Compact Compton sources

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- Introduction : Compton Effect for compact sources
- Compact Compton Sources Why
- Compact Compton Sources How?
- Projects

Compact Sources : Compton backscattering

- **Compact sources -> Compton Backscattering effect (CBS)**

- **Why CBS for Compact Sources?**

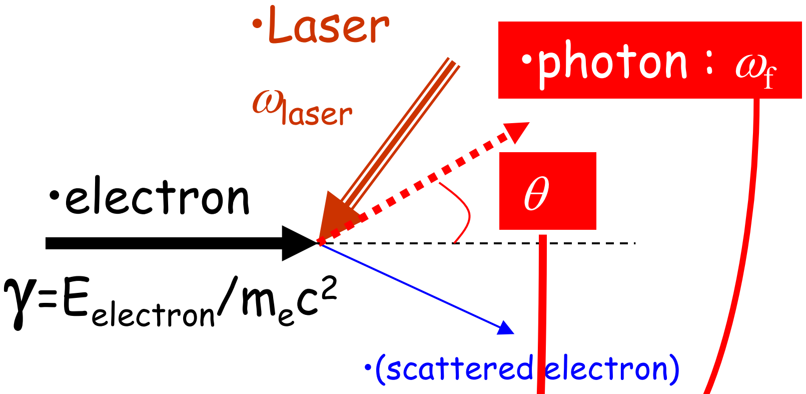
- CBS is by far the most efficient photon energy amplifier : ω_{diff}=$4\gamma^2$ ω_{laser}, for example if γ~100 => it is possible to have at one's disposal hard X rays (50 keV) with a relatively low energy electron machine.

- But for a light source: σ ~ 6.6524 10^{-25} cm^2 , it is low!!!!! Need to increase lasers and accelerators performances

- Two kind of compact source. Strong impact on the accelerator and on the optical system choice :
- High average flux. Mainly based on high repetition frequency. Storage rings / SRF linacs / High average power lasers coupled with FP cavities.
- High peak brillance. Mainly based on the laser pulse energy. Warm linacs/ High power lasers/ Optical re-circulators to increase the flux

- CBS attractiveness :
- 1) relativistic boost and directivity = > f= 1/γ around the electron direction
- 2) Energy angle dependence => monochromatic by diaphragm
- 3) Polarized if needed
- 4) Backscattered spectrum cut off => Energy dependence on collision angle

Compton backscattering



- **We are interested by using the scattered photon**

- **Dynamics of the process**

- **Compton Scattering γ (laser)+e→γ'+e'**
- Photon(laser) + electron scattering
  - Fano, JOSA39(1949)859;
- Simulation programme: CAIN from Yokoya-san http://lcdev.kek.jp/~yokoya/CAIN/cain235/

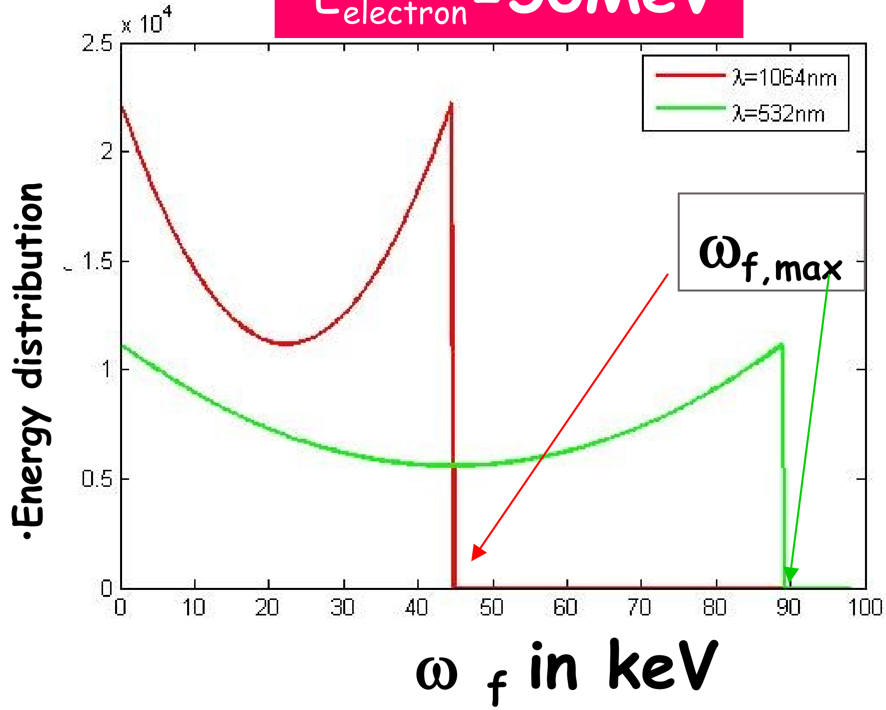
- **Scattered photon properties given by the Compton differential cross-section:**

$$\frac{d\sigma}{d\Omega^*} = \sigma_0 + \sigma_1 + \sigma_2 + \sigma_3 + \sigma_4$$

- Independent from polarisations
- Polarisation of the 4 particles are observed

•1rst interest (and 4th): the energy boost

•$E_{electron}$=50MeV



•Sprangle et al. JAP**72**(1992)5032

Energy distribution ~flat with

$\omega_{f,max}=4\gamma^2\ \omega_{laser}$

with γ~**100** ($E_{electron}$=**50MeV**)

$\omega_{f,max}$=**45000eV if** ω_{laser} ~ **1eV**

Angular emission => 10 mrad

Compton scattering is the most powerful mechanism to boost photon energies

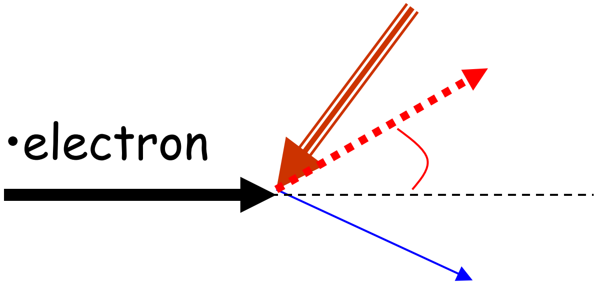
The cut off is dependent on the incidence angle !! (factor two up to π/2)…we can play to make short pulses

2nd interest: the angular energy correlation,
Monocromatic sources

- **Compton scattering**

Photon_laser+e→ photon+e'

2 body process ➔ $\omega_f = f(\theta)$



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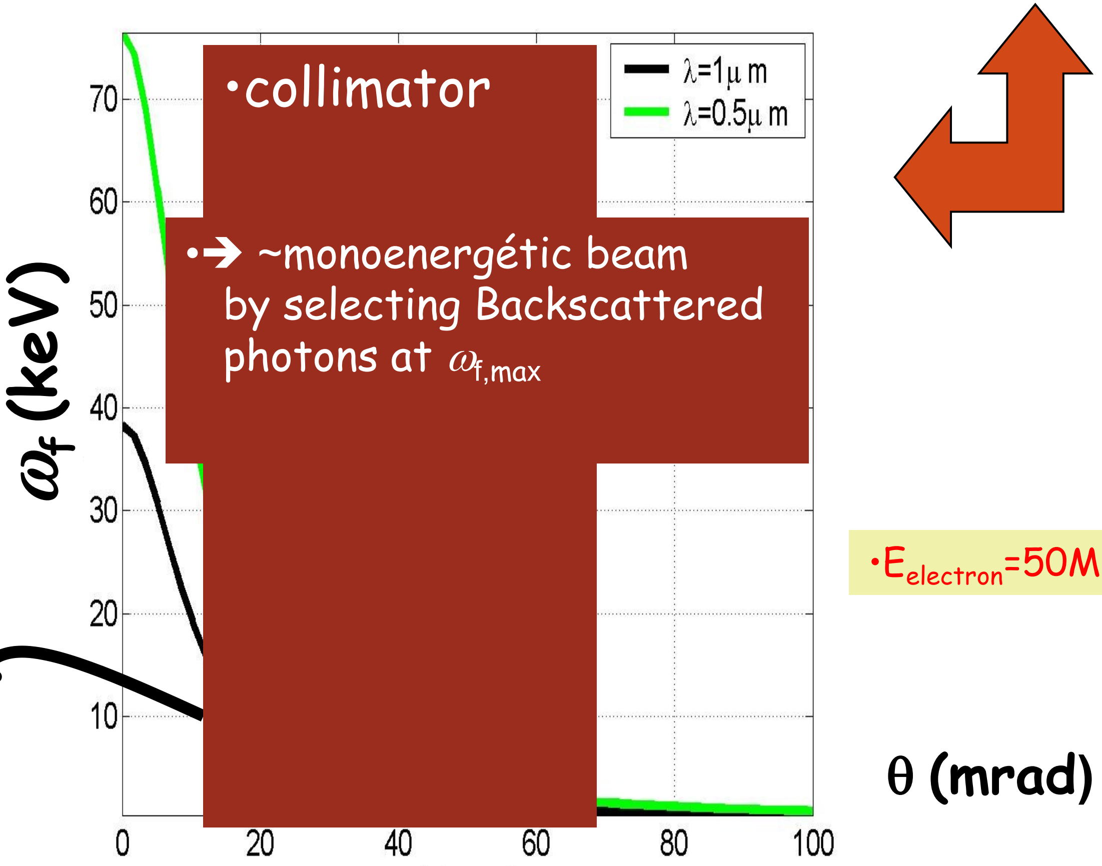
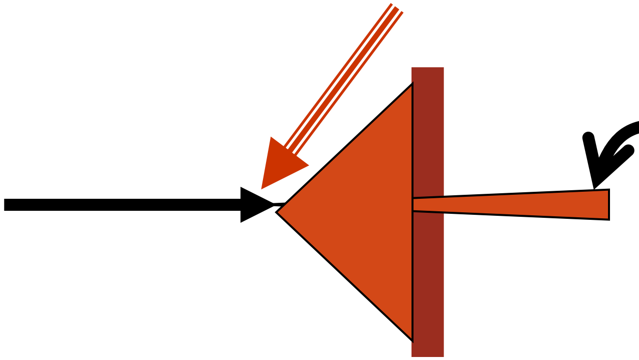


- collimator

- ➔ ~monoenergétic beam by selecting Backscattered photons at $\omega_{f,max}$

- $E_{electron}$=50MeV

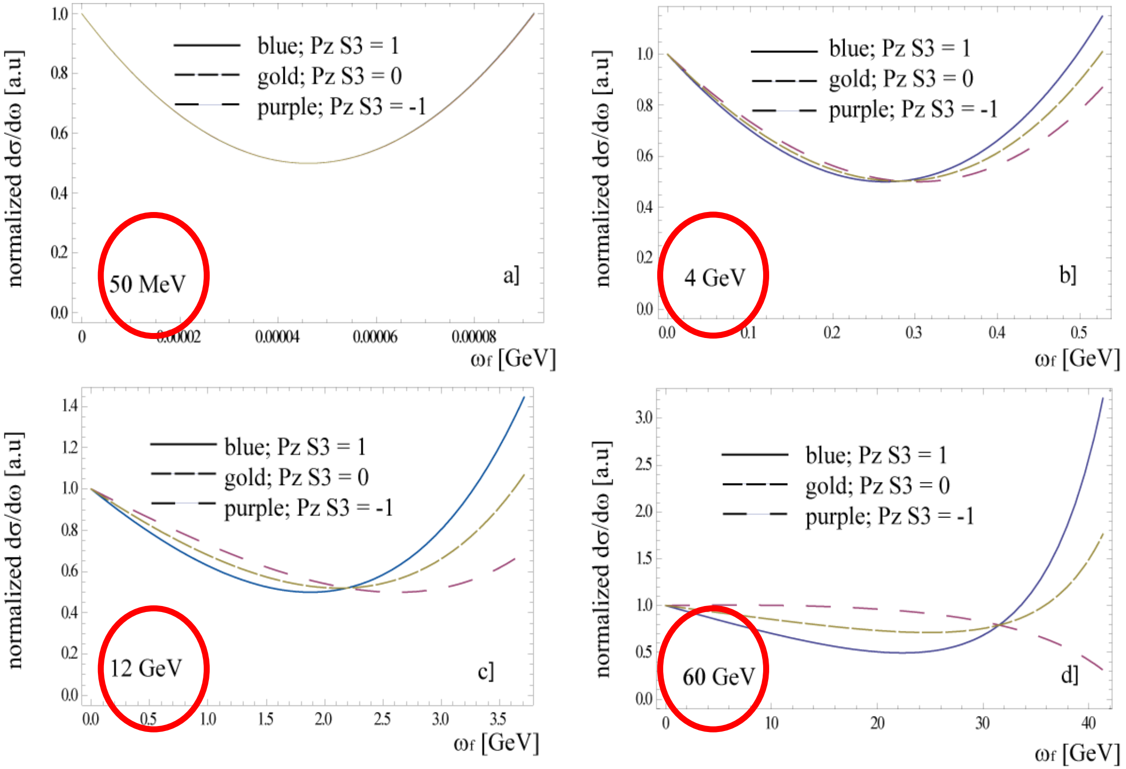


•3rd interest: incident electron and laser polarisation effects

•Differential Compton cross-section with 2 polarisations observed (energy distribution):

- $d\sigma/d\omega_f = A_0(\omega_f) - P_e S_3 A_1(\omega_f)$
- A_0, A_1: known (QED)
- S_3: laser degree of circular
- polarisation

•P_e: e^- longitudinal polarisation



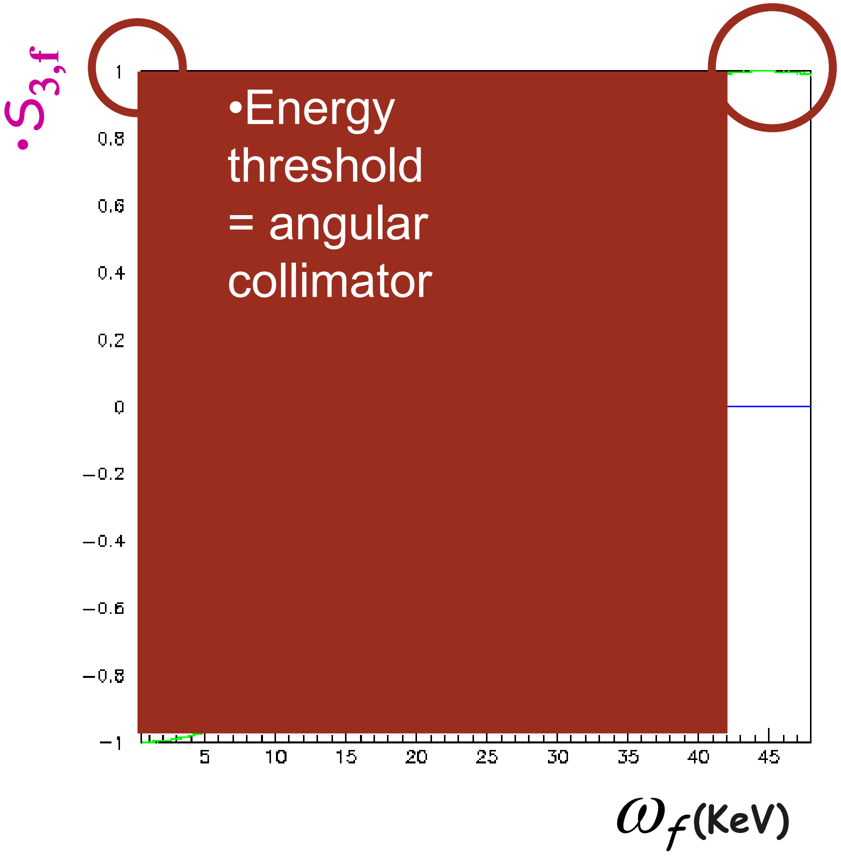
➔Knowing S_3 one can determine the polarisation of electrons above ~ 4GeV

