Potential biomedical imaging with ICS sources

Prospects for dual-energy applications

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Istituto Nazionale di Fisica Nucleare

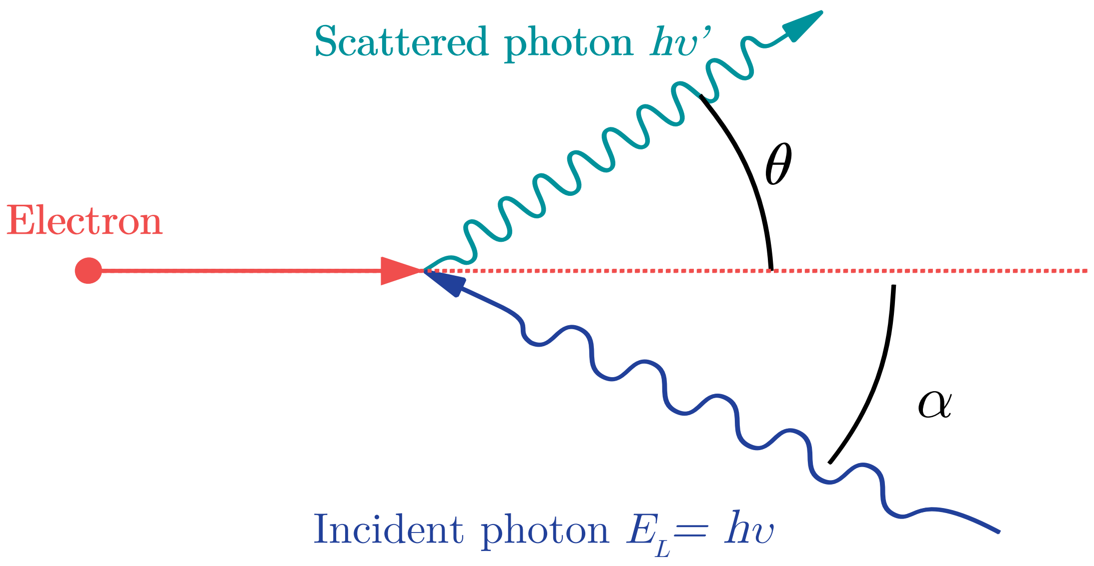
Inverse Compton Scattering (ICS)

- Scatter of a photon by a relativistic electron

$$h\upsilon' = \frac{2E_L\gamma^2(1 + \cos\alpha)}{1 + \gamma^2\theta^2}$$

- The photon increases its energy in the process

- For head-on collision ($\alpha = 0$) and backscatter ($\theta = 0$)
  $\rightarrow 4\gamma^2$ energy boost



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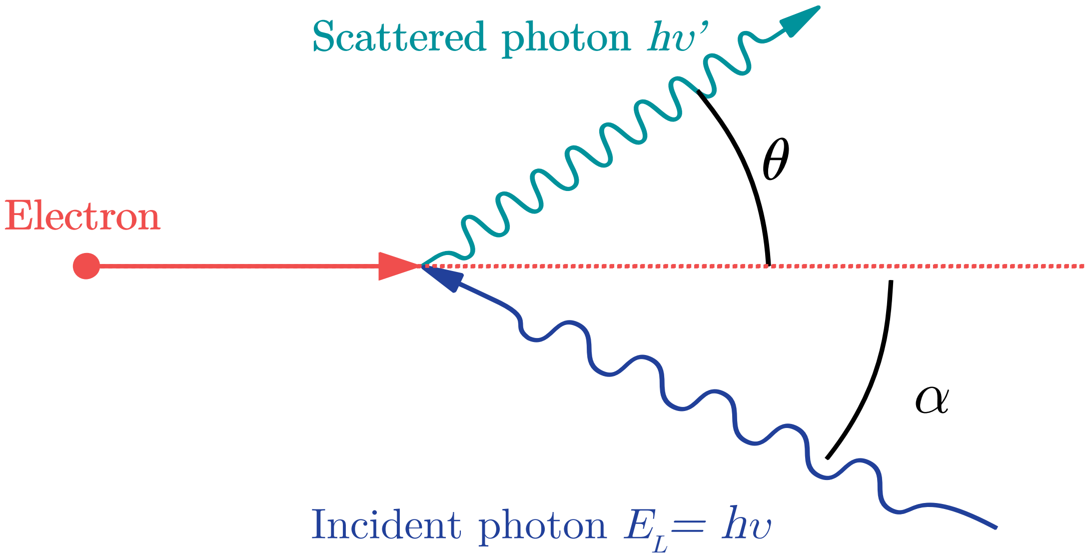

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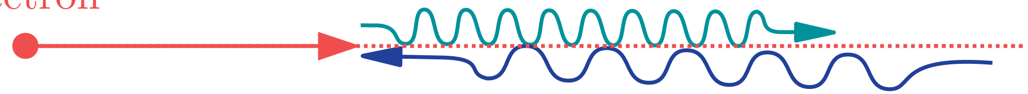

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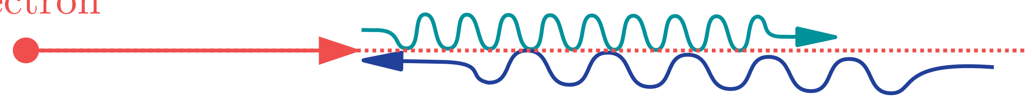

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$E_{\text{laser}} = 1.5$ eV (infrared)

$E_e = 30$ MeV $(\gamma = 60)$

$\rightarrow h\upsilon' =$ **22 keV**

ICS source

- **Interaction accelerated electron beam and laser → ICS source**

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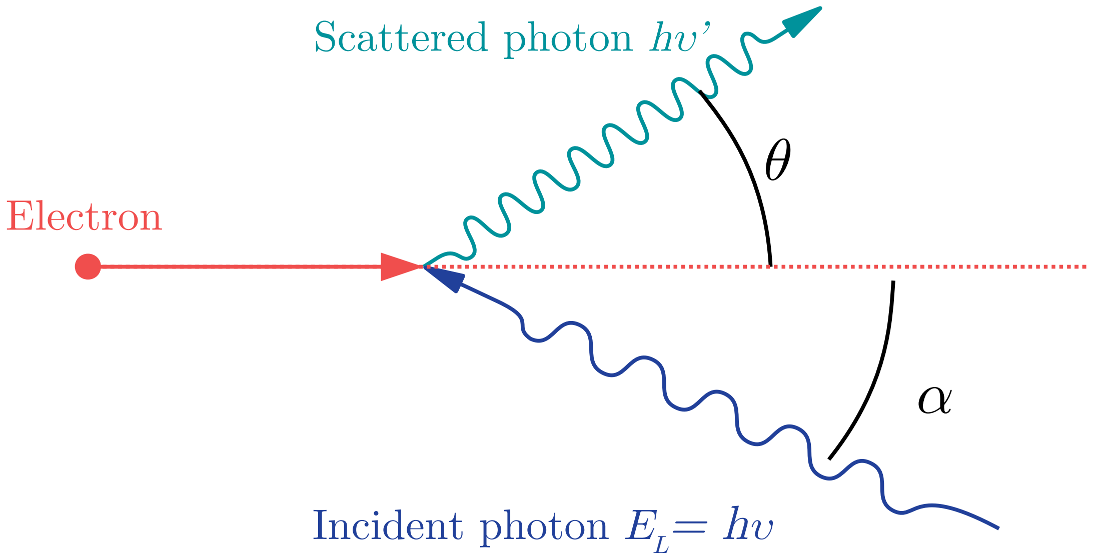

- Due to the relativistic boost the emission is peaked in the direction of motion of the electron ($1/\gamma$ cone)

- The energy decreases as the angle of emission increase
  → **The bandwidth can be adjusted by changing the acceptance angle (collimation)**

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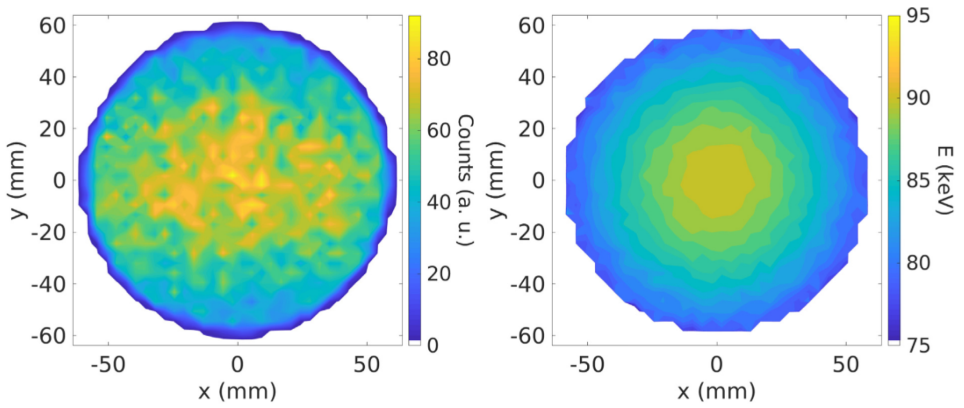

