The ThomX ICS source

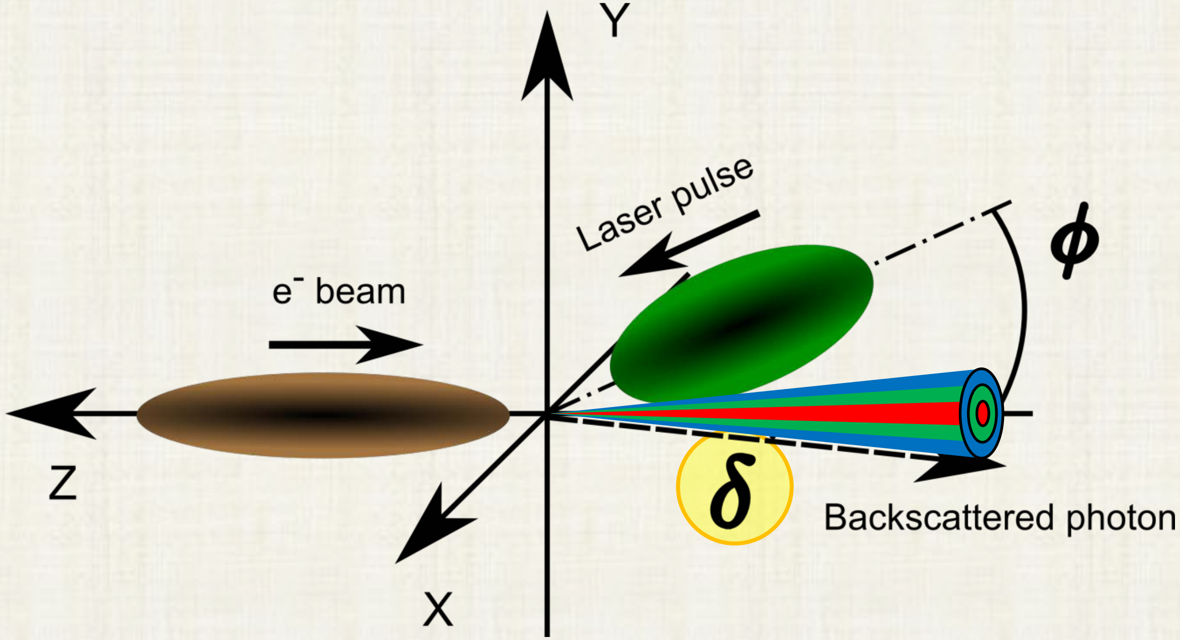
On behalf of ThomX group

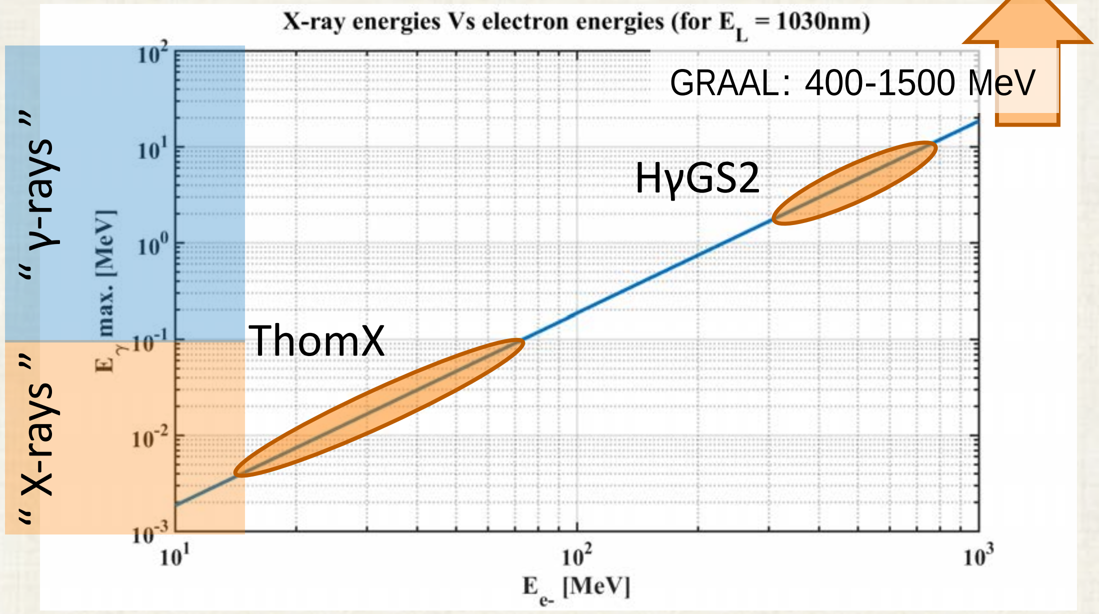
Programme Investissements d’avenir de l’Etat ANR-10-EQPX-51. Financé également par la Région Ile-de-France.
Program « Investing in the future » ANR-10-EQOX-51. Work also supported by grants from Région Ile-de-France.

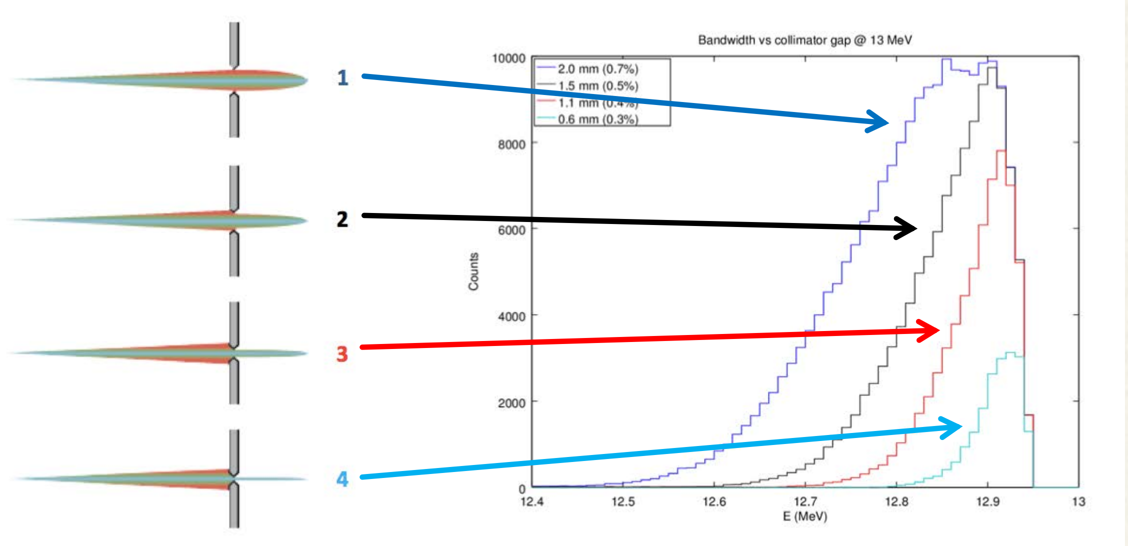
ICS source generalities

Compton Scattering

$$E_\gamma \simeq E_L \frac{4\gamma^2}{1+\gamma^2\delta^2+\frac{\phi^2}{4}}$$







M. Gambiccini, P. Cardarelli et al. technical design meeting collimation and characterisation system review

Compton Sources: scheme

Cross-section ≈ physics

$$\left\langle \frac{\mathrm{d}N}{\mathrm{d}t} \right\rangle = \sigma_T \mathcal{L}$$

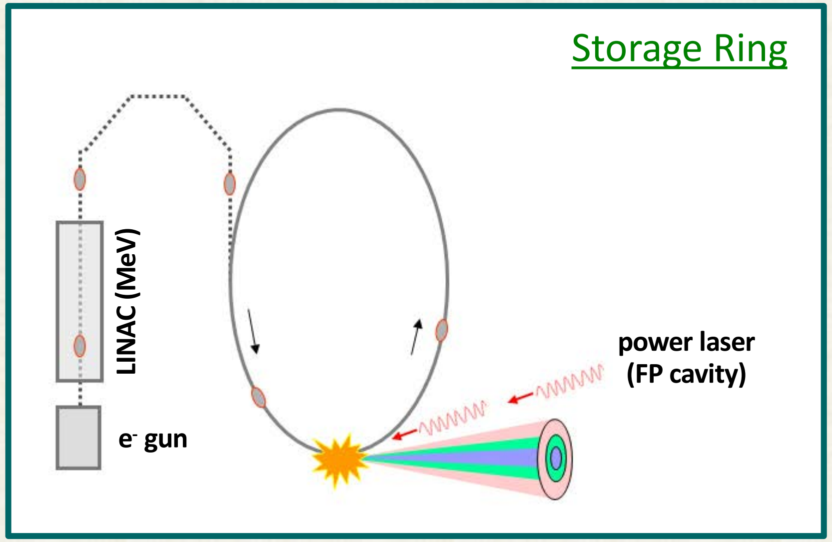
luminosity ≈ geometry

$$\sigma_T \approx 6.6 \times 10^{-25}\ \mathrm{cm}^2$$

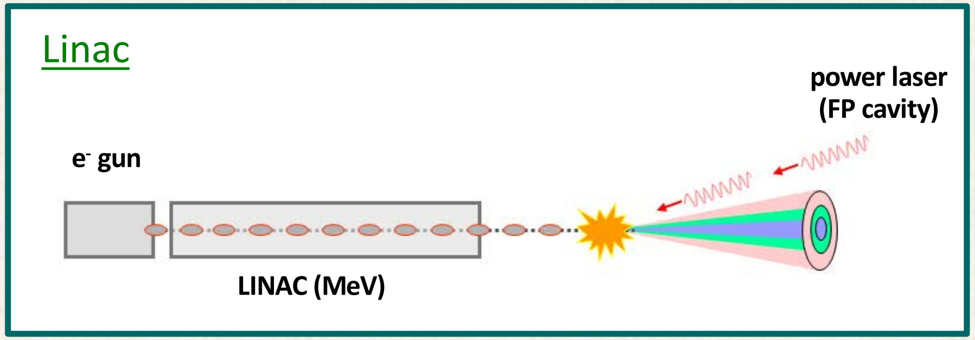
➔ Compton/Thomson cross section is “weak”

$$\mathcal{L} \approx \frac{f_{rep} N_e N_L}{2\pi\left(\sigma_e^2 + \sigma_L^2\right)}$$

2 main scheme



Storage Ring



Linac

1mJ/pulses

To obtain High flux (10^{12} – 10^{14} ph/sec) ➔ f_{rep} (~ 10-100 MHz) ➔ Laser Power = 100kW – 1MW

Brightness

$$B_x(\omega_x) = \frac{N_x K_{\omega_s}}{(2\pi)^{5/2}\Delta t_s x_s^2 x_s'^2}$$

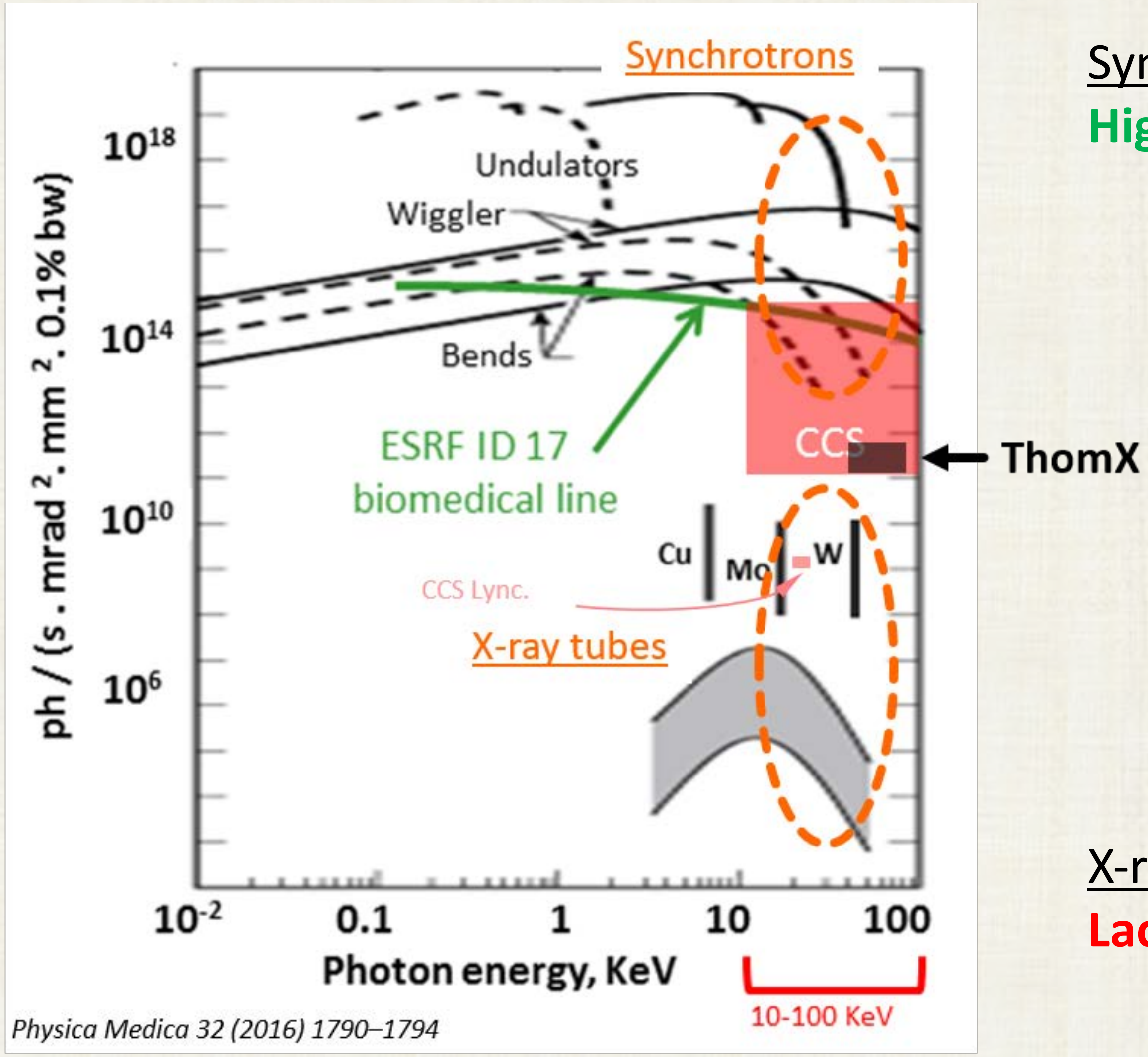
$$Br \approx 1.5\times 10^{-3}\frac{Flux}{(2\pi)^{5/2}}\underbrace{\left(\frac{\sigma_e^2+\sigma_L^2}{\sigma_L^2\Delta_t}\right)}_{\text{Size of the beams}}\underbrace{\left(\frac{\gamma^2}{\epsilon_N^2}\right)}_{\text{electrons}}$$

How to go further (more brilliance):

- More X-ray flux:
  - ↑ Rep. Rate
  - ↑ e- beam charge
  - ↑ laser power
- Less X-ray divergence (better electron beam):
  - ↓ e- beam emittance
  - ↑ e- beam energy
- Smaller source spot size:
  - ↓ laser beam waist size ➔ ↑ beam size on mirrors
  - ↓ e- beam size

Brightness Optimization of Ultra-Fast Thomson Scattering X-ray Sources, *UCRL-PROC-206030, (2004)*

Brightness of X-ray sources



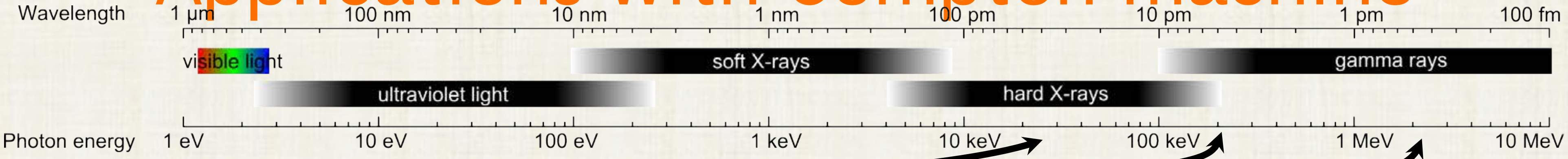
Physica Medica 32 (2016) 1790–1794

Synchrotron: **not very pratical, limited acces** time
High power, high monochromaticity, high coherence.

