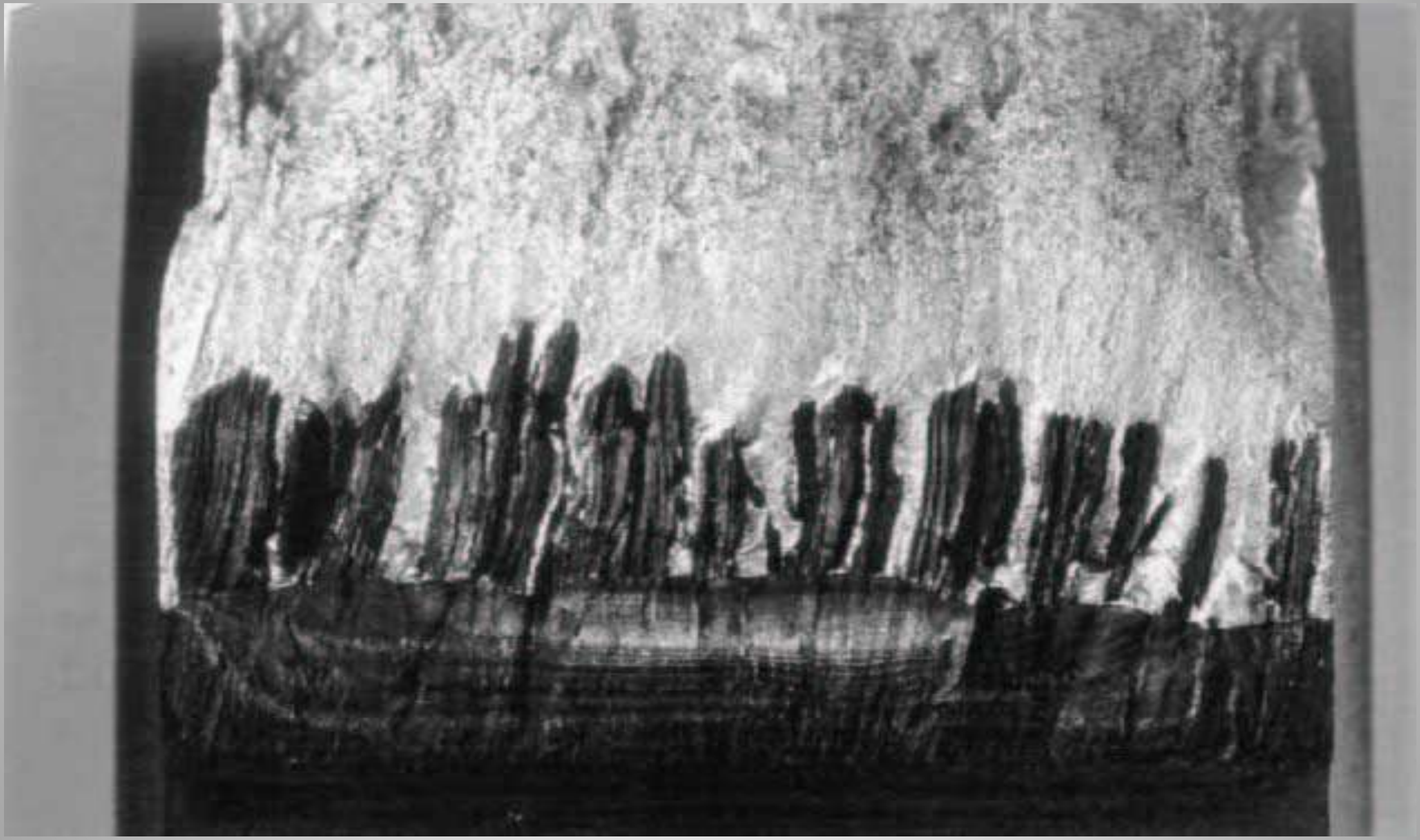
INSPECTION BY CAUSE - A CASE STUDY

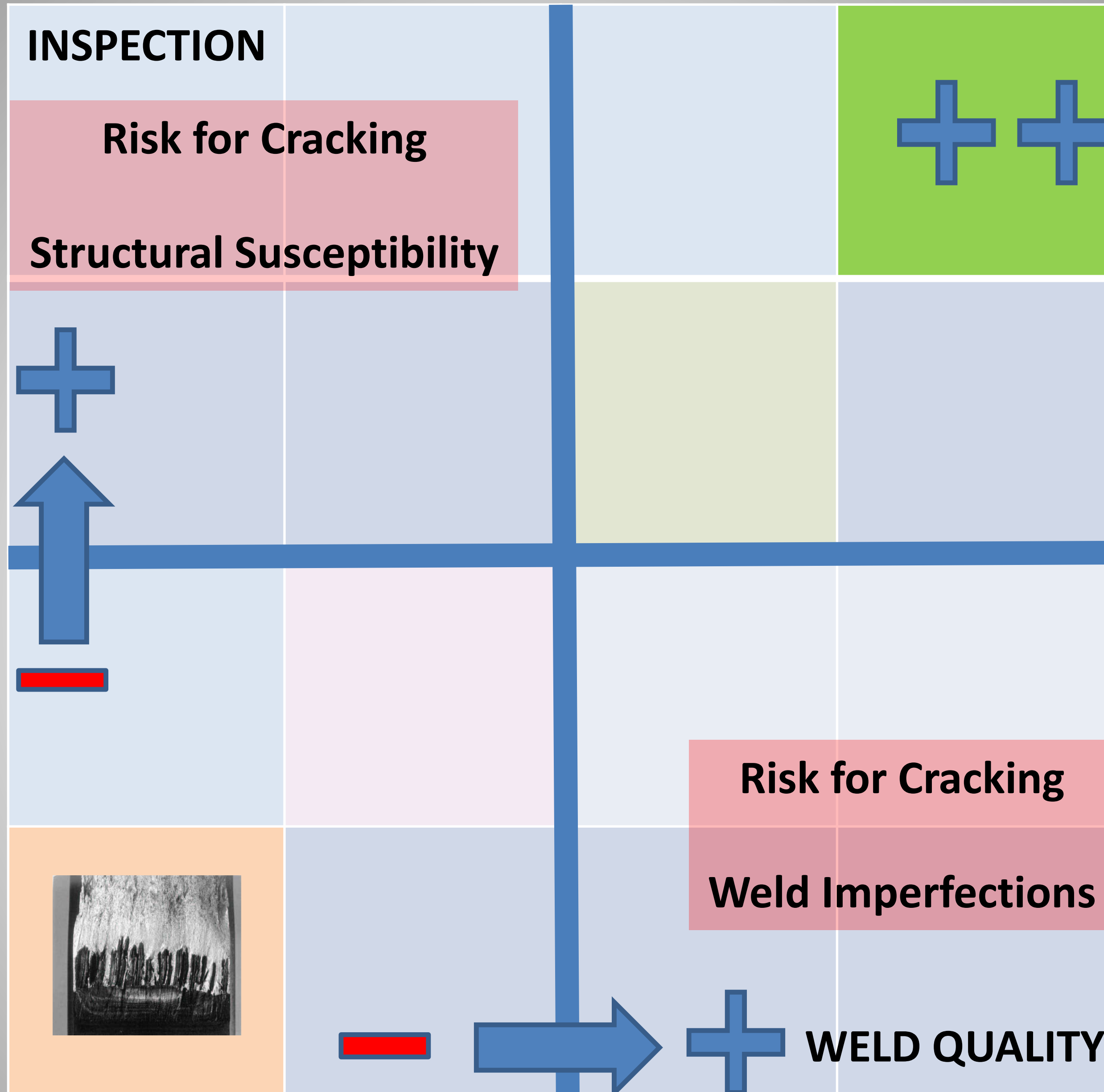
PWSCC



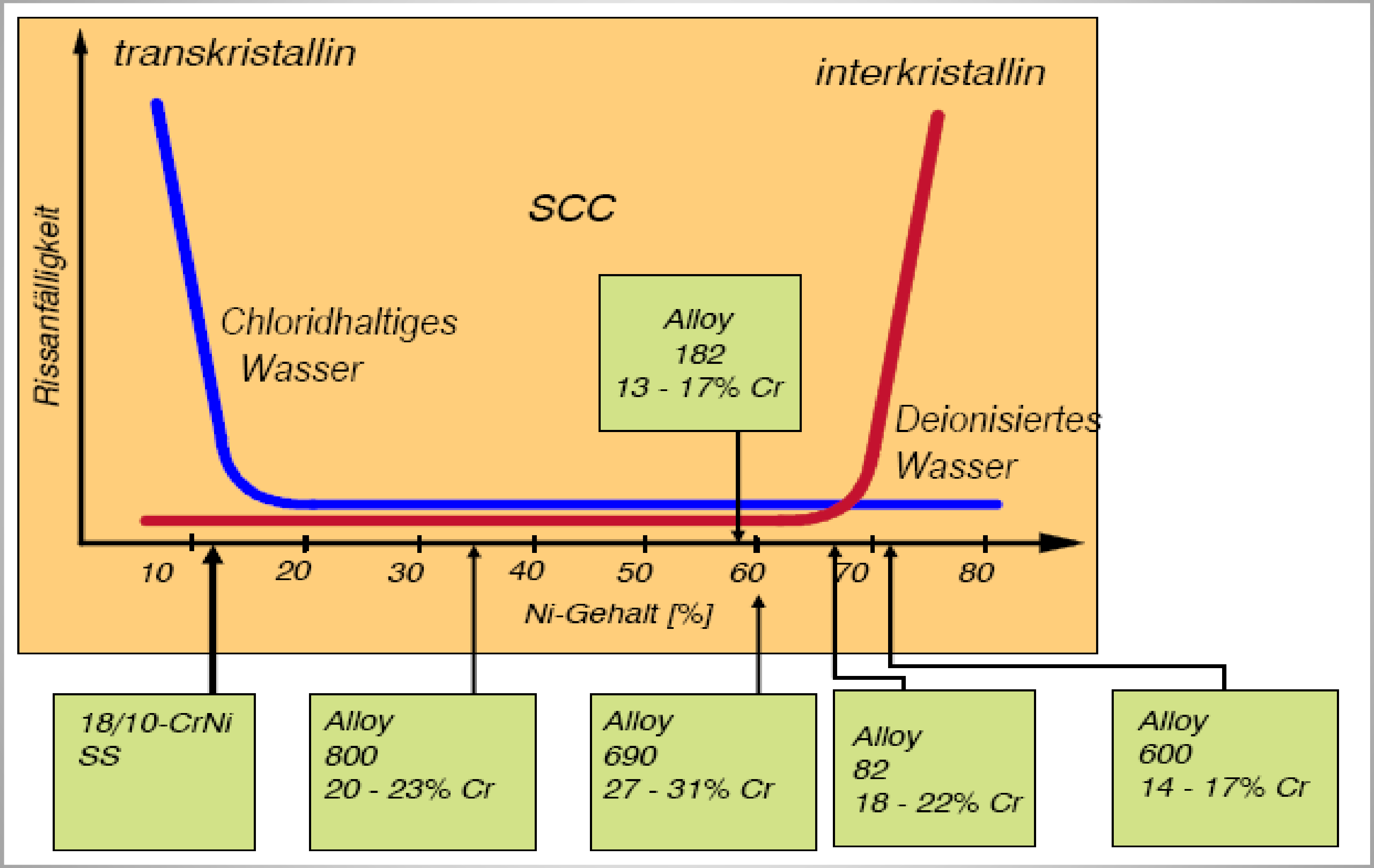
Primary Water Stress Corrosion Crack

INSPECTION BY CAUSE - A CASE STUDY

4.	**Mitigation Strategies – The world is never perfect**
4.1.	Structure Design and NDT
4.2.	Application of NDT
4.3.	Limits of NDT
4.4.	Quantitative NDT
4.5.	Material Characterization
4.6.	Case Study: Inspection by Cause


INSPECTION
Risk for Cracking
Structural Susceptibility
Risk for Cracking
Weld Imperfections
WELD QUALITY

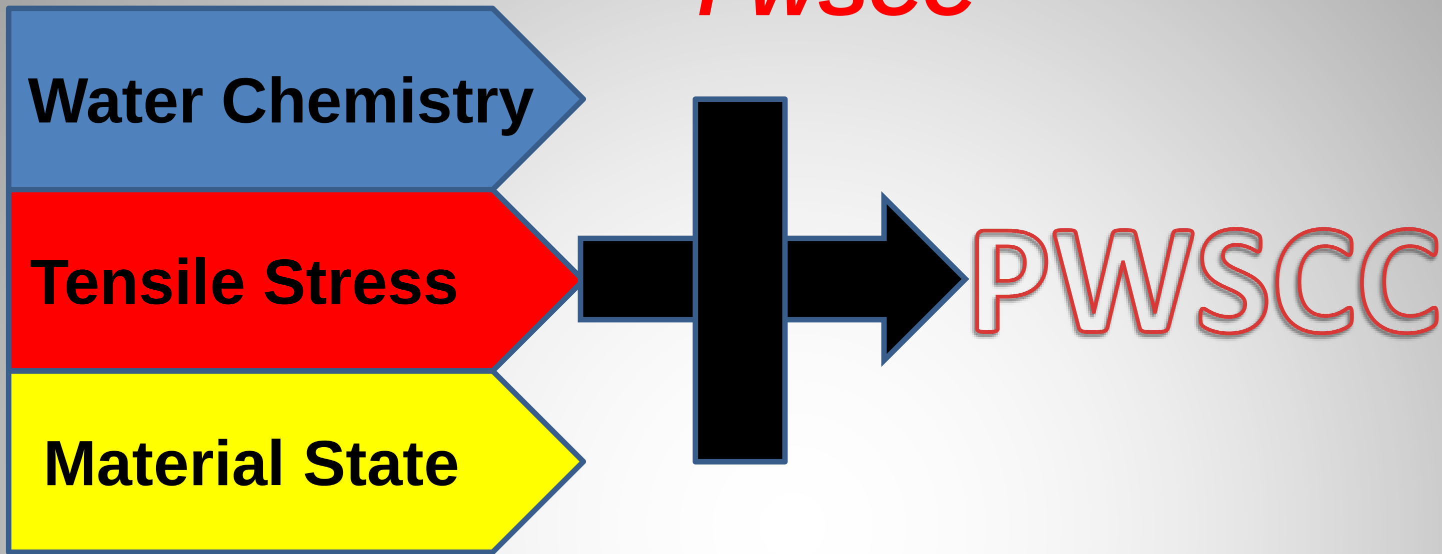
ALLOY SUSCEPTIBILITY TO STRESS CORROSION CRACKING



EVIDENCE
PRIMARY WATER STRESS CORROSION CRACKING

Component Item	Date PWSCC Initially Observed	Service Life[a] (Calendar Years)
Steam Generator Hot Leg Tubes and Plugs	~1973	~2
Pressurizer Instrument Nozzles	1986	2
Steam Generator Cold Leg Tubes	1986	18
Pressurizer Heaters and Sleeves	1987	5
Steam Generator Channel Head Drain Pipes	1988	1
Control Rod Drive Mechanism Nozzles	1991	12
Hot Leg Instrument Nozzles	1991	5
Power Operated Relief Valve Safe End	1993	22
Pressurizer Nozzle Welds	1994	1
Cold Leg Piping Instrument Nozzles	1997	13
Reactor Vessel Hot Leg Nozzle Buttering/Piping Welds	2000	17
Control Rod Drive Mechanism Nozzle/RV Head Welds	2000	27
Surge Line Nozzle Welds	2002	21
Reactor Vessel Lower Head In-Core Instrumentation Nozzles/Welds	2003	14

