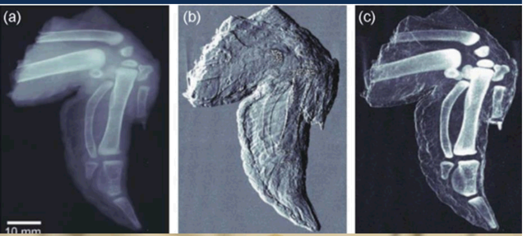
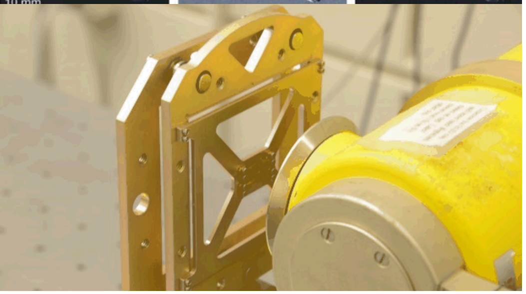
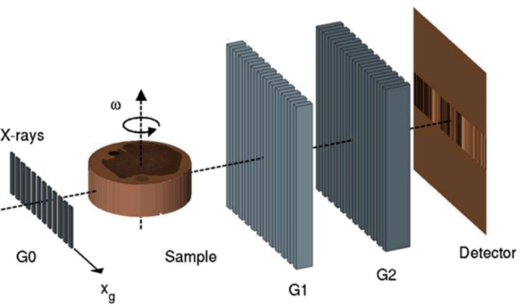
SAND2016-2054PE







AM Defect Detection Using X-ray Phase Contrast Imaging

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Sandia National Laboratories
Albuquerque, NM

February 24, 2016

Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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Outline

- Defect detection and validation & verification in AM
- Introduction to X-ray phase contrast imaging
- Application to defect detection for AM
- Status at Sandia-NM

DEFECT DETECTION AND VALIDATION & VERIFICATION IN AM

Challenge in Verification & Validation

- Inspection is critical to assuring functionality and security
  - "Slice and dice" inspection
  - Randomly selected samples
  - Labor intensive
  - Limited imaging depth
  - Complicated sample preparation
  - Limited in materials that can be inspected
- X-ray phase contrast imaging (XPCI)
  - Non-destructive
  - Three orders of magnitude greater sensitivity to phase over absorption imaging
  - Complementary imaging modalities (absorption, phase, dark-field)
  - Visualization of internal structure
    - Compare part topography to CAD design
    - Look for cracks, voids
    - Identify unfused powder

AM Part Imaged at SNL Using X-ray CT

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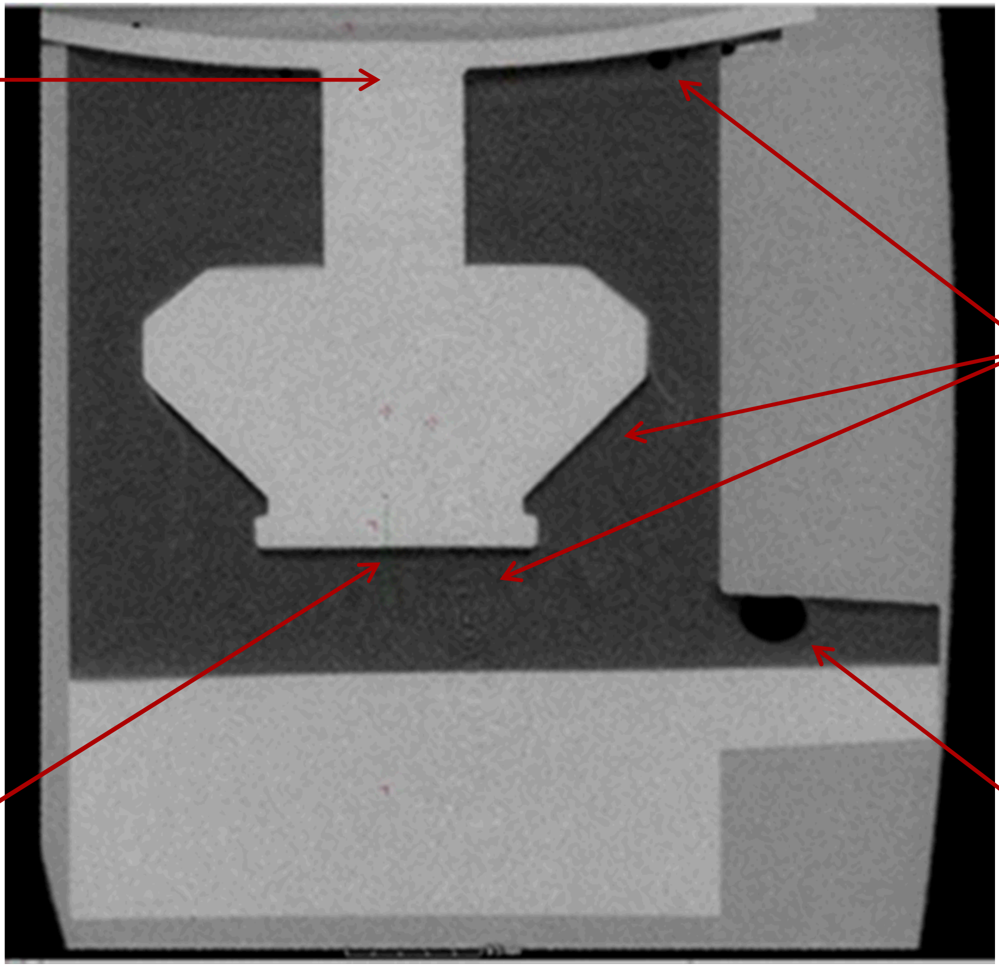
Suspending beam bows from shrinkage