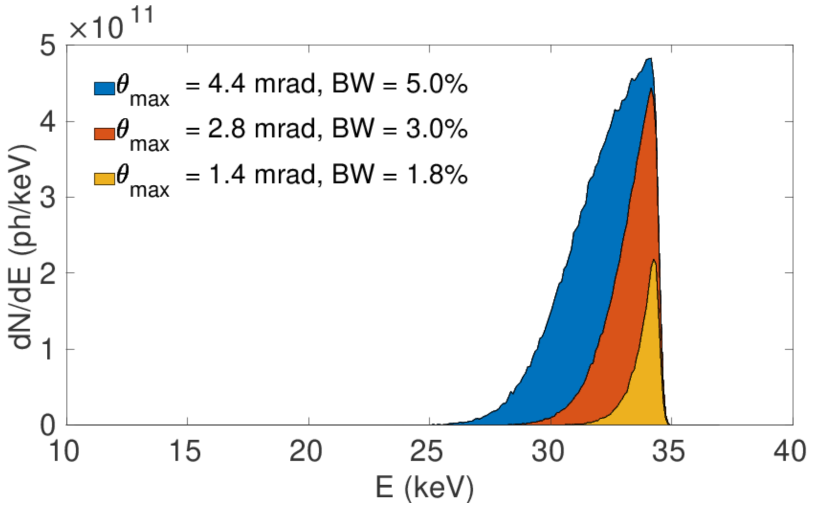

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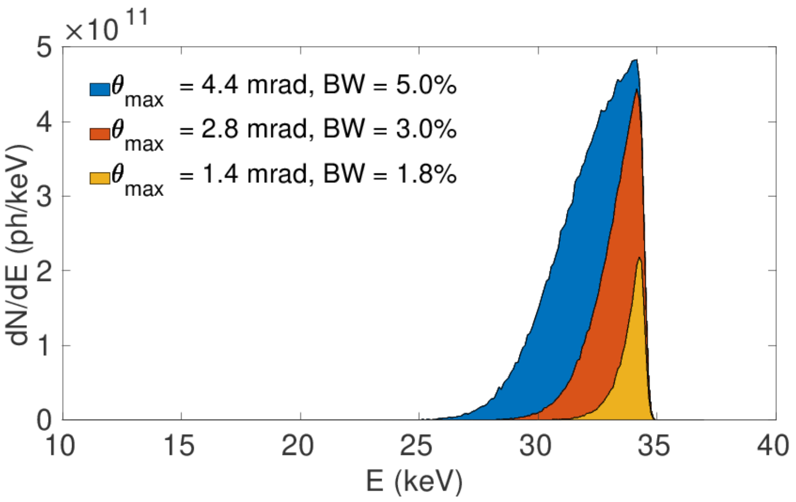
ICS source characteristics

- **(Quasi-)monochromatic** (energy bandwidth depends on angular acceptance)
- **Tunable** (varying electron energy or laser-electron interaction angle)
- **Small focal-spot size** → **coherence** (depends on beams overlap region)
- **Possibility of ultrafast pulses** (the x-ray duration = duration of laser pulse)

- **Compact** (compared to synchrotron)

  → Access higher energies (100 keV - 100 MeV+) → Nuclear, astrophsyics, NdT..

  → synchrotron-like features with lab-sized sources (10-100 keV energy range)



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Journal of Physics G: Nuclear and Particle Physics

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International Workshop on Next Generation Gamma-Ray Source

Calvin R Howell[1], Mohammad W. Ahmed[2], Andrei Afanasev[3], David Alesini[4], John Annand[5], Ani Aprahamian[6], Dimiter Balabanski[7], Stephen Benson[8], Aron Bernstein[9], Carl Brune[10]

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$\rightarrow$ bridge the gap between synchrotron and conventional X-ray tubes
$\rightarrow$ implement advanced X-ray imaging techniques on a laboratory base

Advanced X-ray imaging techniques

One of the limitation of conventional X-ray imaging is often
the visibility (signal to noise ratio) of the features of interest

Low absorption features generating no signal

Coherence → Phase contrast

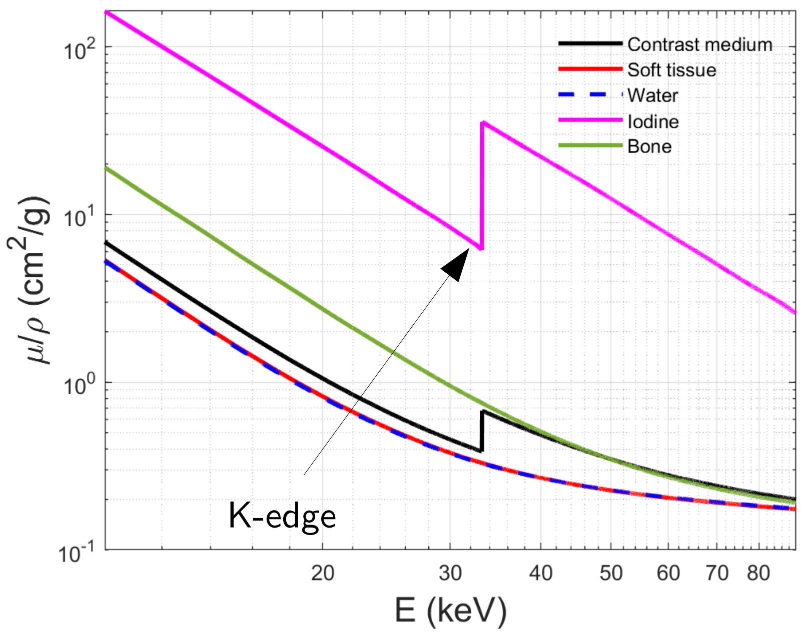
Absoprtion indistinguishable from surrounding tissues

Monochromaticity → K-edge subtraction imaging

→ enhance features or region of the patient/sample

K-edge energy subtraction (KES) imaging

- details of interest are perfused with a **contrast agent** having a **K-edge** (iodine, K-edge @ 33.17 keV)
- two images with X-ray beams having energies above and below K-edge are acquired



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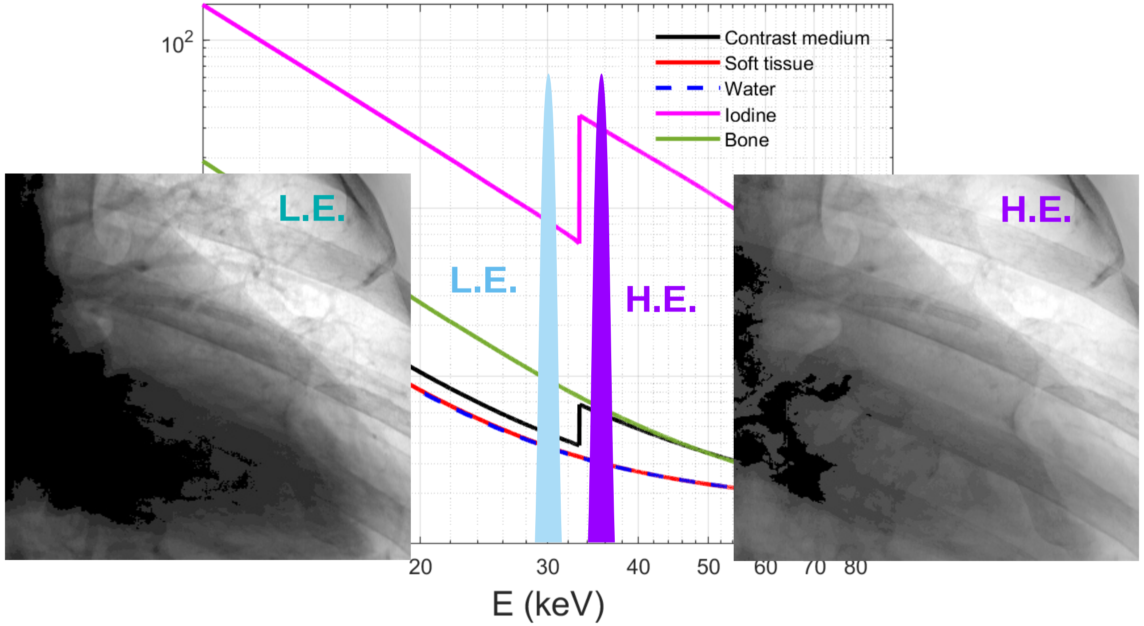
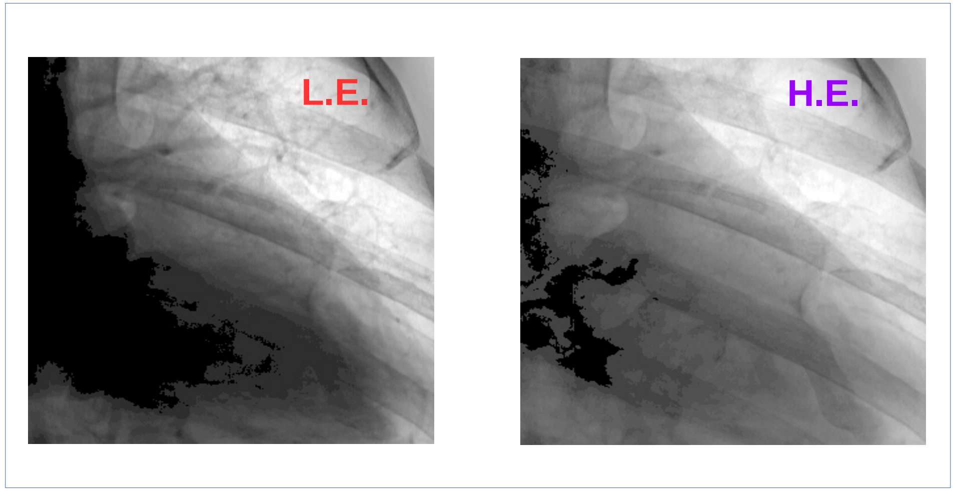


