ThomX : the instrument and its applications

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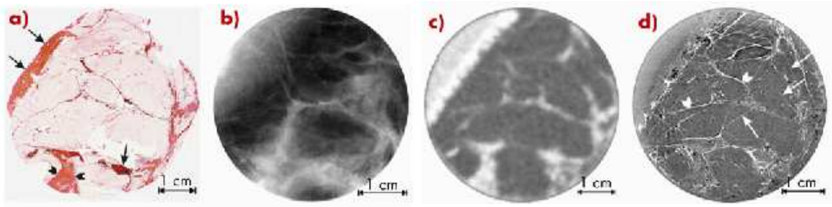
► In many scientific domains **synchrotron sources** are currently the only machines in term of brightness to perform and carry out **the most ambitious analyses and searches** requiring **~ 10-100 keV X-rays.**

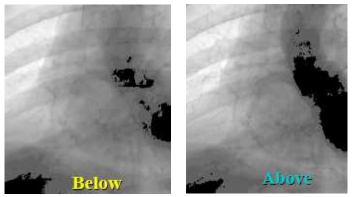


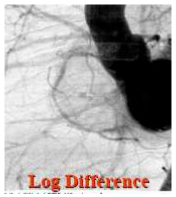
Histological section | Clinical mammography | Clinical scanner

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

ID17 ESRF Phase contrast imaging
(same dose as c)

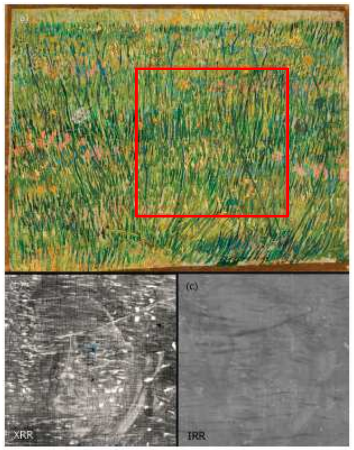
K-edge at ESRF (+contrast agent)





The difference increase the contrast

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



X Transmission IR Reflectography

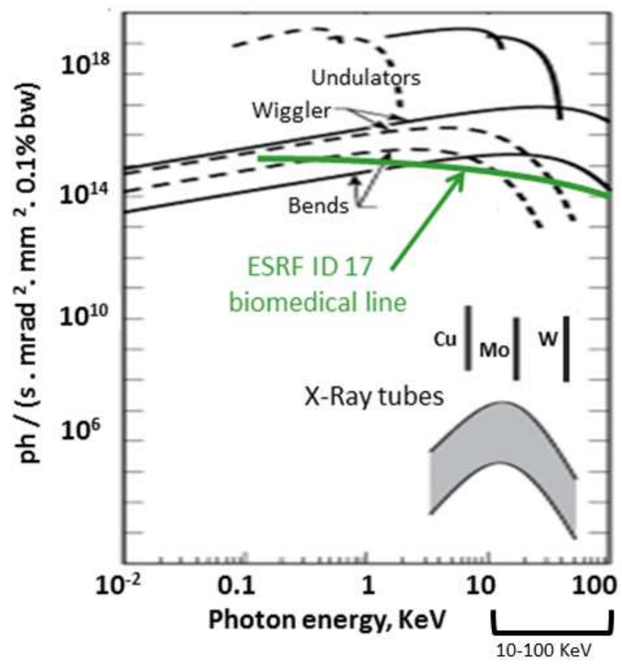
DESY synchrotron - Fluorescence
- XANES

(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 the X-ray source brightnesses



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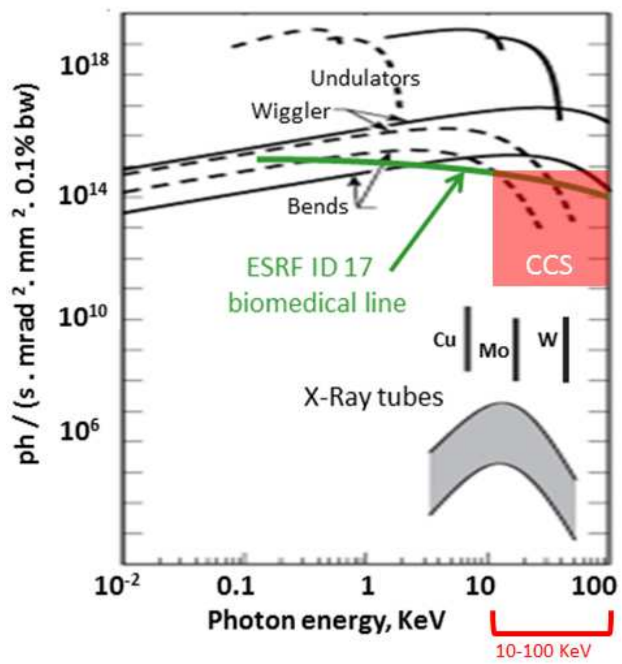

