DEVELOPMENTS OF OPTICAL SYSTEMS FOR X-RAY COMPTON MACHINES @LAL

On behalf of Laser-Electron Interaction group

OUTLOOK

- Compton Scattering
- Laser Beam Circulator (ELI-NP project)
- Standard Resonant Cavity (ThomX project)
- Resonant Burst Cavity (Future project)

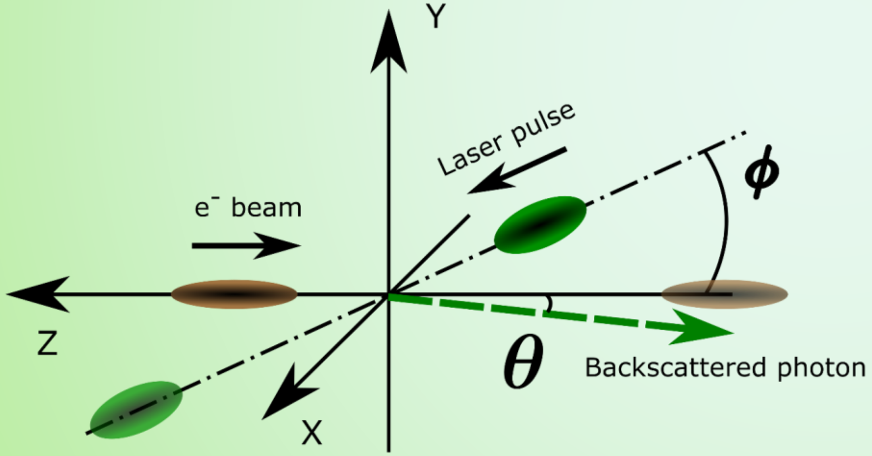
Down Scaling

X-RAY PRODUCTION: COMPTON SCATTERING

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

- E_L : Photon energy (incident photon)
- γ : Lorentz factor (incident electron)
- ϕ : crossing angle
- θ : Scattering angle

Scheme of Compton Scattering



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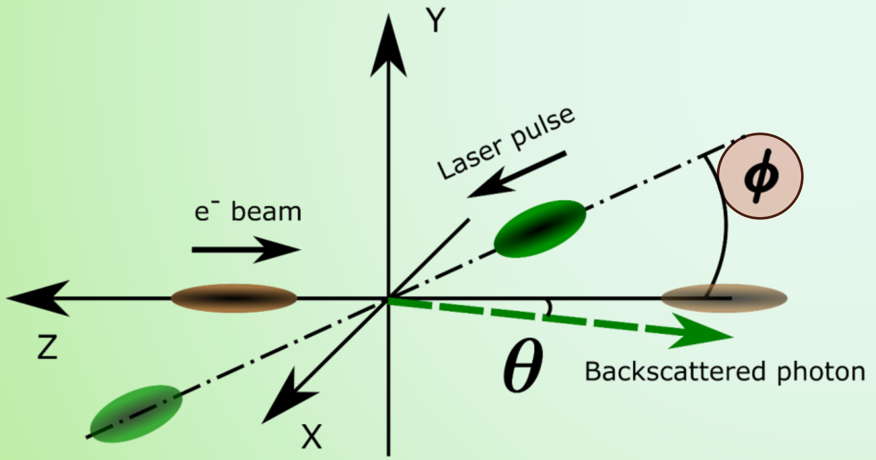

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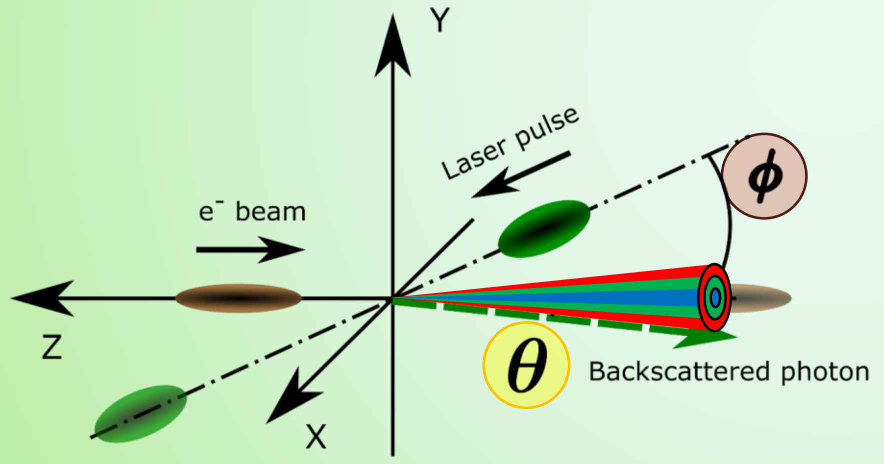

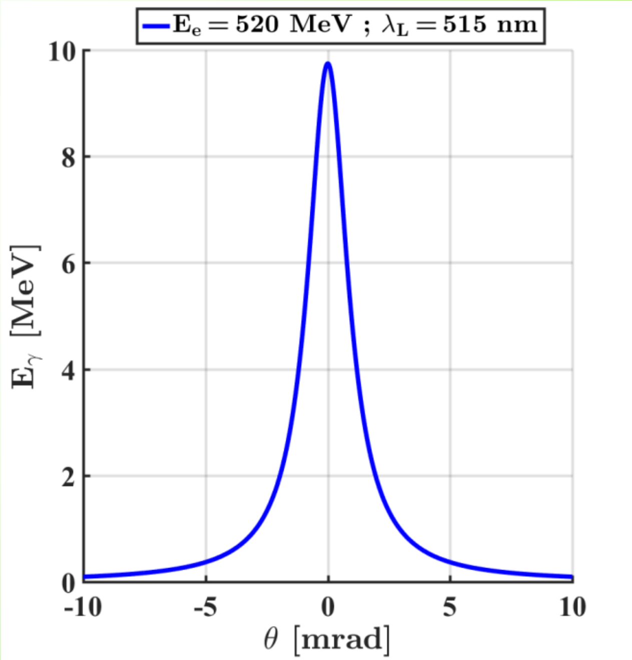

Angular Correlation

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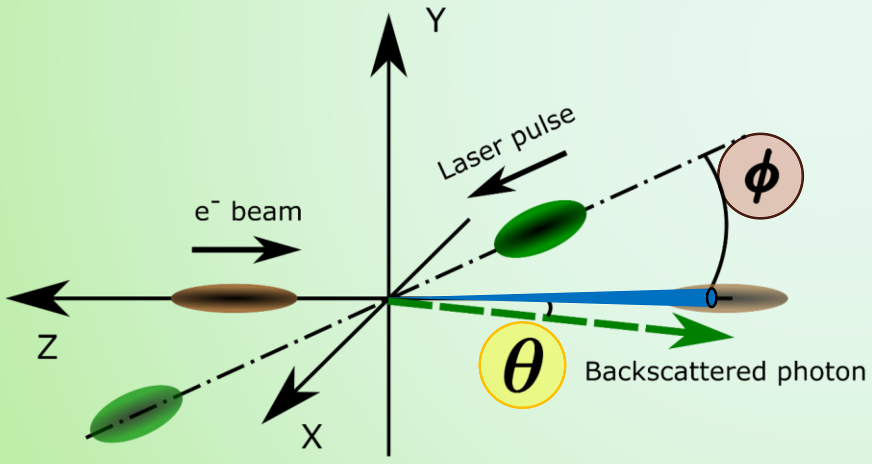
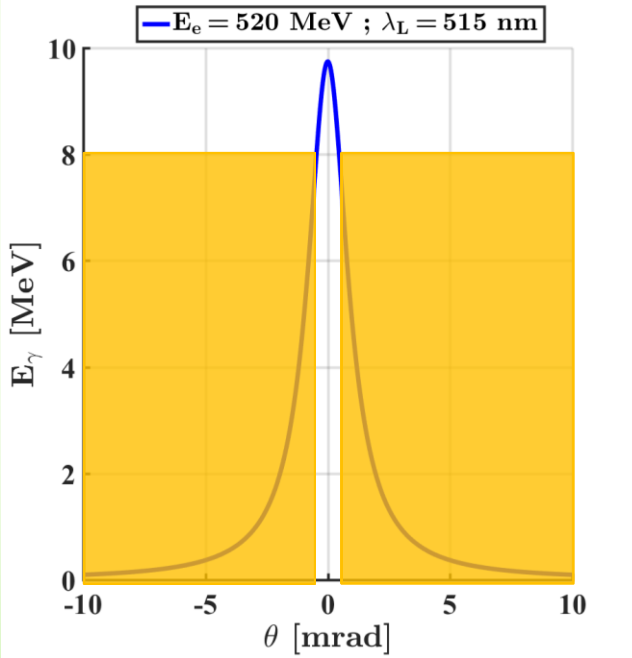




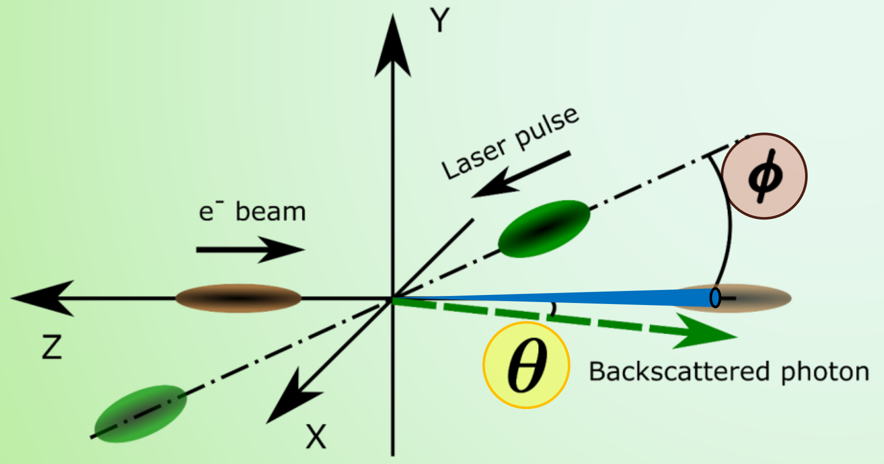
Angular Correlation

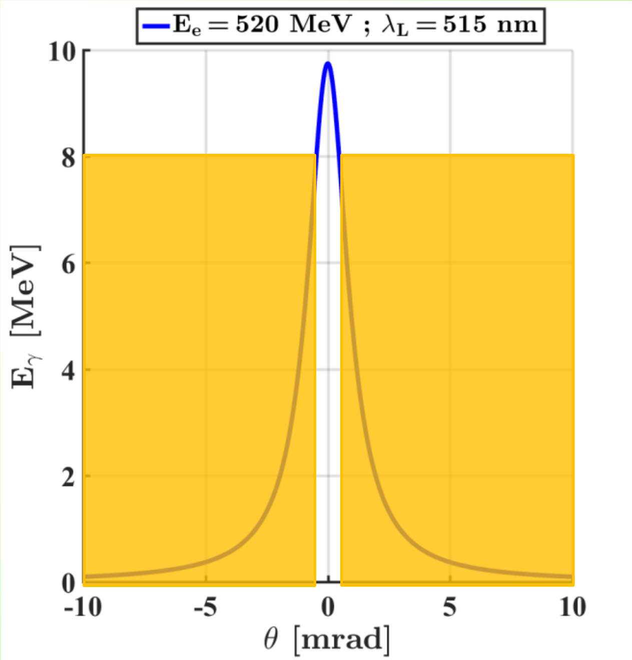
X-RAY PRODUCTION: COMPTON SCATTERING

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

- Compton Scattering = X-ray production
- "Collimation" = energy selection
- Energy tuning = electron energy

