X-ray Characterization of a Table Top Synchrotron Light Source

M. Gambaccini, P.Cardarelli, G. Di Domenico, M.Marziani and A. Taibi

----

Physics Department and INFN Ferrara

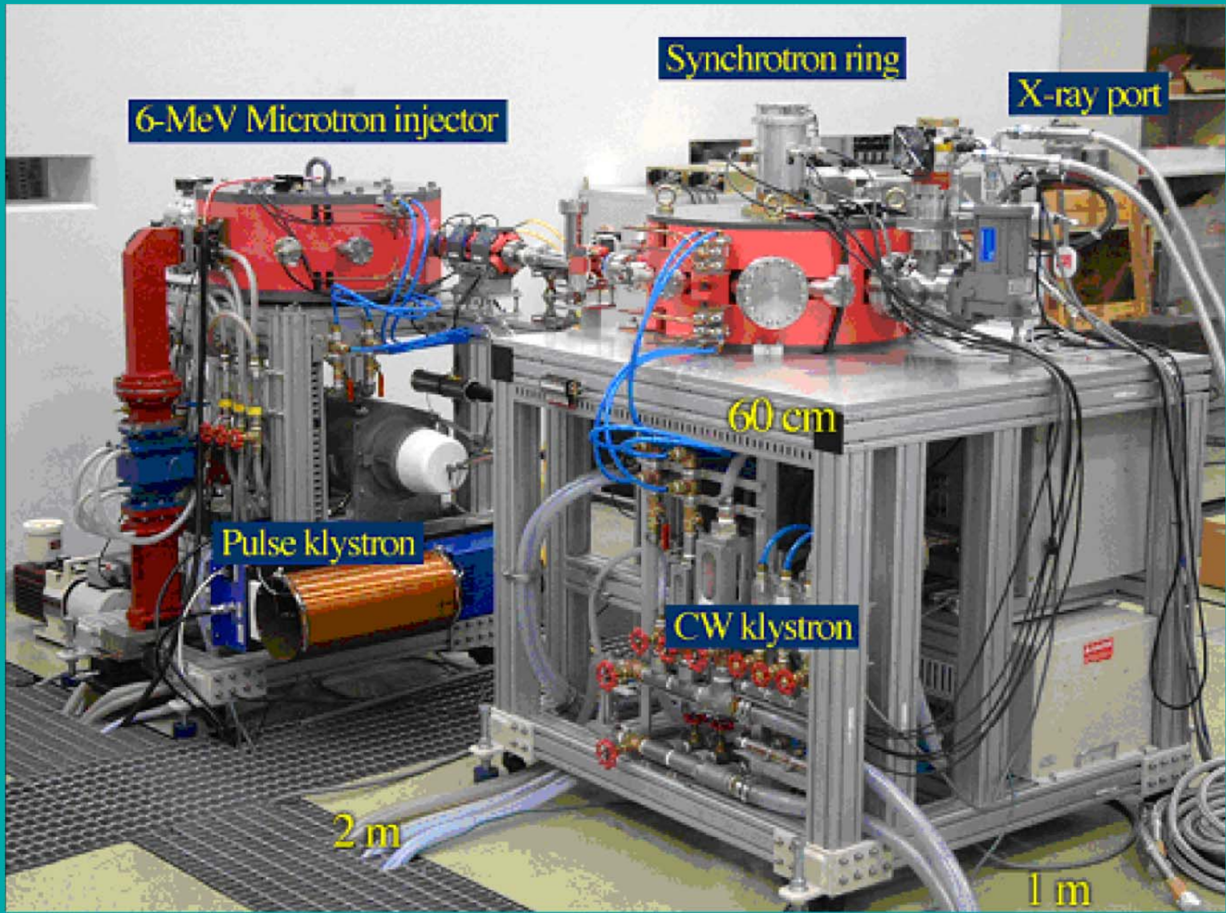
The need for advanced light sources is well documented by the creation of new facilities such as SOLEIL, DIAMOND, MAX IV and the upgrades of older facilities.

The applications of light sources encompass all aspects of sciences spanning the fields of physics, chemistry, biology, material science, electronics and medicine.

An option to provide “more light” to this community is to develop small laboratory sources beyond the standard and rotating anodes.

Recently, several “small scale synchrotron” sources were proposed, whereby the most advanced system is the Mirrorcle© developed by Prof. Yamada (Japan) with three functioning systems.

MIRRORCLE 6X



Mirrorcle© could have four output ports,

1. FIR port,
2. soft X-rays port,
3. hard X-rays
4. full spectrum port

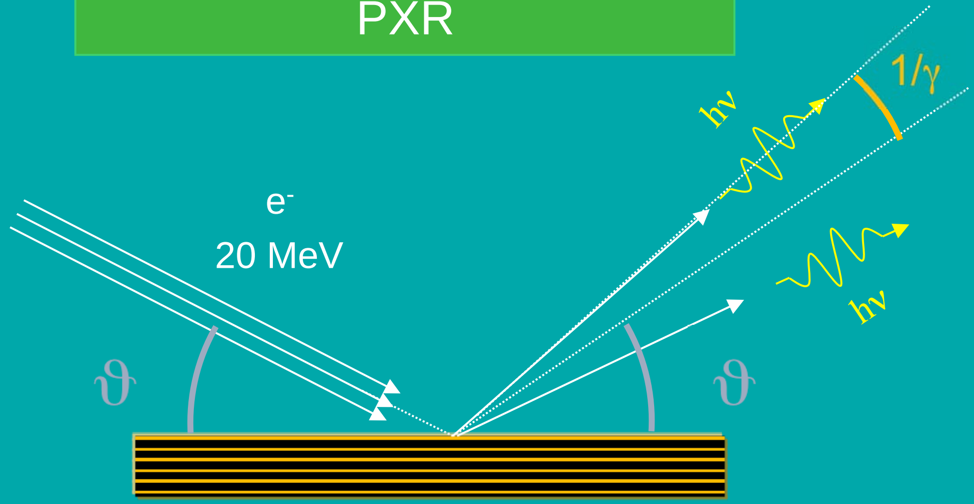
Ferrara unit activity in LABSYNC project:

characterization of Mirrorcle as X ray source for imaging application

20 MeV System

Bremsstrahlung X rays
from thin target

Monochromatic X rays
PXR

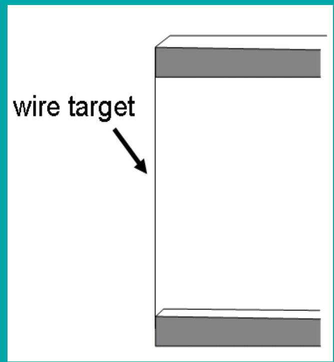


wire target ≅ 0.1 mm
Mo, Rh, W

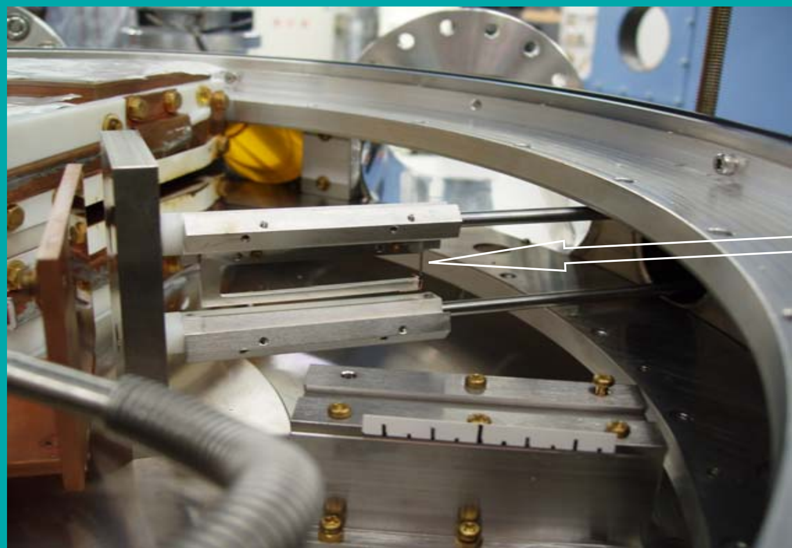
Crystal: Si – graphite - diamond

Discussed in poster section

X ray flux from bremsstrahlung X rays



MIRRORCLE



target

MC simulation of MIRRORCLE x-ray spectra

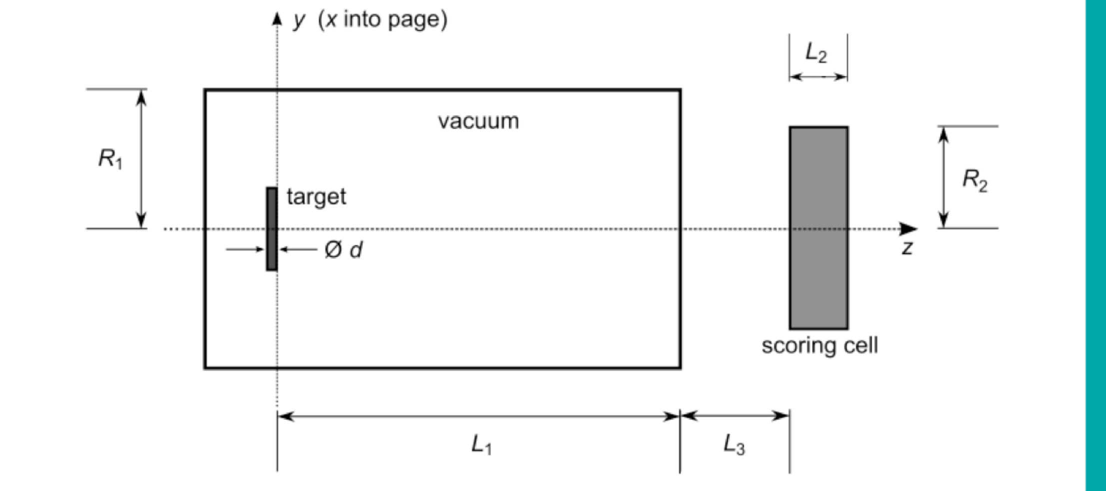


FIG. 1: Geometry used in the Monte Carlo simulation for modelling the measurement of the spectrum of hard x-rays emitted from a MIRRORCLE output port. Parts are not drawn to scale.

