NDT&E Methods: UT

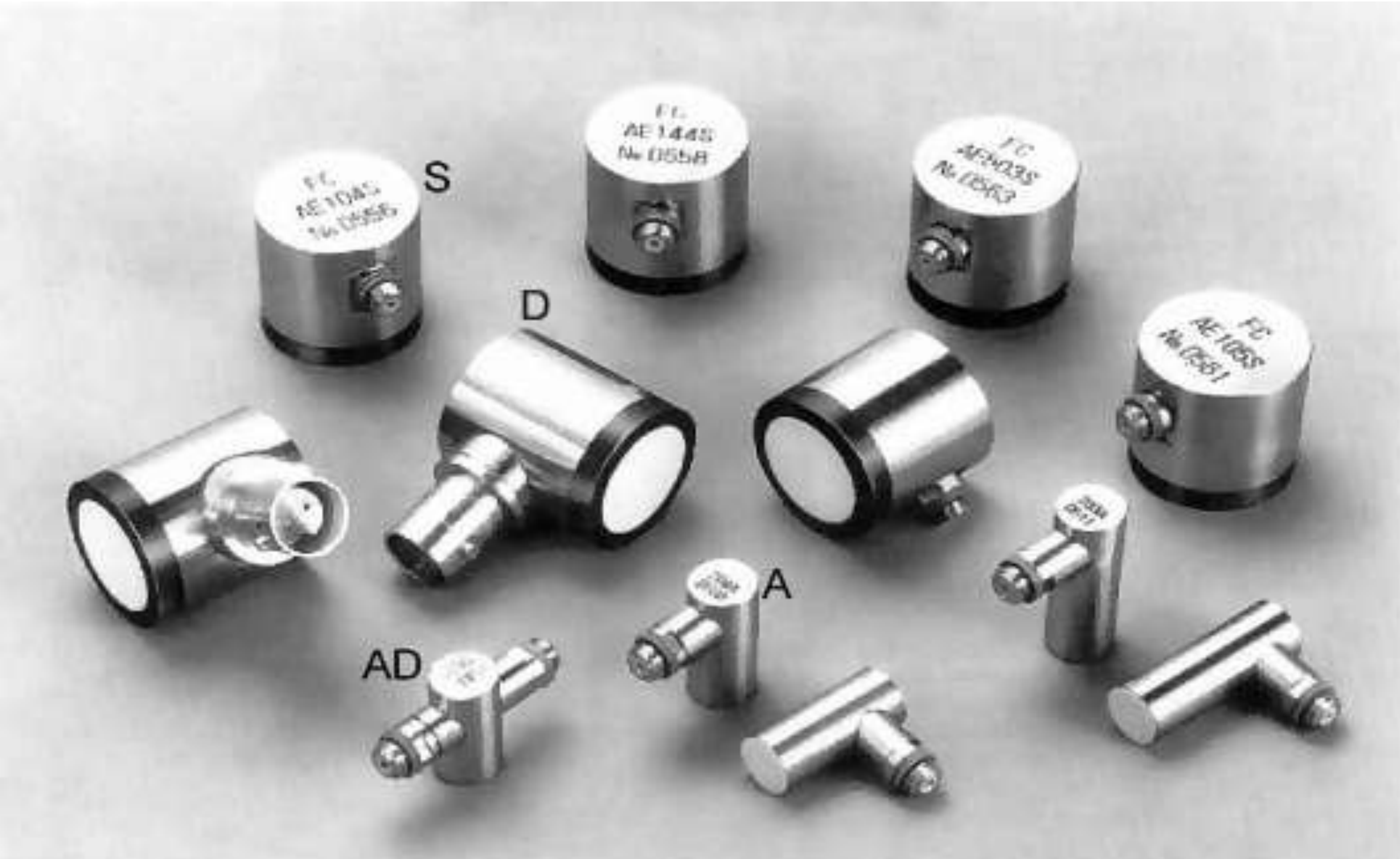
Ultrasound Generation

Michael Kröning

NDT&E Methods: UT

6.	**NDT&E: Introduction to Methods**
6.1.	Ultrasonic Testing: Basics of Elasto-Dynamics
6.2.	Ultrasonic Testing: Ultrasound Generation
6.3.	The Pulse-Echo Method
6.4.	UT-Systems: Transducer, Instrument, Manipulator
6.5.	Current Developments
6.6.	Case Studies by Movies

NDT&E Methods: Ultrasound Generation



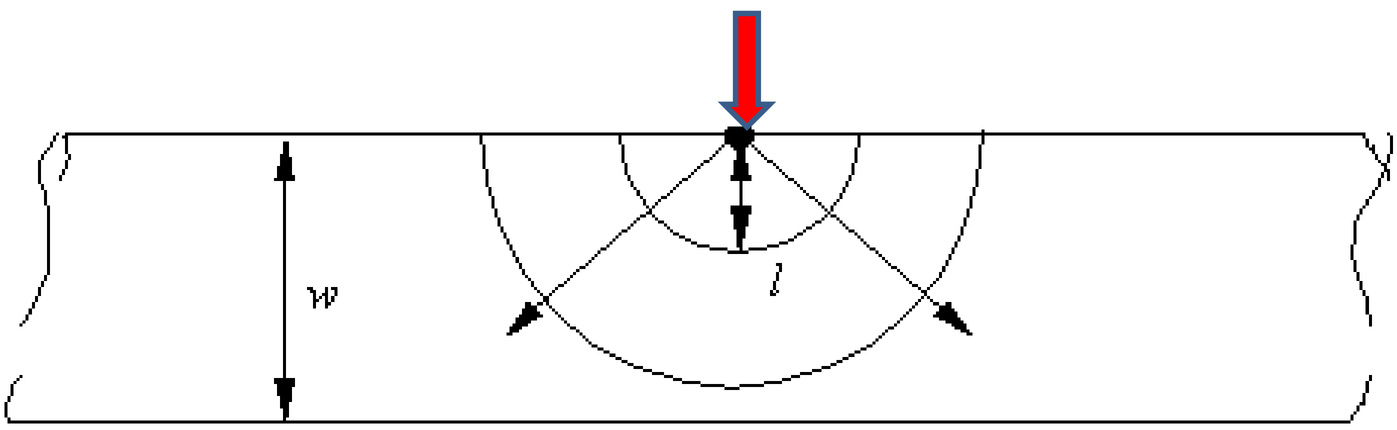
NDT&E Methods: Ultrasound Generation

General Considerations and Requirements on potential stress wave sources:

1. frequency content control;
2. pulse length control (damped pulses)
3. magnitude of loading force control
4. wave mode generation
5. Intensity profile control
6. Control of propagation direction

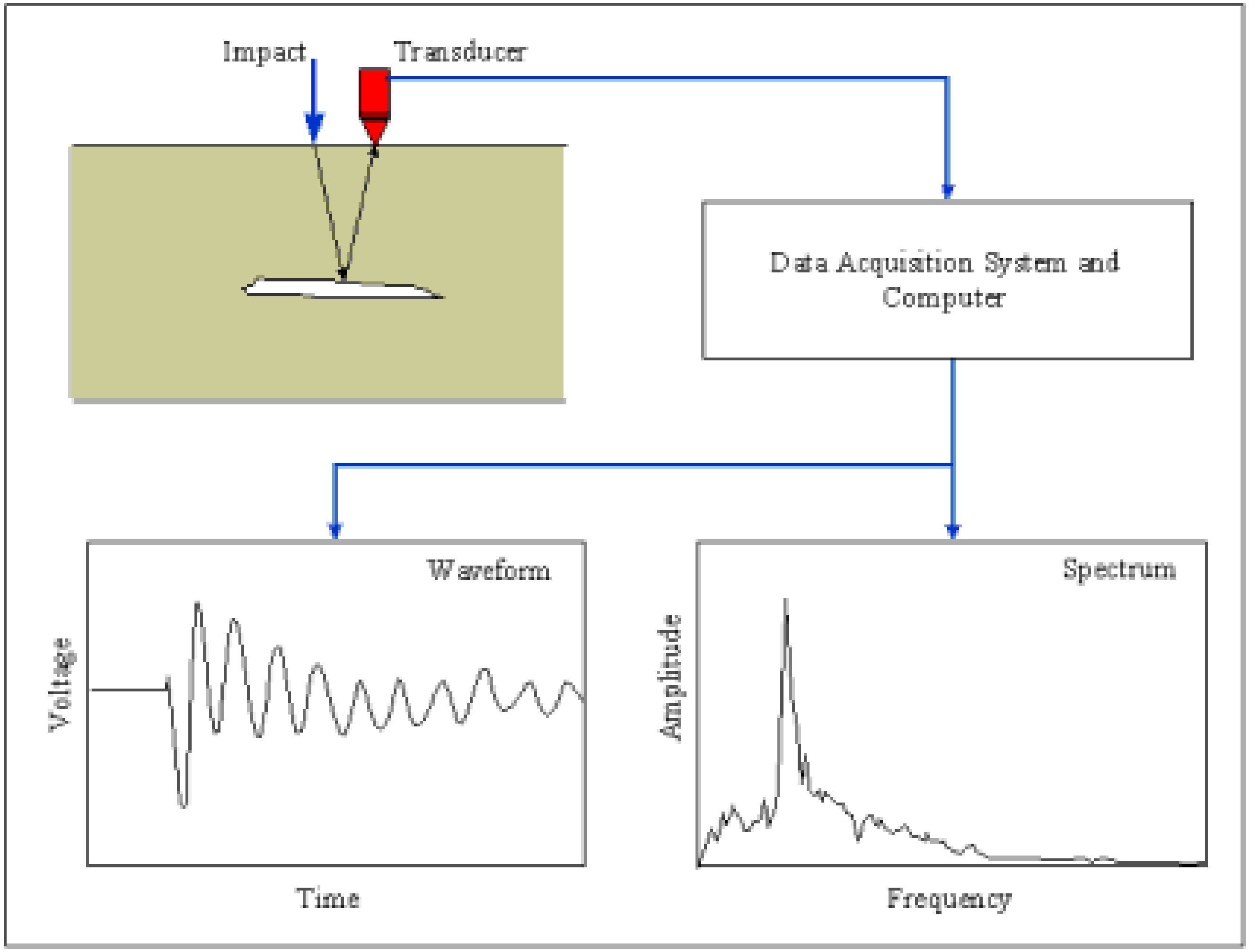
Mechanical Impacts

with solids generate Ultrasound through a linear momentum transfer from the imparting body to the mechanical waves.



NDT&E Methods: Ultrasound Generation

Mechanical Impact



NDT&E Methods: Ultrasound Generation

Mechanical Impact

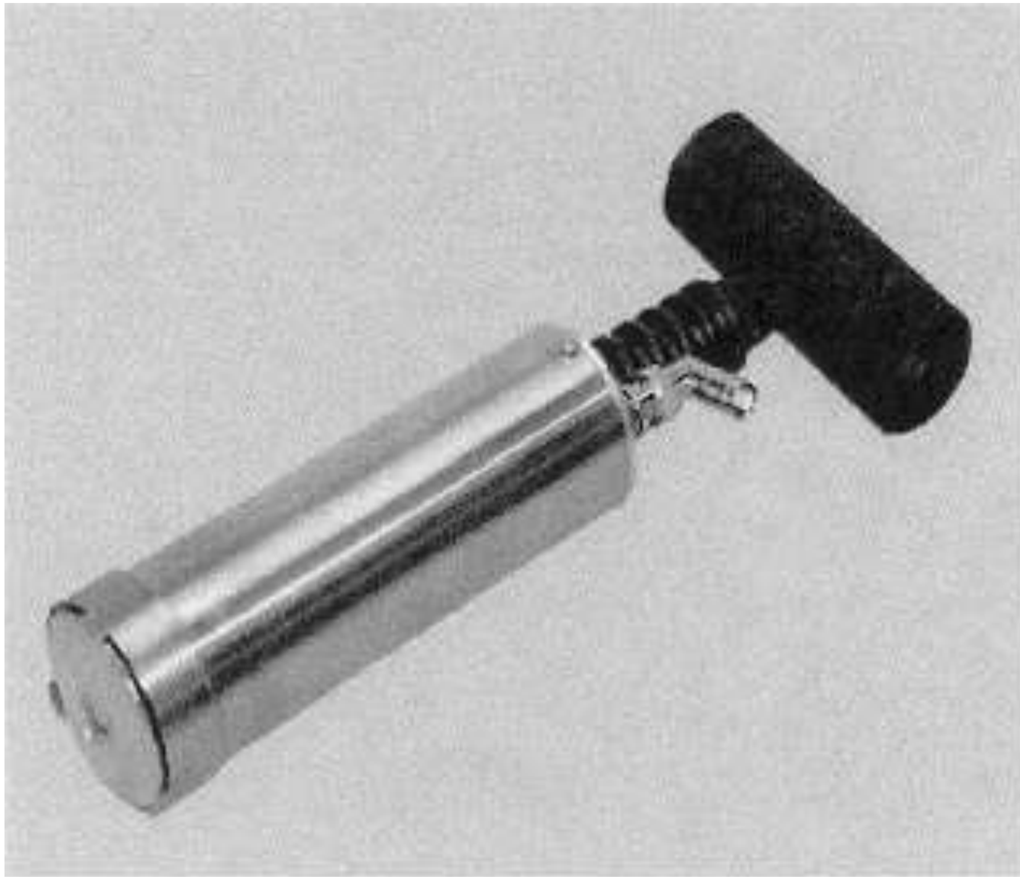
Impact-Echo Testing

Wave Speed Measurement

CONCRETE Inspection with frequencies up to 80 kHz

NDT&E Methods: Ultrasound Generation

Mechanical Impact



Hand-held transducer.
Courtesy of Impact-Echo Instruments, LLC.

