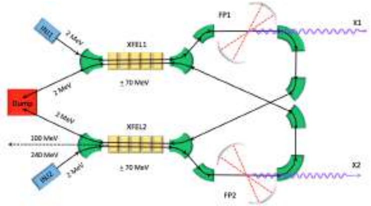
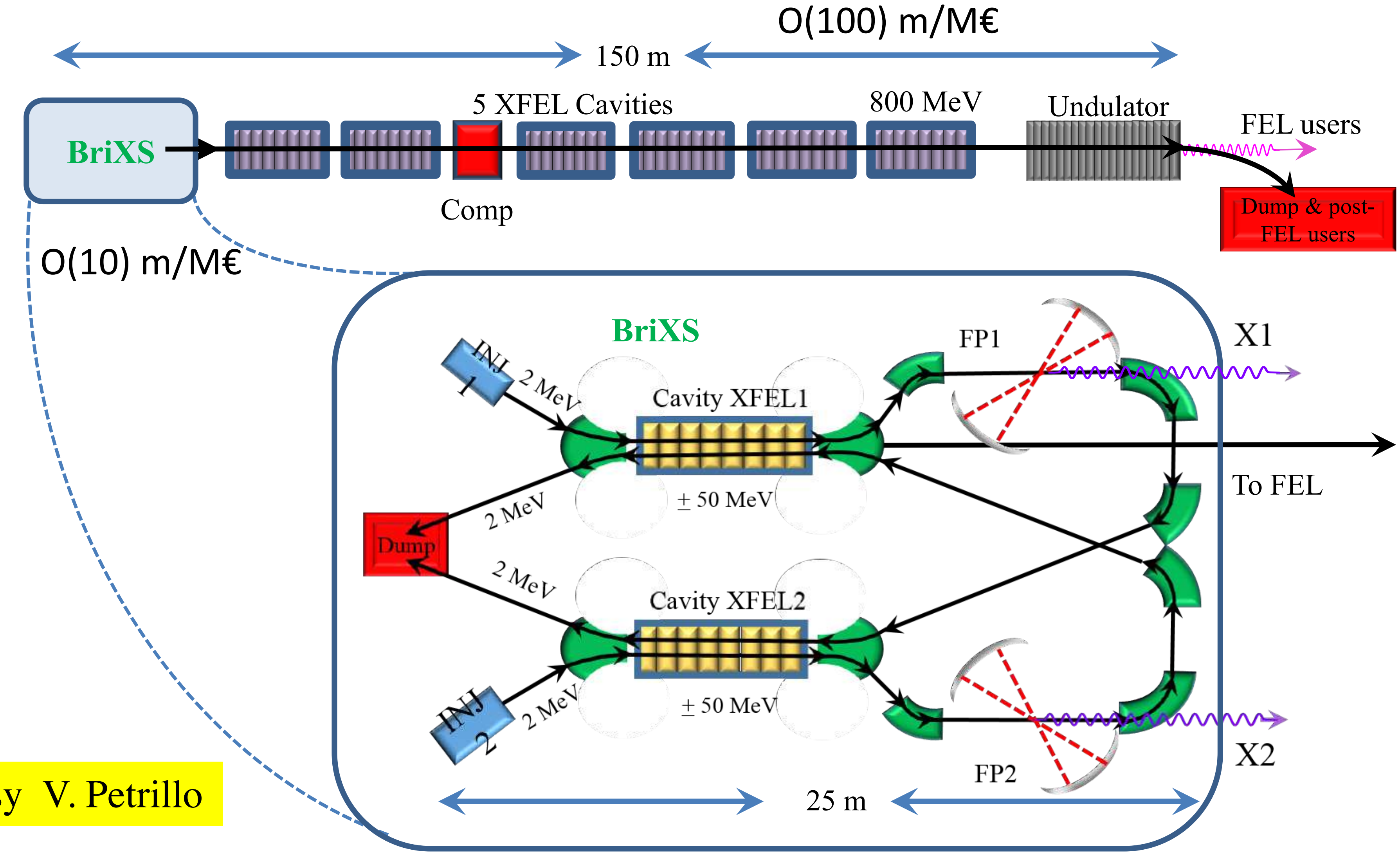
MariX – The Straw Man Design



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

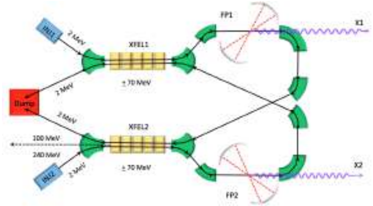
Luca Serafini – INFN-Milan and University of Milan



Courtesy V. Petrillo

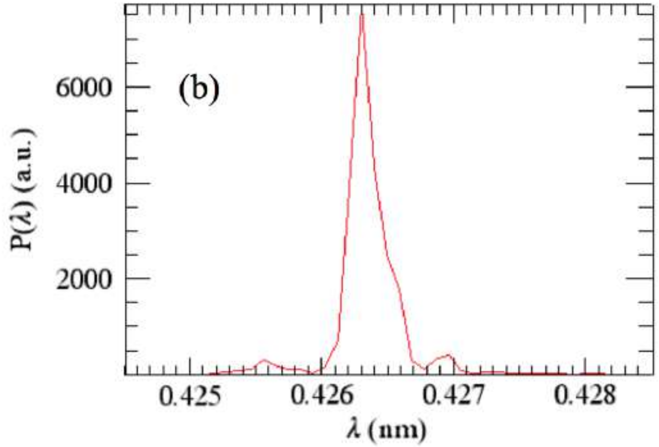
The Challenge: Integrate two different Radiation Sources into a single multi-purpose machine

2 different kinds of photon beams



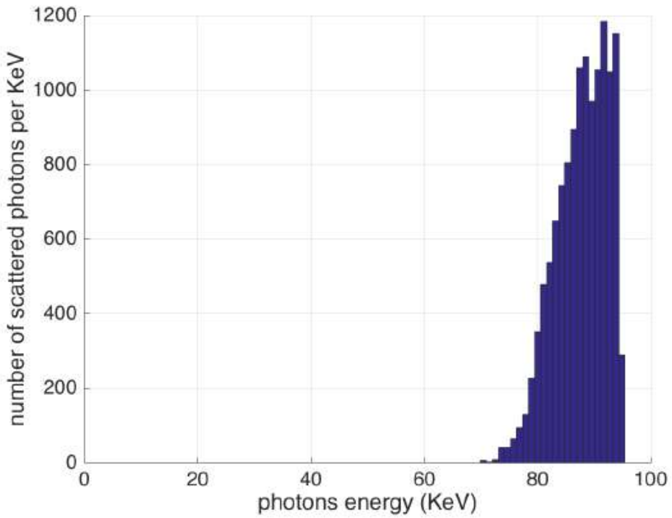
FEL fully coherent diffraction limited X-ray photon beam: 10^8 hν/pulse @ 1 MHz

in 0.05% $\Delta\nu/\nu$, 1-5 keV, σ_t < 50 fsec



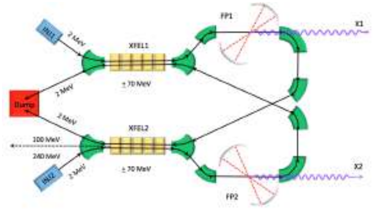
FEL spectrum

Compton X-ray photon beam: 10^{12} - 10^{13} hν/s (@ 100 MHz) in 5% $\Delta\nu/\nu$,
20-150 keV, tunable, polarized, σ_t = 2 psec 10 μm round source spot size,
mrad divergence



Compton spectrum

$2.6 \cdot 10^{12}$ photons/s



Breve descrizione del Caso Clinico in Radiological-Imaging di nuova generazione con raggi X mono-cromatici

Documento Expression of Interest di BriXS: BriXS-EoI-2.3.pdf (ottobre 2016)

Lettera d'Intenti su BriXS per raccolta interesse locale
breve descrizione del caso scientifico/clinico

BriXS: BRIght and compact X-ray Source

scaricabile al link
https://www.researchgate.net/publication/308793009_BriXS_BRIght_and_compact_X-ray_Source_Expression_of_Interest_1

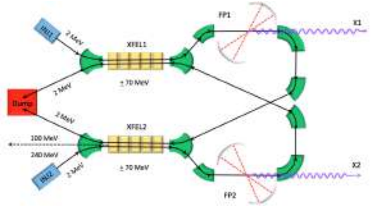
Expression of Interest

This document delineates the motivations and the guidelines for the development of a compact machine to produce beams of high brilliance mono-chromatic tunable *X*-rays with energy in the range from 30 to 150 keV, aimed at constituting a unique facility located in the Milan metropolitan area, with performances comparable to those of modern synchrotron light sources, although associated to costs and dimensions smaller by at least one order of magnitude (from 100x100 m^2 down to 10x10 m^2, and from 100s M€ down to 10s M€), so to be compatible with locations inside a University Campus, a large Hospital, a Museum or a mid-size research infrastructure.

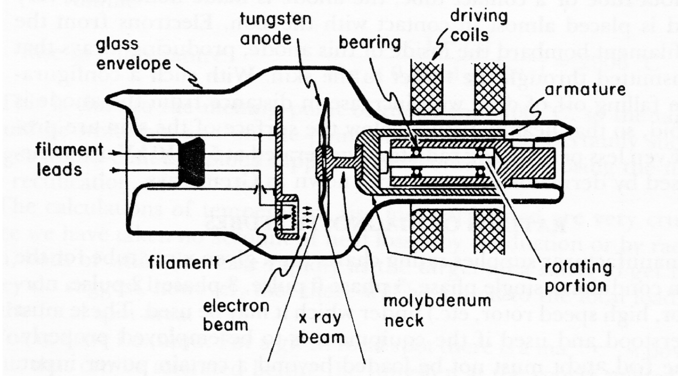
The focus on enabled applications by such a machine is on medical oriented research/investigations, mainly in the radio-diagnostics and radio-therapy fields, exploiting the unique features of mono-chromatic *X*-rays, as well as in micro-biological studies, and, within this mainstream, material studies, crystallography and museology for cultural heritage investigations. Mono-chromatic bright *X*-ray beams have been already proven to be a unique tool for advanced imaging at the sub 0.1 mm resolution scale with tremendous reduction in the radiation dose to tissues, joined to an upgraded signal-to-noise and visibility enhancement via phase contrast imaging.

The underlying enabling technology is the one on the strong rise over the last decade, with an effective ongoing transition from R&D and demonstrative machines towards effective user facilities, based on Thomson/Compton back-scattering *X*/γ-ray Sources, also known as Inverse Compton Sources (ICS).

