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Structural Instruments
2014-2020

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"Investing in Sustainable Development"

Extreme Light Infrastructure-Nuclear Physics
(ELI-NP) - Phase II

Phase Contrast X-ray Imaging with High Power Lasers

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ELI-NP, Romania

Johns Hopkins University, USA

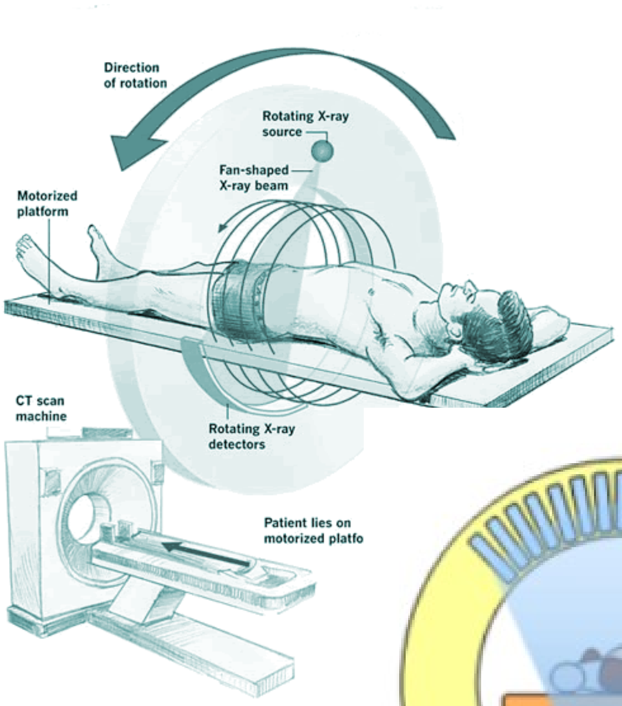
14 December 2019

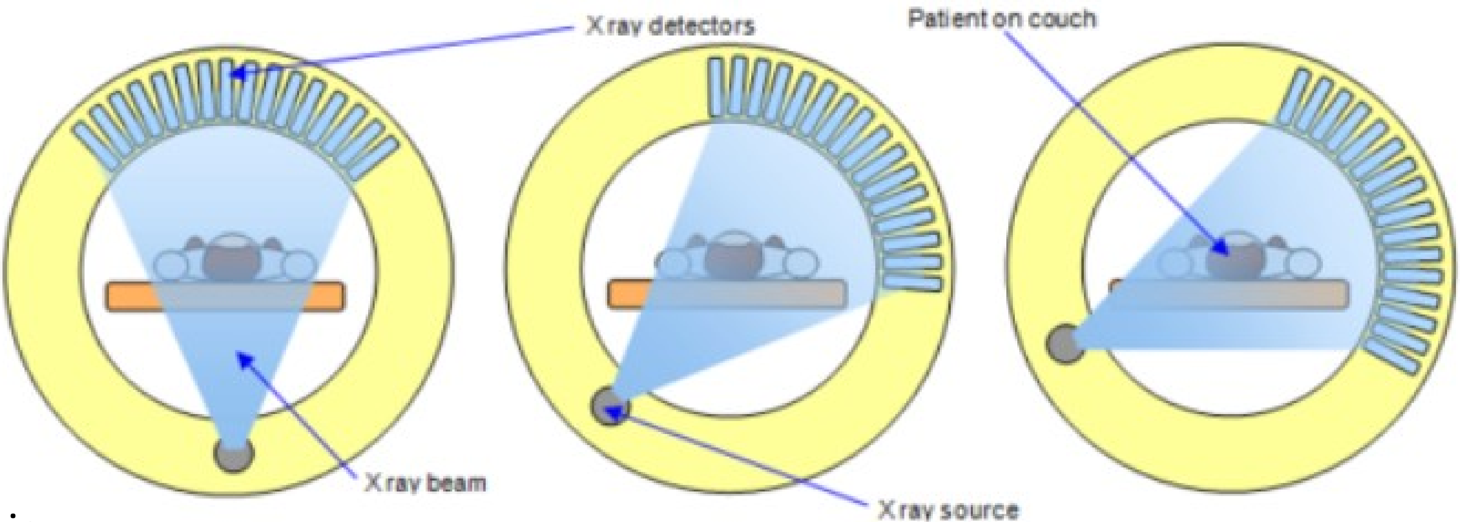
Outline

- ☐ Principles of CT and MRI
- ☐ Basics of phase contrast X-ray imaging (PXI)
- ☐ Main PXI techniques
- ☐ Main applications
- ☐ Potential of high-power lasers for PXI
- ☐ Plans at ELI-NP

How does a Computer Tomography works?

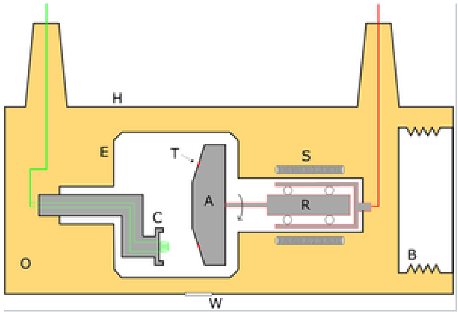
- Key features:
    - Ionizing radiation
    - X –ray attenuation
- 10-20 mGy
- X - ray CCD detector, image processing





CT scanner with the X ray source and detectors shown in three positions

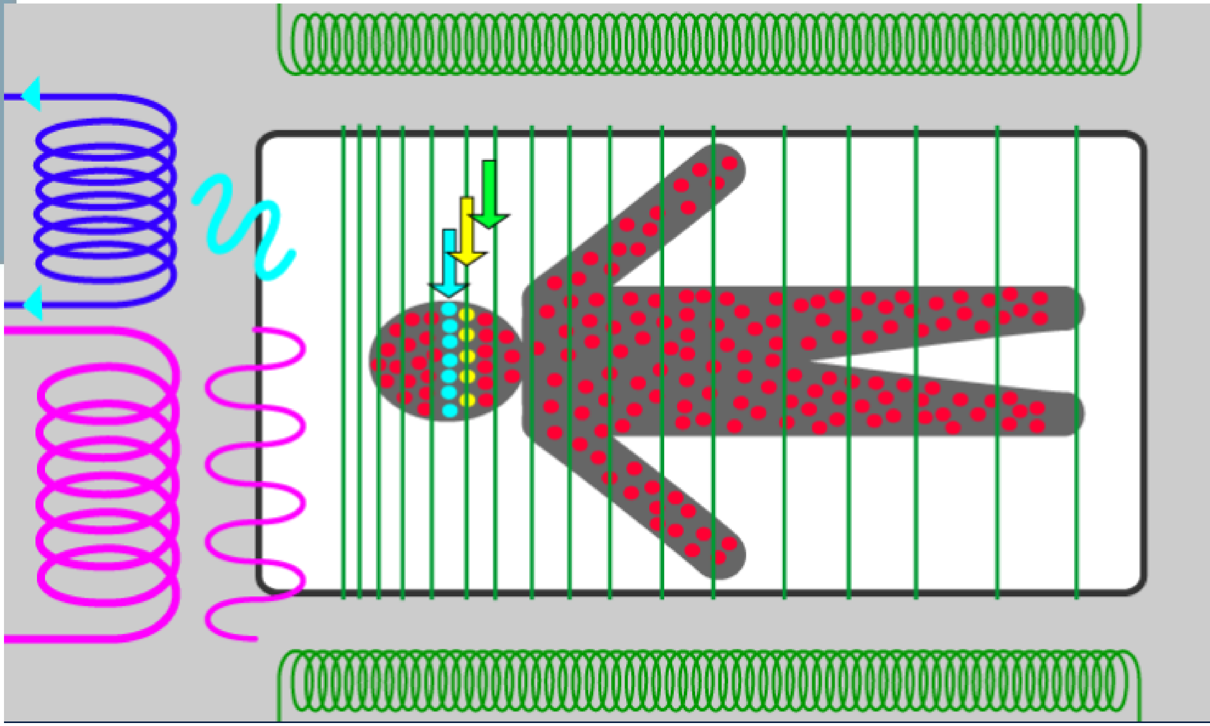
X ray tube schematic



[Wikipedia]

How does an MRI work?

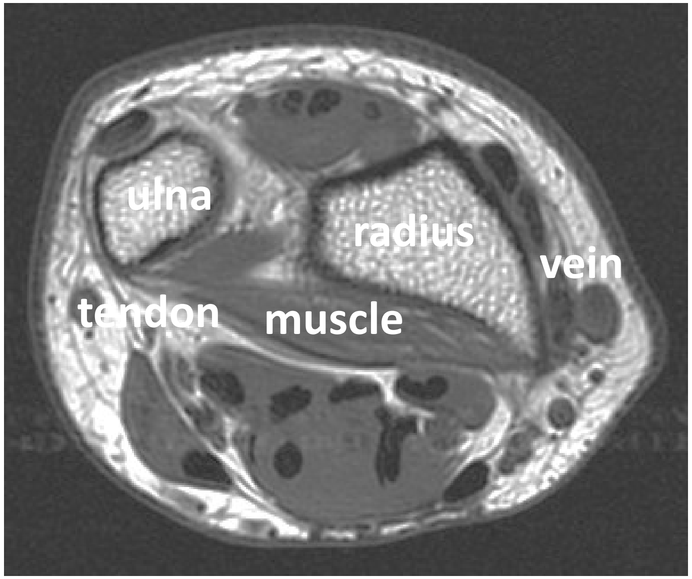
- Key features:
    - Non-Ionizing, radio waves
    - Magnet and RF based
- Typically 1-3 T superconducting magnets
- Sophisticated signal processing



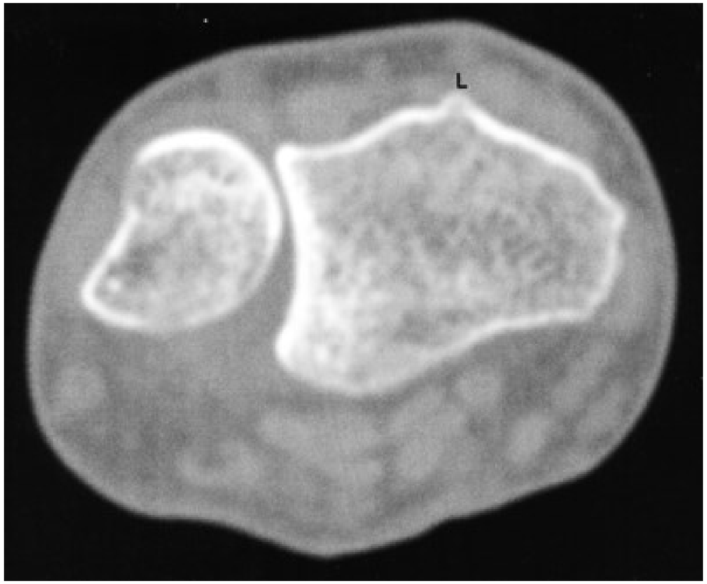
[www]

Low-Z matter poorly discriminated in conventional attenuation based X-ray imaging

MRI

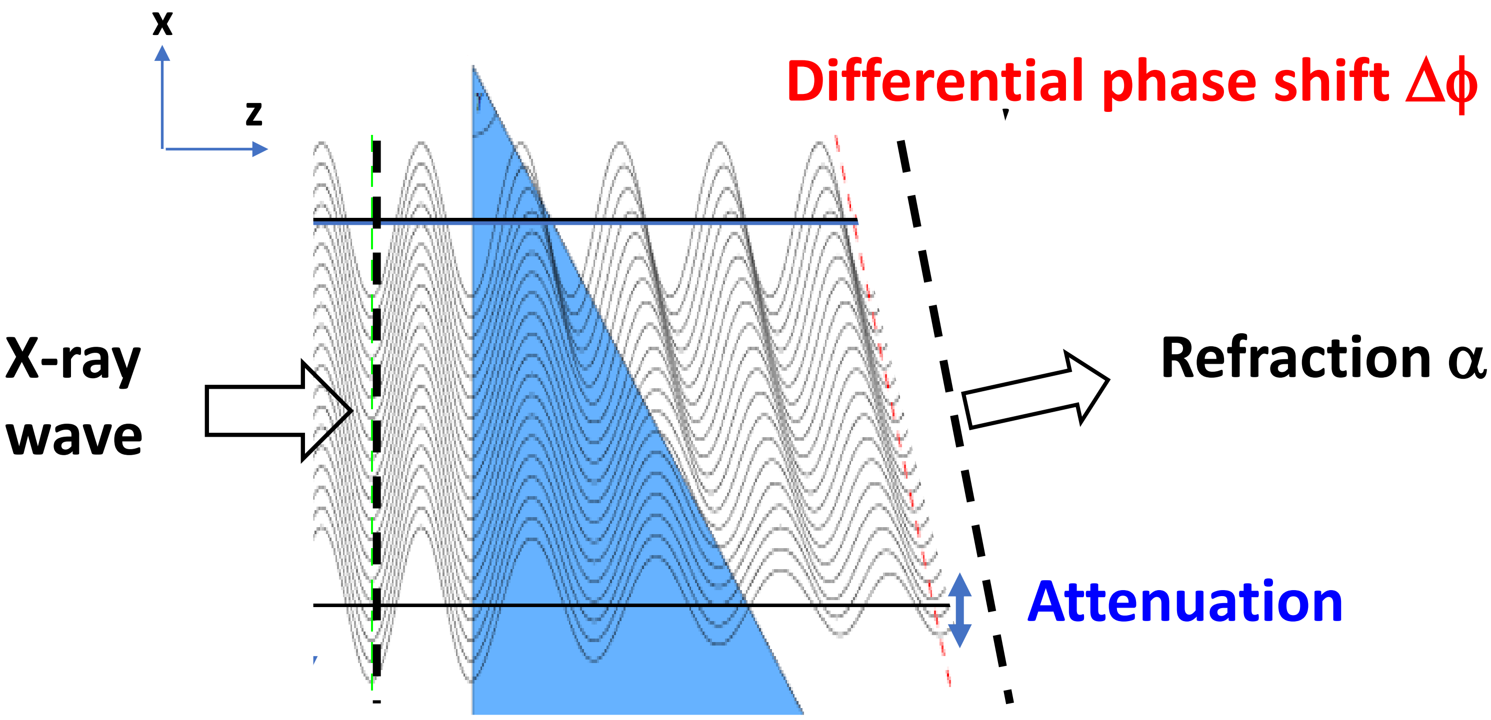


X-ray CT



- X-ray imaging much cheaper, simpler and faster than MRI
- Soft tissue $\Delta\mu < 0.03\ \mathrm{cm}^{-1}$ (3.5 cm for 10% intensity difference)
- Poor visibility, high radiation dose, limited spatial resolution
- Stronger interaction needed for low dose, high res X-ray imaging

