Advanced Imaging and Ultra-fast Material Probing With Inverse Compton Scattering

A proposal to the Brookhaven Accelerator Test Facility

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Scientific goals

- Study of the fundamental electrodynamics of the ICS interaction
- Applications of ICS
    - Medical Applications
    - Cultural Heritage applications
    - etc..

INFN Collaboration

- In Italy there is a growing interest for ICS
- BEATS (BEam lines at Thomson Source): experiments with X-rays, approved and funded by INFN (7 Institutions/ ~ 20 Physicist involved)
- INFN sponsored an international ICFA workshop on ICS last year in Alghero
- Collaborations with important Medical Institutions already in place (San Raffaele Hospital in Milano)

Planned experiments @ INFN/LNF

- SPARC (High Brightness Electron Beams 10^15 A/m^2rad^2)
- FLAME (High Intensity Laser Beams 10^20 W/cm^2)
- PLASMONX (PLasma Acceleration @ Sparc & MONochromatic X-rays)

Applications

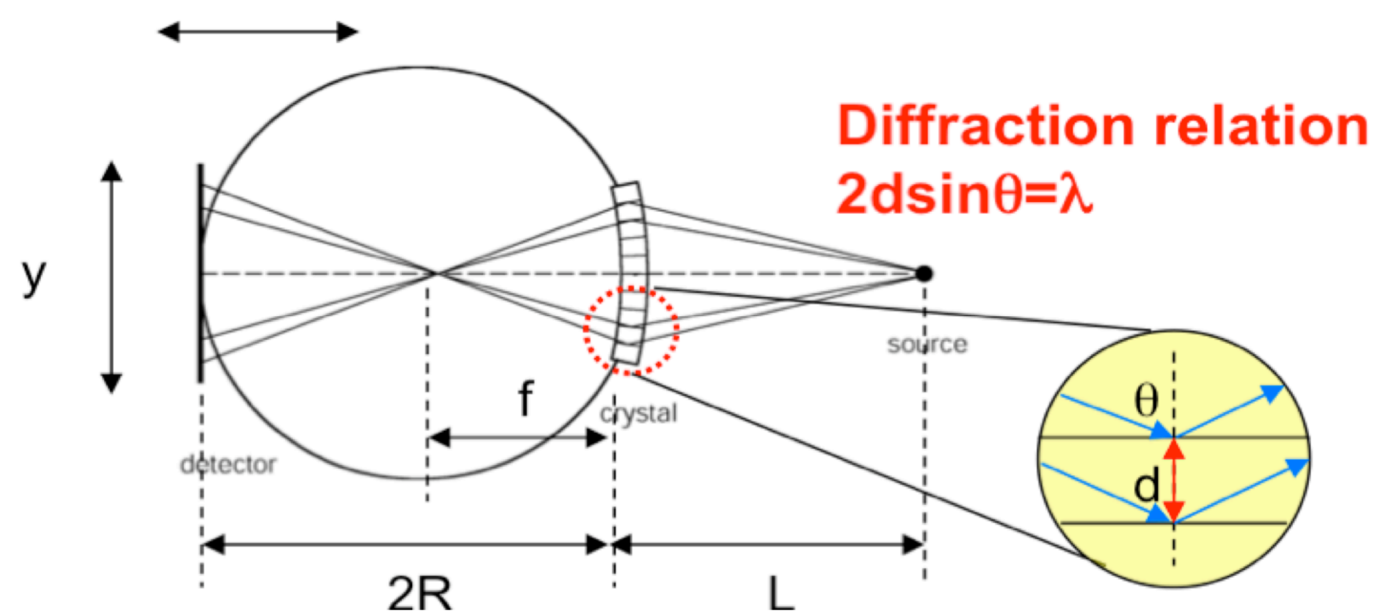
- Dichromatic subtraction
- Phase Contrast Imaging
- Mammography
- Low dose breast and lung CT

For all applications first step is

spectral measurement

Experimental input: Improved spectral measurement

- Need to characterize ICS differential spectrum
  - Linear and nonlinear
- Use UCLA-built focusing spectrometer from PLEIADES



Schematic of focusing spectrometer

Experimental input: Improved spectral measurement

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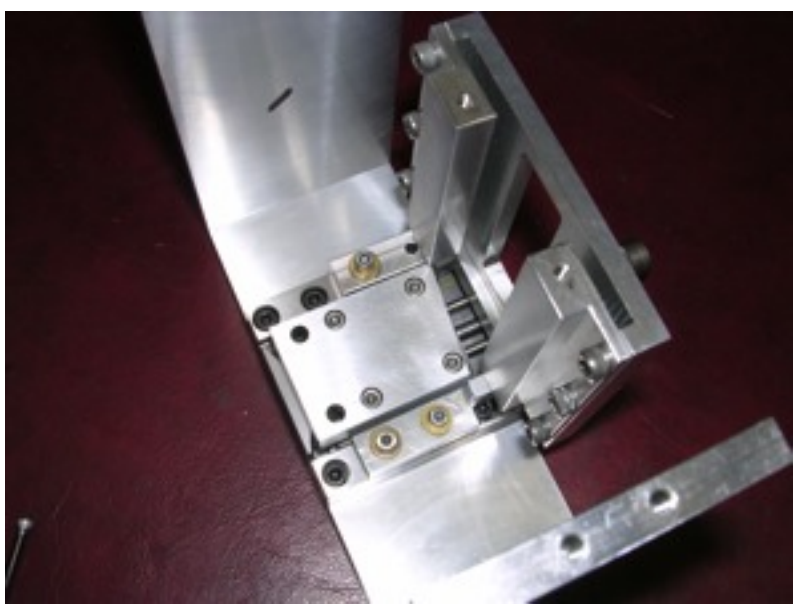
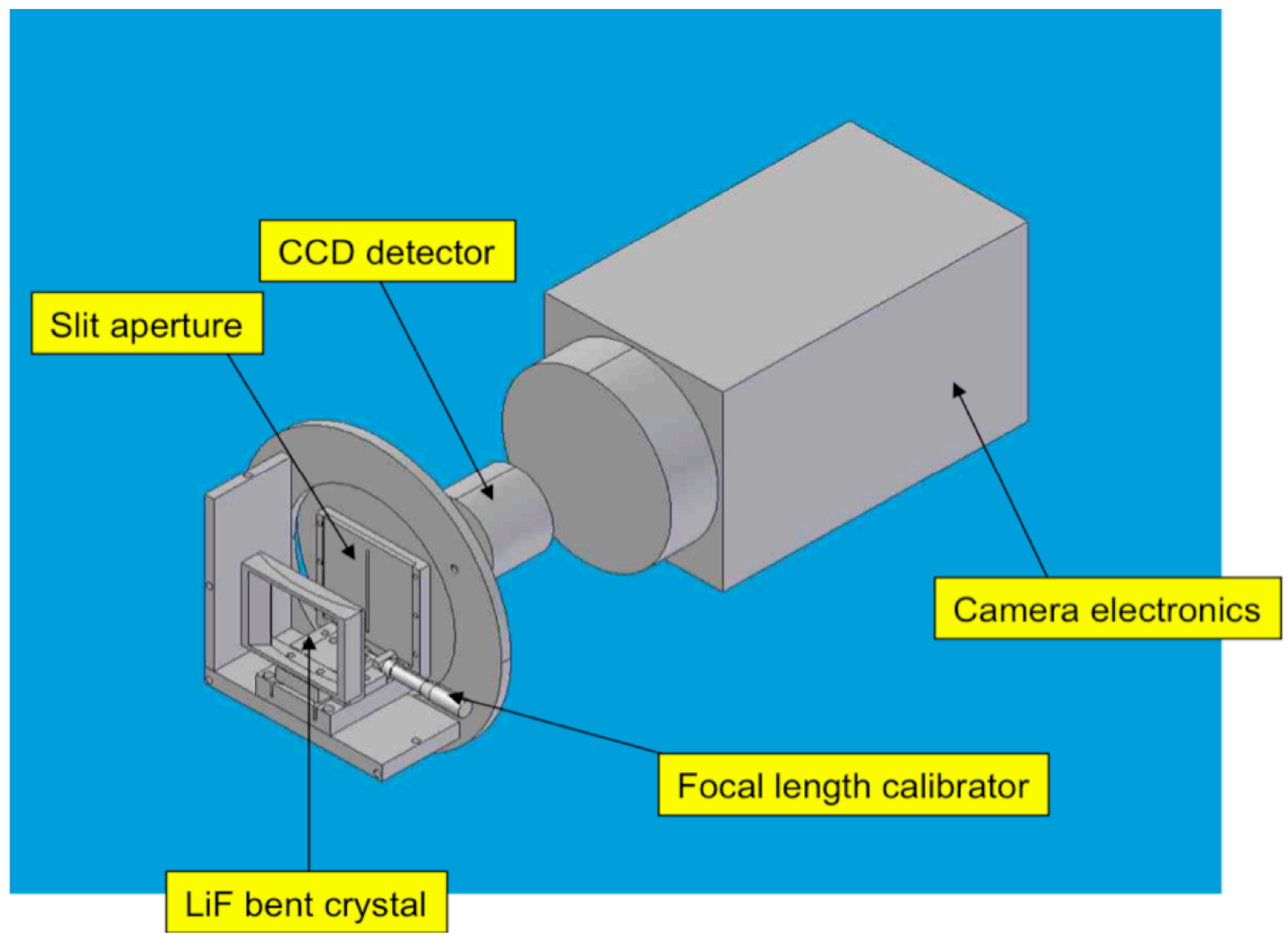
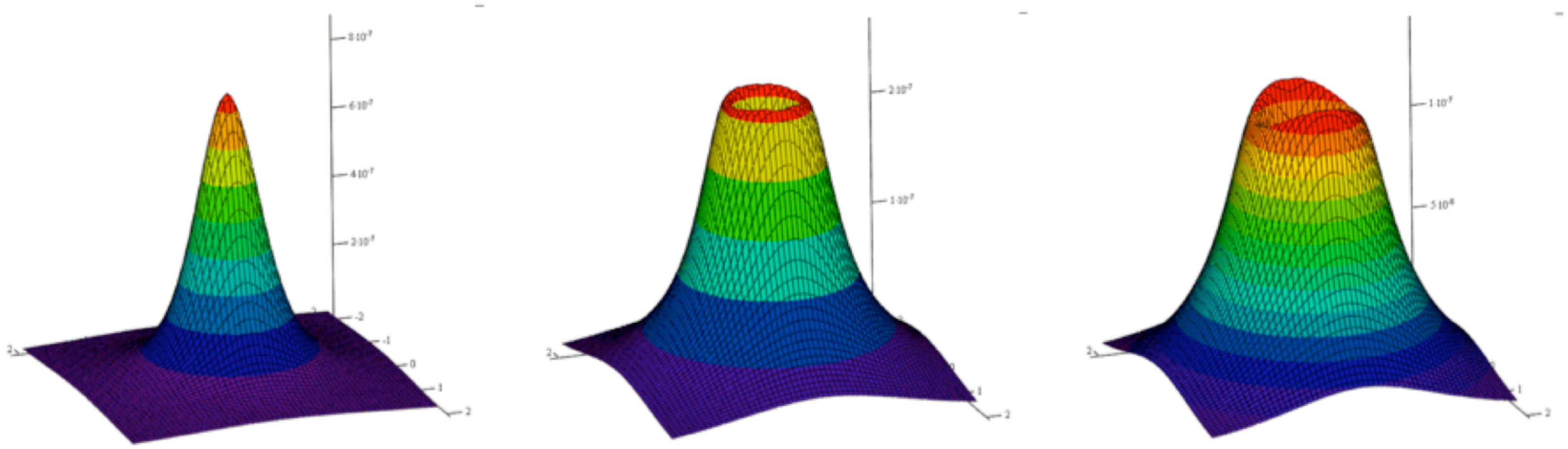
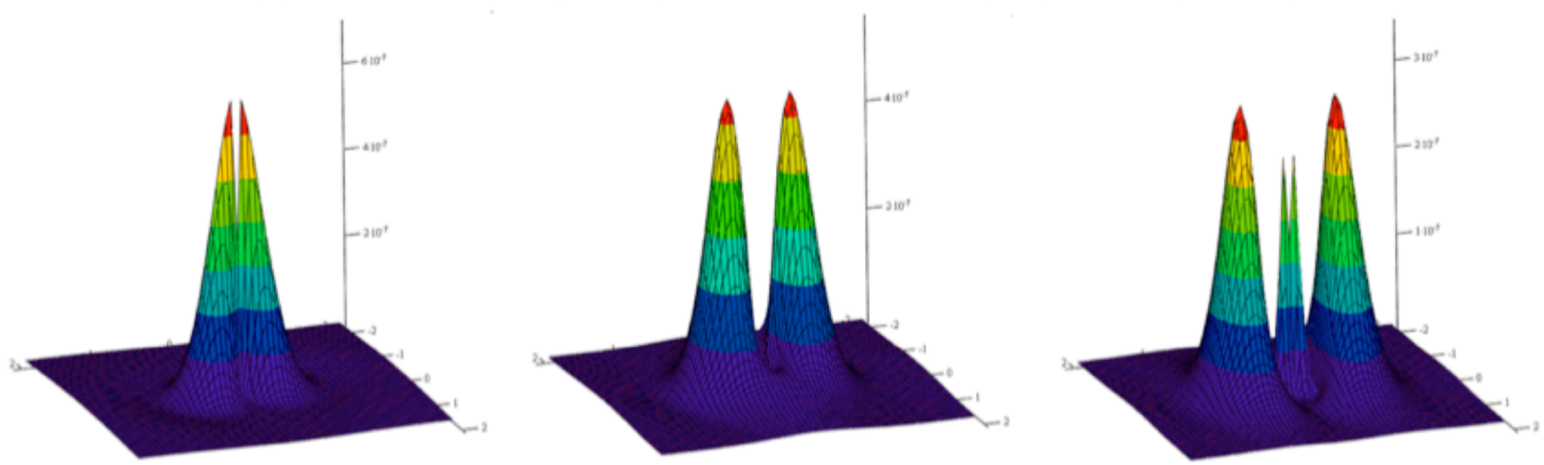



CCD detector
Slit aperture
Camera electronics
Focal length calibrator
LiF bent crystal

Example: Nonlinear ICS spectrum



For linearly polarized laser at 90º geometry where electron's velocity is parallel to plane of polarization



For linearly polarized laser at 90º geometry where electron's velocity is perpendicular to plane of polarization

- Angular dependence of ICS harmonics calculated for the UCLA Neptune nonlinear ICS experiment

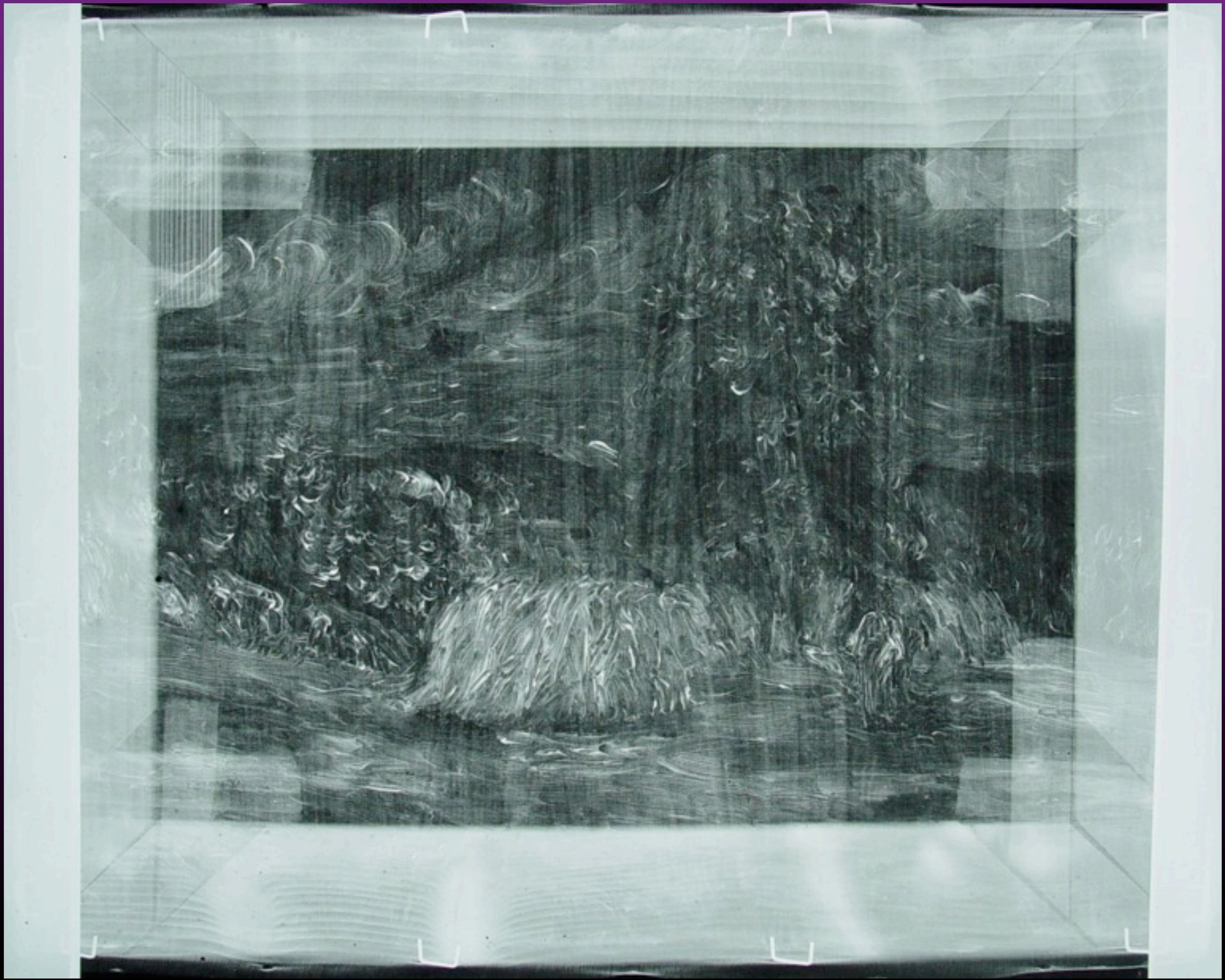
X-ray radiography in cultural heritage

- Non destructive and not invasive diagnostic
- Gives informations on:
  - execution techniques
  - underpainting
  - “pentimenti”
- Does not provide elemental composition

La mietitura a Montfoucault

Copia da Pissarro

Radiografia X



Dual energy digital subtraction radiography

- Use of dichromatic techniques in coronary angiography is well known, using Iodine K-edge
- Application to cultural heritage analysis includes Zn and Cu, contained in several pigments

Dual energy technique

- For a (quasi) monochromatic X-ray beam, the signal is proportional to the number of photons reaching the detector after transmission
- Digital subtractions of two images above and below the K-edge
- Distribution of mass attenuation coefficient of the interesting element (Zn as an example) and of the other elements in the painting

White pigments

- zinc white (ZnO) and titanium white (TiO_2) in linseed oil
- calcium carbonate ($CaCO_3$) and lithopone ($BaSO_4$+ ZnS) on canvas

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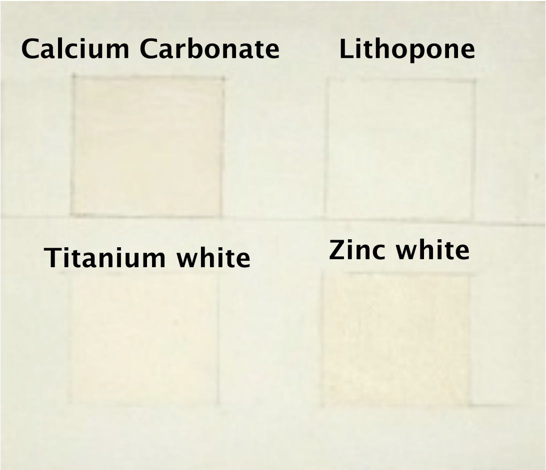
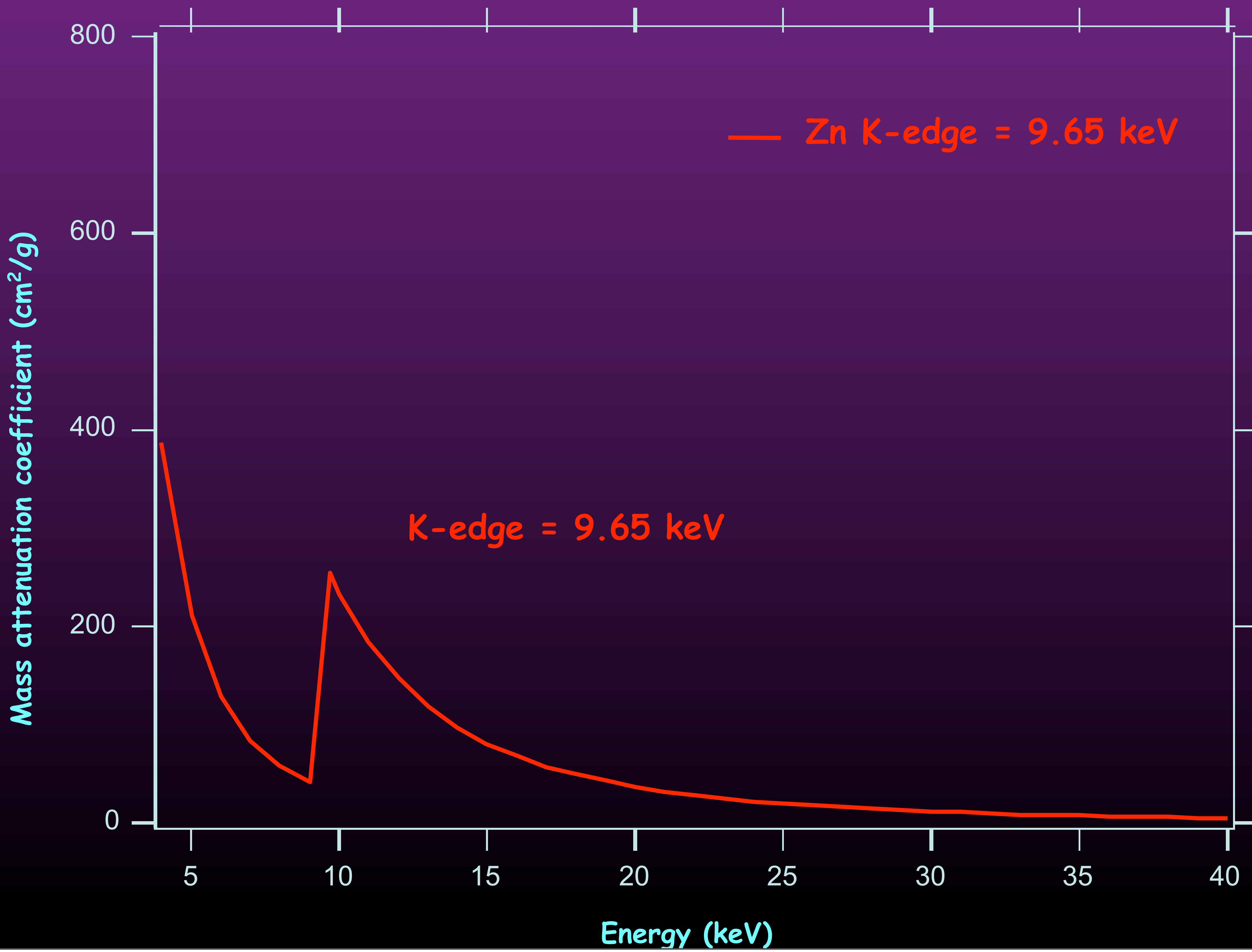
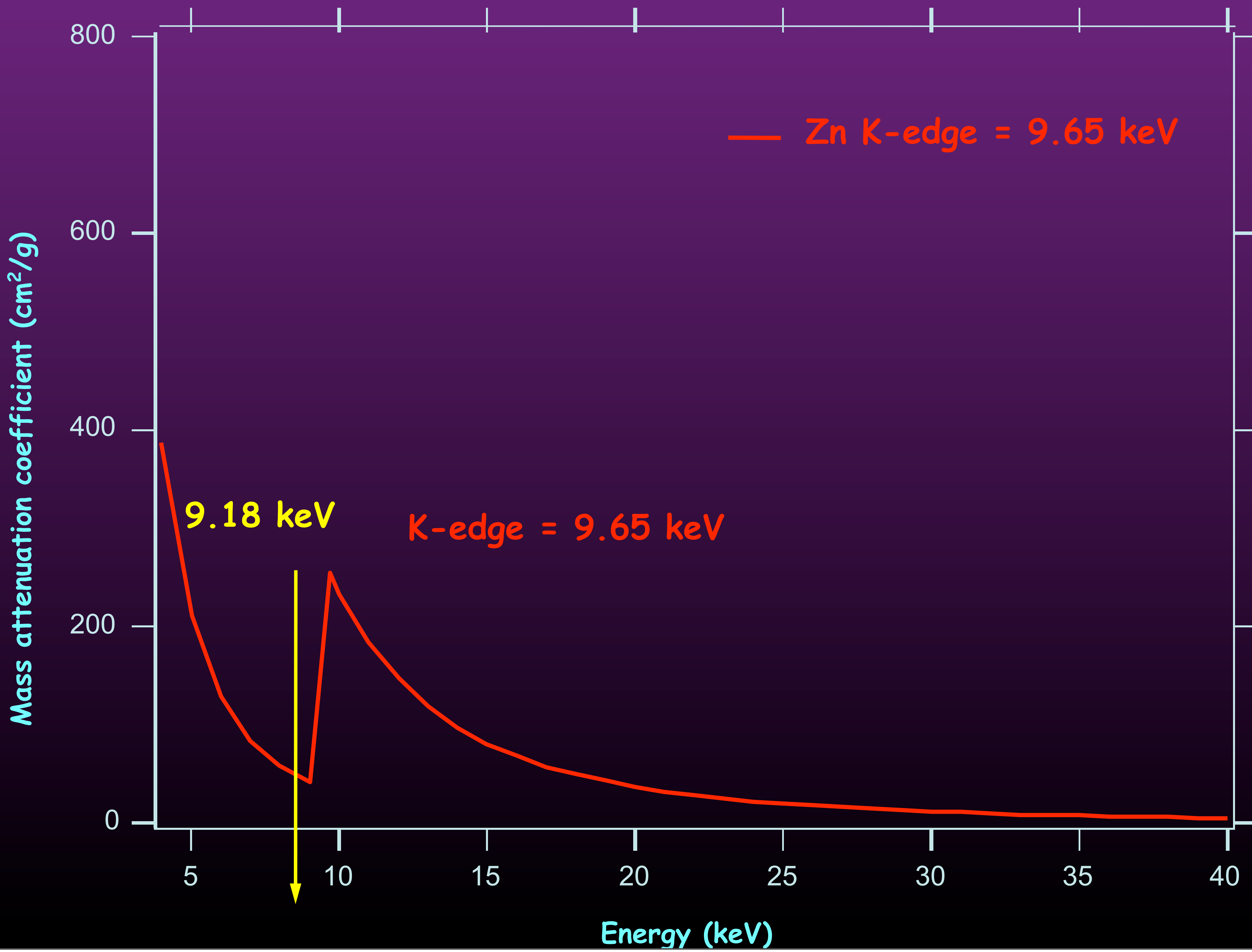


