High flux Compact Compton X-ray Sources

Biomedical and clinical applications

3rd Topical Workshop on Novel Acceleration Techniques

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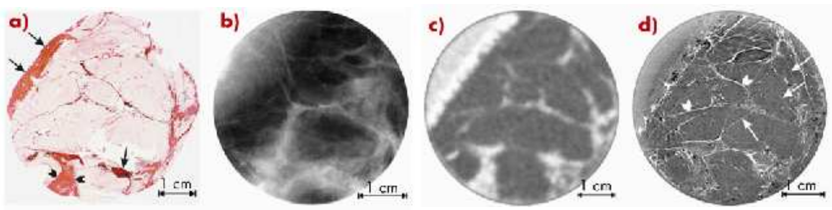
- In many scientific domains **synchrotron sources** are currently the only machines in term of brightness to perform and carry out **the most ambitious analyses and searches** requiring **~ 10-100 KeV X-rays.**

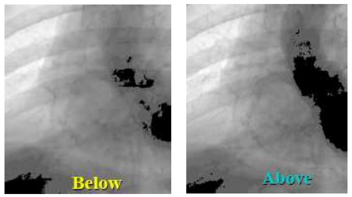


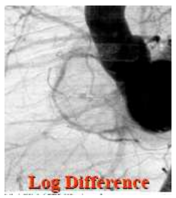
Histological section | Clinical mammography | Clinical scanner

Mapping of a breast tissue sample
(Phys. Med. Biol. 52, 2007, 2197-2211)

ID17 ESRF Phase contrast imaging
(same dose as c)

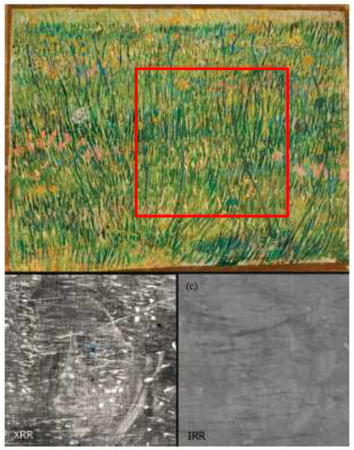
K-edge at ESRF (+contrast agent)





The difference increase the contrast

Vincent van Gogh
“Un coin d’herbe”
(1887)



X Transmission IR Reflectography

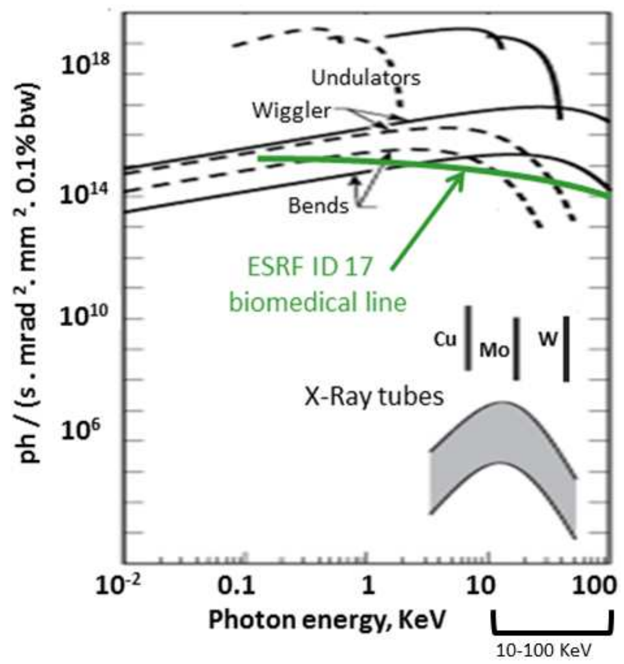
DESY synchrotron - Fluorescence
- XANES

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

- **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

Current panorama of X-ray source average brightnesses



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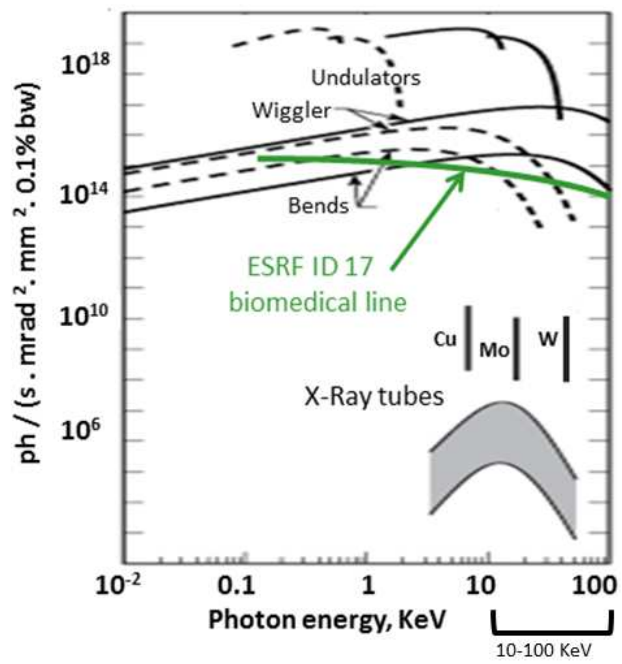

► **Compact Compton Sources (CCS)**

- **Compactness** (surface $\sim 100\ \mathrm{m}^2$)
- **High intensity** ($10^{12} - 10^{14}\ \mathrm{ph/sec}$)
- **Tunable beam**
- **High quality beam**