► **Compact Compton Sources (CCS)**

- **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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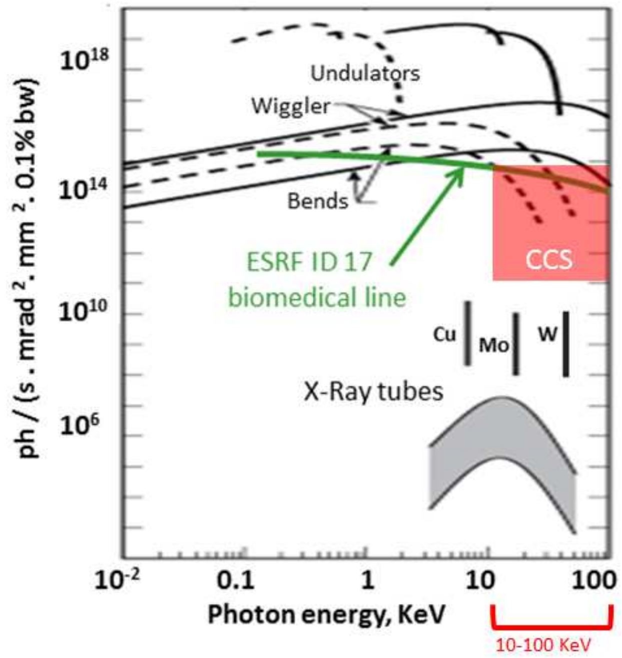

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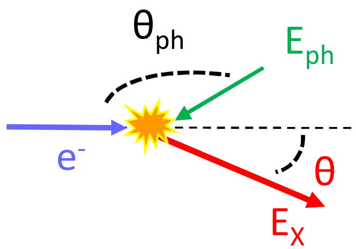
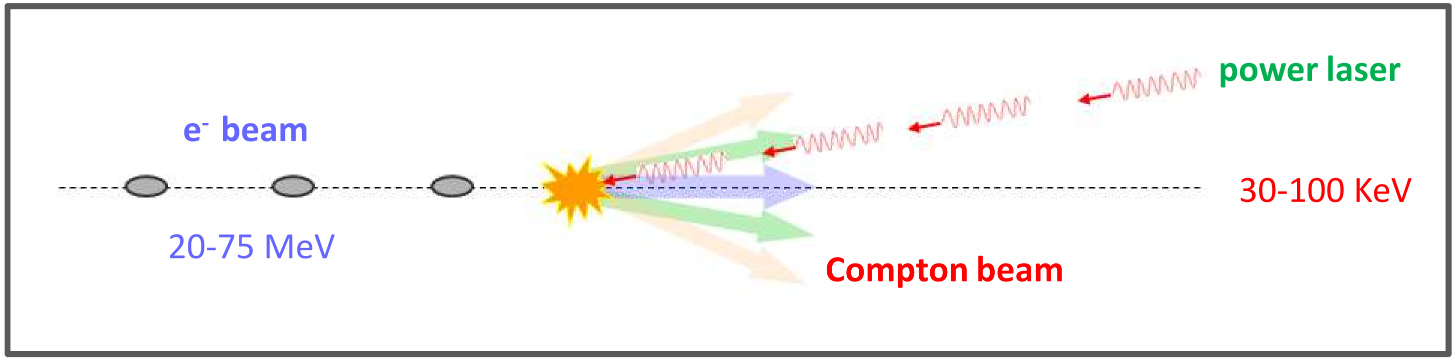
→ Methods currently used at synchrotrons and requiring a high brightness beam could be largely developed in **a lab size environment** (hospitals, labs, museums).

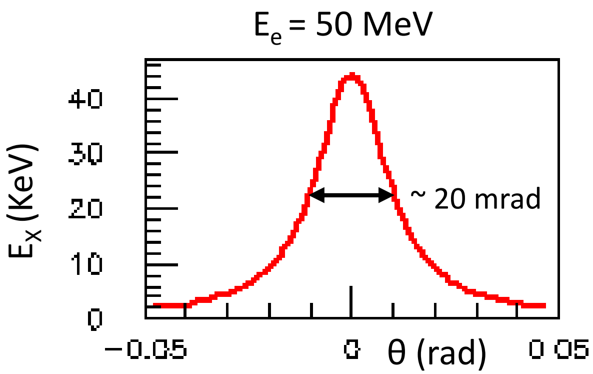
Compton scattering where the electron is no longer at rest → "Inverse Compton" regime

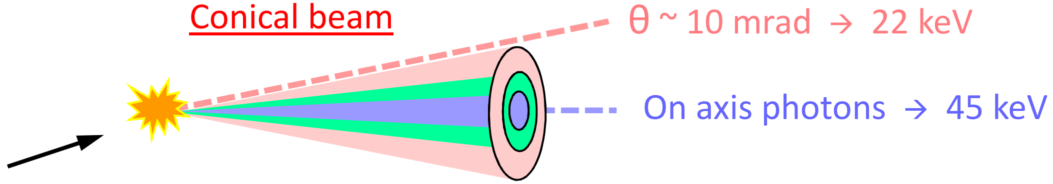


$$E_X \sim \frac{2\,\gamma^2 E_{ph}\,[\,1 - \cos(\theta_{ph})\,]}{1 + (\gamma\theta)^2}$$