X-rays waves both attenuated and phase shifted in matter



X-ray wave

Differential phase shift Δϕ

Refraction α

Attenuation

n=1-δ+iβ

Phase change

Amplitude change

$$\Psi(\mathbf{r}) = \mathbf{E}_0\, e^{in(\mathbf{k}\cdot\mathbf{r})} = \mathbf{E}_0\, e^{i(1-\delta+i\beta)(\mathbf{k}\cdot\mathbf{r})} = \mathbf{E}_0\, e^{i(1-\delta)(\mathbf{k}\cdot\mathbf{r})}\; e^{-\beta(\mathbf{k}\cdot\mathbf{r})}$$

$$\Delta\phi(x) = \frac{2\pi}{\lambda}\int \delta(x,z)\,dz, \qquad \alpha(x) = \frac{\lambda}{2\pi}\frac{\partial\phi}{\partial x} = \frac{\partial}{\partial x}\int \delta(x,z)\,\mathrm{d}z$$

Valid at very small scattering angles

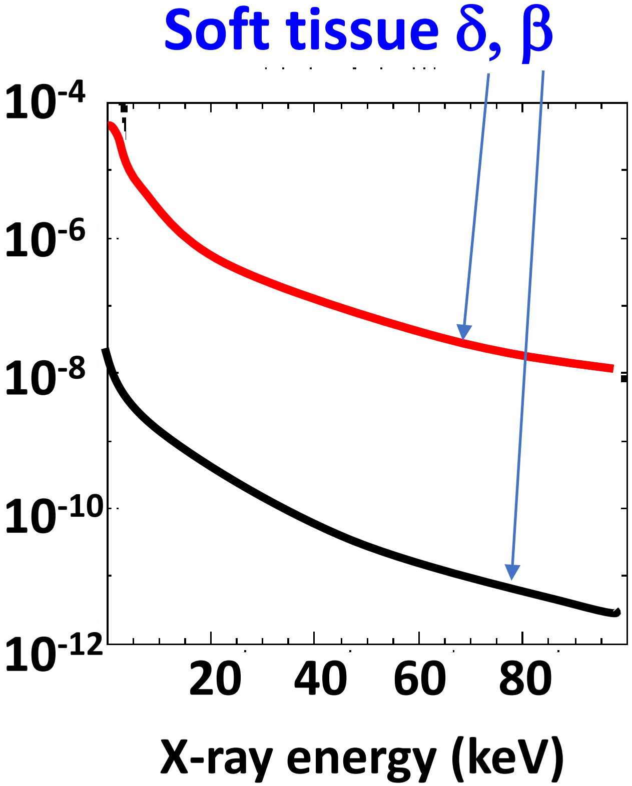
Phase shift coefficient much larger than attenuation one

Attenuation coefficient

$$\mu = 4\pi\beta/\lambda$$

Phase shift coefficient

$$\phi = 2\pi\delta/\lambda$$



$$\frac{2\pi\rho_a Z r_0}{k^2}$$

$$0.01[\mathrm{barn}]\rho_a k_0^3 \left(\frac{Z}{k}\right)^4$$

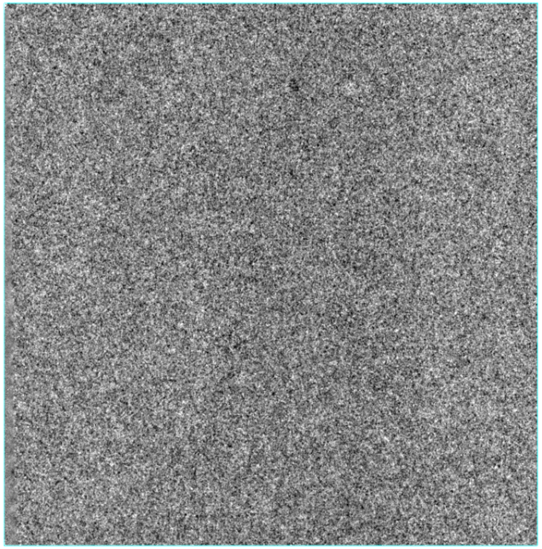
$k_0 = 2\pi/[\lambda = 1\ \text{A}]$

- **Soft tissue $\Delta\phi \approx 20\ \text{cm}^{-1} \approx 700 \times \Delta\mu$ (50 μm for π phase shift)**
- **Φ decreases much slower with X-ray energy than μ**
- **Works with spectrally broad X-ray sources such as medical tubes**

Experiment confirms PXI dramatically increases tissue visibility

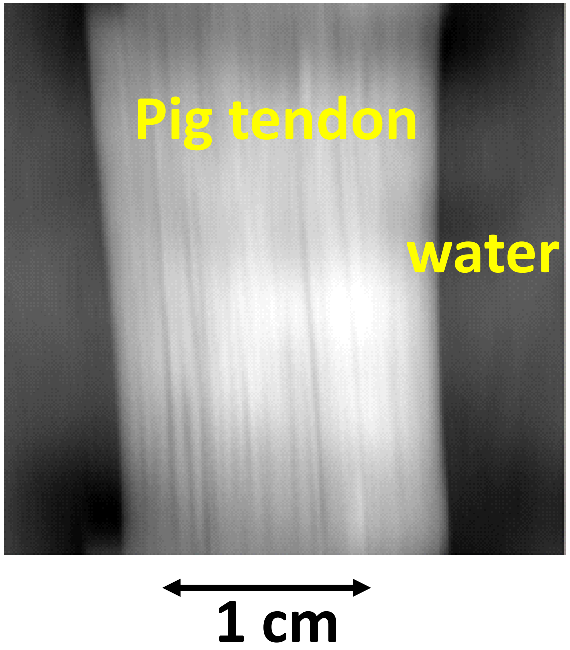
Conventional vs. phase radiography of soft tissue at <E>= 40 keV, 2 mGy dose, Talbot-Lau method

Conventional



PXI

$$\Delta\phi(x) = \frac{2\pi}{\lambda}\int \delta(x,z)\,dz,$$

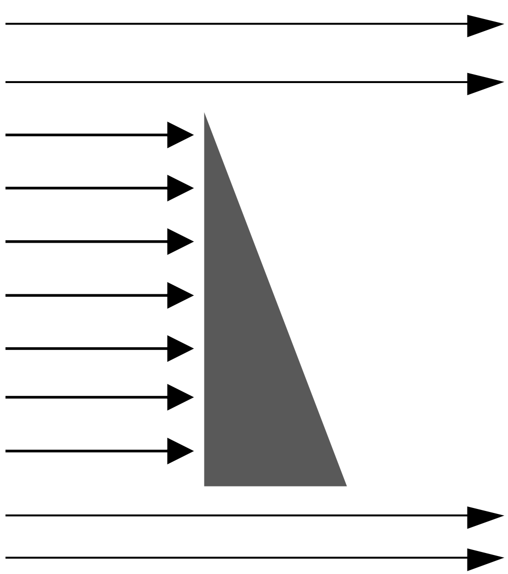


Stutman et al 2014

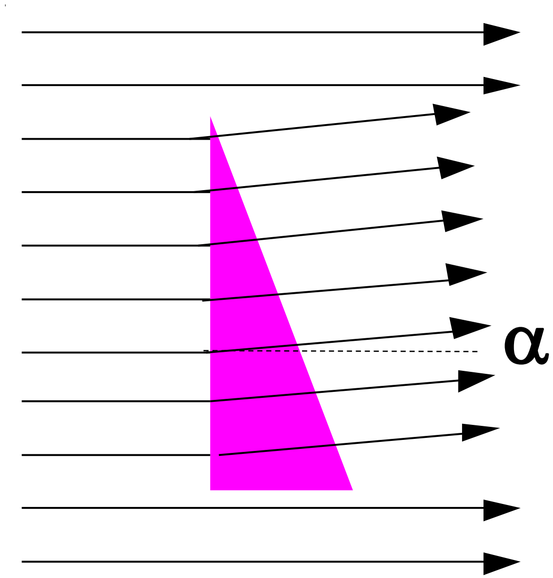
- **PXI could make medical CT better than MRI**

PXI also offers multiple contrast mechanisms

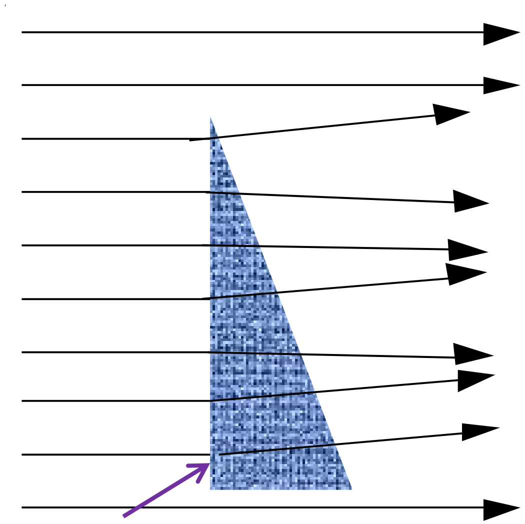
Attenuation



Refraction

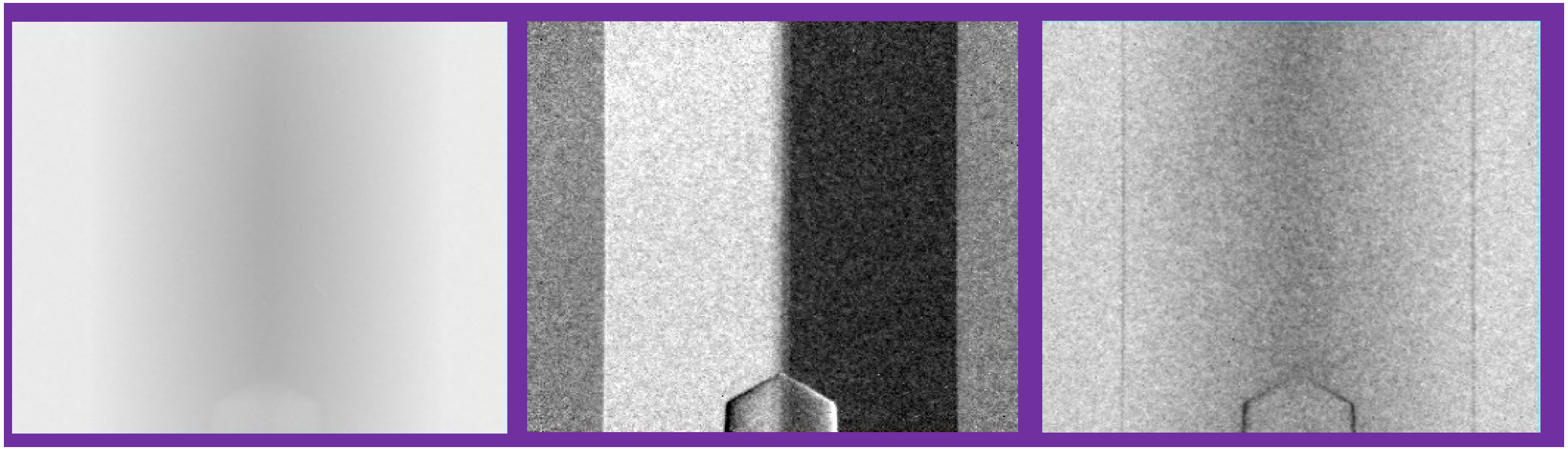


Ultra small angle scatter

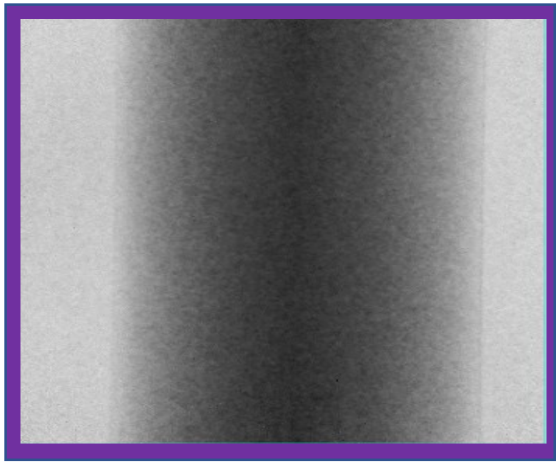


Density gradients
on µm scale (micro
structure)

