# Ultrasound Pulsers for Non-Destructive Testing and Medical Imaging Applications

Federico Guanziroli – Digital Designer, Analog Custom Products
Marco Viti – Application Manager
Piercarlo Scimonelli – Product Marketing Manager

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# Presentation Outline

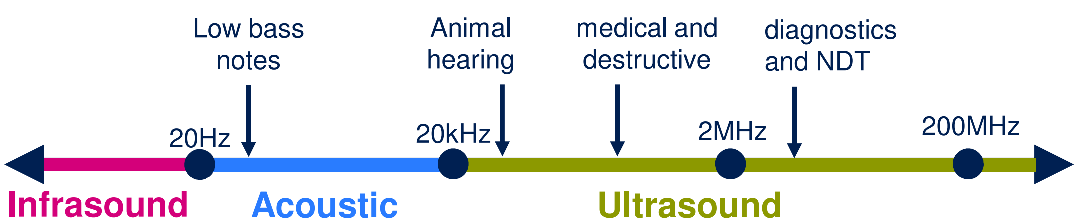


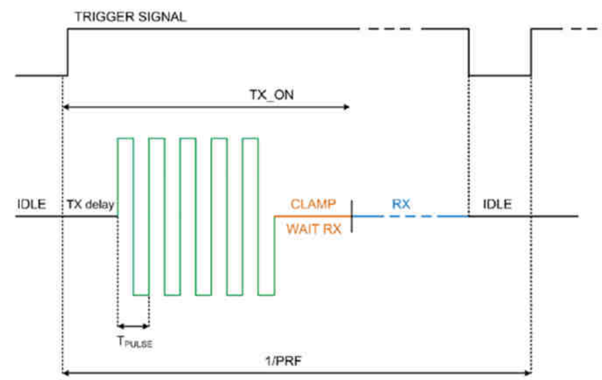
- Ultrasound physics:
  - Ultrasound waves
  - Propagation
  - Transducers
  - Beamforming
  - Doppler effect
- Applications:
  - Medical application
  - NDT application
- System and Products:
  - System Architecture
  - ST portfolio

# 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
- 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 not different from an acoustic wave

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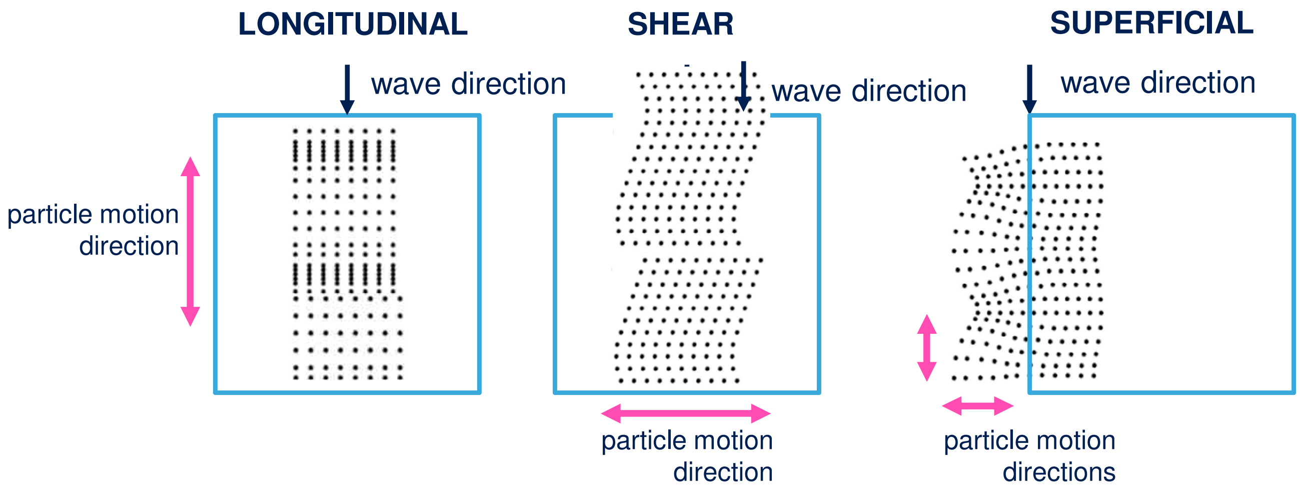
# Ultrasound Wave Propagation



- 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.

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# Main Parameters

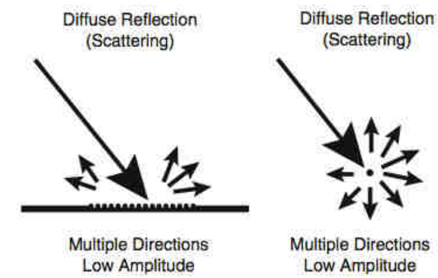


- T [s]: time between two maximums of the waveform (Period)
- v [m/s]: waveform speed, it depends on the material properties (elasticity k and density ρ) where $v = \sqrt{k/\rho}$.
- λ [m]: waveform length. It is the ratio v/f
- α: medium attenuation, used to calculate the wave attenuation vs. penetration $A(x) = A_0 e^{-\alpha x}$
  - Absorption is the transformation of Ultrasound energy in thermal energy
  - Diffusion is the beam dispersion, attenuation in the propagation direction
- Z: acoustic impedance, $Z = \rho \cdot v$. It is the resistance to the ultrasound wave propagation. Impedance mismatch is the cause of scattering, transmission and reflection

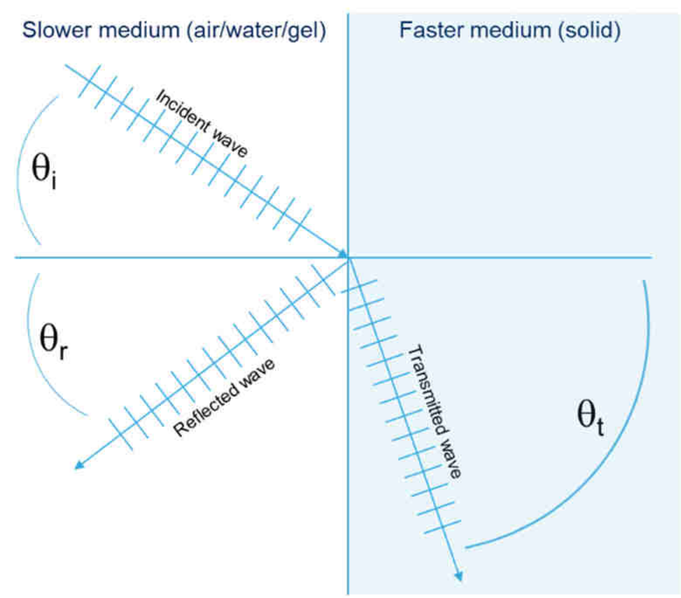
| Medium | v [m/s] | ρ [kg/m³] | Z [MRayl] |
|---|---|---|---|
| Air | 330 | 1.2 | 0.0004 |
| Water | 1480 | 1000 | 1.48 |
| Aluminum | 6320 | 2700 | 17.06 |
| Bronze | 3530 | 8860 | 31.27 |
| Copper | 4660 | 8930 | 41.60 |
| Iron | 5900 | 7700 | 45.43 |
| Lead | 2160 | 11400 | 24.62 |
| Silver | 3600 | 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 |

# Scattering, Reflection & Transmission

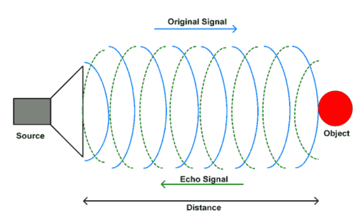
- Scattering: the energy lost when the wave propagates onto a medium interface whose irregularities are comparable with λ (the two mediums must have different acoustic impedance)




- 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*

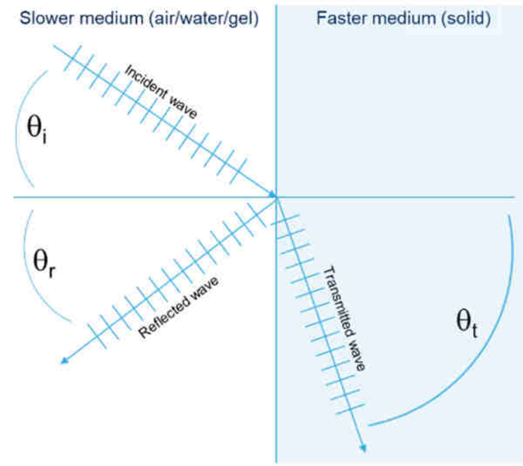


# Transmission and Reflection



- Angle of refraction is defined by Snell's law: $$\frac{\sin\theta_I}{c_1} = \frac{\sin\theta_T}{c_2}$$

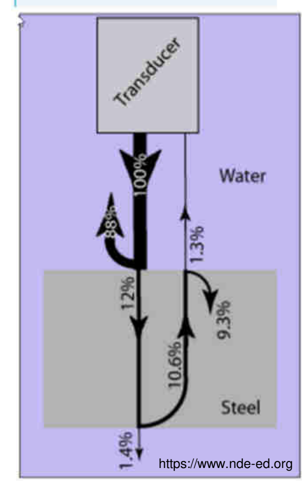
- The angle of reflection is equal to the incident angle




- 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

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

$$T = 1 - R = \frac{(4Z_1Z_2 \cos\theta_i \cos\theta_t)^2}{(Z_1 \cos\theta_t + Z_2 \cos\theta_i)^2}$$