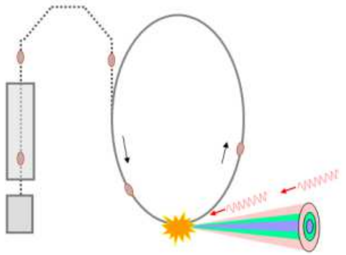
($\gamma = E_e / m_e >> 1$; $E_{ph} << m_e$)

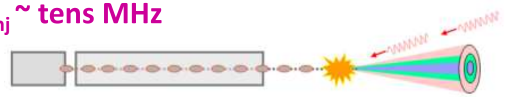






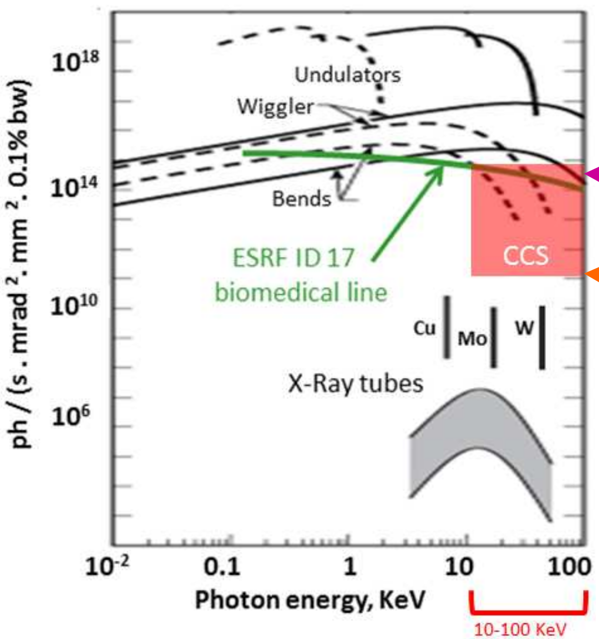
Univocal relation between energy E_X and diffusion angle θ





	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	~10^{11}
•	KEK QB	Linac	35	10^{13}	10	
•	KEK ERL	Linac	67	10^{13}	30	
x	MIT	Linac	3-30	10^{14}	2	~10^{15}

* In operation • Funded x Not funded



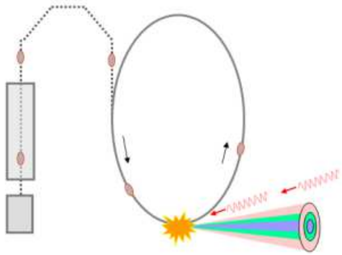
Next future
(supra machines)

Near future
("hot " machines)

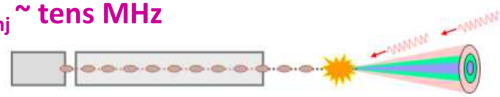
Remaining strong challenges:

- Supra e- gun : 100 MHz of inj. freq.
  ε_N ~ 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

f_{rev} ~ tens MHz



f_{inj} ~ tens MHz



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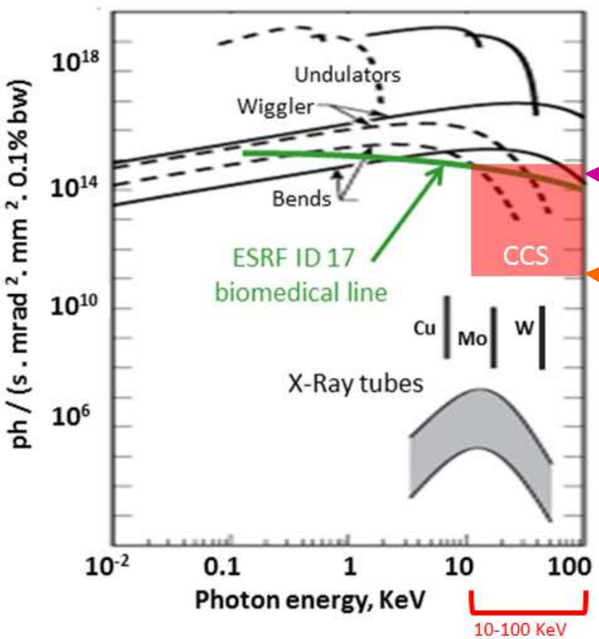