  (brightness $10^{11} - 10^{15}\ \mathrm{ph/sec/\ mm^2\ /\ 0.1\%\ bw\ /\ mrad^2}$)

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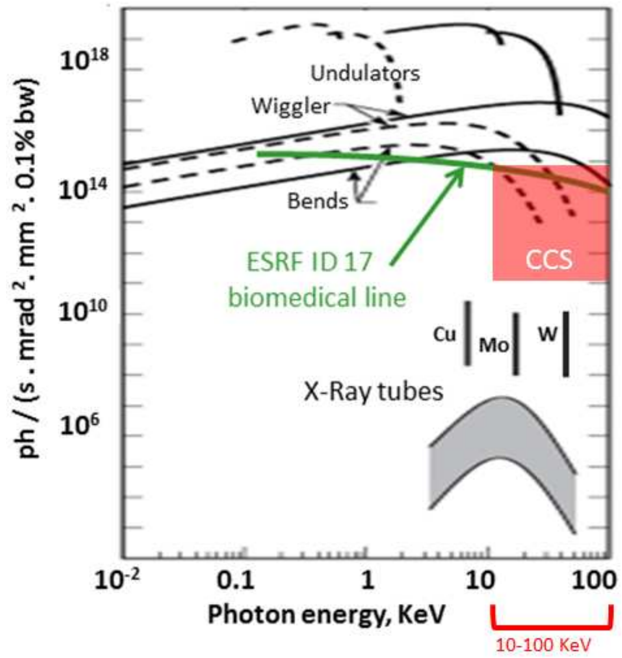

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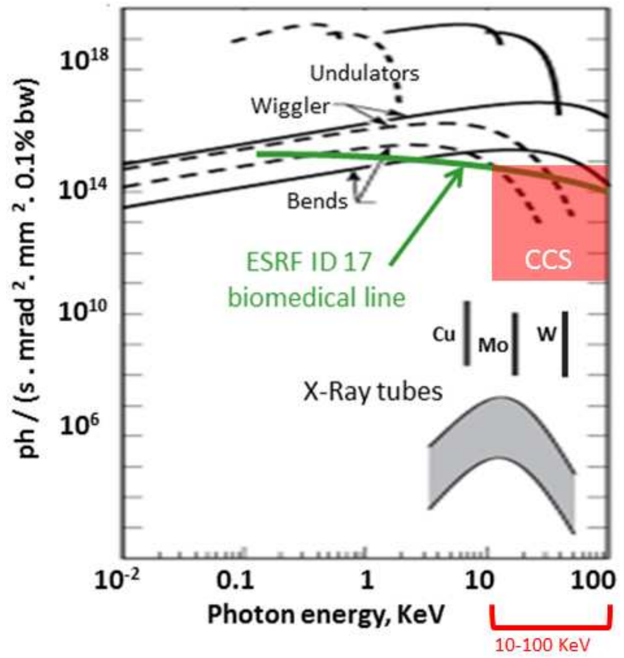

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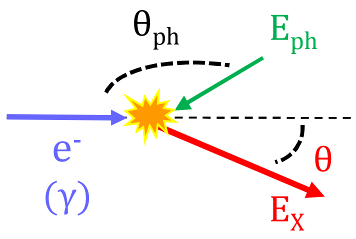
  (brightness $10^{11} - 10^{15}$ ph/sec/ mm^2 / 0.1% bw / mrad^2)

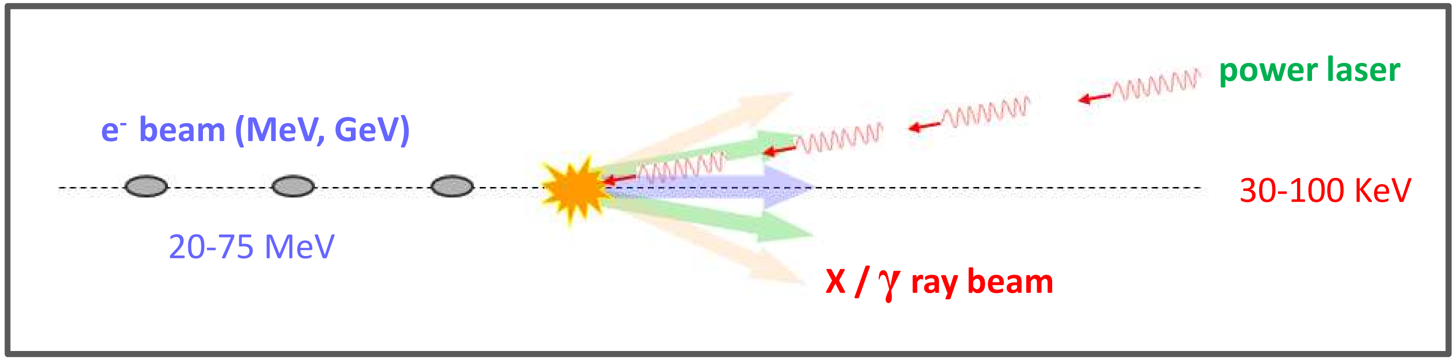
→ Methods currently used at synchrotrons and requiring a high brightness beam could be largely developed in **a lab size environment** (hospitals, labs, museums).