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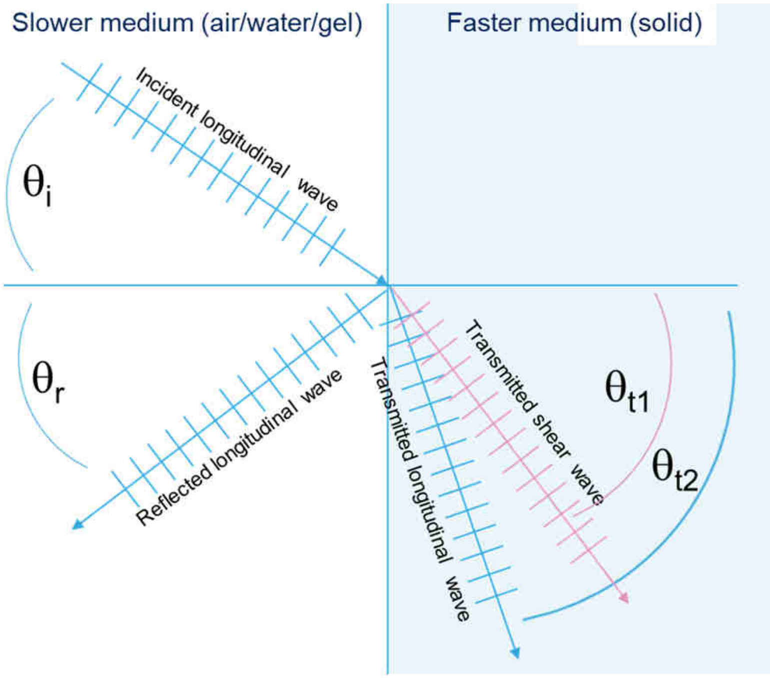
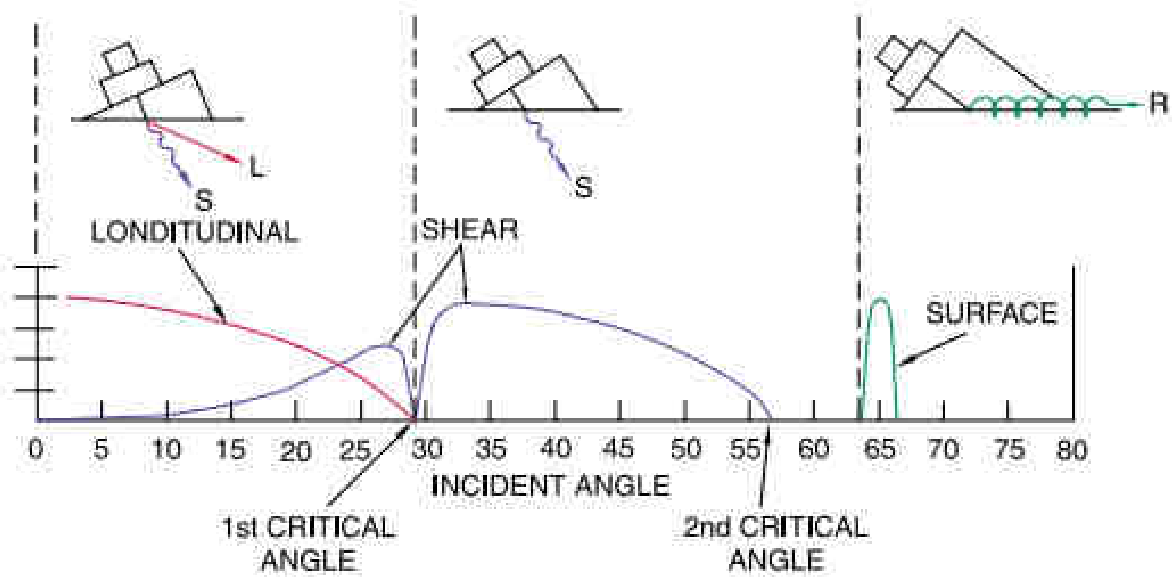
# Critical angle of incidence




http://www.sdindt.com/

# Ultrasonic Transducers

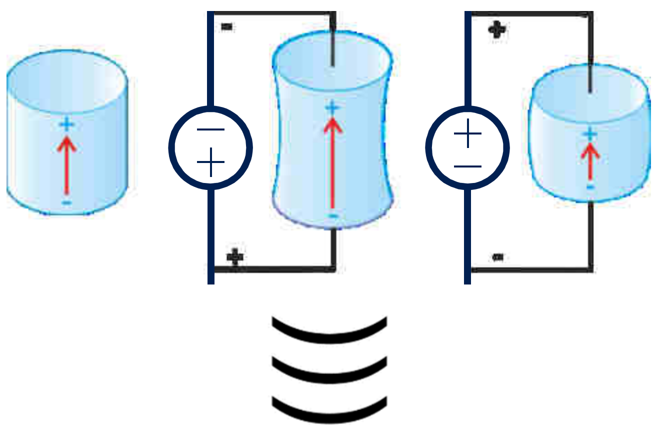


## Piezoelectric transducer

- based on misalignment of the dipoles

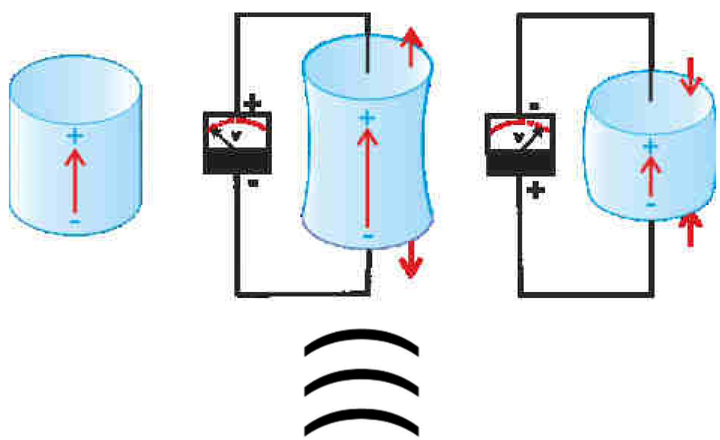
**Transmission (TX) mode**

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



**Receiving (RX) mode**

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



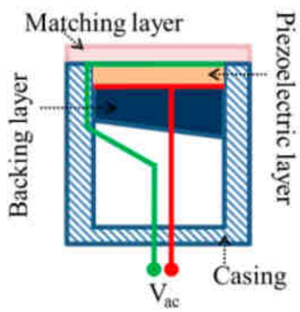
# Transducer Types



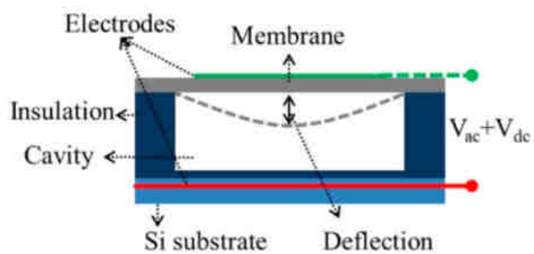
- An Ultrasound transducer is a material able to convert electrical energy into mechanical vibrations (ultrasound wave) and vice versa.

- Mainstream industrial solutions:
  - Piezoceramic (PZT, lead zirconate titanate)
  - CMUT (Capacitive Micro machined Ultrasound Transducer)
  - PMUT (Piezoelectric Micro machined Ultrasonic Transducers)

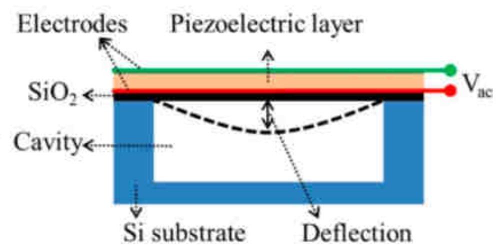
| Parameters | PIEZOCERAMIC | CMUT | PMUT |
|---|---|---|---|
| Bandwidth | narrow | wide | wide |
| Linearity | high | low | low |
| Sensitivity | high | medium | low |
| Cost | high | low | Medium/ low |
| Dimension | large | small | small |
| HV bias in RX | no | yes | no |




Piezoceramic




CMUT




PMUT

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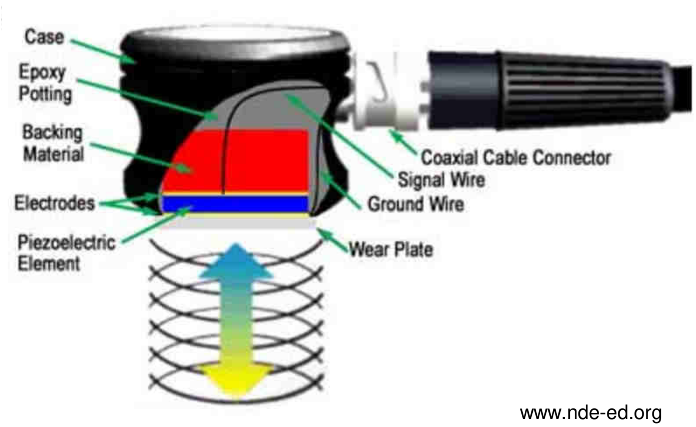
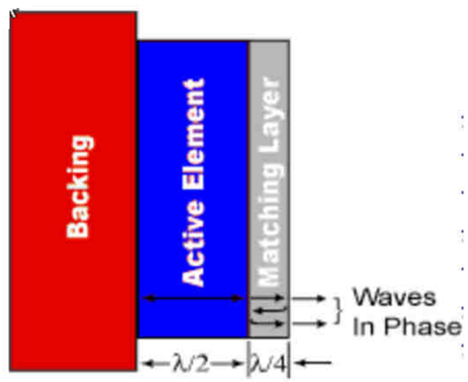
# Physical Structure of Piezo Transducers