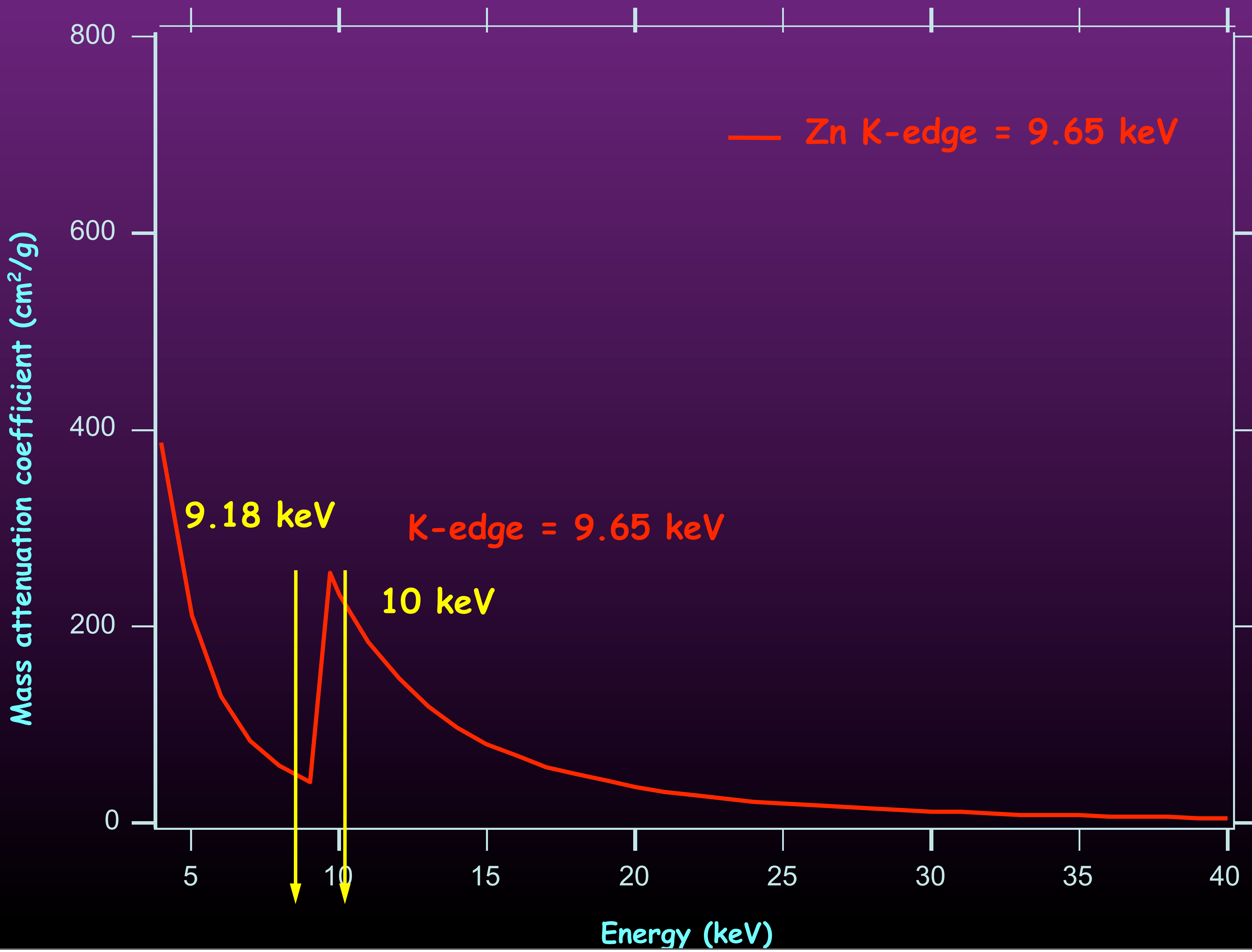
Absorption peaks



Absorption peaks

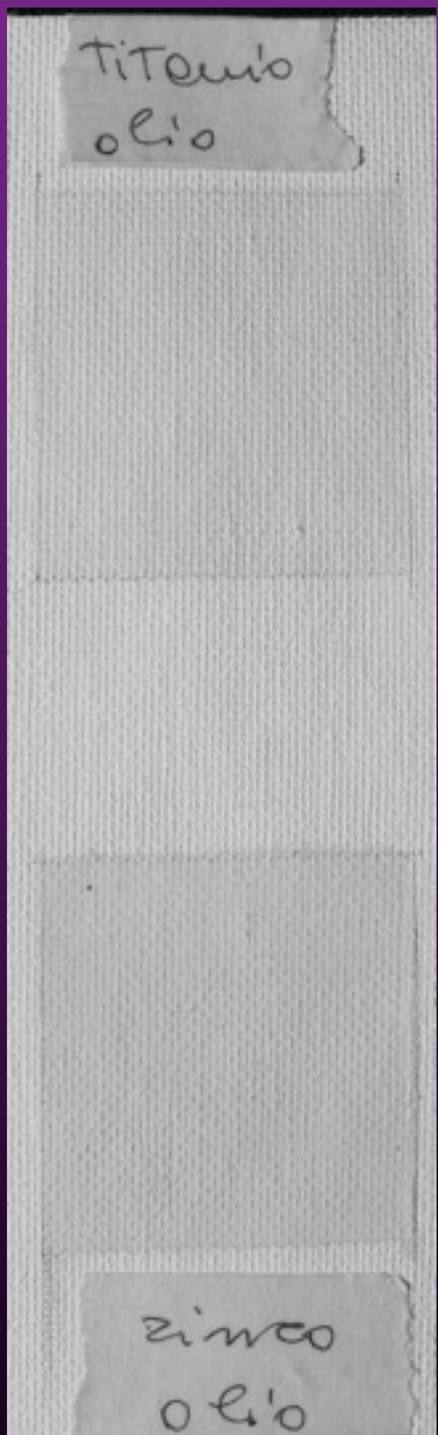


Absorption peaks

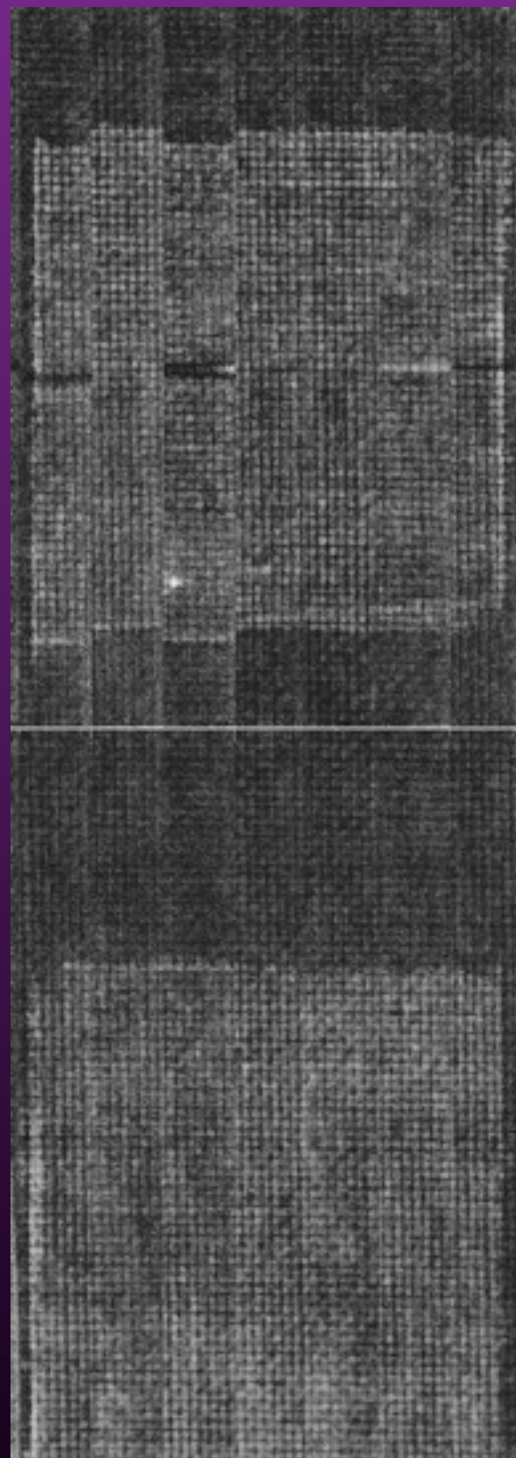


Results

- Two color digital subtraction has been successfully applied (By INFN Ferrara group) using a standard x-ray tube and a Bragg crystal monochromator
- Images have been acquired with two digital detector (CMOS and CCD)

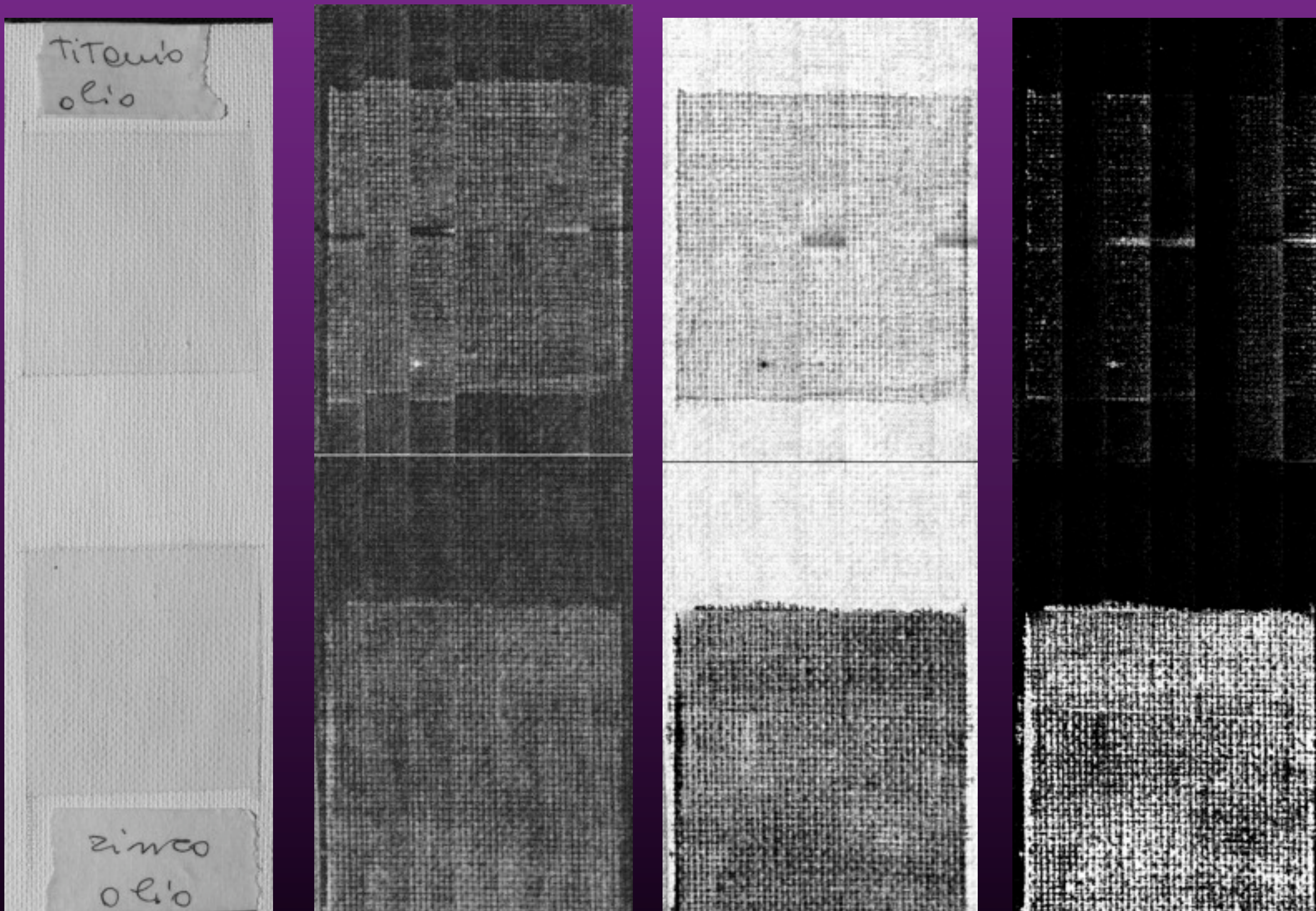


Sample
on canvas

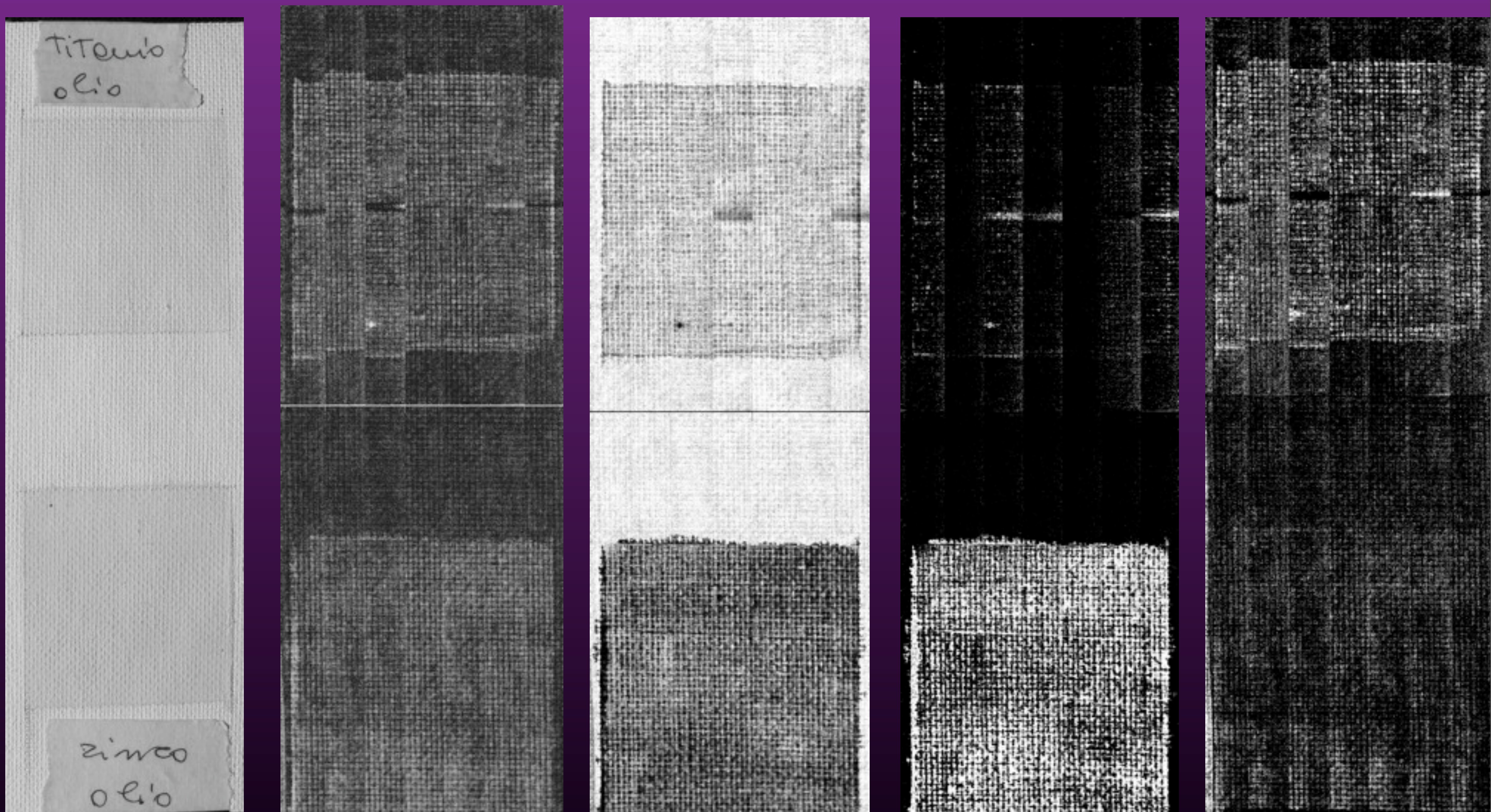


below K_edge

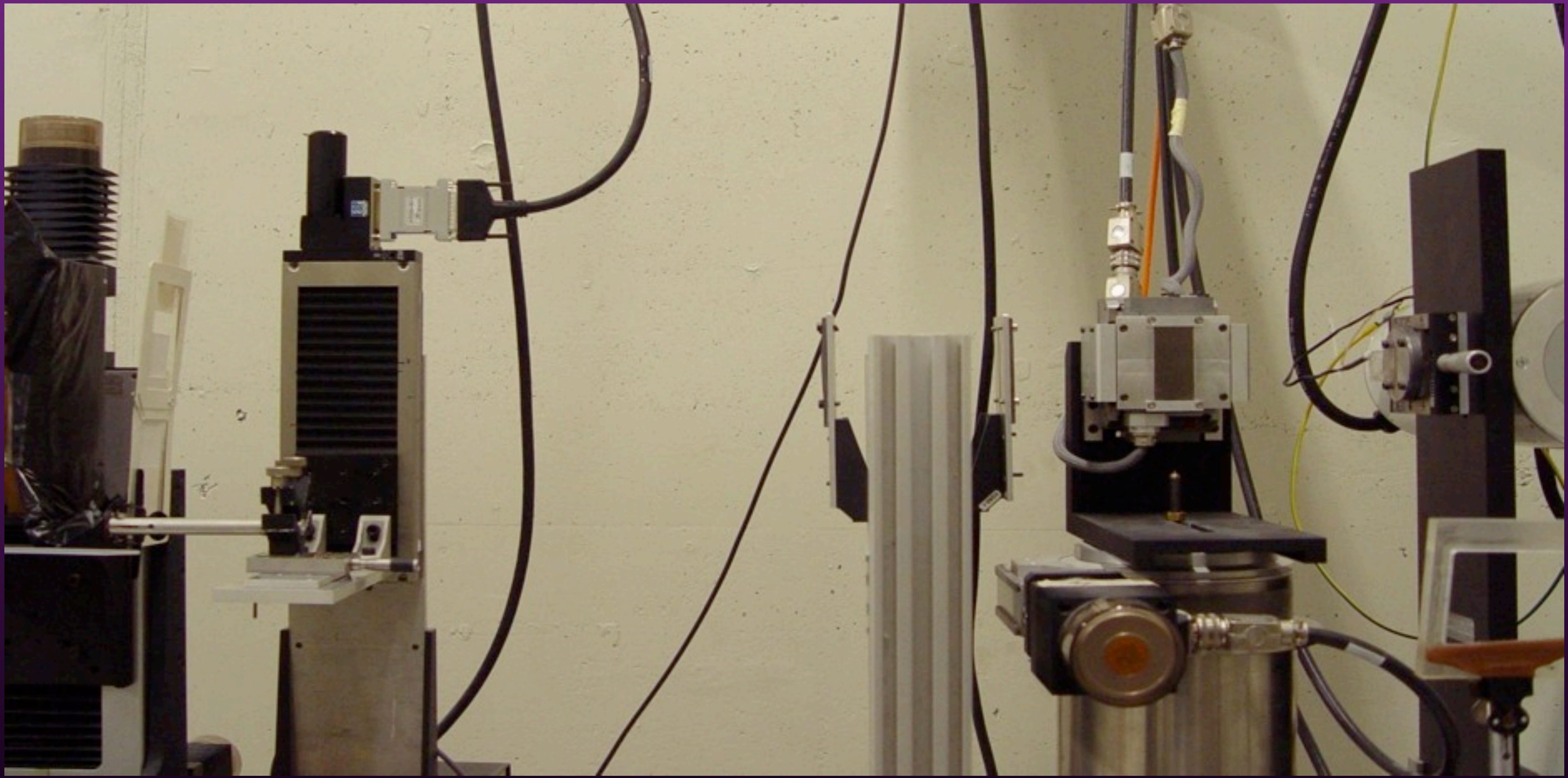
above K_edge



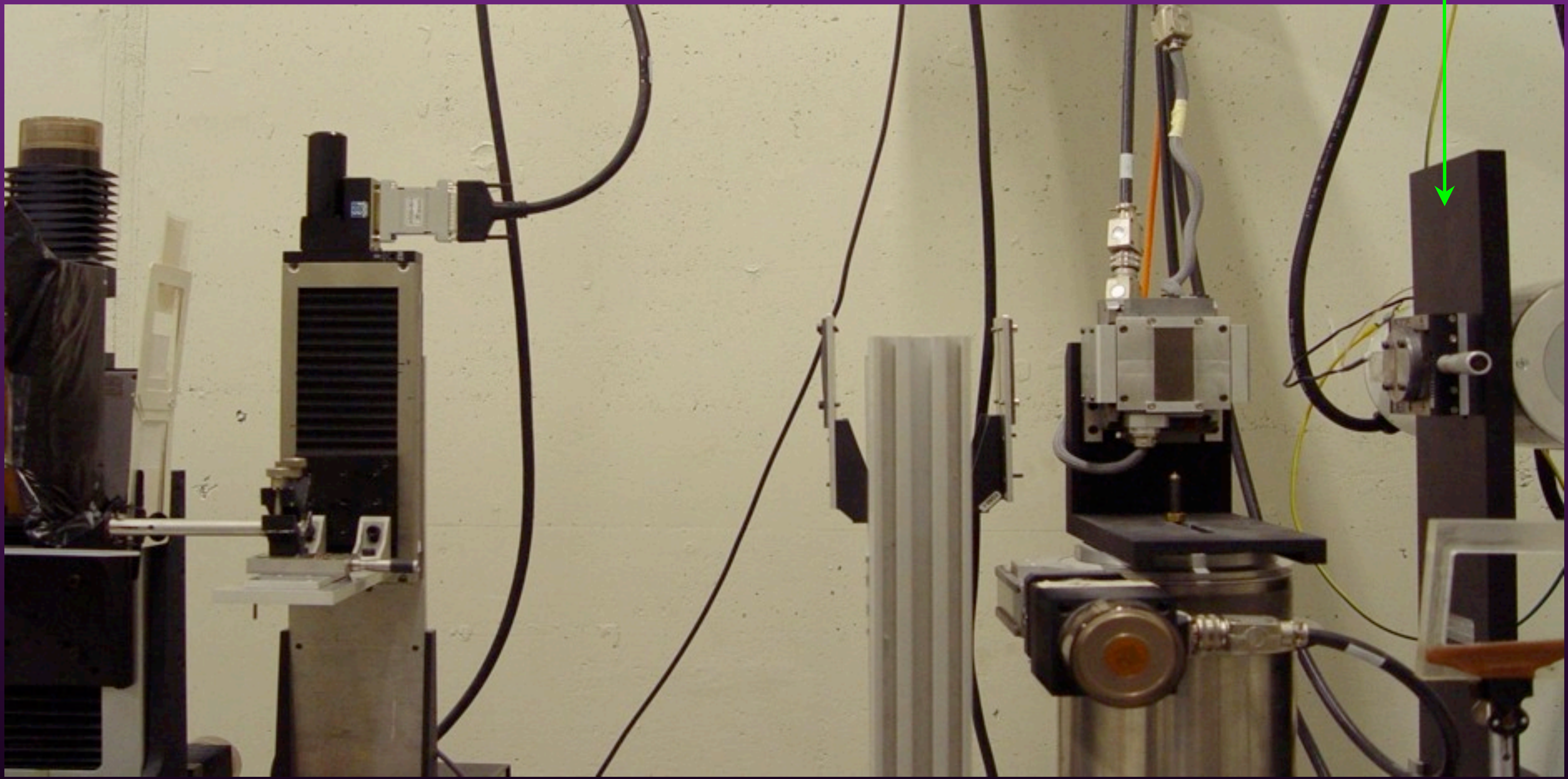
Sample on canvas | below K_edge | above K_edge | Zinc

