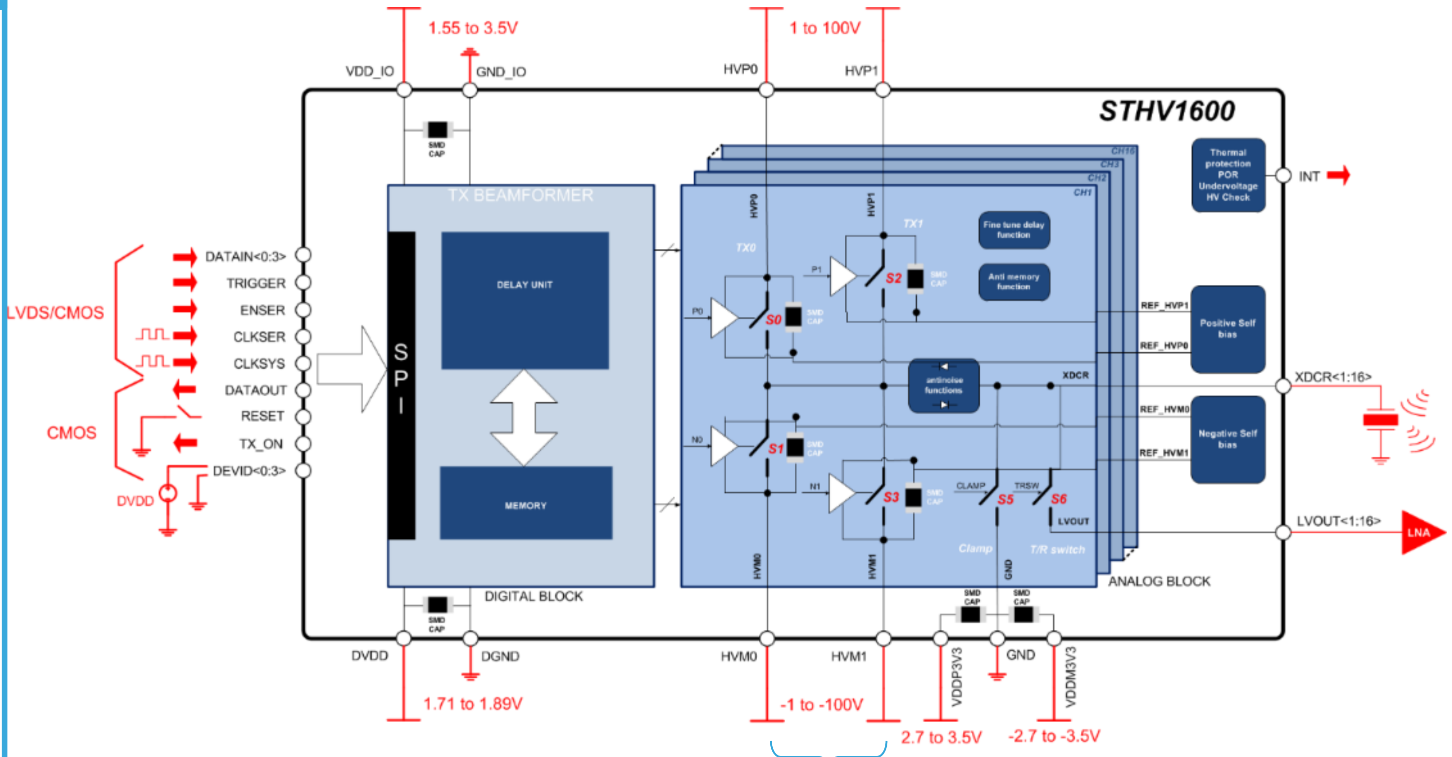


STHV1600

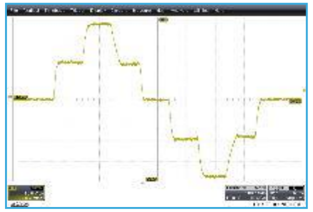
16 channel Pulser with Beamforming

Monolithic 16 ch high-speed ultrasound pulser with integrated transmit beamformer