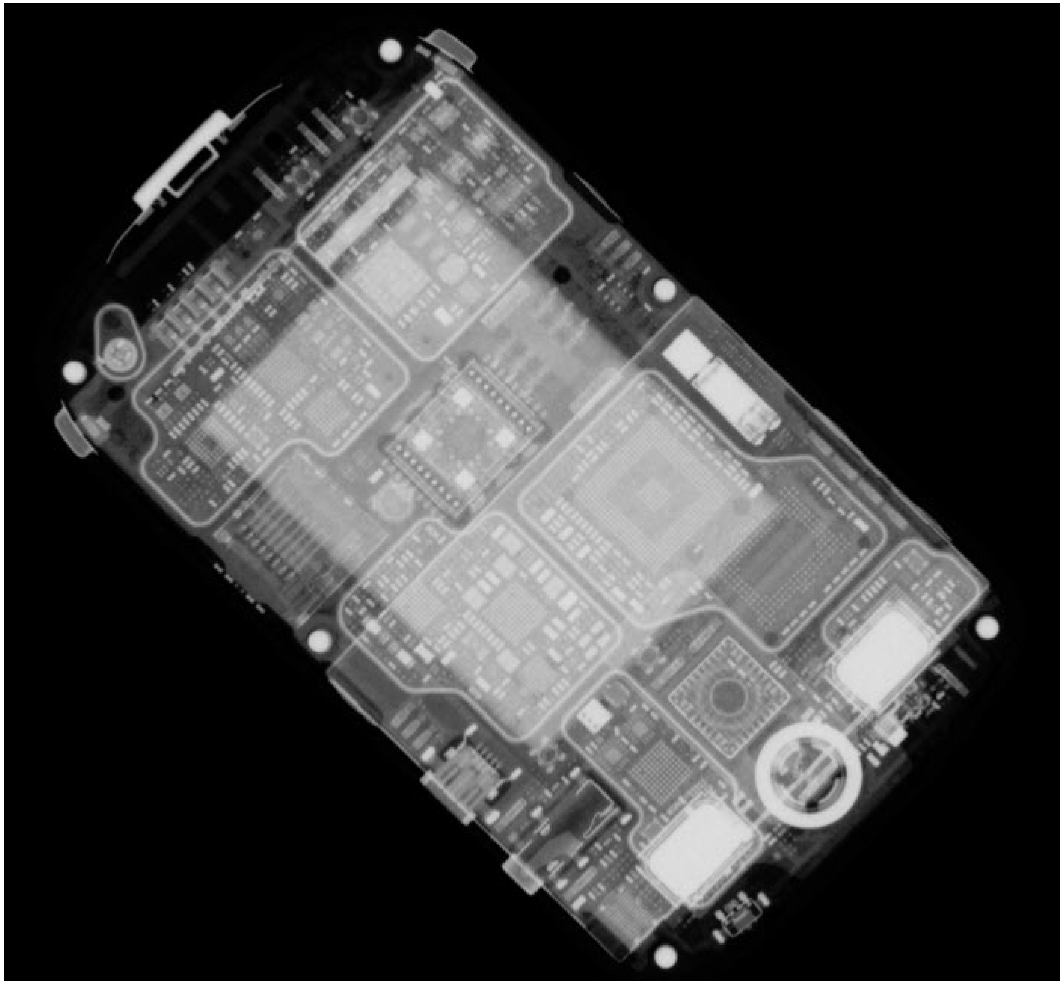
Lower density regions

Void from delamination of epoxy from shape

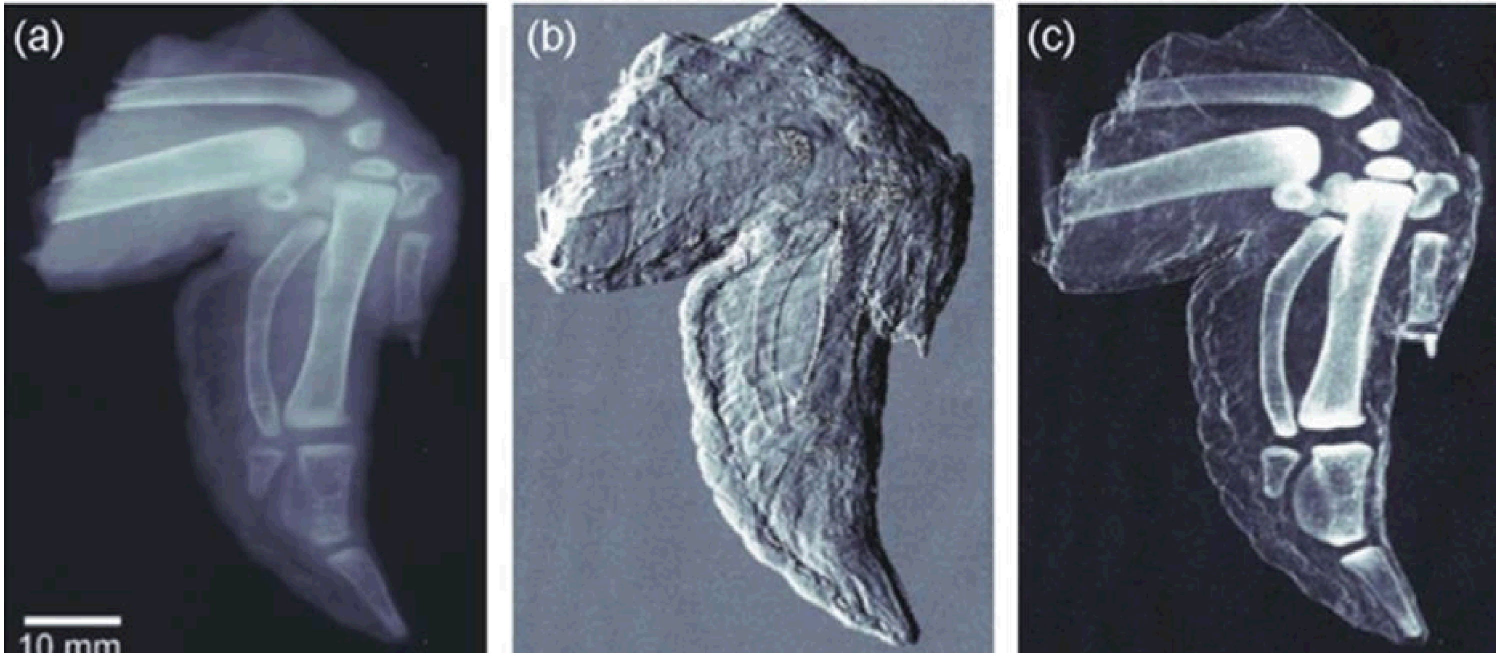
Large bubble causes void

INTRODUCTION TO X-RAY PHASE CONTRAST IMAGING

X-ray Phase Contrast Imaging



X-Ray Phase Contrast Imaging: Complementary Data



Absorption
Contrast between dense and less-dense (low-Z) regions. No material detail.

Phase Contrast
Fine structure within the low-Z regions.

Dark-Field
Sharp contrast at boundaries. Microstructures cause scattering.

To acquire only attenuation data leaves out significant information about the material properties

M. Bech, et. Al., Z. Med. Phys., **20,** 7, 2010.

Greater Sensitivity with Phase Contrast

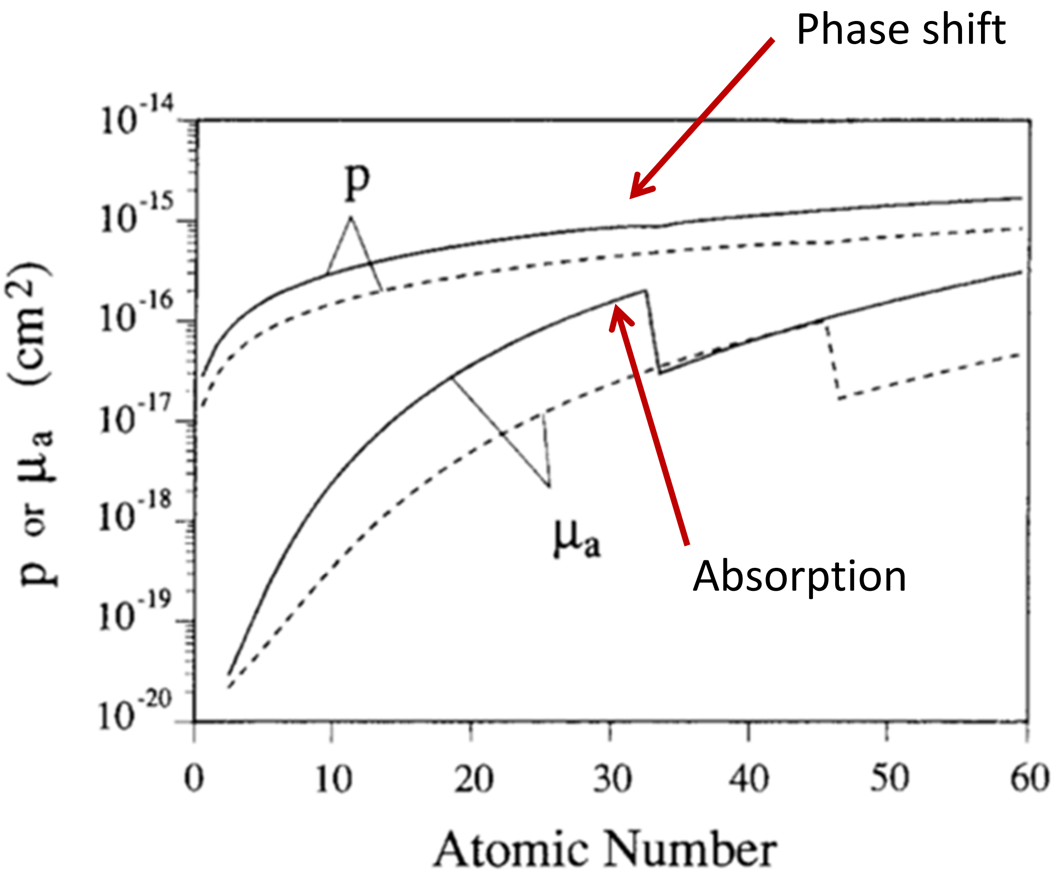


FIG. 1. Atomic x-ray phase shift p and absorption μ_a for 1 Å (solid line) and 0.5 Å (dashed line) x-rays are plotted versus the atomic number Z. The value of p is almost a thousand times larger than μ_a for light elements.