CONDITIONS PRECEDENT TO PWSCC



- *zinc additions to the reactor coolant system (reduction of general corrosion)*
- *welding procedure (bead dimension, stress relief treatment) assessment of operational and residual stress state*
- *material and weld microstructure (No repair!!No weld defects) quality assessment of manufacturing*

Primary Water Stress Corrosion Cracking - PWSCC

WATER CHEMISTRY

Main Parameters

- *hydrogen partial pressure (or corrosion potential)*
- *temperature*

Mitigation Potential

- *zinc additions to the reactor coolant system (Reduction of general corrosion)*
- *temperature reduction (thermally-activated mechanism)*

INSPECTION WITH CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

STRESS
STATE

Main Parameters

- *welding procedure*
- *heat treatment*

Mitigation Potential

- *Mechanical Surface Enhancement (MSE)*
- *stress relief heat treatment*

INSPECTION WITH CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

MATERIAL
STATE

Main Parameters

- *material and weld microstructure*
- *weld defects*

  (relatively large and sharp defects, lack of fusion areas, promote PWSCC by acting as stress concentrators)

Mitigation Potential

- *metals with 30% chromium*

  (threshold for PWSCC resistance: between 22 and 30% chromium)
- *quality assessment*

  (no repair, weld bead size, heat treatment, weld design)

Assessment of Dissimilar Welds: „Risk for PWSCC"
Monitored Subject: „Nickel-Base Weld Metal"
(1 = no risk up to 4 = higher risk)

Design Layout	1	2	3	4
- Nickel-base root	no	yes	yes	yes
- One sided welding	yes	yes	yes	no
- ID repair	no	no	no	yes
- OD repair	no	yes	yes	yes
- Shop weld	n.r.	n.r.	?	no
- E manual/mechanized	n.r.	n.r.	?	manual
- Alloy 182/82	n.r.	n.r.	?	182
- with/without buffer	n.r.	without	?	with
- with/without annealing	n.r.	n.r.	?	with
- ISI yes/no	n.r.	n.r.	?	?
Suspect for PWSCC	**no**	**no**	**?**	**Yes**
NDT recommended	**no**	**no**	**yes**	**yes**

n.r. = nonrelevant ? = unknown

Ultrasonic Dissimilar Weld Inspections at NPP Grafenrheinfeld

Mischnahtprüfungen im Primärkreis in KKG zwischen 1997 und 2011										
Prüfjahr	Prüfstelle									
	YA 10		YA 20		YA 30		YA 40		YP 10	
	Komponente	Bemerkung	Komponente	Bemerkung	Komponente	Bemerkung	Komponente	Bemerkung	Komponente	Bemerkung
1997					106 W	kalte Einsp.				
					115 W	heiße Einsp.				
1998							106 W	kalte Einsp.	16/1	VAL
							115 W	heiße Einsp.		
2001	106 W	kalte Einsp.	106 W	kalte Einsp.	106 W	kalte Einsp.	106 W	kalte Einsp.	16/1	VAL
									138a W	VAL
2006					115 W	heiße Einsp.	115 W	heiße Einsp.	16/1	VAL
									H1	DH-Stutzen
									H2	DH-Stutzen
									H3	DH-Stutzen
									H4	DH-Stutzen
									E2	DH-Stutzen
2008	125 W	TA-Stutzen	125 W	TA-Stutzen	125 W	TA-Stutzen	125 W	TA-Stutzen		
	106 W	kalte Einsp.								
	115 W	heiße Einsp.								
2010			106 W	kalte Einsp.					16/1	VAL
			115 W	heiße Einsp.					138a W	VAL
									1 W	DH-Stutzen zum Abblase-behälter
									H1	DH-Stutzen
									H2	DH-Stutzen
									H3	DH-Stutzen
									H4	DH-Stutzen
									E2	DH-Stutzen
2011					106 W	kalte Einsp.			195 W	VAL
					115 W	heiße Einsp.				

CONCLUSION
Material State

−	+
EVIDENCE OF PWSCC	NO CRACKS FOUND
PROOF OF WELDING PROCEDURE	PROVED QUALITY OF WELDING PROCEDURE
STRESS RELEASE BY HEAT TREATMENT	STRESS RELEASE VIABLE
NO WELDING FLAWS/ NONCONFORMITIES	BASELINE INSPECTION AS REFERENCE

ALLOY 600/182

CONCLUSION
Material State

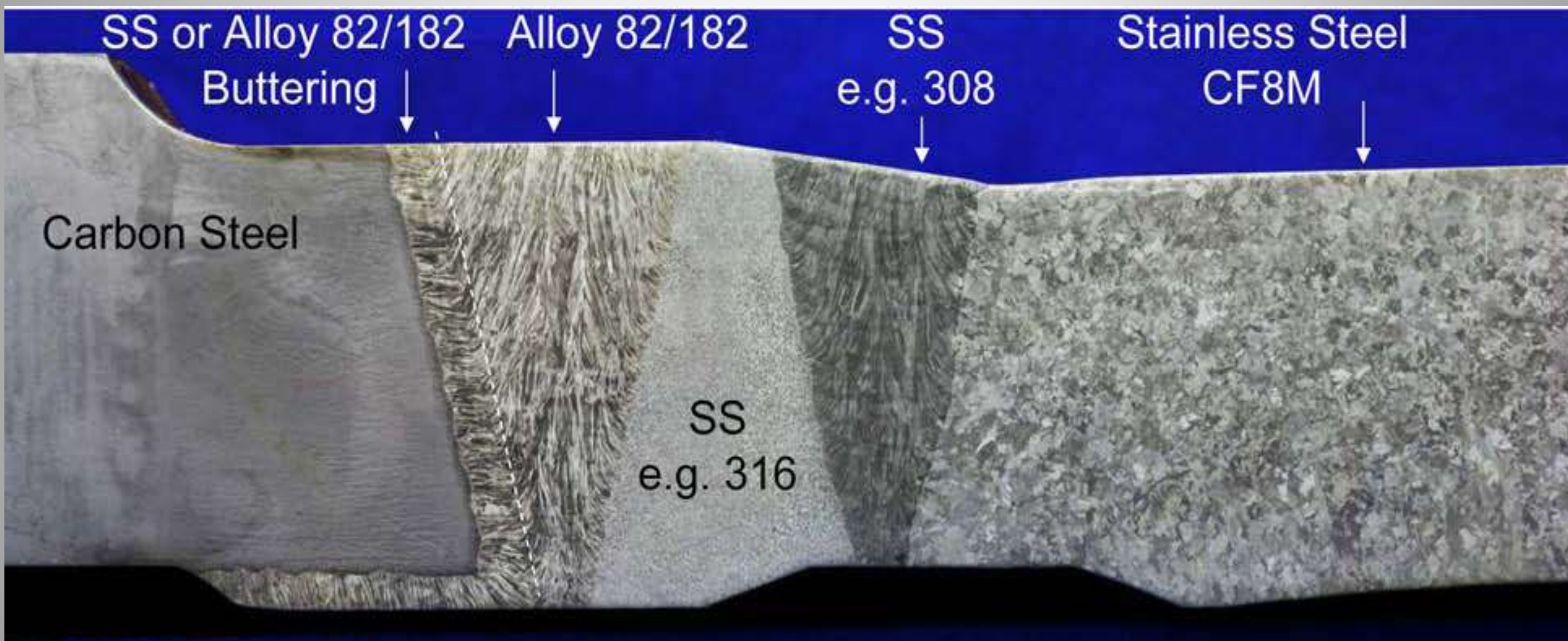
−	+
NO LONG-TERM PROOF (LABORATORY!)	QUALIFIED MATERIAL
POOR WELDABILITY	AUTHORITY ACCEPTANCE
STRESS RELEASE BY HEAT TREATMENT	*STRESS RELEASE VIABLE*
NO WELDING FLAWS/ NONCONFORMITIES	*BASELINE INSPECTION AS REFERENCE*

ALLOY 690
(Higher Chromium Content)

CONCLUSION
SIDE CONSIDEARATIONS

REPLACEMENT	NO REPLACEMENT
WELDING PROCEDURE QUALIFICATION	AUTHORITY ACCEPTANCE
BASELINE INSPECTION AS REFERENCE	*BASELINE INSPECTION AS REFERENCE*
NO WELDING FLAWS/ NONCONFORMITIES	*ENGINEERING PROOF (GRAFENRHEINFELD)*
(COSTS)	*STRESS RELEASE VIABLE*
(TIME DELAY)	*(COMPATIBLE TO ANGRA 2)*

ULTRASONIC INSPECTION
of
DISSIMILAR WELDS

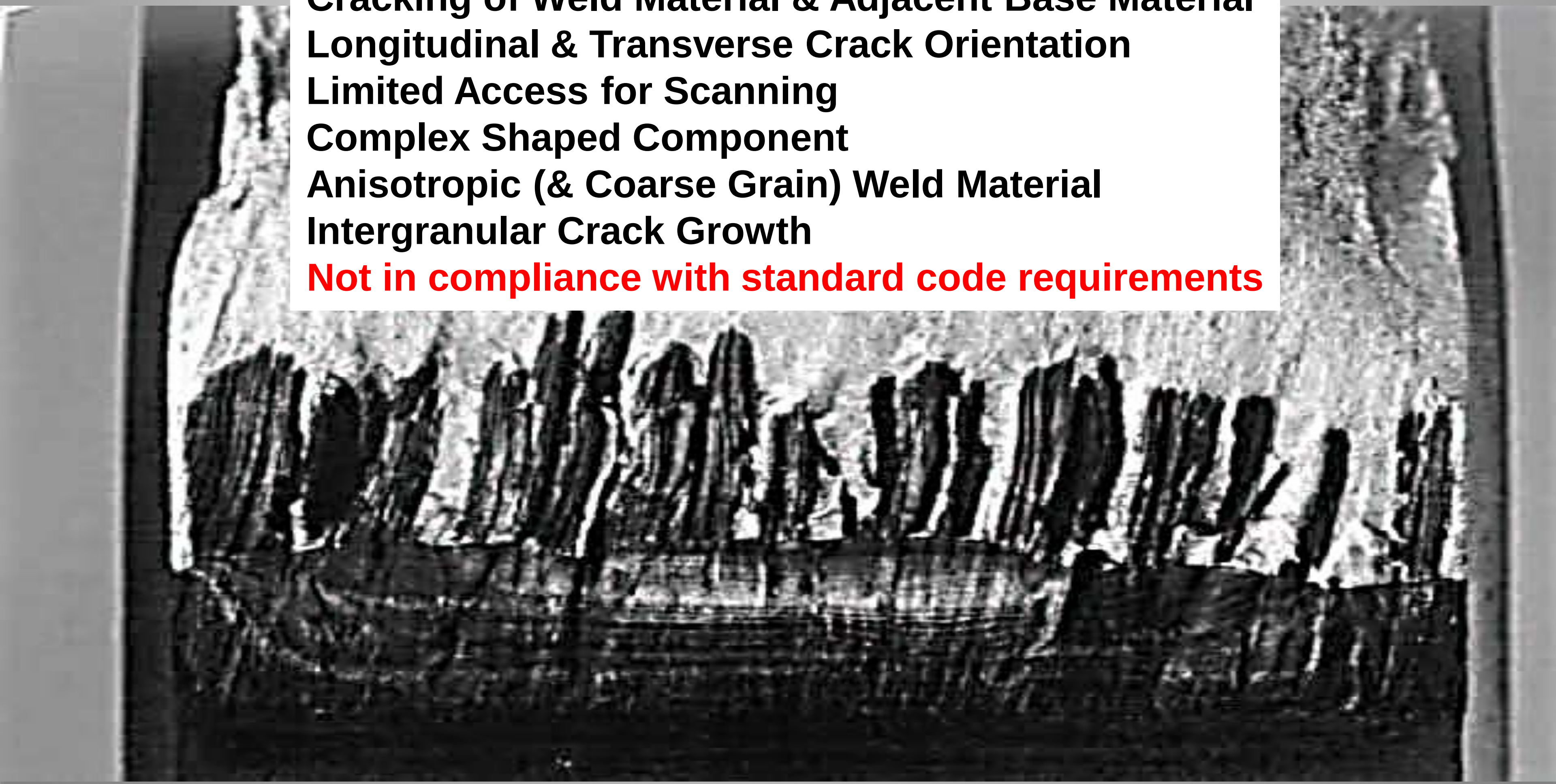


Standard PWR Steam Generator Nozzle DMW Configuration

Ultrasonic Inspection of Dissimilar Welds

INSPECTION PROBLEM

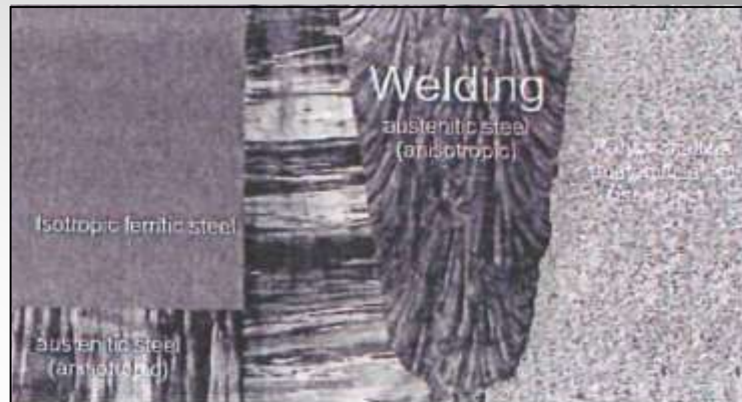
Cracking of Weld Material & Adjacent Base Material
Longitudinal & Transverse Crack Orientation
Limited Access for Scanning
Complex Shaped Component
Anisotropic (& Coarse Grain) Weld Material
Intergranular Crack Growth
Not in compliance with standard code requirements