- 0 to **±100V** output voltage
- Up to **30MHz** operating frequency
- Power-up/down sequence free
- Pulsed wave (**PW**) mode operation:
    - 5/3 RTZ level output, ±2A / ±4A source and sink
- Continuous wave (**CW**) mode operation:
- **Elastography** mode operation
- Programmable delays to minimize 2nd harmonic distortion
- 11Ω integrated **active clamp** to ground (±2 A)
- Integrated 9Ω **T/R switch**
- **Digital Core**
    - **TX Beamforming** in transmission mode
    - Programmable single-channel delay
    - Clock frequency up to 200MHz
    - Delay from 0 to 327µs with 5ns resolution
    - 65Kb embedded RAM to store patterns
    - Waveform compression algorithm
    - Control through serial interface (SPI)
- Package: TFBGA144 10x10x1.4mm

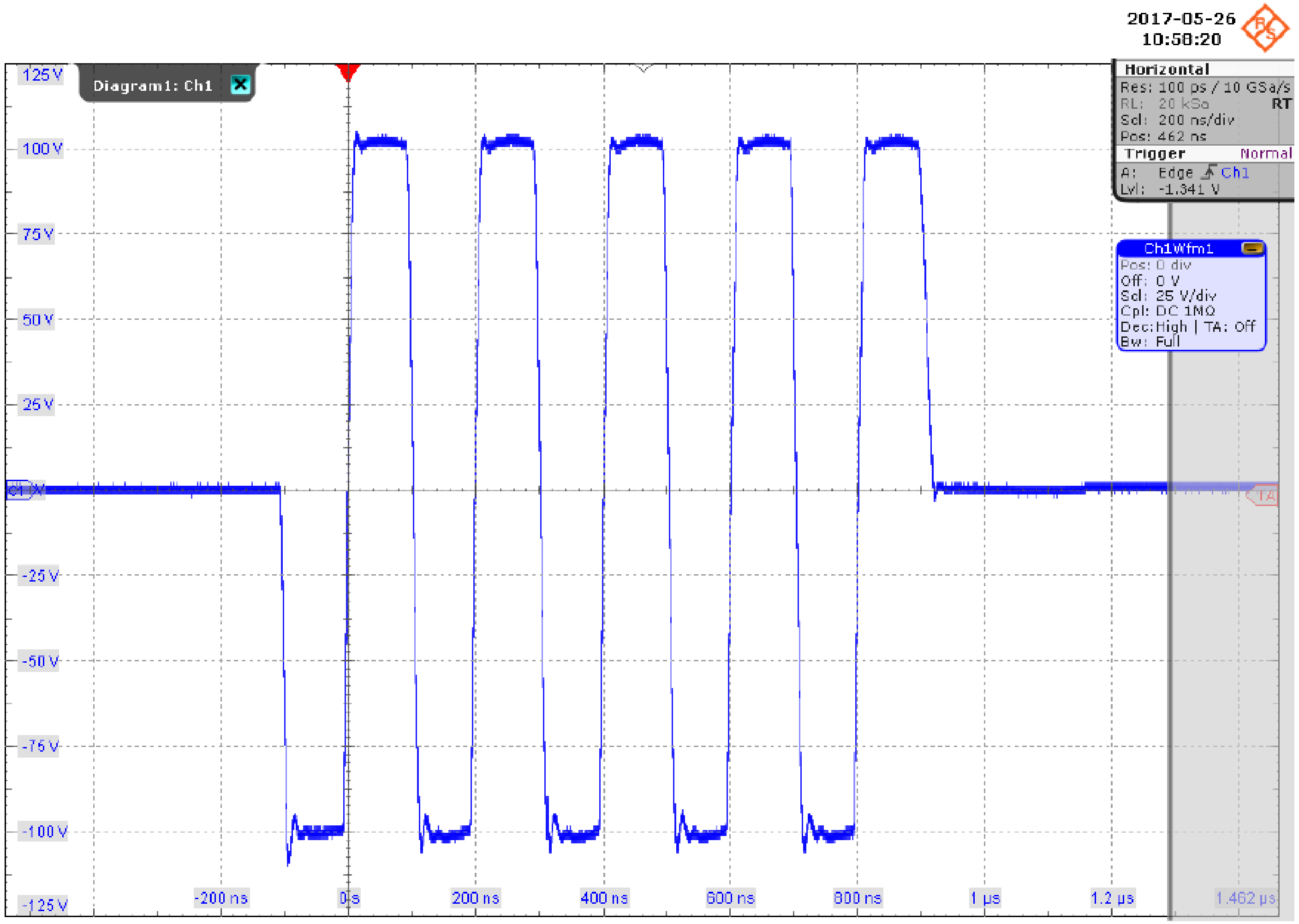


5 level PW mode



Specifically targeted at low power portable systems

Pulse Wave Operation



- Default operating mode for STHV1600
- Example: 5MHz pulses for 1µs at 200Vpp
- In PW mode HV supplies can reach max value, but low PRF (pulse repetition freq) needed to limit power dissipation

- PRF = number of pulses in 1s
- Duty Factor = pulse duration / pulse repetition time (including clamping + Rx interval)

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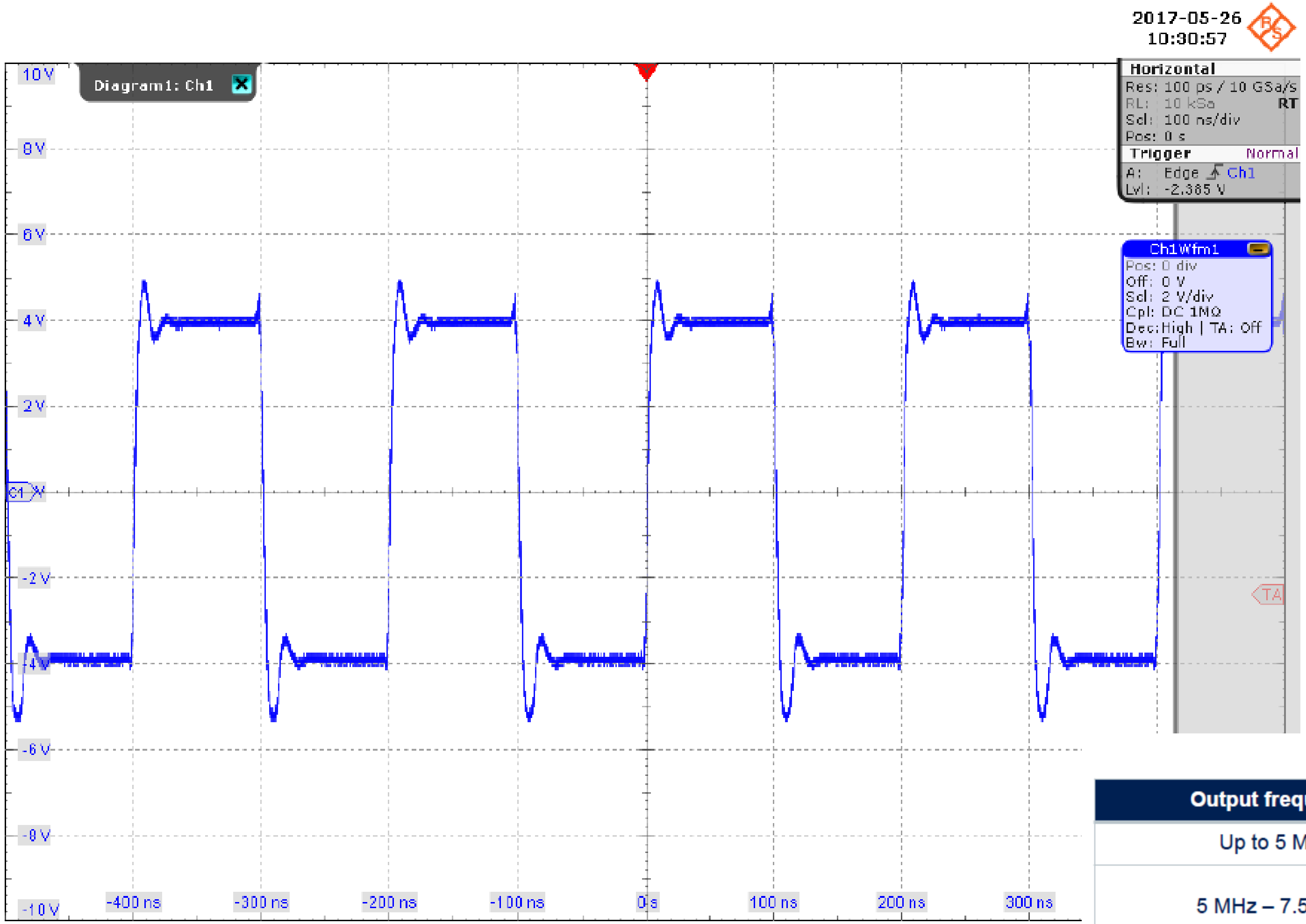
Continuous Wave Operation



