AE45
Advanced Imaging with ICS

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BNL/INFN/UCLA

- AE45 is an experiment funded on the italian side by INFN and University of Sassari, to investigate the potential imaging applications of the Thomson X-ray source
- The collaboration has been started in 2009

Publications

Golosio B et al., Measurement of an inverse Compton scattering source local spectrum using k-edge filters
(2012) Applied Physics Letters, 100 (16), art. no. 164104

Endrizzi M et al., Quantitative phase retrieval with picosecond X-ray pulses from the ATF inverse compton scattering source
(2011) Optics Express, 19 (3), pp. 2748-2753

Oliva P et al., Quantitative evaluation of single-shot inline phase contrast imaging using an inverse compton x-ray source
(2010) Applied Physics Letters, 97 (13), art. no. 134104

Pogorelsky I et al., Lasers as particle accelerators in medicine: From laser-driven protons to imaging with Thomson sources
(2011) AIP Conference Proceedings, 1336, pp. 386-390.

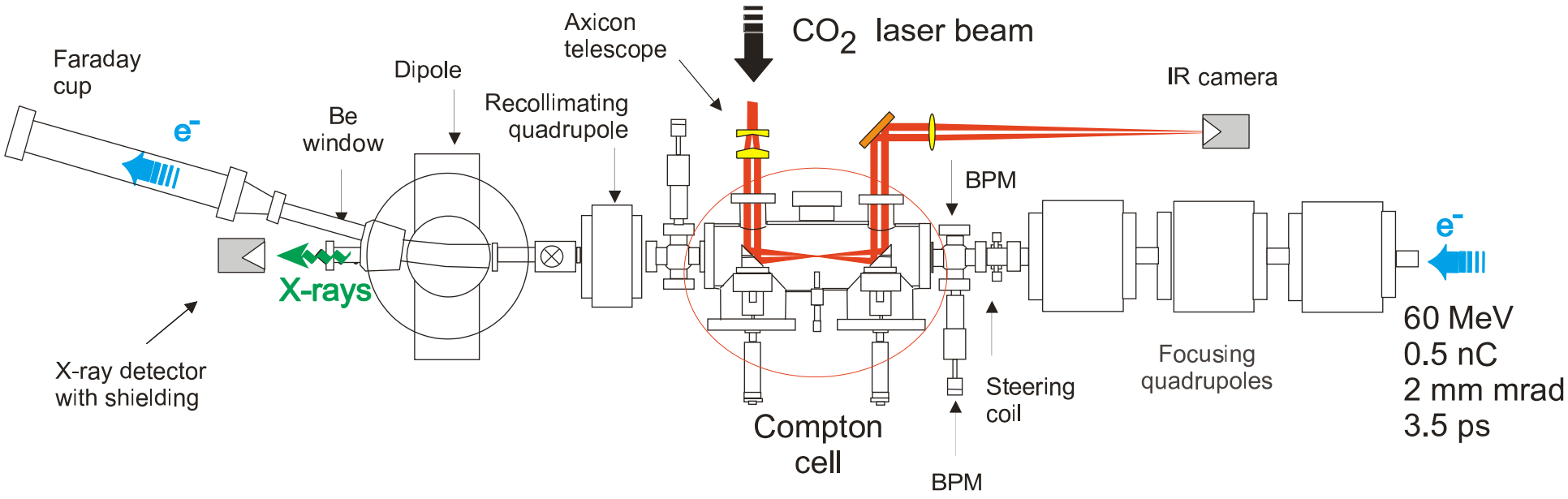
Pogorelsky I et al., Proton- and x-ray beams generated by ultra-fast CO2 lasers for medical applications
(2011) Proceedings of SPIE - The International Society for Optical Engineering, 8079, art. no. 80791L

Endrizzi M et al., X-ray phase-contrast imaging with an inverse compton scattering source
(2010) AIP Conference Proceedings, 1266, pp. 39-41.

Data taking @ ATF

- First run (October 2009)
  - Quantitative phase contrast imaging
  - Quantitative phase retrieval
- Second run (December 2010)
  - Spectral measurement

Layout of the ICS at BNL ATF



ATF running parameters

ATF running parameters in the 2009/2010 runs

60-90 MeV e-beam 0.5nC, 30-50μm RMS (50μm to minimize background), 1-3.5ps

CO2 laser, λ=10.6 μm, 0.6 TW, a_0~0.3 , 5 ps, 30 μm

2 10^7 x-rays per pulse (>10^8 x-rays in high background mode)

E_x: 6 – 13 keV

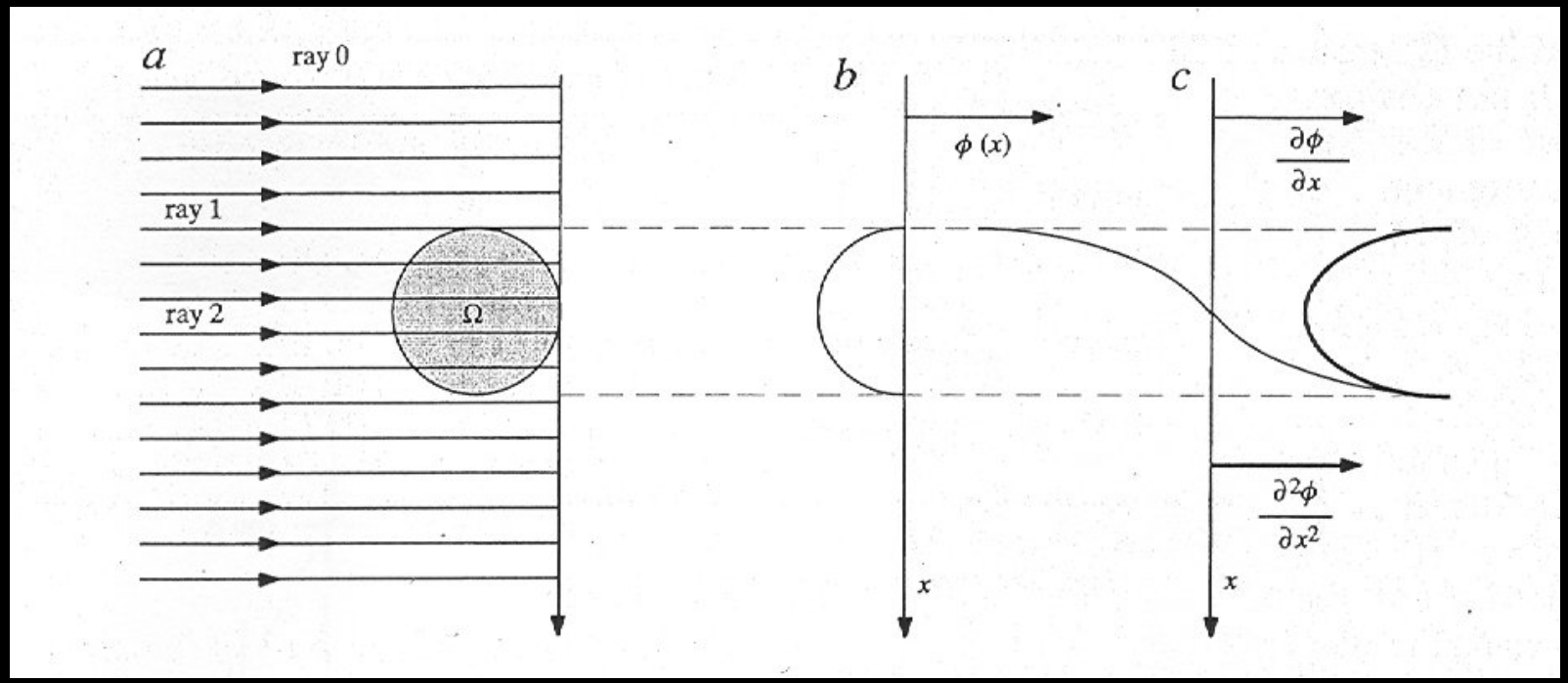
PHASE CONTRAST IMAGING

- For X-rays at energies of interest for medicine and biology, interacting with biological tissues, the phase shiftis generally much more pronounced than absorption. For example, 17 keV X-rays crossing 50 μm of biological tissue are attenuated less than one per cent, while the phase shift is close to π .