- X-ray absorption imaging is used for non-destructive imaging
  - Poor sensitivity to low absorbing (low-Z) materials

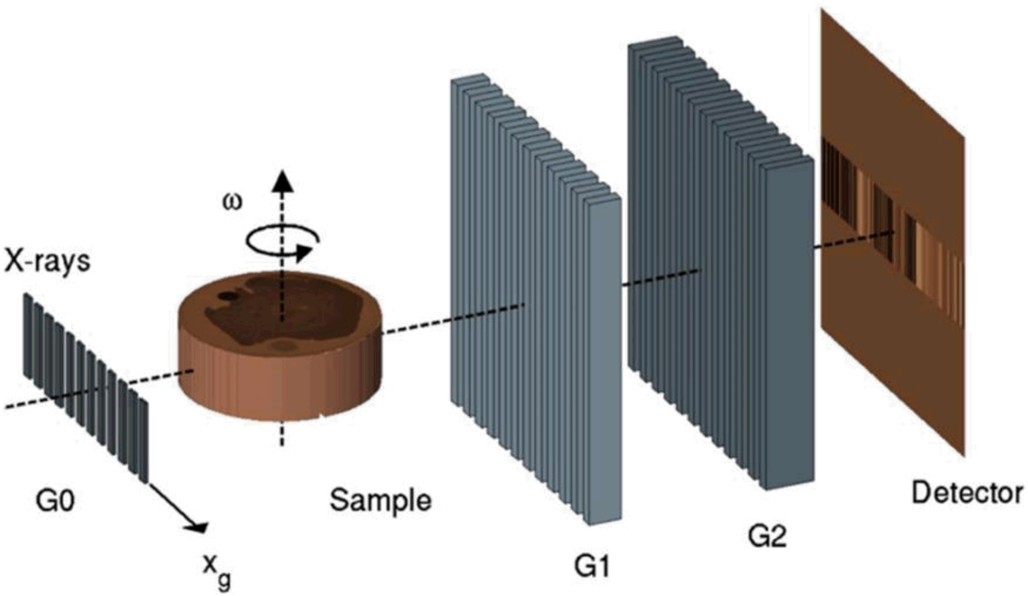
Phase contrast

1000x more sensitive

Ref: A. Momose and J. Fukuda, Med. Phys., **22**, 375, 1995.

Grating-Based XPCI

Talbot-Lau Interferometer



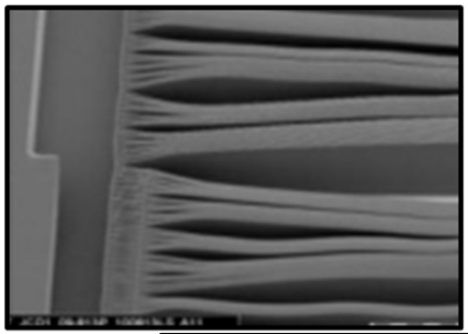
- Source grating: G0
  - Enables use of conventional x-ray tube
- Phase grating: G1
  - Imposes a modulated phase shift on wavefront
- Analyzer grating: G2
  - Converts narrow fringe pattern to intensity signal

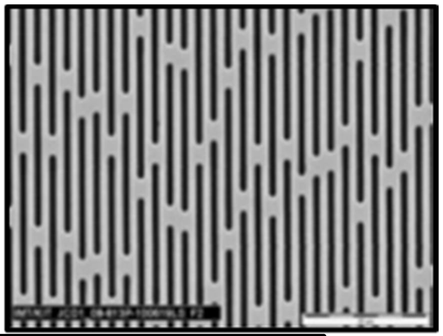
Source grating enables lab-based XPCI

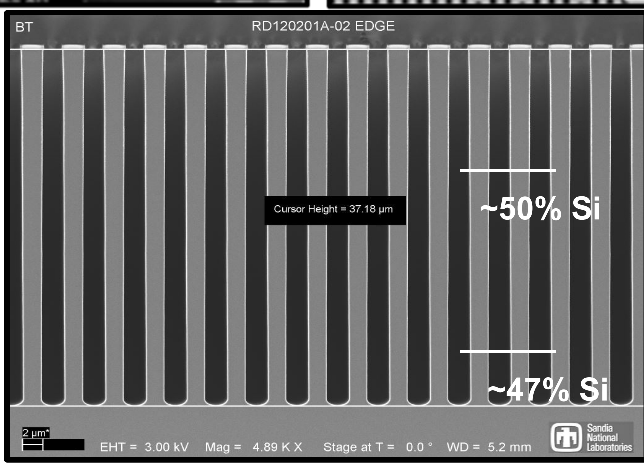
M. Nielsen, et. al., Phys Med Biol, **57**, 5971, 2012.

Why Sandia?

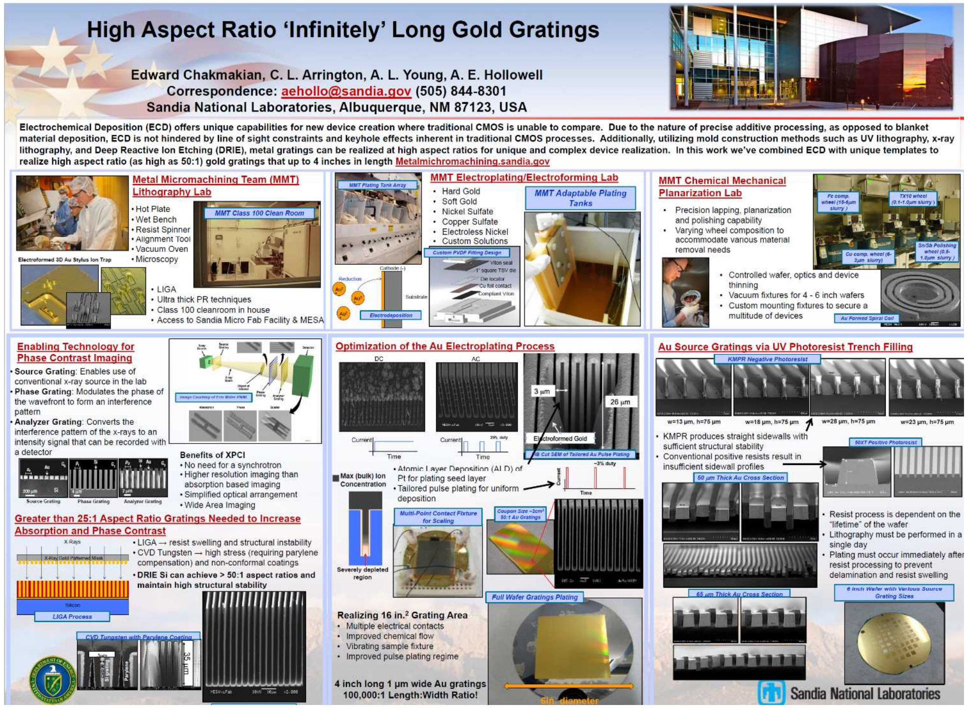
- Unparalleled grating fabrication capability
- Advanced NDE/NDT facilities
- Materials science applications critical to national security