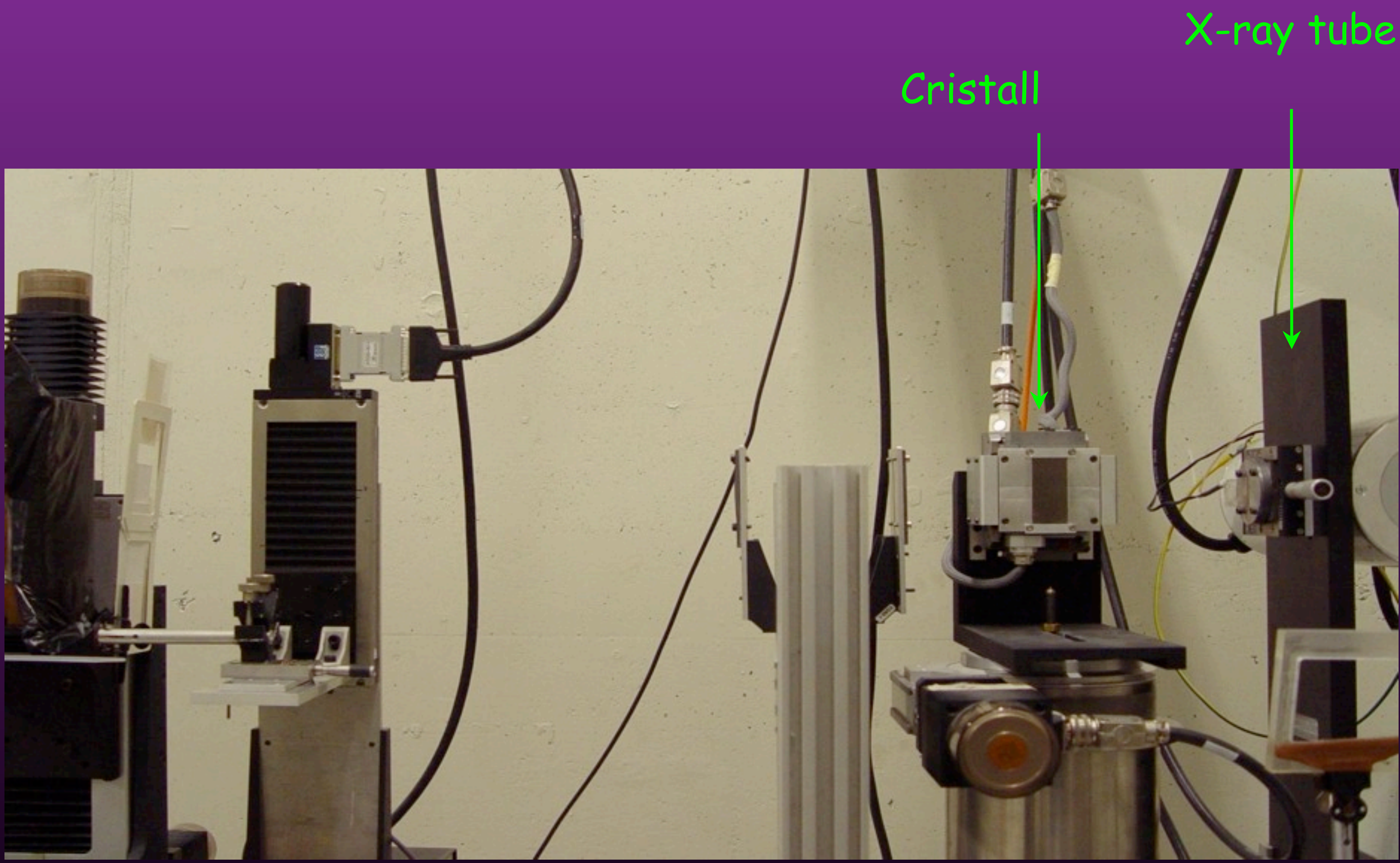


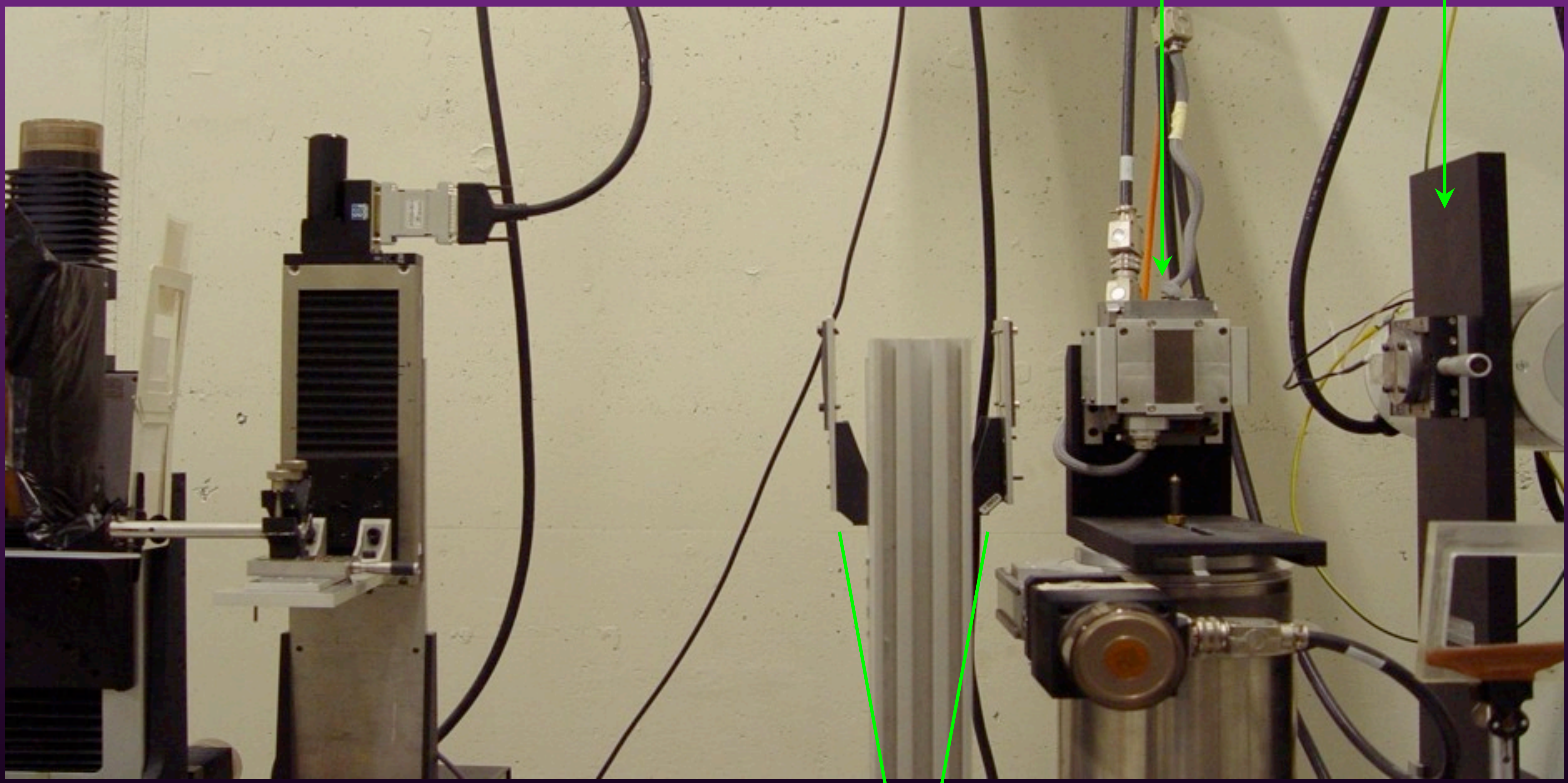
Sample on canvas | below K_edge | above K_edge | Zinc | other elements