Mo, Rh and W targets

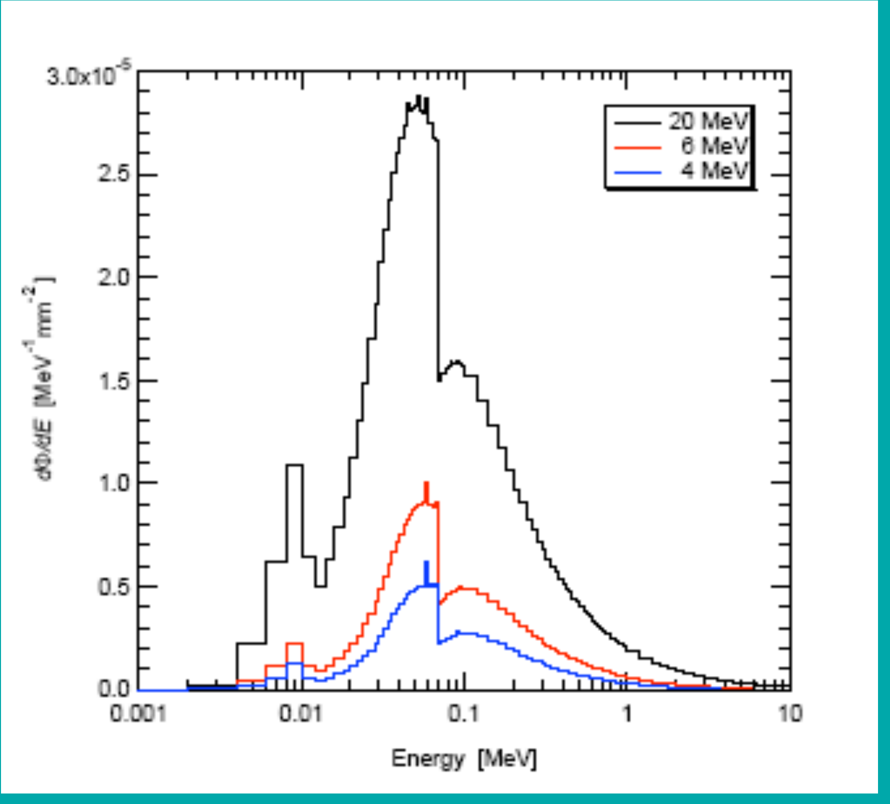
Wire diameter from 5 to 125 μm

Added filtration (diagnostic spectra): Mo, Rh, Al

Energy dependence of bremsstrahlung X rays

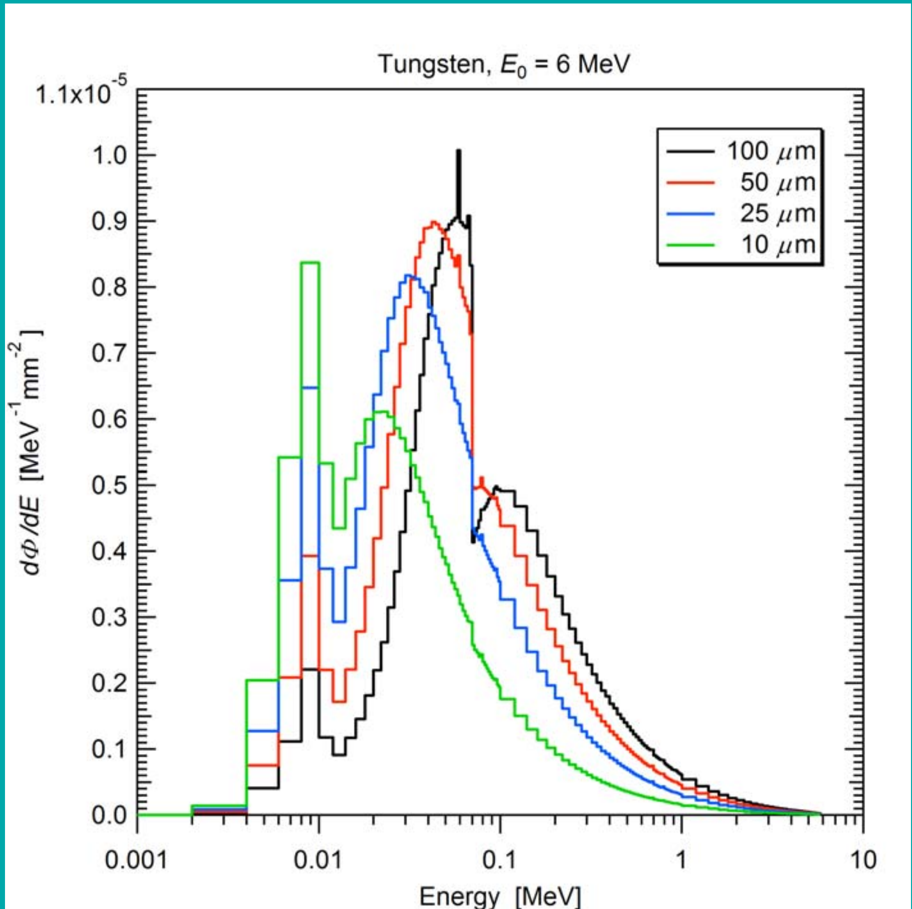
W x-ray spectra 4 – 6 -20 MeV

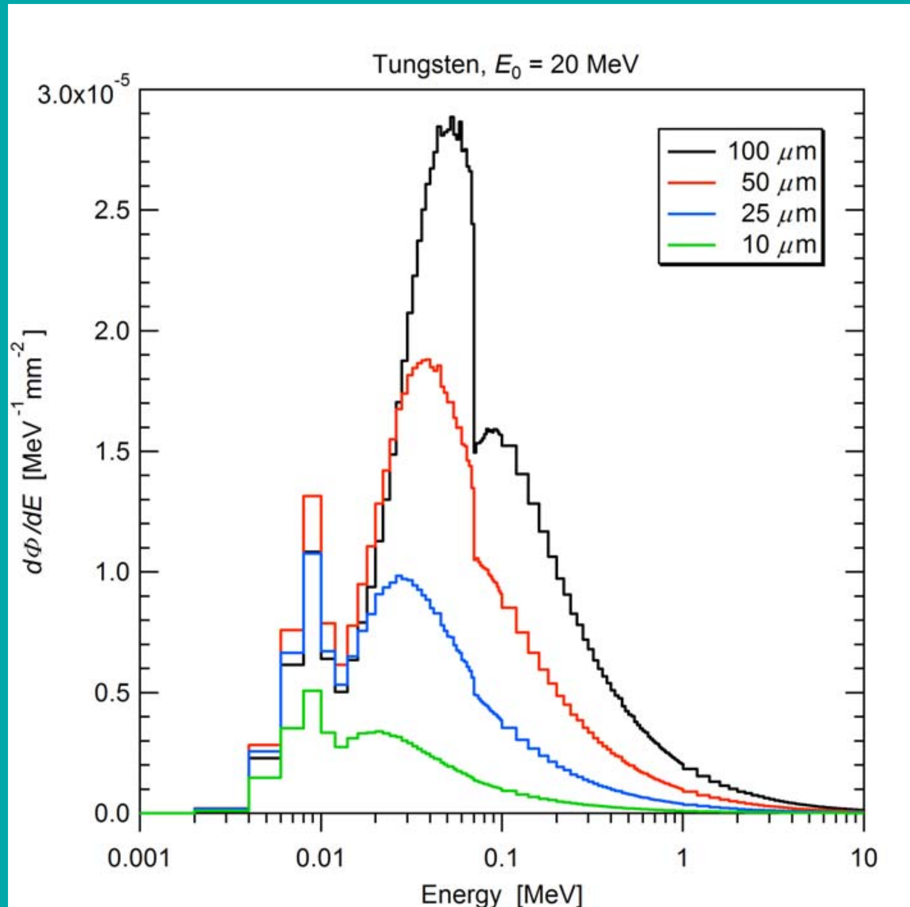
@ 75 cm from target 100 μm kapton window



W x-ray spectra for energy-band monochromatization

40 cm from target 1mm Be window filtration

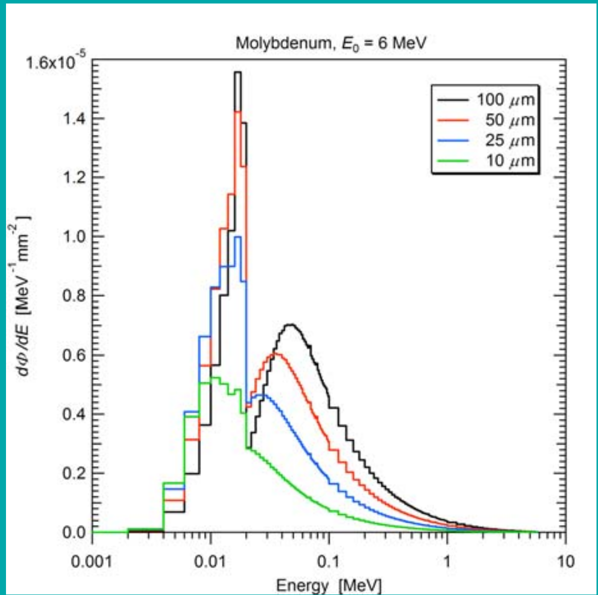


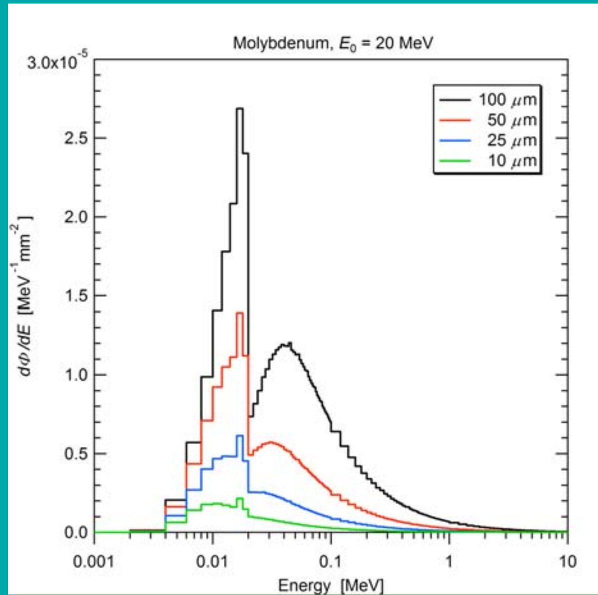


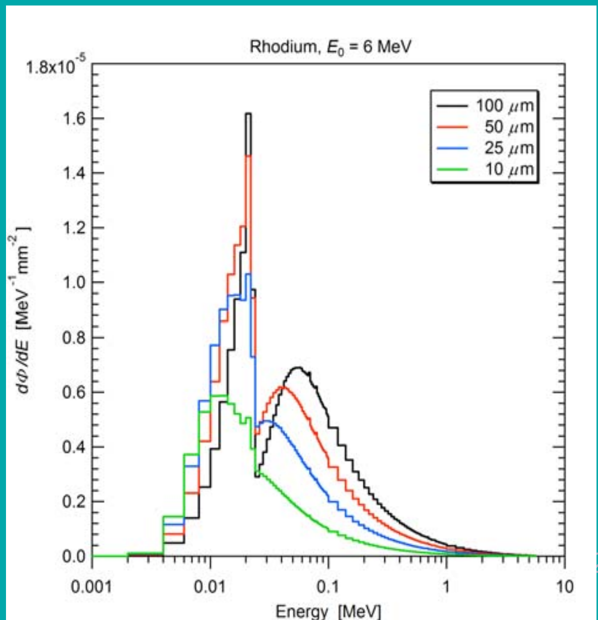
X ray flux from bremsstrahlung X rays

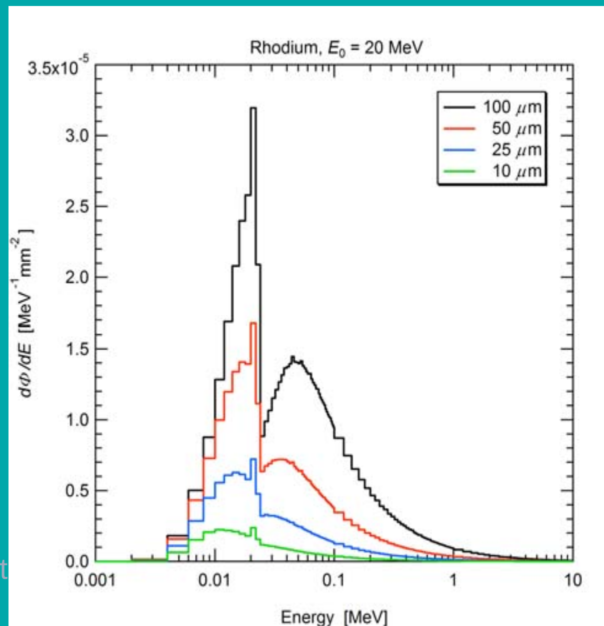
Mo and Rh x-ray spectra

40 cm from target 1mm Be window filtration







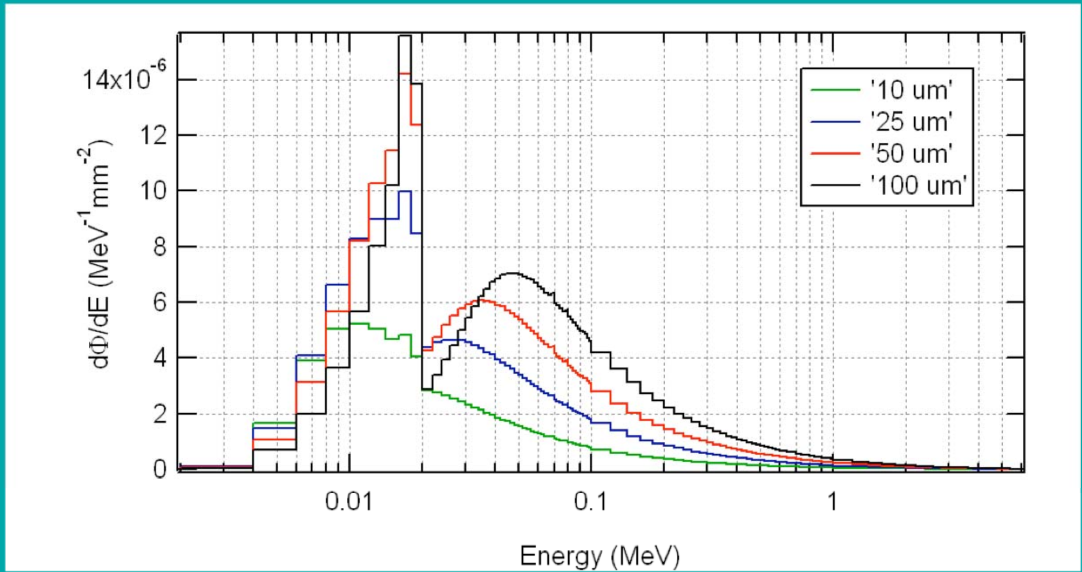


OUTPUT COMPARISON
forward

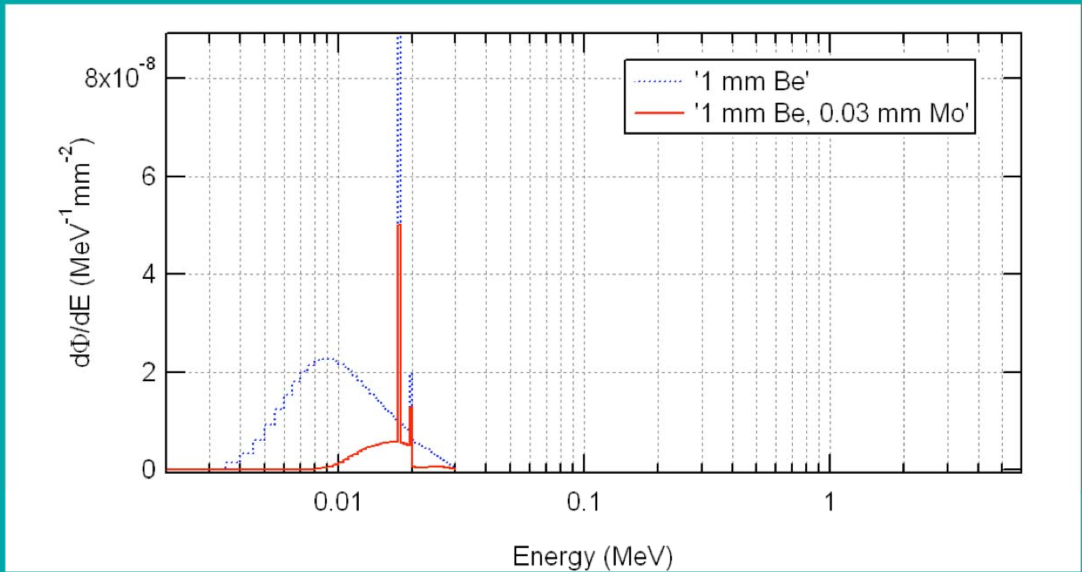
	MIRRORCLE output 0.75 m from target mGy mA^{-1} s^{-1}			
filtration	target	4 MeV	6 MeV	20 MeV
kapton 100 µm	125 µm W	**7.9 E+2**	**2.4 E+3**	**6.9 E+4**
kapton 100 µm	120 µm Rh	**6.4 E+2**	**1.9 E+3**	**5.5 E+4**
kapton 100 µm	125 µm Mo	**6.0 E+2**	**1.8 E+3**	**5.1 E+4**