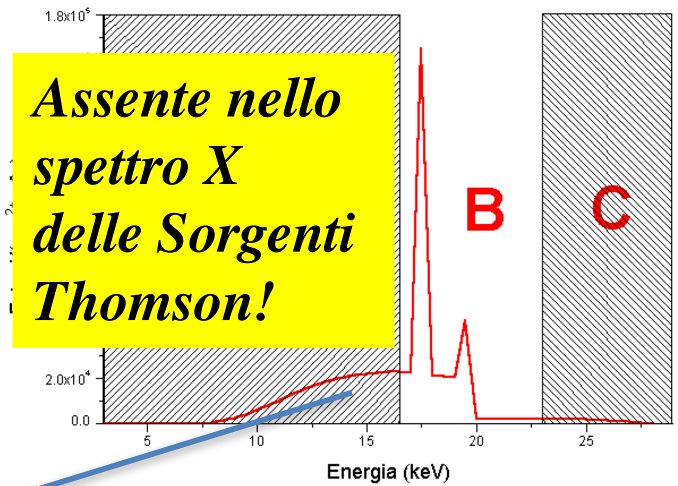
ESEMPIO NOTEVOLE DI IMAGING PER SCREENING DI MASSA: MAMMOGRAFIA



Sorgente Convenzionale per Mammografia: tubo RX.
Risoluzione spaziale richiesta ~100 μm
Alto Flusso ~10^7 γ/(mm^{2}s) equivalente a ~$5 \cdot 10^{11}$ γ/s su un'area di 20x20 cm^2.

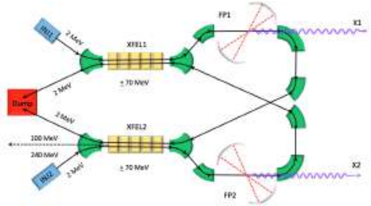


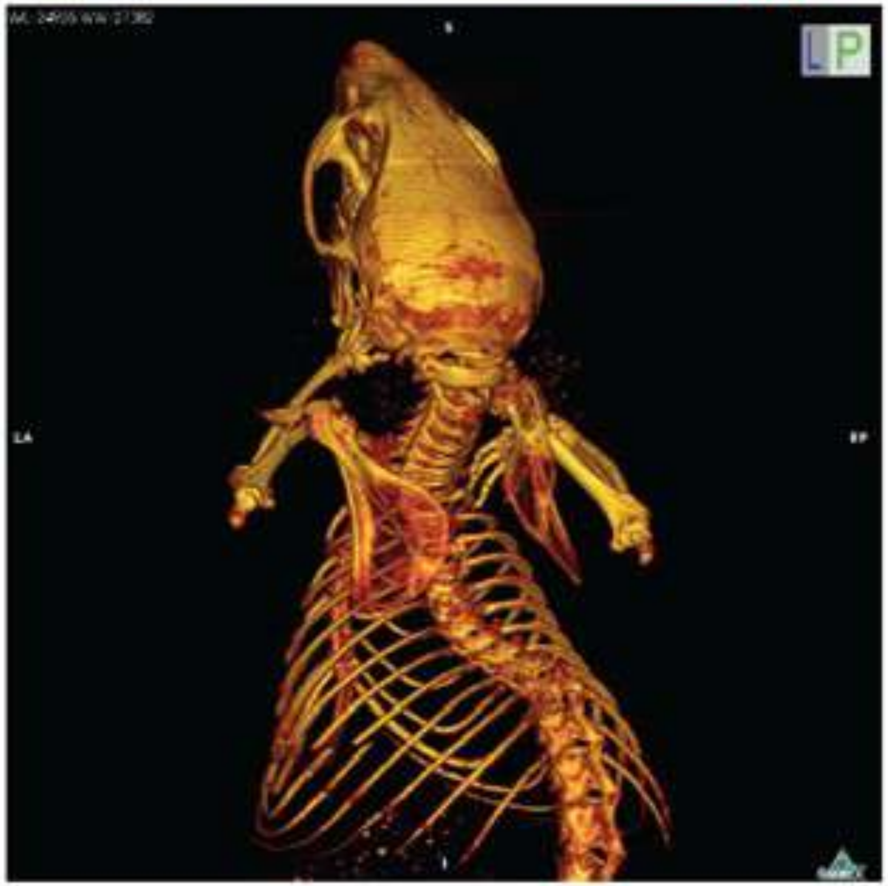
Anode Material	Molybdenum
Anode Angle	12?
Anodic Voltage	28 kV
Filtrations	1 mm Be 0.03 mm Mo 600 mm Air



Assente nello spettro X delle Sorgenti Thomson!

Parte di bassa energia dello spettro di fotoni X che viene assorbita dai tessuti ed aumenta il rischio secondario di indurre tumori, abbassando il rapporto rischio-beneficio dello screening di massa sulla popolazione femminile > 40 anni





small source size → high resolution (81 μm)
monochromatic → no beam hardening artefacts

Imaging a Contrasto di Fase
(risoluzione spaziale < 80 μm)

SCIENTIFIC REPORTS

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Mono-Energy Coronary Angiography with a Compact Synchrotron Source

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Accepted: 06 January 2017
Published: 09 February 2017

Elena Eggl[1,2], Korbinian Mechlem[1,2,3], Eva Braig[1,2,3], Stephanie Kulpe[1,2], Martin Dierolf[1,2], Benedikt Günther[1,2,4], Klaus Achterhold[1,2], Julia Herzen[1,2], Bernhard Gleich[2], Ernst Rummeny[3], Peter B. Noël[1,3], Franz Pfeiffer[1,2,3] & Daniela Muenzel[3]

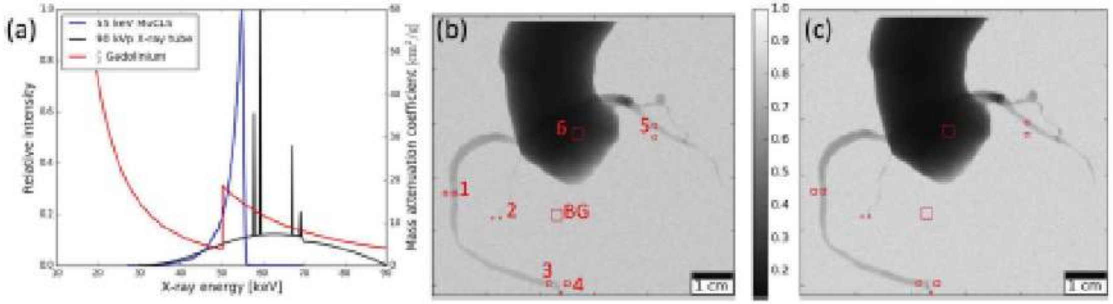


Figure 2. (**a**) MuCLS spectrum rescaled at 55.8 keV peak energy, x-ray tube spectrum at 90 kVp and mass attenuation coefficient of gadolinium. (**b**) Simulated gadolinium-based angiography image for the 90 kVp x-ray tube spectrum. (**c**) Simulated gadolinium-based angiography image for the 55 keV MuCLS spectrum.

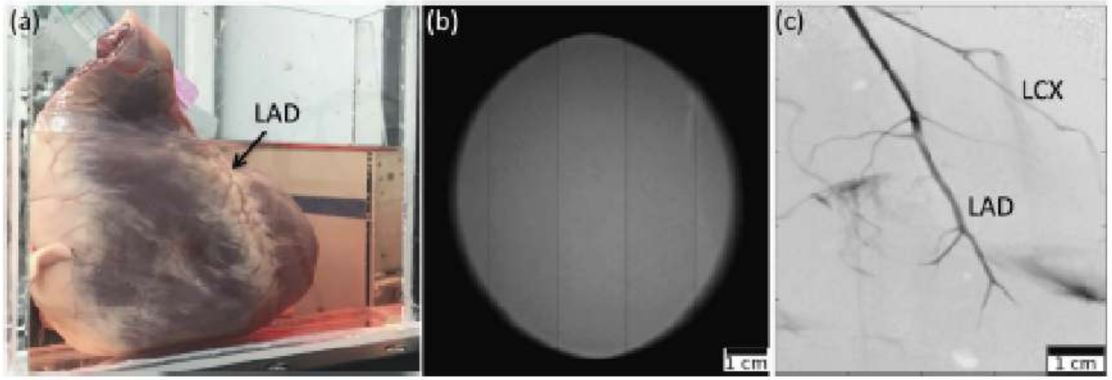
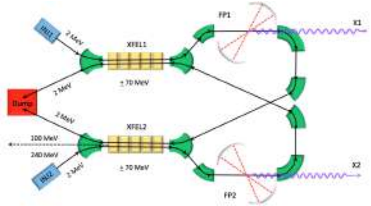


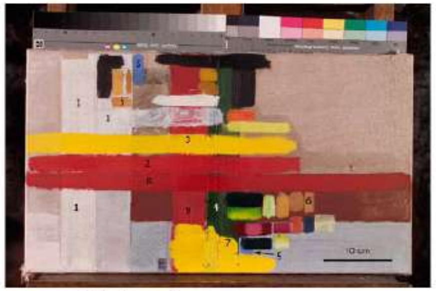
Figure 3. **MuCLS angiography image.** (**a**) Photograph of the sample in waterbath. (**b**) Empty image of full MuCLS beam. (**c**) Quasi-mono-energetic angiography image of a porcine heart acquired at the MuCLS, with iodine-based contrast agent injected into the left coronary artery. Visible are the left anterior descending artery (LAD) and the left circumflex artery (LCX).

ROI	90 kVp	55 keV	gain	90 kVp	55 keV	gain
	75 mg/ml gadolinium			50 mg/ml gadolinium		
1	5.27 ± 0.18	7.42 ± 0.32	41%	3.55 ± 0.17	5.01 ± 0.13	41%
2	1.78 ± 0.41	2.87 ± 0.28	62%	1.27 ± 0.30	1.65 ± 0.22	30%
3	3.91 ± 0.15	5.57 ± 0.20	43%	2.40 ± 0.17	3.62 ± 0.18	51%
4	4.75 ± 0.15	6.75 ± 0.27	42%	3.04 ± 0.21	4.53 ± 0.29	49%
5	3.93 ± 0.17	5.69 ± 0.31	45%	2.64 ± 0.20	3.77 ± 0.16	43%
6	30.19 ± 0.95	33.83 ± 0.89	12%	24.93 ± 0.55	29.45 ± 0.87	18%

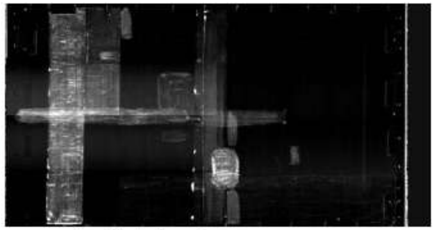
Table 2. CNR calculated from simulated projections for two different concentrations of gadolinium-based contrast media. The standard deviation from the statistical variation of the simulation is given with the mean value of the CNR of the 10 simulation runs.