K-edge energy subtraction (KES) imaging

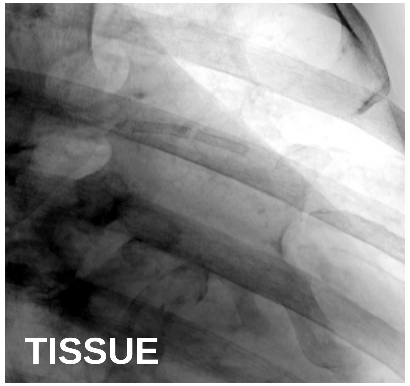
- Two **basis materials** (X and T) are selected → e.g., contrast agent and water/soft-tissue
- By knowing the linear mass attenuation coefficient of 2 basis materials at the LE and HE → Obtain two images mapping the distribution of the two basis materials



$$(\rho t)_X = \frac{\left[\frac{\mu^-}{\rho}\right]_T C^+ - \left[\frac{\mu^+}{\rho}\right]_T C^-}{K_0}$$

$$(\rho t)_T = \frac{\left[\frac{\mu^+}{\rho}\right]_X C^- - \left[\frac{\mu^-}{\rho}\right]_X C^+}{K_0}$$

$$K_0 = \left[\frac{\mu^-}{\rho}\right]_T \left[\frac{\mu^+}{\rho}\right]_X - \left[\frac{\mu^+}{\rho}\right]_T \left[\frac{\mu^-}{\rho}\right]_X .$$



Lehmann, L. A., et al. Medical physics 8.5 (1981): 659-667.

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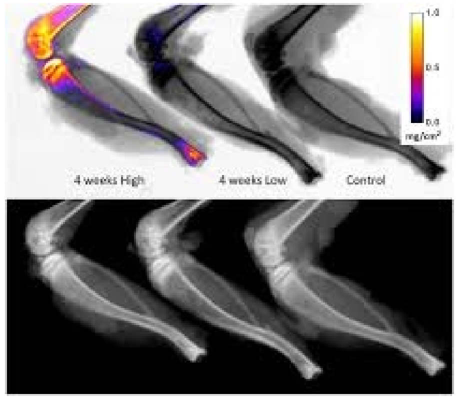
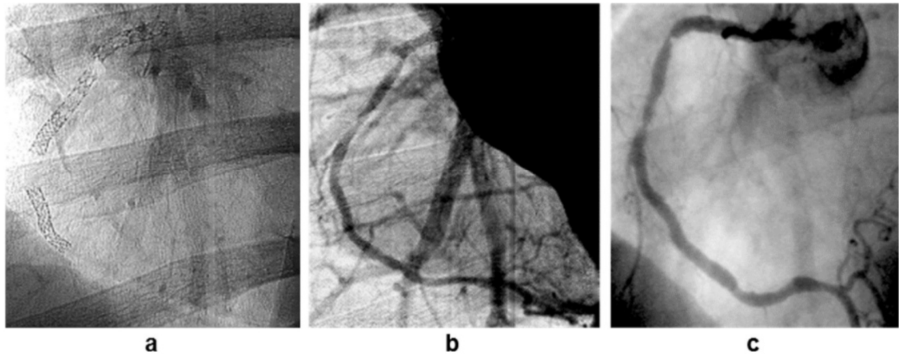
K-edge subtraction imaging @ synchrotron

- Several applications of KES to biomedical imaging with different contrast agents have been tested and demonstrated at various synchrotron facilities

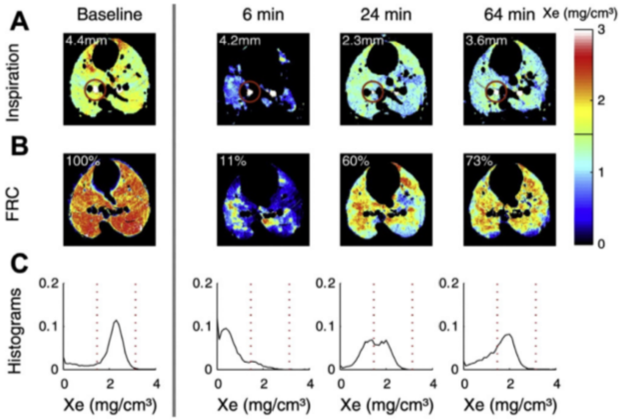
Dynamics of mineralization in growing bones
contrast agent: Ba/Sr



Coronary angiography, contrast agent: Iodine



Lung ventilation, contrast agent: Xe



Review paper

K-edge subtraction synchrotron X-ray imaging in bio-medical research

W. Thomlinson[a,b,*], H. Elleaume[c], L. Porra[a,d], P. Suortti[a]

[a] Department of Physics, University of Helsinki, Helsinki, Finland
[b] Department of Physics, University of Saskatchewan, Saskatoon, Canada
[c] Université Grenoble Alpes, EA-7442 Rayonnement Synchrotron et Recherche Médicale, F-38058 Grenoble cedex 9, France
[d] Helsinki University Hospital, Helsinki, Finland

Physica Medica 49 (2018) 58-76

the small airways of the lung and small vasculature.

The application of K-edge subtraction imaging in the field of bio-medical research has clearly benefitted from technological advances in X-ray sources, optics and detectors. The development of synchrotron sources with high flux, high detector resolution and continuous X-ray spectra covering a wide range of K-edge energies of relevant elements, has allowed the development of diverse applications and new imaging modalities. With the advent of new X-ray sources such as compact Compton sources, KES imaging research and potential clinical applications will continue to be important areas of biomedical research.

Funding

This work was supported by Helsinki University, the Tampere Tuberculosis Foundation, the INSERM and the Labex Primes' (ANR-11-

Prospects of KES imaging with an ICS source ?

ICS emission is different from synchrotron

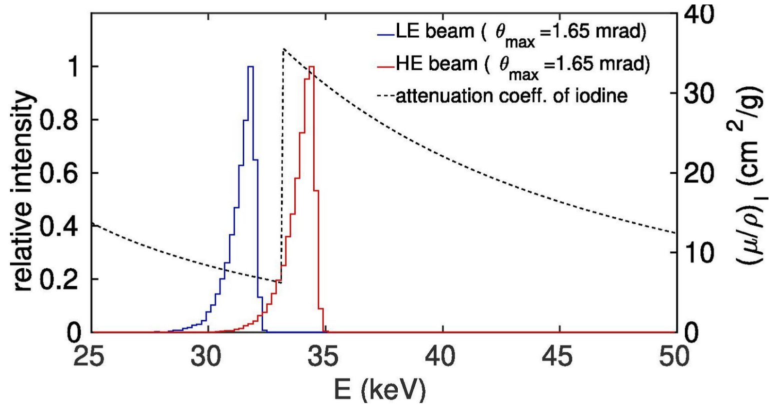
- **Hard X-rays with smaller electron energies (lower γ)**

  $\rightarrow$ compact accelerator

- **symmetrical and larger emission angle ($1/\gamma$)**

  $\rightarrow$ symmetrical 2d irradiation field $\rightarrow$ no scan required

- larger energy bandwidth (1-10%) related to emission angle
- Spatial distribution of energy and intensity
- Lower photon yield / brilliance



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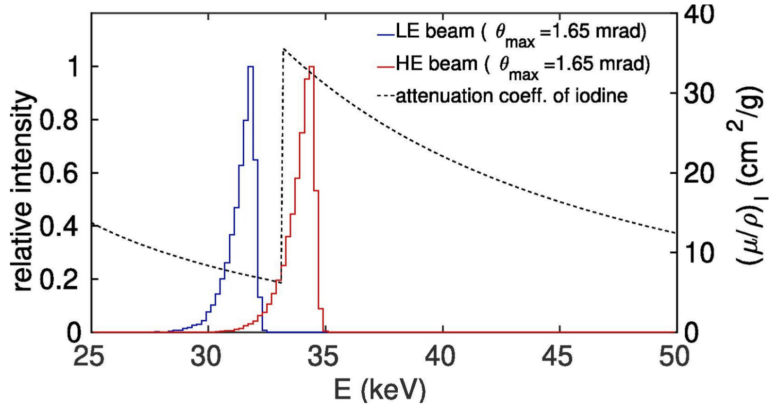