	X RAY TUBE output 0.75 m from target W mGy mA^{-1} s^{-1}		
filtration	80 kVp	110 kVp	140 kVp
Be 1 mm	**2.86**	**2.28**	**1.79**
Al 2.5 mm	**1.6 E-1**	**2.7 E-1**	**4.0 E-1**

Mo: K_α = 17,4 keV; K_β = 19,6 keV

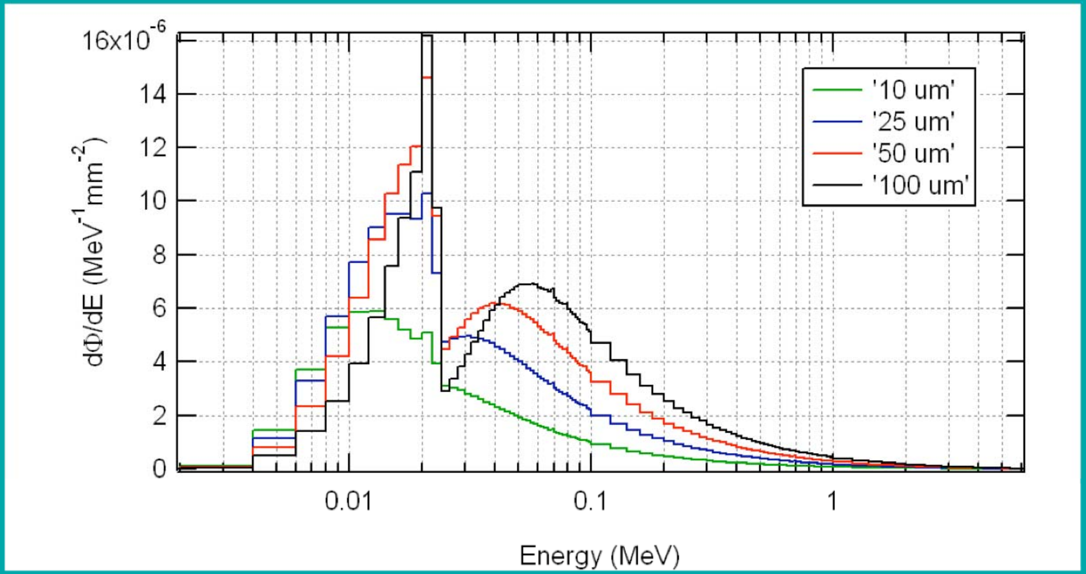


6 MeV

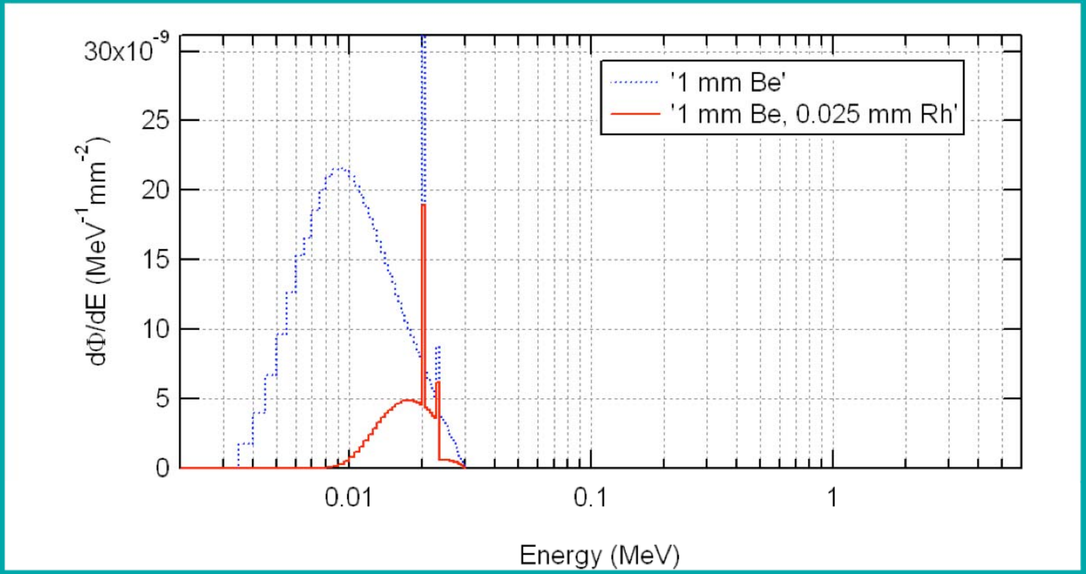


30 kV

Rh: K_{α} = 20,2 KeV; K_{β} = 22,7 keV



6 MeV



30 kV

X ray flux from bremsstrahlung X rays

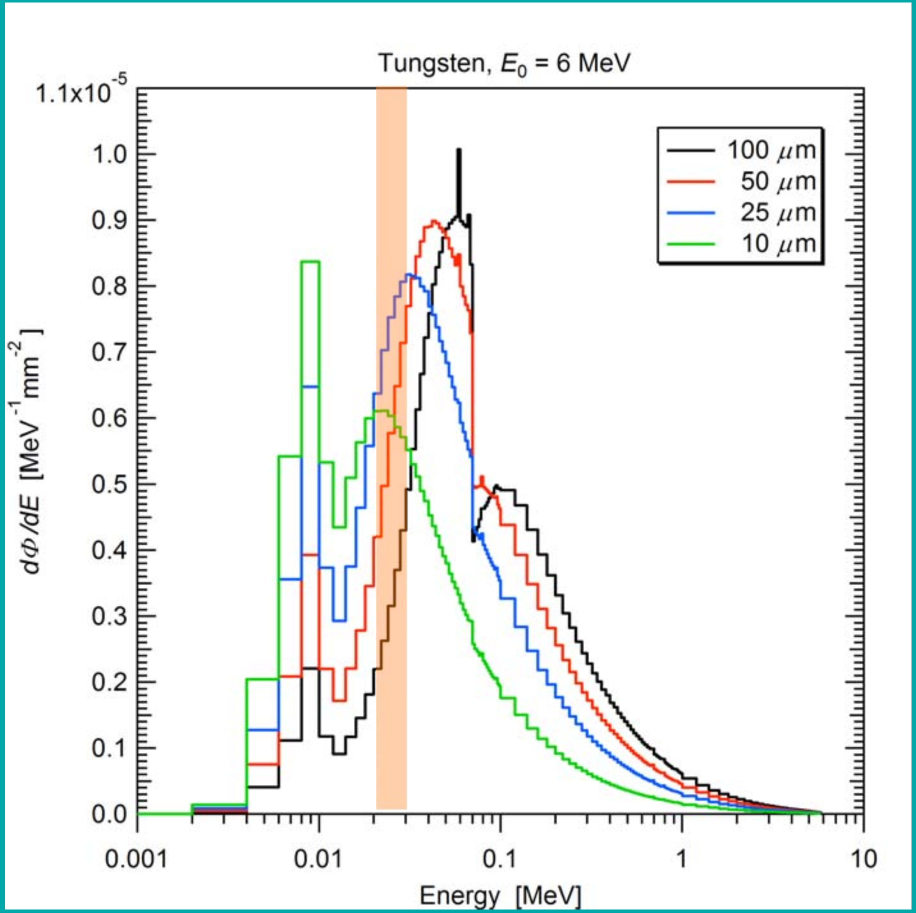
OUTPUT COMPARISON FOR Kα line MONOCHROMATIZATION forward

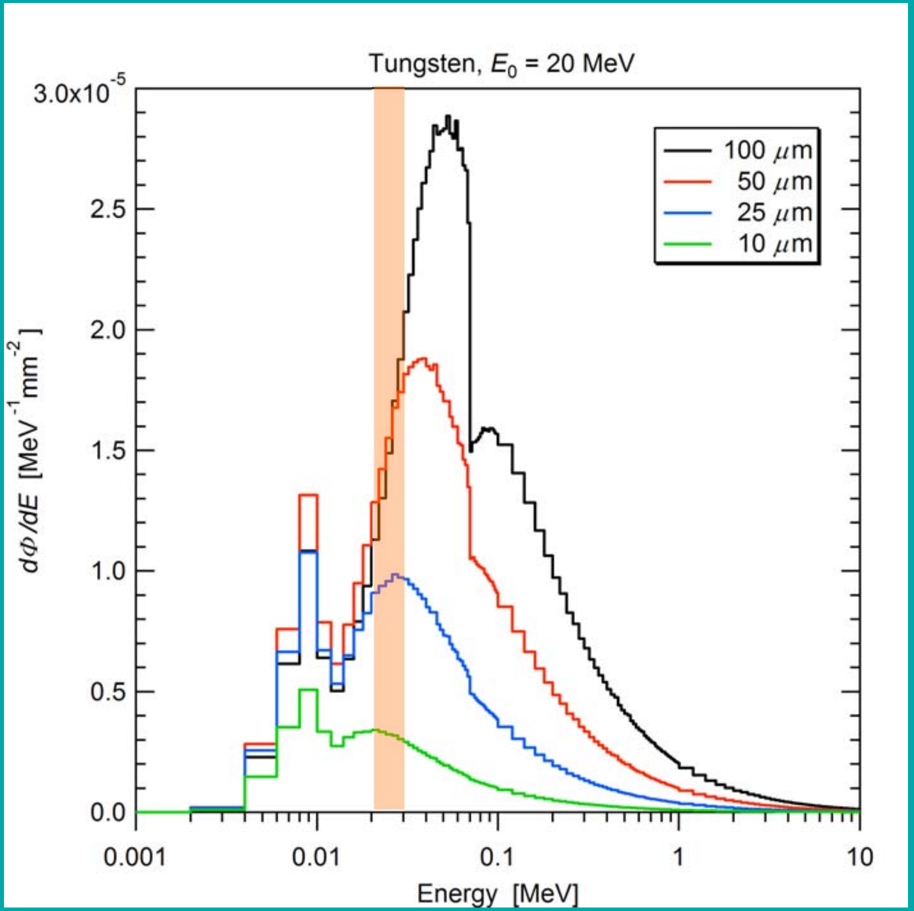
	OUTPUT @ 75 cm from the target (Mo 125 μm - Rh 120 μm) Photons $mA^{-1}\, s^{-1}\, mm^{-2}$				
Target	Energy band ΔE = 1 keV	X – Ray TUBE 50 kVp - Be 1 mm	MIRROCLE 4MeV kapton win.	MIRROCLE 6MeV kapton win.	MIRROCLE 20MeV kapton win.
Mo	Mo K_α (17.4 keV)	1.5 E+6	2.67E+7	4.06E+7	2.82E+8
Rh	Rh K_α (20.2 keV)	6.3 E+5	2.73E+7	4.15E+7	2.74E+8