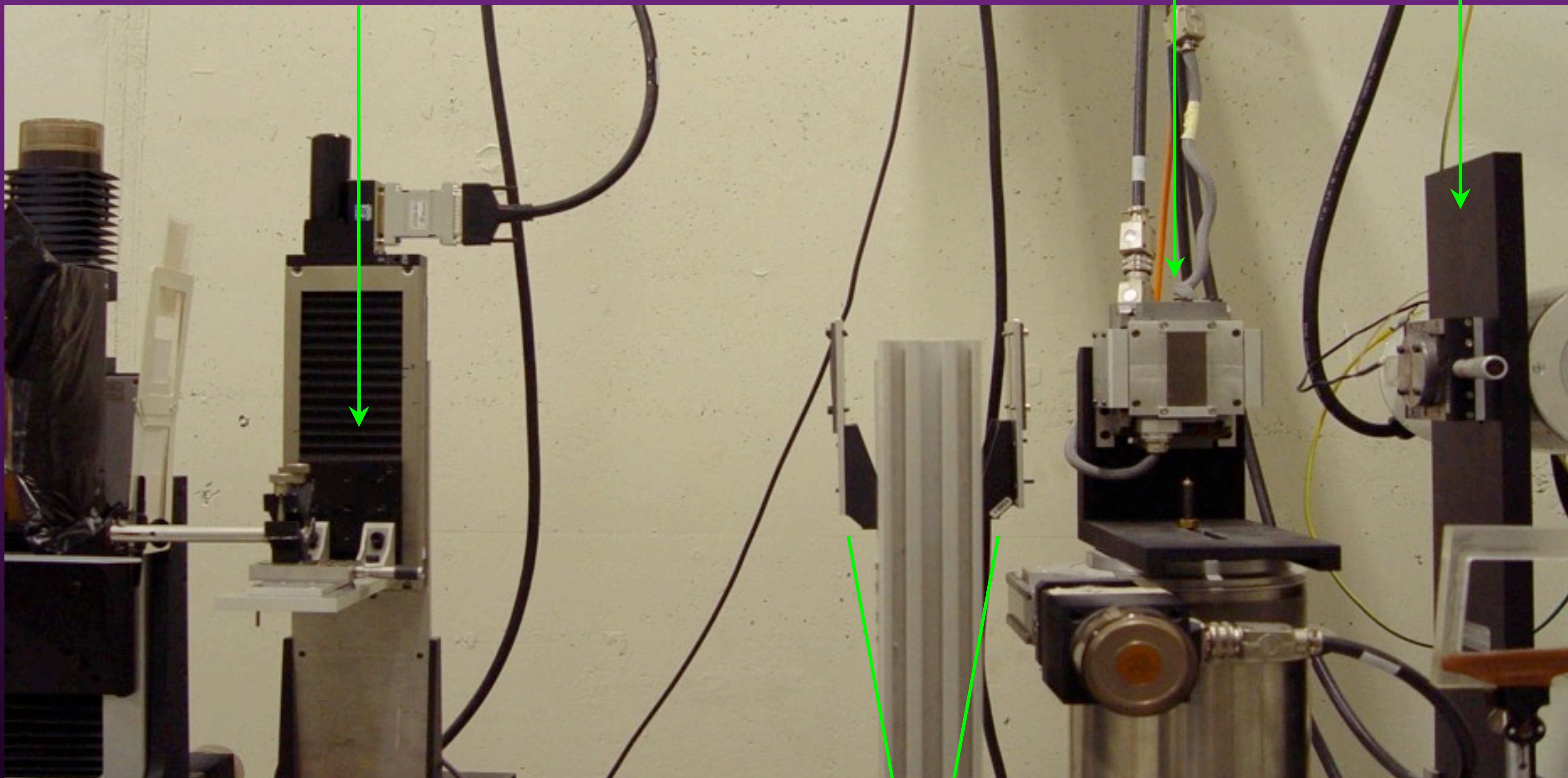


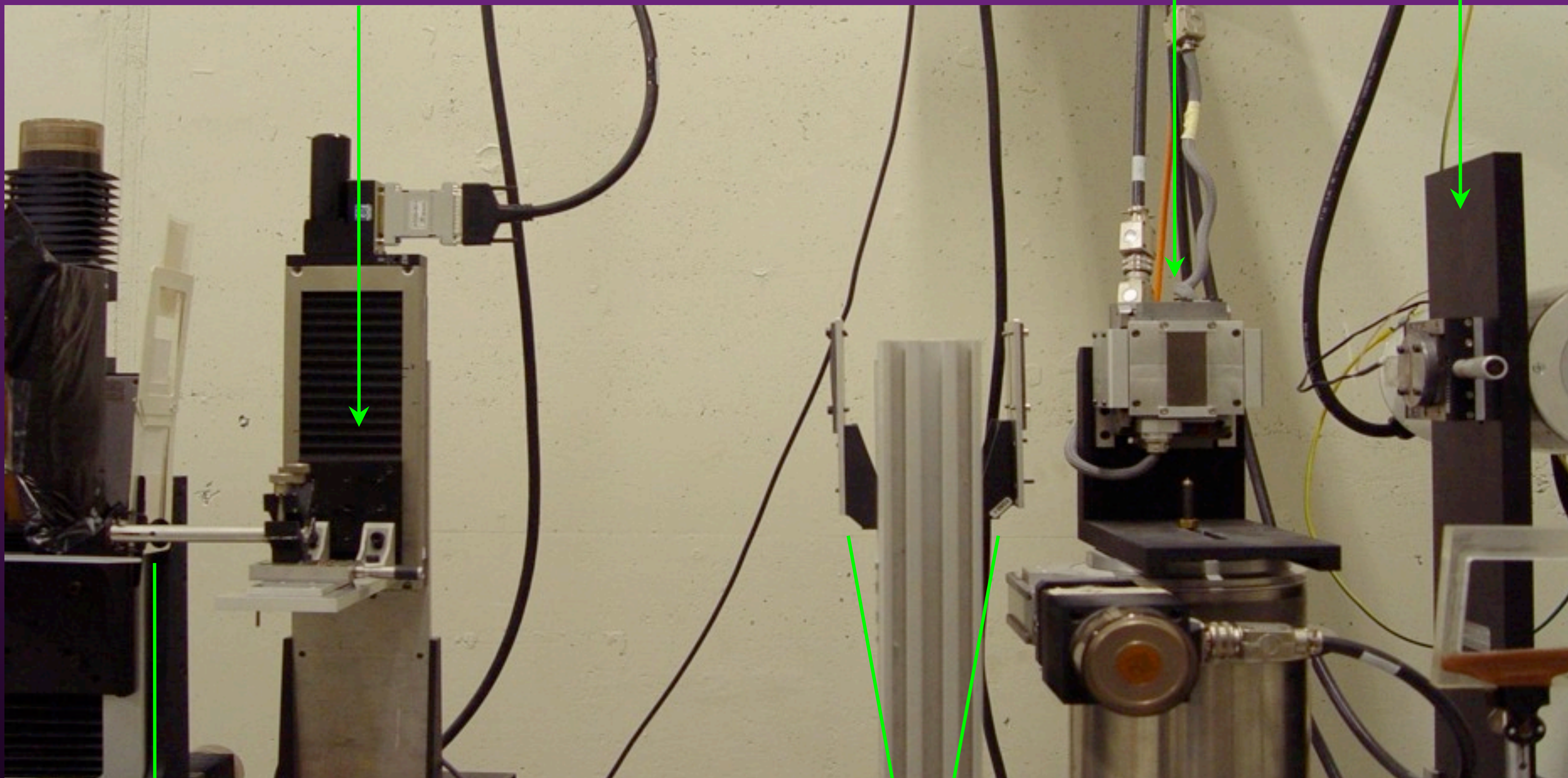
X-ray tube

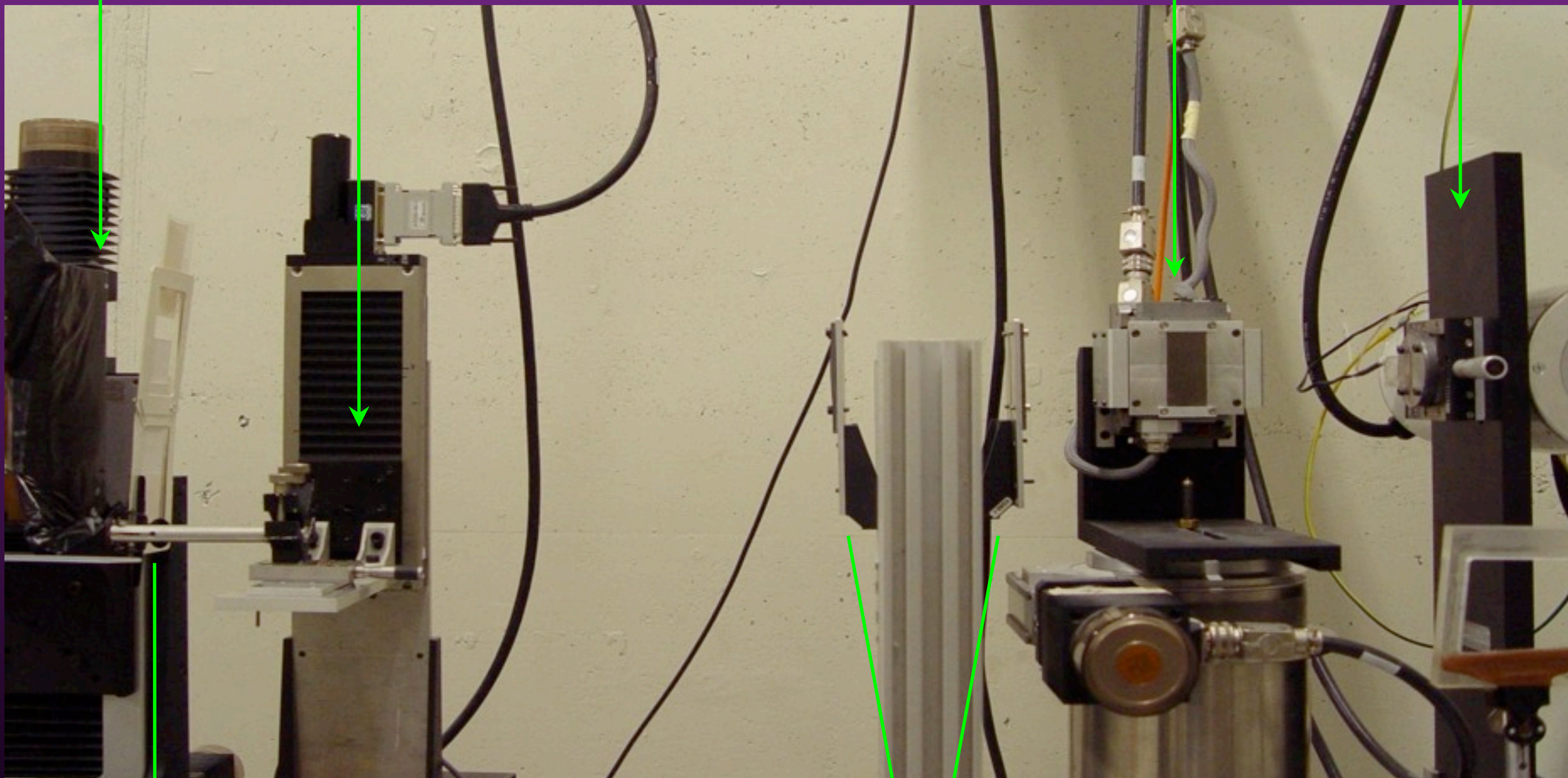



X-ray tube
Cristall


X-ray tube
Cristall
Collimators


Step motor
X-ray tube
Cristall
Collimators


Step motor
X-ray tube
Cristall
Collimators
Test Object


Detector
Step motor
X-ray tube
Cristall
Collimators
Test Object

CCD detector

150x6 mm

3075x128 pixel

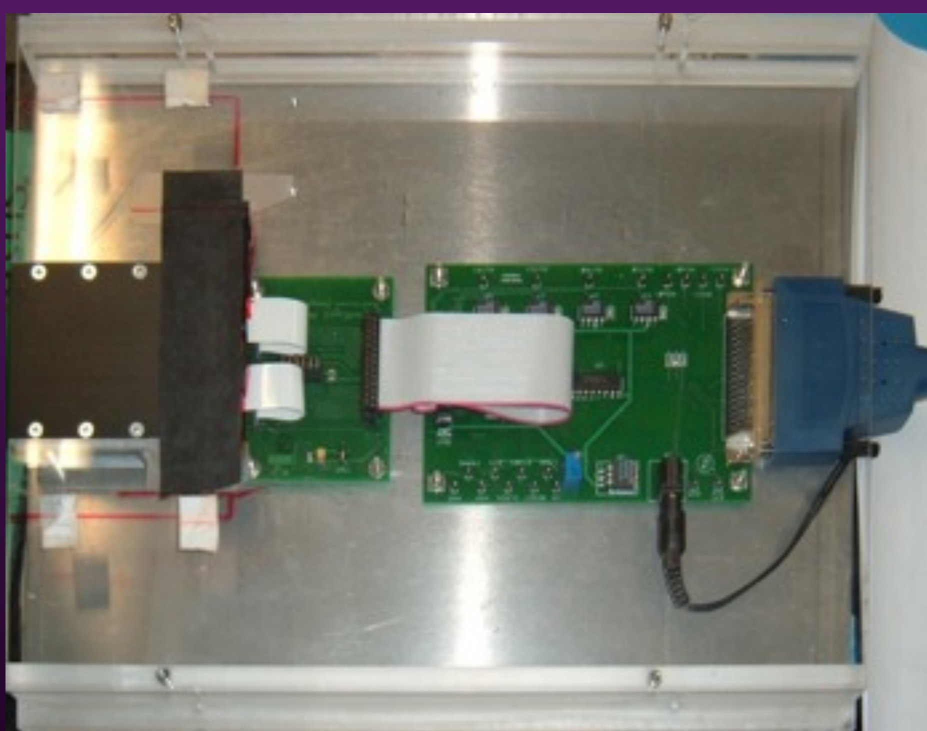
pixel size 48x48 μm

Voltage 19.5 keV; current 80mA; acquisition time 5 sec

E below K-edge = 9.29 keV

E above K-edge = 10.08 keV

CMOS detector



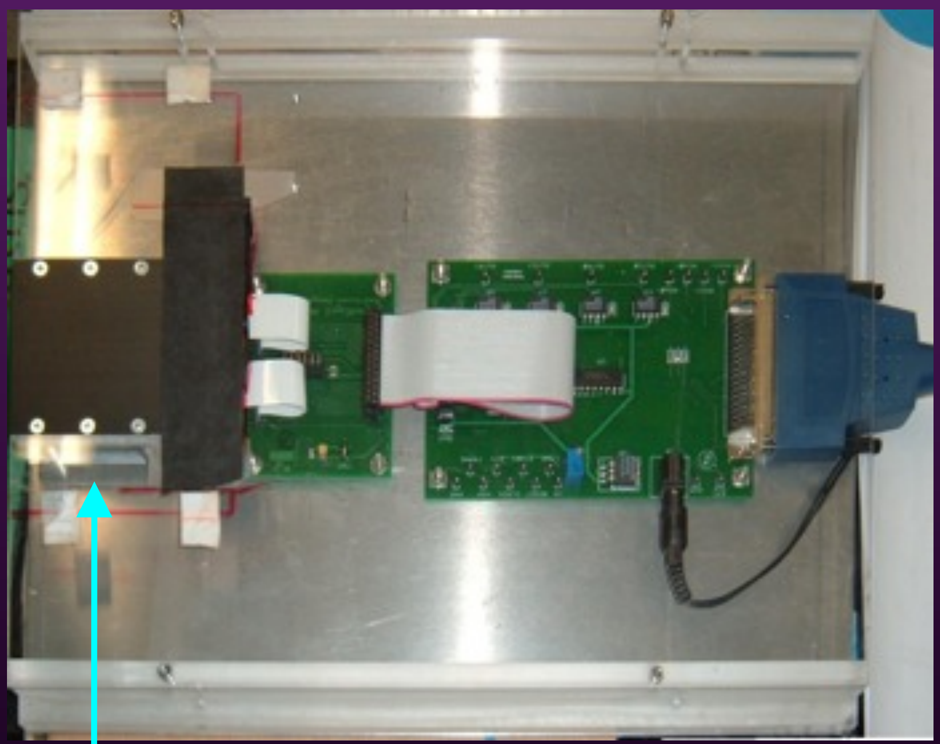
50x50 mm

1024x1024 pixel

pixel size48x48 μm

due differenti aree sensibili di uguali dimensioni

CMOS detector



50x50 mm

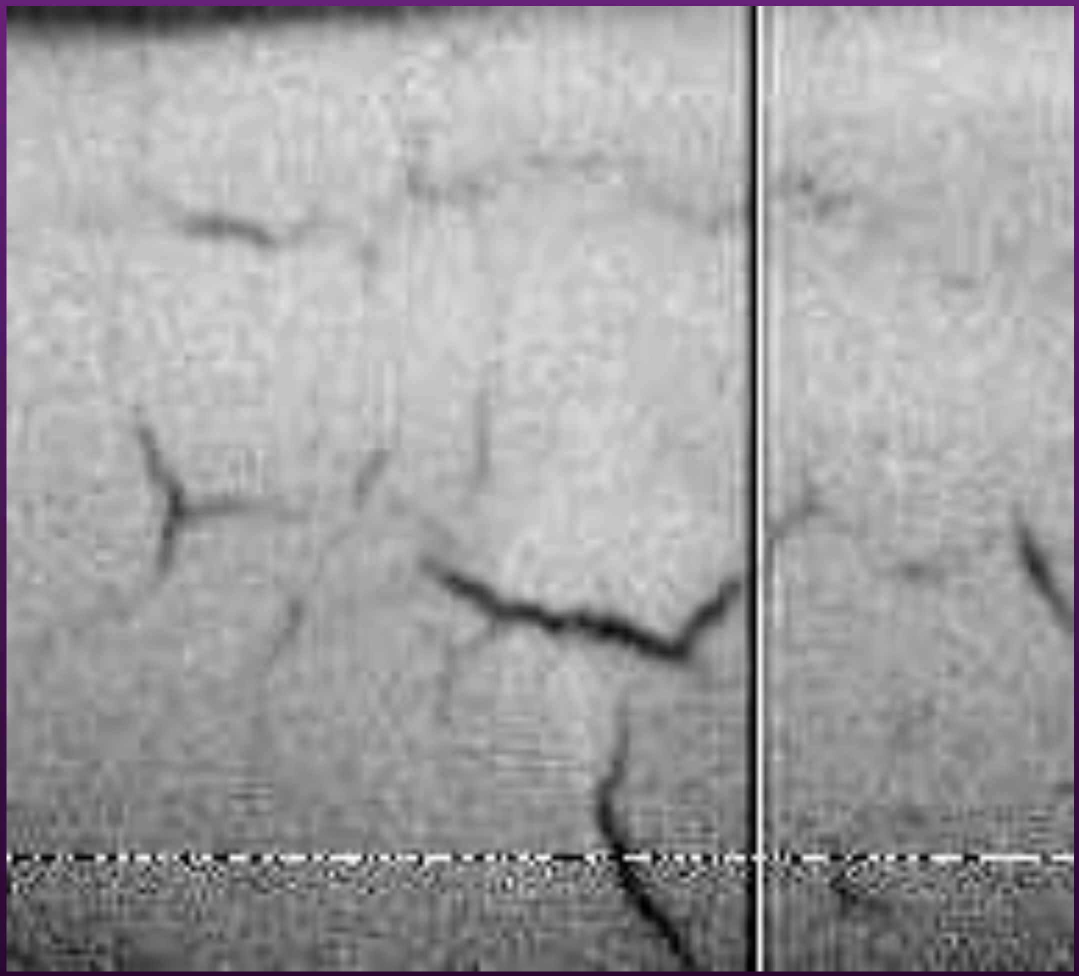
1024x1024 pixel

pixel size48x48 μm

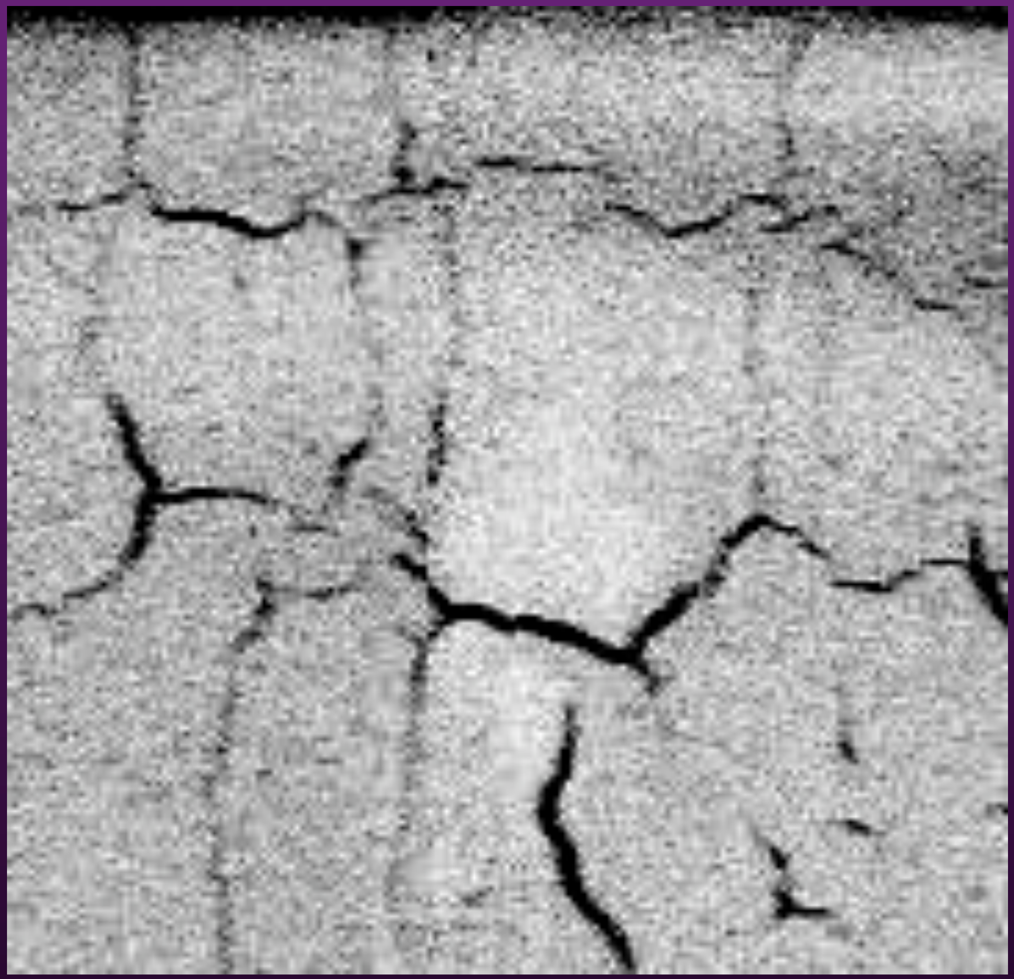
due differenti aree sensibili di uguali dimensioni

Active area

Different resolution



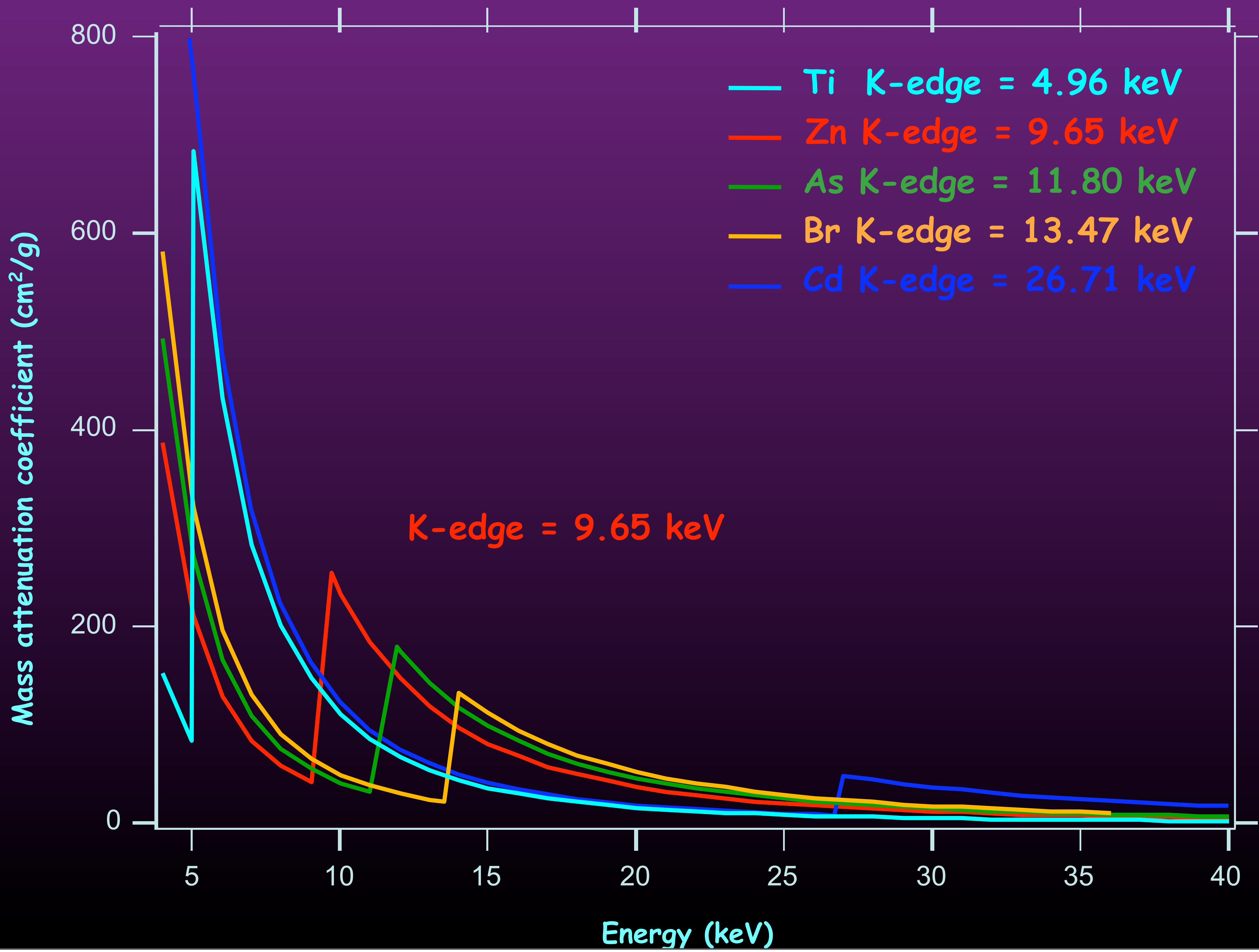
CMOS



CCD

Elements	K (KeV)	L-I (KeV)	L-II (KeV)	L-III (KeV)	Pigments
29 (Cu)	8.9789	1.0961			Azzurrite, Rosso di Smalto, Resinato di Rame, Verde di Smalto, Verde di Malachite, Verde Veronese, Verdigris
30 (Zn)	9.6586	1.1936	1.0428	1.0197	Bianco di Zinco, Giallo di Cadmio, Verde di Cobalto, Verde di Zinco
33 (As)	11.8667	1.5265	1.3586	1.3231	Realgar, Verde Veronese, Violetto di Cobalto
38 (Sr)	16.1046	2.2163	2.0068	1.9396	Giallo di Stronzio
42 (Mo)	19.9995	2.8655	2.6251	2.5202	Arancio di Cromo
48 (Cd)	26.7112	4.018	3.727	3.5375	Arancio di Cadmio, Giallo di Cadmio, Giallo di Smalto, Rosso di Cadmio, Verde di Cadmio
80 (Hg)	83.1023	14.8393	14.2087	12.2839	Cinabro di Miniera
82 (Pb)	88.0045	15.8608	15.2	13.0352	Arancio di Cromo, Giallo di Cromo, Giallo di Napoli, Giallo di Piombo – Stagno, Litargirio, Massicot, Bianco di Piombo,Verde di Cinabro, Minio, Rosso di Cromo
83 (Bi)	90.5259	16.3875	15.7111	13.4186	Bianco di Bismuto

Absorption peaks



Dual energy at ATF

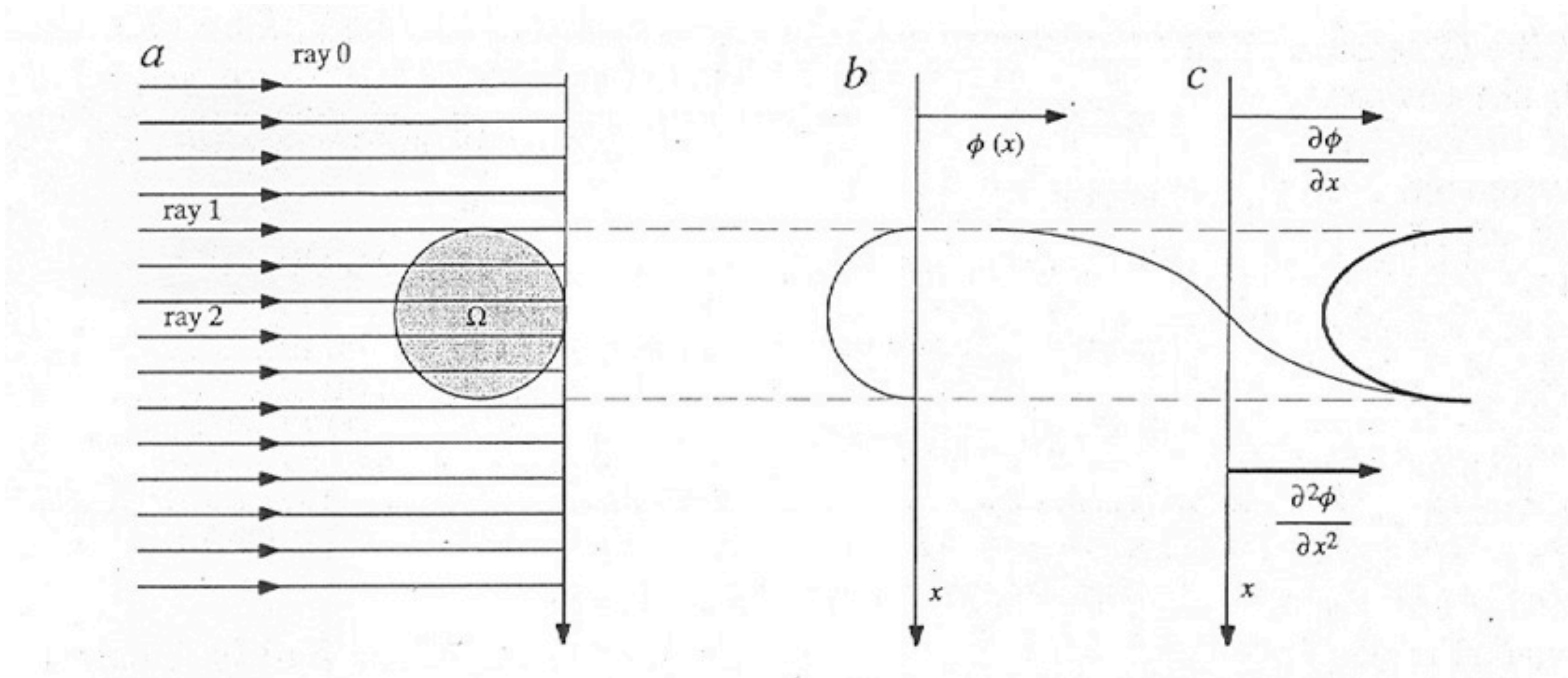
- ICS quasi-monochromatic and tunable X-ray source are very promising to produce in short time maps of several pigments

Phase Contrast Imaging

- Based on the fact that for several biological tissues, elastic cross section (causing a shift in the X-ray phase) is mach bigger then absorption cross section
- Observation of interference pattern
- Edge enhancement in the image
- In-line (propagation based) was first proposed by Snigirev (1995)

PHASE CONTRAST IMAGING

Modulation of the intensity on the detector can be described in terms of refraction index. The real part affect the phase, the imaginary one the absorption. In-line phase contrast sensitive to ∇2φ).

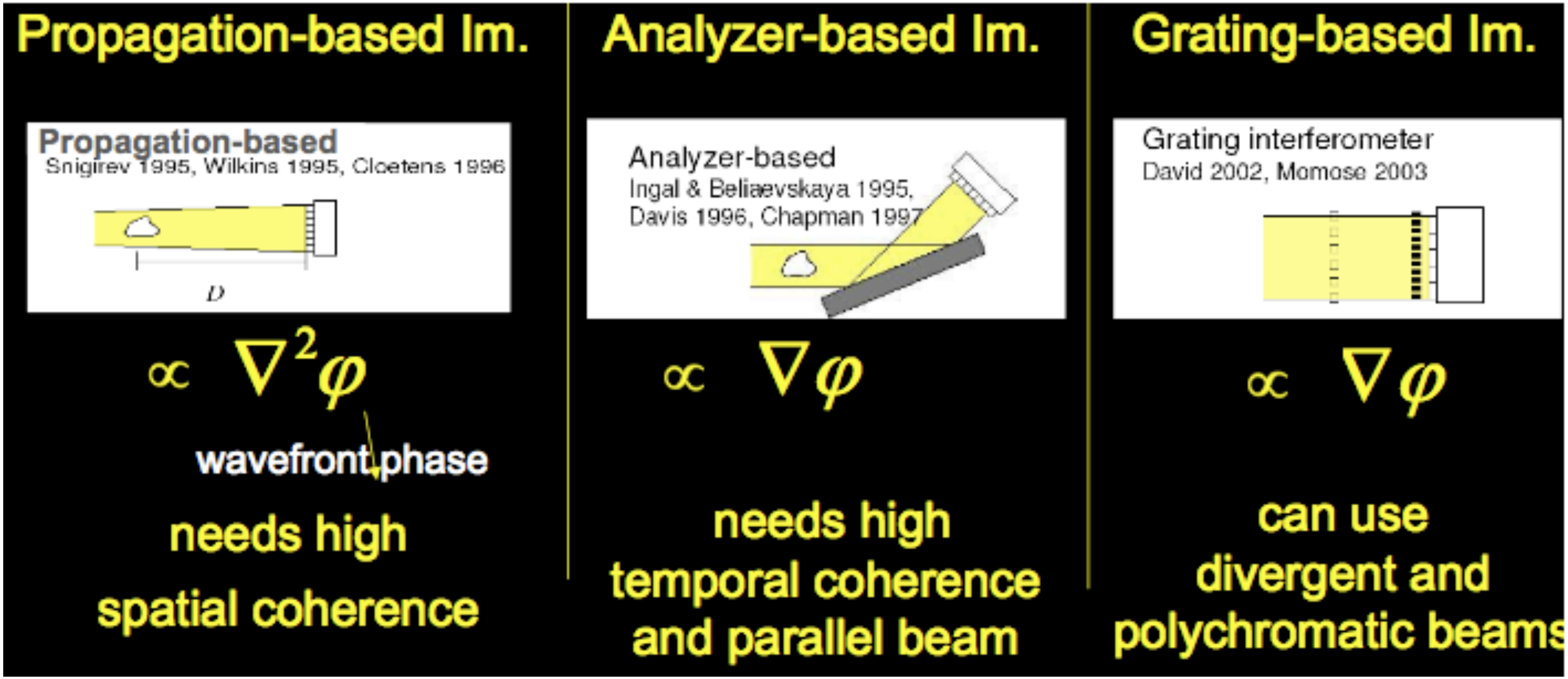


$n=1-\delta-i\beta$

$$\phi = -\frac{2\pi}{\lambda}\int \delta(s)\,ds$$

β: absorption (10^{-9} –10^{-11})*
δ: phase shift (10^{-6} –10^{-8})*
*)biological tissues, for x ray at the 10-100keV range

Various PCI



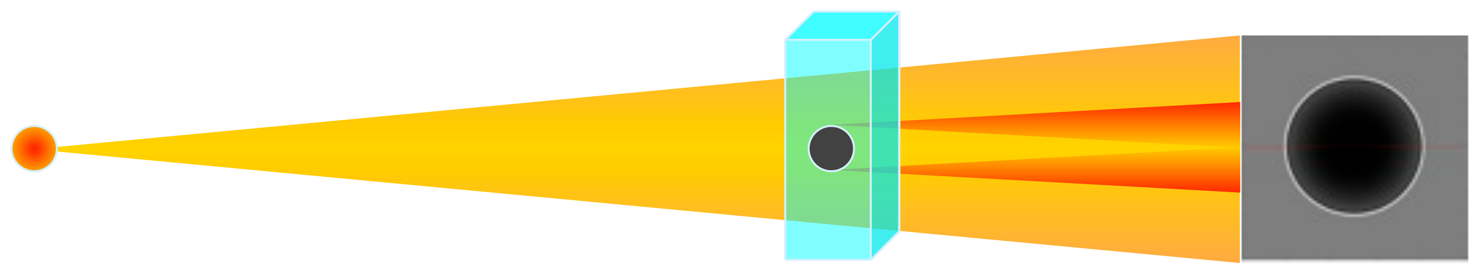
1 image

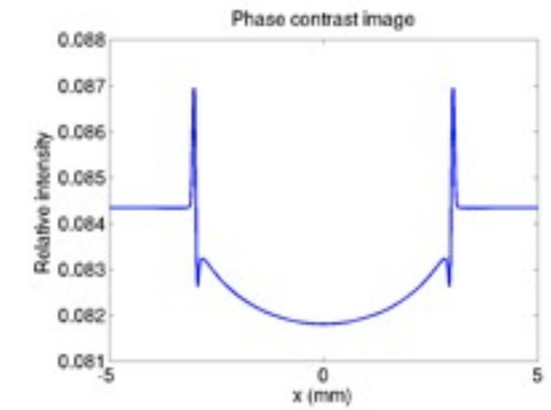
several images

several images

Flux, dose, sample movements have to be considered

X-ray Phase Contrast imaging technique





- ✓ Transverse coherence length:
  - small source linear size
  - large source-object distance

$$l_t \approx \frac{z_{obj}}{S}$$

l_t: coherence length
z_{obj}: source-object distance
λ: wave length
S: linear dimension of the source

- ✓ Longitudinal coherence length
  - small Energy Bandwidth

- ✓ Phase contrast imaging using a polychromatic beam
  - first demonstrated by Wilkins et al.

Some typical ICS source parameters

- ✓ Small source size: FWHM ≈ 10-20 μm
- ✓ Small angular divergence: θ ≈ 5 mrad
  ⇒ relatively high intensity at large distance from the source
- ✓ Quasi-monochromatic spectrum:
  ☛ energy bandwidth relatively small compared to x-ray tube systems

Some typical ICS source parameters

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⇒ ICS sources are suitable for Phase Contrast imaging

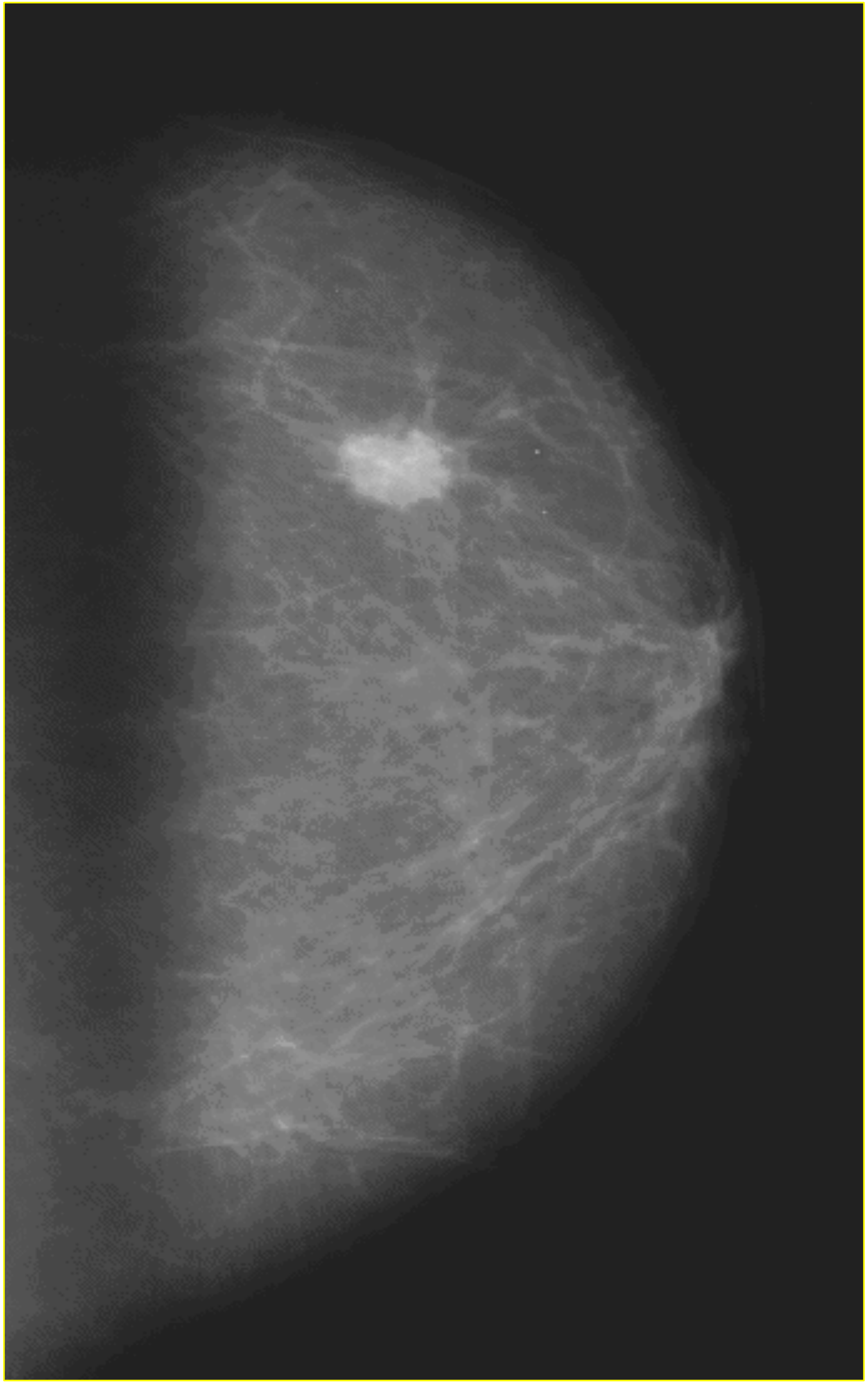
Mammography

- Challenging imaging task:
  - Normal and pathological tissues have very similar attenuation coefficients ⇨ Low contrast
  - Need to image small (100μm) details ⇨ High spatial resolution