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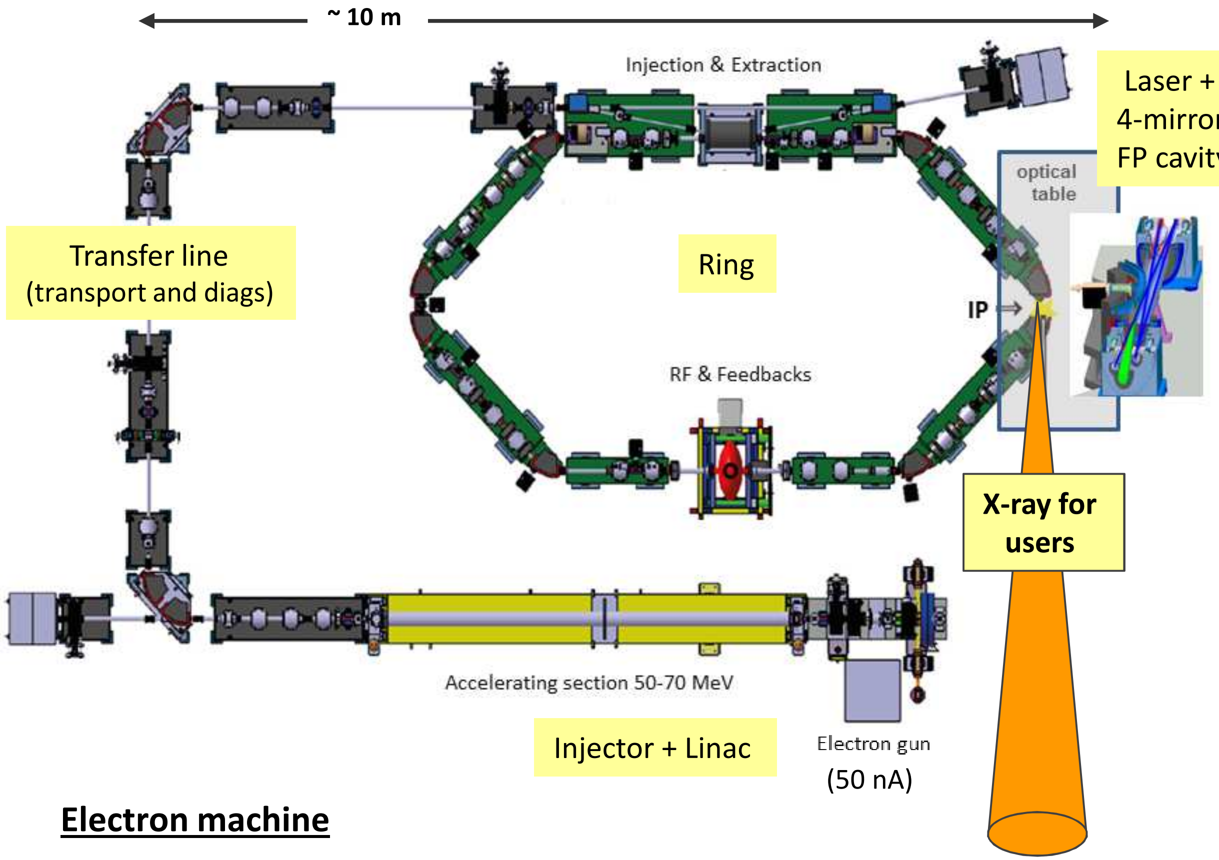
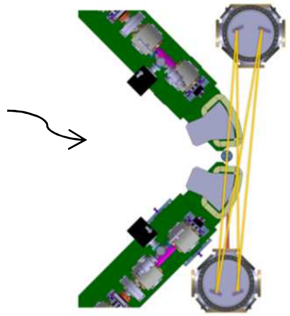




Laser /Cavity system

- Laser ~ 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)