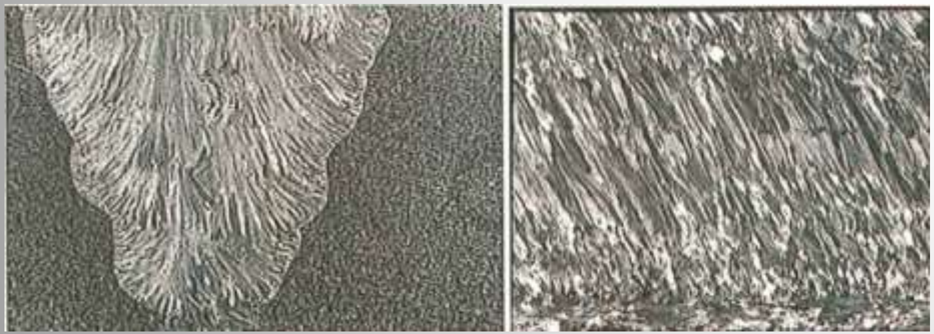
INSPECTION PROBLEM
Acoustic Anisotropy

a - standard pipe to pipe weld

b - narrow gap weld



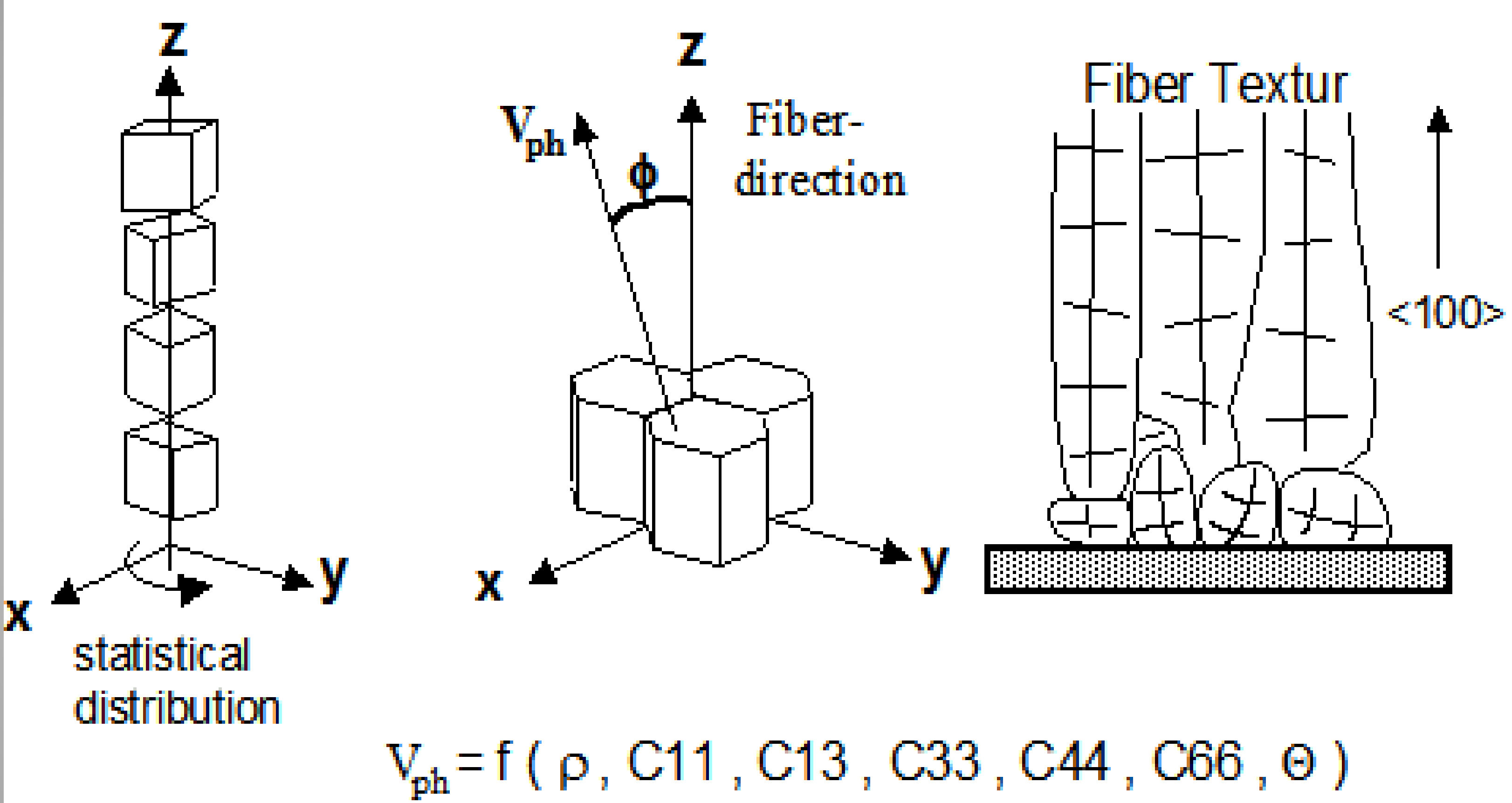
c - dissimilar weld



Transverse and Longitudinal Sections
with
Homogeneous Anisotropic Structure

PHOTOMICROGRAPHS of WELD SECTIONS

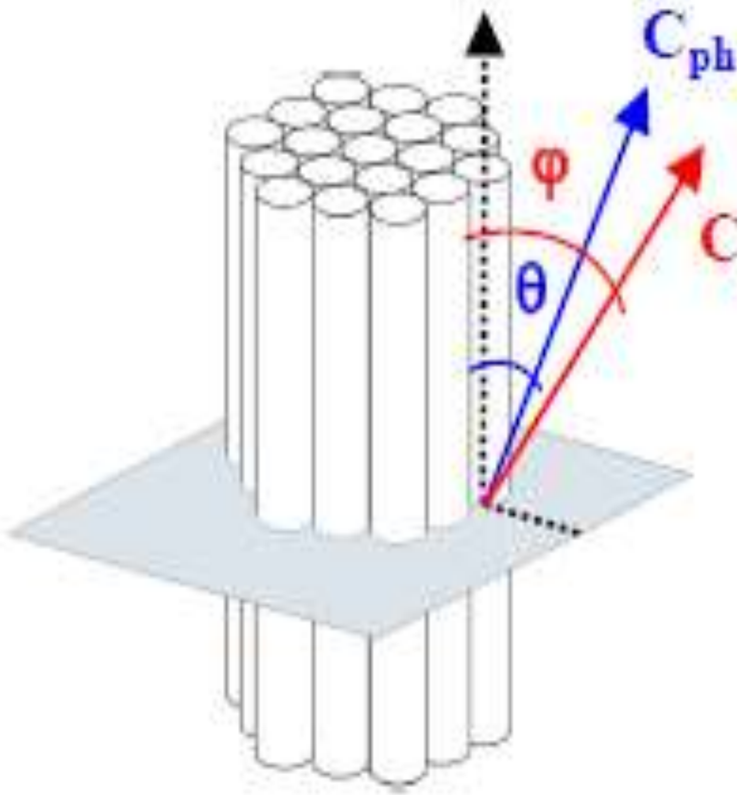
INSPECTION PROBLEM
Acoustic Anisotropy

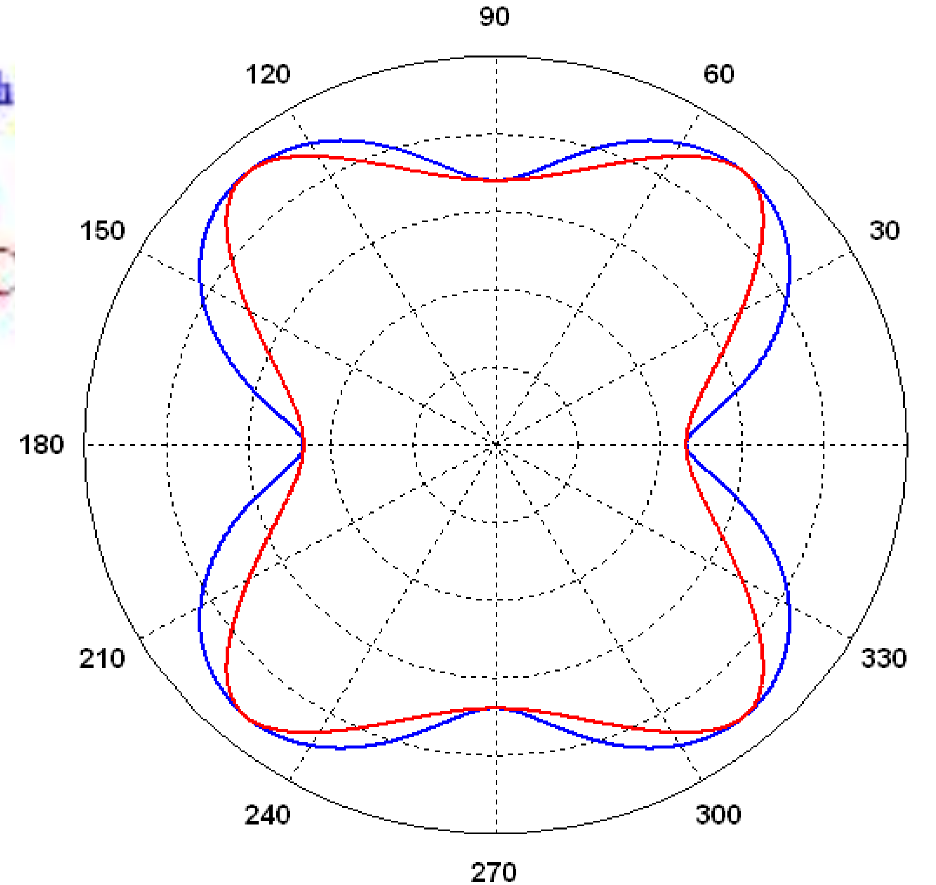


Model of the transverse isotropic structure of stainless steel weld joints

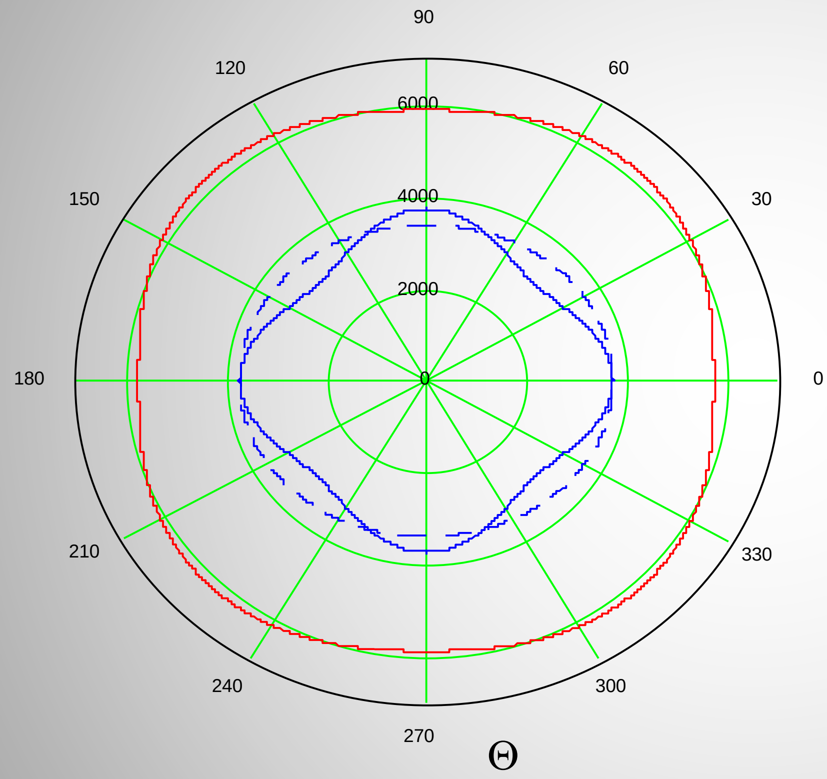
V_{ph} = Phase Velocity; Cij = Elastic Constant; ρ - Density, Φ – Fiber Orientation