X ray flux from bremsstrahlung X rays

W x-ray spectra for energy-band monochromatization

40 cm from target 1mm Be window filtration

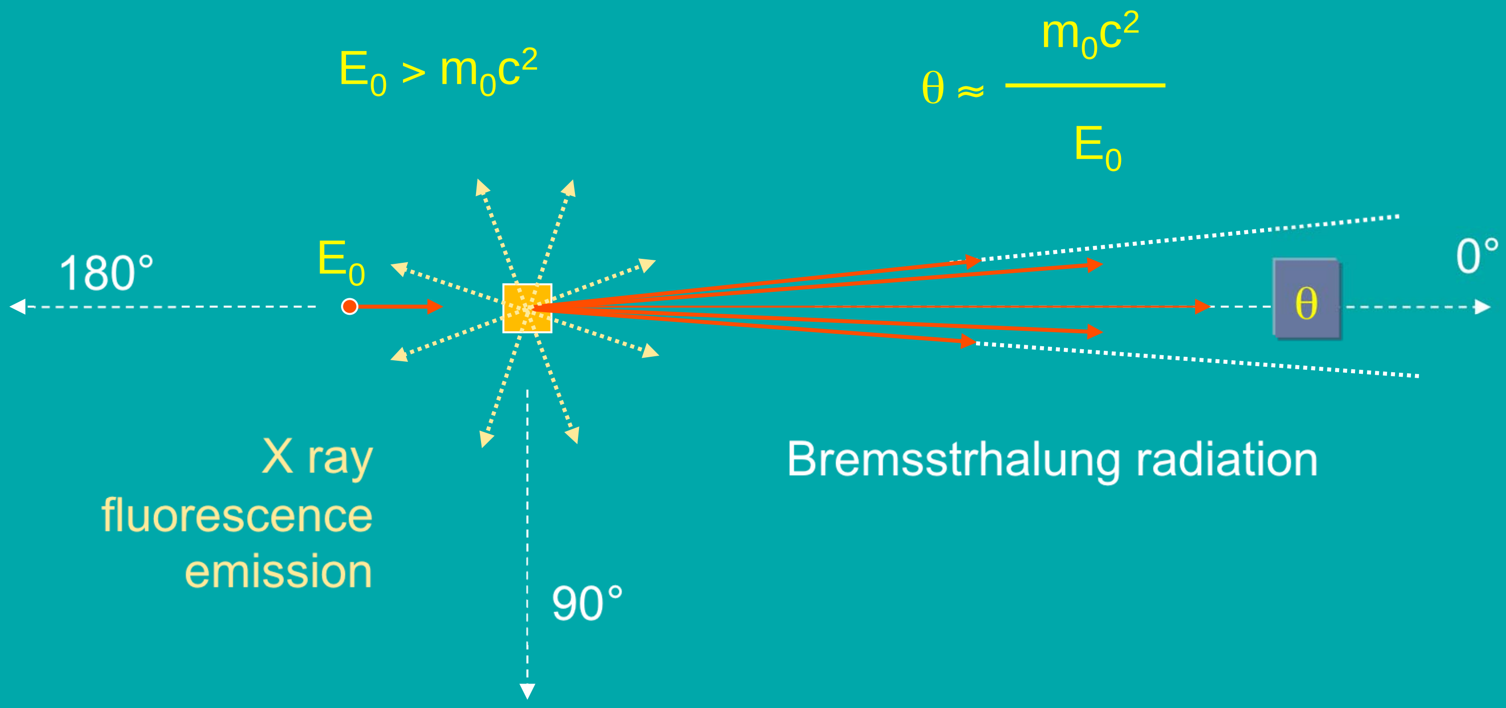




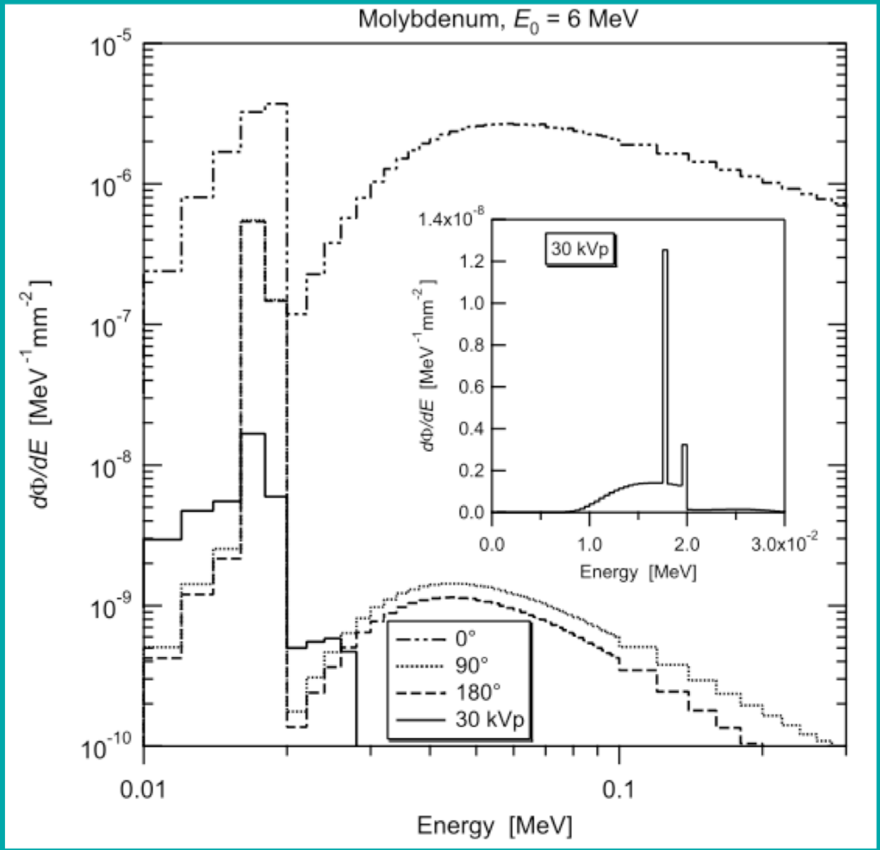
OUTPUT COMPARISON FOR MONOCHROMATIZATION
forward

OUTPUT @ 75 cm from the target (W wire 0.125 mm) Photons mA^{-1} s^{-1} mm^{-2}				
Energy band	X – Ray TUBE 80 kVp - Be 1 mm	**MIRROCLE 4MeV**	**MIRROCLE 6MeV**	**MIRROCLE 20MeV**
20 (19 - 21)	3.24E+5	2.93E+6	5.99E+6	5.82E+7
30 (28.5 – 31.5)	4.48E+5	1.12E+7	2.31E+7	2.23E+8
40 (38 – 42)	4.60E+5	2.82E+7	5.81E+7	5.58E+8

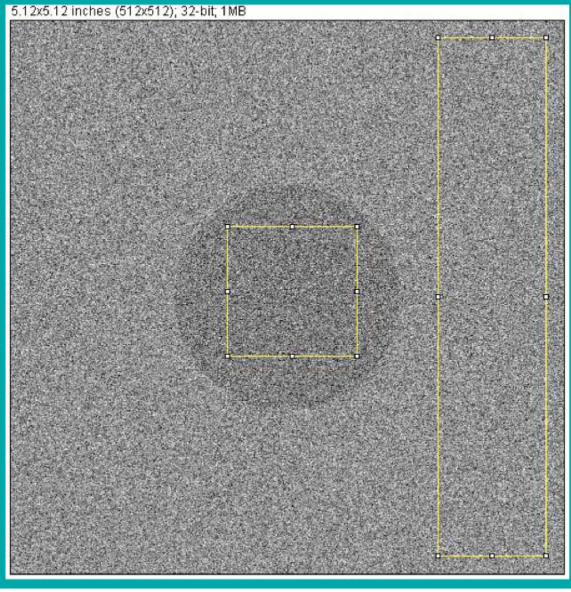
Bremsstrhalung radiation and fluorescence emission



Considering a different point of view ...
Backward emission



X-ray imaging simulation for mammography



Flat panel detector

20 μm-thick Al disk in 4.5 cm plexiglass bulk

5×10^9 incident photons

Spectrum	Contrast	Dose (mGy)	SNR	SNR^2/Dose
Mo 30 kVp, 0.8 mm Be, 30 μm Mo, 13°	2.08%	3.35E-01	8.18	2.00E+02
Rh 32 kVp, 0.8 mm Be, 25 μm Rh, 13°	1.55%	3.38E-01	8.42	2.10E+02
6 MeV e^-, 100 μm Mo target, 0.8 mm Be, 30 μm Mo, 90°	1.76%	3.51E-01	8.05	1.84E+02
6 MeV e^-, 100 μm Mo target, 0.8 mm Be, 30 μm Mo, 180°	1.89%	3.50E-01	8.26	1.95E+02
20 MeV e^-, 100 μm Mo target, 0.8 mm Be, 30 μm Mo, 180°	1.97%	3.51E-01	8.69	2.15E+02
20 MeV e^-, 10 μm Mo target, 0.8 mm Be, 30 μm Mo, 180°	2.49%	3.55E-01	9.18	2.37E+02
6 MeV, 0°	**0.15%**	**6.09E-01**	**2.06**	**6.93E+00**

Optimization for mammography application

OUTPUT COMPARISON backward

Output 0.75 cm from target mGy/mAs								
Mirrorcle							X ray tube	
	6 MeV			20 MeV			32 kV	30 kV
	W	Rh	Mo	W	Rh	Mo	Rh	Mo
0°	2160	1760	1610	62050	49690	45230	0.11	0.15
90°	1.33	1.82	2.22	0.50	1.92	2.46		
180°	0.36	1.61	2.07	0.24	1.83	2.38		

Anodic current

Rh	Mo
80 mA	100 mA

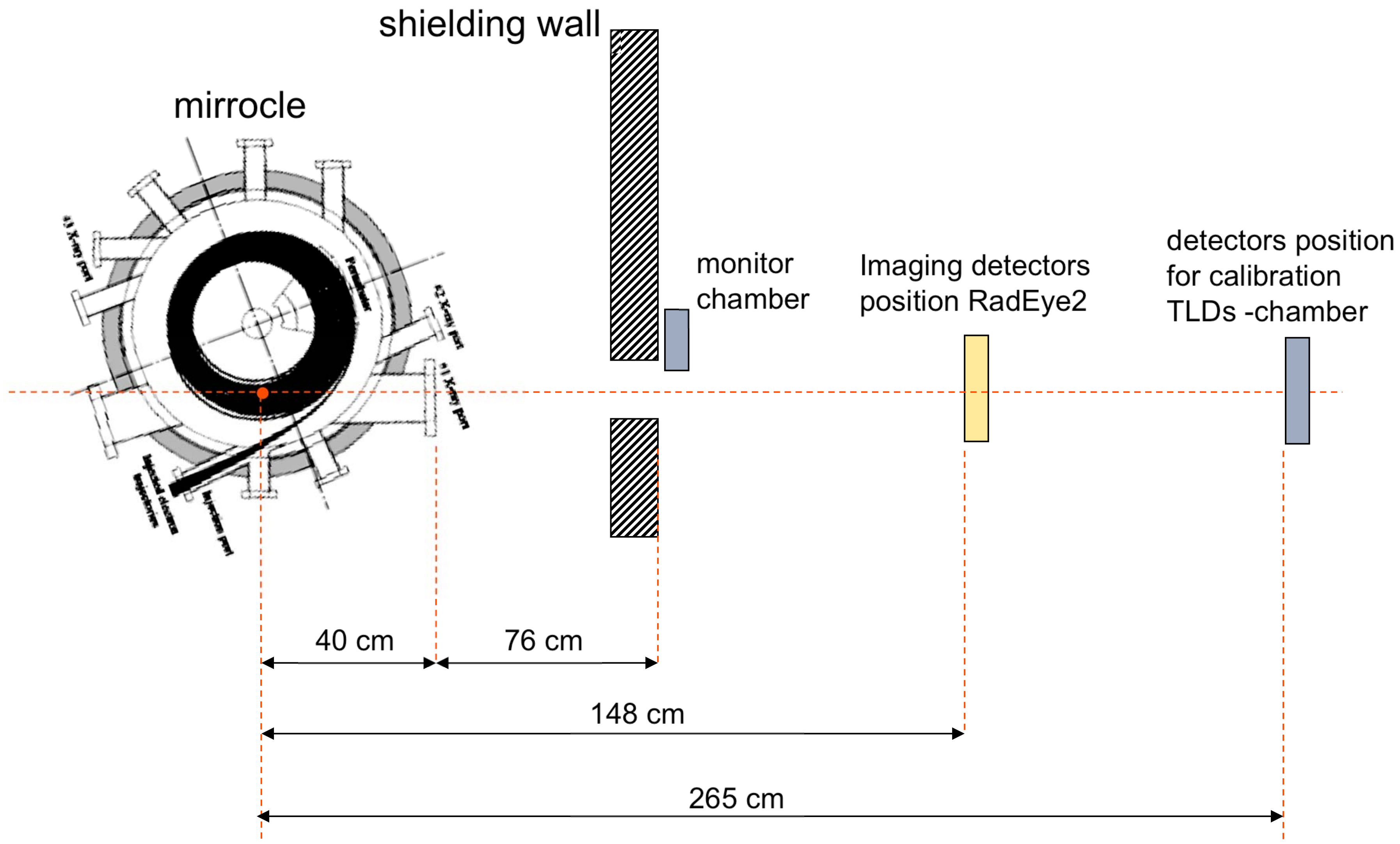
5.6 mA	7.3 mA

4.9 mA	6.3 mA

Equivalent impact current backward (180°)