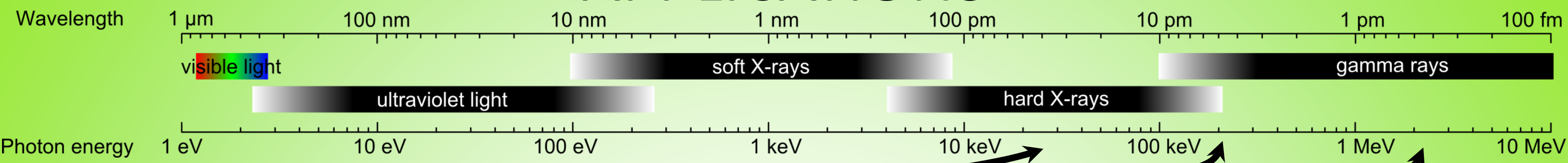
Scheme of Compton Scattering





Angular Correlation

APPLICATIONS



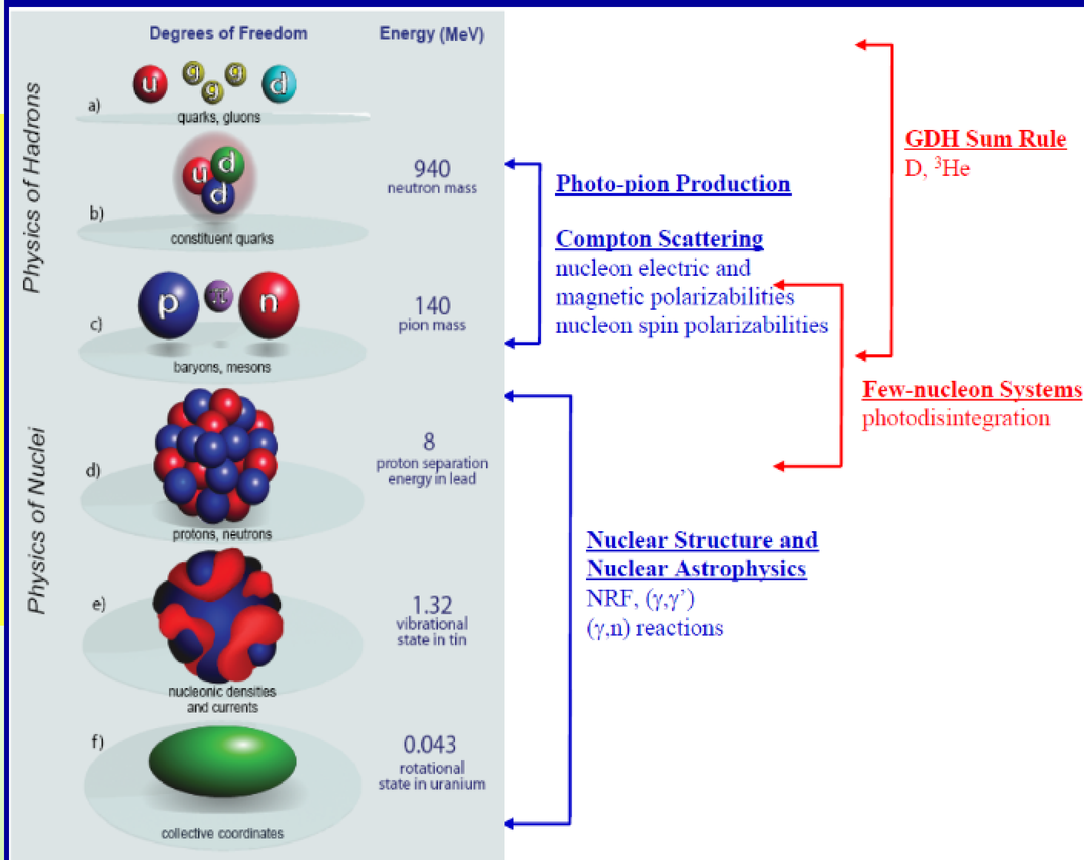
X-ray Imaging

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

Radiotherapy

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

Nuclear Physics



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

LASER BEAM CIRCULATOR (ELI-NP PROJECT)

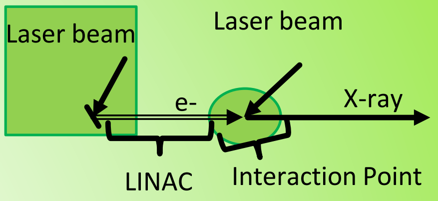
Nuclear Physics

ELI-NP GAMMA BEAM SOURCE

Extreme Light Infrastructure = European Research program

X-ray beam properties:

- X-ray energies: 0.2 – 19.5 MeV
- **X-ray relative bandwidth: <0.5%**
- **Flux: > 10^{10} ph/s**
- Linear Polarization: >95%



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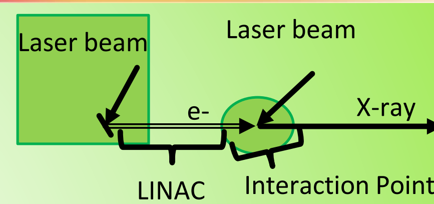

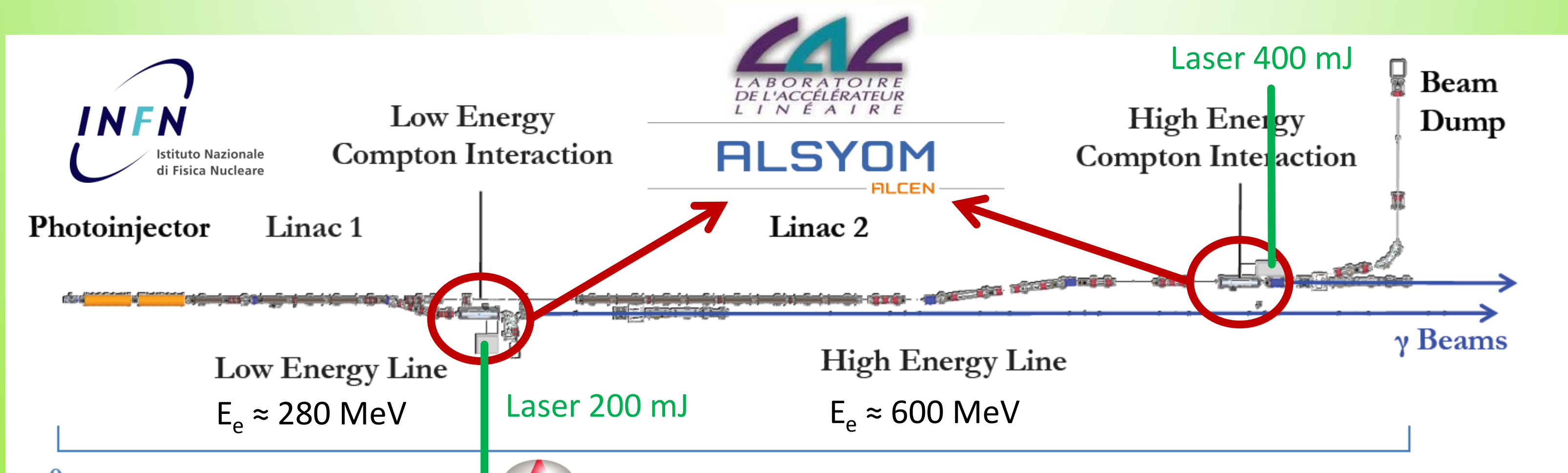

Scheme of ELI-NP-GBS

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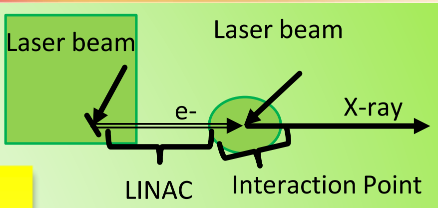
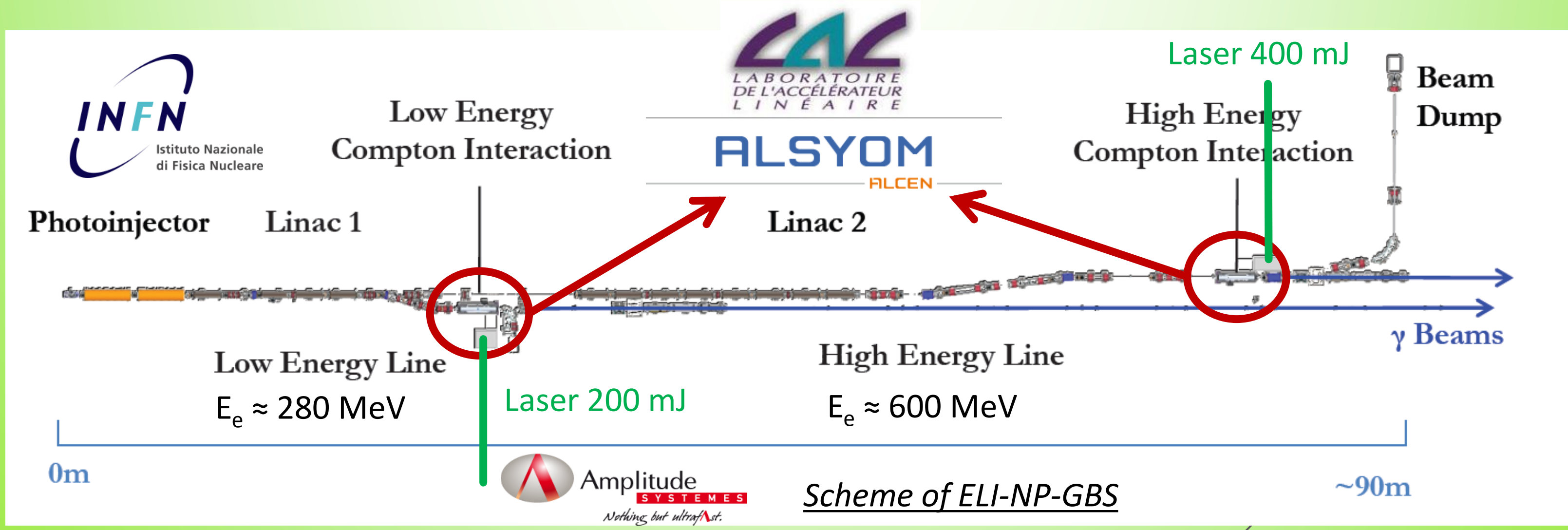


Technological challenges:
➔ synchronization < 500 fs
➔ 32 e- bunches @100Hz

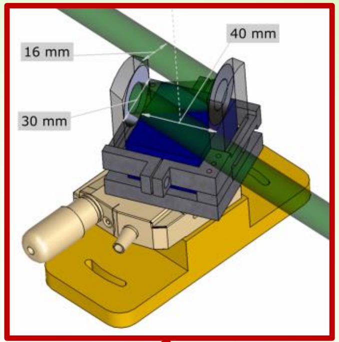


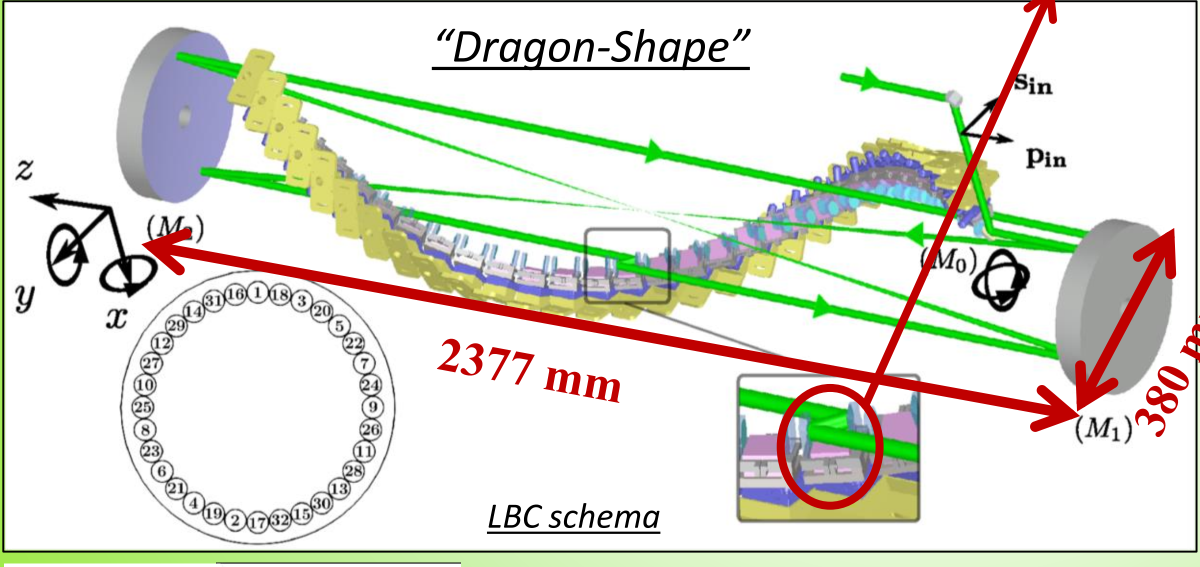
Scheme of ELI-NP-GBS

INTERACTION POINT (LBC)