NDT&E Methods: Ultrasound Generation

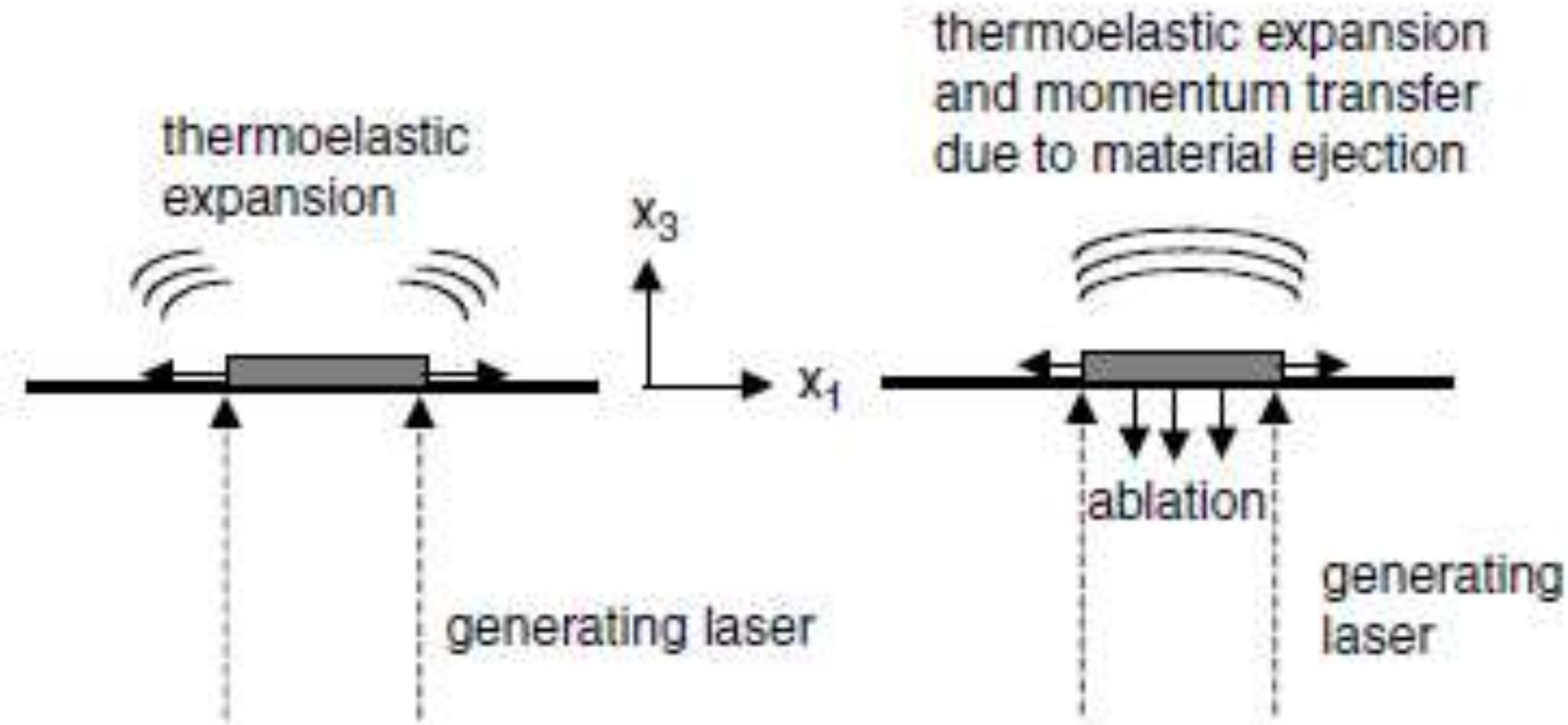
Mechanical Impact

Impact-Echo pistol grip transducer

Courtesy of Impact-Echo Instruments, LLC.