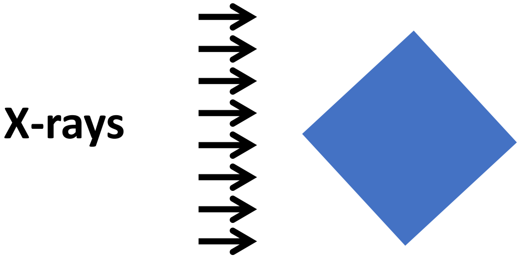
Ultra small angle scatter (“dark field”) PXI


Attenuation
Refraction
Scatter – clear acrylic

Boron micro particle doped acrylic



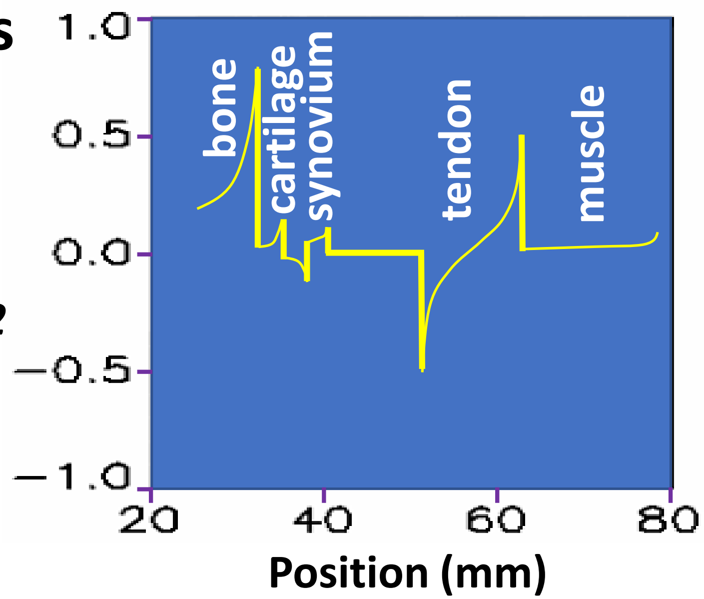
10x10 mm acrylic prism
33 keV mean energy



Scatter imaging of breast calcifications, NDT of cracks, porosity in low-Z materials

X-ray refraction angles are however very small

Refraction angles in human knee phantom at 50 keV

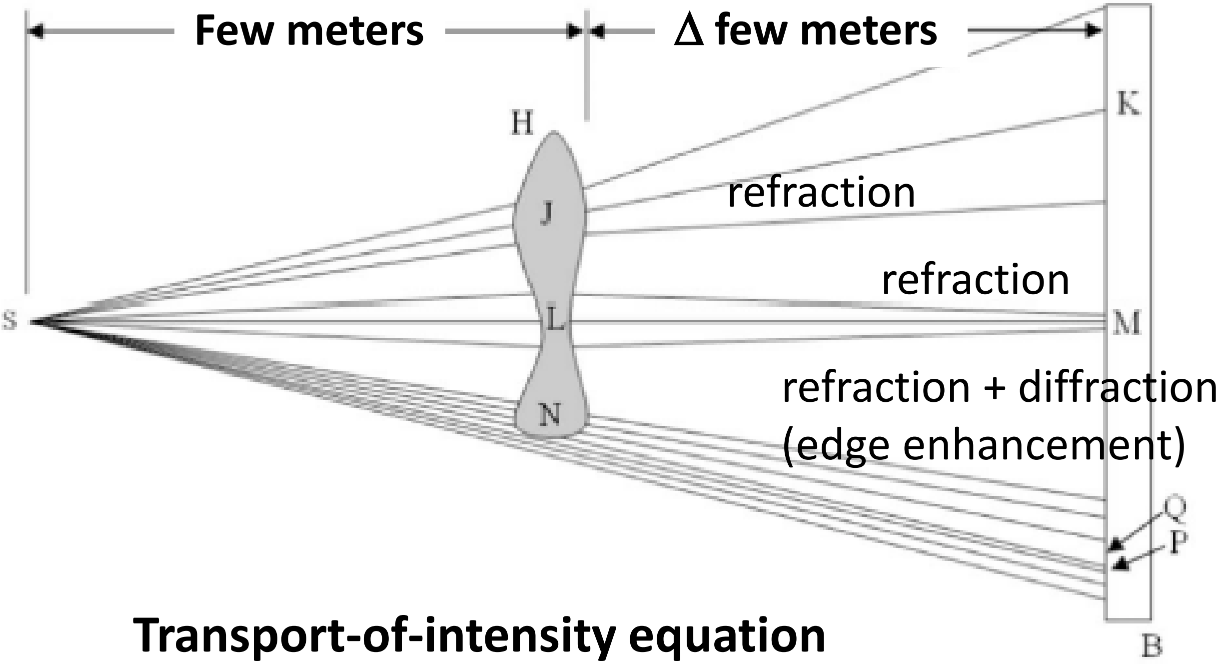


Stutman et al 2012

$$\alpha(x) = \frac{\lambda}{2\pi}\frac{\partial \phi}{\partial x} = \frac{\partial}{\partial x}\int \overset{\cong 10^{-7}}{\delta(x,z)}\,\mathrm{d}z$$

- **Longer X-ray propagation distances than in conventional imaging**
- **X-ray optics generally needed for phase-intensity conversion**
- **Spatially quasi-coherent (µm spot) X-ray source also necessary**

PXI methods: Propagation phase contrast



Few meters

Δ few meters

refraction

refraction

refraction + diffraction
(edge enhancement)

Paganin 2019

Transport-of-intensity equation

thickness

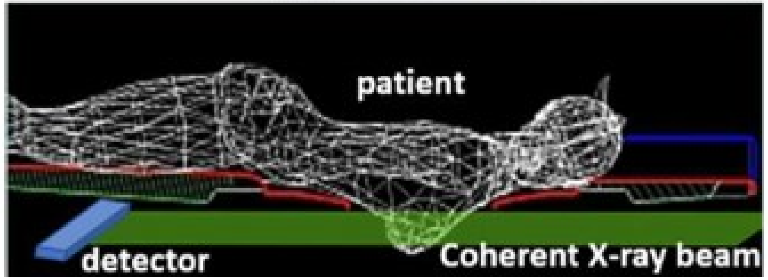
Intensity at detector

$$T(x,y) = -\frac{1}{\mu}\log_e\left(\mathcal{F}^{-1}\left\{\frac{\mathcal{F}\left[I(x,y,z=\Delta)\right]/I_0}{1+(\delta\Delta/\mu)(k_x^2+k_y^2)}\right\}\right)$$

Fourier-space coordinates

- **Few meters object-detector distance for phase-intensity conversion**
- **Phase retrieval through transport-of-intensity equation (TIE)**
- **Typically done at synchrotrons (spatial coherence & brightness)**

Phase-contrast mammography station at ELETTRA synchrotron

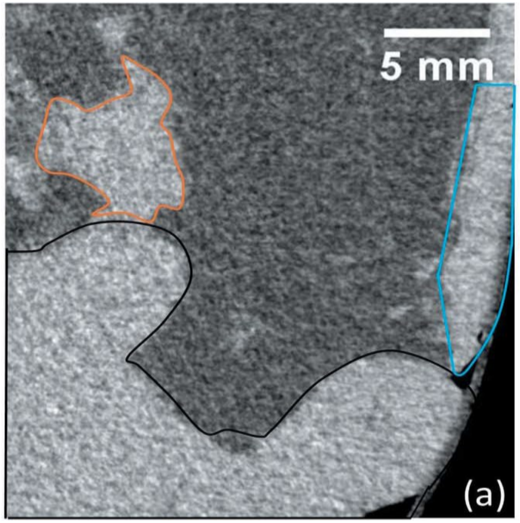


ELETTRA synchrotron

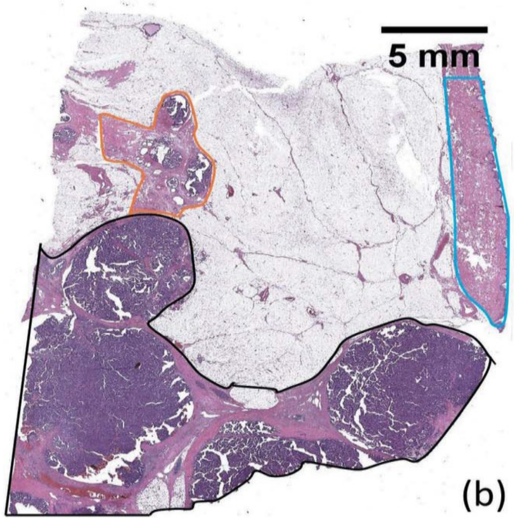
Strong improvement in breast tumor detection recently demonstrated at ELETTRA with propagation based PXI CT

Breast
tumor
1.6 m
propagation
distance
5 mGy dose

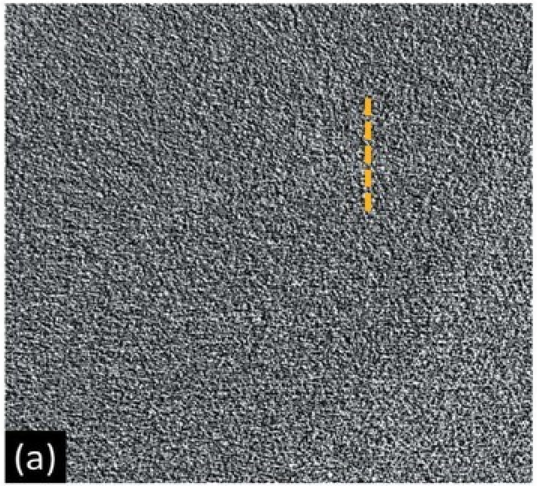
PXI-CT



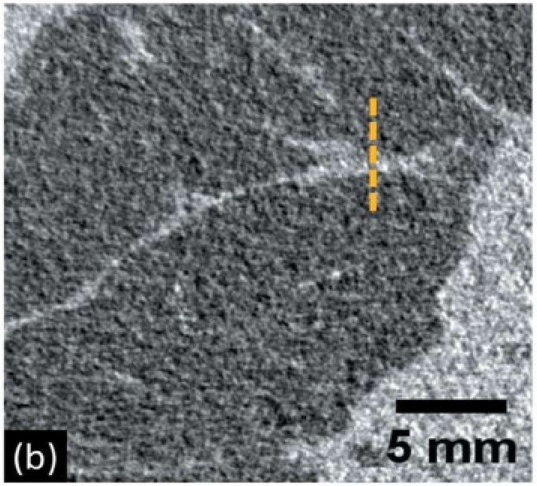
histology



Attenuation CT

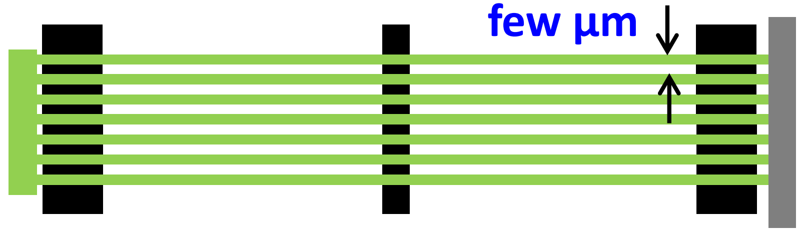


PXI-CT



Longo et al 2018

Grating interferometer (Talbot-Lau) PXI method



Source absorption grating (Au)

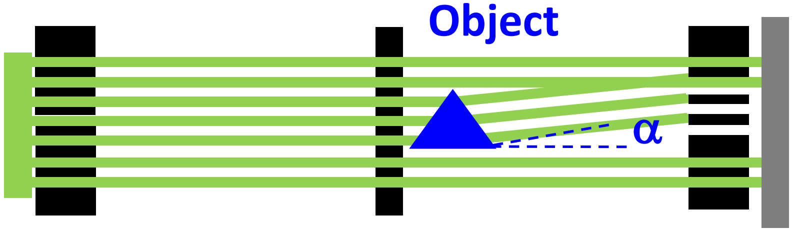
Beam splitter phase grating (Si)

Analyzer absorption grating (Au)

few µm

Incoherent X-ray source

detector pixel (~100 µm)