Properties:

- Unique interaction point laser-electron beams
- Constant crossing angle (low spectral width)
- No optical aberrations (2 parabolic mirrors)
- 32 passes of 1 laser pulse (laser power x32)





LBC schema

Parameters	Value
Nb of passes	32
Crossing angle	8°
Corona radius	166.2 mm
Waist size	28.3 µm
Laser Energy / pulse	400 mJ
Pulse duration	3.5 ps
F_{rep}	100 Hz
Equivalent Power	1.28 KW

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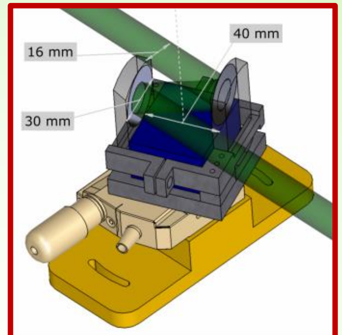
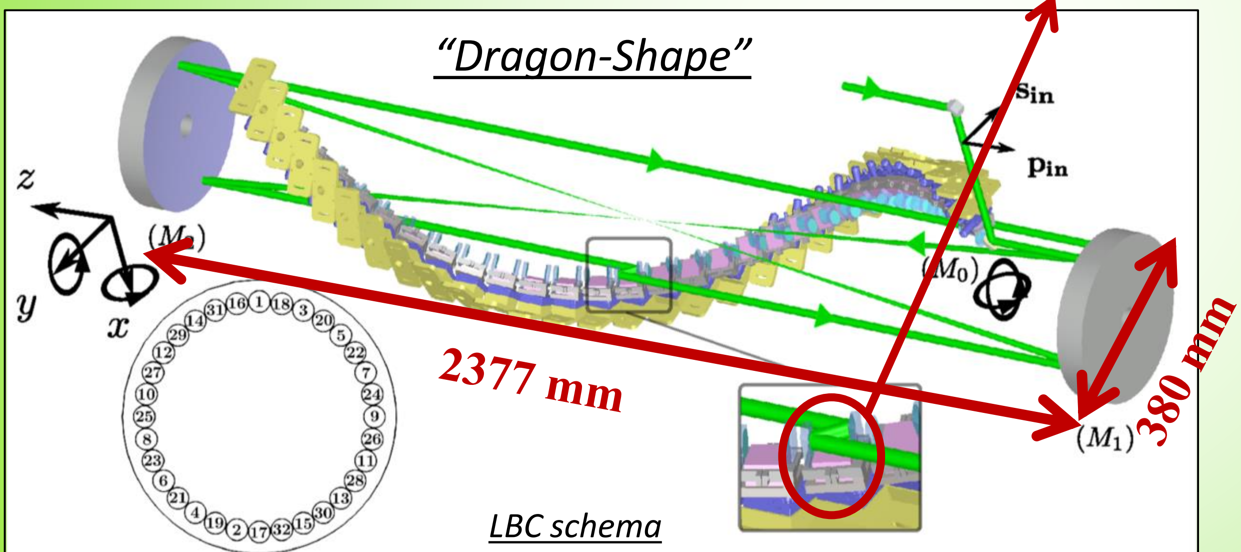


Constraints:
- Alignment < few µm/µrad
- Synchronization ~100 fs
- LBC propagation length ~150m
- Surface defects < few nm



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Laboratoire Charles Fabry INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech — LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE — Amplitude SYSTEMES Nothing but ultrafast. — ALSYOM ALCEN

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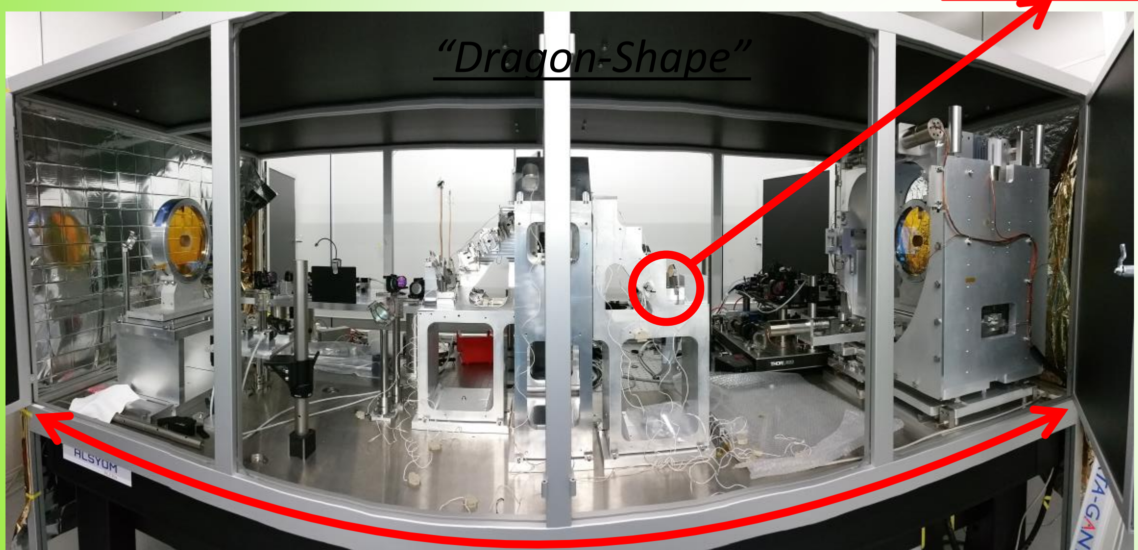

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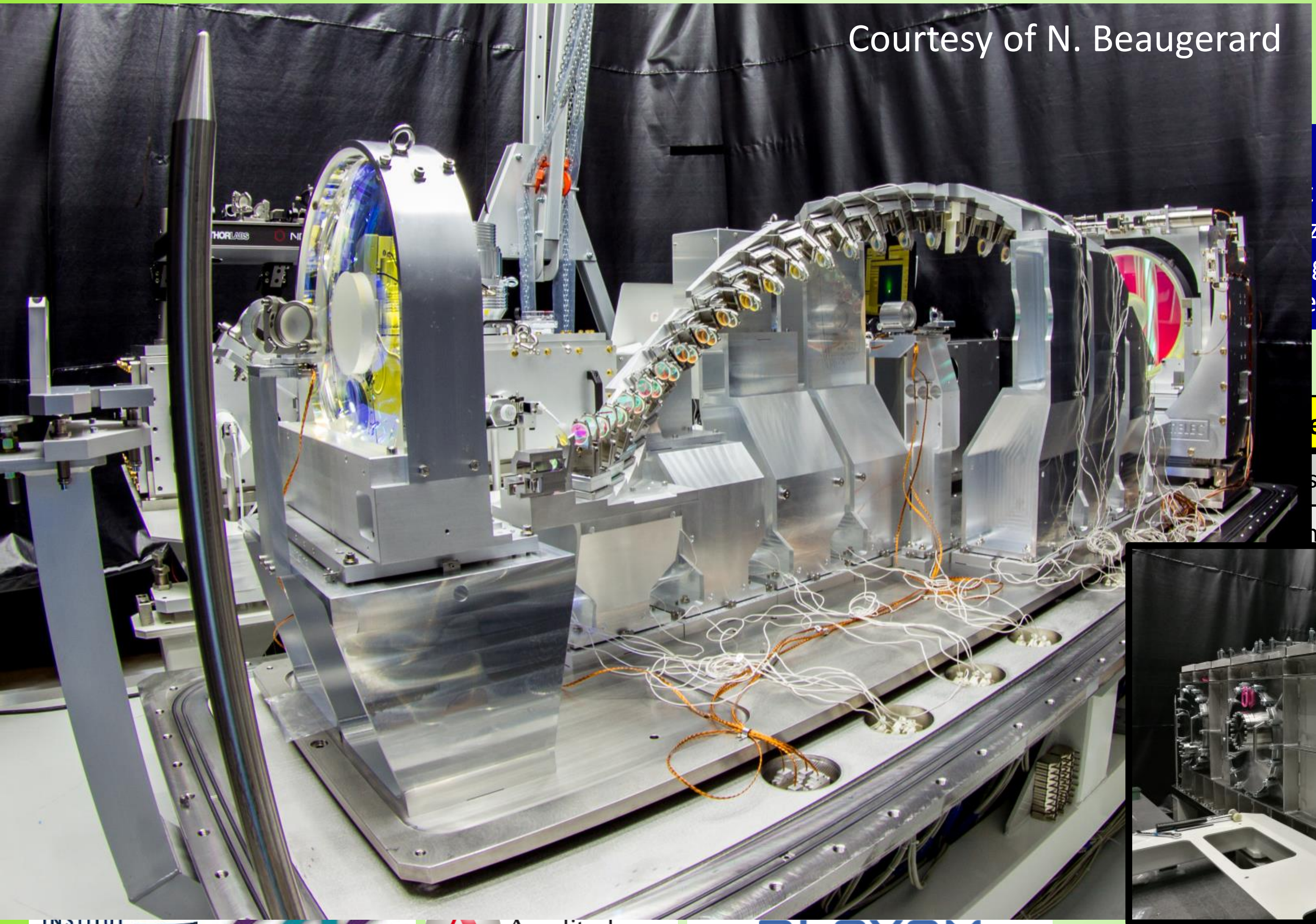
INTERACTION POINT (LBC)



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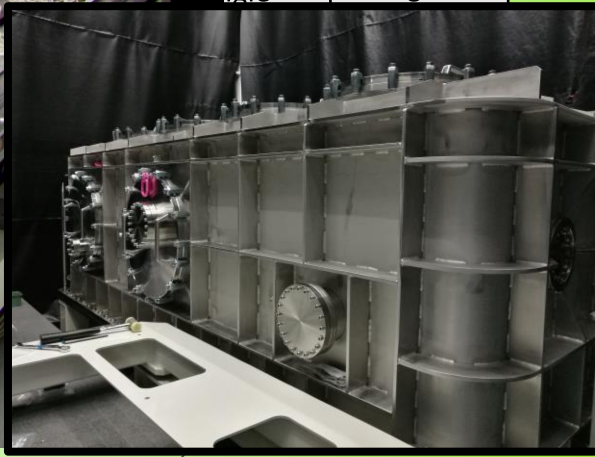

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Amplitude
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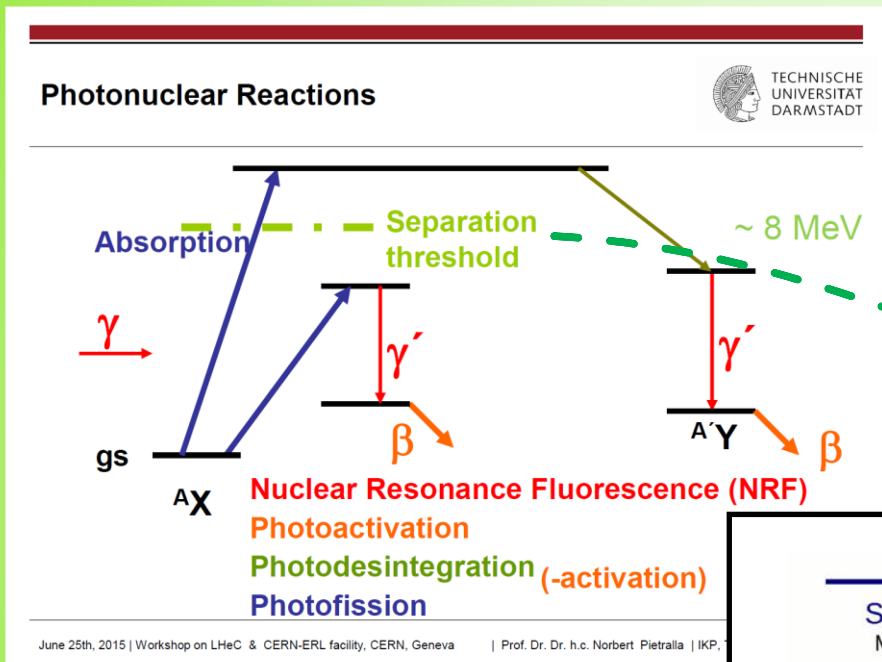
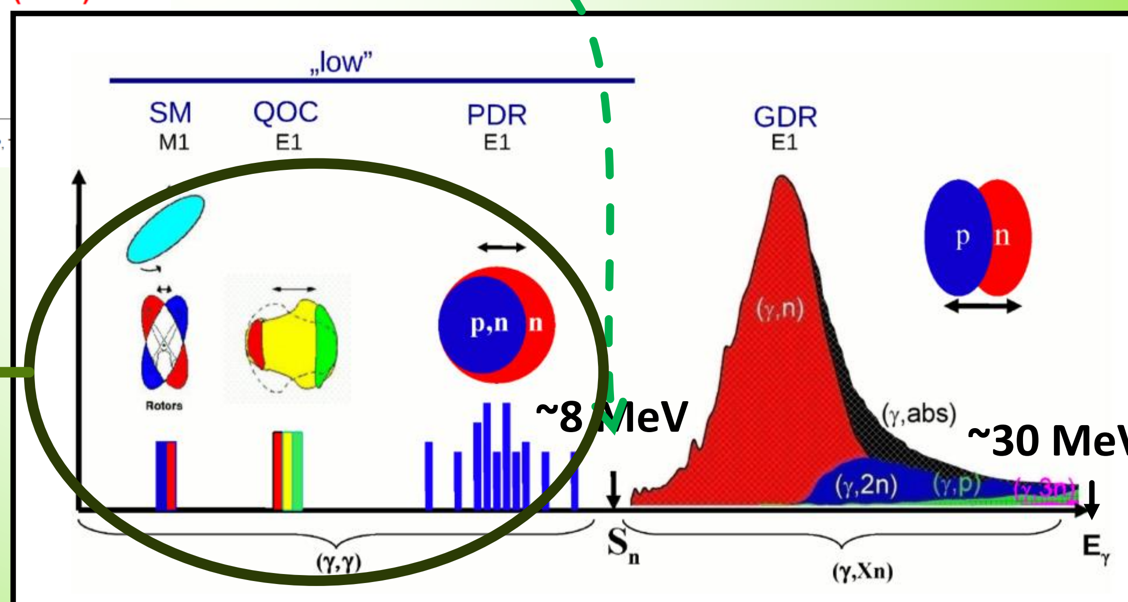
ALSYOM
ALCEN