X ray flux from bremsstrahlung X rays

OUTPUT MEASUREMENT and IMPACT CURRENT EVALUATION

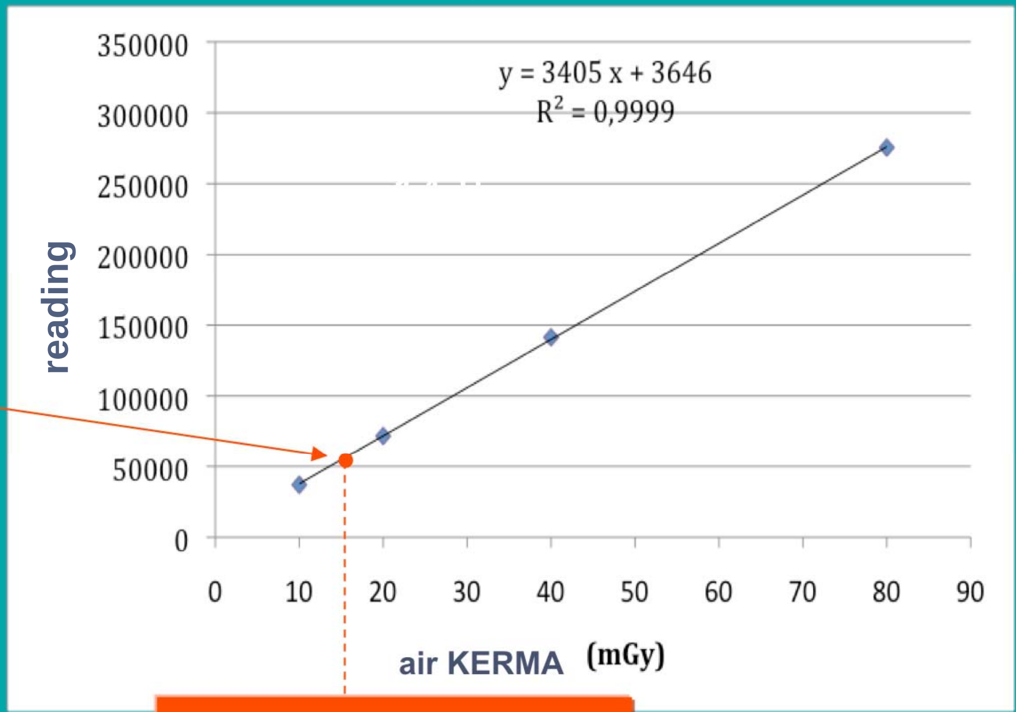


WP4: X ray flux from bremsstrahlung X rays

TLDs exposed at the Department of Experimental Radiotherapy, Katholieke Universiteit of Leuven, Belgium.

TLDs reading vs air KERMA

Reading of TLDs PPL
Exposure time 300 s



14.8 mGy @ 2.65 m

output ⟹ 0.616 mGy/s @ .75 m (MIRRORCLE 6 MeV)

37.0 mGy/min

X ray flux from bremsstrahlung X rays

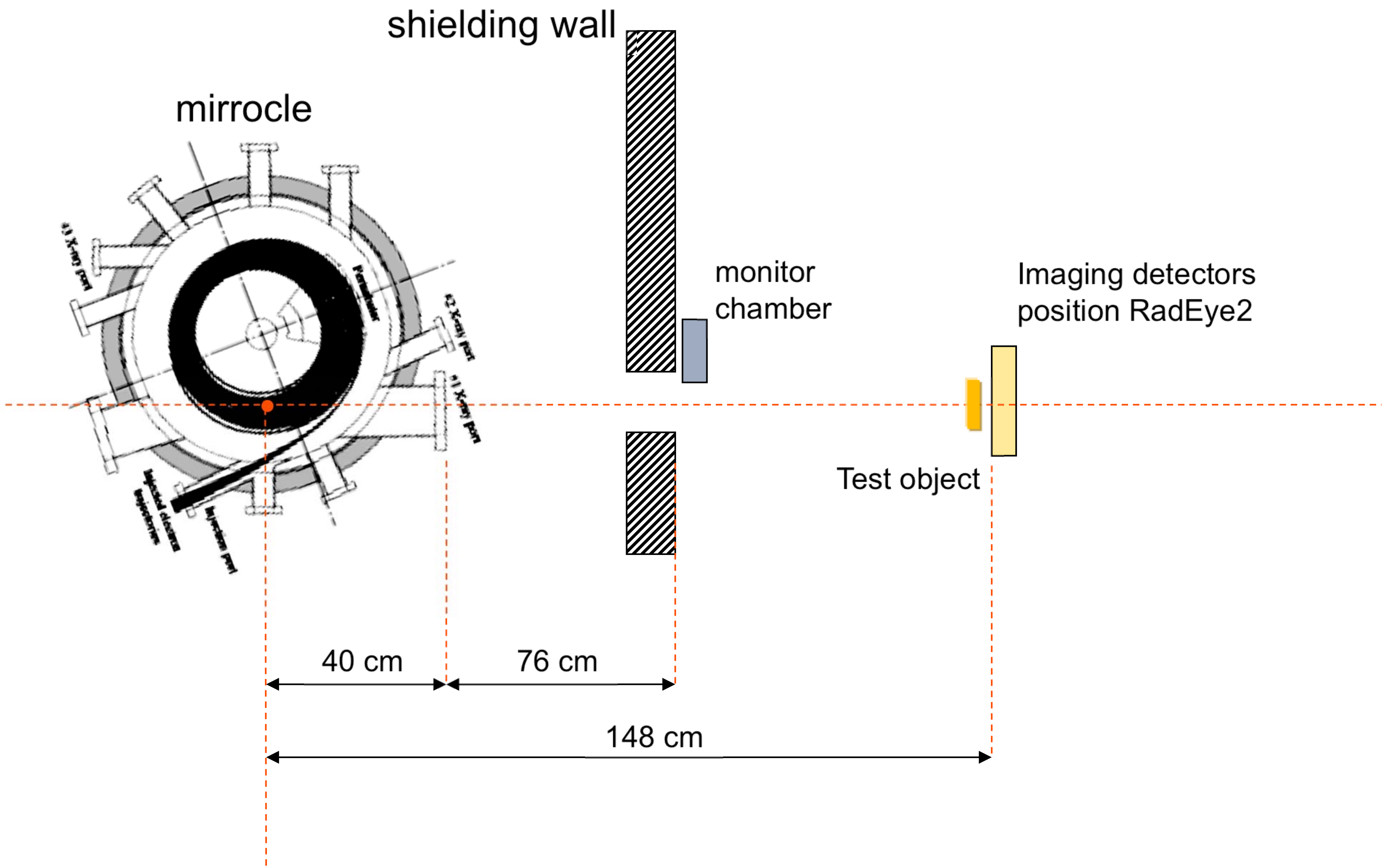
6 MeV MIRRORCLE OUTPUT **0.75 m from target** **mGy s^{-1}**			
target	filtration	TLD	chamber
125 µm W	kapton 100 µm	**0.616**	**0.707**

EVALUATION OF THE IMPACT CURRENT IN MIRRORCLE 6 MeV

1) Digital detector signal (energy absorbed in digital detector)
2) Monitor Chamber measuremet)
3) Direct TLD comparison (Leuven exposure vs PPL exposure
4) Monitor chamber distance scaled

	RadEye2 signal	***monitor chamber PPL***	***Direct TLD compar.***	***monitor chamber** imaging*
target	*i (μA)*	*i (μA)*	*i (μA)*	*i (μA)*
W (125 um)	$6.8 \cdot 10^{-1}$	$9.7 \cdot 10^{-1}$	$8.4 \cdot 10^{-1}$	$5{,}7 \cdot 10^{-1}$
Mo (125 um)	$5.4 \cdot 10^{-1}$	x	x	$6{,}3 \cdot 10^{-1}$
Rh (120 um)	$4.6 \cdot 10^{-1}$	x	x	$5{,}0 \cdot 10^{-1}$

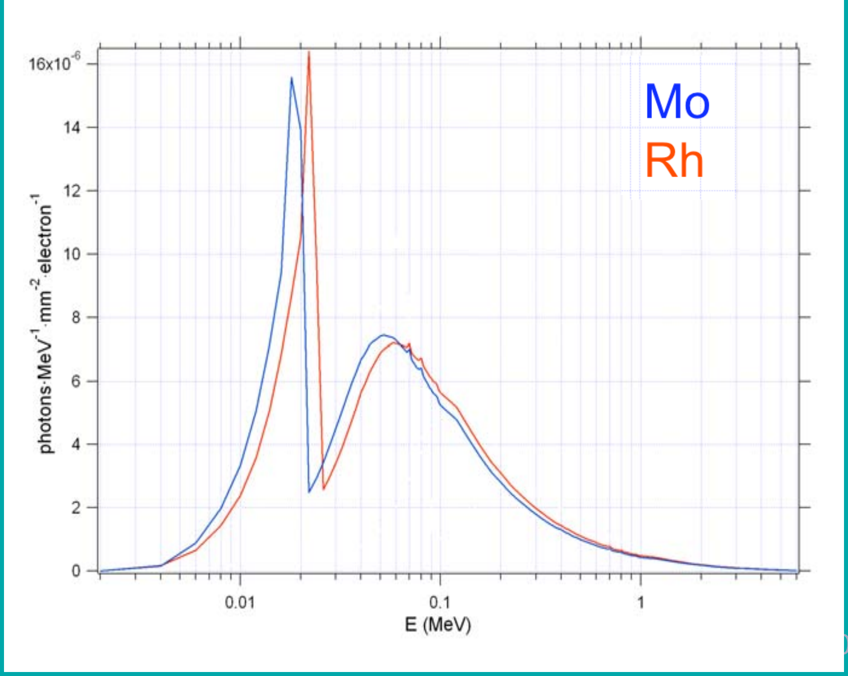
Imaging performance MIRRORCLE 6 MeV

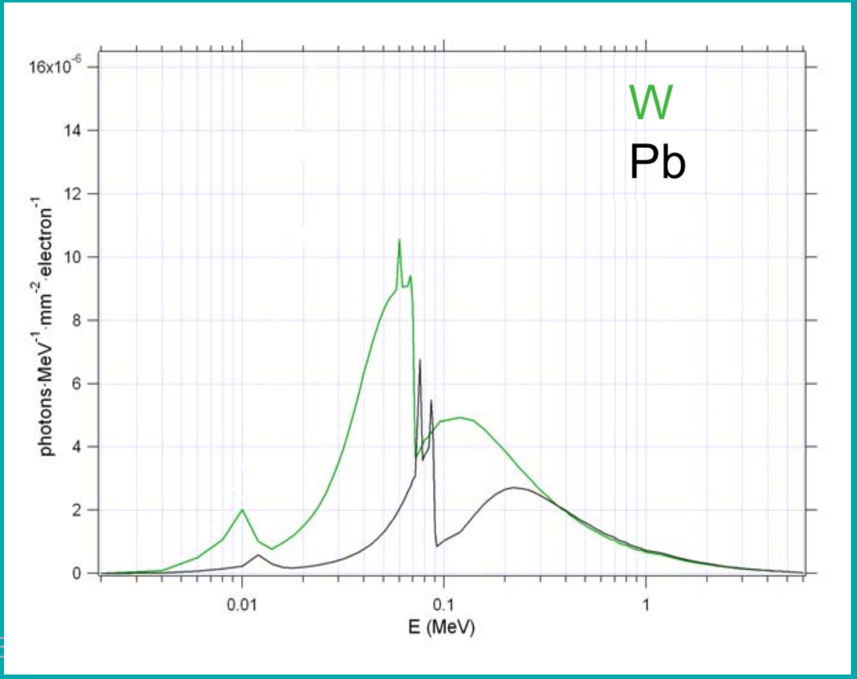


Imaging performance MIRRORCLE 6 MeV

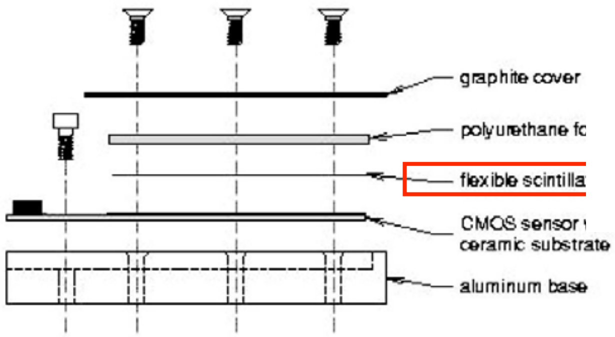
MIRRORCLE produces very wide X-ray spectra