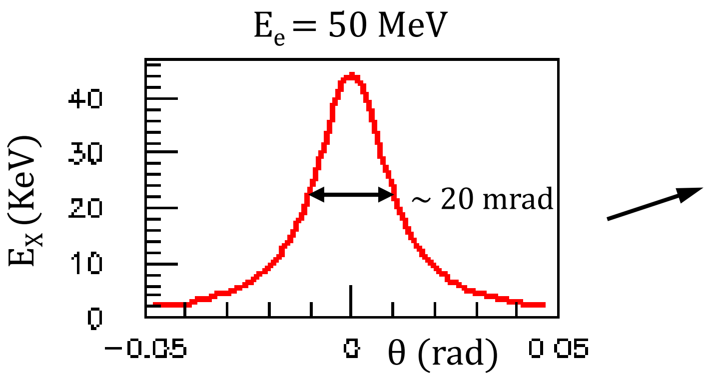
Compton scattering where the electron is no longer at rest → **"Inverse Compton" regime**

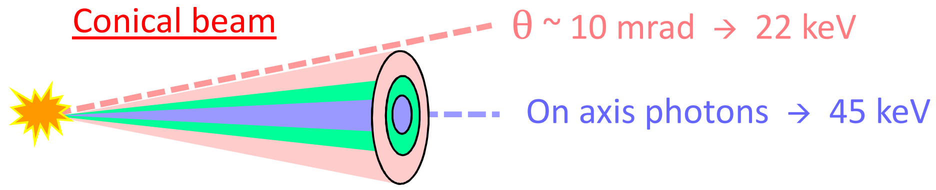


$$E_X \sim \frac{2\,\gamma^2\,E_{ph}\,[1-\cos(\theta_{ph})]}{1+(\gamma\theta)^2}$$

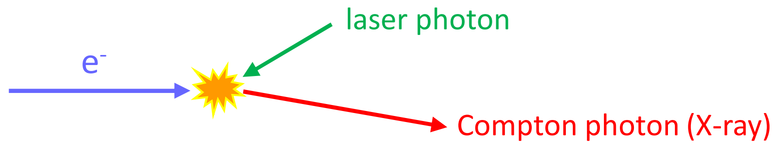
$(\gamma = E_e / m_e >> 1 \; ; \; E_{ph} << m_e)$







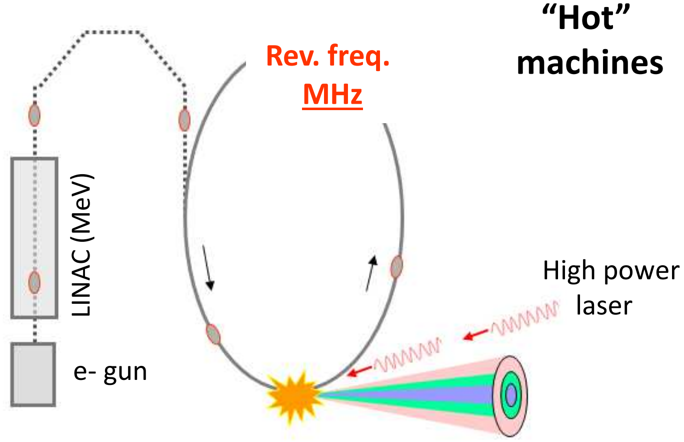
Univocal relation between energy E_X and diffusion angle θ



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

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

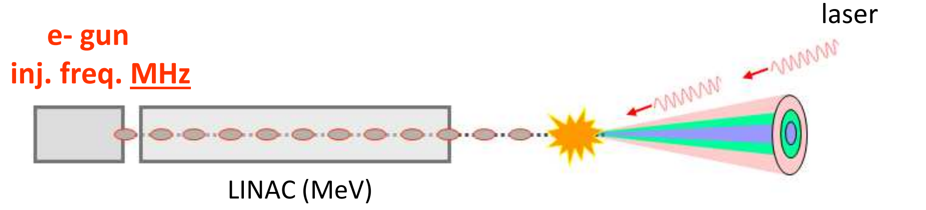
Storage Ring



"Hot" machines

Linac

Superconducting machines (and SC e- gun)



1. Compactness
2. X-ray energy tunable
3. X-ray polarisation controlled
4. High flux
5. Pulse duration
6. High quality beam

= good level of transverse coherence and high brightness

1. **Compactness**
   (~ 100 m^2)

2. **X-ray energy tunable**
   $E_X \sim E_e^2 E_{ph}$

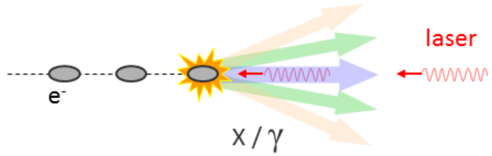
3. **X-ray polarisation controlled**
   → governed by the laser polarisation

4. **High flux**

$$\text{Flux} \sim \frac{\sigma_{comp} N_e N_\gamma f_{rep}}{2\pi(\sigma_e^2 + \sigma_\gamma^2)} \sim 10^{12} - 10^{14} \text{ ph/sec}$$

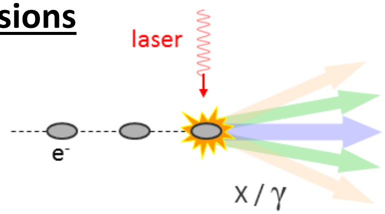
5. **Pulse duration**

Head-on collisions



~ e- bunch duration
~ 0.1 - 10 ps

90º Collisions



~ transit time of interaction
→ Ultra-short pulses **< 100 fs**

6. **High quality beam**

= good level of transverse coherence and high brightness

$$d_{tc} \sim \frac{L_{source\_sample}}{\sigma_S E_X (KeV)} (10^{-9})$$

A large transverse coherence requires a small source size σ_S
→ **a small e^- beam size σ_e**