NDT&E Methods: Ultrasound Generation

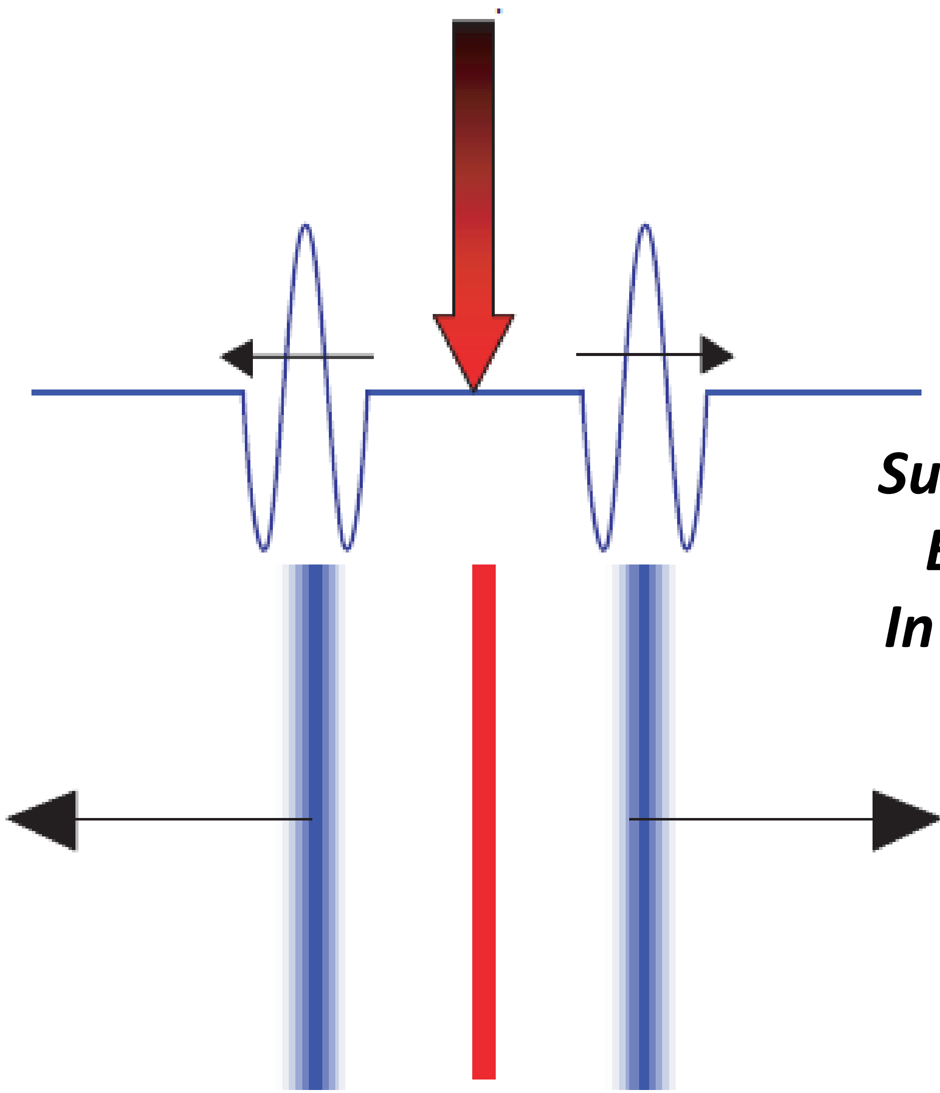
Laser Impact



Thermoelastic Regime **Ablative Regime**

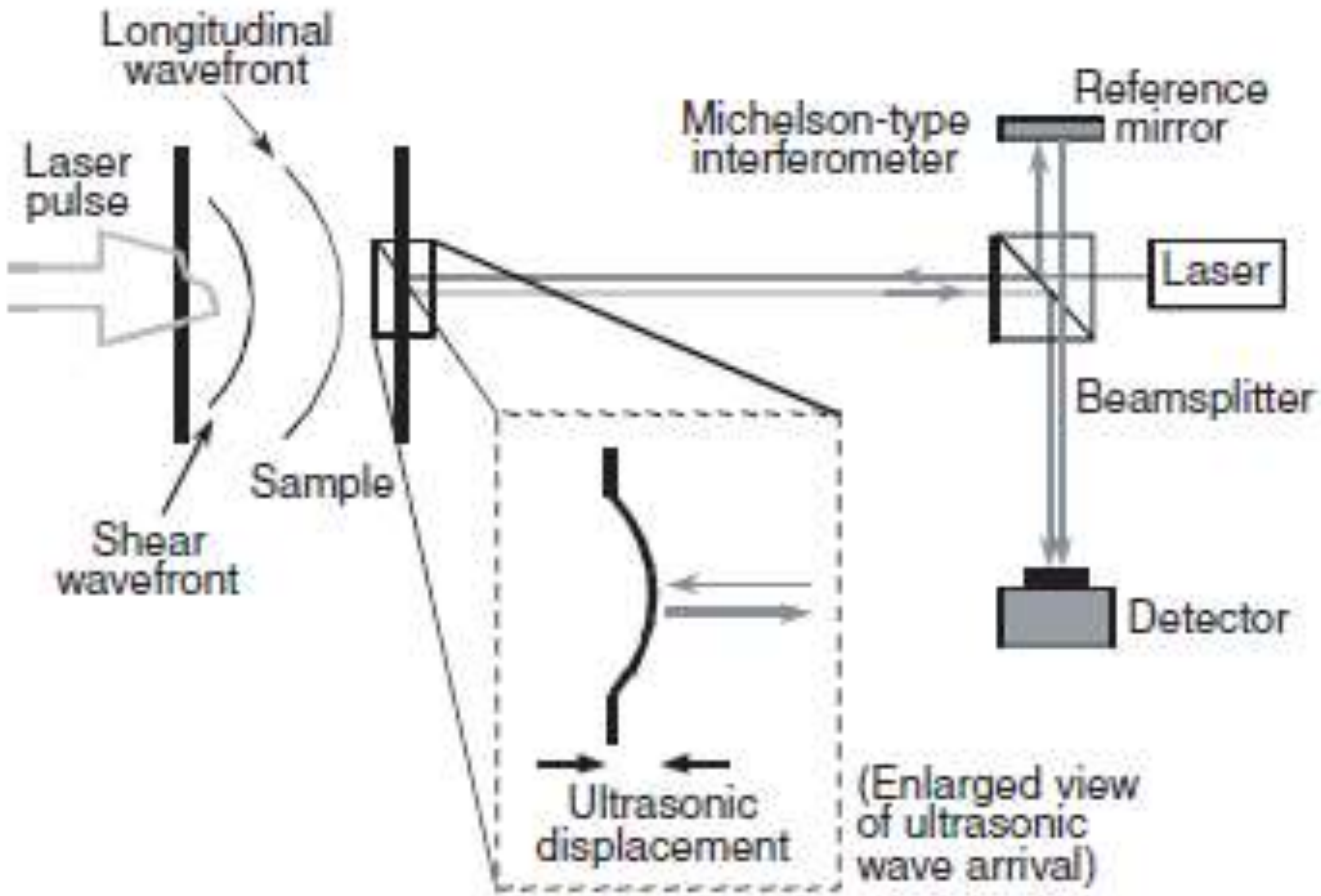
Laser Generation of Ultrasound

NDT&E Methods: Laser based Ultrasound



Surface Wave Generation
By a Laser Line Source
In thermo-elastic Regime

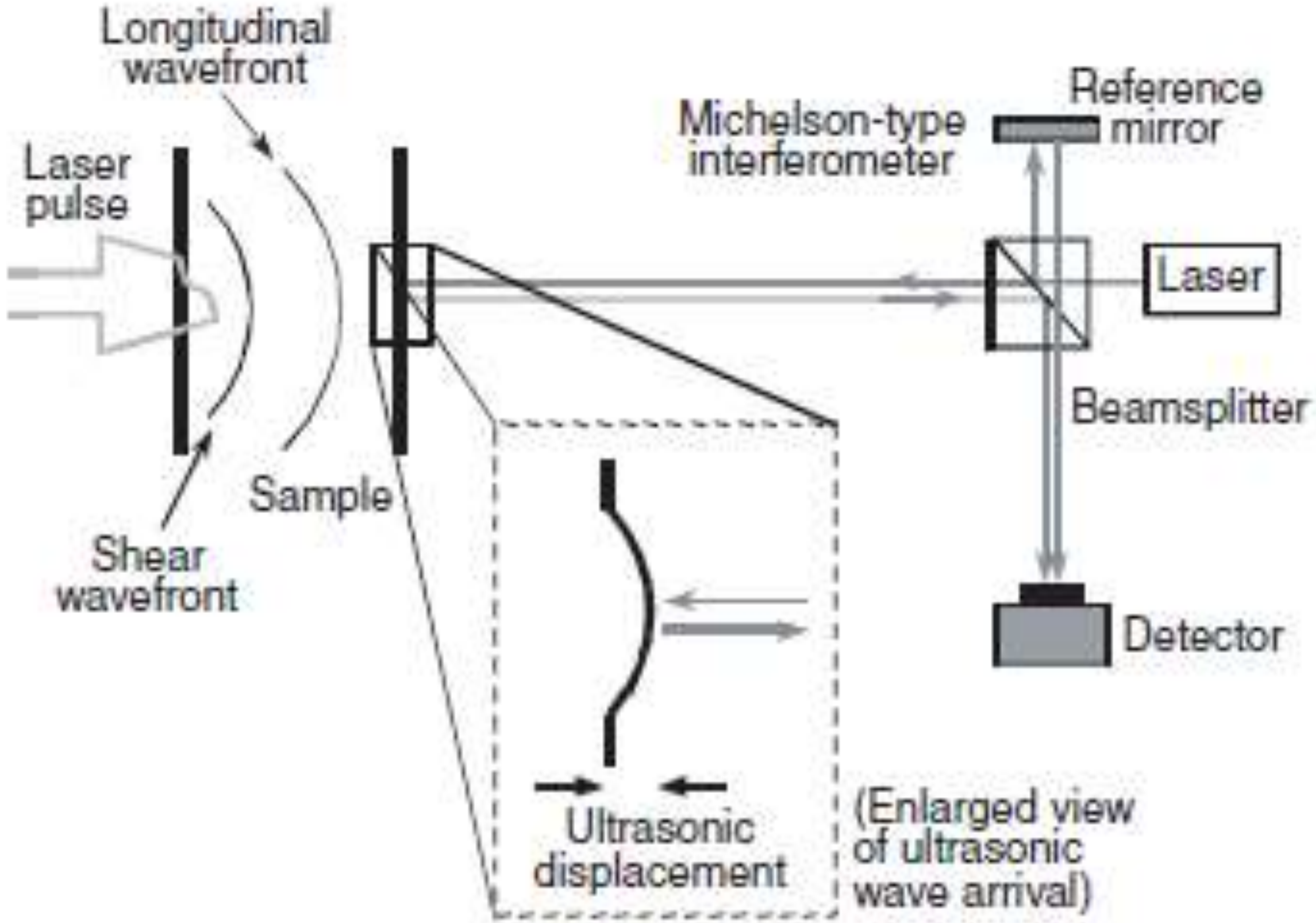
NDT&E Methods: Laser based Ultrasound



Ultrasonic measurement Scheme

using a pulsed laser and a Michelson-type interferometer for ultrasound detection

NDT&E Methods: Laser based Ultrasound



Ultrasonic Measurement Scheme

(Pulsed Laser for Ultrasound Generation, a Michelson-Type Interferometer for Detection)

NDT&E Methods: Laser based Ultrasound

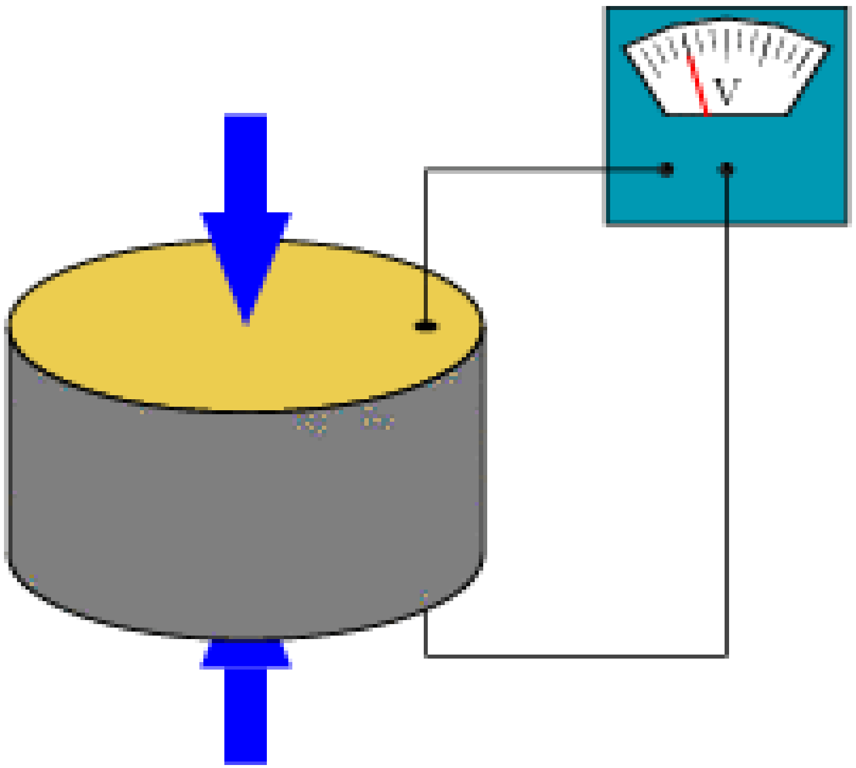
ADVANTAGES & DISADVANTAGES of LBU

NONCONTACT	LOWER SENSITIVITY
REMOTE	RELATIVELY EXPENSIVE
RAPID SCANNING	GENERATION EFFICIENCY DEPENDS ON OPTICAL ABSORPTION
SCANNING OF AWKWARD GEOMETRIES	REQUIRES LASER SAFETY PRECAUTIONS
CAN BE A POINT SOURCE Both temporally and spatially	
BROADBAND (Generation & Detection)	
REPRODUCIBLE SOURCE	
GENERATION OF SURFACE & BULK WAVES	
SHAPING OF SURFACE WAVE FRONTS	
ABSOLUTE CALIBRATION BY LASER INTERFEROMETRY	

NDT&E Methods: Ultrasound Generation

Piezoelectricity - the piezoelectric effect

(„Pressure Electricity“)



NDT&E Methods: Ultrasound Generation

Piezoelectricity - the piezoelectric effect

(„Pressure Electricity“)

is the appearance of an electrical potential across the sides of a crystal when you subject it to mechanical stress:

$$P = ex$$

with P: Polarization; e: piezoelectric stress coefficient; x: strain

In the converse piezoelectric effect,
a crystal becomes mechanically stressed (deformed in shape)
when a voltage is applied across its opposite faces:

$$\mathrm{x} = dE$$

with x: strain, d: piezoelectric strain coefficient, E: electric field

The piezoelectric effect was discovered in 1880 by the brothers Pierre and Paul-Jacques Curie, in crystals of quartz, tourmaline, and Rochelle salt (potassium sodium tartrate). They took the name from the Greek work piezein, which means "to press."

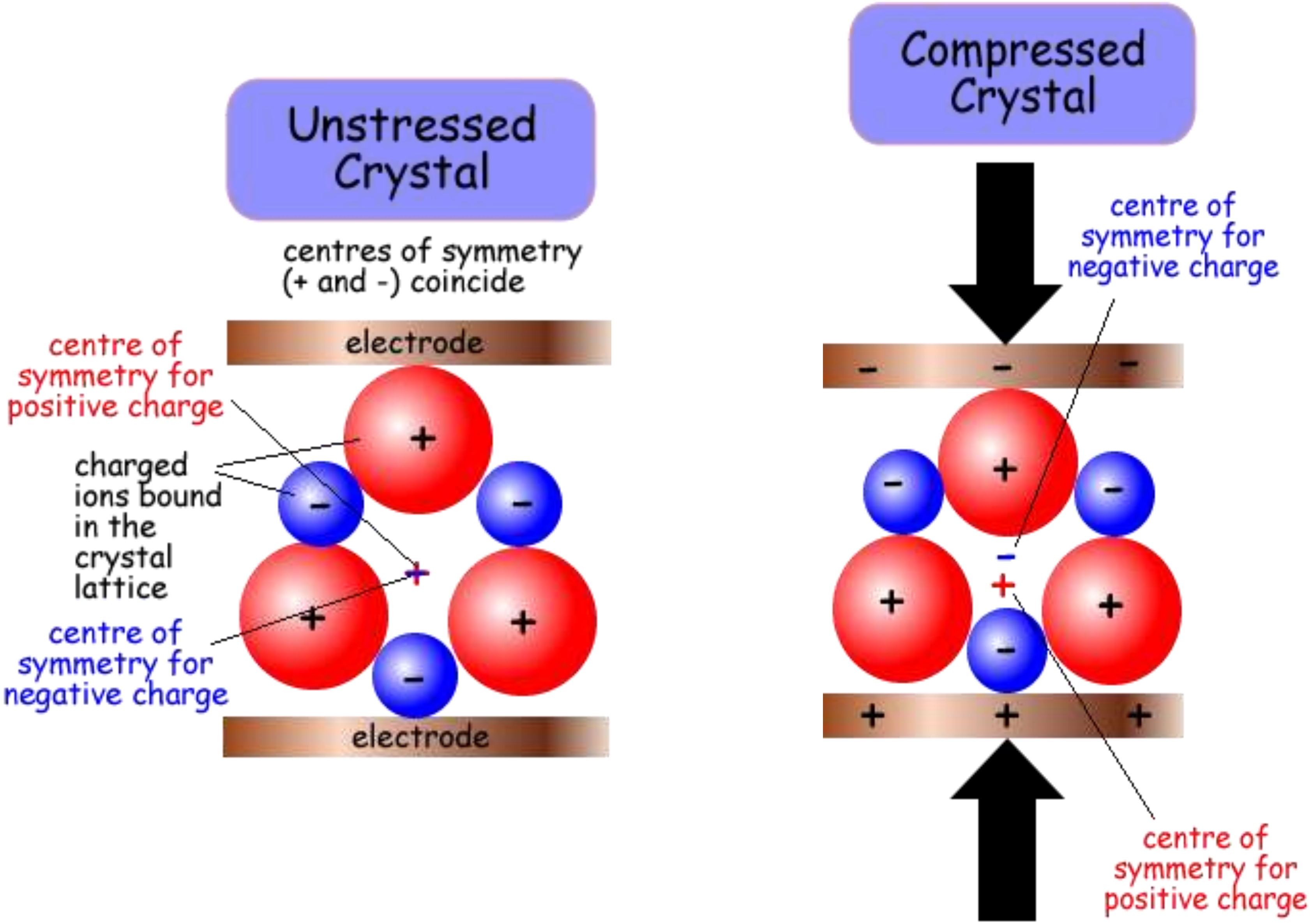
NDT&E Methods: Ultrasound Generation

**It has been discovered that in the 32 crystal classes,
which conventionally separated into 7 crystal systems,
only 20 classes possesses piezoelectric crystals (Nye, 1972).**

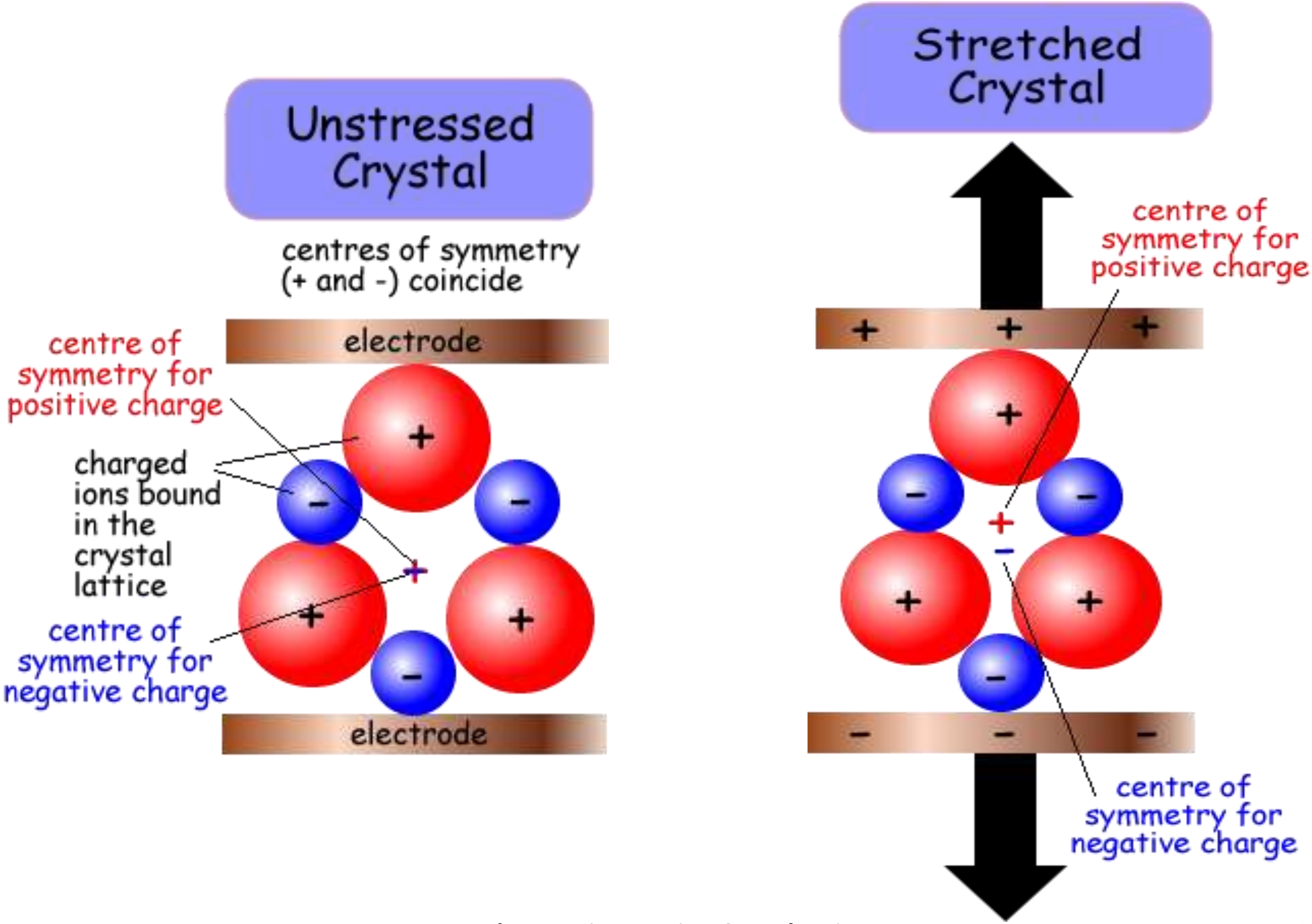
**Only the crystal classes that possess no center of symmetry
are the ones have piezoelectricity.
The dipoles form groups of atoms in the lattice
are the cause of the asymmetric crystal
to have the piezoelectric effects.**