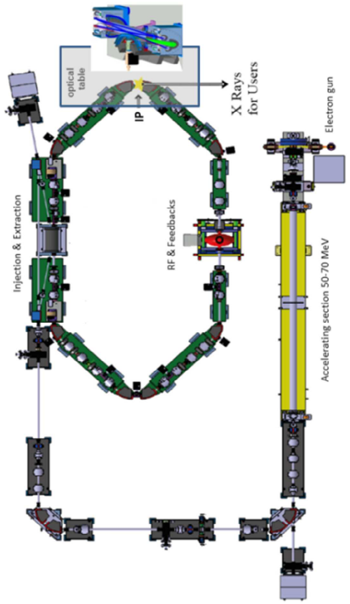
Electron machine

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

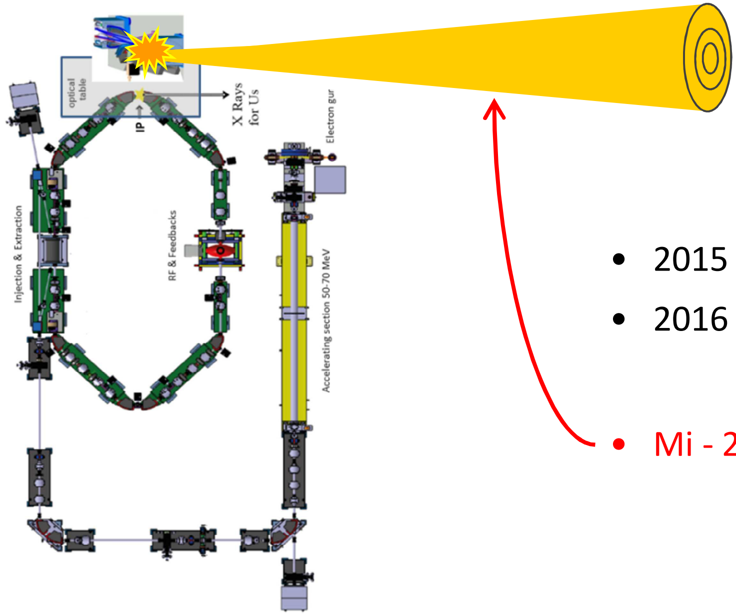
X-ray beam

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

Machine funded
In construction



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



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

→ **With the first ThomX beam**

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

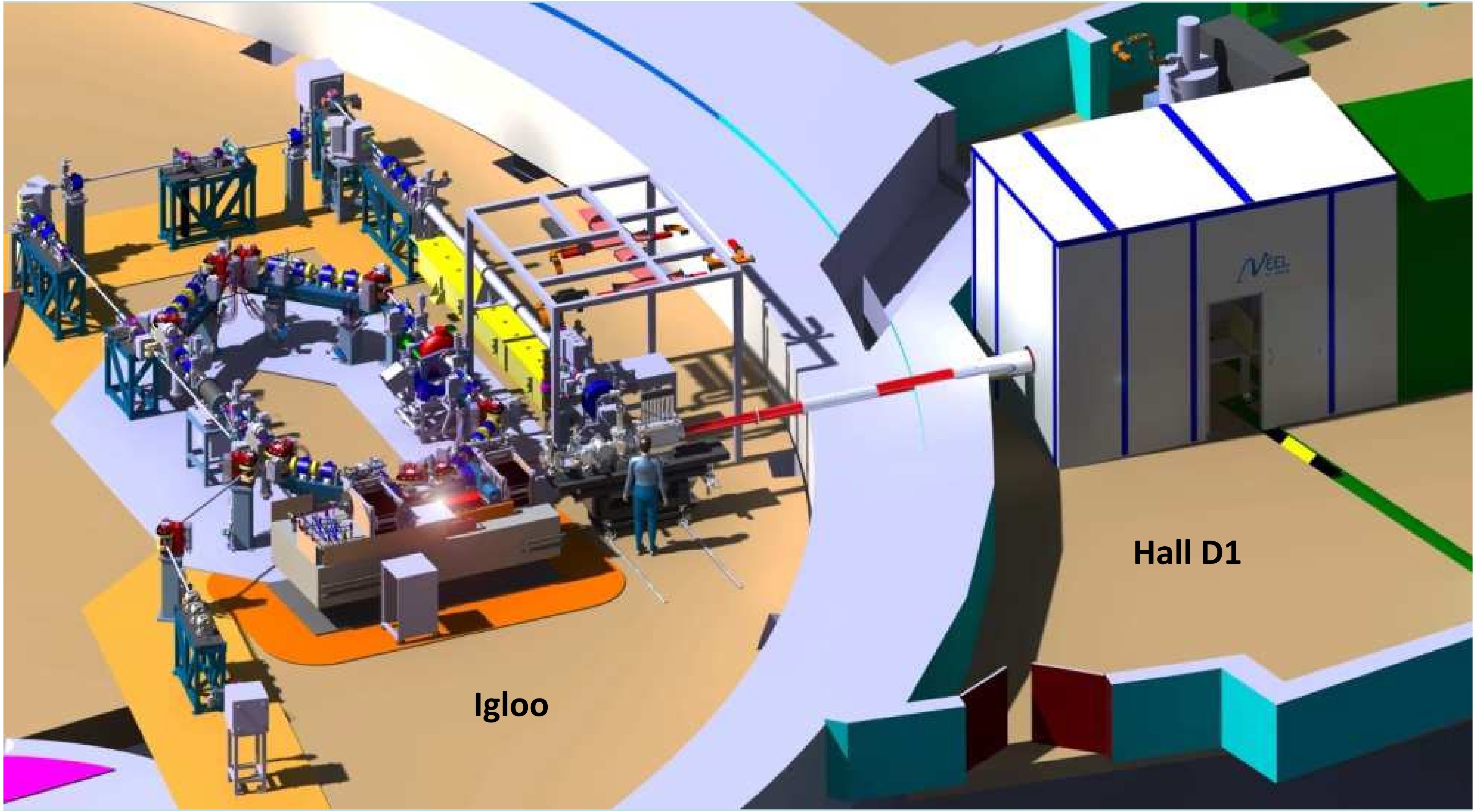
- Conventional imaging (head phantom)
- K-edge substraction imaging (head phantom, drugs)
- Phase contrast imaging (nylon wire)
- Radiotherapy (tumor-like mass sample)