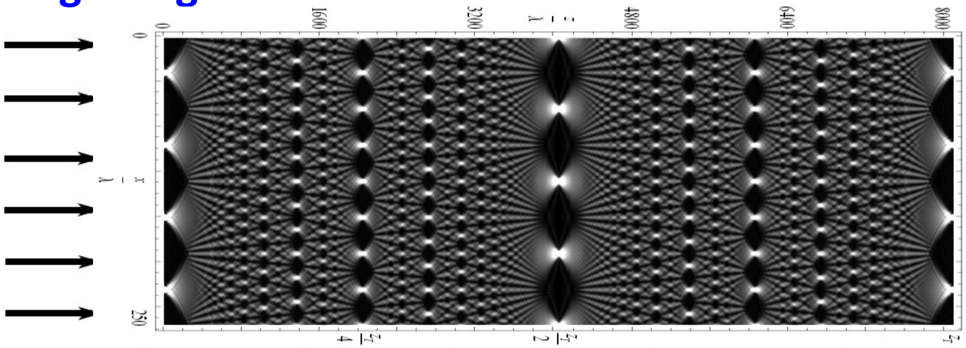


Object

Pfeiffer et al 2006

Momose et al 2006

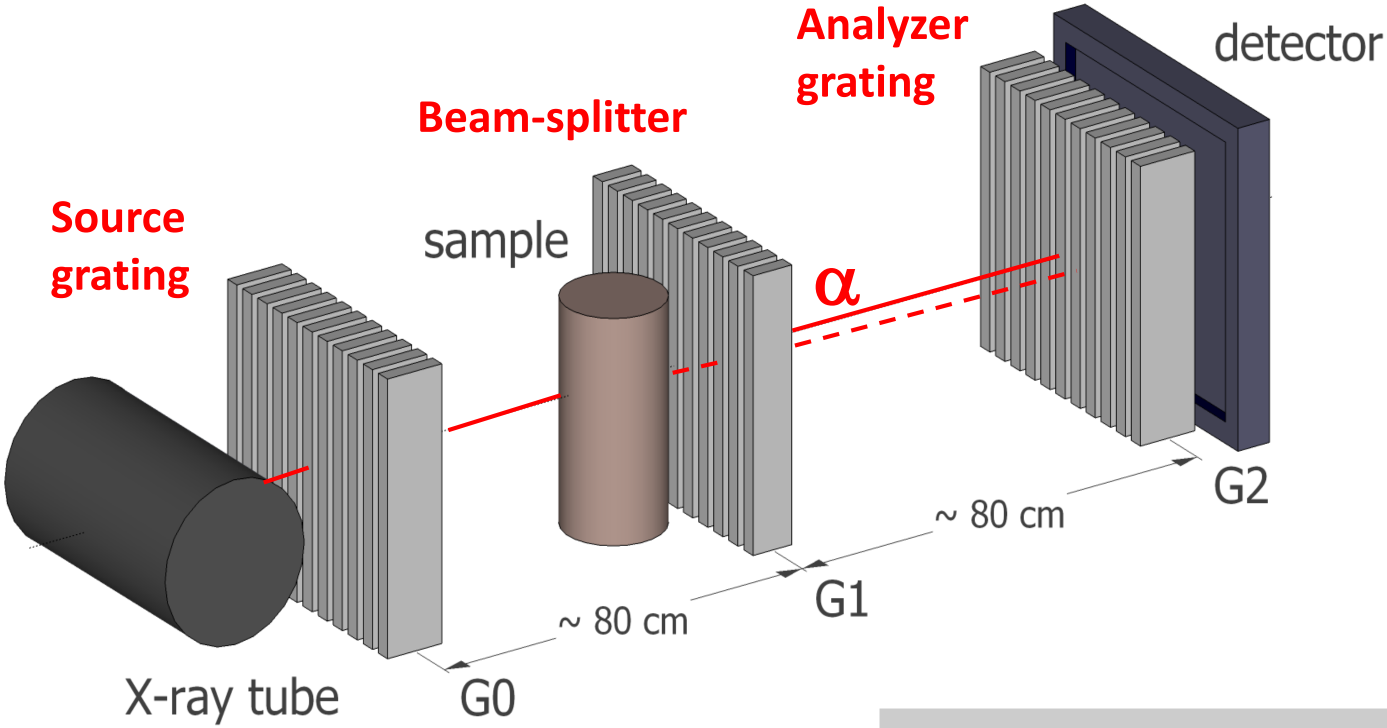
Talbot effect



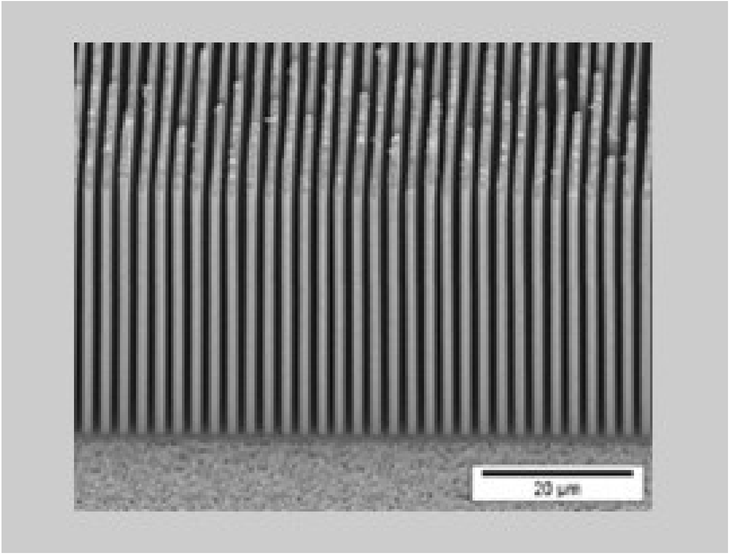
Beam-splitter grating

X-rays

D_T=m $g^2/8\lambda$, m=1,3… (order of the meter)



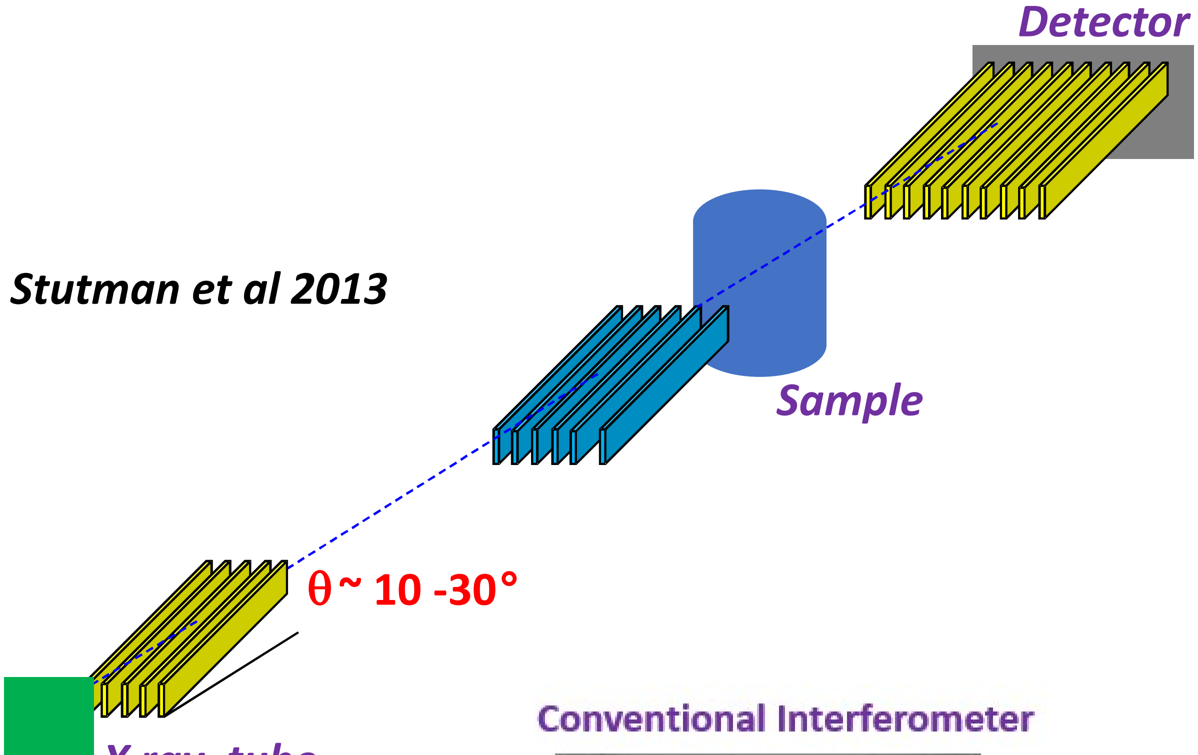
2.4 µm period, 50 µm deep
Au absorption grating
(MicroWorks Inc, Germany)



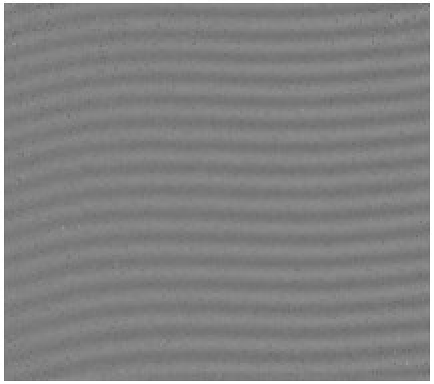
Works up to few tens of keV

Glancing angle interferometer (GAI) enables PXI up to 120 keV

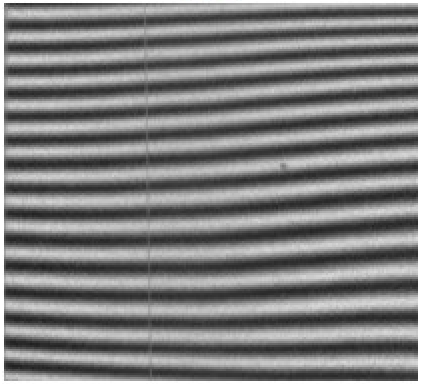
Stutman et al 2013



Conventional Interferometer

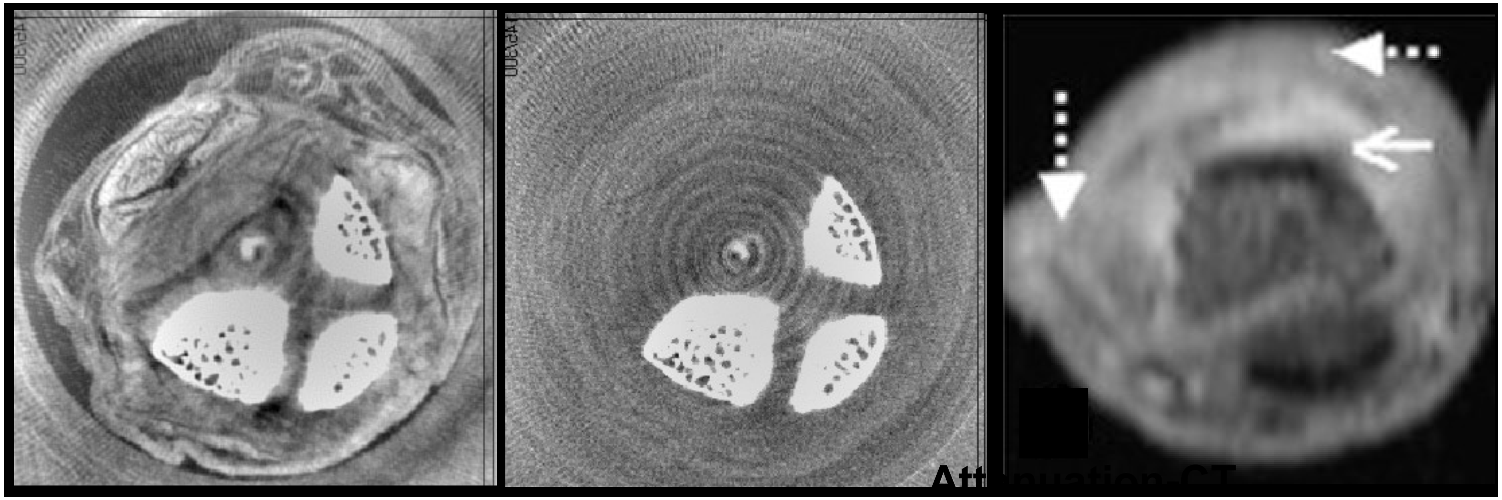


GAI

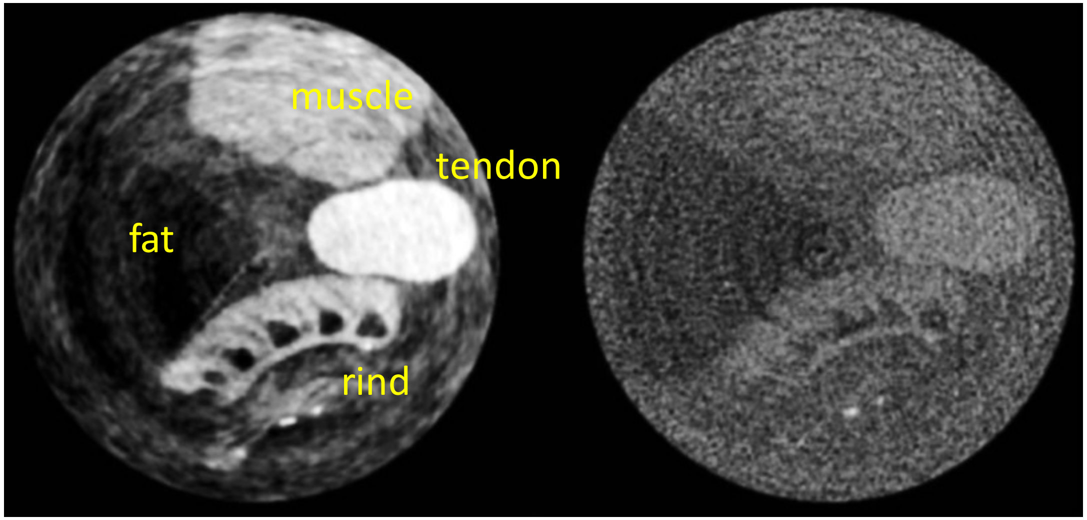


GAI enables PXI CT with clinically compatible energy and dose

80 kVp phase contrast CT of human finger joint


Refraction CT **Attenuation CT** **MRI**

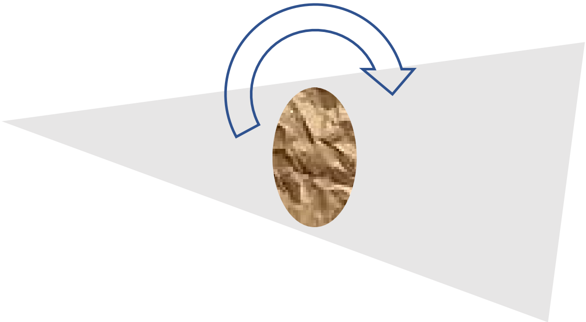
65 kVp phase contrast CT of soft tissues with clinically compatible dose