***Examples of piezo electric cystals:
Quartz
the synthetic ceramic,
lead zirconate, titanate.***

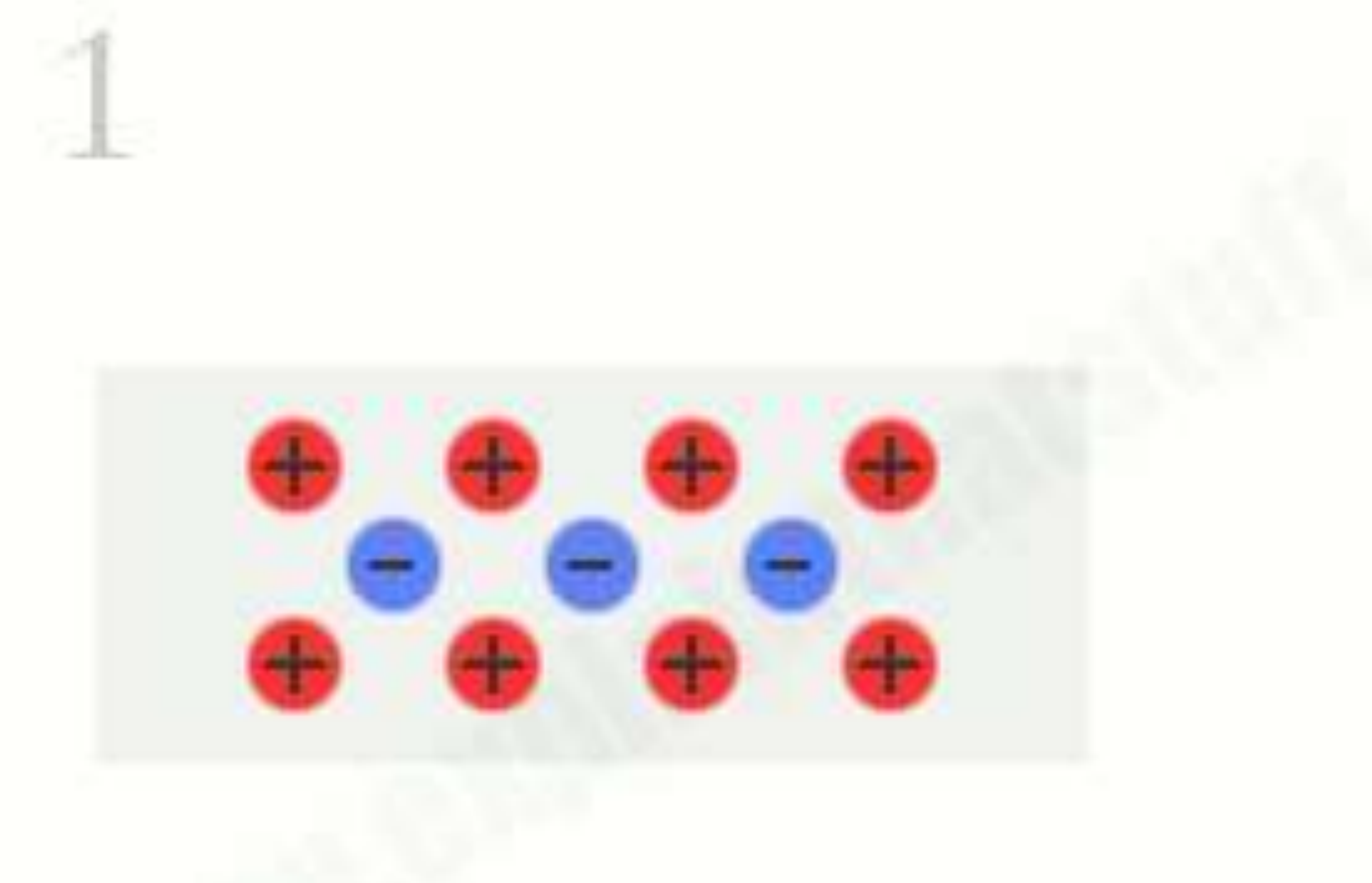
NDT&E Methods: Ultrasound Generation



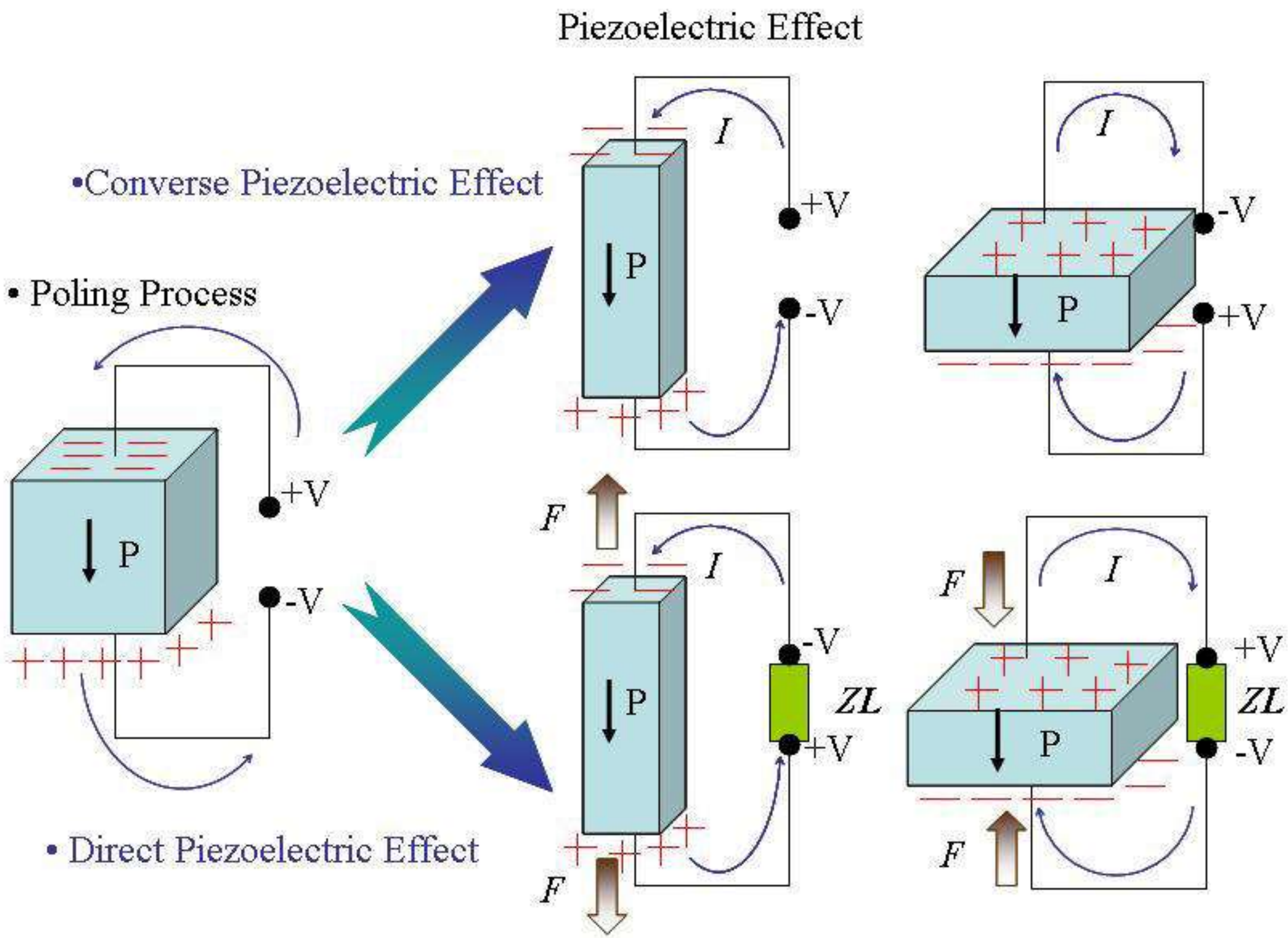
NDT&E Methods: Ultrasound Generation



NDT&E Methods: Ultrasound Generation

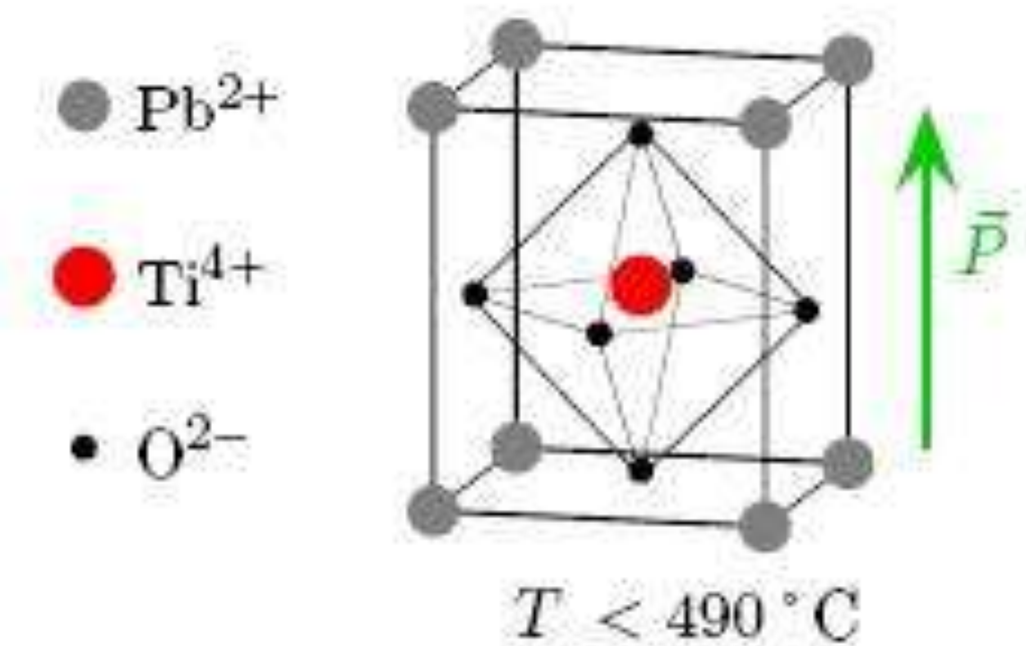


NDT&E Methods: Ultrasound Generation



NDT&E Methods: Ultrasound Generation

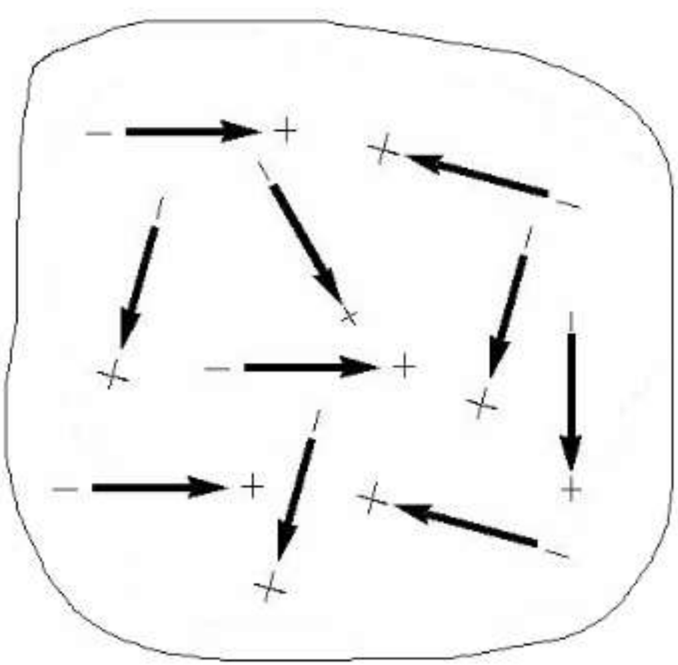
Poling Process of Ferroelectrica



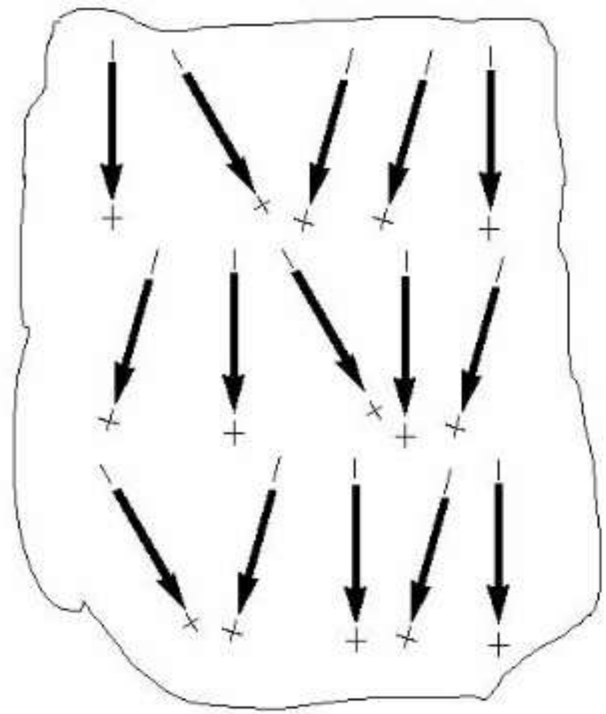
The vector P in the diagram points in the direction of the net dipole resulting from the displacement of charge.