K Edge imaging per Beni Culturali, XRF, realizzato a ESRF

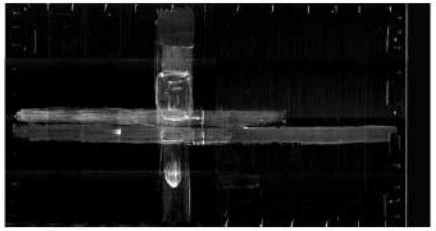




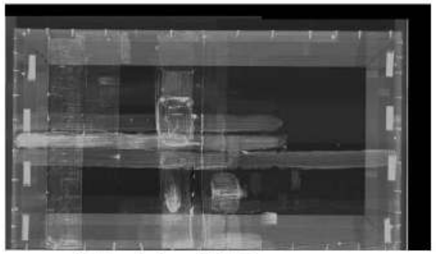
Optical image of test canvas



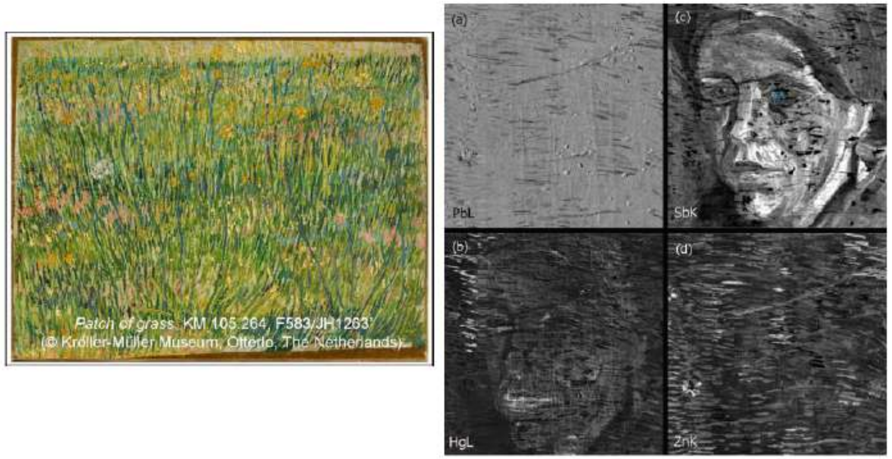
Lead K-edge image of test canvas



Barium K-edge image of test canvas



Radiograph taken at 50 keV of test canvas



Analyse d'une peinture de Vincent Van Gogh par Sy-XRF

K. Janssens, J. Dik, et al. *Anal. Chem*, 2008

J. Dik, ESRF, ID17

Requirements table for the analysis techniques used in heritage studies.

	XRF	XRD	XANES	Tomography	Edge enhancement	Phase contrast	Magnification
Energy range [keV]	6.5–92	10–92	6.5–92	20–100	7–100	10–30	10–100
$\Delta E/E$	1–3%	3–10%	5–10%	3% bw	3–10%	3% bw	3% bw
Source size				10–100 μm	10–100 μm	Very small	Very small
Size on the object	20 μm	20 μm	20 μm	10–50 cm	50 cm	50 cm	1–50 mm
Flux on the object [ph/s]	10^9–10^{10}	10^9 ph/s	10^7 ph/s	10^{11}	10^9	10^{11}	10^{11}
Acquisition time	1–60 s	1–300 s	2000 s				
Coherence				No	No	Yes	No

A collection of more than 1800 carbonized Greek and Latin papyri, discovered in the Roman 'Villa dei Papiri' at Herculaneum in the middle of 18th century, is the unique classical library survived from antiquity. These ancient-Herculaneum-papyri were charred during 79 A.D. Vesuvius eruption, a circumstance which providentially preserved them until now. This magnificent collection contains valuable work by Greek philosophers, such as Epicurus, Chrysippus and Philodemus, in particular an impressive amount of extensive treatises by Philodemus of Gadara, an Epicurean philosopher of the 1st century BC[1,2].

The aim of the present study is to read extended and hitherto unknown portions of text hidden inside carbonized-Herculaneum-papyri using enhanced X-ray-phase-contrast-tomography (XPCT) non-destructive technique[3,4] and a new set of numerical algorithms for 'virtual-unrolling'.

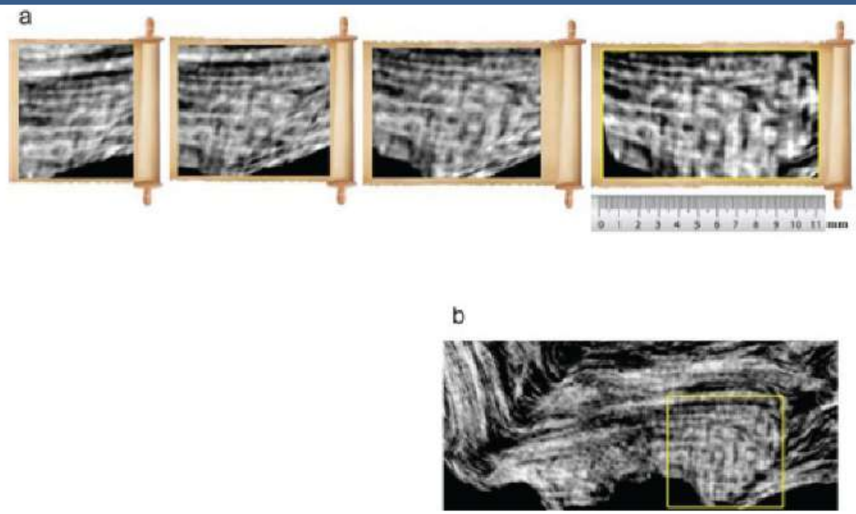


Figure 1: ***PHerc*. 375**. **a,** virtual-unrolling; **b** textual portion.

Radio-terapia con raggi X monocromatici del glioblastoma cerebrale, basato su attivazione Auger di cisplatino nelle cellule tumorali. Gli elettroni Auger attivati mediante K-edge dai fotoni X depositano radiazione solo all’interno del tumore.

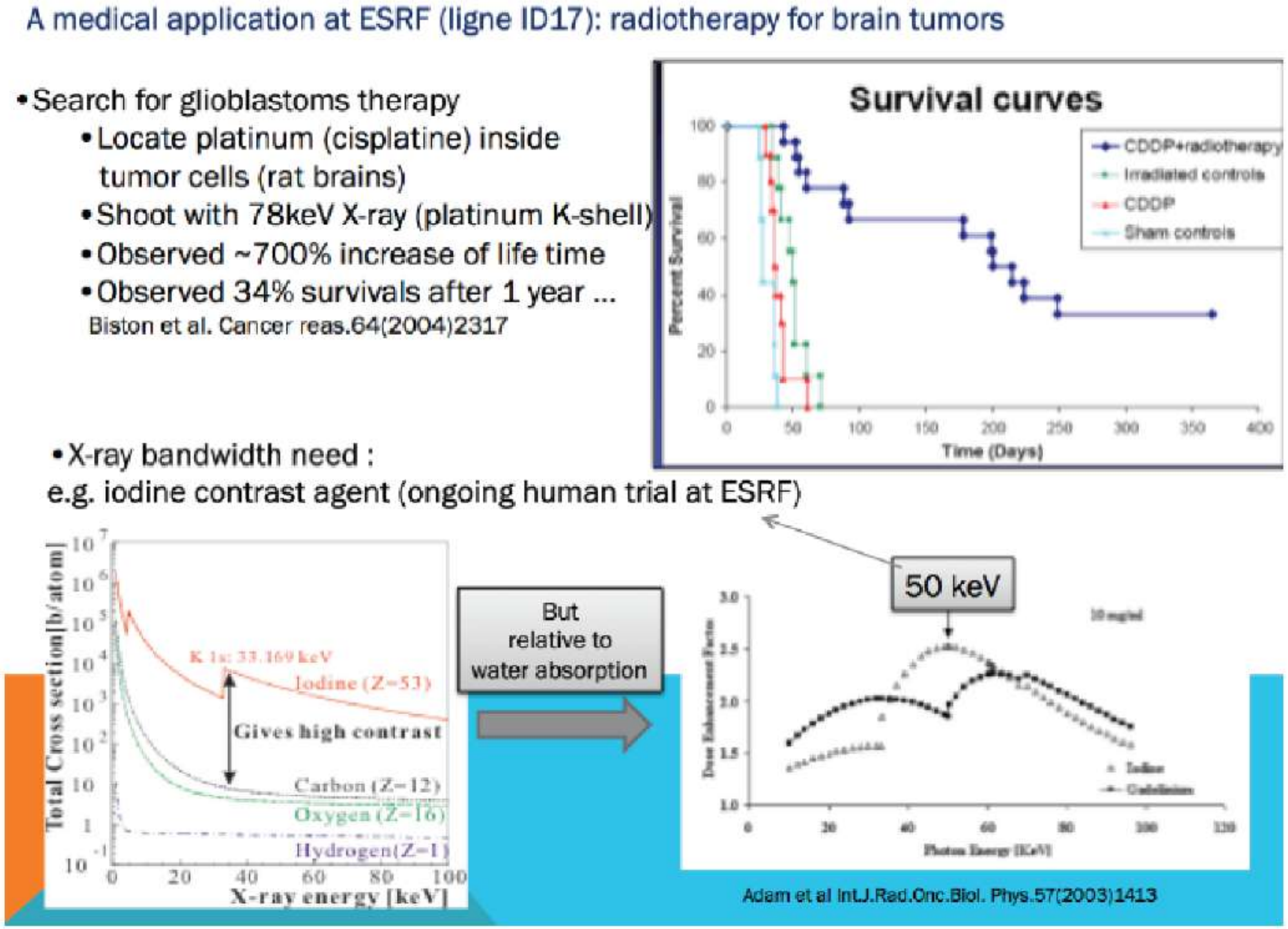
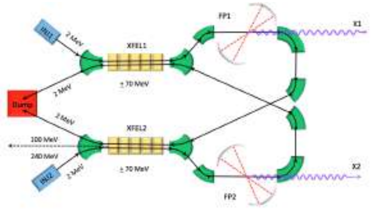


