Tecniche di monocromatizzazione per applicazioni in radiologia diagnostica

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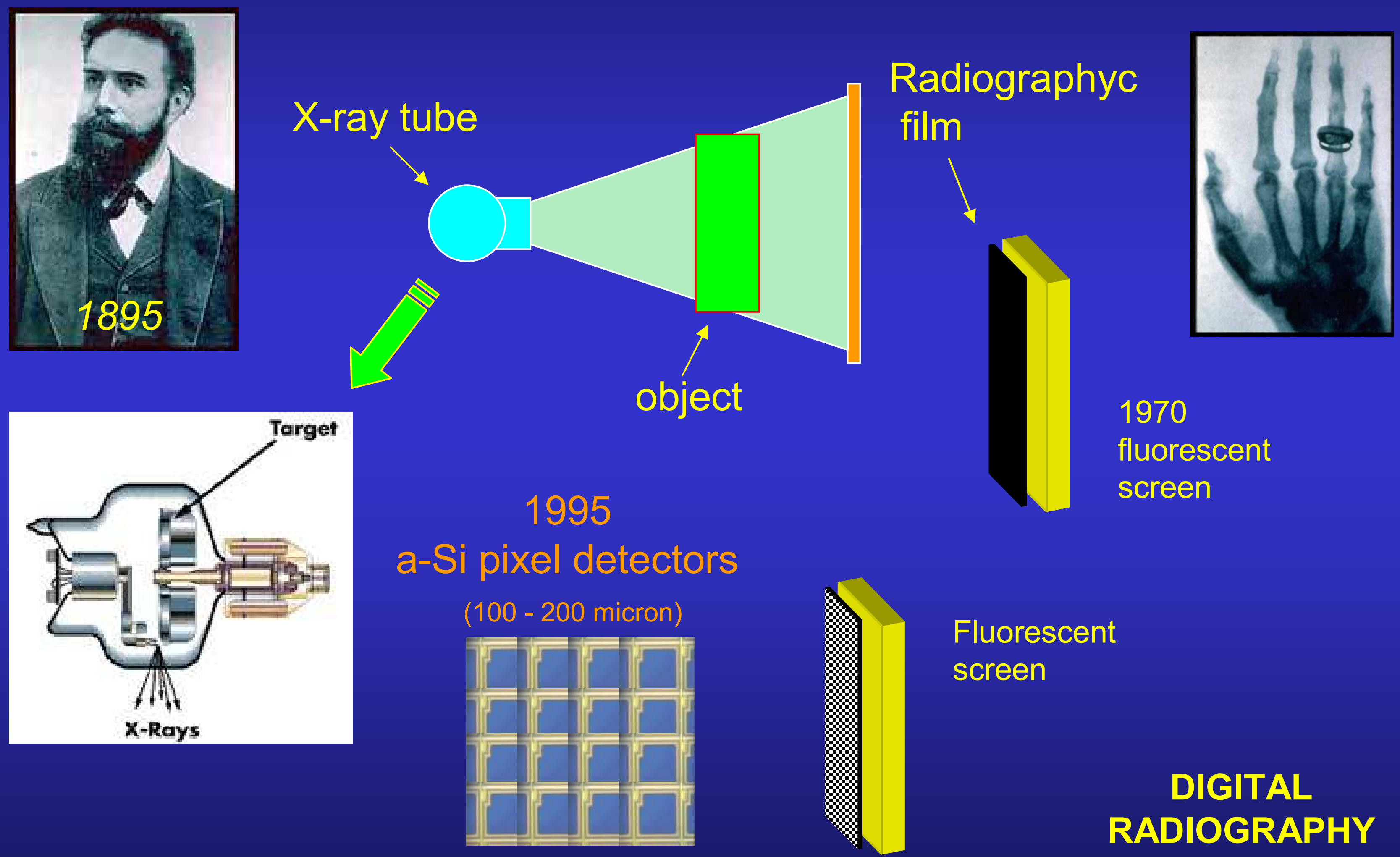
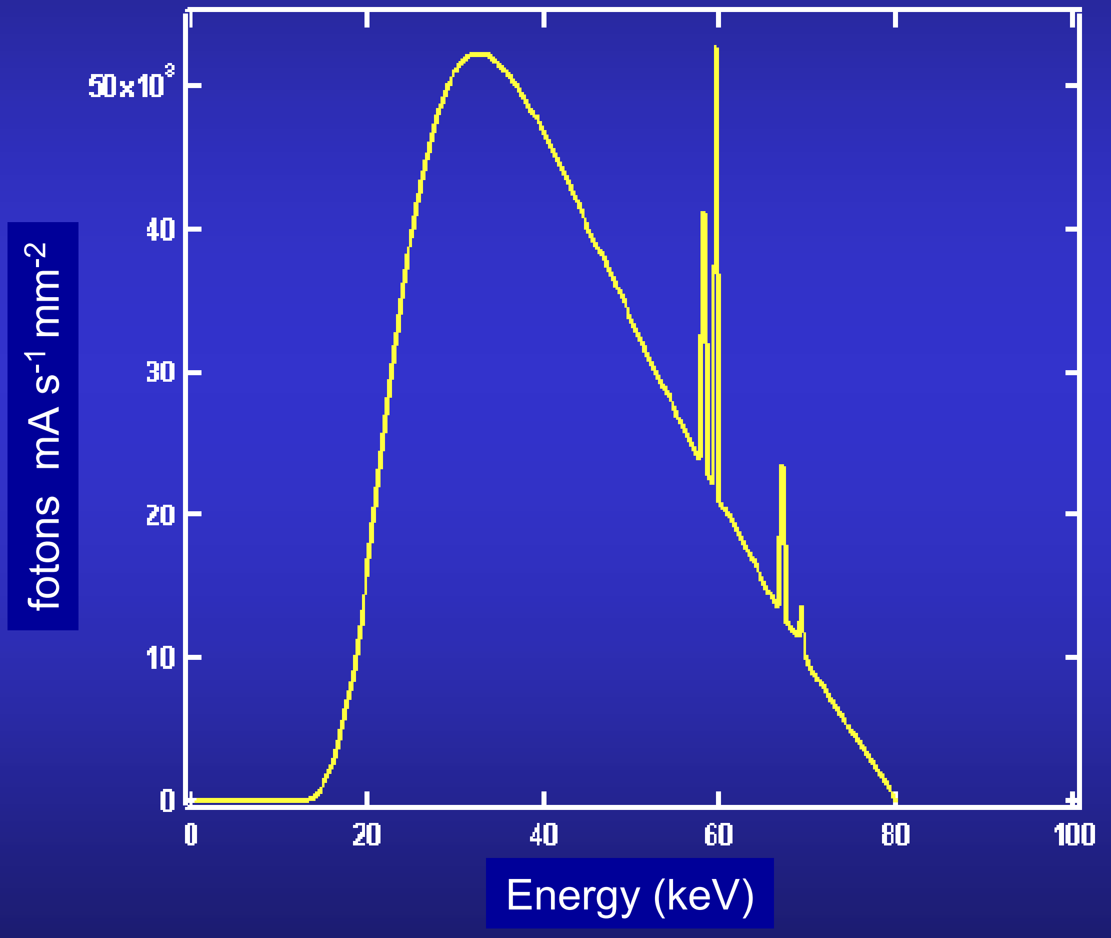
More than a century of X-ray imaging

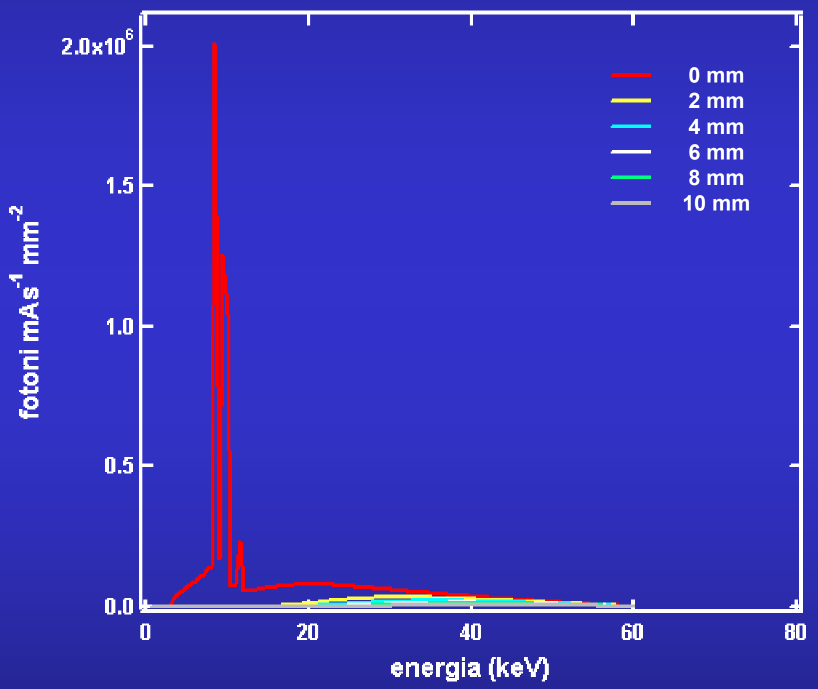


X-ray beam spectrum
from W target at 80 kVp

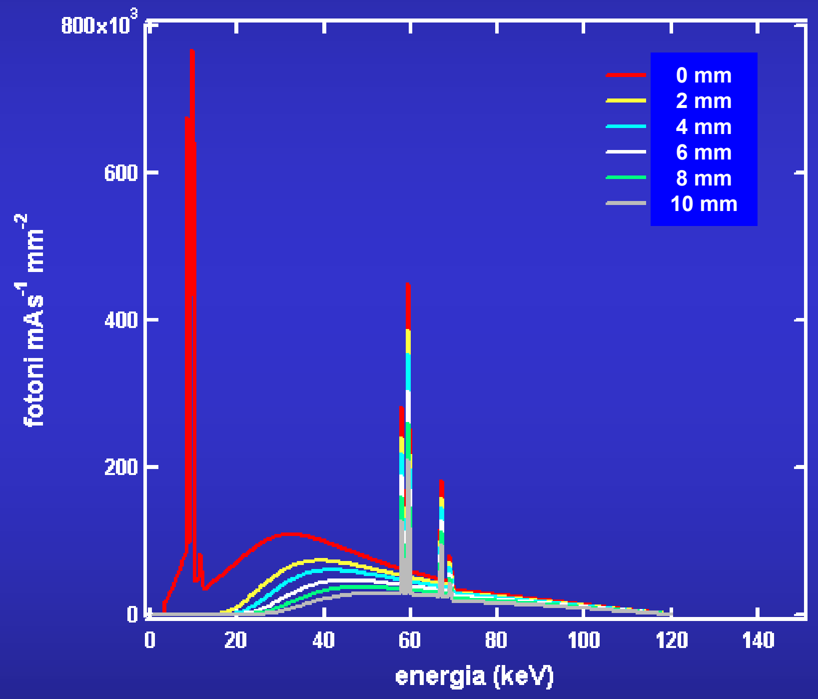


Spettri di Fasci Convenzionali

W/Al 60 kVp

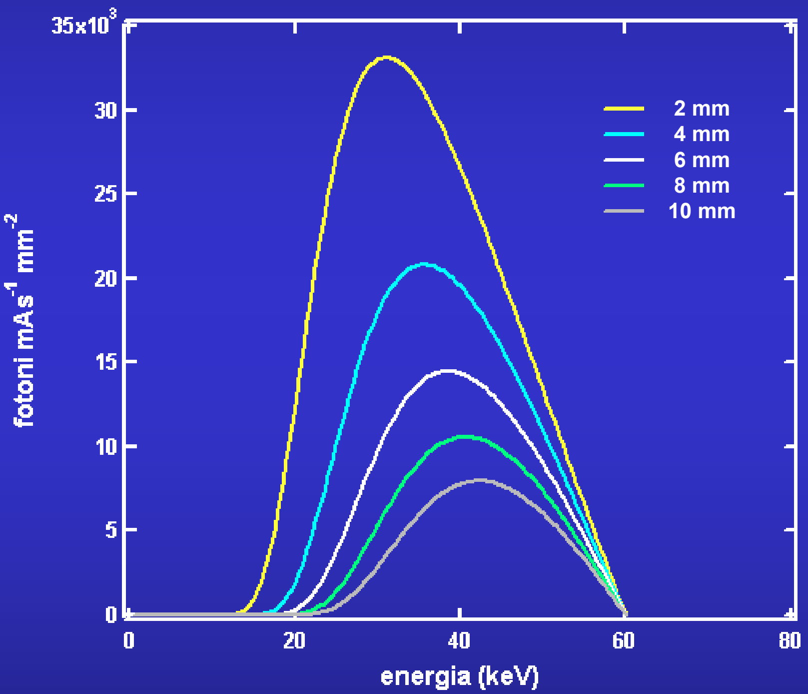


W/Al 120 kVp

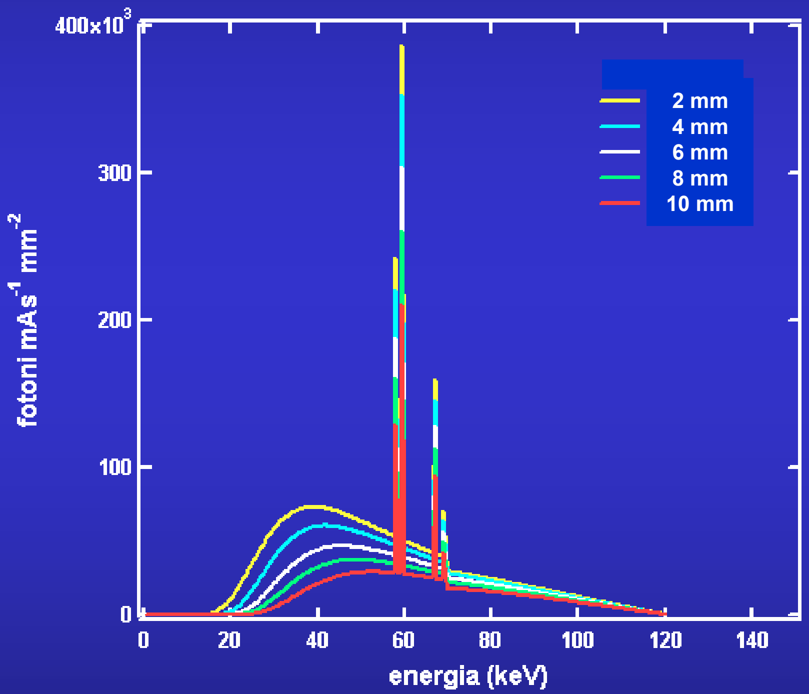


Spettri di Fasci Convenzionali

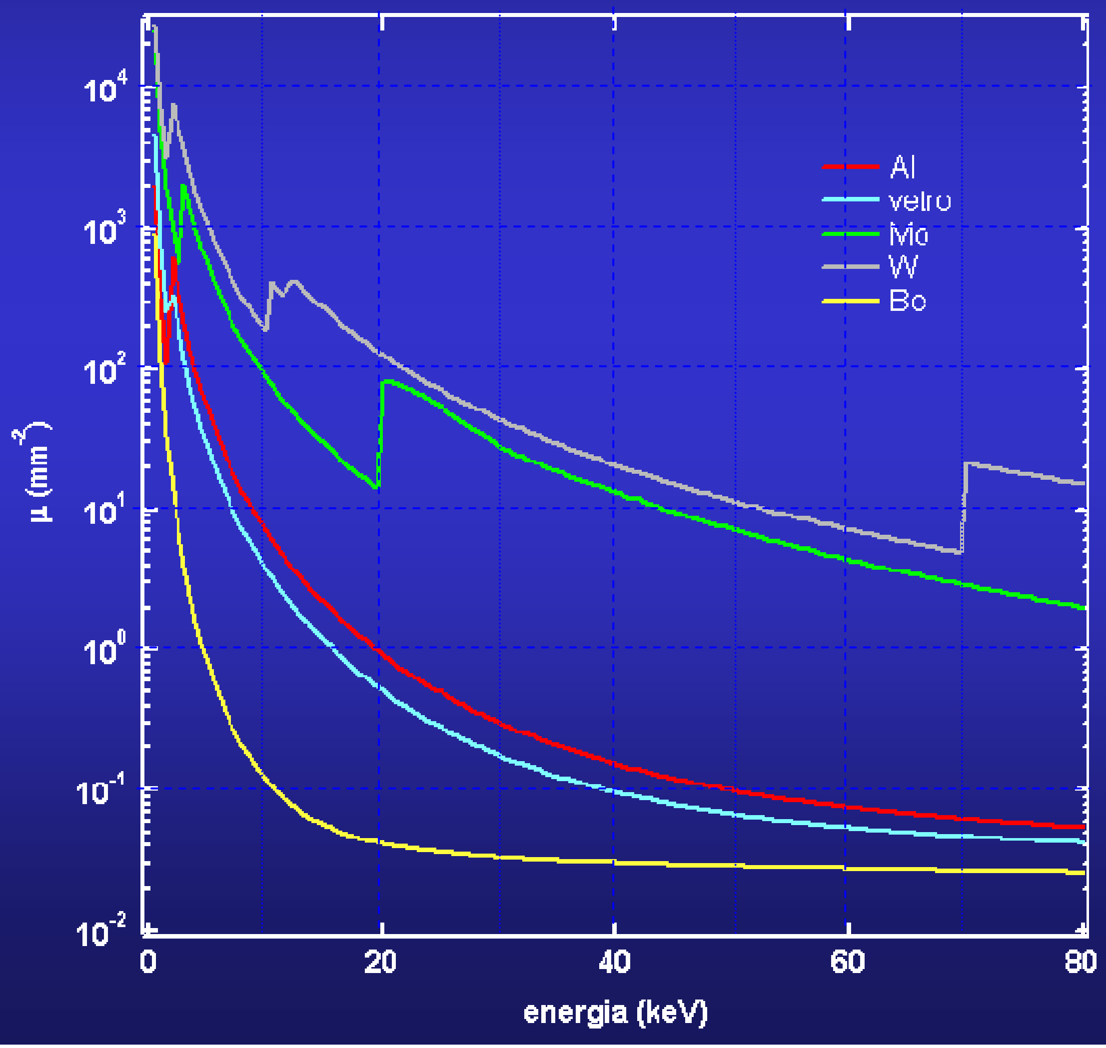
W/Al 60 kVp



W/Al 120 kVp



Coefficiente di attenuazione lineare dei principali materiali costituenti i tubi radiogeni