Lattice of Pb(TiO_2)

NDT&E Methods: Ultrasound Generation



The dipoles in macroscopic sample
can have random orientations
in which case the material has no net moment



Applying a strong electric field
aligns the dipoles.
The oriented dipolar domains
can loose their structure
at high temperature, with wear etc.

Poled ferroelectric materials form materials which are *piezoelectric*

NDT&E Methods: Ultrasound Generation

Mathematical Description

Linear piezoelectricity is the combined effect of the linear electric behavior of the material and Hook's law for linear elastic materials:

$$D = \varepsilon E \text{ with } \nabla D = 0 \text{ and } \nabla x E = 0$$
$$S = sT \text{ with } \nabla T = 0 \text{ and } S = (\nabla u + u\nabla)$$

D: Electric Charge Density Displacement, *ε:* Permittivity, E: Electric Field Strength

S: Strain, s: Compliance, T: Stress

Combined ⇒ STRAIN CHARGE FORM:

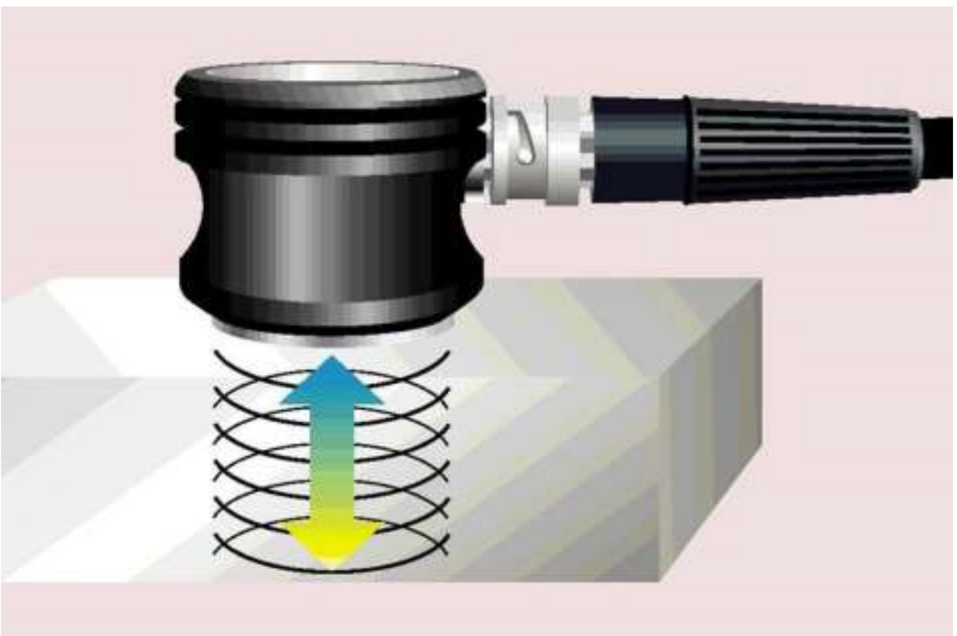
$$S = sT + d^t E$$ **(d^t: Matrix for the converse effect)**

$$D = dT + \varepsilon E$$ **(d: Matrix for the direct effect)**

NDT&E Methods: Ultrasound Generation

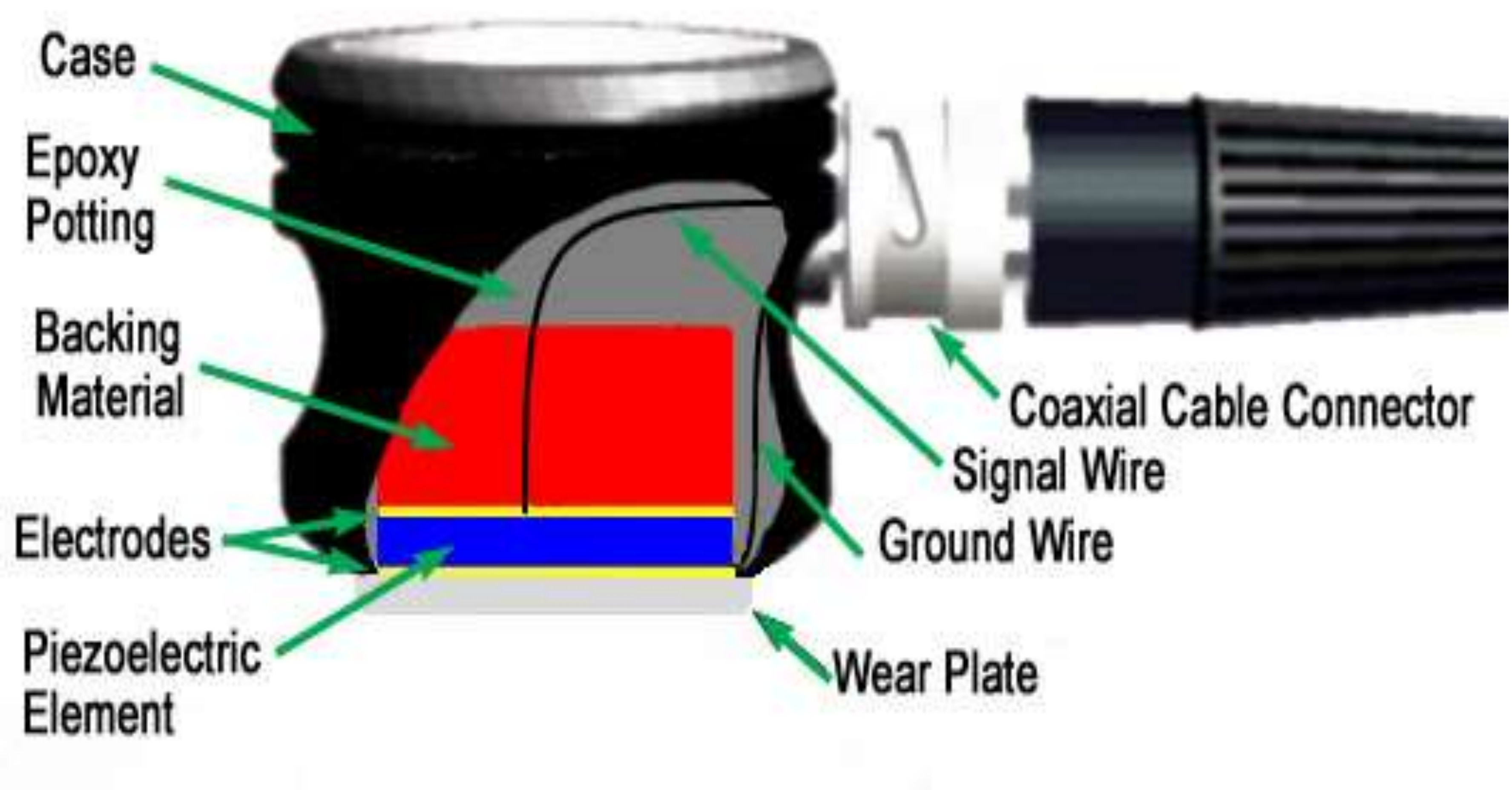
Ultrasound is generated with a transducer.

A piezoelectric element in the transducer converts electrical energy into mechanical vibrations (sound), and vice versa.



The transducer is capable of both transmitting and receiving sound energy.

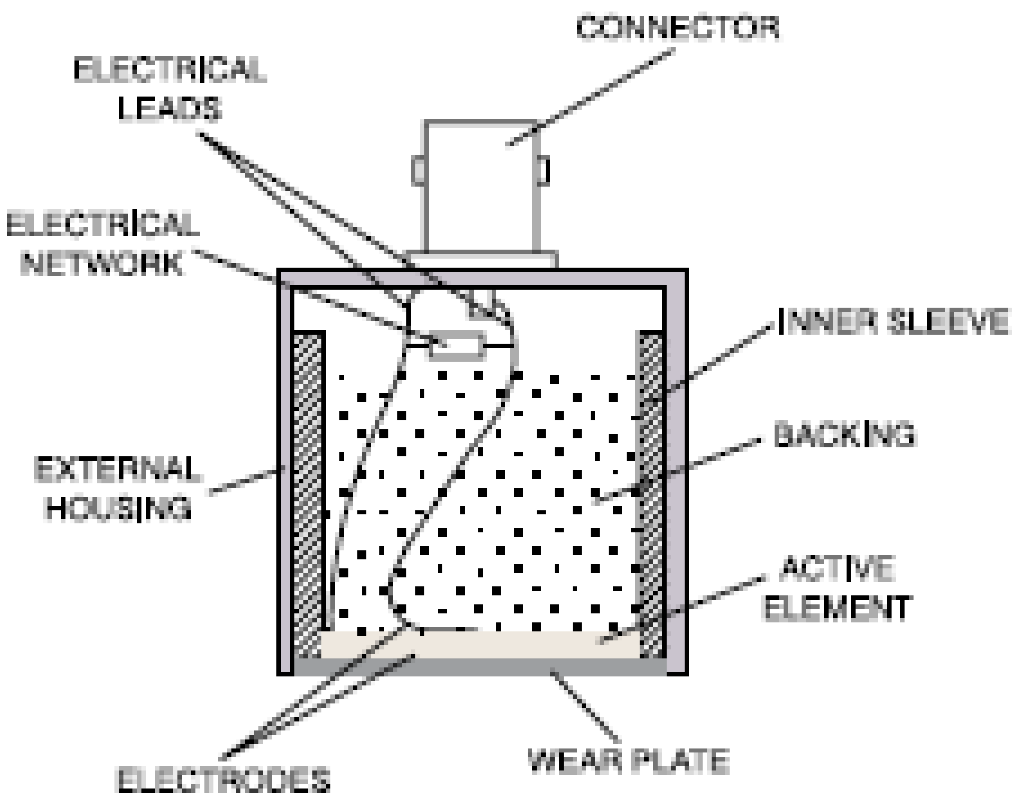
NDT&E Methods: Ultrasound Generation



NDT&E Methods: Ultrasound Generation

What is an Ultrasonic Transducer?

A transducer is any device that converts one form of energy to another.



An ultrasonic transducer converts electrical energy to mechanical energy, in the form of sound, and vice versa (Olympus).

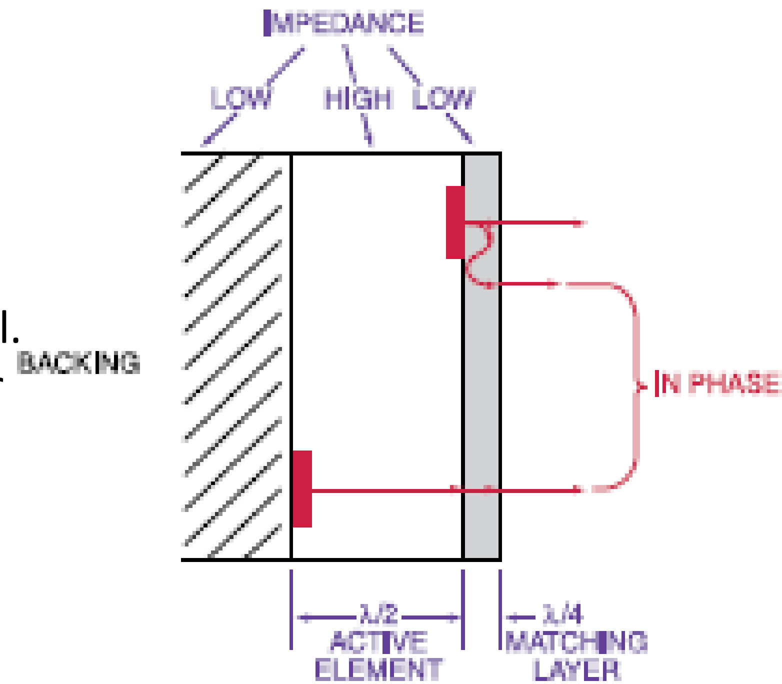
The main components of a piezo-transducer are:

- **The active element**
- **The backing**
- **The wear plate**

NDT&E Methods: Ultrasound Generation

The **active element**
is commonly a polarized ceramics.
It can be cut in a variety of manners
to produce different wave modes.