Fig.10 – *Radio-Therapy using mono-chromatic X-rays joined to cisplatine chemio-therapy for selected X-ray absorption inside tumoral cells.*

Per una review omni-comprensiva delle applicazioni delle sorgenti Thomson/Compton si veda la present. di A. Variola (INFN-LNF) al PAHBB-2016 Workshop (https://conferences.pa.ucla.edu/hbb/index.html)

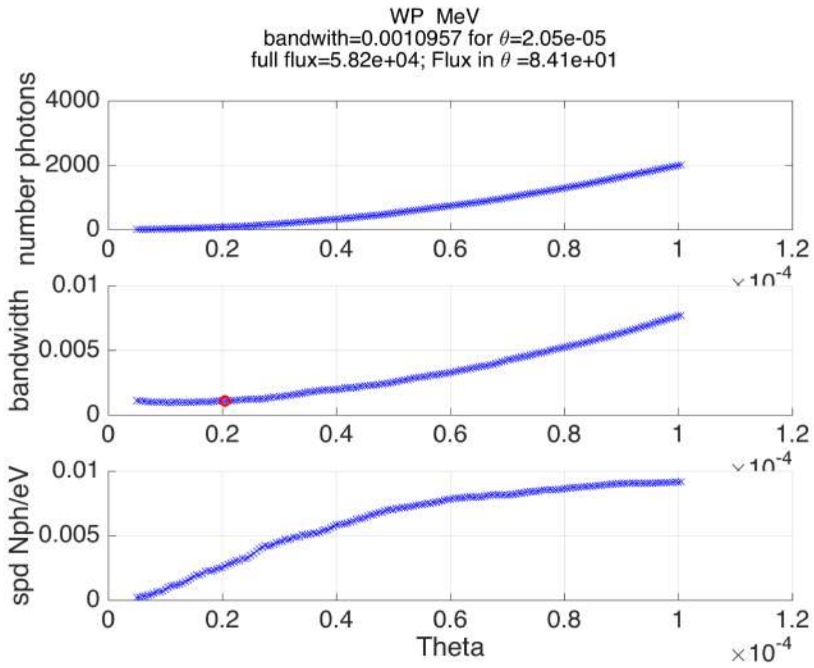


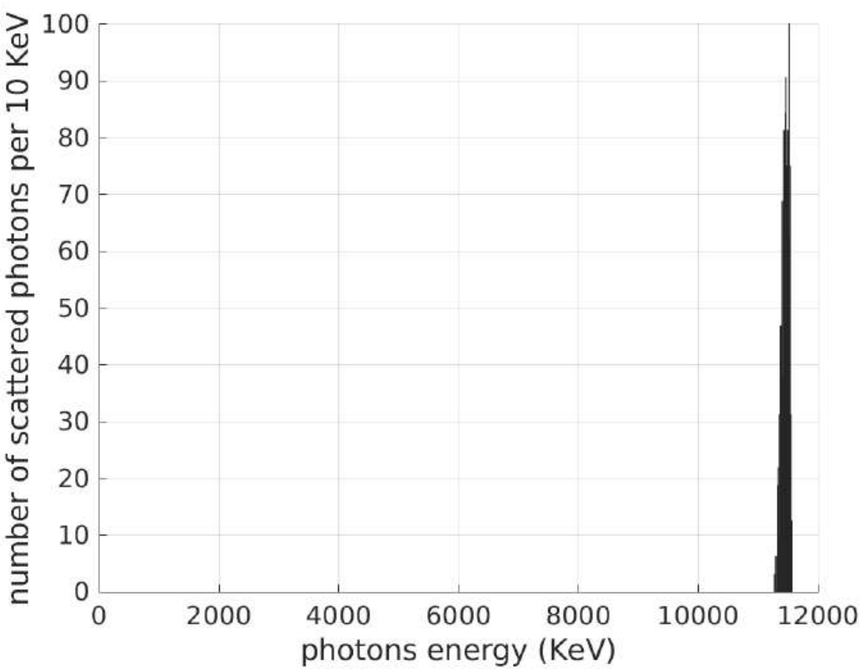
Courtesy I. Drebot

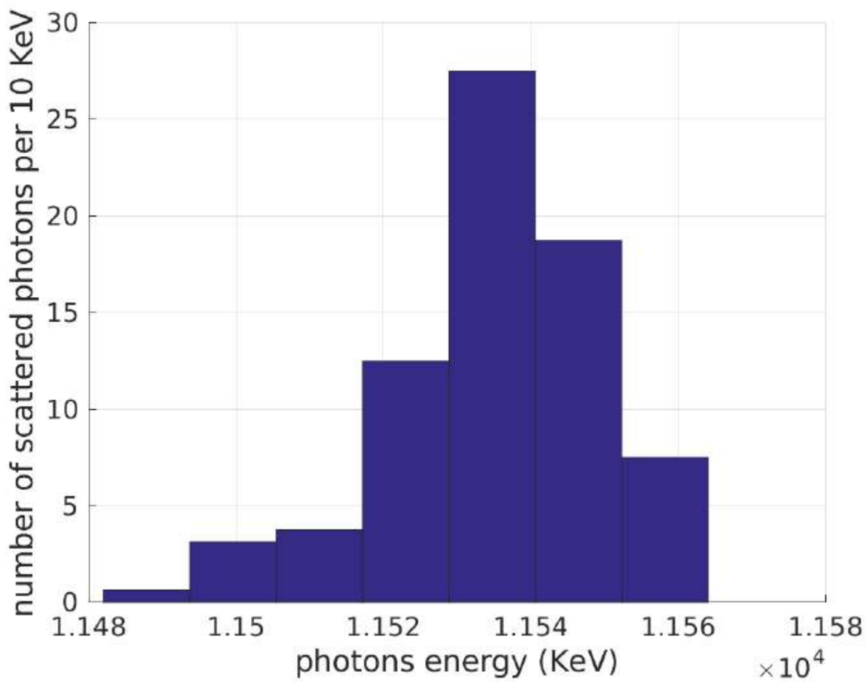
Mono-chromatic MeV γ-ray beam from Compton Source at 800 MeV:

about 100 photons per pulse @ 11 MeV

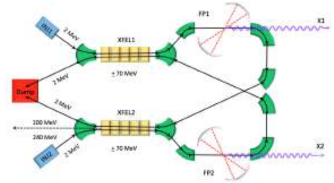
1 MHz rep rate CW in 0.1% $\Delta\nu/\nu$, tunable, polarized, Spectral Density $1.1 \cdot 10^5$ photons/s·eV

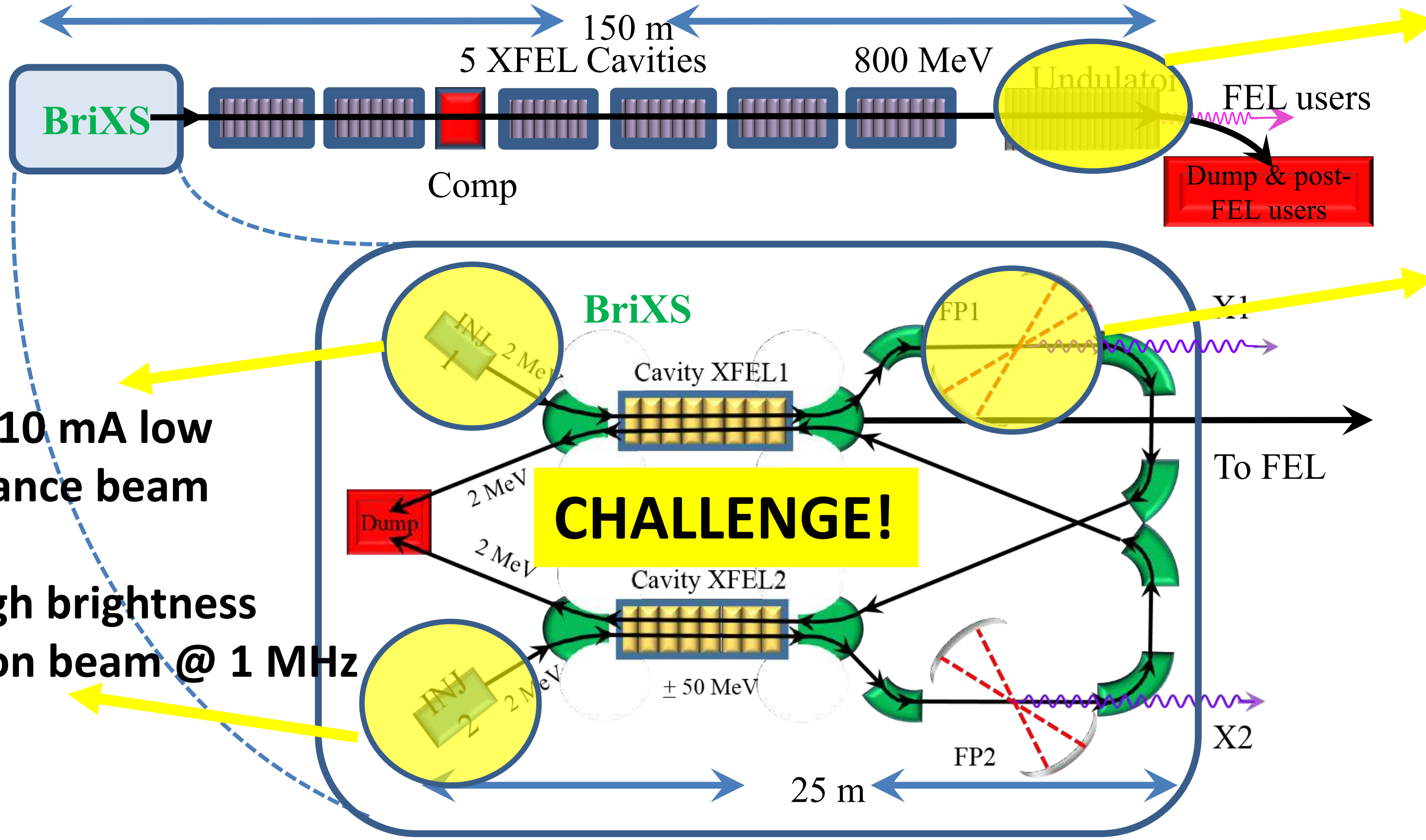






Technical Challenges: overcome the state of the art by a factor 2-4





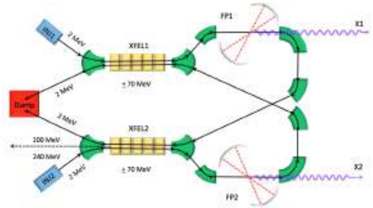
λ_w = 2-4 mm !