Refraction CT **Attenuation CT**

Stutman et al 2014

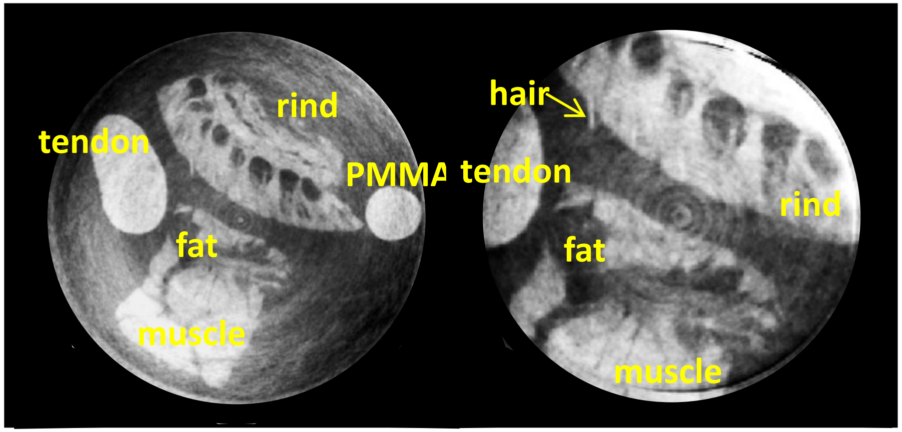
PXI has better tomographic inversion properties

Full field & full scan CT

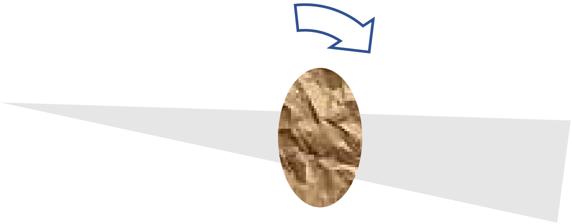


Full field PC-CT

ROI PC-CT



ROI & limited-angle CT



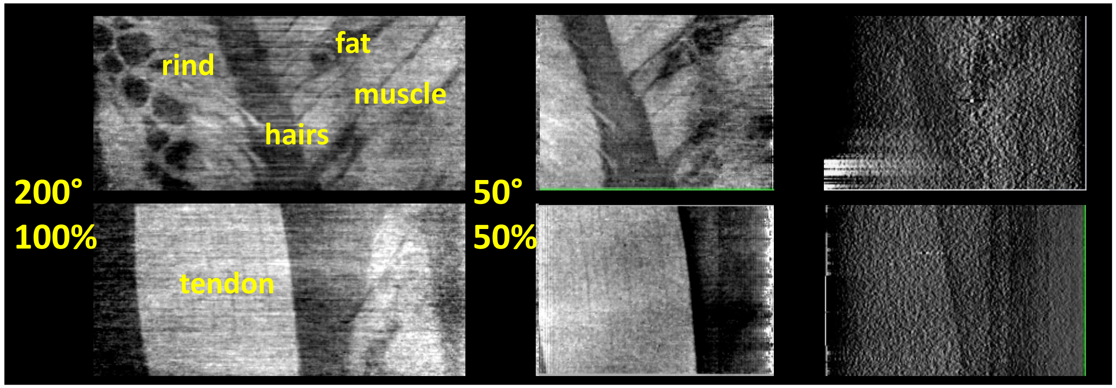
Full field & 200° scan

ROI & 50⁰ scan

PC-CT

PC-CT

Attenuation-CT

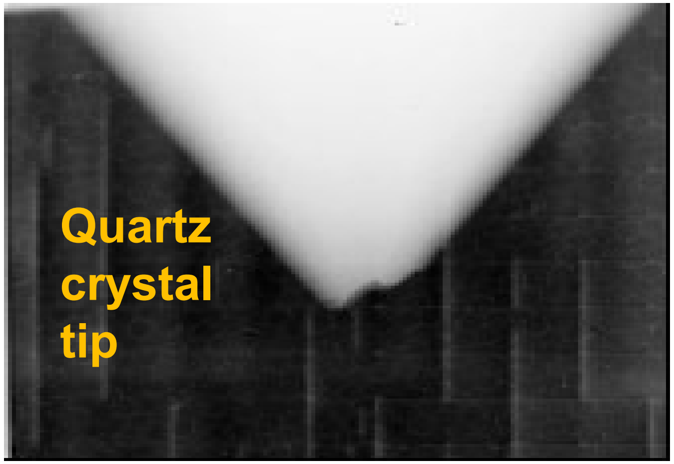


Stutman et al 2015

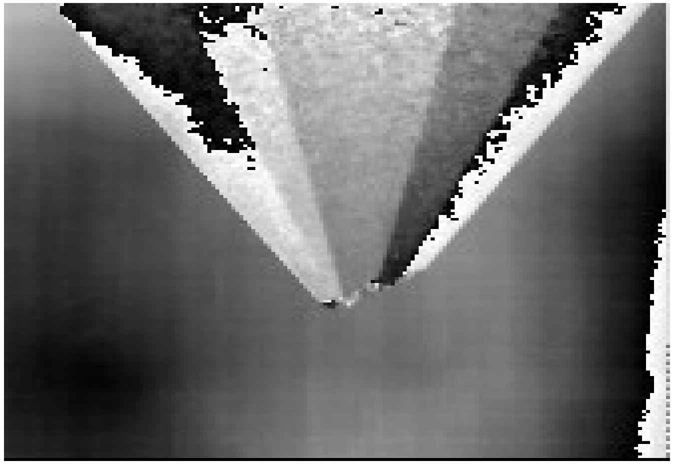
Potential for improved tumor detection with reduced dose

PXI projections contain 3D information (density gradients)

Attenuation radiograph



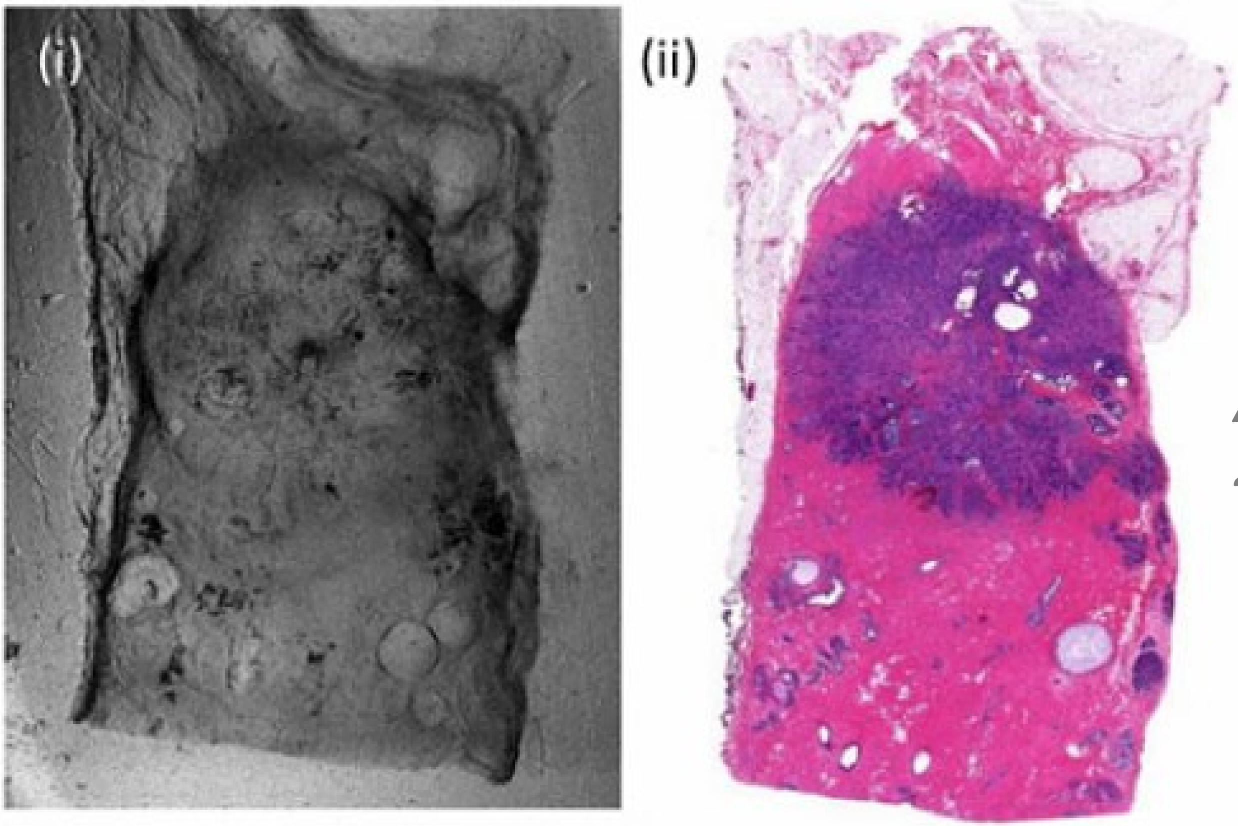
PXI radiograph



Grating PXI mammography shows signature of invasive cancer

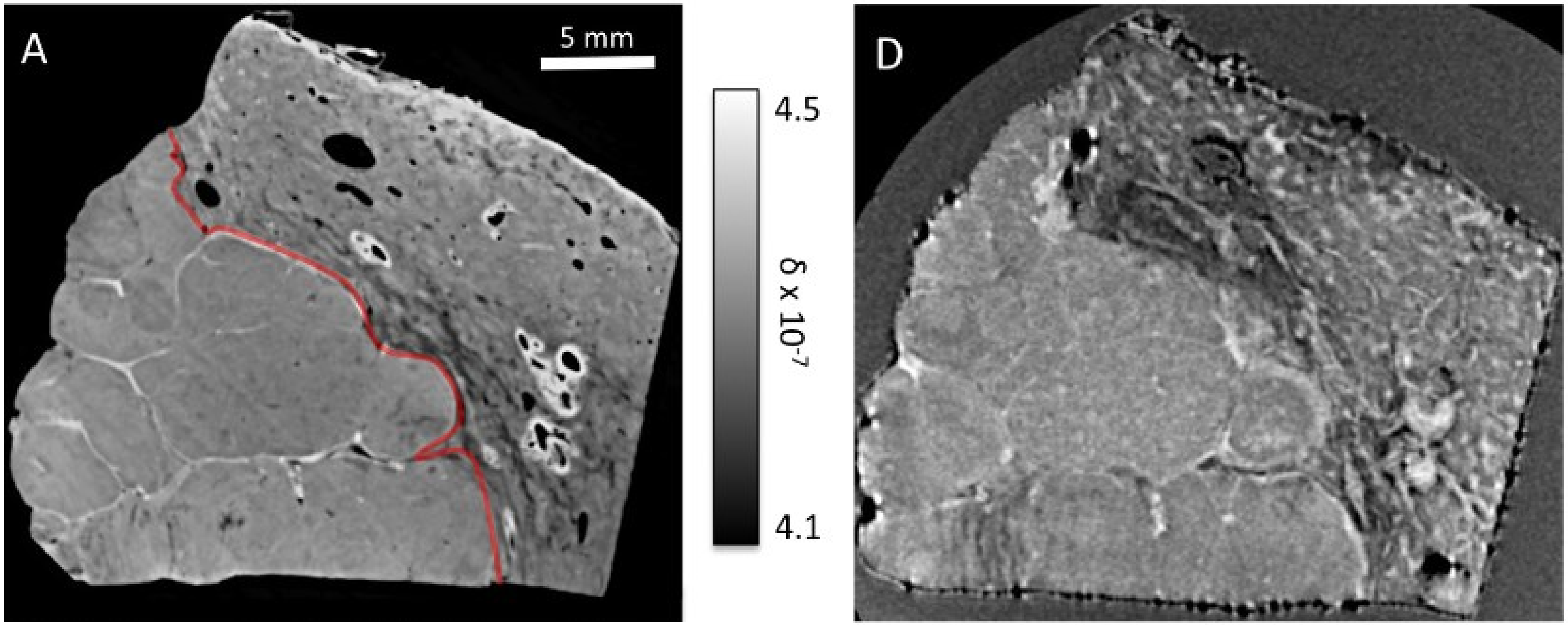
Infiltrating breast carcinoma

PXI radiograph **Histology**



Ando et al 2013

Tumor imaging in internal organs with performance comparable to high resolution MRI