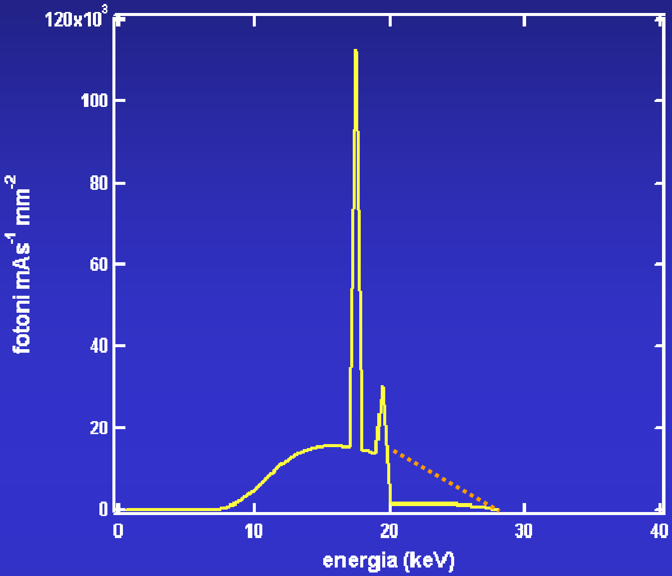


	Z	μ (20 keV) (mm^{-1})	μ (40 keV) (mm^{-1})
Be	4	0.0416	0.0303
Al	13	0.929	0.153
vetro	10.7	0.513	0.0968
Mo	42	81.3	13.2
W	74	127	20.7

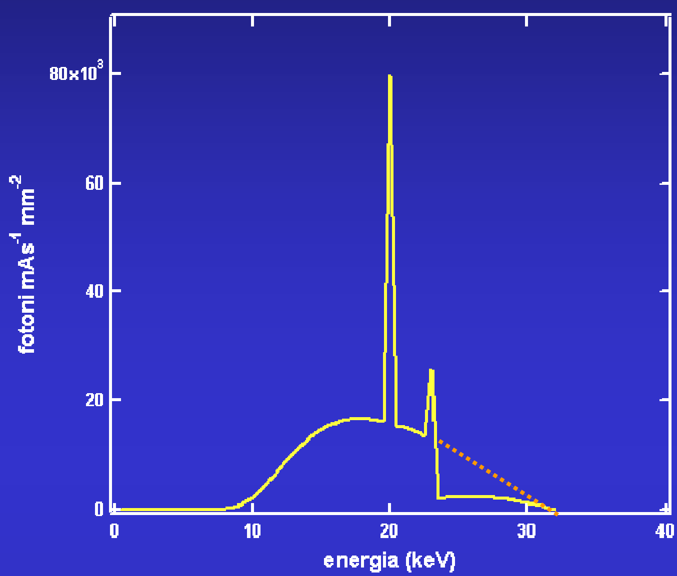
Spettri di Fasci Mammografici

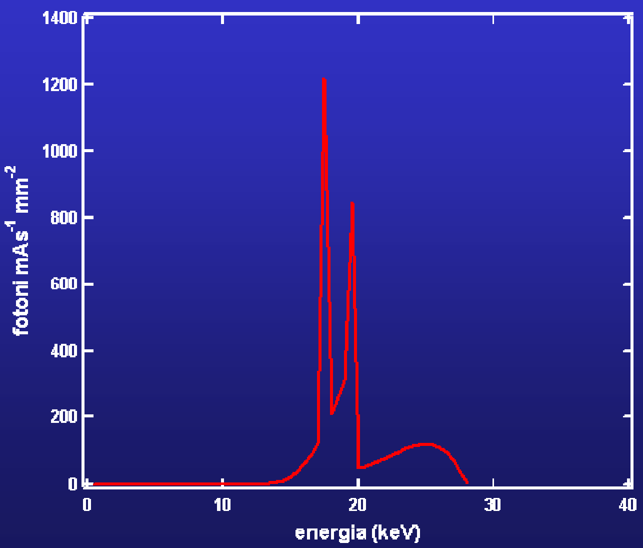
Mo/Mo (30 μm) 28 kVp

Rh/Rh (25 μm) 32 kVp

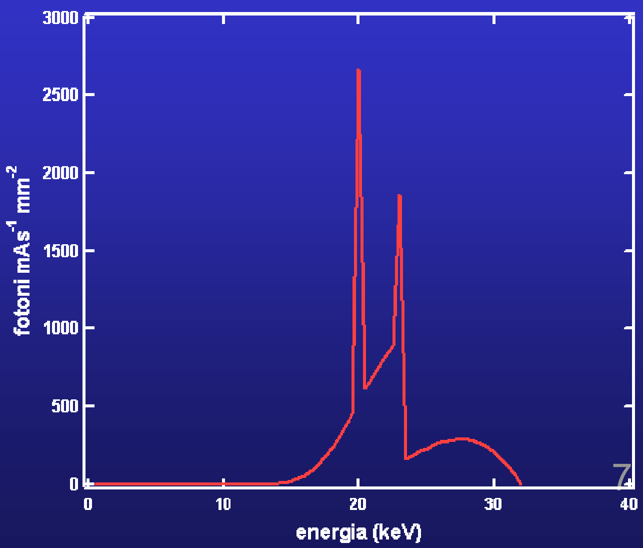


ingresso

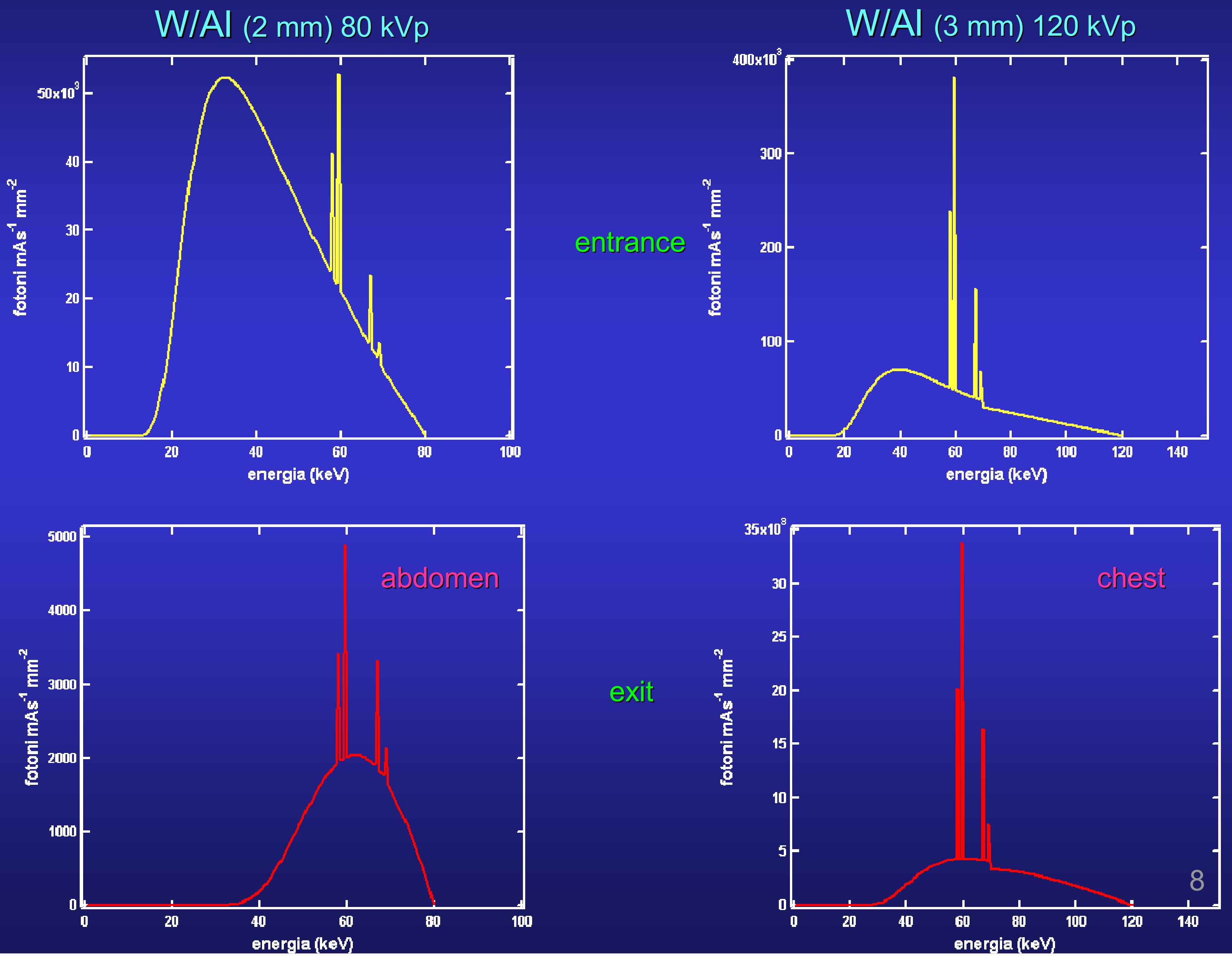




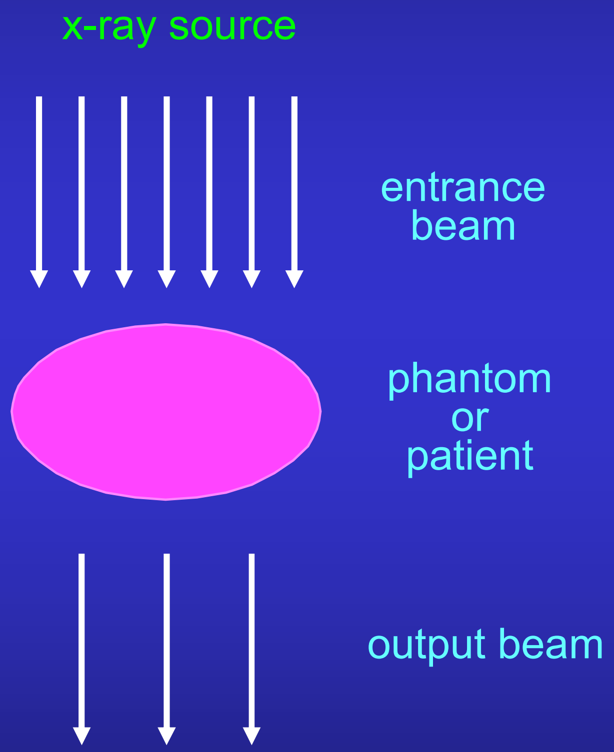
In uscita
da 50 mm
di PMMA



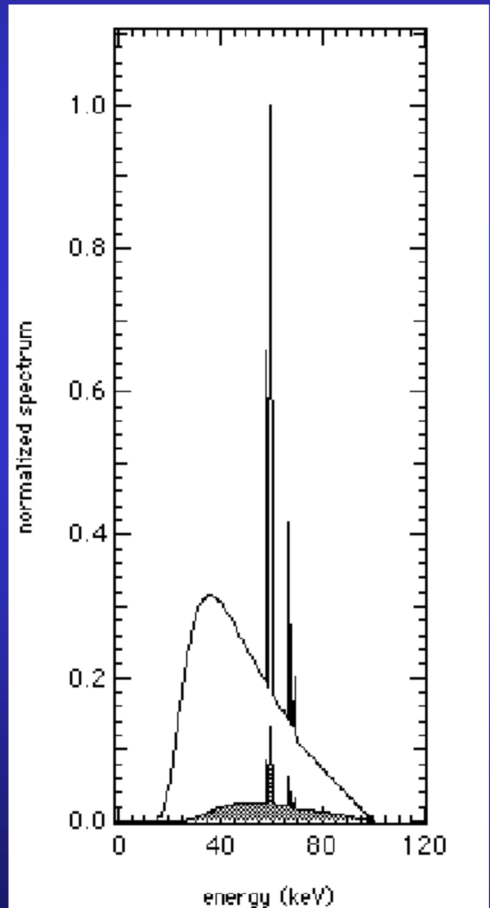
Beam attenuation and hardenig



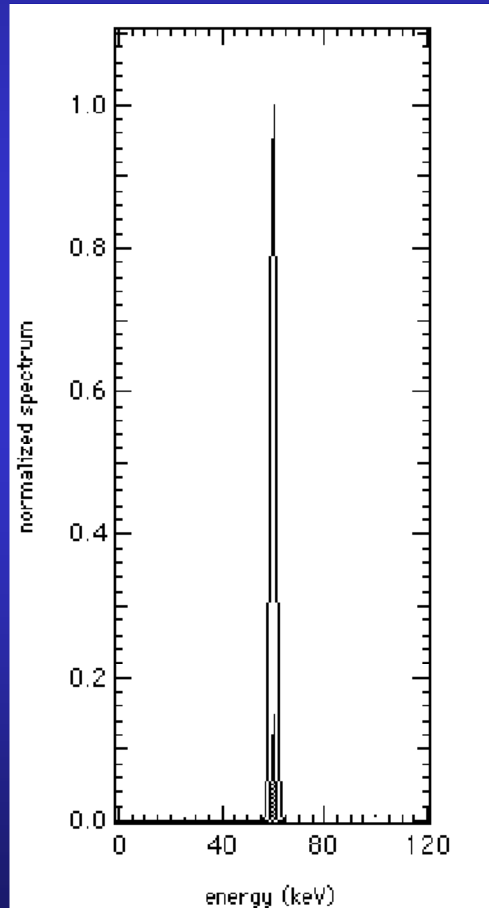
Monochromatic X-ray radiography



conventional source
$\bar{E}_{in} < \bar{E}_{out}$



quasi-monochromatic X-rays
$\bar{E}_{in} = \bar{E}_{out}$

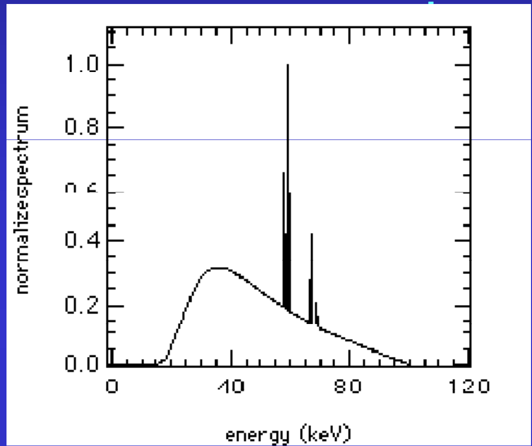


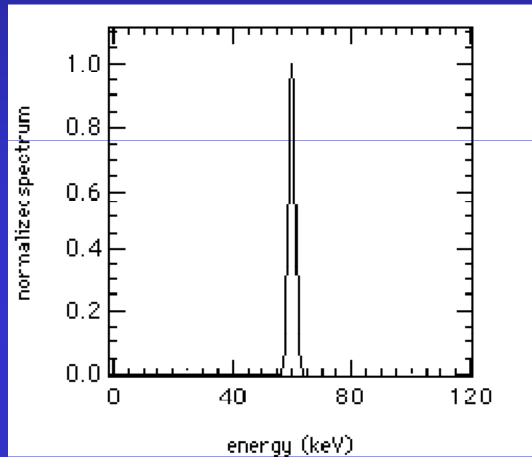
Chest radiography with conventional and monochromatic source

Conventional x-ray tube (W/2.5 mm Al, 100 kVp)

Quasi-monochromatic beam (59.0 keV)

entrance





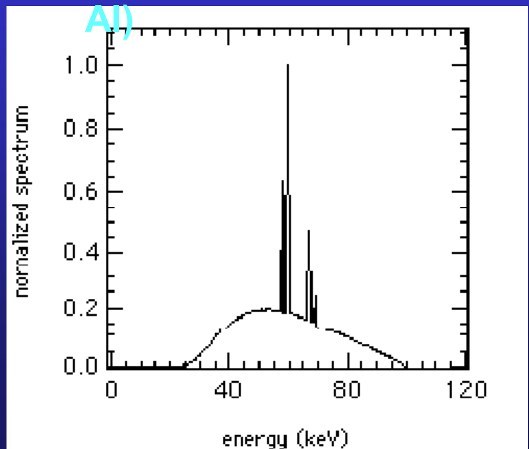
Air Kerma at 750 mm:

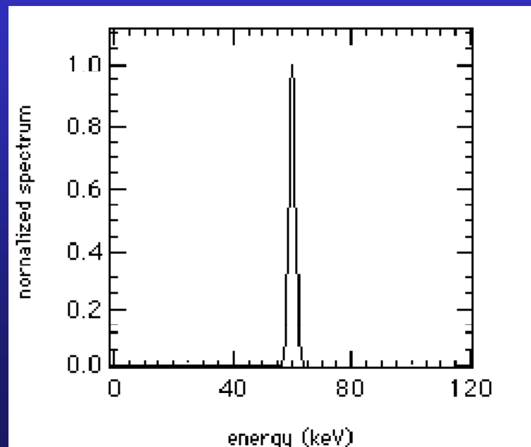
265.8 μGy mA^{-1} s^{-1}

Air Kerma at 750 mm:

126.7 μGy mA^{-1} s^{-1}

Exit beam (CDR phantom – 7.62 cm lucite + 0.41 cm Al)





16.87 μGy mA^{-1} s^{-1}

16.87 μGy mA^{-1} s^{-1}

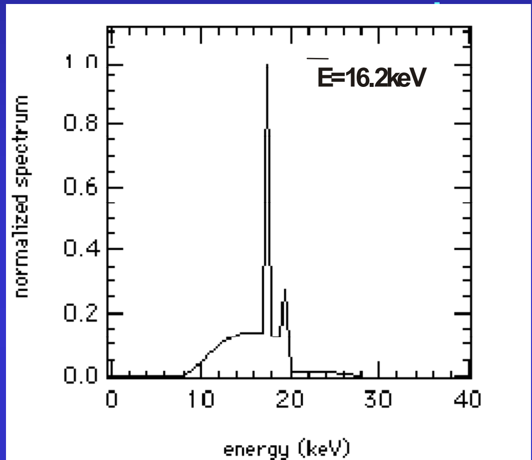
Mammography with conventional and monochromatic source

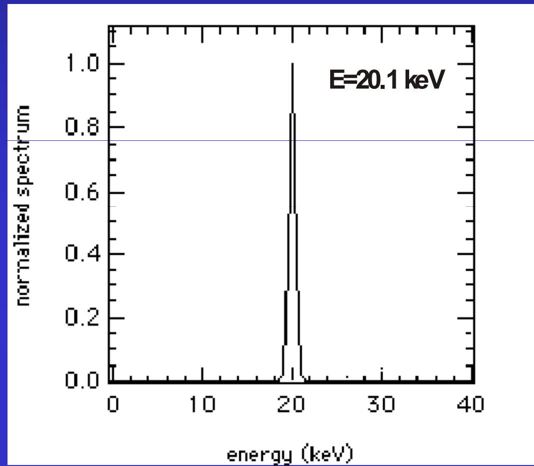
Conventional x-ray tube (Mo/30 µm 28 kVp) | **Quasi-monochromatic beam (20.1 keV)**

entrance

Air Kerma at 750 mm:

123.6 µGy mA^{-1} s^{-1}



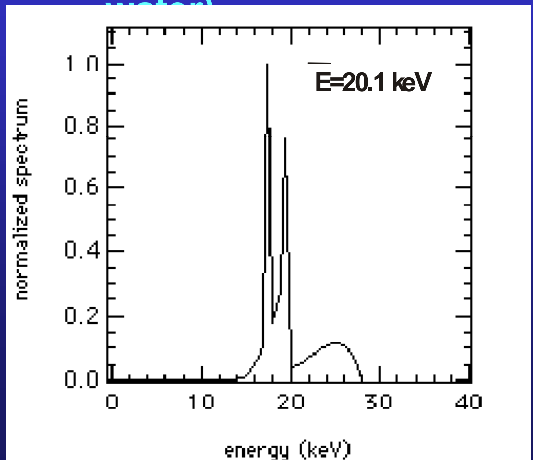


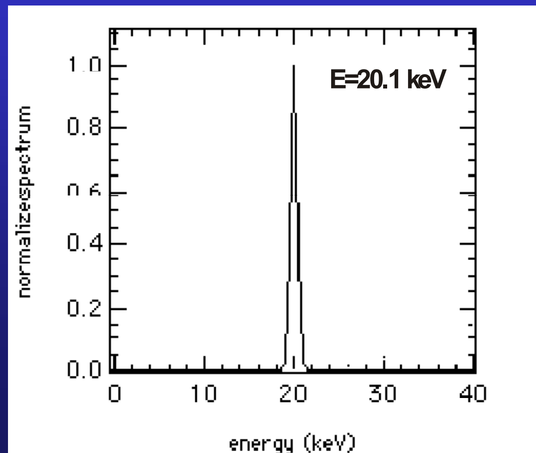
Air Kerma at 750 mm:

19.41 µGy mA^{-1} s^{-1}

Exit beam (50 mm-thick phantom 50% fat/50% water)

0.839 µGy mA^{-1} s^{-1}

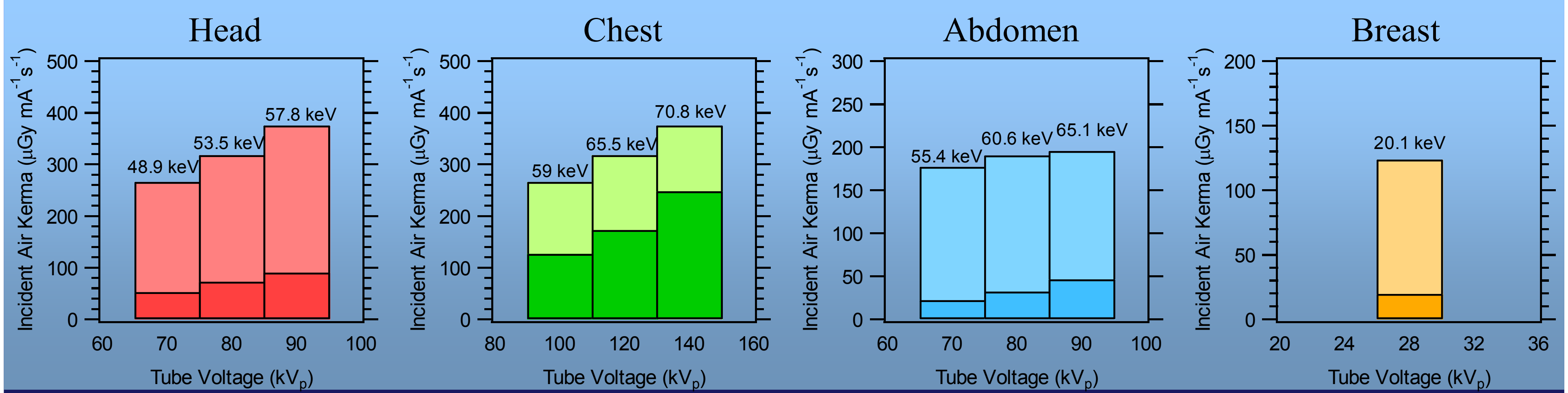




0.839 µGy mA^{-1} s^{-1}

Quasi-monochromatic X-ray beams are desirable in various fields of diagnostic radiology since a reduction of the dose could be achieved

Examination Type	Phantom specifications	Anode Type/Filter	Radiographic Voltage (KV_p)	Mean Energy (keV) In	Mean Energy (keV) Out	Incident Air Kerma Poly	Incident Air Kerma Mono	Air Kerma Ratio
Head	LucWat 1.2 + 14.8 cm	W/2.0 mmAl	70	38	48.9	265.8	52.39	29.62%
		2.0 mm Al	80	42.5	53.5	317.8	72.64	38.17%
		2.5 mm Al	90	46.9	57.8	374.8	90.21	46.17%
Chest	LucAl 7.26+0.41 cm	W/2.5 mm Al	100	48.8	59	265.8	126.6	47.65%
		3.0 mm Al	120	55	65.5	317.8	172.8	54.38%
		3.5 mm Al	140	60.6	70.8	374.8	247.8	66.13%
Abdomen	LucCu 4.0+0.1 cm	W/2.0 mm Al	70	38	55.4	176.9	22.11	12.50%
		2.0 mm Al	80	42.5	60.6	190.3	31.98	16.81%
		2.5 mm Al	90	46.9	65.1	195.4	46.09	23.59%
Breast	BR12 FatWat 2.5+2.5 cm	Mo/30μm Mo	28	16.2	20.1	123.6	19.41	15.71%



Importance of monochromatic X-rays in Diagnostic Radiology

For each examination there is an optimal energy to minimize the dose to the patient and to enhance the contrast.
In fact image contrast is reduced by X-ray scatter which increases with energetic bandwidth of the X-ray beam.

↓

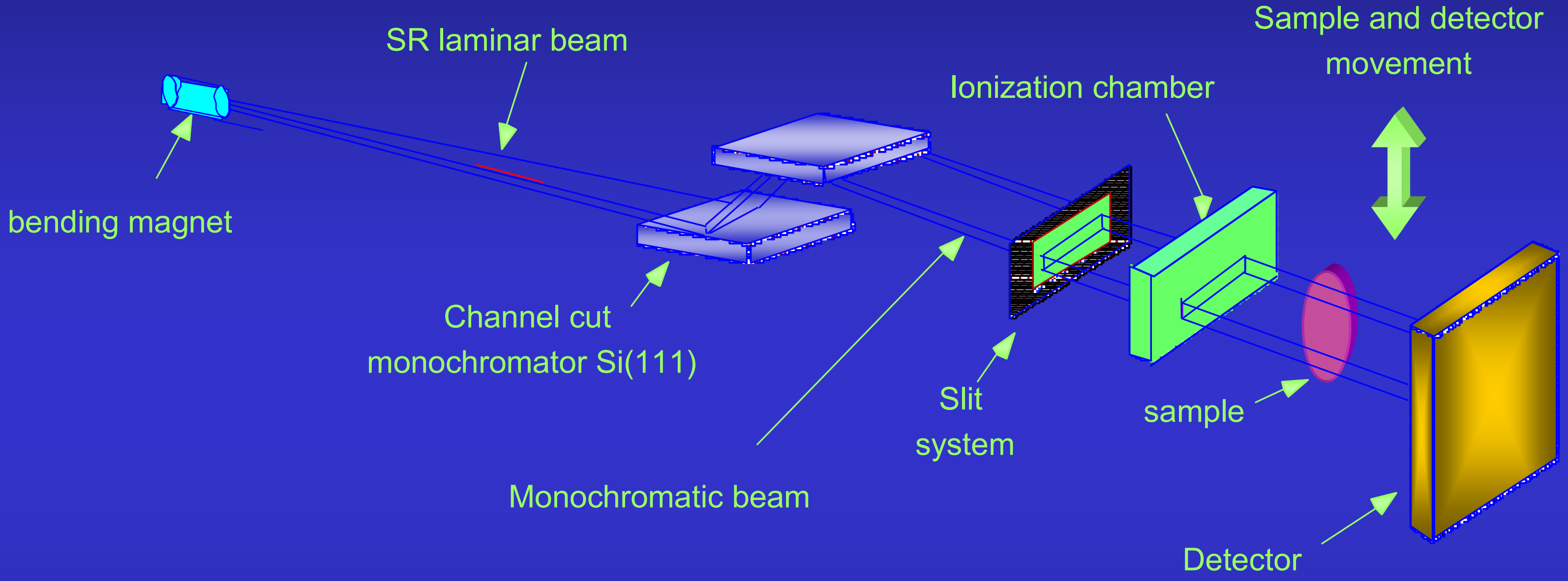
Conventional beam filtration allows only a limited degree of energy selectivity

↓

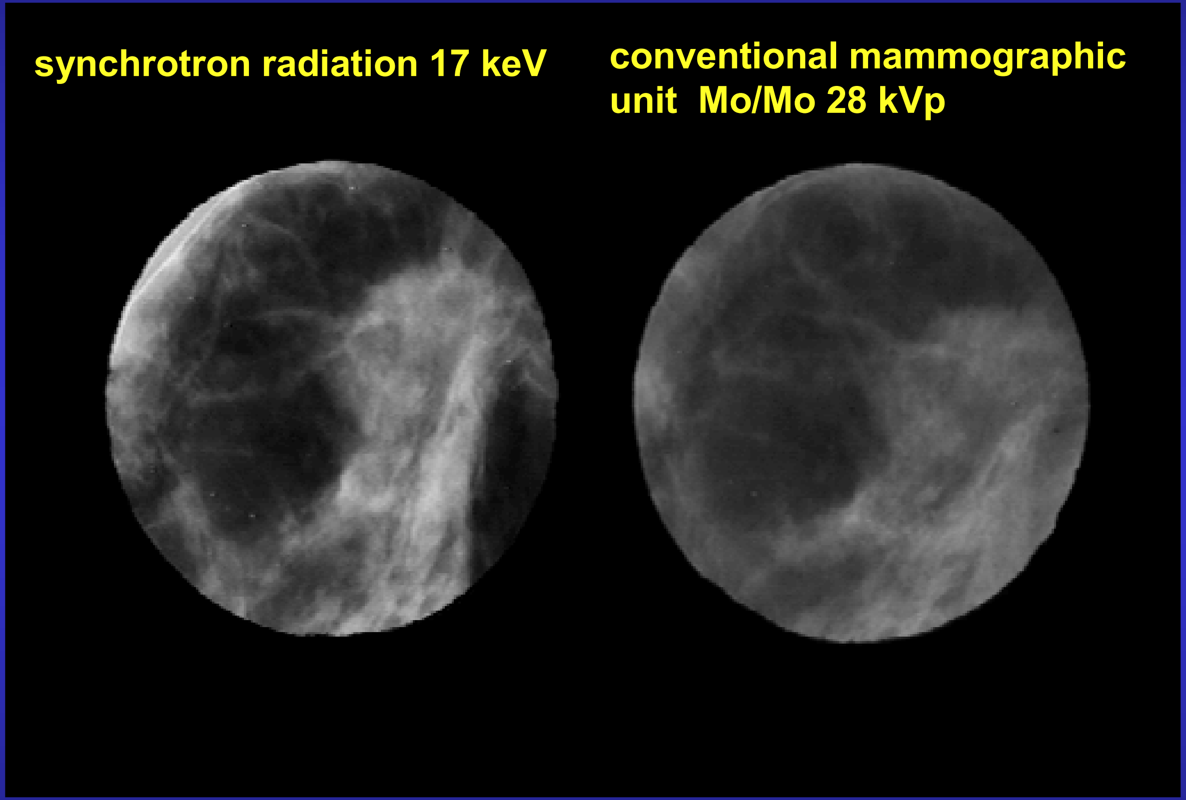
To optimize X-ray examination it's extremely important to improve X-ray source performances

How can we get monochromatic X-ray beams for radiography ?

Synchrotron Radiation



Synchrotron radiation radiographs of the same breast sample (1993)



	17 keV	18 keV	28 kVp grid
Mean glandular dose (mGy)	1.56	0.84	1.41

How to produce quasi-monochromatic x-rays?

Two Different Ways to Produce

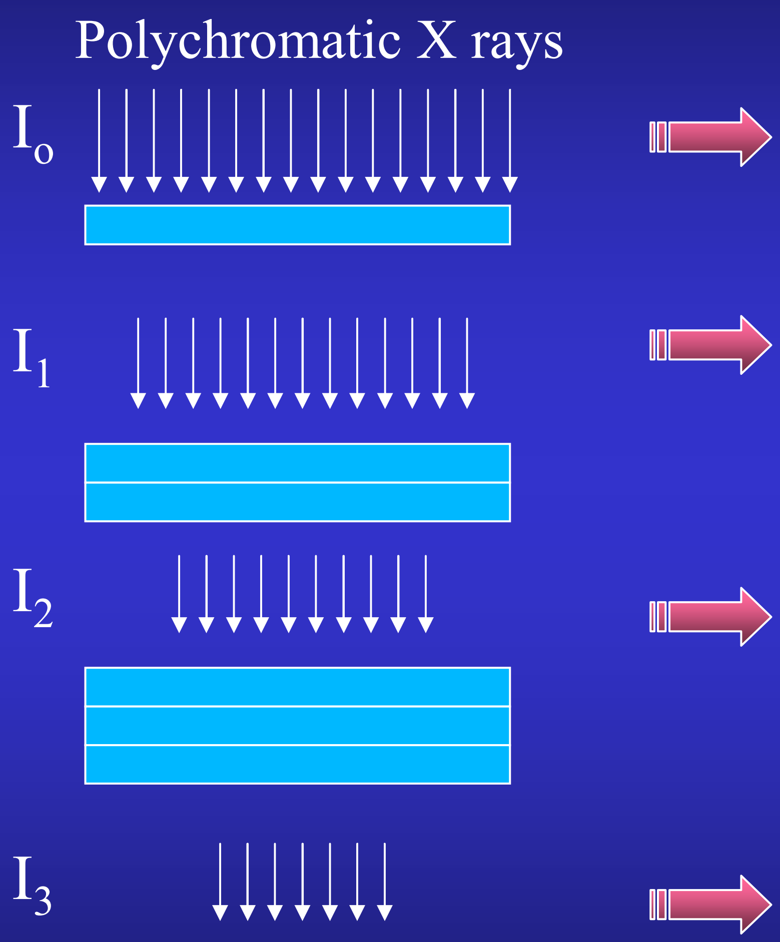
Quasi-monochromatic X-ray Beams

filtration

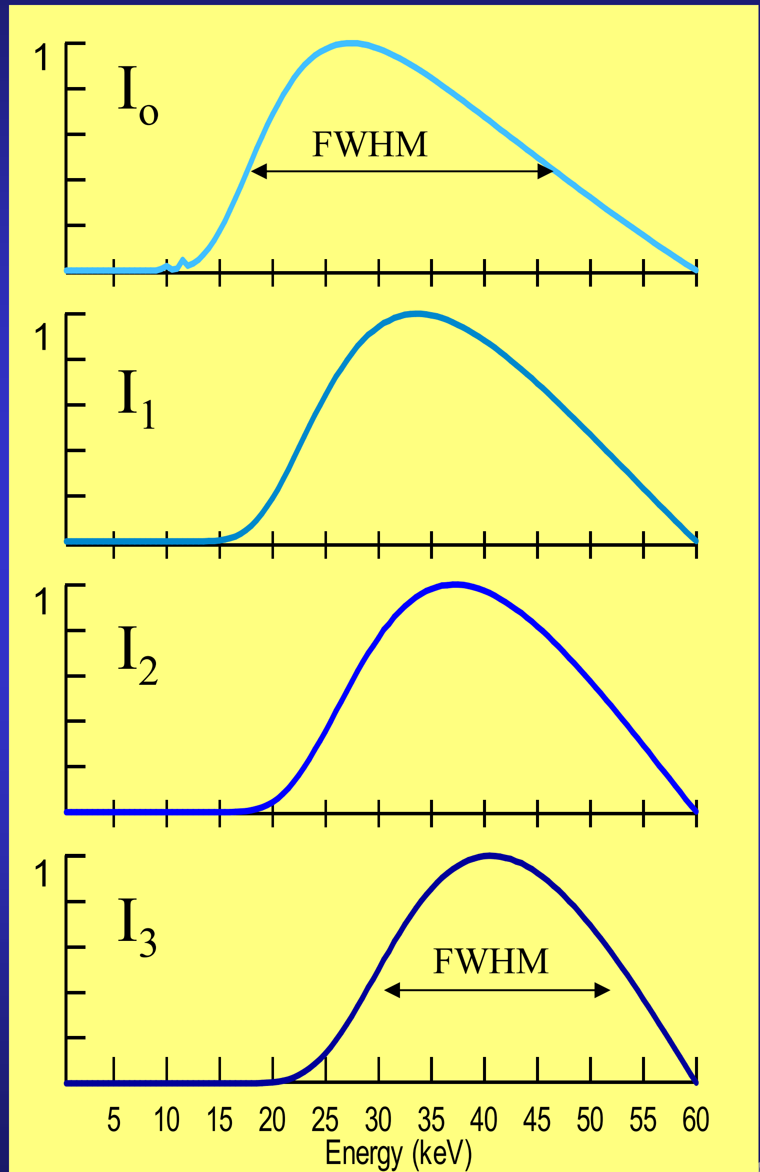
Bragg Diffraction on mosaic crystal

- We have compared quasi-monochromatic X-rays spectra at 20, 30, 40 and 50 keV
- We have studied how the energy resolution and the total flux vary as a function of the energy