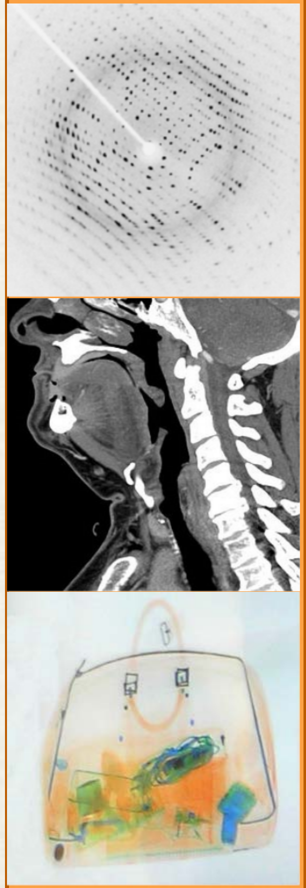
Compact Compton Source: **high brightness** beam in a **lab size** environment (hospitals, labs, museums).
Unusual beam properties
- **Compactness** (surface ~ 100 m^2)
- **X-ray energy tunable**
- **High X-ray energy range keV to MeV**
- High brightness $10^{11} – 10^{15}$ ph/(s.mm^2.mrad^2) in 0.1%BW
- flux 10^{12} - 10^{14} ph/s

X-ray tube: **lab size** sources
Lack of: power, monochromaticity, coherence.

Applications with Compton machine



X-ray Imaging

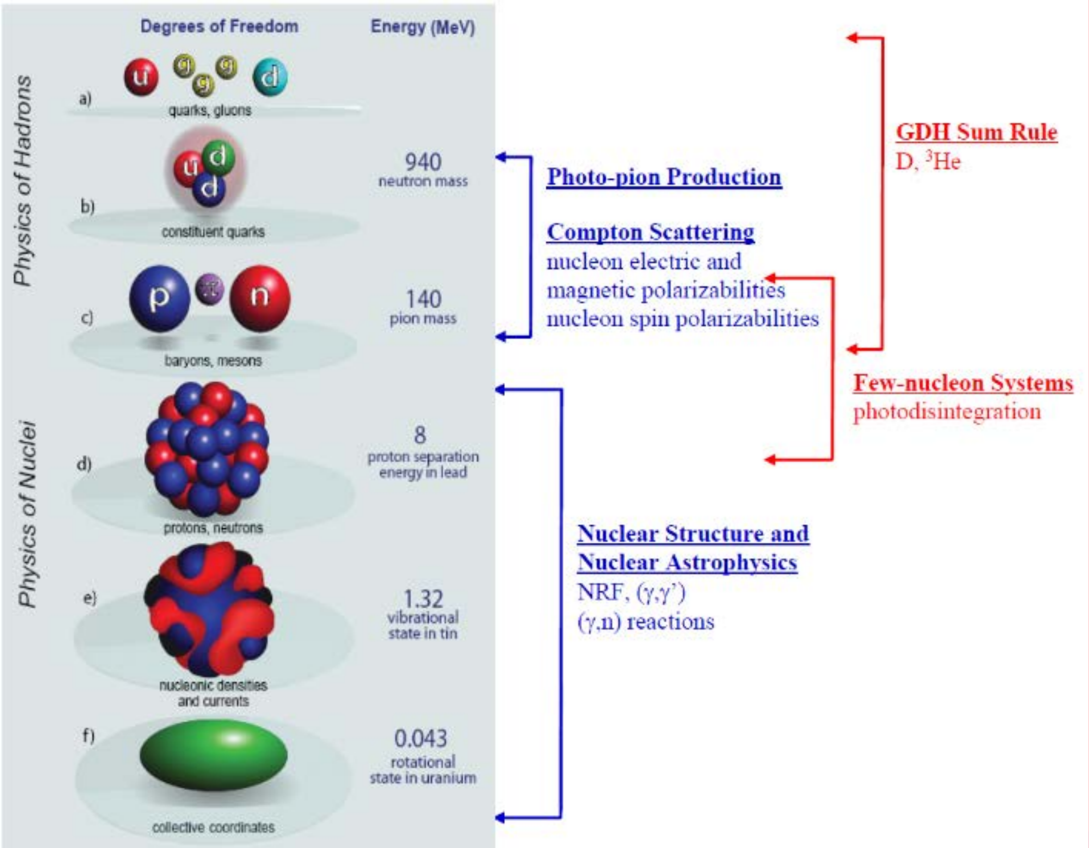


http://en.wikipedia.org/wiki/X-ray

Radiotherapy

http://en.wikipedia.org/wiki/Radiation_therapy

Nuclear Physics



http://www.tunl.duke.edu/documents/public/higs2_prospectus_31aug2012.pdf

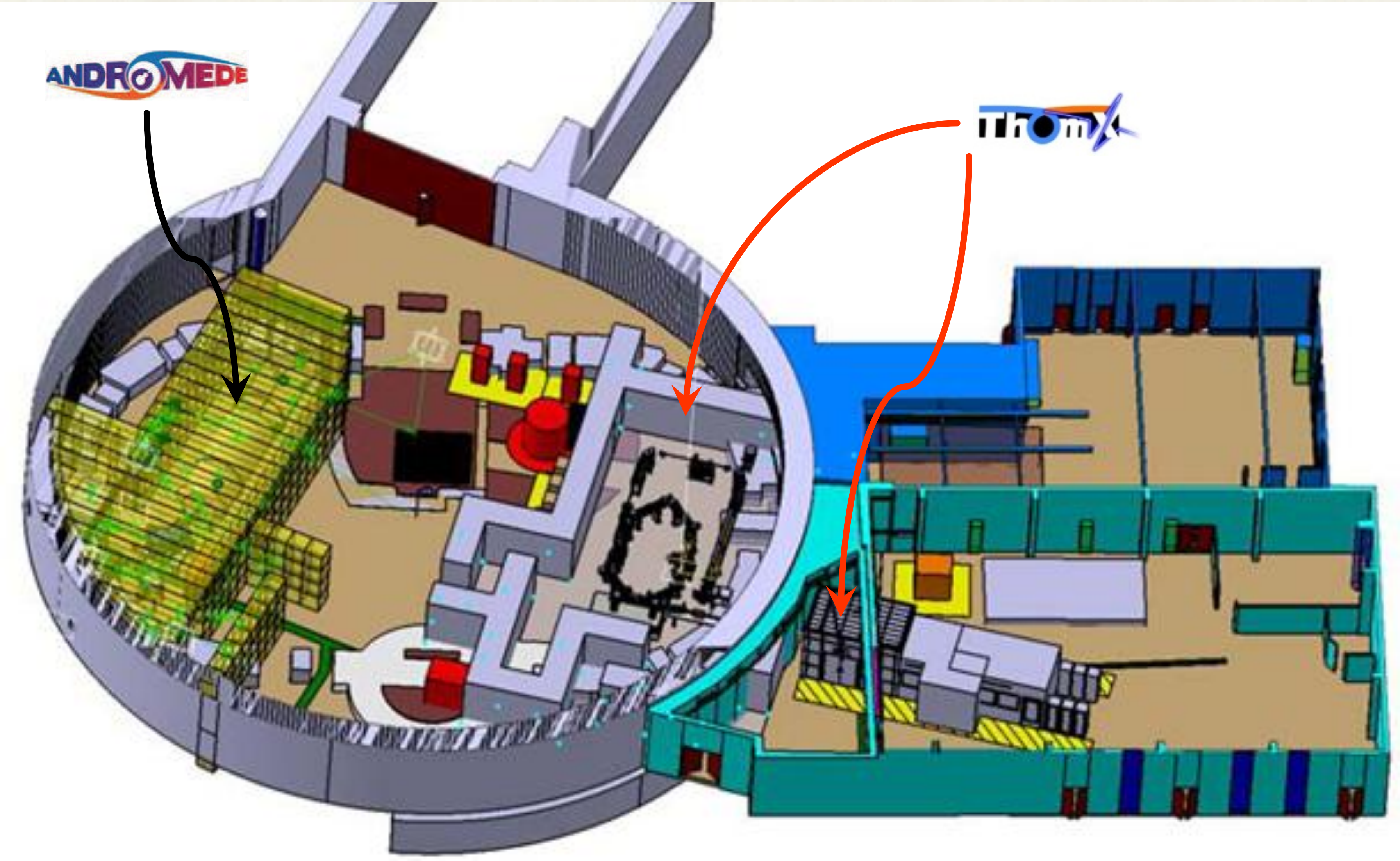
ThomX

A Compact Light Source

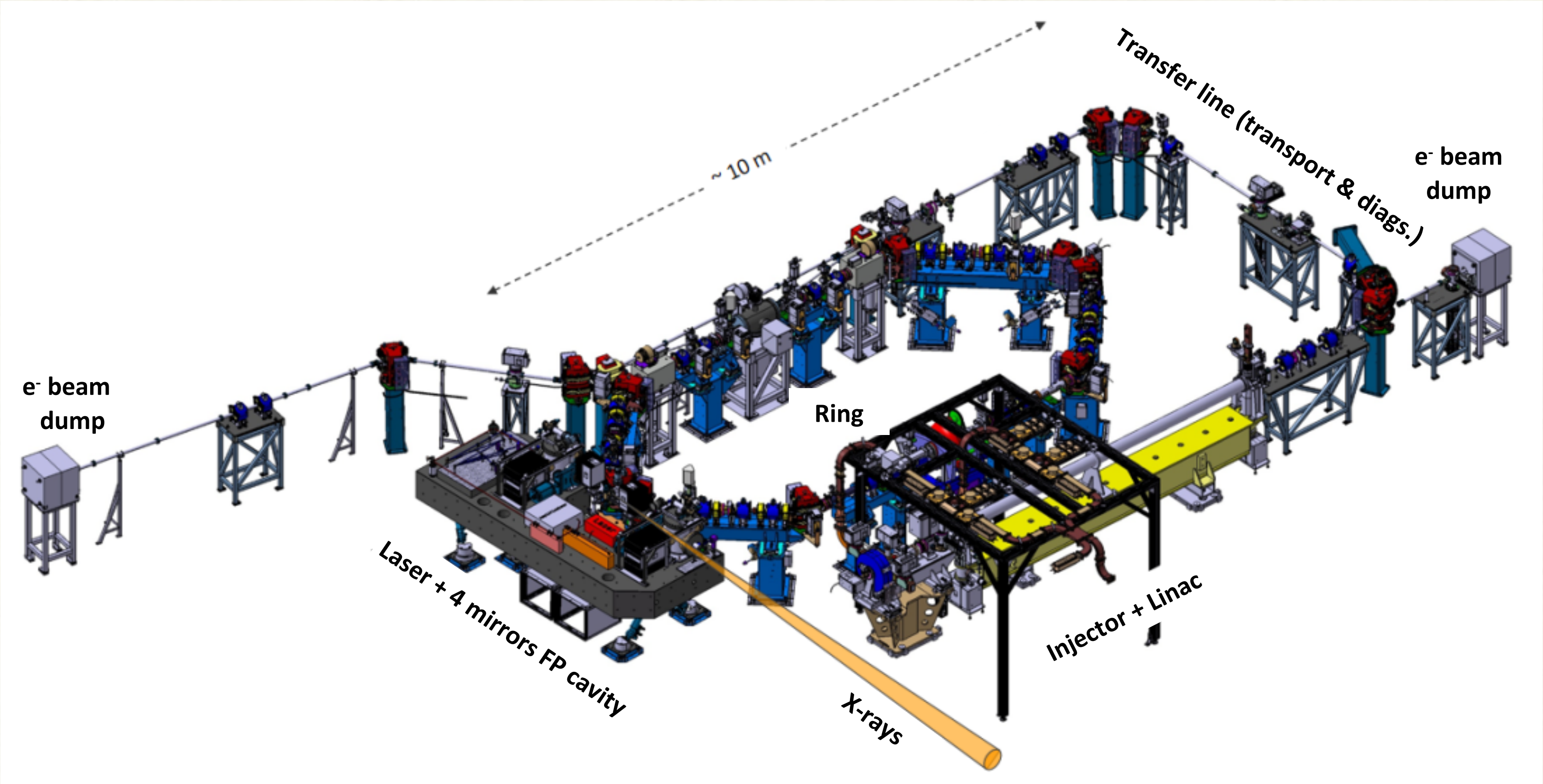
ThomX: on the campus

Paris-Saclay

ThomX: Building configuration



ThomX: specifications



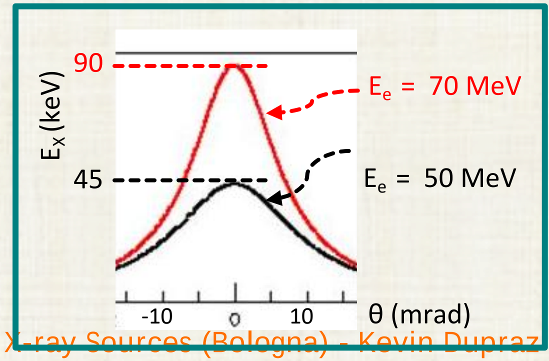
Laser /Cavity system

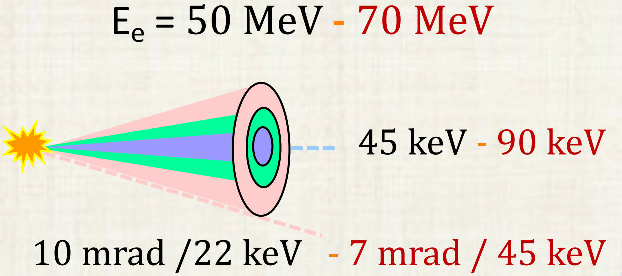
- 100W average power
- **1 MW stored inside the FP cavity** (20-30 mJ/pulse)

Electron machine

- 1 nc / bunch, 50 Hz inj. freq.
- **50-70 MeV**
- Ring, 16 MHz frep.
- **σ_e ~ 70 µm**
- **ε_N ~ 5-10 mm.mrad**
- τ_e ~ 10-20 ps

X-ray beam	
Flux ph/s	**10^{13}**
Brigthness ph/s/ mm^2 / 0.1% bw / mrad^2	**10^{11}**
Transverse source size	**70 µm**
E_X on-axis	**40-90 keV**