X-RAY APPLICATIONS



X-ray beam specifications:

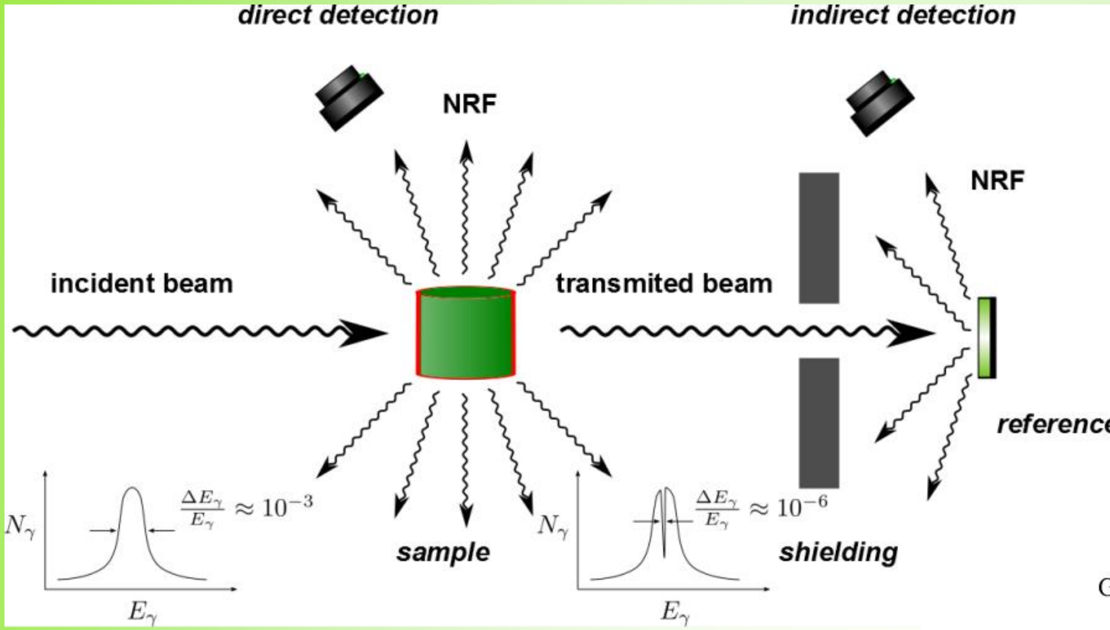
- Energies: 0,2 – 19,5 MeV
- Bandwidth (ΔE/E) : <0.5%
- Spectral density (TASD) : >5000 γ/(s.eV)
- Linear polarization: >95% + switching



AIP Conference Proceedings 1462, 177 (2012)

NUCLEAR RESONANCE FLUORESCENCE

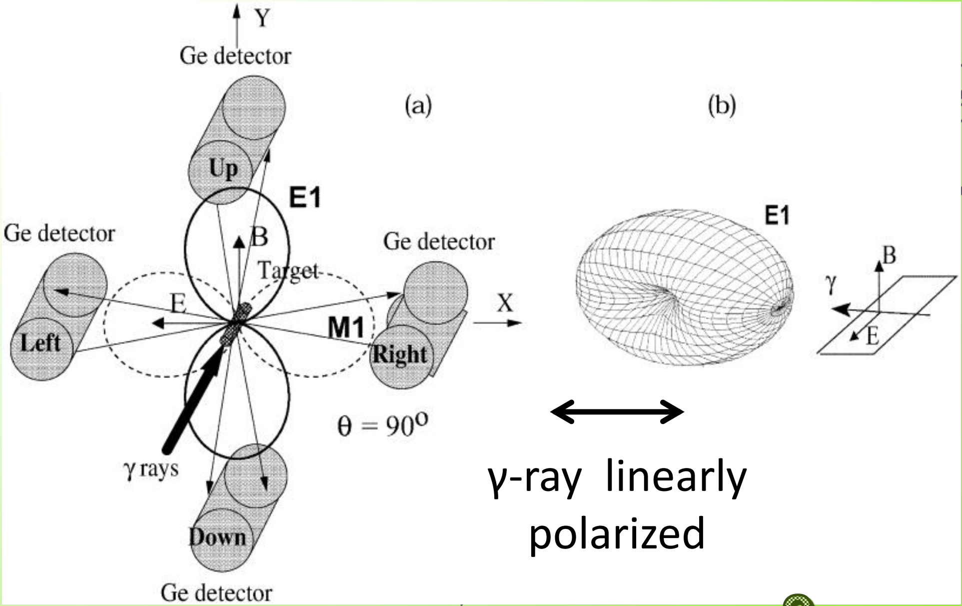
Material detection



➔**Require small bandwidth = Quasi-monochromaticity**

Parity measurement

➔ **Require polarized X-ray**



NIM A 507 (2003) 527–536

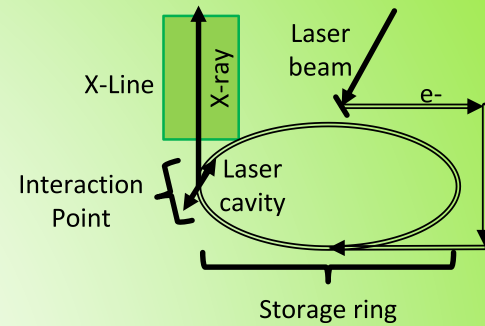
STANDARD RESONANT CAVITY (THOMX PROJECT)

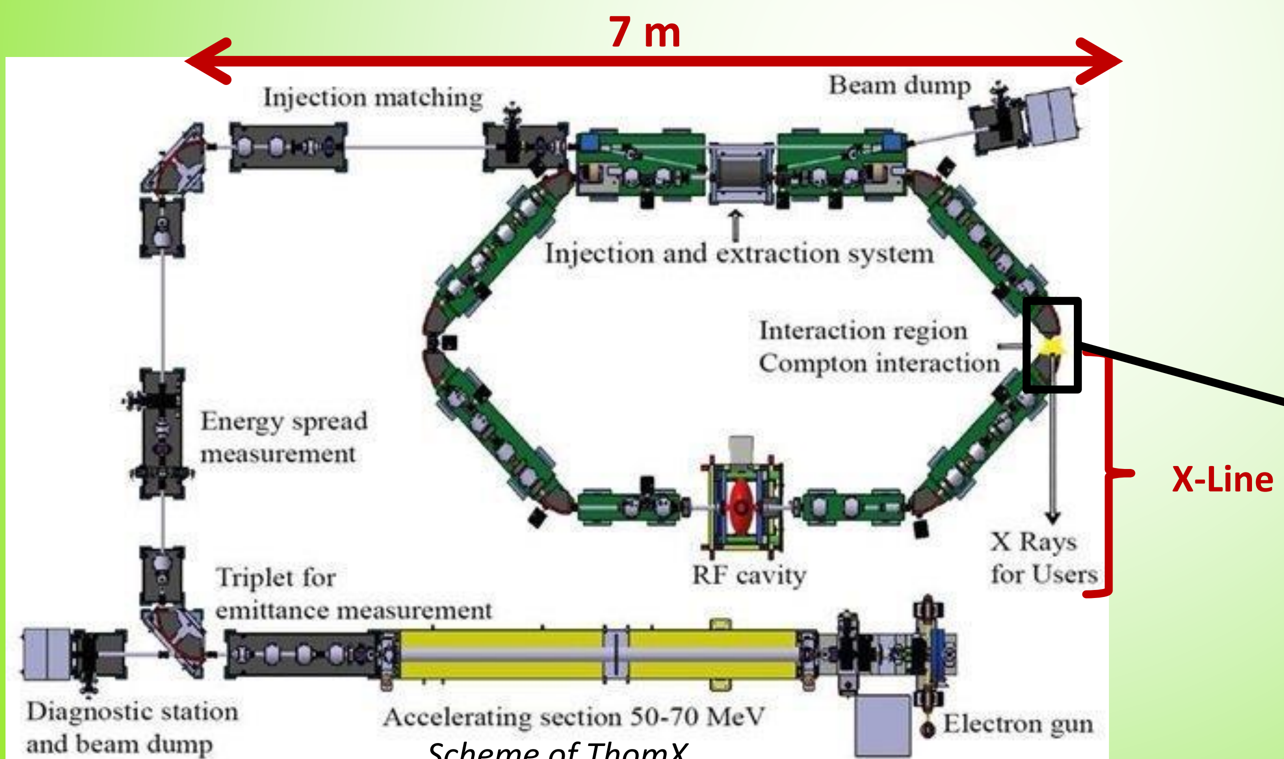
X-ray Imaging (museology, medical, material, …)

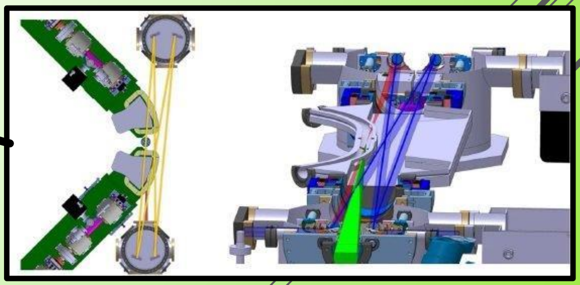
THOMX

X-ray beam properties:

- X-ray energies: 45 – 90 KeV
- X-ray relative bandwidth: 1 - 10%
- **Flux: 10^{11} - 10^{13} ph/s**
- **Brilliance : 10^{11} ph/(s.mm^2.mrad^2) in 0.1% BW**