- Example: 5MHz pulses for 1ms at 8Vpp
- In CW mode the outputs can switch continuously, but HV supplies must be decreased to not exceed max power cons.
- Elastography: all 16 ch. used in parallel at 200Vpp, depending on frequency a max pulse is duration allowed

Table 4. Device overstress avoidance guidelines **Elastrography mode**

Output frequency	High voltage supply	Pulse train duration
Up to 5 MHz	Up to ±100 V	Up to 1 ms
5 MHz – 7.5 MHz	Up to ±90 V	Up to 1 ms
	±100 V	Up to 750 µs
7.5 MHz – 10 MHz	Up to ±80 V	Up to 1 ms
	±100 V	Up to 500 µs

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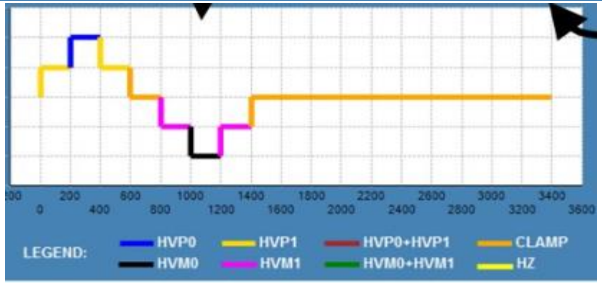
STHV1600 Evaluation Kit