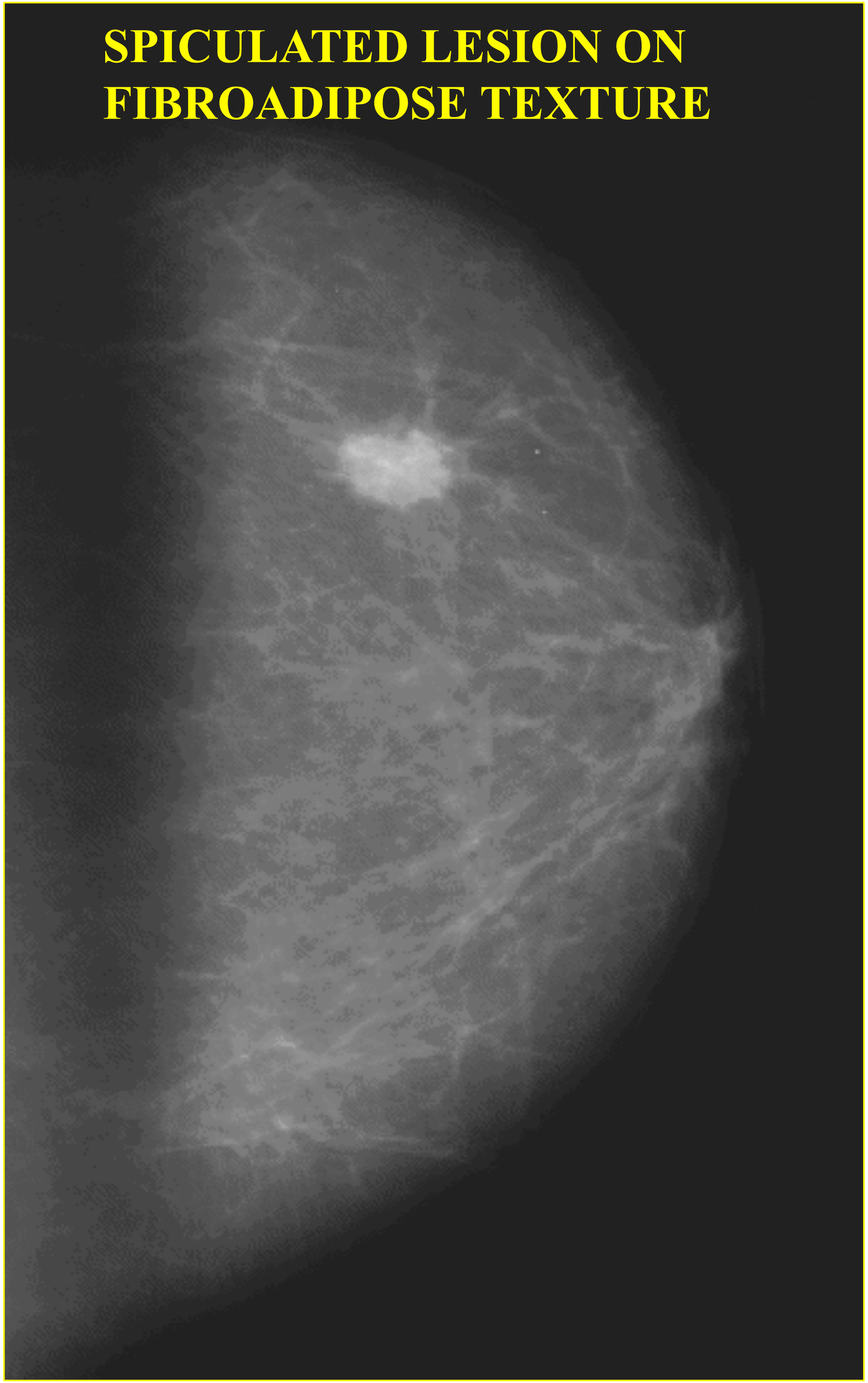
- Fluence: compromise between image quality and delivered dose
- Best energy: depends on breast thickness and composition
- It has to match imaging detector efficiency.
- Accepted values for the best energy useful in mammography range:

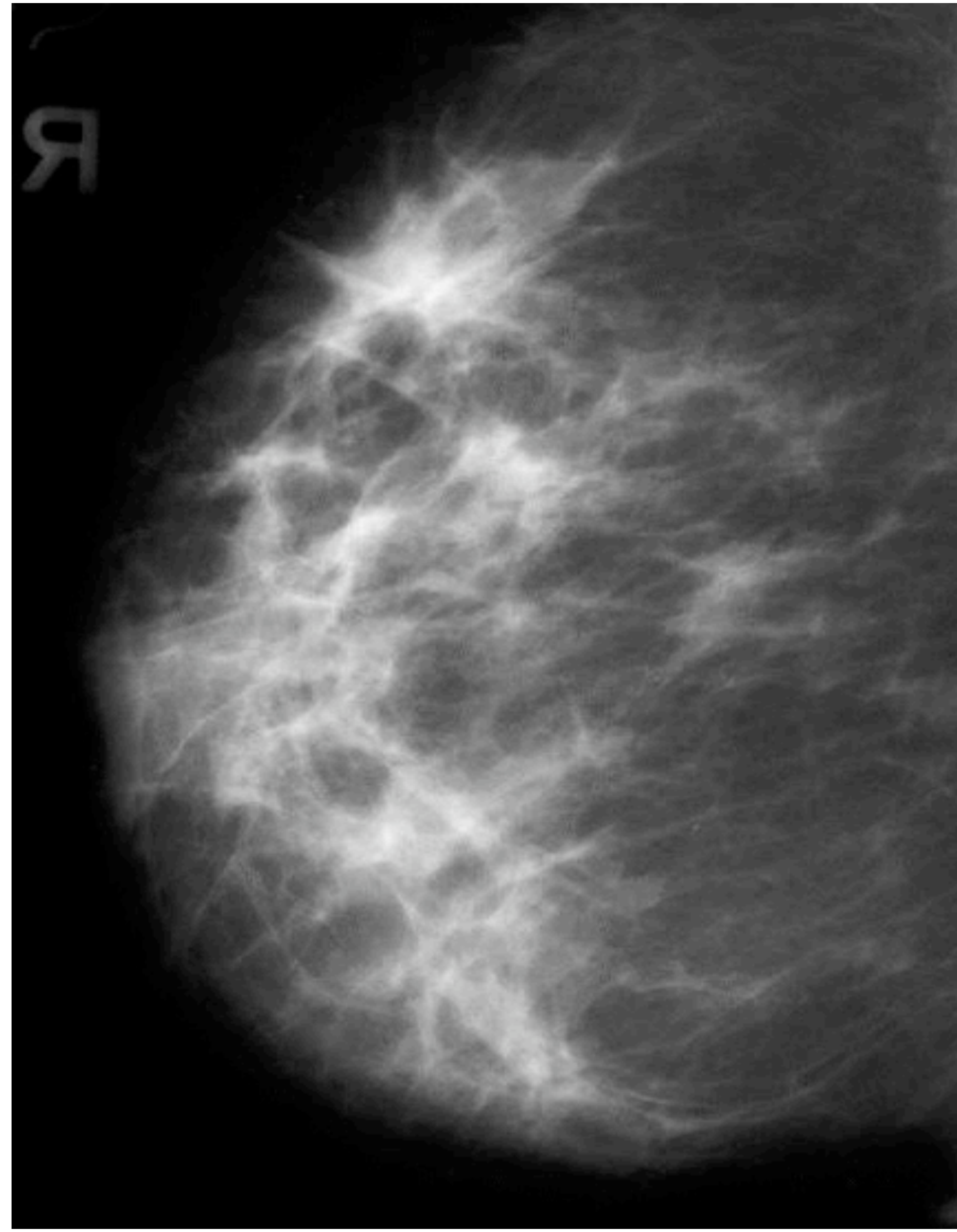
from 17keV to 25keV

MAMMOGRAPHY - MASSIVE TUMORS



MAMMOGRAPHY - MASSIVE TUMORS





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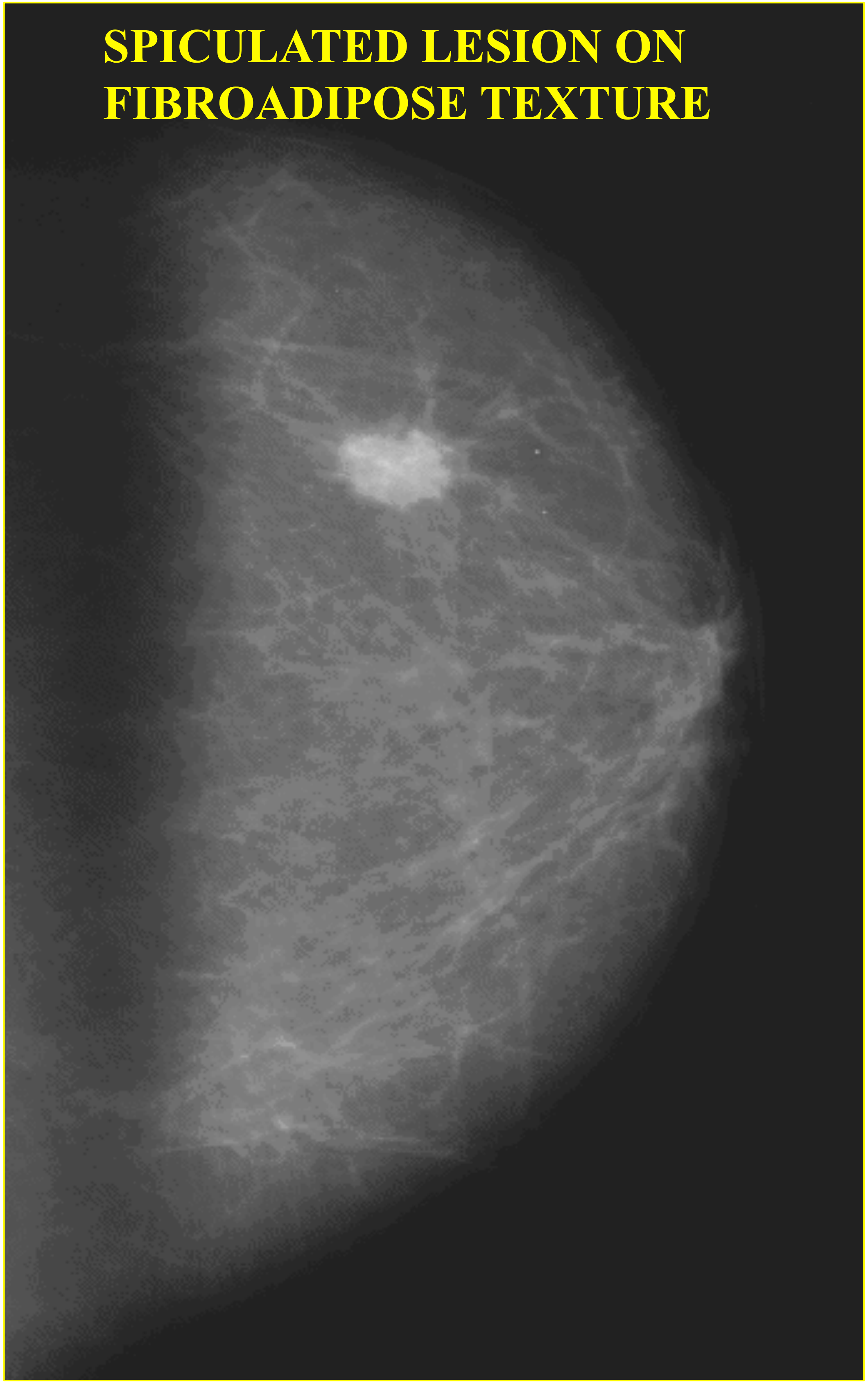

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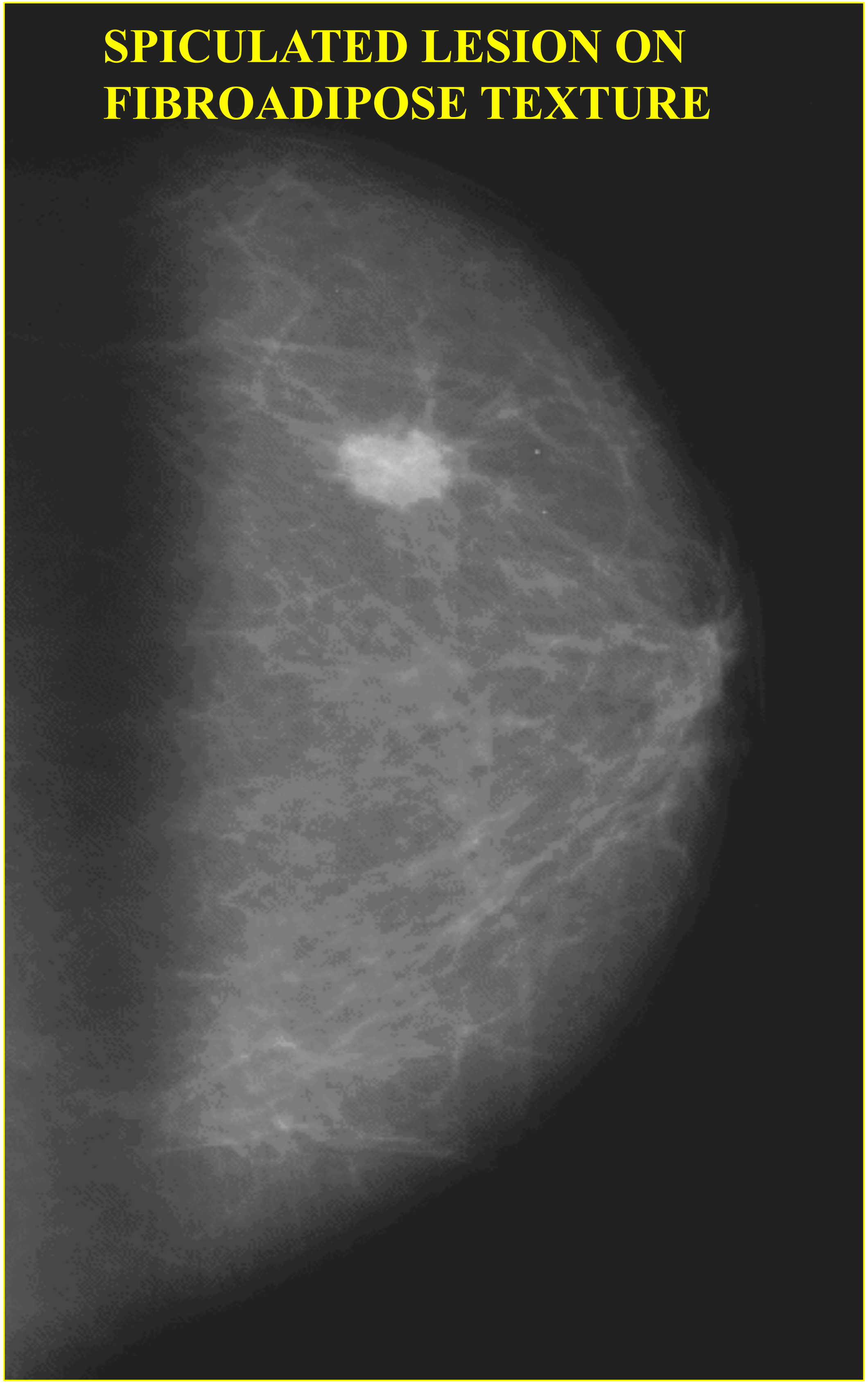
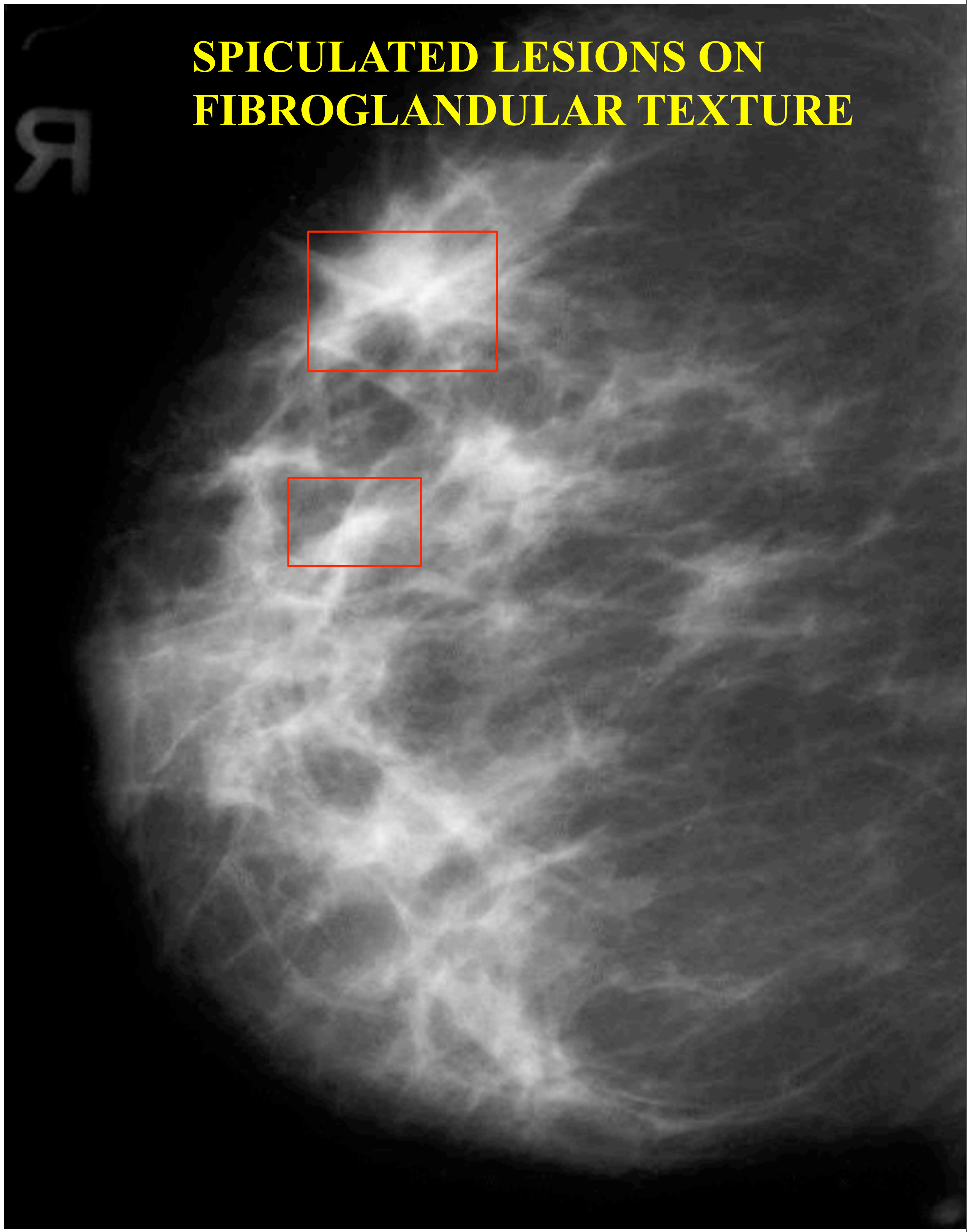
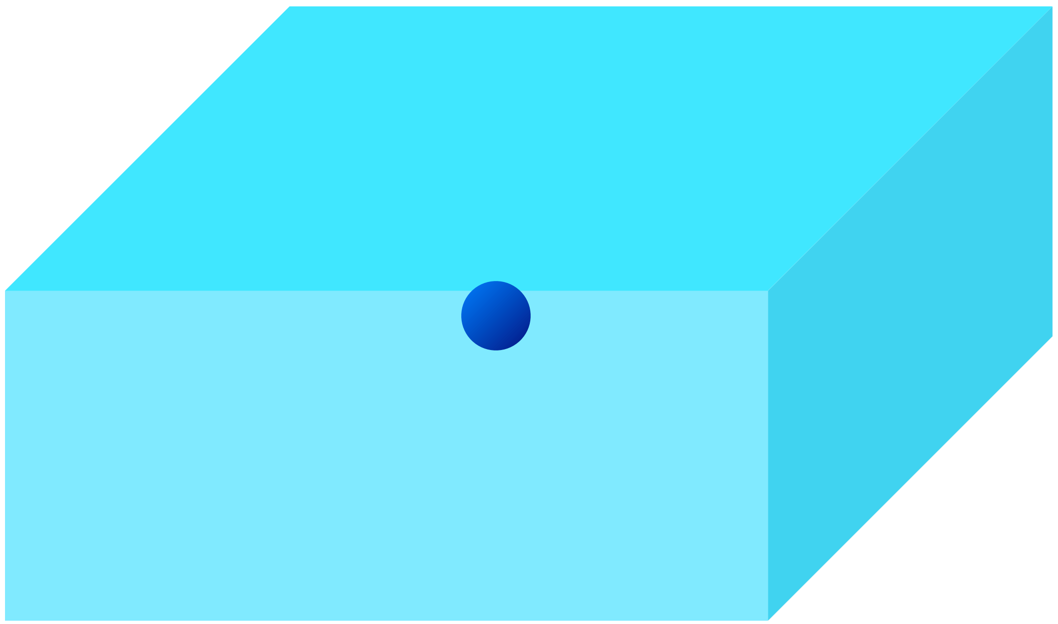




Simulated Reference Sample and parameters for mammography

- Tumor like mass
  - Spherical shape
  - 1 mm diameter
  - glandular tissue composition
  - density 1.044 g/cm^3
- Breast tissue
  - 4 cm thickness
  - 50 % glandular tissue
  - 50 % adipose tissue
  - density 0.984 g/cm^3
- Compositions from ICRU 44
- Dose: 1.5 mGy
- Fluence: $2.09 \cdot 10^7$ photons/mm^2 at 20 keV monochromatic energy



Simulation tools

- ✓ XRAYLIB: software libraries of x-ray fundamental parameters
  ⇒ compound materials refractive index real and imaginary part relatively

- ✓ Specialized Monte Carlo simulation software based on variance reduction techniques, much faster than other general purpose Monte Carlo Codes
  ⇒ detailed study of absorption imaging using monochromatic, polychromatic and quasi-monochromatic sources, role of scattering background, etc.