Scheme of ThomX

THOMX

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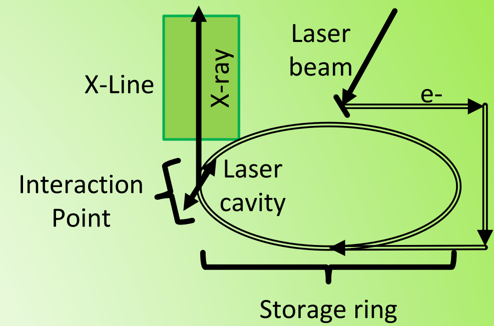
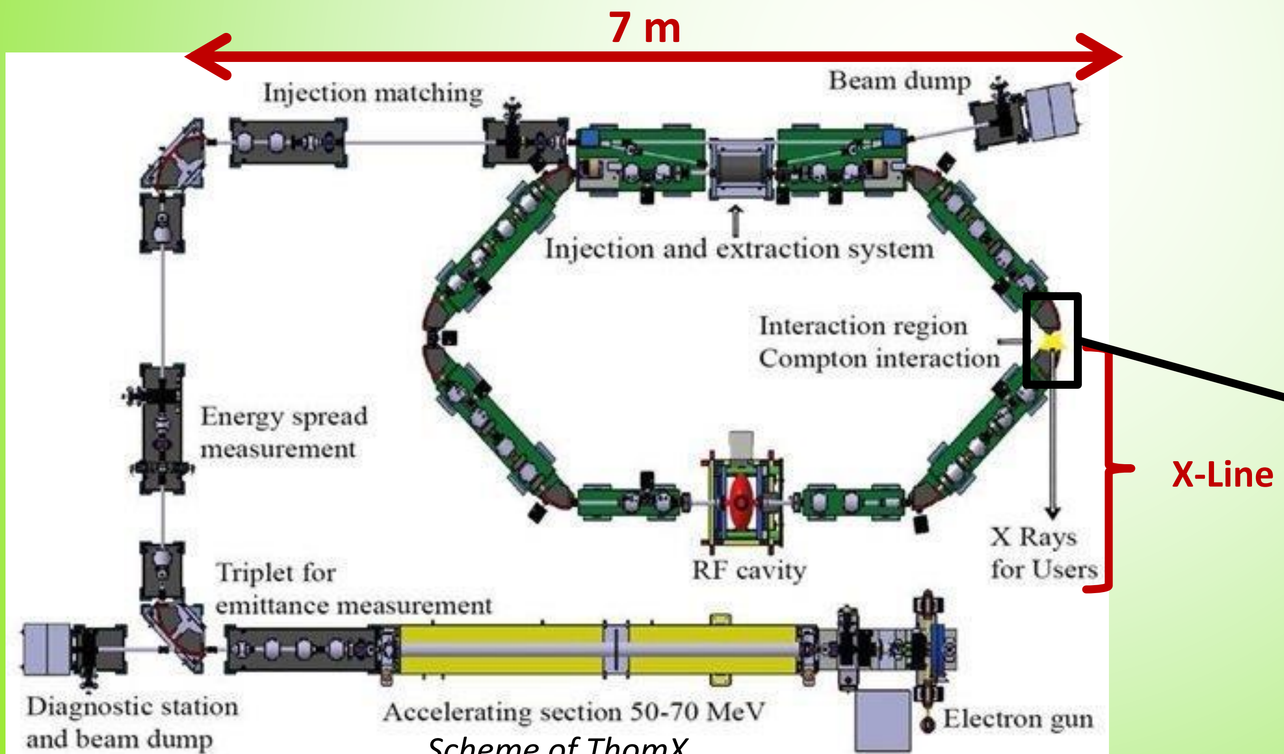
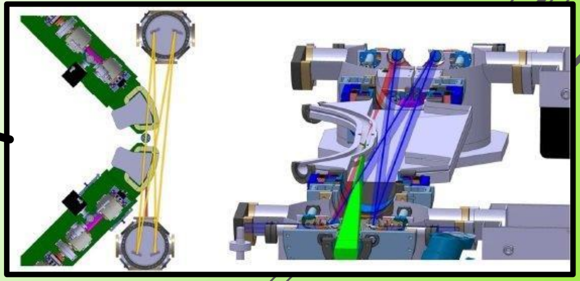


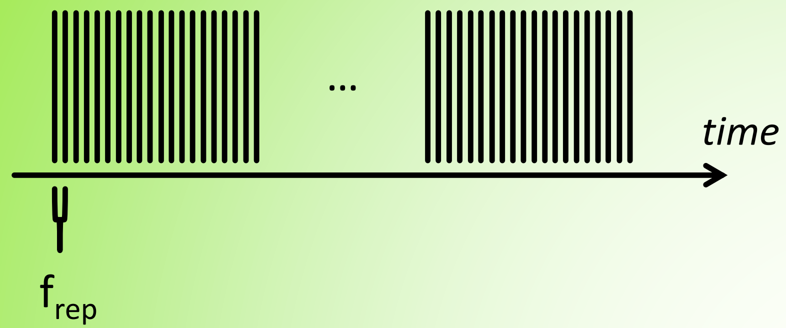
Technological challenges:
➔ Low energies ring
➔ Cavity Power

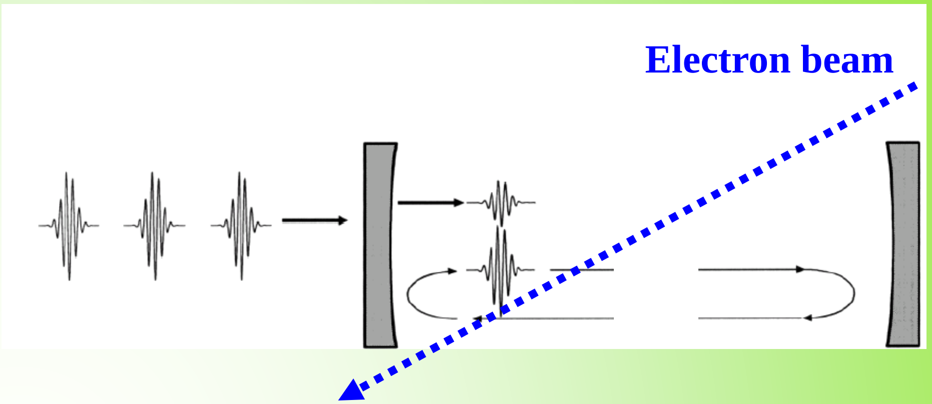




Scheme of ThomX

OPTICAL CAVITY





Gain = $\frac{\langle \boldsymbol{Power\ stacked} \rangle}{\langle \boldsymbol{Power\ injected} \rangle}$ = $\frac{\boldsymbol{Finess}}{\boldsymbol{\pi}}$

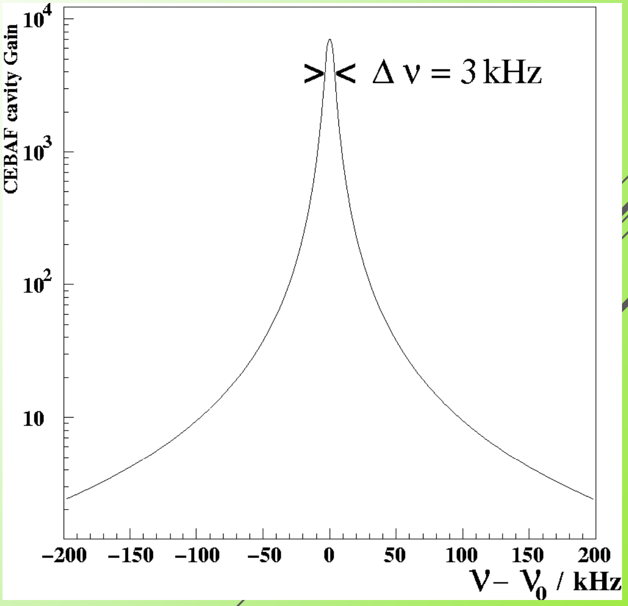
High power enhancement factor reachable in permanent regime

➔ G~10 000 for the ThomX project

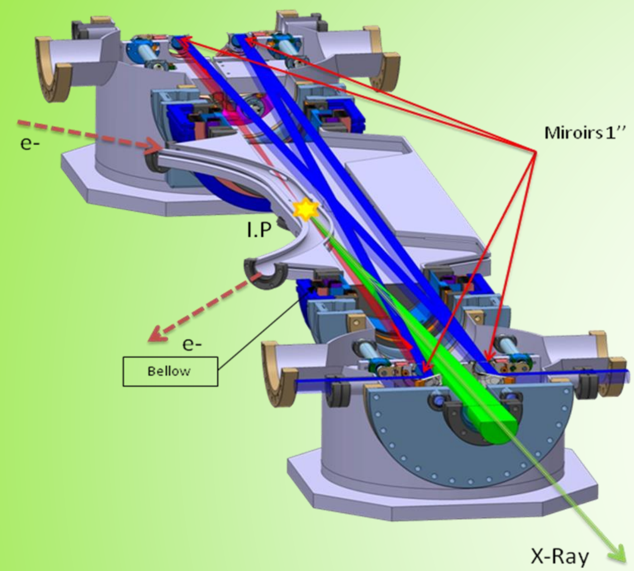
Efficient with Storage ring

➔But laser frequency control at $\frac{\partial \nu}{\nu} \sim 10^{-11}$ for 'high finesse'

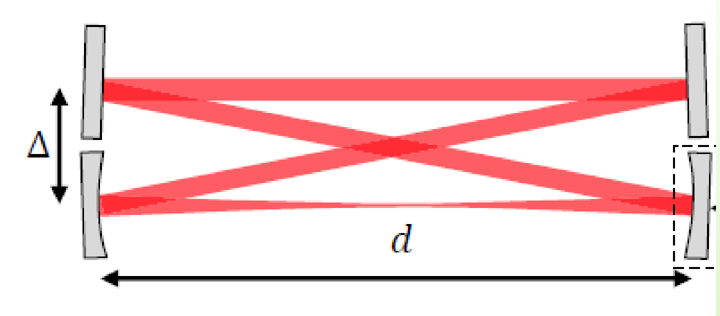
➔Implementation of metrological techniques in accelerator environment



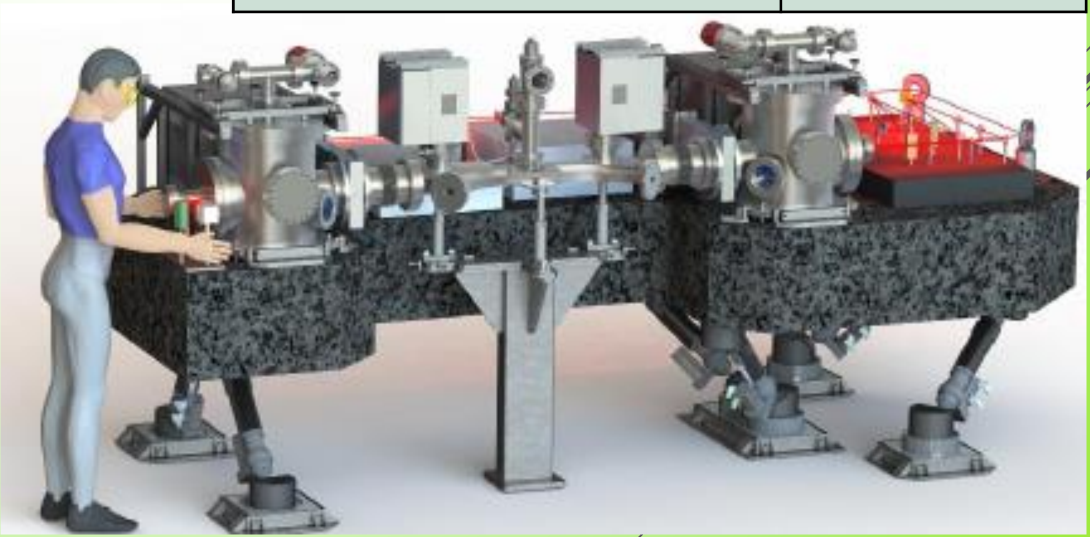
THOMX CAVITY



Parameters	Typical values
Laser repetition frequency	33.3 MHz
Laser wavelength	1031 nm
Cavity optical length	8.994 m
Cavity finesse	30 000
Cavity waist size	70 µm
Injected power	150 W
Circulating power	~600 kW



