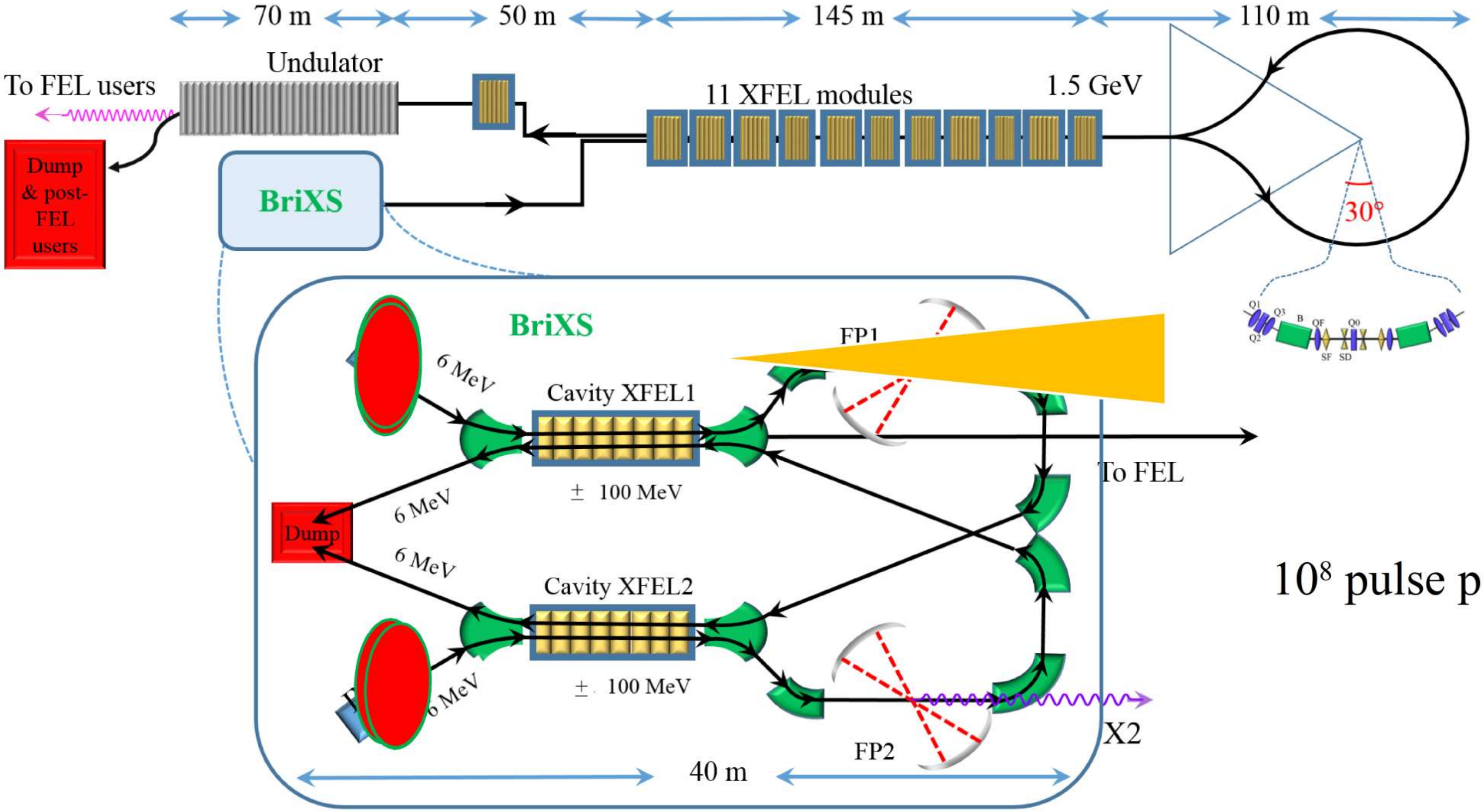
Report BriXS Compton Source User Meeting

Paolo Cardarelli Università Ferrara – INFN-FE

BriXS at MariX

Multi-disciplinary Advanced Infra-structure for Research with X-rays
Macchina Analitica per Ricerca Inter-disciplinare con raggi X



10^8 pulse per second

Marix Compton source - applications

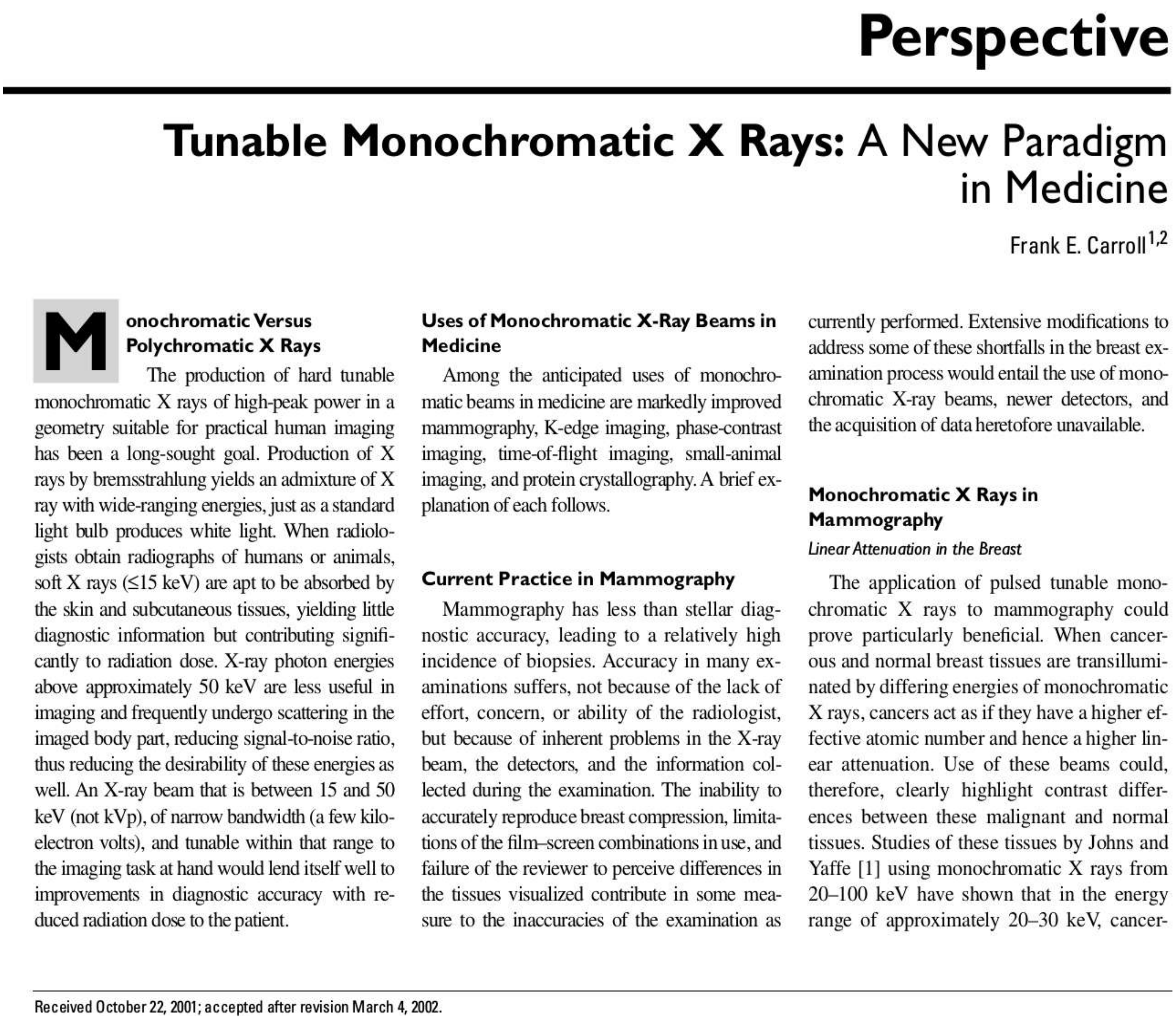
- **MEDICAL**
  - Monochromatic radiography
  - Dual-energy, k-edge imaging and spectral imaging
  - Phase contrast imaging
  - Radiotherapy (Mettivier)
- **IMAGING/NDT interdisciplinary**
  - Elemental / composition mapping
  - Microtomography
  - k-edge Microtomography

↔

Source parameters and beamline layout

Medical imaging applications

- **Monochromatic** radiography → dose reduction
- **Tunable energy monochromatic** source → advanced imaging techniques (dual energy etc)
- **Coherent** source → interference effects → phase-contrast imaging



Perspective

Tunable Monochromatic X Rays: A New Paradigm in Medicine

Frank E. Carroll[1,2]

Monochromatic Versus Polychromatic X Rays

The production of hard tunable monochromatic X rays of high-peak power in a geometry suitable for practical human imaging has been a long-sought goal. Production of X rays by bremsstrahlung yields an admixture of X ray with wide-ranging energies, just as a standard light bulb produces white light. When radiologists obtain radiographs of humans or animals, soft X rays (≤15 keV) are apt to be absorbed by the skin and subcutaneous tissues, yielding little diagnostic information but contributing significantly to radiation dose. X-ray photon energies above approximately 50 keV are less useful in imaging and frequently undergo scattering in the imaged body part, reducing signal-to-noise ratio, thus reducing the desirability of these energies as well. An X-ray beam that is between 15 and 50 keV (not kVp), of narrow bandwidth (a few kilo-electron volts), and tunable within that range to the imaging task at hand would lend itself well to improvements in diagnostic accuracy with reduced radiation dose to the patient.

Uses of Monochromatic X-Ray Beams in Medicine

Among the anticipated uses of monochromatic beams in medicine are markedly improved mammography, K-edge imaging, phase-contrast imaging, time-of-flight imaging, small-animal imaging, and protein crystallography. A brief explanation of each follows.

Current Practice in Mammography

Mammography has less than stellar diagnostic accuracy, leading to a relatively high incidence of biopsies. Accuracy in many examinations suffers, not because of the lack of effort, concern, or ability of the radiologist, but because of inherent problems in the X-ray beam, the detectors, and the information collected during the examination. The inability to accurately reproduce breast compression, limitations of the film–screen combinations in use, and failure of the reviewer to perceive differences in the tissues visualized contribute in some measure to the inaccuracies of the examination as currently performed. Extensive modifications to address some of these shortfalls in the breast examination process would entail the use of monochromatic X-ray beams, newer detectors, and the acquisition of data heretofore unavailable.

Monochromatic X Rays in Mammography

Linear Attenuation in the Breast

The application of pulsed tunable monochromatic X rays to mammography could prove particularly beneficial. When cancerous and normal breast tissues are transilluminated by differing energies of monochromatic X rays, cancers act as if they have a higher effective atomic number and hence a higher linear attenuation. Use of these beams could, therefore, clearly highlight contrast differences between these malignant and normal tissues. Studies of these tissues by Johns and Yaffe [1] using monochromatic X rays from 20–100 keV have shown that in the energy range of approximately 20–30 keV, cancer-

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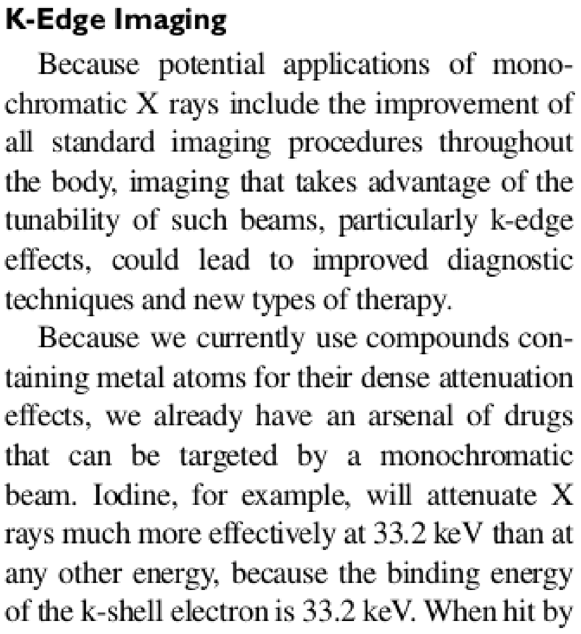
Received October 22, 2001; accepted after revision March 4, 2002.

