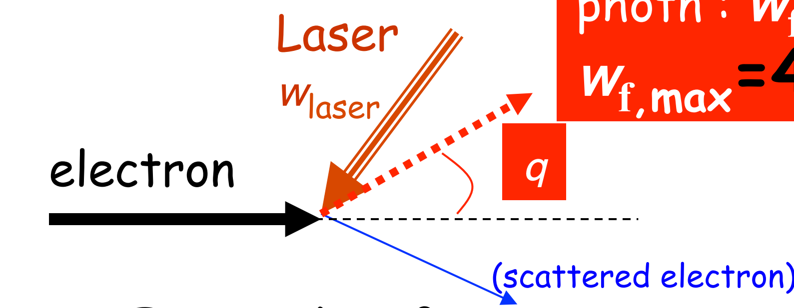
The compact X-ray source ThomX

- The machine
- Some technical issues (optics)
- Applications

- LAL (Laboratoire de l'Accélérateur Linéaire)
- SOLEIL (National Synchrotron facility)
- CELIA (Centre Lasers Intenses et Applications)
- Institut Néel
- UPMC-LAMS (Laboratoire d'Archéologie Moléculaire et Structurale)
- ESRF (European Synchrotron Radiation Facility)
- INSERM (Institut National de la Santé et de la Recherche Médicale)
- Thales TED (industrial partner)