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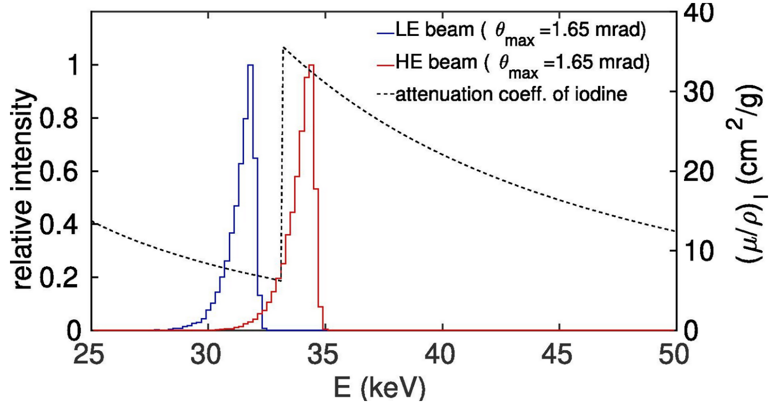

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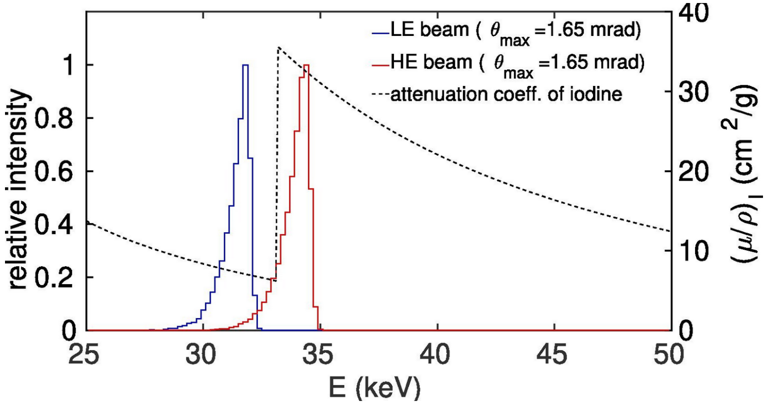

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Is a dual-energy configuration (fast switch between two energy levels) available?

MariX_rad project (INFN)

Italian collaboration: INFN divisions of Ferrara, Milano, Napoli and Bologna + San Raffaele Hospital (Milano) and Rizzoli Orthopaedic Institute (Bologna)

Started in 2019, in the context of the **proposal** for a new facility: MariX*, which included an **ICS source:**
BriXS with a layout enabling dual-energy emission

*(ww.marix.eu – MariX proposal CDR)

Physica Medica 77 (2020) 127–137

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/ejmp

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Original paper

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P. Cardarelli[a], A. Bacci[f], R. Calandrino[e], F. Canella[f,h], R. Castriconi[e], S. Cialdi[g,f], A. Del Vecchio[e], F. di Franco[d,c], I. Drebot[f], M. Gambaccini[a,b], D. Giannotti[f], A. Loria[e], G. Mettivier[d,c], G. Paternò[a], V. Petrillo[g,f,*], M. Rossetti Conti[f], P. Russo[d,c], A. Sarno[d,c], E. Suerra[g,f], A. Taibi[a,b], L. Serafini[f]

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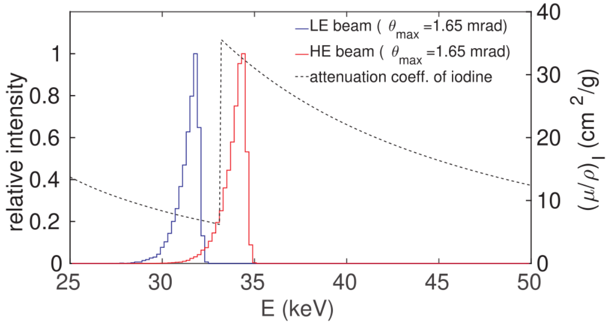

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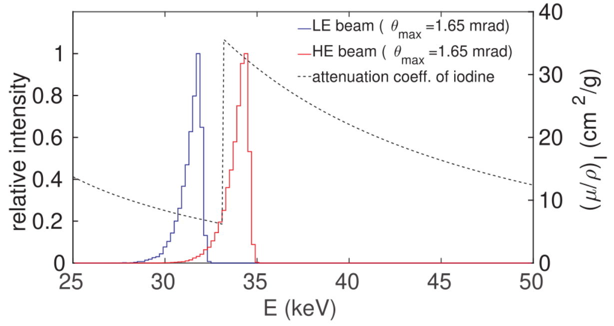

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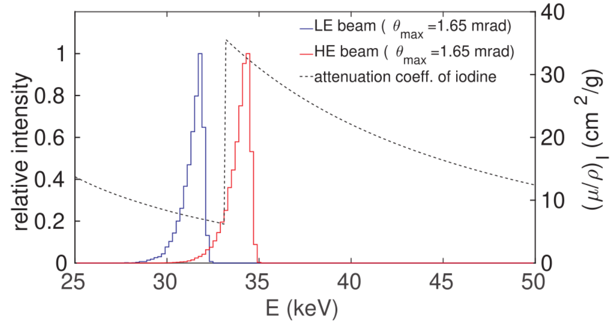

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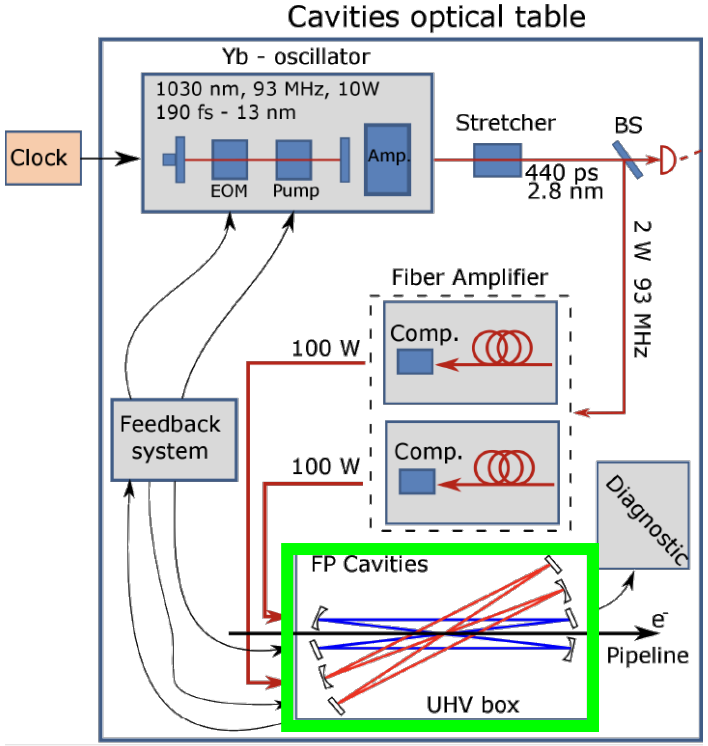
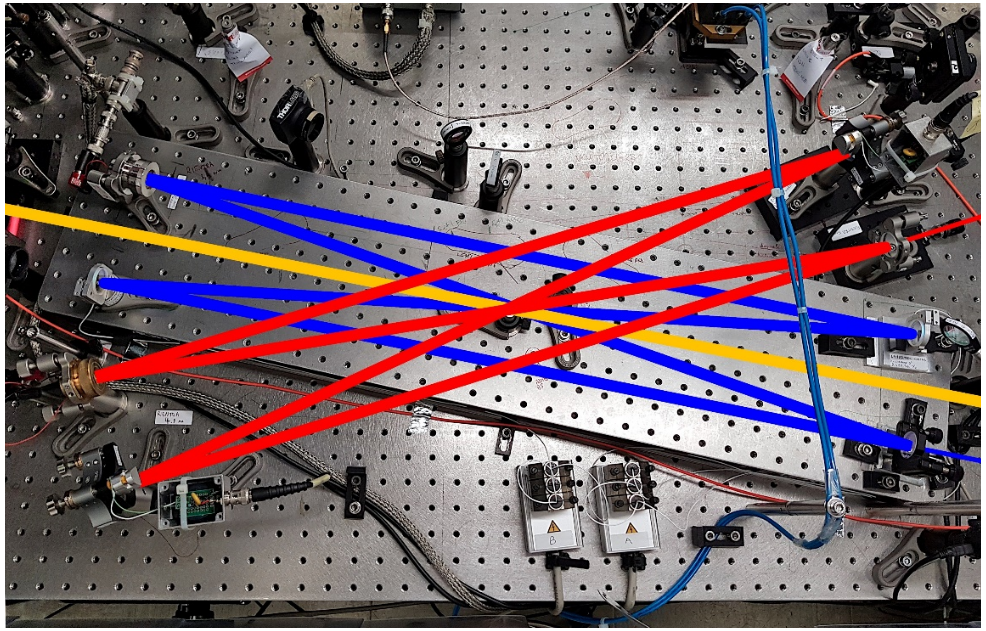
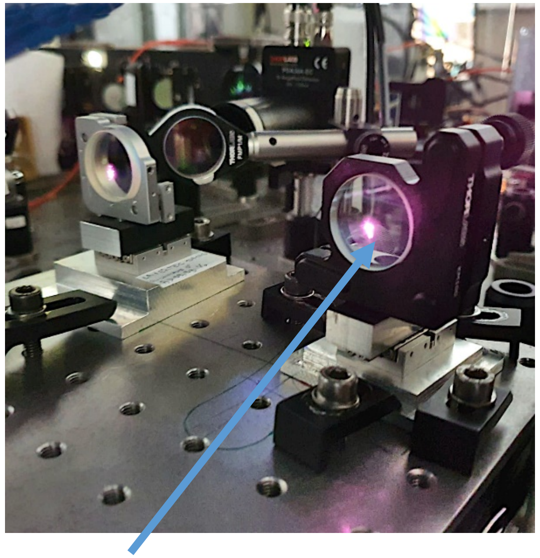
Optical cavities MariX_rad / BriXSino R&D

- **two X-ray energies** → **interaction** of the same electron beam with laser at **2 different angles,** stored in 2 optical cavities
- Prototype was realized and is being tested at Milano laboratories
- The preparation of a BriXS demonstrator (BriXSino) TDR were funded, currently TDR is in the final revision phase







Laser spot at 10 kW (goal 200 kW)

Courtesy of Simone Cialdi et al.