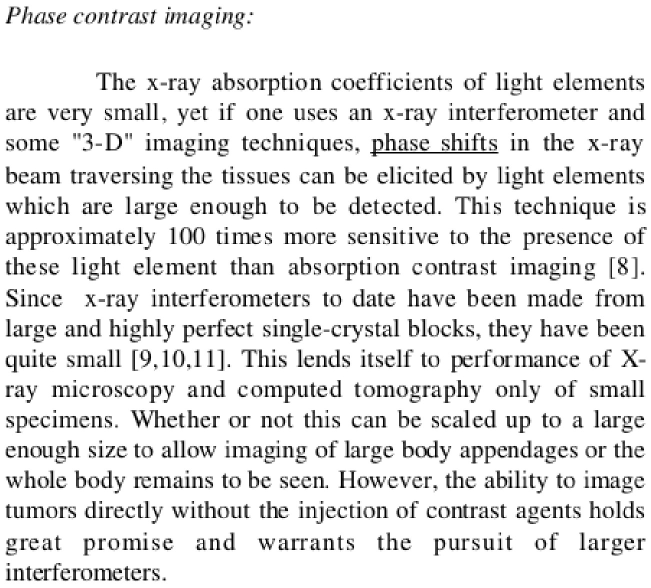
Monochromatic applications in medical physics



K-Edge Imaging

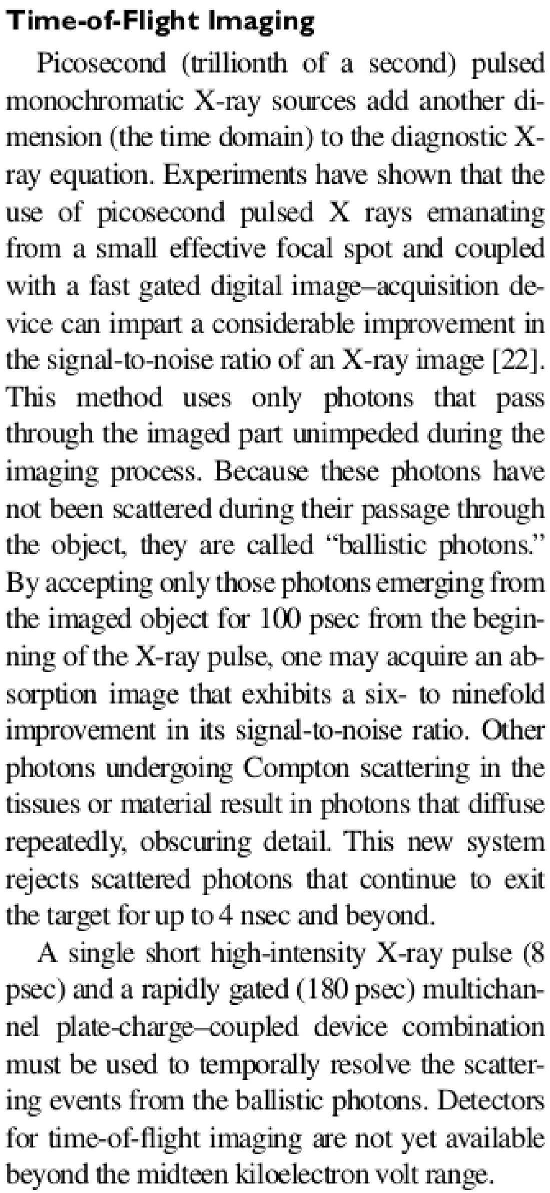
Because potential applications of monochromatic X rays include the improvement of all standard imaging procedures throughout the body, imaging that takes advantage of the tunability of such beams, particularly k-edge effects, could lead to improved diagnostic techniques and new types of therapy.

Because we currently use compounds containing metal atoms for their dense attenuation effects, we already have an arsenal of drugs that can be targeted by a monochromatic beam. Iodine, for example, will attenuate X rays much more effectively at 33.2 keV than at any other energy, because the binding energy of the k-shell electron is 33.2 keV. When hit by



Phase contrast imaging:

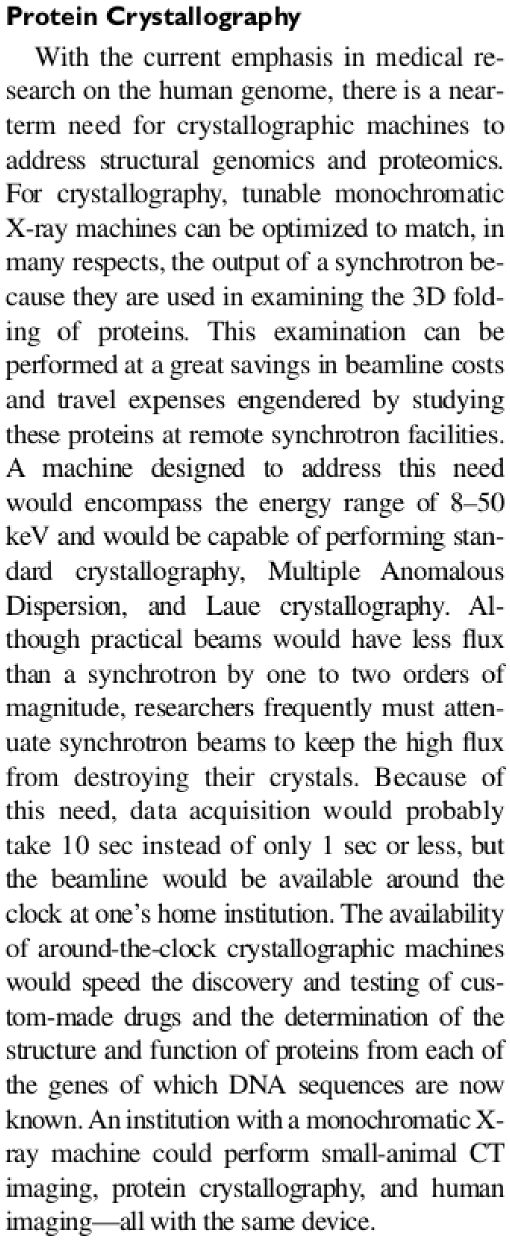
The x-ray absorption coefficients of light elements are very small, yet if one uses an x-ray interferometer and some "3-D" imaging techniques, phase shifts in the x-ray beam traversing the tissues can be elicited by light elements which are large enough to be detected. This technique is approximately 100 times more sensitive to the presence of these light element than absorption contrast imaging [8]. Since x-ray interferometers to date have been made from large and highly perfect single-crystal blocks, they have been quite small [9,10,11]. This lends itself to performance of X-ray microscopy and computed tomography only of small specimens. Whether or not this can be scaled up to a large enough size to allow imaging of large body appendages or the whole body remains to be seen. However, the ability to image tumors directly without the injection of contrast agents holds great promise and warrants the pursuit of larger interferometers.



Time-of-Flight Imaging

Picosecond (trillionth of a second) pulsed monochromatic X-ray sources add another dimension (the time domain) to the diagnostic X-ray equation. Experiments have shown that the use of picosecond pulsed X rays emanating from a small effective focal spot and coupled with a fast gated digital image–acquisition device can impart a considerable improvement in the signal-to-noise ratio of an X-ray image [22]. This method uses only photons that pass through the imaged part unimpeded during the imaging process. Because these photons have not been scattered during their passage through the object, they are called "ballistic photons." By accepting only those photons emerging from the imaged object for 100 psec from the beginning of the X-ray pulse, one may acquire an absorption image that exhibits a six- to ninefold improvement in its signal-to-noise ratio. Other photons undergoing Compton scattering in the tissues or material result in photons that diffuse repeatedly, obscuring detail. This new system rejects scattered photons that continue to exit the target for up to 4 nsec and beyond.

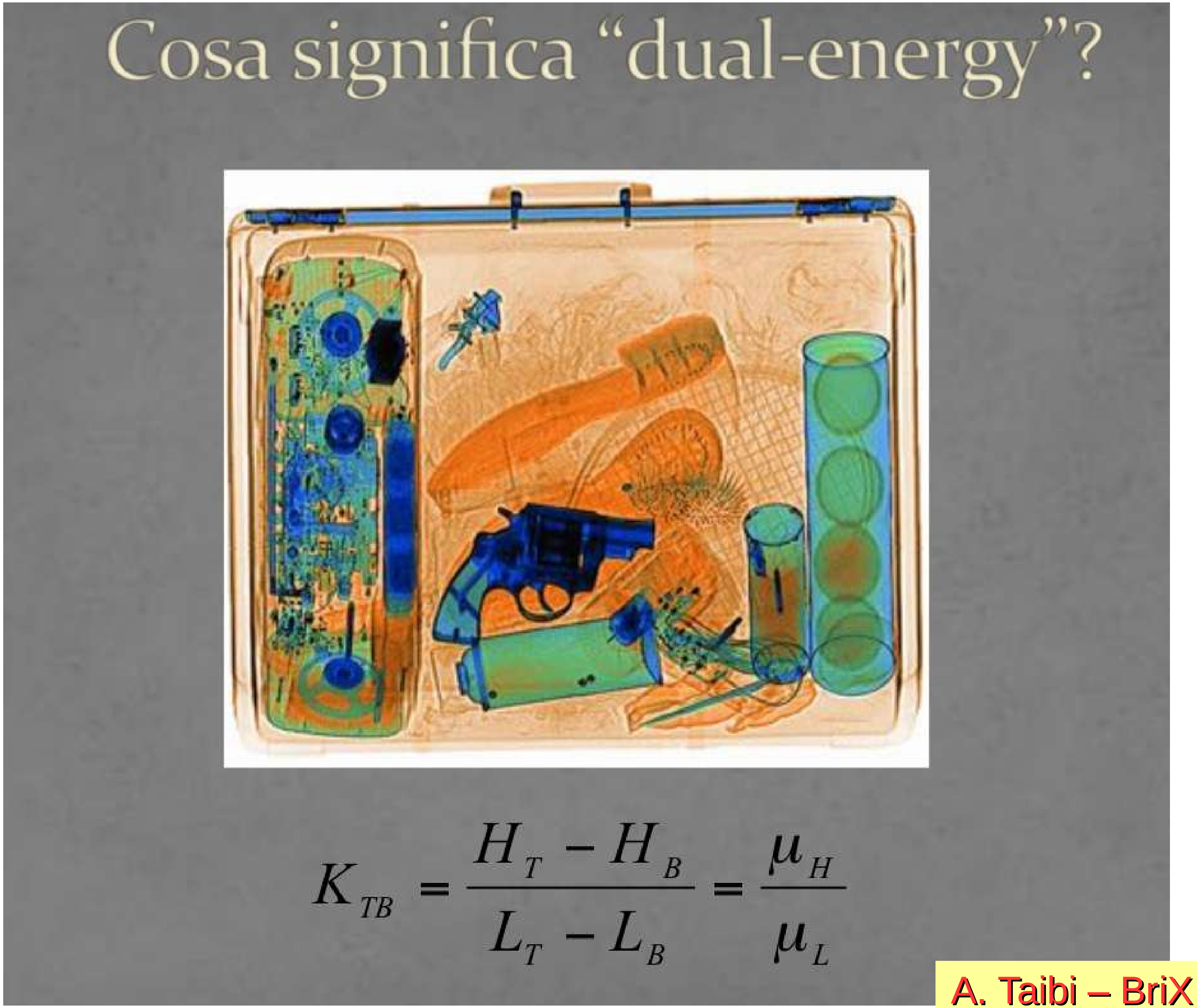
A single short high-intensity X-ray pulse (8 psec) and a rapidly gated (180 psec) multichannel plate-charge–coupled device combination must be used to temporally resolve the scattering events from the ballistic photons. Detectors for time-of-flight imaging are not yet available beyond the midteen kiloelectron volt range.



Protein Crystallography

With the current emphasis in medical research on the human genome, there is a near-term need for crystallographic machines to address structural genomics and proteomics. For crystallography, tunable monochromatic X-ray machines can be optimized to match, in many respects, the output of a synchrotron because they are used in examining the 3D folding of proteins. This examination can be performed at a great savings in beamline costs and travel expenses engendered by studying these proteins at remote synchrotron facilities. A machine designed to address this need would encompass the energy range of 8–50 keV and would be capable of performing standard crystallography, Multiple Anomalous Dispersion, and Laue crystallography. Although practical beams would have less flux than a synchrotron by one to two orders of magnitude, researchers frequently must attenuate synchrotron beams to keep the high flux from destroying their crystals. Because of this need, data acquisition would probably take 10 sec instead of only 1 sec or less, but the beamline would be available around the clock at one's home institution. The availability of around-the-clock crystallographic machines would speed the discovery and testing of custom-made drugs and the determination of the structure and function of proteins from each of the genes of which DNA sequences are now known. An institution with a monochromatic X-ray machine could perform small-animal CT imaging, protein crystallography, and human imaging—all with the same device.