37µm deep



APPLICATION OF XPCI TO ADDITIVE MANUFACTURING

Porosity Measurements

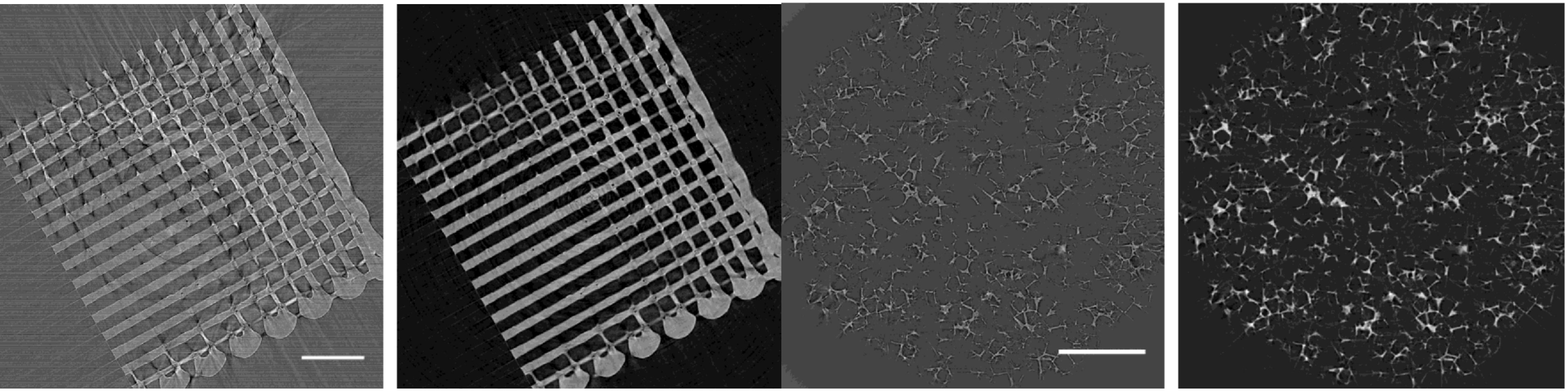
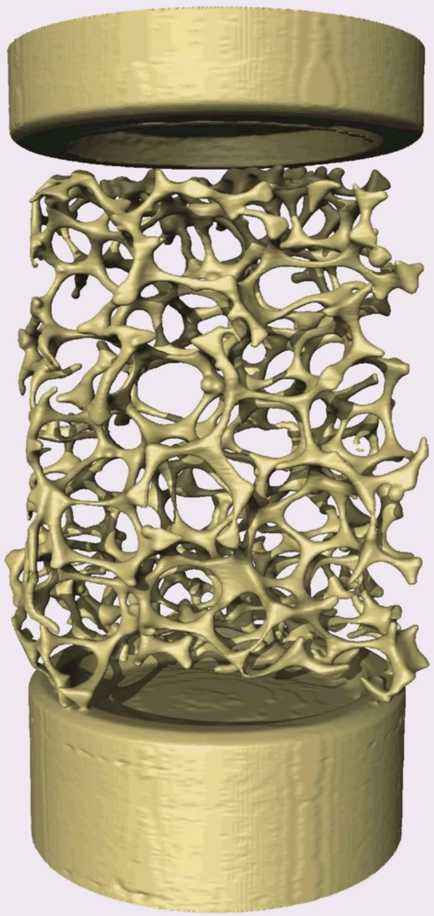


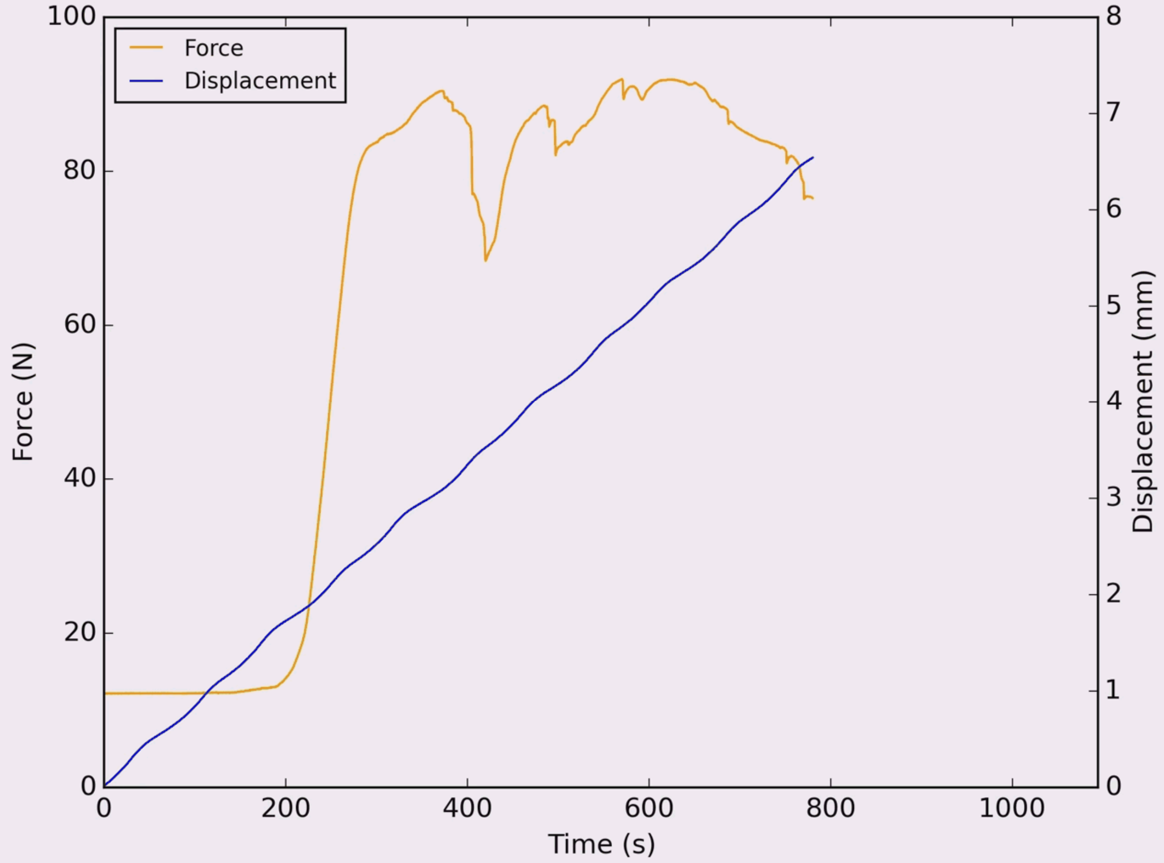
Table 1. Results of the quantitative image analysis of the considered VOIs.

	Additive Manufacturing	Conventional
Porosity [-]	47 %	89 %
Specific Surface Area [mm^{-1}]	4.87	7.45
Pore size: mean $\pm$ SD (min $\div$ max) [mm]	0.36 ± 0.02 ($0.27 \div 0.42$)	0.25 ± 0.08 ($0.03 \div 0.52$)
Throat size: mean $\pm$ SD (min $\div$ max) [mm]	0.23 ± 0.06 ($0.10 \div 0.37$)	0.12 ± 0.06 ($0.02 \div 0.36$)
Connection density [mm^{-3}]	4.20	22.61
Coordination number: mean $\pm$ SD (max) [-]	3.8 ± 1.1 (9)	5.0 ± 3.5 (34)

Ref: Brun, F., et. al. (2013). *Journal of Instrumentation*, *8*, 1–6.