STEVAL-IME014V1B

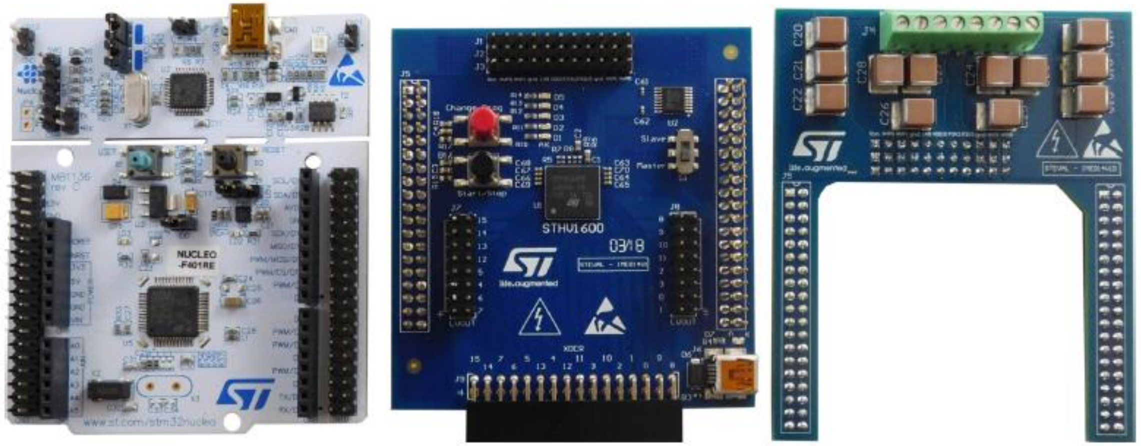
GUI – HV waveforms builder



The kit consists of three connected modules:

- **Pulser module (STEVAL-IME014V1):**
  - STHV1600 16-channel pulser and buttons
  - Four preset programs and waveforms
  - USB interface to change programs and waveforms
  - Pushbutton interface to control waveform generation
  - Status LEDs
- **Power supply module (STEVAL-IME014V1D):**
  - Four high voltage and one low voltage supply lines
  - Four low voltage supplies generated on-board
- **STM32 Nucleo microcontroller module:**
  - STM32 microcontroller → to generate correct signals for STHV1600

1. Nucleo F401RE 2. STEVAL-IME014V1 3. STEVAL-IME014V1D



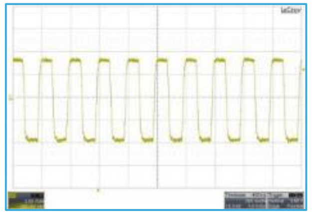
STHV748S

4 channel pulser

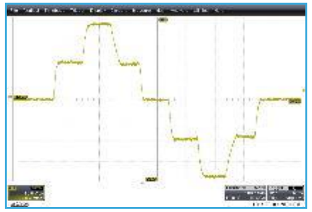
Monolithic 4 channel, 5 level, high voltage pulser