Compton scattering applications



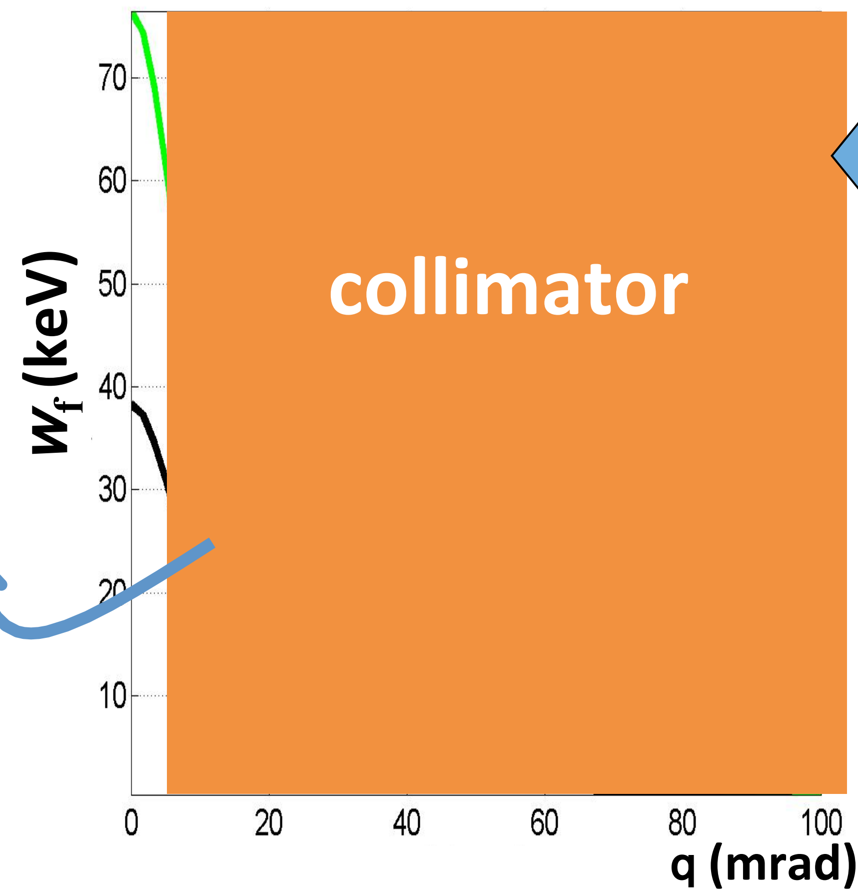
photn : w_f

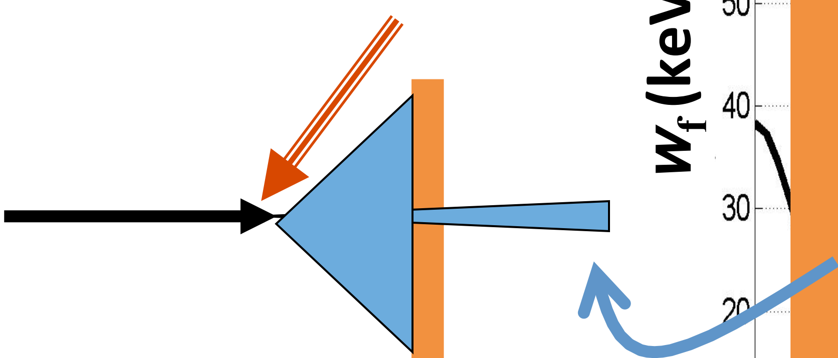
$w_{f,max}=4g^2 w_{laser}$

Compton scattering