(a) Standard bow-tie (SBT) cavity

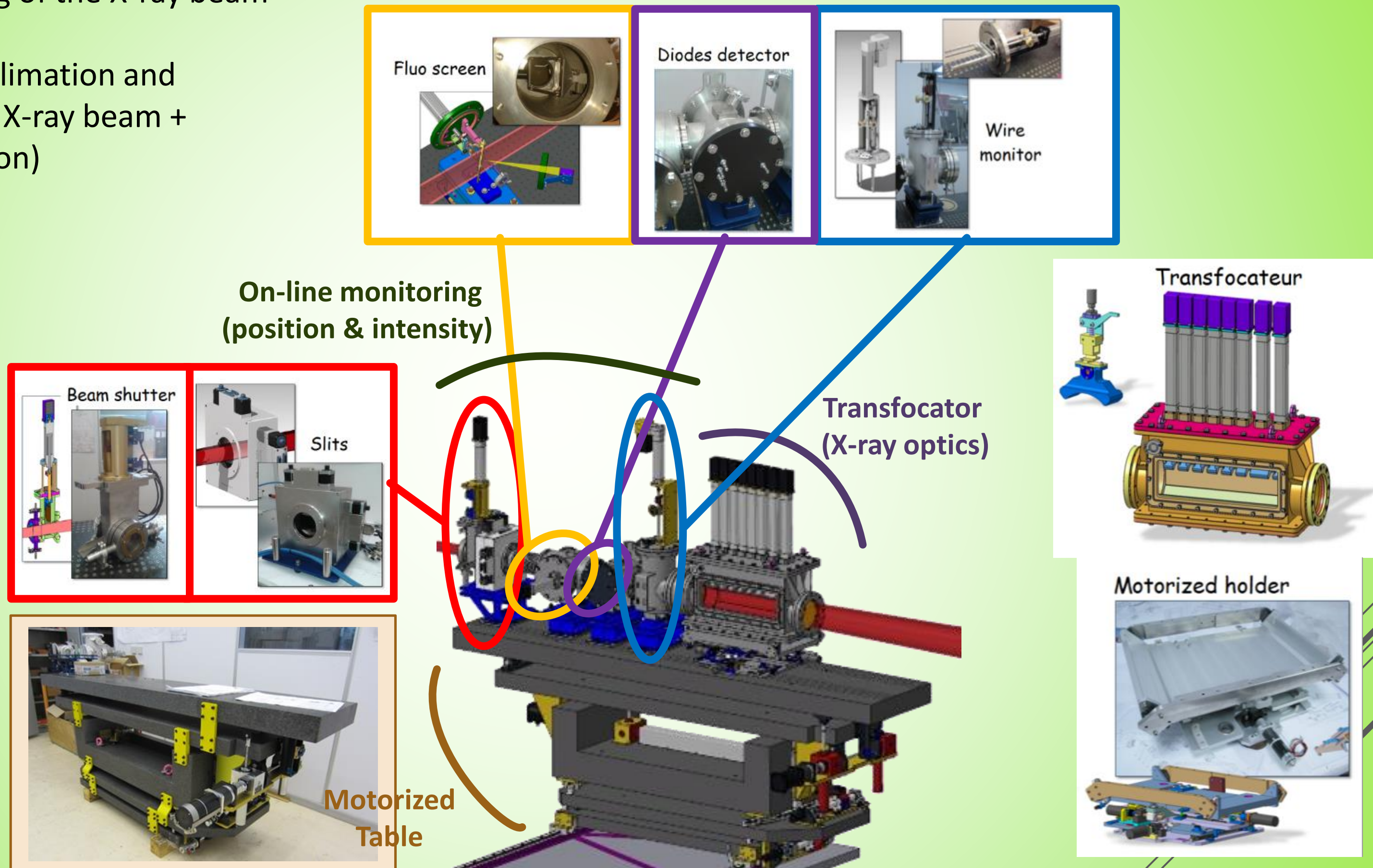


➔ Laser oscillator rep. rate & CEP locking

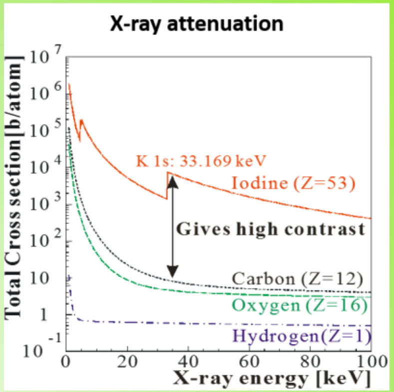
X-RAY LINE

Goals:

- On-line monitoring of the X-ray beam
- Beam shaping (collimation and focalization of the X-ray beam + bandwidth selection)

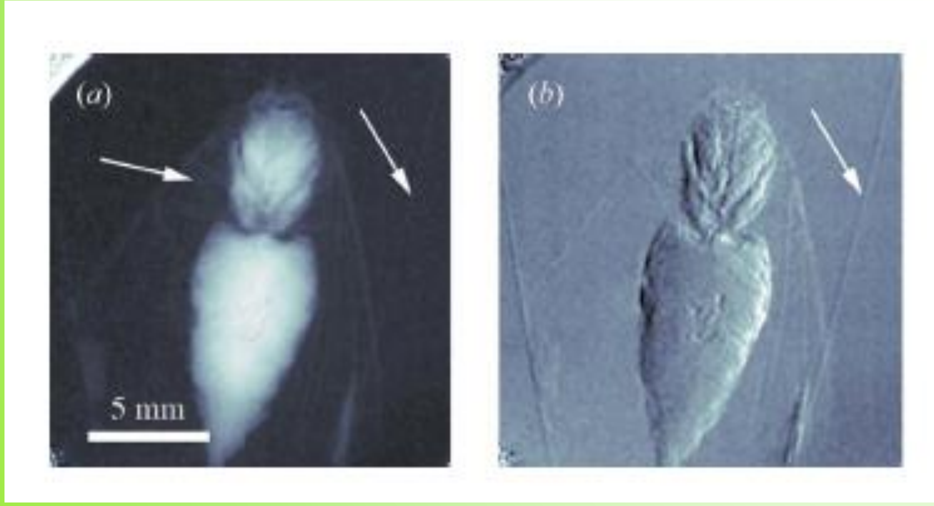


APPLICATIONS



PHASE CONTRAST

- 1st Phase contrast image at Lyncean CLS (Proof of principle, but long acquisition time, high dose, not soft tissues …)



standard absorption phase-contrast

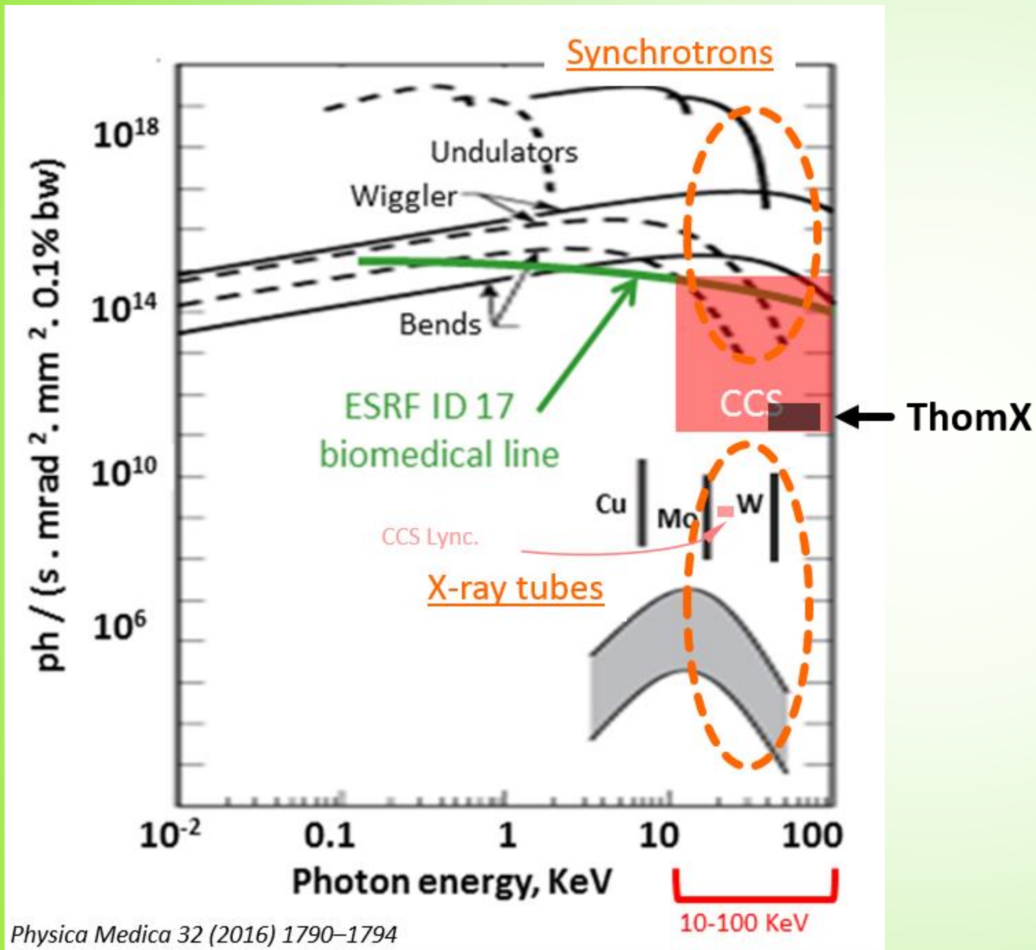
[Synch. Rad. 16, 2009, 43-47]

K-EDGE

- Heavy chimical elements are contained in painting pigments (Pb➔white, Hg➔ vermillion…) **Characterised by K absorption edges**

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

THOMX VS OTHER X-RAY SOURCES



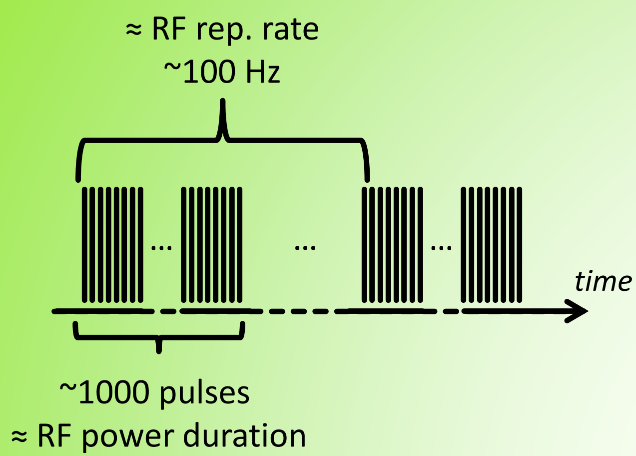
How To Go Further (more brilliance):

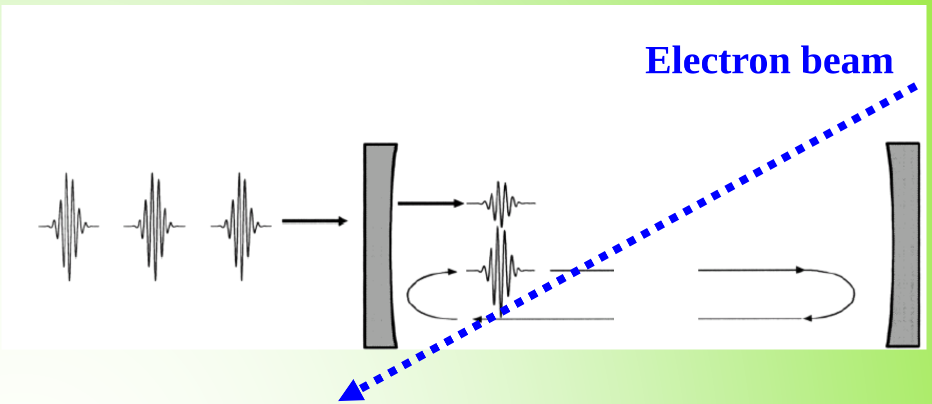
- More X-ray Power:
  - **↑ Rep. Rate**
  - ↑ e- beam charge (current)
  - **↑ laser power**
- Less X-ray bandwidth:
  - ↓ e- beam emittance
- Smaller source spot:
  - ↓ laser beam waist size ➔ ↑ beam size on mirrors
  - ↓ e- beam size