Dual energy

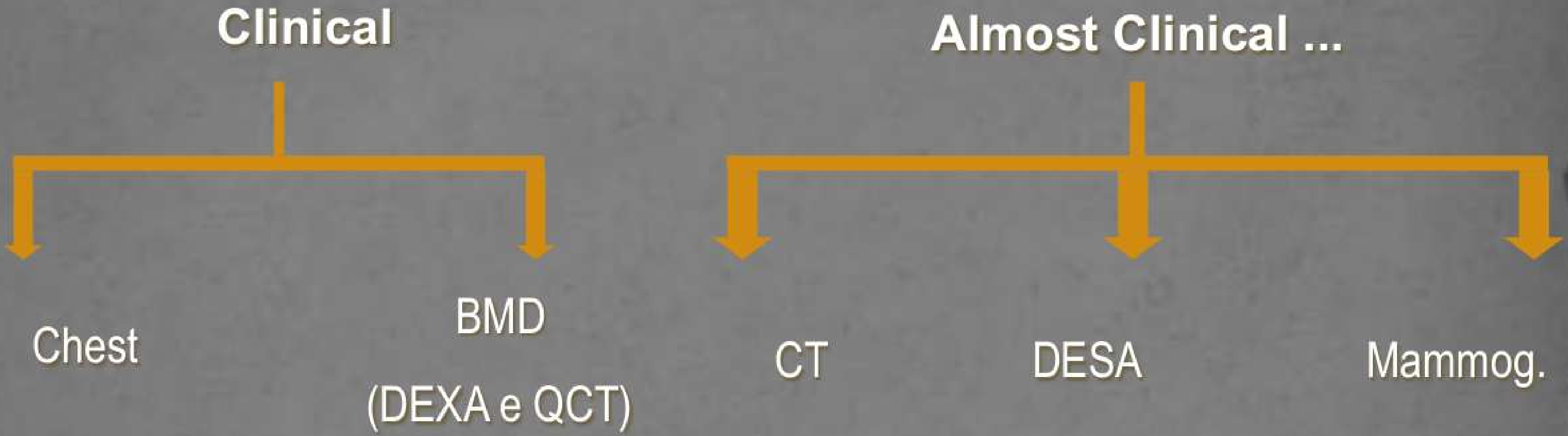


Cosa significa "dual-energy"?

$$K_{TB} = \frac{H_T - H_B}{L_T - L_B} = \frac{\mu_H}{\mu_L}$$

A. Taibi – BriX user meeting

Current applications of Dual-energy

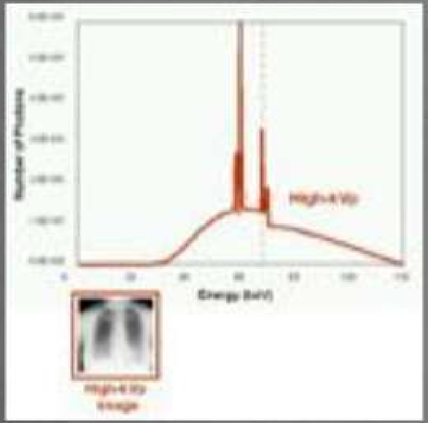


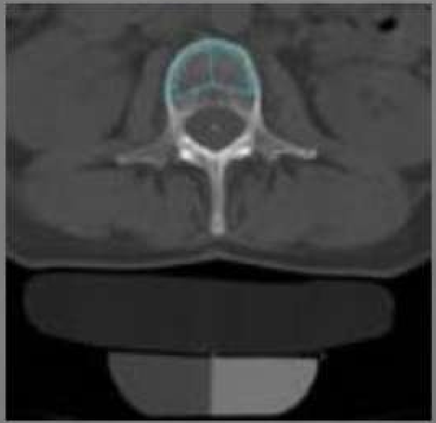
Clinical

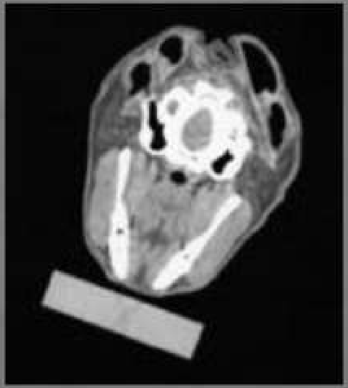
- Chest
- BMD (DEXA e QCT)

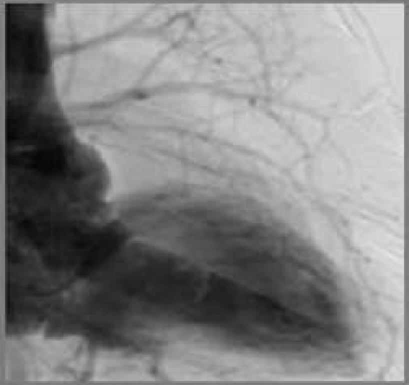
Almost Clinical ...

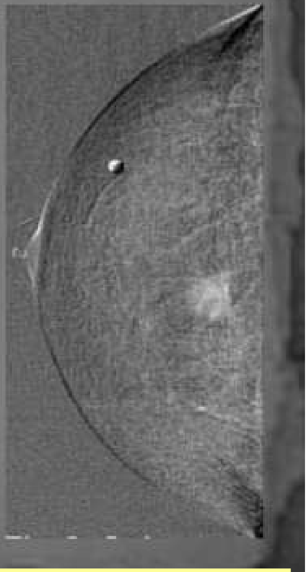
- CT
- DESA
- Mammog.



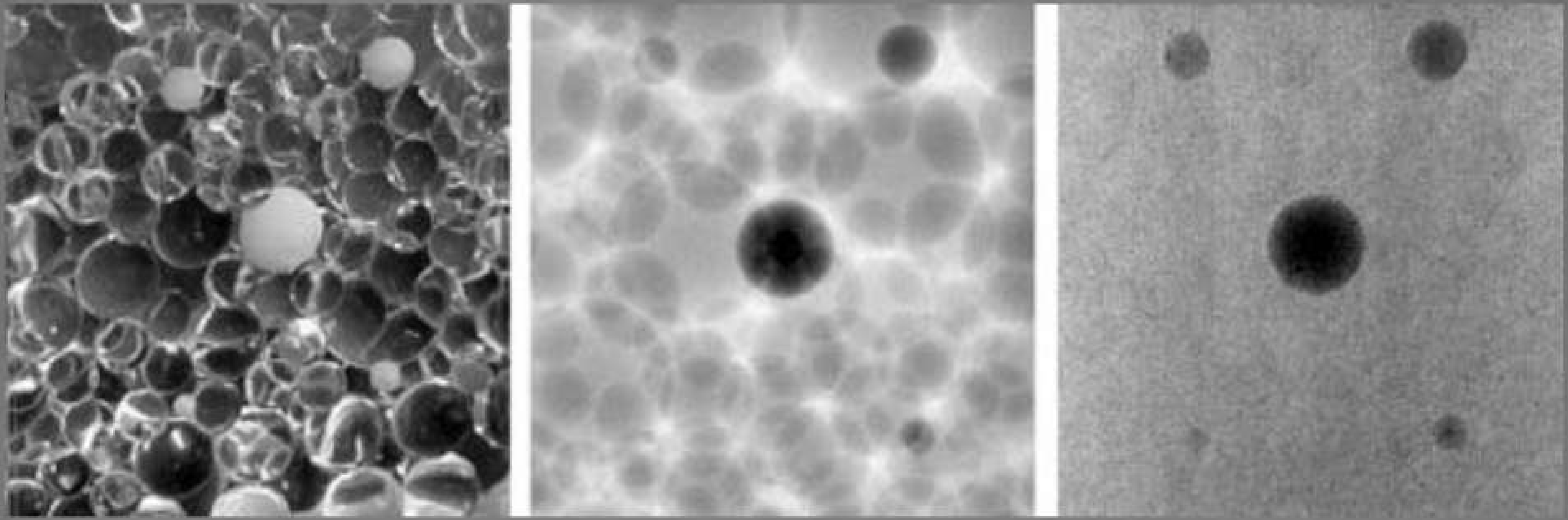






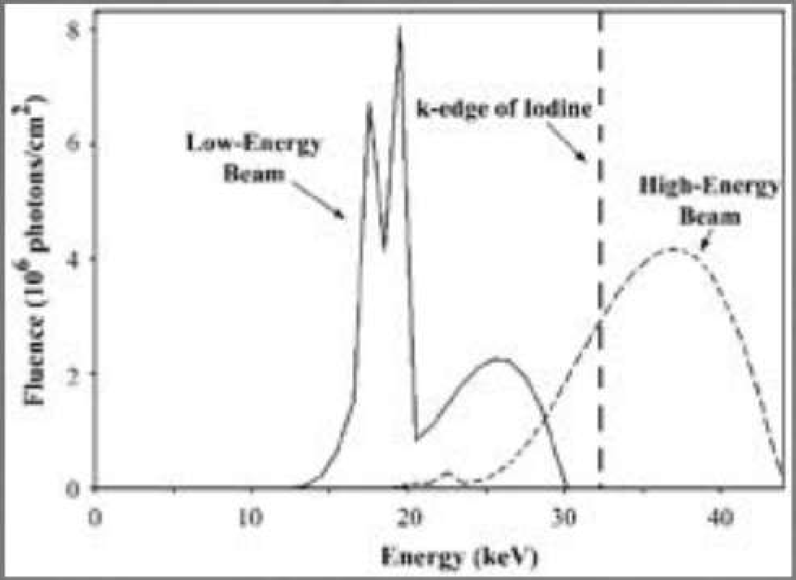


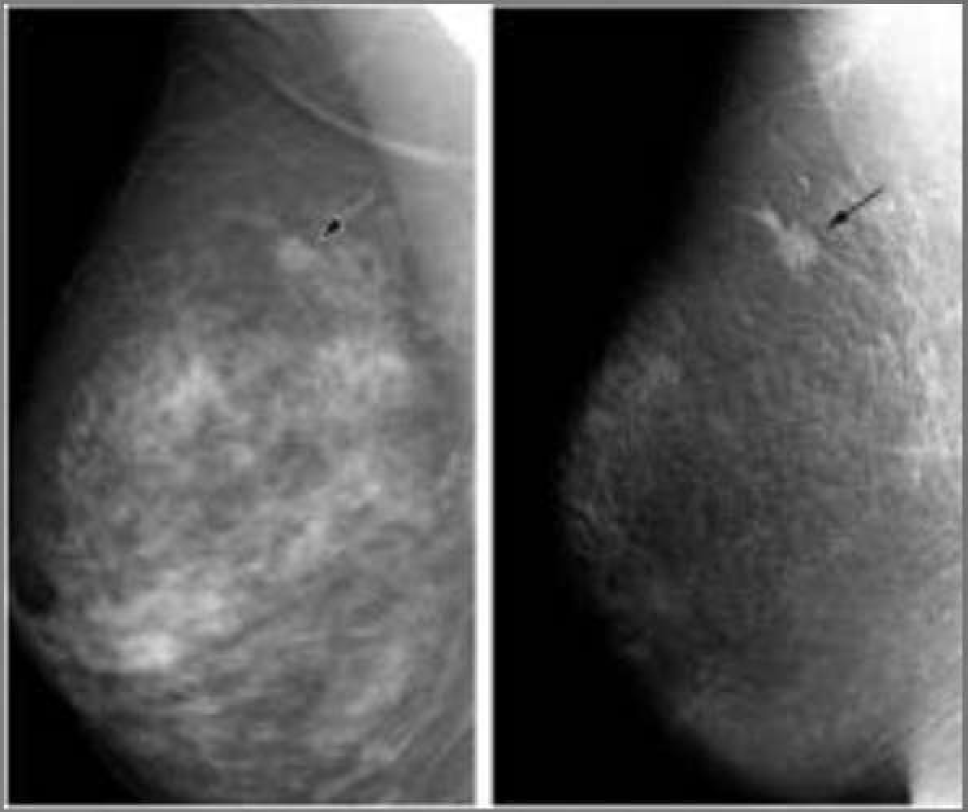
Dual-Energy in Mammography?



A Taibi *et al*, Phys Med Biol 48, 2003

Dual-energy CEDM



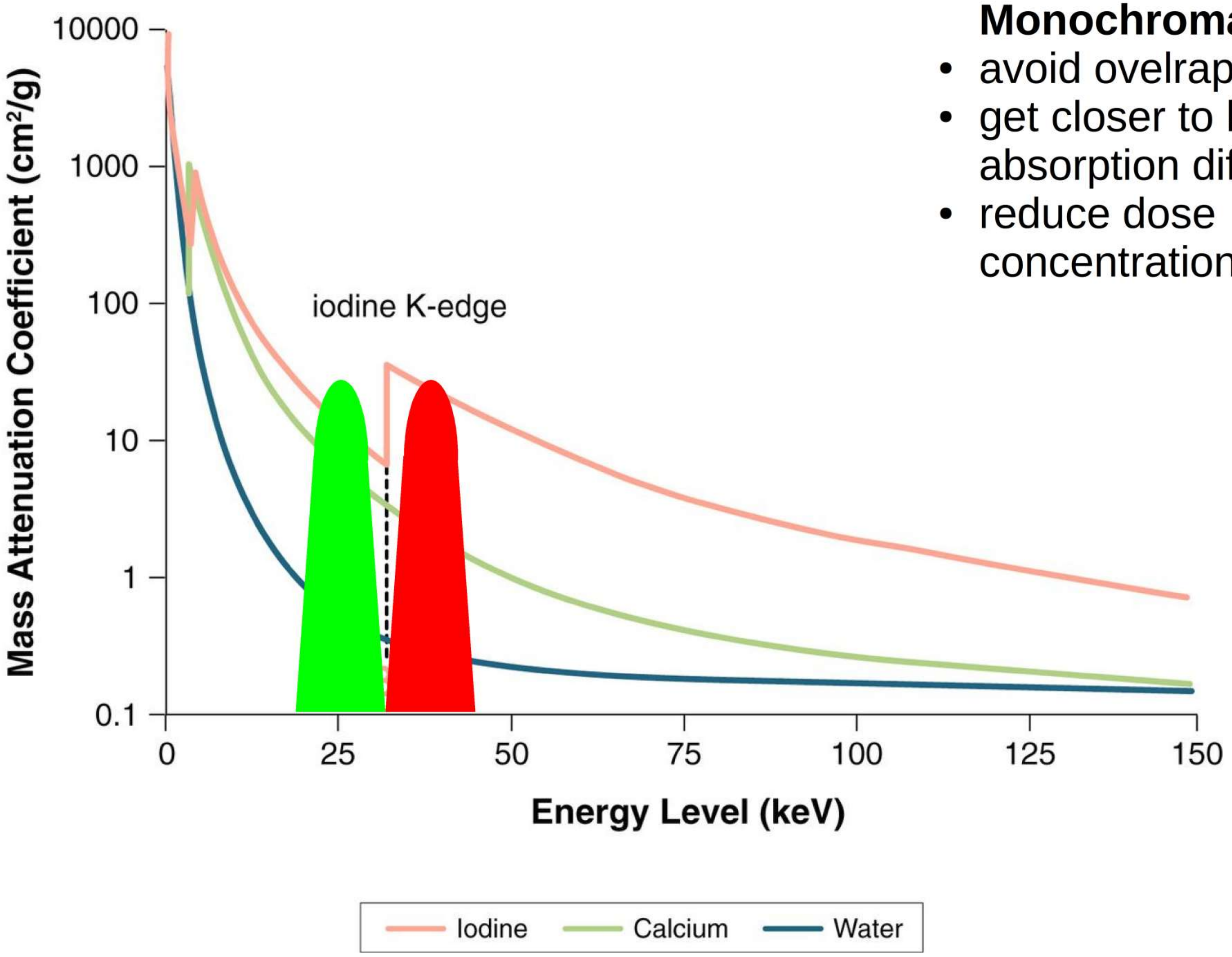


Conventional

Dual-energy

Lewin *et al*, Radiology 229, 2003

Contrast enhnaced dual energy – monochromatic x-rays



Monochromatic allows:

- avoid ovelrap in the spectra
- get closer to k-edge to increase absorption difference
- reduce dose → decrease contrast agent concentration

Riflessioni di contesto

L’evoluzione della tecnologia di questi ultimi 20 anni ha fatto sì che, sia a livello diagnostico, che a livello radioterapico la complessità ed i costi delle apparecchiature subissero un incremento di almeno un fattore 5. Abbiamo visto la trasformazione delle PET in CT PET e da ultimo in RM PET; Abbiamo visto la trasformazione dei Linac per la radioterapia in Tomotherapy LINAC e poi nella robotizzazione della Cyberknife.