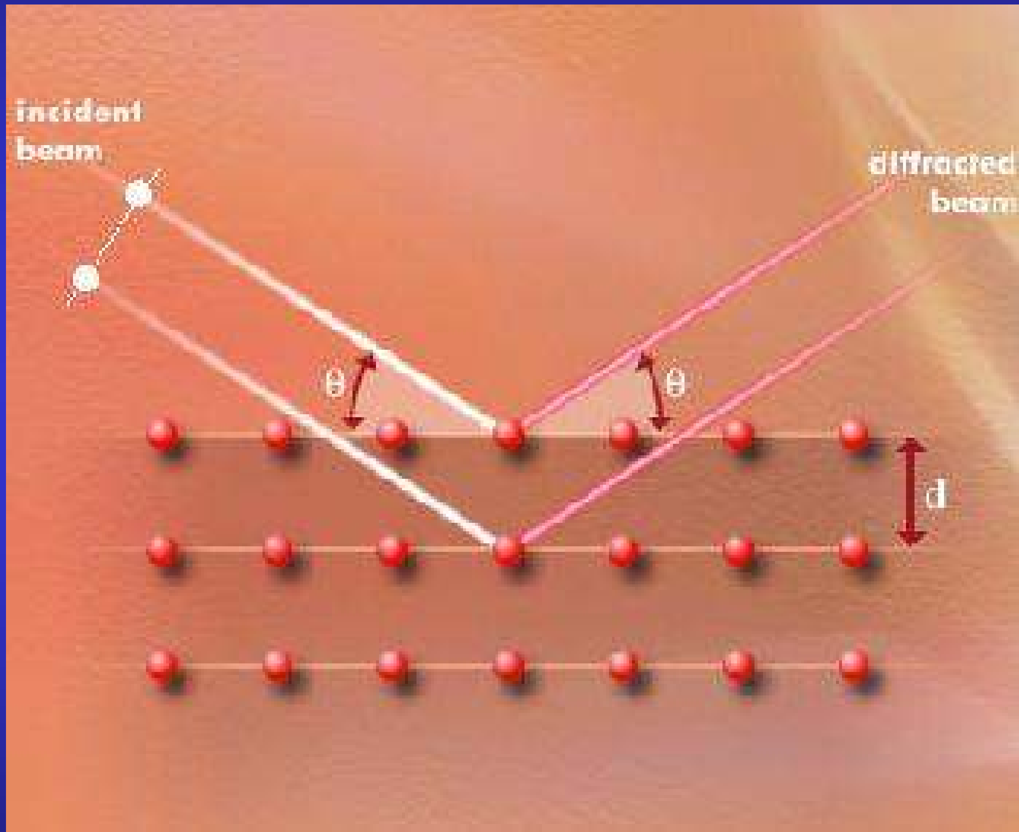
Beam Filtration



Beam Hardening

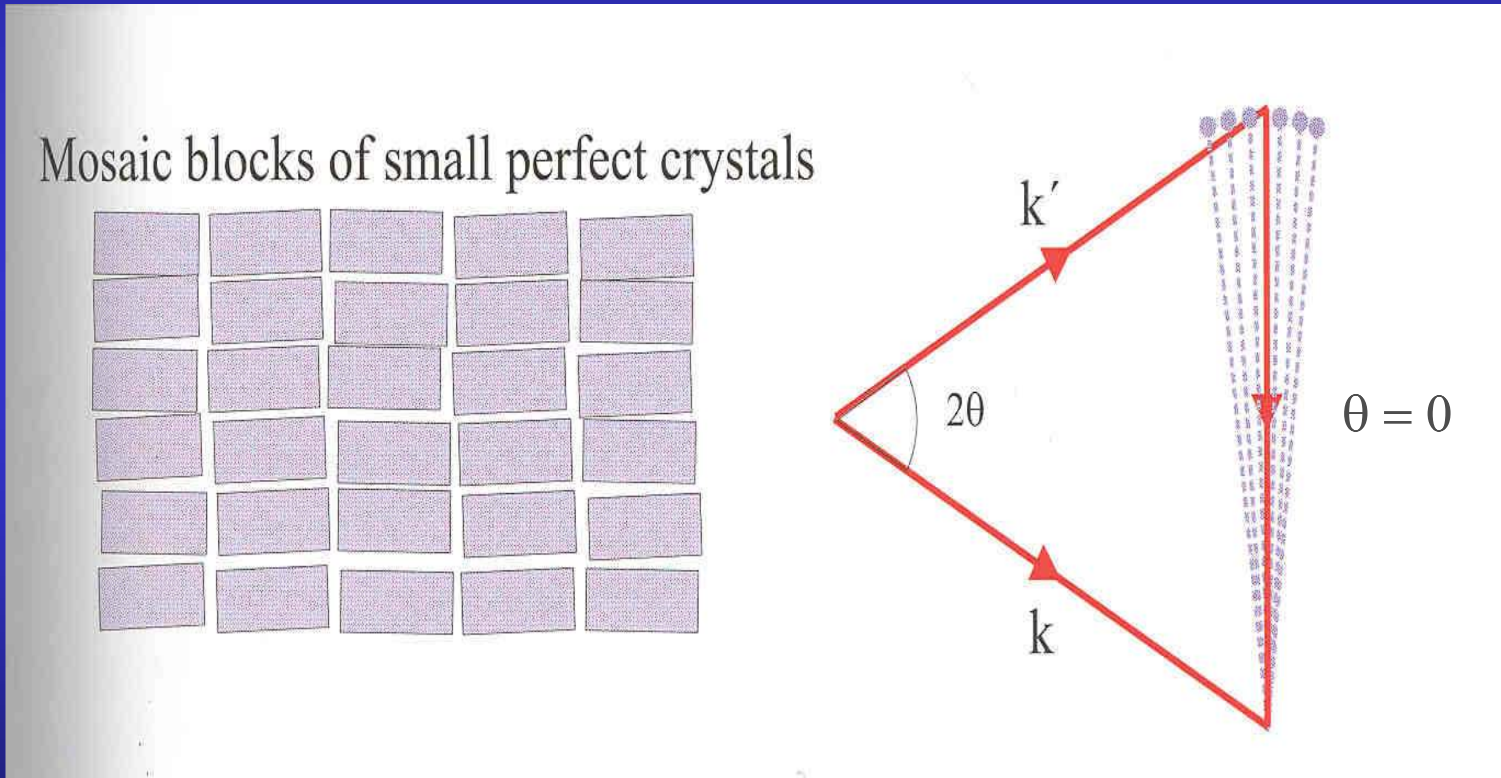


Bragg Diffraction



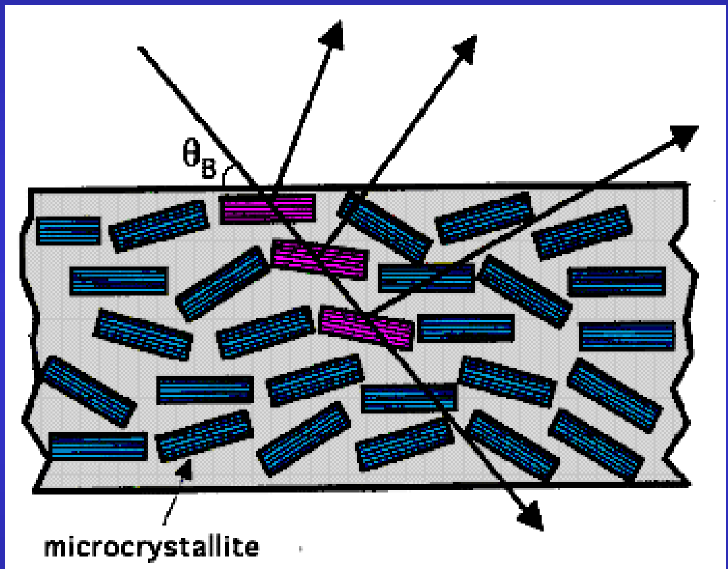
$$n\lambda = 2d \sin \theta$$

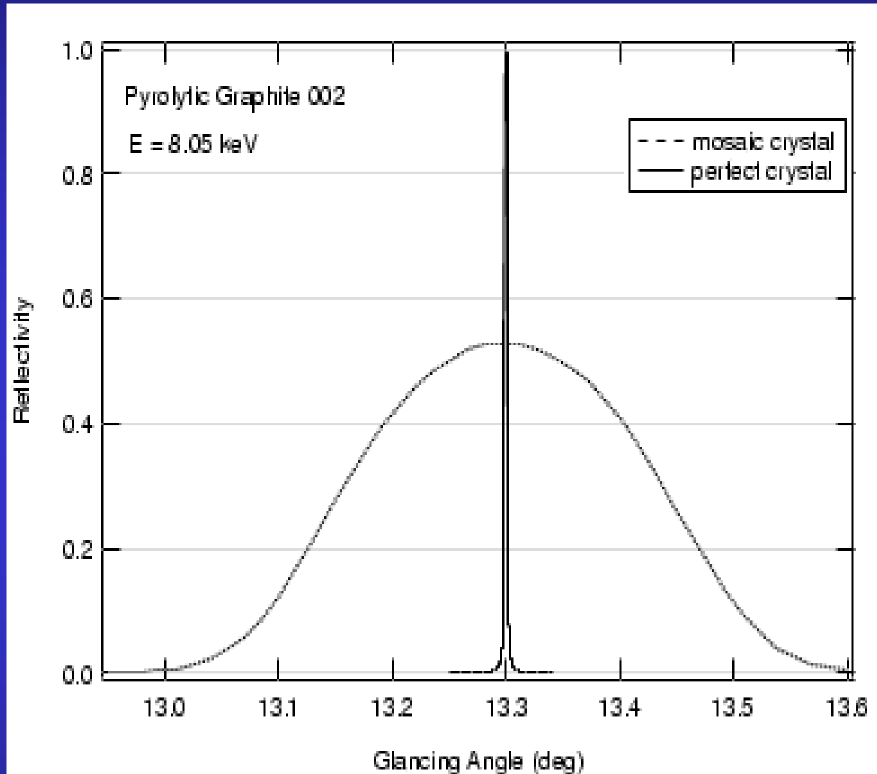
Mosaic crystal



Why Mosaic Crystals?

$$2d\sin\theta_B = n\lambda$$

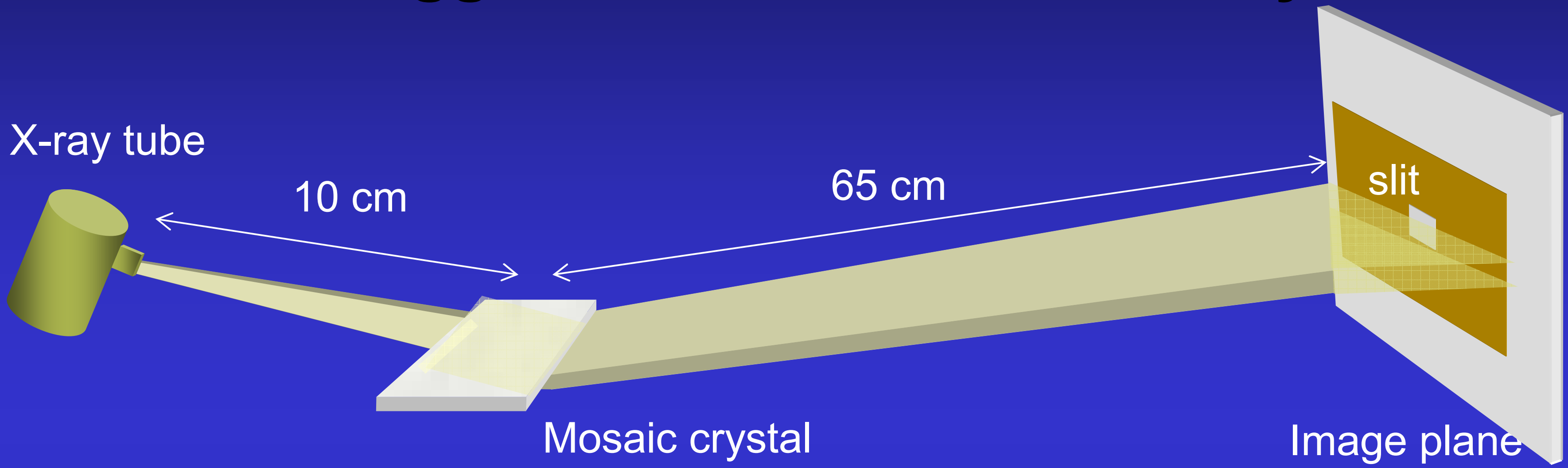




The diffraction of a single X-ray from a mosaic crystal. The photon penetrates the crystal until it encounters a mosaic block oriented so as to allow Bragg diffraction. This means that mosaic spread produces a wider bandpass compared to perfect crystal

Rocking curve comparison for mosaic and perfect crystal structures (pyrolytic graphite)

Quasi-monochromatic X-rays via Bragg Diffraction on Mosaic Crystal



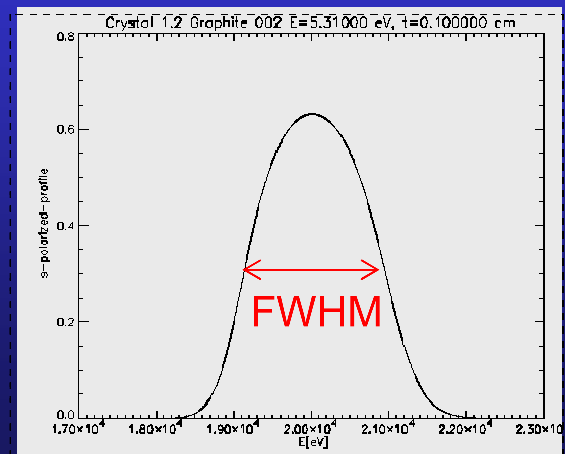
Source

- Focal spot: 0.5mm x 0.5mm
- Angle distribution: uniform
- Beam divergence: ranging between 0.5-3 FWHM of the reflectivity curve

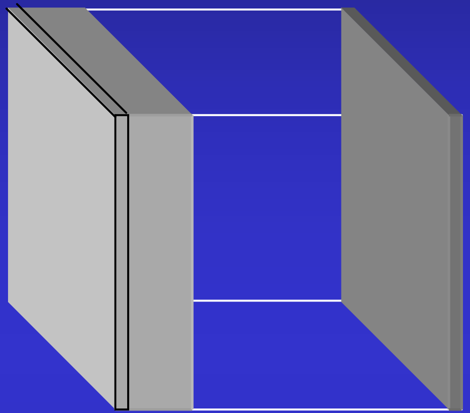
Mosaic crystal

- HOPG (highly oriented pyrolytic graphite)
- mosaic spread = 0.4°
- Thickness = 1 mm
- infinite dimension

Reflectivity curve

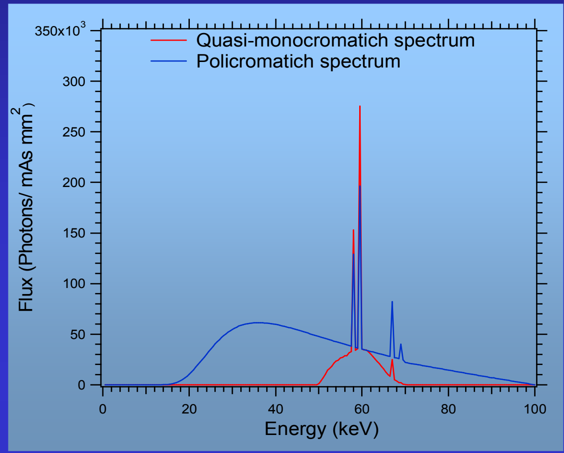


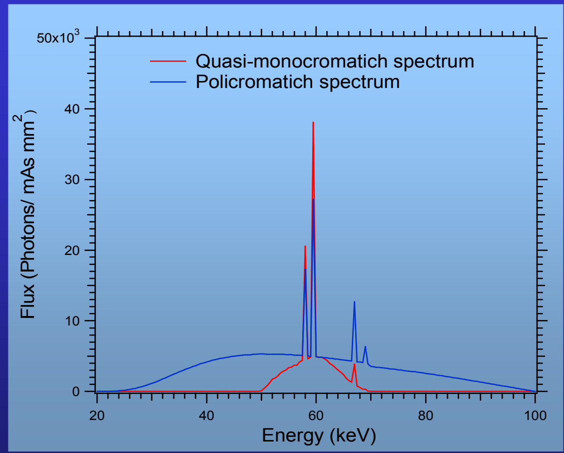
Chest Radiography with Conventional Spectrum and quasi-monochromatic spectrum



CDRH Standard Dosimetric/ Calibration Phantom for radiography of the chest

- Lucite (7.26 cm)
- Air gap (19 cm)
- Alluminium (0.41 cm)





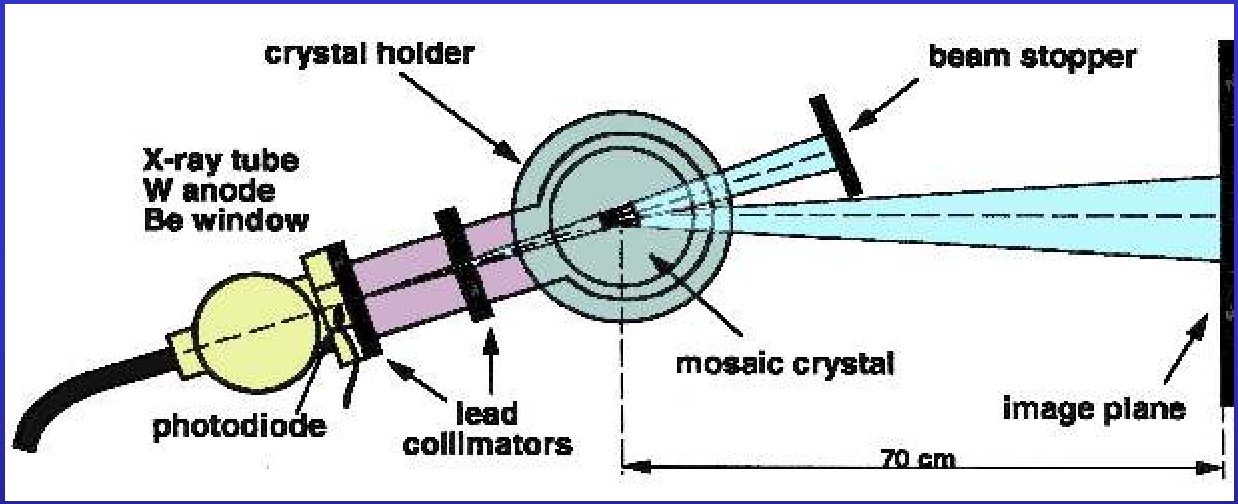
118 kV, W-anode , Mosaic crystal HOPG 1 mm

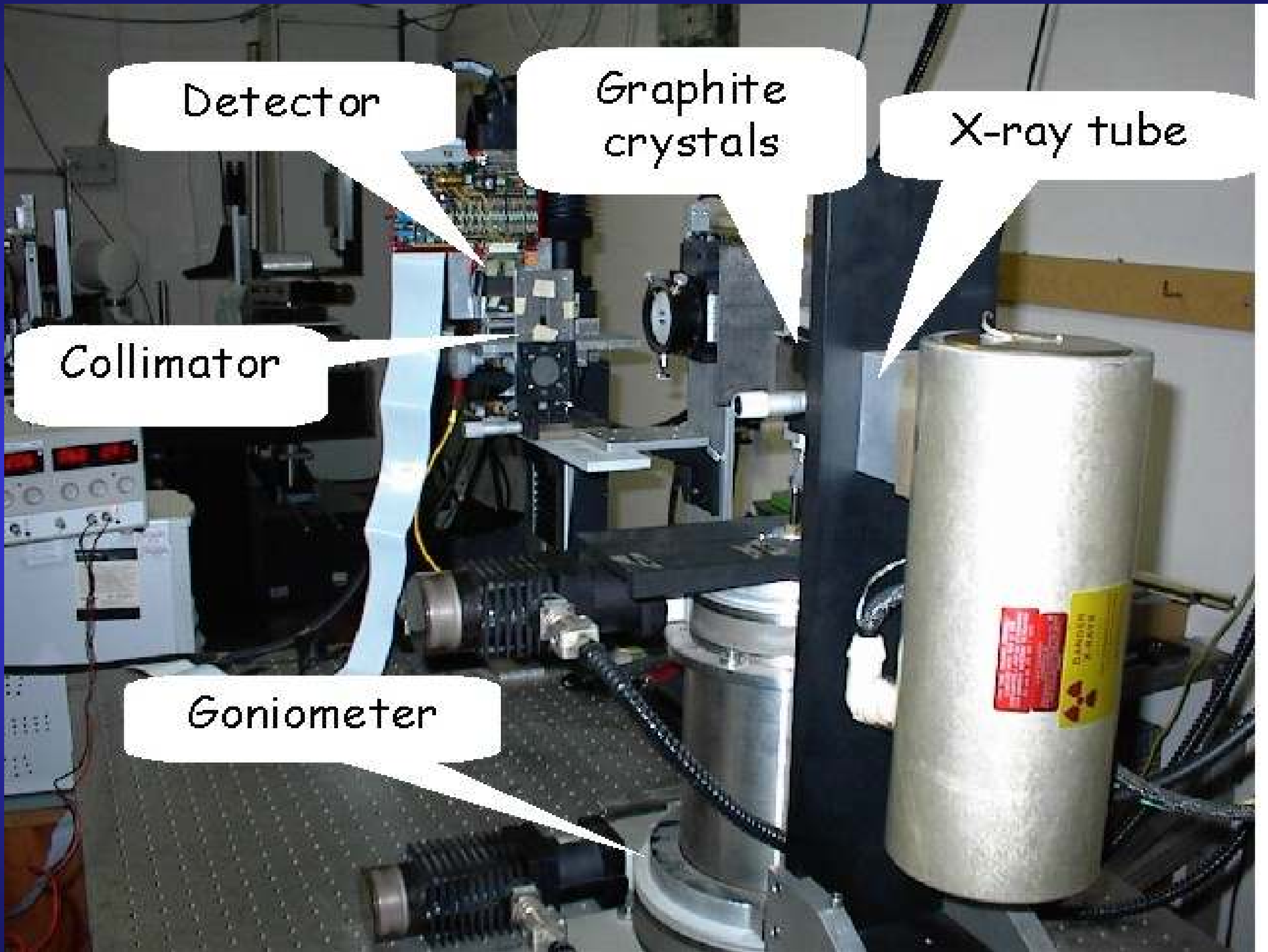
	$Energy_{in}$ (keV)	$Energy_{out}$	$Flux_{in}$ (Photons/mAs mm^2)	$Flux_{out}$
Quasi-monochromatic	59.1	59.3	1.2×10^6	1.6×10^5
Polychromatic	49.0	58.6	5.4×10^6	5.1×10^5