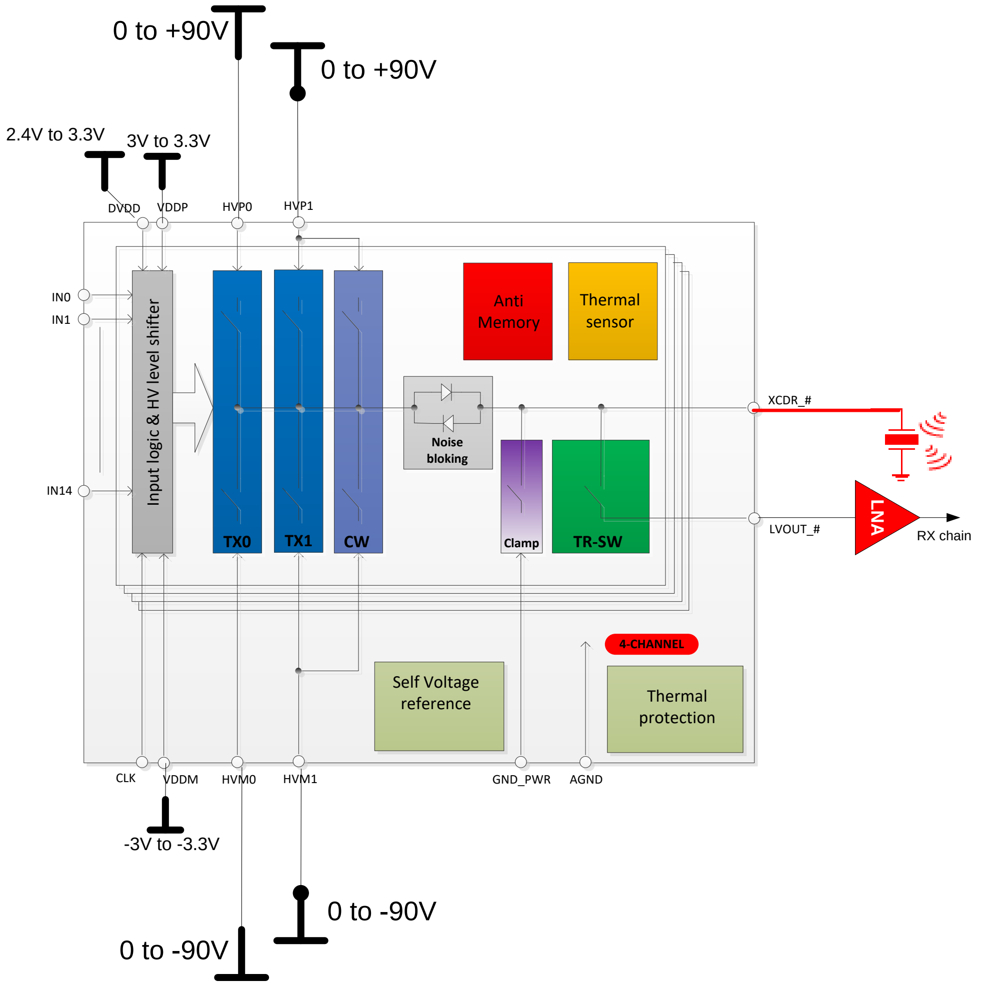
- Pinout compatibility with best selling STHV748
- 0 to **±90V** output voltage
- Up to **20MHz** operating frequency
- **PW** operation: **Dual half bridge**
  - 3/5-level output waveform
  - ±2 A source and sink current per half bridge
  - ≤ 20 ps jitter
- Cont. wave (**CW**) operation: **Dedicated half bridge**
  - ≤ 0.1 W power consumption
  - ±0.6 A source and sink current
  - 205 fs RMS jitter [100 Hz-20 kHz]
- Integrated 8 Ω synchronous **active clamp**
- Integrated **T/R switch**
  - 13.5 Ω on-resistance
  - Up to 300 MHz BW
  - Receiver multiplexing function
- **Anti Memory** function → grounds floating HV nodes before new pulse, better 2nd harmonic distortion
- 1.8V to 3.6V CMOS logic interface
- Package: QFN64 9X9 mm