Photon_laser+e→photon+e'
is a
2 body process → $w_f = f(q)$

$g=E_{electron}/m_e c^2$

PRL138(1965)B1546

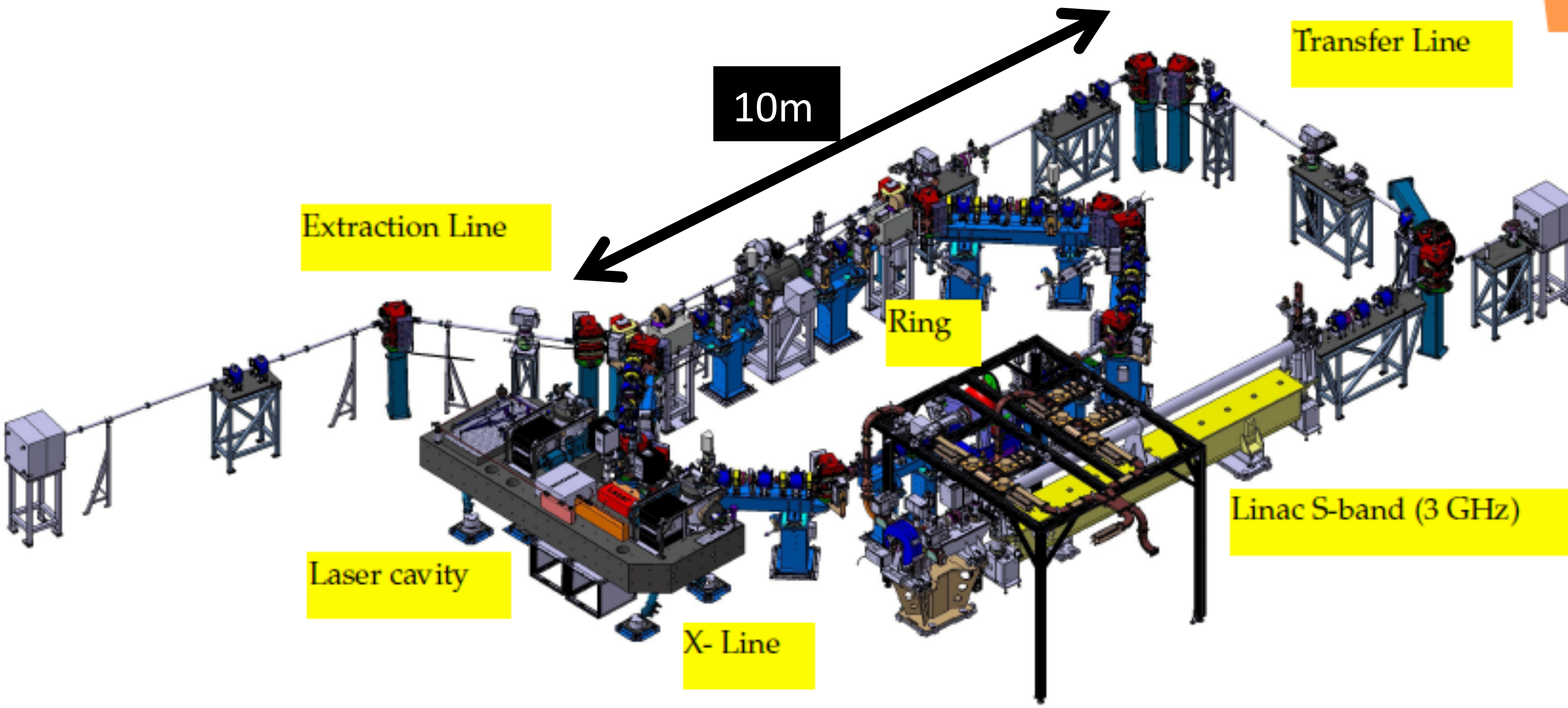




Quasi monochromatic X/gamma ray beam