➔ electron/positron Compton polarimeters used in accelerators

e.g. Barber at al. Nucl.Instrum.Meth.A329(1993)79

•4th interest: polarisation effects in the final state

— •(P_e , $S_{3,laser}$) = (0 , 1)



•Energy threshold = angular collimator

•S_{3f}=1 for $\omega_f = \omega_{f,max}$ & $S_{3,laser}$=1

•Compton scattering acts as a mirror for circular polarisation at low energy **if** highest values of ω_f are selected

•(i.e. backscaterred photons are selected)

➔γγ collider ($E_{electron}$~250-500 GeV)
Ginzburg et al. NIM219(1984)5

➔Polarised positron source ($E_{electron}$~1GeV)

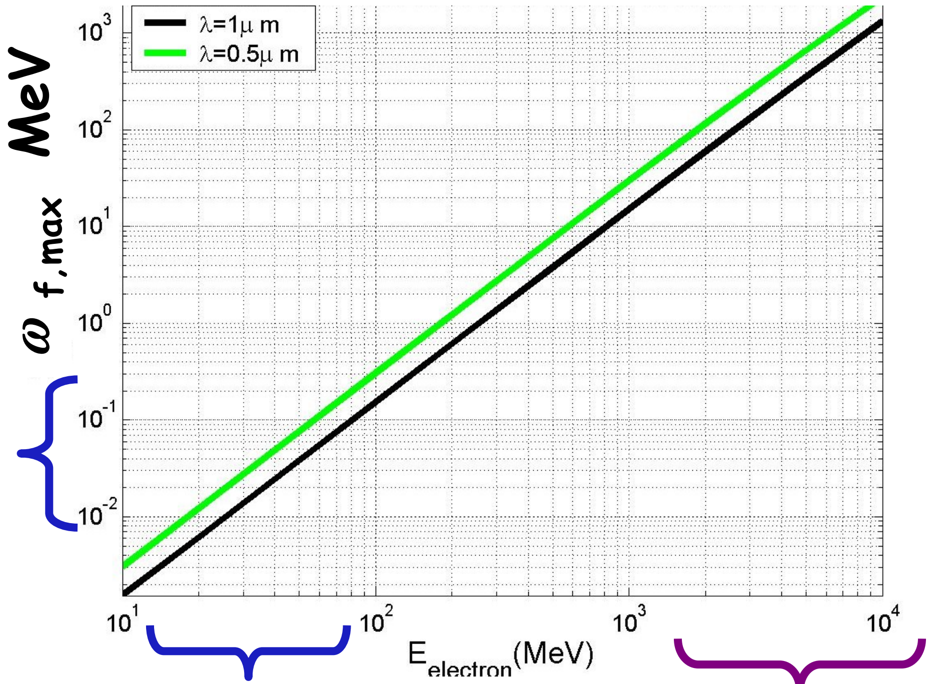
➔Polarised Light source

•SUMMARY :Applications of Compton scattering. Quasi monochromatic X/γ ray beam

γ ~100 MeV

γ ~ 1MeV

•X ray ~10-100keV



- Elec.~20-100MeV
- Elec. 1GeV

•Elec.~100-500MeV

•*Low energy applications*
•Medical:
 radiography
&radiotherapy
•Museology
•Material science
•crystallography

•*Nuclear fluorescence applications*
•Nuclear survey
•Nuclear waste management

High energy applications
- Compton polarimeter ➔LEP energy measurement
- Laser wire
- gg collider

•Polarised positron source

A more classical point of view…intense laser as an helical ondulator

- Helical undulator and laser wave (v=c=1 -> ultrarelativistic case)
- Fields : Undulator

$$H_{LabSys} = B(e_1 \cos(\mathrm{kz}) + \rho\, \mathrm{e}_2 \sin(kz)), \quad \mathrm{k} = 2\pi/\lambda_{\mathrm{u}}$$

$$\rho = \pm 1 = Helicity\ (\mathrm{p}_\perp\, sense\, of\ rotation)$$

- In the Electron rest system an E field appears:

$$H_{RSys} = \gamma B(e_1 \cos(\theta) + \rho\, \mathrm{e}_2 \sin(\theta)),$$

$$E_{RSys} = \gamma B(-\rho\, \mathrm{e}_1 \sin(\theta) + e_2 \cos(\theta)),$$

- The laser field is :

$$A_{LabSys} = a(e_1 \cos(\mathrm{kz}) + \rho\, \mathrm{e}_2 \sin(kz)), \quad \mathrm{k} = 2\pi/\lambda_{\mathrm{l}}$$

And in rest system

$$H_{Rsys} = -2\rho\gamma k_l a(e_1 \cos(\vartheta) + \rho\, \mathrm{e}_2 \sin(\vartheta))$$

$$E_{Rsys} = -2\rho\gamma k_l a(-\rho e_1 \sin(\vartheta) + \mathrm{e}_2 \cos(\vartheta))$$

- Same ' kind ' of trajectory solution : $\overline{p}_\perp = \langle \overline{p}_\perp \rangle + p_\perp (e_1 \cos(\theta) + \rho\, \mathrm{e}_2 \sin(\theta)),$

Field intensity : important factor

- Radiation depends on the laser intensity parameter

$$\xi^2 = \frac{e^2 \langle A^2 \rangle}{m^2} \quad \text{that in the undulator case} = \mathrm{K}^2 = \frac{e^2 B^2}{(k\, m)^2}$$

For a laser $\xi^2 = 3.66\ 10^{-19}\ \lambda^2\ (\text{mm}) P(\text{W/cm}^2)$

For an undulator = $(0.935\ B(\text{T})\ \lambda_u\ (\text{cm}))^2$

- Meaning (going back to equations) $p_\perp = \xi\ \mathrm{m}$

So in the ultrarelativistic case and $v_\perp << 1$

$$\xi^2 = \frac{\langle p_\perp^2 \rangle - \langle p_\perp \rangle^2}{m^2} \quad \textit{deviation from a straight line (average angular deviation)}$$

$$\xi^2 \approx \alpha\, N_{\mathrm{int}} \qquad N_{\mathrm{int}} = \textit{number} \text{ of laser photons in the interacting volume } V_{\mathrm{int}}$$

$$V_{\mathrm{int}} = \lambda_c^2\, \lambda_{laser} \qquad \text{with } \lambda_c = 3.86\, 10^{-11}\, cm$$

- Why a “compact” Compton X(γ)-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.

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

- **With Compact sources :**

  Methods currently used at synchrotrons (diffraction, absorption, diffusion, imaging, spectroscopy…) could be largely developed in a laboratory size environment (hospitals, labs, museums).

What about 'compact' source for nuclear physics photons (MeV range)?
-Nuclear safety
-Nuclear waste management
-Radioisotopes detection

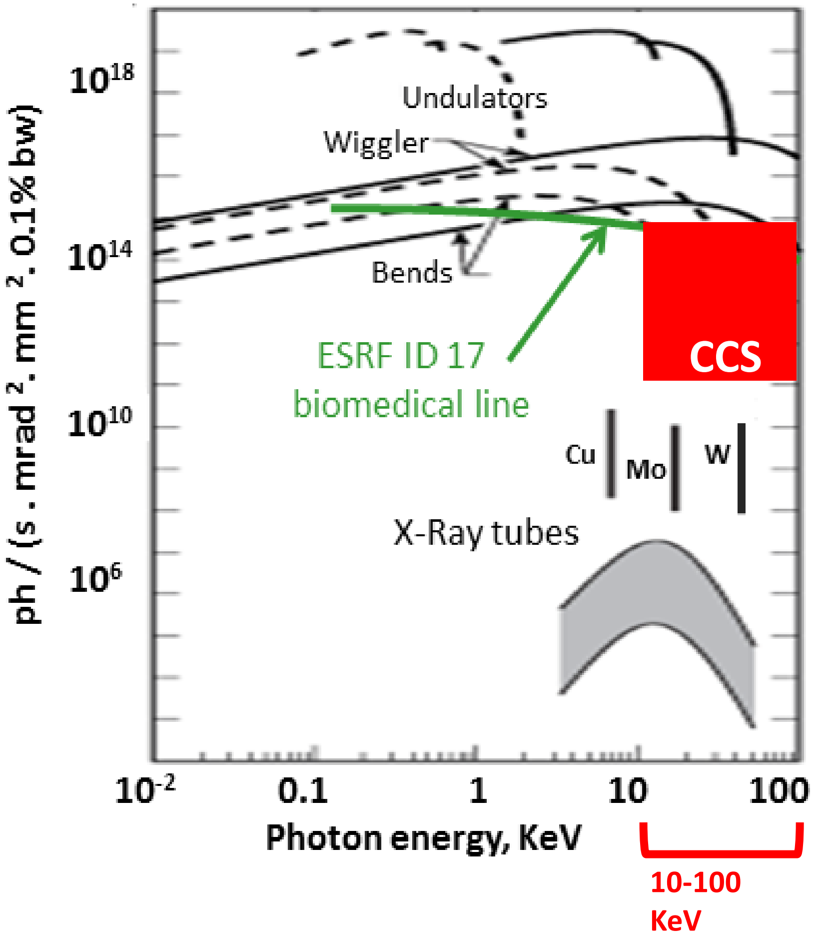
The compact X-sources today

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

- **Plasma sources**

  Ultra-short pulses ~ fs ,
  but very low fluxes.

→ **These sources does not allow to carry out many of the techniques used at synchrotrons**



- **Compact Compton Sources (CCS)**

→ **Compactness** **(surface ~ 100 m^2)**
(Integration in hospitals, labs, museums)

→ **Relative high intensity** **(10^{12} - 10^{14} ph/sec)**

→ **Tunable beam** **(Linac configuration)**

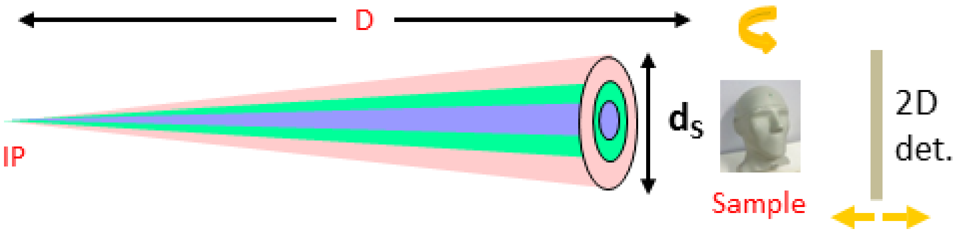
→ **High quality beam** **(brightness 10^{11} - 10^{15} ph/sec/ mm^2 / 0.1% bw / mrad^2)**

Potential of applications of X-ray CCS

1. <u>Using the 2D divergent beam</u>
   (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. <u>Using the central part of the beam</u>
   (cultural heritage / material science applications)

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

Toward sample
+ Optics : mono, …

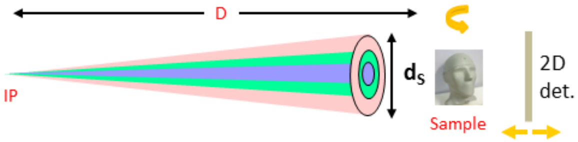
Quasi-monochromatic beam (~ 0.1% - 0.01 % bw)

- Example : medical application

Potential of applications of X-ray CCS: Examples

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

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

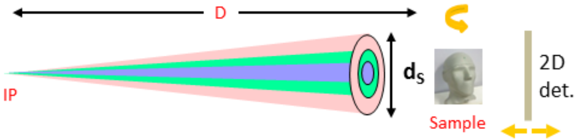
CCS and Synchrotron (ID17/ESRF) → comparable

→ reduction of the dose
→ better image quality

compared to hospital sources
(broad spectrum, low flux)

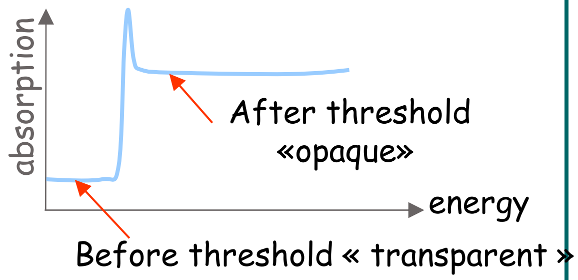
1. Using the 2D divergent beam

(biomedical and cultural heritage applications)

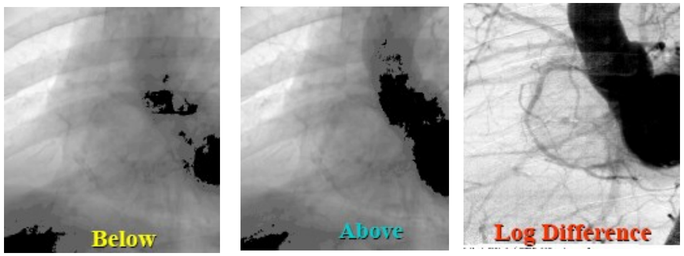


- Conventional radiography
- **K-edge substraction imaging**
- Phase contrast imaging
- Magnification
- Radiotherapy

- **Tunable energy**
- **bw 2-3%**



K-edge at ESRF (using a contrast agent)

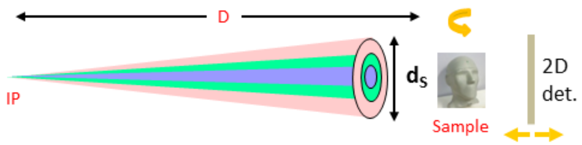


→ The difference of both increase the contrast

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

Potential of applications of X-ray CCS: Examples

1. Using the 2D divergent beam
(biomedical and cultural heritage applications)

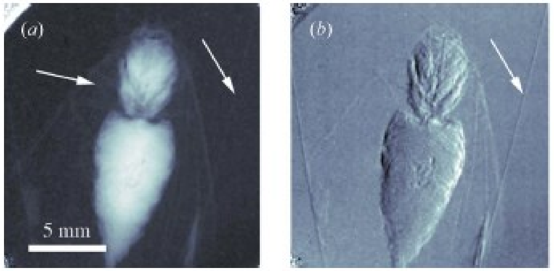


- bw 2-3%
- Small source size (to have transv. coherence)

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

[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

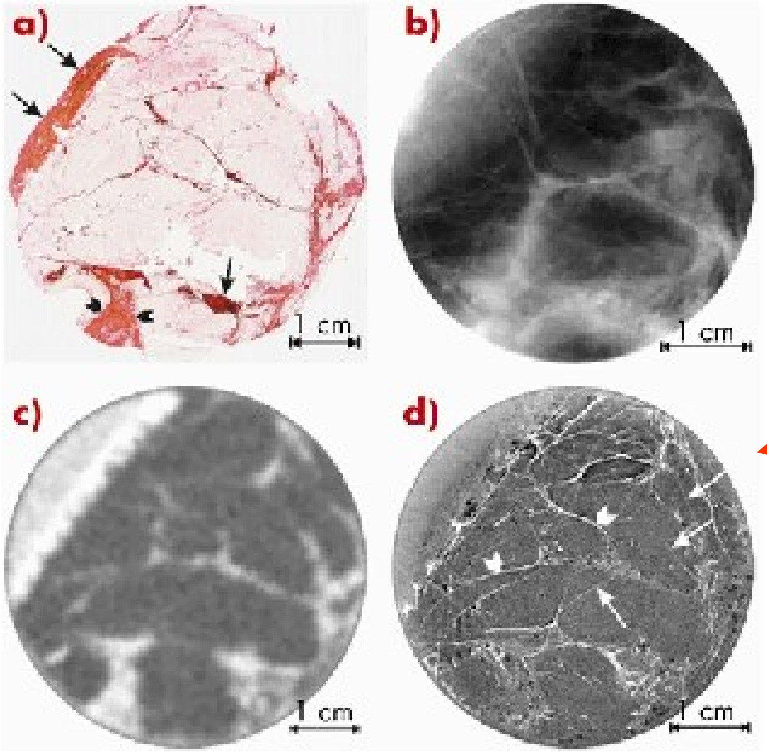
Proof of principle

- 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)