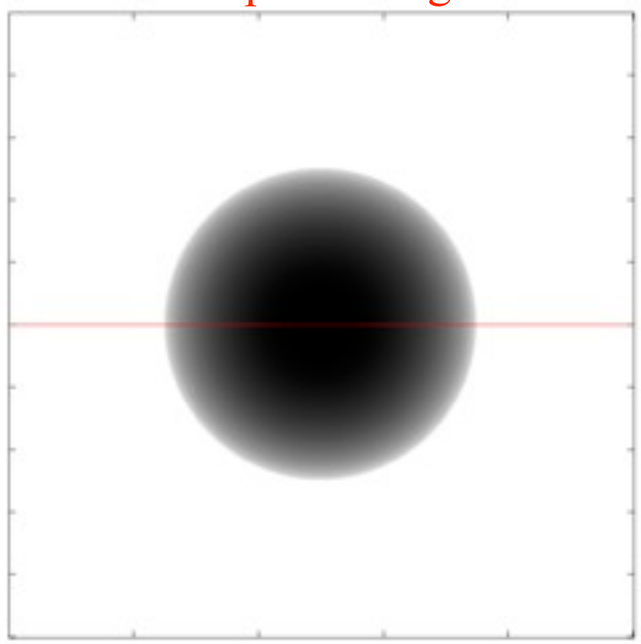
- ✓ Phase Contrast imaging simulation software based on Geometrical Optics

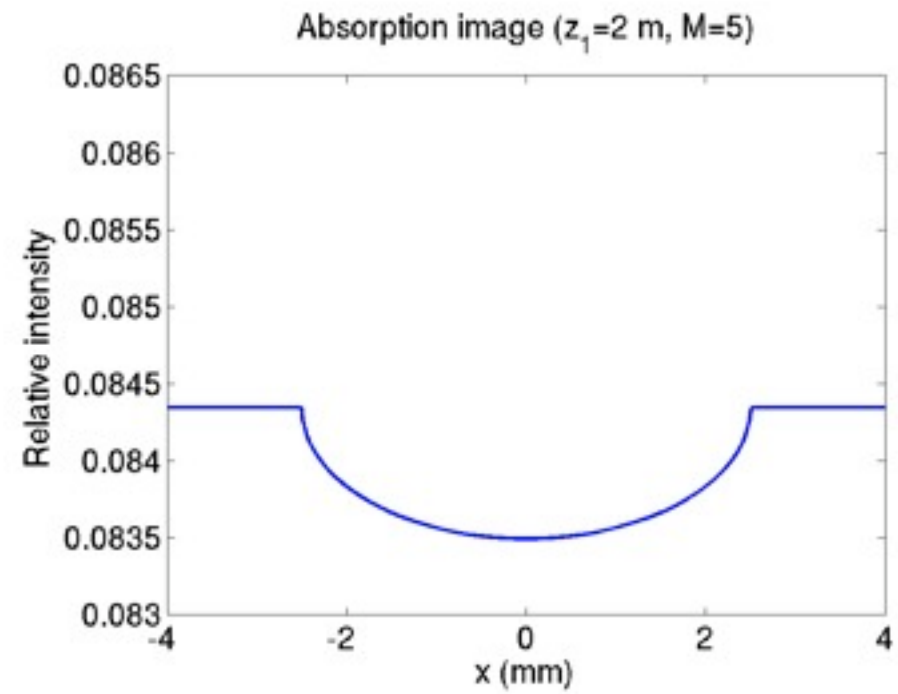
- ✓ Phase Contrast imaging simulation software based on Fresnel-Kirchhoff integrals

- ✓ Comparison among Phase Contrast imaging simulation methods and experimental measurements

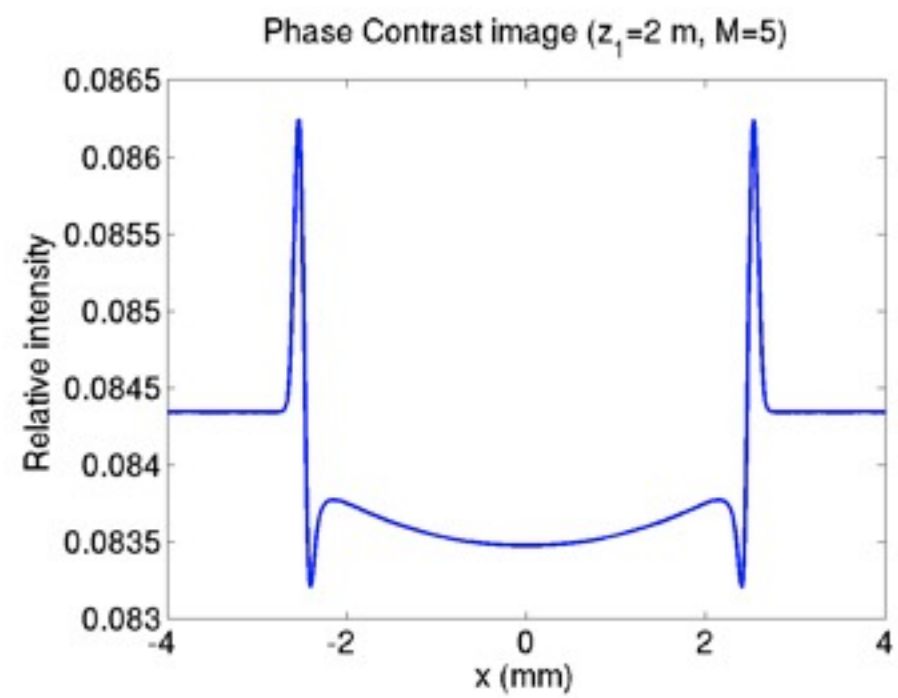
Simulated image of a tumor-like object (d=1mm) in breast tissue

Absorption image

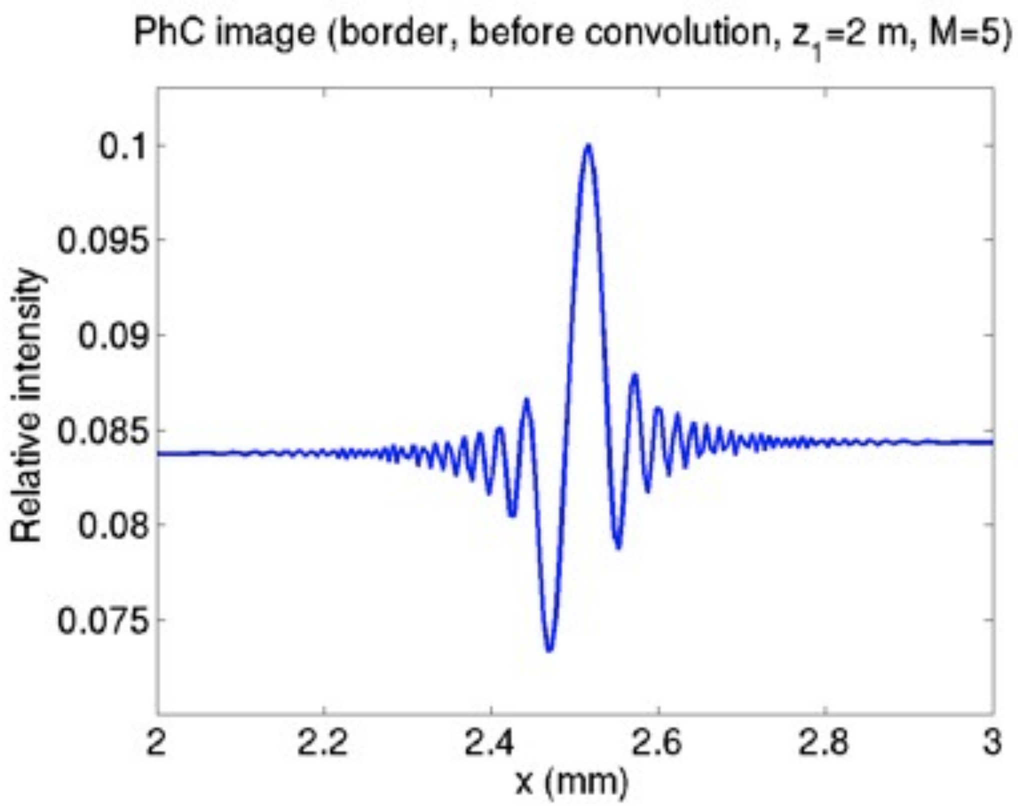


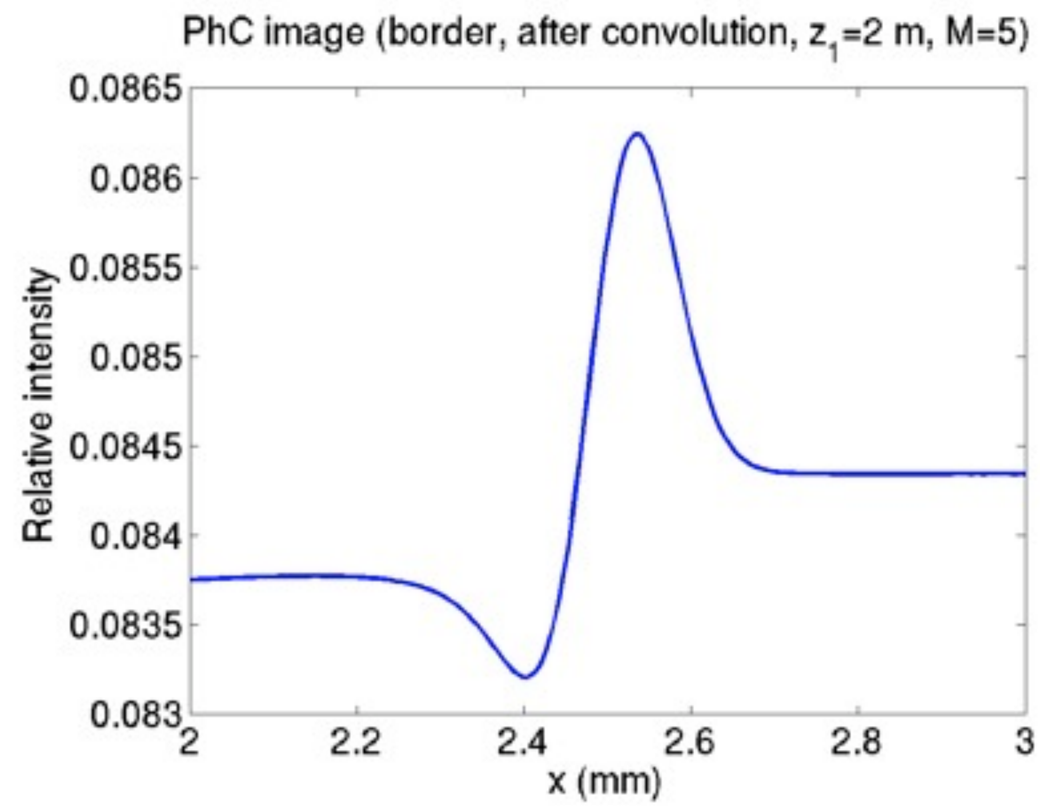


Phase Contrast image

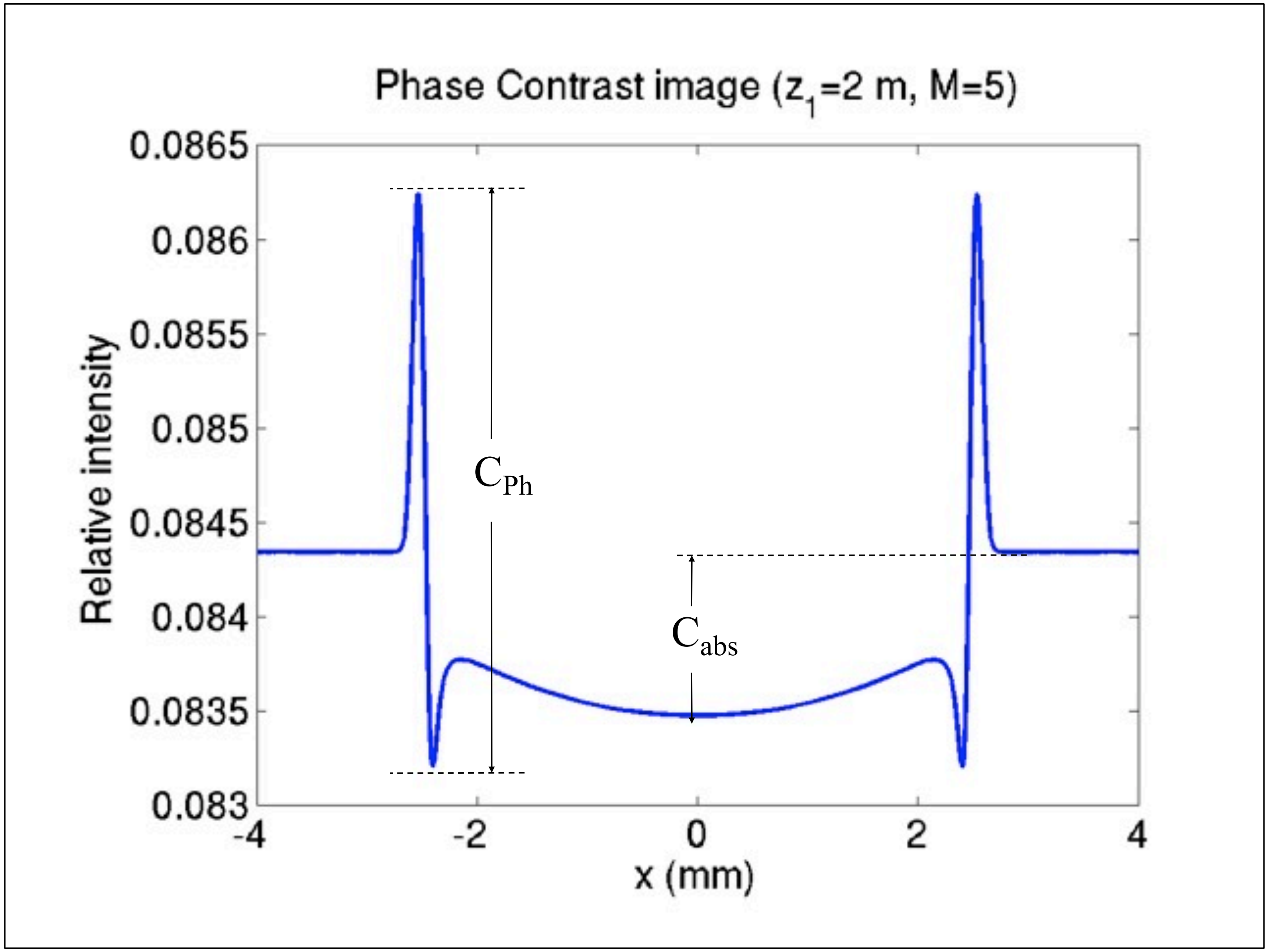


Effect of source size and detector PSF





Edge Enhancement Index (EEI)



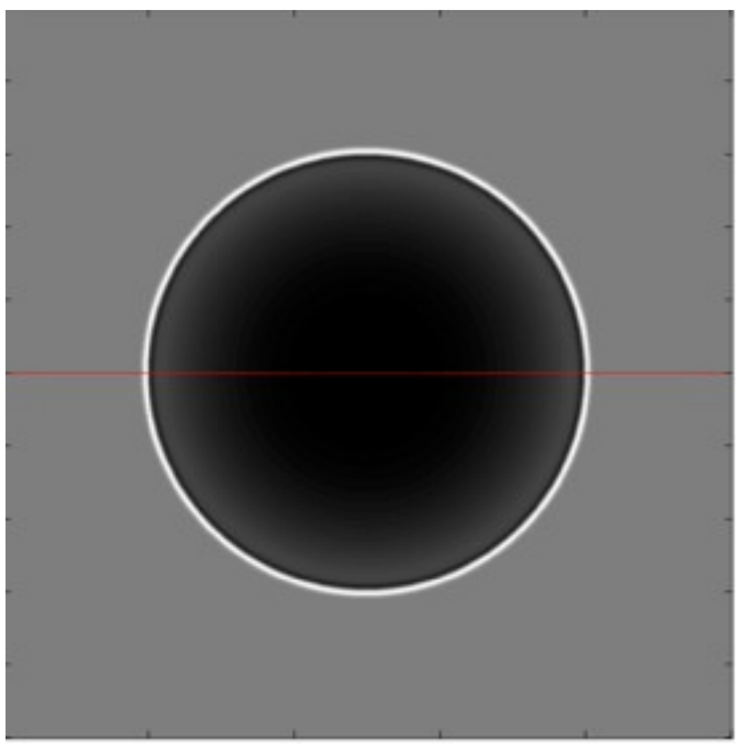
C_{Ph} : Phase Contrast

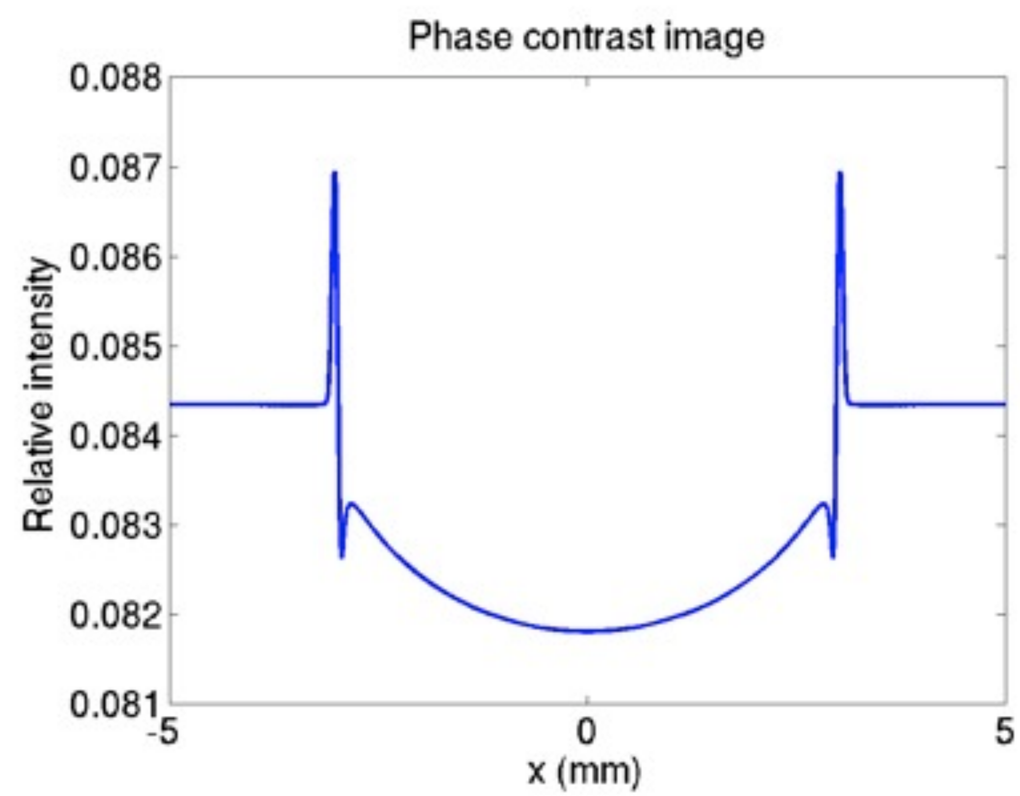
C_{abs} : Absorption Contrast

$$EEI = \frac{C_{Ph}}{C_{abs}}$$

Simulated PhC image of tumor-like object in breast tissue

- ✓ Detail diameter: 3 mm, slab thickness 4 cm
- ✓ monochromatic energy 1 keV
- ✓ detector PSF FWHM 100 μm, source size FWHM 13 μm
- ✓ source-object distance 5 m, object detector distance 5 m



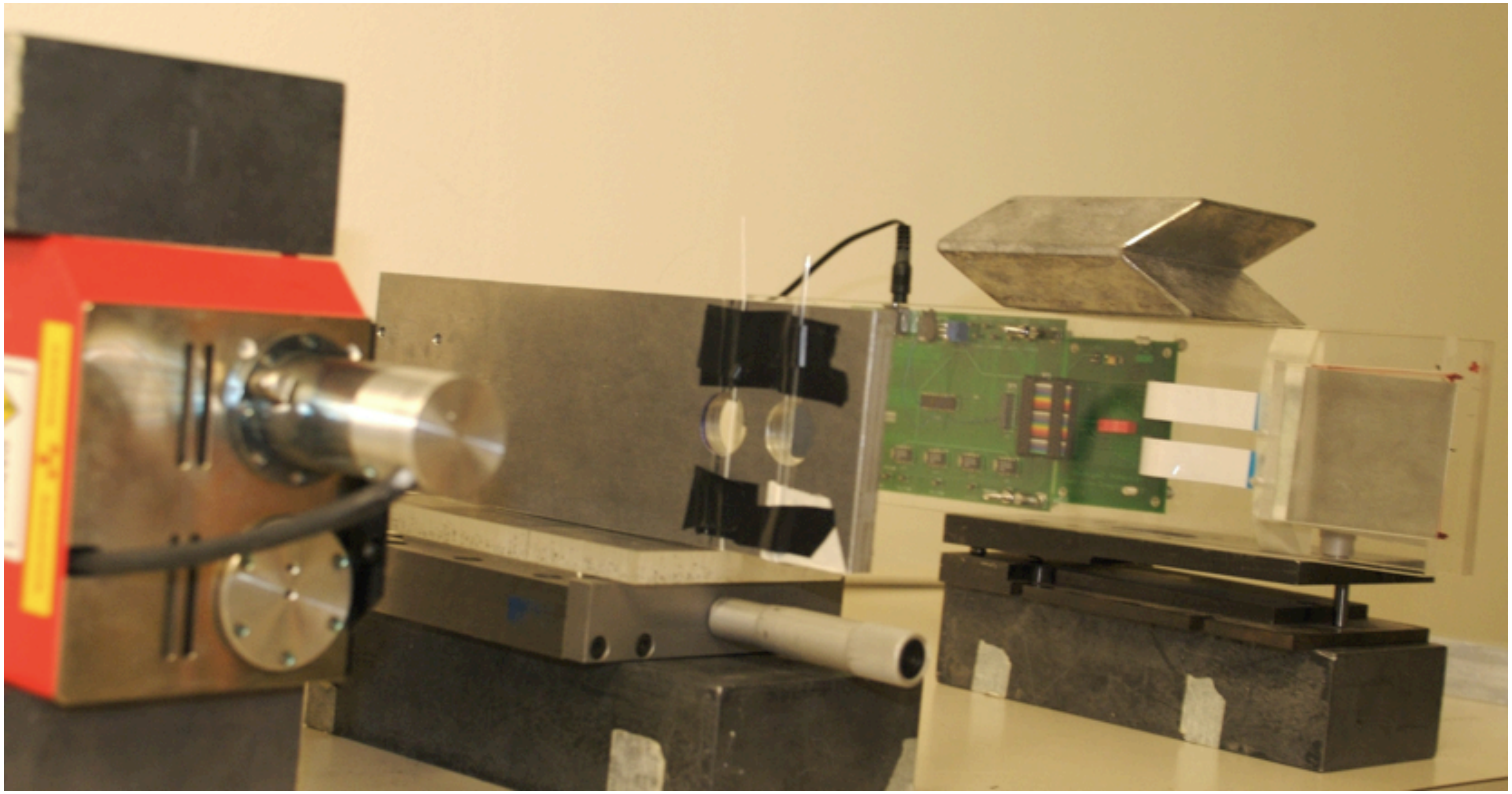


- ✓ Edge enhancement index: EEI>1

Phase Contrast Imaging using standard source

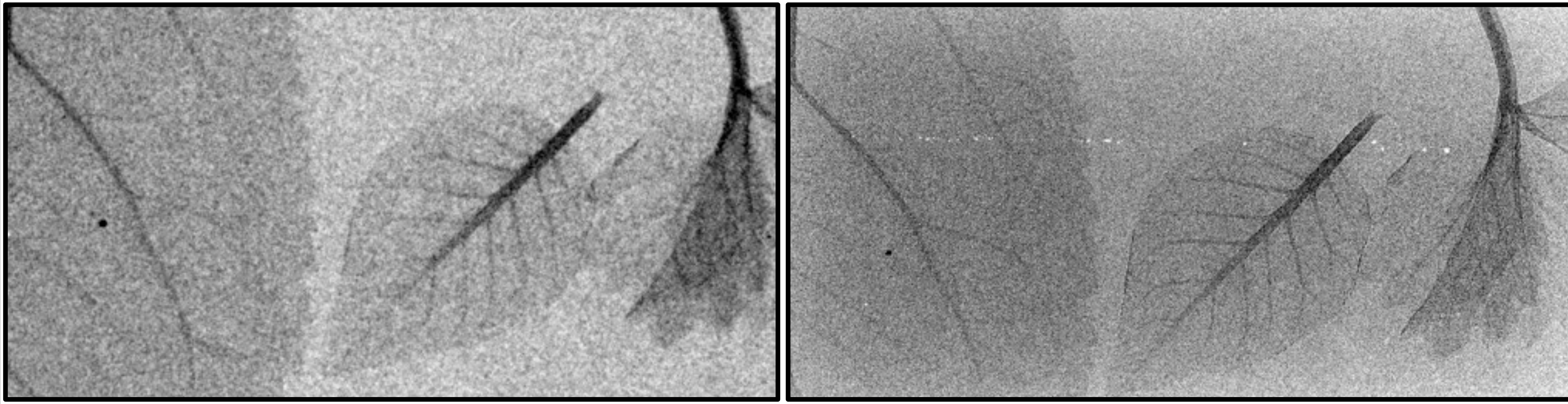
- The Sassari and Pisa group have already performed PCI experiment with standard X-ray source
- Microfocus x-ray tube
- Polymer monofilaments (300 μm–2 mm thickness) in air (if possible also in vacuum/helium)
- CMOS detector