End 2018

Oct 2018

sept 2017

X-Line

An original part of ThomX

The X-line main components

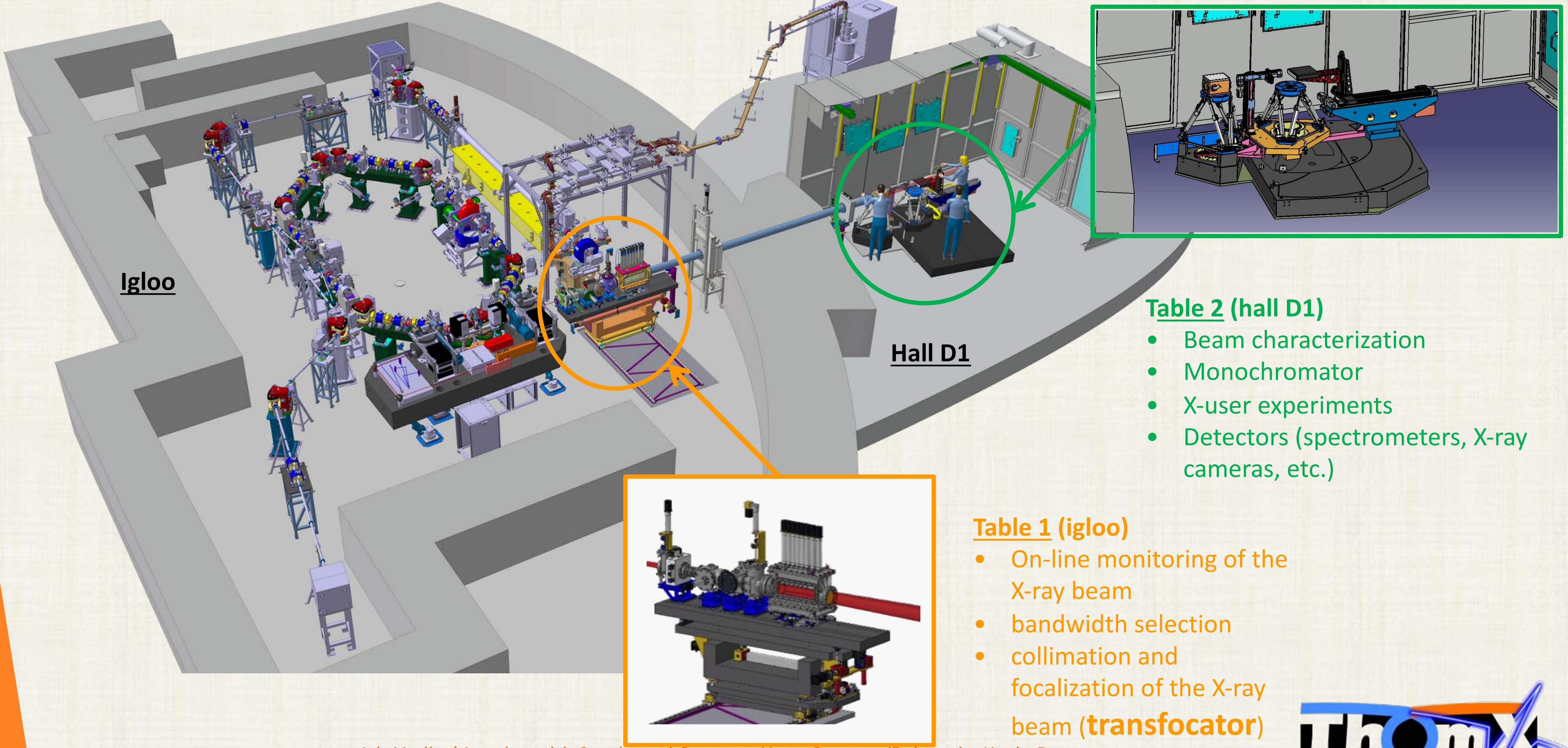


Table 2 (hall D1)

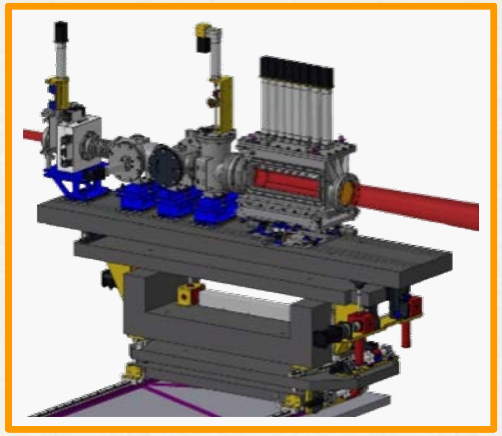
- Beam characterization
- Monochromator
- X-user experiments
- Detectors (spectrometers, X-ray cameras, etc.)

Table 1 (igloo)

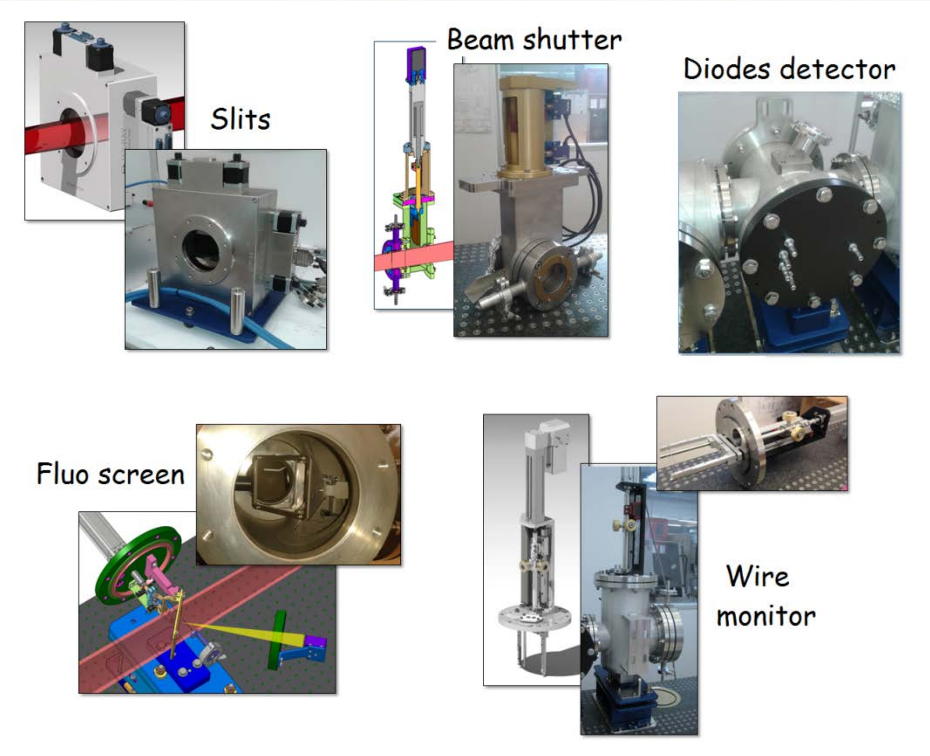
- On-line monitoring of the X-ray beam
- bandwidth selection
- collimation and focalization of the X-ray beam (**transfocator**)

X-Line: table 1

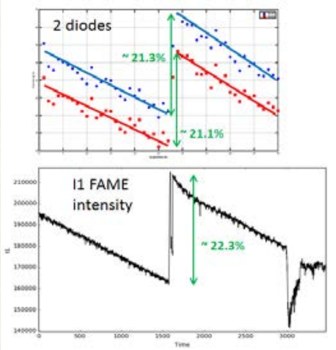
Table 1 (Beam monitoring & Focus device)

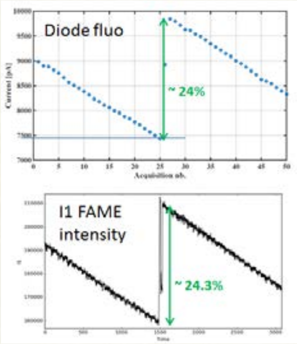


Beam shutter - Beam monitoring

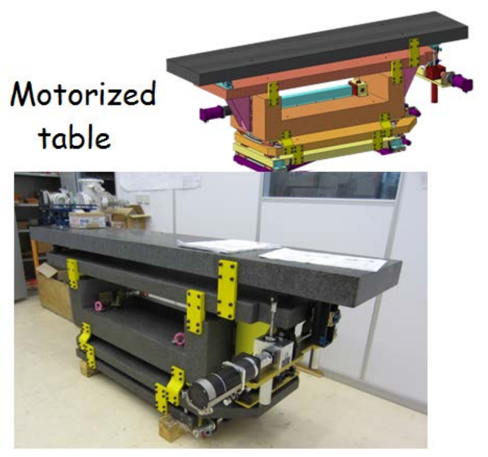


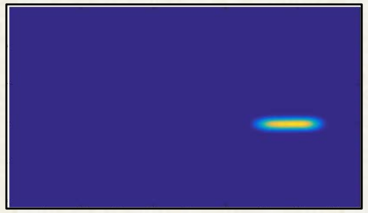
ESRF beam tests (almost all ok)



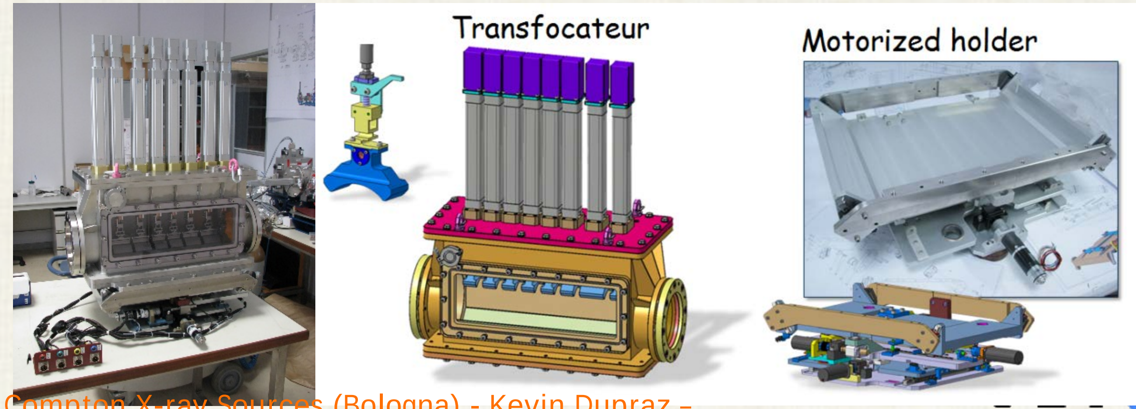


Motorized Table

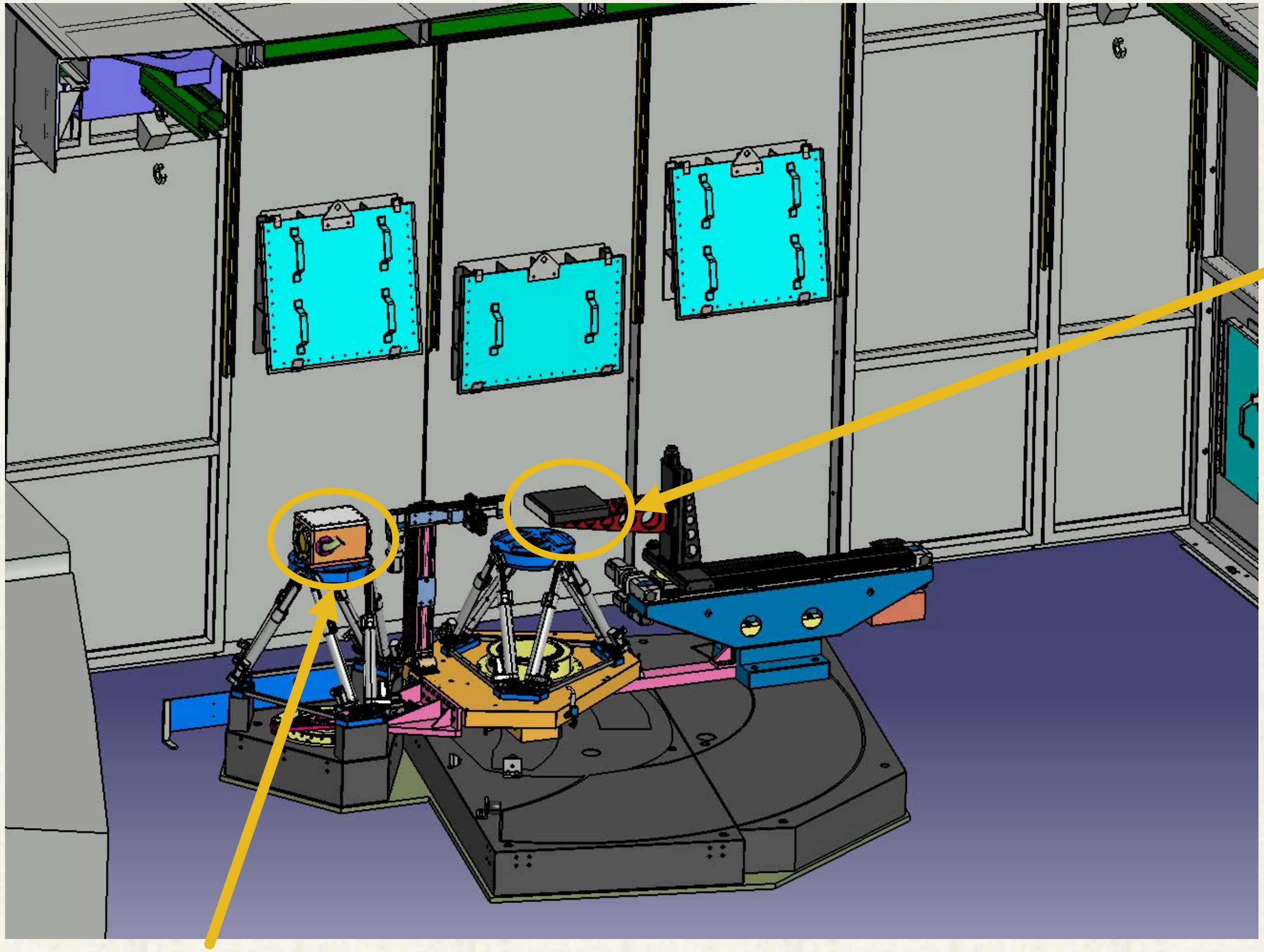




Transfocator (focusing device)



X-Line: Table 2



detectors:

- CdTe spectrometer (High Energies)
- 2x Si spectrometer (Low Energies)
- CdTe Camera (diffraction pattern, low resolution)
- Scintillator Camera (medical camera, high resolution)
- Si Calibrated diode (to be purchase)

Monochromator:

- design in progress
- same as synchrotron to obtain a relative bandwidth $<10^{-4}$

X-Line: Summary

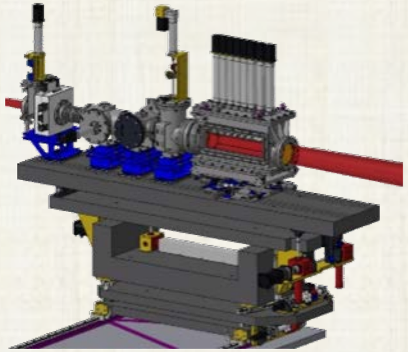
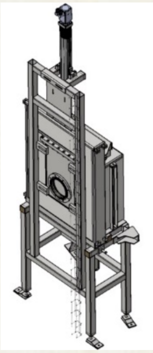


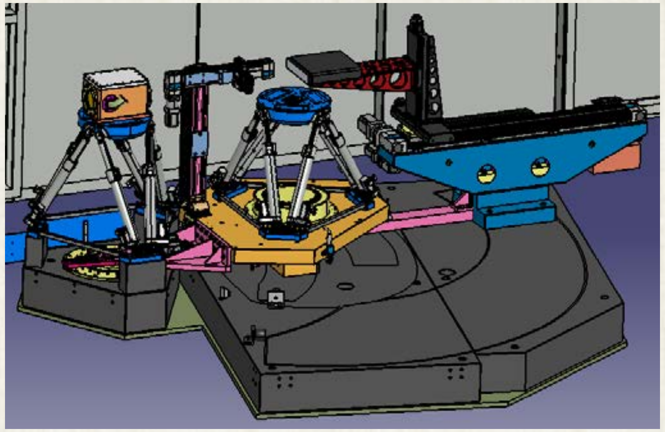
Table 1 (Monitoring):