Biomedical : imaging human breast tissue at synchrotron ESRF

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

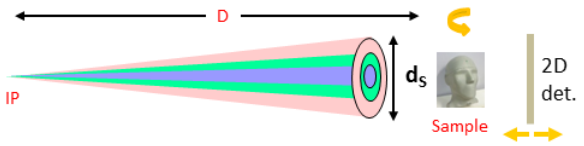
d) ID17 ESRF (Phase contrast imaging)
Same dose as c)

Stronger contrast

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

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**

- **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

- Example : cultural heritage application

Examples : Cultural Heritage

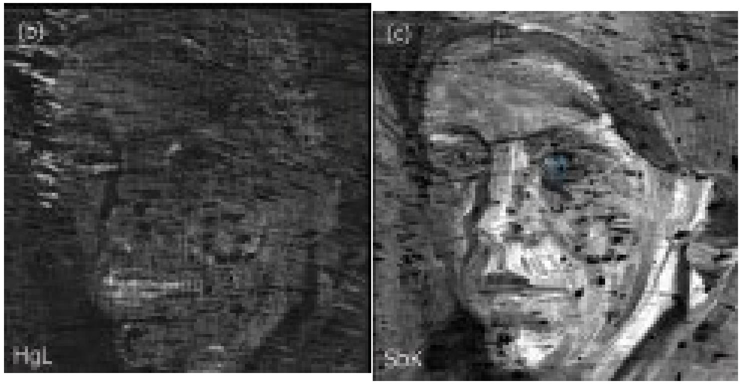
(Anal. Chem. 80, 2008, 6436-6442)

Conventional
X Radiography & IR Reflectography

X Transmission IR Reflectography

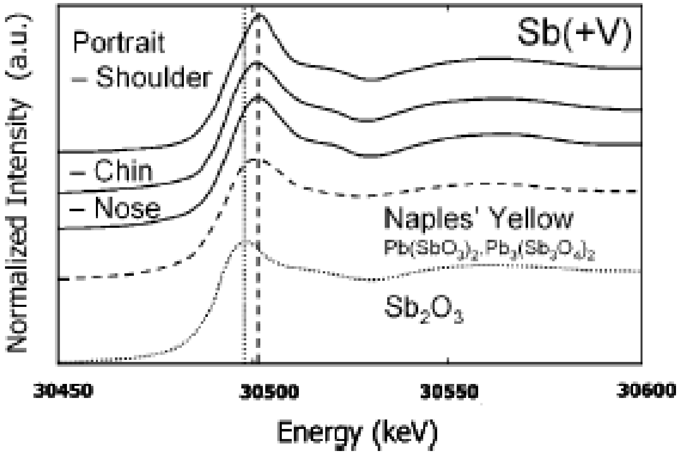
Analyses at synchrotron DESY
(non destructive)

Fluorescence X (38.5 KeV) → Pigment identification



Vermillon Antimoine

XANES : absorption at the K-edge of an element to identify precisely the chemical components (colors)



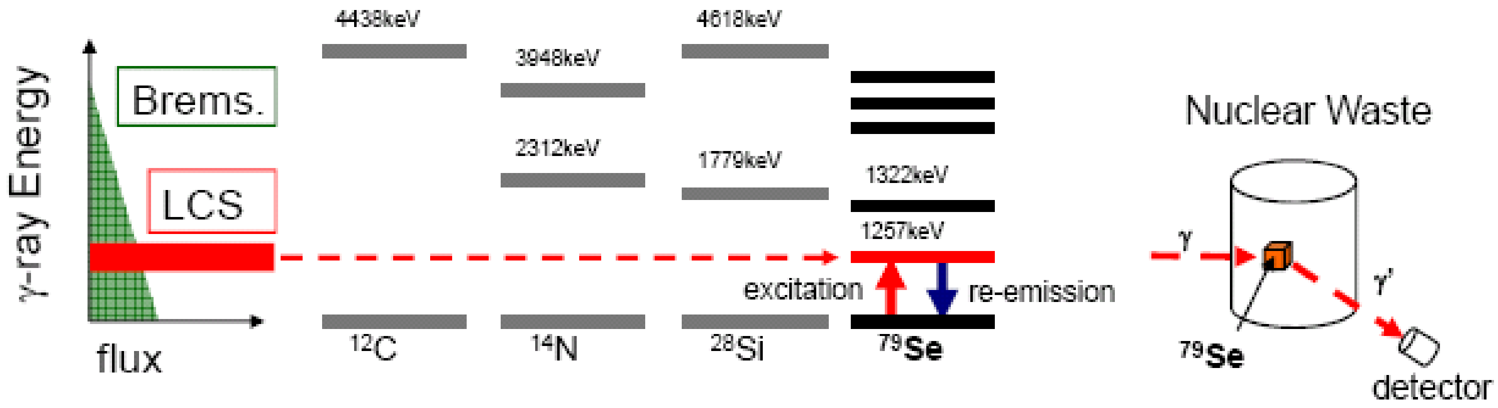
Vincent van Gogh "Un coin d'herbe" (1887) at synchrotron DESY

Colored reconstruction

Work painted
some years before

- Example : nuclear science application

Nondestructive Assay by Nuclear Resonant Fluorescence

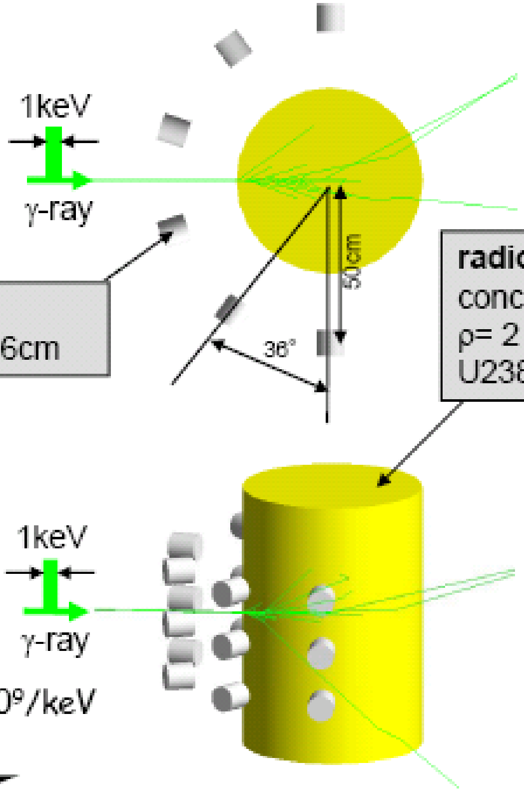


- Irradiation of γ-rays tuned at a NRF energy of nuclide to detect
- Detection of scattered γ-rays by energy-resolved detectors
- NRF is a unique fingerprint of nuclides → radioactive and stable nuclides can be detected
- Using MeV γ-rays → applicable to thick objects

Courtesy R.Hajima

Nondestructive Detection of Isotopes

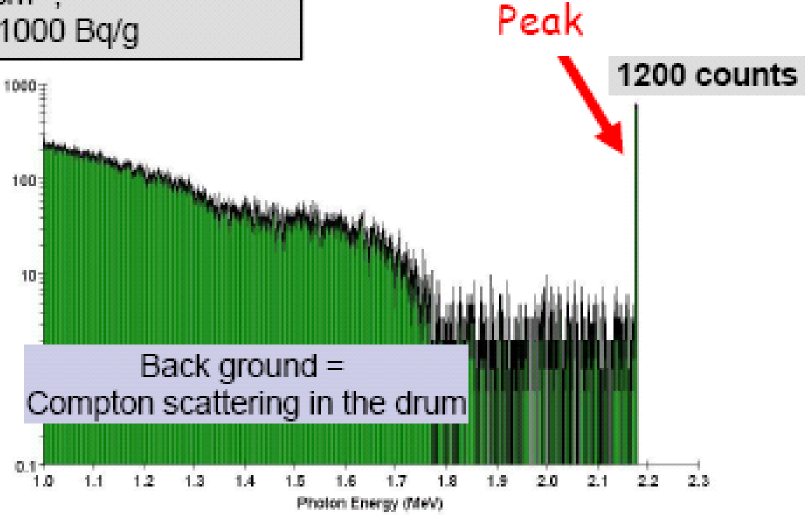
tuning the γ-ray energy to the NRF
↓
separation of the NRF signal from the background



Ge Detector
ϕ8.4cm, L=8.6cm

radioactive waste drum
concrete + U238 (8 wt%)
ρ= 2 g/cm^3 ,
U238 : 1000 Bq/g

N_γ=1x10^9/keV
⇩
irradiation time ~ 0.1 sec.



Back ground =
Compton scattering in the drum

σ_{NRF} = 28 mbarn·keV @ 2.176MeV

Simulation by GEANT4 (with NRF routine)

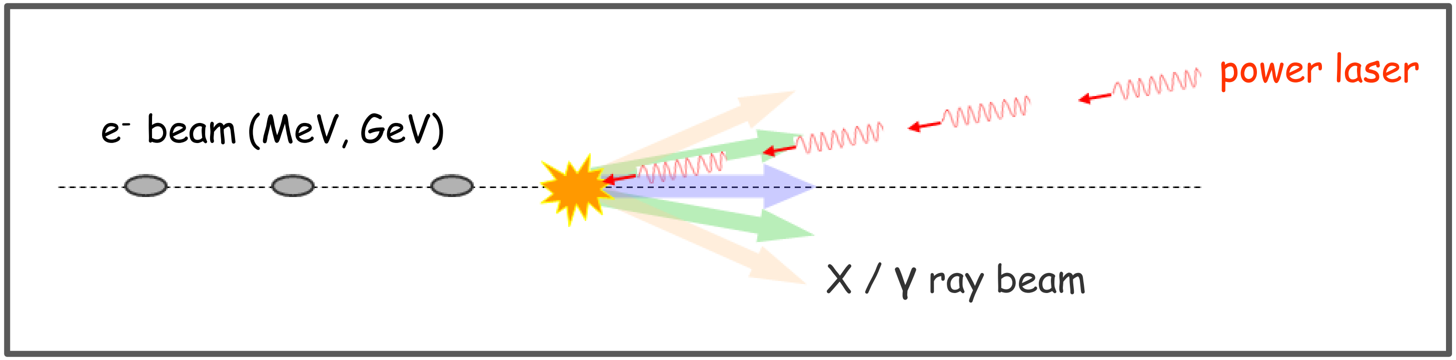
Courtesy R.Hajima

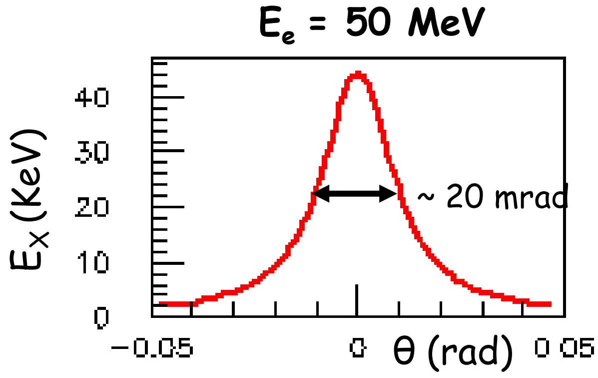
Compact Compton Sources (CCS) → How ?

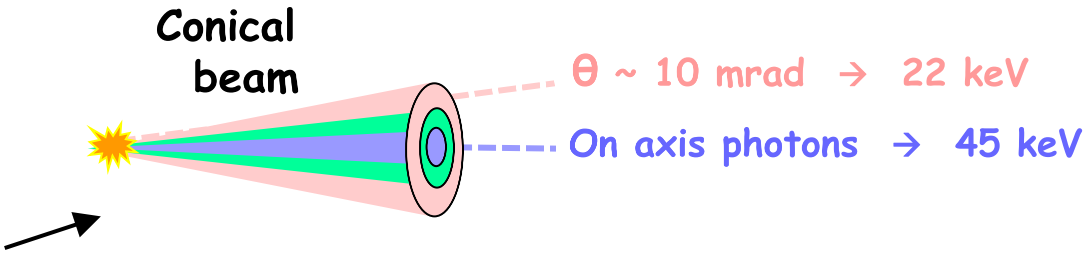
→ Principle

→ Characteristics / Specifications

Compton Sources : principle

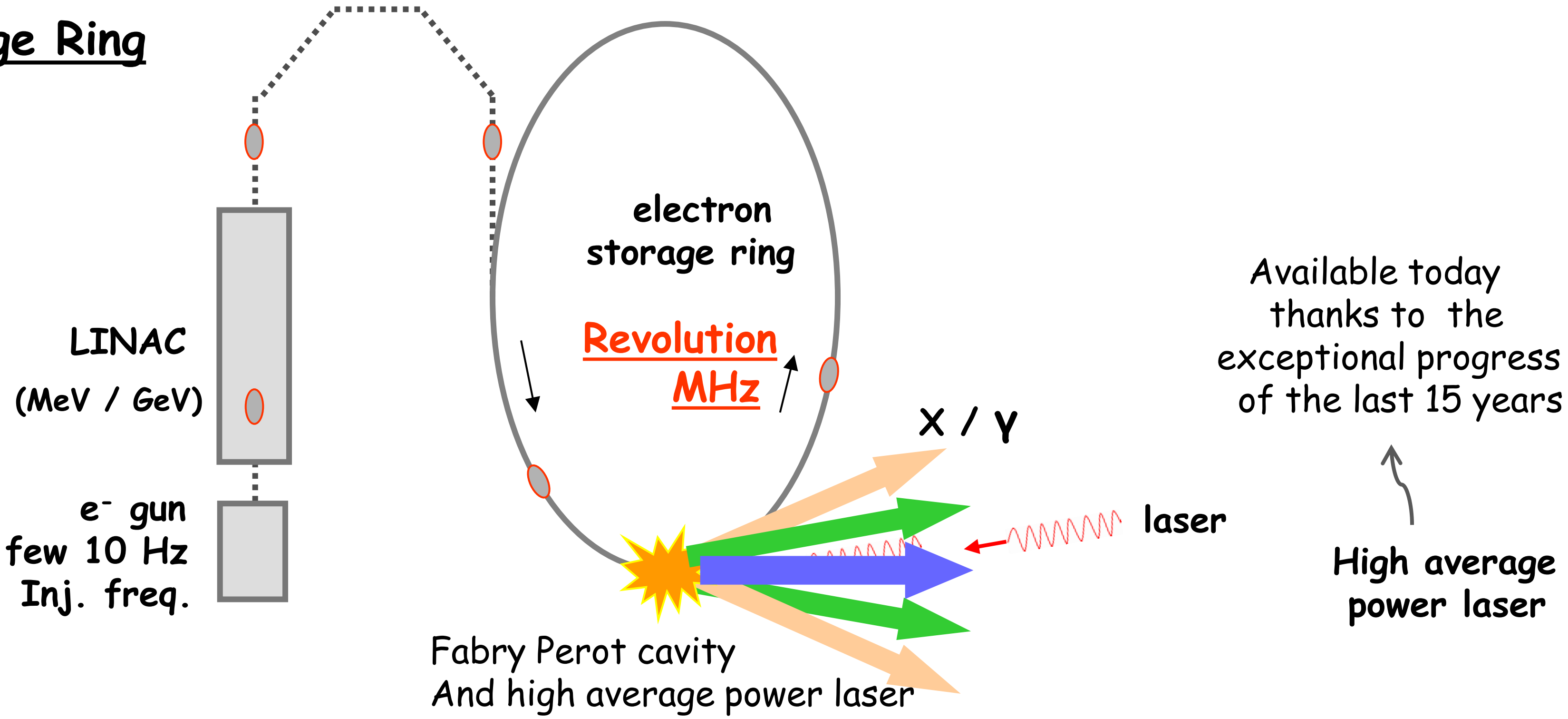






High flux (10^{12} - 10^{14} ph/sec) → Increase f_{rep} e^- / laser (~ 10-100 MHz) → 2 main schemes

Storage Ring



LINAC
(MeV / GeV)

e^- gun
few 10 Hz
Inj. freq.

electron
storage ring

Revolution
MHz

X / γ

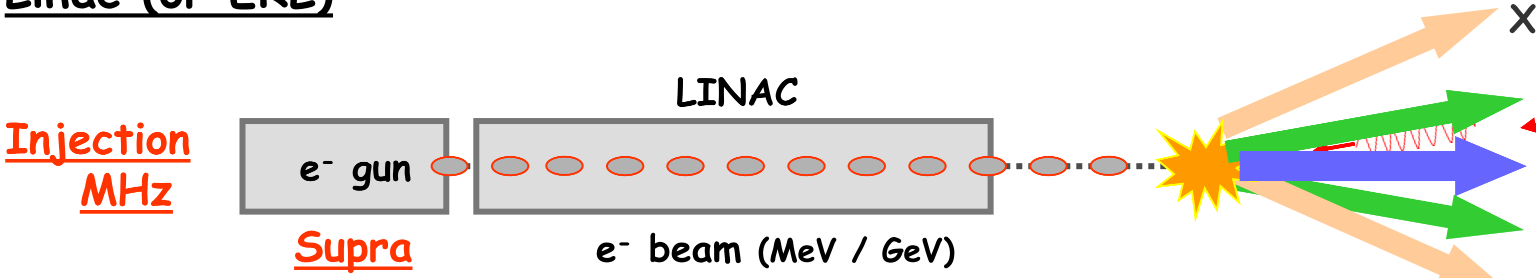
laser

Fabry Perot cavity
And high average power laser

Available today
thanks to the
exceptional progress
of the last 15 years

High average
power laser

Linac (or ERL)



Injection
MHz

e^- gun

Supra

LINAC

e^- beam (MeV / GeV)

X / γ

laser

Fabry Perot cavity and high average power laser CW
Or High peak power laser and optical recirculator

- Source Parameters and Characteristics

Characteristics / specifications of a high flux CCS

- **Compactness** (surface $\sim$ 100 m^2) → Integration in an hospital, a lab, a museum

- **X-ray energy is tunable (LINAC is better)**

$E_X \sim E_e^2 \; E_{ph}$ → E_X can "easily" be tuned by changing the electron beam energy

- **X-ray polarisation is controlled**

The polarisation of the X-ray beam is governed by the laser polarisation.

