BTML 2013
13 septembre 2013

High flux Compact Compton X-ray Sources
ThomX, a demonstrator

Marie Jacquet

Laboratoire de l'Accélérateur Linéaire
Orsay, France (IN2P3,CNRS)

mjacquet@lal.in2p3.fr

Why X-ray users need "compact" X-ray source ?

► In many scientific domains **synchrotron sources** are currently the only machines in term of brightness to perform and carry out **the most ambitious analyses and searches** requiring **~ 10-100 KeV X-rays.**

Conventional
X Radiography & IR Reflectography

(Anal. Chem. 80, 2008, 6436-6442)

X Transmission IR Reflectography

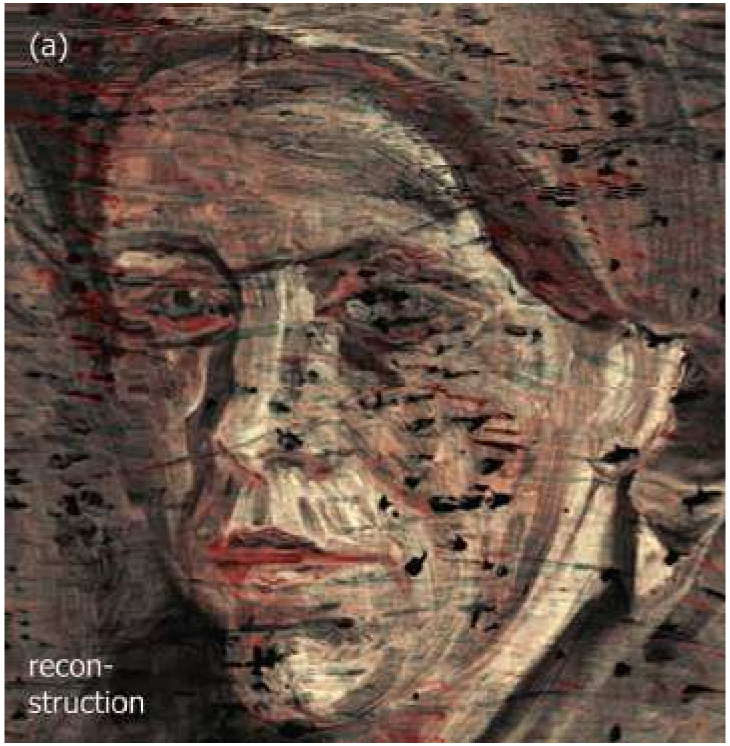
Conventional
X Radiography & IR Reflectography

(Anal. Chem. 80, 2008, 6436-6442)

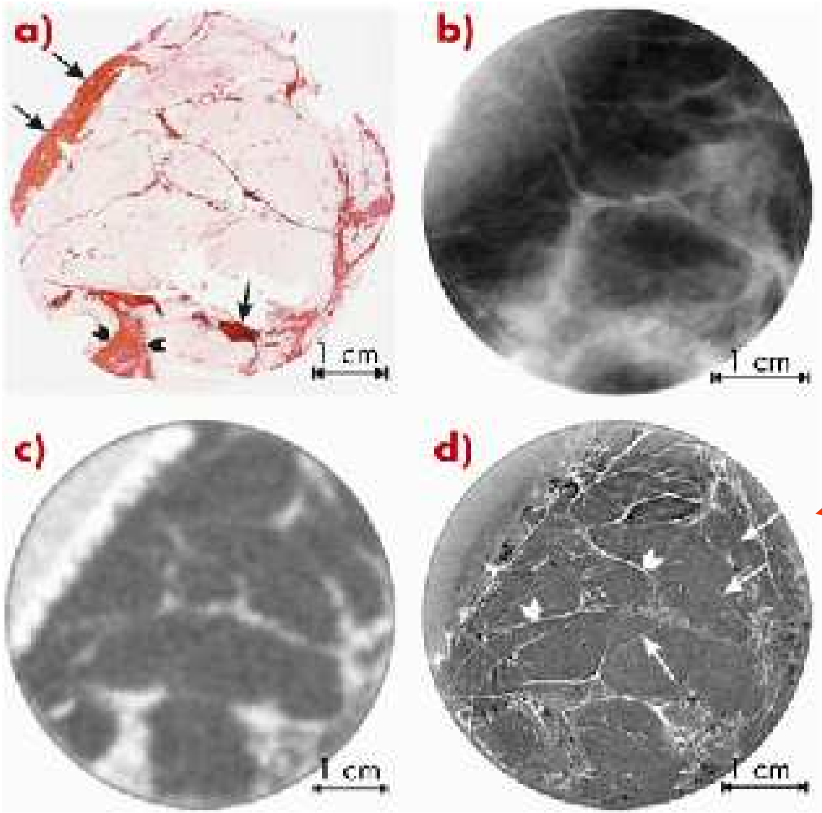
X Transmission IR Reflectography

Analyses at synchrotron DESY
(non destructive)

Colored reconstruction



Mapping of a breast tissue sample



(Phys. Med. Biol. 52, 2007, 2197-2211)

a) Histological section
(used as a standard for interpretation)

b) Clinical planar screen-film
mammogram taken at the hospital

c) Clinical scanner

d) **ID17 ESRF** (Phase constrast imaging)
Same dose as c)

Stronger contrast

→ Improvement in the visualisation of the morphology and of the overall architecture of the breast tissues

Why X-ray users need "compact" X-ray source ?