CW mode



5 level PW mode





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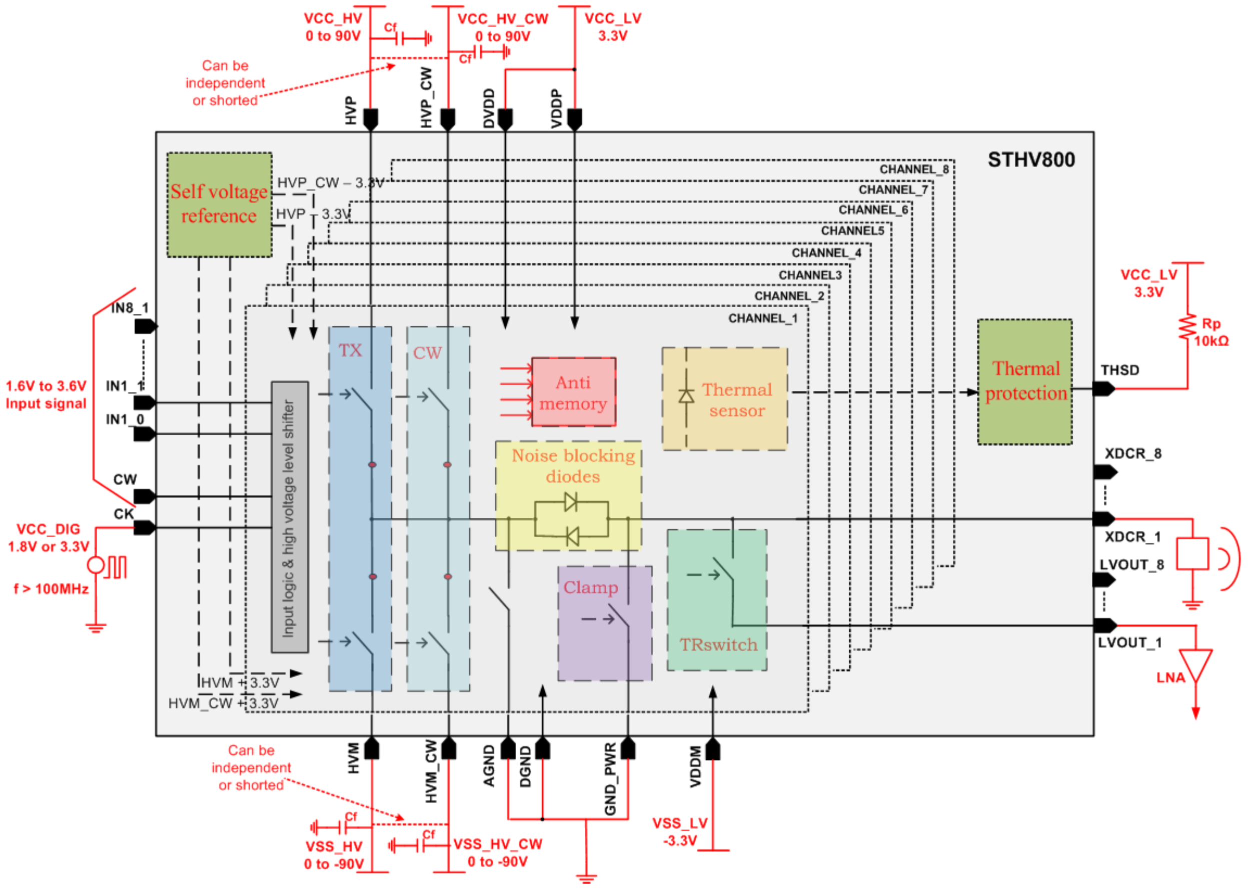
STHV800

8 channel pulser

Monolithic 8 channels, 3 level, high voltage pulser

- Up to **±90V** output voltage
- Up to **20MHz** operating frequency
- Two independent half-bridges per channel, one dedicated to continuous wave (CW) mode
- **PW**: Main half bridge
  - ±2A source and sink current
  - 20ps jitter
- **CW: Dedicated half bridge** with independent power supplies
  - ±0.3A source and sink current
  - 10ps jitter
- Integrated **T/R switches** (8Ω, 300MHz BW)
- Integrated **active clamp** switches (8Ω, ±2A)
- **6 capacitors** integrated in package → few external components
- Power up free
- Self-biasing circuitry → Current consumption down to 10μA in RX
- **Anti memory** function
- 1.8V to 3.6V CMOS logic interface
- Package: LGA 8X8 mm – 56 leads