- **Relative High intensity beam**

CCS flux $\sim$ 10^{12} - 10^{14} ph / sec

$$\text{Flux} \sim \frac{\sigma_{compt} \, N_e \, N_\gamma \, f_{rep}}{2\pi \, (\sigma_e^2 + \sigma_\gamma^2)} \quad (= \text{nb ph/sec})$$

High flux → lots of photons
lots of electrons
small beam sizes
large f_{rep}

- **High quality beam**
  - **Transverse coherence**
  - **High brightness**

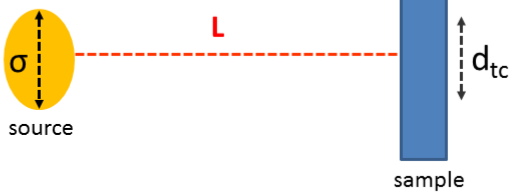
Characteristics / specifications of a high flux CCS

- **High quality beam**
  - **Transverse coherence**
  - **High brightness**

Quality of the X-ray beam ≈ Quality of the e- beam

L : distance source-sample

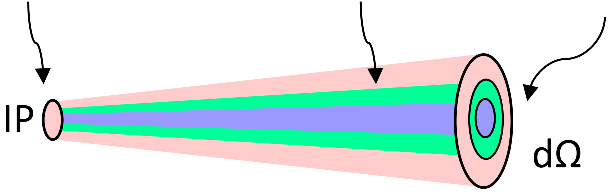
σ : transverse source size



$$d_{tc} \sim \frac{L}{\sigma \; E_x\,(\mathrm{KeV})} \; (10^{-9})$$

A large transverse coherence requires a small source size → **a small e⁻ beam size**

$$Br_X = \frac{\text{Flux}}{(\text{mm}^2\ \text{source})\ (\text{energy bin})\ (\text{mrad})^2}$$



CCS $Br_X \sim 10^{11} - 10^{15}$ ph / sec / mm² / 0.1% bw / mrad²

Brightness of a high flux CCS

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

X-ray spectral bandwidth

laser divergence

$dE_x/E_x \sim \frac{1}{4}\,(d\theta_{ph})^2$

laser energy spread

$dE_x/E_x \sim dE_{ph}/E_{ph}$

e- energy spread

$dE_x/E_x \sim 2\,(d\gamma/\gamma)$

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

(dominant effect)

e⁻ beam divergence → $dE_x/E_x \sim (\gamma\,\sigma'_e)^2$

Typical e⁻ divergence values:

$\sigma'_e \sim 0.5$ mrad → $dE_x/E_x \sim 0.25\ \%$

$\sigma'_e \sim 2$ mrad → $dE_x/E_x \sim 4\ \%$

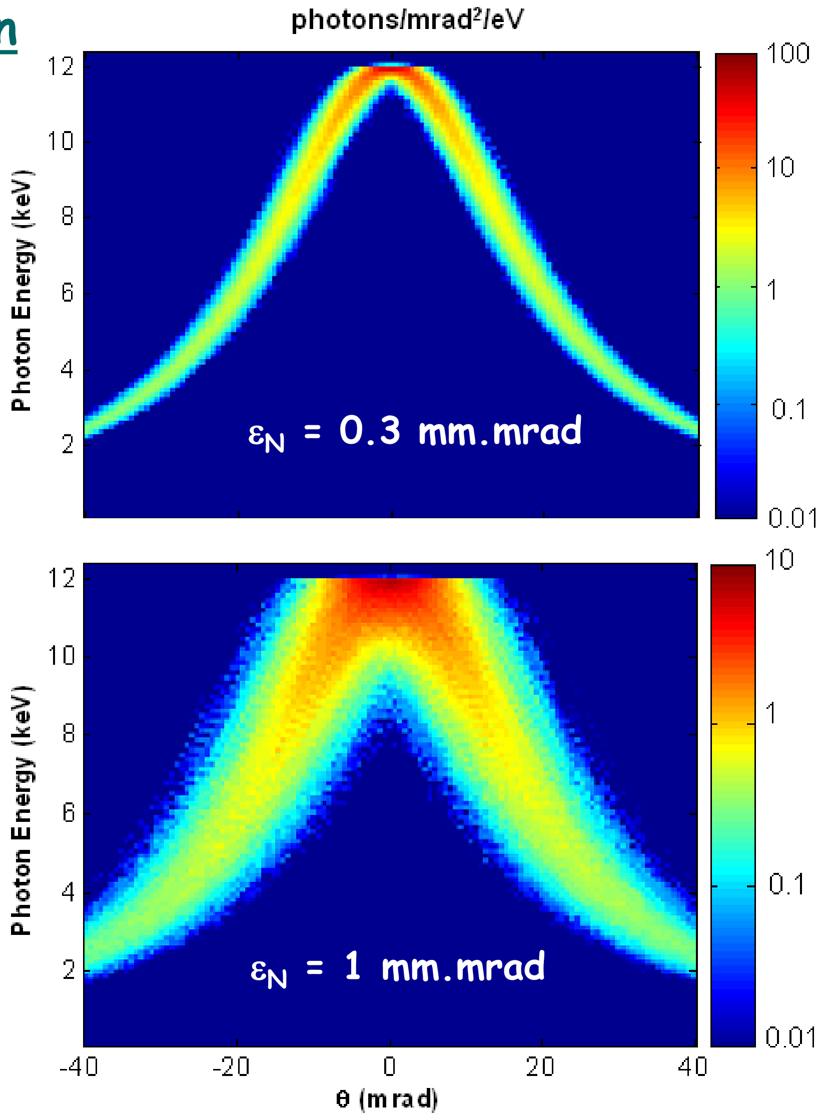
$$Br_X \sim \frac{\text{Flux}}{(\text{mm}^2\ \text{source})\ (dE_x/E_x)\ (\text{mrad})^2} \sim \frac{\text{Flux}\,.\,\gamma^2}{\varepsilon_N^2}$$

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

→ **High brightness = small e⁻ beam emittance**

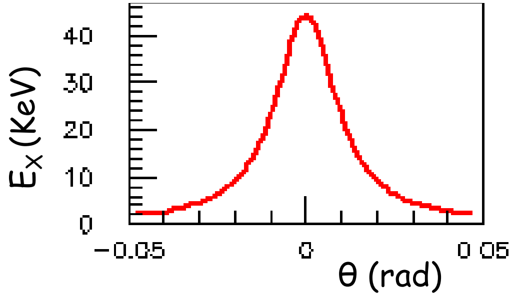
Characteristics / specifications of a high flux CCS

→ … **Illustration**



[W.S. Graves, Alghero Workshop 2008]

Theoretical distribution



→ The e^- beam emittance is a crucial parameter for the brightness

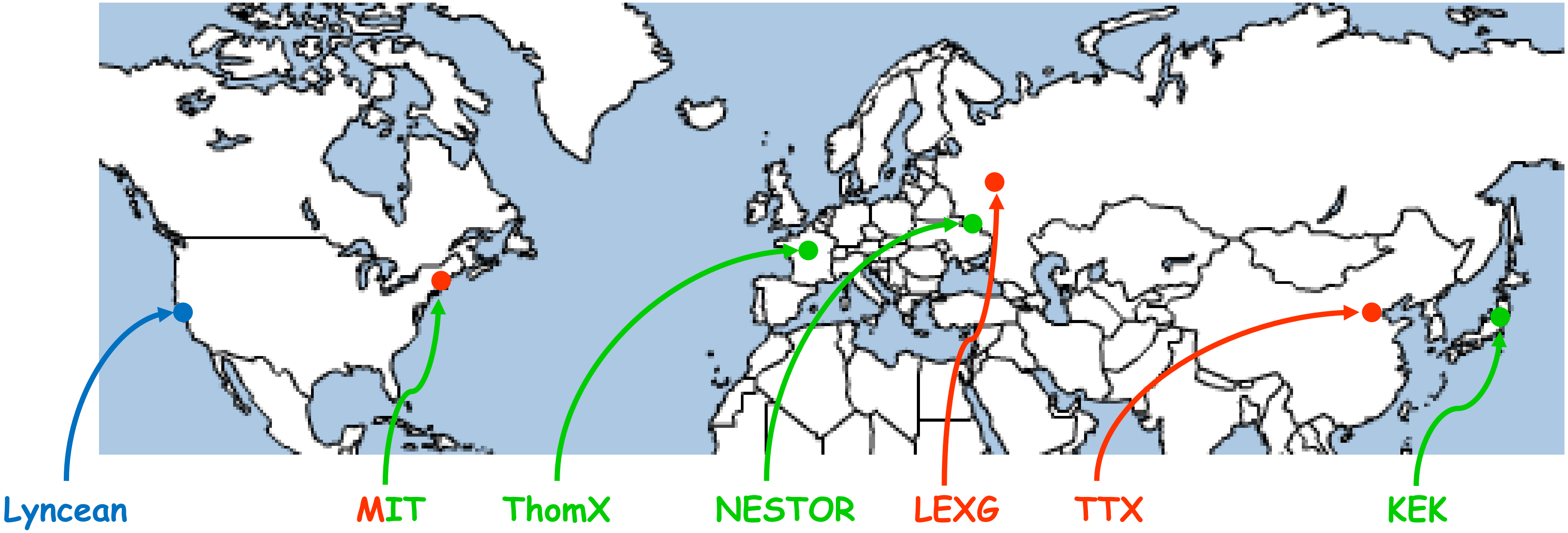
High flux X-ray CCS projects

→ Illustration through projects

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

Project	Type	f_{rep}(MHz)	E_X(KeV)	ph/sec	σ_S(μm)	τ_S(ps)
Lyncean	SR	80	10–20	10^{11}	50	
TTX	SR	25	20–80	10^{12}	50	10
LEXG	SR (sc)	100	33	10^{13}	20	10
NESTOR	SR	20	30–500	10^{13}	70	50
ThomX	SR	20	20–90	10^{13}	70	10
KEK QB	Linac (sc)	160	35	10^{13}	10	
KEK ERL	Linac (ERL/sc)	130	67	10^{13}	30	3
KEK CSR	Linac (ERL/sc)	1300	0.04–4	10^{13-14}		0.1–1
MIT	Linac (sc)	100	3–30	10^{14}	2	0.1

- ● In operation
- ● Funded
- ● Project

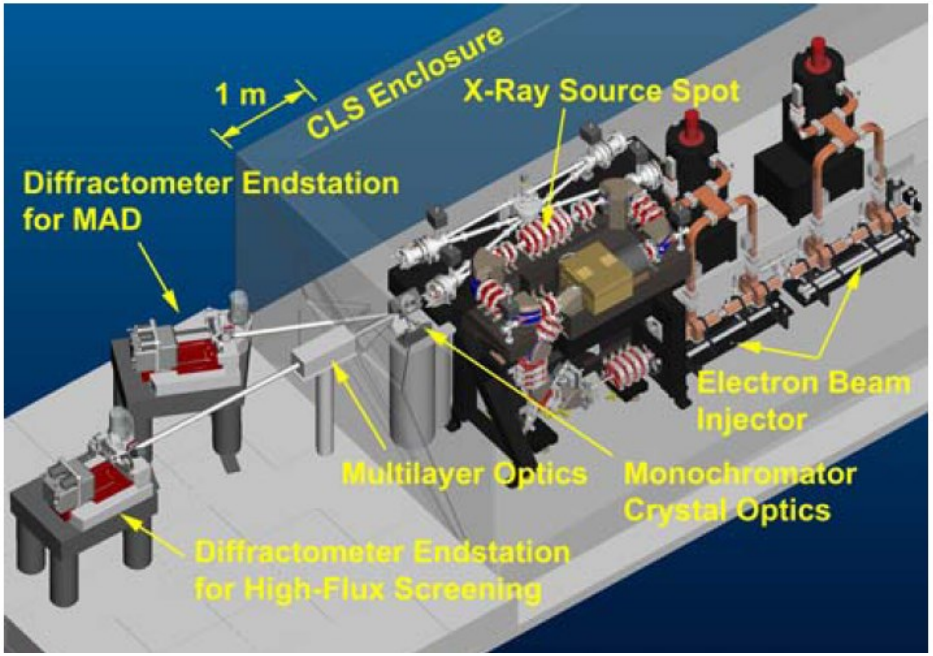


LYNCEANTECH : Diffraction : 3D structural analyses

3D structure of macro-molecules (proteins)

Knowledge of the structure of a protein → acceed to its function in the cell

First determination of the 3D structure of a protein at CS Lyncean Tech.