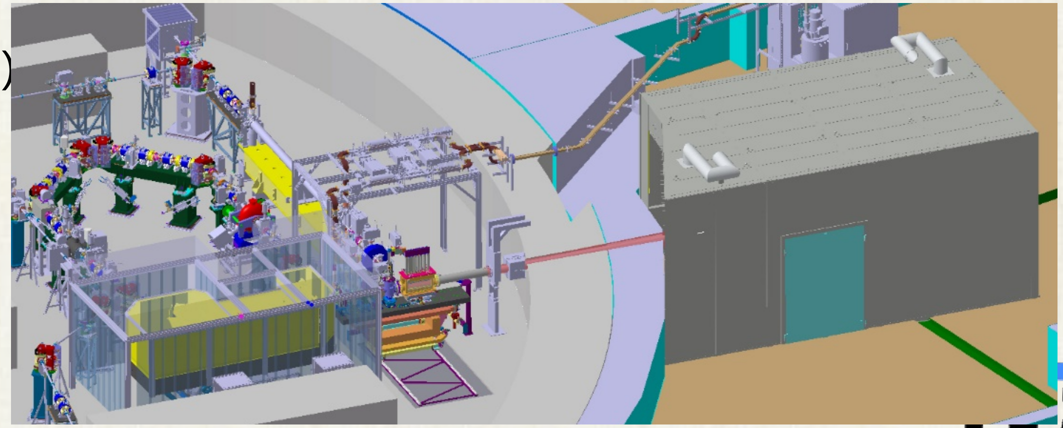


- Table 1 (motorization)
- Slits
- Beam shutter (shutter for experiment)
- Diode detector (flux)
- Fluo. Screen (transverse profile, flux)
- Wires detector (position, flux, scan)
- Transfocator (focus, collimate the beam)
- Security beam shutter (table 2 user access)

Table 2 (experiments):

- Table 2 (positioning)
- Slits 2
- Monochromator
- Slits 3
- Sample positionner
- Detectors





- CONTROL-COMMAND:

ThomX commissioning phases

- Commissioning: expected first X-ray mid-2020 (until 2021)
  - Laser Power: 100 KW
  - Beam charge: ~50 pC @10Hz
  - Beam energy: 50 MeV
- Power UP (end of 2021 - ?)
  - Laser Power: 500 KW
  - Beam charge: ~100 pC @50Hz
  - Beam energy: 50 MeV
- Final performances (?)
  - Laser Power: 1 MW
  - Beam charge: 1 nC @50Hz
  - Beam energy: 50-70 MeV

X-ray beam	
Flux ph/s	10^{10}
Brigthness ph/s/ mm^2 / 0.1% bw / $mrad^2$	10^8
E_X on-axis	45 KeV

X-ray beam	
Flux ph/s	10^{11} - 10^{12}
Brigthness ph/s/ mm^2 / 0.1% bw / $mrad^2$	10^9 - 10^{10}
E_X on-axis	45 KeV

X-ray beam	
Flux ph/s	10^{13}
Brigthness ph/s/ mm^2 / 0.1% bw / $mrad^2$	10^{11}
E_X on-axis	40-90 KeV

applications

Applications: 2 ways to use a Compton beam

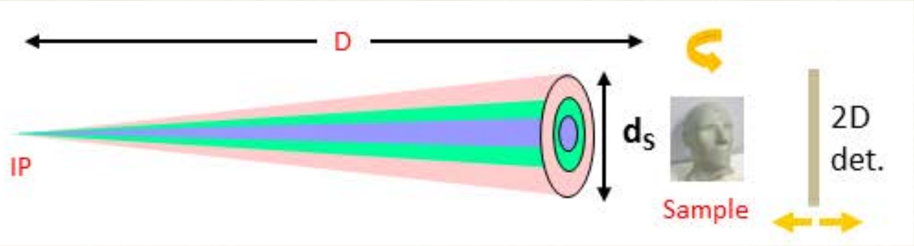
1. Using the 2D divergent beam

(biomedical / cultural heritage)

- Conventional radiography
- K-edge substraction imaging
- Phase contrast imaging

IMAGING

- RADIOTHERAPY



- Several cm diameter beam
- Pink beam (few % - 30% bw)
- Flux ~ 10^{11} - 10^{13} ph/s
- 40 - 90 keV

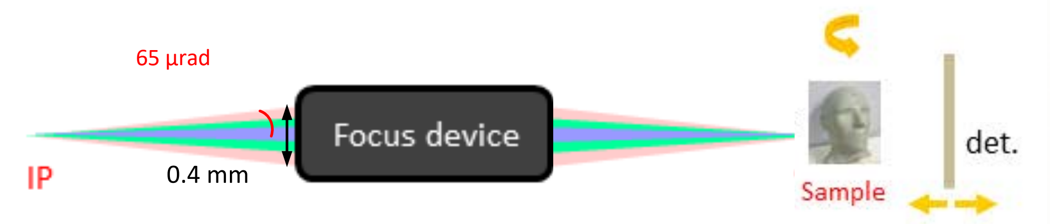
→ Measure large sample with no more need to move it (patient, materiel …)

2. Using the central part of the beam

(cultural heritage / material science / biomedical)

- Fluorescence Spectroscopy
  → chemical composition
- Diffraction
  → structural analyses

Focus device = refractive lenses = Transfocator



- Submilimetric beam mm to < 150 µm
- few % bw (to 0.01 % bw with mono.)
- Flux ~ 10^{8} - 10^{10} ph/s
- 40 - 90 keV

Applications: X-ray Imaging

CT: Computed tomography
PCI: phase contrast imaging

1. Using the 2D divergent beam

(biomedical / cultural heritage)

- Conventional radiography
- K-edge substraction imaging
- Phase contrast imaging

IMAGING

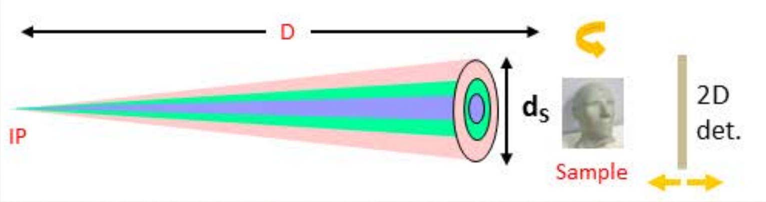
- RADIOTHERAPY

2. Using the central part of the beam

(cultural heritage / material science / biomedical)

- Fluorescence Spectroscopy
  → chemical composition
- Diffraction
  → structural analyses

M. Jacquet / Phys Med 32 (2016) 1790–1794



d_S = 5 cm (D = 10 m)
45 - 90 keV, bw ~ 10%
~ 10^{12} ph/s

Detector pixel size
~ 50 µm

~ 1.3 10^6 ph/s/pixel

→ CT, conventional, PCI, in few seconds

👍 - Large beam size, quasi monochromatic

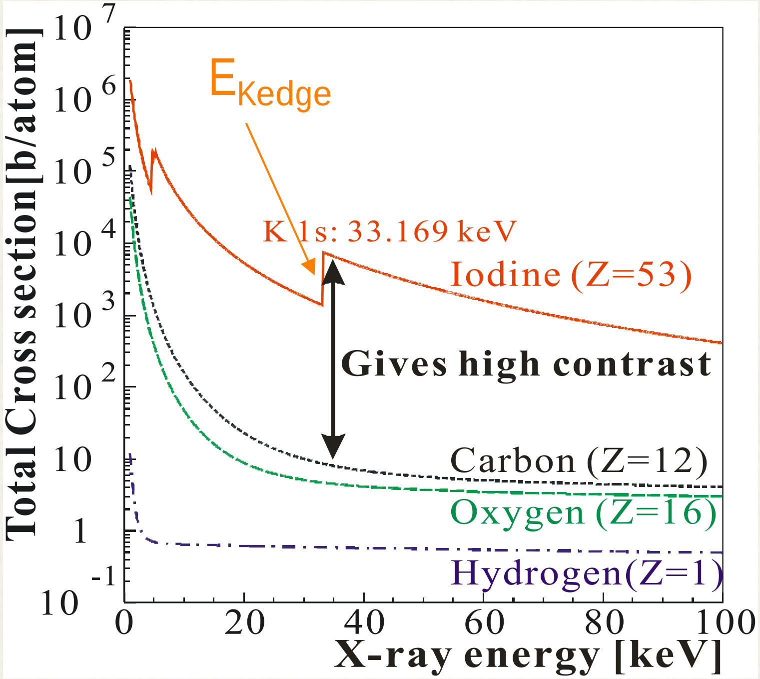
👎 - PCI: Source-sample distance: only 10 m
- PCI : Source size: ~ 50 - 100 µm

- Spatially inhomogeneity over the irradiation field
(45 keV: 1% @ 0.5 cm / 8% @1.5 cm / 20% @ 2.5 cm)

K edge: painting / archeology analyses

‘K edge imaging’

- Heavy chimical elements are contained in painting pigments
    - Characterised by K absorption edges



K-edge imaging (Pb➔white, Hg➔ vermillion…) of a Van-Gogh’s painting

Analytical Chemistry, **2008**, *80*, 6436
http://www.vangogh.ua.ac.be/

But ~30k€ insurance for 2 days

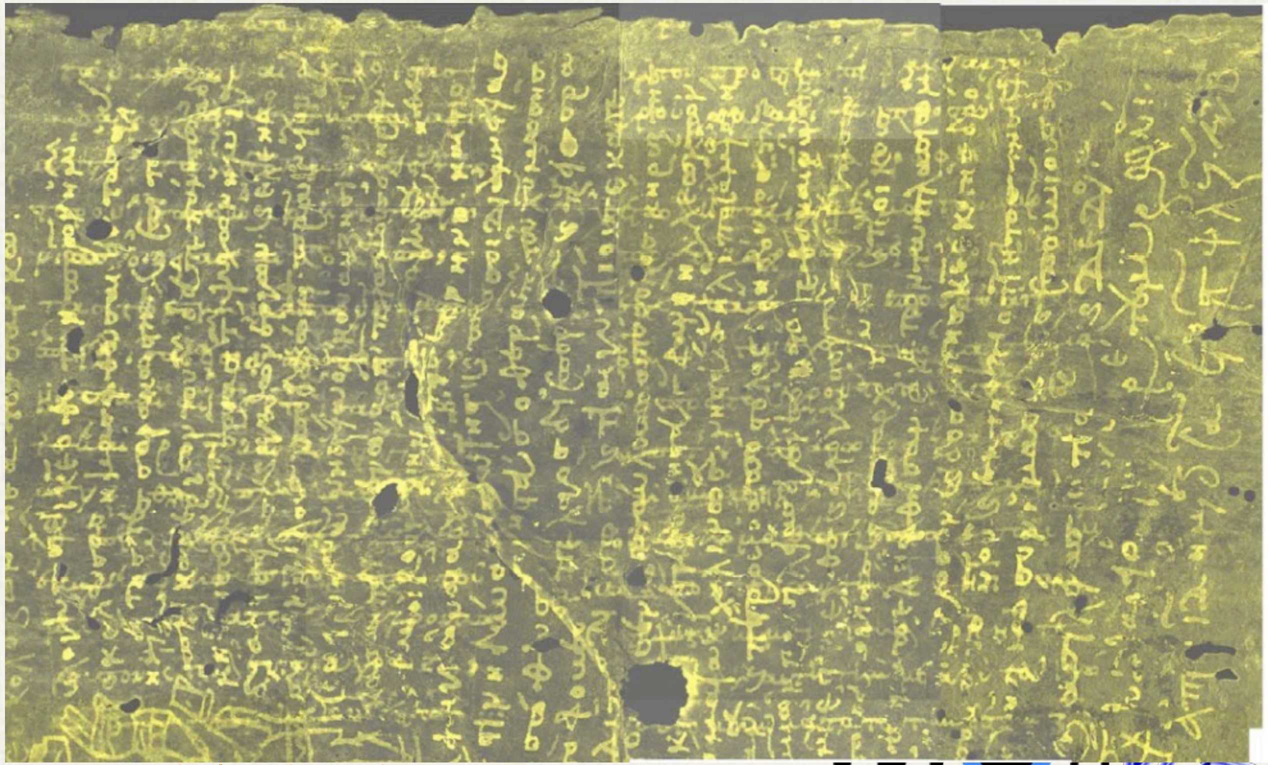
➔Compact machine inside Louvre museum was foreseen (E_X~10-100keV)…

➔This was the *original motivation* of ThomX with Le Louvre museum

K edge imaging (lead)

X-ray images of the Archimedes Palimpsest taken at SLAC

BERGMANN@SLAC.STANFORD.EDU



Applications: Phase contrast

1. Using the 2D divergent beam

(biomedical / cultural heritage)

- Conventional radiography
- K-edge subtraction imaging
- Phase contrast imaging

IMAGING

- RADIOTHERAPY

2. Using the central part of the beam

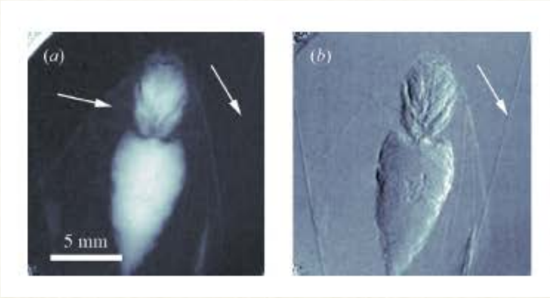
(cultural heritage / material science
/ biomedical)

- Fluorescence Spectroscopy
  → chemical composition
- Diffraction
  → structural analyses

Phase contrast @ CS Lyncean Tech.
(only CCS in operation in the word)

Proof of principle

[Synch. Rad. 16, 2009, 43-47]



standard absorption phase-contrast

13.5 KeV , 3% bw
10^9 ph/sec
σ = 165 µm

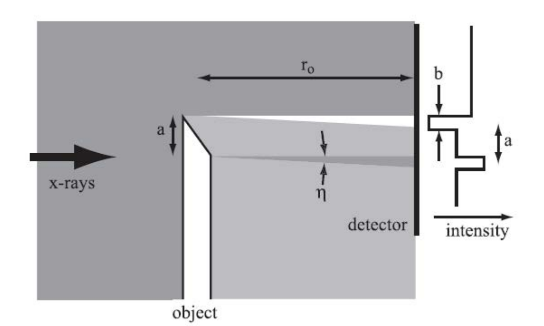
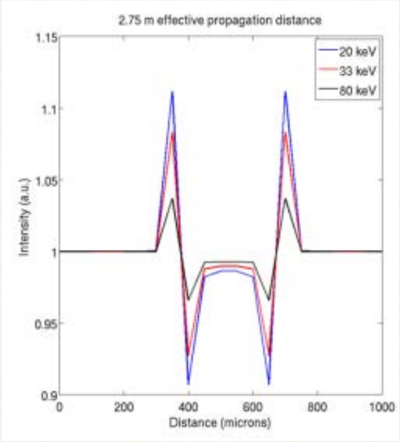


Figure 10. Schematic explanation of the edge enhancement by the 'refraction' mechanism.