**Transducer main characteristics:**

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

**Backing material:** absorbing material used to increase beam penetration (on back side)

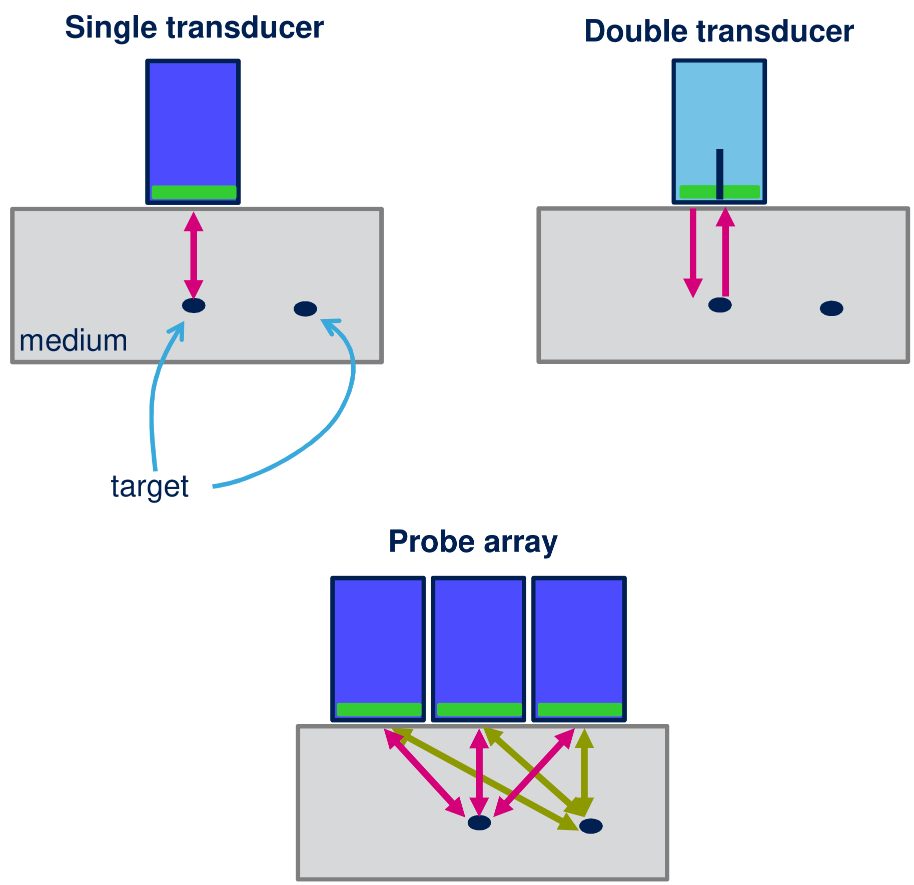
**Active element:** Piezoelectric material, whose dimension depend on wave characteristic

**Matching Layer:** material used to improve the coupling between active element and the medium

# Transducer arrangement



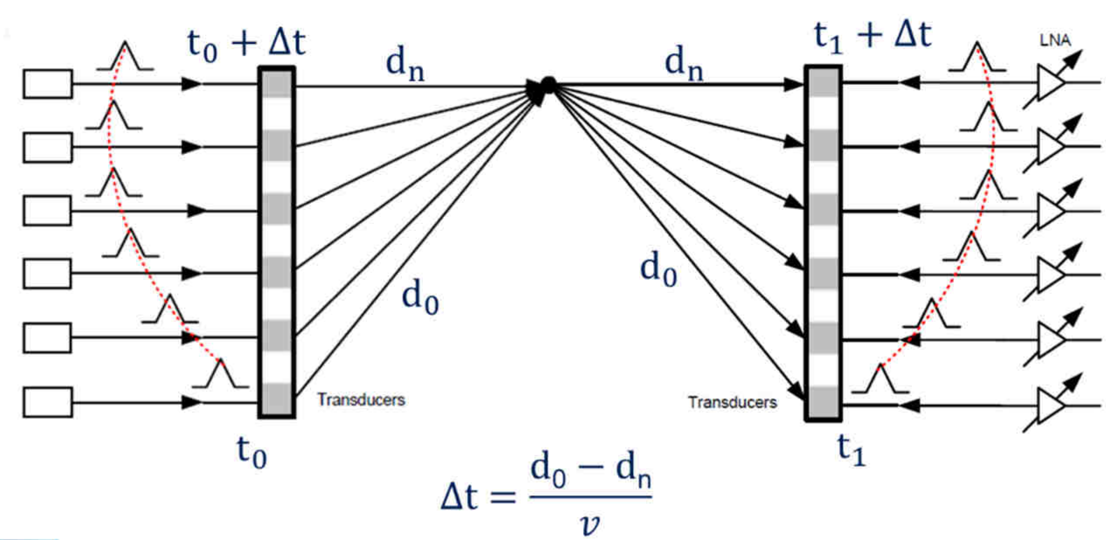
- Single transducer
  - Used for both RX and TX
  - Alternate phases (TX, wait, RX)
- Double transducer
  - Dedicated transducer for TX
  - Dedicated transducer for RX
  - Continuous analysis
- Probe array
  - More elements side-by-side
  - Dynamic focusing (beamforming)

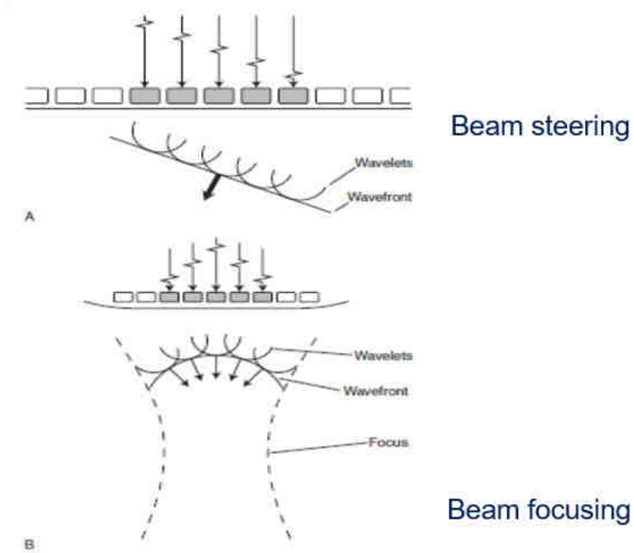


# Beamforming



- In a probe array application, a delay profile can be used to maximize the energy sent  in particular area in TX
- The delay is important also in RX to realign the echo and improve SNR



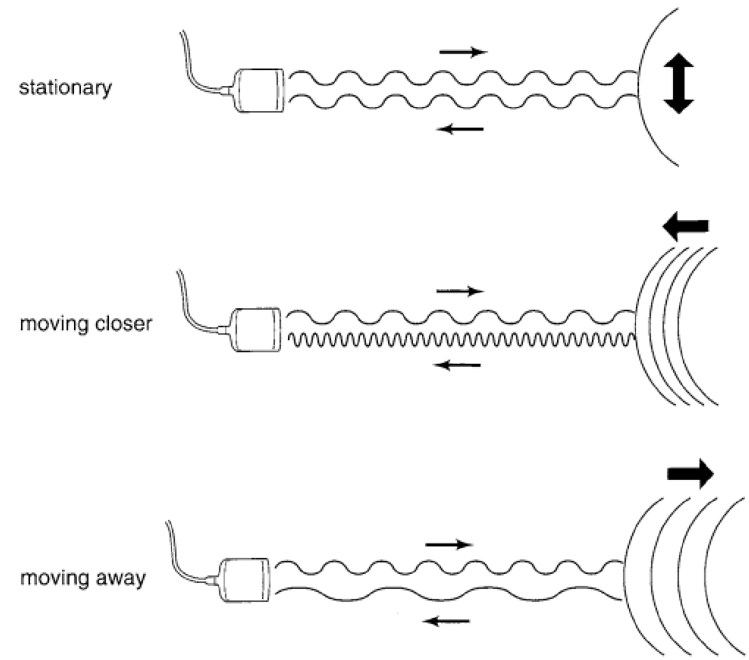



# Doppler Effect

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

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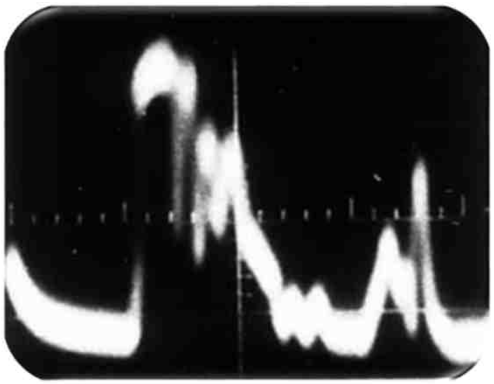
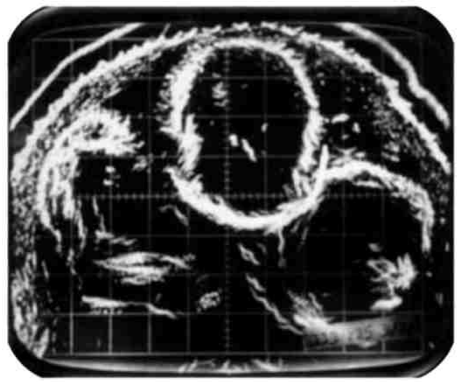
# Ultrasound and Medical Imaging





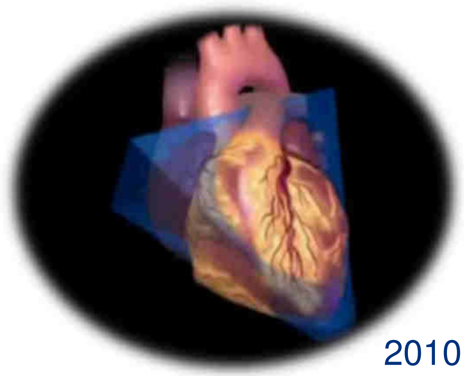
Early ’50: A-mode (amplitude) image



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

’60: real time B-mode imaging

2000: 3D ultrasound imaging



2010: 4D ultrasound imaging

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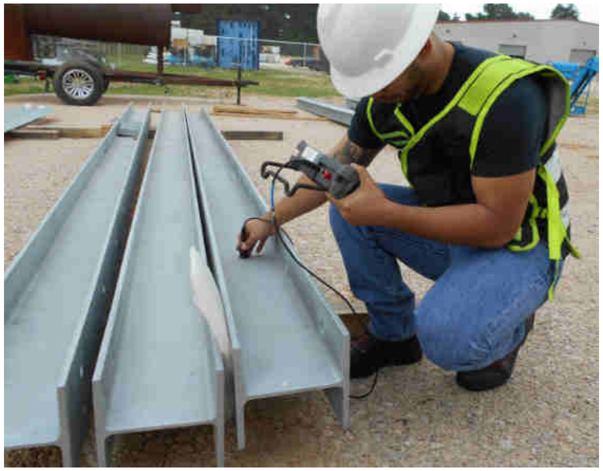
# Ultrasound NDT application