Quantitative Analysis





Ref: XRE Engineering, Van Loo Lab, Ghent, Belgium

XPCI to Validate & Verify 3D Printed Parts

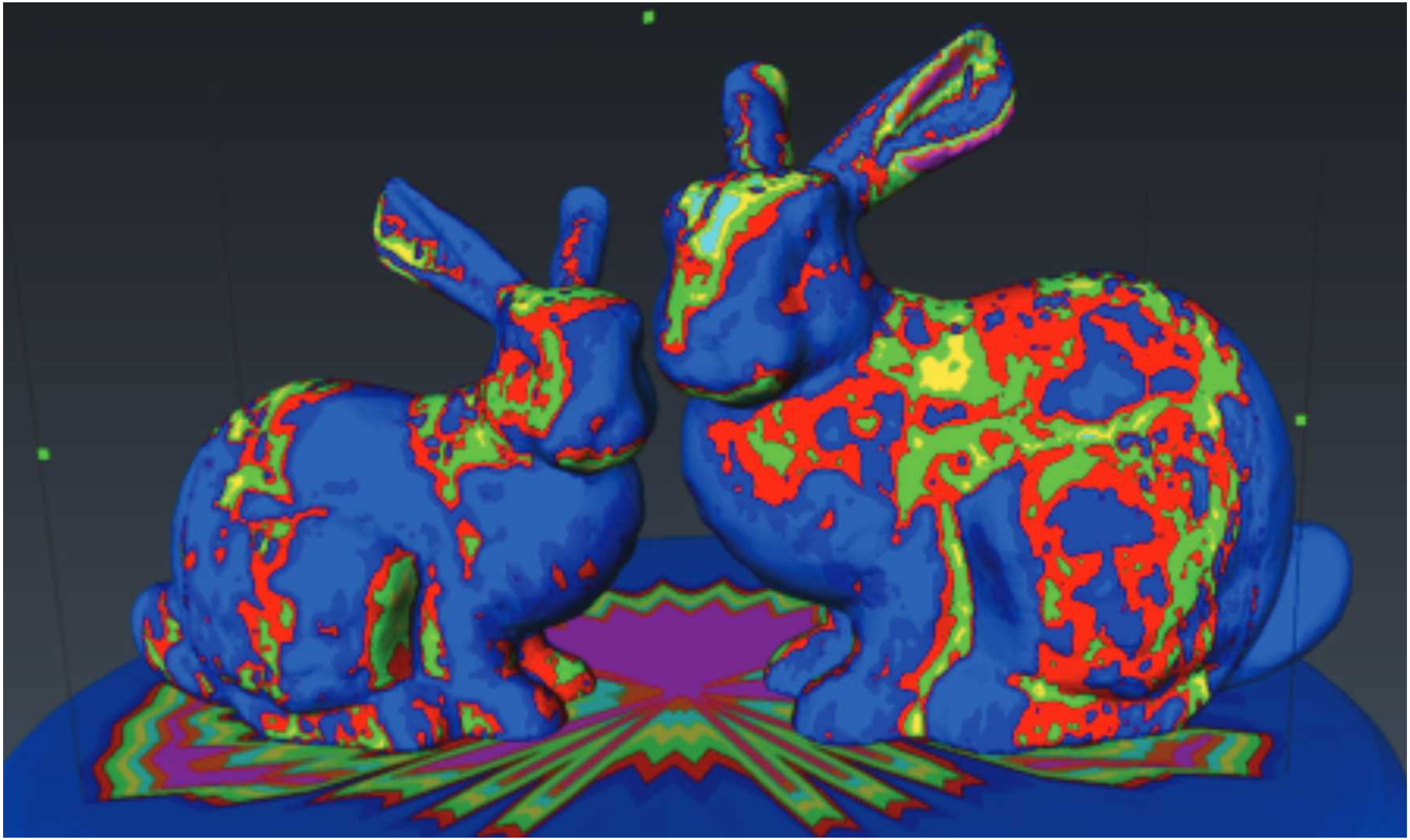
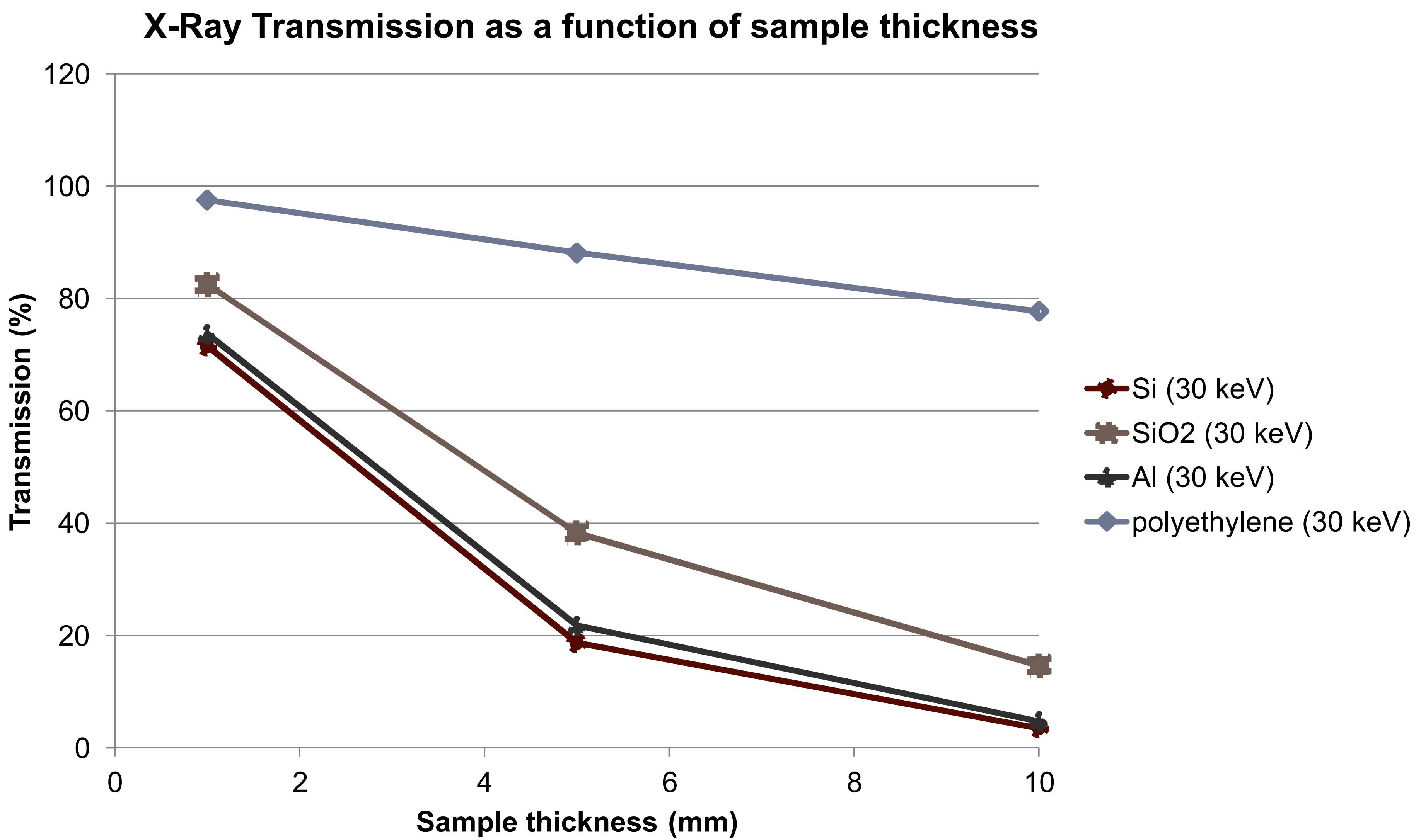
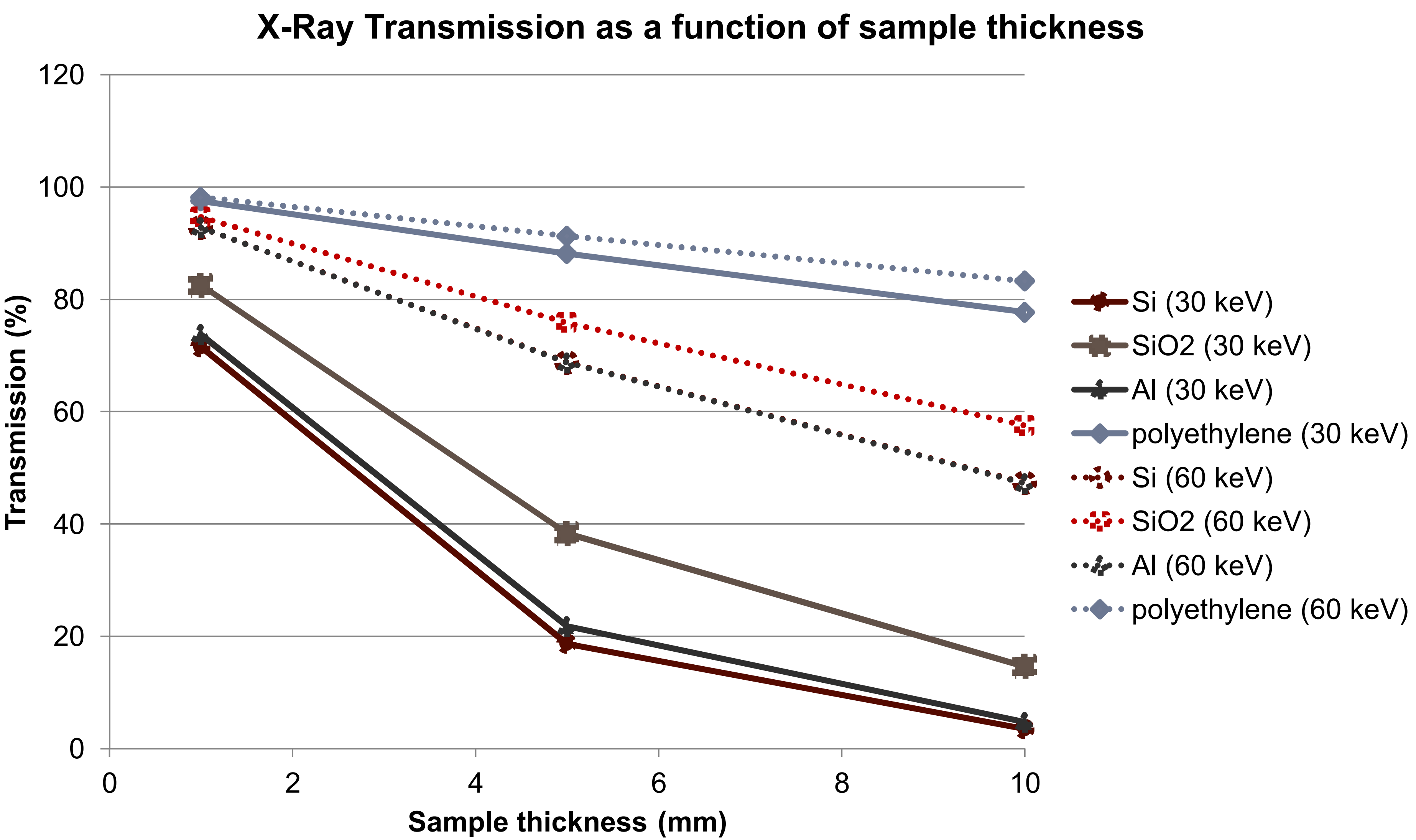