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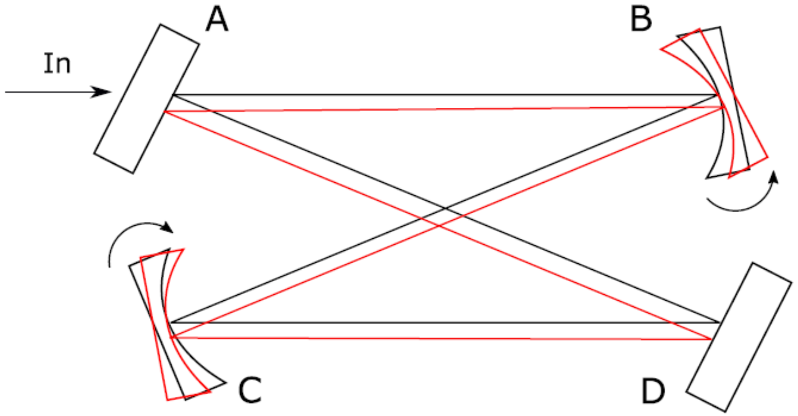
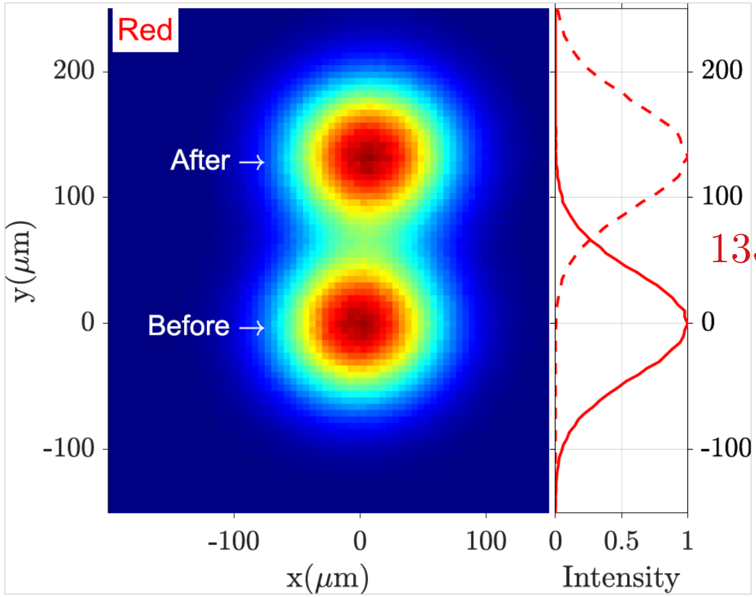
Optical cavities: shift focus

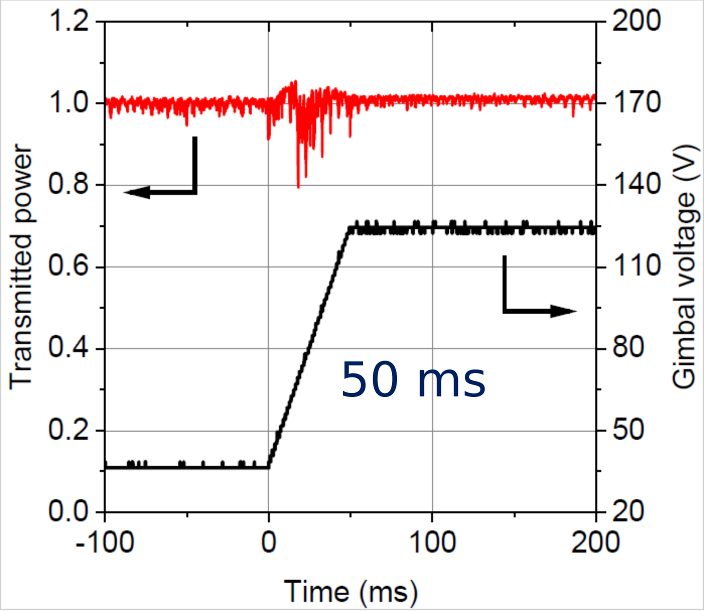
- A new technique to shift the focus of the cavities while they are stabilized, based on mirror rotation was developed and tested
  → It is possible to move the laser focus position on/off beam in ∼50 ms



Focus imaging before and after the shift



Transmitted power during the shift




Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

A new method for spatial mode shifting of stabilized optical cavities for the generation of dual-color X-rays

Edoardo Suerra [a,b,*], Dario Giannotti [b], Francesco Canella [c,b], Illya Drebot [b], Stefano Capra [a], Daniele Cipriani [a,b], Giovanni Mettivier [d,e], Gianluca Galzerano [f,c], Paolo Cardarelli [g], Simone Cialdi [a,b], Luca Serafini [b]

Courtesy of Simone Cialdi et al.

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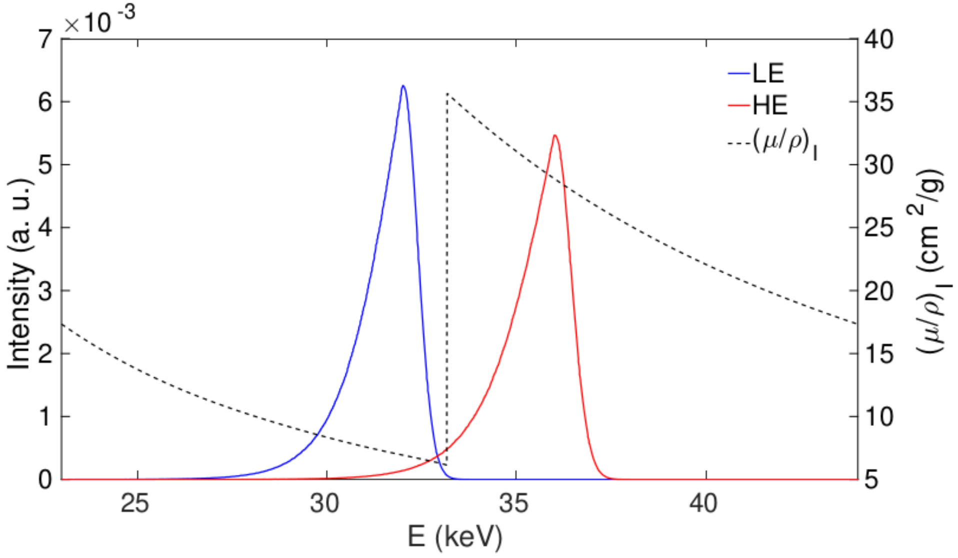
Energy distribution for KES imaging

To optimize the dual-energy KES reconstruction:

1) minimize the overlap of the two spectra

2) minimize the “leakage” of each spectrum across the K-edge

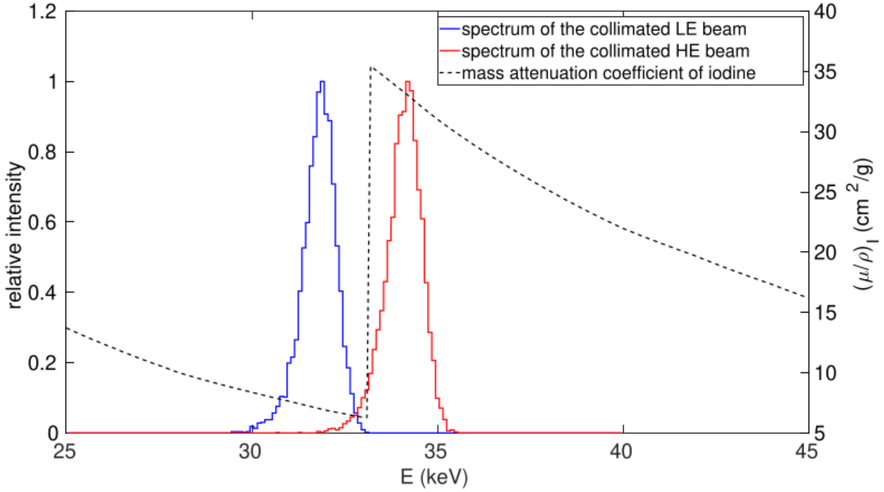


Limitations of narrow bandwidth with ICS

- By reducing the acceptance angle → very narrow bandwidth (comparable to synchrotron)