100 kV, W-anode, Al filtration 2.5mm

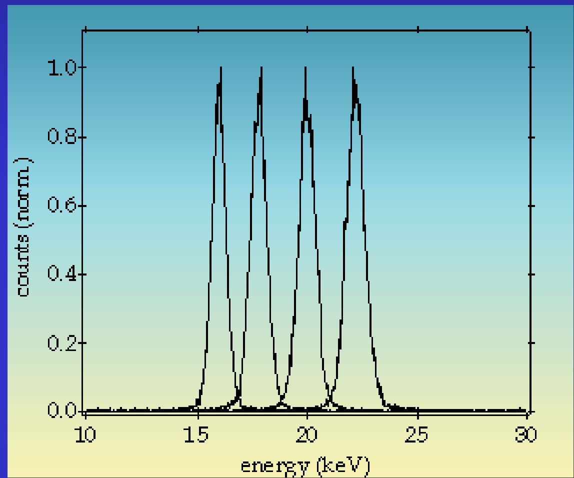
quasi-monochromatic x-rays for mammography applications

Diffractometer for the Monochromatization of the Polychromatic Beam Produced by a Conventional X-ray Tube




Detector
Graphite crystals
X-ray tube
Collimator
Goniometer

Small Field Quasi-monochromatic Beams (Single Mosaic Crystal)



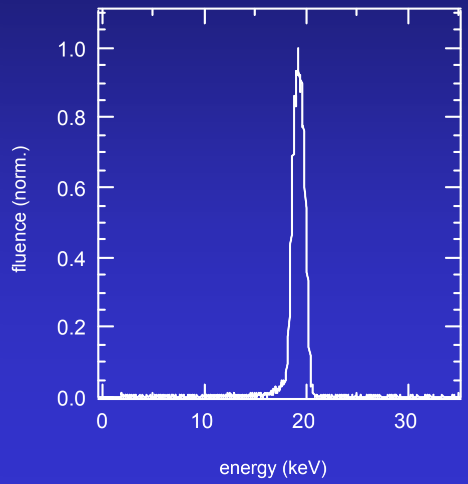
Energy (keV)	Photon flux (ph. mAs^{-1} mm^{-2})	Energy (FWHM)	Resolution (%)	Photon flux at makV (ph. mAs^{-1} mm^{-2})
16	$(0.86 \pm 0.09) \times 10^4$	0.57	3.6	0.93×10^4
18	$(1.1 \pm 0.1) \times 10^4$	0.69	3.9	1.4×10^4
20	$(1.2 \pm 0.1) \times 10^4$	0.87	4.3	1.9×10^4
22	$(1.3 \pm 0.1) \times 10^4$	0.97	4.4	2.4×10^4

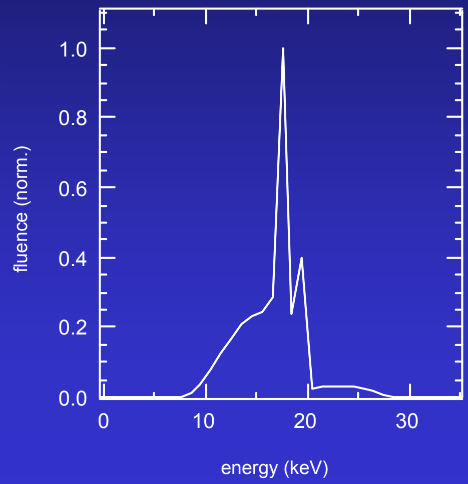
Mammography Spectra

Quasi-monochromatic X-ray beam (19 keV)

Conventional X-ray tube (Mo/ Mo 28 kVp)

Entrance beam

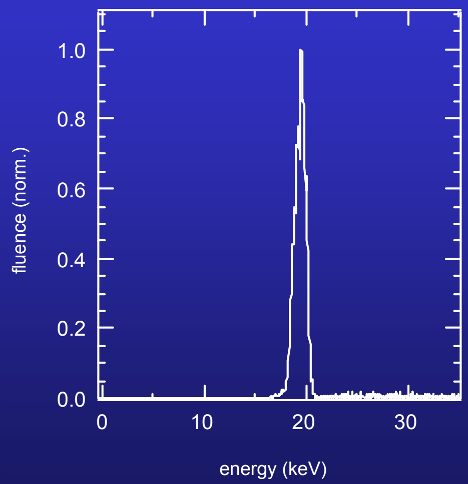


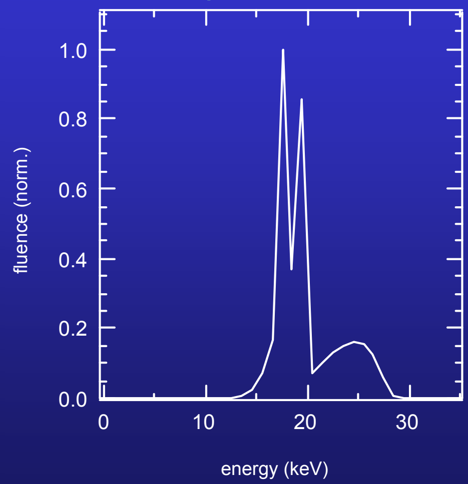


EXPOSURE = 0.7 mR mA^{-1} s^{-1}
PHOT. FLUX = 2.24 x 10^{4} ph mm^{-2} mA^{-1} s^{-1}

EXPOSURE = 12.3 mR mA^{-1} s^{-1}
PHOT. FLUX = 3.57 x 10^{5} ph mm^{-2} mA^{-1} s^{-1}

Output beam (PMMA 4.5 cm)





EXPOSURE = 0.03 mR mA^{-1} s^{-1}
PHOT. FLUX = 9.01 x 10^{2} ph mm^{-2} mA^{-1} s^{-1}

EXPOSURE = 0.19 mR mA^{-1} s^{-1}
PHOT. FLUX = 9.26 x 10^{3} ph mm^{-2} mA^{-1} s^{-1}

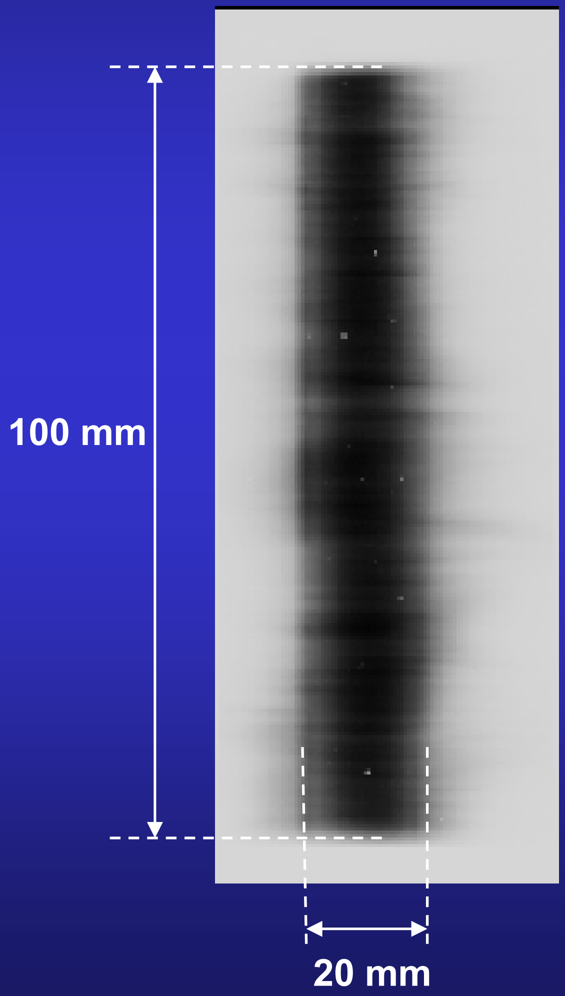
In order to evaluate the clinical potential of the quasi-monochromatic beams a comparison with a Mo/Mo conventional X-ray tube is shown entrance and exit exposure rate and photon fluxes for a plexiglas bulk 4.5 cm-thick are been measured at a distance of 75 cm from the X-ray tube

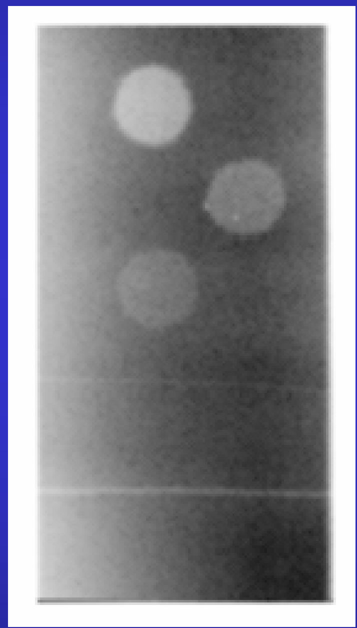
Quasi-monochromatic input exposure rates are more than one order of magnitude less than those obtained with the conventional source an exposure rate ratio equal to six is obtainedat the exit of the phantom.

This means that an anode current of 400-600 mA is needed to achieve the photon flux used in clinical application

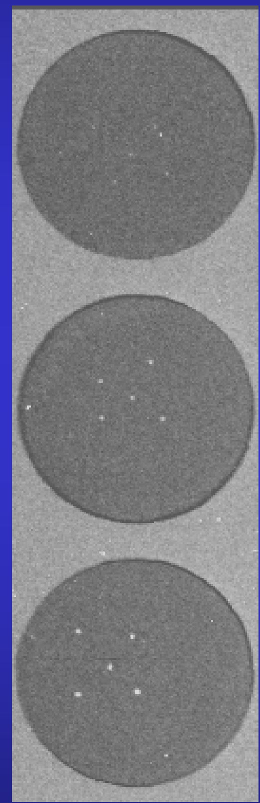
Imaging Test

(performed with a screen-film system at 19 KeV)





Radiograph of a plexiglas phantom containing Al disks and wires

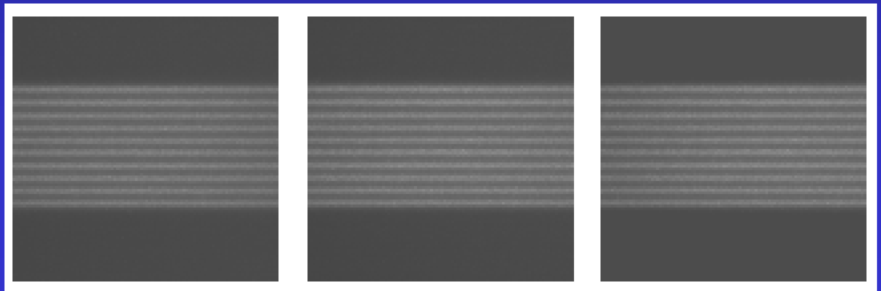


Radiograph of a plexiglas phantom containing quartz microspheres embedded in wax

What about image quality?

Spatial Resolution Properties:
Radiograph of Bar Pattern

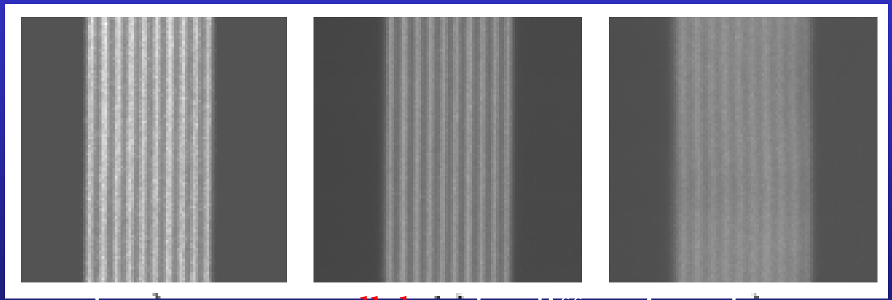
R = crystal-X ray focus distance
α = divergency of the beam incident on the crystal



bar pattern orthogonal to the diffraction plane

R = 210 mm α = 0.4 deg	R = 210 mm α = 1.0 deg	R = 467 mm α = 0.7 deg

If the bar pattern is orthogonal to the diffraction plane the sharpness of the image is independent of the geometrical setup



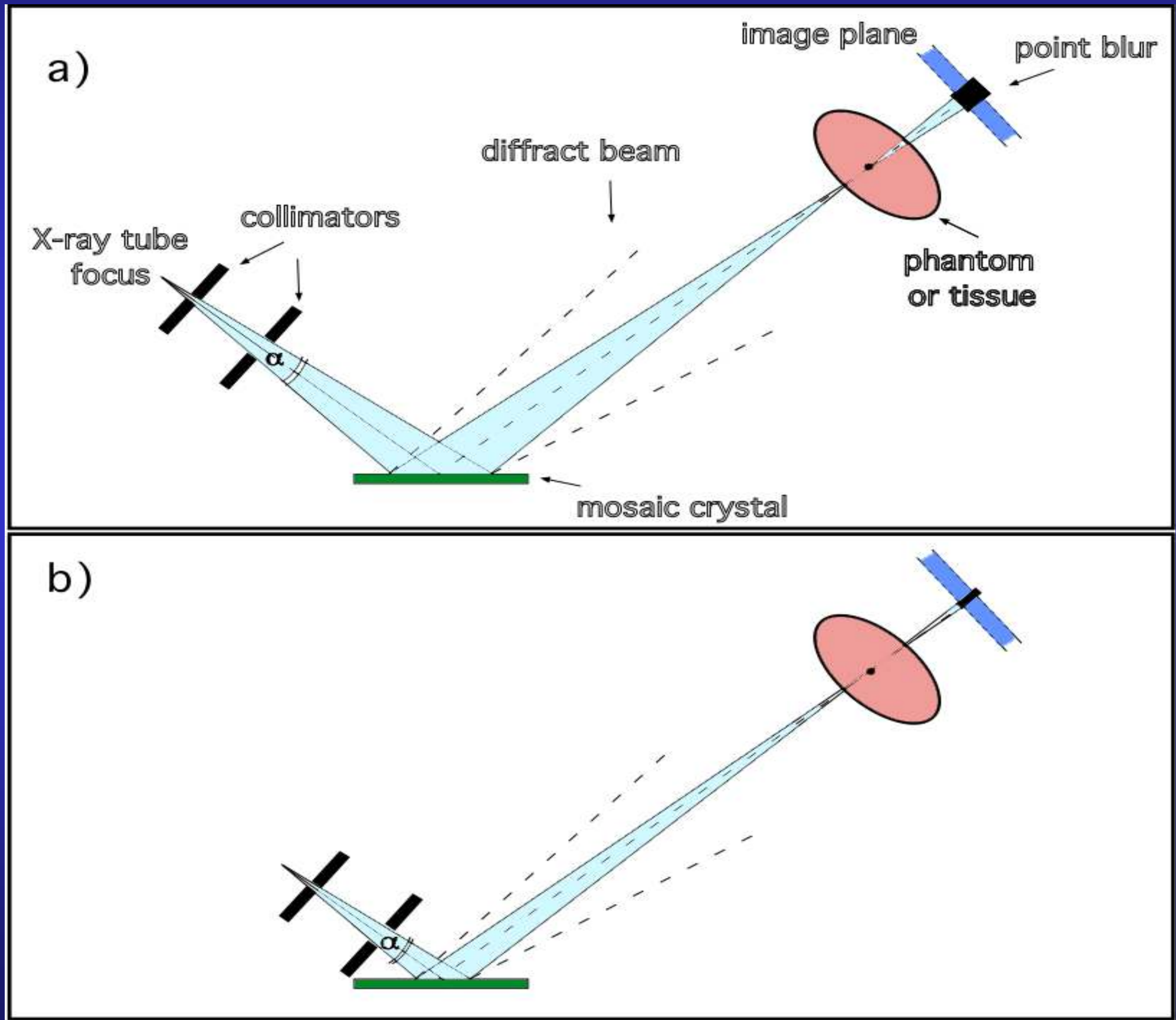
bar pattern parallel to the diffraction plane

R = 210 mm α = 0.2 deg	R = 210 mm α = 1.0 deg	R = 467 mm α = 0.7 deg

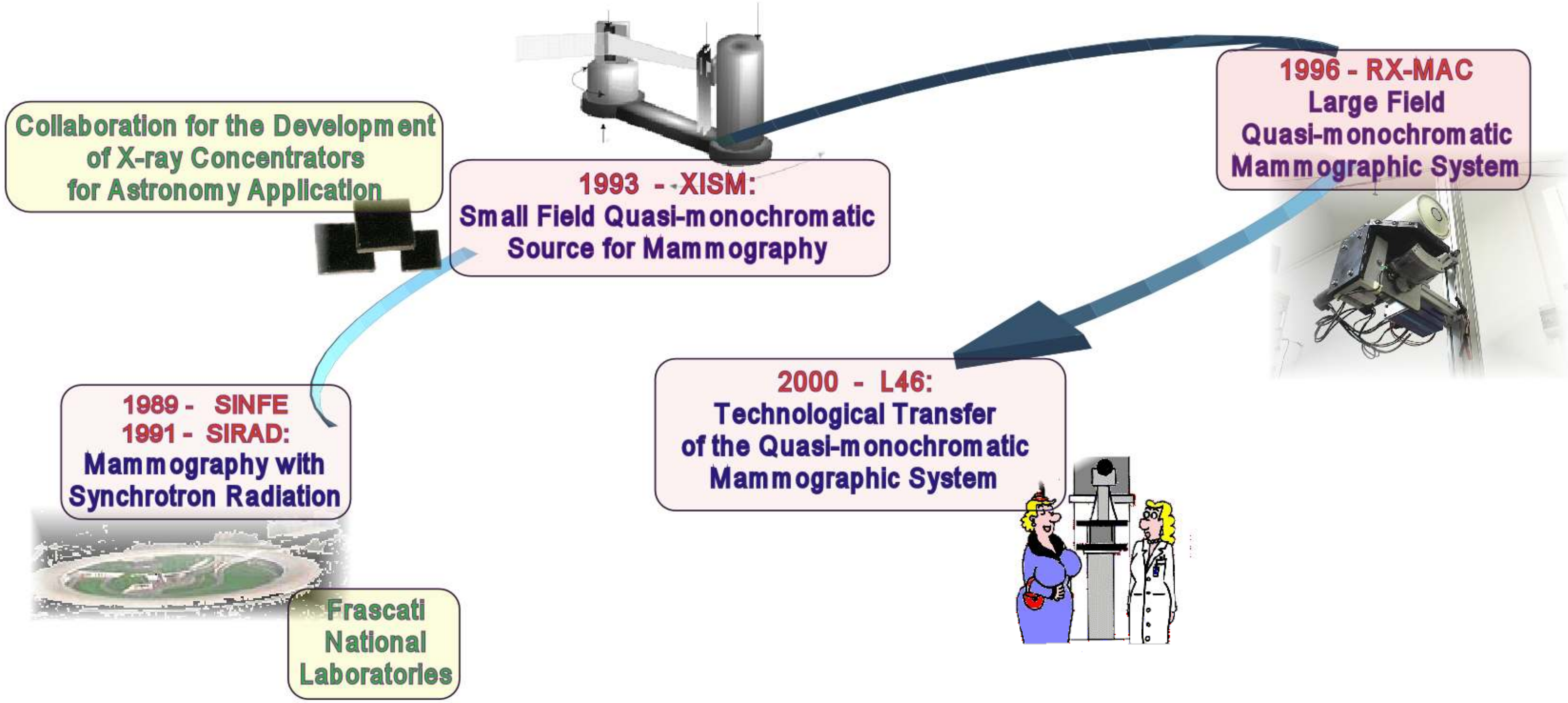
If the bar pattern is parallel to the diffraction plane the unsharpness increases as the irradiated area of the crystal increases (for large values of R and α)

The crystal behaves as a secondary source !