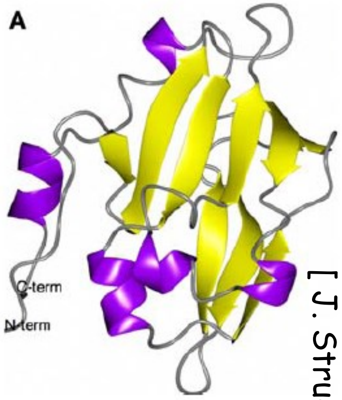


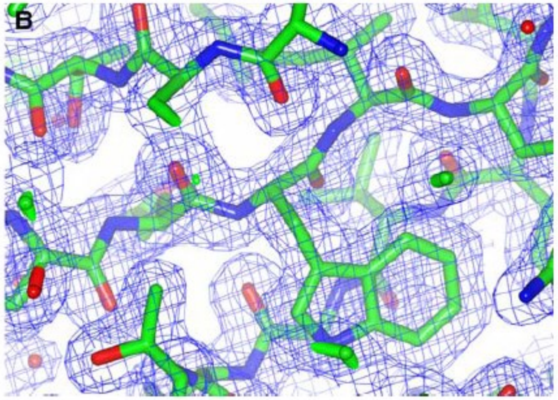
5.10^6 ph/sec
X beam : 120 µm on crystal

E=15 KeV
$\Delta E/E$ = 1.4%

Protein MytuGCSPH (crystal size : 250 X 250 X 100 µm)

Fig. 6 Structure and electron density of MytuGCSPH. **a** Overview of the structure for MytuGCSPH in ribbon representation. **b** Electron density from the MytuGCSPH CLS data set at 2.0 Å resolution centered around Trp 14



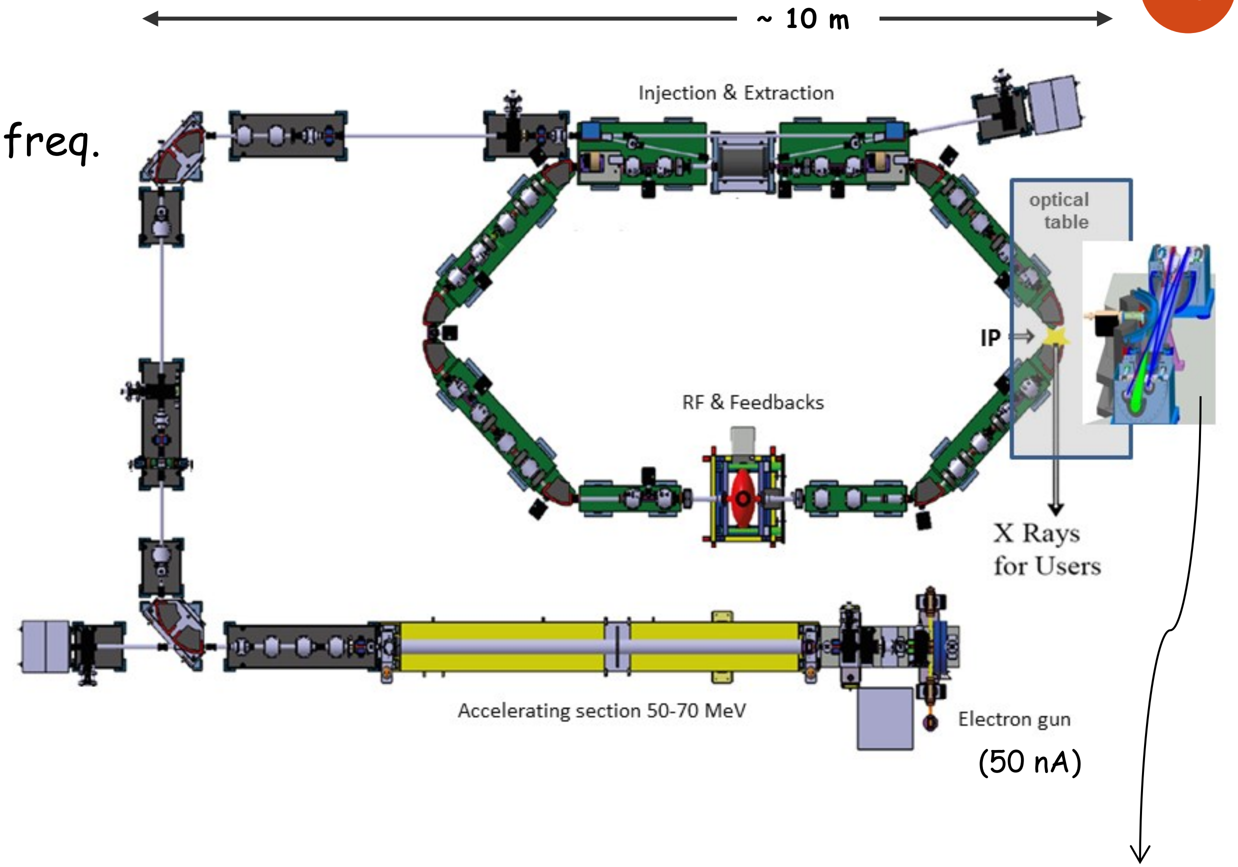


[J. Struct. Funct. Gen. 11, 2010, 91-100]

Storage ring : ThomX design

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



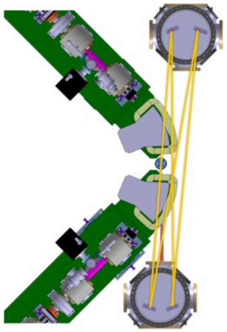
Machine funded
In construction

X-ray beam

Flux	10^{13}
Brigthness	10^{11}
Size	70 µm

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)



Expected beams characteristics

Injector	
Charge	1 nC
Laser wavelength and pulse power	266 nm, 100 μJ
Gun Q and Rs	14400, 49 MW/m
Gun accelerating gradient	100 MV/m @ 9.4 MW
Normalized r.m.s emittance	8 π mm mrad
Energy spread	0.36%
Bunch length	3.7 ps

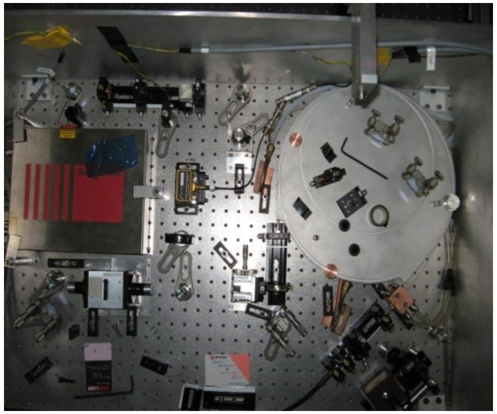
Laser and FP cavity	
Laser wavelength	1030 nm
Laser and FP cavity Frep	36 MHz
Laser Power	50 - 100 W
FP cavity finesse / gain	30000 / 10000
FP waist	70 μm

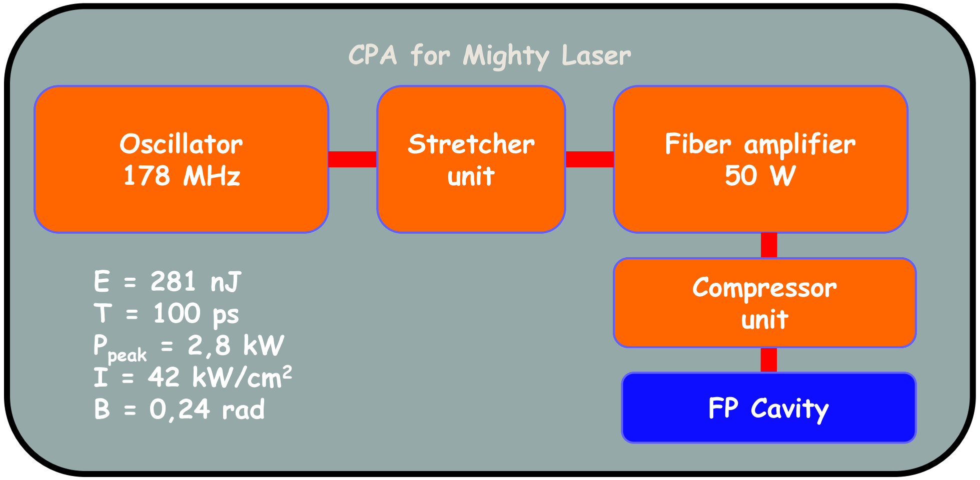
Ring	
Energy	50 MeV (70 MeV possible)
Circumference	16.8 m
Crossing-Angle (full)	2 degrees
$B_{x,y}$ @ IP	0.2 m
Emittance x,y (without IBS and Compton)	$3\ 10^{-8}$ m
Bunch length (@ 20 ms)	30 ps
Beam current	17.84 mA
RF frequency	500 MHz
Transverse / longitudinal damping time	1 s /0.5 s
RF Voltage	300 kV
Revolution frequency	17.8 MHz
σ_x @ IP (injection)	78 mm
Tune x / y	3.4 / 1.74
Momentum compaction factor α_c	0.013
Final Energy spread	0.6 %

Source	
Photon energy cut off	46 keV (@50 MeV), 90 keV (@ 70 MeV)
Total Flux	10^{11}-10^{13} ph/sec
Bandwidth (with diaphragm)	1 % - 10%
Divergence	$1/\gamma$ ~ 10 mrad without diaphragm @ 50 MeV

Injector, ring, laser, Fabry-Perot resonator and the source

Laser





CPA for Mighty Laser

Oscillator 178 MHz

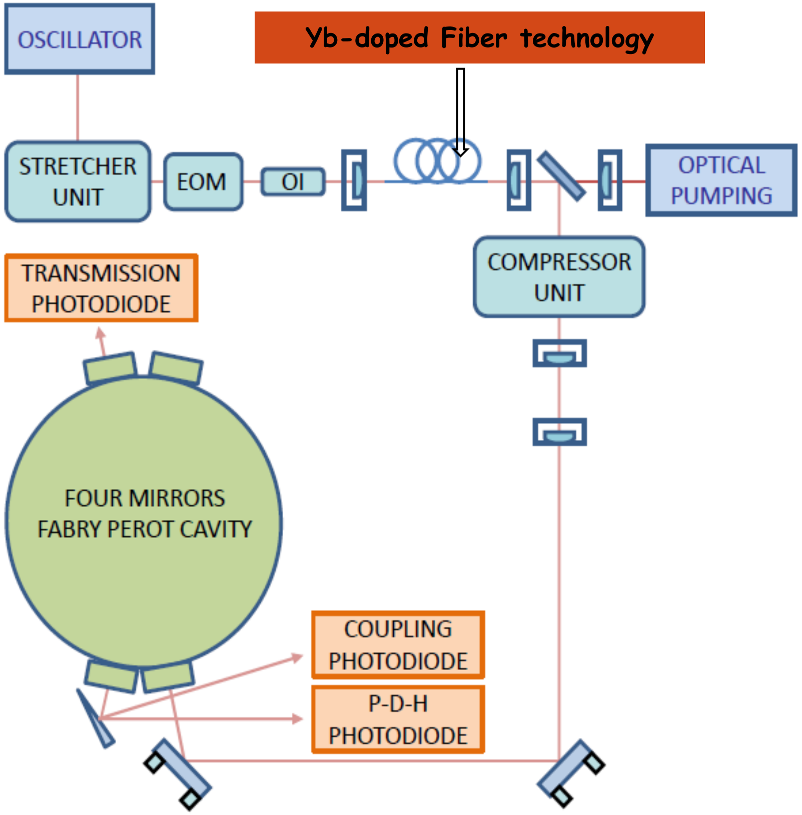
Stretcher unit

Fiber amplifier 50 W

Compressor unit

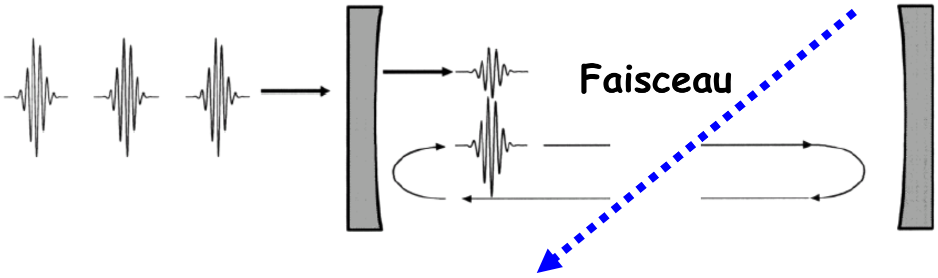
FP Cavity

$E = 281$ nJ
$T = 100$ ps
$P_{peak} = 2{,}8$ kW
$I = 42$ kW/cm^2
$B = 0{,}24$ rad

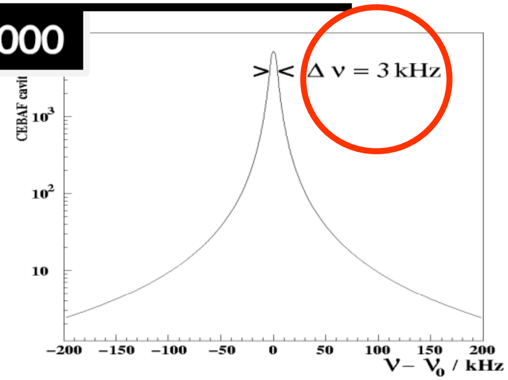


Compatible with low noise amplification

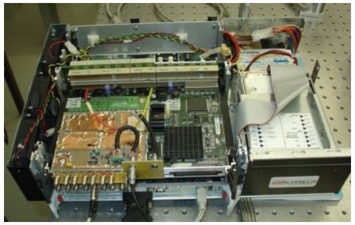
Fabry-Perot cavity

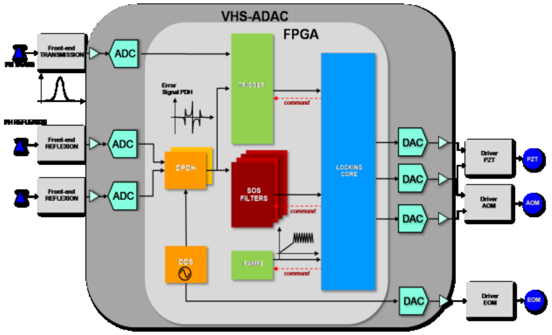


Gain=1/(1-R)~10000

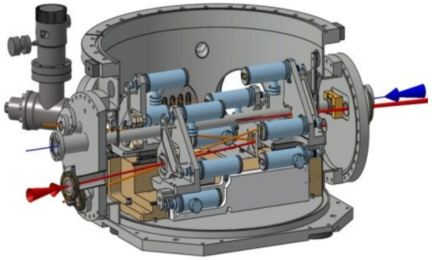


Digital Pound-Drever-Hall feedback





Vacuum and mechanics : MightyLaser experience



PLIC and MightyLaser : record in stable finesse locking (30000).

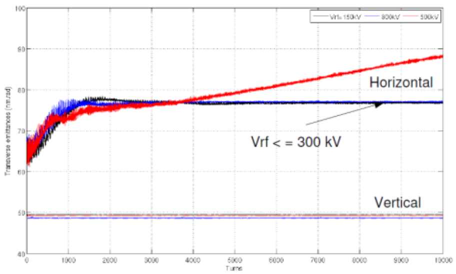
Beam Dynamics

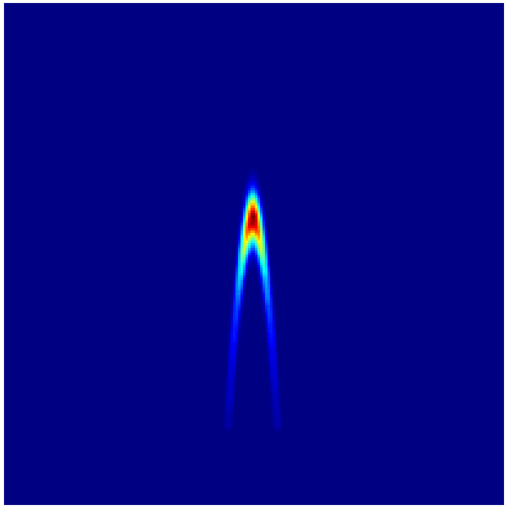
- Transient dynamics (no equilibrium)
- Compton recoil
- Collective instabilities
- CSR, Ions, Vacuum scattering, IBS…..
- Injection mismatching

Feedbacks!!!!
Ion clearing
Simulations

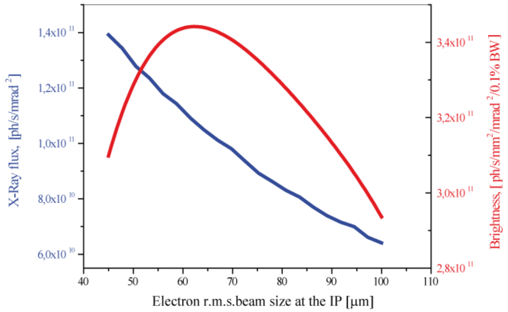
→

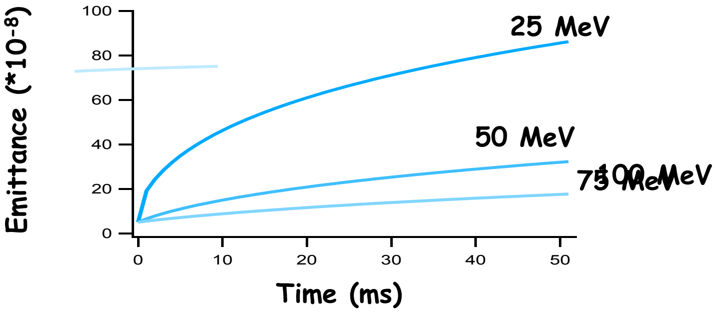
3 Phases
Injection
Turbulent regime
Stabilization (thousand turns)

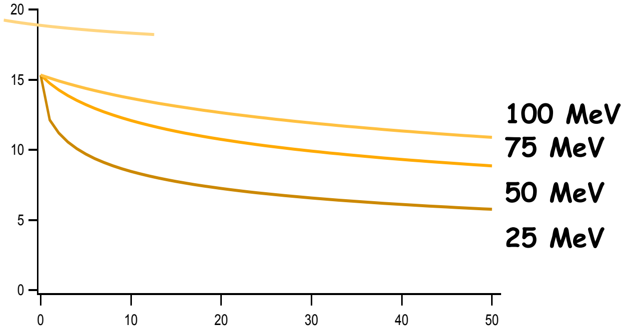




Careful to the brillance !!!