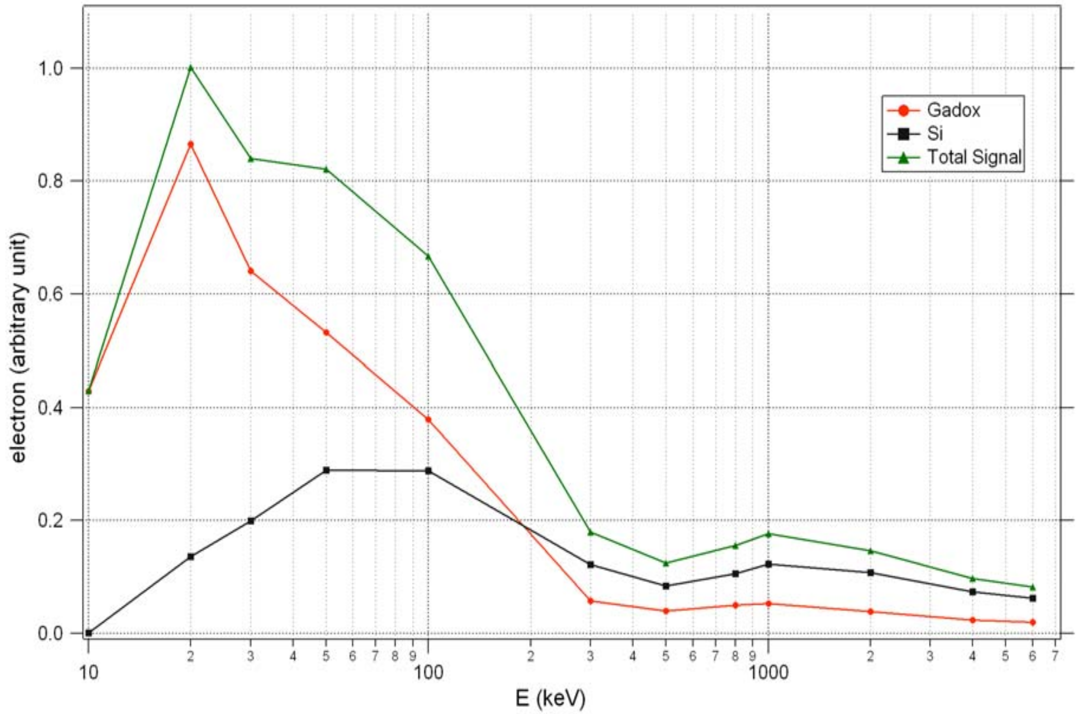
TARGET			
Mo wire	≈ 0.7 mm^2	Impact area	(0.125 mm) x (5.8 mm)
Rh wire	≈ 0.7 mm^2	Impact area	(0.120 mm) x (5.8 mm)
W wire	≈ 0.7 mm^2	Impact area	(0.125 mm) x (5.8 mm)
Pb sphere	≈ 0.8 mm^2	Impact area	(Φ = 1.0 mm)





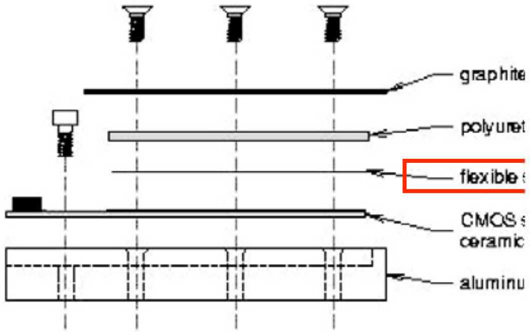
RadEye2™ C-MOS detector for digital radiography

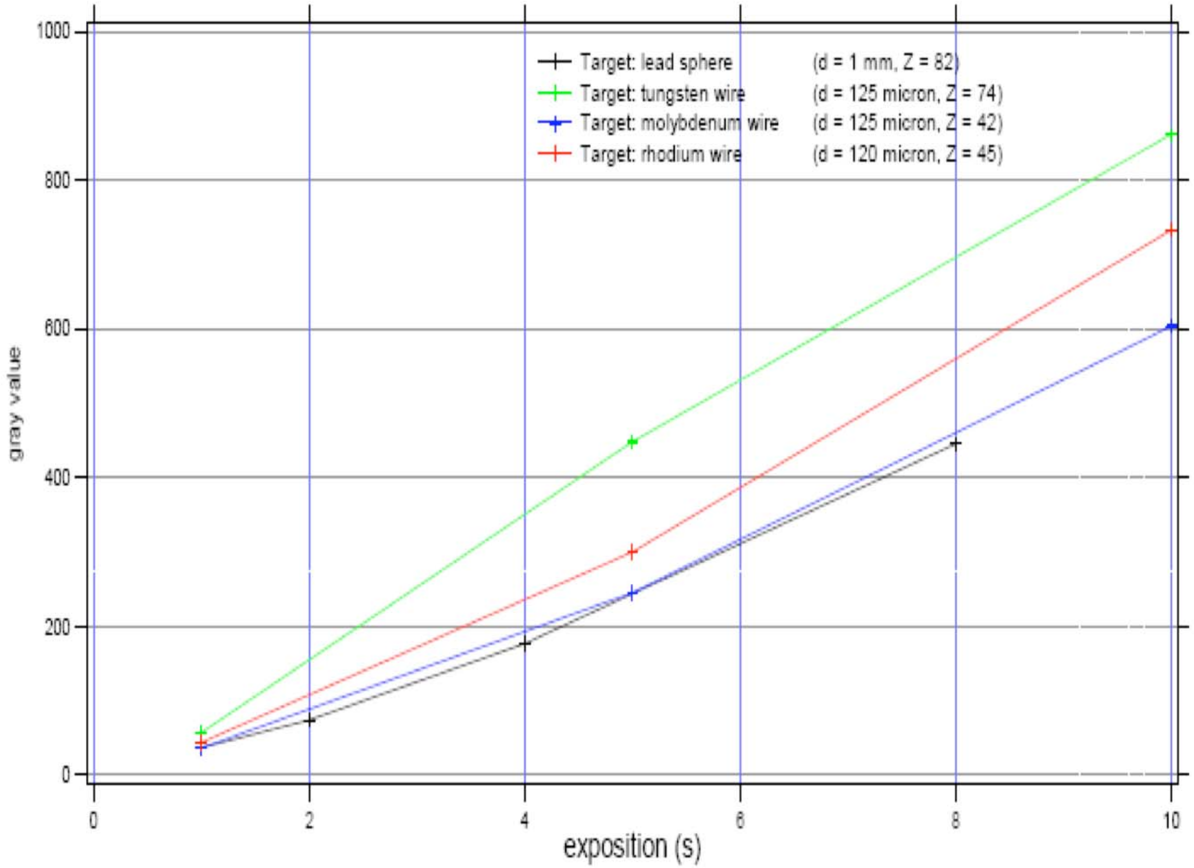




Electrons collected (arbitrary normalization) per fluence unit of a monochromatic photon beam vs energy E (keV) of the incident monochromatic beam. In red electrons collected on photodiode coming from **scintillation of gadox screen**, in black electrons produced by **direct interaction** of radiation **in the collection area** of photodiode.