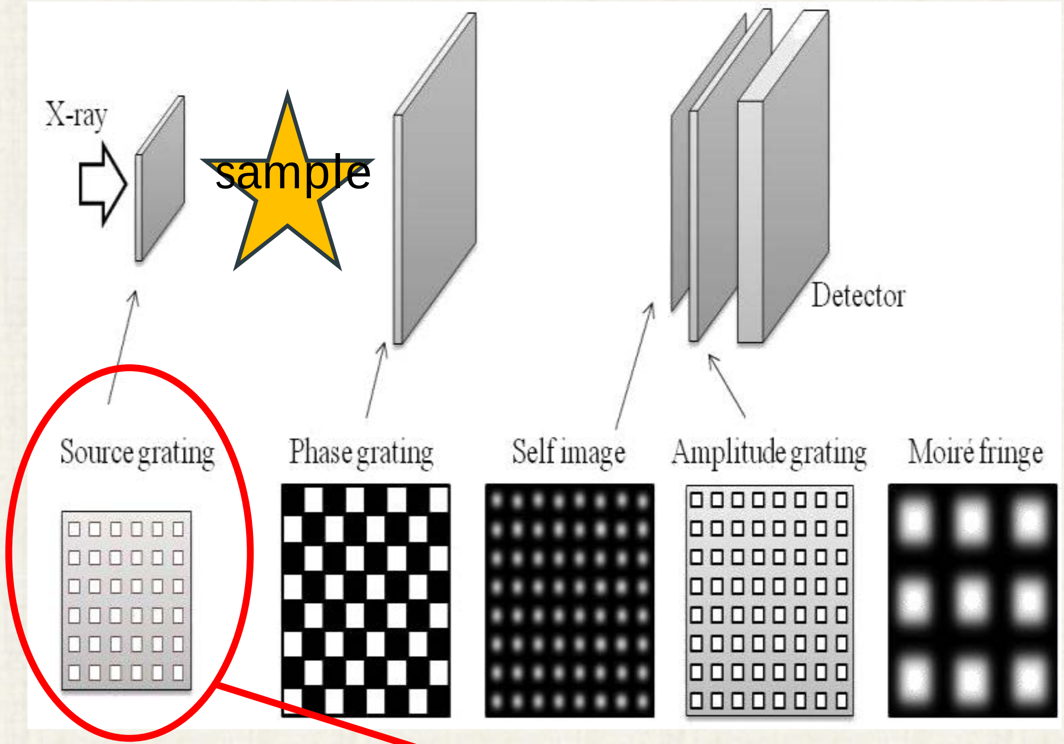
d_S = 3 cm (D = 10 m)
45 keV, bw ~ 2-3%
~ 4. 10^{11} ph/s

a 300 µm nylon wire

[TDR ThomX]

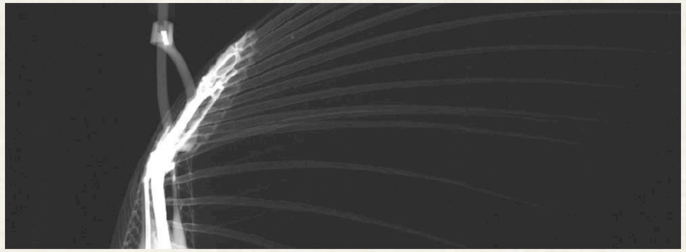
Phase Contrast

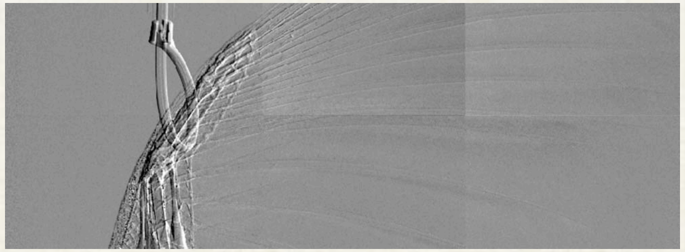
Single shoot = 2D (Moiré effect)
Else scan with reconstruction phase

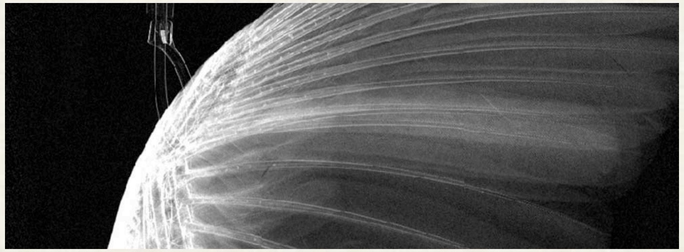


Not require with quasi mono-chromatic beam

AIP Conference Proceedings 1466, 29 (2012)


absorption


Phase difference (refraction)


Dark field (scattering)

JOURNAL OF APPLIED PHYSICS 105, 102006 2009

Applications: Radiotherapy

1. Using the 2D divergent beam

(biomedical / cultural heritage)

- Conventional radiography
- K-edge substraction imaging
- Phase contrast imaging

IMAGING

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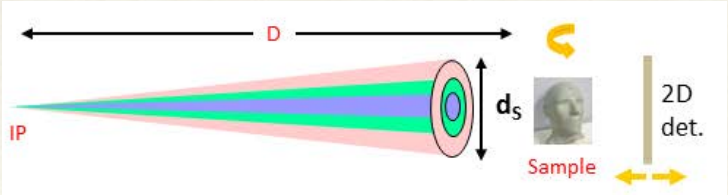
2. Using the central part of the beam

(cultural heritage / material science / biomedical)

- Fluorescence Spectroscopy
  → chemical composition
- Diffraction
  → structural analyses

M. Jacquet, P. Suortti / Phys Med 31 (2015) 596-600



d_S = 3 cm (D = 10 m) ; 80 keV ± 10 keV

- ThomX: ~ 2. 10^9 ph/s/mm^2
- SSRT ESRF: ~ 10^9 ph/s/mm^2

→ Innovative form of preclinical radiotherapy studies (PAT …)

→ Test the efficiency of high Z drugs, understand biological mechanisms & effects on tissues …

(& micro or mini beam therapy ?)

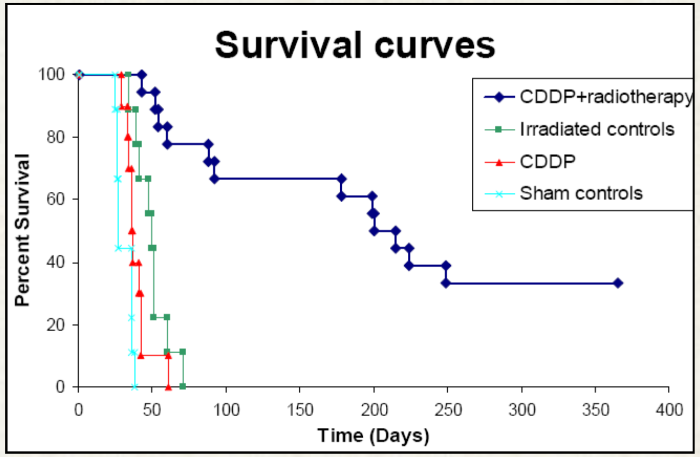
👍
- Large beam size
- Dose rate comparable to SSRT ESRF

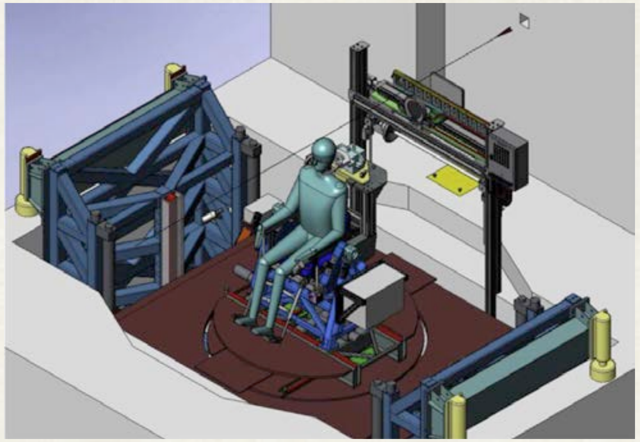
👎
- Spatially inhomogeneity over the irradiation field
  (80 keV: 1.7% @ 0.5 cm / 14% @1.5 cm)

radiotherapy (as at ESRF, ID17)

- Search for glioblastoms therapy
  - Locate platinum inside tumor cells
  - Shoot with 78keV X-ray (platinum K-shell)
  - Observed ~700% increase of life time

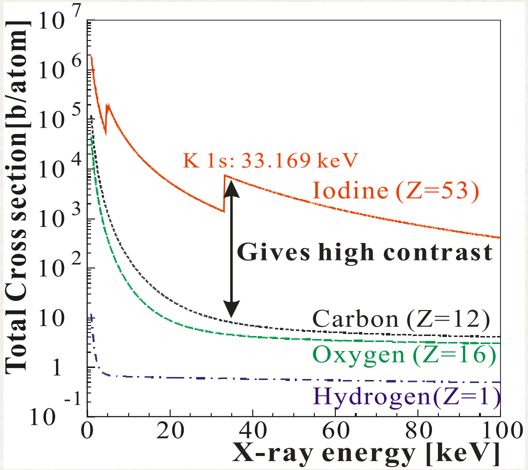
(Biston et al. Cancer reas.64(2004)2317)



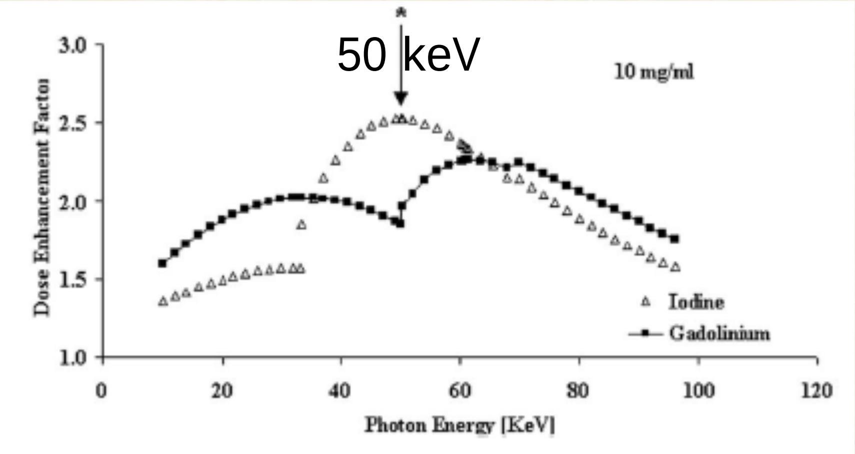


Physica Medica 31 (2015) 596-600

- X-ray imagery/therapy can also use contrast agent: e.g. iodine (ongoing human trial at ESRF)



But
relative to
water absorption



Adam et al Int.J.Rad.Onc.Biol. Phys.57(2003)1413

Applications: Fluorescence

1. Using the 2D divergent beam

(biomedical / cultural heritage)

- Conventional radiography
- K-edge substraction imaging
- Phase contrast imaging

IMAGING

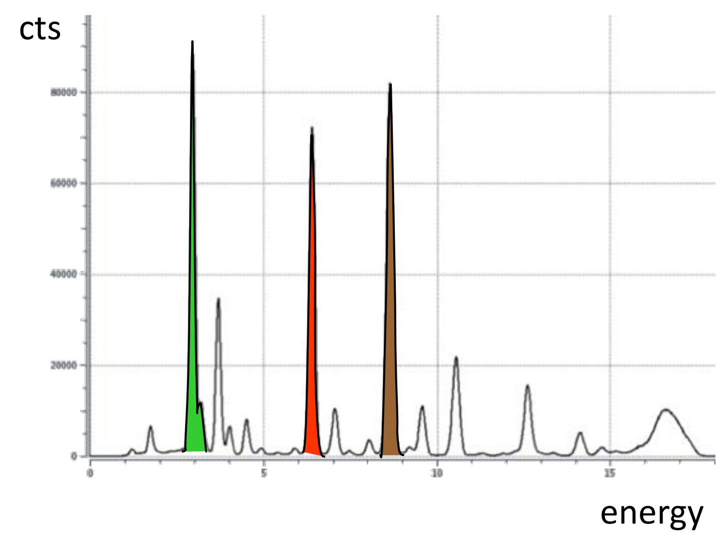
- RADIOTHERAPY

2. Using the central part of the beam

(cultural heritage / material science / biomedical)

- Fluorescence Spectroscopy
  → chemical composition
- Diffraction
  → structural analyses

- Quasi-monochromatic beam
- Tunable energy



Synchrotrons increase the sensisibility of detection by 1 to 2 orders of magnitude compared to X-ray tubes.

Ex : Detection limit of Cu

- X-ray tube ~ 2000 ppm
- Synchrotron ~ 60 ppm

→ ThomX: between both

Applications: Diffraction

1. Using the 2D divergent beam

(biomedical / cultural heritage)

- Conventional radiography
- K-edge substraction imaging
- Phase contrast imaging

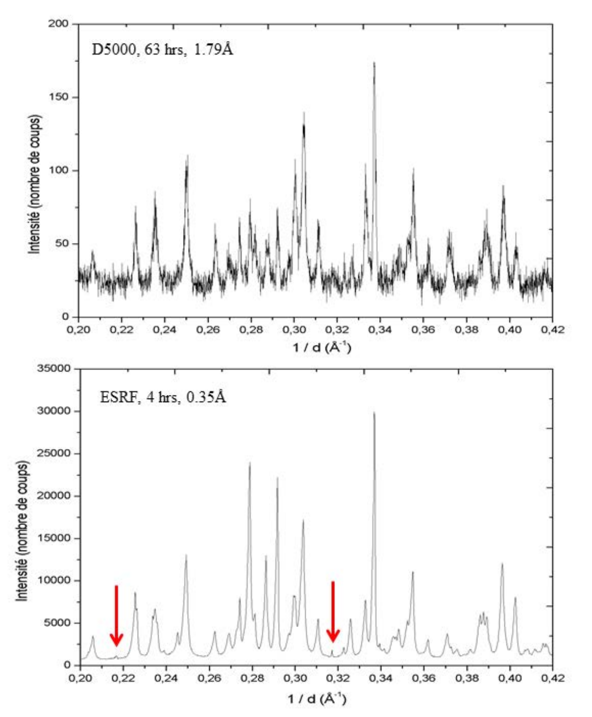
IMAGING

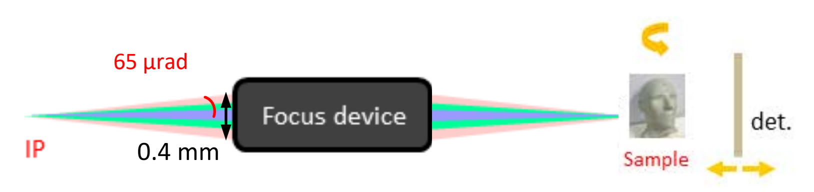
- RADIOTHERAPY

2. Using the central part of the beam

(cultural heritage / material science / biomedical)

- Fluorescence Spectroscopy
  → chemical composition
- Diffraction
  → structural analyses





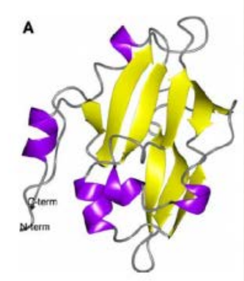
→ 3D structure determinations

Ex: Protein MytuGCSPH @ CS Lyncean Tech

Proof of principle

(crystal size : 250 X 250 X 100 µm)

- E = 15 keV
- 5. 10^6 ph/sec with 1.4% bw
- X beam: 120 µm on crystal

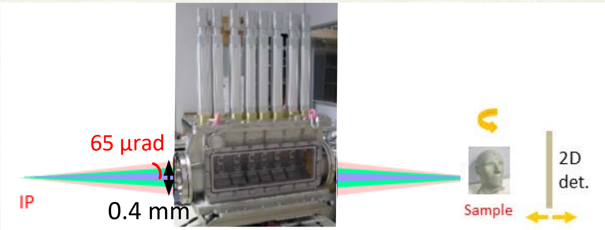


Flux and results comparable with the same analysis realized at a rotating anode

[J. Struct. Funct. Gen. 11, 2010, 91-100]