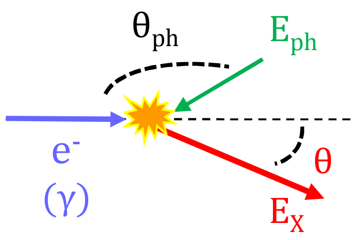
$$Br \sim \frac{\text{Flux}}{(mm^2 \text{ source})(dE_x/E_x)(mrad)^2} \sim 10^{11} - 10^{15}$$

X-ray spectral bandwidth

High brightness → narrow dE_x/E_x

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

On-axis X-ray spectral bandwidth :



$$dE_x / E_x \sim 10^{-3} \otimes 10^{-3} - 10^{-5} \otimes 10^{-3} \otimes 10^{-3} - \text{few } 10^{-2}$$

laser energy spread	laser divergence	e- energy spread	e- divergence
dE_{ph}/E_{ph}	$\frac{1}{4}\,(d\theta_{ph})^2$	$2\,(d\gamma/\gamma)$	$\gamma^2\,\sigma_e'^2$

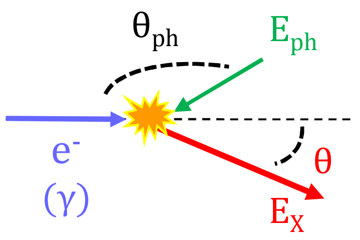
Dominant effect

$\sigma_e' = 1$ mrad , $\gamma = 100$
→ $dE_x / E_x \sim 1\%$

$$Br \sim \frac{Flux\,.\,\gamma^2}{\varepsilon_N^{\,2}}$$

High brightness requires small e^- beam emittance

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



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laser energy spread	laser divergence	e- energy spread	e- divergence
dE_{ph}/E_{ph}	¼ $(d\theta_{ph})^2$	$2\ (d\gamma/\gamma)$	$\gamma^2\ \sigma_e'^2$

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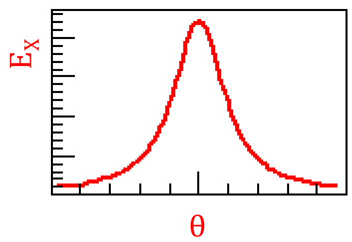
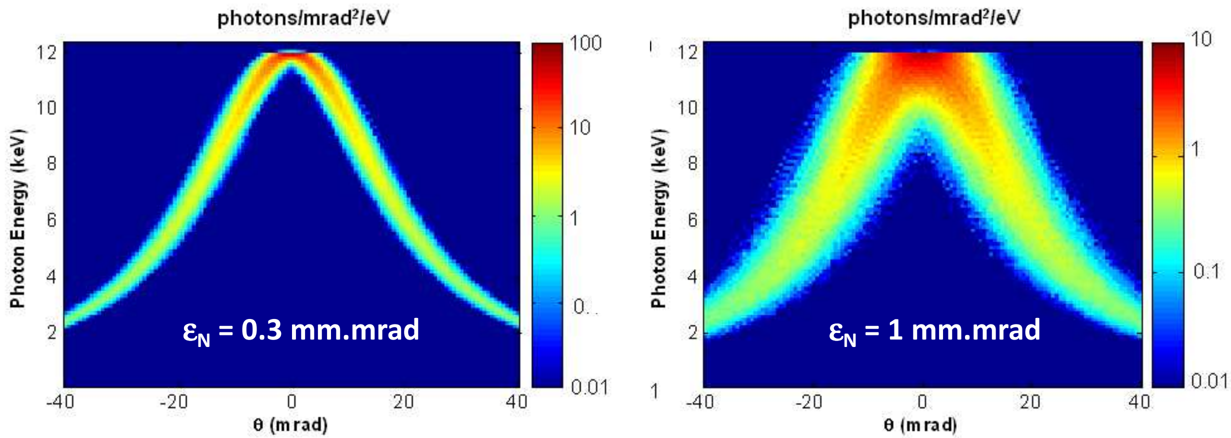
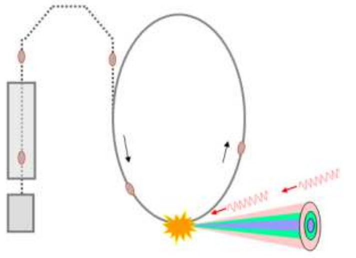
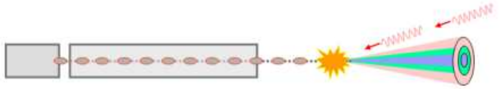
Only kinematic





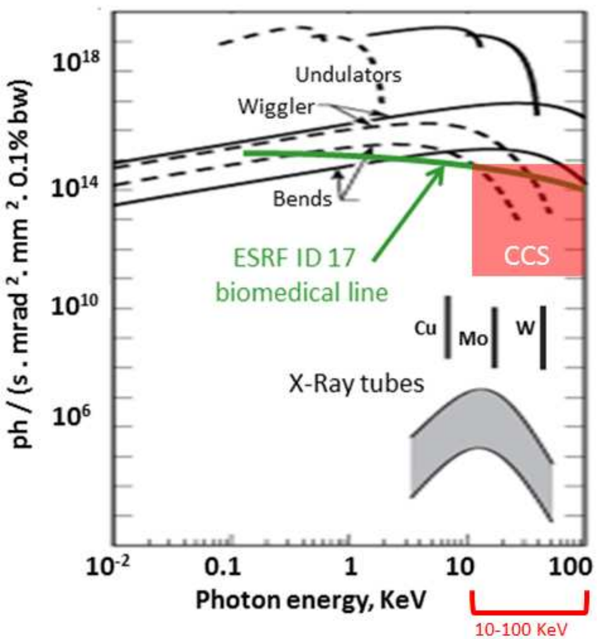
[W.S. Graves, Alghero Workshop 2008]