- In many scientific domains **synchrotron sources** are currently the only machines in term of brightness to perform and carry out **the most ambitious analyses and searches** requiring **~ 10-100 KeV X-rays.**

- **Compact lab sources today does not allow to carry out many of the techniques used at synchrotrons.**

  X-ray tubes : The most efficient are rotating anodes
  (Rigaku ~ 10^{10} ph/sec , polychromatic)

Synchrotron sources are **very powerful**, but,
- **not very "pratical"** for some applications,
- with a **limited access time**.

→ **Developing intense lab sources should avoid these limitations**

- **Compact Compton Sources (CCS)**

  Methods currently used at synchrotrons and requiring a high brightness beam could be largely developed in a lab size environment (hospitals, labs, museums).

  - **Compactness (surface ~ 100 m^2)**
  - **High intensity (10^{12} – 10^{14} ph/sec)**
  - **Tunable beam**
  - **High quality beam (brightness 10^{11} – 10^{15} ph/sec/ mm^2 / 0.1% bw / $mrad^2$)**

Why X-ray users need “compact” X-ray source ?

► In many scientific domains **synchrotron sources** are currently the only machines in term of brightness to perform and carry out **the most ambitious analyses and searches** requiring **~ 10-100 KeV X-rays.**

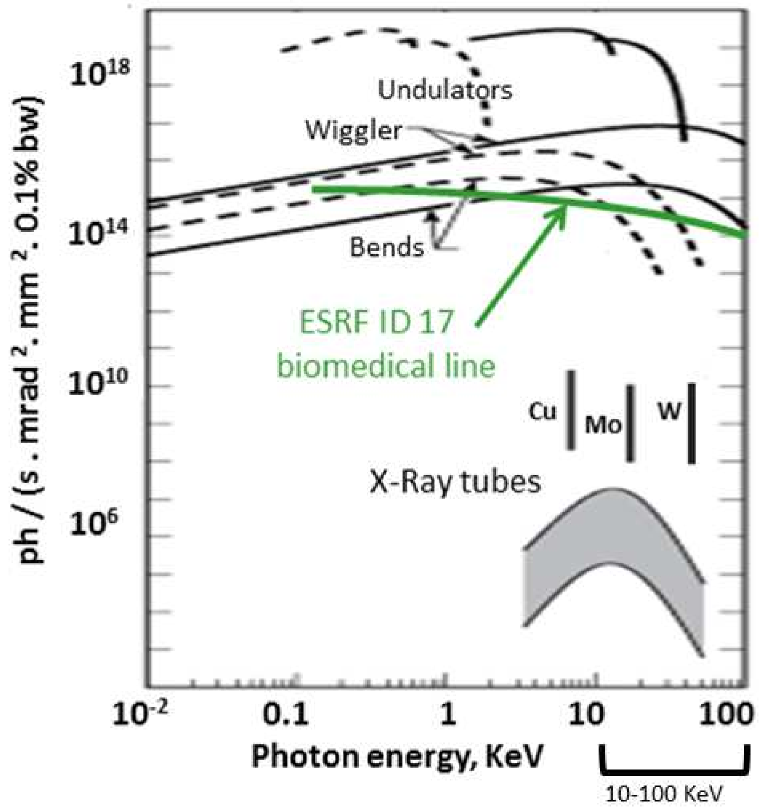
► **Compact lab sources today does not allow to carry out many of the techniques used at synchrotrons.**

<u>**X-ray tubes**</u> : The most efficient are rotating anodes (Rigaku ~ 10^{10} ph/sec , polychromatic)

<u>Synchrotron sources</u> are **very powerful**, but,

- **not very “pratical”** for some applications,
- with a **limited access time**.

→ **Developing intense lab sources should avoid these limitations**



► <u>Compact Compton Sources (CCS)</u>

Methods currently used at synchrotrons and requiring a high brightness beam could be largely developed in a lab size environment (hospitals, labs, museums).

- **Compactness** **(surface ~ 100 m^2)**
- **High intensity** **(10^{12} – 10^{14} ph/sec)**
- **Tunable beam**
- **High quality beam** **(brightness 10^{11} – 10^{15} ph/sec/ mm^2 / 0.1% bw / $mrad^2$)**

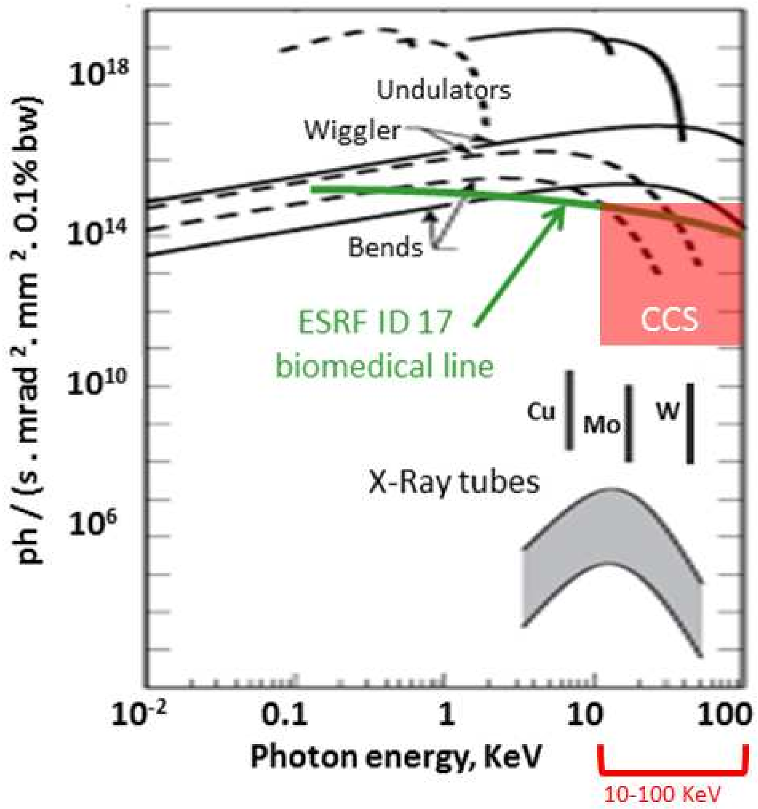
- In many scientific domains **synchrotron sources** are currently the only machines in term of brightness to perform and carry out **the most ambitious analyses and searches** requiring **~ 10-100 KeV X-rays.**