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

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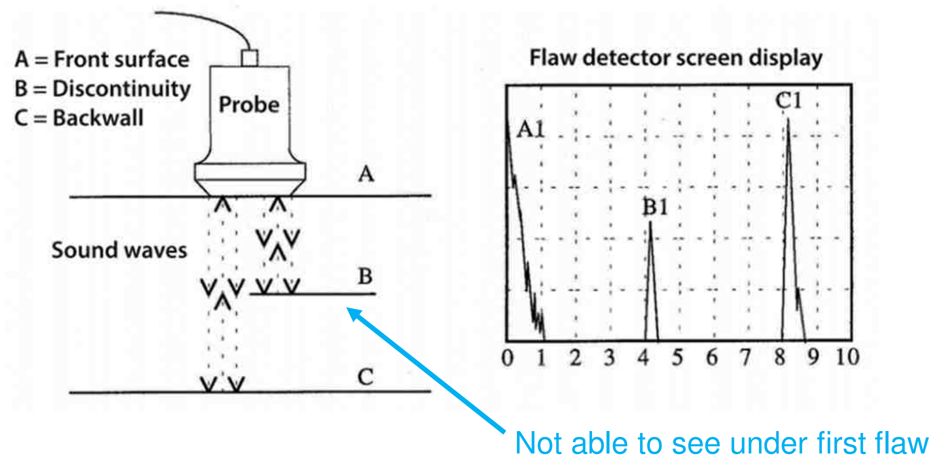
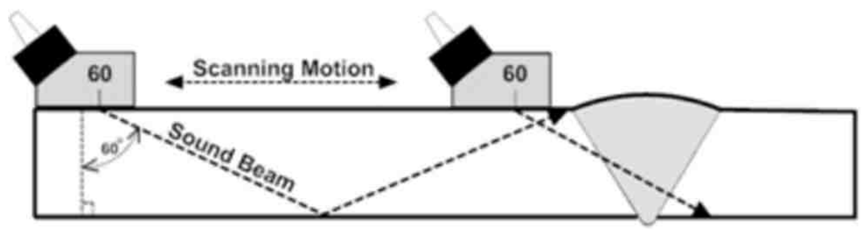
# Inspection Methodologies



- 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
  - Works on area with no irregular surface (welded areas)

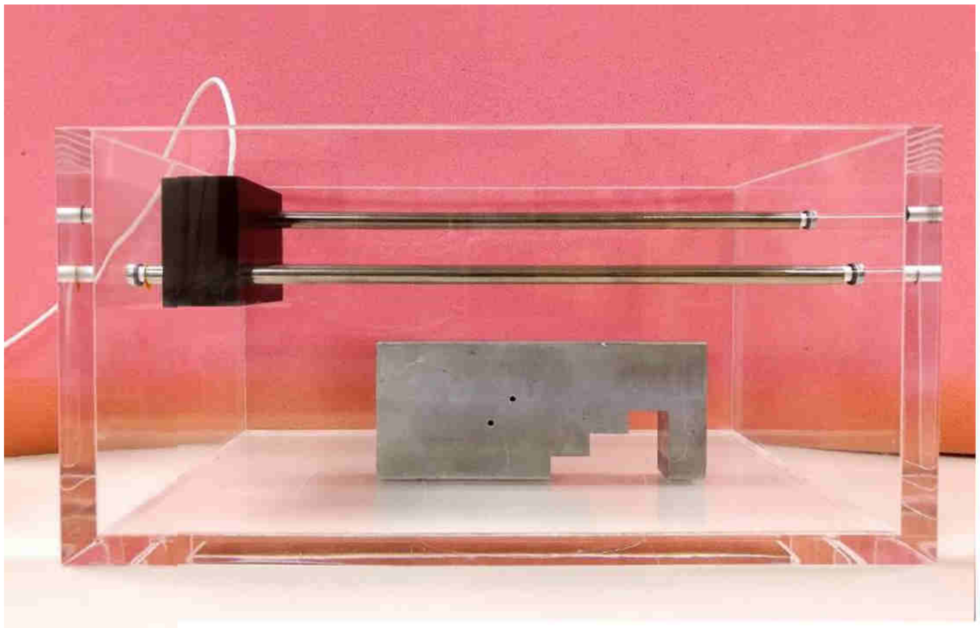


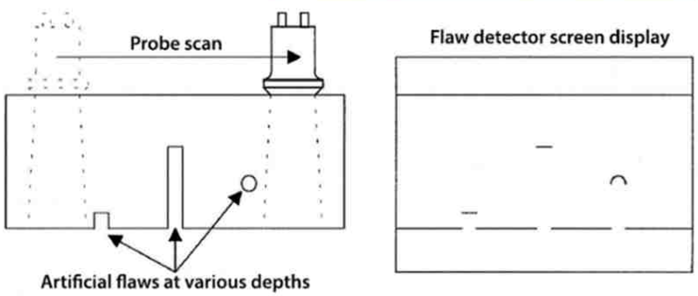



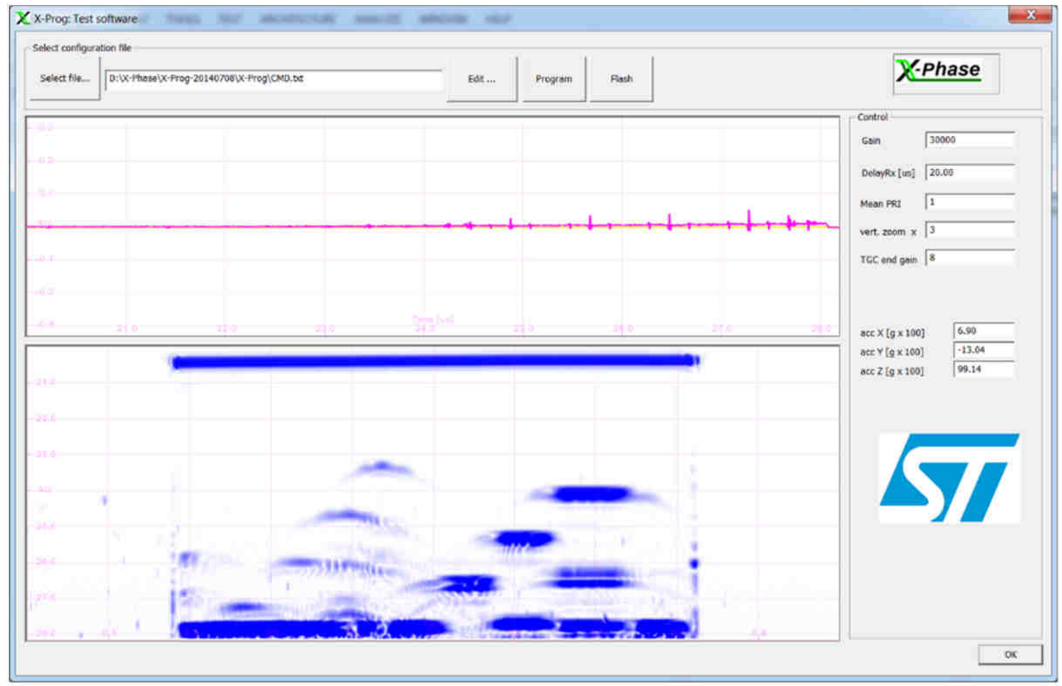

Angle Beam Testing

# Ultrasound NDT Demo





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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 |

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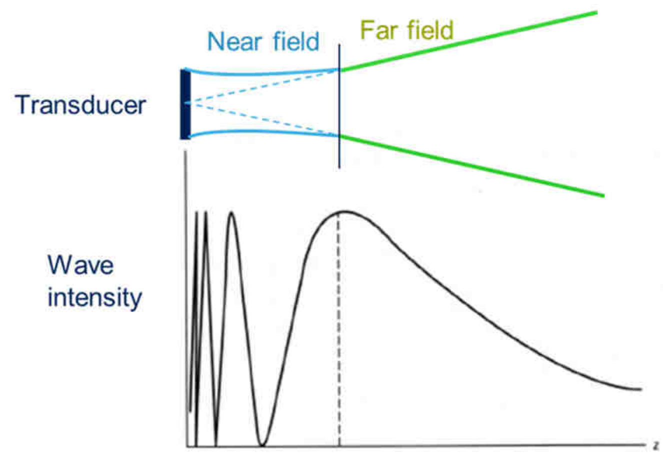
# Quality Parameters



- **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 $\lambda$ 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 | Low frequency signal |
|---|---|---|
| Attenuation | HIGH | LOW |
| Penetration | LOW | HIGH |
| Resolution | HIGH | LOW |