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

* In operation • Funded x Not funded



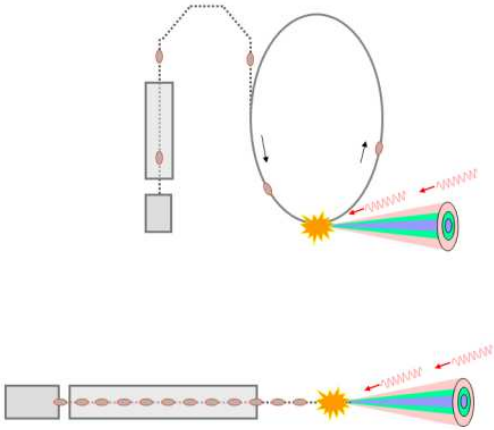
Next future
(SC machines)

Near future
("hot " machines)

Remaining strong challenges:

- SC e- gun : 100 MHz of inj. freq.
  ~ 1 mA average current
  $\varepsilon_N \sim 0.1$ mm.mrad
- Radioprotection
  - 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

Compact Compton source projects (X-ray flux > 10^{12} - 10^{13} ph/sec)



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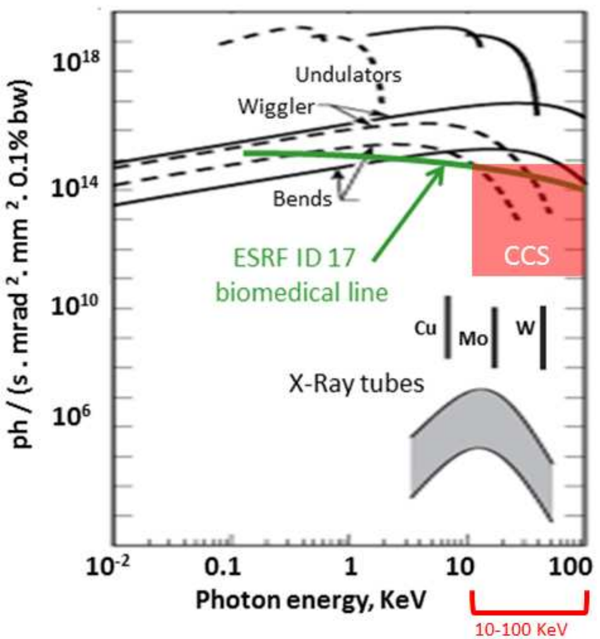

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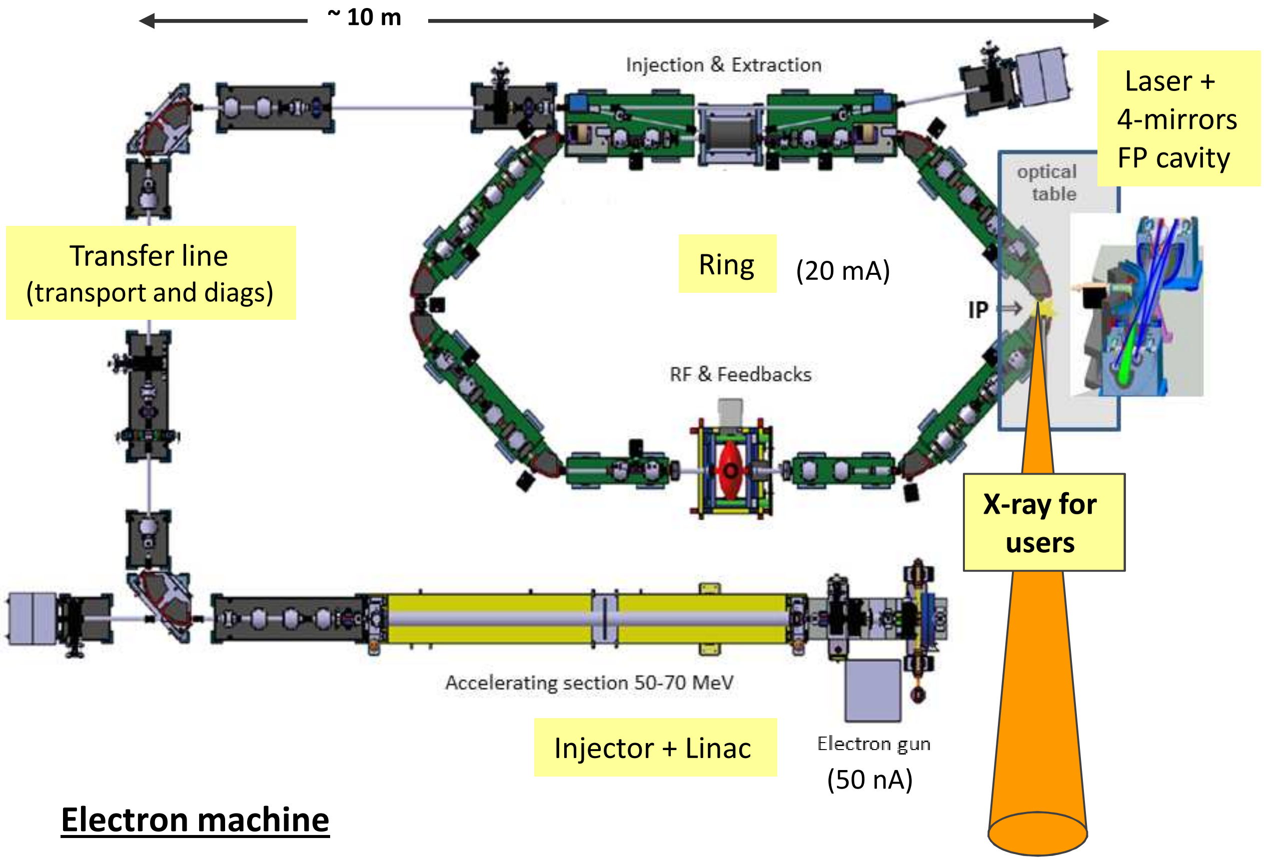
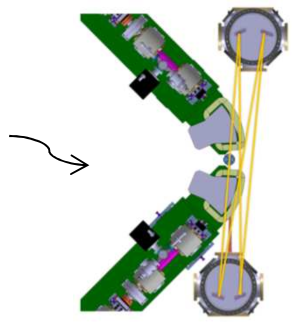
ThomX design