- **Compact lab sources today does not allow to carry out many of the techniques used at synchrotrons.**

  X-ray tubes : The most efficient are rotating anodes (Rigaku ~ 10^{10} ph/sec , polychromatic)

  Synchrotron sources are **very powerful**, but,
  - **not very “pratical”** for some applications,
  - with a **limited access time**.

  → **Developing intense lab sources should avoid these limitations**



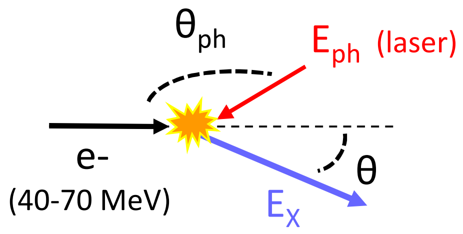
- **Compact Compton Sources (CCS)**

  Methods currently used at synchrotrons and requiring a high brightness beam could be largely developed in a lab size environment (hospitals, labs, museums).

  - **Compactness** **(surface ~ 100 m^2)**
  - **High intensity** **(10^{12} – 10^{14} ph/sec)**
  - **Tunable beam**
  - **High quality beam** **(brightness 10^{11} – 10^{15} ph/sec/ mm^2 / 0.1% bw / $mrad^2$)**

X-ray Compton Sources : principle and specifications

Compton scattering where the electron is no longer at rest



$$E_X \sim \frac{2\,\gamma^2\,E_{ph}\,[\,1 - \cos(\theta_{ph})\,]}{1 + (\gamma\theta)^2}$$

$\gamma = E_e / m_e >> 1$

$E_{ph} << m_e$

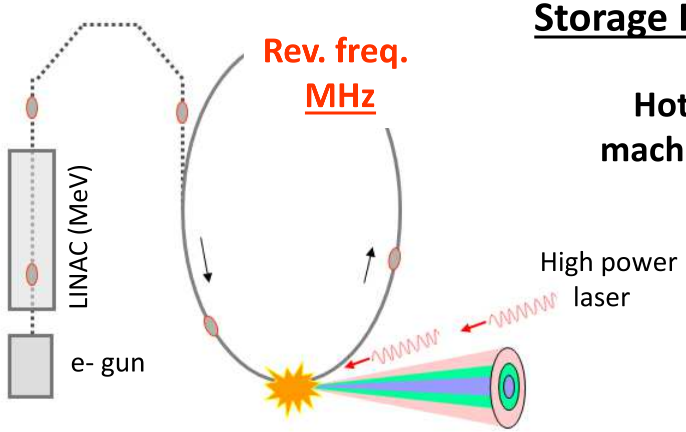
Compton cross section is "weak" ($6.6\ 10^{-25}\ cm^2$)

1. High flux ($10^{12} - 10^{14}$ ph/sec) → **Increase f_{rep} e^-/laser** (~ 10-100 MHz) → 2 main schemes

Storage Ring

Rev. freq. MHz

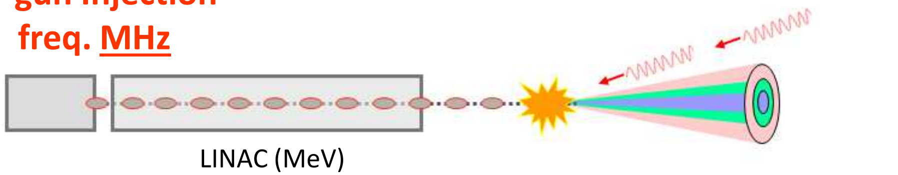
Hot machines



Linac

Superconducting machine (and e- gun)

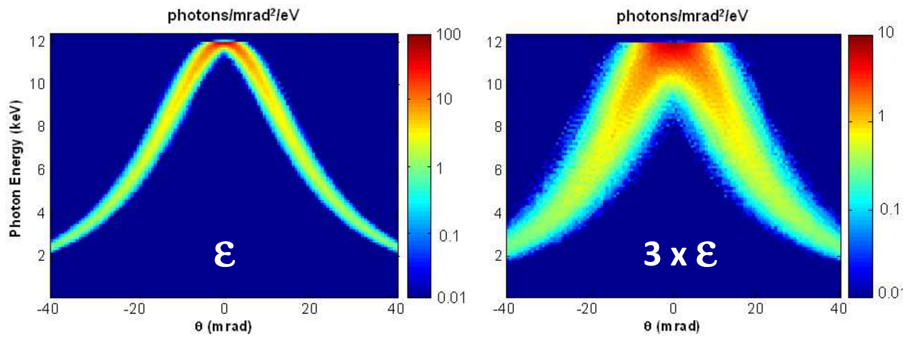
e- gun Injection freq. MHz



2. High brightness ($10^{11} - 10^{15}$)

$$Br \sim \frac{Flux}{(mm^2\ source)\ \ (dE_x/E_x)\ (mrad)^2} \sim \frac{Flux\ .\ \gamma^2}{\varepsilon_N^2}$$