0.5 MW optical power stored in FP cavity!

up to 10 mA low emittance beam

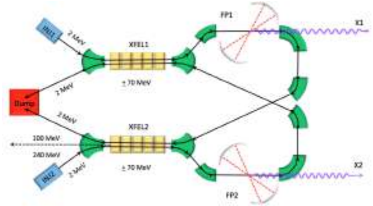
FEL high brightness electron beam @ 1 MHz

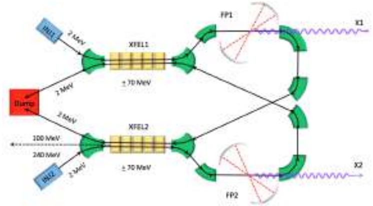
R&D necessary for the next 3-4 years on critical components

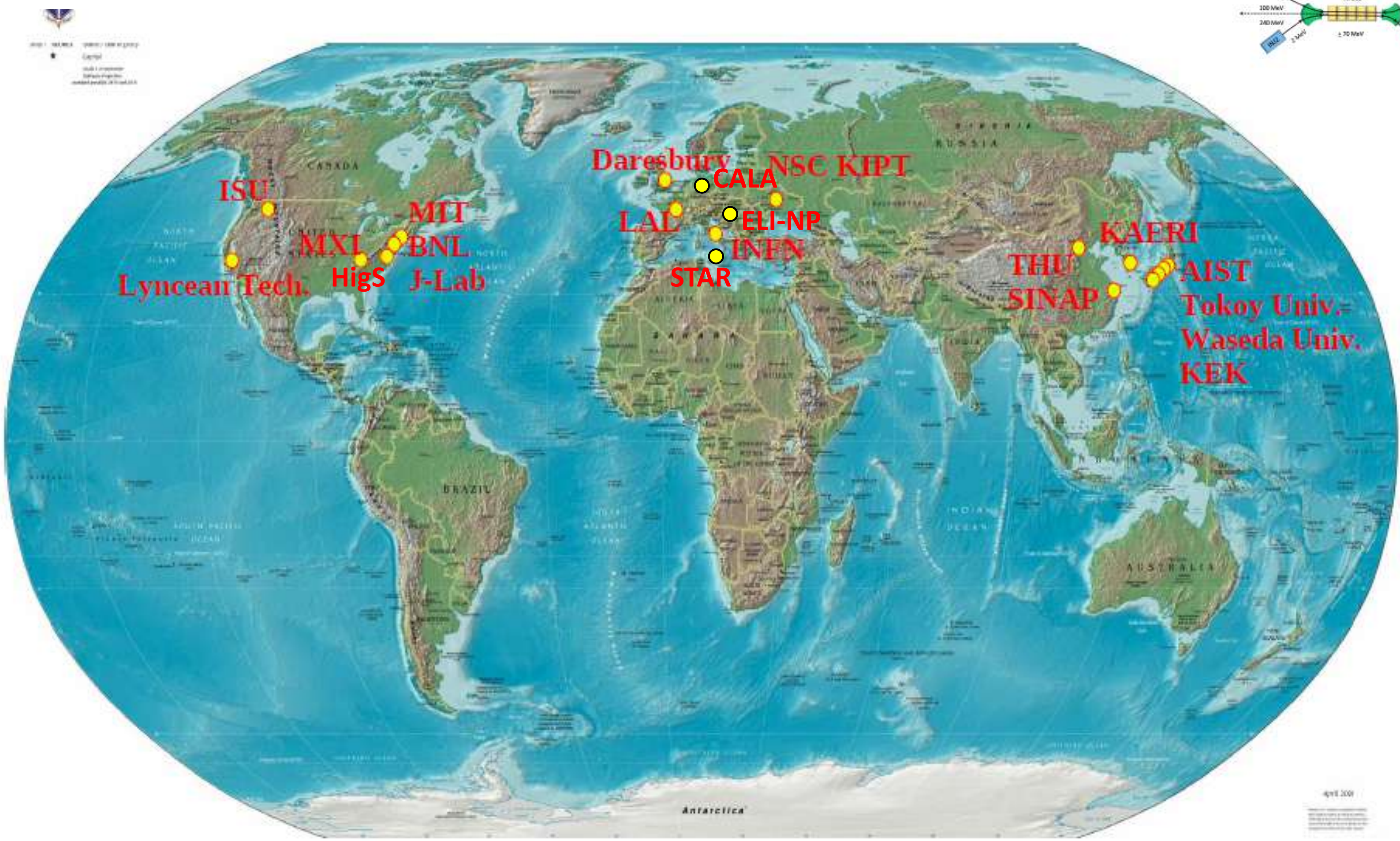


MariX/BriXS - Working Groups

1. Interactions, X-Ray Spectra
2. FEL Theory and Simulations
3. Beam Dynamics, Transport lines
4. Lasers and Fabry-Perot Cavities
5. Injectors
6. Magnets, Power Supply
7. RF Power Sources
8. SC RF Cavities and Cryo-Modules
9. Energy Recovery and Beam Dumps
10. Beam, Collision Diagnostics & Collimation
11. X-ray Detectors
12. FEL undulators
13. FEL beam lines
14. Electronic Systems and Controls
15. Engineering, CAD
16. Infrastructure, Plants
17. Radiation Safety
18. Liaison with Users and Applications
19. Post FEL dump and additional beam lines


FP1
X1
XFEL1
± 70 MeV
XFEL2
100 MeV
240 MeV
± 70 MeV
X2
FP2





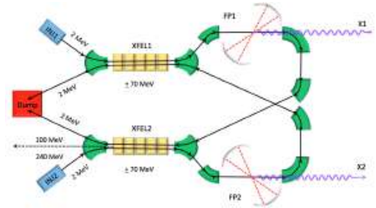
Le Sorgenti Thomson/Compton sono gli "acceleratori di fotoni" piu' efficaci

"$4\gamma^2$ boost effect"

$$E_{X/\gamma} = 4\gamma^2 E_{laser}$$

Courtesy A. Variola

$$with\ T = 100 MeV\ (\gamma = 197)\ E_{laser} = 1.2\ eV \Rightarrow E_{X/\gamma} = 186\ keV$$



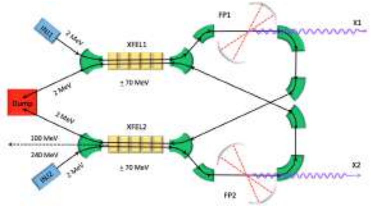
I competitors in ambito Europeo:

STAR a UniCAL (Cosenza)

ThomX a Orsay/LAL (Francia)

Collisore elettrone-fotone altamente asimmetrico e compatto* (cfr. LHC)

*10 m, 10 M$



Fascio secondario di fotoni prodotto grazie al grande boost di Lorentz del sistema di riferimento del centro di massa elettrone-fotone (cfr. LHC, simmetrico, zero boost di Lorentz)

Fig.2 *– STAR machine as an example of Paradigm A. Overall length about 12 m.*

Nuova Generazione

Elettroni con energia nel range 10-100 MeV collidono contro fotoni laser con energia nel range 1-3 eV

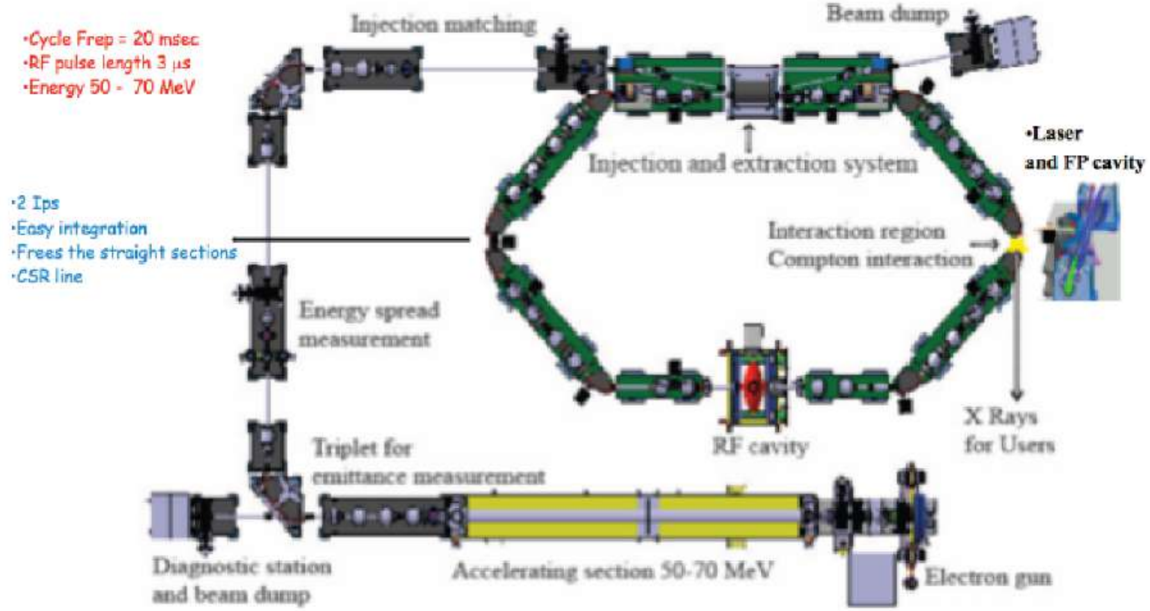
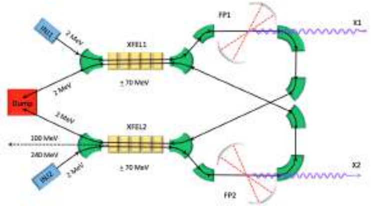