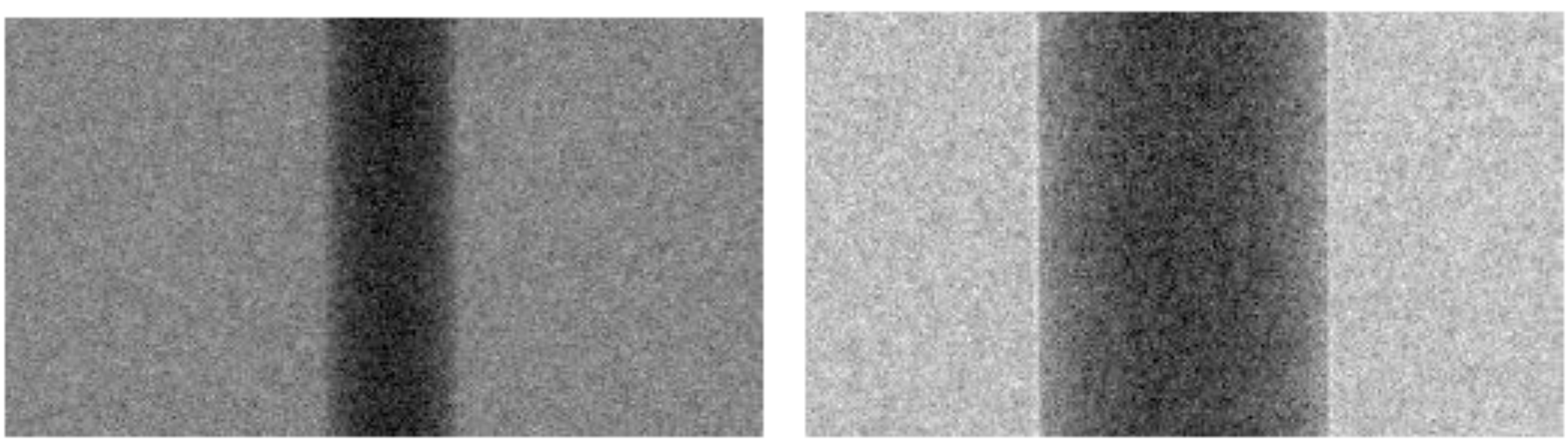
Experimental set-up



microfocus X-ray tube   Phantom   CMOS detector

EDGE ENHANCEMENT

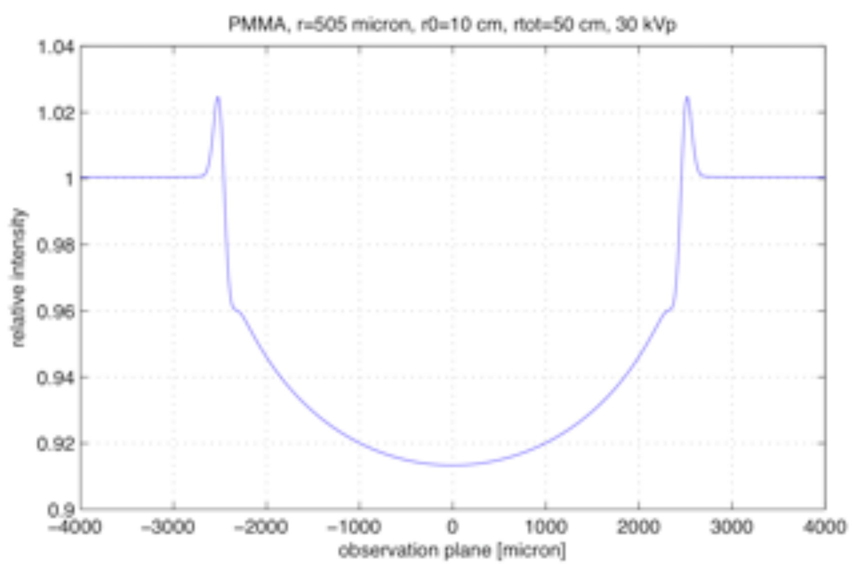




(a) Immagine in assorbimento (b) Edge - enhancement

BEATS – PHASE CONTRAST IMAGING

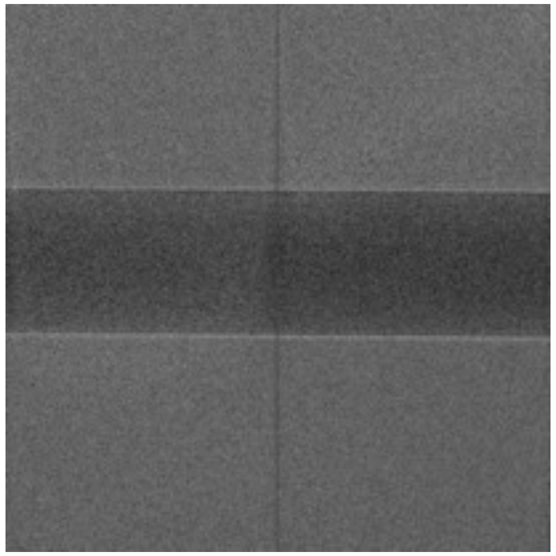
Simulation



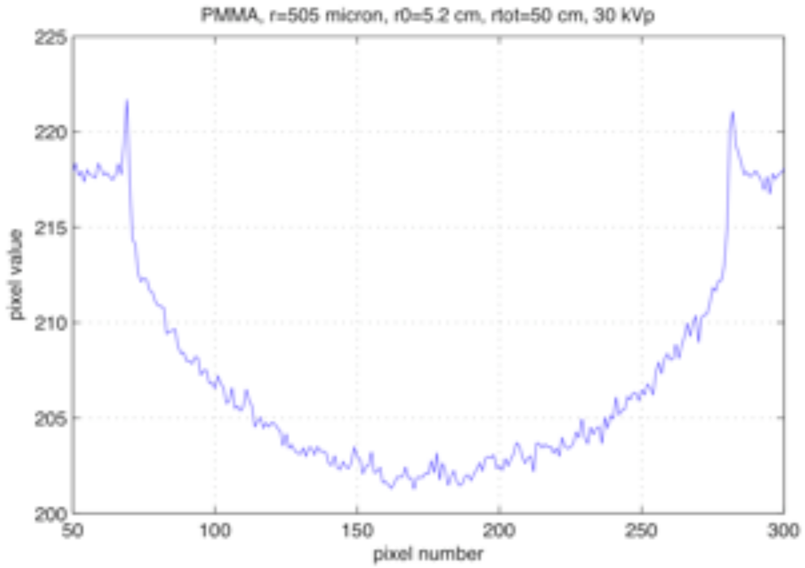
Imaging of a 1 mm PMMA wire in air

Source:
- W microfocus x-ray tube
- Spot size 10μm
- Voltage up to 40 kV

Acquired image



profile

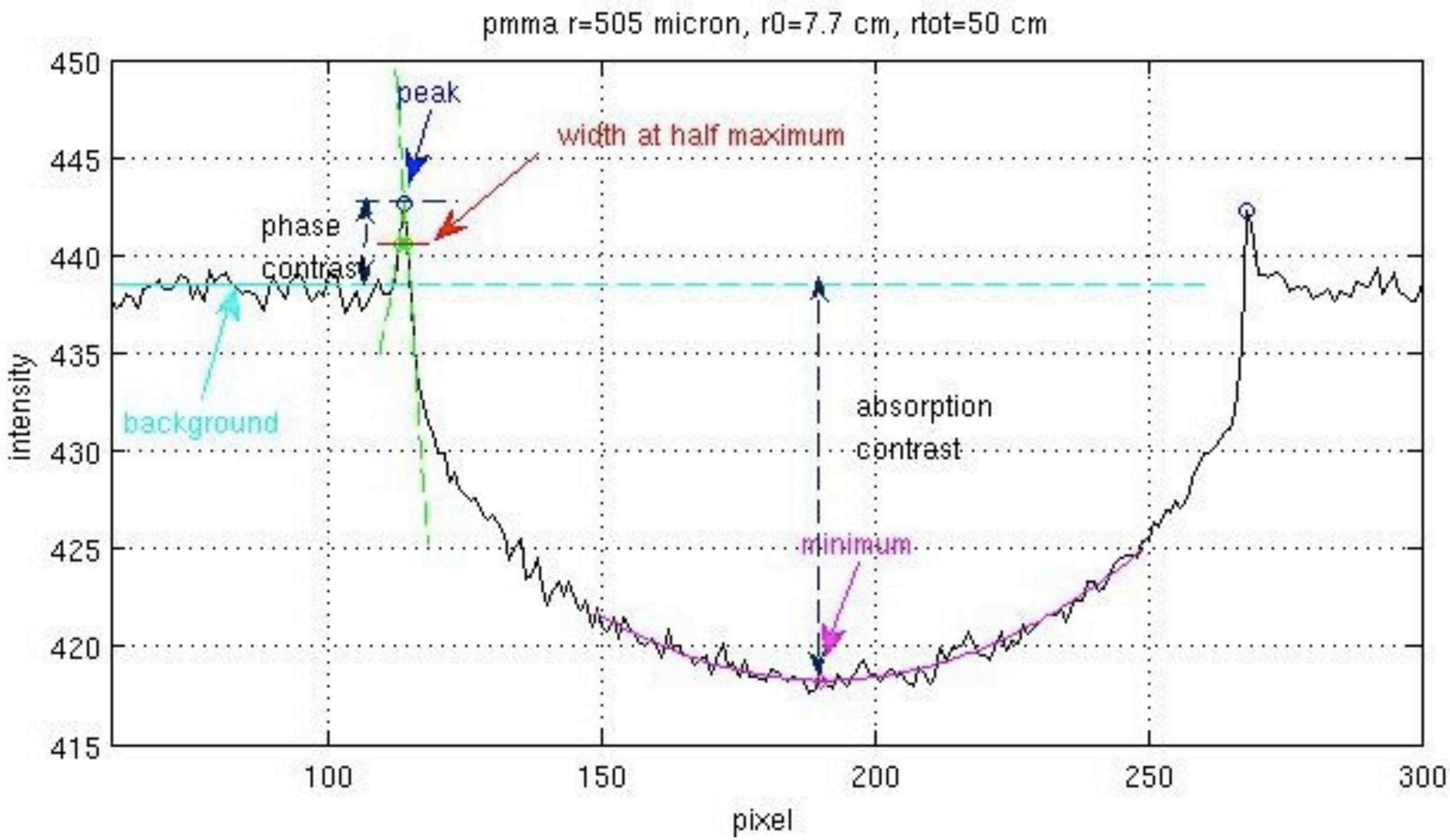


Geometry:
- distance soource-object ~0.1m
- distance source-detector up to 1.5m

CMOS detector:
- pixel size 48μm
- PSF (~ 125μm FWHM)

BEATS – PHASE CONTRAST IMAGING

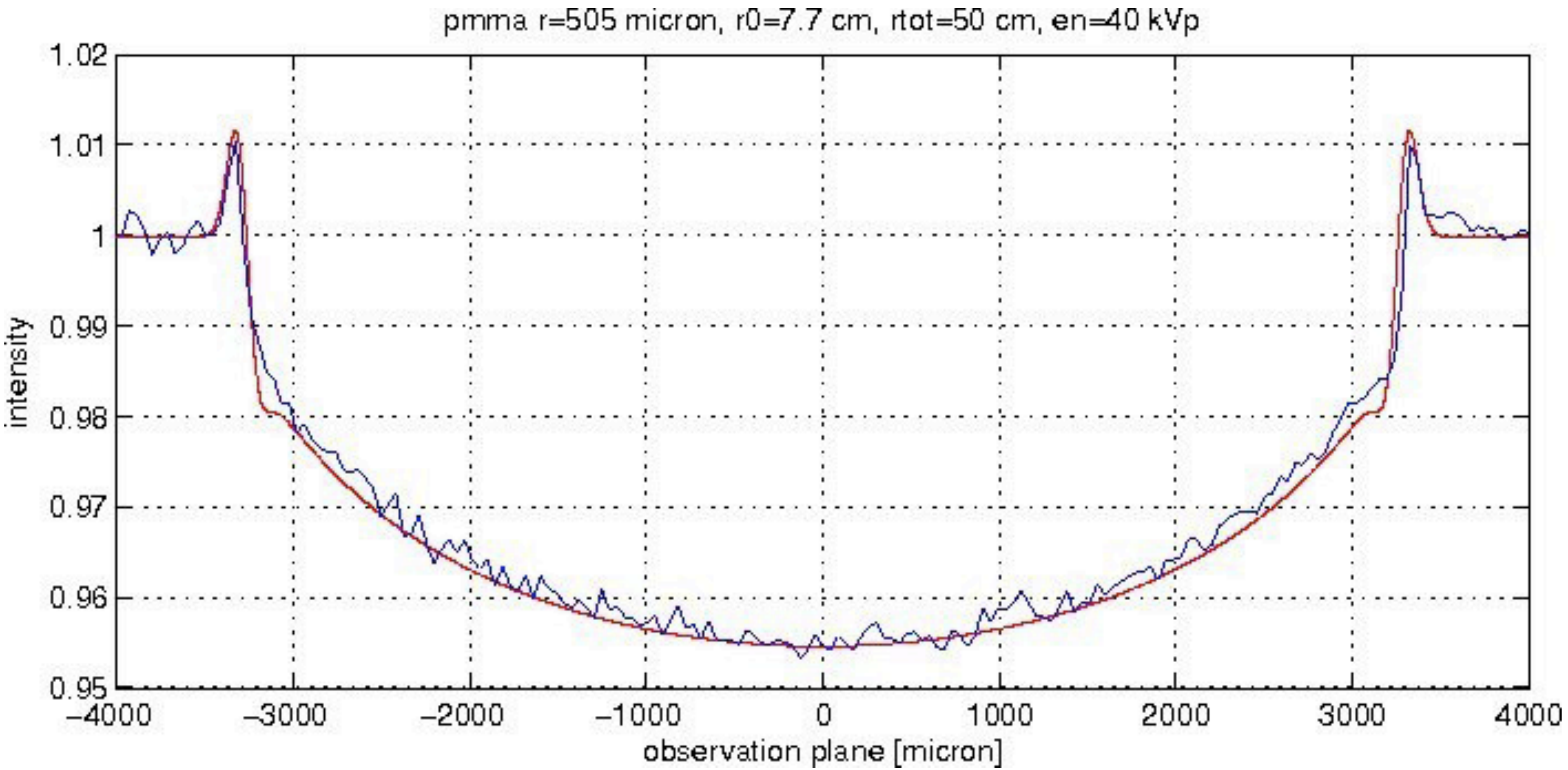
Image propreties



Several geometries (distance source-wire, wire-detector), Voltage (20-40 kVp) and different wire materials (PET, PMMA e Nylon-6) and size (300 µm-2 mm)

BEATS – PHASE CONTRAST IMAGING

Simulation validation

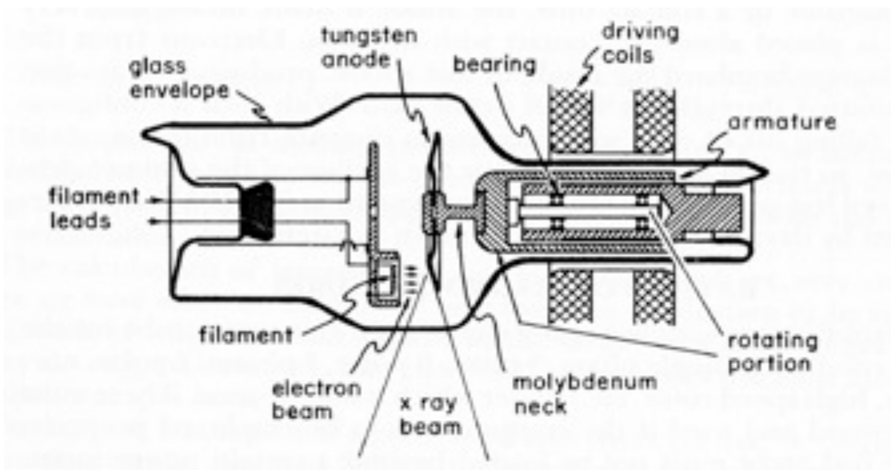


Dose reduction

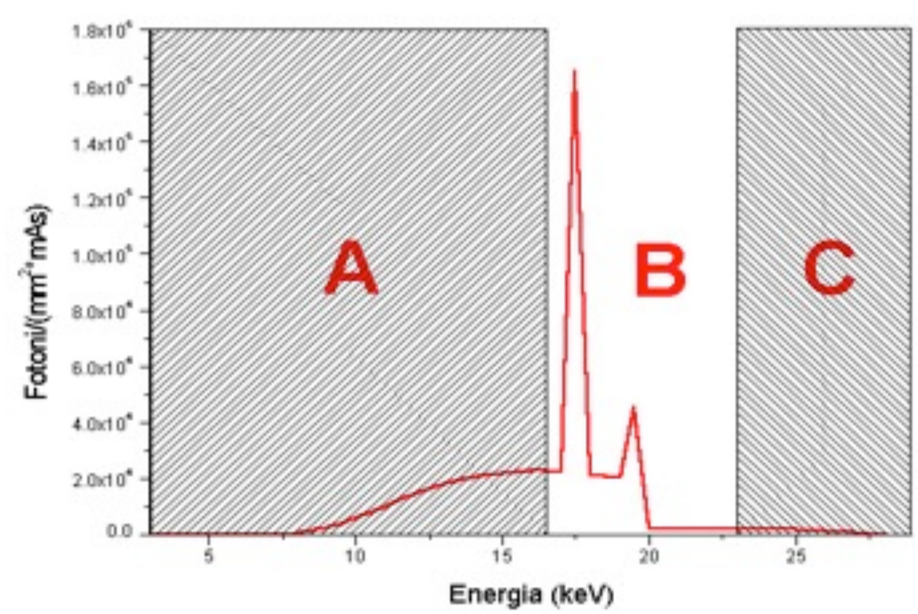
- Dose is a limiting factor in all the screening program
- Standard x-ray tube have a wide spectrum
- Non optimal energies increase the dose without improving the image quality
- Given the quasi-monochromatic x-ray spectrum of ICS the dose can be reduced

Standard Mammography

Standard X-ray source (Röntgen tube)
Required spatial resolution ~100 μm
High Flux ~10^7 $\gamma/(mm^2\ s)$.



Anode Material	Molybdenum
Anode Angle	12°
Anodic Voltage	28 kV
Filtrations	1 mm Be 0.03 mm Mo 600 mm Air



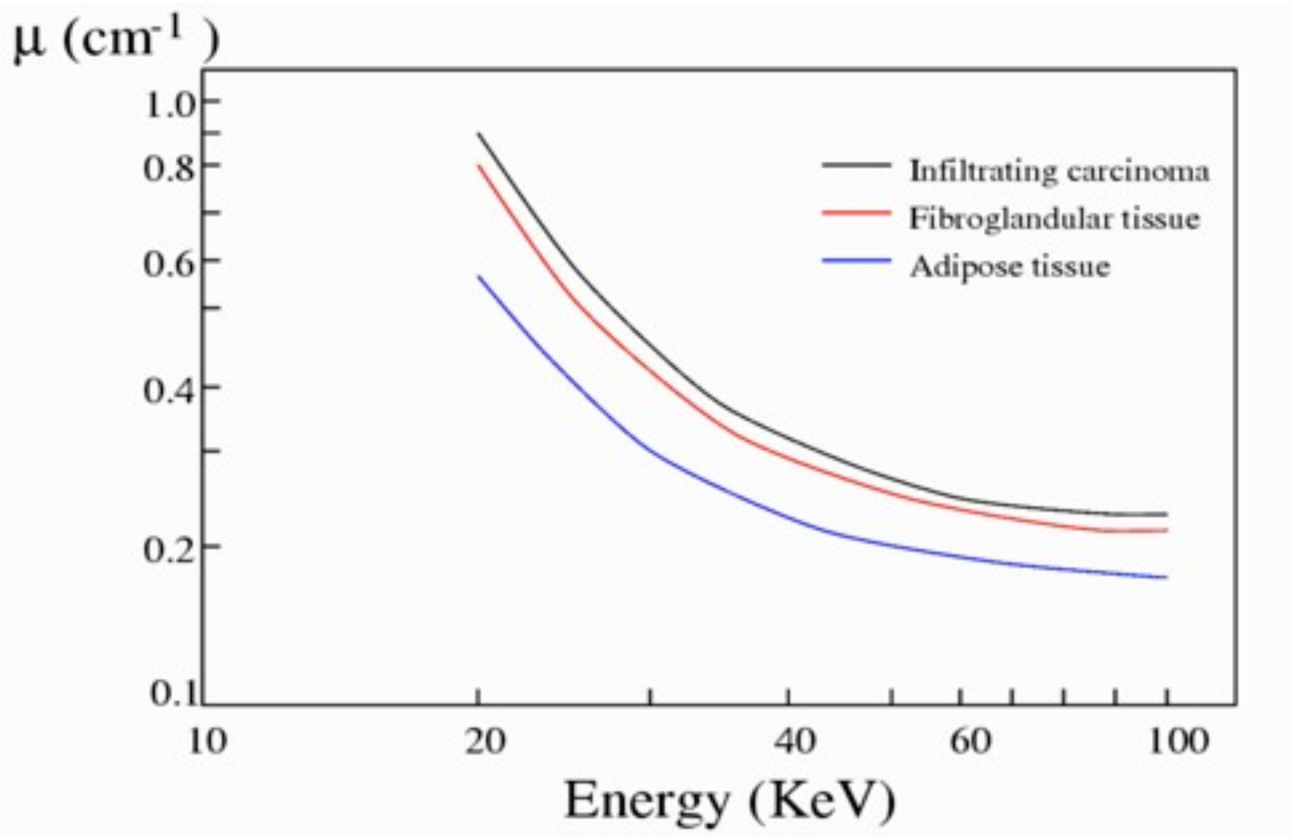
Optimal energy in mammography

The best energy for imaging is a compromise between image quality and dose delivered

It depends on the breast size and compositions and on the efficiency of the detector

Tipical values are in the range

17keV - 25keV



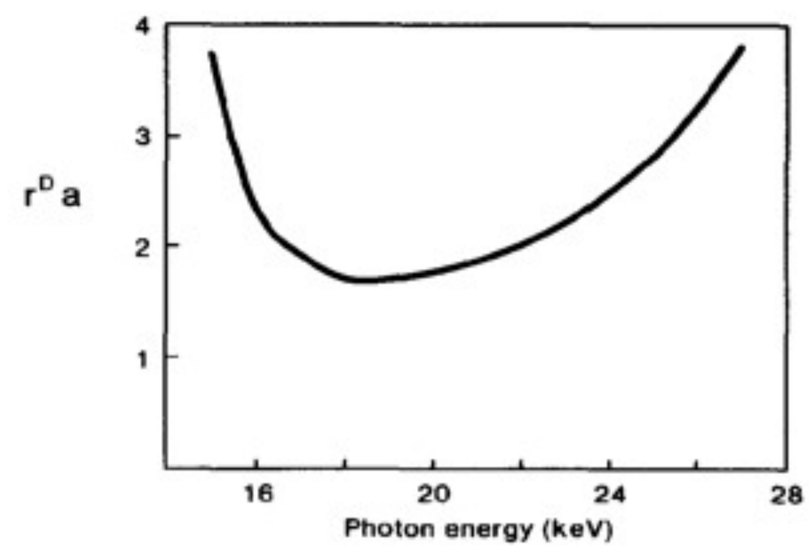


FIG. 1. Relative average absorbed dose, D_a to the breast required for threshold visualization of a 0.1-cm cube of muscle within a breast 5 cm thick, composed entirely of adipose tissue, using an ideal detector.

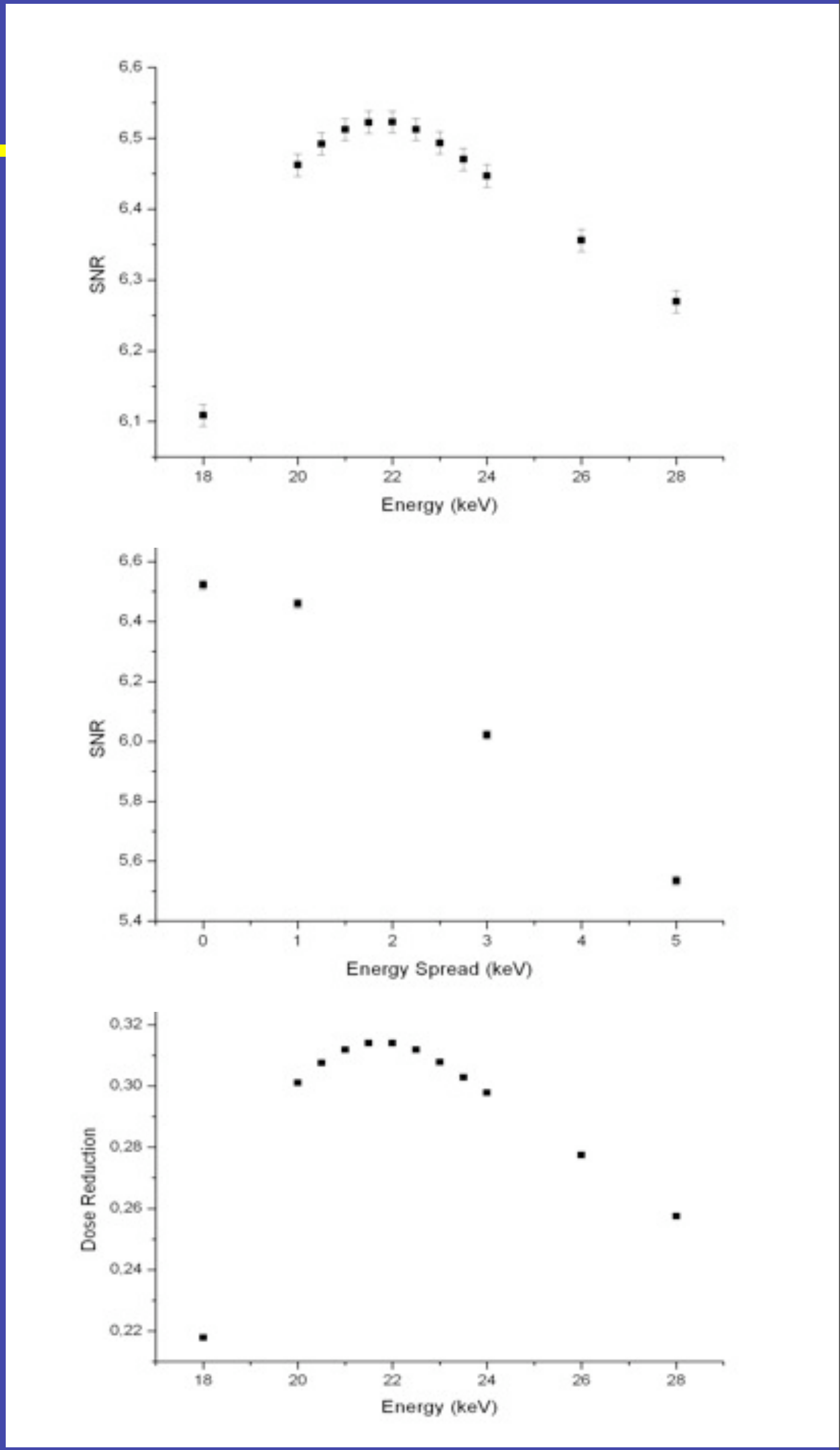
M,W. Ragozzino, Med. Phys 9(4), 1982, p. 493