Ciò ha portato, insieme ad altri fattori, ad una continua crescita dei costi del Sistema Salute, che in Italia è, nella sua massima parte, a carico dello Stato

Riflessioni di contesto

Forse il punto di debolezza di questo progetto di realizzare sorgenti Compton capaci di generare radiazione X coerente , per una diagnostica in vivo, sta proprio in questi due fattori : Alti costi e dimensioni troppo superiori rispetto all’ingombro del tubo radiogeno attuale.

Ovviamente questa problematica non attiene alla fase della ricerca che potrebbe rivelare specificità tali da giustificare un aumento del costo sociale dell’utilizzo di queste apparecchiature per patologie e/o sottogruppi ristretti di pazienti.

Non potrà altresì essere dimenticato che il trend attuale della radiologia è quello di andare verso un imaging multi energetico lavorando sulla evoluzione dei rivelatori tipo Photon counting…..Riuscirà una stessa sorgente Compton a lavorare su 2 , 3….6 energie ?

Il core dell’Accordo Quadro

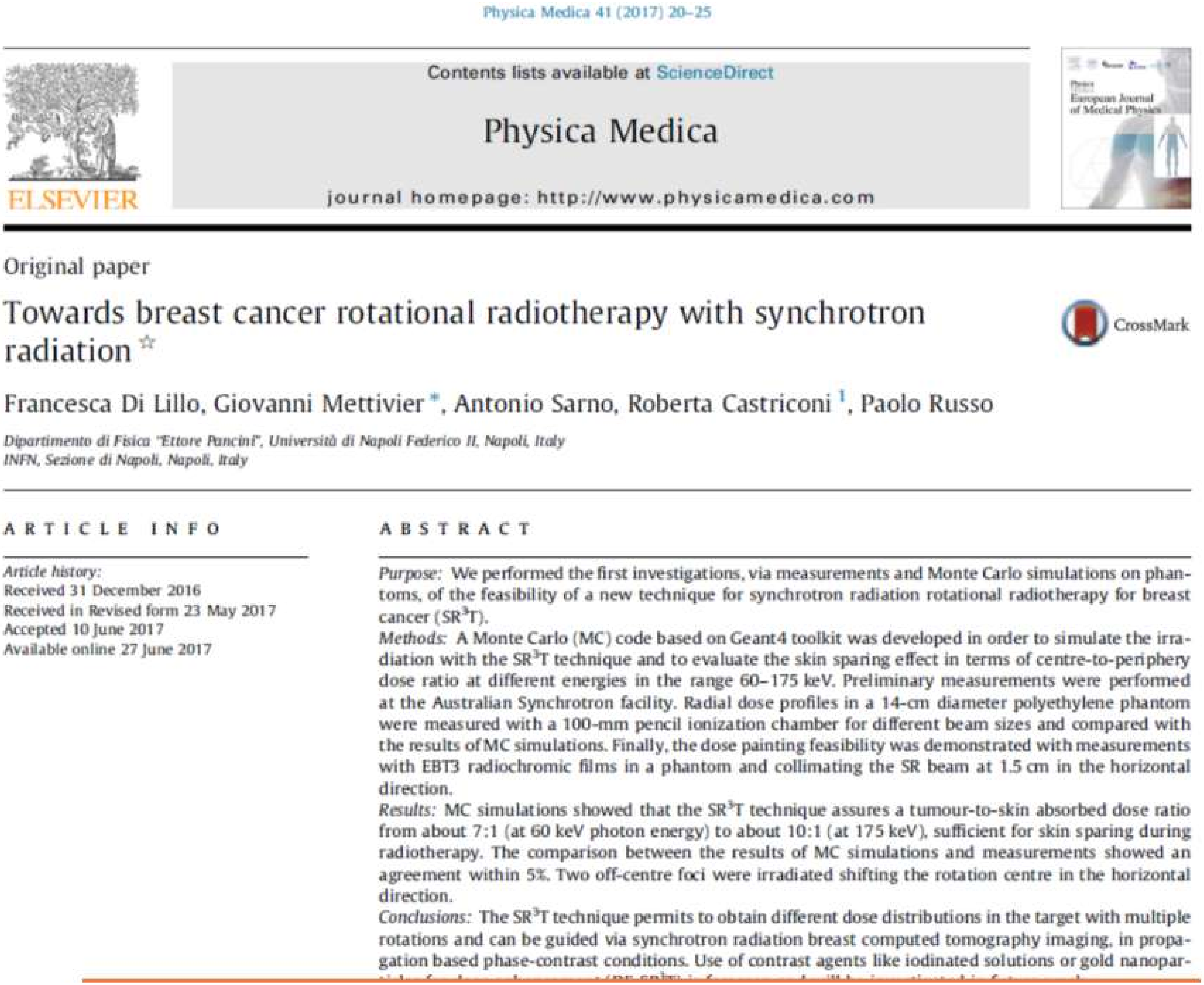
- L’INFN e l’ IRRCCS San Raffaele intendono collaborare allo sviluppo di progetti riguardanti sorgenti di raggi X mono-cromatici e relative tecnologie che ne consentono l’applicazione all’imaging radiologico da utilizzarsi in ambito medicale, nonche’ alle tematiche di radio protezione e valutazione di dose in radio-diagnostica e radio-terapia

- In particolare, l’attività di ricerca congiunta tra l’INFN e l’ IRCCS San Raffaele è dettata dalla comune esigenza di raggiungere i seguenti obiettivi: cooperare ad un significativo avanzamento delle tecniche di imaging basate su raggi X mono-cromatici e sviluppare in collaborazione design studies di apparati innovativi al fine di condurre tests pre-clinici di validazione.

Summary comments dott. Calandrino

- Avanzamento e sviluppo di tecniche di imaging basato su sorgenti monocromatiche
- Attività di ricerca e pre-clinica
- Imaging multi-energetico (possibilità detector spettroscopici o photon-counting?)

Breast radiotherapy using monochromatic X-rays



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journal homepage: http://www.physicamedica.com

Original paper

Towards breast cancer rotational radiotherapy with synchrotron radiation ☆

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ABSTRACT

Purpose: We performed the first investigations, via measurements and Monte Carlo simulations on phantoms, of the feasibility of a new technique for synchrotron radiation rotational radiotherapy for breast cancer (SR^{3}T).

Methods: A Monte Carlo (MC) code based on Geant4 toolkit was developed in order to simulate the irradiation with the SR^{3}T technique and to evaluate the skin sparing effect in terms of centre-to-periphery dose ratio at different energies in the range 60–175 keV. Preliminary measurements were performed at the Australian Synchrotron facility. Radial dose profiles in a 14-cm diameter polyethylene phantom were measured with a 100-mm pencil ionization chamber for different beam sizes and compared with the results of MC simulations. Finally, the dose painting feasibility was demonstrated with measurements with EBT3 radiochromic films in a phantom and collimating the SR beam at 1.5 cm in the horizontal direction.

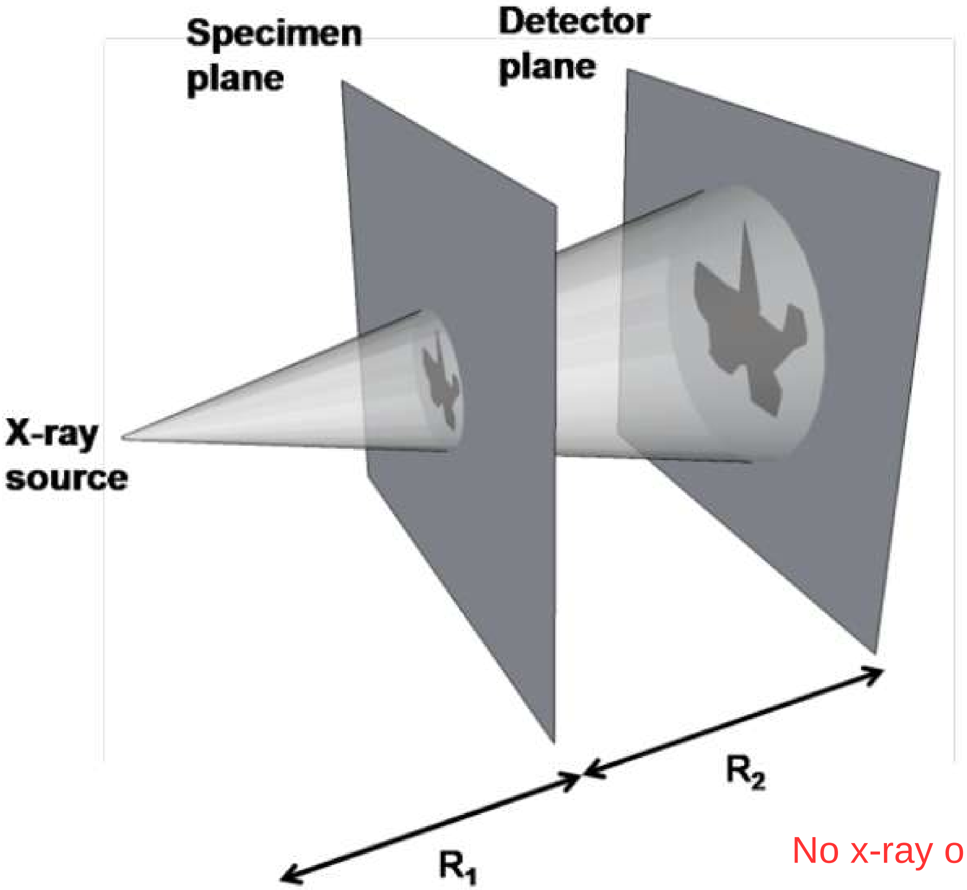
Results: MC simulations showed that the SR^{3}T technique assures a tumour-to-skin absorbed dose ratio from about 7:1 (at 60 keV photon energy) to about 10:1 (at 175 keV), sufficient for skin sparing during radiotherapy. The comparison between the results of MC simulations and measurements showed an agreement within 5%. Two off-centre foci were irradiated shifting the rotation centre in the horizontal direction.