$$\sigma_e^2\ \sigma_e'^{\,2} = \varepsilon^2$$



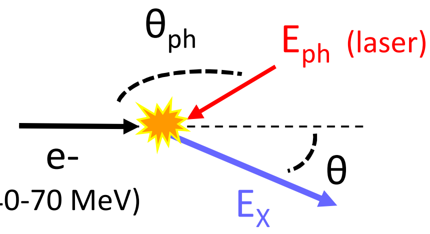
[Graves, Alghero Workshop 2008]

→ **small electron beam emittance**

X-ray Compton Sources : principle and specifications

Compton scattering where the electron is no longer at rest

Compton cross section is "weak" ($6.6\ 10^{-25}\ cm^2$)



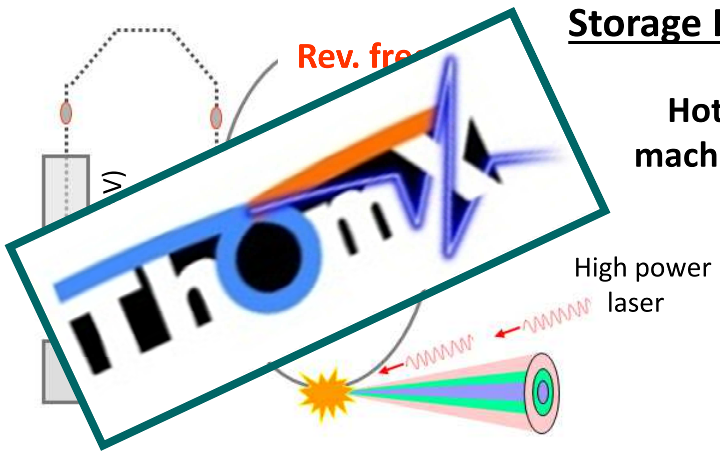
$$E_X \sim \frac{2\,\gamma^2\, E_{ph}\,[\,1 - \cos(\theta_{ph})\,]}{1 + (\gamma\theta)^2}$$

$\gamma = E_e / m_e >> 1$
$E_{ph} << m_e$

1. High flux ($10^{12} - 10^{14}$ ph/sec) → **Increase f_{rep} e^-/laser** (~ 10-100 MHz) → 2 main schemes

Storage Ring

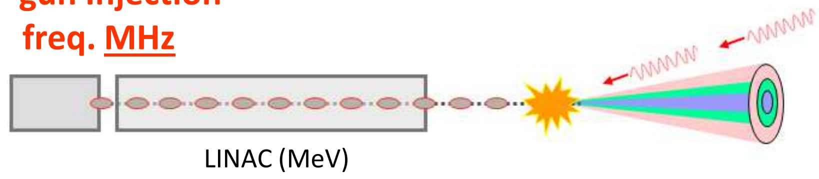
Hot machines



Linac

Superconducting machine (and e- gun)

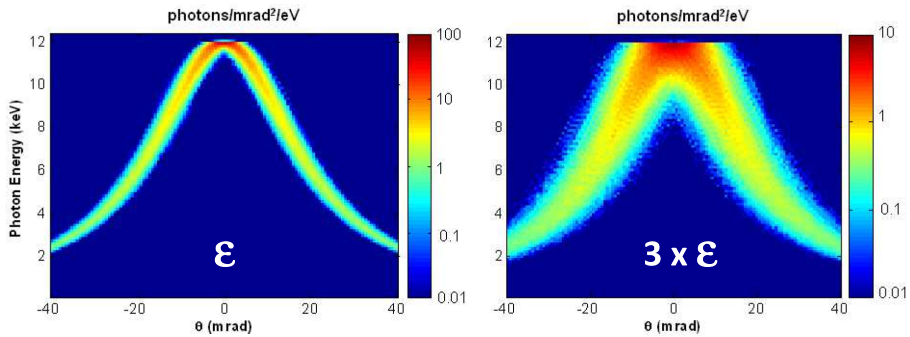
e- gun Injection freq. MHz



2. High brightness ($10^{11} - 10^{15}$)

$$Br \sim \frac{\text{Flux}}{(\text{mm}^2\ \text{source})\ \ (dE_x/E_x)\ (\text{mrad})^2} \sim \frac{\text{Flux}\ .\ \gamma^2}{\varepsilon_N^2}$$