- Very small divergence → flux reduction and large distance from IP to cover the required field of view

- High flux is fundamental for demanding applications with high absorption
  → coronary angiography ~ 10^8 ph/mm^2 on a surface at least 10 cm of diameter



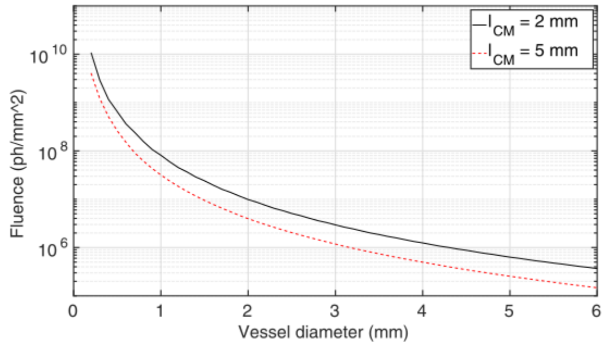
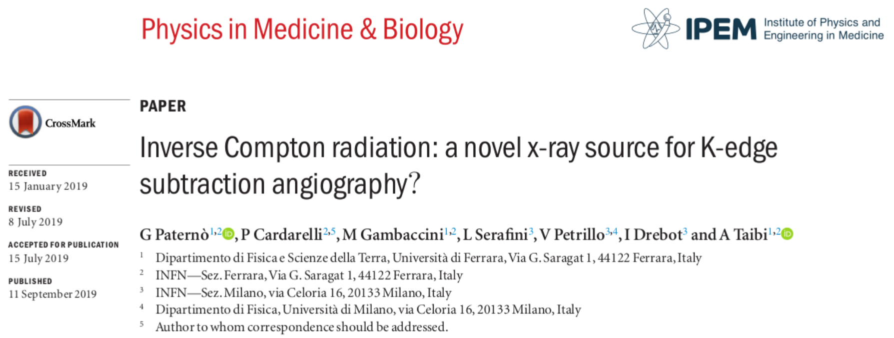


Figure 8. Photon fluence required to obtain a SNR of 5 as a function of the vessel diameter for an iodine concentration of 10 mg ml^{-1}. Two values of detail length l_{CM} were considered.



Physics in Medicine & Biology
IPEM Institute of Physics and Engineering in Medicine
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Inverse Compton radiation: a novel x-ray source for K-edge subtraction angiography?

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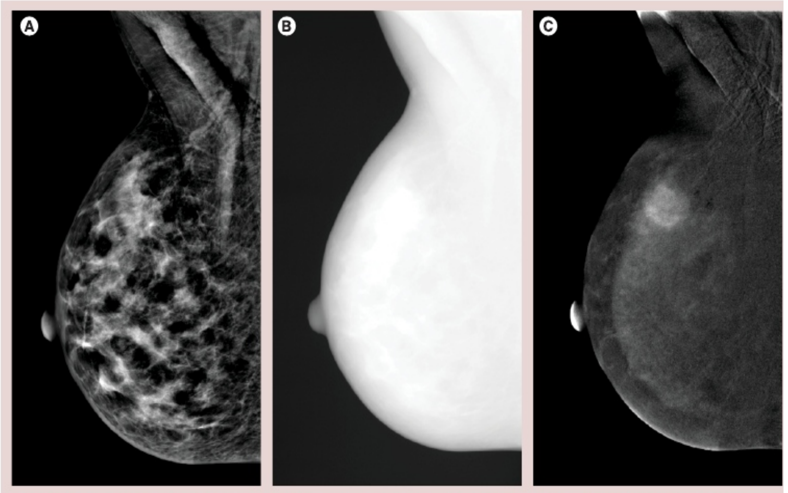
5 Author to whom correspondence should be addressed.

KES imaging with ICS emission

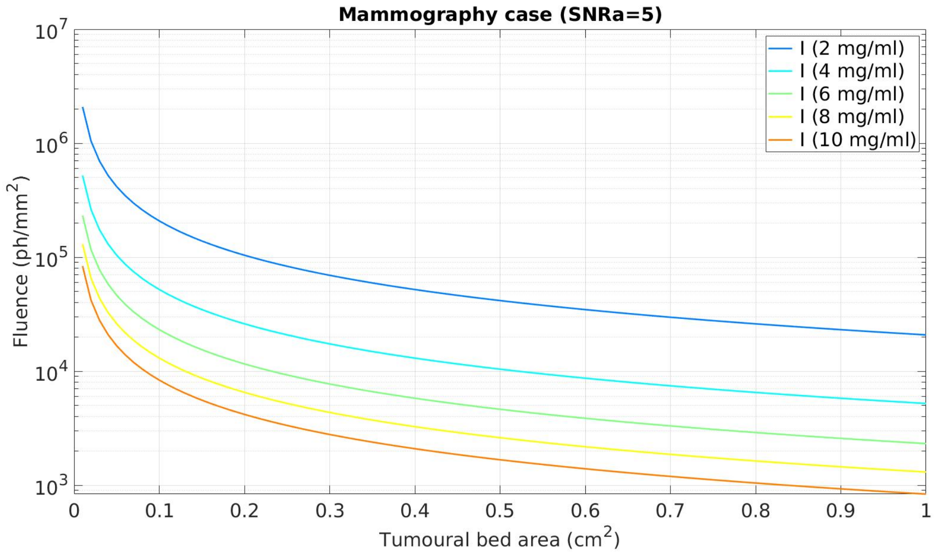
Also, several other application, which are not so demanding in terms of absorption/flux, would benefit from a relaxation of bandwidth constraints

In particular if a wide field of view is required (radiology ~tens of cm) $\rightarrow$ reduce distance / exposure time

Contrast enhanced dual-energy mammography (CEDEM)

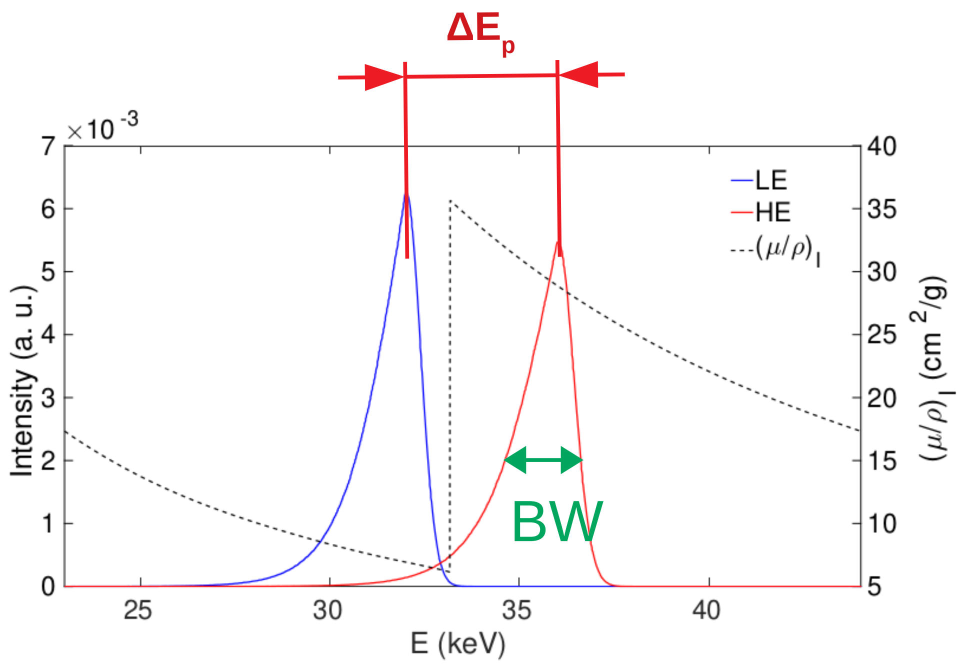


M. B.I. Lobbes, J Cancer 2015; 6(2):144-150.



Energy distribution for ideal reconstruction

How much can we "play" with peak energy separation and bandwidth



How this affect the reconstruction of contrast and tissue image?