Figure from Butler lab, LSU-CAMD

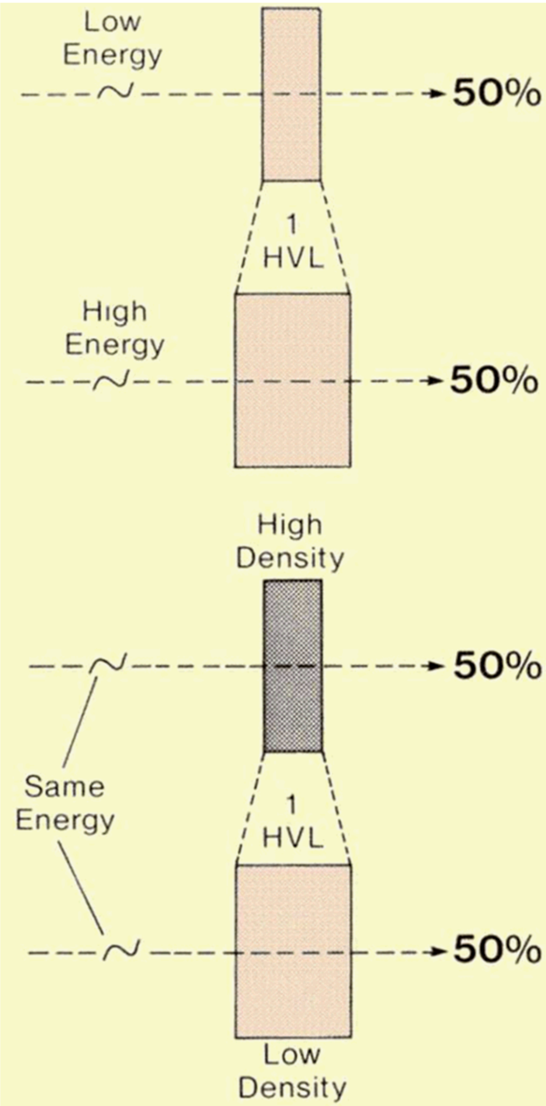
Material Examples

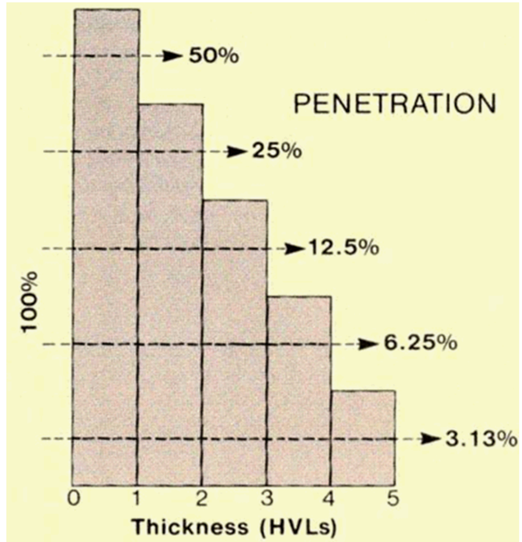


Effect of Increasing X-ray Energy



Representative Half Value Layers





$$I = I_0 e^{-\mu x}$$

$$0.5 = 1.0 e^{-\mu x}$$

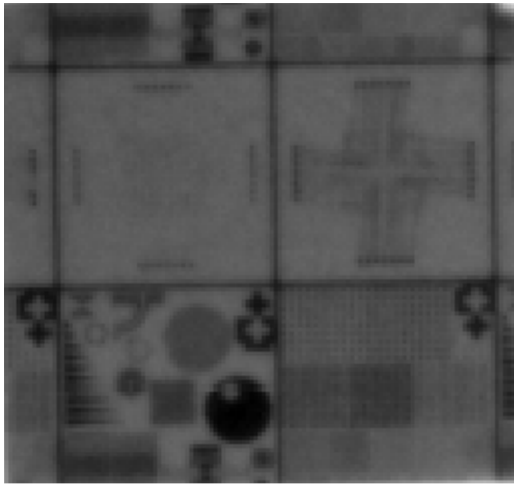
$$HVL = \frac{0.693}{\mu}$$

	HVL (mm)	
	30 keV	**60 keV**
Polyethylene	27.54	37.83
Water	18.45	33.66
Mylar	16.69	26.88
Teflon	7.65	16.38
Borosilicate	3.89	12.86
Concrete	3.14	11.33
Bone	2.71	11.47
Aluminum	2.28	9.24
Silicon	2.07	9.27
304L steel	0.11	0.73
CdTe	0.05	0.17
Lead Glass	0.05	0.29

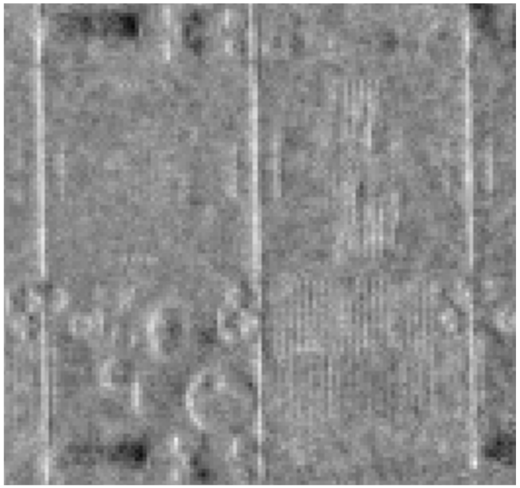
HVL cartoons from: http://www.sprawls.org/ppmi2/RADPEN/

Inspection Of Commercial Components

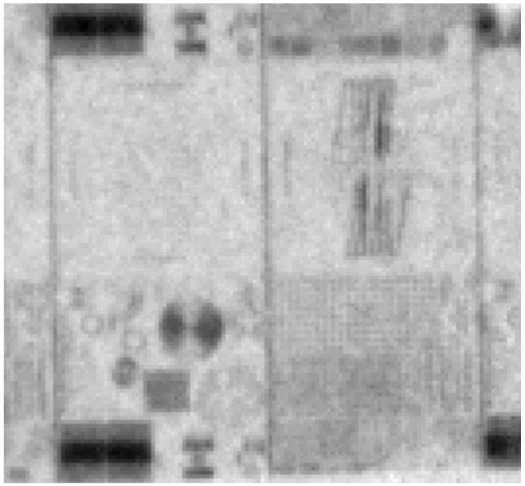
- Critical to assuring the functionality and security of integrated circuits (ICs)
  - "Slice and dice" inspection
  - Randomly selected samples
  - Labor intensive
  - Limited imaging depth
  - Complicated sample preparation
  - Limited in materials that can be inspected
- XPCI: non-destructive imaging of internal composition
  - 1000x more sensitive than x-ray absorption imaging for low-Z materials
  - Differences between ICs
    - Cracks or intentional/unintentional addition and deletion of materials