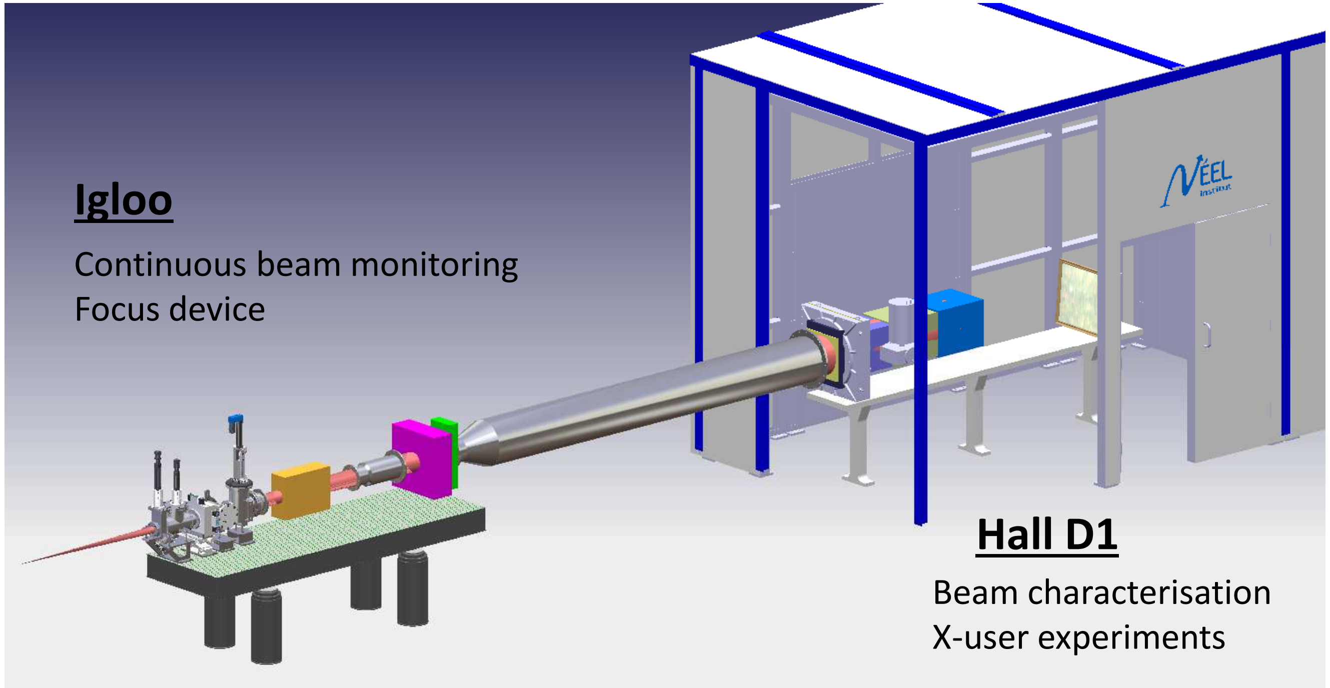
Biomedical

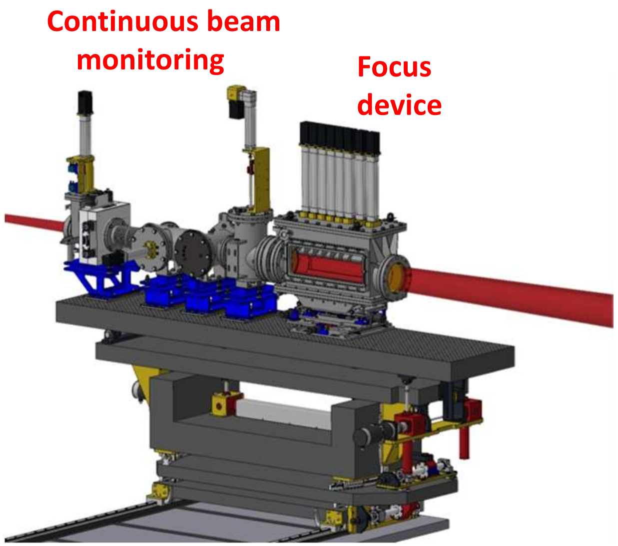
- Fluo Spectroscopy
- Diffraction

Materiel science

Techniques where the synchrotron community has already a lot of knowledge and experience

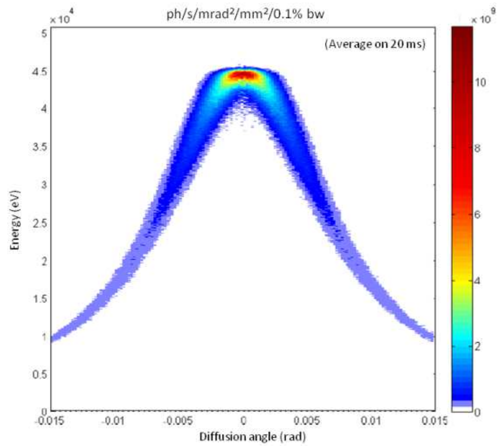

Hall D1
Igloo





Beam characterisation

1. Mean absolute $Flux_{X,Y}(E)$



2. Bunch to bunch intensity variations (20 MHz)

3. Spatial coherence

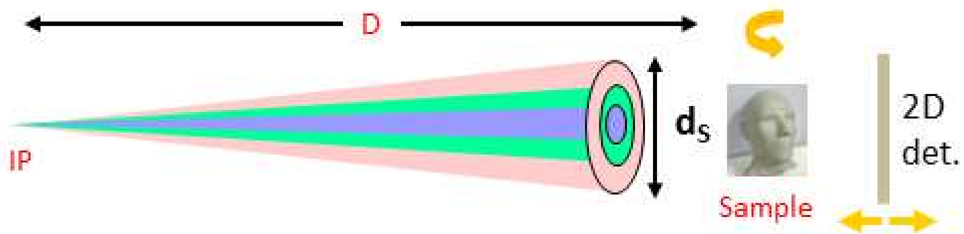
1. Using the 2D divergent beam

- 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 ΔE/E ~ 3-30% bw , several cm diameter , > 10^{12} ph/s