MEDICAL PHYSICS

The International Journal of Medical Physics Research and Practice

Radiation imaging physics

Effect of x-ray energy dispersion in digital subtraction imaging at the iodine K-edge—A Monte Carlo study

F. Prino, C. Ceballos, A. Cabal, A. Sarnelli, M. Gambaccini, L. Ramello

First published: 11 December 2007 | https://doi.org/10.1118/1.2815360 | Citations: 4

Physics in Medicine & Biology

Quantitative analysis of the effect of energy separation in k-edge digital subtraction imaging

A Sarnelli[1], A Taibi[2], P Baldelli[2], M Gambaccini[2] and A Bravin[3]

Published 8 May 2007 • 2007 IOP Publishing Ltd

Physics in Medicine & Biology, Volume 52, Number 11

Citation A Sarnelli *et al* 2007 *Phys. Med. Biol.* **52** 3015

Physics in Medicine & Biology

K-edge digital subtraction imaging based on a dichromatic and compact x-ray source

A Sarnelli[1], A Taibi[1], A Tuffanelli[1], G Baldazzi[2], D Bollini[2], A E Cabal Rodriguez[3], M Gombia[2], F Prino[4], L Ramello[4], E Tomassi[4] + Show full author list

Published 5 July 2004 • 2004 IOP Publishing Ltd

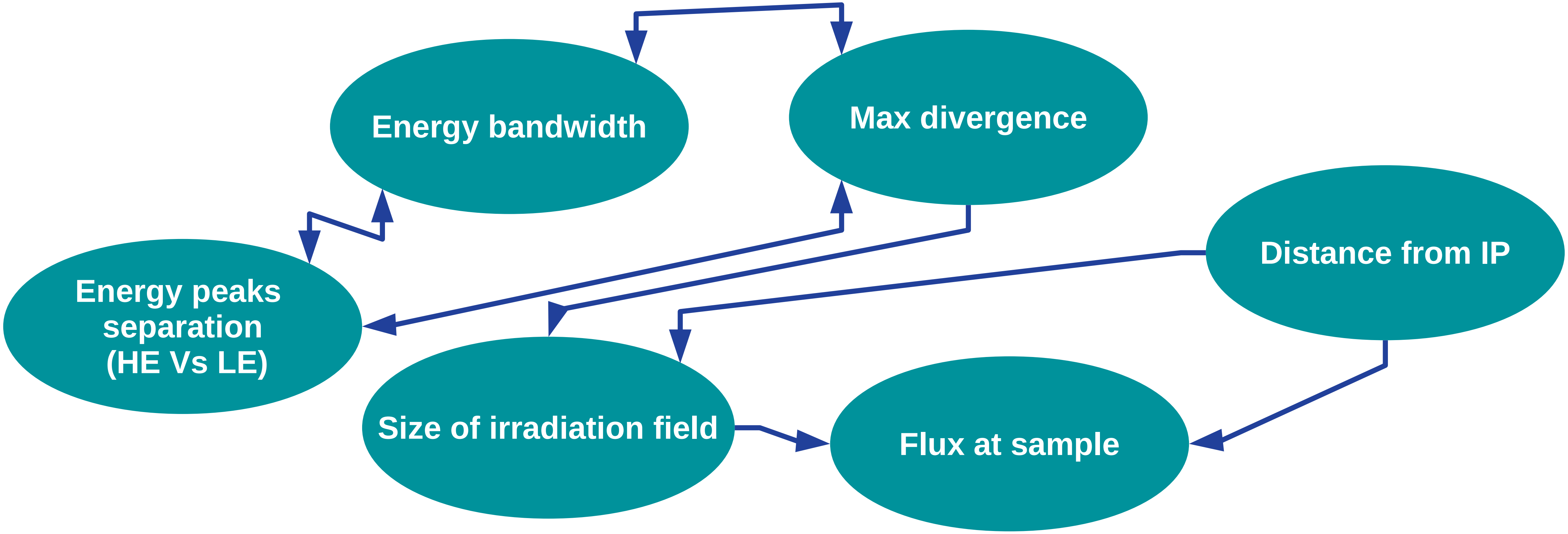
Physics in Medicine & Biology, Volume 49, Number 14

Citation A Sarnelli *et al* 2004 *Phys. Med. Biol.* **49** 3291

INFN

Not an easy task

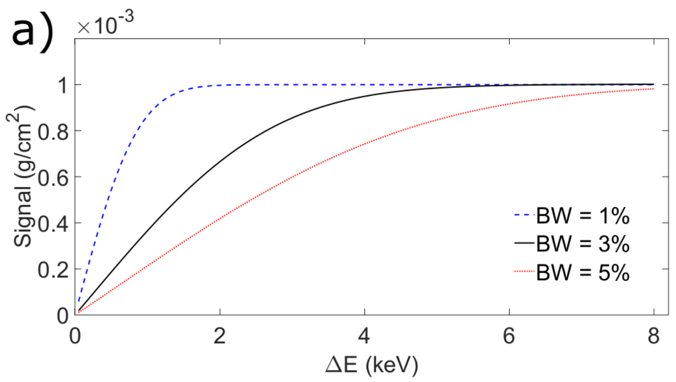
All the parameters at play are interconnected and difficult to disentangle

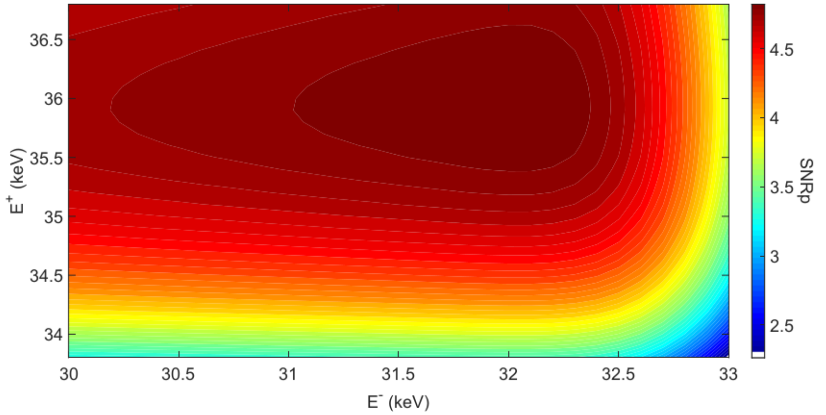


The process is strongly dependent on the foreseen imaging task, there **is not a good-for-all recipe**

Study of the performance

Analytical studies for specific imaging tasks (mammo and coronary angiography), by simulating known phantom compositions and absorption images → monitoring the reconstruction performance





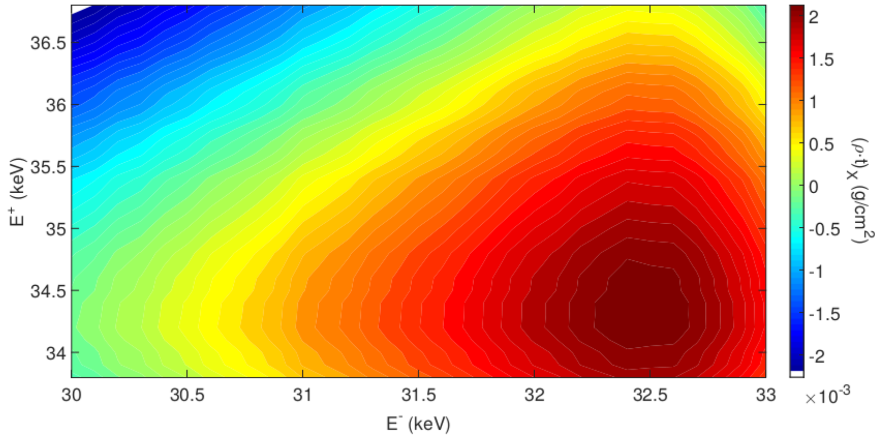


Figure 7. Coronary angiography case: detail mass thickness reconstructed, as a function of the peak values of the two ICS spectra bracketing the iodine K-edge. The spectra featured an energy bandwidth of 3% RMS. A detail with a thickness of 5 mm and a contrast medium concentration of 10 mg mL^{-1}, embedded in a bulk composed of 19 cm of soft tissue and 1 cm of bone, was considered.

Article

Dual-Energy X-ray Medical Imaging with Inverse Compton Sources: A Simulation Study

Gianfranco Games Paternò [1], Paolo Cardarelli [2,*], Mauro Gambaccini [1] and Angelo Taibi [1]

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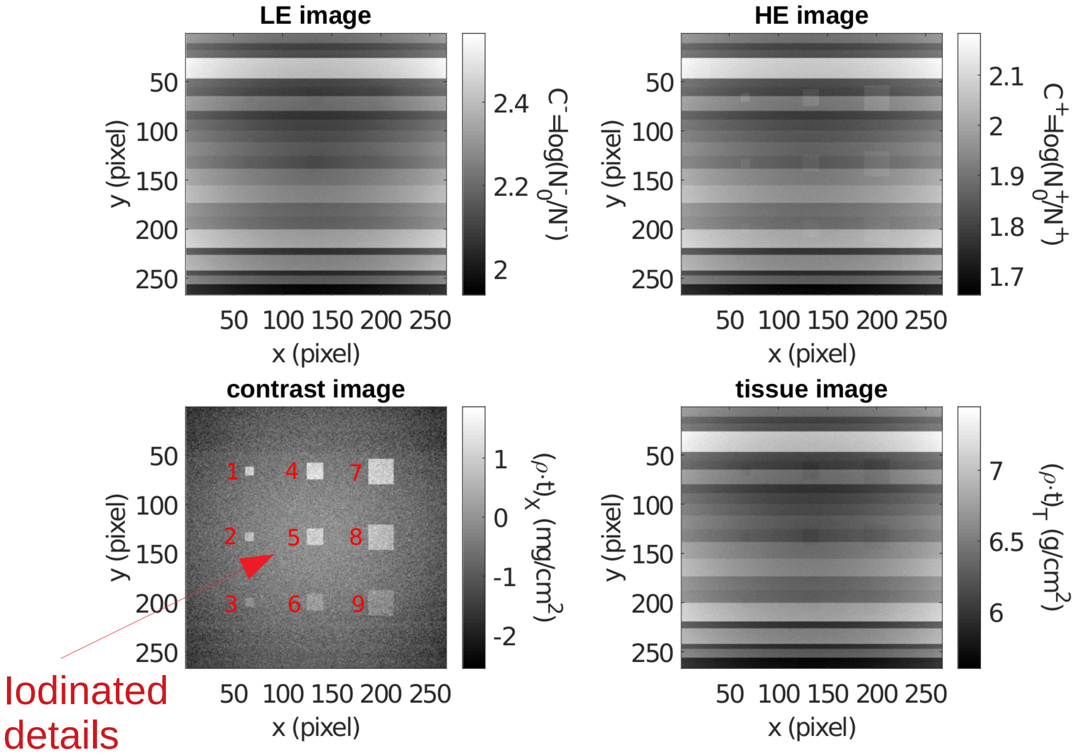
Crystals, 10(9), 834. (2020)