$$\sigma_e^2\ \sigma_e'^2 = \varepsilon^2$$



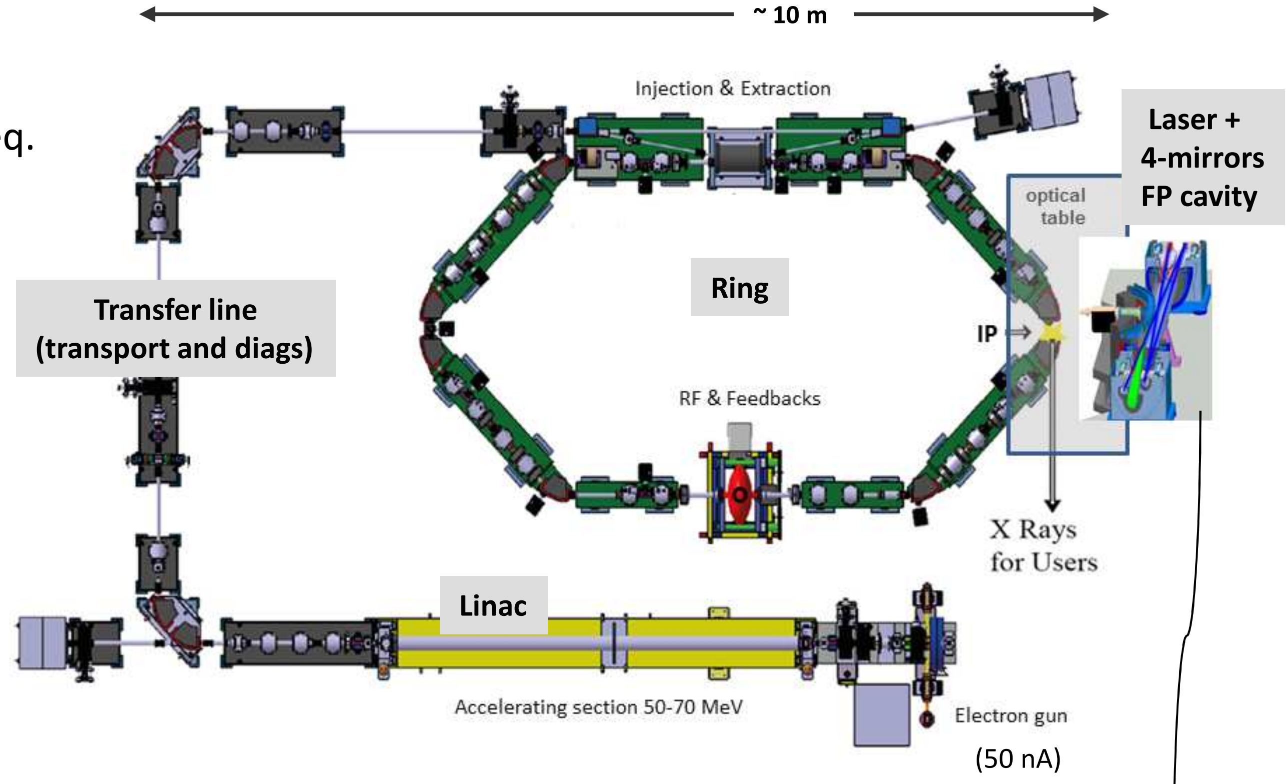
[Graves, Alghero Workshop 2008]

→ **small electron beam emittance**

Electron machine

- 1 nc / bunch , 50 Hz inj. freq.
- Ring, 20 MHz frep.
- σ_e ~ 70 µm
- ε_N ~ 4 mm.mrad
- τ_e ~ 10-20 ps

Machine funded
In construction

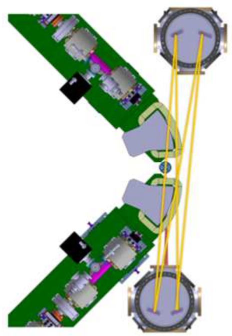


X-ray beam

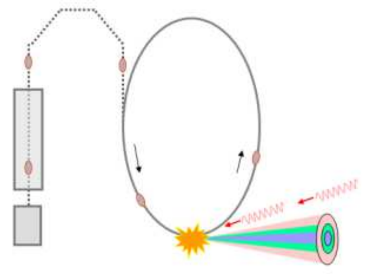
Flux	10^{13}
Brigthness	10^{11}
Transv. size	70 µm
E_X	20-90 KeV

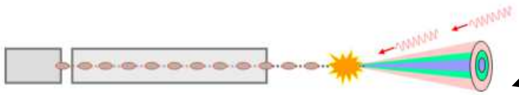
Laser /Cavity system

- Laser ~ 1W
- Optical fiber amplification (100 W) 2-3 µJ/pulse
- Optical FP cavity amplification (gain 10000)
- 1 MW stored inside the cavity (20-30 mJ/pulse)