INSPECTION PROBLEM
Acoustic Anisotropy



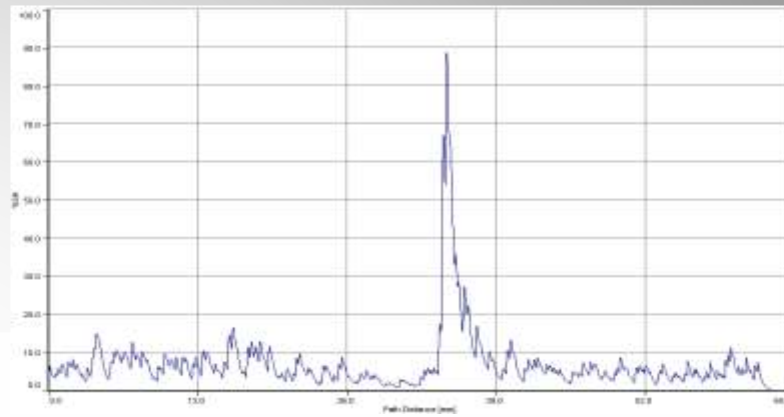


INSPECTION PROBLEM
Acoustic Anisotropy of Transverse Isotropic Materials



---- pressure wave
---- vertical shear wave
---- horizontal shear wave

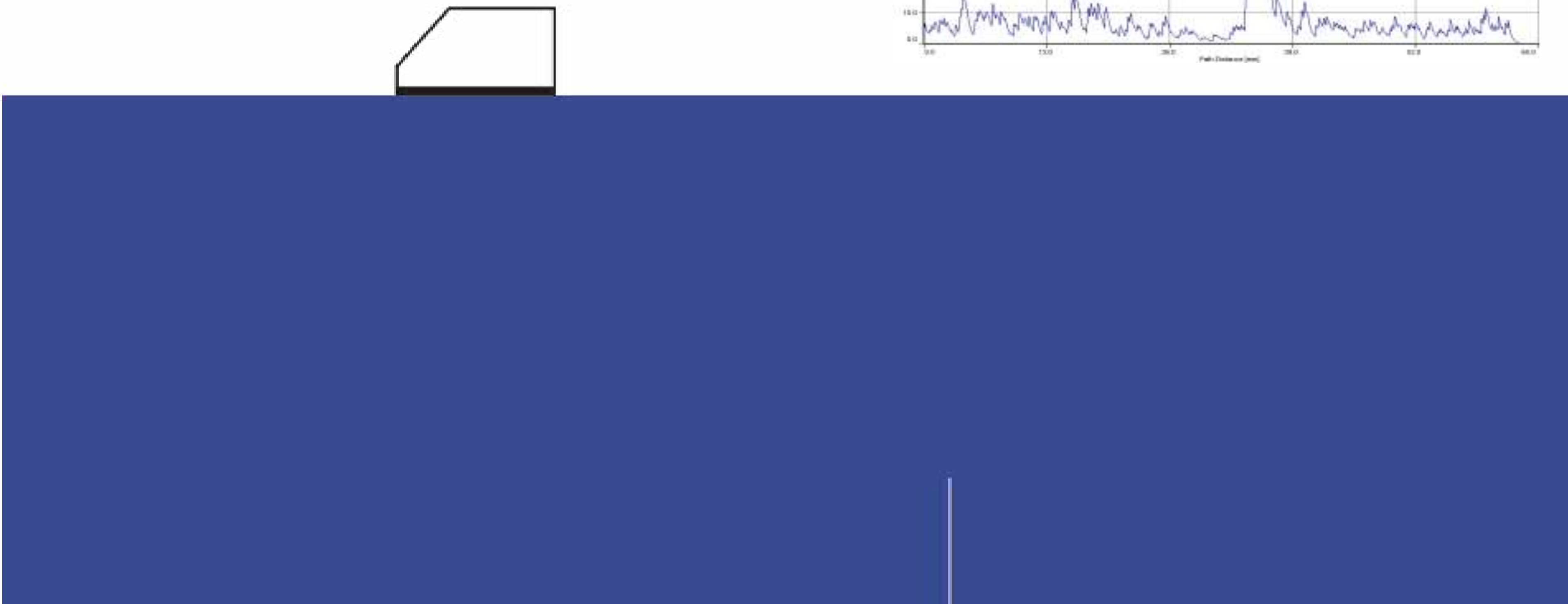
INSPECTION PROBLEM
Acoustic Anisotropy



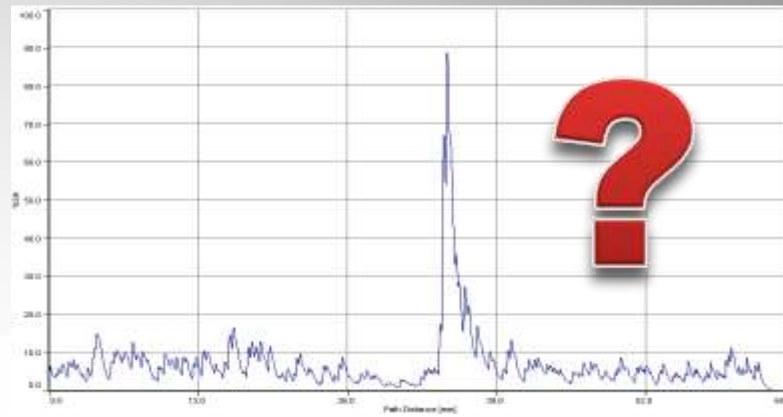
SIMULATION
acoustically isotropic

Impulse – Echo Technique

45° Shear Wave Transducer



INSPECTION PROBLEM
Acoustic Anisotropy

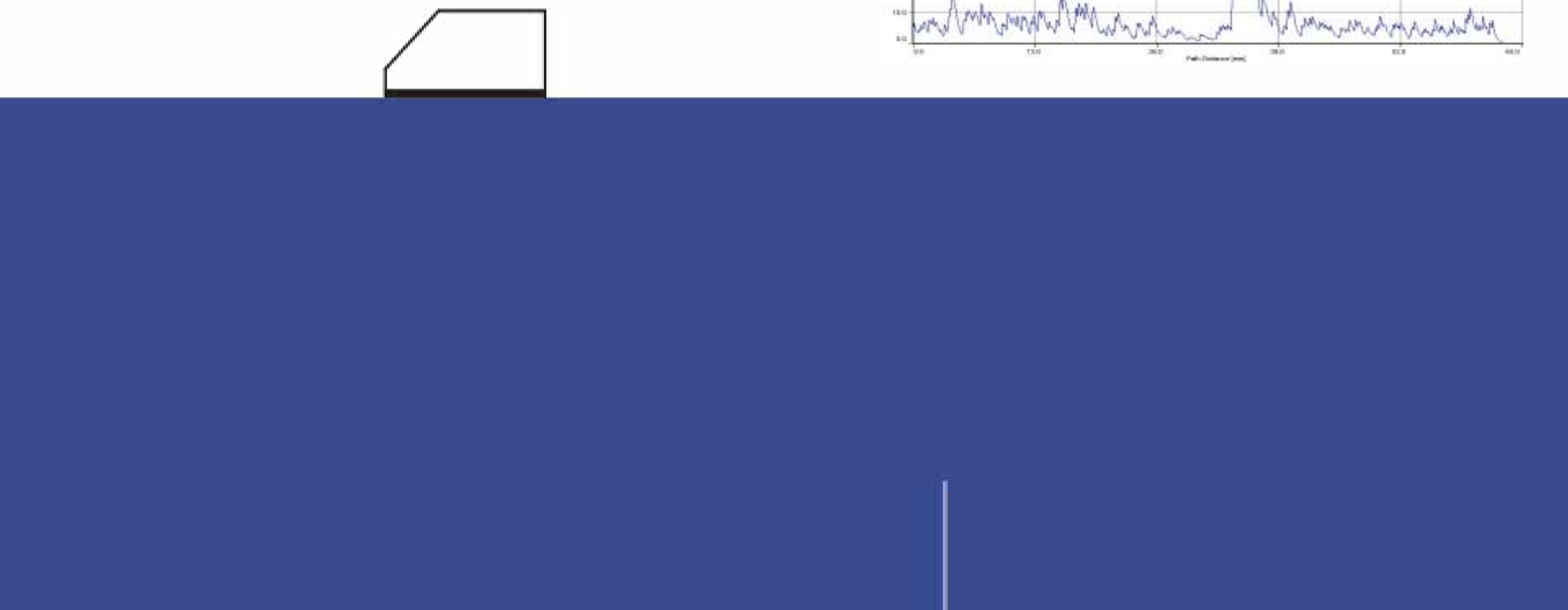


SIMULATION

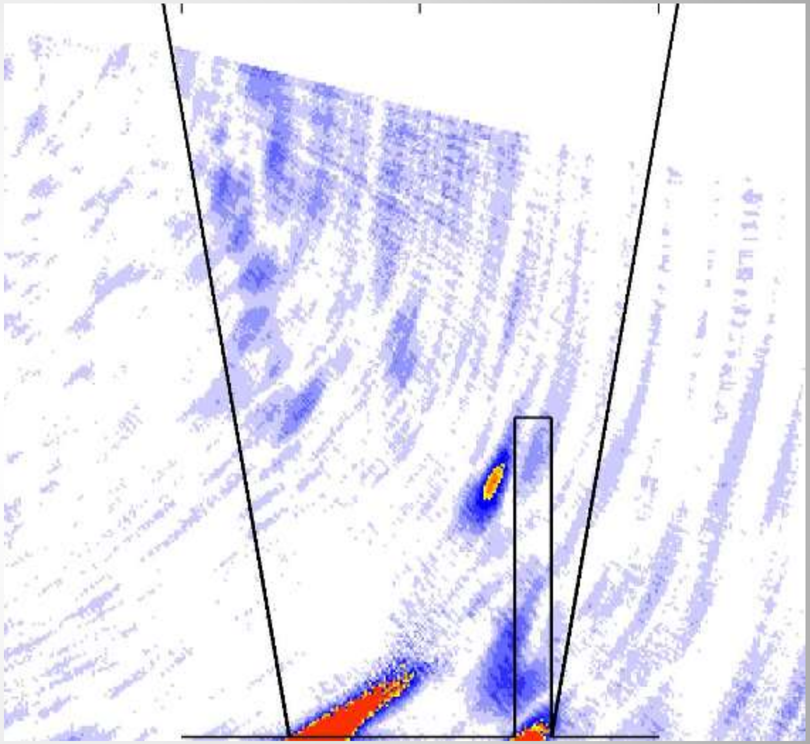
transversal isotropic

Impulse – Echo Technique

45° Shear Wave Transducer



INSPECTION PROBLEM
False Calls



S. PUDOVIKOV, A. BULAVINOV, R. PINCHUK, R. SRIDARAN VENKAT
Quantitative Ultraschallprüfungen an anisotropen Materialien mittels Sampling Phased Array Technik,
DGZfP-Jahrestagung 2010

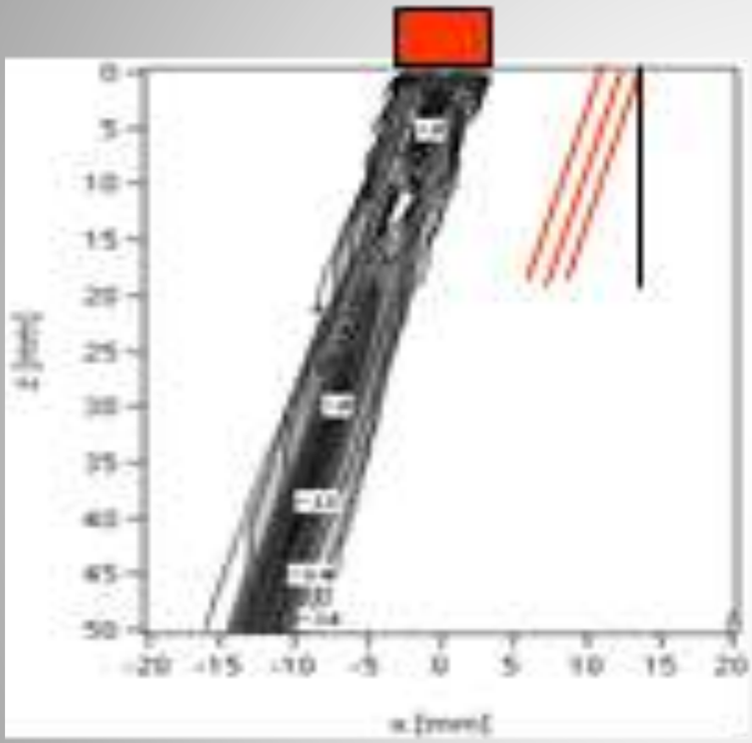
INSPECTION PROBLEM
Acoustic Anisotropy

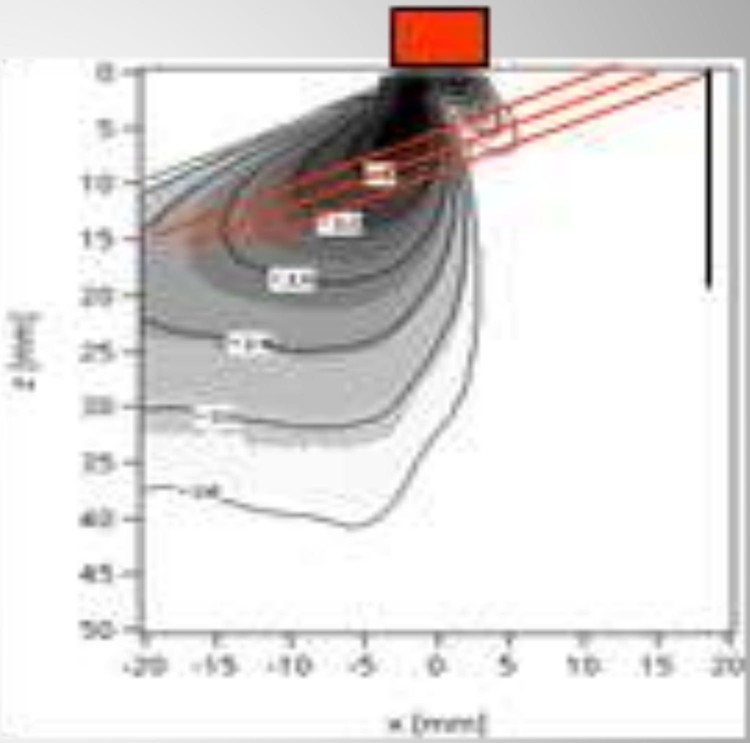
Rules for Practitioners

SCATTERING:

- LONGITUDINAL MODE
  ~ 8 times less than shear mode
- FOCUSSING (T/R Transducers)
  limits the contribution of scattering
- FILTERING and BEAM FORMING
  reduction of scattering contribution
  (TOPIC of R&D)

INSPECTION PROBLEM
Acoustic Anisotropy





FOCUSSING & DEFOCUSSING OF SOUND FIELDS IN TRANSVERSE ISOTROPIC MATERIALS

INSPECTION PROBLEM
Acoustic Anisotropy

Rules for Practitioners

BENDING:

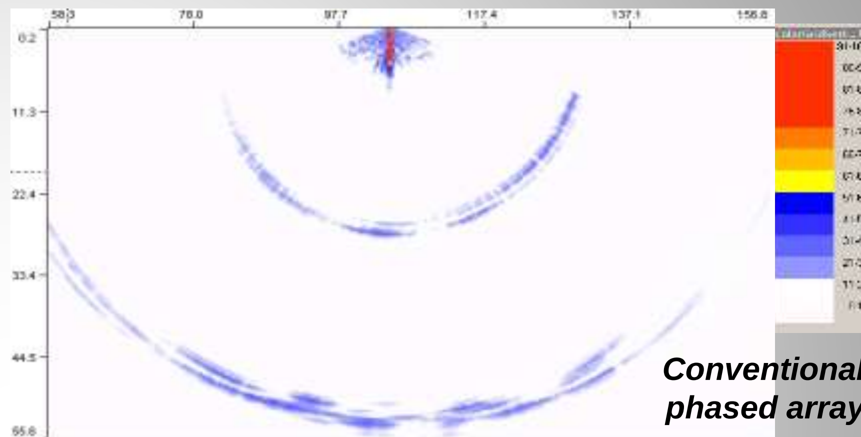
- LONGITUDINAL & SHEAR MODE opposite behavior
- FOCUSSING of LONG. MODE at intersecting angles of 0° and 90°
- DEFOCUSSING of LONG. MODE at intersecting angles of +/- 45°