Fig.3 *– ThomX as an example of Paradigm B. Size is about 10x10 m^2.*



E17 Lehrstuhl für Biomedizinische Physik

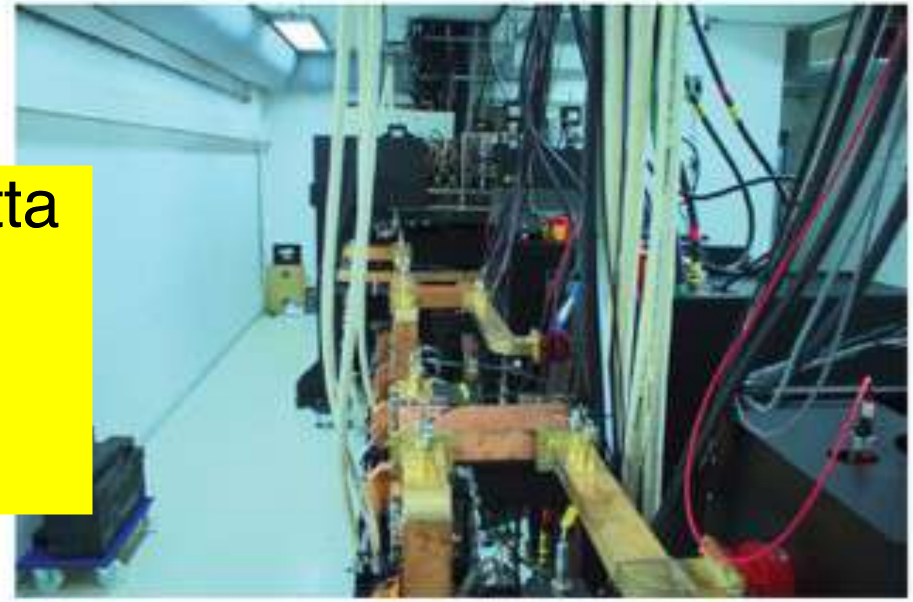
CALA

Technische Universität München TUM

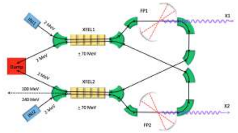
Biomedical imaging with the lab-sized laser-driven synchrotron source Munich Compact Light Source

Klaus Achterhold

Biomedical Physics, Physics-Department E17, Technische Universität München

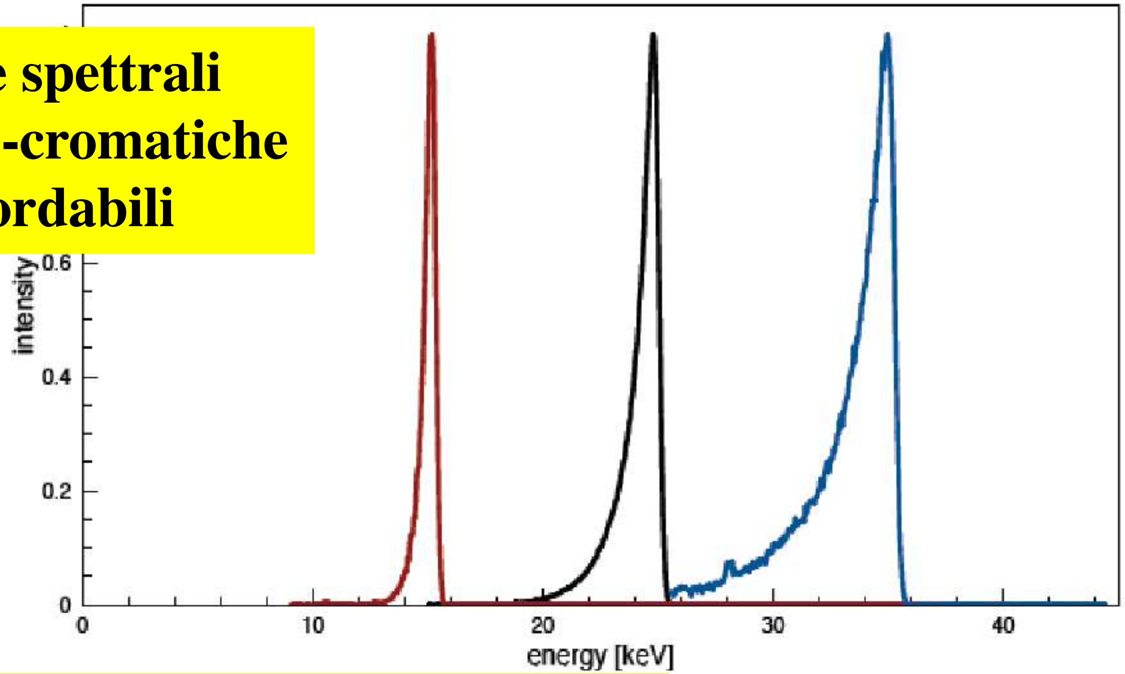


macchina compatta
10x10 m^2
In operazione dai
primi del 2015



$$E_x\left(\Theta,\alpha,E_L,T\right)=\frac{\left(1+\beta\cos\alpha\right)E_L}{1-\beta\cos\Theta+\left(E_L/mc2\right)\left(1+\cos\left(\Theta+\alpha\right)\right)}$$

Righe spettrali mono-cromatiche e accordabili



measured

Spectrum of X-rays into +/- 2 mrad

Bandwidth

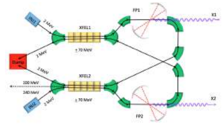
Flusso misurato

$1.5 \cdot 10^{10}$ fotoni/s con 10 mA

$35000+0.0016 \cdot \Delta T$ with $\Delta T/T=0.3\%$

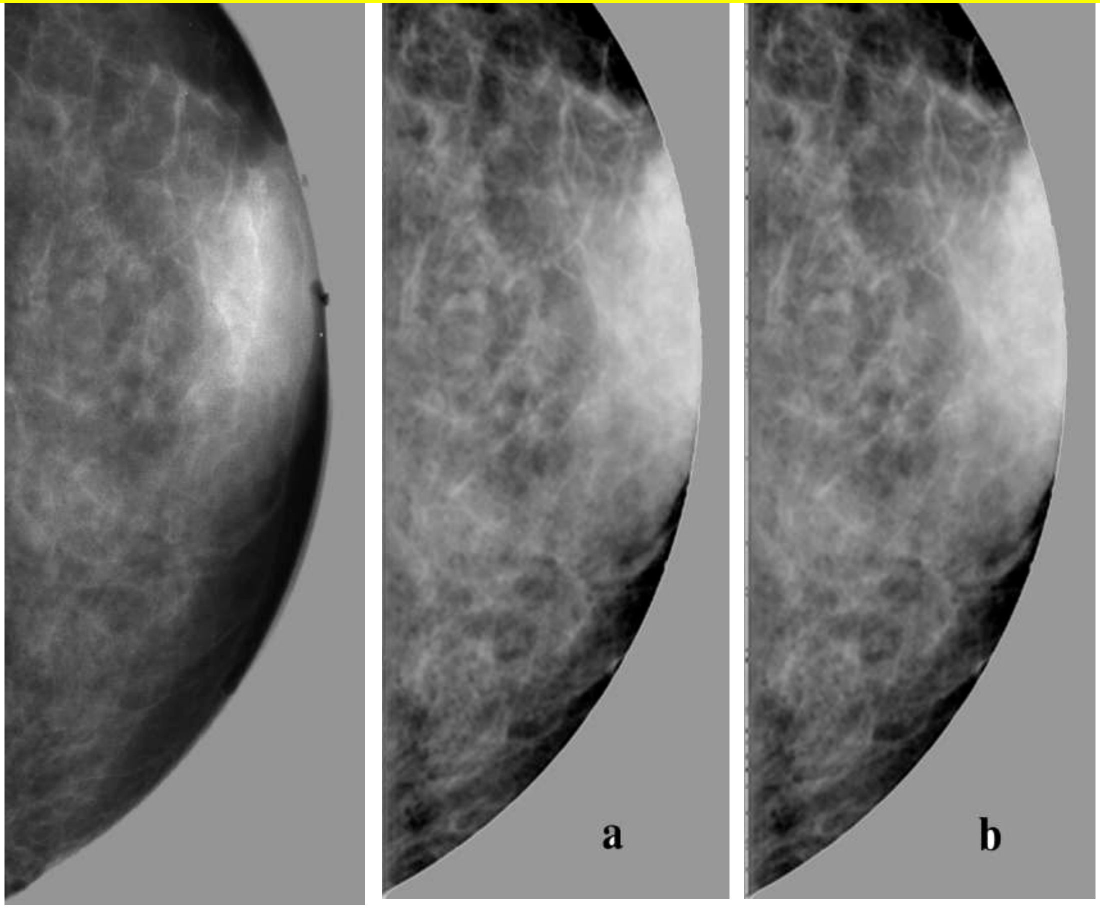
$35000+30000 \cdot \Delta E_L$ with $\Delta E_L/E_L=10^{-12}$

$35000-9000 \cdot \Delta\alpha^2$ with $\Delta\alpha=0.03$



La Mammografia con Raggi X Mono-cromatici a 20 keV e' gia' stata dimostrata essere di gran lunga superiore nel rapporto Segnale-Rumore rispetto ai tubi Mammografici convenzionali, con una dose di radiazione ai tessuti di gran lunga inferiore (esperimenti alle facilities di Luce di Sincrotrone)

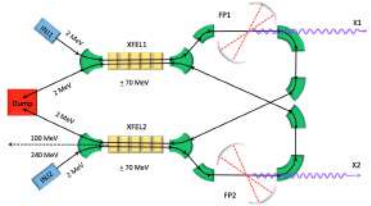
Conventional
X-ray tube 26 kVp
MGD 1 mGy



a) SR digital image
Energy 17 keV
Scan step 100 mm
MGD 1 mGy

b) SR digital image
Energy 20 keV
Scan step 100 mm
MGD 0.33 mGy

3 cm thick in vitro human breast tissue



Basso rate di pazienti diagnosticati al Sincrotrone, in pratica solo i dubbi falsi positivi vengono indirizzati al Sincrotrone a valle della diagnostica con strumenti convenzionali

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Phys. Med. Biol. 61 (2016) 1634–1649 — doi:10.1088/0031-9155/61/4/1634

Towards breast tomography with synchrotron radiation at Elettra: first images

Portare i pazienti in Ospedale non al Sincrotrone…
realizzare un Sincrotrone-equivalente (Sorgente Thomson) che possa funzionare all'interno dell'Ospedale