- The registration of this phase shift, together with the absorption, allows to increase significantly the image contrast.

PHASE CONTRAST IMAGING

Spatial variations of the real part of the refraction index cause the wave phase shift, that can be observed by means of the so-called *phase imaging* techniques



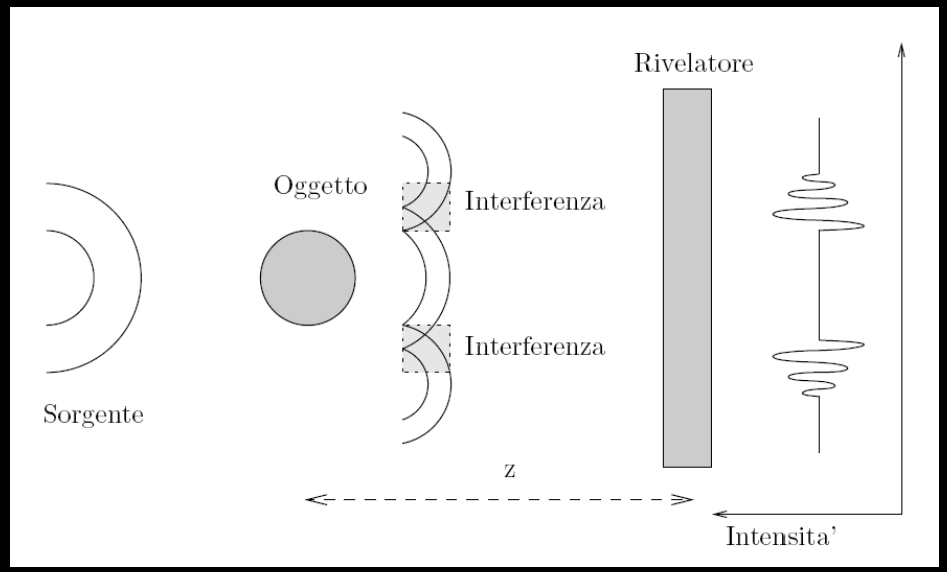
$n=1-\delta-i\beta$

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

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

INLINE PHASE CONTRAST

Free space propagation (in-line) (Snigirev, 1995)



The shifted wave propagates in free space up to the detector.
During propagation, the wavefronts having different phase shift interfere.
This effect is more intense at the border of zones with different refraction index or different thickness

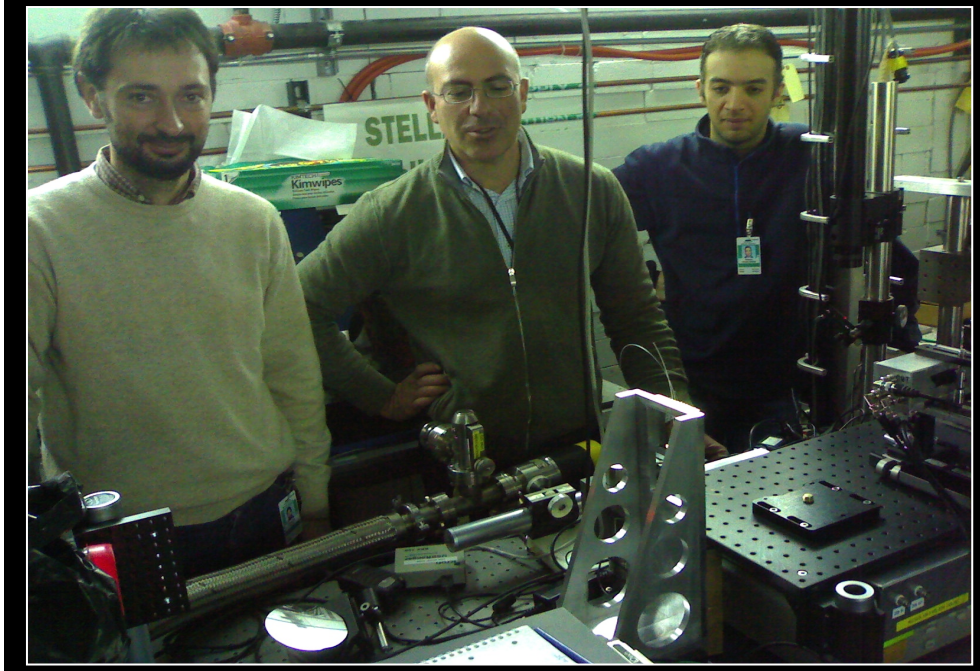
Partially (spatially) coherent beams

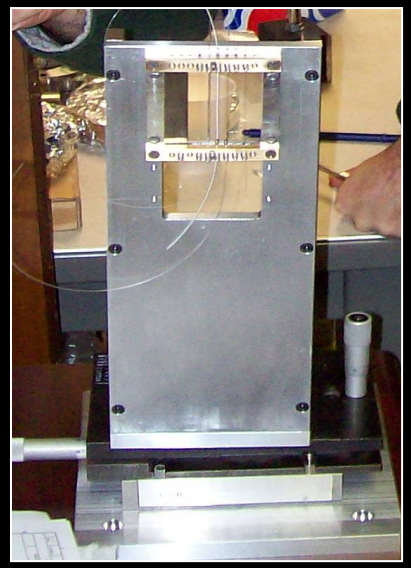
- For source-object and object-detector distances of the order of one meter the source size should be ~10 μm

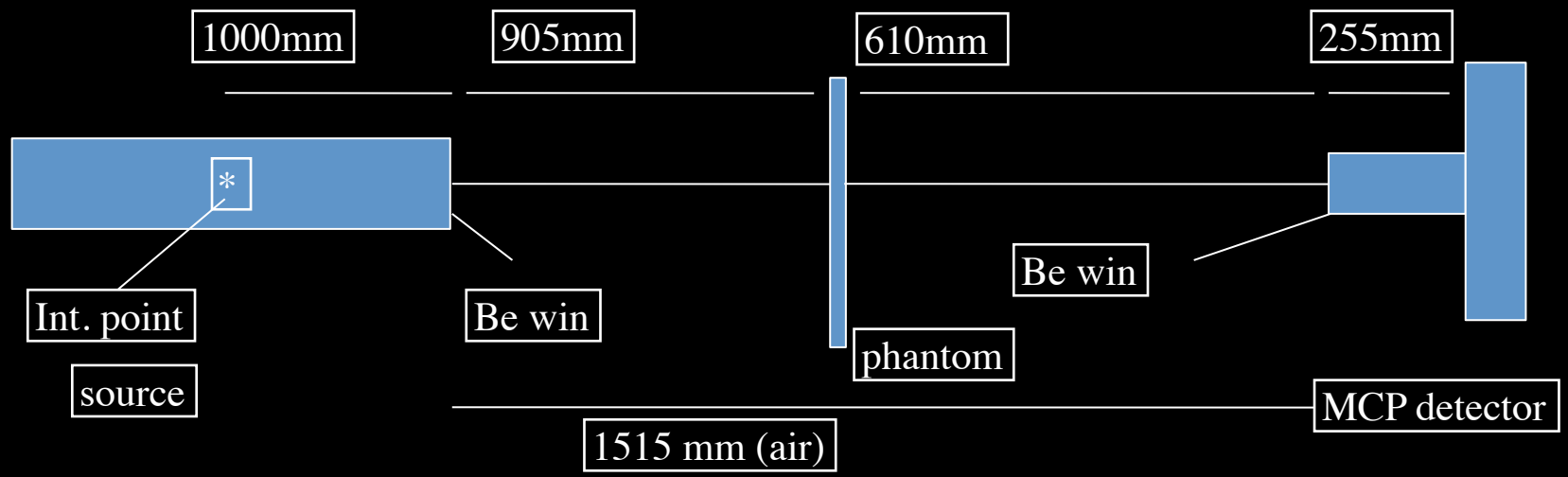
- It can be observed also using polychromatic sources