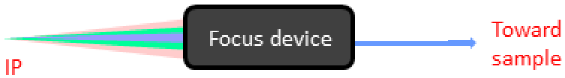
2. Using the central part of the beam

- Diffraction
- Spectroscopy (fluo, XANES)

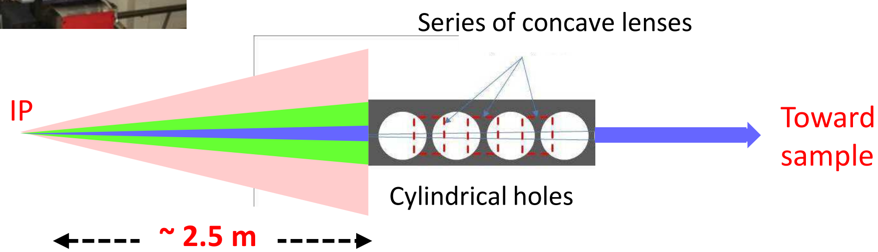
MATERIEL SCIENCE

- Radiotherapy

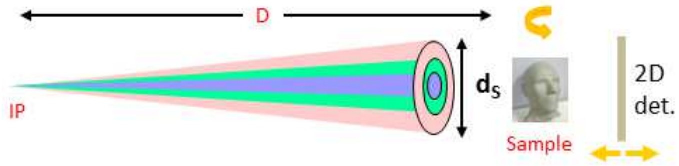
MRT THERAPY ?
(micro/mini beam radiation)



Focus device : Refractive lenses or Capillary optics



Quasi-monochromatic beam ΔE/E ~ 10^{-2} - 10^{-3} , mm diameter , ~ 10^{9} ph/s



1. Using the 2D divergent beam

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

IMAGING

- **Radiotherapy**

THERAPY

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

ThomX

Ex. : **Human head phantom radiography**

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

ThomX and Synchrotron (ID17/ESRF) → doses comparable

(hospital sources : broad spectrum, low flux)

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

2. Using the central part of the beam

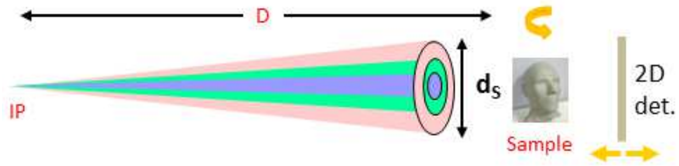
- **Diffraction**
- **Spectroscopy (fluo, XANES)**

MATERIEL SCIENCE

- **Radiotherapy**

MRT THERAPY ?
(micro/mini beam radiation)

1. Using the 2D divergent beam



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

IMAGING

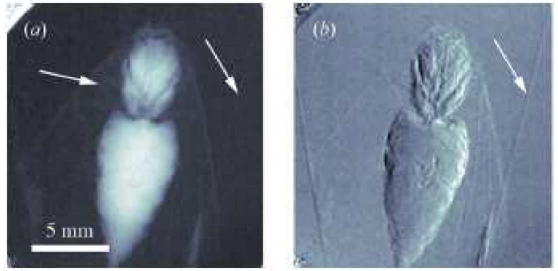
- Radiotherapy

THERAPY

- 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
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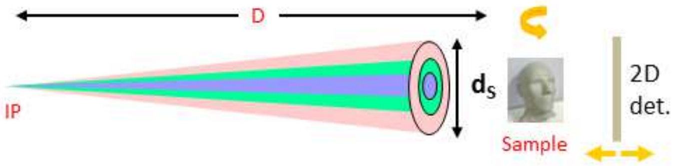
MATERIEL SCIENCE

- Radiotherapy

MRT THERAPY ?
(micro/mini beam radiation)



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

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

IMAGING

- **Radiotherapy**

THERAPY

- **High energy** (~ 80KeV)

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

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

- ThomX → 9 mGy/sec → 20-30 min of irradiation
- ESRF/ID17 (~ 6 mGy/sec)

- **80 KeV ± 0.5 KeV**
- **d_S = 1 cm** at D ~ 10 m
- **6.10^{10} ph/s**

Researches on **Photon Activation Therapy**

2. Using the central part of the beam

- Diffraction
- Spectroscopy (fluo, XANES)

MATERIEL SCIENCE

- Radiotherapy

MRT THERAPY ?
(micro/mini beam radiation)

1. Using the 2D divergent beam

- Conventional radiography
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IMAGING