Conclusions: The SR^{3}T technique permits to obtain different dose distributions in the target with multiple rotations and can be guided via synchrotron radiation breast computed tomography imaging, in propagation based phase-contrast conditions. Use of contrast agents like iodinated solutions or gold nanopar-

See G.Mettivier presentation– previous Marix meeting

Projection microscopy

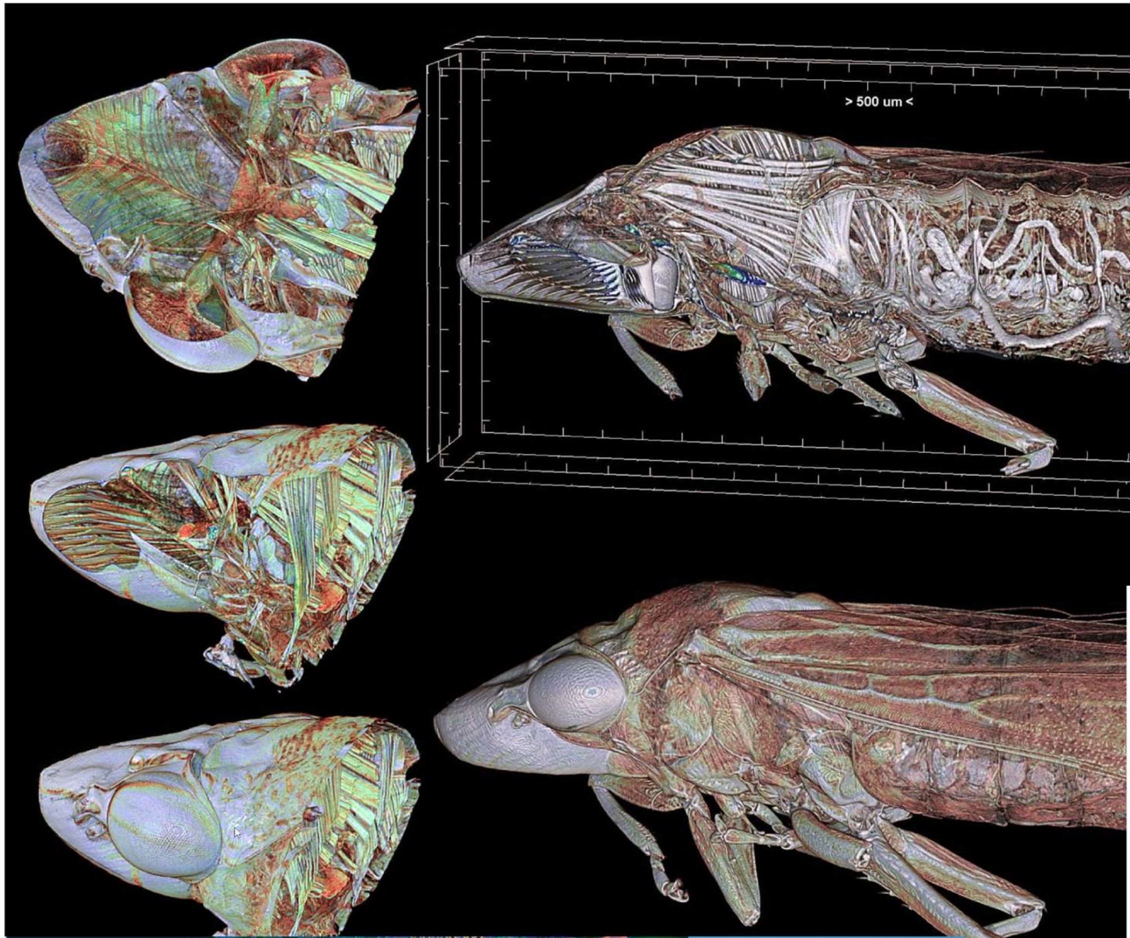
Scheme of a projection microscope with the source to specimen plane distance R_1 and specimen to detector distance R_2

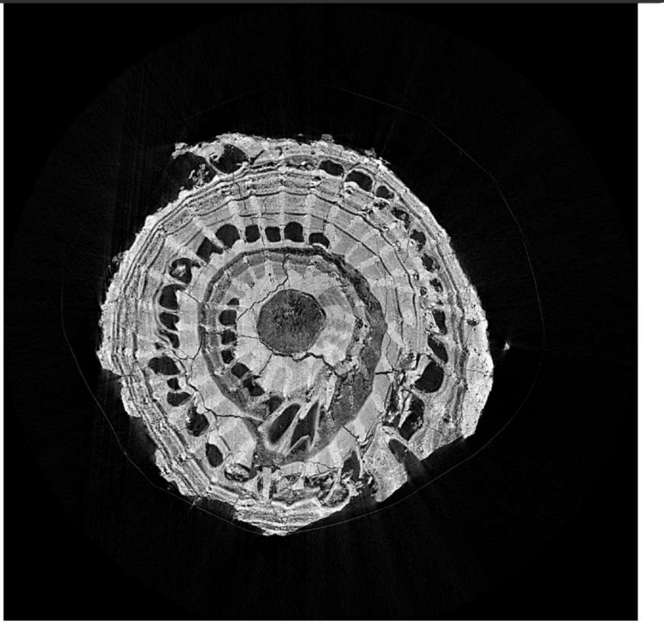


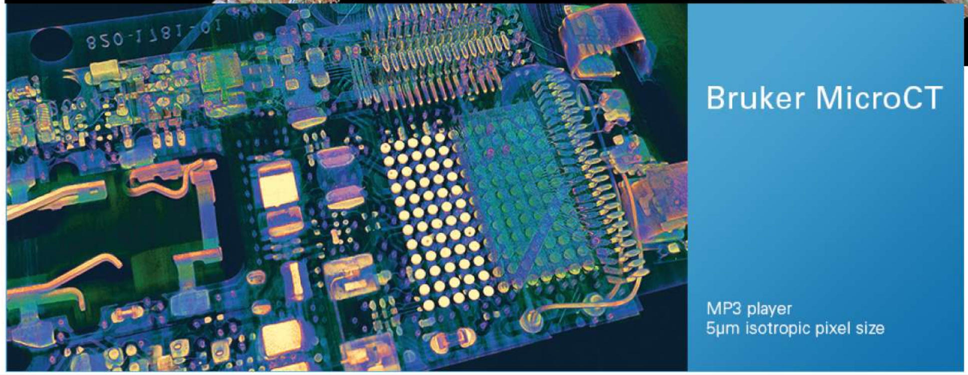
No x-ray optics

Kaulich B., Thibault P., Gianoncelli A., Kiskinova M. "Transmission and emission x-ray microscopy: operation modes, contrast mechanisms and applications" *Journal of Physics: Condensed Matter*, Vol. 23 - 8, pp. 083002 (2011)

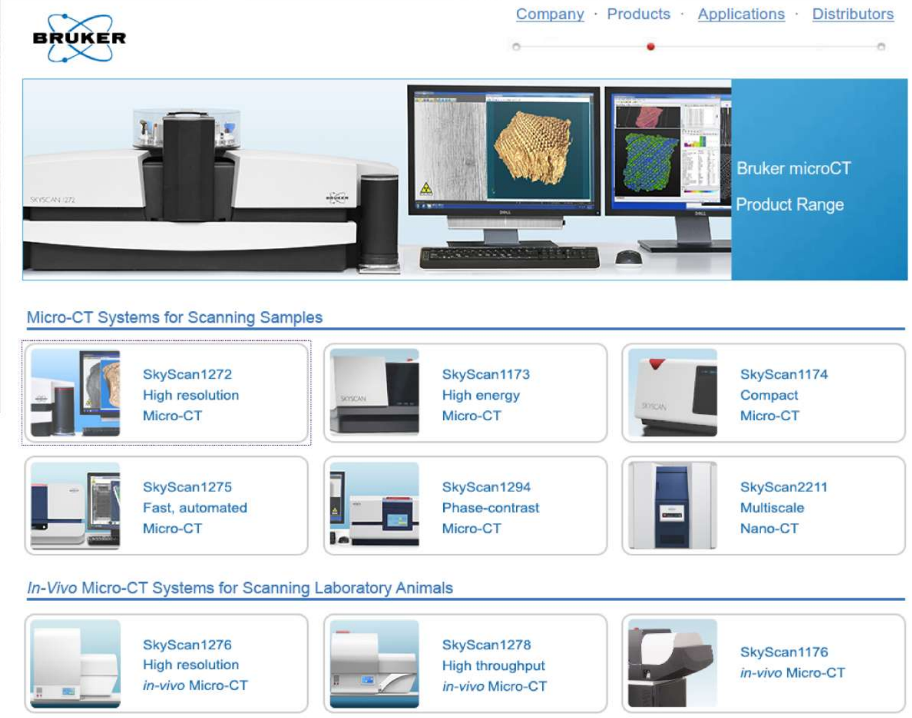
Microtomography (lab x-ray tube)






Bruker MicroCT

MP3 player
5µm isotropic pixel size



Bruker microCT

Product Range

Micro-CT Systems for Scanning Samples

SkyScan1272
High resolution
Micro-CT

SkyScan1173
High energy
Micro-CT

SkyScan1174
Compact
Micro-CT

SkyScan1275
Fast, automated
Micro-CT

SkyScan1294
Phase-contrast
Micro-CT

SkyScan2211
Multiscale
Nano-CT

In-Vivo Micro-CT Systems for Scanning Laboratory Animals

SkyScan1276
High resolution
in-vivo Micro-CT

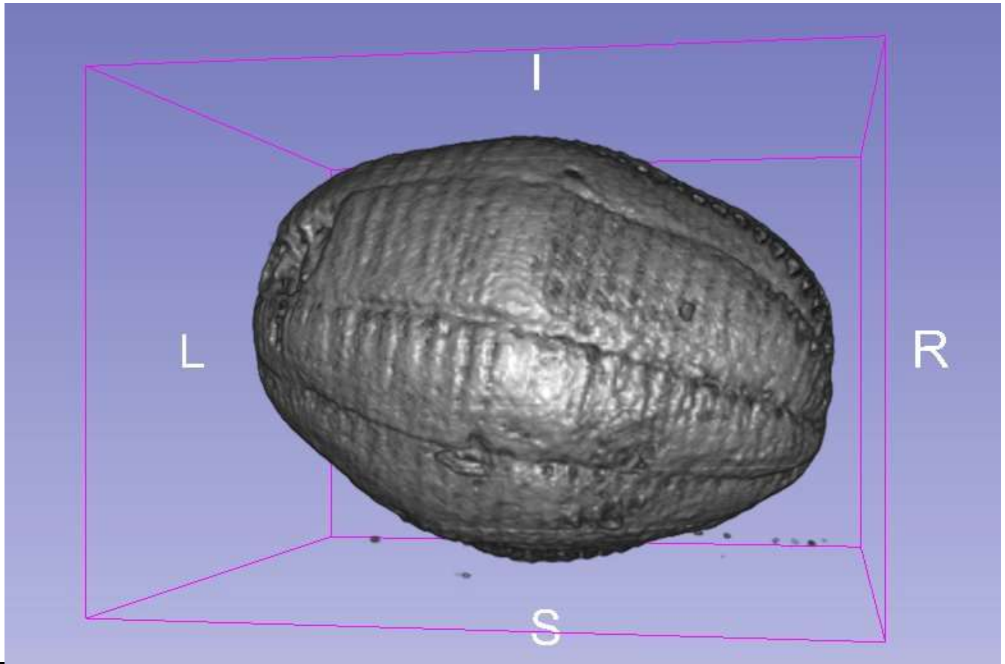
SkyScan1278
High throughput
in-vivo Micro-CT

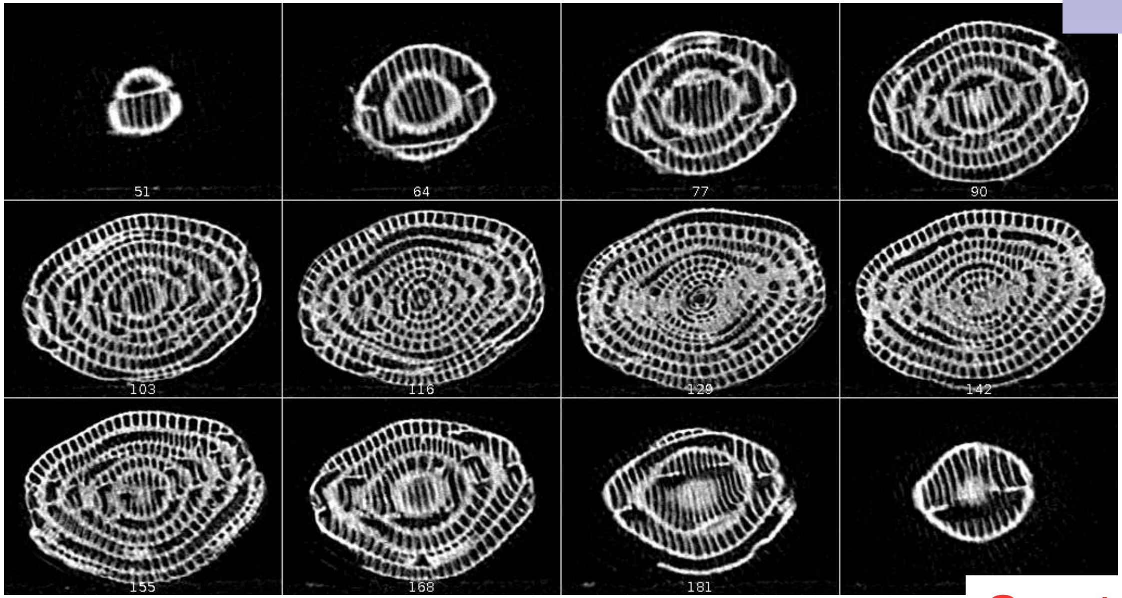
SkyScan1176
in-vivo Micro-CT

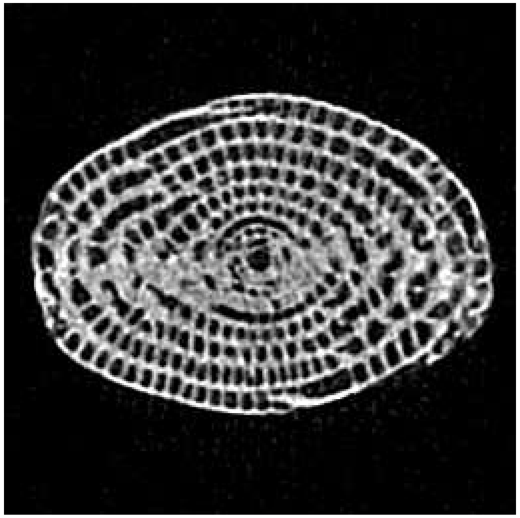
Microtomography – here at LARIX-B UNIFE

Foraminifero del mar Rosso
Size: 1.140 x 0.785 x 0.840 mm^3,

H.V. - 70 kVp, 100 uA, 1s per vista, 360 viste
detector: radeye-2
Magnificazione: 12.7
pixel di ricostruzione: 5 um