- The acquisition of a single image is required

MEASUREMENTS AT ATF

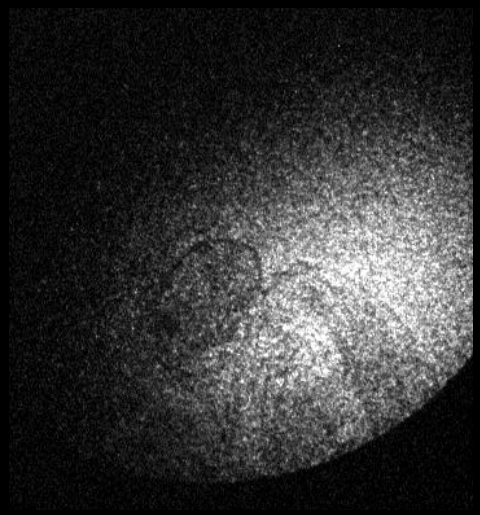






COMPARISON OF DETECTORS

Beam energy: 11 keV



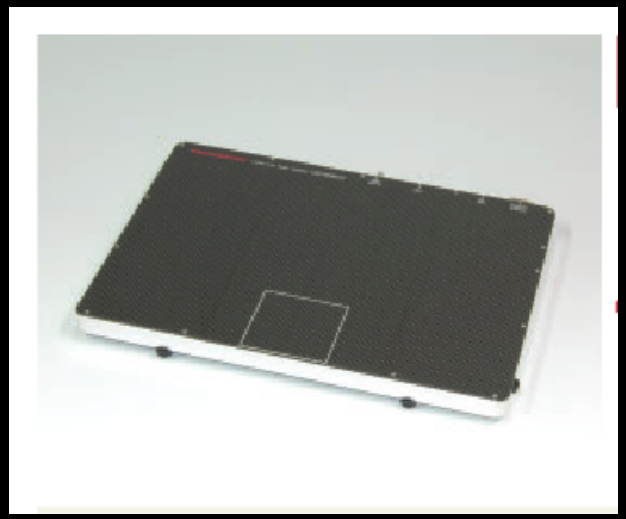
MCP detector

PPS CMOS
(Si direct detection)

APS CMOS +
CsI scintillator

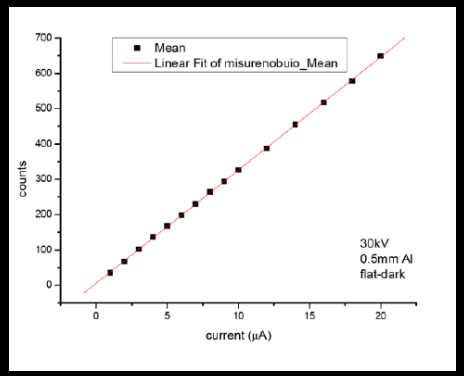
CMOS APS DETECTOR

The detector used is a flat panel (Hamamatsu C9728DK − 10) based on a CMOS sensor coupled to a scintillator (CsI).

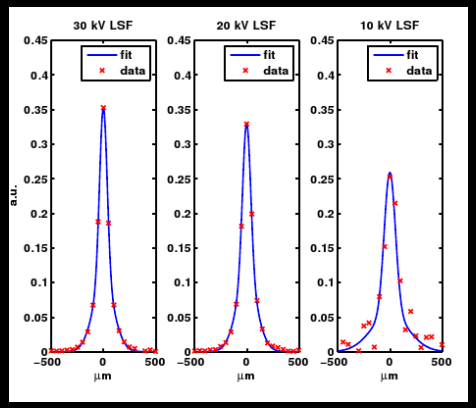


- Active pixels readout
- Low noise: 80 electrons
- 1032 × 1032 pixels (50 μm pitch)
- High resolution
- 14-bit digital output

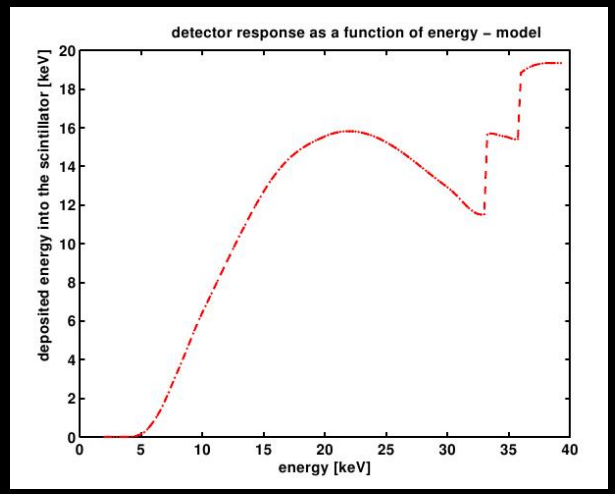
CHARACTERIZATION OF THE CMOS



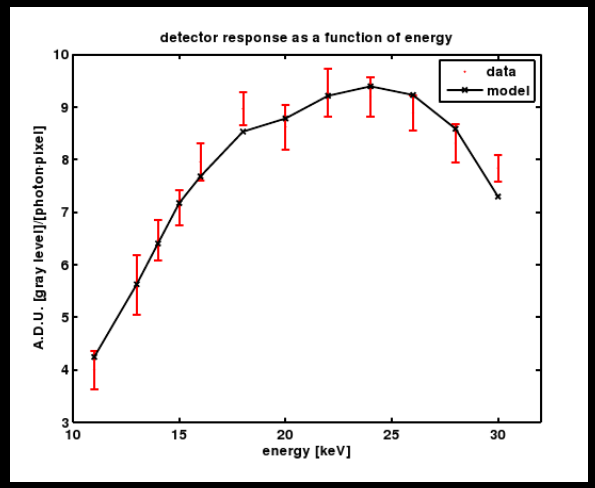
Linearity



Line Spread Function (FWHM)



Detector modeling

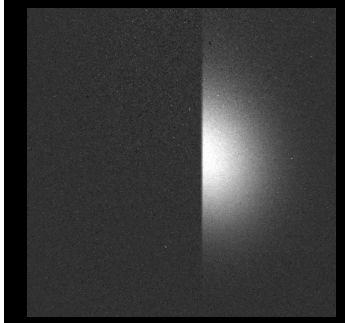


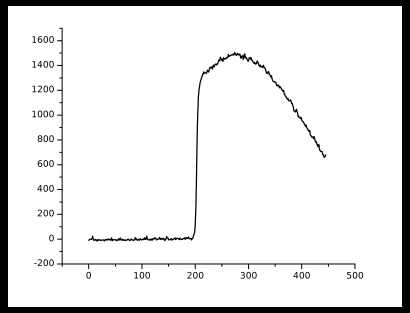
Measurements at the Elettra synchrotron

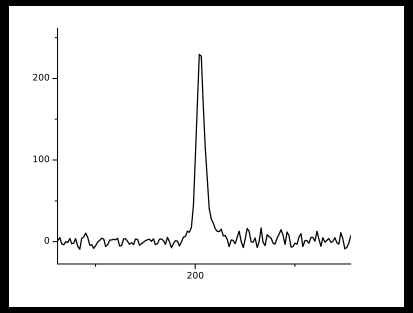
Endrizzi, M., Oliva, P., Golosio, B., Delogu, P., CMOS APS detector characterization for quantitative X-ray imaging (2013) NIM A, 703, pp. 26-32.