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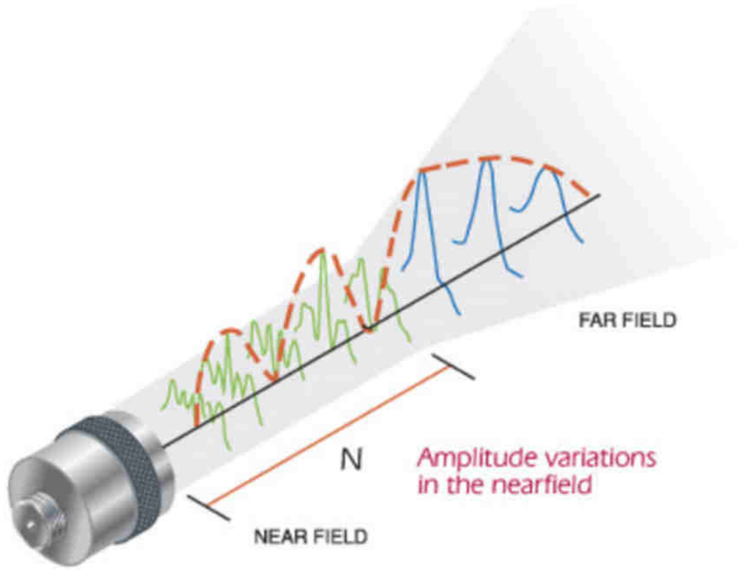
# Near Field and Far Field






www.olympus-ims.com

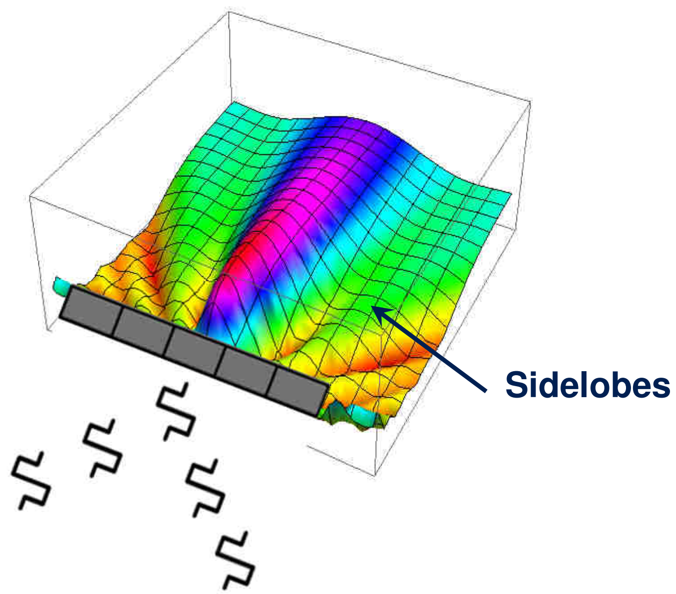
Ultrasound wave intensity along the  beam is not constant because of transducer finite dimension

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

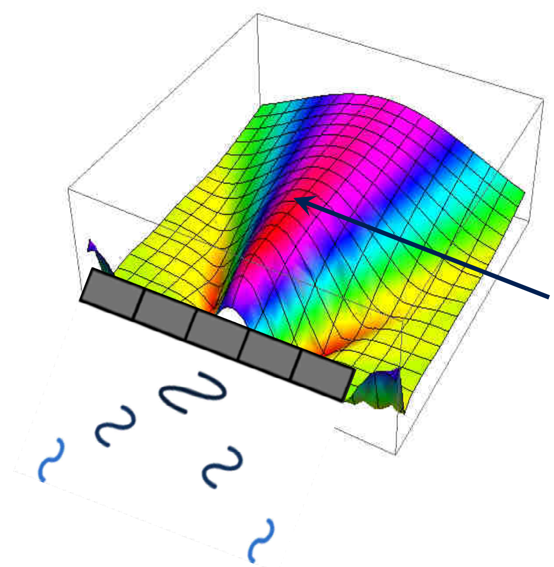
# Signal Excitation 

**Acoustic Pressure In transmission**

Square waveform




Sinusoidal waveform



# ST Ultrasound Pulsers

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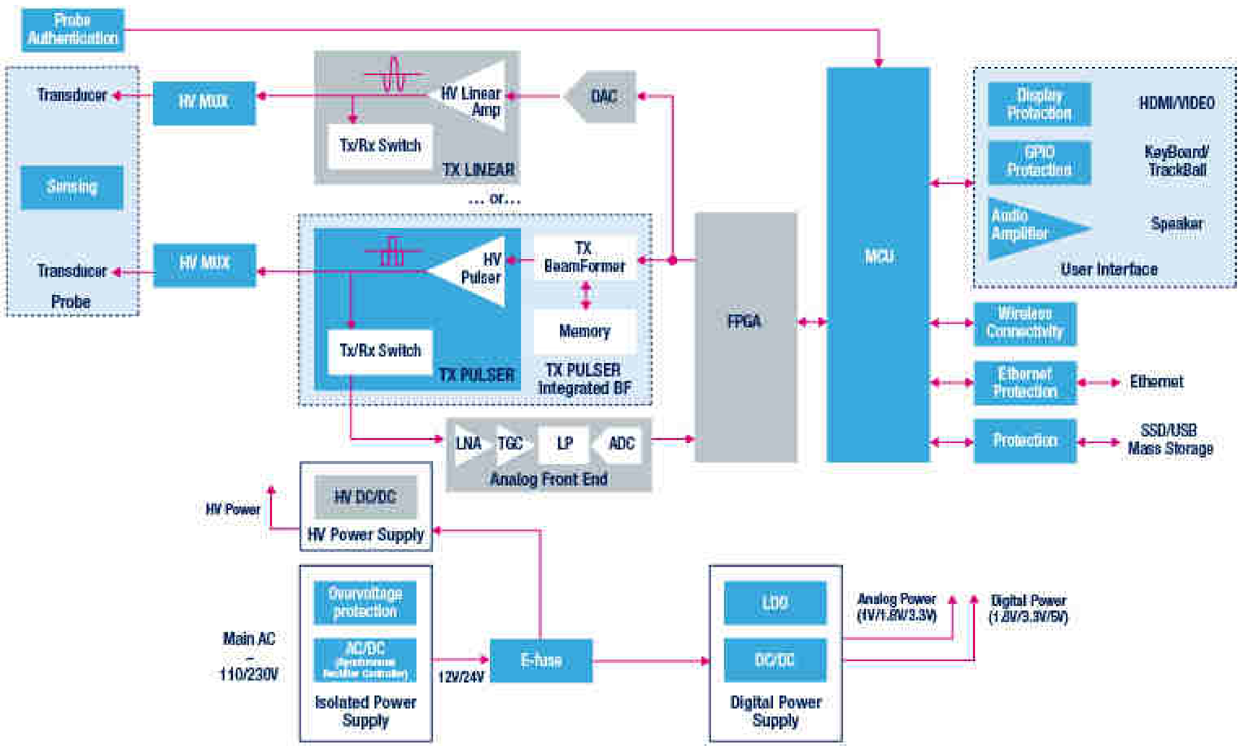
# Medical Ultrasound



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

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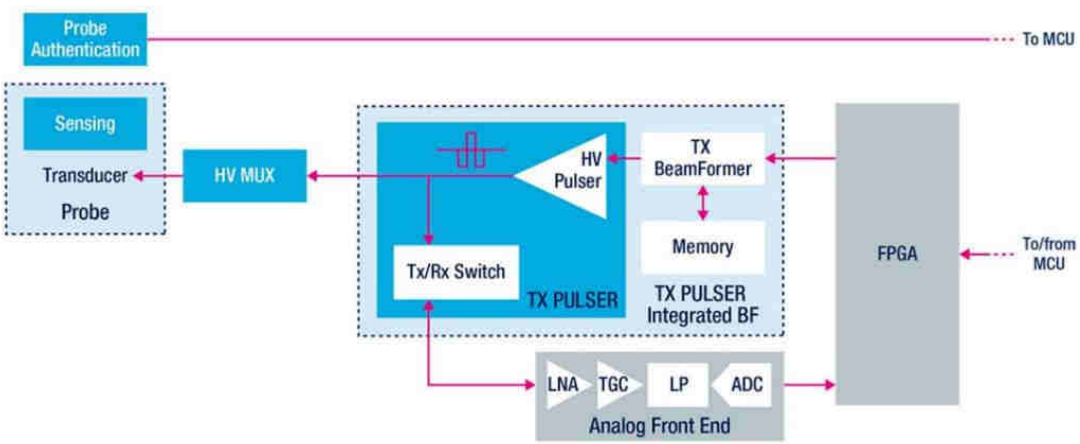
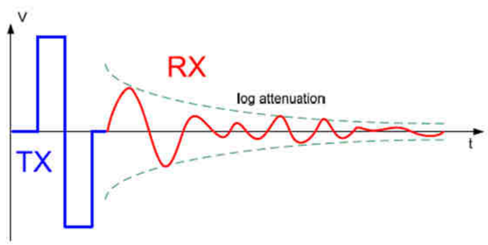
# Medical Ultrasound Partitioning