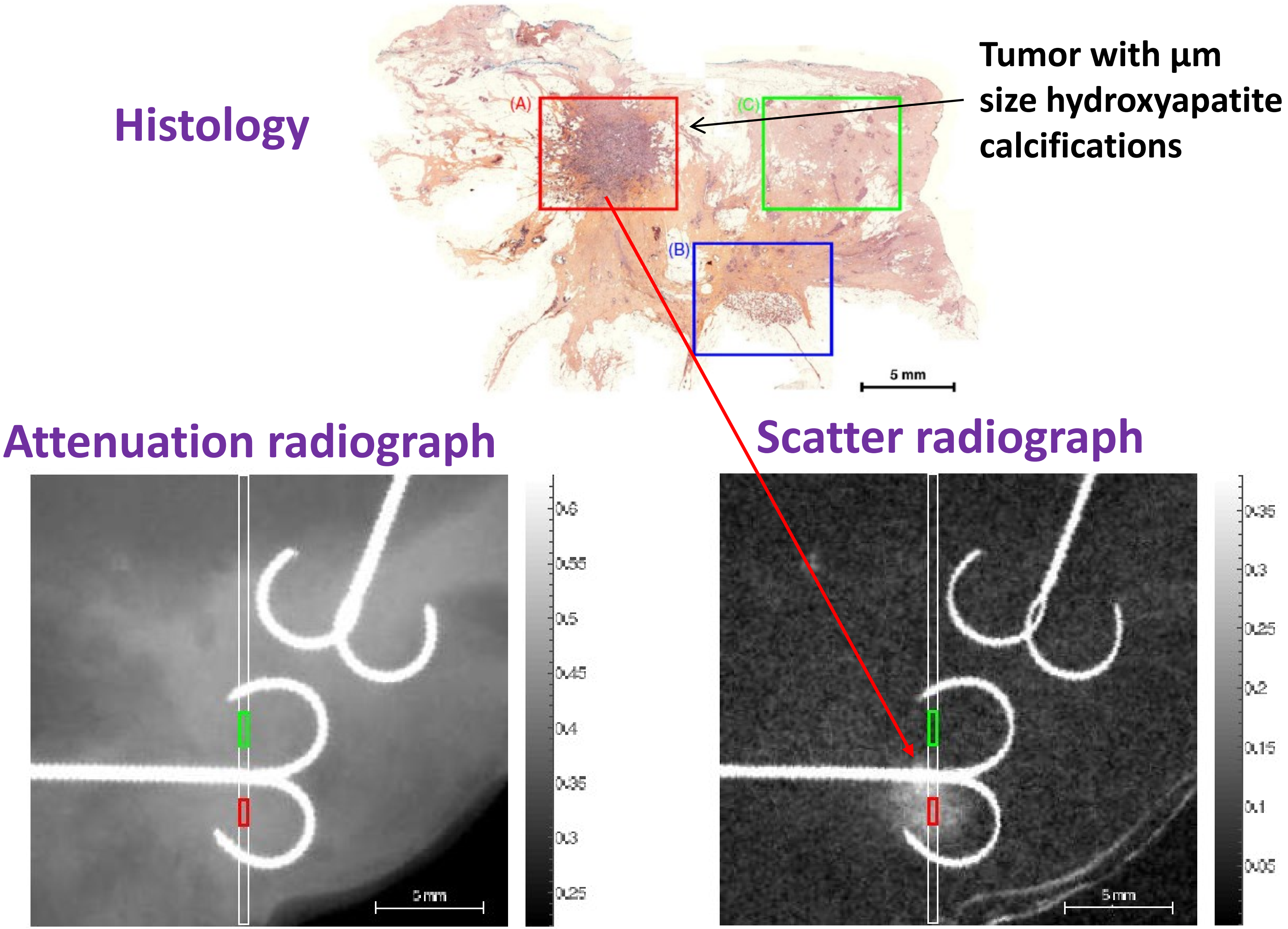
PXI CT

High resolution MRI

Metastasized liver tumor

Noel et al 2013

Scatter mammography detects µm-size calcifications



Histology

Tumor with µm size hydroxyapatite calcifications

Attenuation radiograph

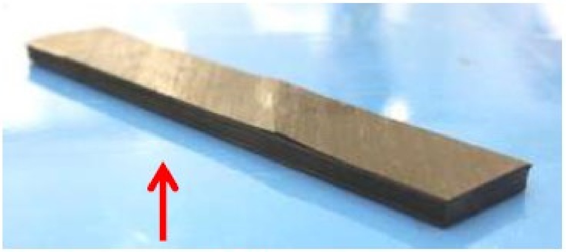
Scatter radiograph

Michel et al 2013

Important industrial applications also possible

Kottler et al 2012

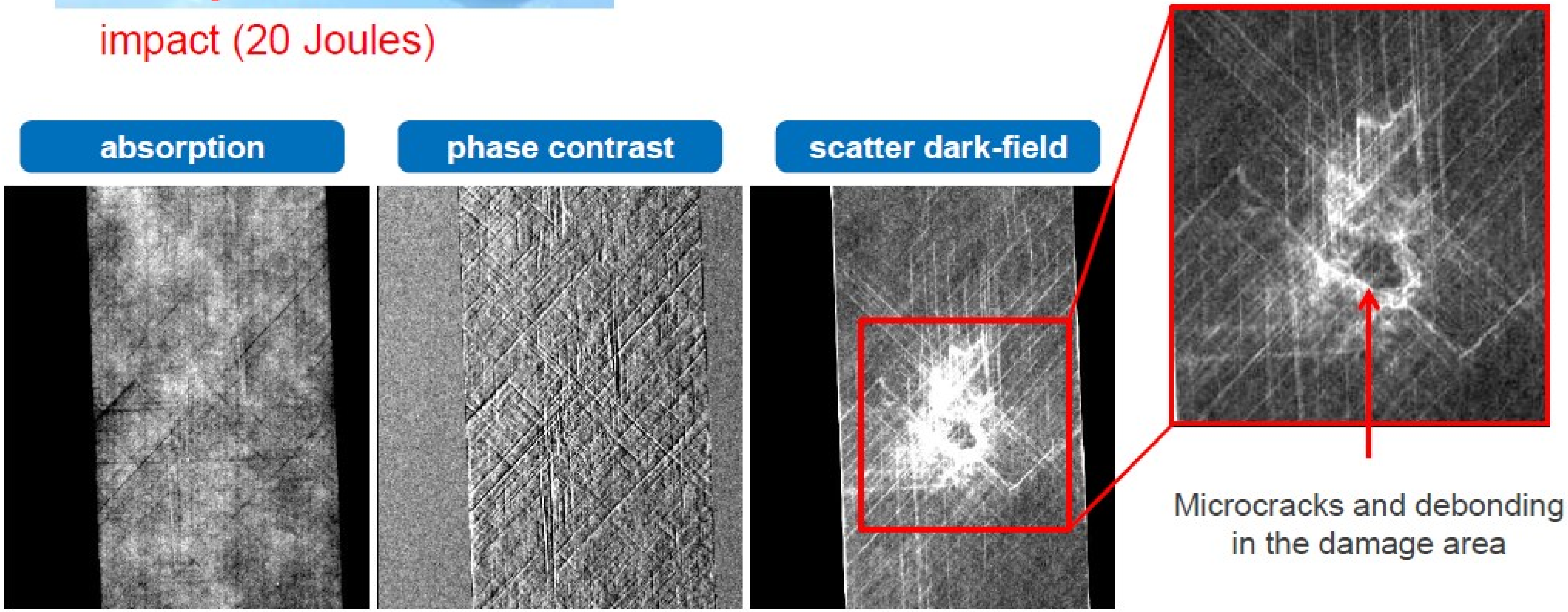
Impact Damage in Composite Materials



impact (20 Joules)

Fiber Composite Materials

- quasi-isotropic CFRP
- lay up $[0°/+45°/90°/-45°/0°]_s$



Microcracks and debonding in the damage area

Sensitivity, resolution and dose efficiency of current PXI methods nevertheless limited with conventional X-ray sources (tubes)

Why laser driven X-ray sources for PXI

Dose efficiency ratio of grating PXI CT vs attenuation CT

$$\eta \approx \lambda^2 \cdot [L/G]^2 \cdot V^2 \cdot [\Delta\phi/\Delta\mu]^2 \cdot a^{-2}$$

L = inteferometer length

G = grating period

V = Talbot fringe contrast

a = spatial resolution

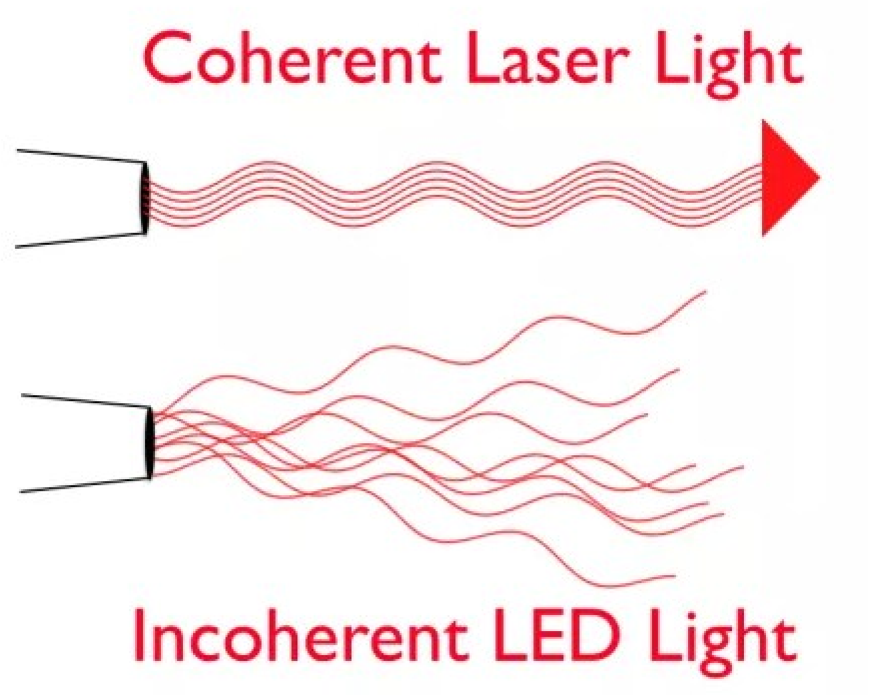
Raupach & Flohr 2012

L~ 5 meters

for η=10, G=5 μm, V=25%, a=50 μm, E= 50 keV (clinical CT)

- PXI needs coherent, bright, and directional X-ray sources
- X-ray flux of conventional X-ray tubes too low at long distances
- Synchrotrons too expensive and large for practical applications
- *X-ray sources driven by high power lasers may be ideal solution: directional because of relativistic effects, quasi-coherent and bright*

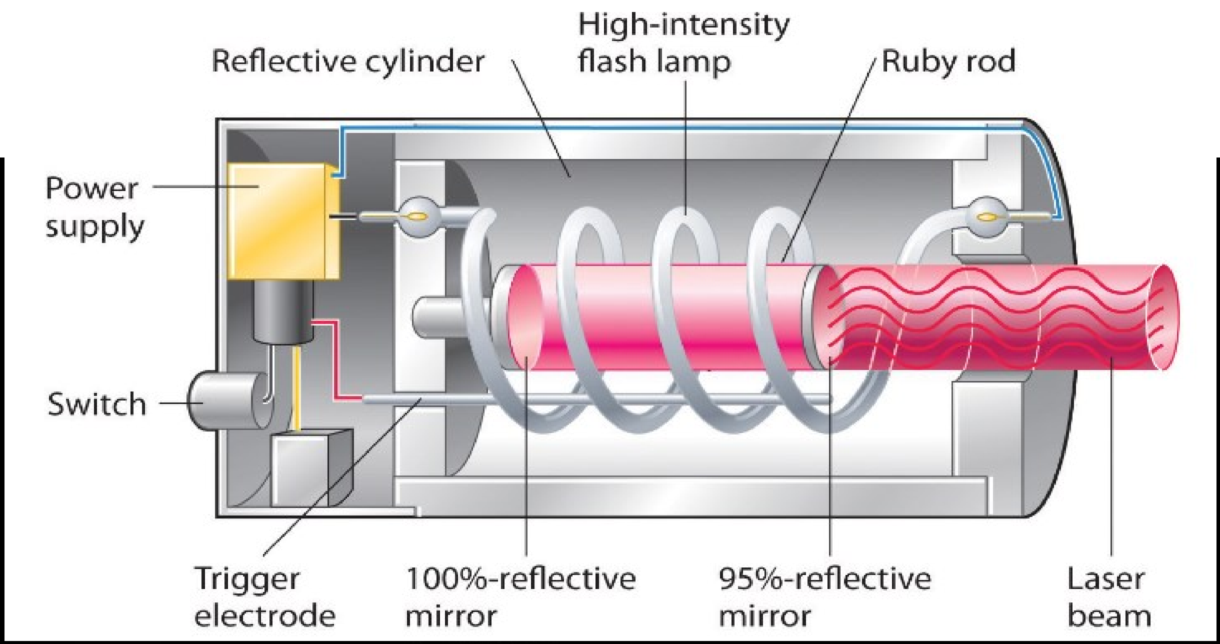
How is a Laser different from a LED?