Courtesy of G. Di Domenico (UNIFE – INFN-FE)

Microtomography – here at LARIX-B UNIFE

Foraminifero del mar Rosso

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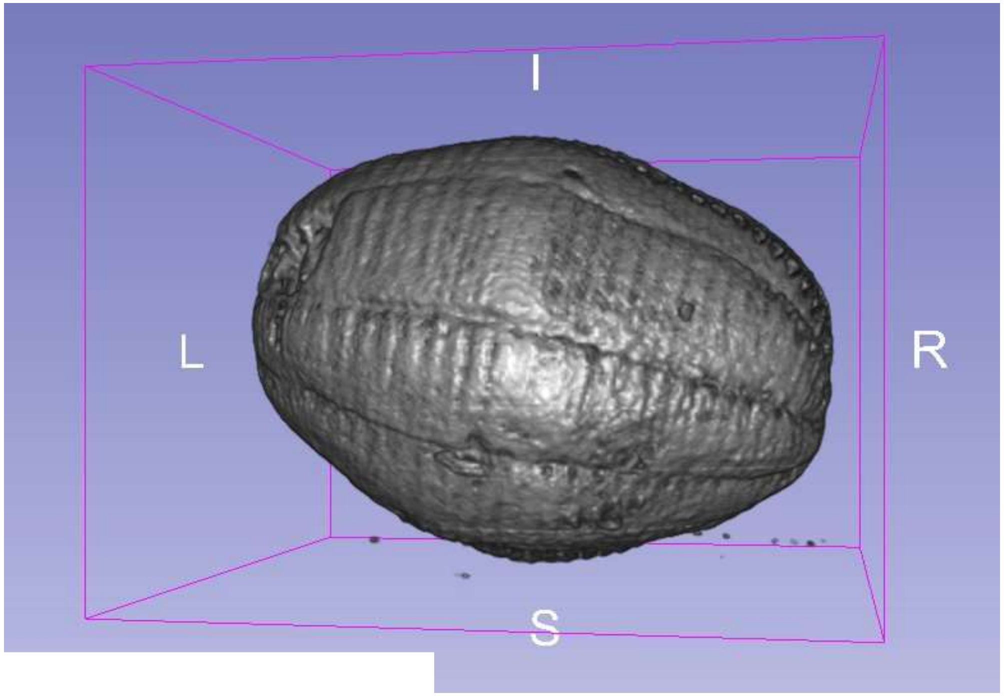
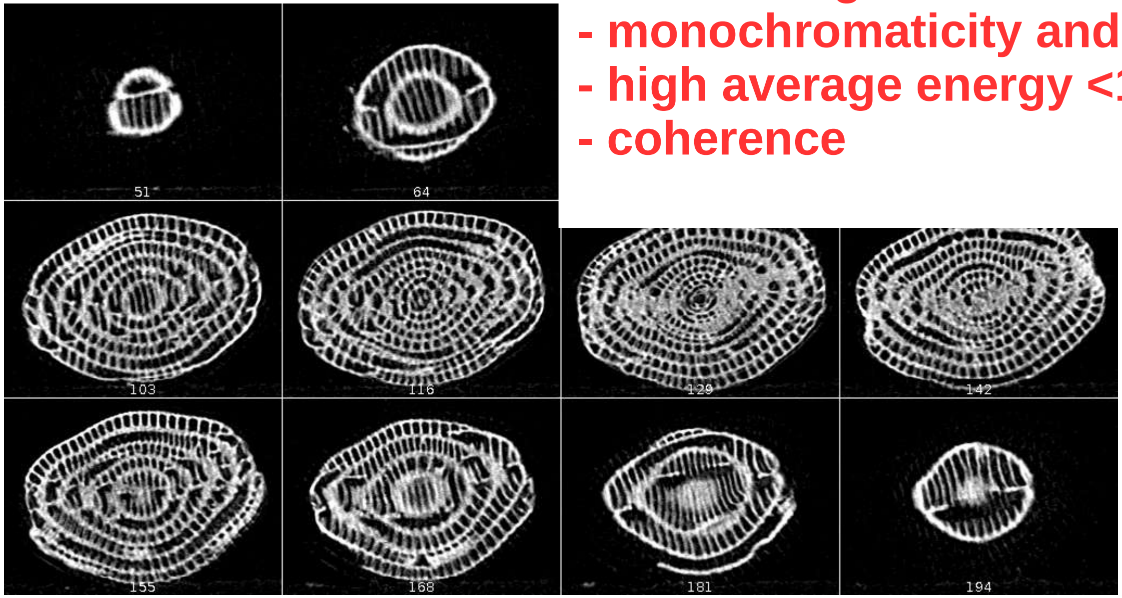
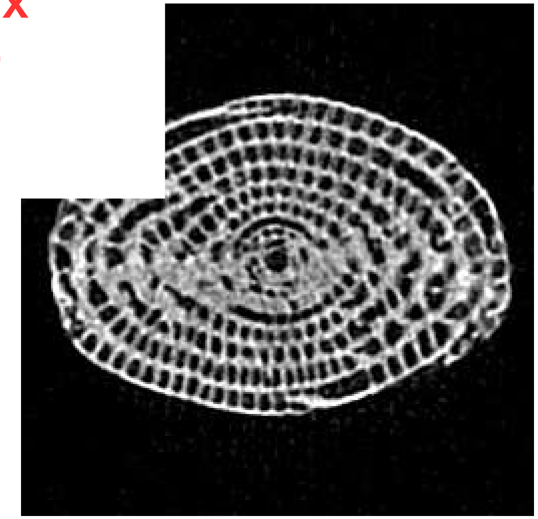


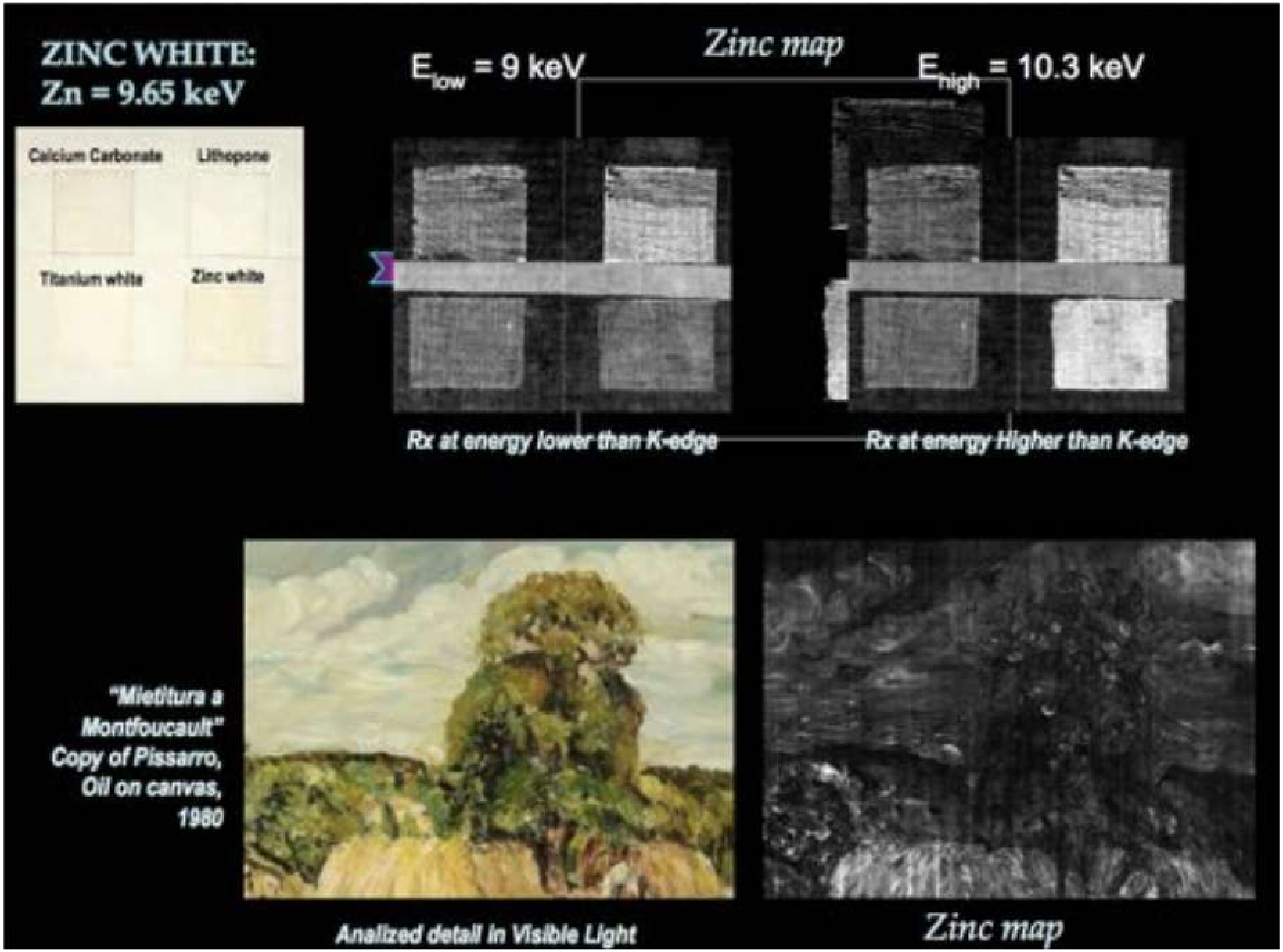
Marix strength:

- **monochromaticity and high flux**
- **high average energy <100 keV)**
- **coherence**





Pigment composition map – k-edge imaging



ZINC WHITE:
Zn = 9.65 keV

Calcium Carbonate
Lithopone
Titanium white
Zinc white

Zinc map

E_{low} = 9 keV

E_{high} = 10.3 keV

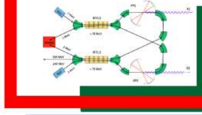
Rx at energy lower than K-edge

Rx at energy Higher than K-edge

"Mietitura a Montfoucault"
Copy of Pissarro,
Oil on canvas,
1980

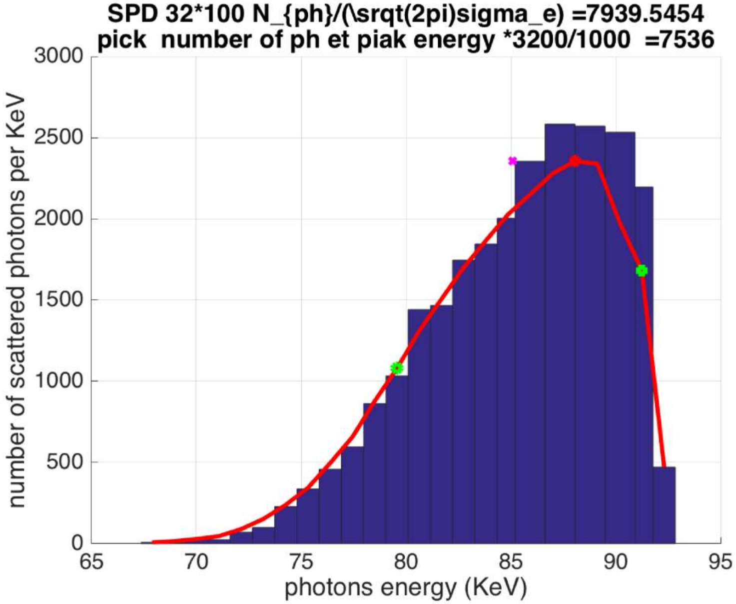
Analized detail in Visible Light

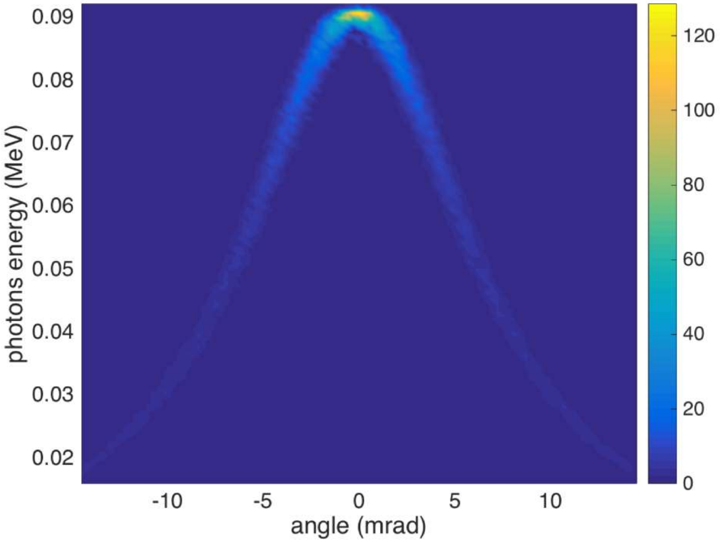
Zinc map

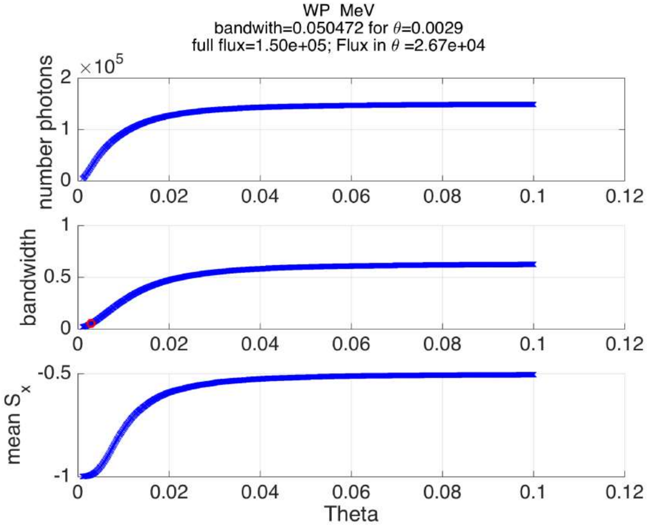


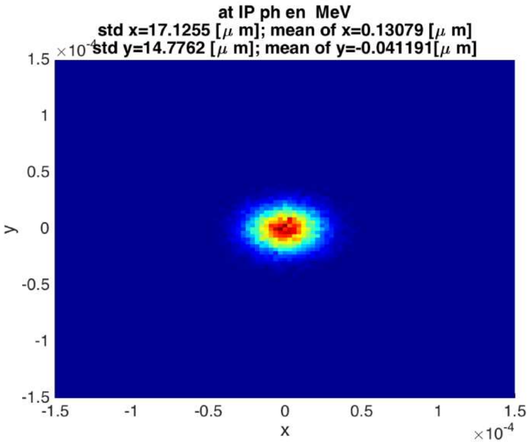
BriXS

Main parameters	
Energy	40-180 KeV
Flux per sec	10^{12}
BW	~1-10%
Spot size at 10 M	10-30 mm
Divergence	1-3 mrad