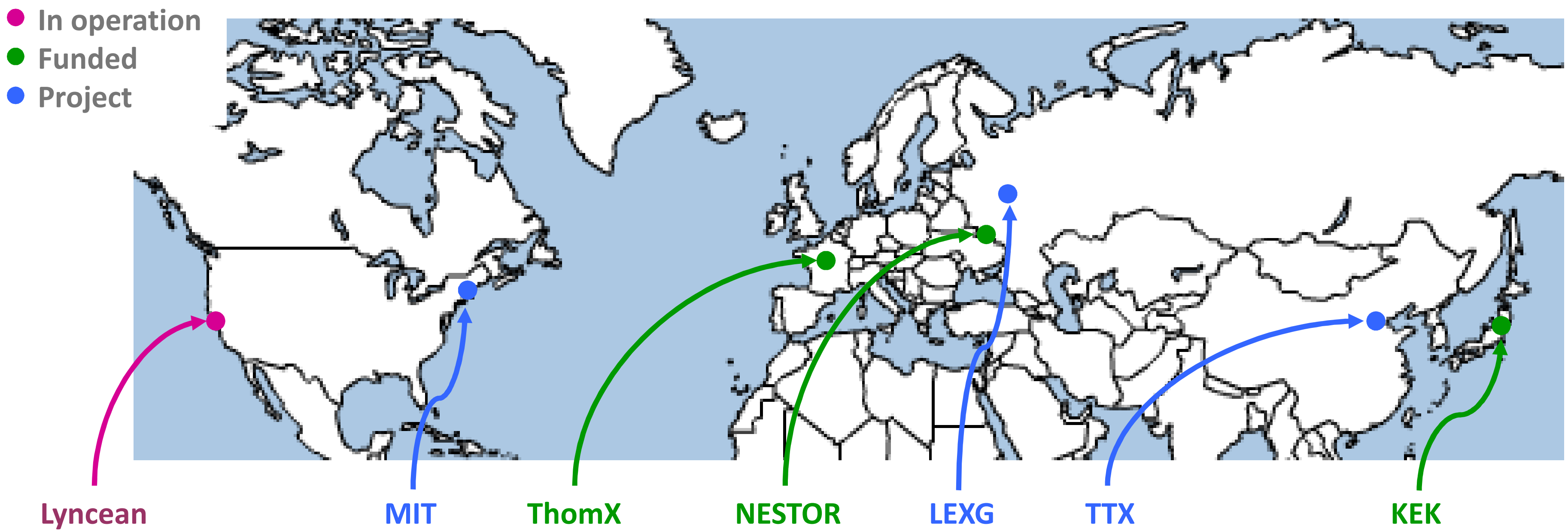


Compact Compton projects (X-ray flux > 10^{12} ph/sec)





Project	type	E_X (KeV)	Flux	σ_S (µm)	Brightness
Lyncean	SR	10-20	10^{11}	50	
TTX	SR	20-80	10^{12}	50	
LEXG	SR	33	10^{13}	20	
NESTOR	SR	30-500	10^{13}	70	
ThomX	SR	20-90	10^{13}	70	$\sim10^{11}$
KEK QB	Linac	35	10^{13}	10	
KEK ERL	Linac	67	10^{13}	30	
MIT	Linac	3-30	10^{14}	2	$\sim10^{15}$



Compact Compton projects (X-ray flux > 10^{12} ph/sec) → Chalenges

Achieve the laser/cavity system requirements

→ 1 MW stored inside the cavity

Acquire the control of a low energy storage ring

→ keep a stable & good quality beam

Project	type	E_X (KeV)	Flux	σ_S (µm)	Brightness
Lyncean	SR	10-20	10^{11}	50	
TTX	SR	20-80	10^{12}	50	
LEXG	SR	33	10^{13}	20	
NESTOR	SR	30-500	10^{13}	70	
ThomX	SR	20-90	10^{13}	70	~10^{11}
KEK QB	Linac	35	10^{13}	10	
KEK ERL	Linac	67	10^{13}	30	
MIT	Linac	3-30	10^{14}	2	~10^{15}

LINAC scheme machine : 2 main technical challenges

- Construction/validation of **a superconducting electron gun** delivering bunches with an extremely low emittance and ~ 100 MHz of injection frequency
- Difficulties in **radioprotection for integration**:

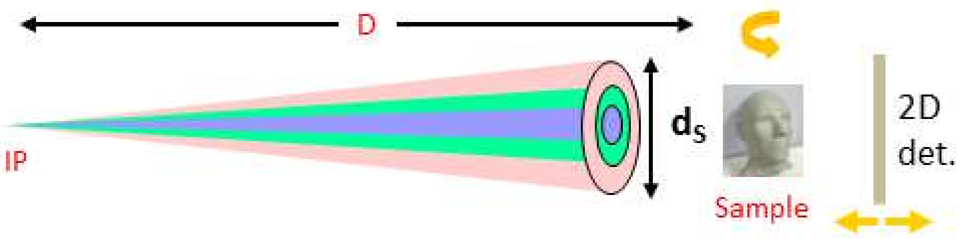
MIT → 0.01 nc / bunch , 100 MHz, 40 MeV → 40 KW to be absorbed
ThomX → 1 nc / bunch , 50 Hz, 50 MeV → 2.5 W

1. Using the 2D divergent beam

(biomedical and cultural heritage applications)

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

IMAGING

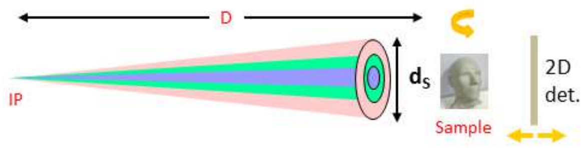


→ Measure large sample with no more need to move it (patient, materiel …)

Pink beam (3-30% bw)

1. Using the 2D divergent beam

(biomedical and cultural heritage applications)



- **Conventional radiography**
- **K-edge substraction imaging**
- **Phase contrast imaging**
- **Magnification**
- **Radiotherapy**

- **High energy** (~ 80KeV) to test high-Z element drug
- **No need of monochromaticity** (pink beam, bw ~ 30%)

Ex. : Human head phantom

ThomX:

- 5 mrad opening angle
- d_S = 12 cm at D ~ 15 m
- 6.10^{12} ph/s
- bw 60-90 KeV

ThomX and Synchrotron (ID17/ESRF) → comparable

Compared to hospital sources :

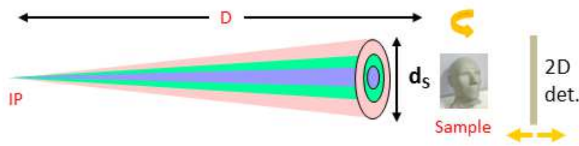
→ allow the reduction of the dose
→ better image quality

Potential of applications of X-ray CCS

1. Using the 2D divergent beam

(biomedical and cultural heritage applications)