TENDENCY of BENDING into the columnar grain orientation

INSPECTION PROBLEM
Acoustic Anisotropy – Sound Field Bending

<u>Inspection of carbon-fiber structures</u>

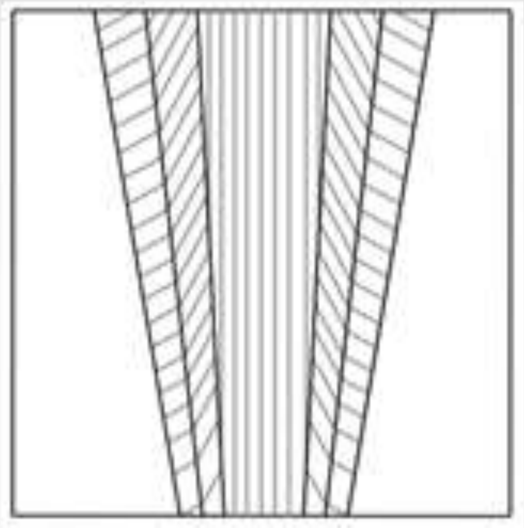
R&D
Reverse Phase Matching



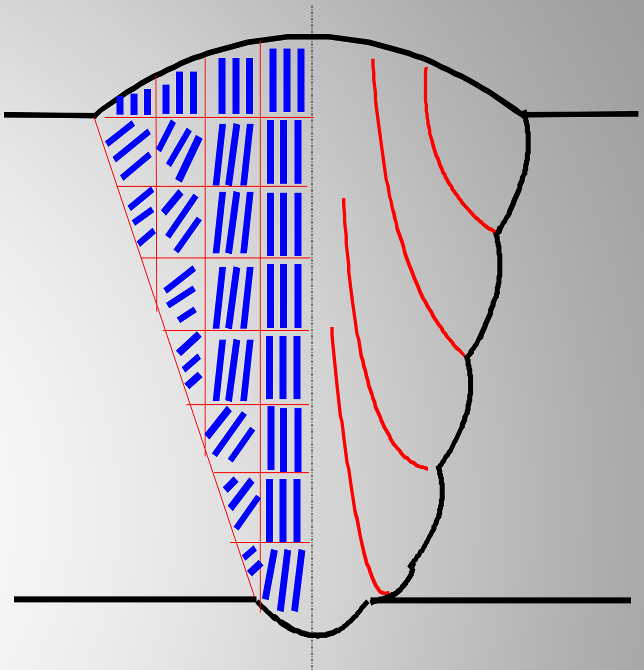
Conventional phased array

Sampling Phased array

INSPECTION PROBLEM
Acoustic Anisotropy



STRIP MODEL



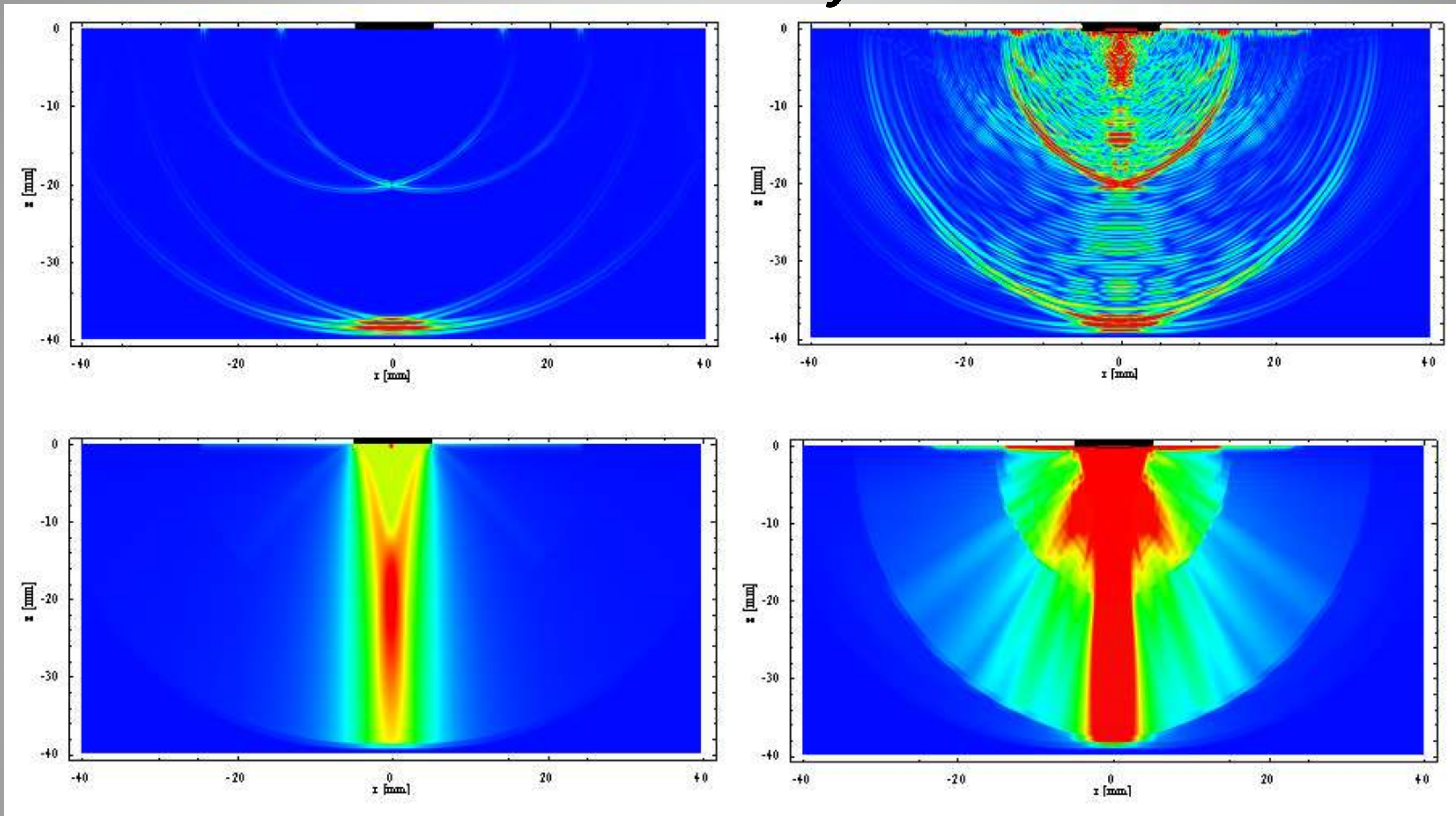
PIXEL/VOXEL MODEL

DEFINITION:

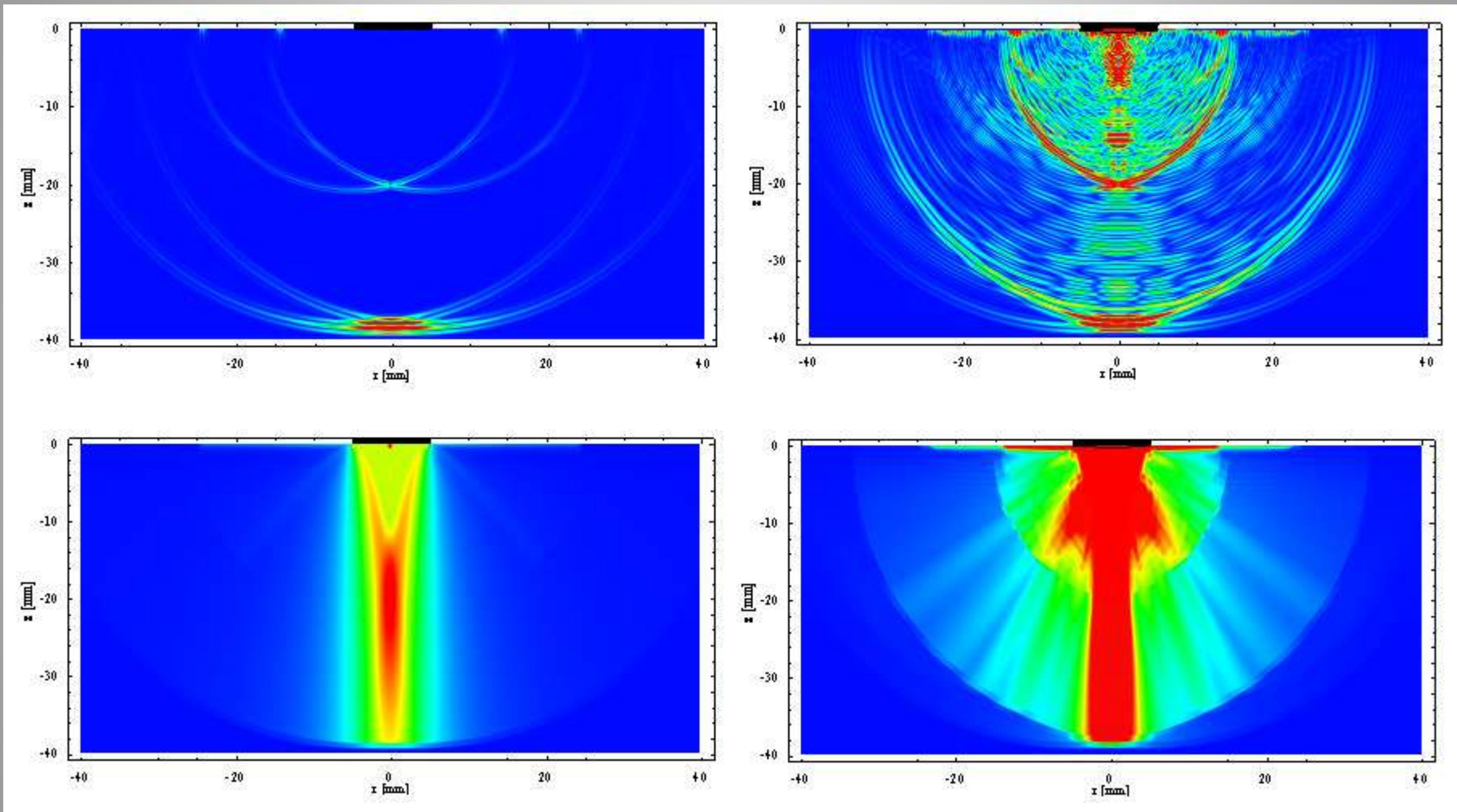
ACOUSTIC TRANSVERSAL ISOTROPIC DOMAINS TID
SECTIONS WITH HOMOGENEOUS ACOUSTIC PROPERTIES

TRANSVERSAL ISOTROPIC DOMAINS TID

INSPECTION PROBLEM
Geometry

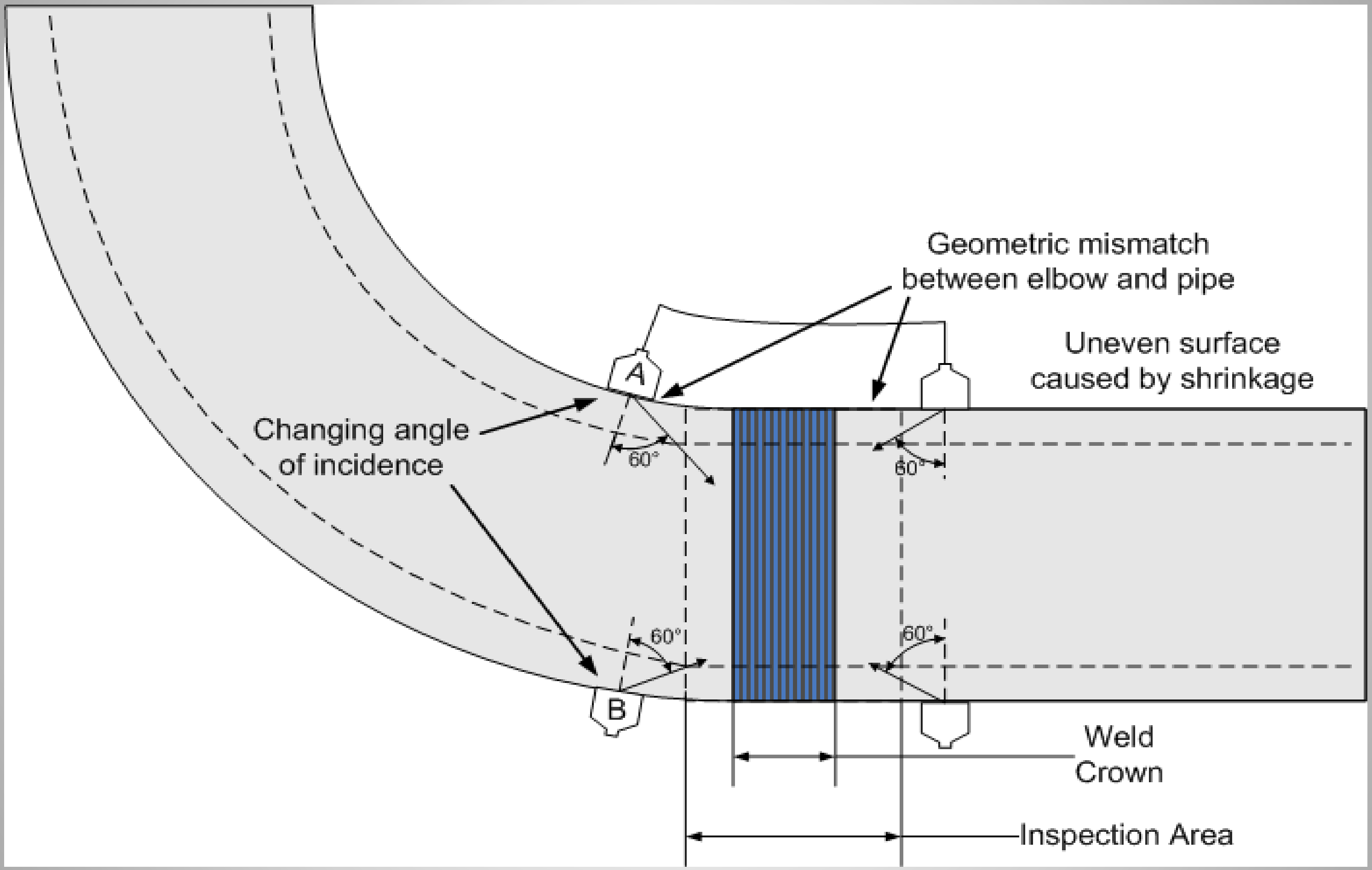


Water gap depth (lens shaped):
0.18 mm (λ/8 in steel, λ/2 in water)

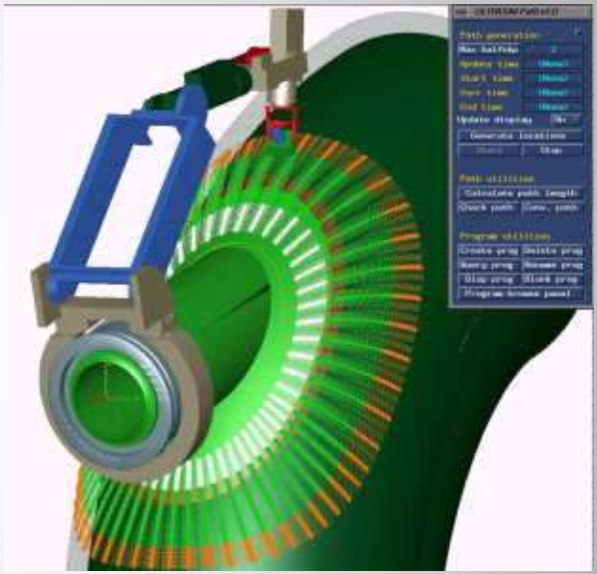


Water gap depth (lense shaped): 0.18 mm
(λ/8 in steel, λ/2 in water)