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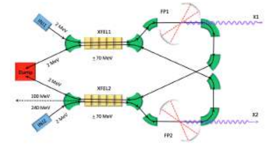
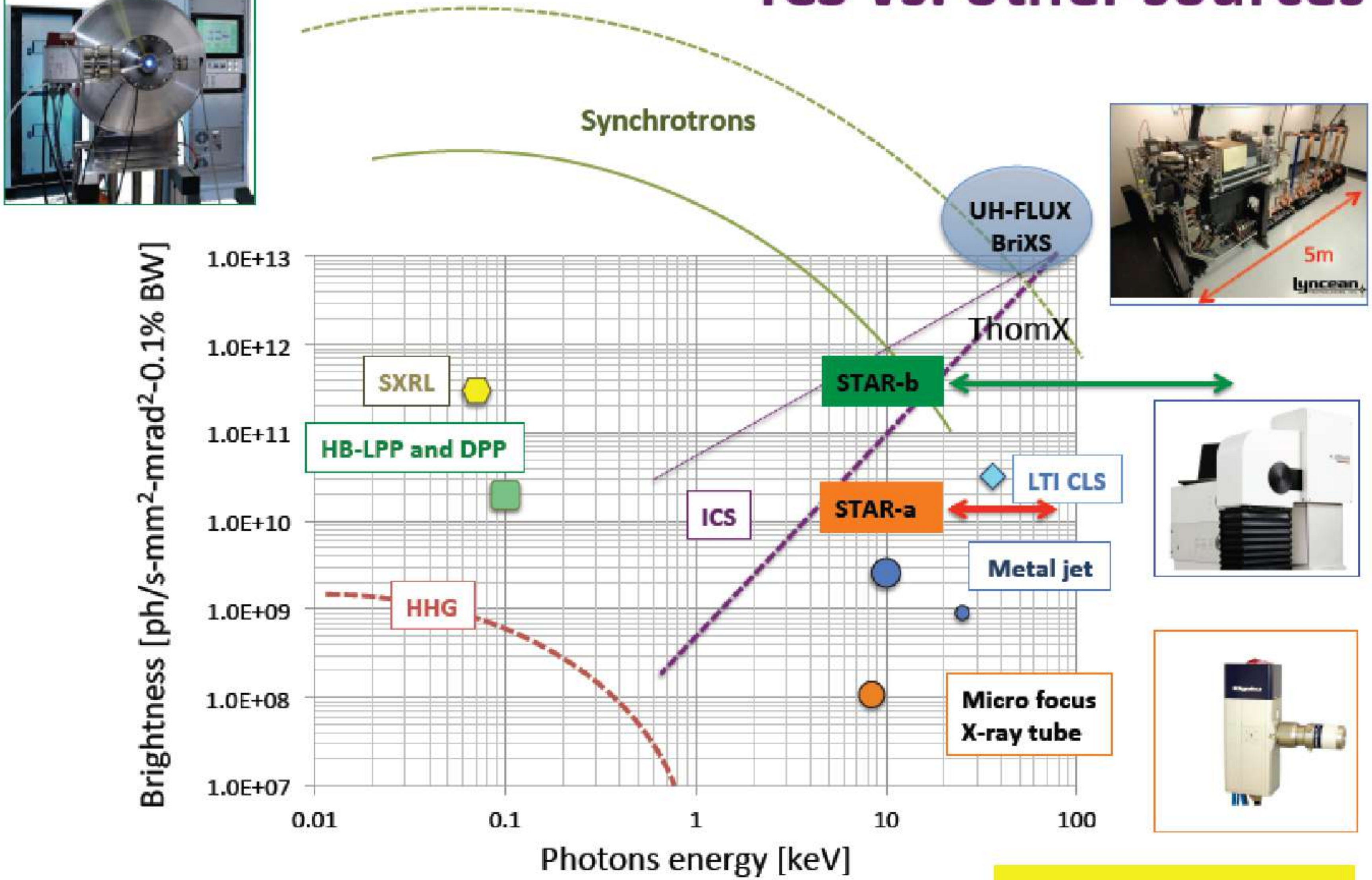
P Russo[9], A Sarno[9], G Spandre[3,4], G Tromba[10] and
F Zanconati[13]



ICS vs. other sources



Courtesy of A. Murokh
RadiaBeamTechnology

Brilliance of Lasers and X-ray sources

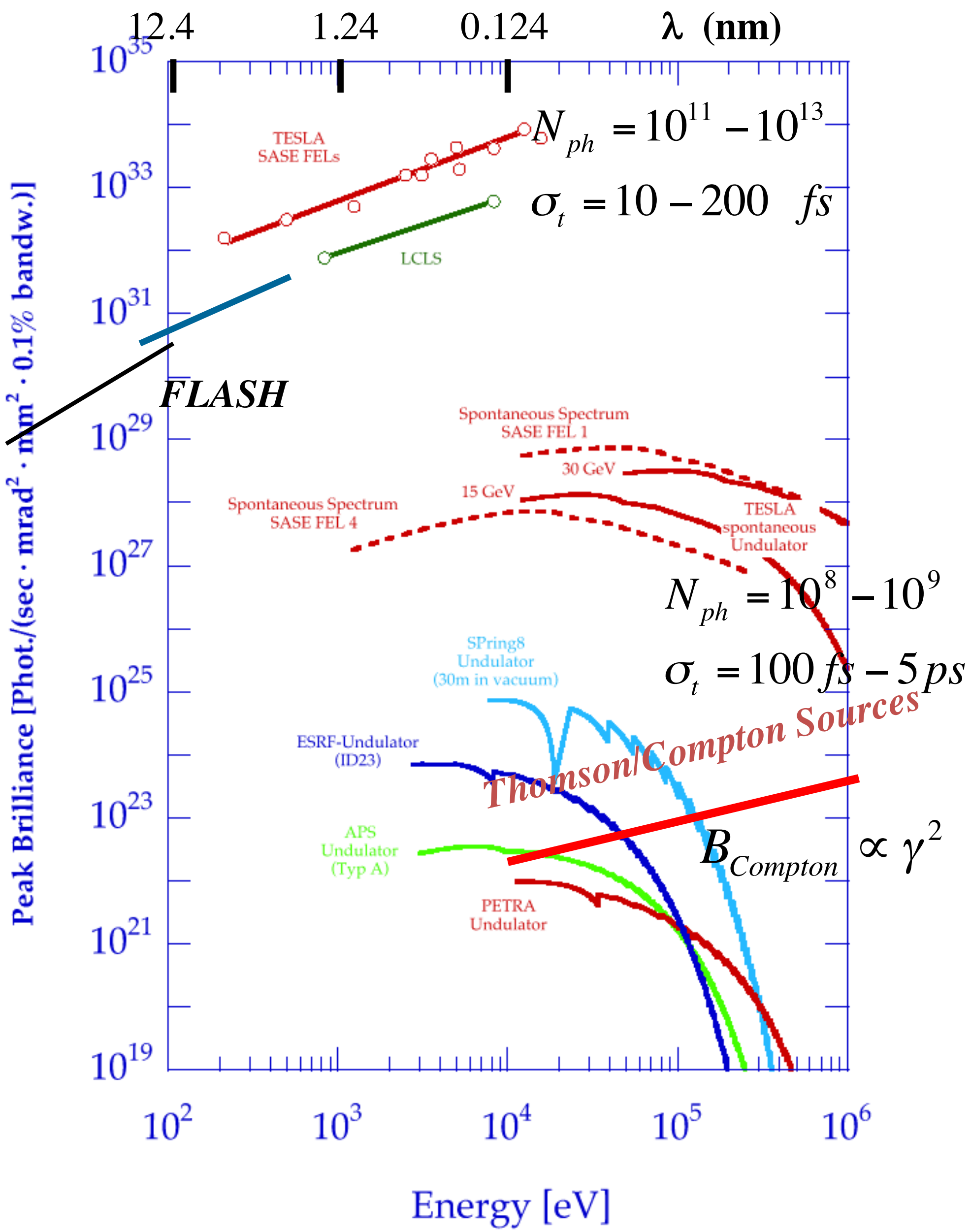
ELI

BELLA

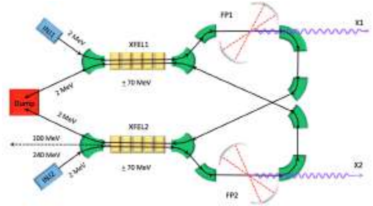
$$N_{ph} = 10^{19} - 10^{20}$$

$$\sigma_t = 10 - 20 \quad fs$$

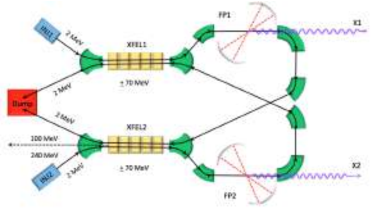
$$B = \frac{N_{ph}}{\sqrt{2\pi}\sigma_t \left(M^2\lambda\right)^2 \frac{\Delta\lambda}{\lambda}}$$



Outstanding X/γ photon beams for Exotic Colliders


FP1
X1
XFEL1
± 70 MeV
Dump
XFEL2
100 MeV
240 MeV
± 70 MeV
X2
FP2

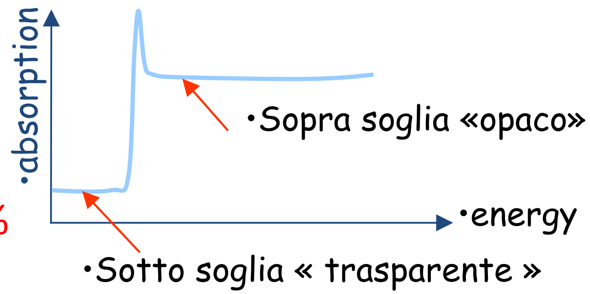
Imaging con tecnica K Edge: richiede fascio X monocromatico e accordabile con energie al di sotto e al di sopra della soglia (K-edge) del materiale di contrasto impiegato



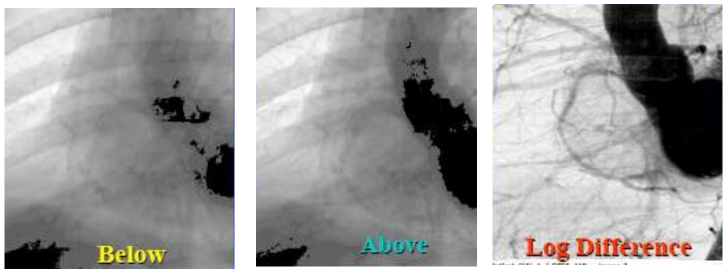
Imaging a sottrazione, a cavallo del K-edge (substraction imaging)

presso European Synchrotron Radiation Facility (la Sorgente di Luce di Sincrotrone Europea a Grenoble)