~ 10^8 ph/s @ 1% bw
~ 10^7 ph/s @ 0.01% bw

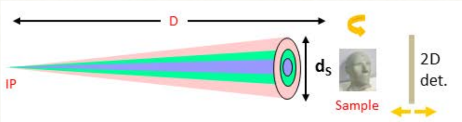
X-ray Beam for first users



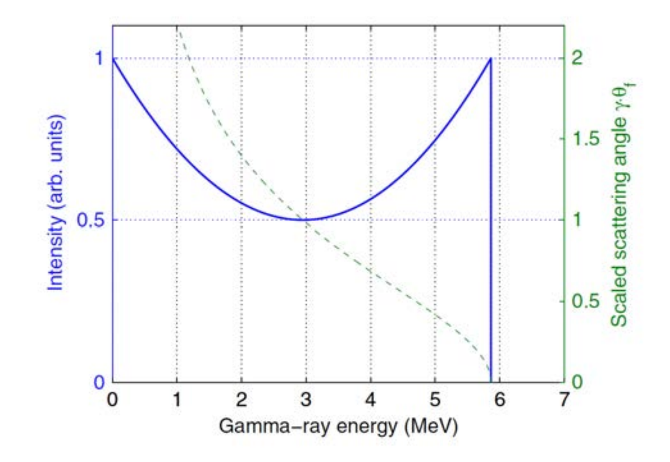
1/γ is ~ ½ of total photon flux and max energy

Al lenses with 0.4mm of aperture

Full Beam



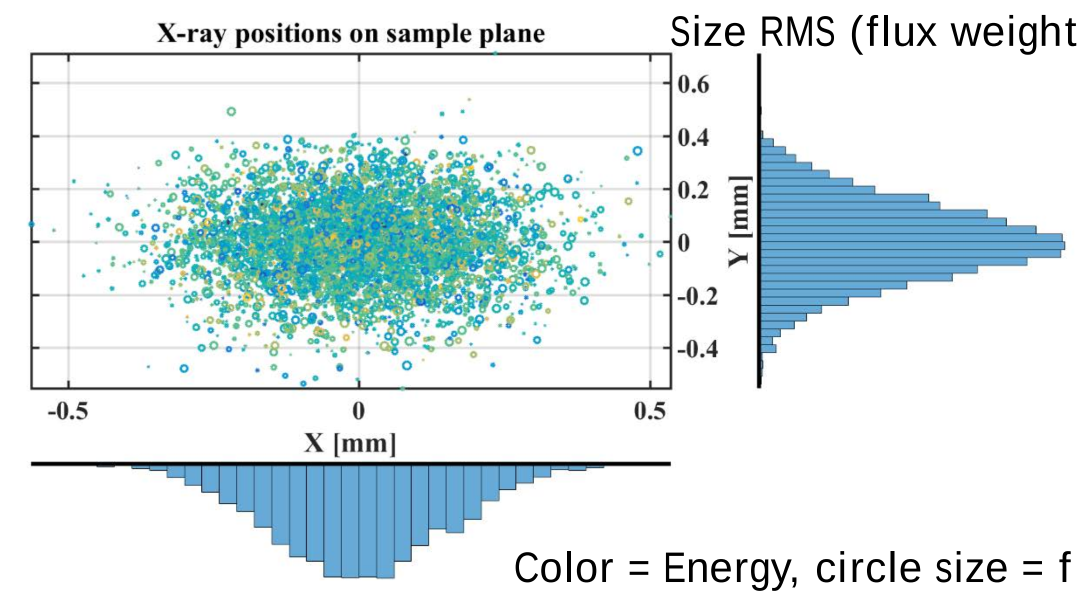
- Source to sample dist.: 10.6 m
- Divergence: ~1/γ = 7.5 mrad (~15cm on sample)
- Flux: ~10^9 ph/s
- Energy spread: <40%



Phys. Rev. ST Accel. Beams 14, 044701 (2011)

Focused Beam (= 39 lenses)

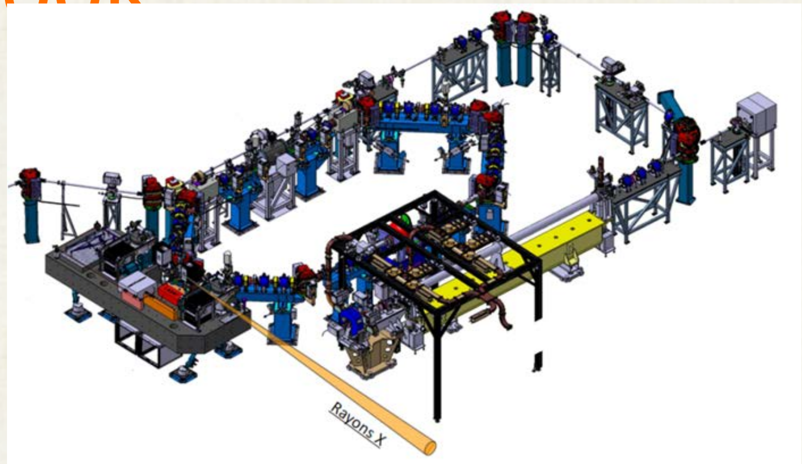
- Source to sample dist.: 10.6 m
- Divergence: ~65 µrad (~380 µm on sample without focusing)
- Flux: ~10^5 ph/s (22% transmission included), x2 wrt pinhole only



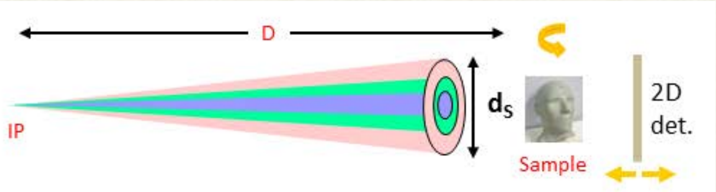
Size RMS (flux weighted) = 150 µm

Color = Energy, circle size = flux

ThomX: Summary/Outlook

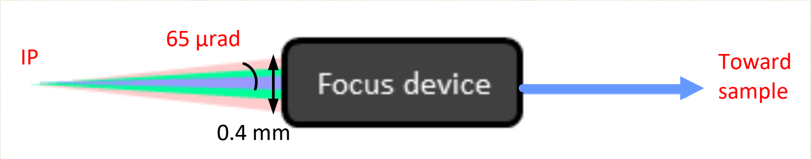


- With nominal parameters of ThomX
  - frep = 16 MHz ; σe = 0.5% ; laser power = 1 MW
  - 40-90 keV ; Brightness = 10^{11} ph/(s.mm2.mrad2) in 0.1% bw
- 2 ways to use the Compton X-ray beam:
  - With the large 2D conical beam
    - Conventional radiography
    - K-edge subtraction imaging
    - Phase contrast imaging
    - Radiotherapy



- 10^{11} - 10^{12} ph/s @ 1% - 30% bw
- Few cm diameter beam

  - with the pencil (focused) beam
    - Fluorescence Spectroscopy
    - Diffraction

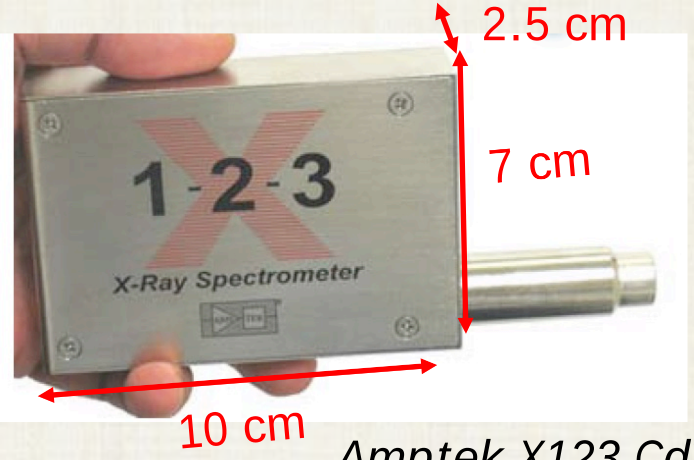


- ~ 10^8 ph/s @ 1% bw
  ~ 10^7 ph/s @ 0.01% bw
- 0.4 mm → 150 µm beam

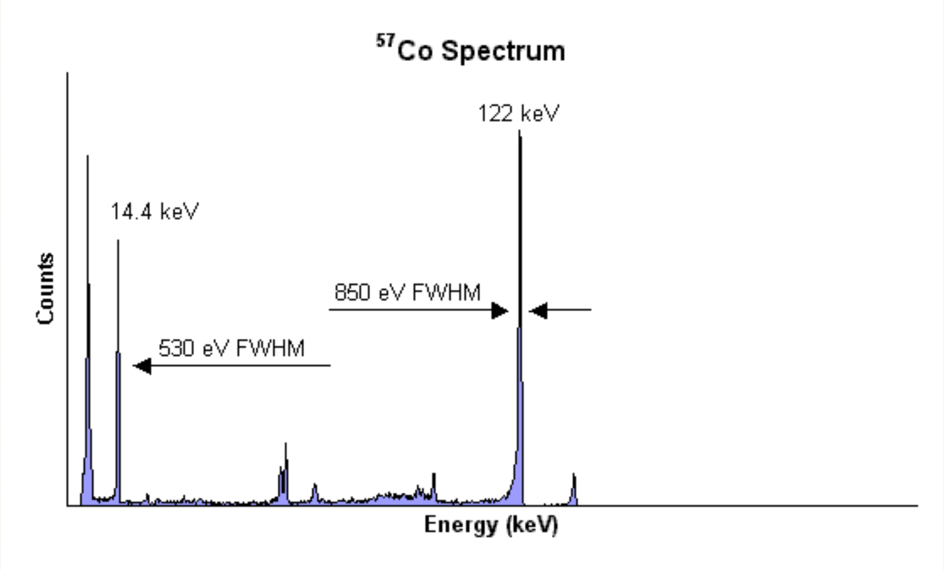
Thanks for your attention

Detectors

CdTe spectrometer (High Energies)



Amptek X123 CdTe spectrometer



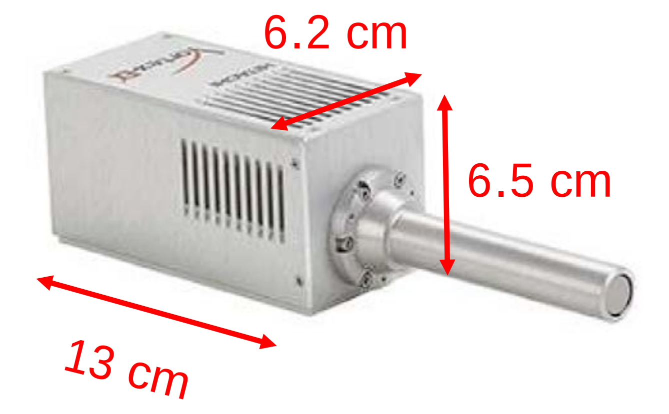
Main characteristics:

- Compact integrated system
- Resolution @122 keV <1.2 keV (FWHM)
- Optimum energy range: 5 keV to 150 keV
- Max count rate: Up to 2 x 10^5 cps
- Thickness: 1 mm
- 12 K€ H.T.

Main applications:

- High energies fluorescence
- Absorption spectrum
- X-ray beam characterization

Si spectrometer (Low Energies)



Hitachi Si Vortex 90EX Spectrometer

XIA FalconX dedicated electronics (fast digital pulse processor)

Fluorescence line	Resolution det.1 [eV]	Resolution det.2 [eV]
Mn-KL3 (5.9 keV)	191	189
Pb-L3M5 (10.55 keV)	198	221

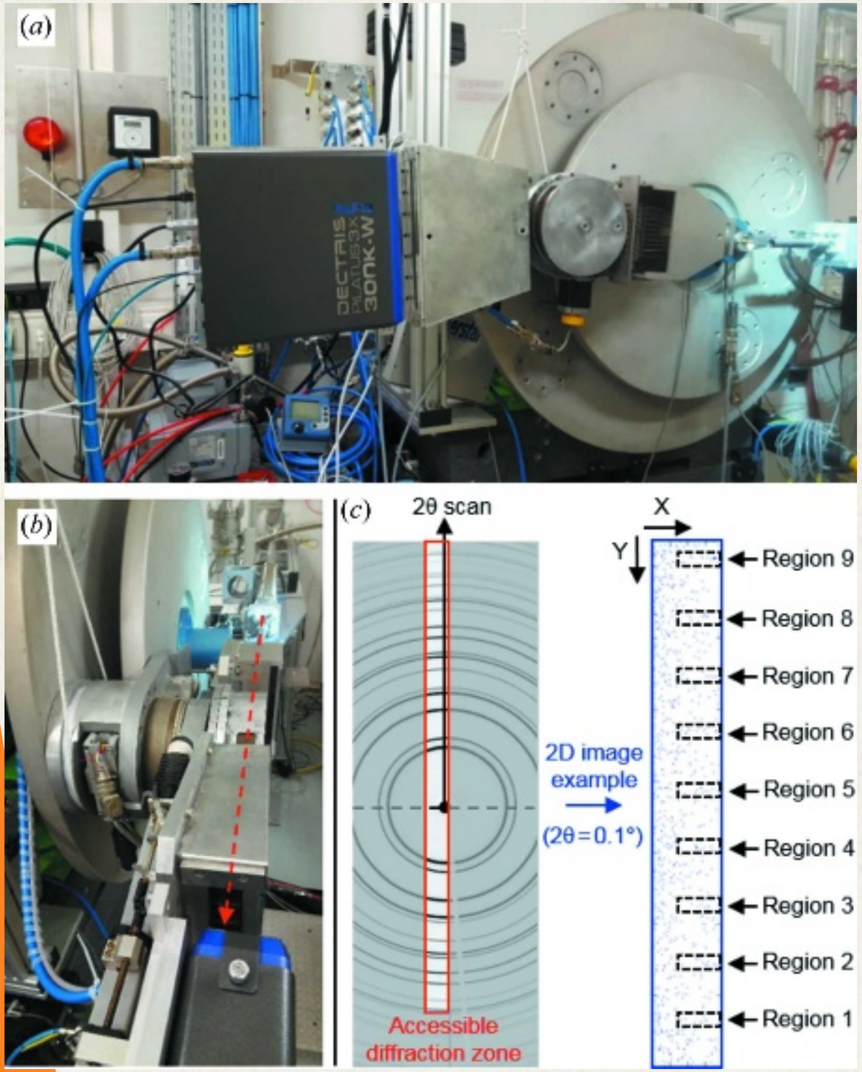
Main characteristics:

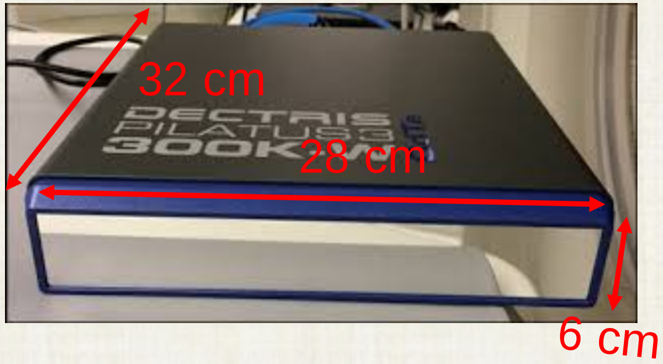
- Resolution @5.9 keV <180 eV (FWHM)
- Optimum energy range: 800 eV to 30 keV
- Max count rate: Up to 1M cps
- Thickness: 1 mm
- 20 K€ + 20 K€ H.T.