Spatial Resolution Properties:
Size and Position of the Focal Spot



From Basis Research to Technological Transfer



The quasi-monochromatic system

$16 \text{ keV} < E < 25 \text{ keV}$

X RAY TUBE

Anode	Tungsten
Window	Berillium
Maximum voltage	50 kV
Maximum current	600 mA
Maximum time	10 s
Focal spot	2mm x 1mm

COLLIMATION SYSTEMS

Material: Pb
Thickness: 1 mm

Primary collimation system :
17mm x 2mm (at the exit of the x-ray tube)
40mm x 2.5mm (10 cm from the focal spot)

Secondary collimation system
90mm x 5.2mm (10 cm from the crystal)
180mm x 10.5mm (35 cm from the crystal)
210mm x 2→20mm (45 cm from the crystal)

SCANNING SYSTEM

Path = 180 mm
Scanning speed = 20 → 90 mm/sec

Dedicated X-ray Tube

-W-anode, Be-window;

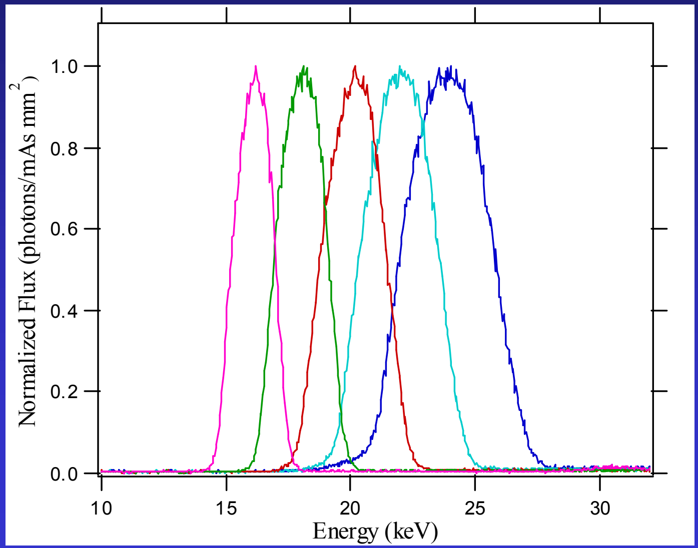
- anode diameter 90 mm;
- HV max. 50 kV;
- max. anode current:

  340 mA f.s. 1.2 x 2.0 mm^2

  600 mA f.s. 1.3 x 2.8 mm^2

X-ray beam characteristics

Energy (keV)	Flux (photons/mAs mm²)	ΔE/E (%)
16	$(4.4 \pm 0.02) \times 10^4$	10.0%
18	$(5.6 \pm 0.02) \times 10^4$	11.8%
20	$(6.6 \pm 0.02) \times 10^4$	13.2%
22	$(8.0 \pm 0.02) \times 10^4$	15.3%
24	$(8.7 \pm 0.02) \times 10^4$	17.2%



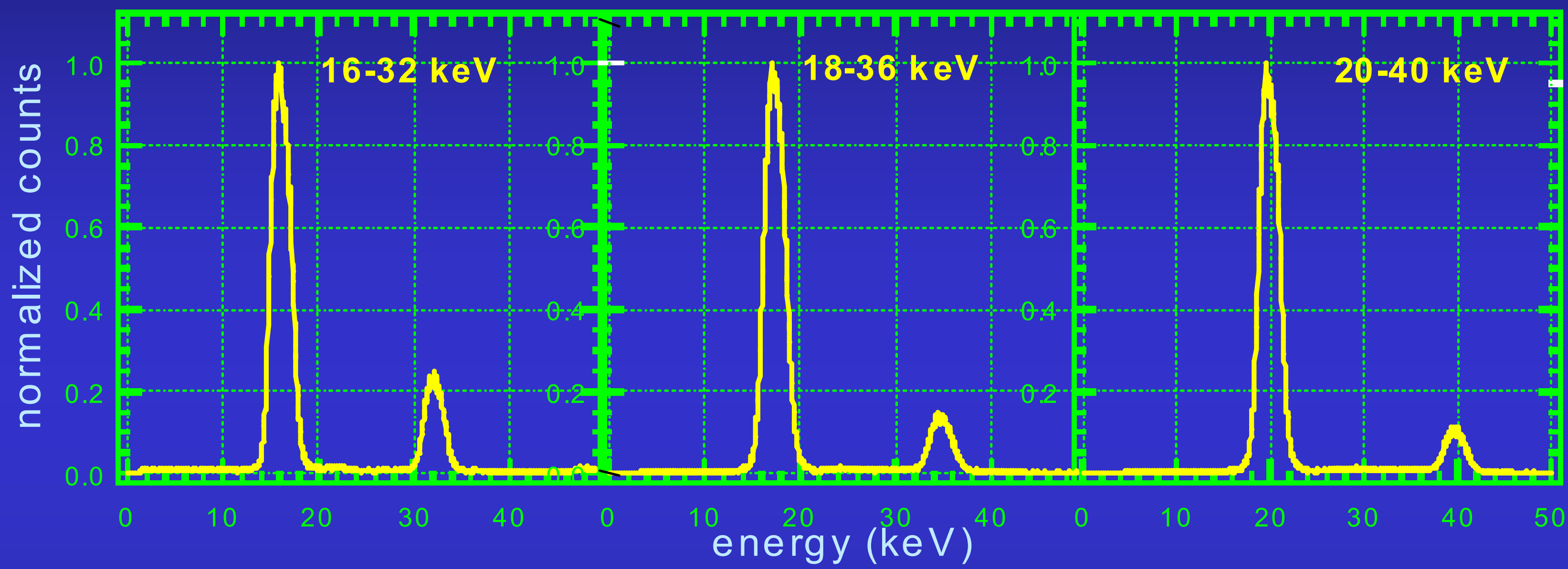
Spectrum	Exp(out) conventional / Exp(out) quasi-monocromatic
Mo-Mo 28 kV	
16	23
18	6.0
20	3.2
22	2.2
24	1.7

Exposure ratio measured after the attenuation of 45 mm Plexiglass at 67 cm from the focal spot.

Data show the anode current needed to achieve the same amount of radiation which produces an optical density comparable with that used in clinical application.

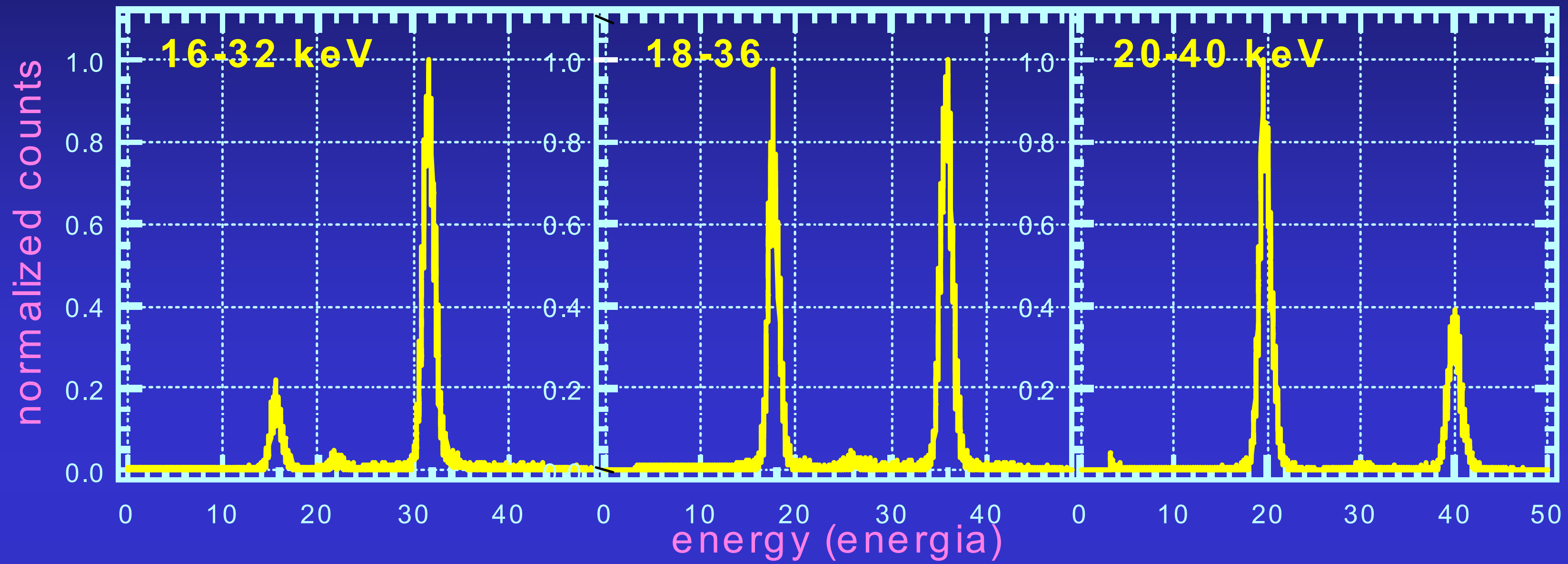
Quasi-dichromatic incident spectra

Voltage= 50.4 kVp, Current = 4.4 mA, Lifetime = 120 s



Mean Energy (keV)	Flux (ph mm^{-2} mA^{-1}s^{-1})	FWHM (keV)
15.63	$(1.40 \pm 0.12) \times 10^4$	1.04
31.79	$(3.17 \pm 0.18) \times 10^3$	1.03
17.80	$(1.66 \pm 0.13) \times 10^4$	1.11
36.11	$(2.45 \pm 0.16) \times 10^3$	1.40
19.95	$(1.78 \pm 0.13) \times 10^4$	1.13
39.83	$(1.63 \pm 0.13) \times 10^3$	1.36

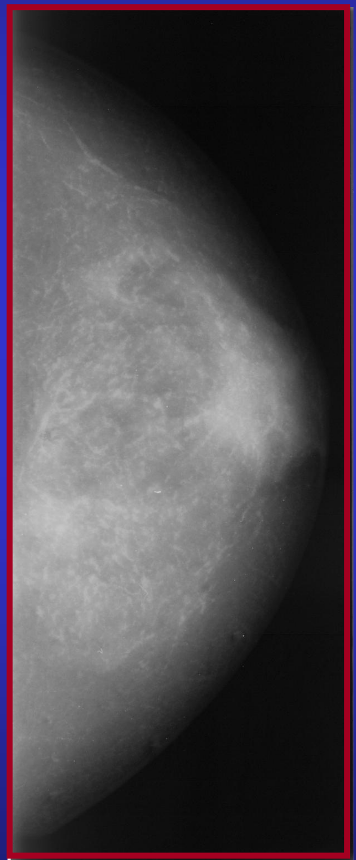
Spectra transmitted through 5-cm of equivalent tissue



Mean energy (keV)	Flux (ph mm^{-2} $mA^{-1}s^{-1}$)	FWHM (keV)
15.46	(1.38 ± 0.12) x10^2	1.11
31.61	(8.24 ± 0.29) x10^2	1.39
17.57	(4.84 ± 0.22) x10^2	1.20
36.89	(6.40 ± 0.25) x10^2	1.48
19.65	(11.0 ± 0.33) x10^2	1.29
40.14	(4.81 ± 0.22) x10^2	1.68

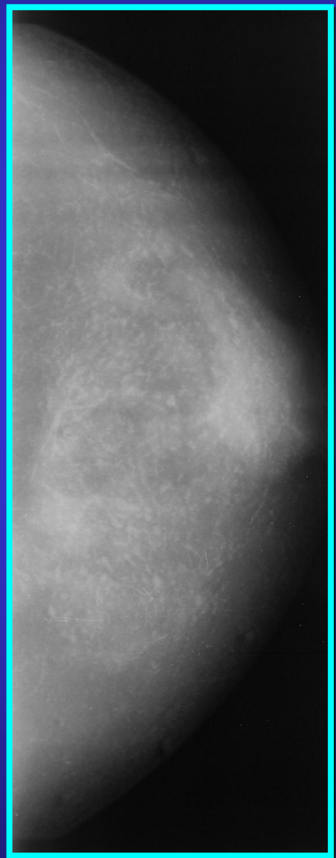
Radiographic test: RACHEL phantom

Conventional,
Mo-Mo 28 kV 80 mAs



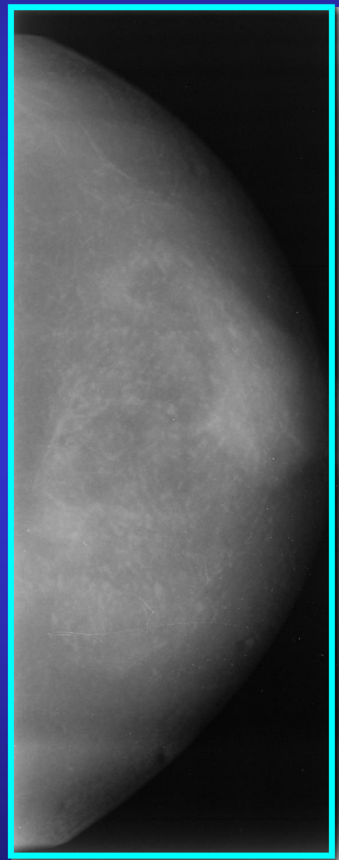
AGD = 1.3 mGy

18 keV
34 kV, 300 mA, 3 sec



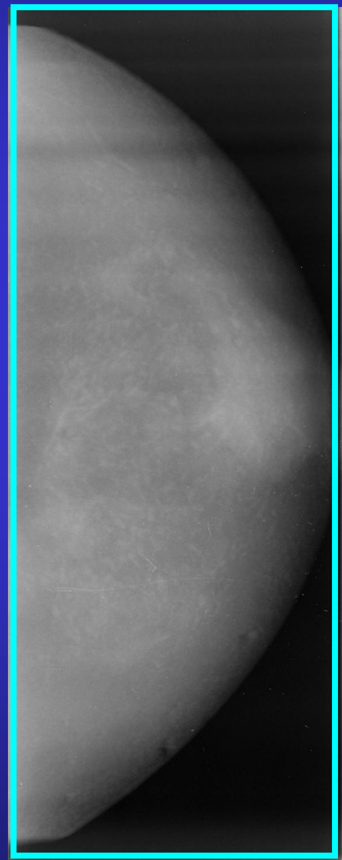
AGD = 0.76 mGy

21 keV
40 kV, 70 mA, 2.7 sec



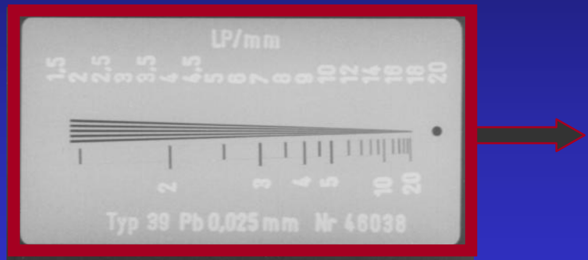
AGD = 0.23 mGy

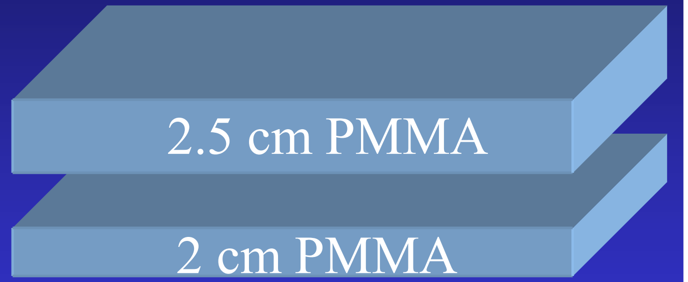
23 keV
44 kV, 70 mA, 2.7 sec

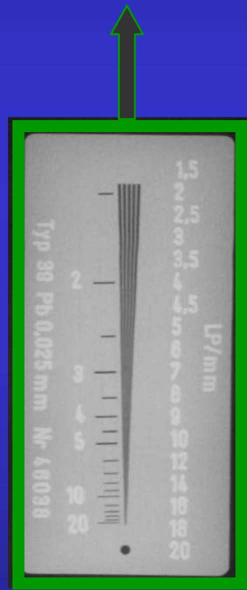


AGD = 0.12 mGy

Spatial resolution properties







Energy	Spatial resolution ⊥ Diffraction plane	Spatial resolution ‖ diffraction plane
18 keV	10 lp/mm	6.5 lp/mm
21 keV	9.5 lp/mm	5.5 lp/mm
23 keV	8.5 lp/mm	4.5 lp/mm

Conventional system Mo/Mo 28 kV ≈ 15 lp/mm

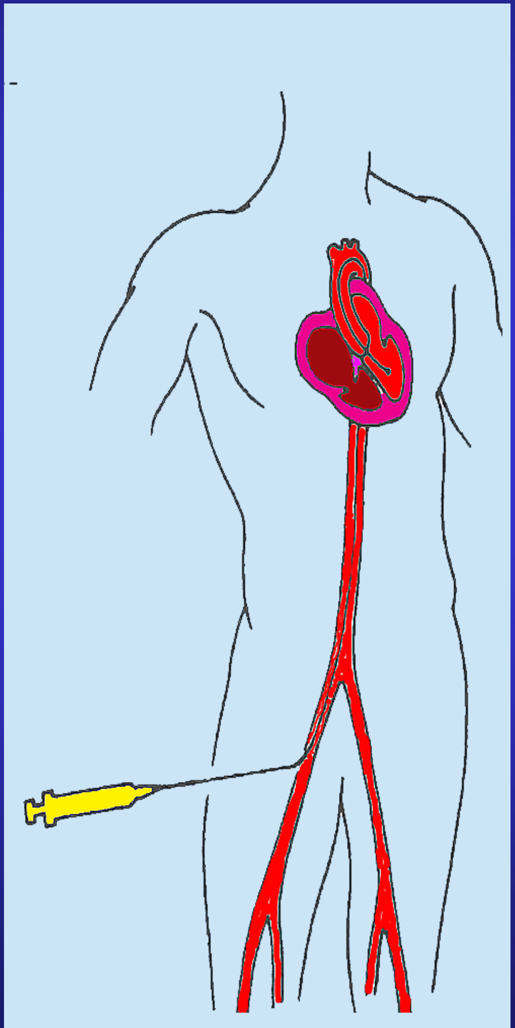
From mammography to other medical applications

Coronary Angiography

Angiography is one of the most invasive diagnostic techniques

- iodate contrast medium

- x-ray exposures of long duration.