- Energia accordabile
- Banda fotoni X: 2-3%



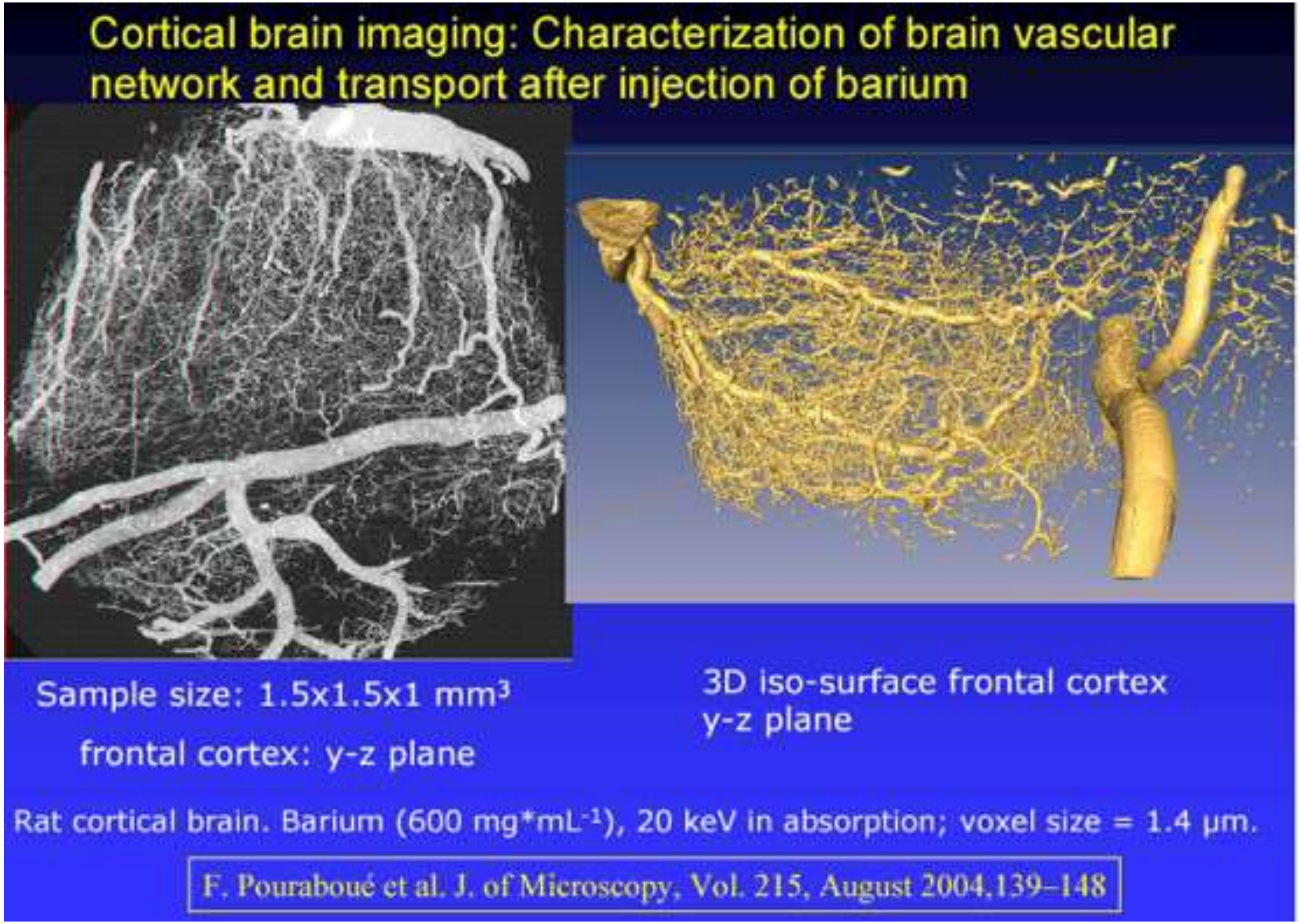
- K-edge a ESRF (usando un agente di contrasto)

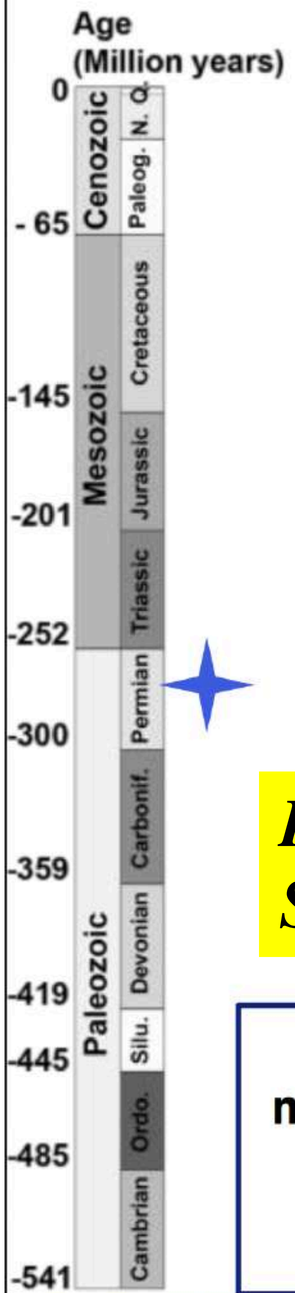


→ La differenza delle due immagini (digitale) aumenta grandemente il contrasto

courtesy of A. Bravin (ESRF)

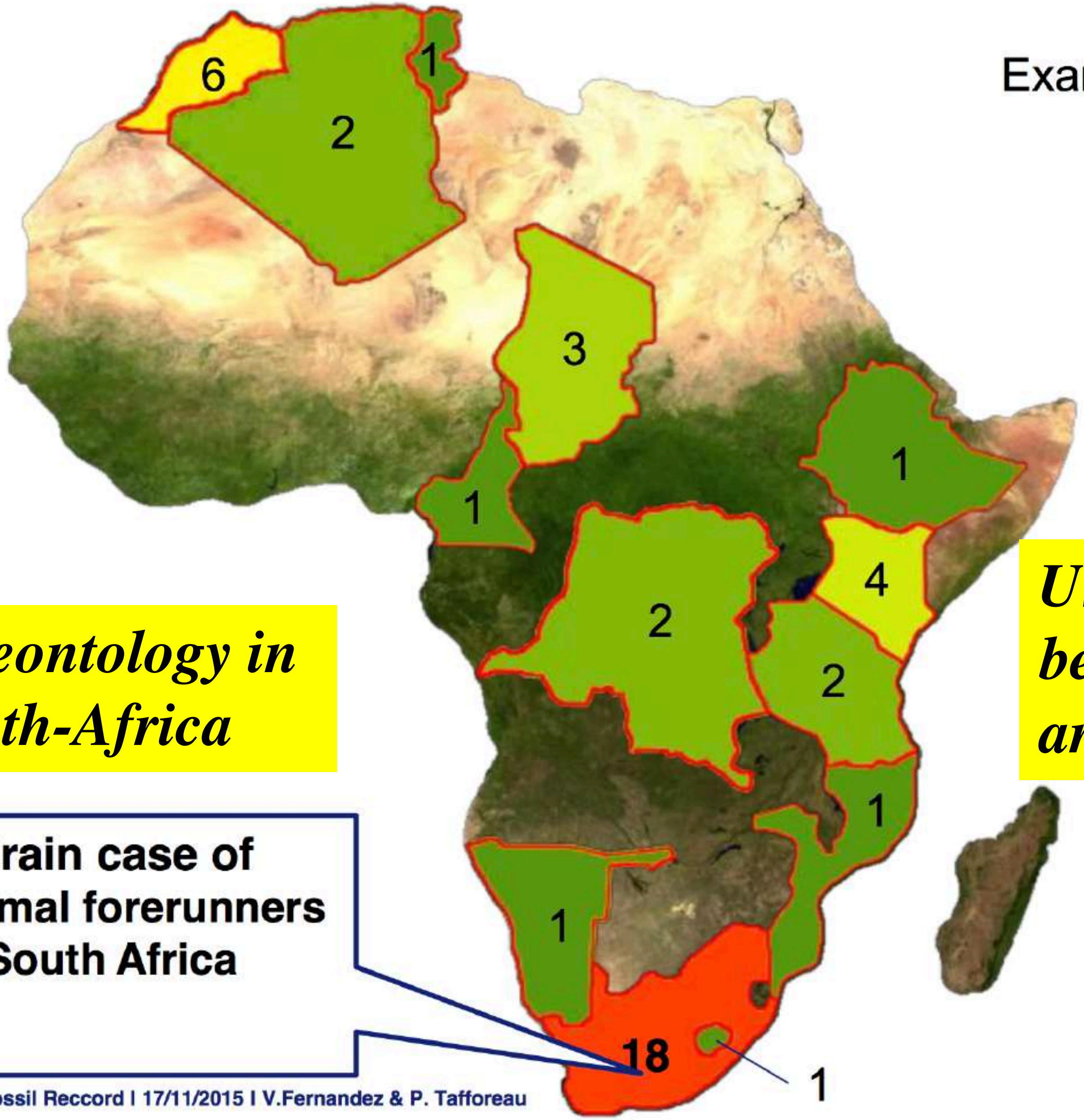
Esempi di Imaging Avanzato Bio-Medicale con raggi X monocromatici.





Number of articles or (ongoing) projects per country

Example of ongoing projects



Paleontology in South-Africa

Users for X-ray beam lines are there!

Brain case of mammal forerunners South Africa

Firmatari

INFN/Milan and Universita' degli Studi di Milano: *Alberto Bacci, Francesco Broggi, Fabrizio Castelli, Simone Cialdi, Camilla Curatolo, Carlo De Martinis, Illya Drebot, Grazia Gambarini, Dario Giove, Flavia Groppi, Maurizio Maugeri, Paolo Michelato, Stefano Olivares, Carlo Pagani, Matteo Paris, Vittoria Petrillo, Paolo Pierini, Nicola Piovella, Paolo Piseri, Marco Potenza, Massimiliano Rome', Andrea R. Rossi, Giorgio Rossi, Luca Serafini*[3]*, Daniele Sertore, Roberta Vecchi, Ivan Veronese*

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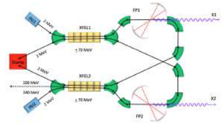

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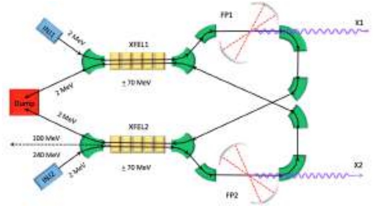
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