Absorption



Phase Contrast

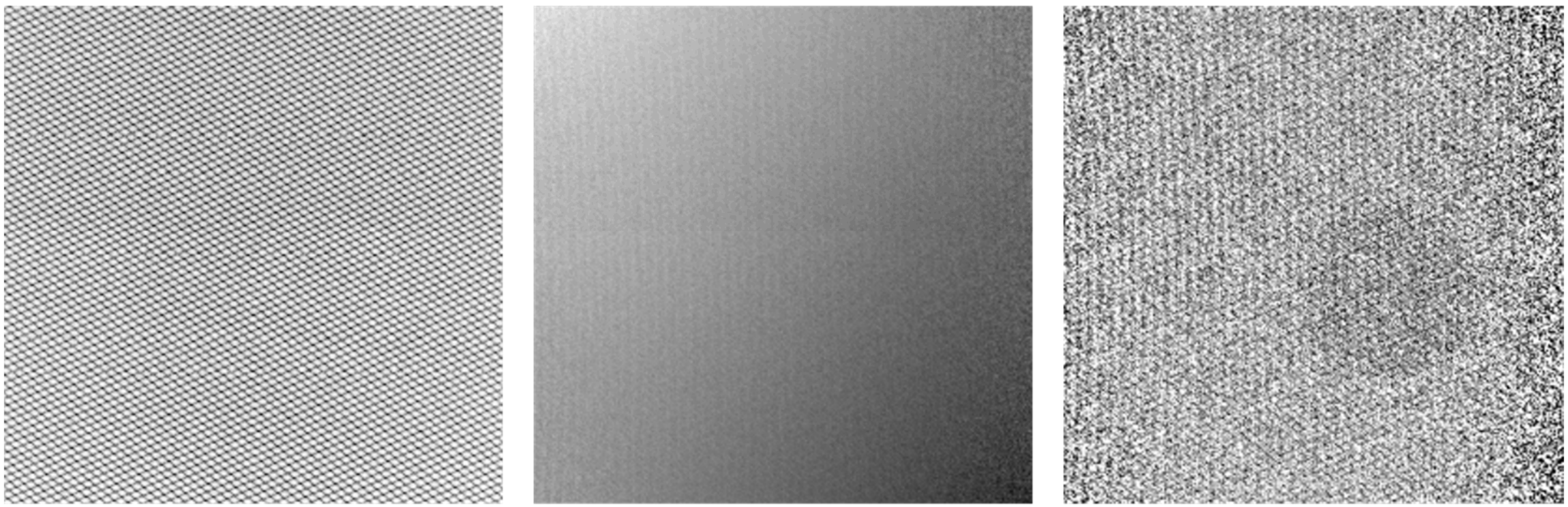


Dark Field

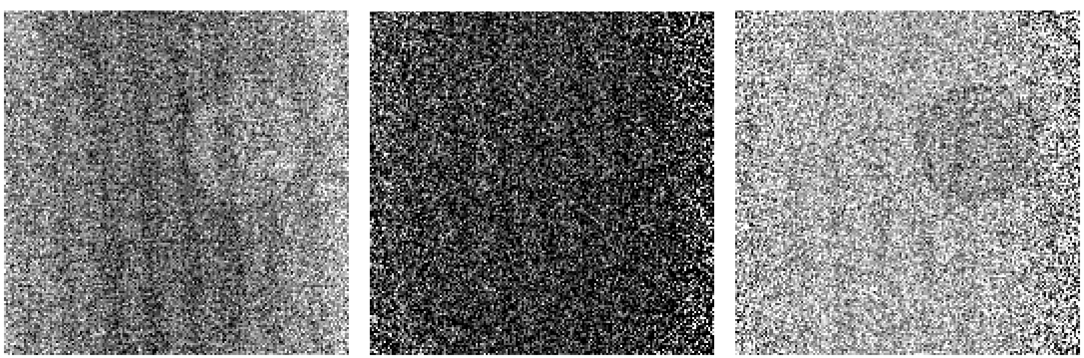
Grafoil in Aircraft Laminate

8 Ply laminate, copper mesh side, single 8-step sequence GF

Transmission | Differential Phase | Dark Field



Transmission | Differential Phase | Dark Field



8 Ply laminate
NO copper mesh side
single 8-step sequence

STATUS AT SANDIA-NM

Laboratory Based System at Sandia

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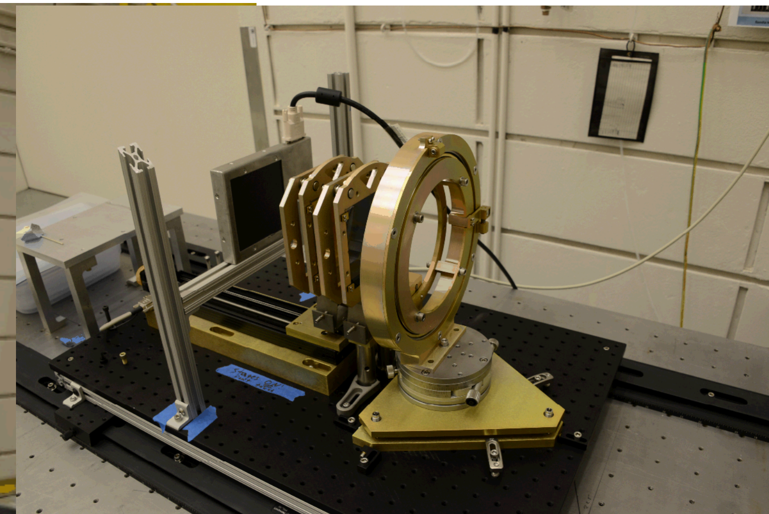
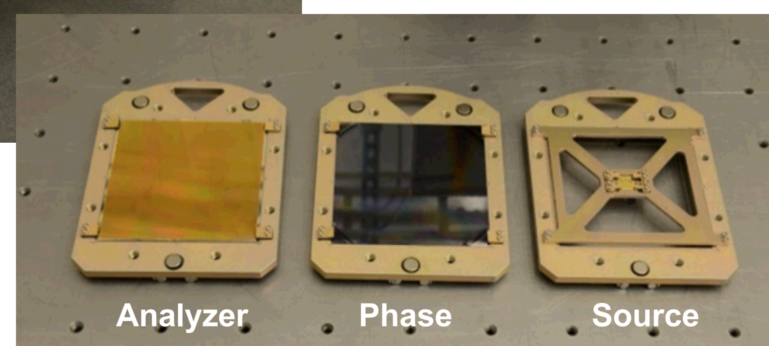
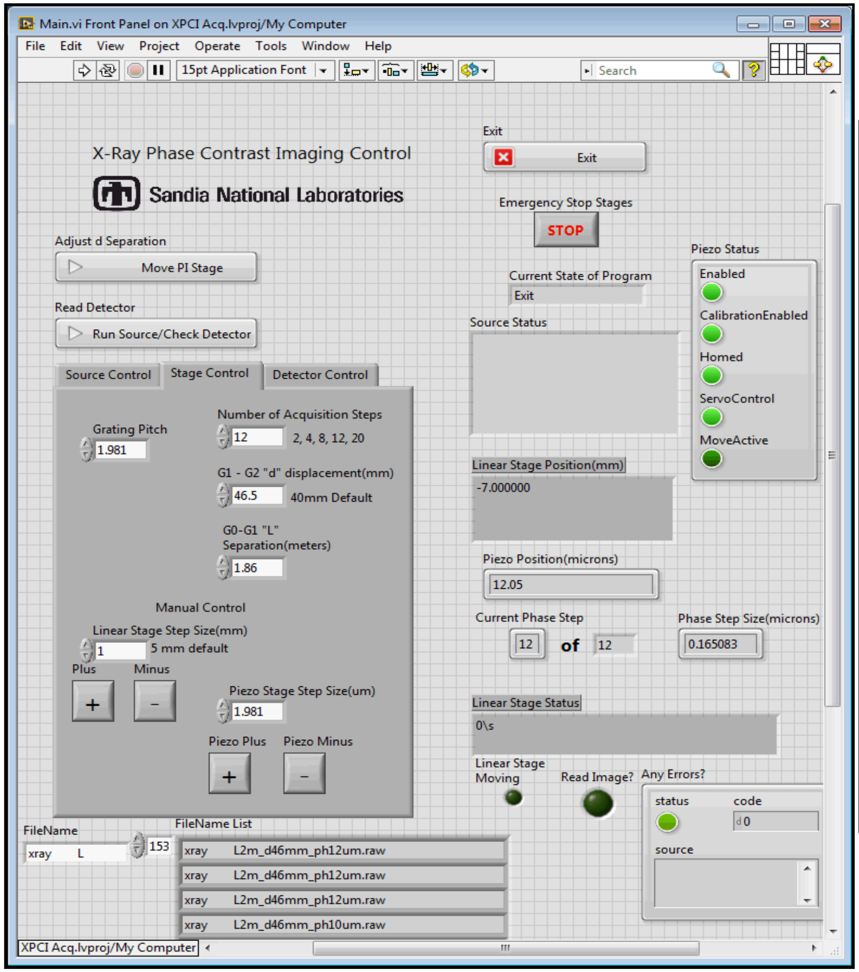
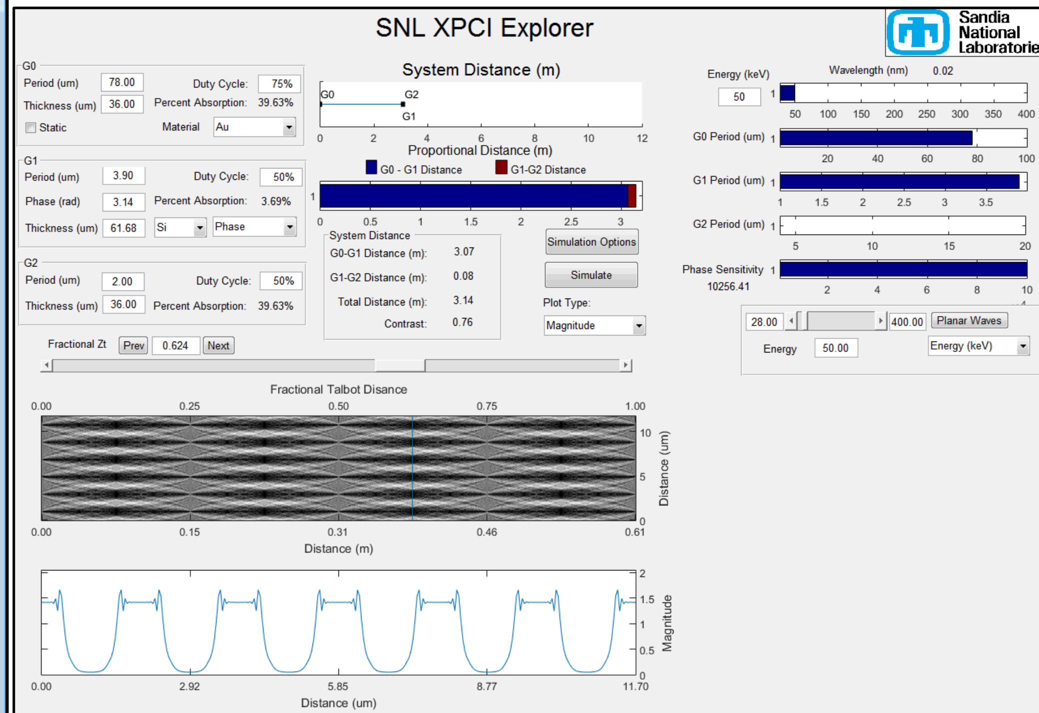