New Techniques

Are being investigated, with the aim of reduce the risk connected with the coronographic investigation, in the case of:

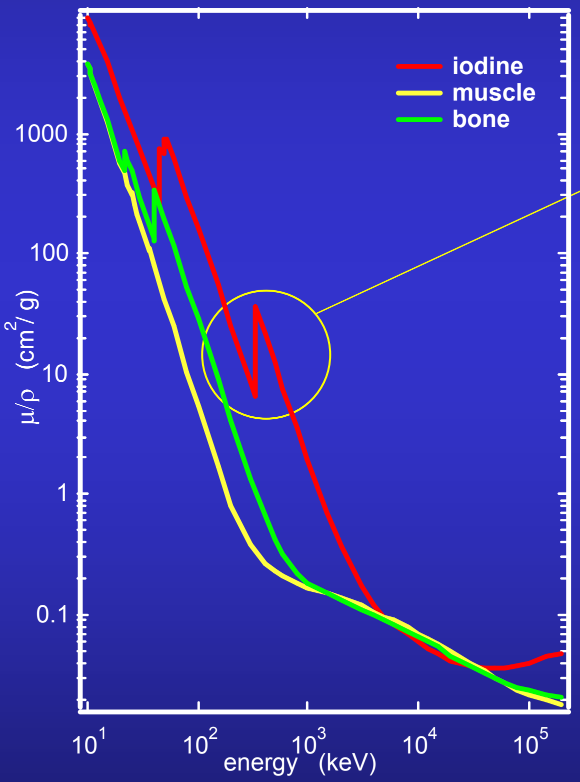
✓ people with diagnosed pathology or post-operative follow-up;

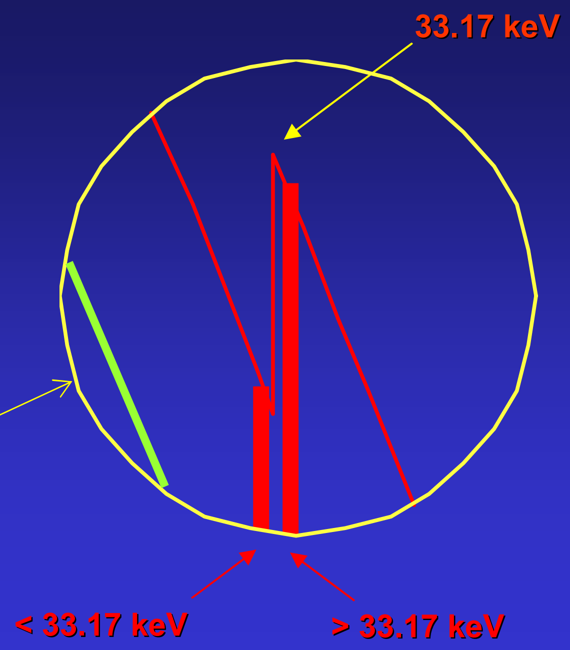
✓ screening of healthy population.

⬇

Dual Energy Subtraction Angiography (DESA)

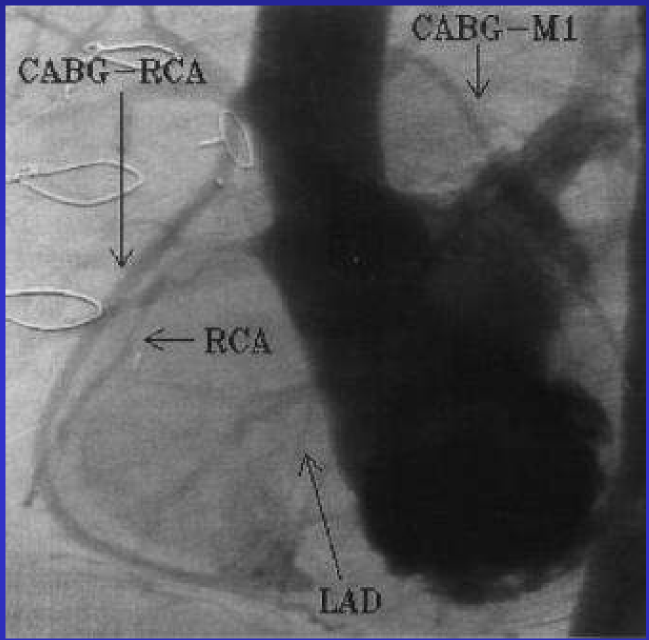
Dual Energy Subtraction Angiography



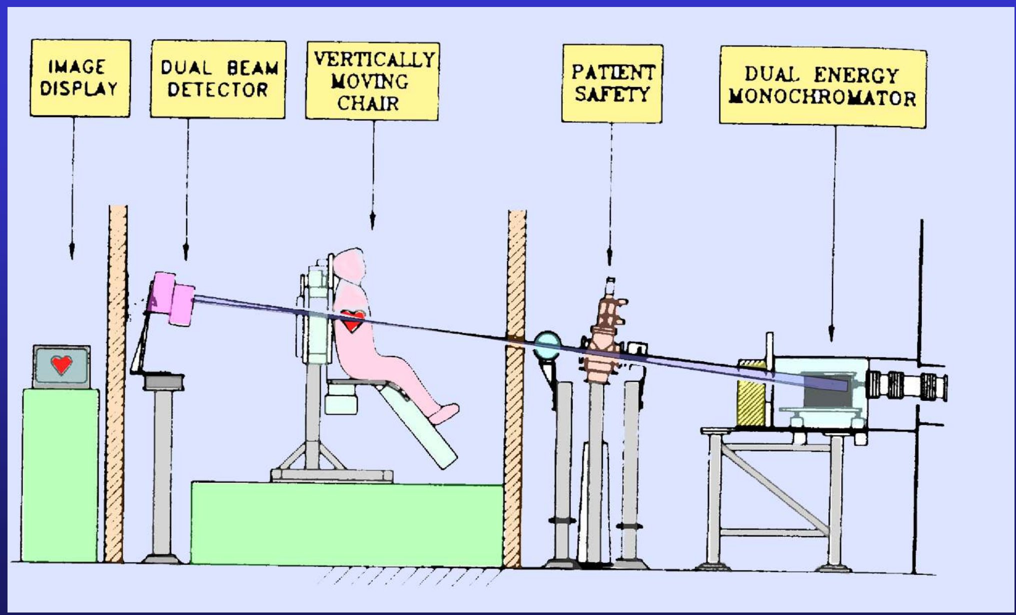


- ✓ The concentration of the contrast medium in the artery may be reduced.
- ✓ No arterious insertion of catheter.

Synchrotron radiation

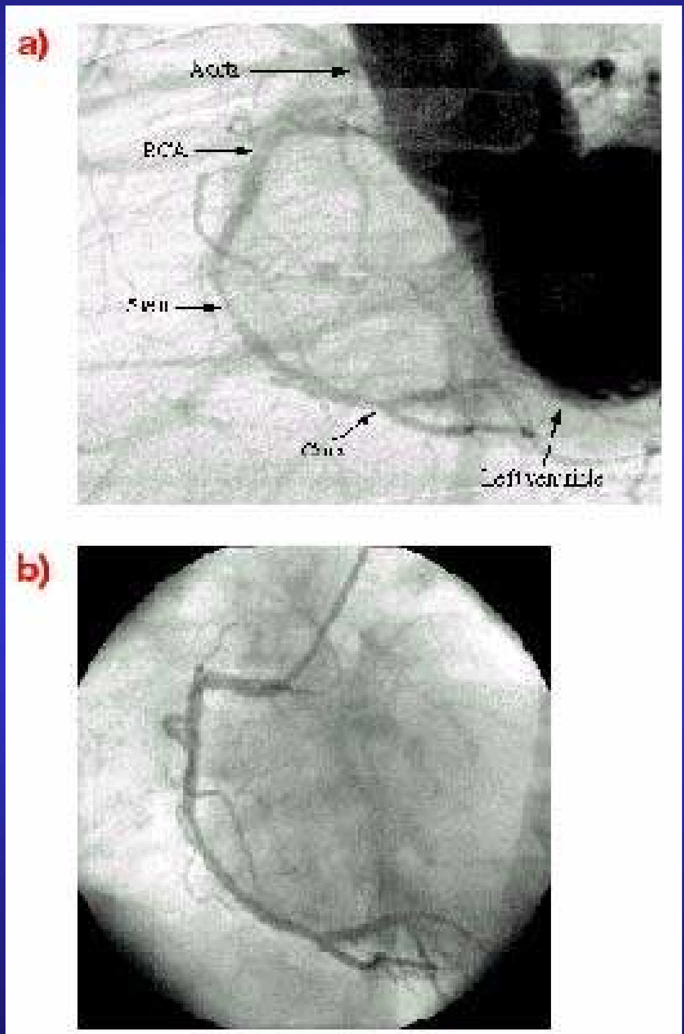


- Nicht-Invasive Koronarangiographie mit Synchrotrrahlung (NIKOS) (HASYLAB, Germany, 1994)



- Until today it has been experienced on more than 400 patients, obtaining images of excellent quality

Synchrotron radiation



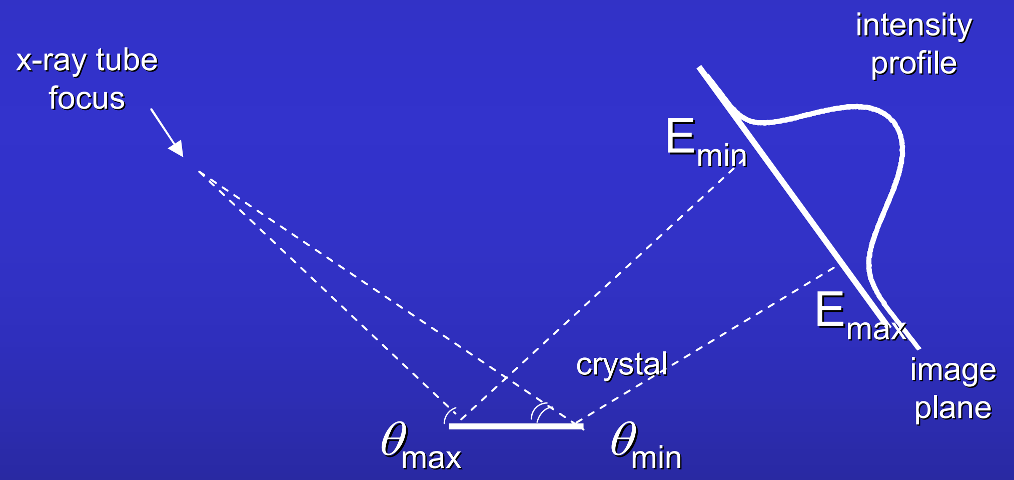
Medical Beamline (ESRF, France, 1991)

a) Intravenous synchrotron angiogram;
b) Conventional angiogram.

Stenosis appears visible inside the stent in the second segment C2, and a known distal stenosis visible at the crux remains mild (less than 50%). The excellent visualisation of the distal part of the right coronary artery (RCA) should be noted. These findings are in excellent agreement with the conventional selective coronary angiogram performed a few hours later in the hospital cardiology unit.

Characteristics of the Diffracted Beam

direction parallel to Bragg diffraction

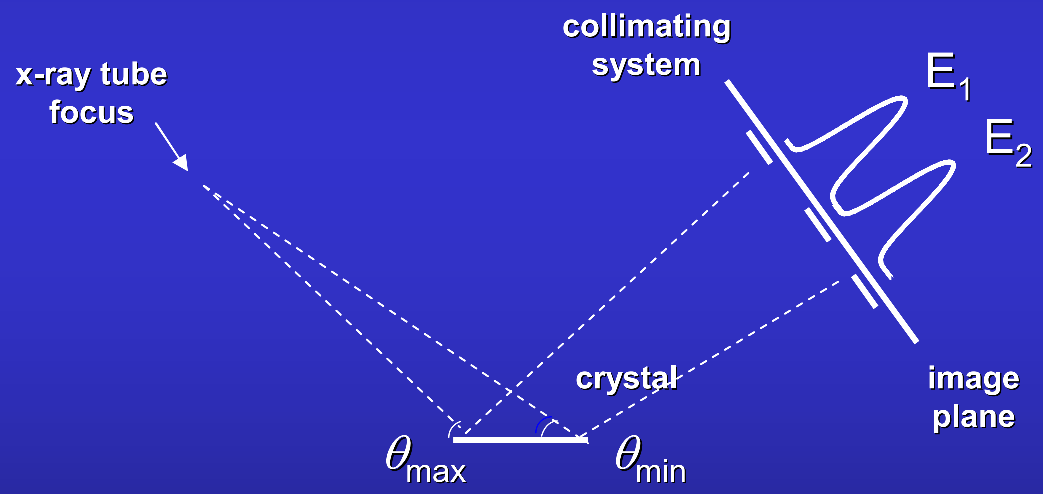


Beam size depends on geometrical set-up and on energy spread.

When a polychromatic and divergent beam impinge on the mosaic crystal, the diffracted beam presents an energy gradient in the plane parallel to Bragg diffraction plane.

Characteristics of the Diffracted Beam

direction parallel to Bragg diffraction



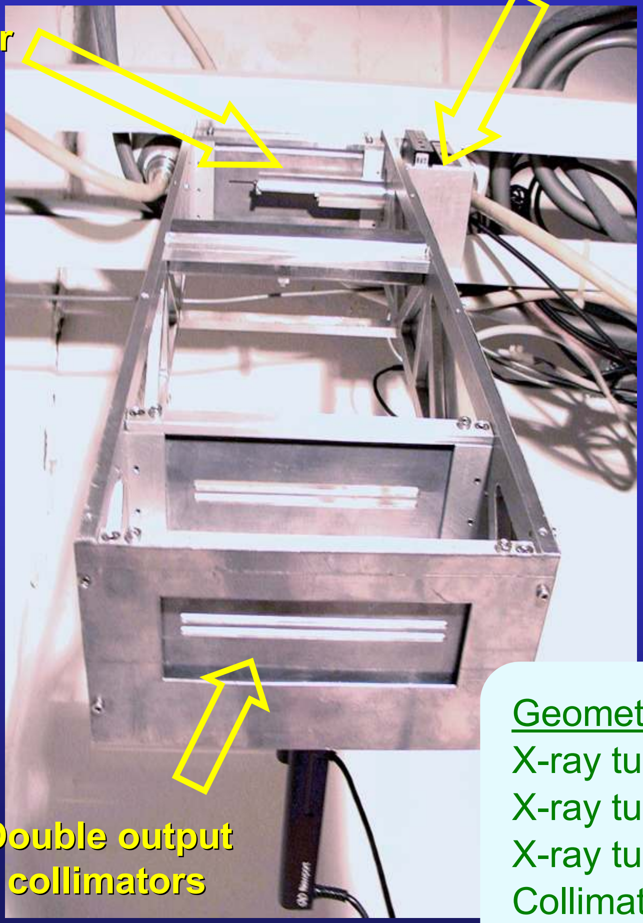
Quasi-monochromatic x-rays obtained by Bragg diffraction onto a mosaic crystal may be splitted in two beams, by means of a collimating system.

In order to apply dual-energy angiography we must have:
- a good spatial separation of the two beams;
- a good energy separation of the two beams (E1 < 33.17 keV < Emax).

The Monochromator

<u>Crystal Parameter:</u>

Type	HOPG
Size	60 x 28 x 1 mm^3
Mosaic Spread	0.26 degrees

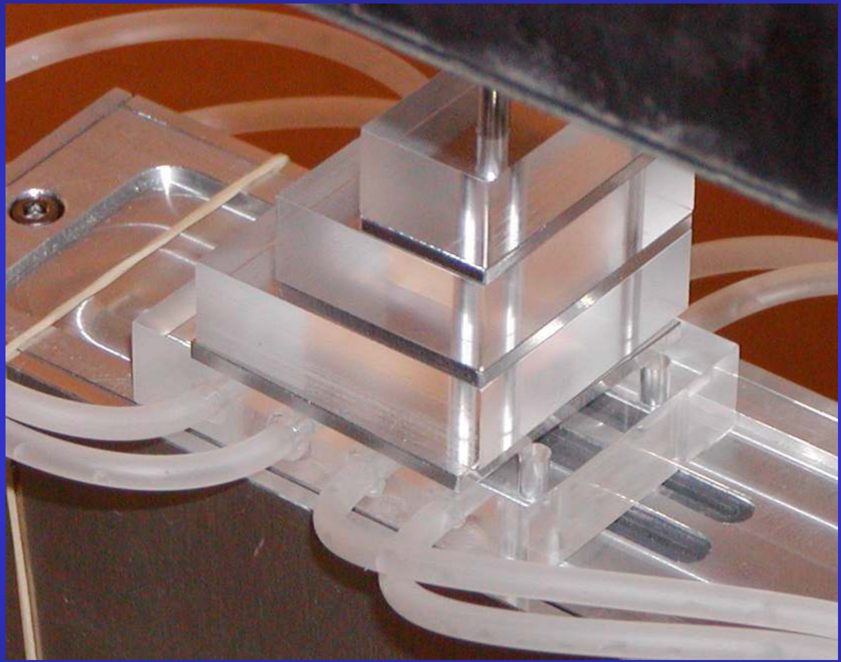


<u>Geometrical characteristics:</u>

X-ray tube focus-to-crystal distance	130 mm
X-ray tube focus-to-first output collimator distance	500 mm
X-ray tube focus-to-second output collimator distance	600 mm
Collimators' width	4 mm
Collimators' separation	3 mm