INSPECTION PROBLEM
Geometry

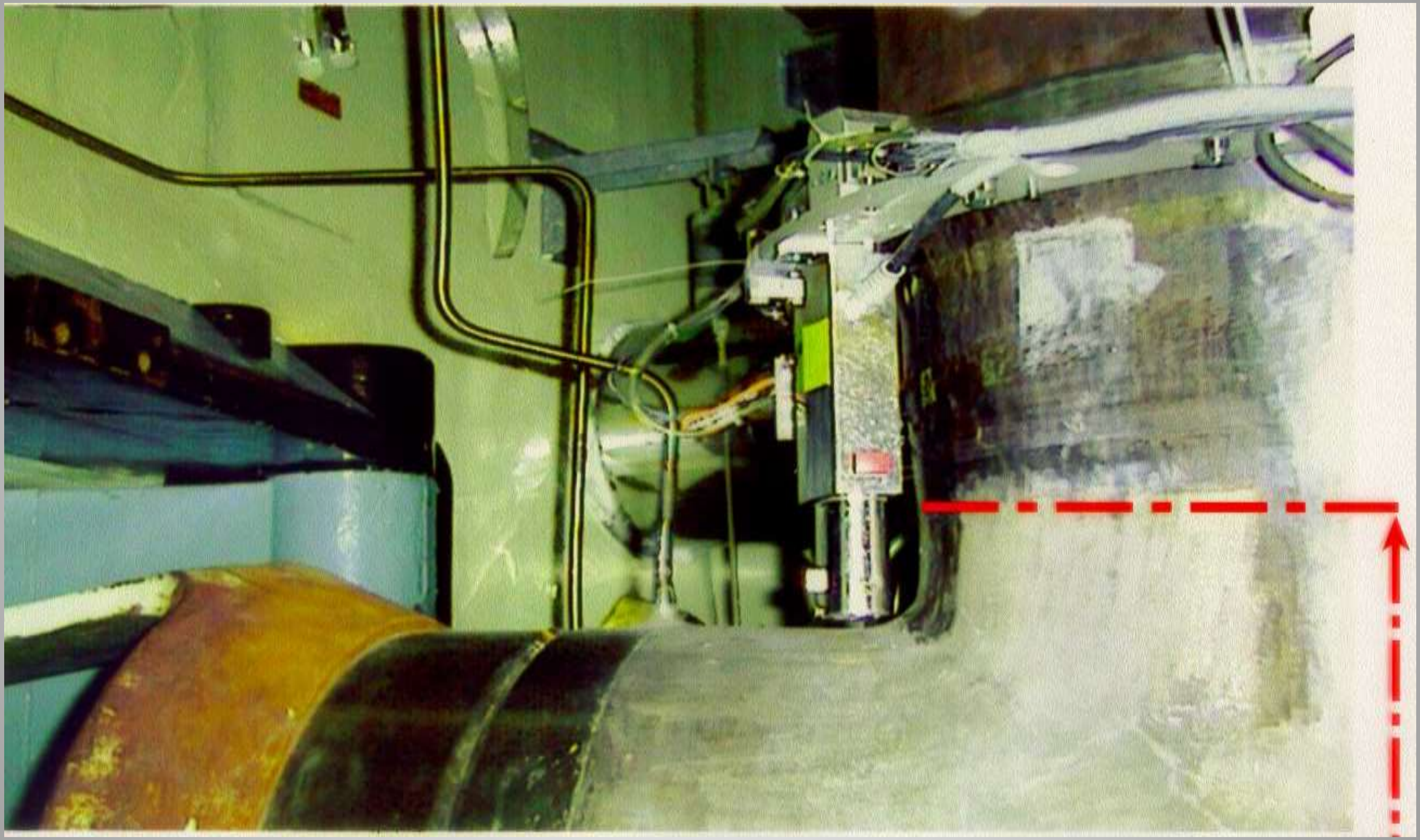


INSPECTION PROBLEM
Geometry



LOCALIZATION
OF
REFLECTOR INDICATIONS

INSPECTION PROBLEM
Geometry



INSPECTION PROCEDURE
Best Practice

STANDARD PROCEDURE NOT APPLICABLE

REGISTRATION:

AMPLITUDE CRITERIA IN REFERENCE TO CALIBRATION REFLECTORS

EVALUATION:

LOCALIZATION, CONTRAST & RESOLUTION SENSITIVITY

Coupling; Bending; Attenuation; Scattering;
Shaped Inspection Geometry; Systematic Indications; False Calls

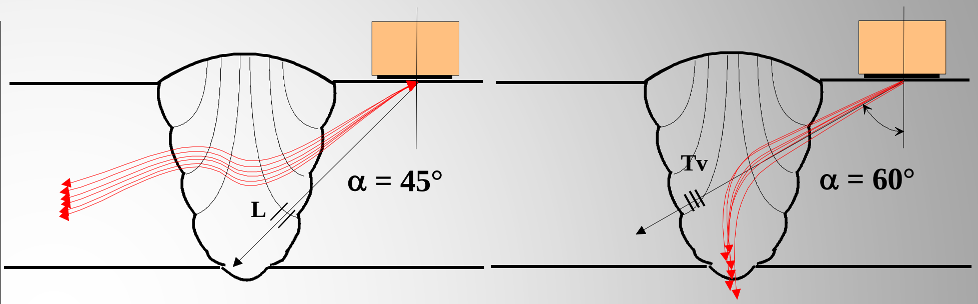
IMAGING OF SYSTEMATIC INDICATIONS
BY
PHASED ARRAYS

INSPECTION PROBLEM OPTIMIZATION

List of Possible Transducers

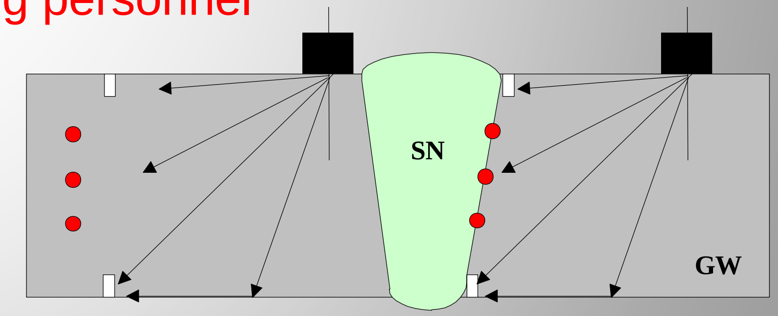
- 45°, 60°, 70° Shear Wave
- 45°, 60°, 70° Longitudinal Wave
- Double Element Transducers ADEPT
- LLT Transducers
- Mode Conversion Transducers
- **'Creeping wave'** Transducers

(1) Simulation of US wave propagation

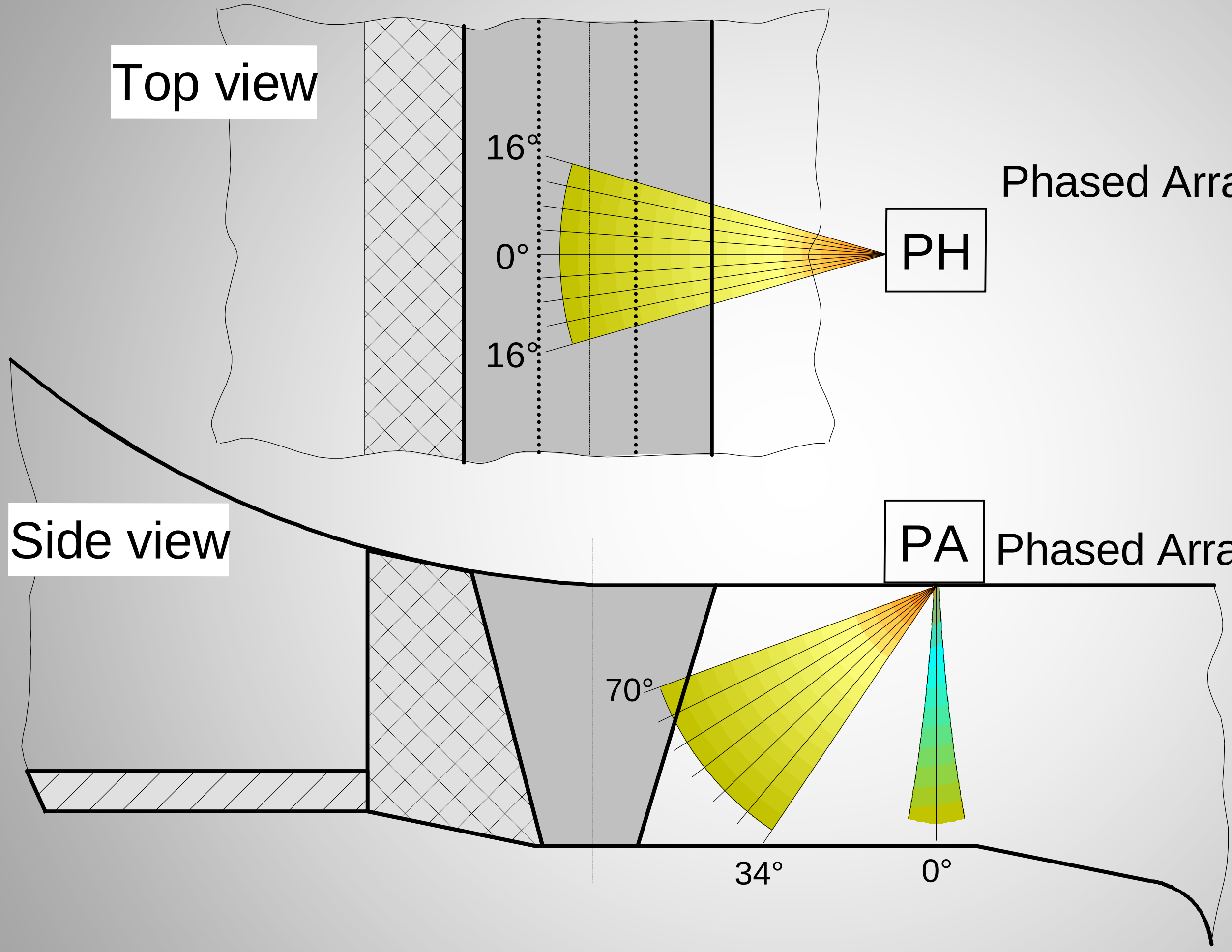


(2) Choice of appropriate transducers

(3) Qualification of inspection technique & testing personnel



INSPECTION PROCEDURE
Best Practice



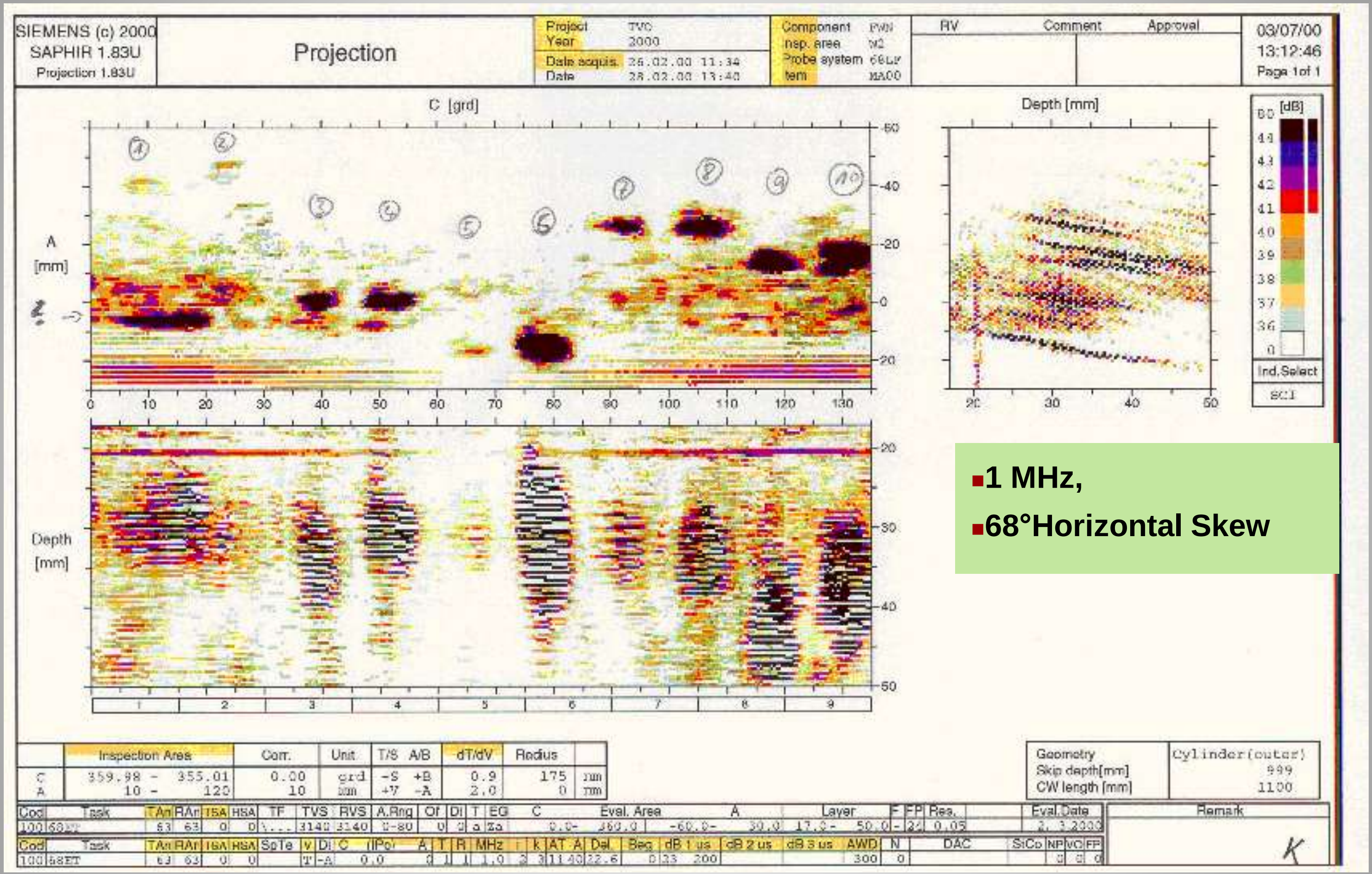
Phased Array horizontal

mainly for normal and skewed defects, steering in dual and single crystal mode

Phased Array vertical

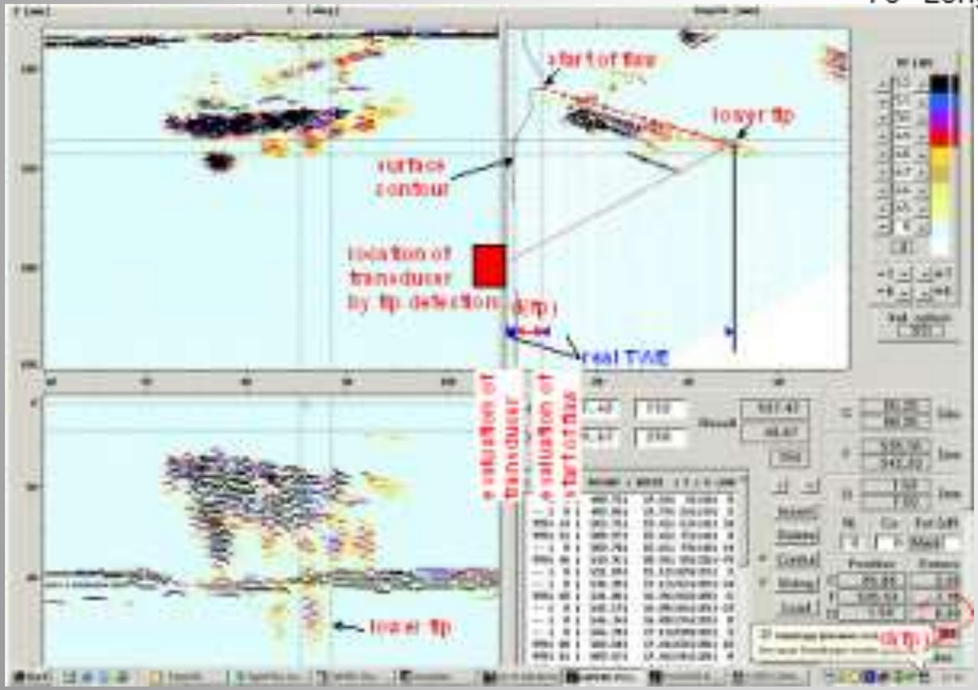
mainly for normal and tilted defects, steering in dual and single crystal mode