Laser /Cavity system

- Pulsed laser : ps , ~ 1W average
- 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)

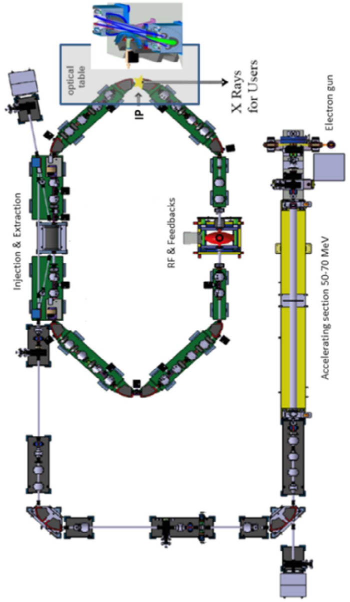
Electron machine

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

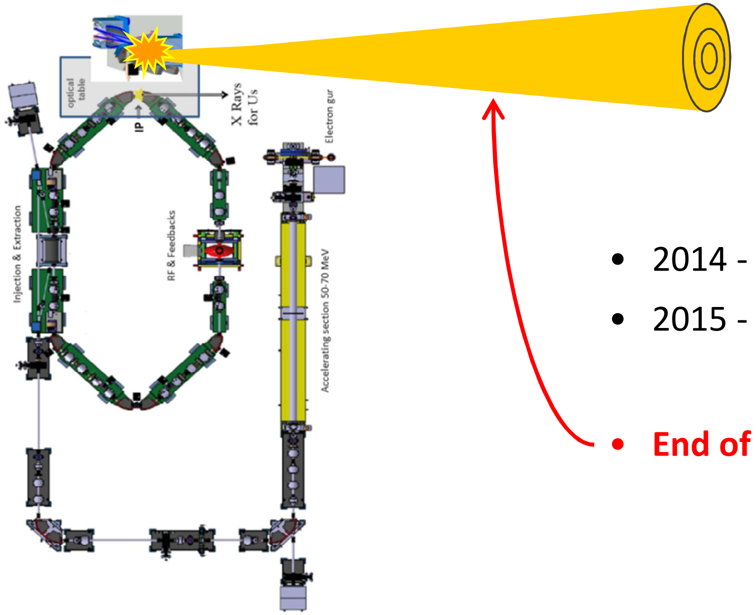
X-ray beam

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

Machine funded
In construction



- 2014 - 2015 → Building infrasctructure
- 2015 - 2016 → ThomX installation and commissioning



- 2014 - 2015 → Building infrasctructure
- 2015 - 2016 → ThomX installation and commissioning
- **End of 2015**

→ **With the first ThomX beam**

1. **Characterization of the Compton beam** (spectral flux, source size, energy, degree of coherence)
2. **Realization of simple demonstration experiments**

Biomedical
Cultural heritage studies
Materiel Science

Using techniques where the synchrotron community has already a lot of knowledge and experience.

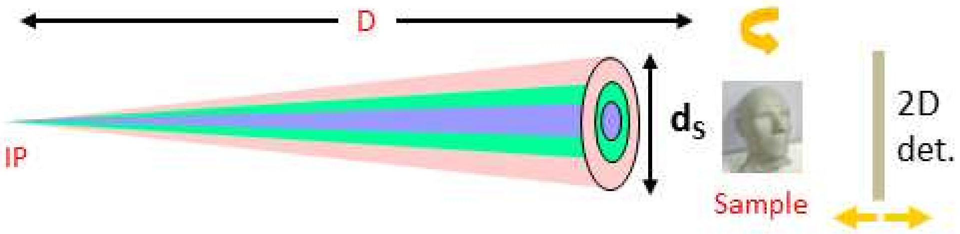
1. **Using the 2D divergent beam**

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

IMAGING

- Radiotherapy

THERAPY

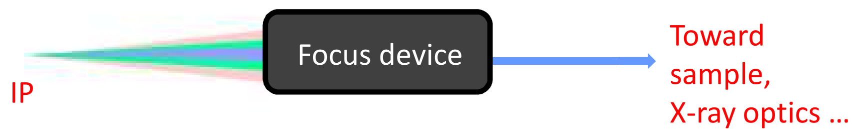


→ **Measure large sample with no more need to move it (patient, materiel …)**

Pink beam (3-30% bw)