CHARACTERIZATION OF THE SOURCE

- Spot size







New setup:
- $2*10^7$ photons per shot
- energy: 11 keV
- He pipe

M=(z2-z1)/z1=2.1

FWHM=90 μm

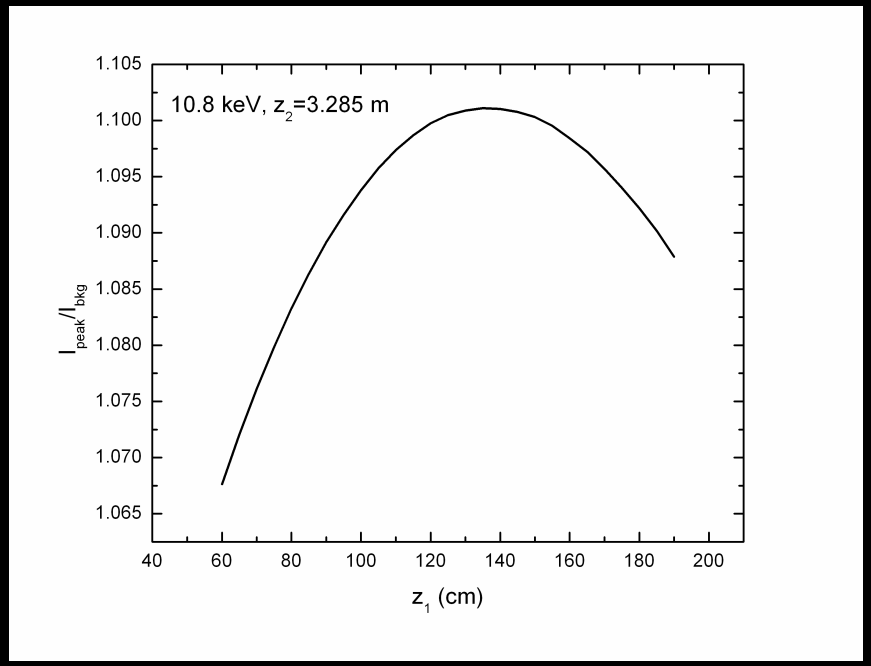
- High shot-to-shot variability
- Maximum measured number of photons: 10^8 ph/shot
- Energy 10.8 keV

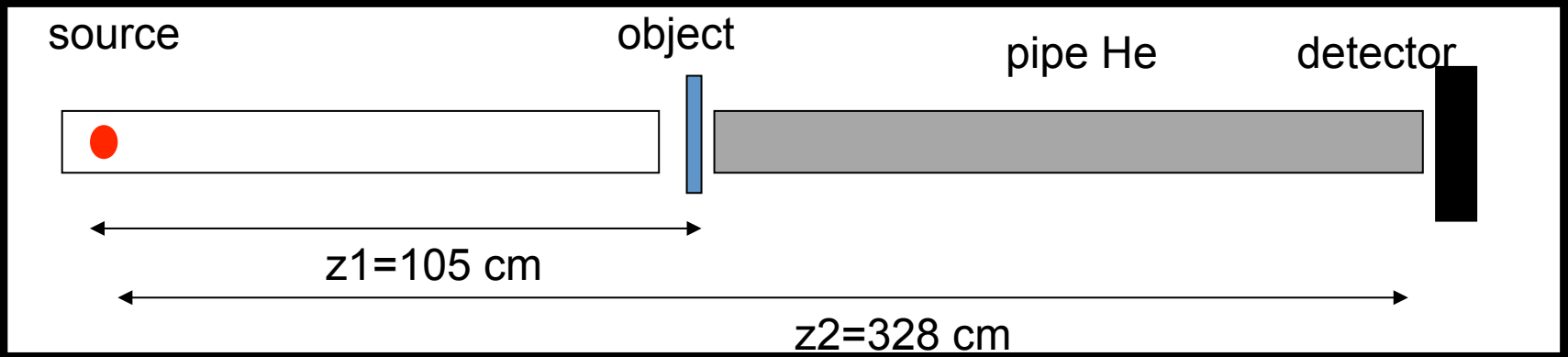
DEFINITION OF THE OPTIMAL CONFIGURATION

The optimal source-object distance (z1) was defined by means of simulations, searching for a maximum in the phase contrast signal.

The simulation takes into account:

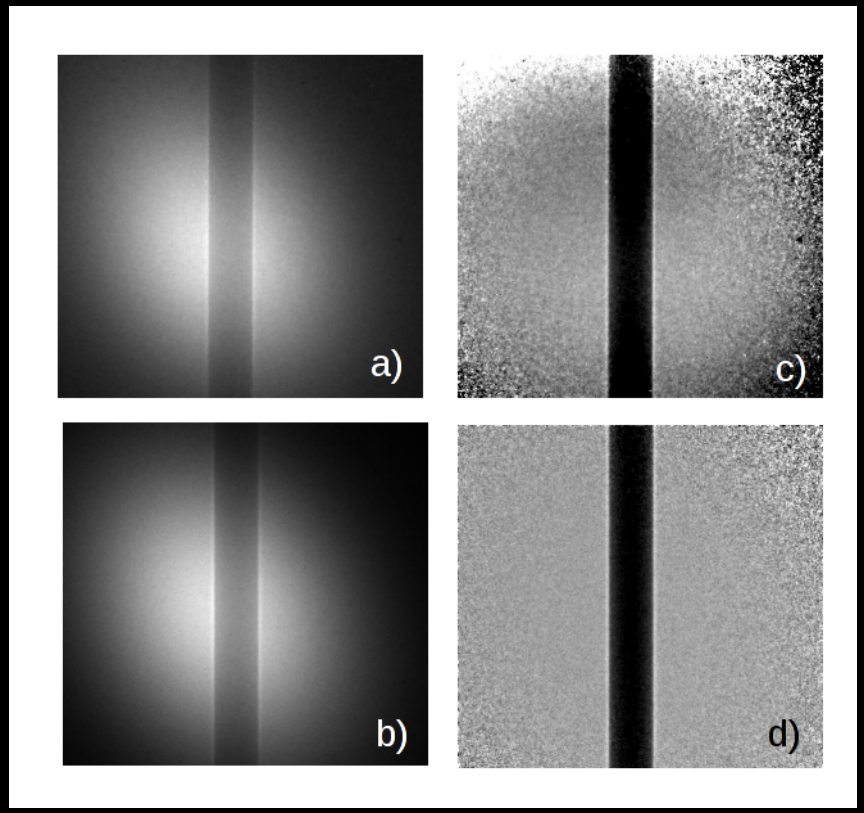
- LSF of the detector
- Source size
- Maximum source-detector distance
- Number of photons/shot