Simulation of the performance for specific imaging tasks

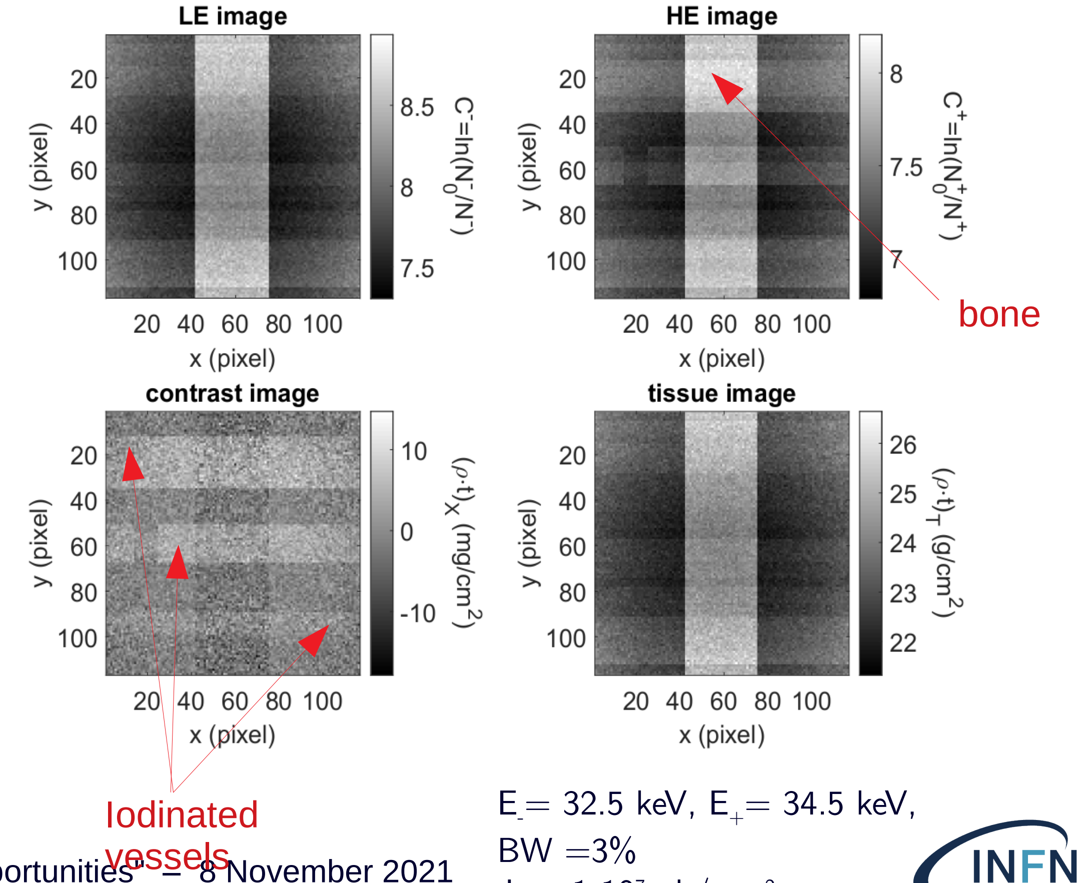
SNR studies on **simulated phantom images** versus X-ray beams parameters

Simulated mammography phantom



$E_- = 32$ keV $E_+ = 36$ keV
BW $= 3\%$
$\Phi = 5 \ 10^6$ ph/mm^2

Simulated angiography phantom



$E_- = 32.5$ keV, $E_+ = 34.5$ keV,
BW $= 3\%$
$\Phi = 1 \ 10^7$ ph/mm^2

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Summary

- Previous experimental results at synchrotron and ICS sources simulations **showed the potential of KES techniques**
- Major limitations of ICS implementation are related to applications which demand high-flux / broad irradiation field
- Demanding imaging task (coronary angiography) → higher energies K-edge (gadolinium) accessible by ICS sources
- **Many tasks** less demanding

  absorption → mammography,

  size → pre-clinical,

  size / exposure time → ex-vivo samples (biology/ tissue reconstruction engineering),

  are **accessible with X-ray beam parameters of current operating/foreseen machines** (dual-energy configuration required)

Preliminary experimental testing of KES with ICS sources

No experimental testing yet, due to the lack of operating facility with an available dual-energy configuration.

Nonetheless..

Nuclear Instruments and Methods in Physics Research B 331 (2014) 257–260

Contents lists available at ScienceDirect

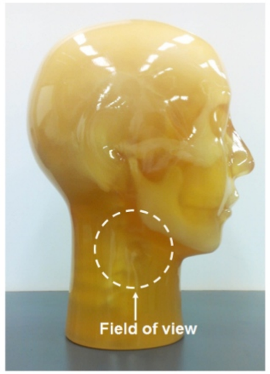
Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

K-edge imaging with quasi-monochromatic LCS X-ray source on the basis of S-band compact electron linac

R. Kuroda *, Y. Taira, M. Yasumoto, H. Toyokawa, K. Yamada

National Institute of Advanced Industrial Science and Technology ...



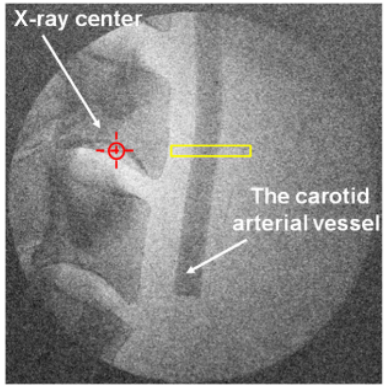


Fig. 5. X-ray image of the human phantom's neck.

Physica Medica 79 (2020) 137–144

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Review paper

Spectroscopic imaging at compact inverse Compton X-ray sources

Stephanie Kulpe [a,*], Martin Dierolf [a], Benedikt Günther [a], Johannes Brantl [a], Madleen Busse [a], Klaus Achterhold [a], Franz Pfeiffer [a,b], Daniela Pfeiffer [b]

[a] Chair of Biomedical Physics, Department of Physics and Munich School of BioEngineering, Technical University of Munich, James-Franck-Str. 1, 85748 Garching, Germany

[b] Department of Diagnostic and Interventional Radiology, Munich School of Medicine and Klinikum rechts der Isar, Ismaniger Str. 22, 81675 Munich, Germany

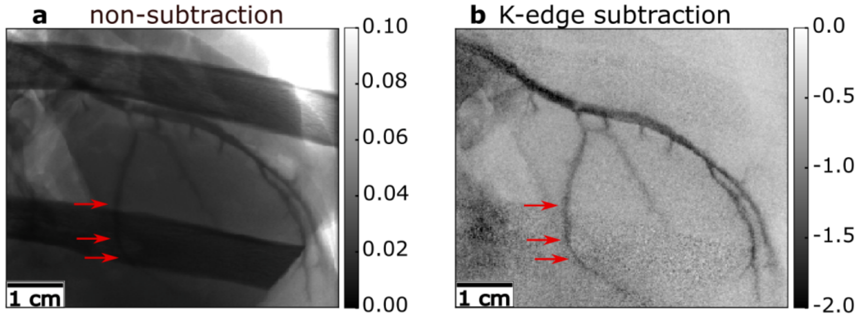


Fig. 3. Projection images of an excised porcine heart embedded in a rib cage. **a** Monochromatic X-ray image of coronary arteries overlaid by bones of rib cage. Especially the visibility of smaller vessels is compromised; **b** KES image of the same sample. KES levels out differences in absorption and separates the contrast agent from the background structures. The visibility of the blood vessels is increased, especially for those previously overlaid by bone structures. The gray scale for the non-subtraction image shows the relative intensity/transmission of the X-ray beam, while the gray values in the KES image show the negative logarithmic differences in the absorption. Figure adapted from [50].

Conclusions

- ICS sources can brigde the gap between table-top sources and synchrotron facilities
  - implementation of advanced imaging techniques for specific imaging tasks
- Dual-energy emission technological solutions are available and very promising
- Preliminary experimental results and simulations showed the potential of KES techniques