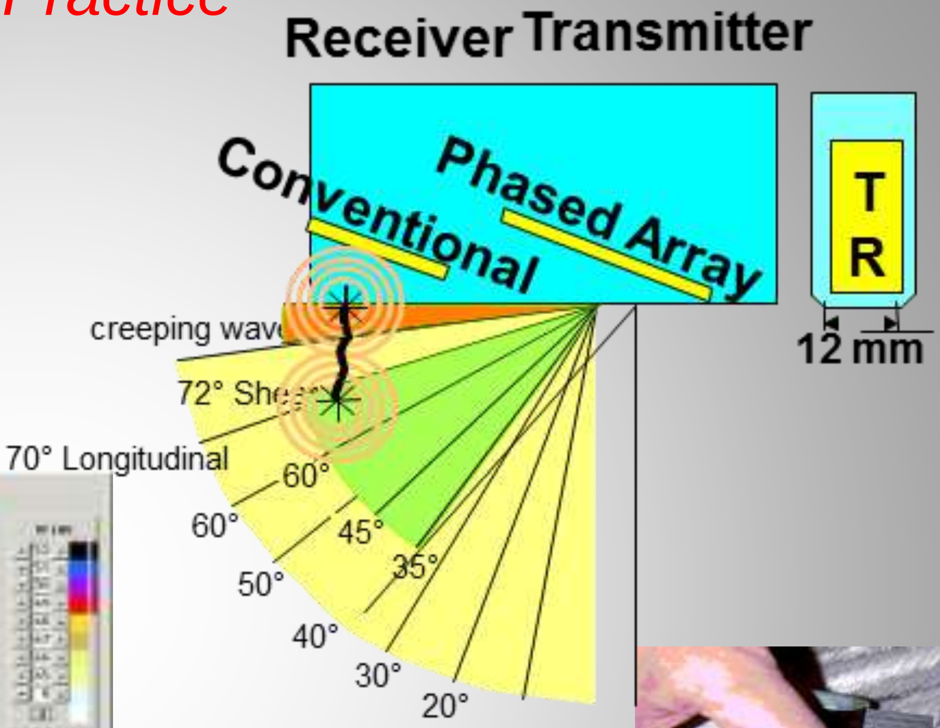
INSPECTION PROCEDURE
Best Practice



- 1 MHz,
- 68°Horizontal Skew

INSPECTION PROCEDURE
Best Practice

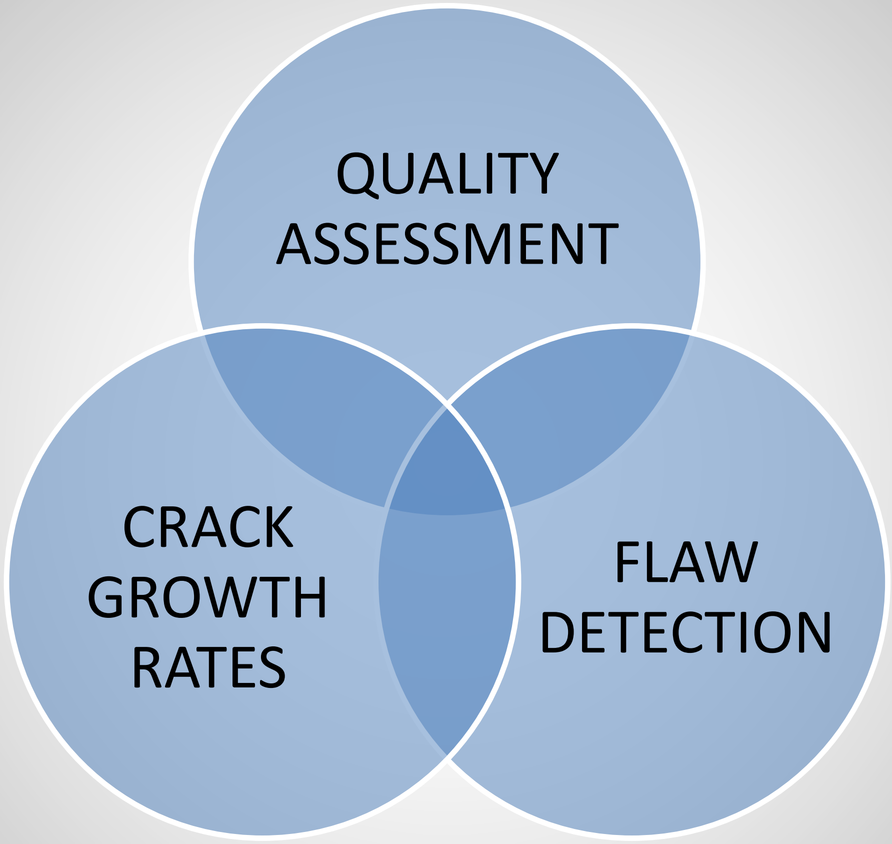




Real Surface Condition

CONCLUSION

NDT SUPPORTED MITIGATION CONCEPT



Assessment of Dissimilar Welds: "Risk for PWSCC"

CONCLUSION

Advanced Inspection Technique

- **Specially designed Phased Array Transducers with several inspection techniques in one housing:**

FIT: Fit for Inspection Transducer:

Multiple modes (longitudinal and transversal),
Multiple beam angles and focusing,
Tandem (SSS, LLS)

- **Accurate absolute and relative position data**
- **Accurate system repositioning for repeated inspections (manipulator technology)**
- **Selectable imaging of reflector systematics**

CONCLUSION

We can inspect dissimilar welds!

However,
We need proof of

- **Inspection procedure and performance (validation)**
- **Advanced inspection equipment (phased array imaging)**
- **Precise transducer positioning by smart manipulators**
- **3D localization of reflectors in the component geometry**

And a lot of professional experience

Ultrasonic Inspection of Dissimilar Welds

RESEARCH & DEVELOPMENT

INSPECTION TECHNIQUE	*MIGRATION ARRAYS*
SIGNAL PROCESSING	*BEAM FORMING & FILTERING*
MATERIAL STRUCTURE	*REVERSE PHASE MATCHING*
IMAGE EVALUATION	*PAGING & REFERENCING*