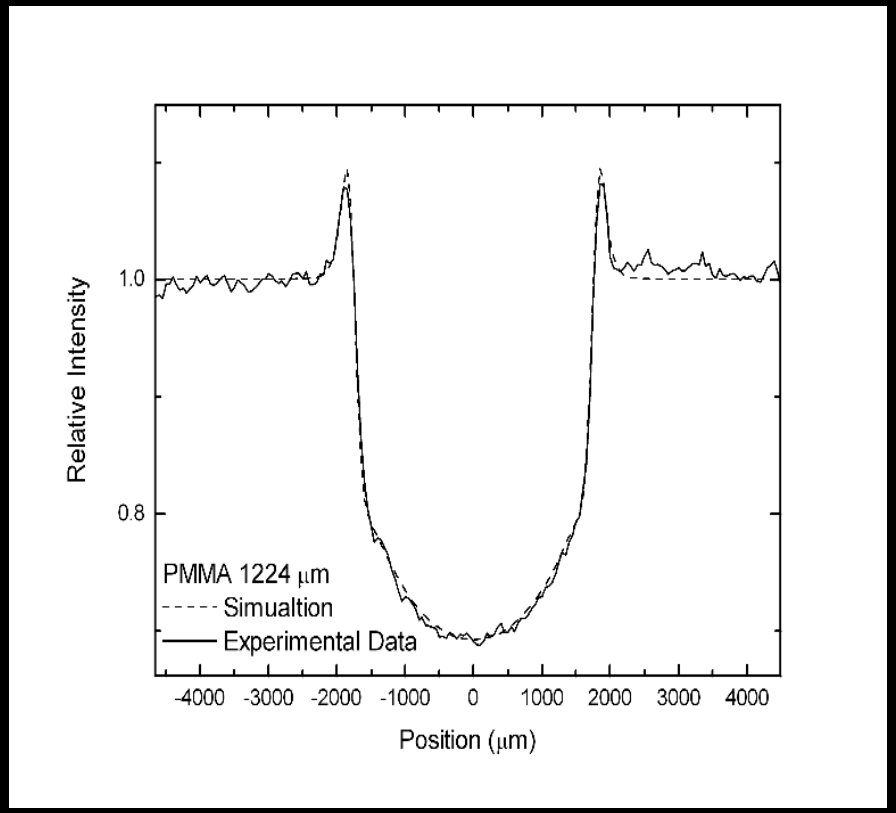




WIRE IMAGES

SINGLE SHOT IMAGES



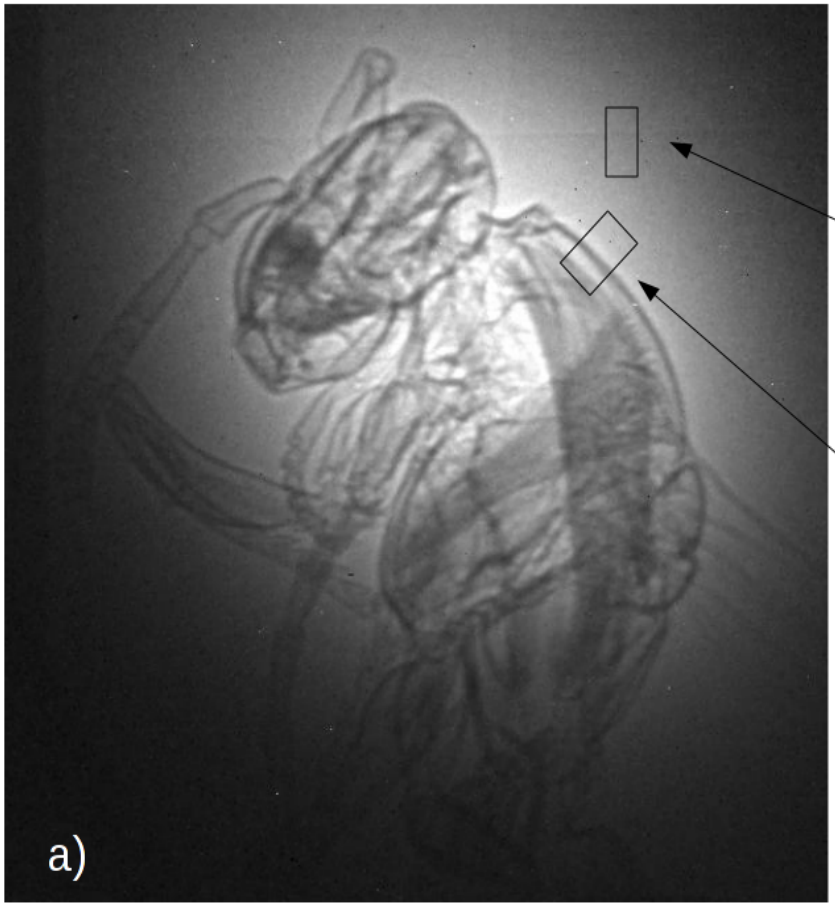


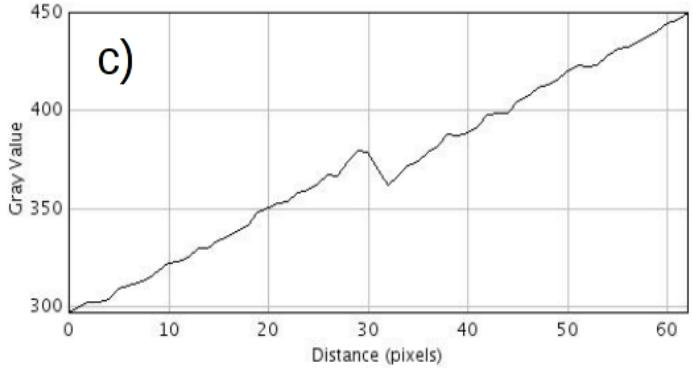
published in Applied Physics Letters

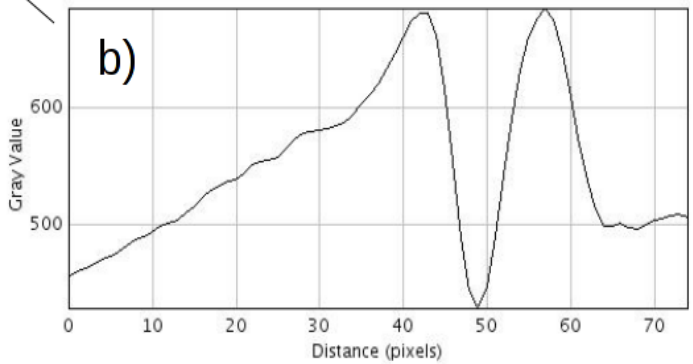
Single shot, pulse: 4ps. Integration time: 5s.

IMAGE OF A BIOLOGICAL SAMPLE

SINGLE SHOT IMAGES







CONCLUTIONS ON SINGLE-SHOT PHC IMAGING

In conclusion, We have investigated the feasibility of single-shot inline phase contrast imaging with the ATF ICS X-ray source.

The PhC in the images is clearly visible.

The experimental data are in agreement with simulations within the experimental errors.

Images on a biological sample were also obtained, showing the potential imaging applications of this state-of-the-art ICS source.

Phase Retrieval

•When a partially coherent X-ray beam crosses an object, the possibility of detecting the phase shift of the wave function together with the attenuation allows more information on the sample to be obtained.

• X-rays interact with the sample and different variations of the phase of the radiation are induced by the details. The resulting interference patterns propagate in free space. The amplitude of the interference fringes produced on the detector is particularly large around the border of structures having a refractive index different from adjacent material.