Main applications:

- Low energies fluorescence
  - Painting analysis
  - material analysis
- Particule Induced X-ray Emission (PIXE)

CdTe Camera (diffraction pattern, low resolution)





Dectris PILATUS3 R CdTe 300K-W

Main characteristics:

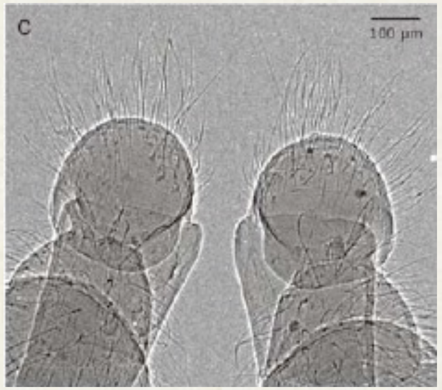
- Quantum Efficiency: ~65% @90KeV, Thickness: 1mm
- Exposure time: 1ms to 1000s @20Hz
- Optimum energy range: 15KeV to 80 keV, Resolution 1KeV
- Max count rate: 10^7 ph/s/pix (20 bits)
- Pixel size: 172 um, area: 253.7x33.5 mm
- 120 K€ (135K CHF net)

Main applications:

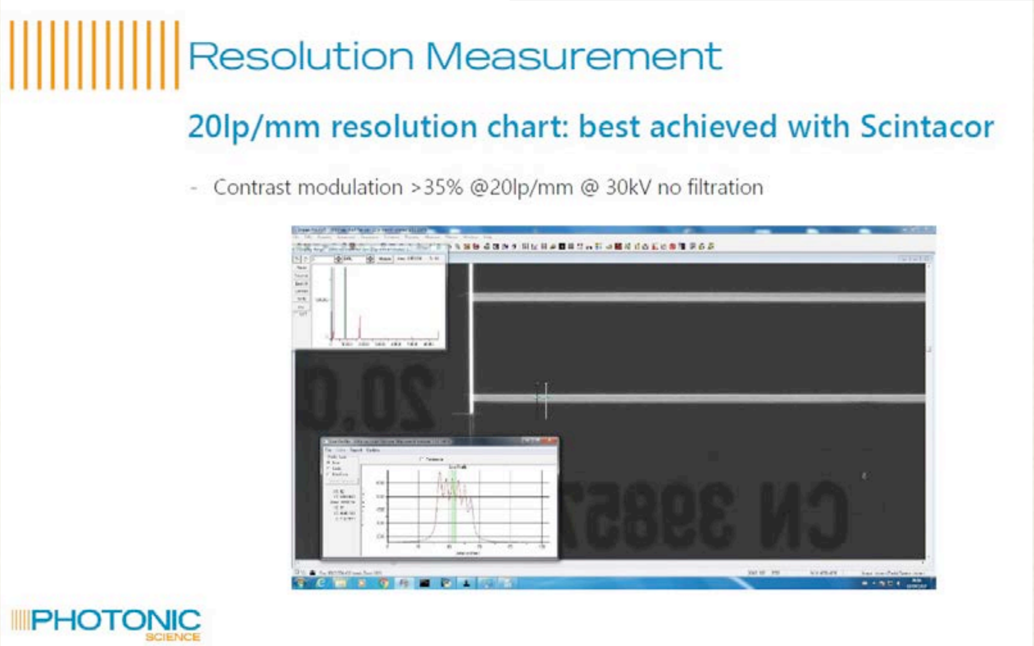
- Diffractogram
- Low resolution image
- K edge imaging

Scintillator Camera (medical camera, high resolution)

Photonic Science X-ray sCMOS 16MP Detector



Spider leg, courtesy Excillum, T.Tuohimaa 5µm pulsed liquid jet source, 50kV, 0.8mA, magnification x1 (left), x4, right, 4k x 4k resolution, voxel size 9µm



Resolution Measurement

20lp/mm resolution chart: best achieved with Scintacor

- Contrast modulation >35% @20lp/mm @ 30kV no filtration

PHOTONIC SCIENCE

Main characteristics:

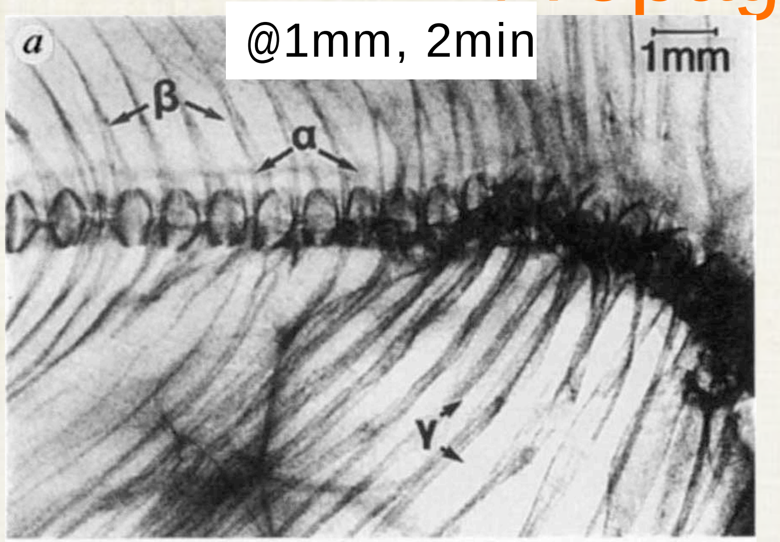
- Quantum Efficiency: ~60% @35KeV
- 10 fps
- Optimum energy range: 10KeV to 100 keV
- Max count: 70.000 electrons/pix (16 bits)
- Pixel size: 13.42 um, area: 55x55 mm
- 40 K€

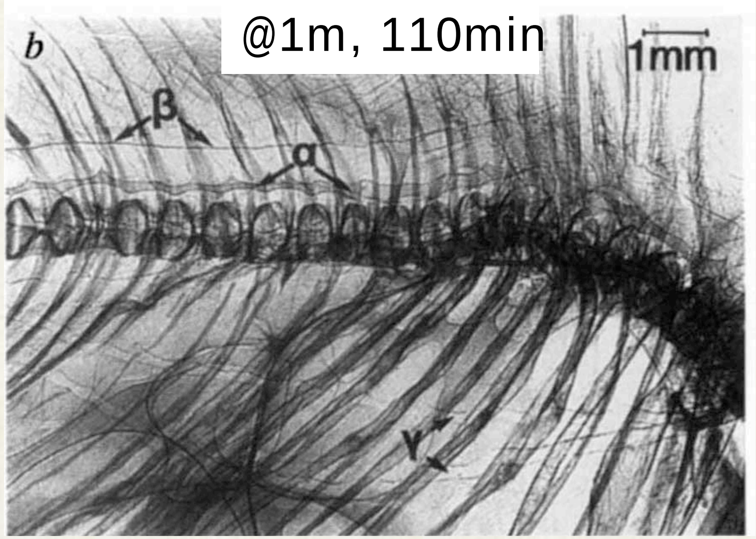
Main applications:

- High resolution imaging
  - medical imaging
  - phase contrast imaging
  - tomography

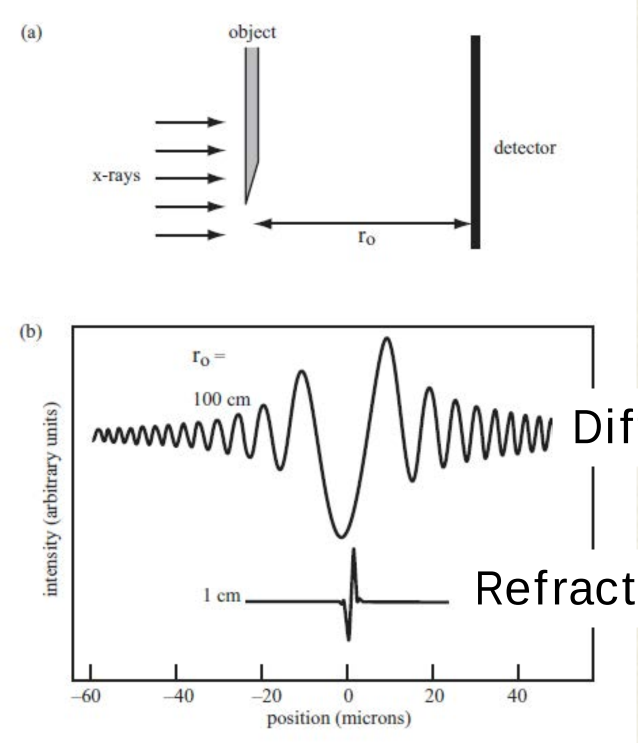
applications

Propagation based phase contrast


@1mm, 2min


@1m, 110min

Nature, vol. 384, 28 Nov. 1996



Diffraction (ondulatoire)

Refraction (Snell-Descartes)

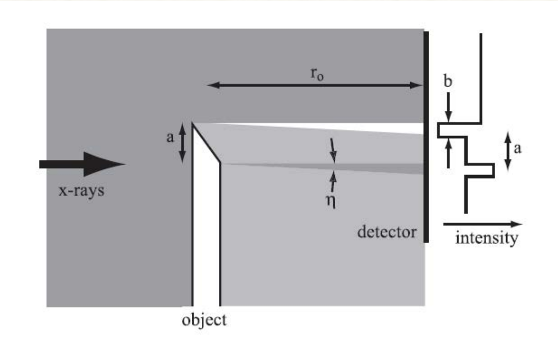
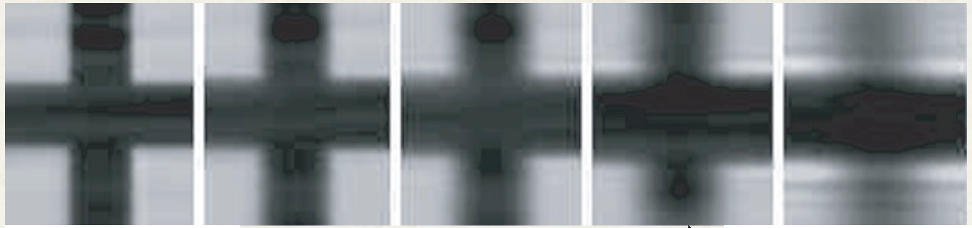
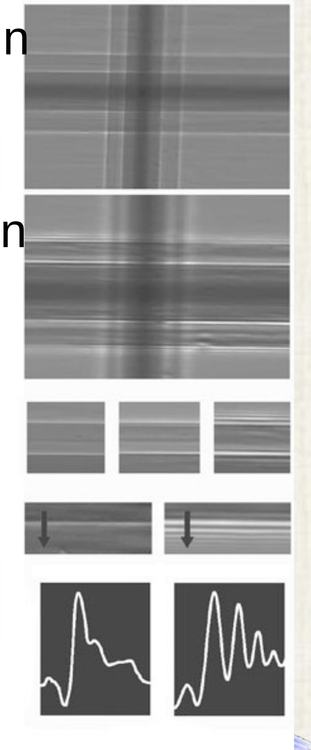


Figure 10. Schematic explanation of the edge enhancement by the 'refraction' mechanism.

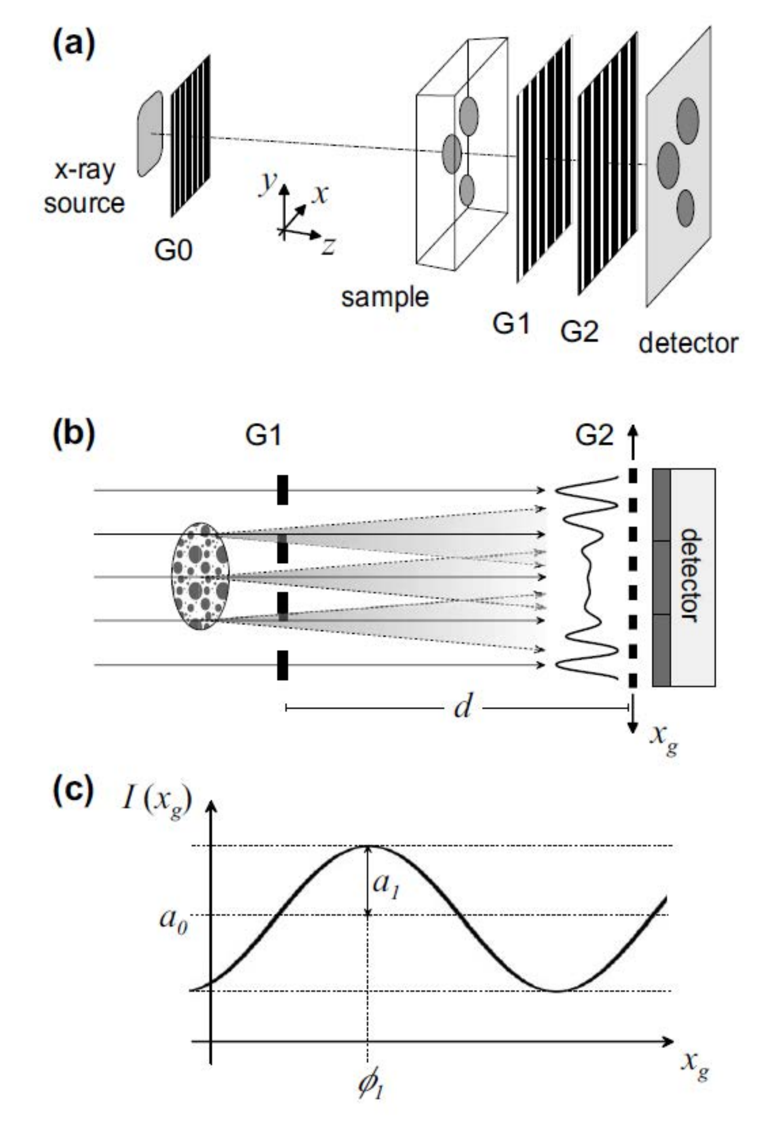

refraction → diffraction

2002 J. Phys. D: Appl. Phys. 35 R105


refraction

diffraction

Dark Field



J. Appl. Phys. 105, 102006 2009

$$I(m,n,x_g) = \sum_i a_i(m,n)\cos[ikx_g + \phi_i(m,n)]$$

$$\approx a_0(m,n) + a_1(m,n)\cos[kx_g + \phi_1(m,n)], \qquad (1)$$

Φ_i: phase coefficient

$k = \frac{2\pi}{p_2}$: with p_2 the period of the grating G2

$$T(m,n) = \frac{a_0^s(m,n)}{a_0^r(m,n)}$$

« Dark Field »

s: with sample
r: reference

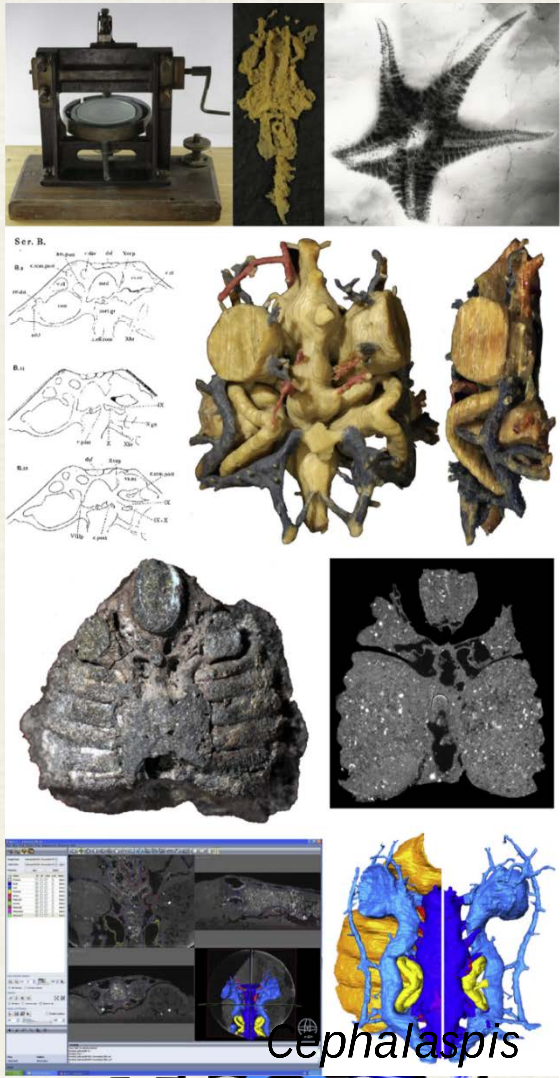
$$V^r(m,n) \equiv \frac{I_{\max}^r - I_{\min}^r}{I_{\max}^r + I_{\min}^r} = \frac{a_1^r(m,n)}{a_0^r(m,n)}, \qquad (2)$$

$$V(m,n) \equiv \frac{V^s(m,n)}{V^r(m,n)} = \frac{a_0^r(m,n)a_1^s(m,n)}{a_0^s(m,n)a_1^r(m,n)}. \qquad (3)$$

Tomography : analogic to digital

tomography (from Greek root tomê, slice, then it’s a slicing representation)

The grinding machine used by Sollas in the first paleontological tomographic studies.