MIGRATION ARRAYS

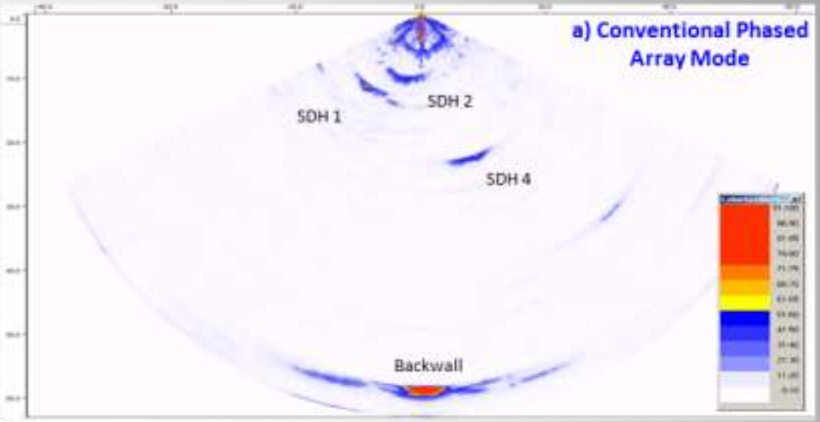
SAFT

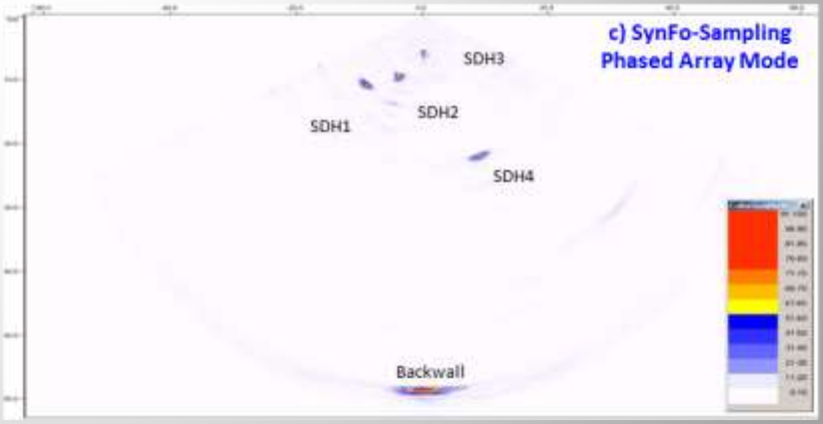
Phased Array

Migration Array

Phased Array – Migration Array

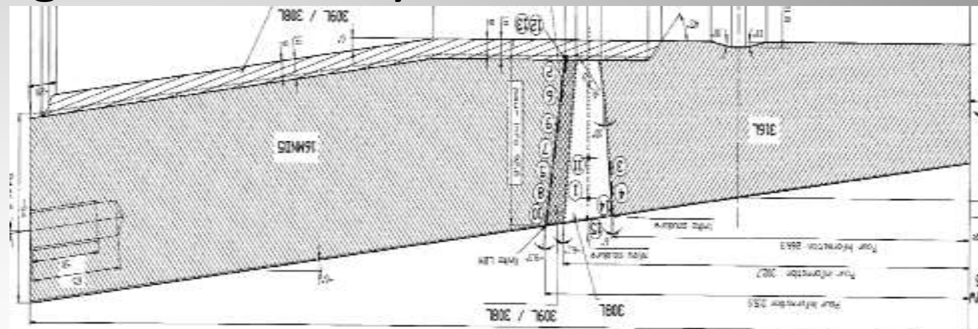
Test specimen
with
4 boreholes



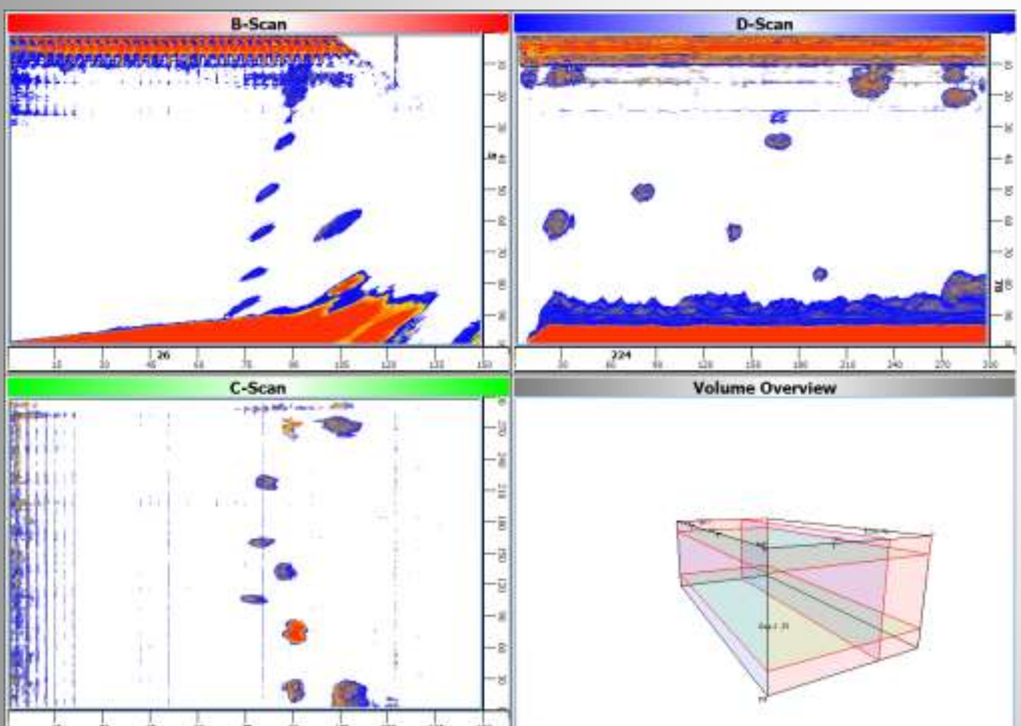


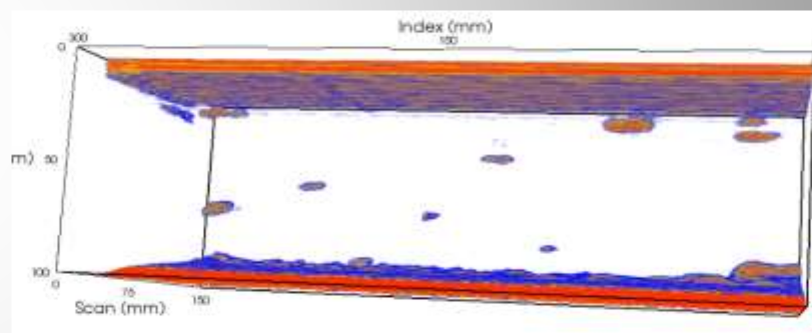
Experience in DM-Welds at iNDT

Results by Sampling Phased Array from ID



DM Test Block





3-D Representation

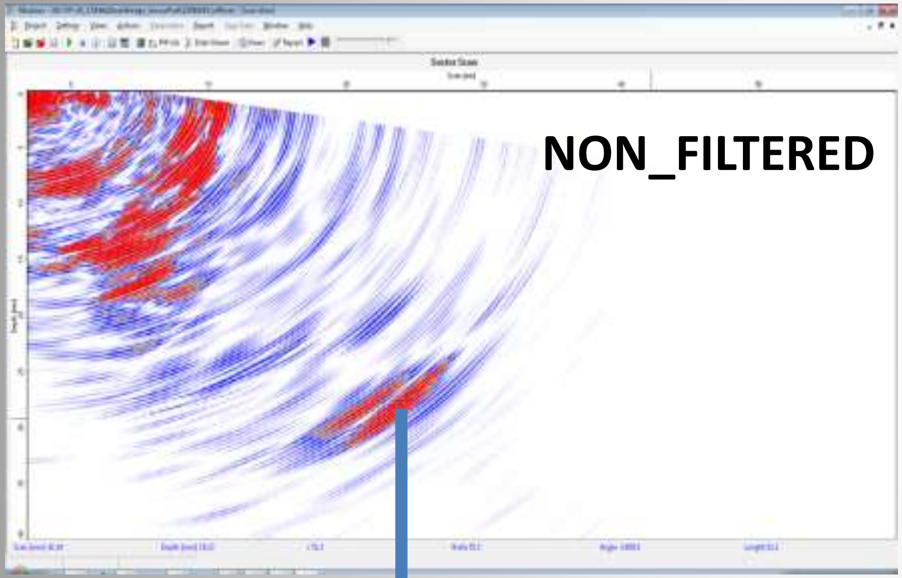
MIGRATION ARRAYS

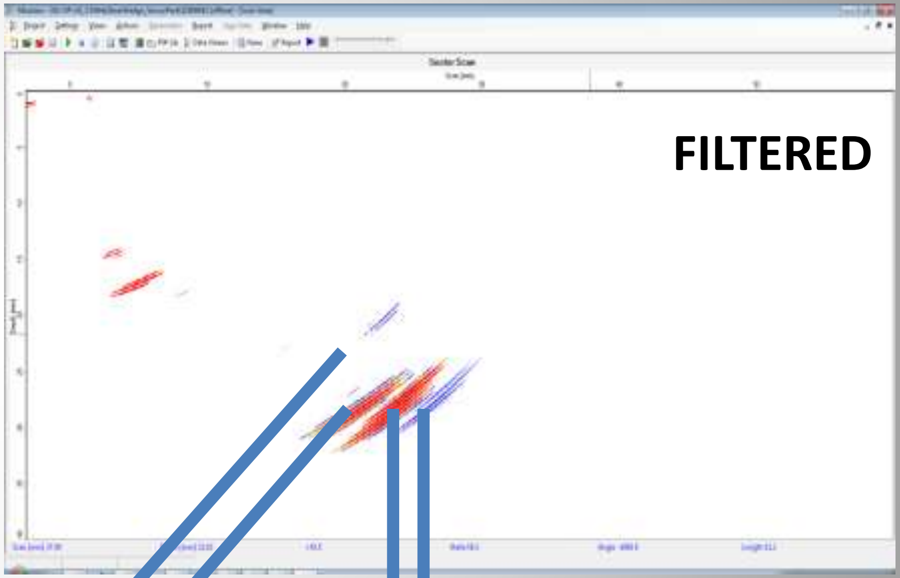
Some (new) Statements

- Position Controlled Measurement
- Array aperture determines near field with synthetic focusing
- Resolution depends on Element Aperture
- One set of A-Scan data of array elements received in parallel allows full and complete image reconstruction with:

Excellent Contrast Sensitivity (all space angle of incidence)
Highest possible Resolution Contrast through synthetic focusing

BEAM FORMING & FILTERING
COARSE GRAIN MATERIAL



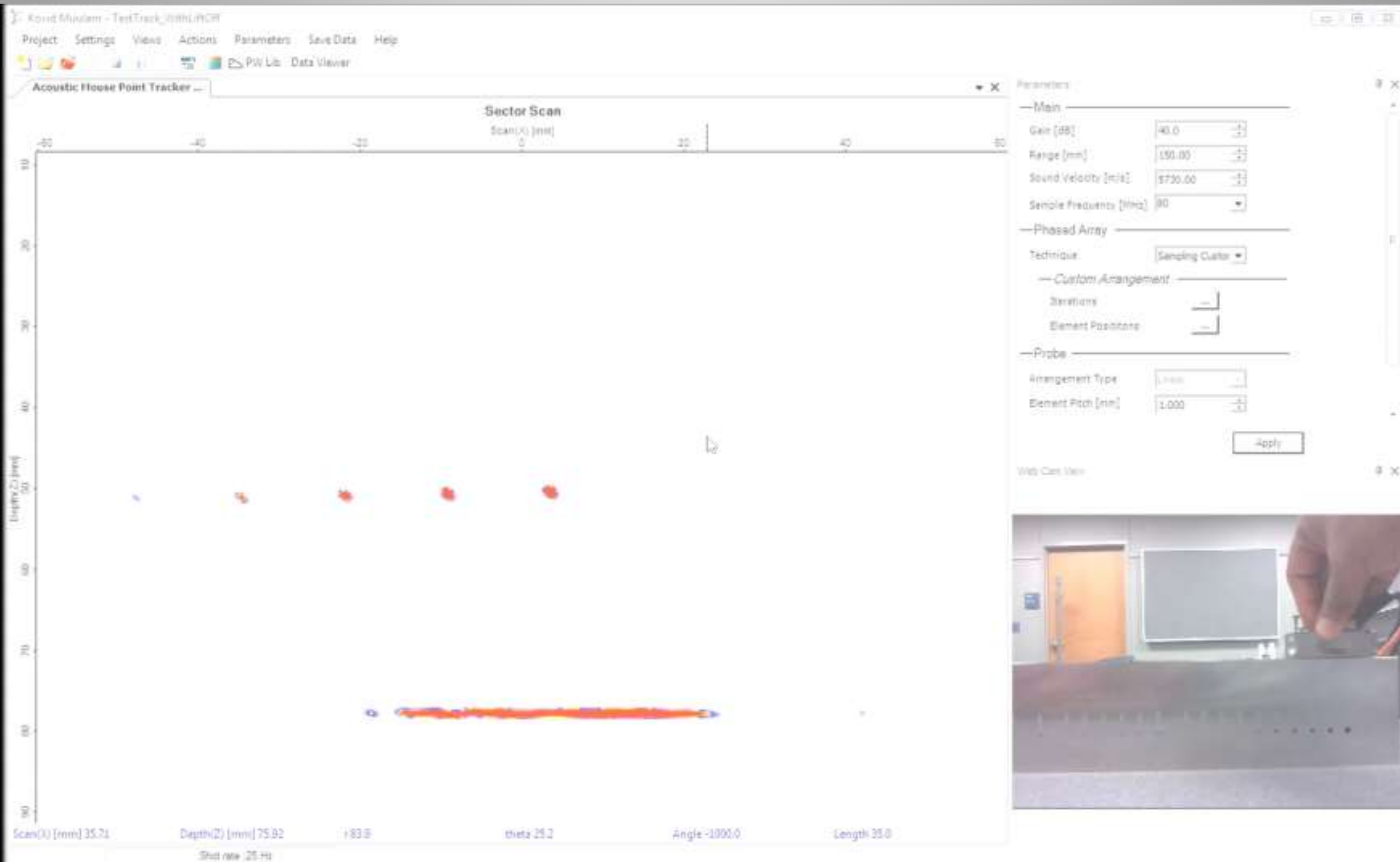


WELD ROOT

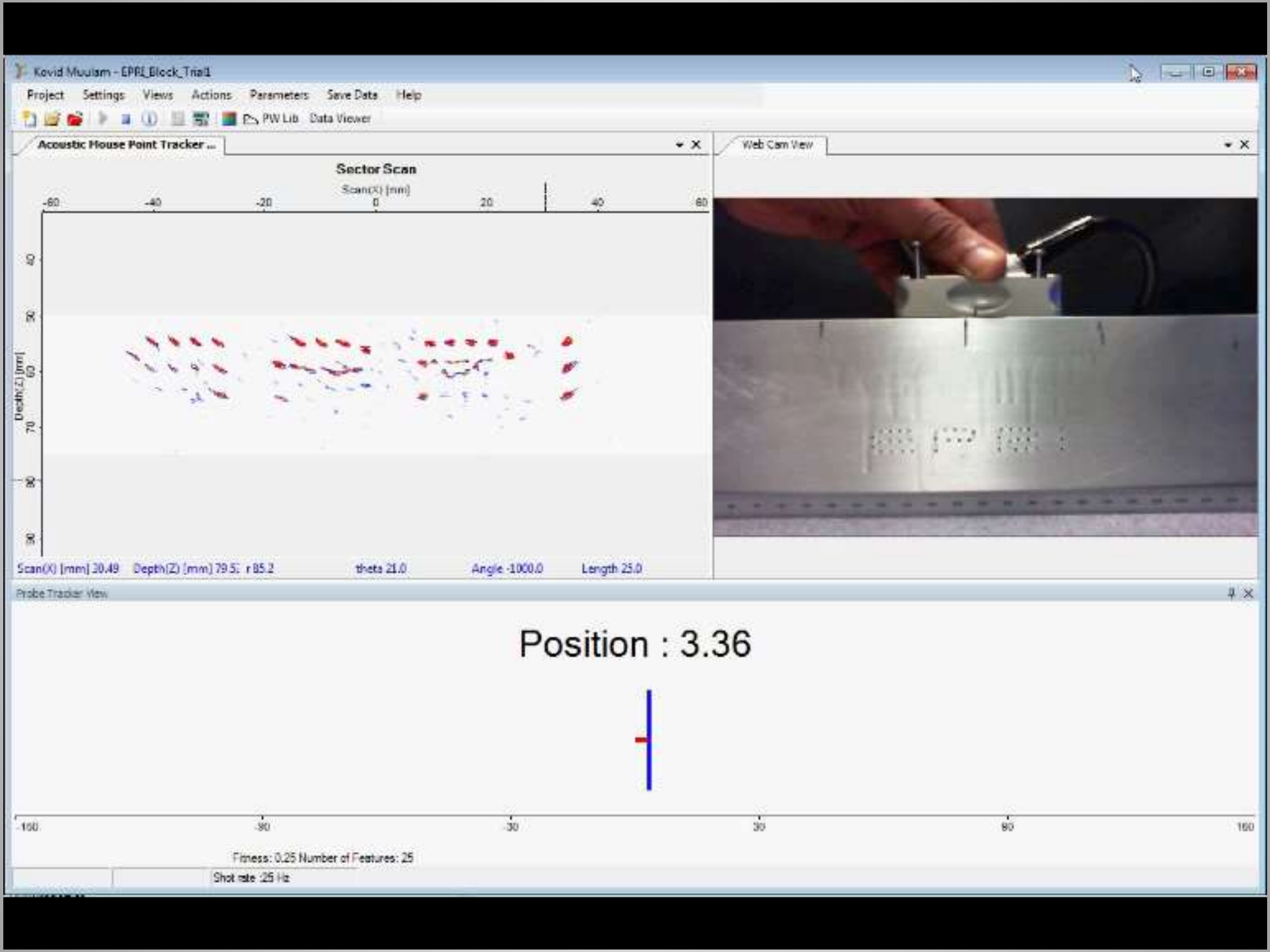
CRACK OPENING
& TIP

WELD ROOT

BEAM FORMING & FILTERING
HIGH RESOLUTION AND CONTRAST SENSITIVITY

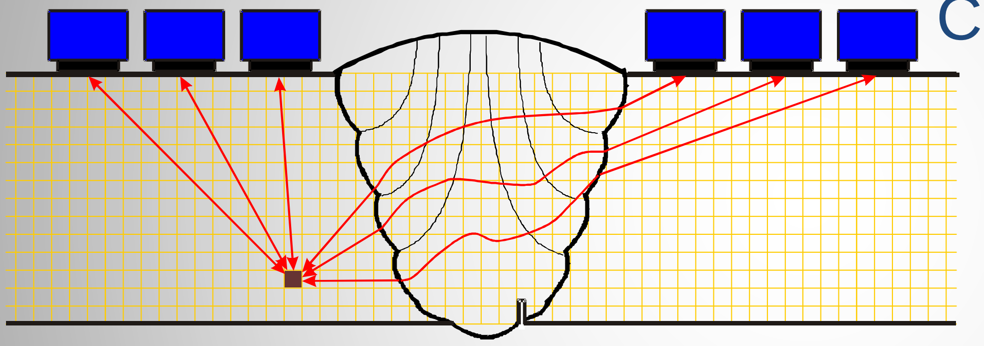


TRANSDUCER TRACKING



REVERSE PHASE MATCHING

$$\sum A_{ij}\left(t+\Delta\varphi_{ij}\right)$$

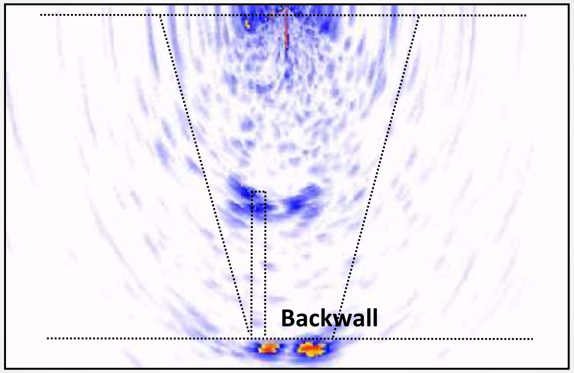


Calculation of time of flight in consideration of acoustic anisotropy

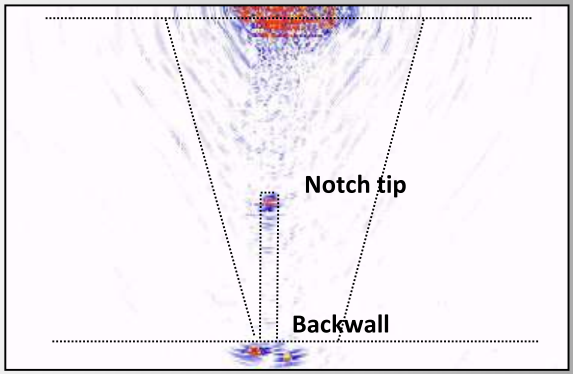
Phase corrected summation

REVERSE PHASE MATCHING

Phased array transducer and test specimen



Conventional Phased Array



Sampling Array with Reverse Phase Matching

THANK YOU FOR YOUR INTEREST

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