2. **Using the central part of the beam**

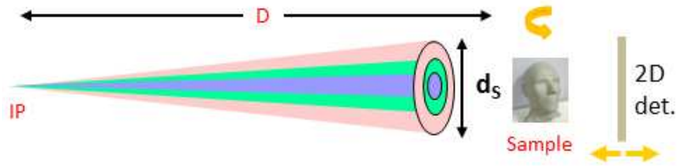
- **Diffraction**
  - Structural analyses
  - Pump-probe experiments using ultra-short pulses
- **Spectroscopy** (fluorescence, XANES)
- **Radiotherapy ?** MRT THERAPY ? (micro beam radiation)



Quasi-monochromatic beam (~ 1% - 0.1 % bw)

1. Using the 2D divergent beam

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



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

Ex. : Human head phantom

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

CCS and **Synchrotron (ID17/ESRF)** → **doses comparable**

(with hospital sources : broad spectrum, low flux)

→ **reduction of the absorbed dose**
→ **with a better image quality**

2. Using the central part of the beam

- Diffraction
  - Structural analyses
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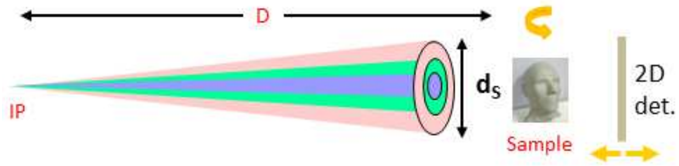
1. Using the 2D divergent beam

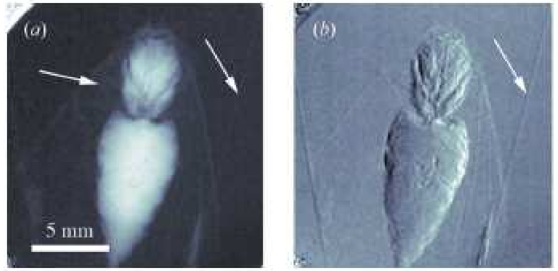


- Conventional radiography
- K-edge substraction imaging
- **Phase contrast imaging**
- Radiotherapy

- **bw 2-3%**
- **Small source size** (to have transverse 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

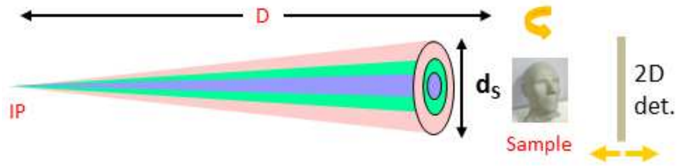
Proof of principle

- **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)

2. Using the central part of the beam

- Diffraction
  - Structural analyses
  - Pump-probe experiments using ultra-short pulses
- Spectroscopy (fluorescence, XANES)
- Radiotherapy ? MRT THERAPY ? (micro beam radiation)



1. Using the 2D divergent beam

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

2. Using the central part of the beam

- Diffraction
  - Structural analyses
  - Pump-probe experiments using ultra-short pulses
- Spectroscopy (fluorescence, XANES)
- Radiotherapy ? MRT THERAPY ? (micro beam radiation)

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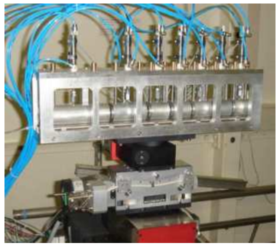
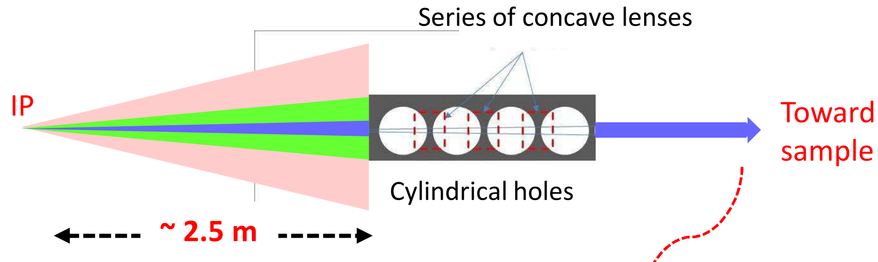


Focus device : Refractive lenses, or Capillary optics



~ 1 mm diameter beam

Estimated flux ~ 10^9 ph/s

$\Delta E/E$ ~ 10^{-2} - 10^{-3}

1. Using the 2D divergent beam

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

2. Using the central part of the beam

- Diffraction
  - Structural analyses → 3D structure determination of proteins
  - Pump-probe experiments using ultra-short pulses → Visualisation and studies of dynamic movies of molecules/atoms in motion
- Spectroscopy (fluorescence, XANES) → Analyses of cultural heritage works of art
- Radiotherapy ? MRT THERAPY ? (micro beam radiation) → A working group has started to study the feasibility