The **backing**
Is usually a highly attenuative, high density material.
It is used to control the vibration of the transducer
by absorbing the energy radiation
from the back face of the active element.
When the acoustic impedance matches
the impedance of the active element,
the transducer is highly damped.



The **wear plate**
protects the transducer active element. It serves as an acoustic transformer between the active element and the media (water, Perspex, etc) of lower acoustic impedance.
This is accomplished by selecting a matching layer of ¼ wavelength thickness.
The waves generated by the active element of ½ wavelength thickness are in phase with the wave reverberating in the matching layer.
When signals are in phase, their amplitudes are additive.

NDT&E Methods: Ultrasound Generation

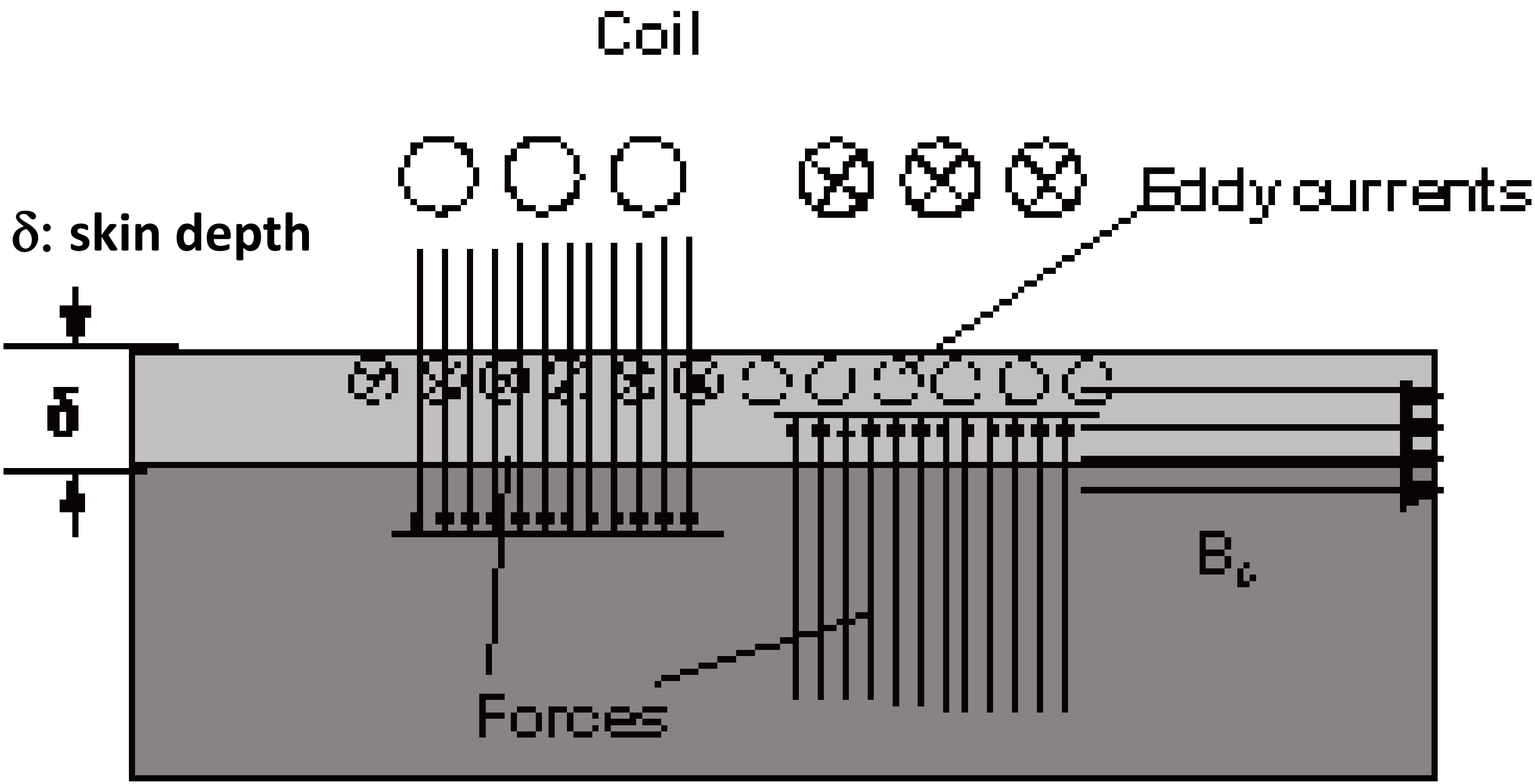
Lorentz Force

$$\mathbf{F} = q\left[\mathbf{E} + (\mathbf{v} \times \mathbf{B})\right]$$

A combination of electric and magnetic force on a point charge due to electromagnetic fields

OLYMPUS EMAT Transducer

NDT&E Methods: EMAT



$$F(z) = (j(z) \times B_0)/n_0$$

Speed, density

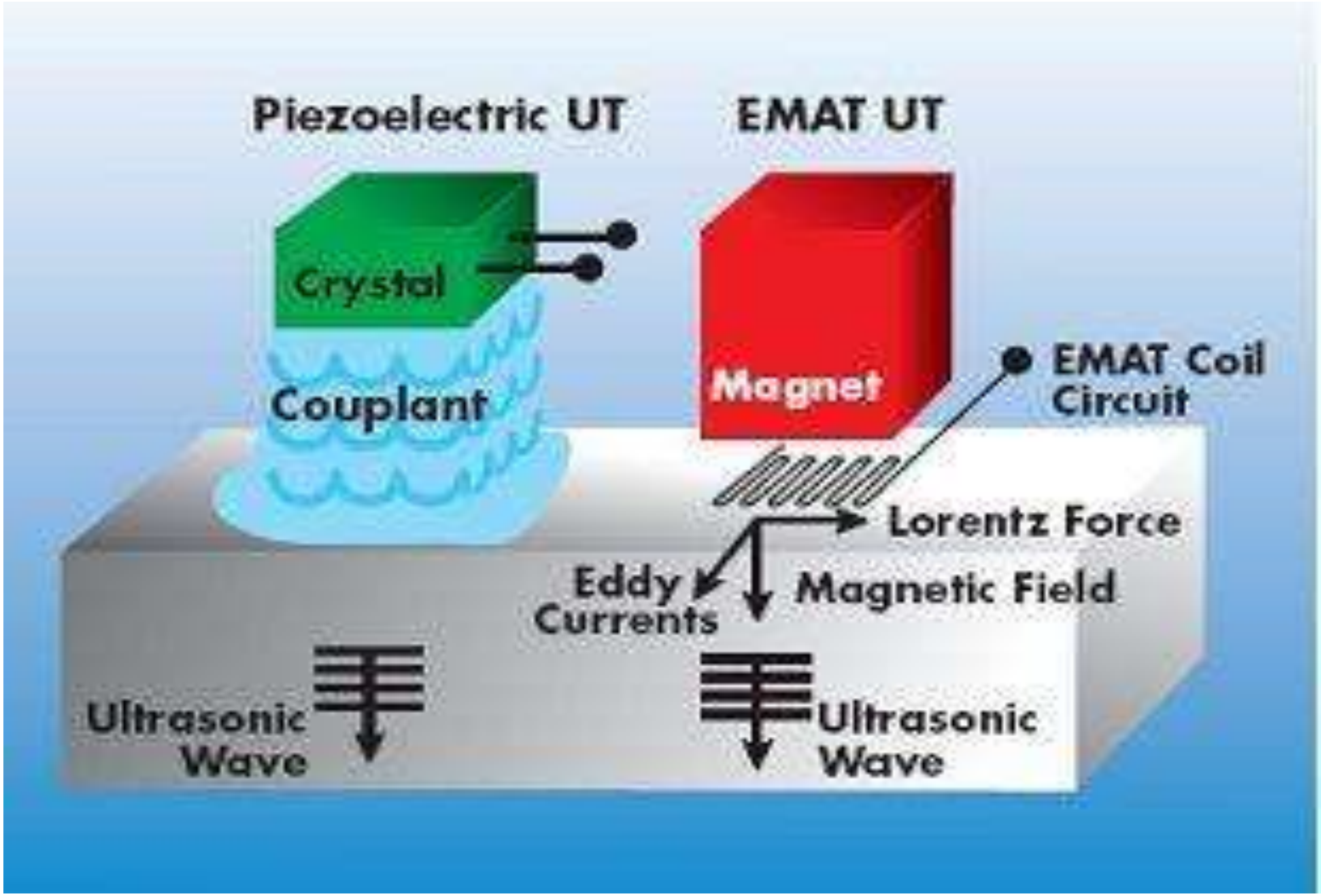
NDT&E Methods: EMAT

$$\mathbf{F}(z) = (\mathbf{j}(z) \times \mathbf{B_0}) / n_0$$

$$\frac{\partial^2 \xi}{\partial t^2} - s^2 \frac{\partial^2 \xi}{\partial z^2} = \frac{\left| \mathbf{j} \times \mathbf{B}_0 \right|}{d}$$

s: Sound velocity
d: Density

NDT&E Methods: Ultrasound Generation



NDT&E Methods: Ultrasound Generation

Basic Components in EMAT Transducer

There are two basic components in an EMAT transducer.

- **a magnet**
- **an electric coil.**

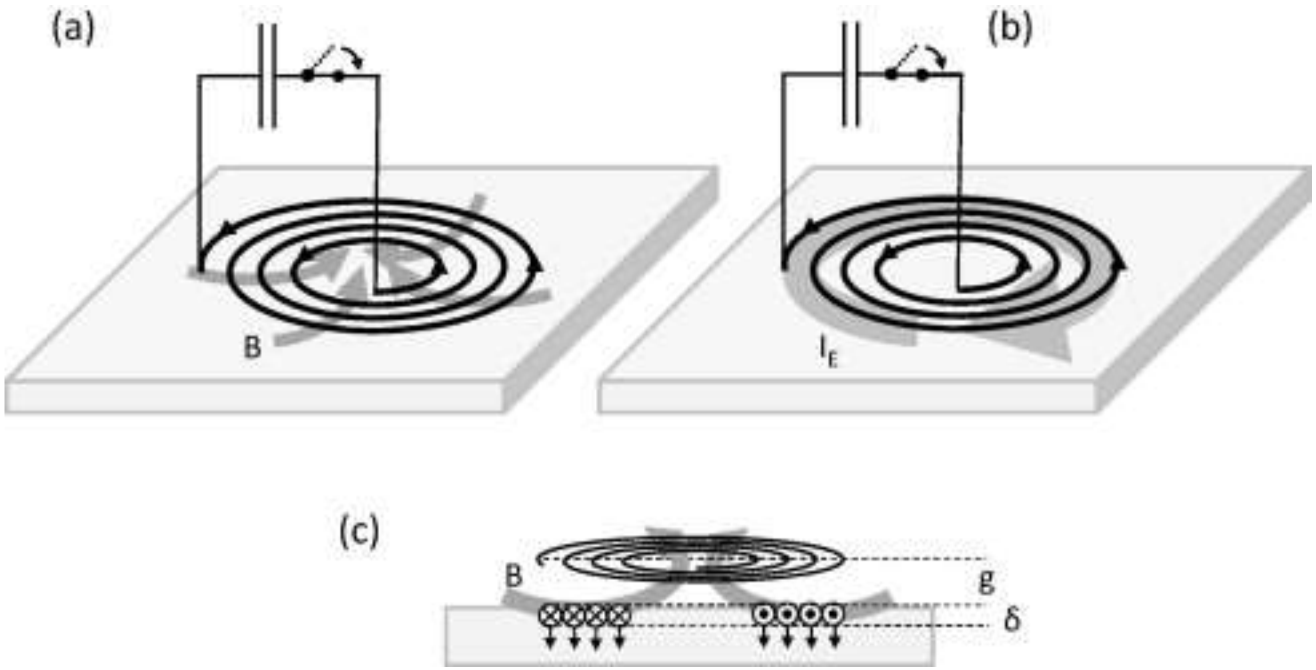
The magnet *can be a permanent magnet or an electromagnet, which produces a static or a quasi-static magnetic field. In EMAT terminology, this field is called bias magnetic field.*

The electric coil *is driven with an AC electric signal at frequency, typically in the range from 20 kHz to 10 MHz.*

Based on the application needs, the signal can be a continuous wave, a spike pulse, or a tone-burst signal. The electric coil with AC current also generates an AC magnetic field. When the test material is close to the EMAT, ultrasonic waves are generated in the test material through the interaction of the two magnetic fields.