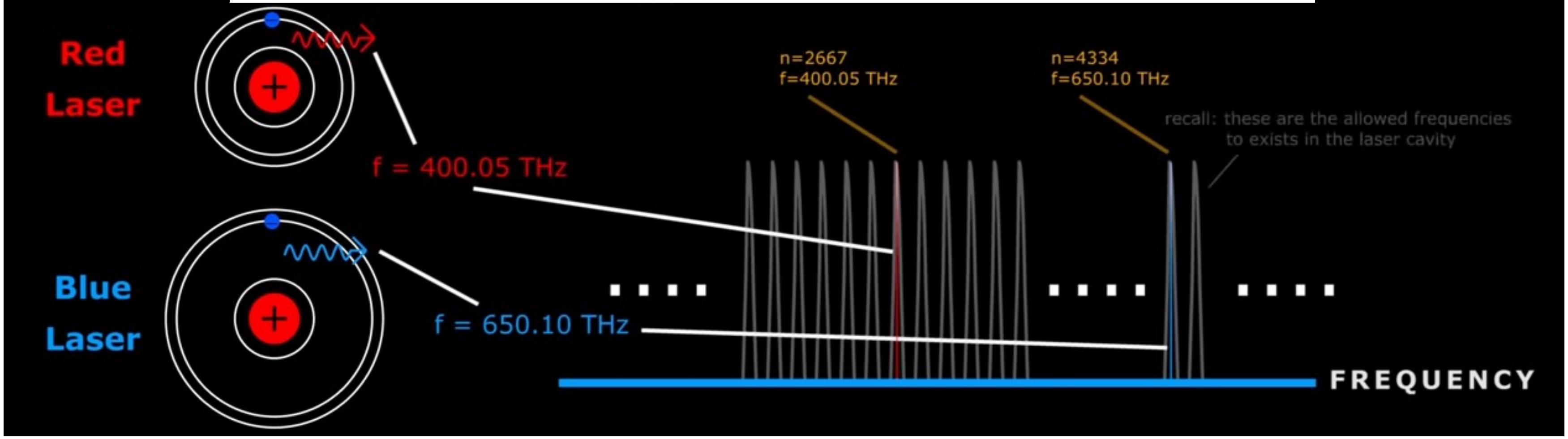


LASER:
- Spatial coherence
- Temporal coherence
- Ultrashort pulse durations possible

Typical light source:
- No spatial coherence
- No temporal coherence

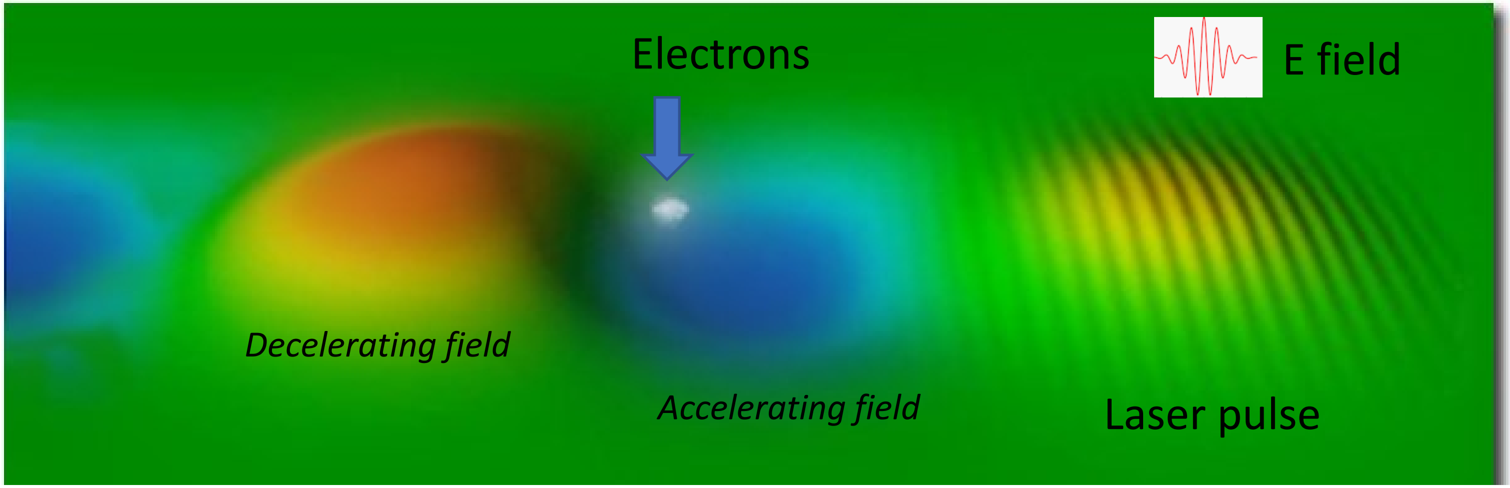
Lasers basics





Lasers plasma accelerator

A speedboat leaves a wake that a surfer can ride

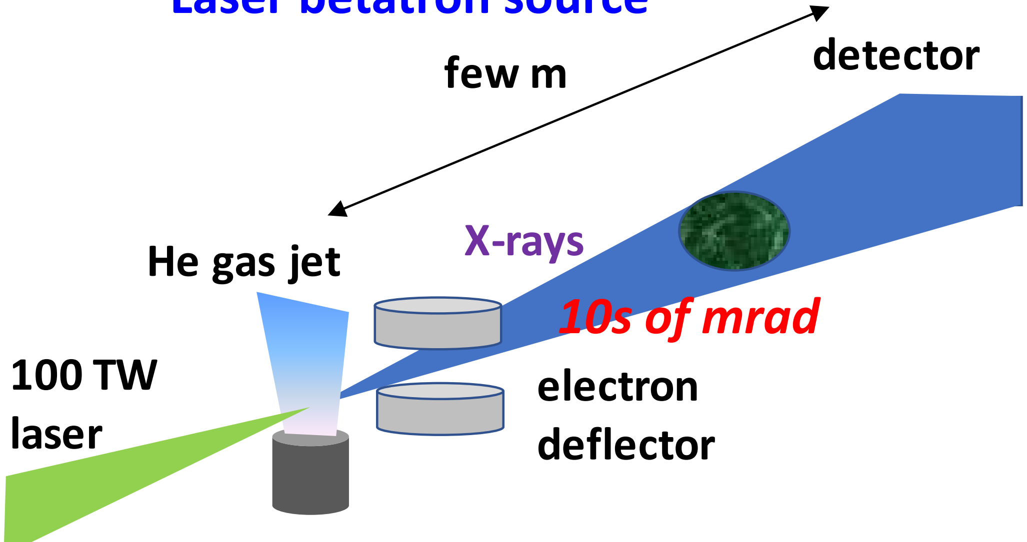


A laser pulse in a laser-plasma wakefield accelerator creates a wake in the plasma that an electron beam "surfs" to high energy.

(Original boat-surfing photo by Sean C. Fulton)

100 TW laser makes coherent, bright and directional X-ray source

Laser betatron source



few m

detector

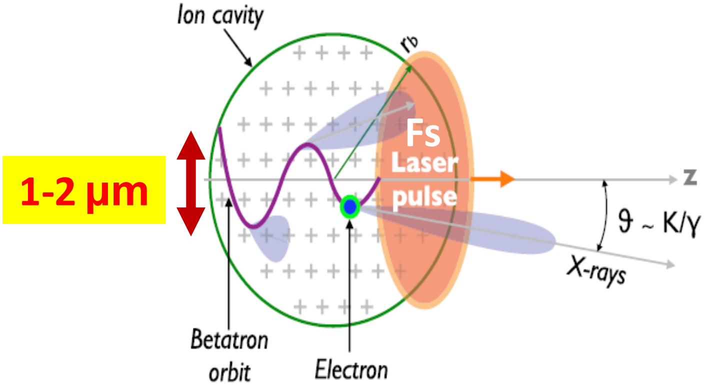
He gas jet

X-rays

10s of mrad

100 TW
laser

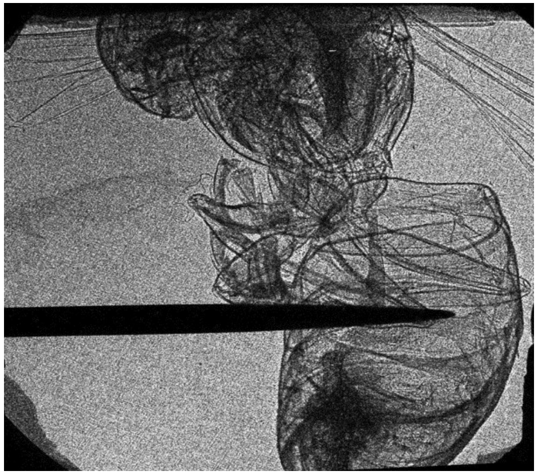
electron
deflector



1-2 µm

Fourmeaux et al 2011

Single shot propagation PXI with µm resolution

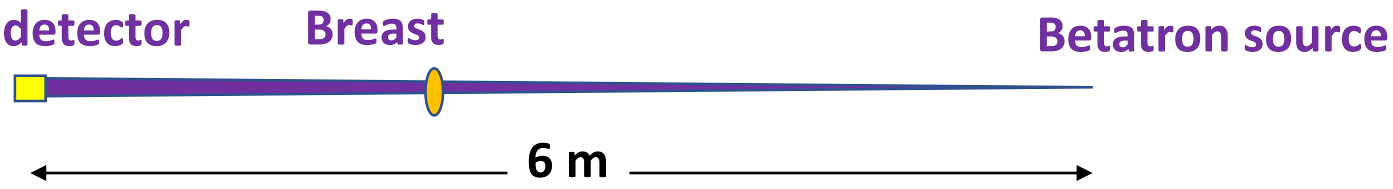


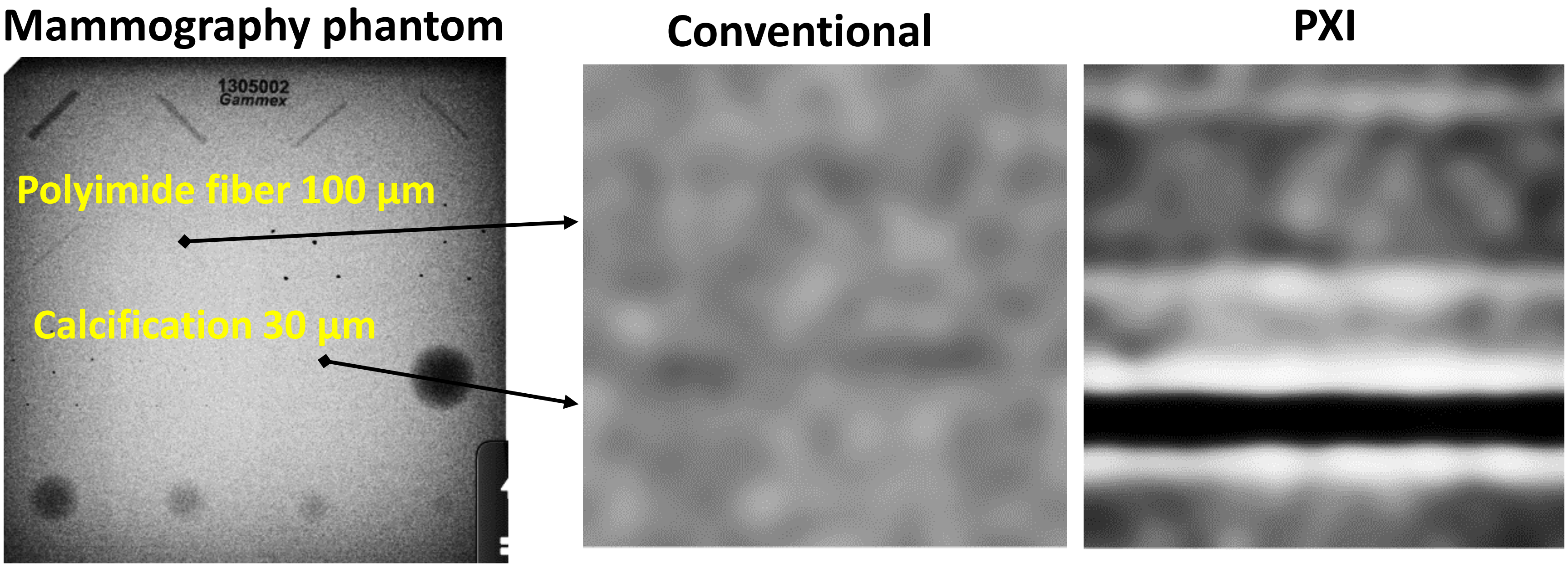
Kieffer et al 2016

- ☐ Electrons in gas accelerated and wiggled by the laser ("table-top synchrotron")
- ☐ Methods to increase X-ray source brightness and energy under development