RadEye2™ C-MOS detector for digital radiography



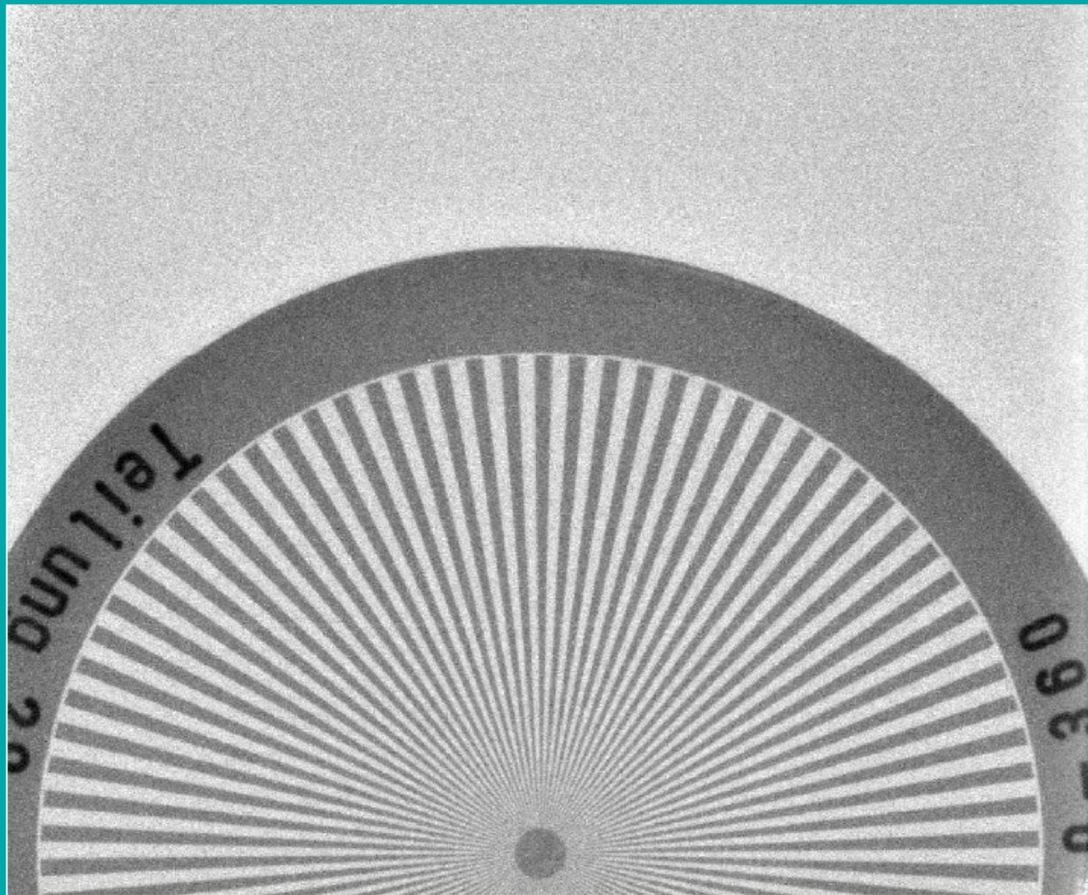


Spatial resolution analysis

Lead Star pattern image obtained with MIRROCLE 6 MeV

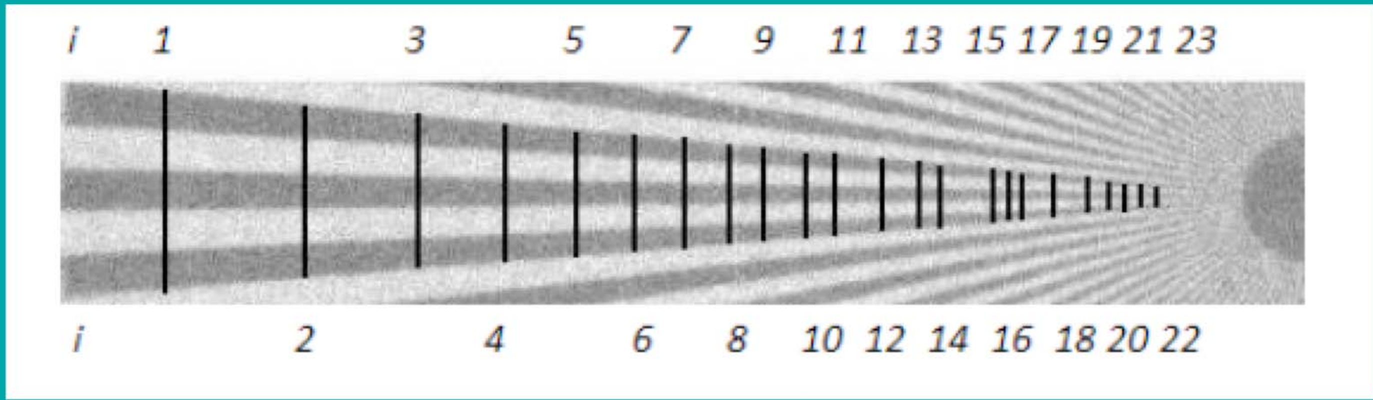
Rh target

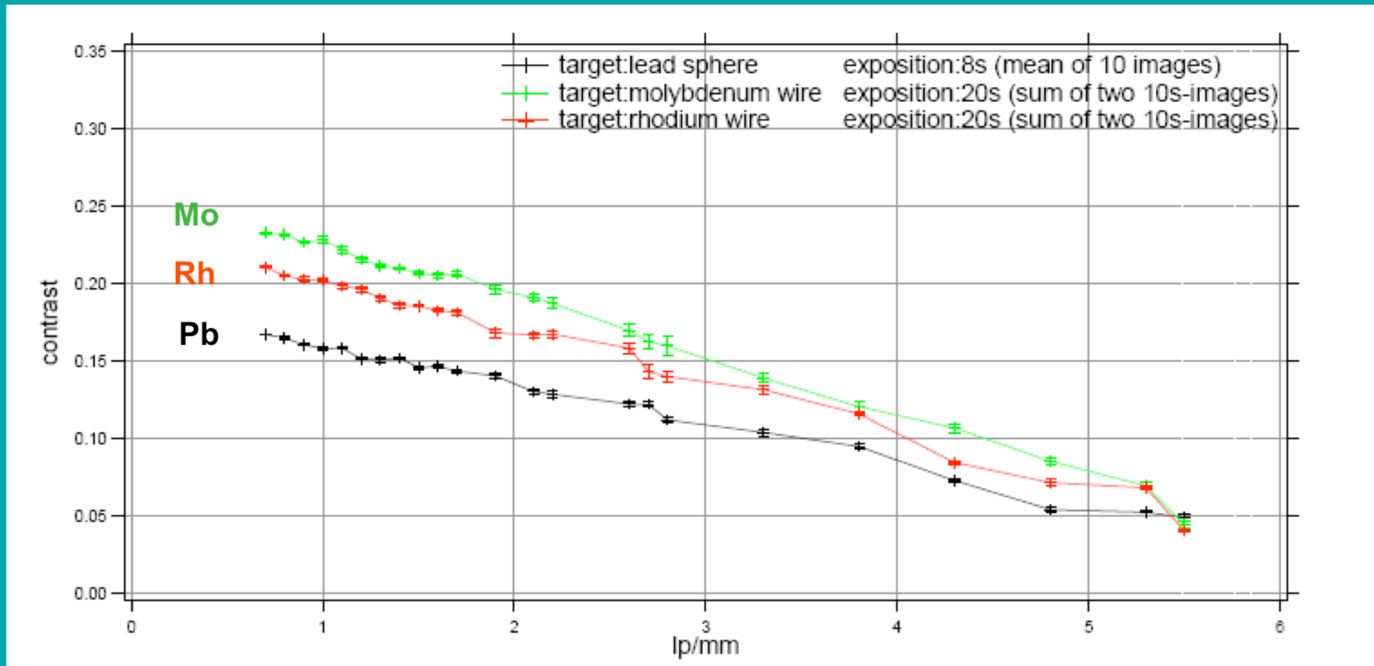
RadEye 2 C-MOS detector



Imaging performance MIRRORCLE 6 MeV

CONTRAST OF 0.02 mm Pb enbedded in PMMA

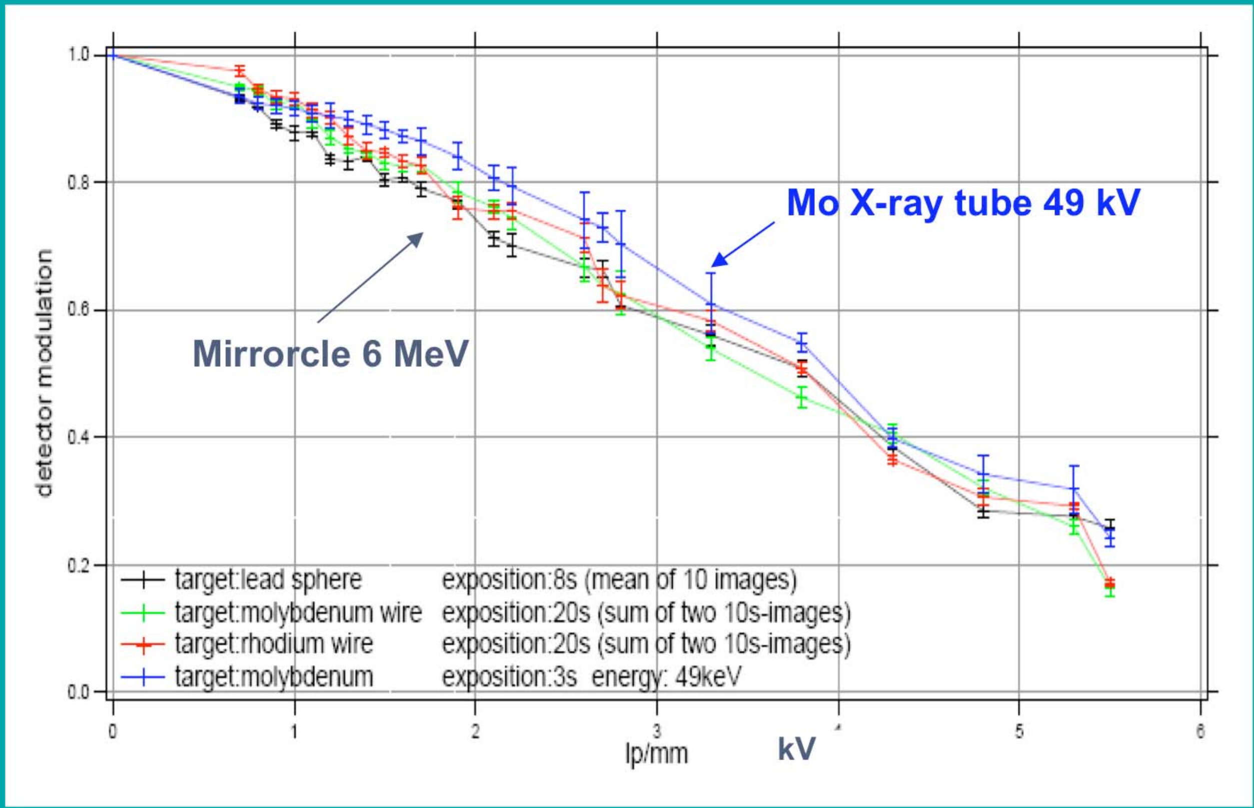




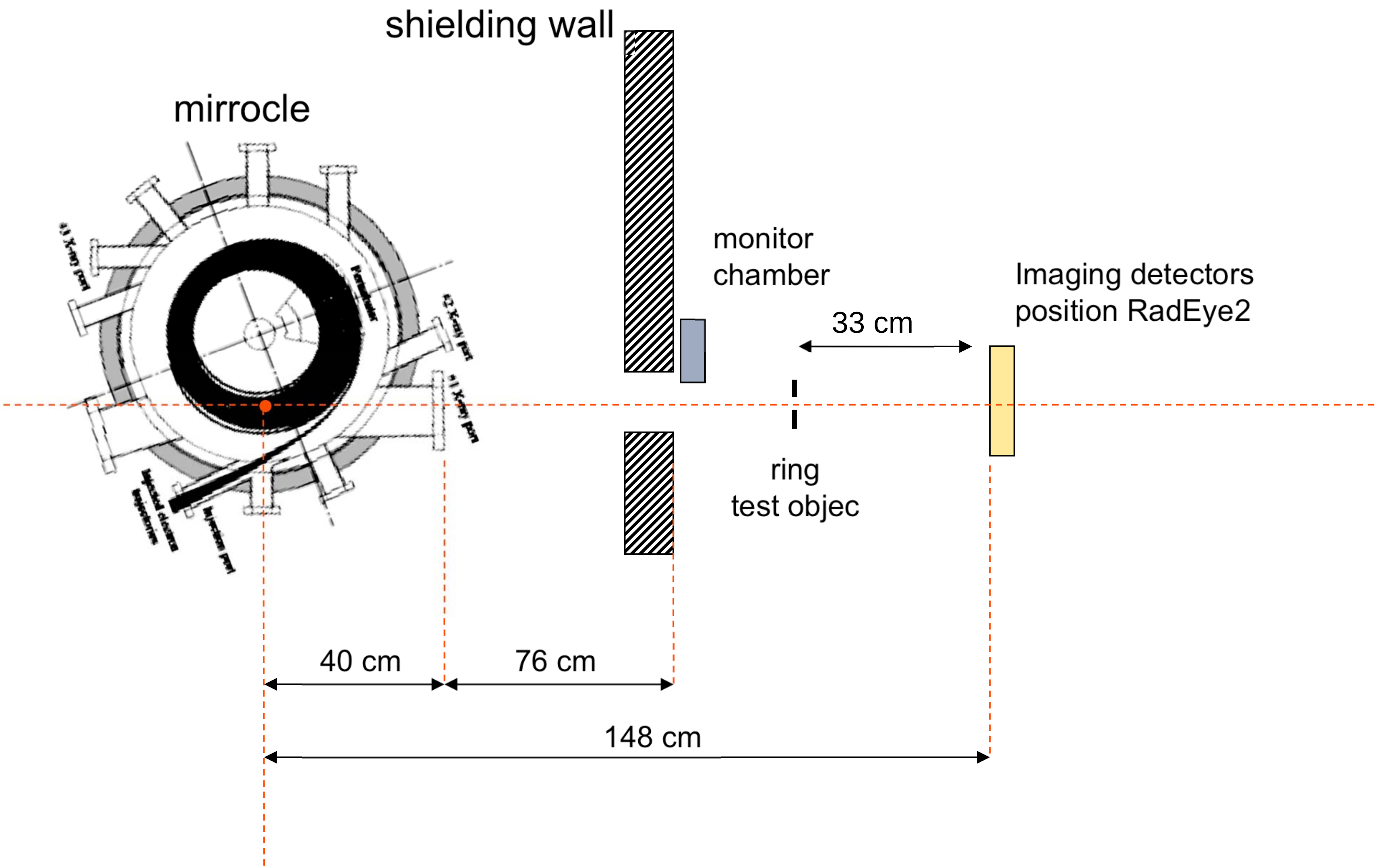
Imaging performance MIRRORCLE 6 MeV

Comparison of spatial frequency response of the digital detector
in terms of SWRF *(MTF)* between
Diagnostic X-ray beam and MIRRORLE X-ray Beam

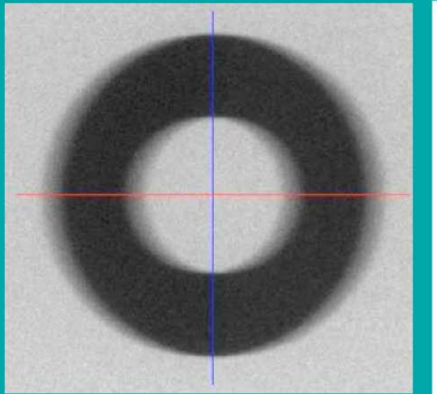
SWRF normalized to zero frequency

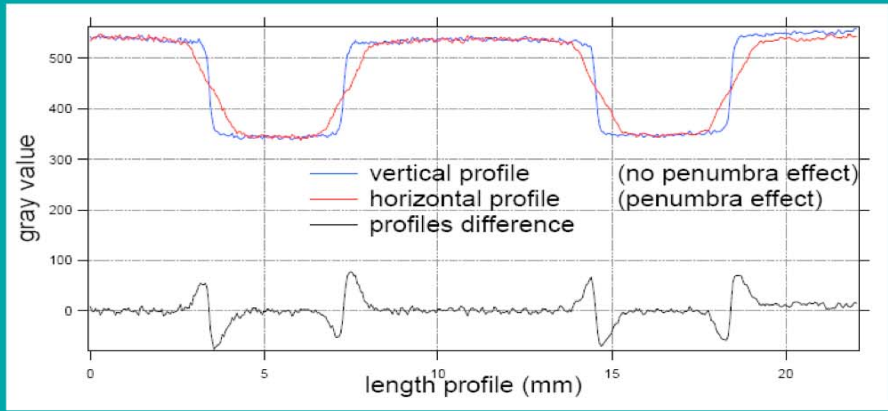


Focal spot measurement MIRRORCLE 6 MeV



Focal spot measurement MIRRORCLE 6 MeV

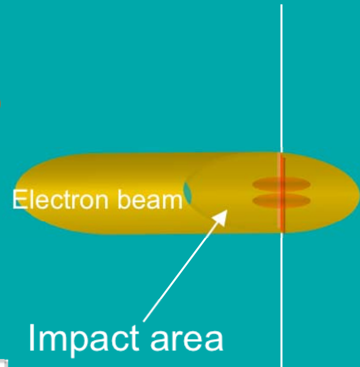




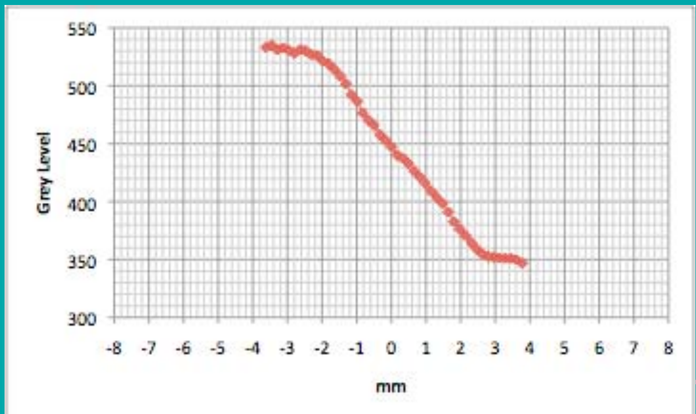
b (mm)	o (mm)	i (mm)	M	a (m)	p (mm)	l (mm)
326,0±0,5	11,7±0,1	15,0±0,1	1,28±0,01	1,1±0,01	1,6±0,1	5,8±0,2