Linac : MIT design (superconducting machine)

Electron machine

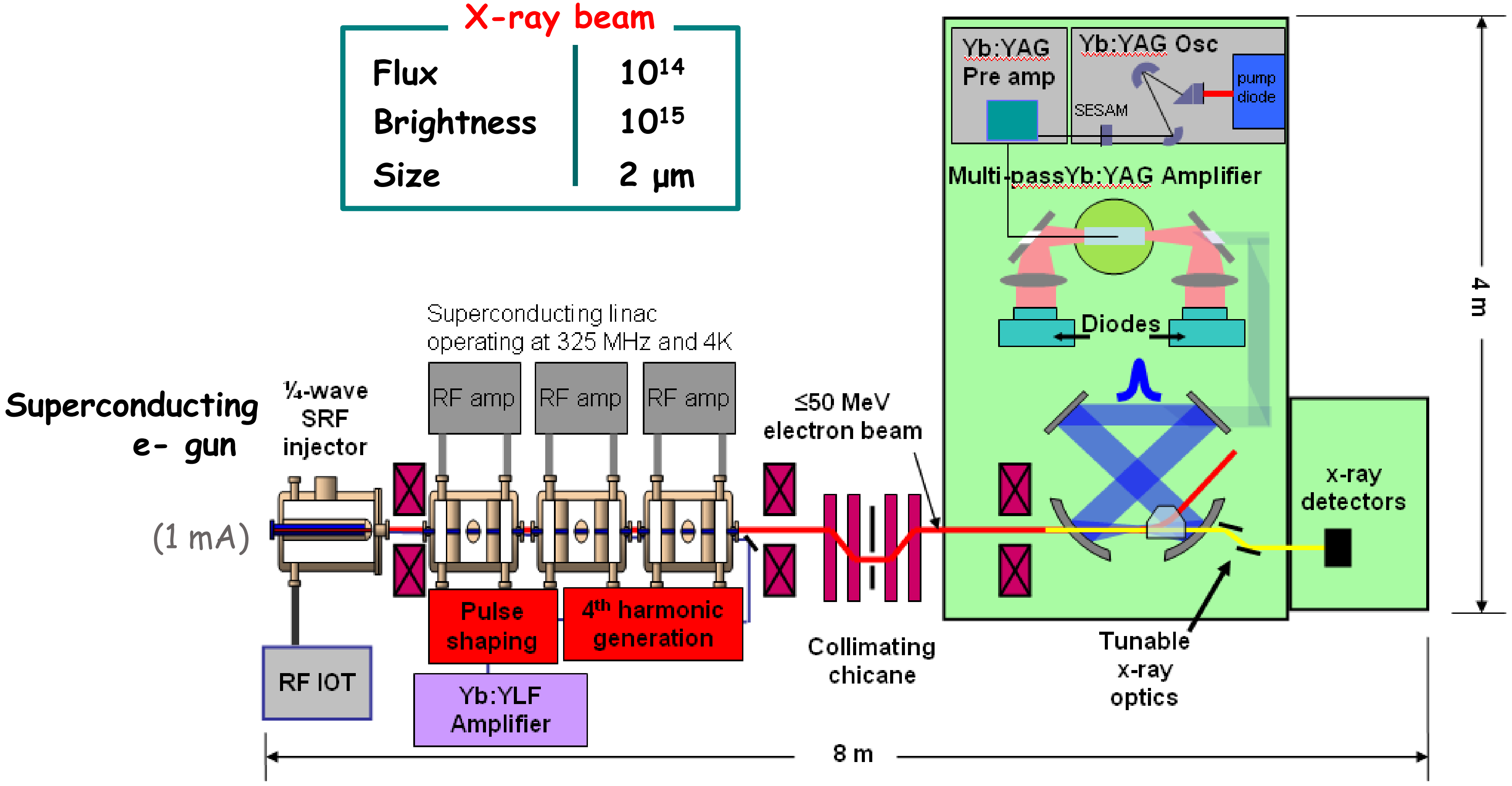
- 0.01 nc / bunch , 100 MHz inj. freq.
- σ_e ~ 2 μm
- ε_N ~ 0.1 mm.mrad
- τ_e ~ 0.1 ps

Laser /Cavity system

- Laser ~ 10W
- Cryogenic fiber amplification (1 KW) 10 μJ/pulse
- Optical cavity amplification (gain 1000)
- 1 MW stored inside the cavity (10 mJ/pulse)

X-ray beam

Flux	**10^{14}**
Brightness	**10^{15}**
Size	**2 μm**

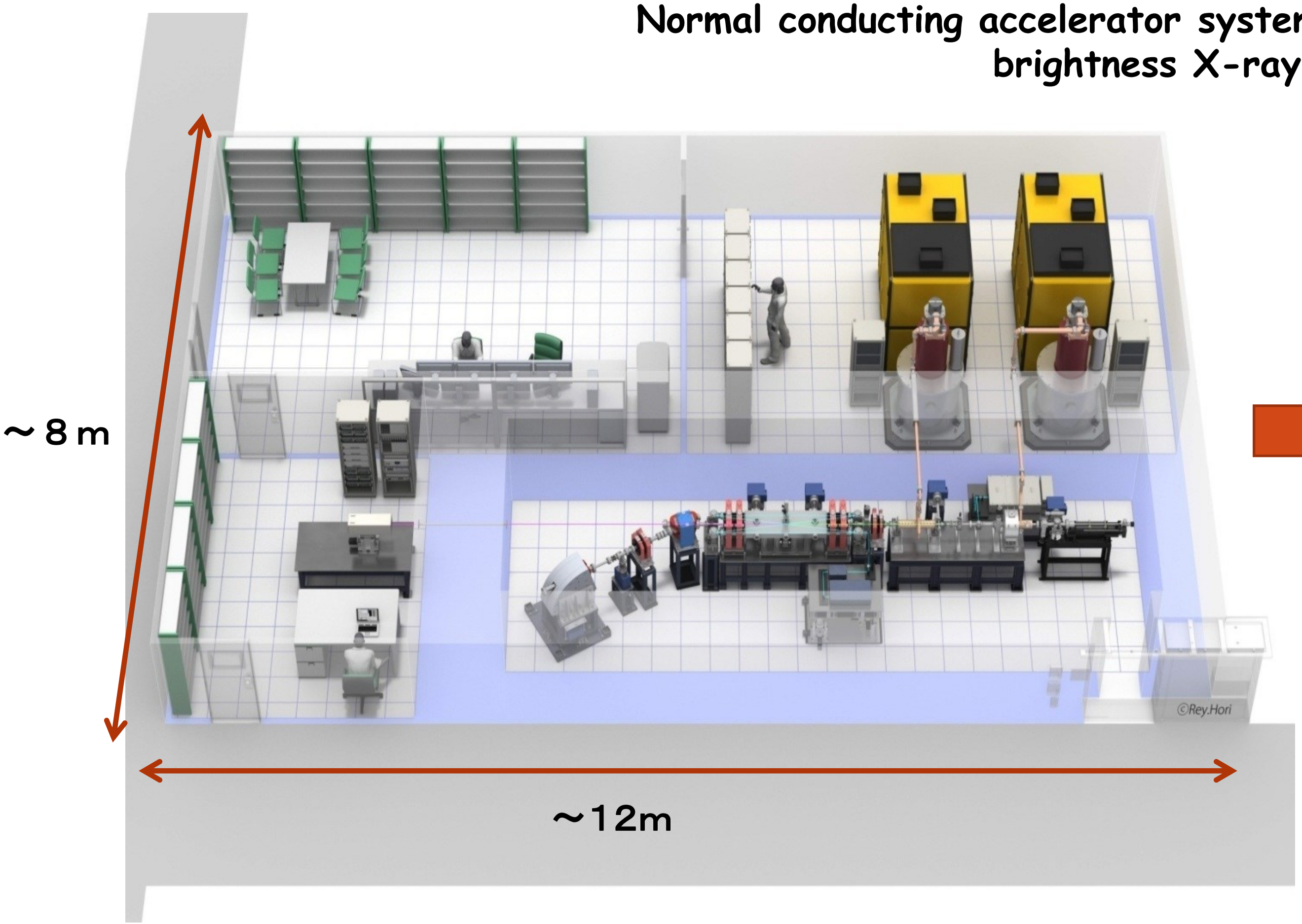


[W.S. Graves, Alghero Workshop 2008]

New Quantum Beam Technology Program(NQBTP) is supported by MEXT from 2013.8 to 2018.3 (~5 years project).

Approved project included two Japanese Companies at least and the development for CW super conducting acceleration technologies. Normal conducting accelerator system and super conducting accelerator system for compact high brightness X-ray source should be realized by joint research with companies.

Normal conducting accelerator system for compact high brightness X-ray



Downsizing to 6m x 8m

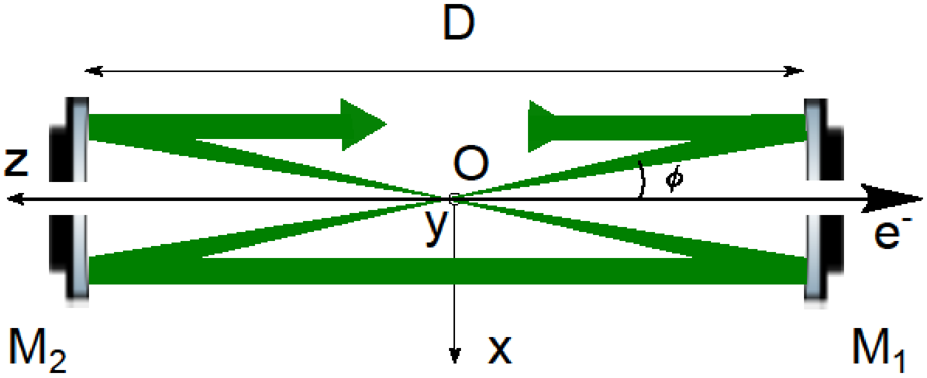
ELI-NP gamma source specifications
A future application to X rays?

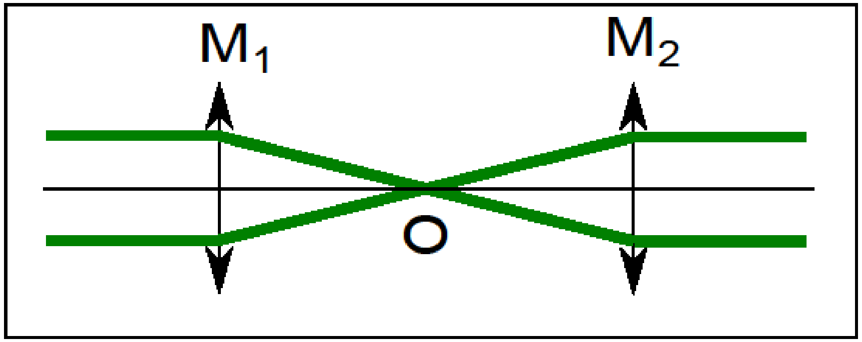
- Energies γ (E_γ) : 0.2 – 19.5 MeV
- Bandwidth ($\Delta E/E$) : 0.5%
- Spectral density (flux) : 5000 γ/(s.eV)
- Linear polarization : 95%