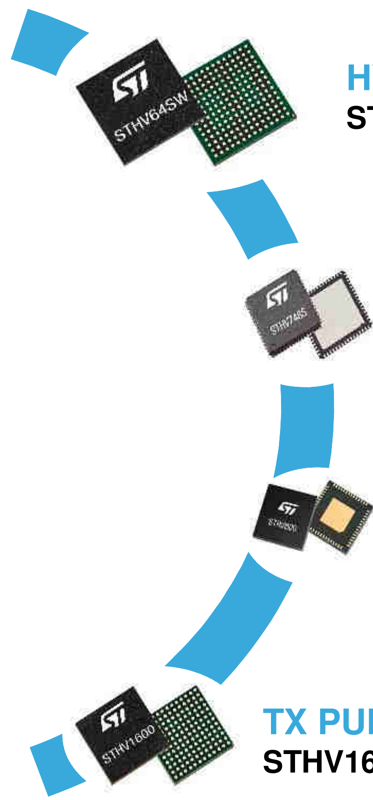


## High Voltage Stage and Smart Probe




**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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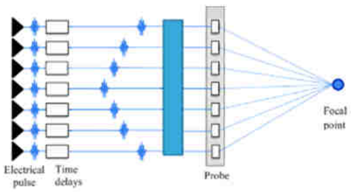
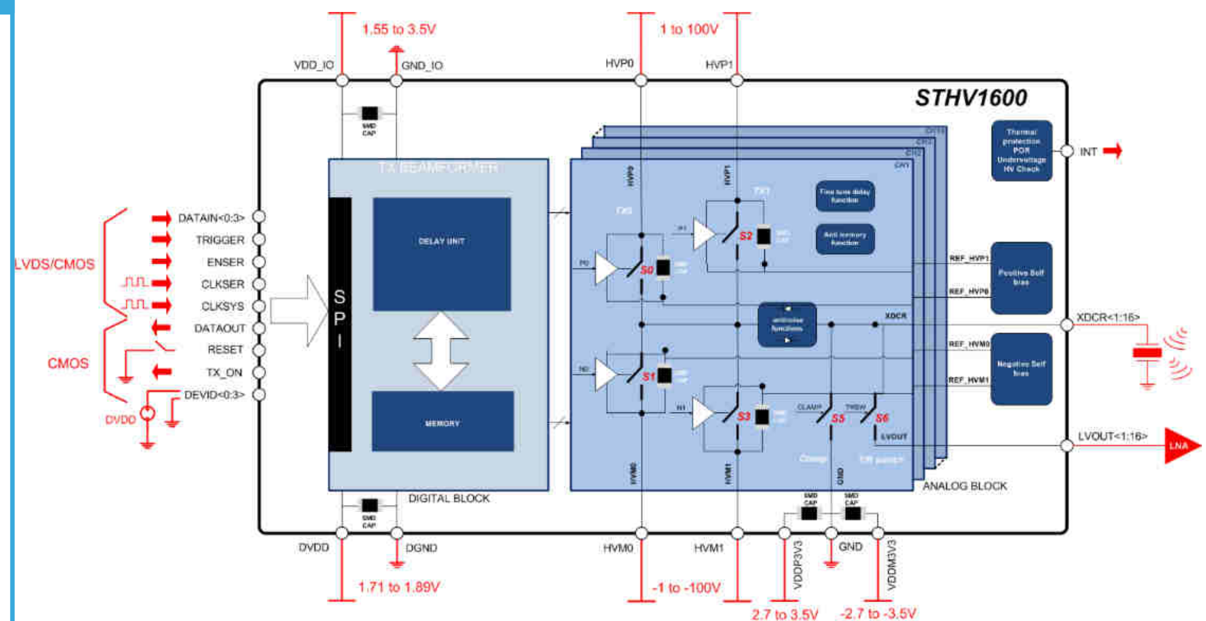



# STHV1600

## 16 channel Pulser with Beamforming

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

- 0 to 200V peak-to-peak output signal
- 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

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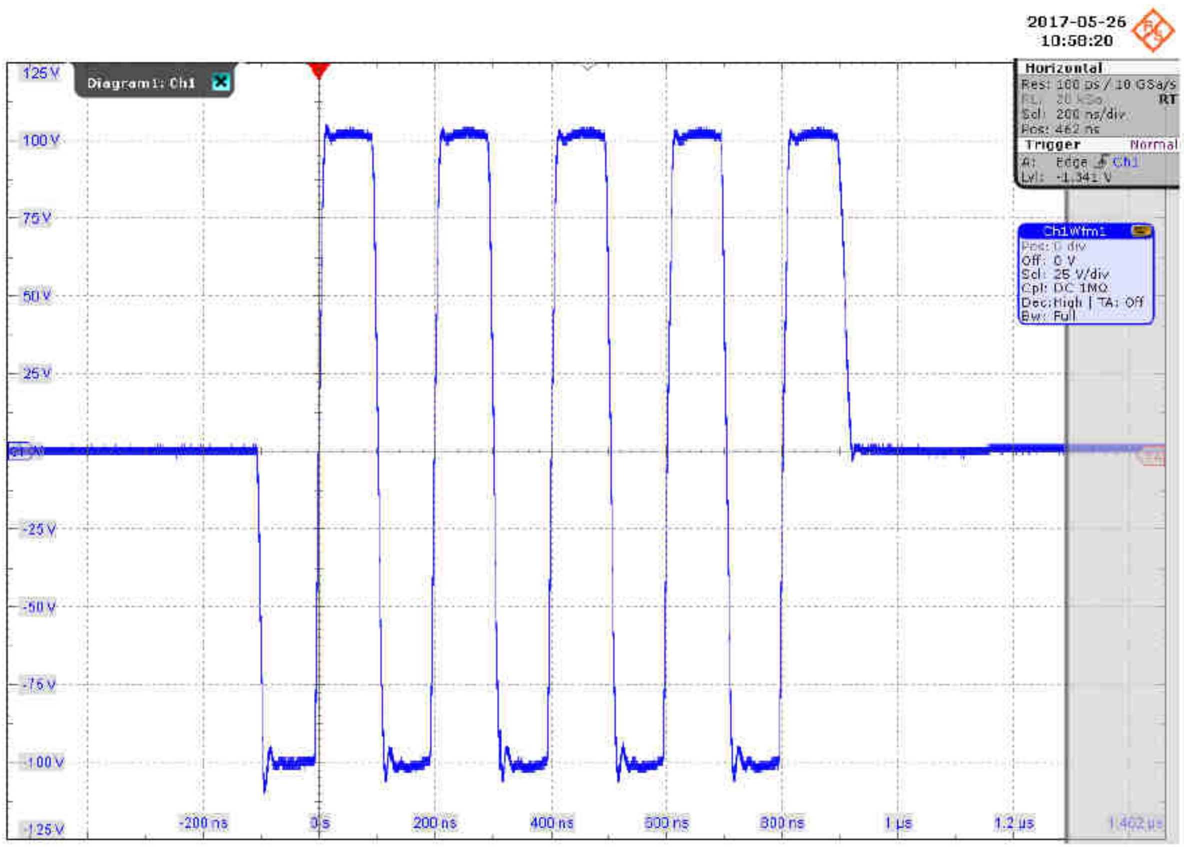
# Pulse Wave operation

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# Continuous Wave operation



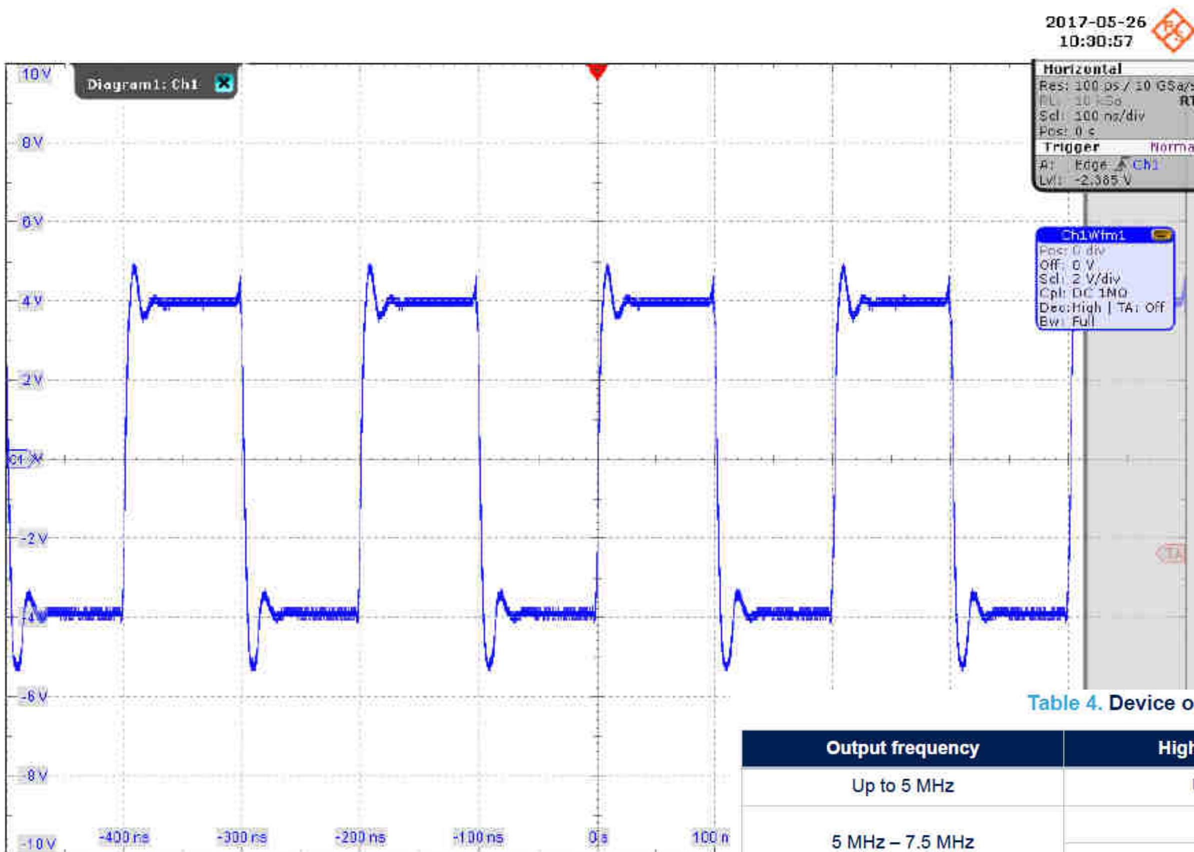


Table 4. Device overstress avoidance guidelines **Elastrography mode**

| 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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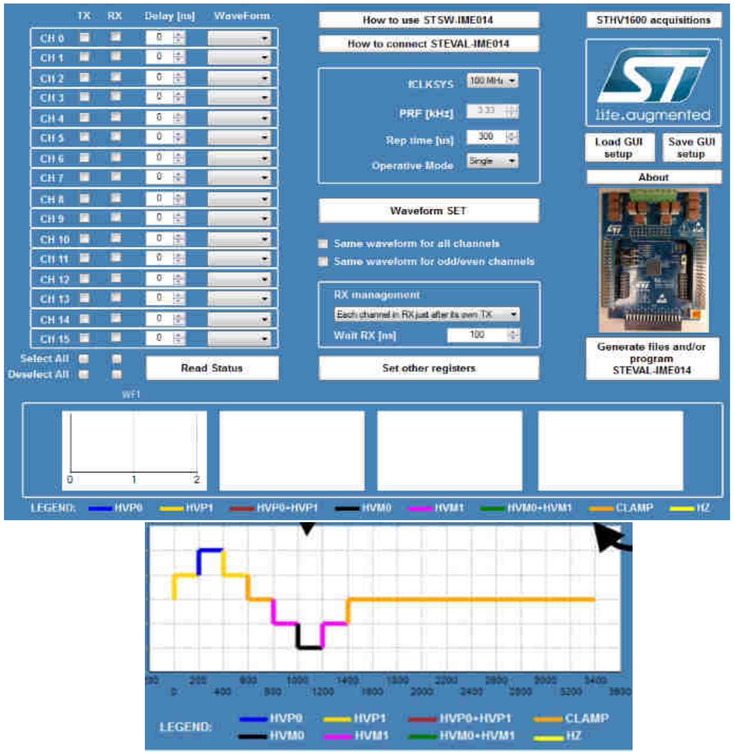
# STHV1600 evaluation kit