SPD 32*100 N_{ph}/(\srqt(2pi)sigma_e) =7939.5454
pick number of ph et piak energy *3200/1000 =7536




WP MeV
bandwith=0.050472 for θ=0.0029
full flux=1.50e+05; Flux in θ =2.67e+04


at IP ph en MeV
std x=17.1255 [μ m]; mean of x=0.13079 [μ m]
std y=14.7762 [μ m]; mean of y=-0.041191[μ m]

Expected parameters

First Phase	
Photon energy	20 - 70 *keV*
Bandwidth (rms)	≤ 5. %
# photons per shot within FWHM bdw.	$\leq 5.0 \cdot 10^{4}$
# photons/sec within FWHM bdw.	$\leq 1.25 \cdot 10^{12}$
Source rms size	≤ 20 μm
Source rms divergence	2 - 6 *mrad*
Photon beam spot size (FWHM) at z=10 m	4 – 12 *cm*
Peak Brilliance ($N_{ph}/sec \cdot mm^2 mrad^2 \cdot 0.1\%$)	10^{20} - 10^{23}
Radiation pulse length (rms, *psec*)	0.7 - 1.5
Linear/Circular Polarization	> 99 %
Repetition rate	25 M*Hz*
Pulse-to-pulse separation	40 *nsec*

Second Phase	
Photon energy	20 - 150 *keV*
Bandwidth (rms)	≤ 10. %
# photons per shot within FWHM bdw.	$\leq 1.0 \cdot 10^{5}$
# photons/sec within FWHM bdw.	$\leq 1.0 \cdot 10^{13}$
Source rms size	≤ 20 μm
Source rms divergence	1 - 6 *mrad*
Photon beam spot size (FWHM) at z=10 m	2 -12 *cm*
Peak Brilliance ($N_{ph}/sec \cdot mm^2 mrad^2 \cdot 0.1\%$)	10^{20} - 10^{23}
Radiation pulse length (rms, *psec*)	0.7 - 1.5
Linear/Circular Polarization	> 99 %
Repetition rate	100 M*Hz*
Pulse-to-pulse separation	10 *nsec*

Application → source and beamline

- **Source (laser -electron interaction)**
  - Energy range 20-180 keV, could be useful to reach E<20 keV
  - Expected flux → compatible with imaging applications $\sim 10^7$ photons/mm^2 @ detector
  - Application dependent:
    - High brilliance → igh collimation, high monocromaticity
    - Uniformity of energy distribution and flat spatial profile → medical imaging
  - Time required to change the working-point (over entire range) → as fast as possible
  - Dual-energy quick switching solutions (detector acquisition time is bottle-neck)
  - Coherence and polarization not necessary for med imaging (except PCI), interesting for other apps

- **X-ray beamline and experimental area**
  - Expperimental area → as long as possible (~50 m or more) 3 mrad → r=15 cm @ 50 m
  - Experimental area simultaneous access/operation → shielding and rad safety
  - X-ray beam collimation system, monitoring and diagnostics flexible to accommodate a wide range of applications
  - R&D of x-ray optics and x-ray (monochromators, mirrors, lenses..)

Conclusions

- **Marix Compton source strength**
  - Fluxes/brilliance comparable with synchrotron, accessibility
  - Max energy 180 keV
  - Emission divergence (transverse) bigger tha synchrotron radiation → 2d images
  - Dual energy fast switch ($\sim$ ms), if implemented

- Main applications requirements and guidelines to finalize preliminary design are defined

- **Open points /discussion**
  - More interaction points? (lower quality beam?)
  - Involve more potential users to include possible different requirements in the source design?

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The Munich Compact Light Source: initial performance measures

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Table 2
Stability analysis of flux, source size and source position at a peak X-ray energy of 24.8 keV (values averaged over 3 h).

Quantity	Mean value	Standard deviation	Standard deviation (%)
Total flux (photons s^{-1})	9.654×10^9	0.478×10^9	4.95
Horizontal r.m.s. source size (μm)	41.5	0.4	1.0
Vertical r.m.s. source size (μm)	42.4	0.9	2.1
Horizontal source position† (μm)		1.5	
Vertical source position (μm)		3.9	

† Around average position.

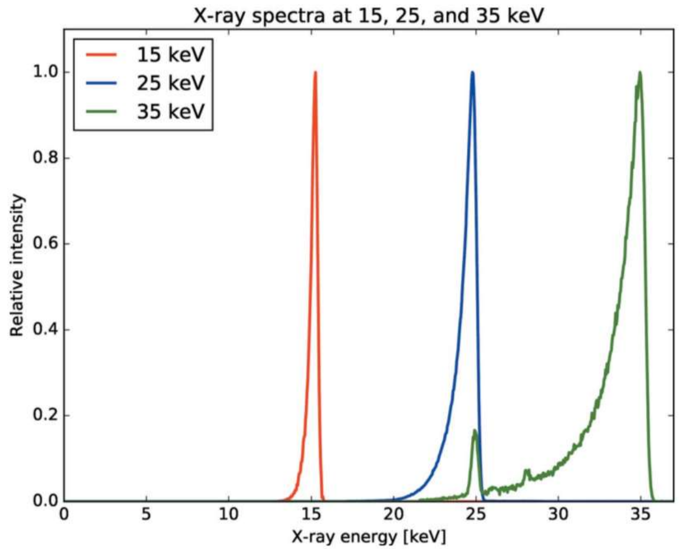


Figure 3
Measured spectra at peak energies of 15.2 keV, 24.8 keV and 35.0 keV.

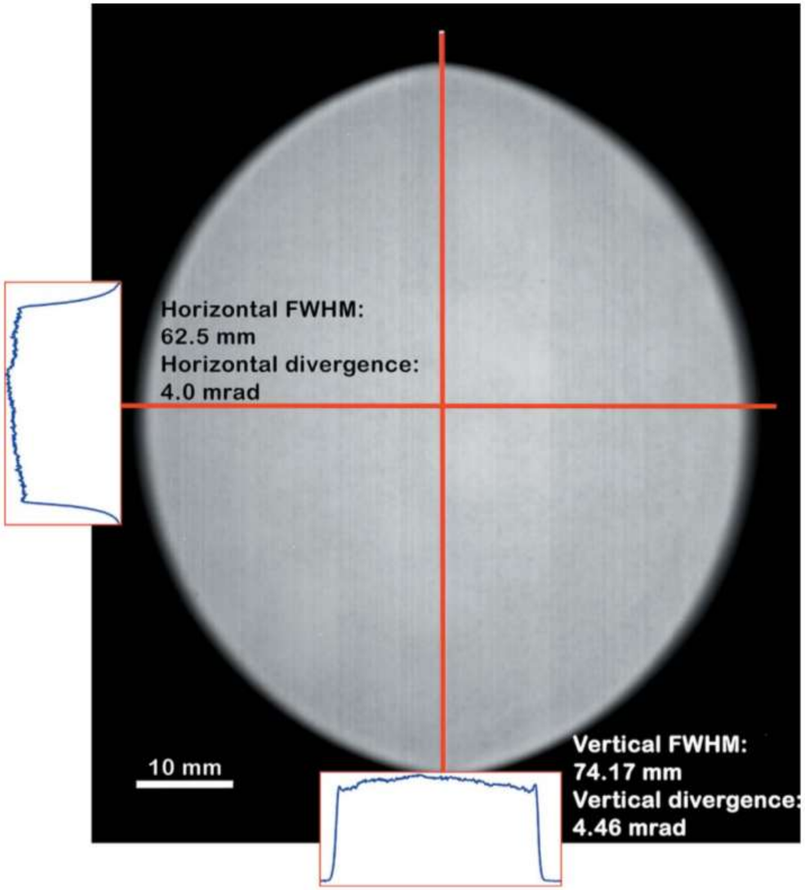
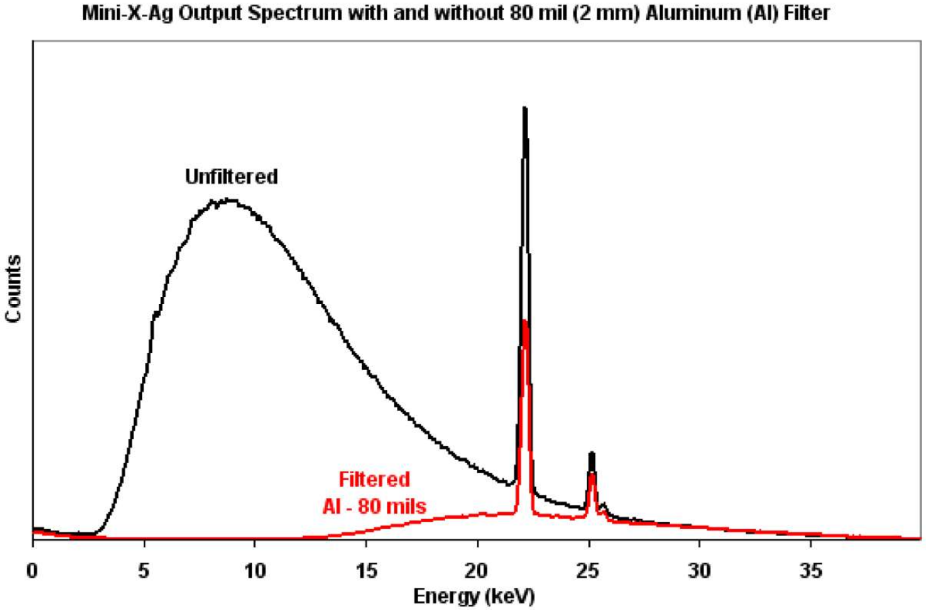
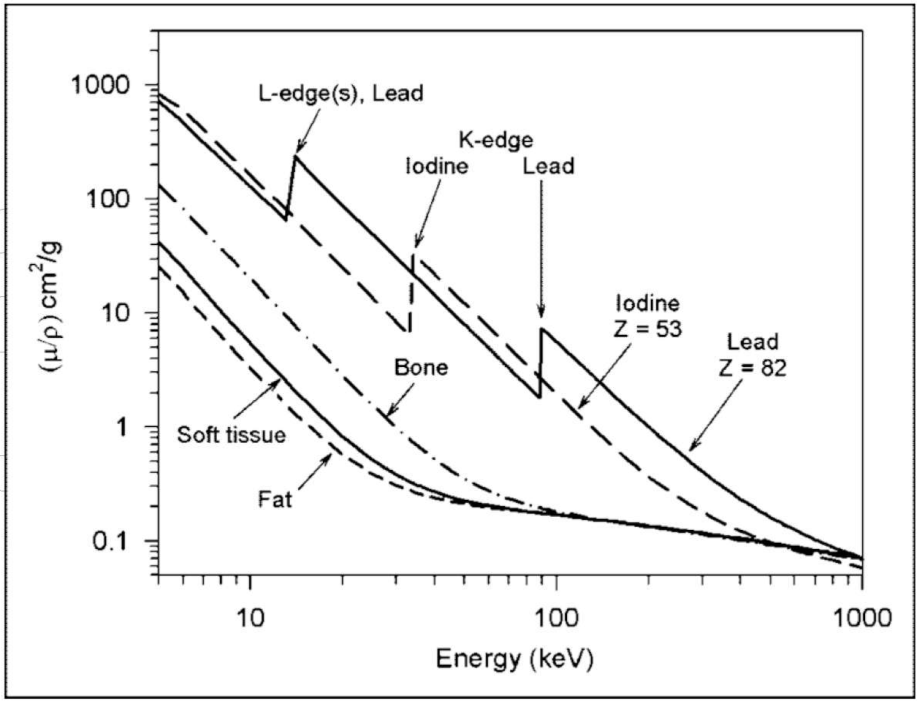


Figure 2
Detector image of the X-ray beam at 16.6 m distance from the interaction point taken with the Varian PaxScan, showing the divergence of approximately 4 mrad and the flatness of the beam.