•The transport of intensity equation (TIE) can be derived under the assumptions of a homogeneous and weakly scattering object and paraxial incident illumination. From the final image and the knowledge of the TIE, phase retrieval can be obtained.

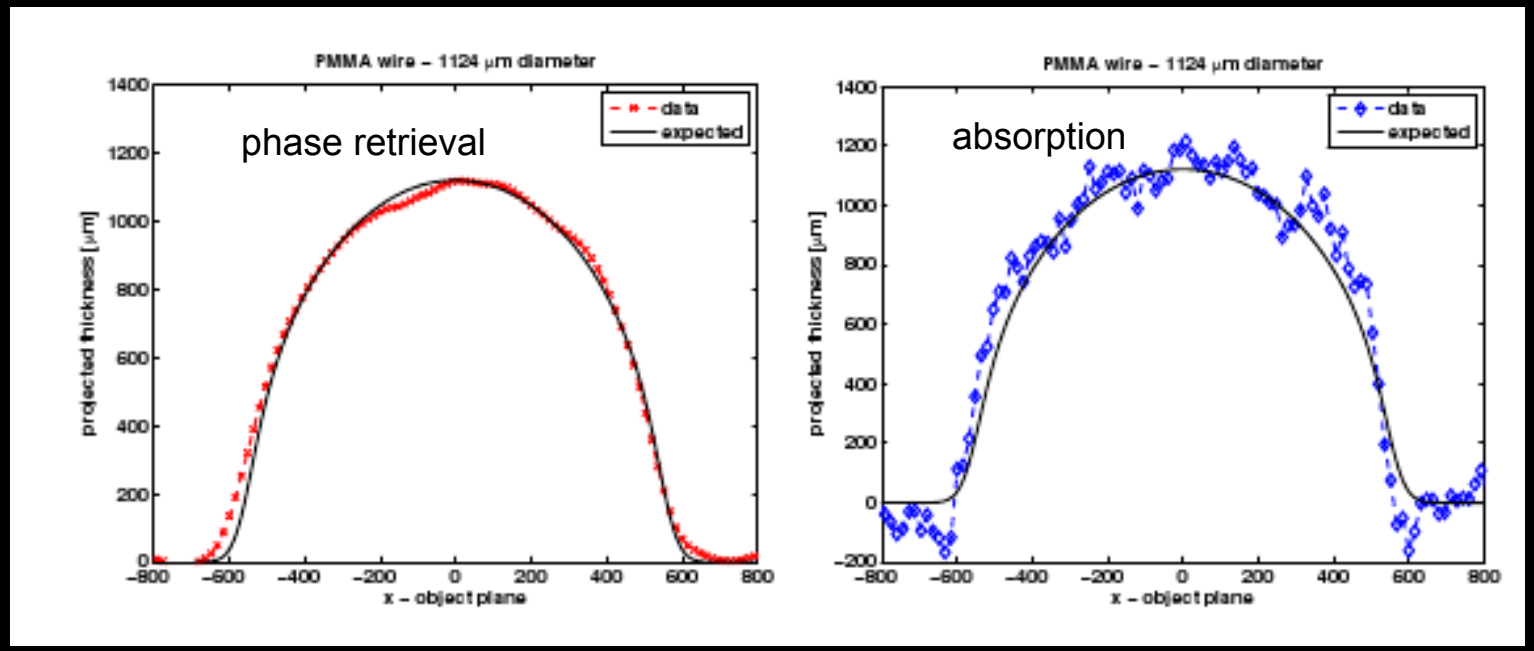
•Phase retrieval enables the recovery of quantitative information from phase-contrast images and improves the quality of tomographic reconstruction.

•In particular, it is possible to reconstruct the projected thickness of the sample

Phase Retrieval

- A phase retrieval algorithm has been used to reconstruct the projected thickness of the wires

- For comparison, the same thickness has been estimated also from absorption only



Published in Optic Express

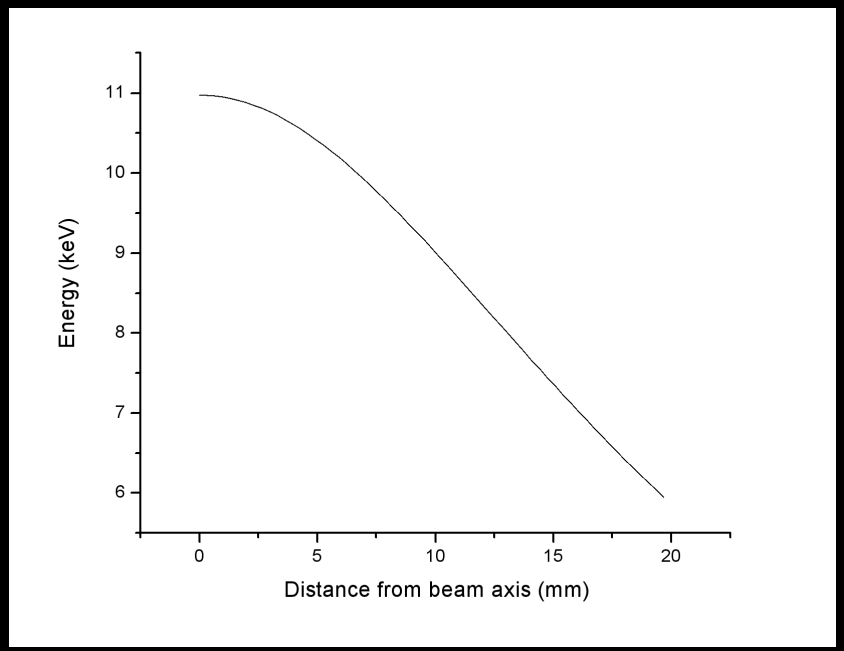
collaboration with Materials Science and Engineering, CSIRO, VIC, Australia