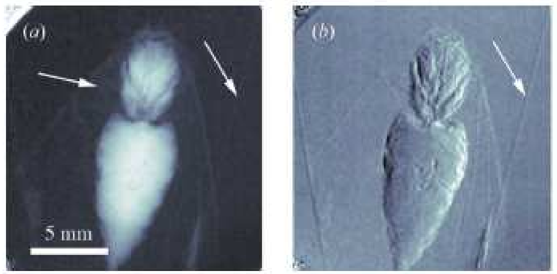
- Conventional radiography
- K-edge substraction imaging
- **Phase contrast imaging**
- Magnification
- Radiotherapy



- **bw 2-3%**
- **Small source size** (to have transv. coherence)

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

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



standard absorption

phase-contrast

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

Proof of principle

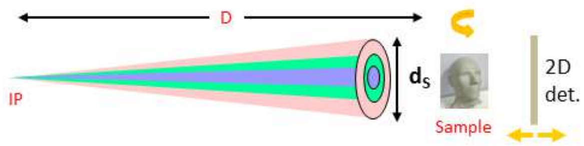
- 70 KeV, 2-3% bw, σ ~ 70 µm
- d_S = 4 cm at D ~ 15 m
- 10^{12} ph/s

Hospital sources

(large focal spot size, broad spectrum, low flux)

1. Using the 2D divergent beam

(biomedical and cultural heritage applications)



- Conventional radiography
- K-edge substraction imaging
- Phase contrast imaging
- Magnification
- **Radiotherapy**

- **High energy** (~ 80KeV)
- **bw ~ 10%**

ThomX

- 80 KeV ± 10 KeV
- d_s = 5 cm at D ~ 10 m
- 3.10^{12} ph/s

Ex. : Human head tumor
(tumor deliver dose ~ 10-20 Gy)

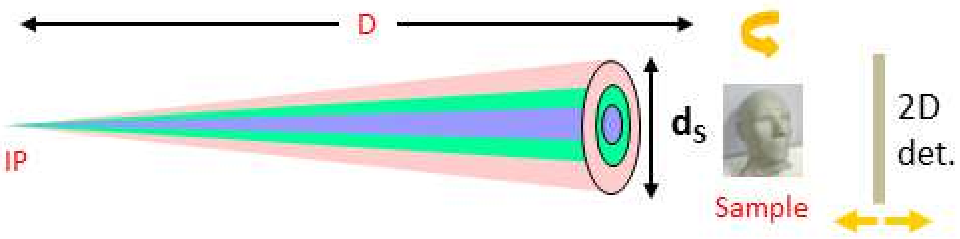
- **ThomX** → 9 mGy/sec → **20-30 min of irradiation**
- **ESRF/ID17** (~ 6 mGy/sec)
- **Hospital sources** → **broad spectrum, and continuously operation not possible**

1. Using the 2D divergent beam

(biomedical and cultural heritage applications)

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

IMAGING



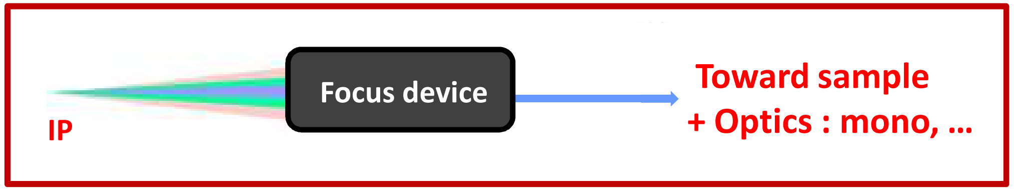
→ Measure large sample with no more need to move it (patient, materiel …)

Pink beam (3-30% bw)

2. Using the central part of the beam

(cultural heritage / material science applications)

- Fluorescence Spectroscopy
- XANES Spectroscopy
- Diffraction
  - → Structural analyses
  - → Pump-probe experiments



Quasi-monochromatic beam (~ 1% - 0.01 % bw)

Potential of applications of X-ray CCS

1. Using the 2D divergent beam

(biomedical and cultural heritage applications)

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

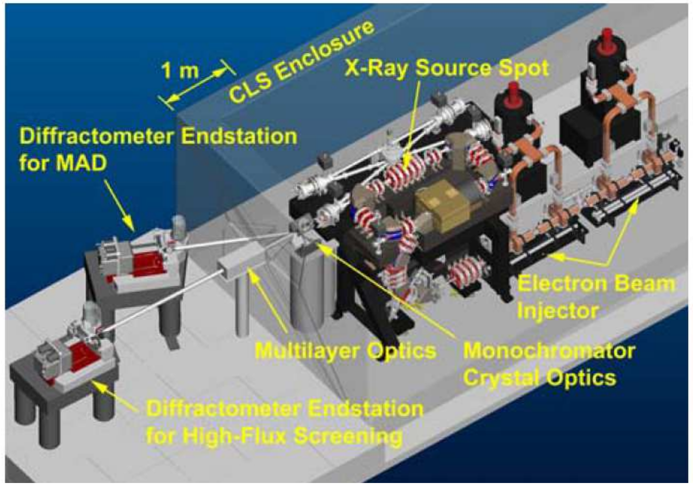
2. Using the central part of the beam

(cultural heritage / material science applications)

- Fluorescence Spectroscopy
- XANES Spectroscopy
- **Diffraction**
  - → **Structural analyses**
  - → Pump-probe experiments