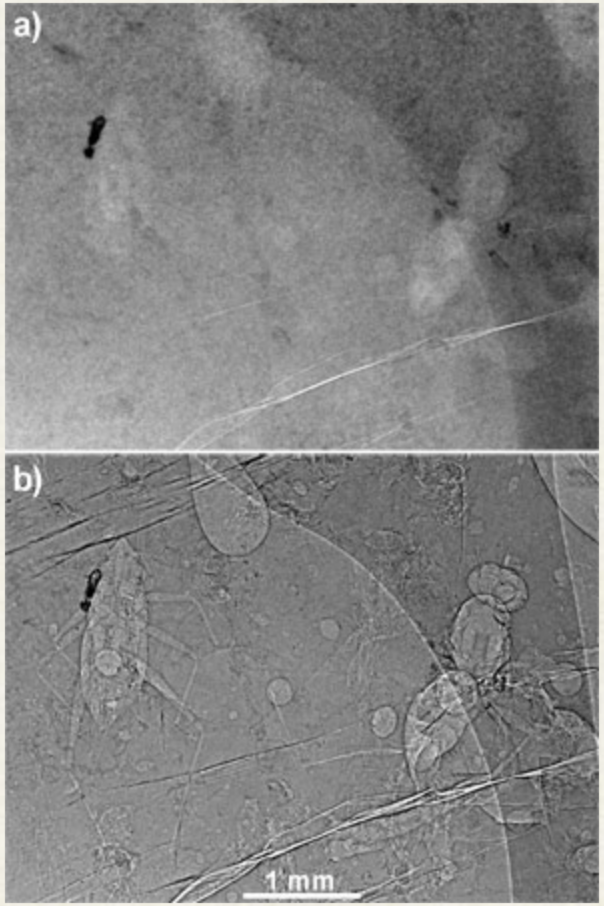
Trends in Ecology & Evolution, June 2014, Vol. 29, No. 6

Applications: Paleontology

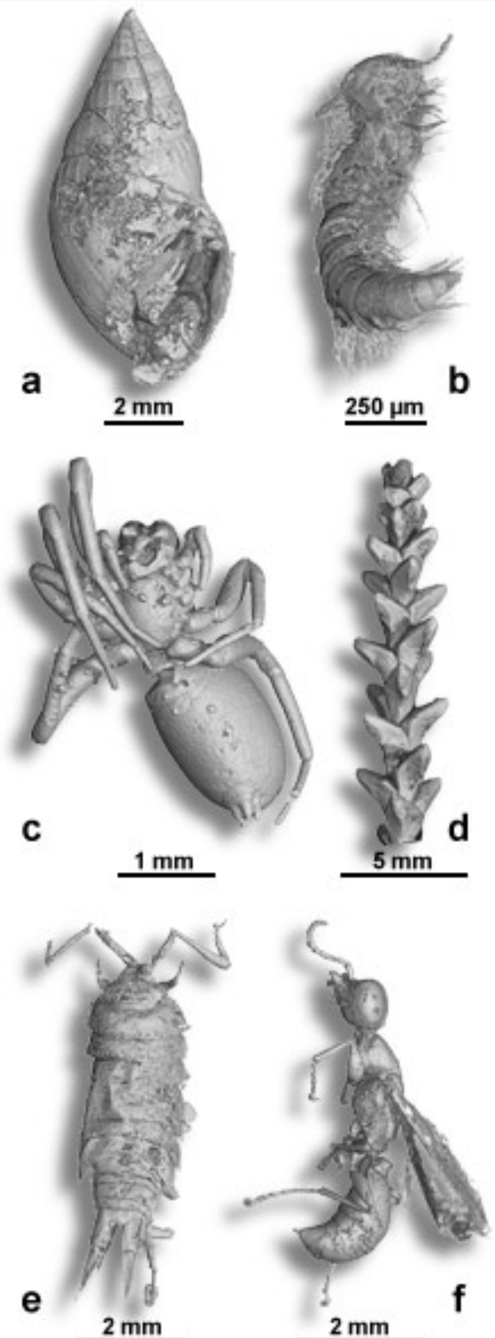
http://www.esrf.eu/news/general/amber/amber/

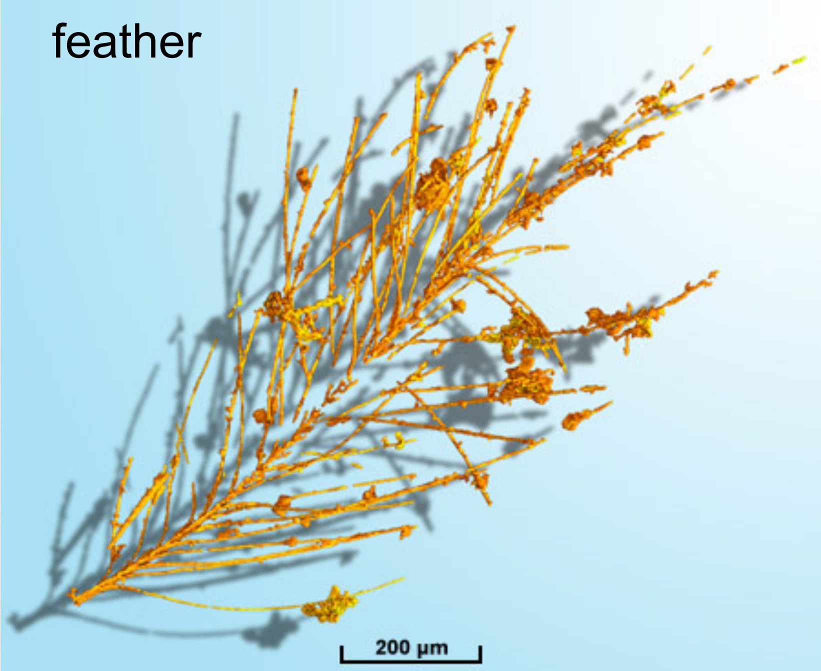
Piece of amber dated from
100 millions years before JC (charentes)

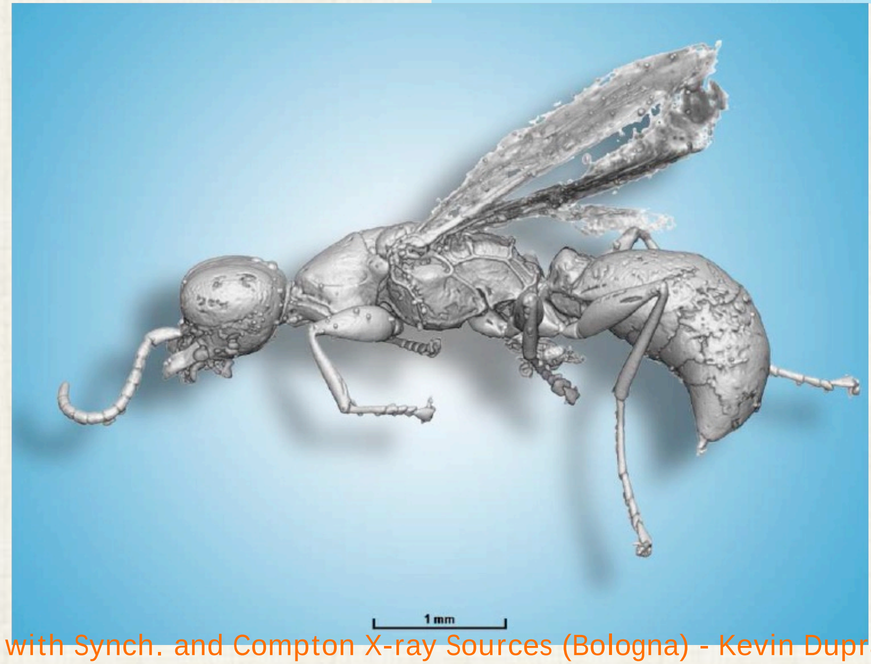
**Monochromatic
X-rays
few tens of
KeV
ESRF**



➔ 3D tomography

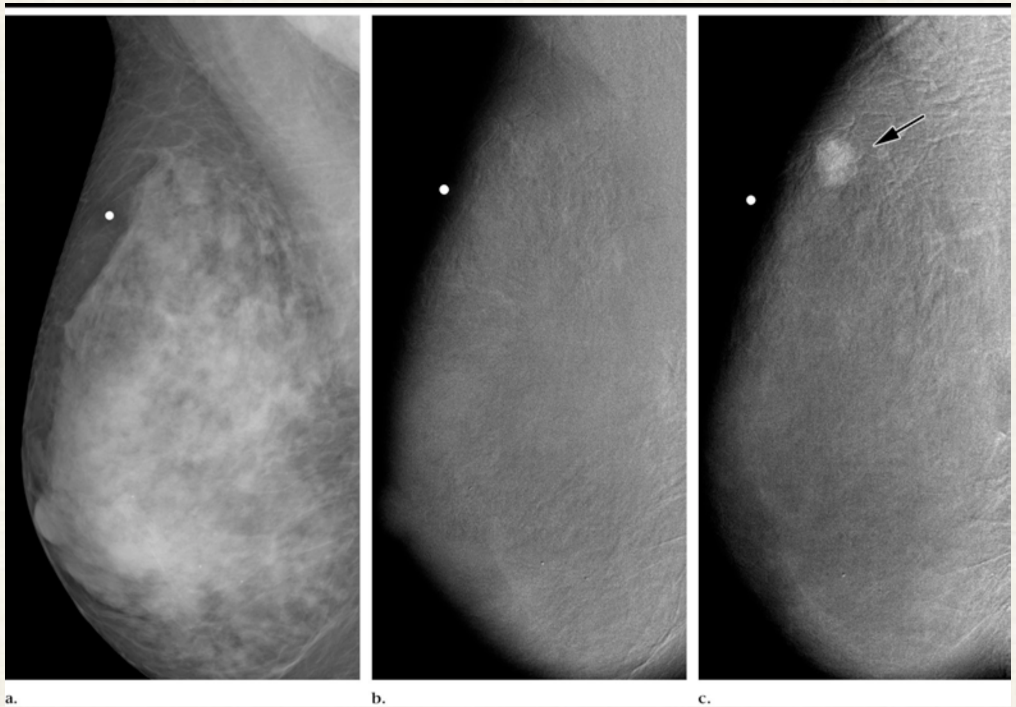






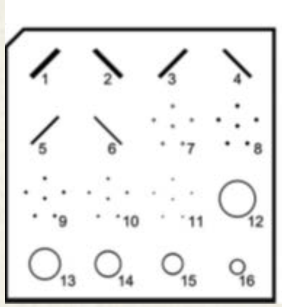
Tafforeau, ESRF

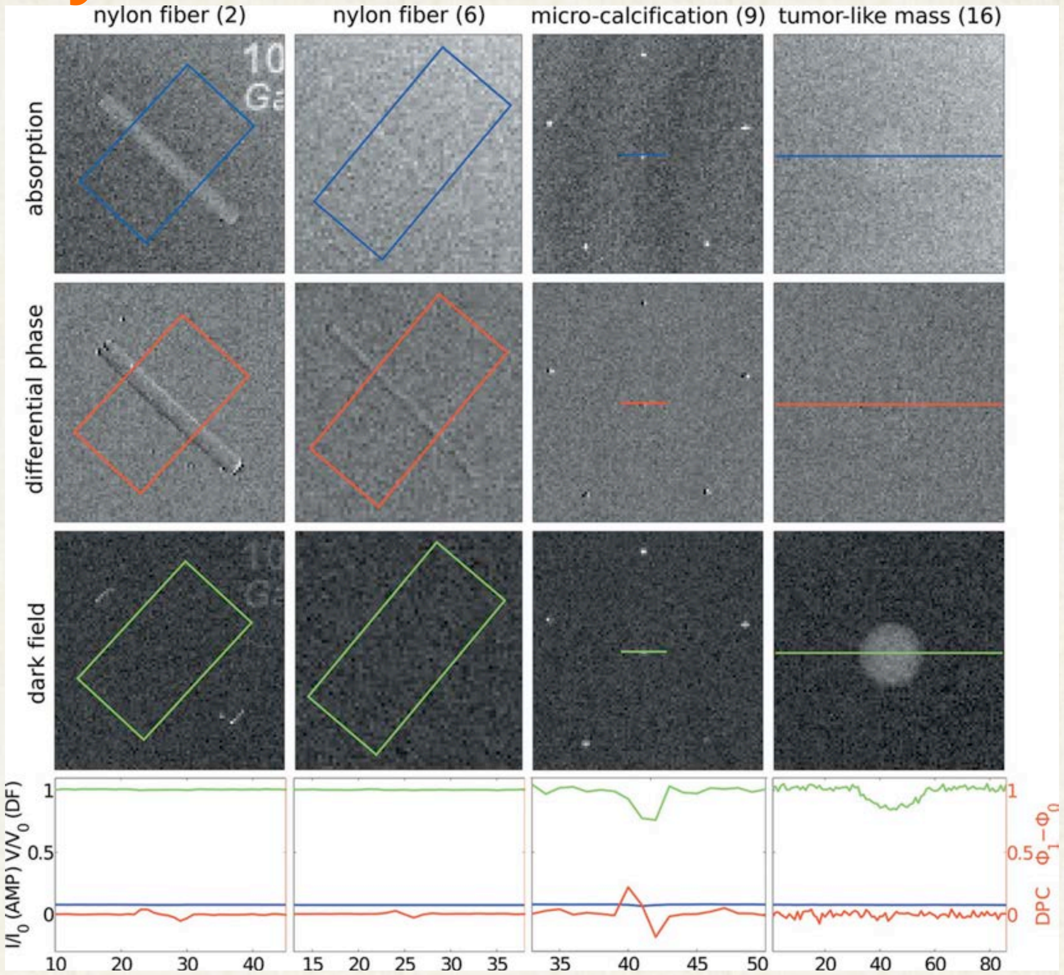
Mammography



mammography in double energies (with and without contrast agent: typ. iodine)

Radiology October 2003





J. Synchrotron Rad. (2012). 19, 525–529

Multimodal ➔ better resolution / discrimination ➔ lower dose