⇒ LINAC multi-bunch 100Hz

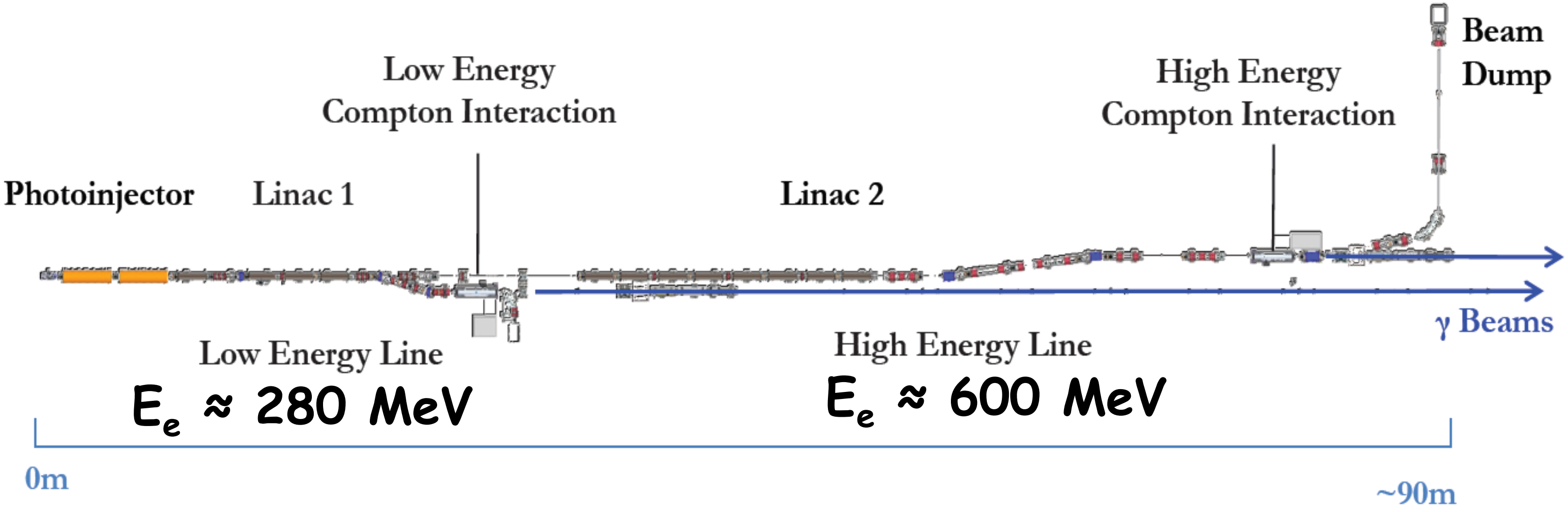
+

optical circulator

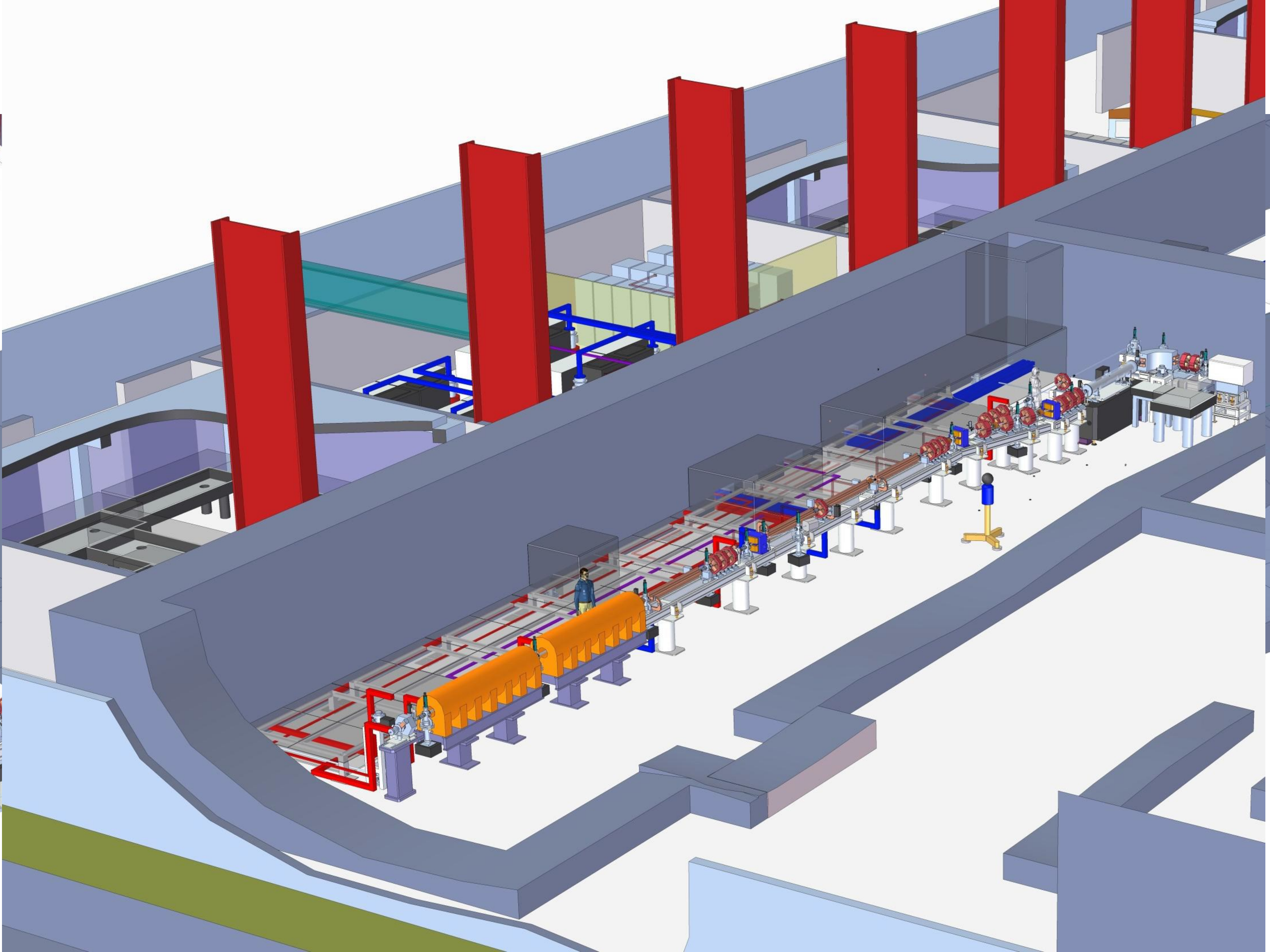




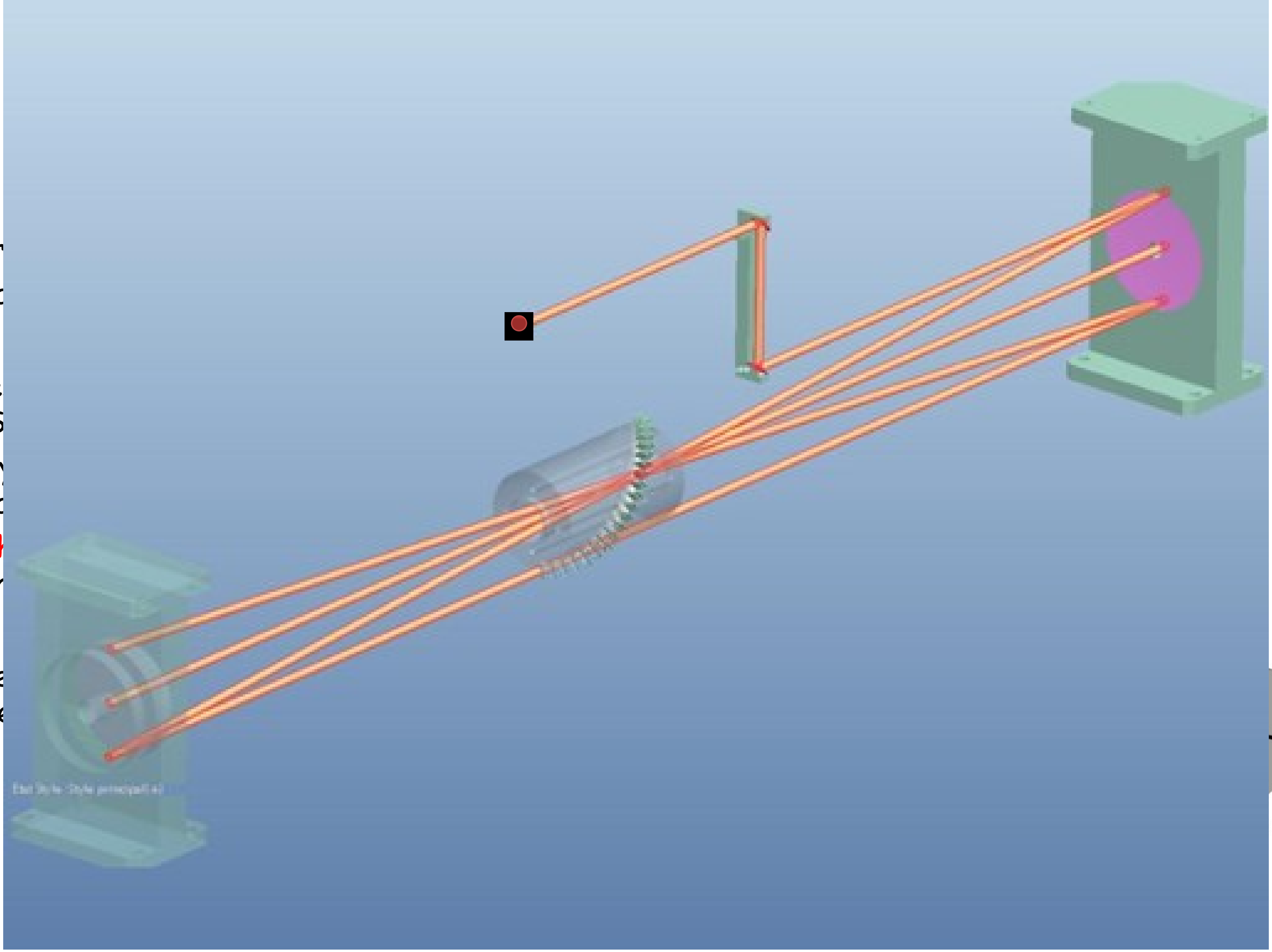
Source layout



- 2 points d'interactions :
  - 1 lasers 200mJ Yb@515nm (3.5ps) par point d'interaction
  - LINAC hybride bandes S et C (~100 - 720 MeV)



Système optique : circulateur



- 2 mir
  - Po
- Paire (MPS
  - Sy po
  - *Ch* ch

⇒ Angle faible

Outlook

- Compton effect has various advantages as far as compact sources are concerned. ENERGY BOOST
- Complementarity to SR
- New generation of 'compact' X rays and nuclear gamma sources
- Different fields of application. Each requires a custom design and choice of accelerator and laser systems. High average power or high peak brillance
- Worldwide increasing interest. Many projects ongoing
- Fascinating projects, they join the top of th accelerator and laser science with the laser-beam interaction physics

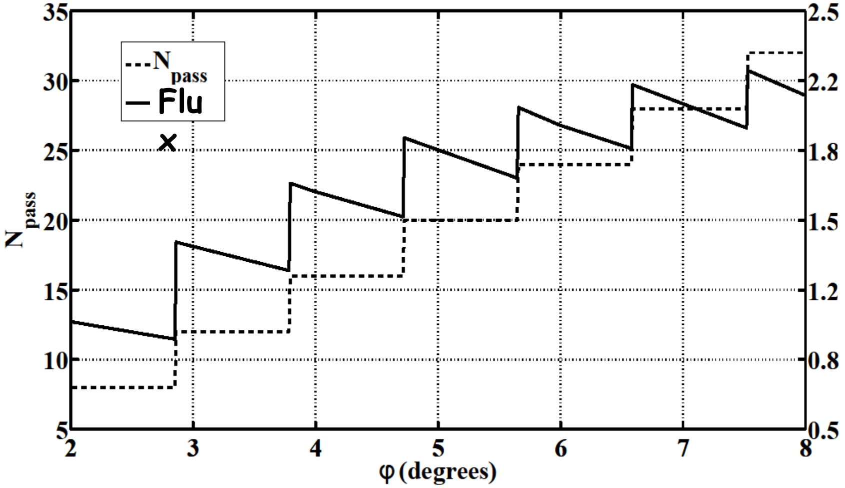
Thank you

Design

Design du circulateur

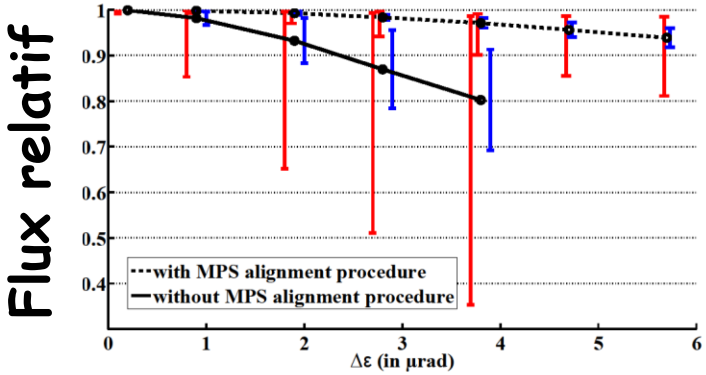
- ω_0 ↑ => flux ↓
- ϕ ↑ =>
  - flux ↓
  - Nb passages ↑ => flux ↑

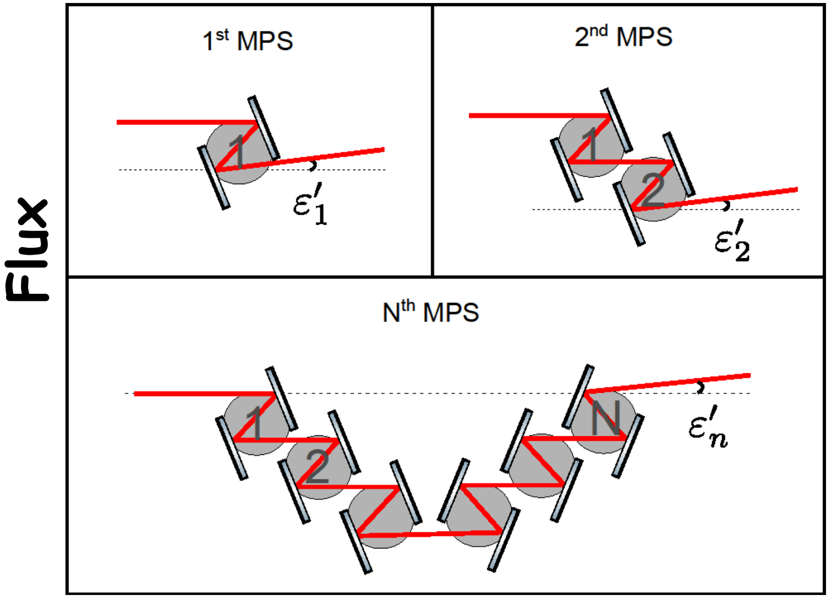
⇒Optimisation



=> 32 passages, φ = 7.54°

Parallélisme des paires de miroirs à face parallèles





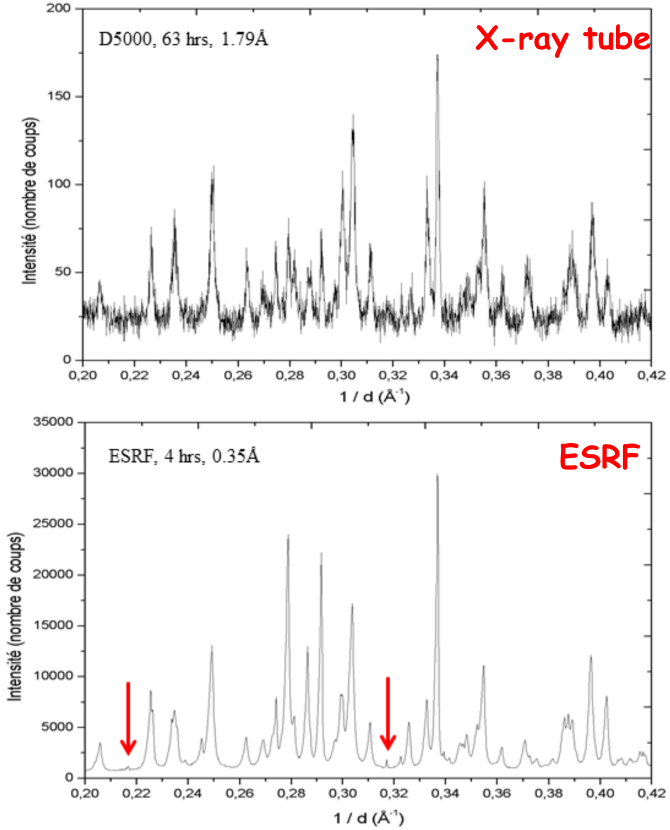
Potential of applications of X-ray CCS: Examples

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
- Tunable energy

Diffraction patterns

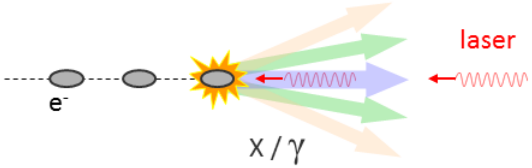


→ ESRF : minor phases present in the powder visible

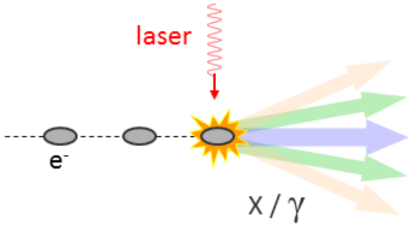
Pulse duration of a CCS

Pulse duration

Head-on collisions



90° collisions



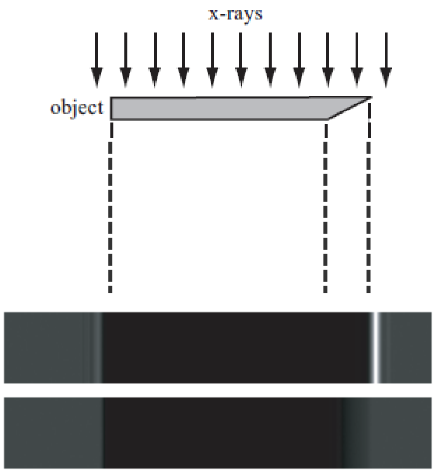
→ 0.1 - 10 ps

(depending on the e$^-$ and laser pulses length, and the collision angle)

Analysis techniques

Imaging

→ Study of **absorption contrast and phase contrasts** of the **transmitted photons**