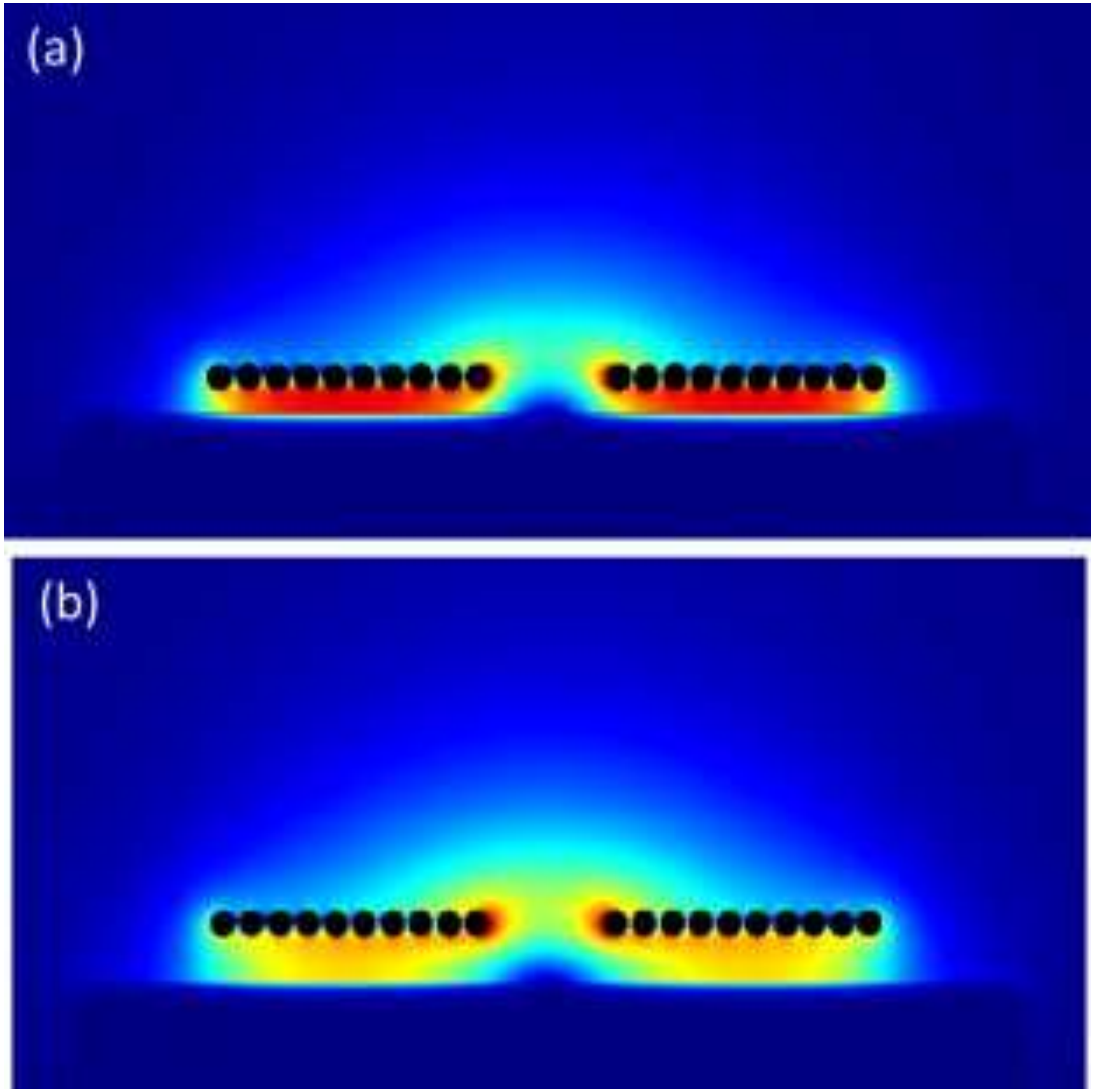
NDT&E Methods: Ultrasound Generation

The electric coil with AC current also generates an AC magnetic field. When the test material is close to the EMAT, ultrasonic waves are generated in the test material through the interaction of the two magnetic fields.



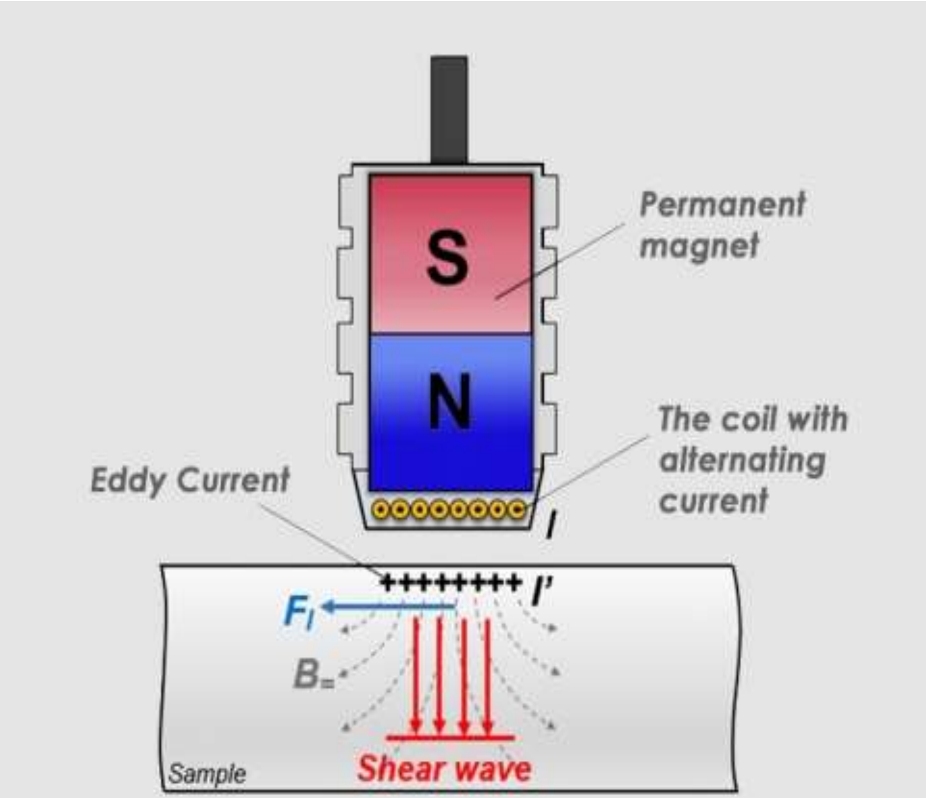
Based on the application needs, the signal can be a continuous wave, a spike pulse, or a tone-burst signal.

NDT&E Methods: Ultrasound Generation

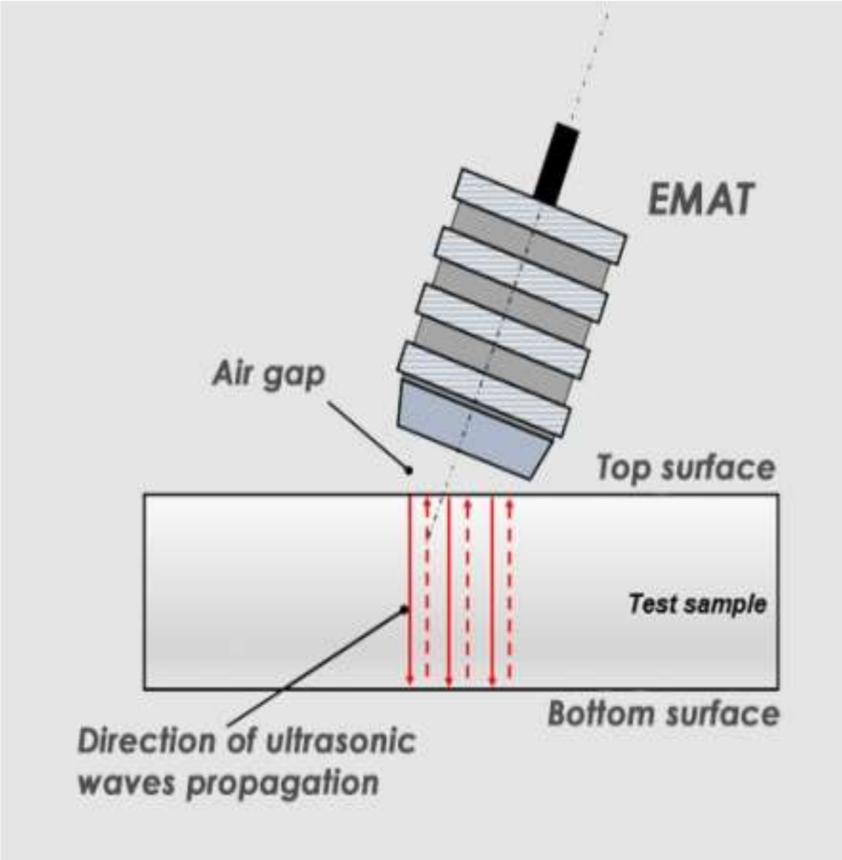


NDT&E Methods: Ultrasound Generation

Effect of Air Gap (Lift-off and Tilt)



NORDINKRAFT



Michael Kröning

A MASTERTHESIS

D. Rueter, T. Morgenstern. *Ultrasound generation with high power and coil only EMAT concepts,* Ultrasonics vol. 54, issue 8, Elsevier, 2014

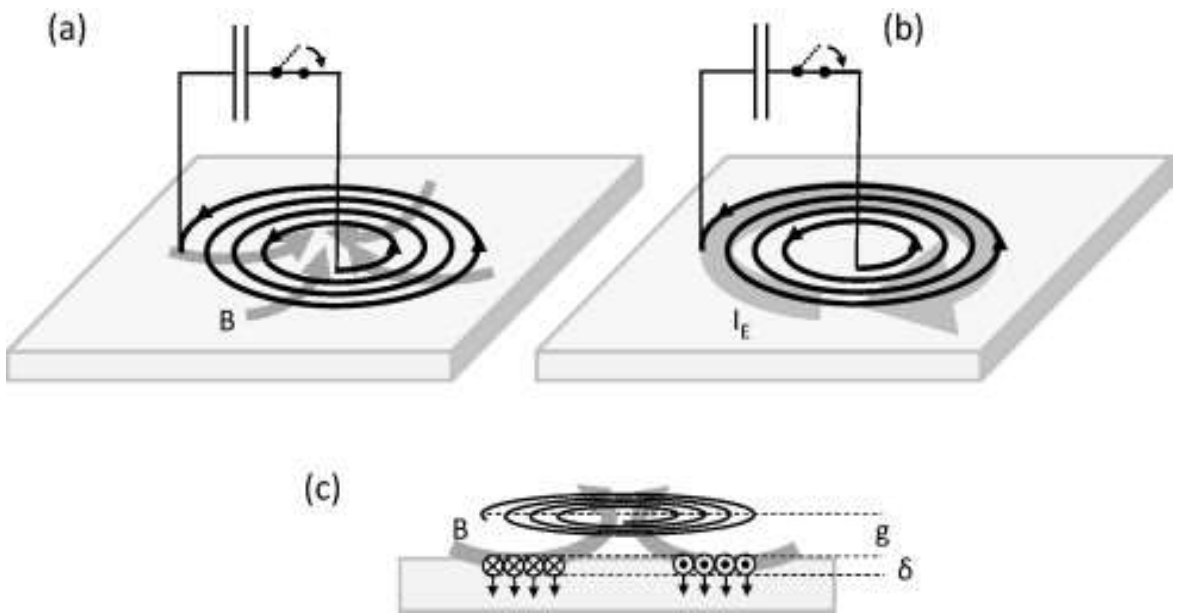
Our intention

- ***is the investigation of powerful and magnetically induced (non-contact) ultrasound at notably higher frequencies (i.e., >1 MHz instead of 300 kHz or less), suitable for NDT.***
- ***Furthermore, increased lift off distances towards 1 cm instead of just 1 mm or less are approached, interesting for more or new application fields like prepackaged products.***

The approach

- via magnetic pressure appears to be more convenient here and it still reasonably describes the actual findings from experiments.
- The underlying physics is viewed under the terminology *magnetic pressure* (more common in EMF technologies) instead of explicitly evaluating eddy currents and Lorentz forces (as typically done in EMAT considerations).