Radiography

- 2d transmission
- Not considering optical elements (E>10 keV very difficult to built an efficient performing lens)



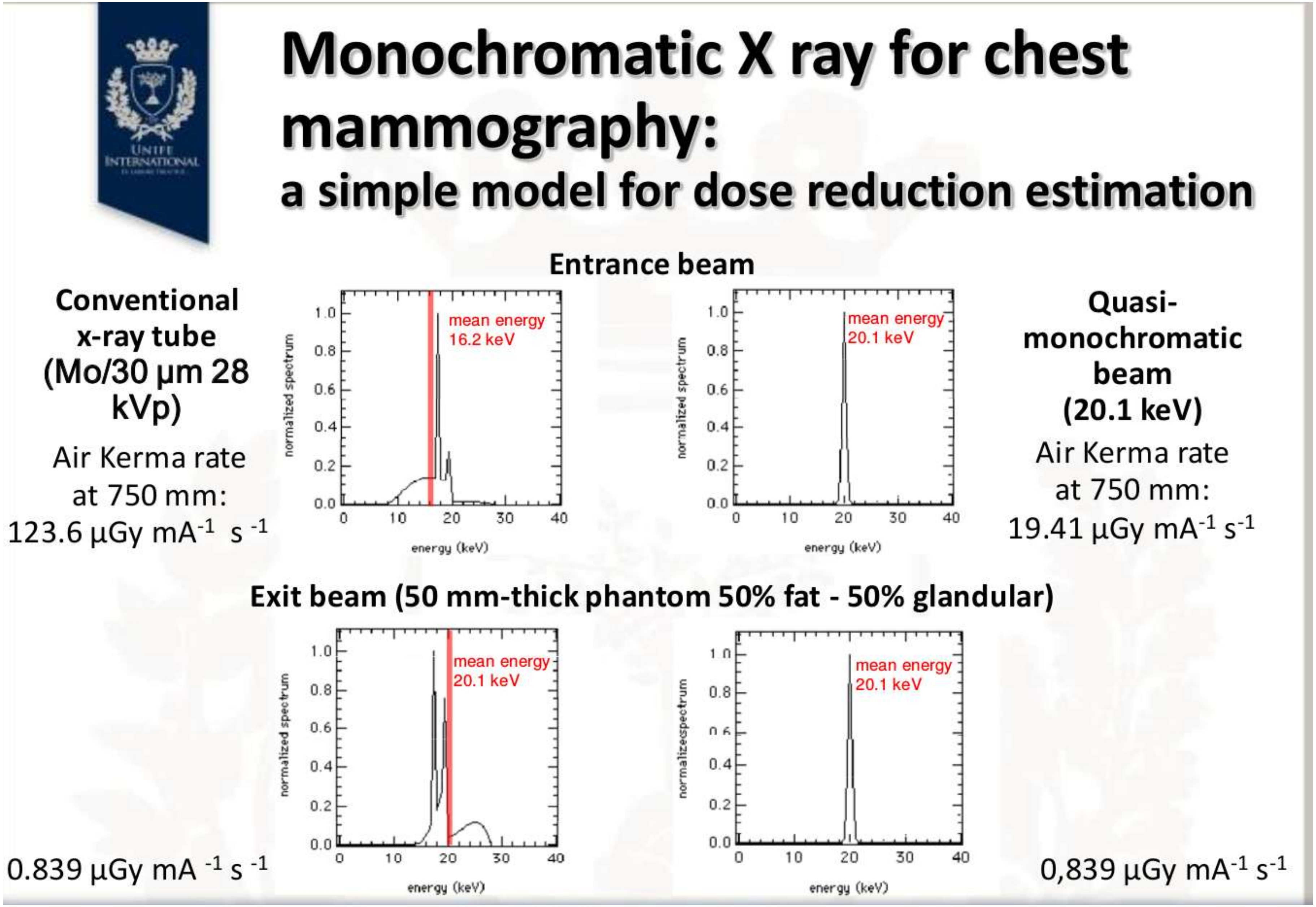


- Energy
  - → thickness of sample
  - → contrast of details
  - → Dose (J/Kg) delivered in sample

Optimisation using monochromatic beam

- Divergence → max irradiation field vs distance → sample transverse size
- Photon flux → time required for a significant signal (detector size dependent)
- Size of focal spot → maximum magnification

Monochromaticity for dose reduction



Monochromatic X ray for chest mammography:

a simple model for dose reduction estimation

Entrance beam

Conventional x-ray tube (Mo/30 μm 28 kVp)

Air Kerma rate at 750 mm: 123.6 μGy mA^{-1} s^{-1}

Quasi-monochromatic beam (20.1 keV)

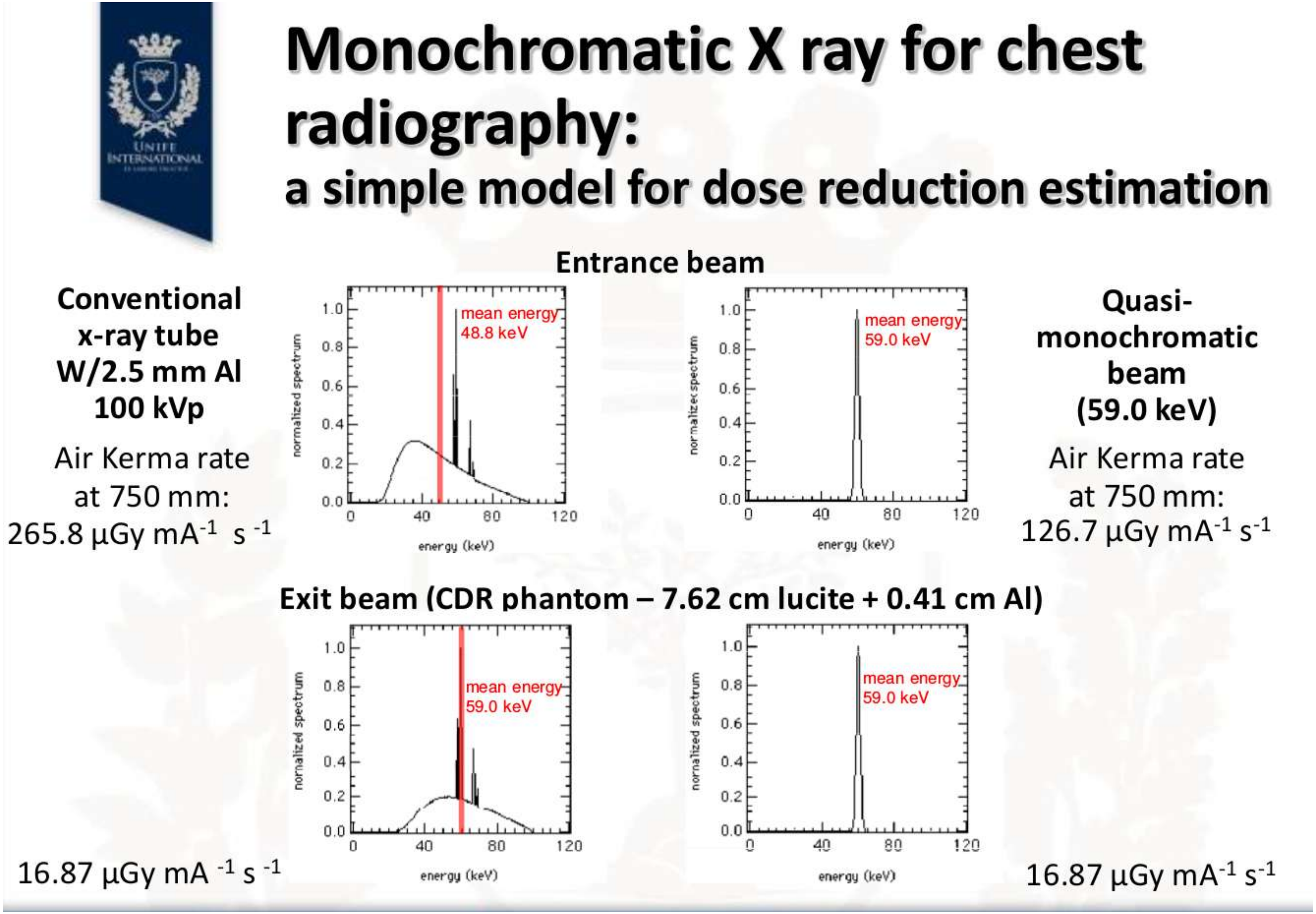
Air Kerma rate at 750 mm: 19.41 μGy mA^{-1} s^{-1}

Exit beam (50 mm-thick phantom 50% fat - 50% glandular)

0.839 μGy mA^{-1} s^{-1}

0,839 μGy mA^{-1} s^{-1}

Monochromaticity for dose reduction



Monochromatic X ray for chest radiography:

a simple model for dose reduction estimation

Entrance beam

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

Air Kerma rate at 750 mm: 265.8 μGy mA^{-1} s^{-1}

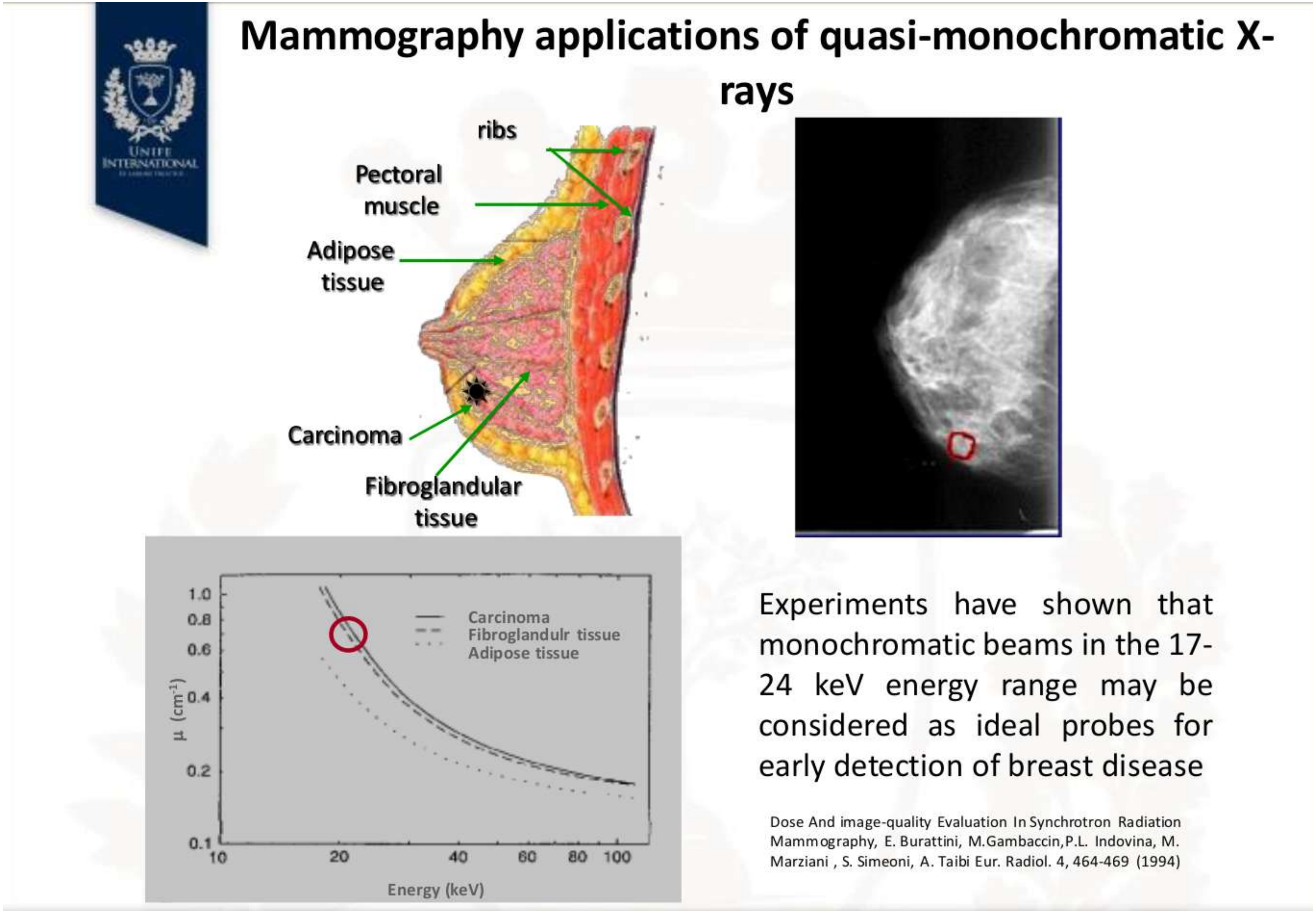
Quasi-monochromatic beam (59.0 keV)

Air Kerma rate 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 applications of quasi-monochromatic X-rays

Experiments have shown that monochromatic beams in the 17-24 keV energy range may be considered as ideal probes for early detection of breast disease

Dose And image-quality Evaluation In Synchrotron Radiation Mammography, E. Burattini, M.Gambaccin,P.L. Indovina, M. Marziani , S. Simeoni, A. Taibi Eur. Radiol. 4, 464-469 (1994)