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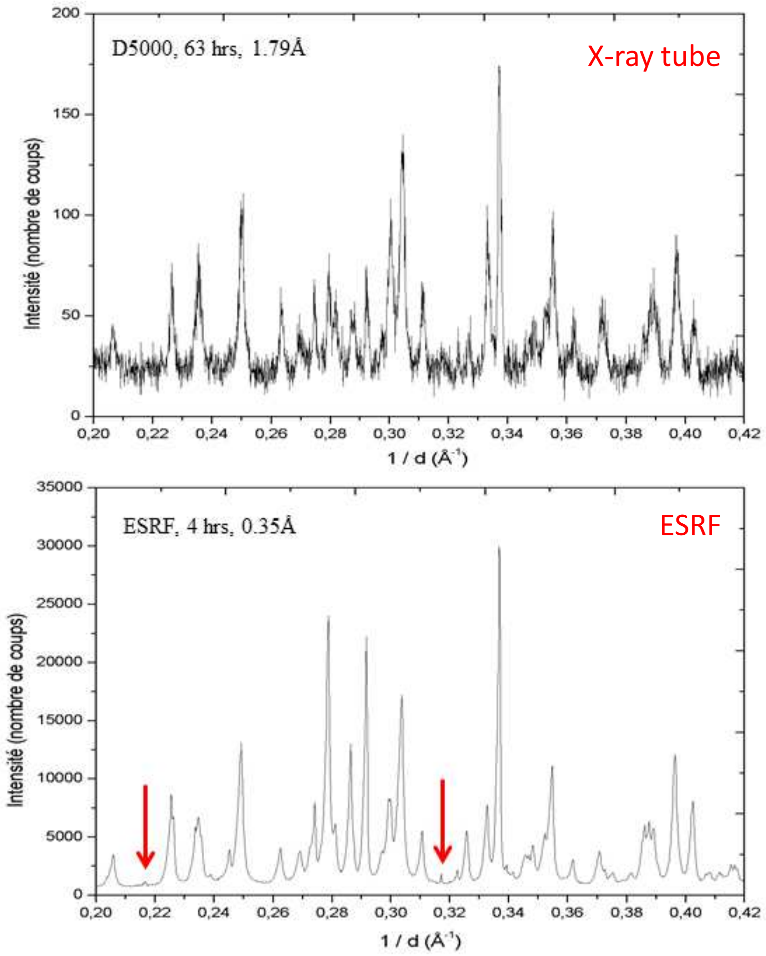
2. Using the central part of the beam

- **Diffraction**
  - Structural analyses
  - Pump-probe experiments using ultra-short pulses
- Spectroscopy (fluorescence, XANES)
- Radiotherapy ? MRT THERAPY ? (micro beam radiation)

Quasi-monochromatic beam

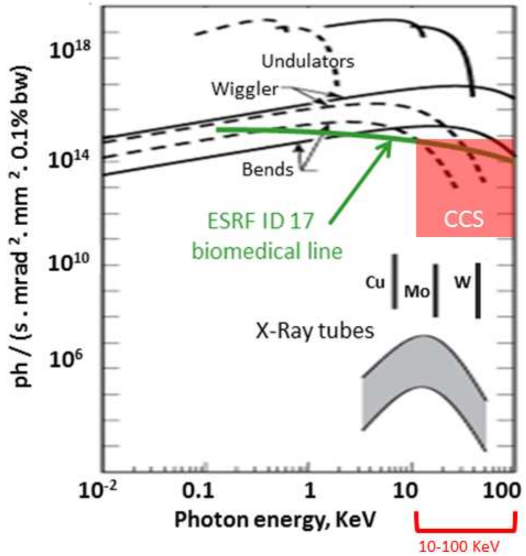
Diffraction patterns



→ **ESRF : minor phases present in the powder are visible**

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

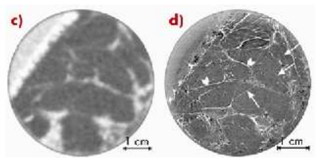
- **The machines of today**
  → Hot machines
  → Flux ~ 10^{13}
  → Brightness ~ 10^{11}



- **… and tomorrow**
  → SC machines (e- gun)
  → Flux ~ 10^{13}-10^{14}
  → Brightness ~ 10^{13}-10^{15}

Two strong challenges remain
- Superconducting injector
  (100 MHz, 1mA, very small emittance)
- Radioprotection shielding for integration

- **The goal** Fill the great lack of intense and bright lab sources
  → Develop in lab size environments
  powerful analysis techniques
  currently used only at synchrotrons :
  - imaging
  - therapy
  - diffraction
  - spectroscopy
  - tomography …



- **In the particular biomedical / clinical field**

→ Very promising, and soon. **With storage ring scheme machines :**

→ **Using the large 2D Compton beam : ~ 10^{12} - 10^{13} ph/s , 3 - 30% bw , few centimeters beams**

The use of CCS beams in the near future for conventional imaging and radiotherapy

- should provide results comparable to the ones of the current ESRF/ID17 biomedical line,
- with the great advantage of no need to move samples in the beam.

→ **Using the focus central part of the beam : ~ 10^{9} ph/s , 0.1 - 1% bw , < mm beam**

- Micro beam radiation therapy ?
- Realize rapid and precise protein 3D structure determination.

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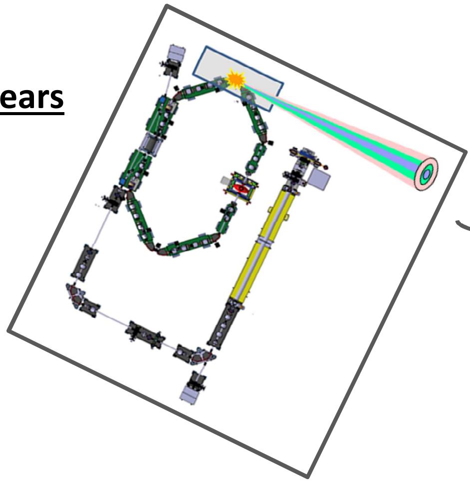
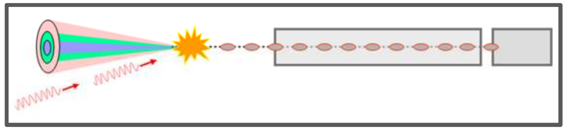
- **Next years**



- **Next future**



Thank you for your attention