## STEVAL-IME014V1B

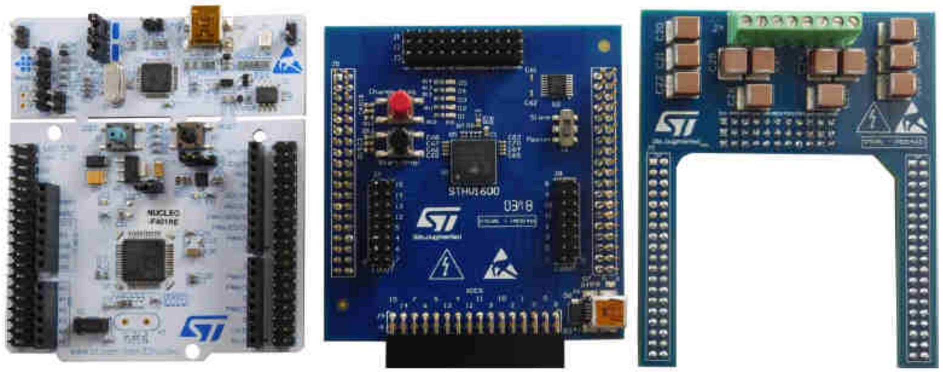
GUI – HV waveforms builder



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
  - All low voltage supplies generated on-board
- **STM32 Nucleo microcontroller module:**
  - STM32 microcontroller

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



# STHV748S

## 4 channel pulser

**Monolithic 4 channel, 5 level, high voltage pulser**

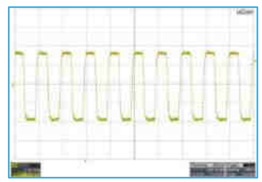
- Pinout compatibility with best selling STHV748
- 0 to ±90V output voltage
- Up to 20MHz operating frequency
- PW operation:
    - 3/5-level output waveform
    - ±2 A source and sink current
    - ≤ 20 ps jitter

Continuous wave (CW) operation:

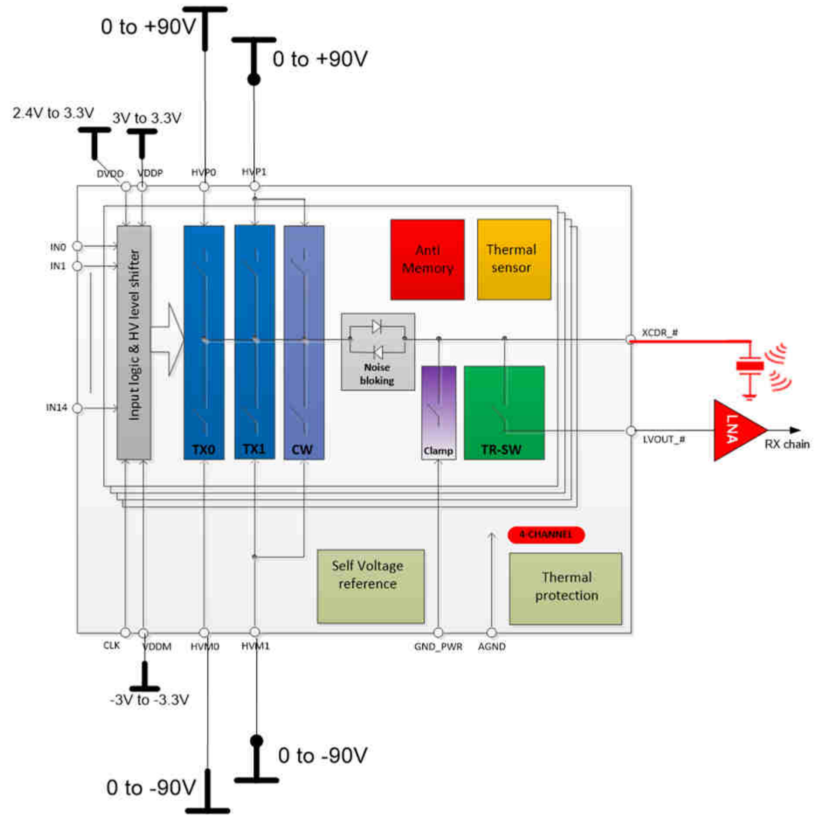
- ≤ 0.1 W power consumption
- ±0.6 A source and sink current
- 205 fs RMS jitter [100 Hz-20 kHz]

- Integrated 8 Ω synchronous active clamp
- Integrated T/R switch
    - 13.5 Ω on-resistance
    - Up to 300 MHz BW
    - Receiver multiplexing function
- 1.8V to 3.6V CMOS logic interface
- Package: QFN64 9X9 mm


CW mode



5 level PW mode

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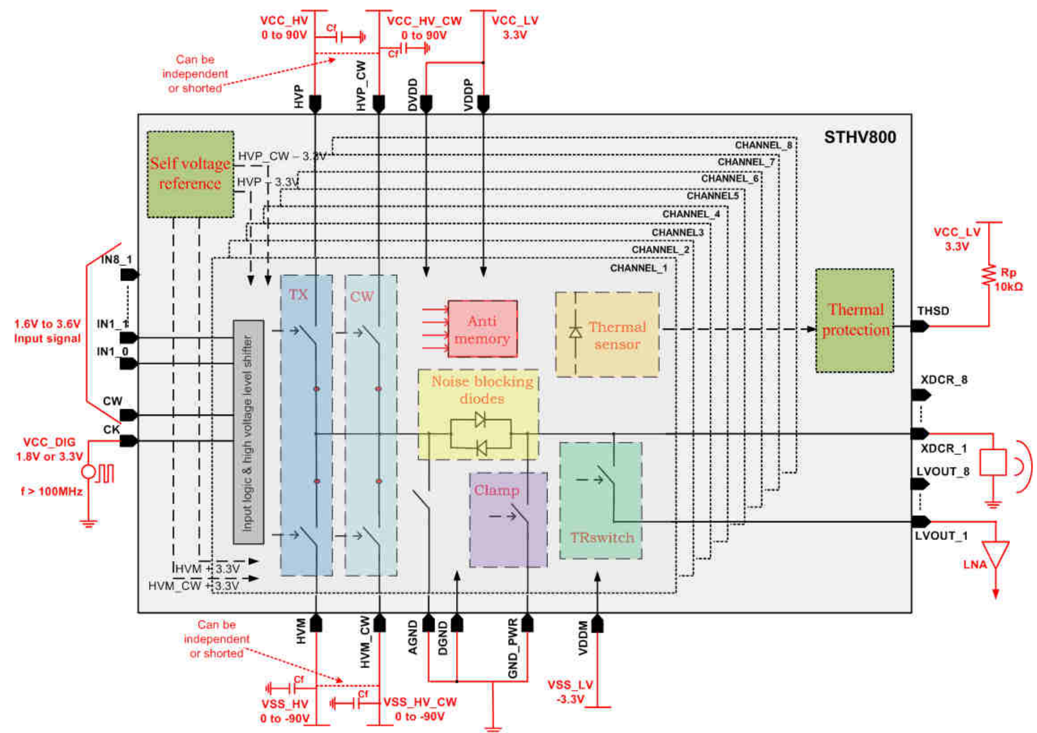
# STHV800

## 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
- Main half bridge (±2A source and sink current, 20ps jitter
- CW half bridge (±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 the package
- Power up free
- Current consumption down to 10μA in RX phase
- Anti memory function
- 1.8V to 3.6V CMOS logic interface
- Package: LGA 8X8 mm – 56 leads