- Radiotherapy

THERAPY

2. Using the central part of the beam

- **Diffraction**
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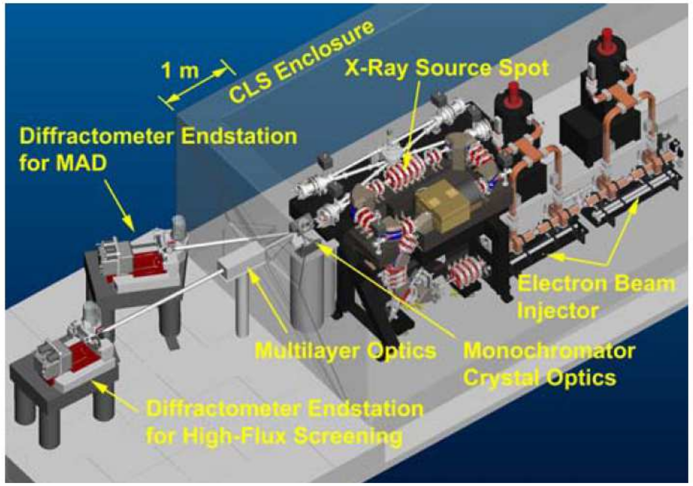
MATERIEL SCIENCE

- Radiotherapy

MRT THERAPY ?
(micro/mini beam radiation)

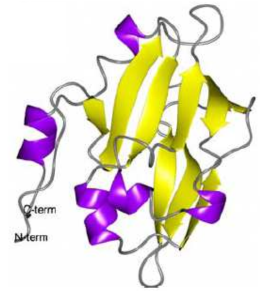
Quasi-monochromatic beam

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

1. Using the 2D divergent beam

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

IMAGING

- Radiotherapy

THERAPY

2. Using the central part of the beam

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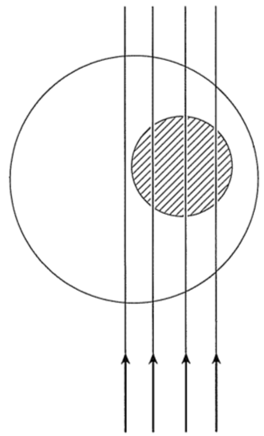
MATERIEL SCIENCE

- **Radiotherapy**

MRT THERAPY ?
(micro/mini beam radiation)

MRT R&D ?

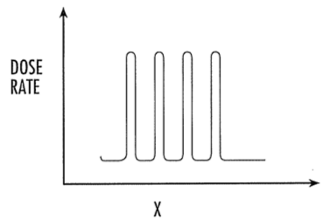


Microbeam Radiotherapy (MRT)

Ability to **eradicate tumors** while **sparing normal tissue**

Typically :

MRT uses arrays of narrow **25-75 µm wide microbeams** separated by **100-400 µm spaces**.



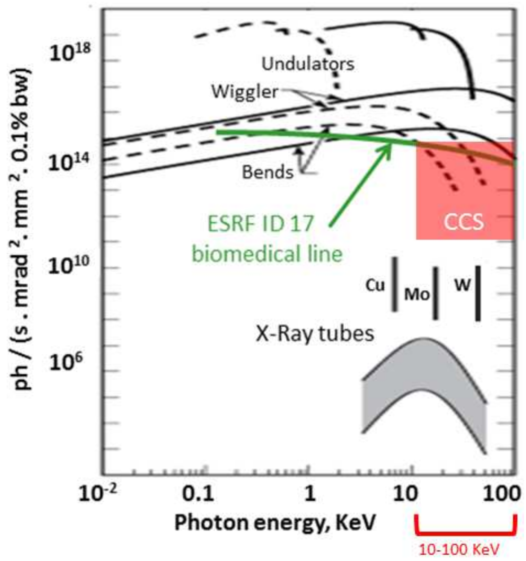
(Feasibility studies started in the SYRA3 working group)

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

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

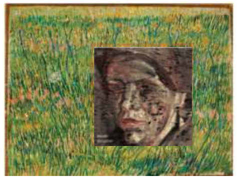
- **… and tomorrow**
  → Supra machines (e- gun)
  → Flux ~ 10^{13}-10^{14}
  → Brightness ~ 10^{13}-10^{15}

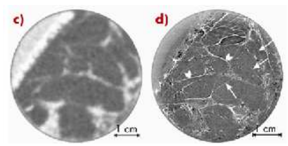
Two strong challenges remain
- Superconducting injector (100 MHz, very small emittance)
- Radioprotection shielding for integration



- → **Fill the great lack of intense and bright lab sources**

Develop in lab size environments powerful analysis techniques currently used only at synchrotrons.





1. **With the large 2D Compton beam**

~ 10^{12} - 10^{13} ph/s , 10% bw , few centimeters beam
- Conventional imaging
- K-edge
- Phase contrast
- Radiotherapy
- High-Z drug tests

→ with the great advantage of a large 2D beam (compared to synchrotrons)

2. **With the focus central part of the beam**

~ 10^{9} ph/s , 0.1-1% bw , mm beam
- Diffraction
- Spectroscopy
- MRT ?