See
P. Piot
G Paterno
talks

ThomX Accelerator Facility



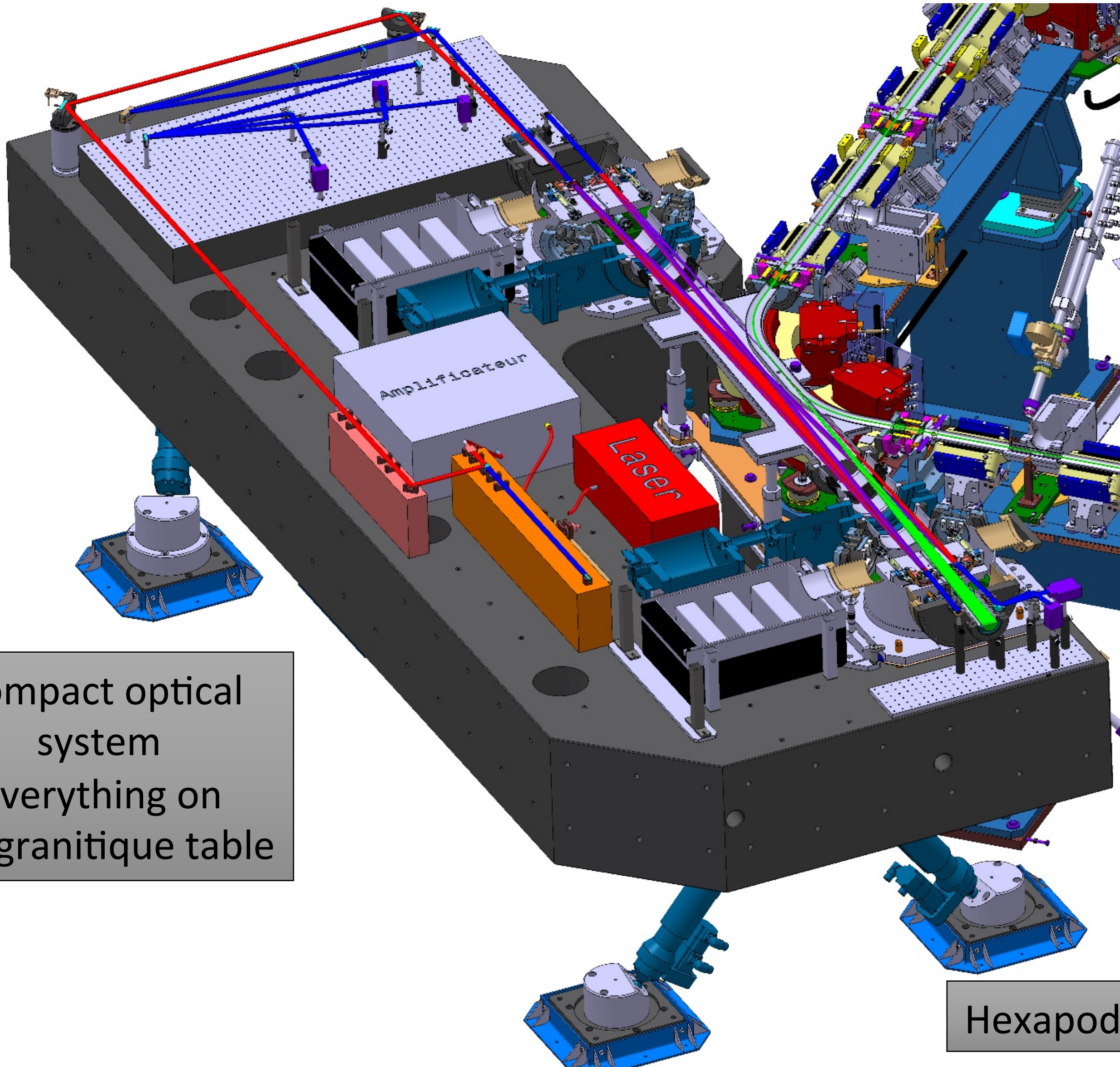
3 GHz gun and linac delivering 1 bunch of 1 nC every 20 ms (50 Hz)