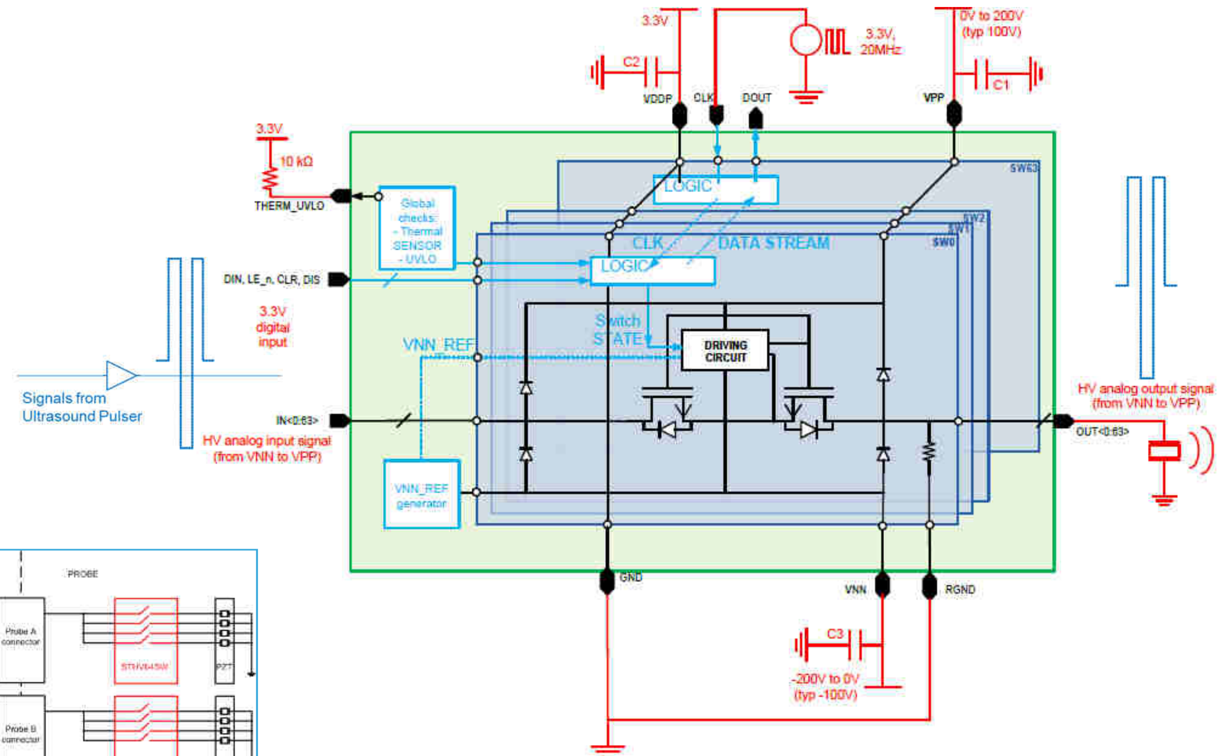



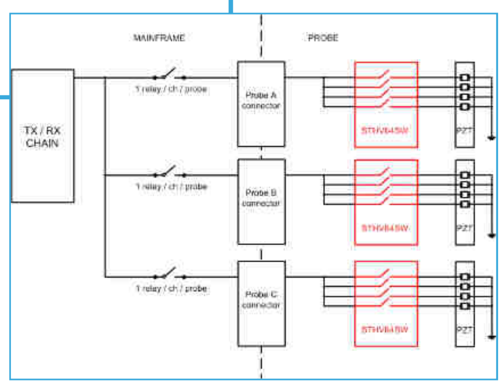
# STHV64SW

## 64 channel HV Switches

### Monolithic 64 independent High Voltage Analog Bi-directional Switches

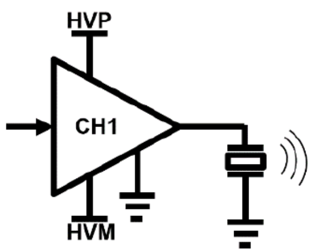
- 200 V peak-to-peak input and output signal
- Three main operating ranges:
  - From -100 V to +100 V
  - From 0 V to 200 V
  - From -200 V to 0 V
- ±3 A peak output current.
- Very fast input slew rate (40V/ns at no load)
- Low on-resistance (10OHM)
- Low cross-talk between channels
- 40kOHM bleed resistor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



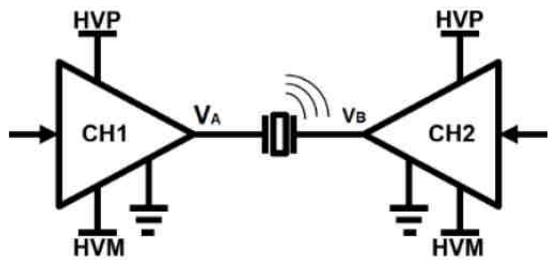



# Differential drive for very high voltage

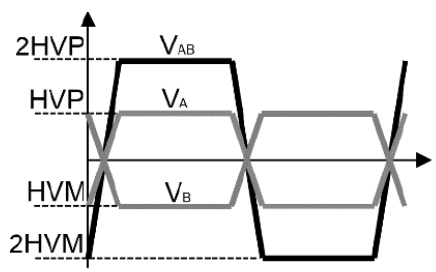


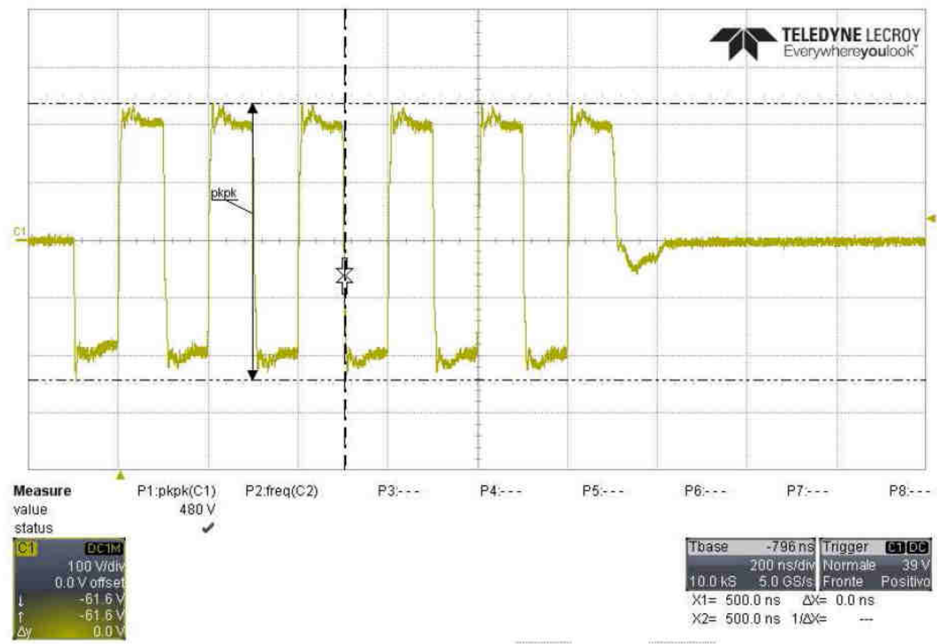



Single ended drive




Differential drive with two pulsers




400Vpp differential pulsed wave with two channels supplied at +/-100V

# 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

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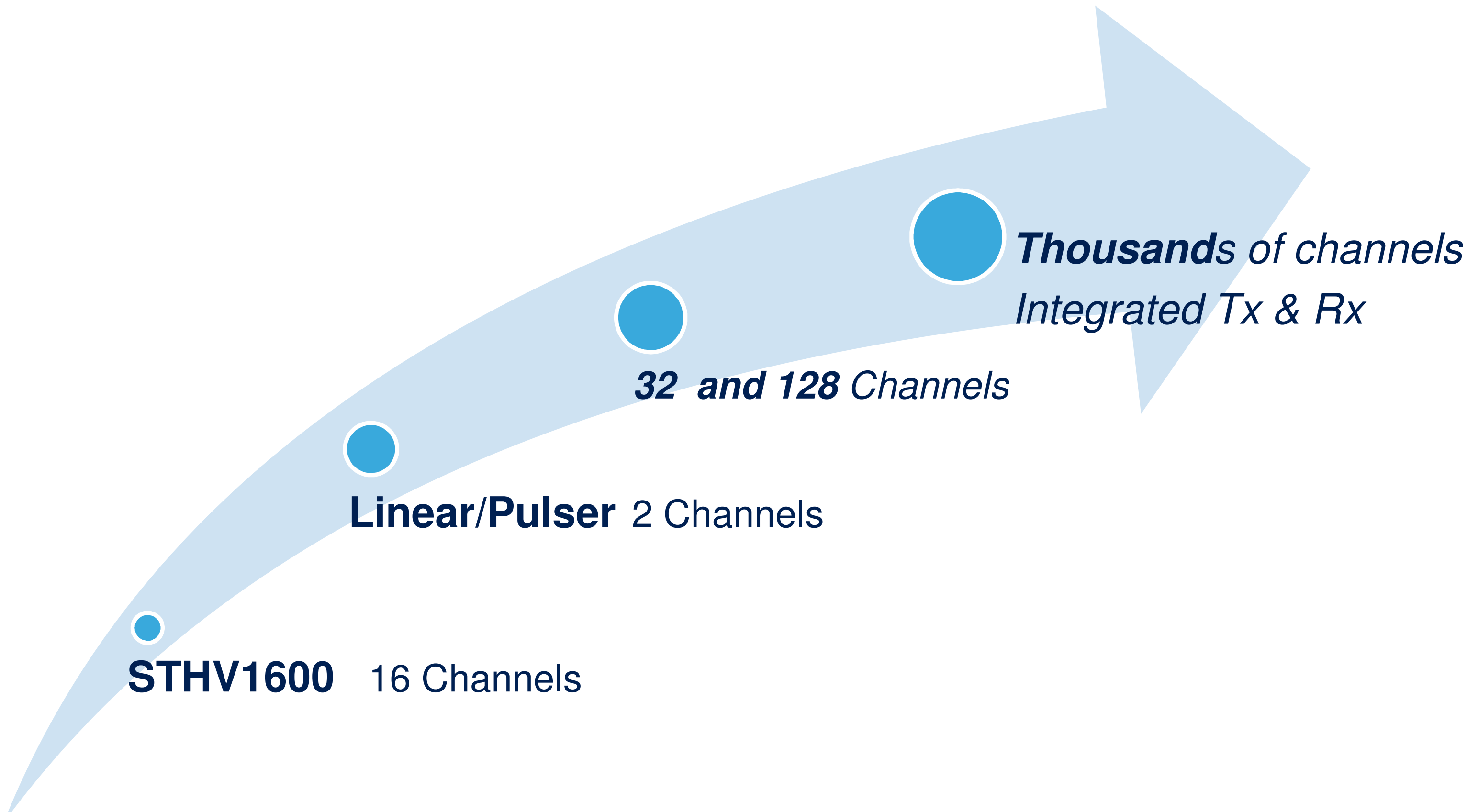
# ST Vision

## Towards higher integration

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