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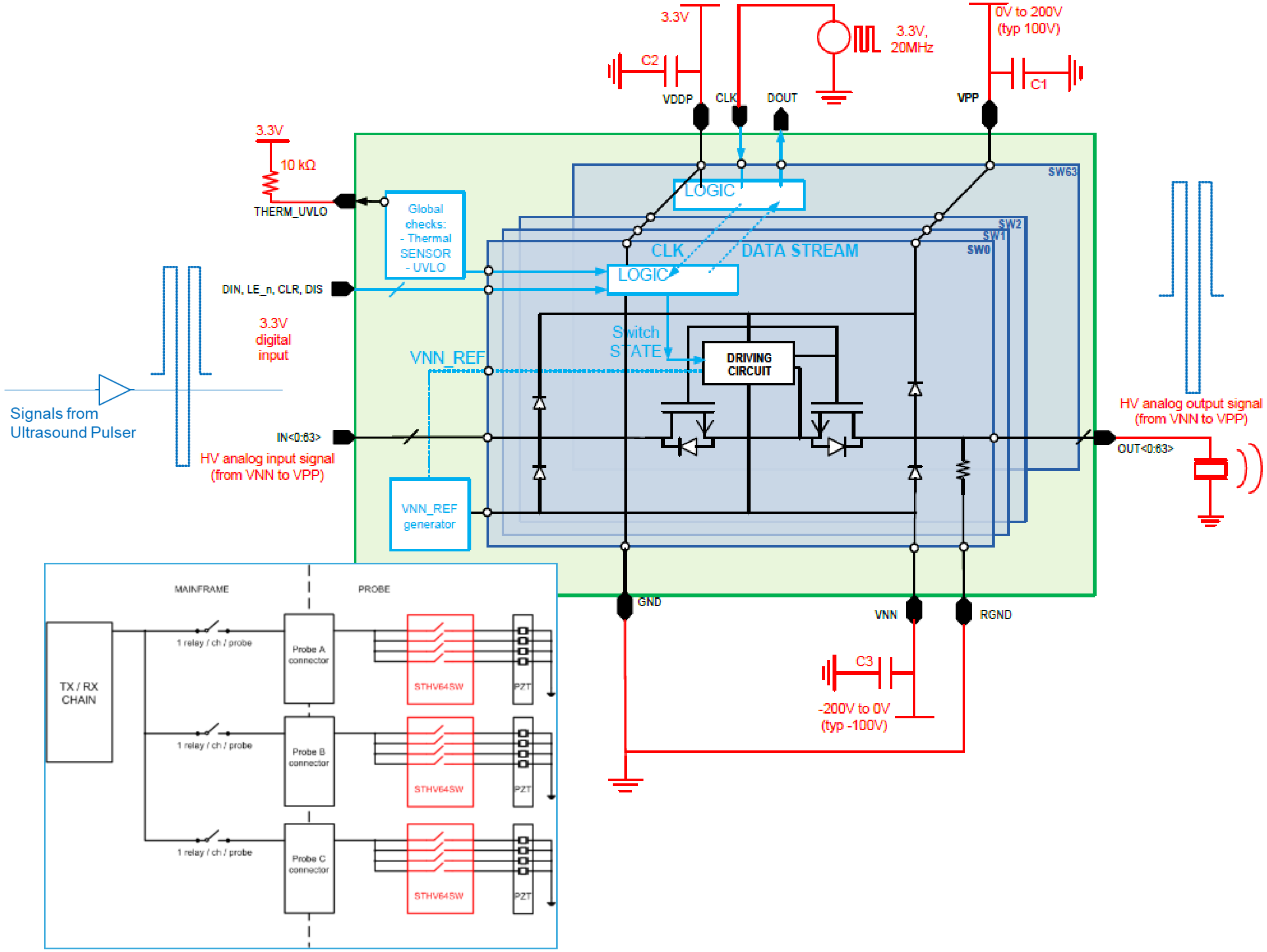
STHV64SW

64-channel HV Switches

Monolithic 64 independent High Voltage Analog Bi-directional Switches

- **200 V** peak-to-peak input and output signal
- Three main operating ranges:
  - From -100 V to +100 V
  - From 0 V to 200 V
  - From -200 V to 0 V
- **±3 A** peak output current.
- Very fast input slew rate (40V/ns at no load)
- Low on-resistance (**10Ω**)
- Low cross-talk between channels
- 40kΩ bleed resistor on the outputs
- Recirculation current protection on input and output
- Control through serial interface
- 20 MHz data shift clock frequency
- TFBGA196 12x12

- Mux/de-mux to drive more transducers with the same pulsers
- Replacement for mechanical relays



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Ultrasound Imaging
ST Key Differentiators

Customized BCD8SOI technology, optimized for ultrasound

3/5/7/9 output levels to enhance image quality

Integrated T/R switch and Beamforming

Very low 10ps jitter for accurate frequency response in echo-doppler

Very short 5ns HV pulse piezo transducer control, for superior image quality

ST Vision

Towards higher integration