The bunch is stored in a compact ring (Rev freq ~ 17 Mhz)

An Fabry-Perot cavity to store the laser pulse (max ~ 20 mJ) @33MHz

Up to 10^{13} photons / s (photon max energy of 90 keV)

The optical cavity & Compton Interaction point



Compact optical system
Everything on the granitique table

Hexapode feets

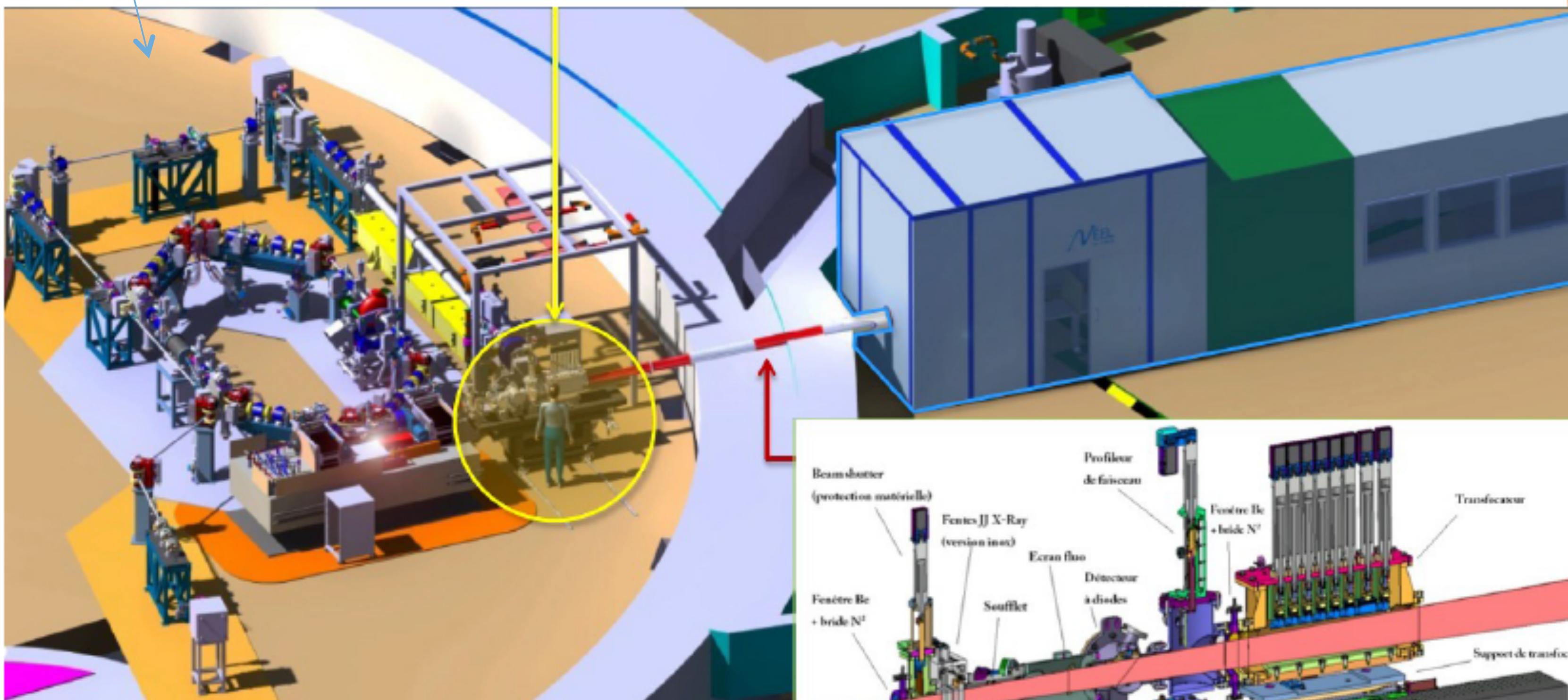
Located in the old LURE igloo at Orsay

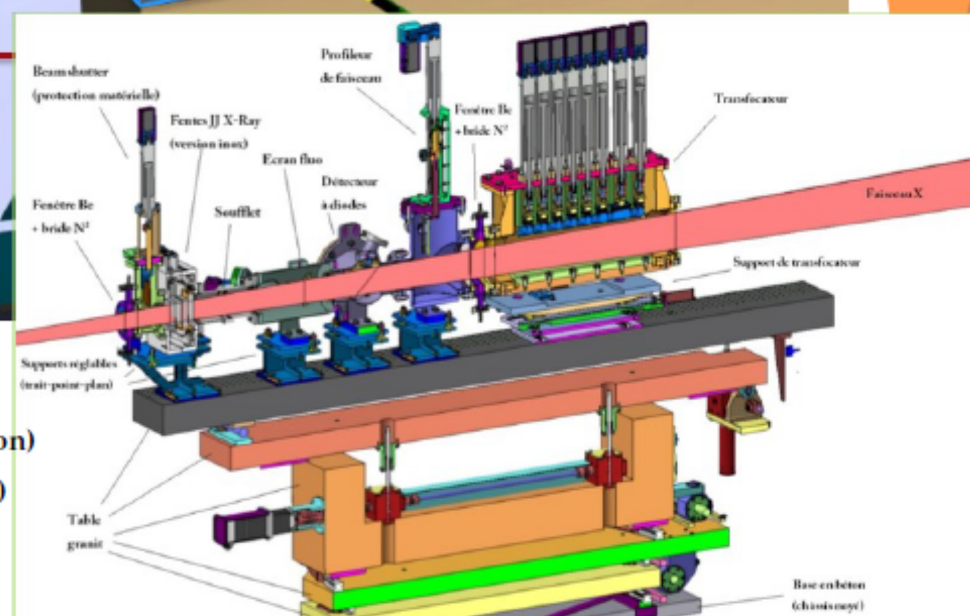
X line

Phase of manufacturing and tests at SERAS and ESRF

Table 1 - Continuous monitoring

Working zone
X-hutch (exp & control)





- X-ray obturator
- Slits system (alignment/beam shape)
- Fluorescent screens (beam detection)
- Diode detector (intensity)
- Beam profiler (abs. position)
- Transfocator (beam focus)