Angiography system

Angiographic Phantom



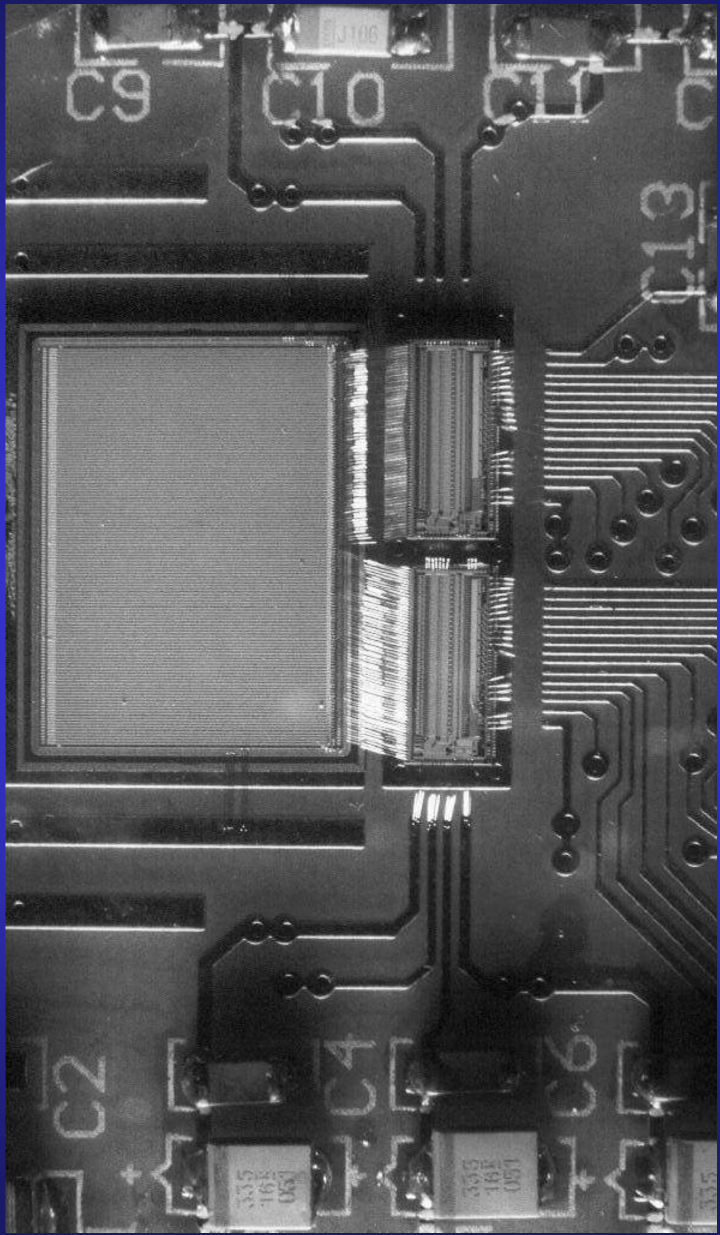
Detector

- step wedge plexiglass phantom
- 40 mm-high, 30-mm wide
- thickness range 10-45 mm
- 3 cylindrical cavities filled with iodate contrast medium (concentration 370 mg/ml)

Digital Detectors

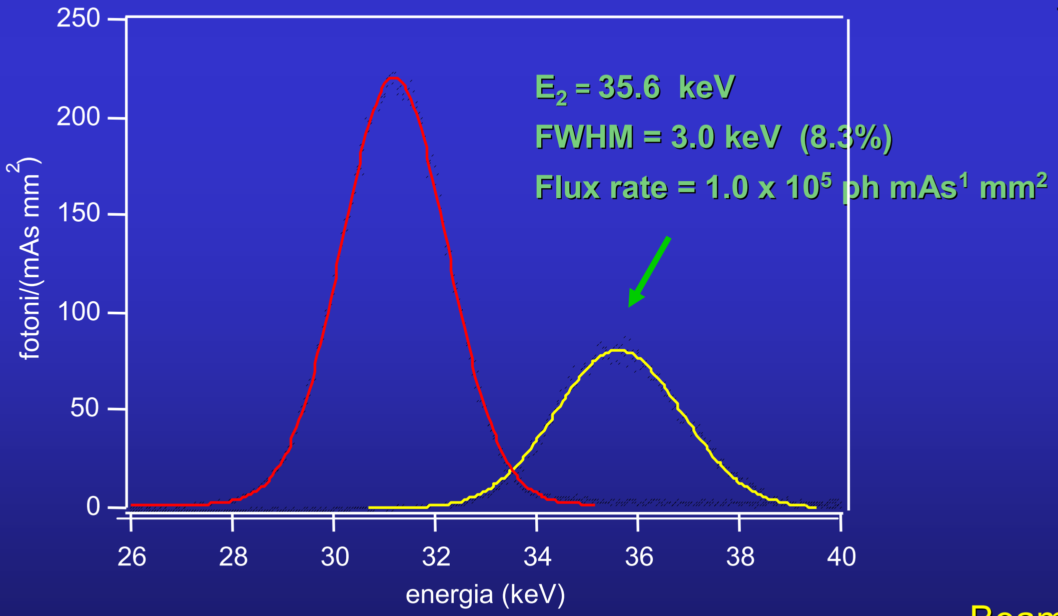
- Two linear silicon microstrip detectors
- Edge operation mode
- Thickness: 10 mm
- 128 pixels
- Pixel size: 300 x 100 μm^2

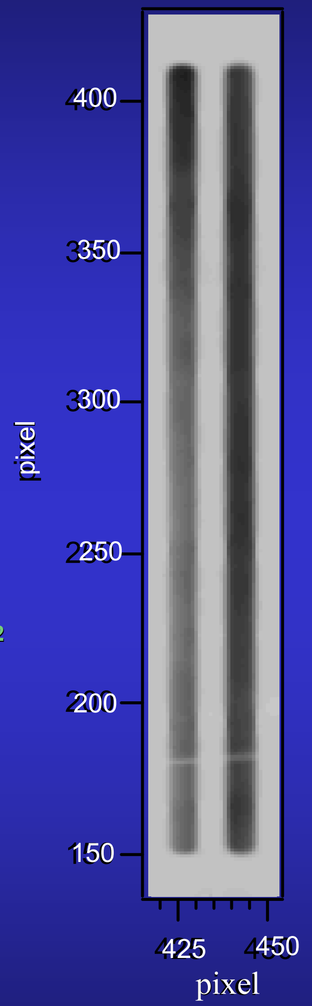
- Low noise read-out electronics
- Good counting rate
  (200 KHz per strip)



X-ray beams carachteristics

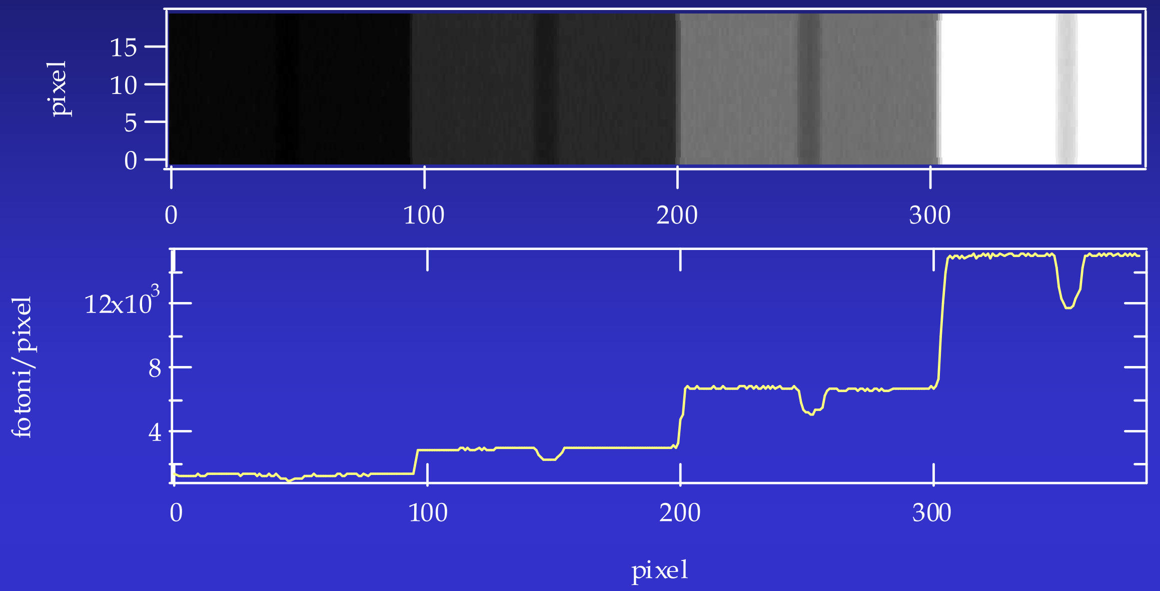
E_1 = 31.2 keV
FWHM = 2.5 keV (7.9%)
Flux rate = 2.2 x 10^5 ph mAs^1 mm^2





Beam size 120 x 4 mm^2
Beams gap 6 mm

Acquired images

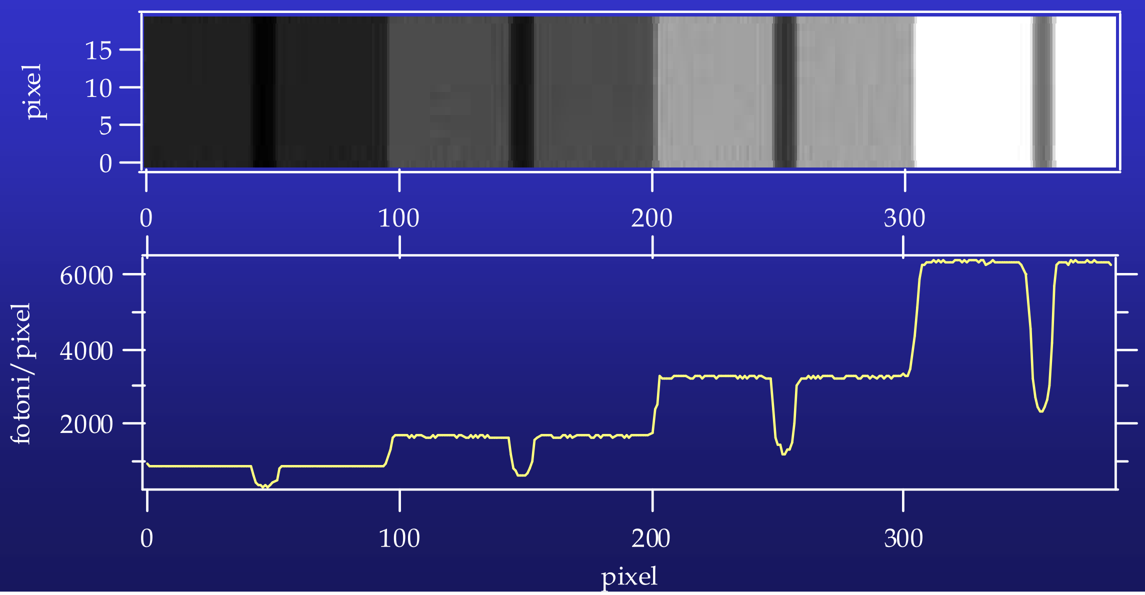


E=31.2 keV

c=370 mg/ml

x_d=1 mm

65 kV, 40 mAs



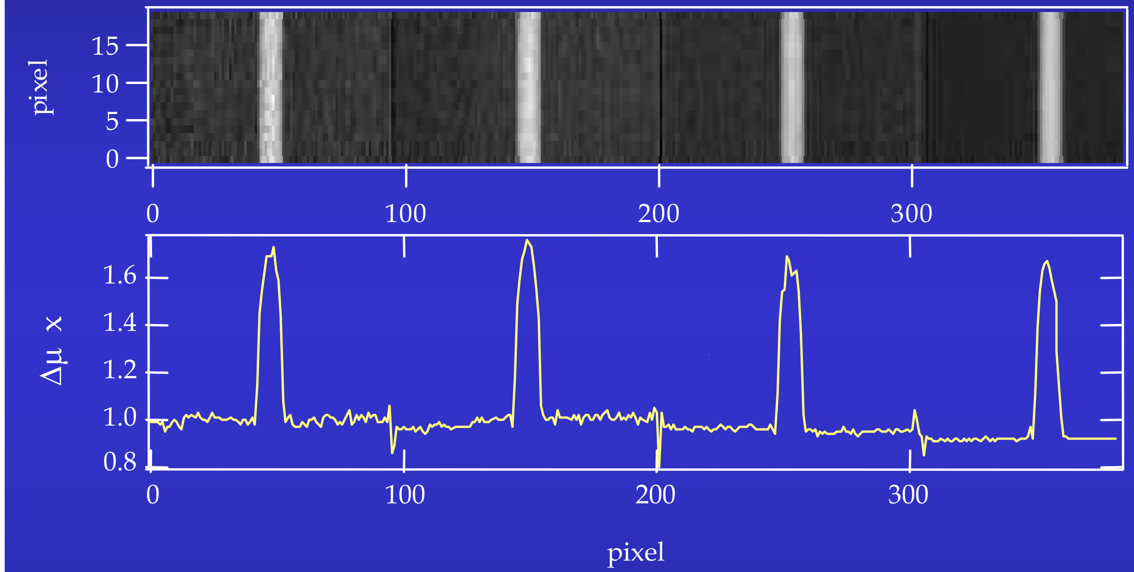
E=35.5 keV

c=370 mg/ml

x_d=1 mm

65 kV, 40 mAs

Processed image



	Signal	SNR
Cavity 1	0.7	100
Cavity 2	0.8	213
Cavity 3	0.7	176
Cavity 4	0.8	250

➊ Absence of the gradient due to the attenuation characteristics of the step wedge phantom;

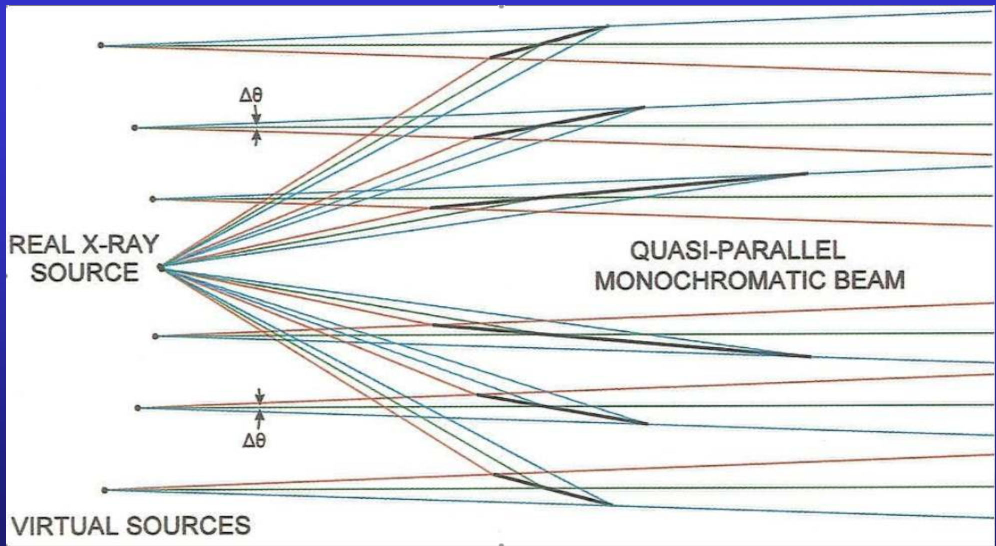
➋ Very high contrast generated by the iodate solution: each vessel with the same diameter and iodine concentration presents the same gray level in the final image, independently from the phantom thickness and composition

Other X-ray optical systems

- Grazing Incidence X-ray Optics
- Polycapillary Optics
- Multilayers

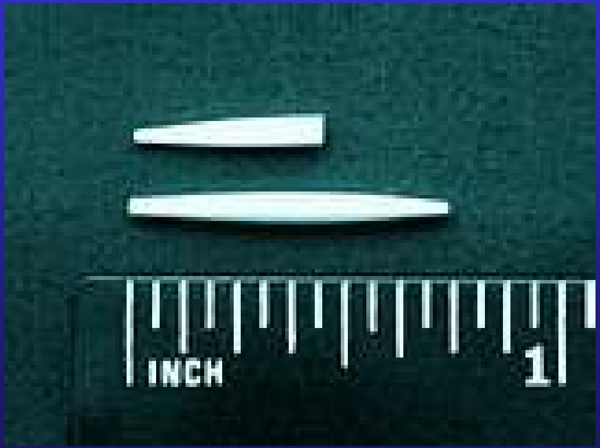
Grazing Incidence X-ray Optics

INAF: OAB & OAPA



Polycapillary optics

(Kumakhov lenses)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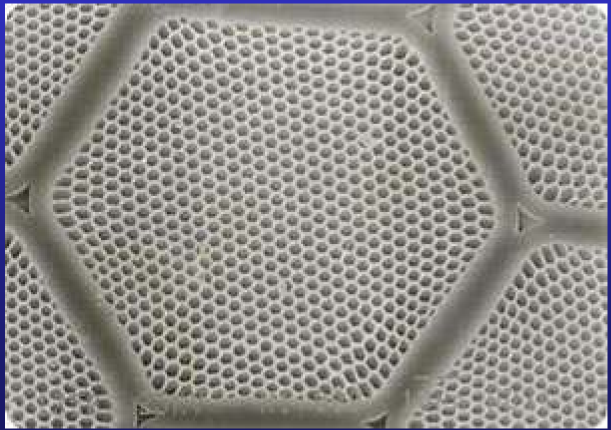
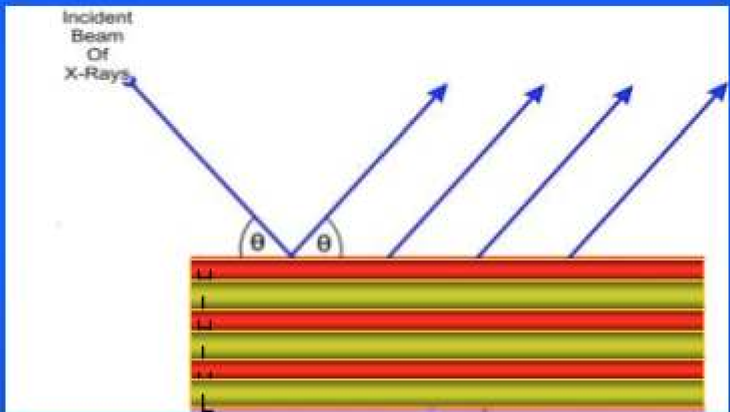


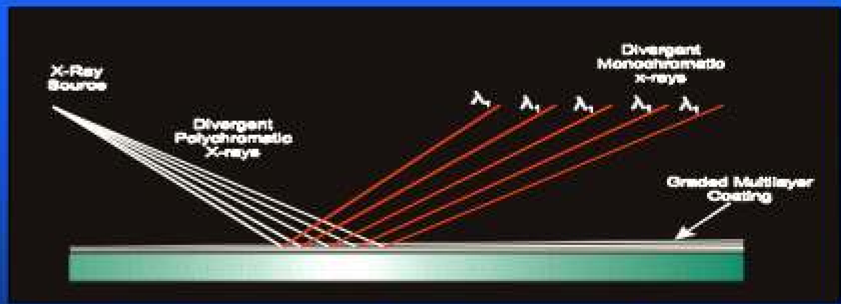
MXFTECHNOLOGIES
INNOVATION IN X-RAY IMAGING

X-ray Diffraction from Multiple Surfac es of a Multi-Layer Coating



Bragg's Law: $n\lambda = 2d \sin \theta$

Parallel multilayer coating gives polychromatic output.



Graded multilayer coating gives monochromatic output.

Conclusions

A dichromatic X-ray source cold be used in DER for simultaneous acquisition of high and low energy images

A dichromatic X-ray source coul be used for k-edge subtraction radiography.

The advantages of quasi-monochromatic X-ray beams can be exploited in every radiological examination especially in mammography