Characterization o the Energy Spectrum of a Thomson source

$$E_x = \frac{4\gamma^2}{1 + \frac{a_L^2}{2} + \gamma^2\theta^2} E_L$$

$$a_L = 0.85 \times 10^{-9} \lambda_L[\mu m]\sqrt{I_0[W]}$$

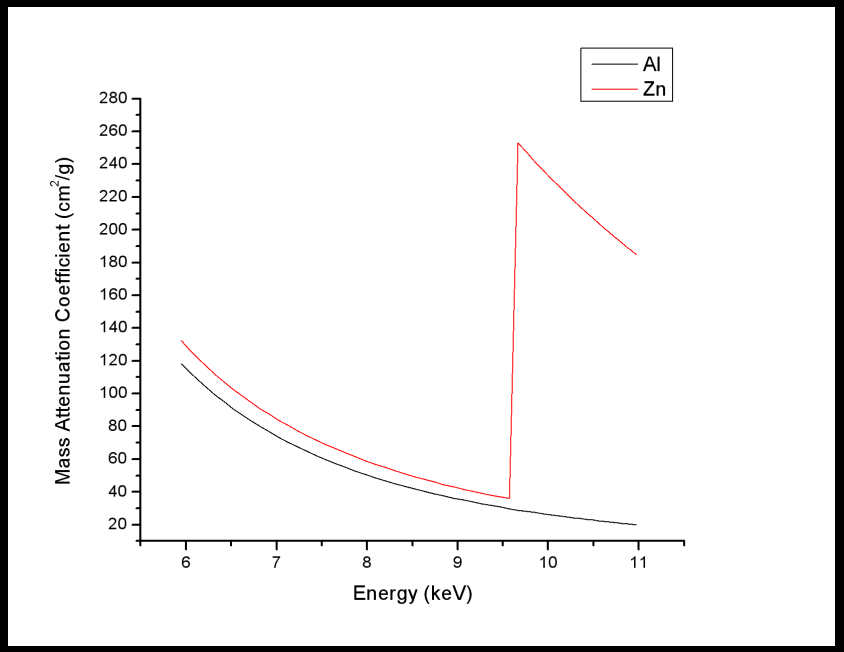
E_{e-}=80 MeV
λ_L=10.6 μm

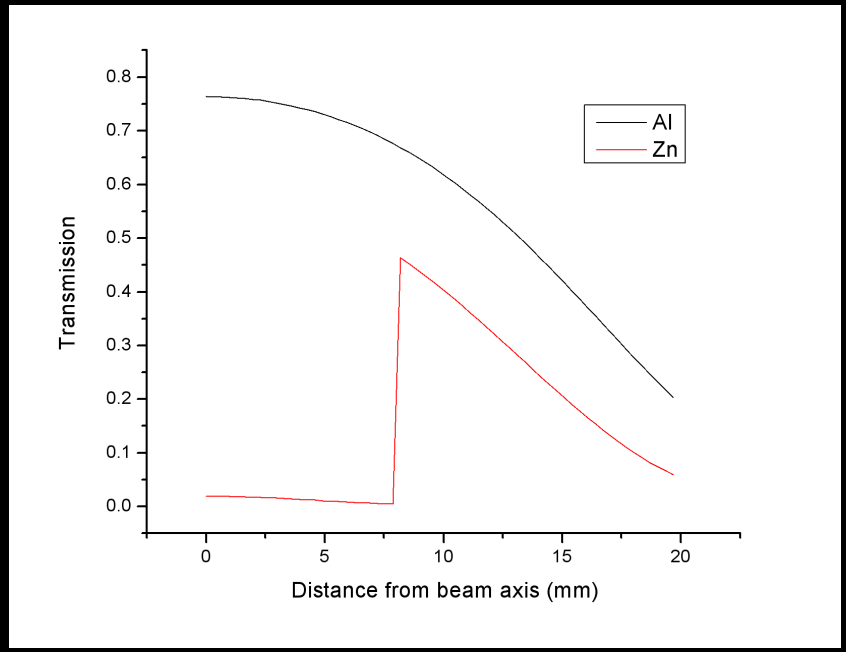


The actual energy distribution is supposed to be bell-shaped, with a small energy spread

Effect of a k-edge filter

Third run (December 2010)





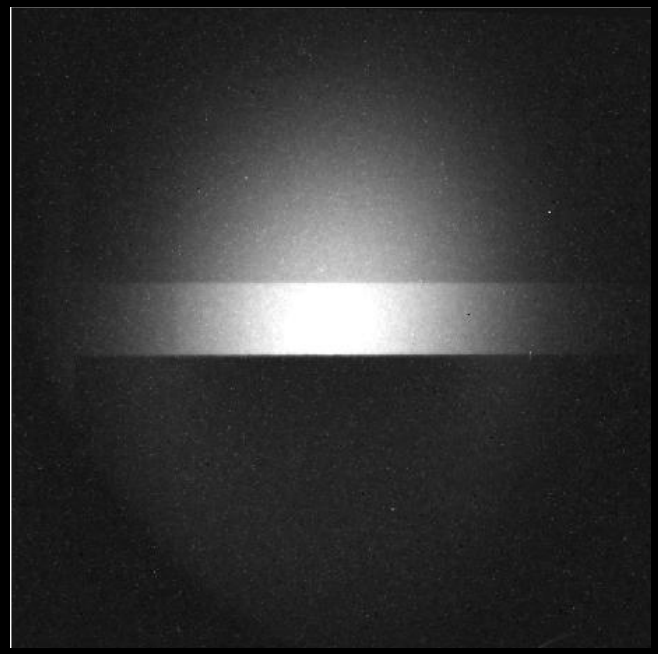
Monochromatic beam, with E(x) given by the undulator equation