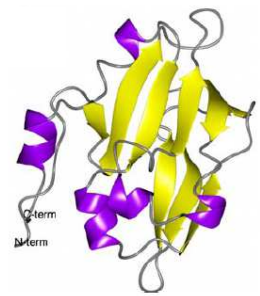
- Quasi-monochromatic beam

1st determination of the 3D structure of a protein
CS Lyncean Tech. source



15 KeV, 1.4% bw
5.10^6 ph/sec
σ = 120 µm

Ribbon representation



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

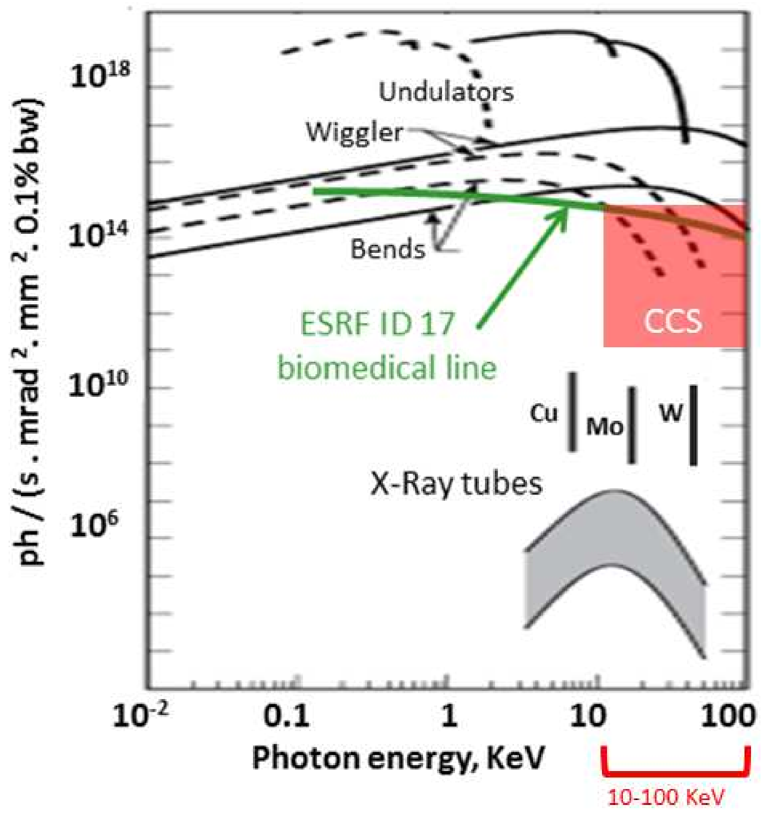
Proof of principle (~ Rigaku rotating anode)

- 10^9 ph/s , ΔE/E ~ 10^{-2} - 10^{-3}

- **CCS combine**
  - Compactness
  - High flux/brightness
  - Tunable energy
  - Transverse coherence

- **Today**
  - → Hot machines
  - → Brightness ~ 10^{11}

- **… and tomorrow**
  - → Supra machines (e- gun)
  - → Brightness ~ 10^{13}-10^{15}

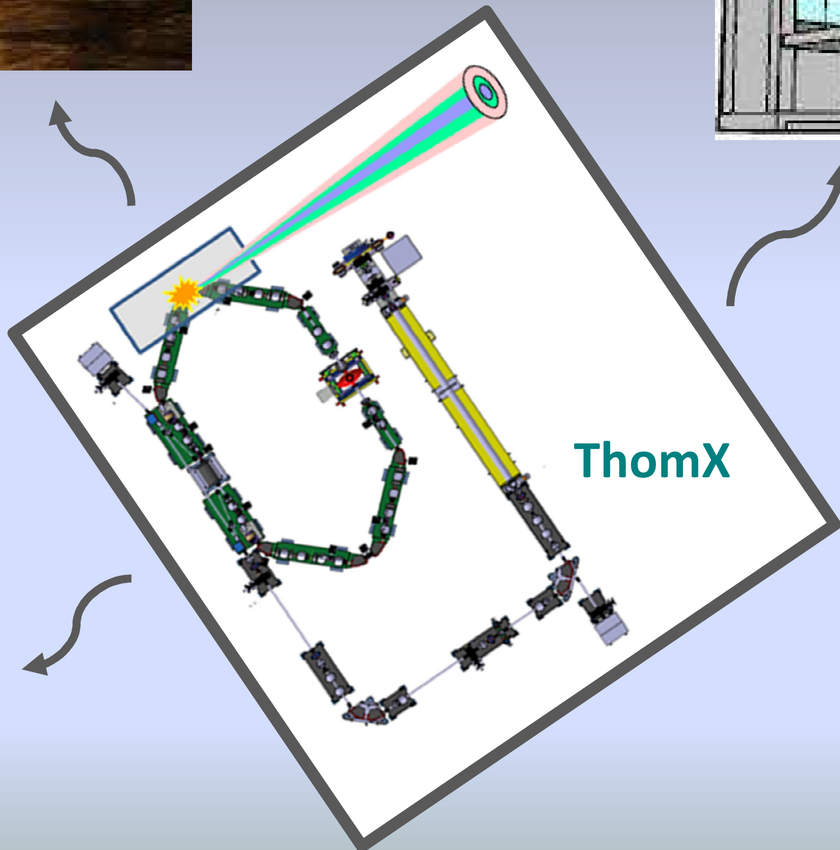


- **CCS will open a new approach in research and development of applications**

- Biomedical science
- Cultural heritage research
- Material science

→ Imaging techniques using a large 2D beam = golden applications

→ Fill the great lack of intense lab sources.



Thank you