Main.vi Front Panel on XPCI Acq.lvproj/My Computer
File Edit View Project Operate Tools Window Help
15pt Application Font
X-Ray Phase Contrast Imaging Control
Sandia National Laboratories
Exit
Emergency Stop Stages
STOP
Adjust d Separation
Move PI Stage
Read Detector
Run Source/Check Detector
Current State of Program
Exit
Source Status
Piezo Status
Enabled
CalibrationEnabled
Homed
ServoControl
MoveActive
Source Control
Stage Control
Detector Control
Grating Pitch
1.981
Number of Acquisition Steps
12
2, 4, 8, 12, 20
G1 - G2 "d" displacement(mm)
46.5
40mm Default
G0-G1 "L"
Separation(meters)
1.86
Manual Control
Linear Stage Step Size(mm)
1
5 mm default
Plus
Minus
Piezo Stage Step Size(um)
1.981
Piezo Plus
Piezo Minus
Linear Stage Position(mm)
-7.000000
Piezo Position(microns)
12.05
Current Phase Step
12 of 12
Phase Step Size(microns)
0.165083
Linear Stage Status
0\s
Linear Stage Moving
Read Image?
Any Errors?
status
code
0
source
FileName
xray L
FileName List
153
xray L2m_d46mm_ph12um.raw
xray L2m_d46mm_ph12um.raw
xray L2m_d46mm_ph12um.raw
xray L2m_d46mm_ph10um.raw
XPCI Acq.lvproj/My Computer



SNL XPCI Explorer
Sandia National Laboratories
G0
Period (um) 78.00
Duty Cycle: 75%
Thickness (um) 36.00
Percent Absorption: 39.63%
Static
Material Au
G1
Period (um) 3.90
Duty Cycle: 50%
Phase (rad) 3.14
Percent Absorption: 3.69%
Thickness (um) 61.68
Si
Phase
G2
Period (um) 2.00
Duty Cycle: 50%
Thickness (um) 36.00
Percent Absorption: 39.63%
System Distance (m)
Proportional Distance (m)
G0 - G1 Distance
G1-G2 Distance
System Distance
G0-G1 Distance (m): 3.07
G1-G2 Distance (m): 0.08
Total Distance (m): 3.14
Contrast: 0.76
Simulation Options
Simulate
Plot Type:
Magnitude
Energy (keV)
50
Wavelength (nm) 0.02
G0 Period (um)
G1 Period (um)
G2 Period (um)
Phase Sensitivity
10256.41
28.00
400.00
Planar Waves
Energy 50.00
Energy (keV)
Fractional Zt
Prev 0.624 Next
Fractional Talbot Distance
Distance (m)
Distance (um)
Magnitude

Growth Opportunities

Sandia National Laboratories

Applications

Additive manuf

NW (N

Material addition or deletion

Voids, cracks

Defect detection

Material interfaces

…ics

Joint porosity

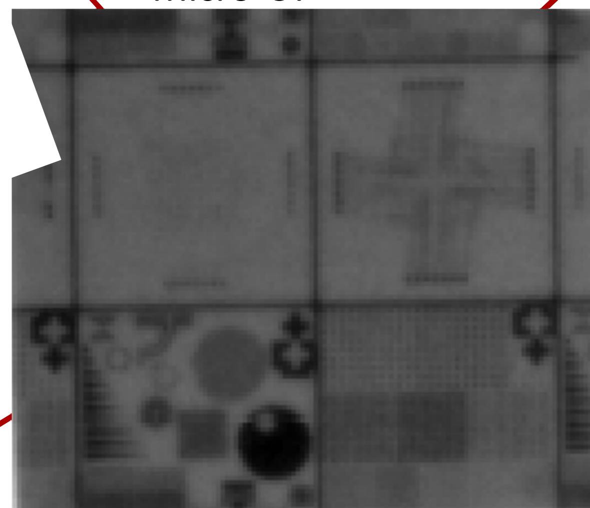
Explosives/chemical inspection

Gratings
- Matched set
- Higher energy
- Phase-only
- Process development
- Micro-CT

System Optimization

Source
- Higher flux
- Narrower band

Detector
- Smaller pixels
- CCD
- Higher efficiency
- Faster



Higher energy
- Grating fabrication
- Expands sample space

Visualization of internal structure in 3-D
Add 4th dimension: time
Sample rotation: known pattern

3-D Tomography

Information Theory
- i.d. complementary data
- Compressed sensing
- Information extraction

Advanced Algorithms
- Acquisition
- Reconstruction
- Phase Unwrapping

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