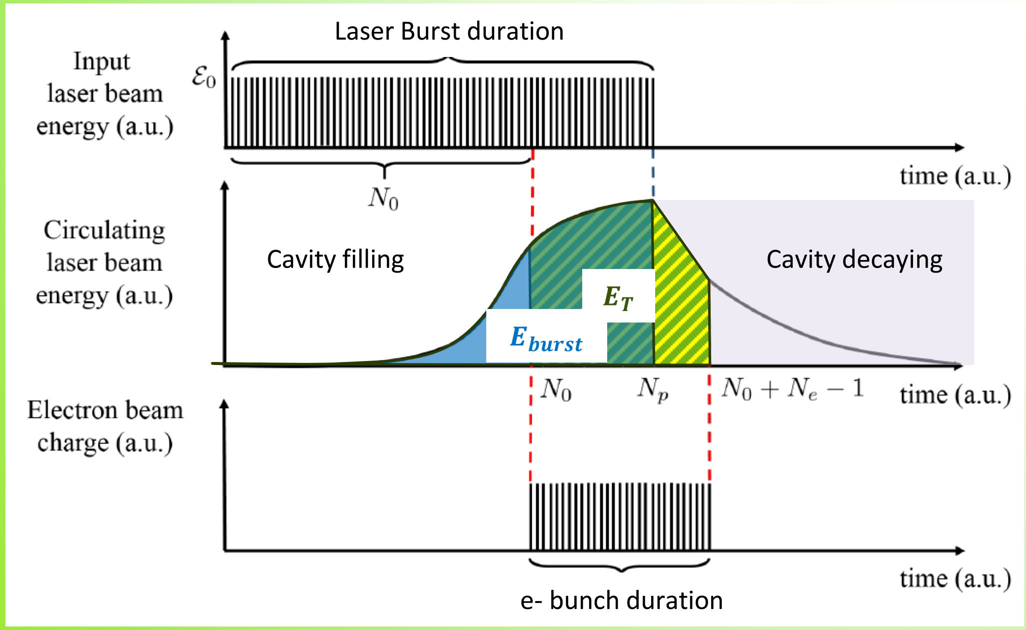
RESONANT BURST CAVITY (FUTURE PROJECT)

X-ray Imaging (medical, material, …)

OPTICAL CAVITY (THEORY)







$$g_{eff} = \frac{E_T}{E_{burst}}$$

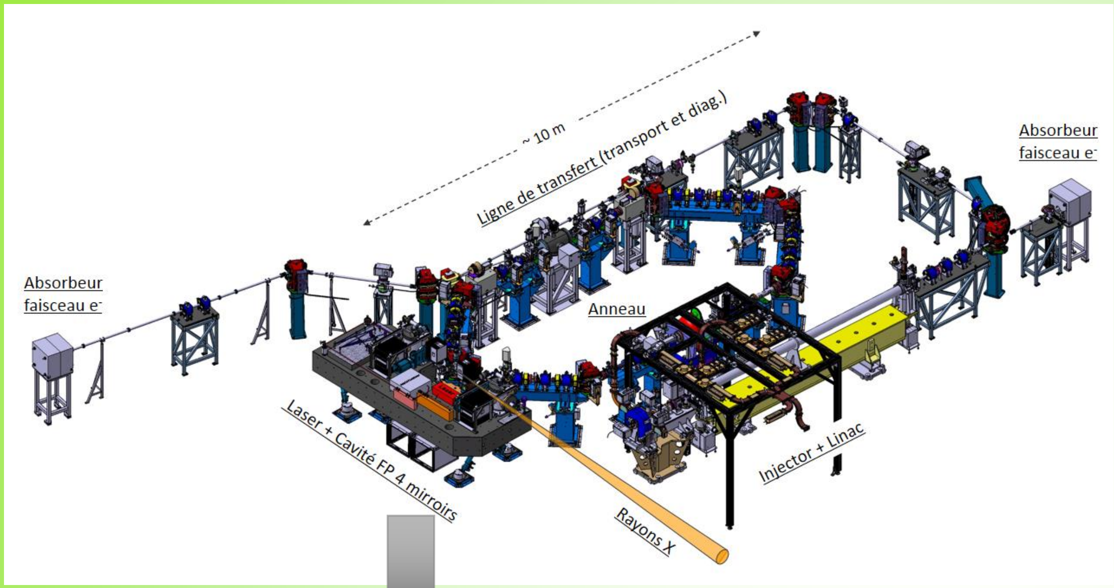
Efficient with linac (low f_{rep}) in burst mode

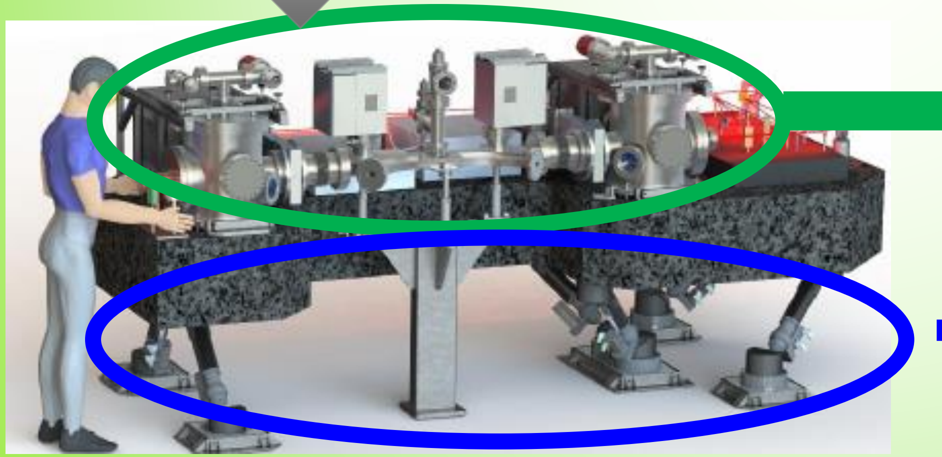
➔But cavity have to be maintained at resonance

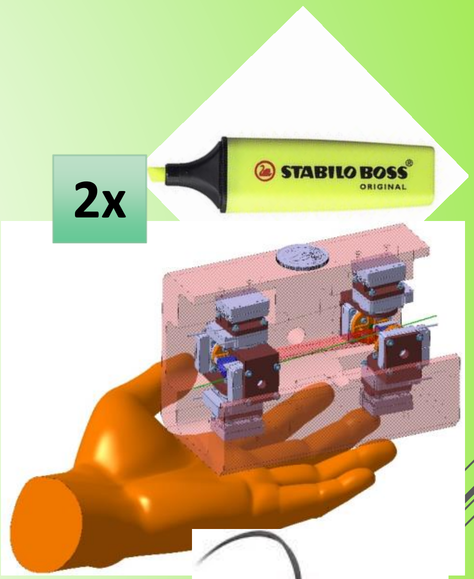
➔Bunch spacing ~GHz ➔ small optical cavity (few 10's cm)

➔Implementation of advanced technics for locking

COMPARISON WITH THOMX





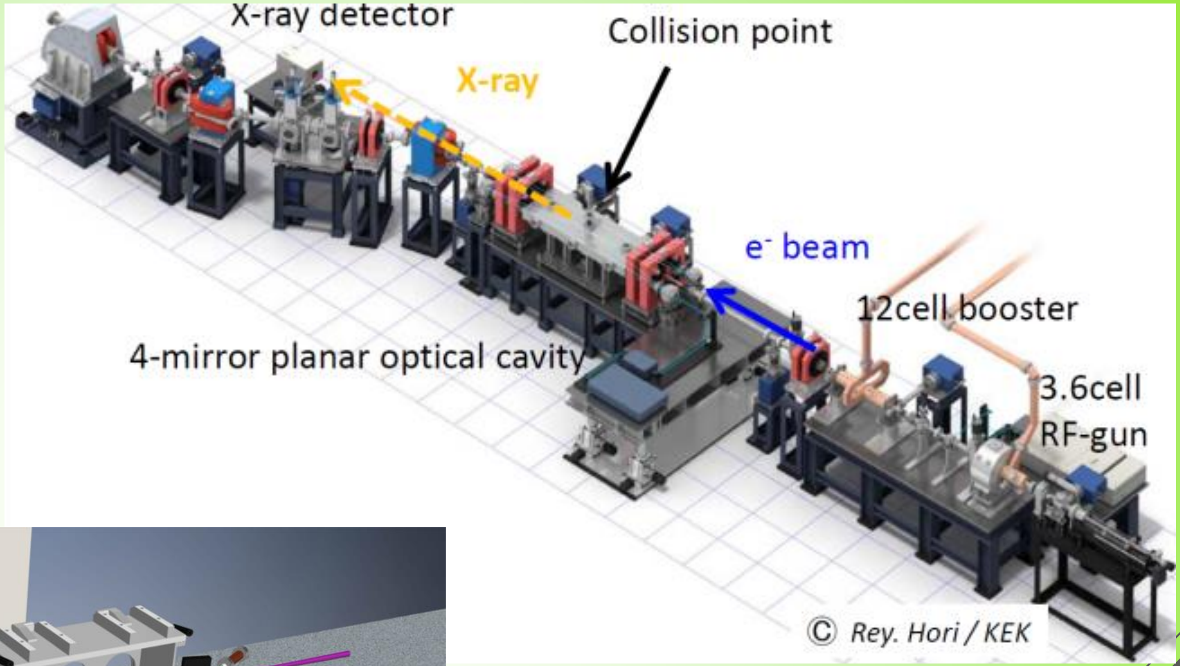


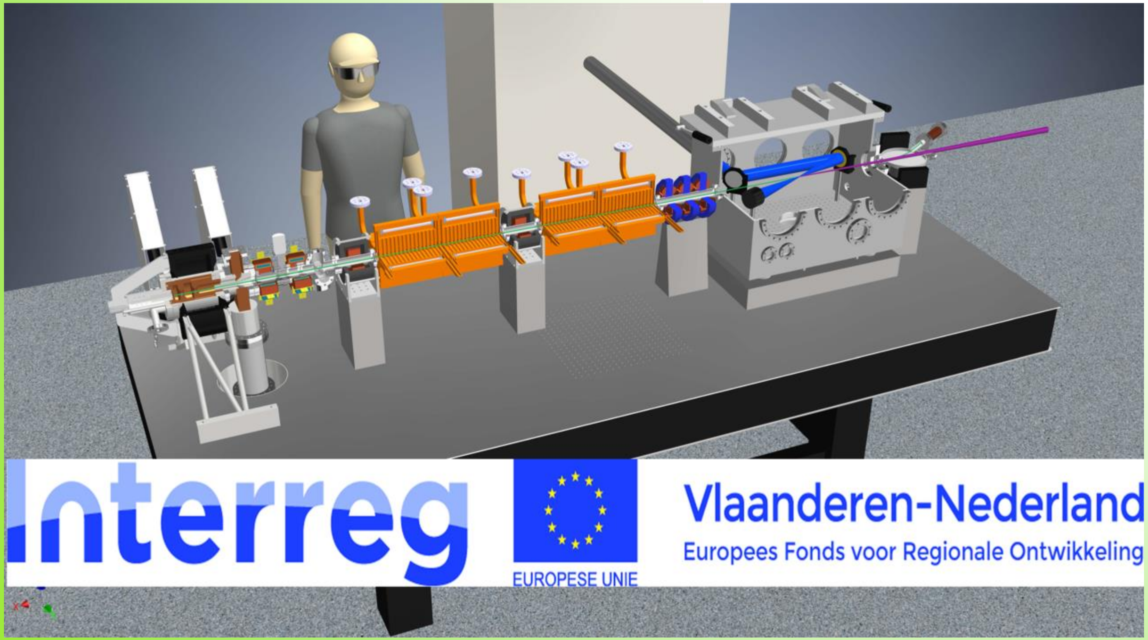
POSSIBLE IMPLEMENTATION

e.g.: 2 existing projects

LUCX (LASER UNDULATOR COMPACT X-RAY). Japan project at KEK

➔Already with burst cavity





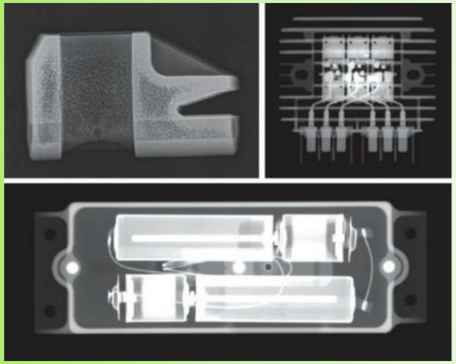
Smart*Light: a Dutch table-top synchrotron light source. European Dutch project

➔ adapted for burst cavity

APPLICATIONS

X-RAY FOR MATERIAL INSPECTION

- Material inspection in lab (electronics, mechanical part, etc.)