NDT&E Methods: Ultrasound Generation



A simple LC-Oscillation Circuit

$$E = 1/2\ CU^2$$

stored Energy
in the Capacitor

$$E = 1/2\ LI_{el}^2$$

for ideal elements the stored Energy in the Capacitor is fully converted into a magnetic field of the inductor L with discharge current I_{el}

Characteristic Frequency:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Electric Impedance

$$Z_{el} = \sqrt{\frac{L}{C}}$$

NDT&E Methods: Ultrasound Generation

For NDT ultrasound,
L-C-frequencies in the order of 10^6 Hz are interesting

elements *L* and *C* with relatively small values

MAXIMUM ELECTRIC POWER
Reference Power for Efficiency Considerations

$$P_{el,max} = \frac{1}{4}\,\frac{U^2}{Z_{el}} = \frac{1}{4}\frac{1}{\sqrt{LC}}CU^2 = \pi f E$$

NDT&E Methods: Ultrasound Generation

Magnetic Pressure p

equals the energy density
of an oscillating transient magnetic field

$$p = \frac{1}{2}\frac{B^2}{\mu_0}$$

F ~ B
I_{EC} ~ B

Effective Sound Intensity

The effective sound intensity I of an ultrasound wave at sound pressure p (peak value) in a material is:

$$I = \frac{p^2}{2Z_M}$$ ***(Z_M: Acoustic Impedance)***

FINAL GENERATED ULTRASOUND POWER

$$P_{US} = \frac{1}{32}\frac{1}{Z_M A}\left(\frac{E}{g}\right)^2$$

EFFICIENCY

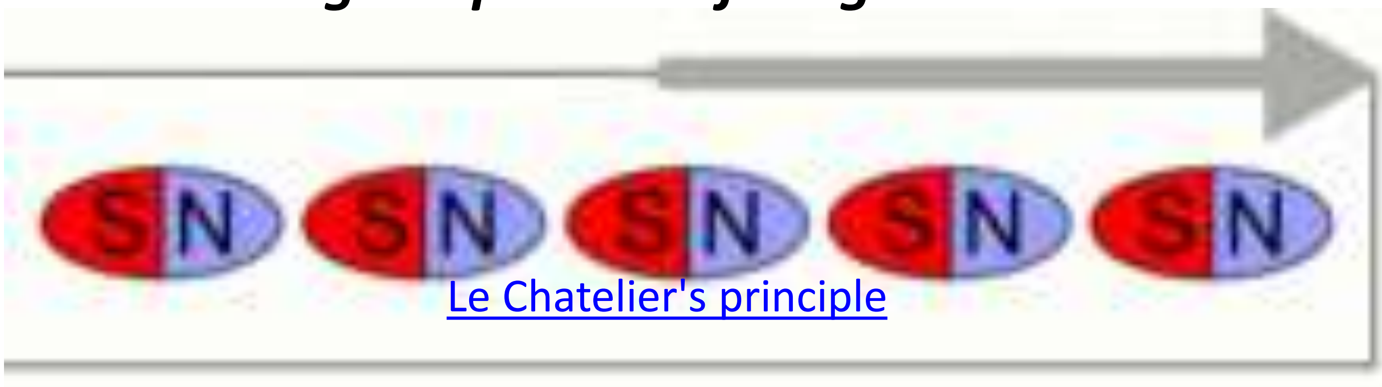
$$\eta = \frac{1}{32}\frac{1}{\pi\mu_0}\frac{B^2}{Z_M g f}$$

NDT&E Methods: Ultrasound Generation

MISTRAS, USA

NDT&E Methods: Ultrasound Generation
MAGNETOSTRICTIVE EFFECT

Ferromagnetic materials change their shape or dimensions during the process of magnetization.



[Le Chatelier's principle]

The reciprocal effect, the change of the susceptibility (response to an applied field) of a material when subjected to a mechanical stress, is called the Villari effect.

Le Chatelier's Principle

$$\left(\frac{d\lambda}{dH}\right)_\sigma = \left(\frac{dB}{d\sigma}\right)_H$$

λ: magnetostriction
H: magnetizing field strength
B: flux density
σ: mechanical stress

NDT&E Methods: Ultrasound Generation

CAPACITIVE ULTRASONIC TRANSDUCER

Total Force exerted on a membrane of a capacitor

$$F_{elec} = \frac{\varepsilon_0 A V^2}{2(d_0 - x)^2}$$

A: Area; V: applied dc voltage; x: membrane displacement; d_0: initial gap height

EQUILIBRIUM CONDITION:

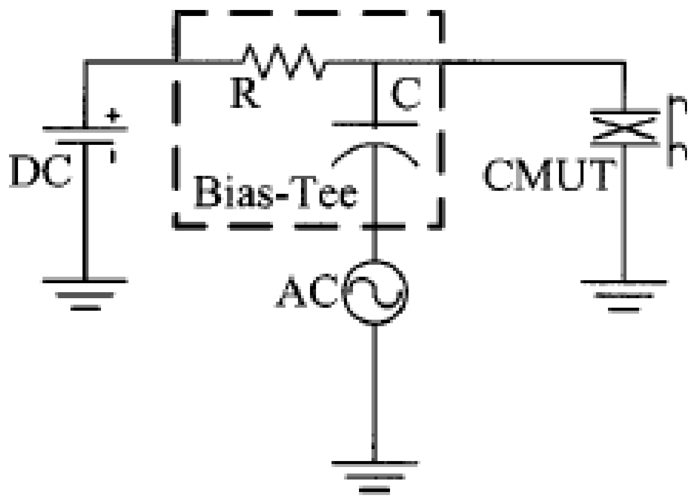
Electrical force balances mechanical restoring force $F_{mech} = kx$

Relation between the membrane displacement and applied dc voltage

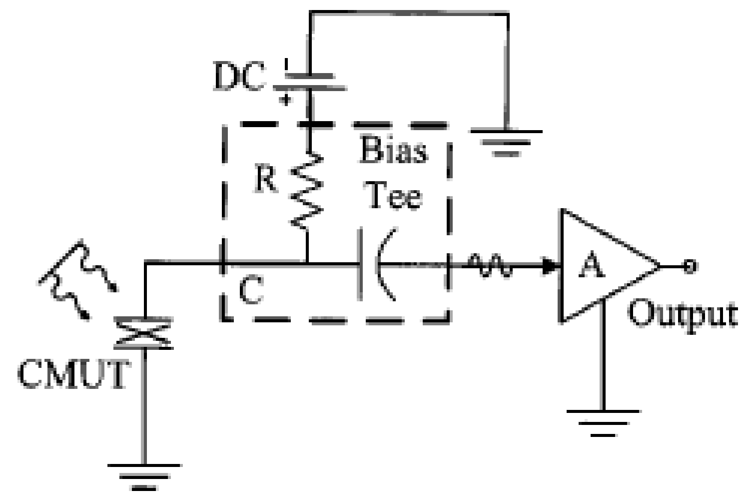
$$V = \sqrt{\frac{2kx}{A\varepsilon_0}}(d_0 - x)$$

NDT&E Methods: Ultrasound Generation

CAPACITIVE ULTRASONIC TRANSDUCER



Transmit Mode

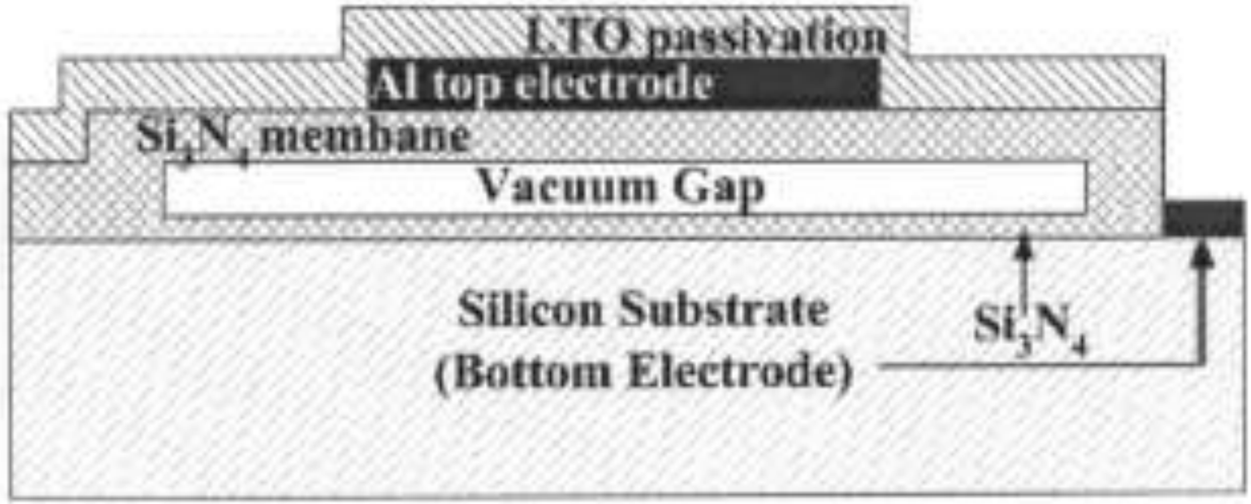


Receive Mode

Electrical Circuits to Drive CMUTs

NDT&E Methods: Ultrasound Generation

CAPACITIVE ULTRASONIC TRANSDUCER



Cross-sectional Schematic Drawing of Membrane

NDT&E Methods: Ultrasound Generation

CAPACITIVE ULTRASONIC TRANSDUCER

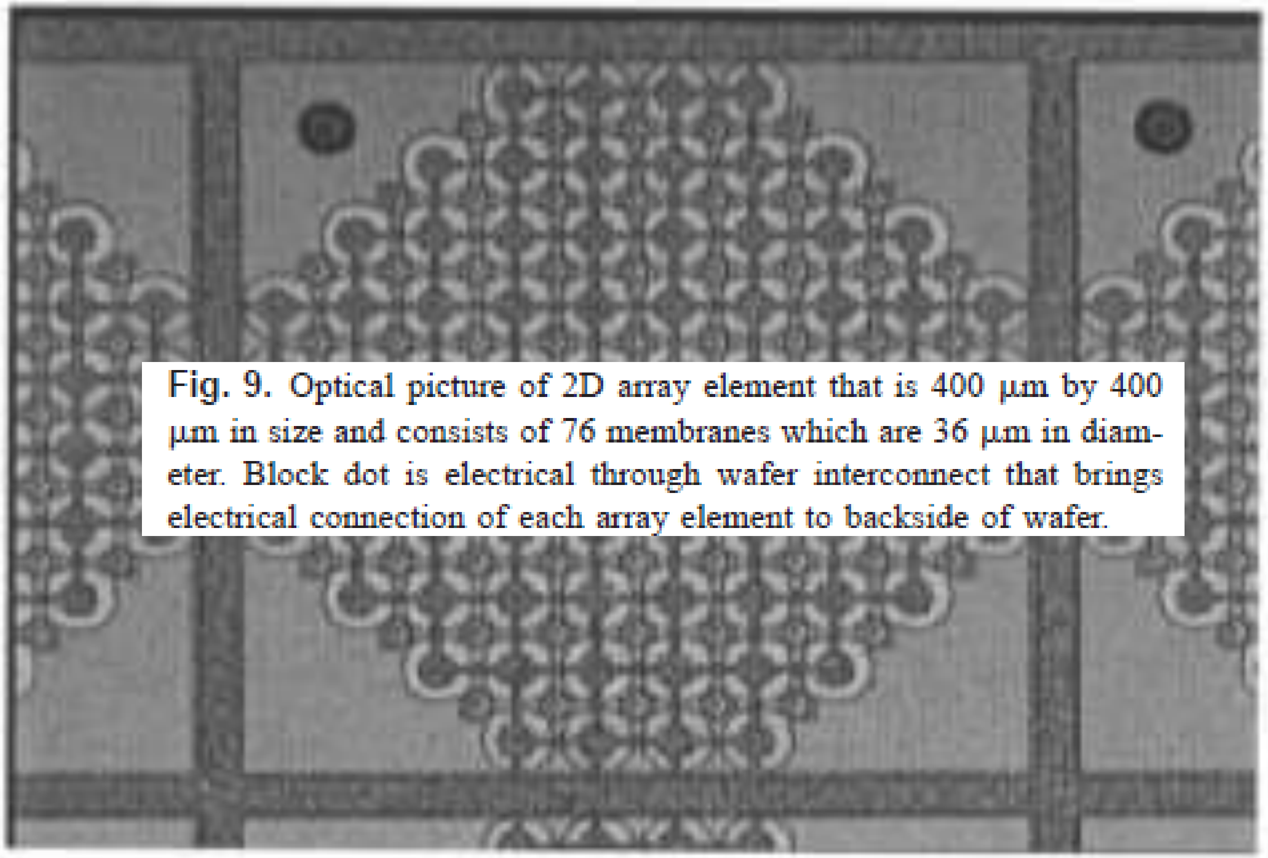


Fig. 9. Optical picture of 2D array element that is 400 µm by 400 µm in size and consists of 76 membranes which are 36 µm in diameter. Block dot is electrical through wafer interconnect that brings electrical connection of each array element to backside of wafer.

Optical Picture of 2D Array Element that is 400µm by 400µm in size. It Consists of 76 membranes which are 36 µm in Diameter.

NDT&E Methods: UT

Literature

1. M. J. Sansalone, W. B. Street. *Impact-Echo: Nondestructive Evaluation of Concrete and Masonry*, Bullbrier Press, Ithaca, NY, 1997
2. Paul E. Mix. *Introduction to nondestructive testing – a training guide,* John Wiley & Sons, Inc., Hoboken, New Jersey, 2005
3. R.B. Thompson. *Physical Principles of Measurements with EMAT Transducers,* Ultrasonic Measurement Methods, Physical Acoustics Vol XIX, Edited by R.N. Thurston and Allan D. Pierce, Academic Press, 1990
4. D. Rueter, T. Morgenstern. *Ultrasound generation with high power and coil only EMAT concepts,* Ultrasonics vol. 54, issue 8, Elsevier, 2014
5. A. S. Ergun, G. G. Yaralioglu, B. T. Khuri-Yakub. *Capacitive Micromachined Ultrasonic Transducers: Theory and Technology,* Journal of Aerospace Engineering 76 © ASCE, 2003