Energy optimization

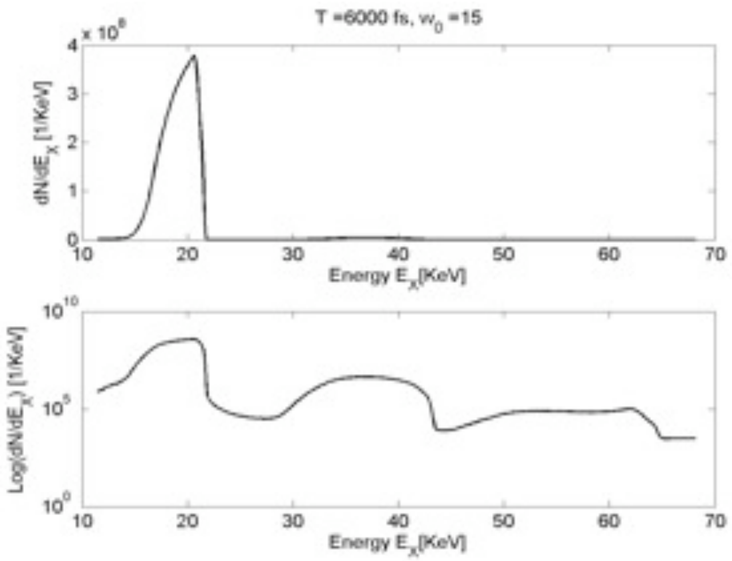
- Optimal energy definition

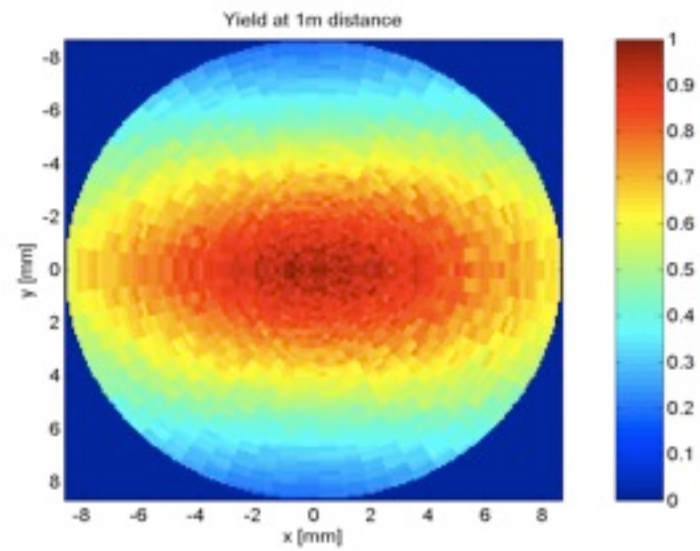
- Study of the dependence of image quality on energy spread

- Evaluation of dose reduction wrt to a standard x-ray tube

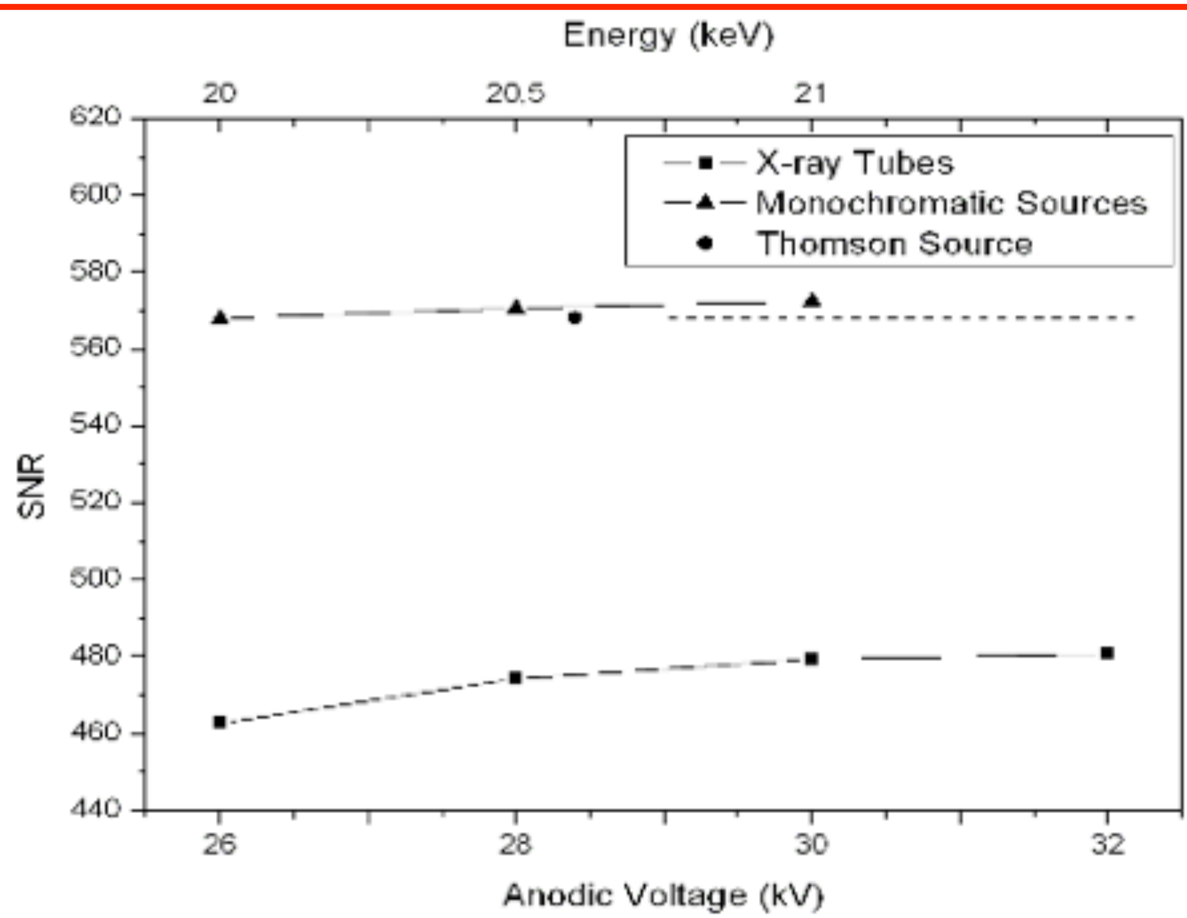


Energy optimization





Mean: 20.6 keV , σ: 1.7 keV



SNR at constant Dose (1.5 mGy)

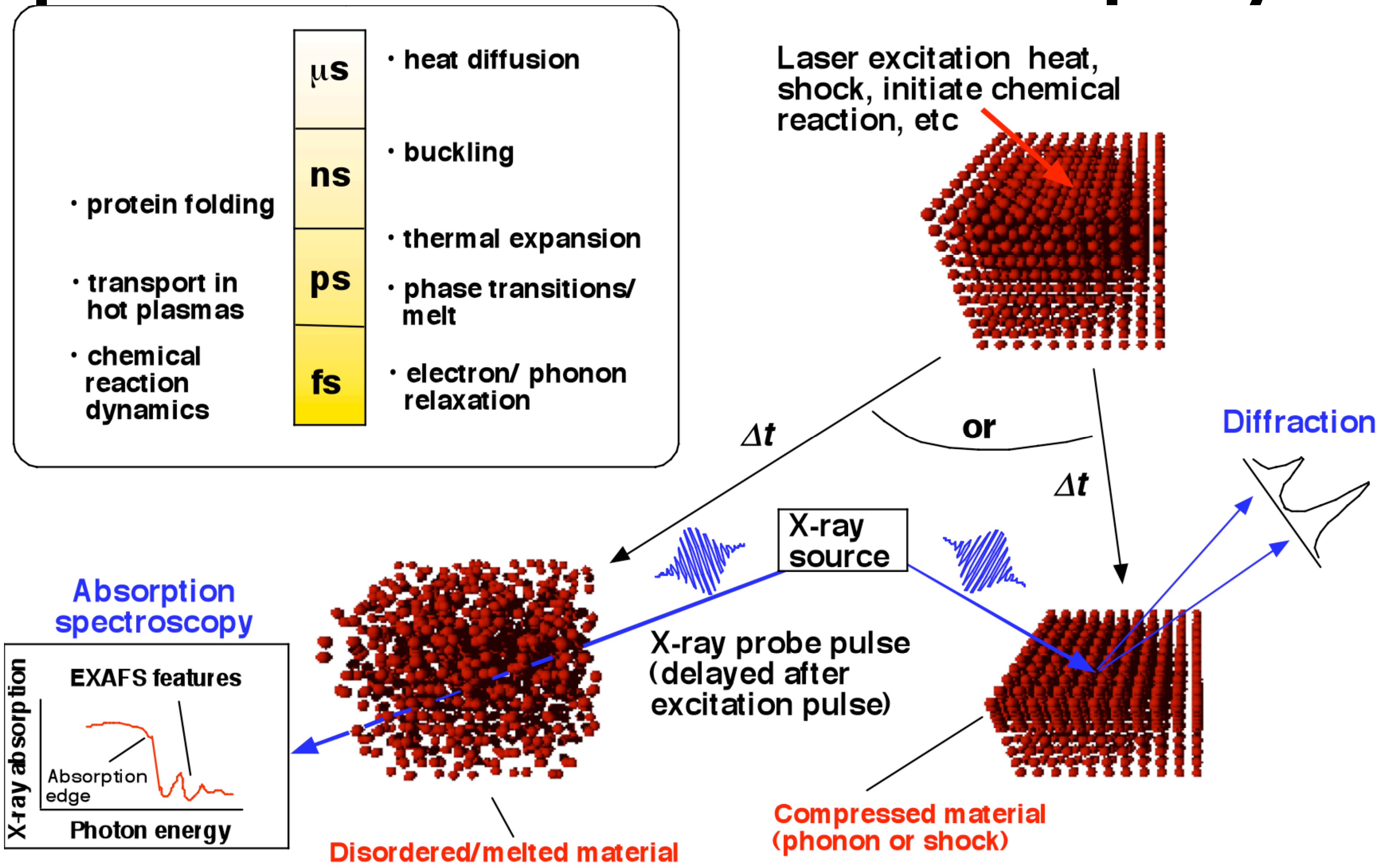
Breast and lung CT

- Source linear size is one of the limiting factor in the spatial resolution
- PSF ~ d(obj.–det.)/d(source–obj.)*source size
- Some dose reduction advantage as fot standard mammography
- Relatively easy extension of the plane imaging

Breast and lung CT (2)

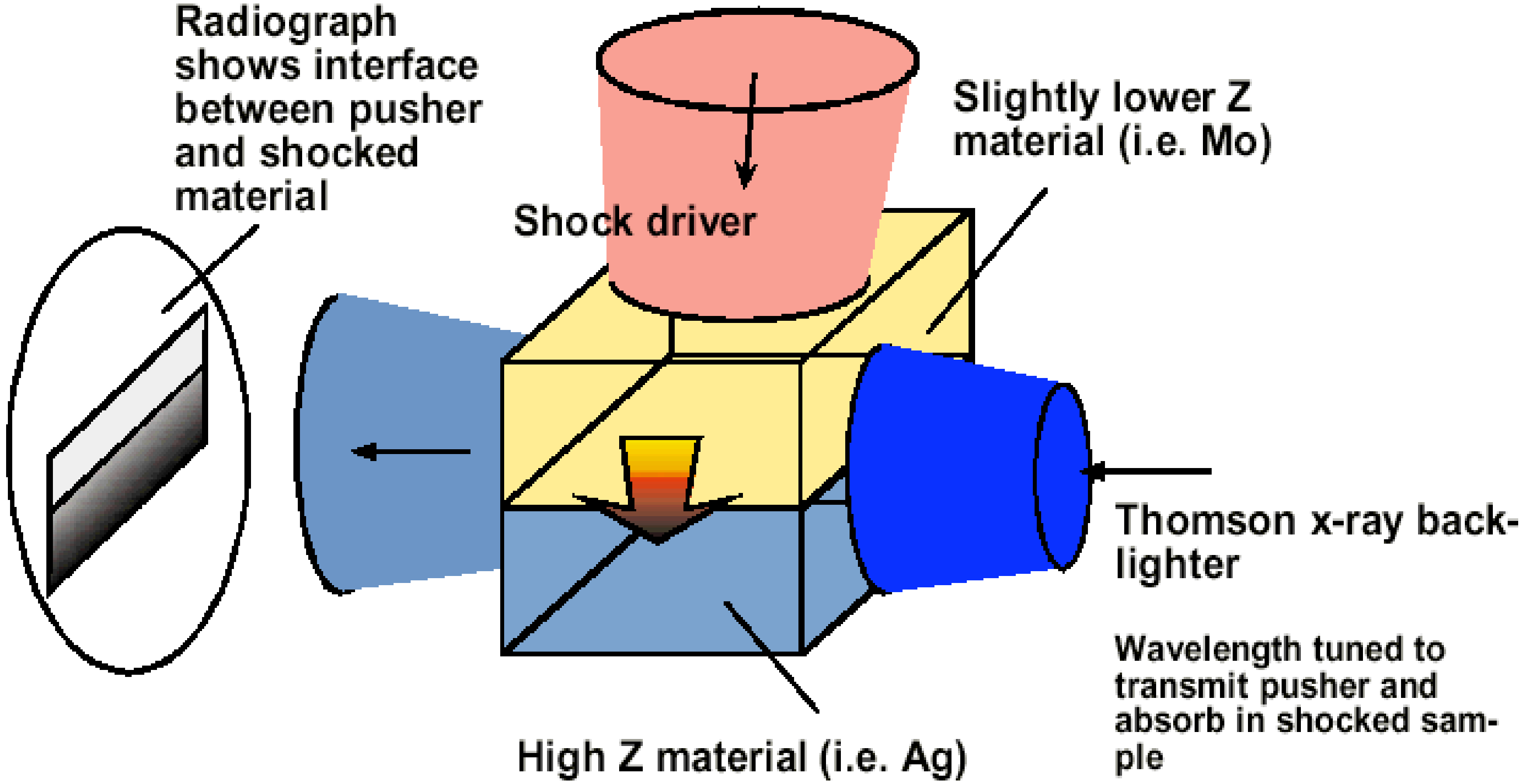
- Feasibility study on small biological sample
- The same detector used for plane imaging can be used
- The sample will be placed on a step by step rotating stage
- The tomographic reconstruction will be made using algorithms such as filtered back-projection and Fourier reconstruction

Next step: ICS as sub-psec X-ray probe of ultra-fast physics

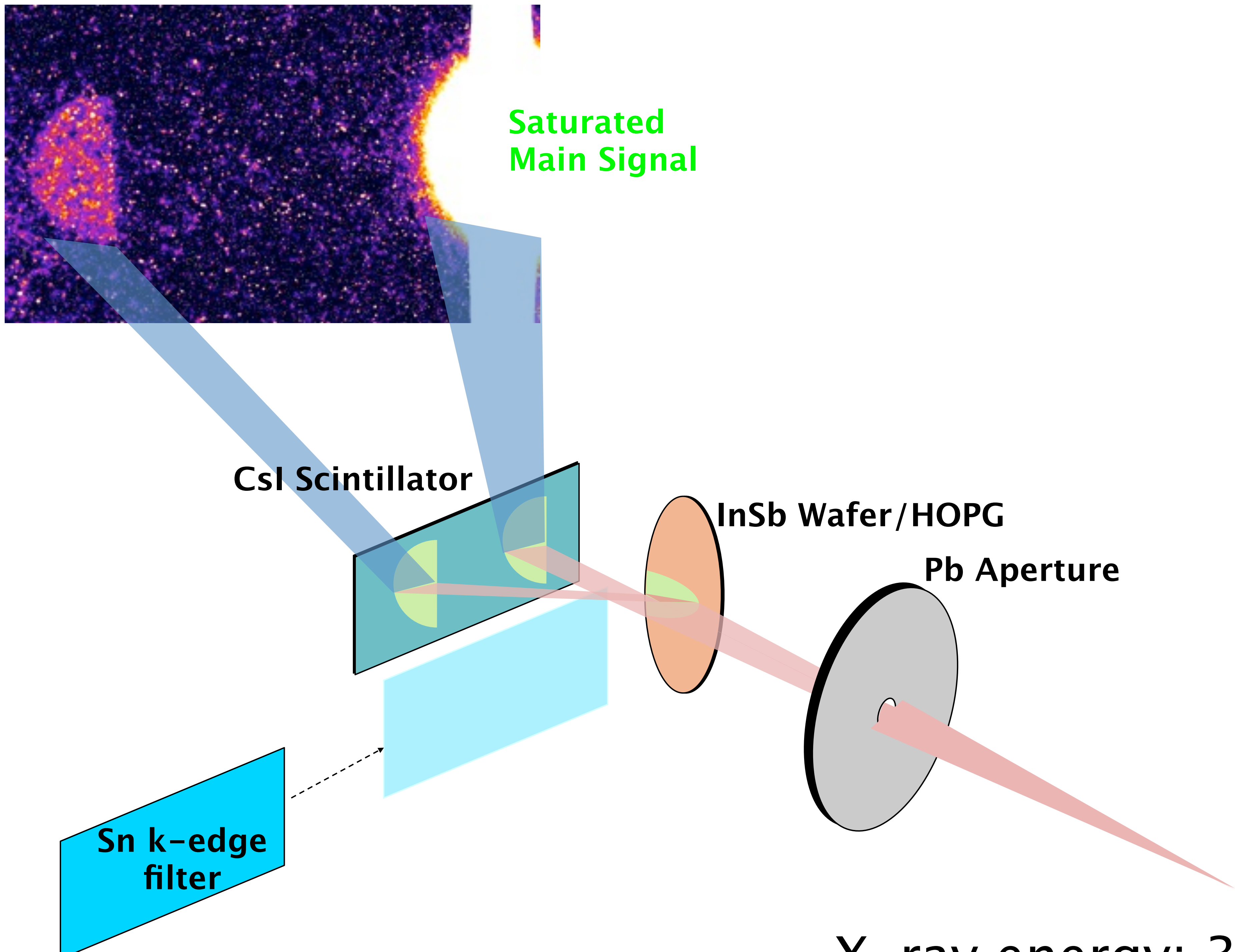


- Demands on monochromaticity excessive for approaches like EXAFS
- Diffraction, radiography can take advantage of unique aspects of ICS spectrum and sub-psec time structure

Example: observation of shock propagation using radiography



Static diffraction demonstrated



X-ray energy: 35 keV

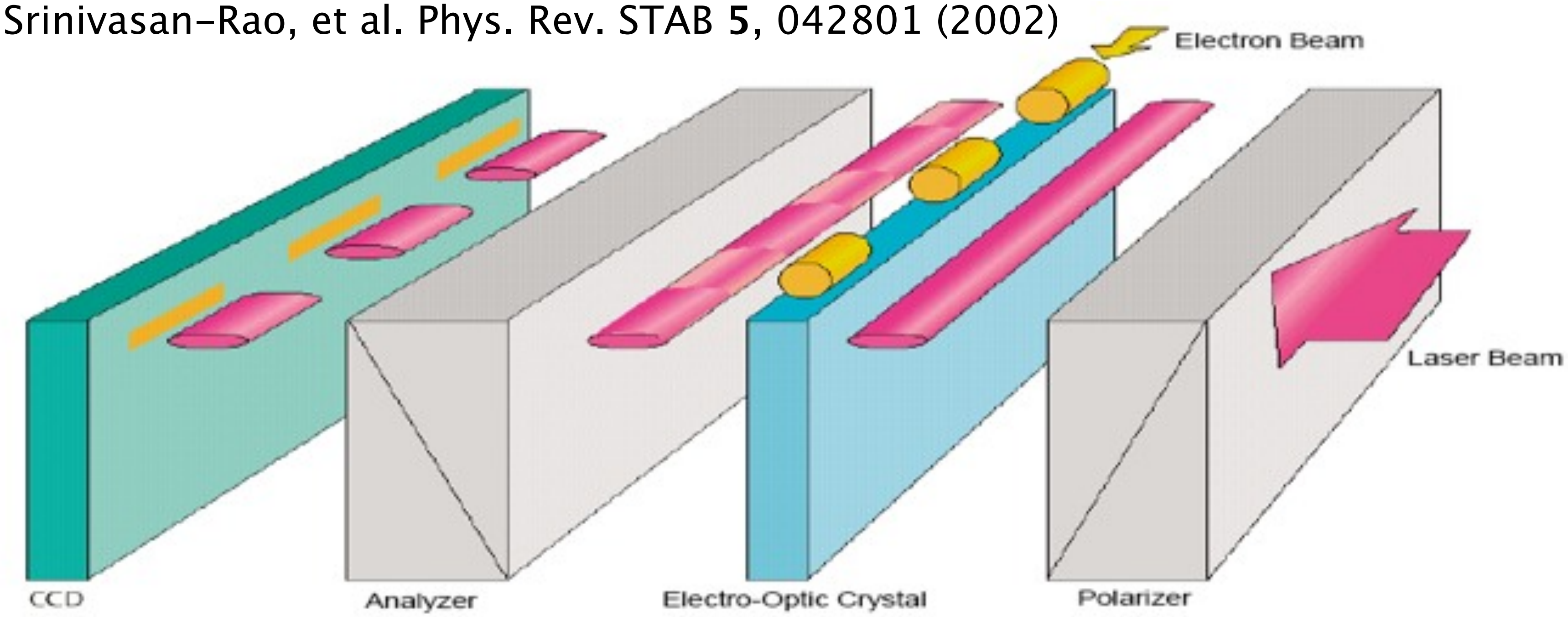
X-ray Diffraction at ATF

- Staged approach:
  - initially static diffraction, then dynamic, using pump-probe
  - Follow PLEIADES example
- Use Au sample, high energy ICS γ's (13 keV)
- Induce melting with CO_2 driver
  - Split from ICS collision pulse
  - Psec time scale for electron-phonon coupling, phase transition

Experimental issues

- Demands high number of γ's per pulse
  - ATF is ~ best in the business due to CO_2 now
- Pump-probe timing
  - Jitter due to electron time of arrival
  - Autoscanning of arrival times
- Need relative timing measure
  - Electro-optic sampling, now done at UCLA Pegasus (Musumeci)

T. Srinivasan-Rao, et al. Phys. Rev. STAB **5**, 042801 (2002)



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Schematic of EOS@Pegasus

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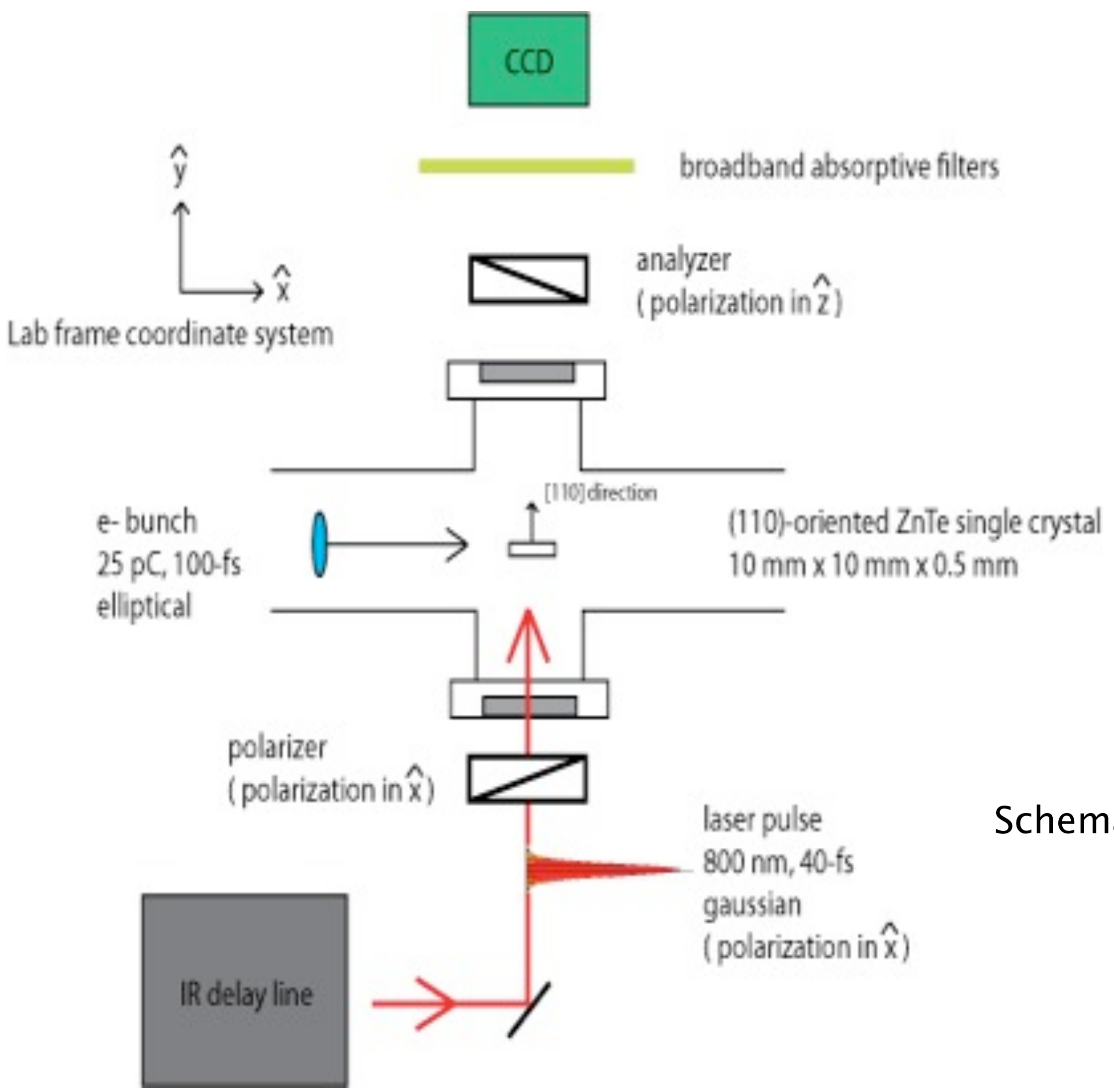

Schematic of EOS@Pegasus

Conclusions

- The agenda outlined is rich with possibilities, and thus represents, given manpower and funding limitations, a two-to-three year program
- 6 weeks of run time per year in at least one-week blocks

Conclusions

- BNL ATF laboratory is perfect to accomplish this challenging scientific program

Thank you very much to every one at BNL ATF