“Inspecting Plastics and Electronics with Conventional X-ray”, NDT, June 2016

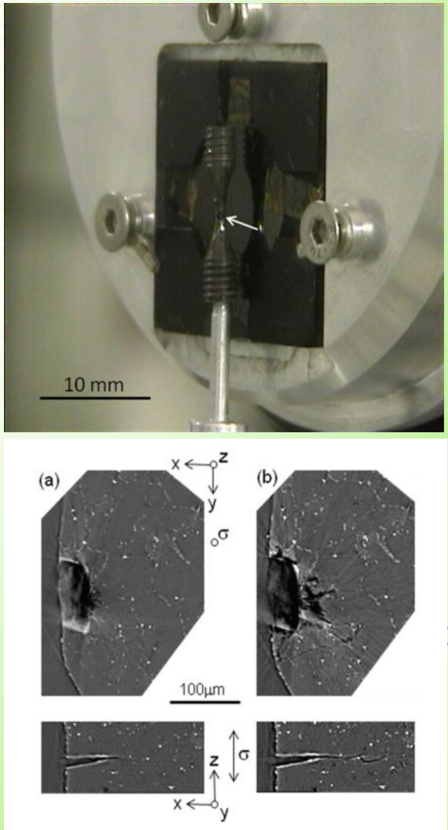
https://www.labtesting.com/wp-content/uploads/2012/08/xray_inspection.jpg

- FUTUR (Dream) = material inspection in situ (gantry)

https://www.par.com/technologies/non-destructive-testing/radiography/

X-RAY FOR MATERIAL SCIENCES

- Cracks evolution, 3D printing material properties (porosity, etc.)



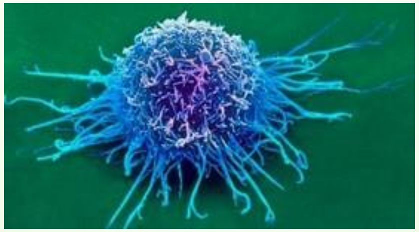
King Andrew, Wolfgang Ludwig, Michael Herbig, Jean-Yves Buffière, T.J Marrow, et al.. Threedimensional in situ observations of short fatigue crack growth in magnesium. Acta Materialia, Elsevier, 2011, 59, pp.6761-6771.

X-RAY FOR MEDICAL IMAGING

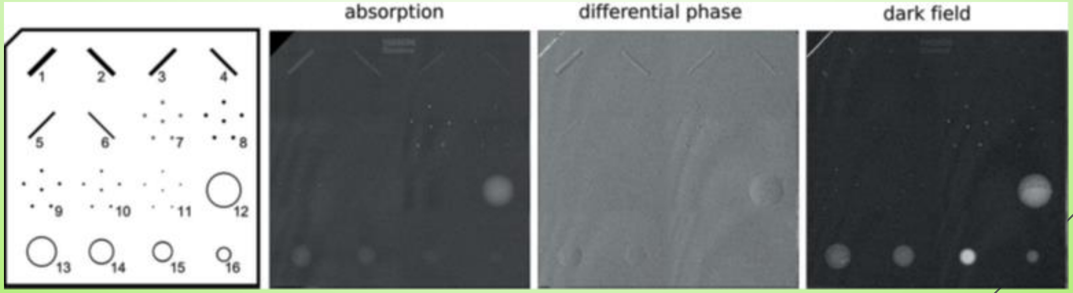
- **E.g. mammography:**
  - **High contrast (monochromaticity and small source size)**
  - **Wide beam (Compton scattering is broad angle)**

- ThomX is a demonstrator: but to low X-ray flux ➔ to much dose

➔ Burst cavity can reach the desire flux



Cancer cell of "thistle" type



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

OPTICAL SYSTEMS *BY LAL*

LAL-made for HERA/Hambourg 2003

LAL-made for ATF KEK/Japon MightyLaser ANR 2010-2013

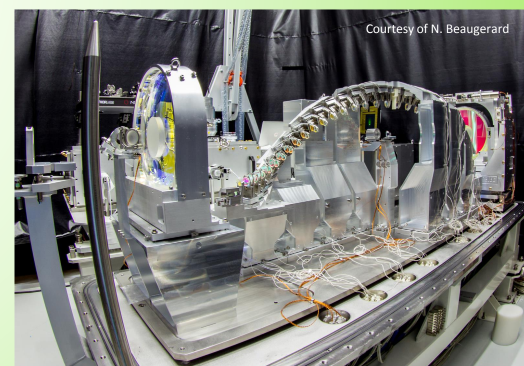
LAL-made for ThomX EQUIPEX 2016-

LAL-made mini-cavity (2017)

Smallest

Size scaling (few cm to few m)

Biggest



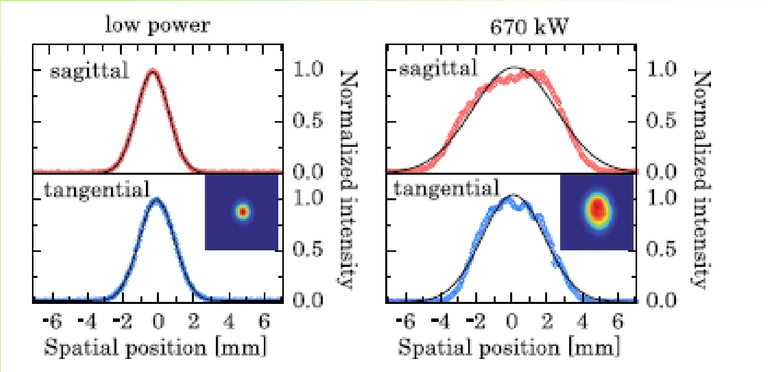
LAL-design ELI-NP-GBS European project (2013 -)

THANKS FOR YOUR ATTENTION

STORED POWER

STATE OF THE ART

- Cavity average power = **670kW@10ps ; 400kW@250fs**
- Laser + amplifier : 420W @ 250 MHz
- Cavity enhancement factor ~ 2000



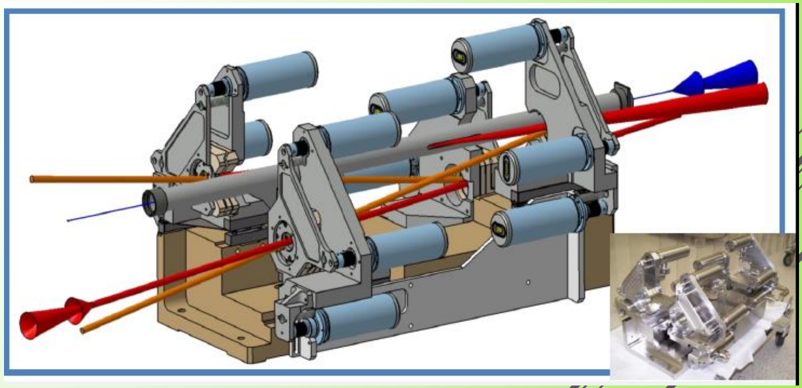
Carstens et al. Opt Lett 39 (2014) 2595

LAL RECORD

- 4-mirror high finesse cavity tested at KEK on ATF (1.3 GeV ring) 100kW
  French-Japanese collaboration

➔400kW stored power (at Lab)

- Mirror surfaces deformation
  ➔ runs with 200kW at most (stable)



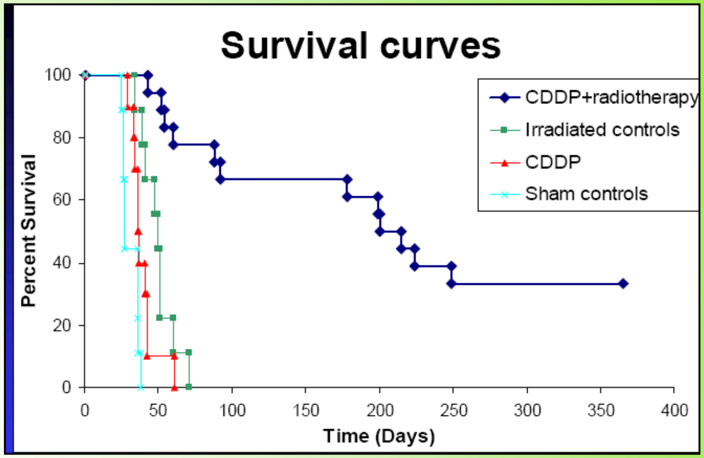
'Huge' average power can be stored inside the optical cavity
➔mirror thermoelastic deformations & damage

To further increase circulating power
➔ Reduce fluence on the mirrors

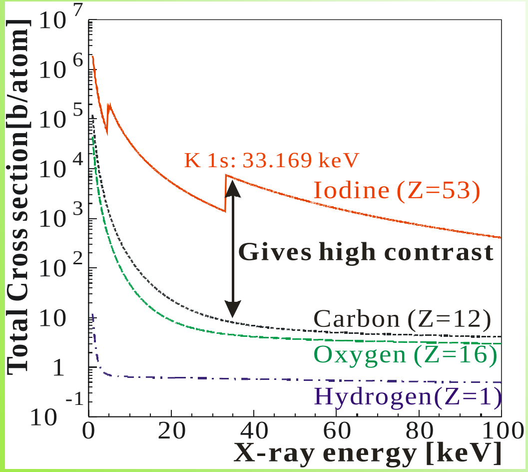
MEDICAL APPLICATION AS AT ESRF (ID17)

- **Search for glioblastoms therapy**
  - Locate platinum (cisplatine) inside tumor cells (rat brains)
  - Shoot with 78keV X-ray (platinum K-shell)
  - Observed ~700% increase of life time
  - Observed 34% survivals after 1 year …

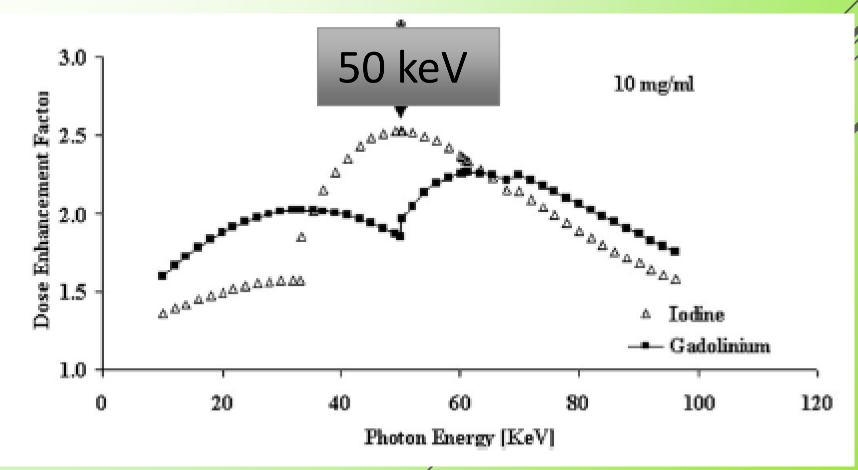
  (*Biston et al. Cancer reas.64(2004)2317)*



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



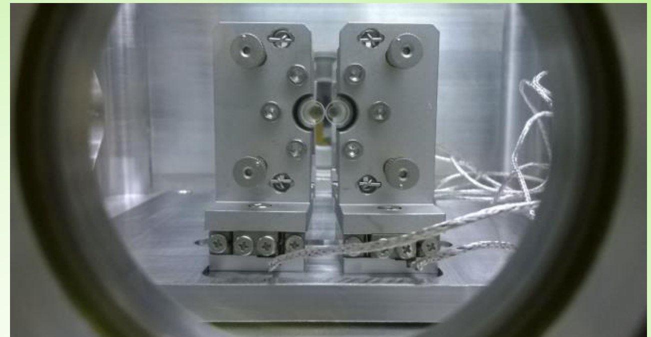
But
relative to
water absorption

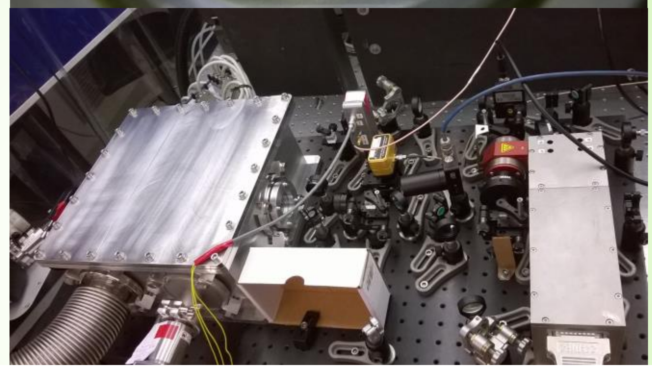


Adam et al Int.J.Rad.Onc.Biol. Phys.57(2003)1413

OPTICAL CAVITY (REALITY)

LAL-made cavity for MightyLaser ANR (2008-2012)





LAL-made mini-cavity (2017)