Laser PXI could revolutionize breast cancer diagnostic

Simulation of laser PXI of breast phantom at 30 keV



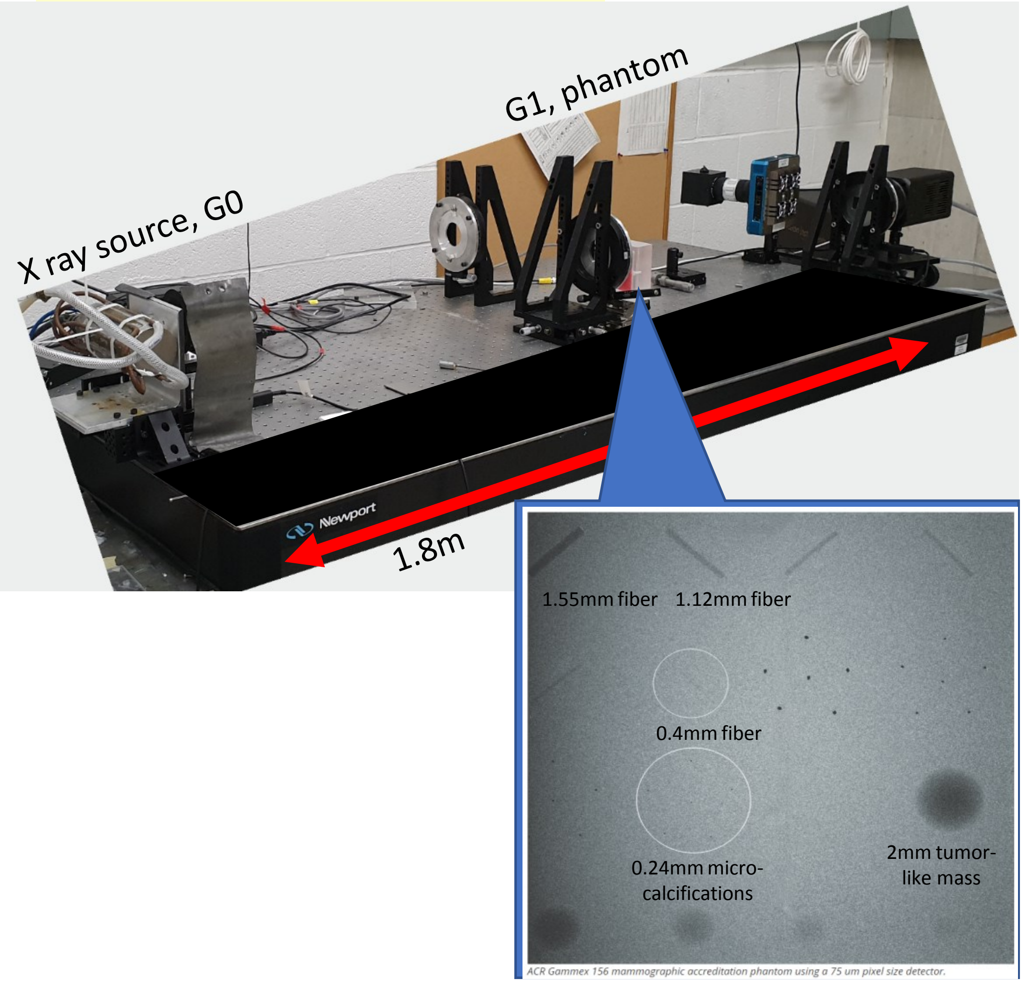


- Potential to reduce dose (major issue in mammography)
- Cardiologic imaging systems for arterial diseases also possible

Recent experimental results support potential of laser based PXI

M Cernaianu, D Stutman
in preparation

2 m long Talbot-Lau interferometer
<E>=30 keV

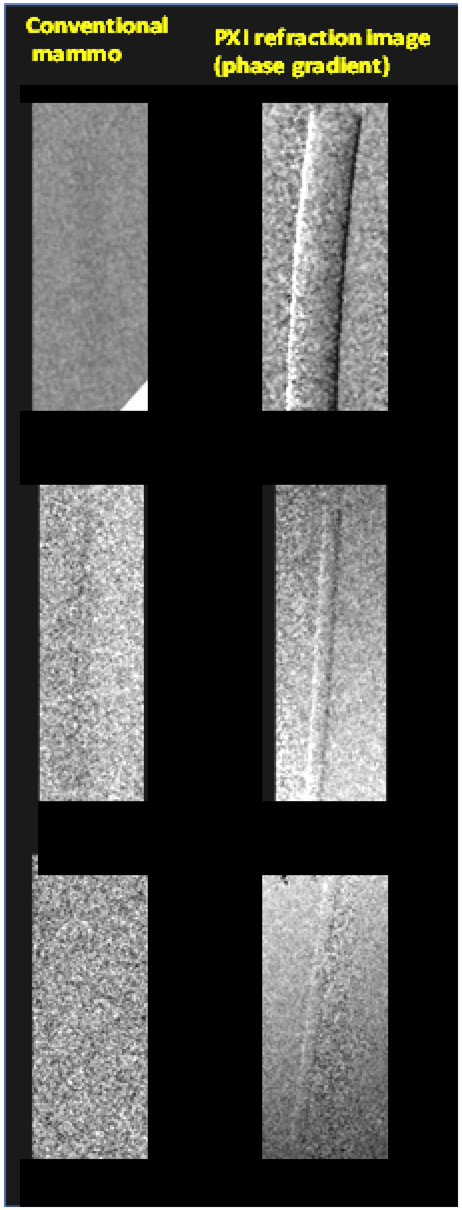


ACR Gammex 156 mammographic accreditation phantom using a 75 um pixel size detector.

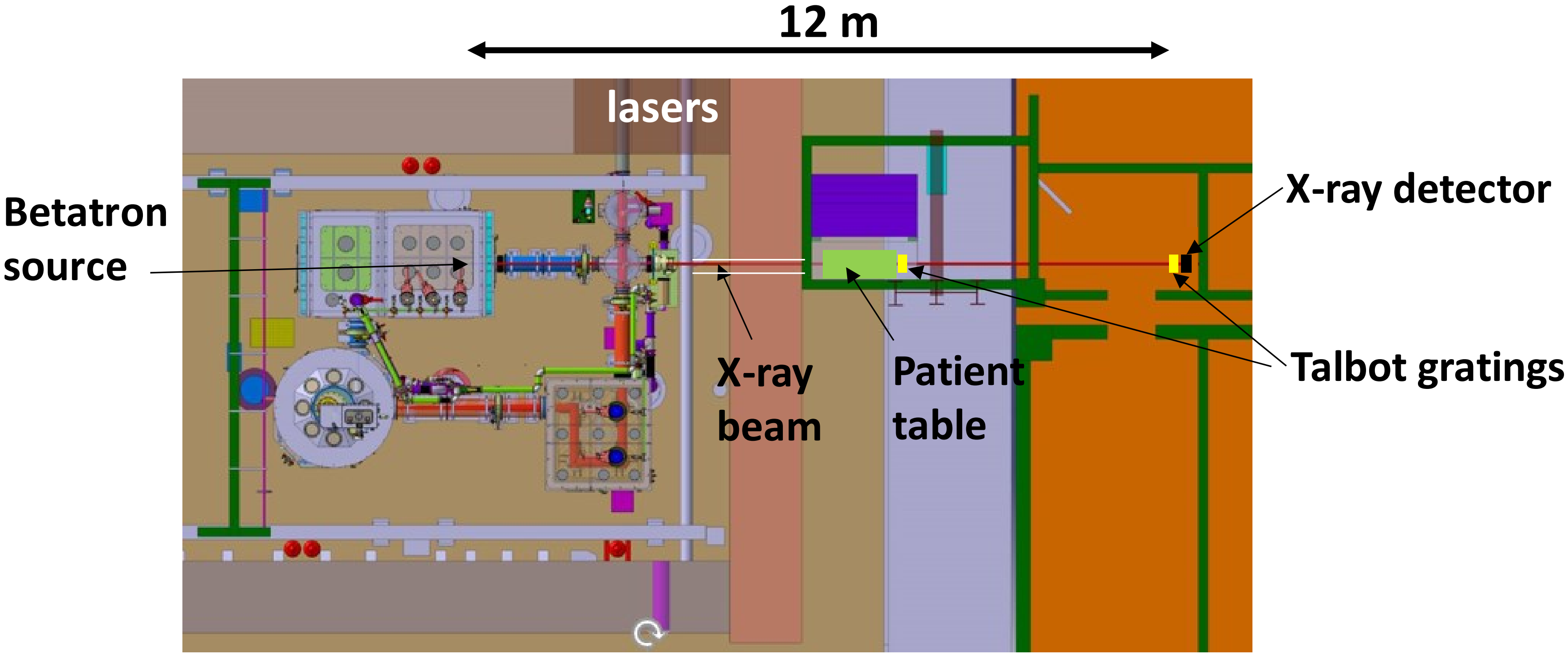
400 μm fiber clinical dose

100 μm fiber clinical dose

100 μm fiber ¼ clinical dose



Medical PXI station planned at the 1 PW/100 TW ELI-NP area



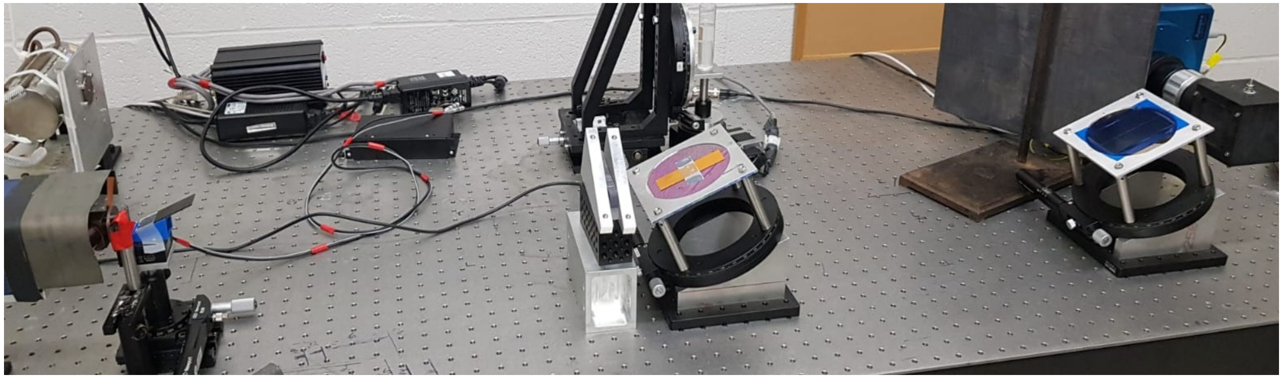
- ☐ 2x1 PW at 1 Hz and 2x100 TW at 10 Hz
- ☐ PXI station similar to ELETTRA one, but with laser X-ray source
- ☐ Preclinical (animal model) and clinical studies of cancer diagnostic
- ☐ In-vivo tumor monitoring for radiobiology research

Industrial PXI potential

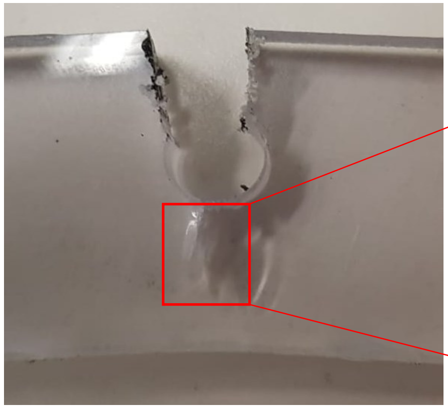
☐ Nondestructive testing important for industrial applications: automotive, civil engineering, aeronautical, mechanical engineering, security, …

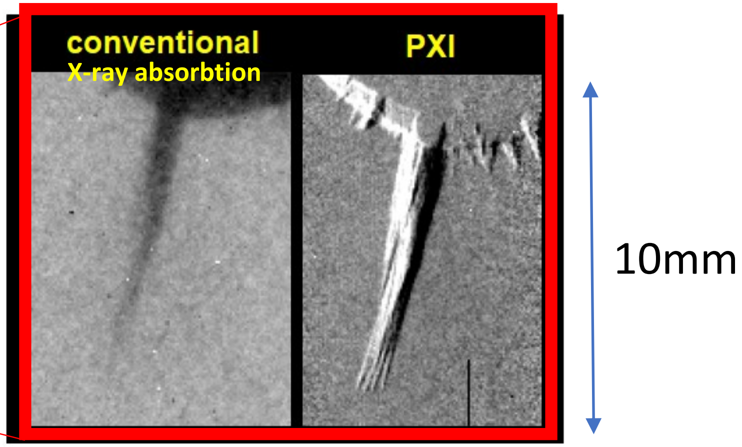
☐ Typical methods involving X-ray imaging do not reveal details

High energy X-ray phase contrast GAI setup



Test sample, acryl





Summary

- ☐ PXI has potential to revolutionize medical imaging
- ☐ Also important industrial, security and scientific (e.g. plasma diagnostic) applications
- ☐ PXI performance with conventional X-ray sources nevertheless limited
- ☐ Bright, coherent and directional X-ray sources driven by high power lasers (betatron, Thomson, …) will make possible high performance PXI
- ☐ Worldwide effort to develop such sources
- ☐ Medical PXI with laser source + X-ray optics to be developed at ELI-NP