length of the impact area

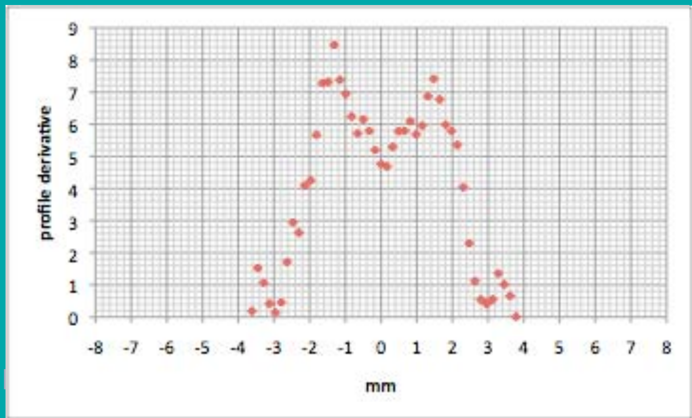
Target wire
Φ = 0.125 mm



penumbra profile

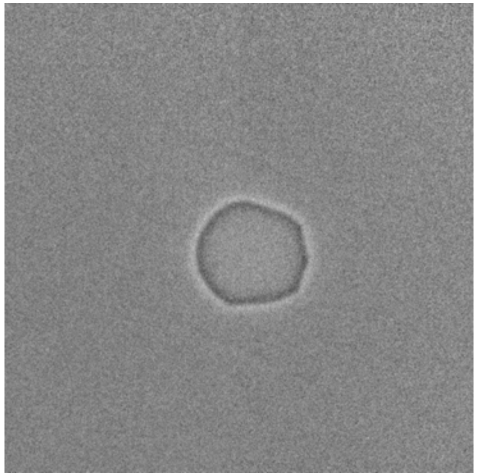


profile of the impact area

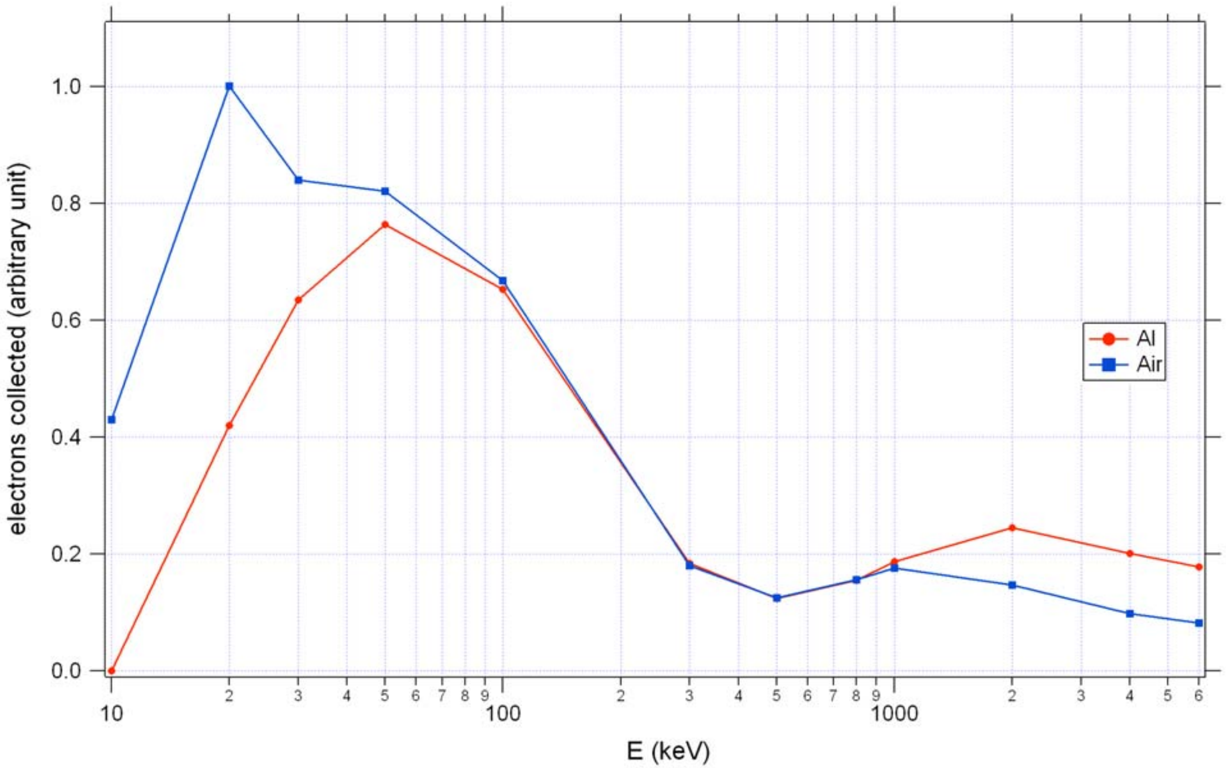


X ray imaging with very wide X-ray spectrum (10 keV - 6 MeV)

0.1 mm Al disk

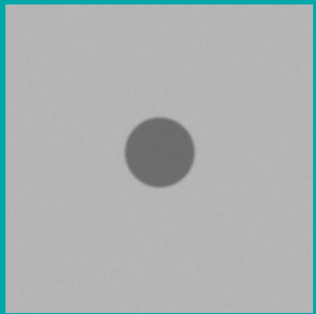


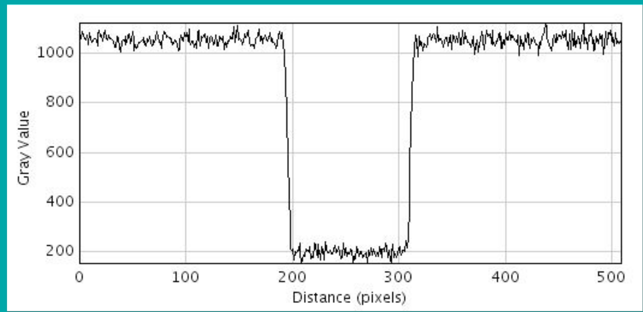
Edge enhancement in radiographic image of a 0.1 mm-thick Al disk in contact with detector surface



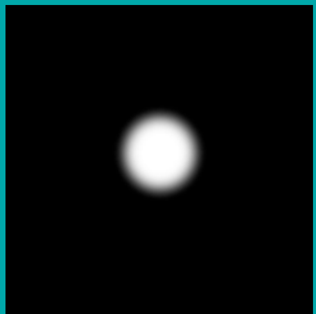
Electrons collected (arbitrary normalization) per fluence unit of a monochromatic photon beam vs energy E (keV) of incident monochromatic beam, **in air** (blue) and passing **through 0.1 mm of Al** (red).

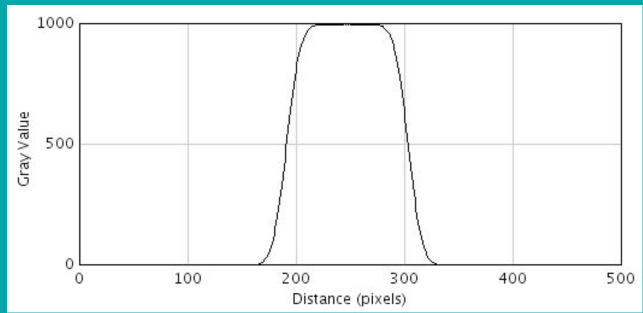
Edge enhancement model



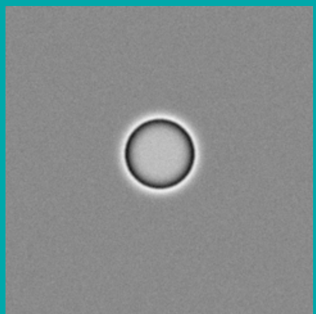


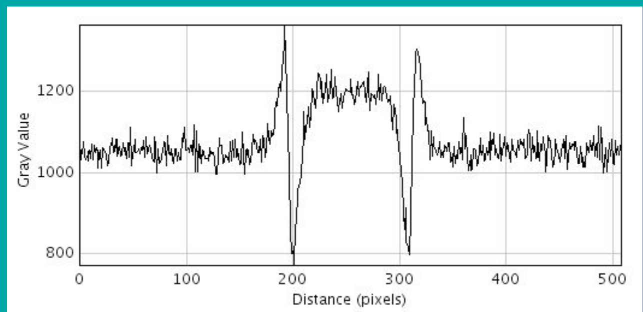
Absoption image due to **low energy** part of spectrum (E < 150 keV)





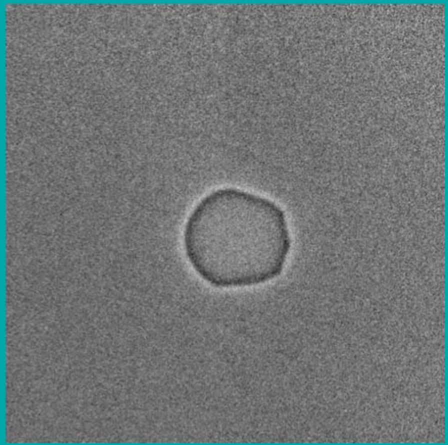
Emission image due to **high energy** part of spectrum (E > 1 MeV)

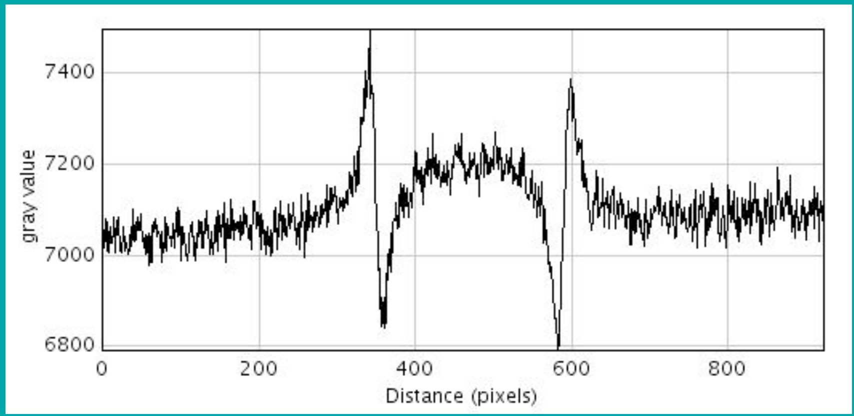




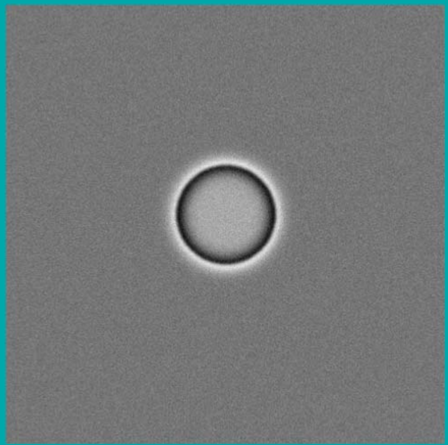
Edge enhancement as a result of sum of absorption and emission images.

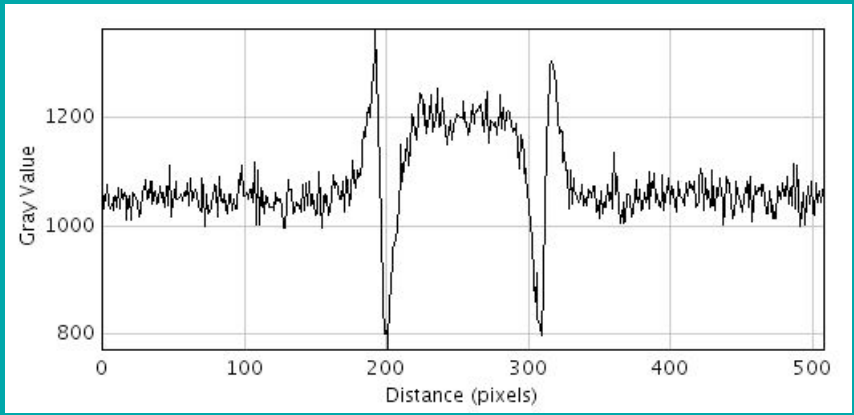
Measured profile





Model profile





Conclusions

MC simulations have demonstrated that x-ray beams generated by the interaction of MeV electrons with target materials of diagnostic interest are far more intense than those generated by conventional x-ray tubes.

Significant improvement in x-ray beam monochromaticity can be achieved by viewing the x-ray emission from a direction orthogonal or antiparallel to that of the incident electron beam.

X-ray imaging performance of the current MIRRORCLE system allows one to obtain radiographs of test object with experimental conditions similar to clinical systems.

To take advantage of the better efficiency of the compact synchrotron in terms of the number of x-ray photons produced per electron impinging on the target, an optimization of electron current and/or injection rate is desirable.