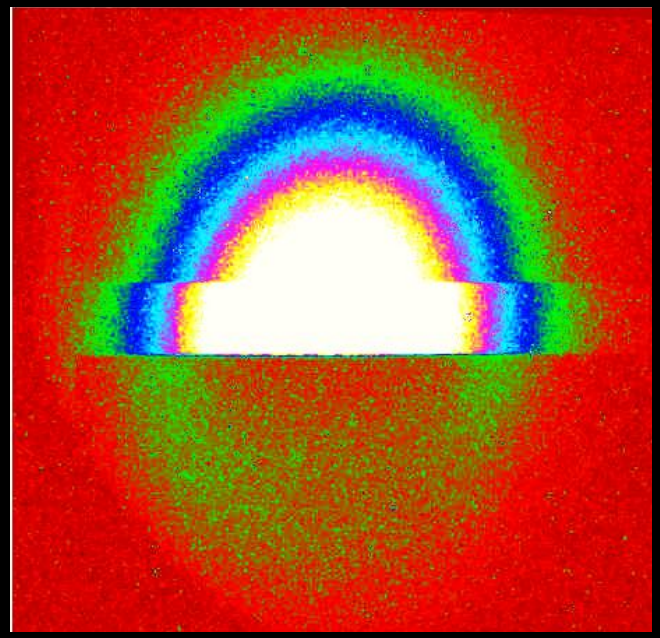
Image of the foils

Al

Unfiltered

Zn

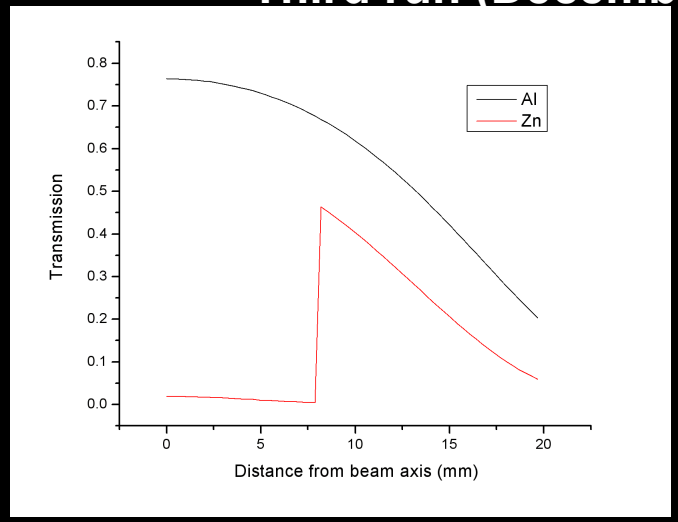


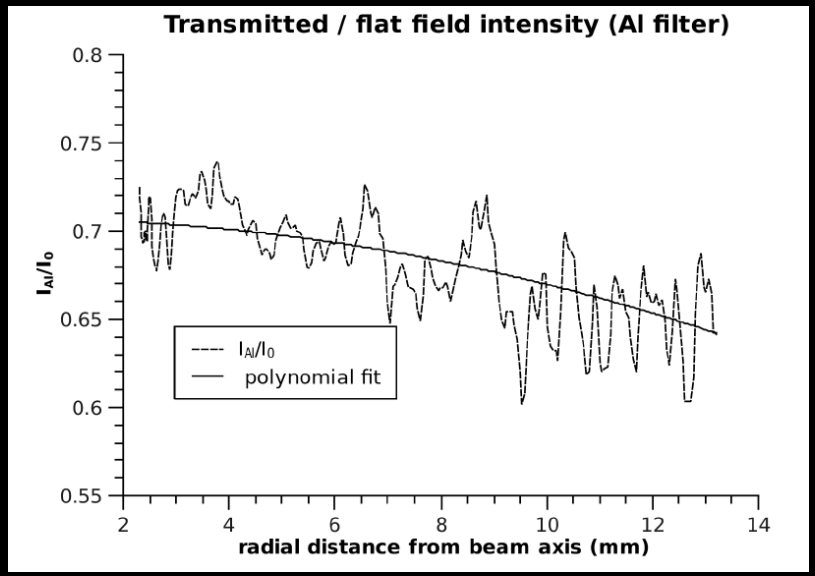


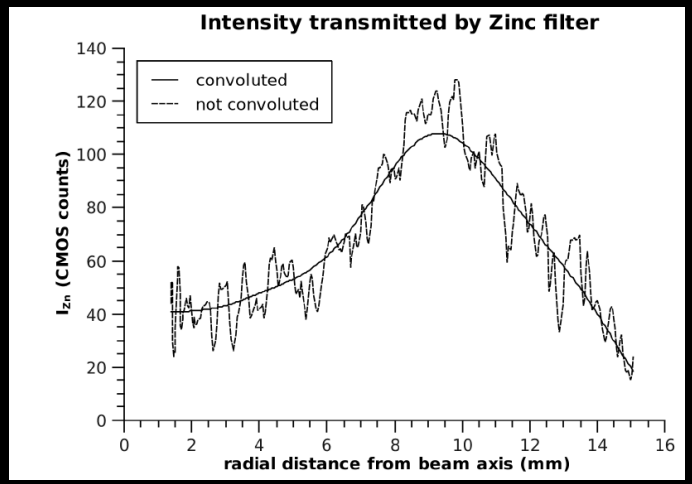
The attenuation of the two foils is recorded in a single shot (plus no attenuation)
The unfiltered part is used to measure the counts of the unattenuated beam (flat field).
The Al filter is used to estimate the mean (effective) energy of the beam as a function of the position.
The Zn filter is used to estimate the energy spread of the spectrum at 9.66 keV (Zn K-edge).

Characterization of the Energy Spectrum

Third run (December 2010)







Golosio B. et al, *Measurement of an inverse Compton scattering source local spectrum using k-edge filters*, Appl. Phys. Lett. 100, 164104 (2012)

Characterization of the Energy Spectrum

Close to the K-edge of a material, the transmission function can be written as:

$$T(E) = T_0(E) - DH(E - E_k),$$

The spectral distribution is supposed to be an approximately Gaussian function.
The transmitted intensity is hence:

$$\widetilde{R}(E_m) = \frac{I(E_m)}{I_0(E_m)}$$

$$\tilde{R}(E_m) = \int_0^{\infty} G(E - E_m)[T_0(E) - DH(E - E_k)]dE,$$

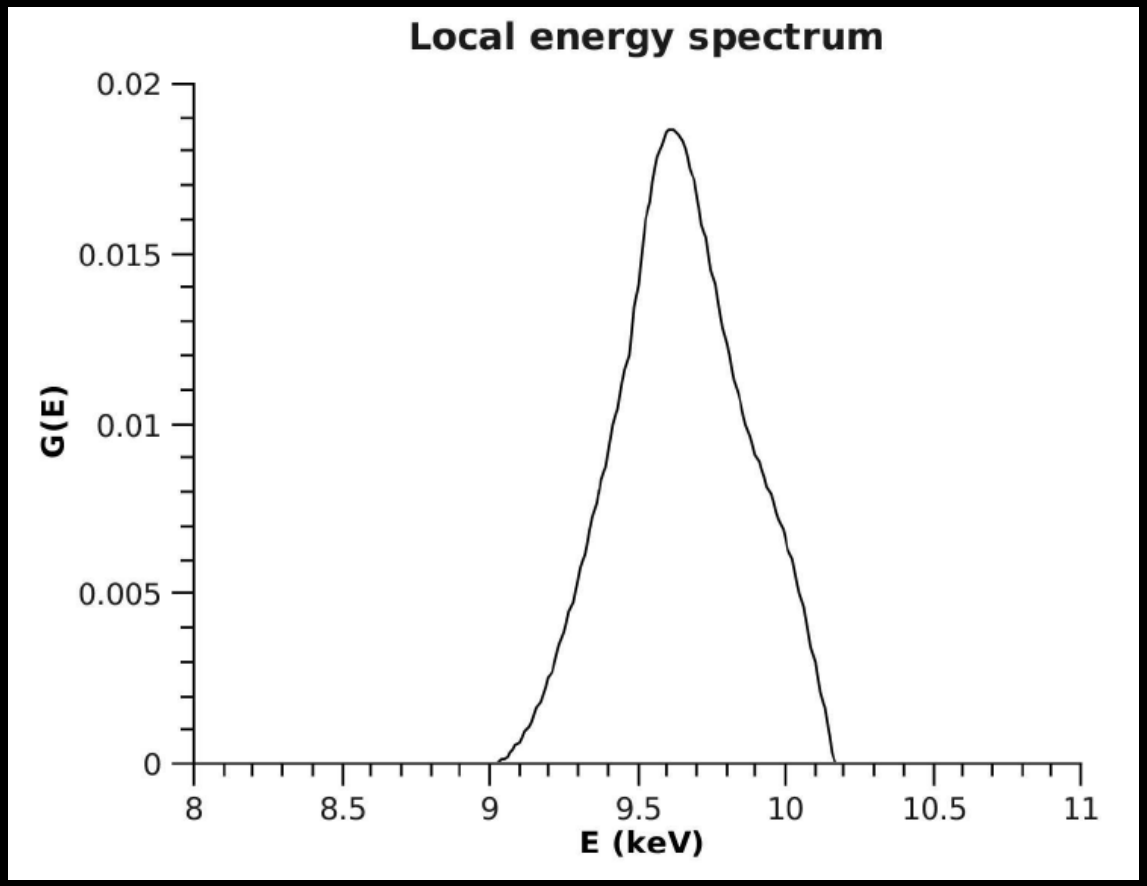
G can be obtained by differentiating R(Em):

$$G(E_k - E_m) = \frac{\tilde{R}'(E_m) - T_1{}'(E_m)}{D}.$$

$$T_1(E_m) = \int_0^{\infty} G(E - E_m)T_0(E)dE,$$

The spectral distribution can be obtained iteratively from the prevoiuos equation

Characterization of the Energy Spectrum



Em = 9.66 keV
FWMH = 0.49 keV
+/- 38%

Published in Appl.Phys.Lett

Future Plans

- BioMedical Imaging using ICS X-ray
- Characterization of ICS source
- Synergy of chemo and radiation therapies using ICS X-ray
- Laser-driven Ion production and acceleraion for hadrontherapy (with INFN LNS)
- The extremely narrow time structure of ICS has not been exploited yet

Conclusions

- We intend to keep active the collaboration with ATF and continue to work to strengthen the scientific cooperation between our countries
- Not yet ready for a new full proposal but we expect a new one early 2015

Available Instrumentation

Imaging detectors (HAMAMATSU):

- C9728DK (5cmx5cm, active pixel, 50 μm, 10-40 keV)
- C9732DK-11 (12cmx12cm, active pixel, 50 μm, 10-40 keV)
- C10013SK (5cmx5cm, active pixel, 50 μm, 30-150 keV)

IONIZATION CHAMBER:

- PTW 34047 (5-20 keV)

Detector for spectroscopy:

- Silicon-drift-detector (1-30 keV)
- CdTe (5-80 keV)

XRMC:

- Monte Carlo tool for simulation of X-ray interactions for imaging and fluorescence experiments, also able to simulate phase contrast