Absorption + Phase contrasts

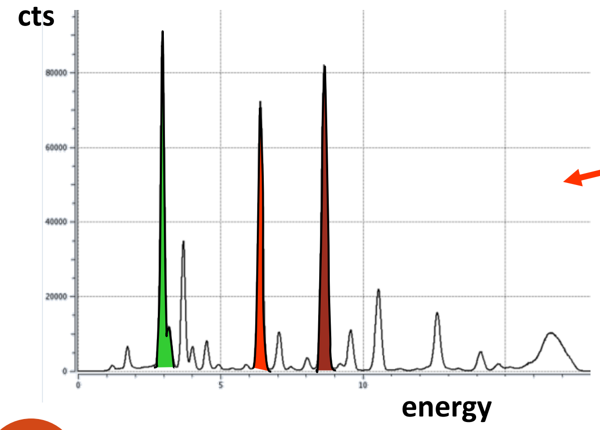
Absorption contrast only

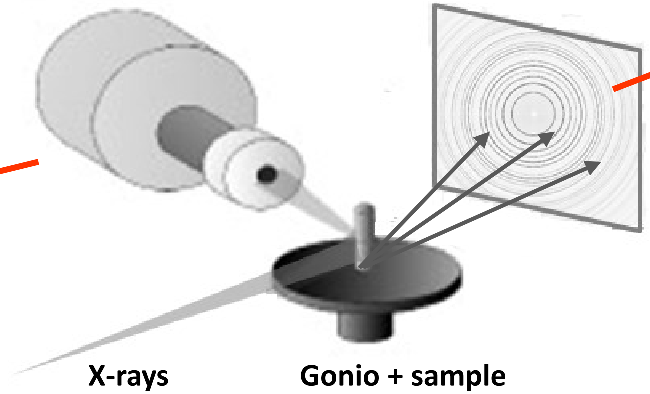
Use the information of the phase of the x-ray wave

Diffraction / Spectroscopy

→ Study of **the reemitted photon spectra**

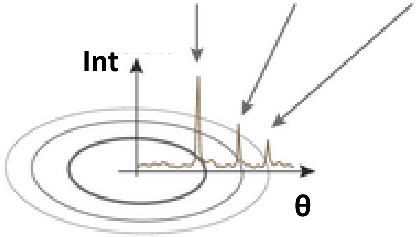
Fluorescence spectro





Diffraction

Depending on θ and intensity peak
→ mesh, types of atoms …



Phase contrast

Interactions wave/matter described by the refraction index

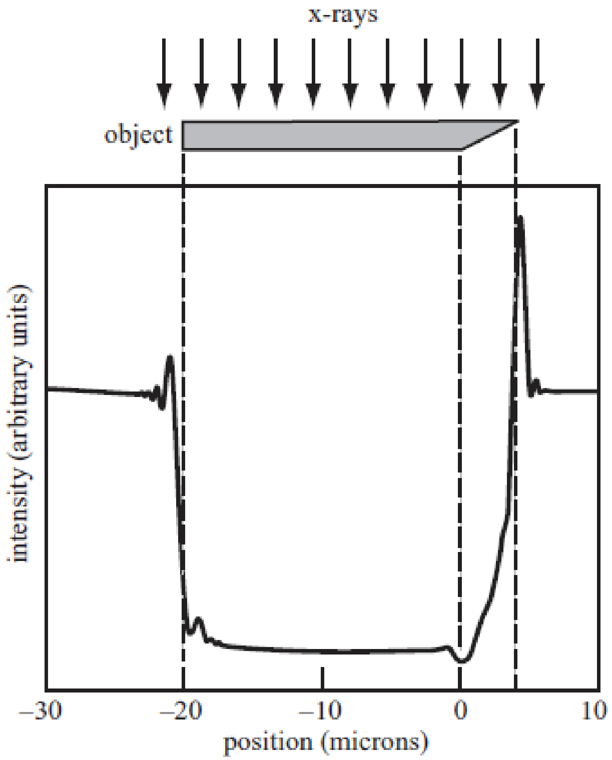
$$N = n_R + i\,n_A$$

Phenomena of
→ refraction
→ diffraction
→ interferences
(effects related to the phase of the wave)

Absorption Contrast

Wave superposition
→ classical phenomena
refraction/diffraction
(Fresnel integrals)

→ **Phase Contrast**

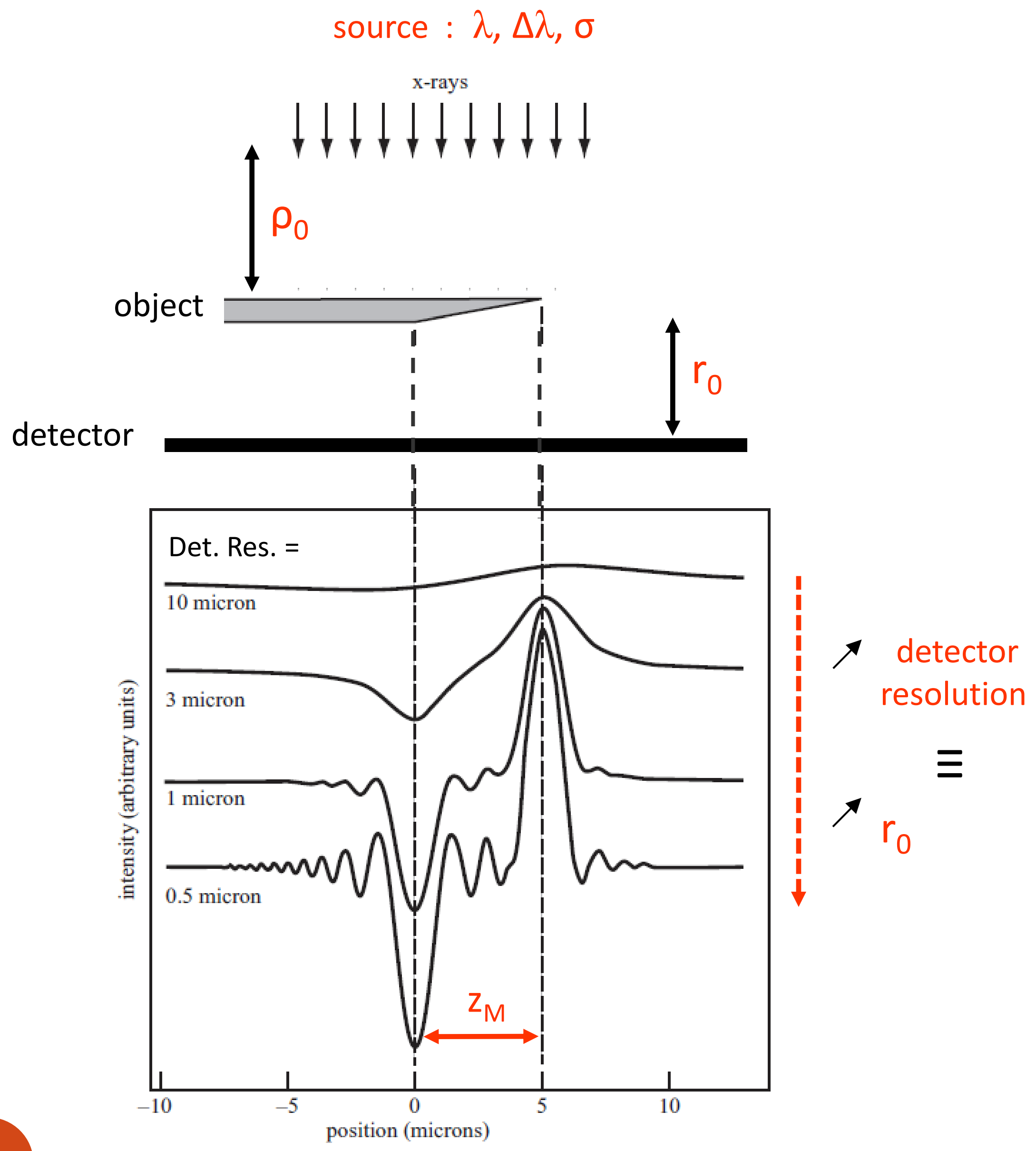


Absorption
+ Refraction

Absorption
only

[J. Phys. D: Appl. Phys 35 (2002) R105-R120]

Phase contrast

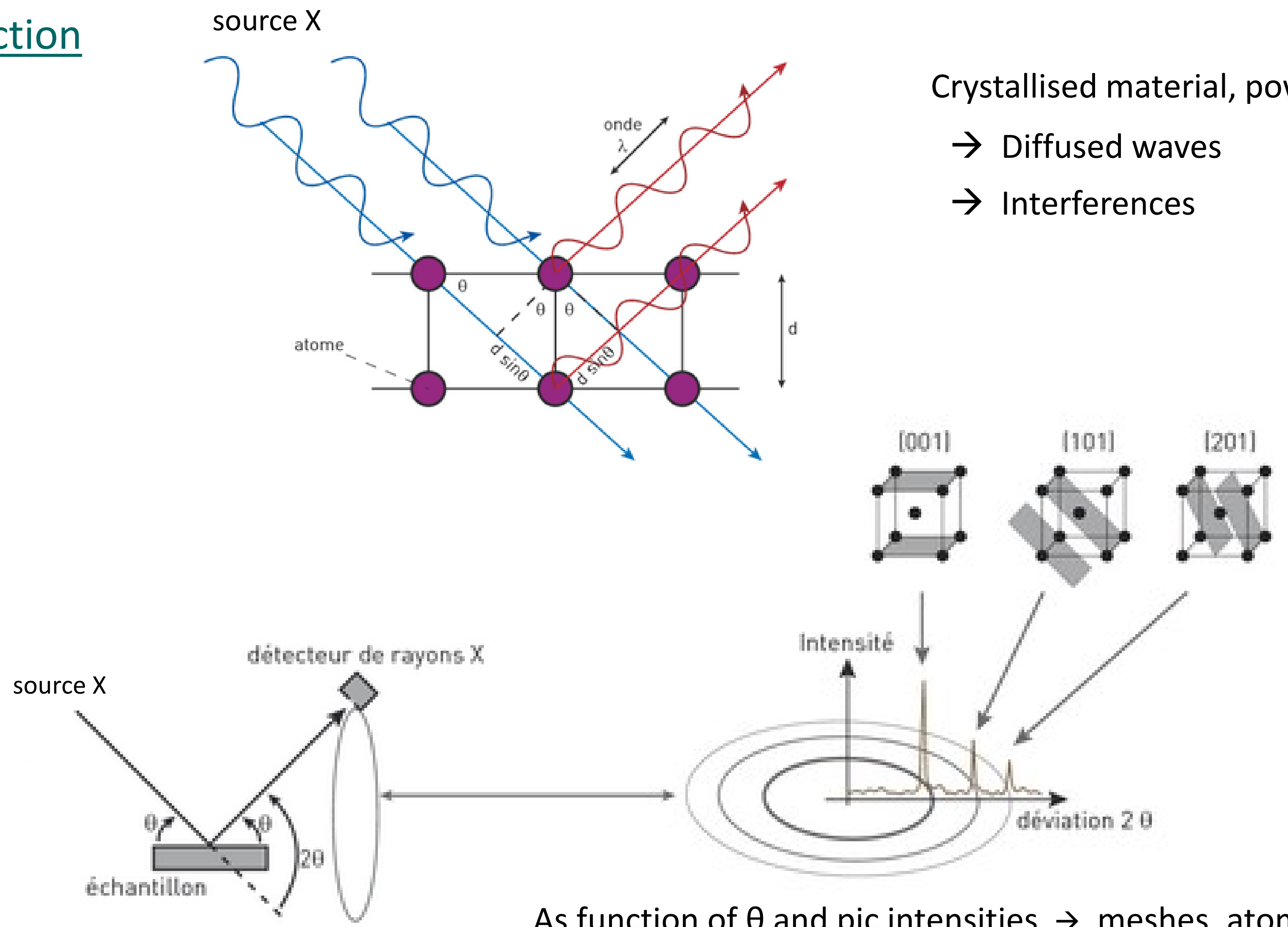


Conditions to detect the main maximum (frange)

- $\Delta z_M / z_M \sim \Delta\lambda / \lambda \ll 1$
- $(r_0 / \rho_0)\, \sigma \ll z_M$

Diffraction

Diffraction



Crystallised material, powders …

→ Diffused waves

→ Interferences

As function of θ and pic intensities → meshes, atoms types …

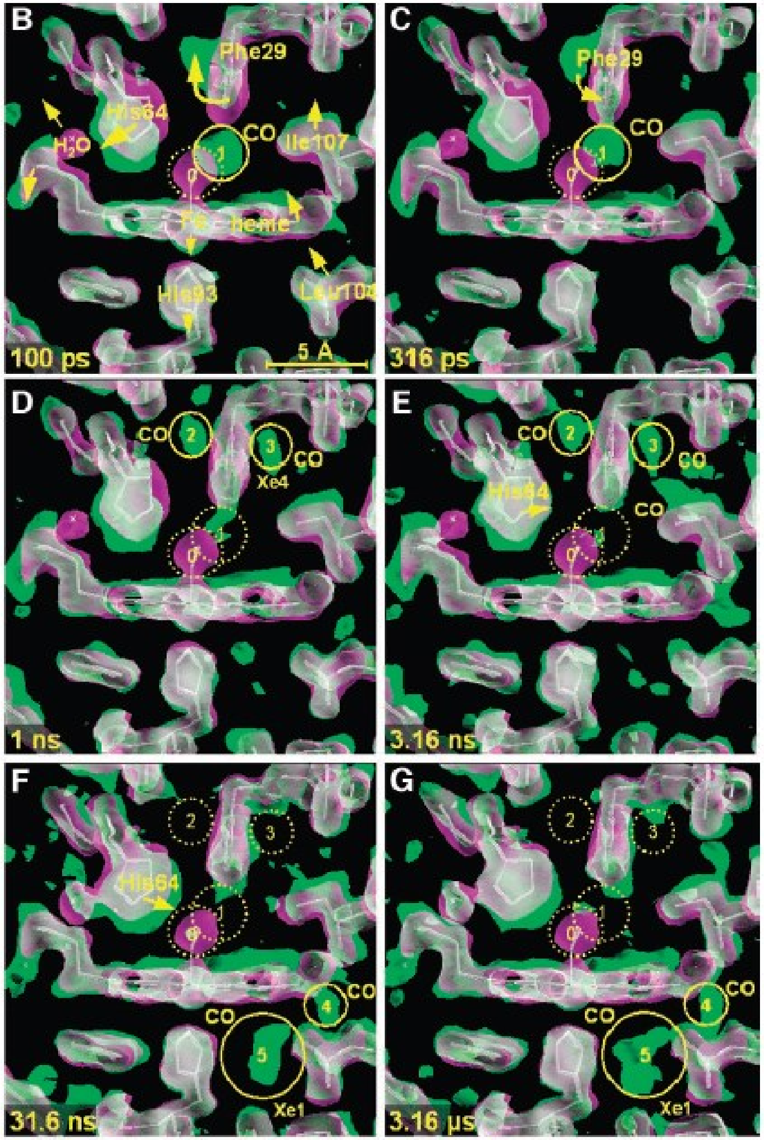
Diffraction : Pump-probe experiments : Dynamic system studies

→ **Visualisation in real time of atomic/molecular processes**

→ **“Pump-probe” experiments**
Currently: resolution ~ 100 ps)

“Live” view of the interaction between a protein and a ligand

(ESRF, Resolutions 2Å, 100 ps)



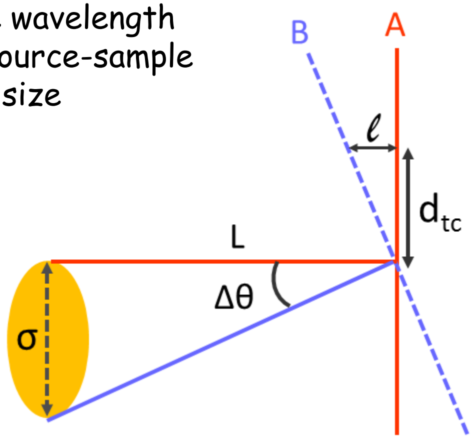
[Science 300, 1944, 2003]

→ **Time scale of molecular movements ~ 10 -100 fs**

→ **Compact ICS with ultra-short pulses**

Transverse coherence

λ : source wavelength
L : dist. source-sample
σ : source size



The wave fronts A et B
arrive in phase if $l \sim \lambda$

$$\rightarrow \quad d_{tc} \quad \frac{L}{\tilde{\sigma} \; E_x\,(KeV)} \, (10^{-9})$$

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