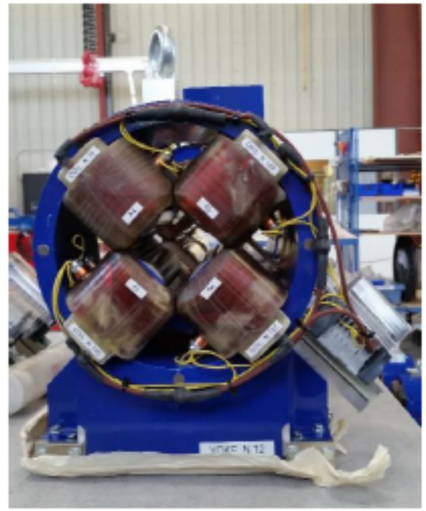
X-ray cone emission ~10mrad

Transfer Line - Storage Ring

Magnets: produced by SIGMAPHI, measurements at ALBA (QUAD + DIP) + LAL (SEXT)

15 DIP

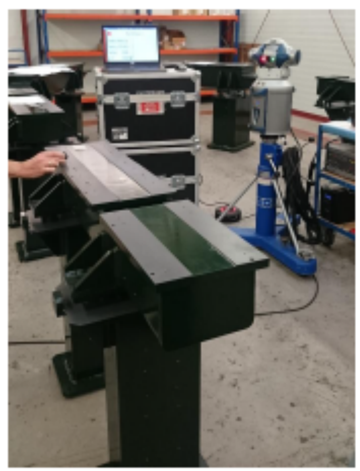
34 QUAD



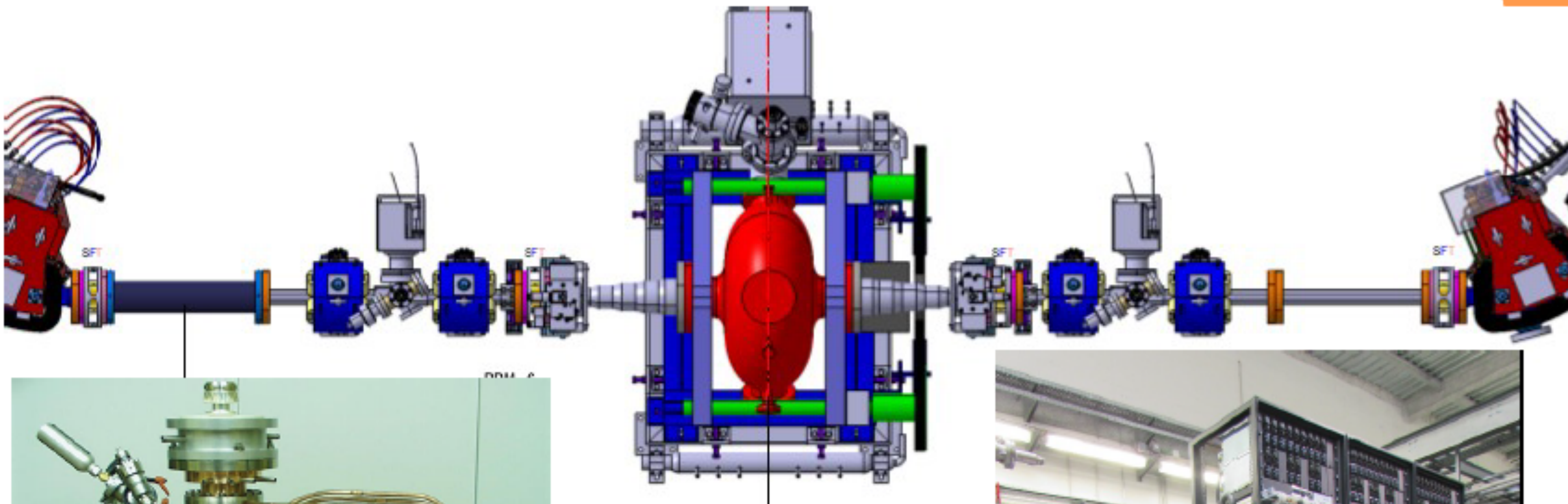
13 SEXT

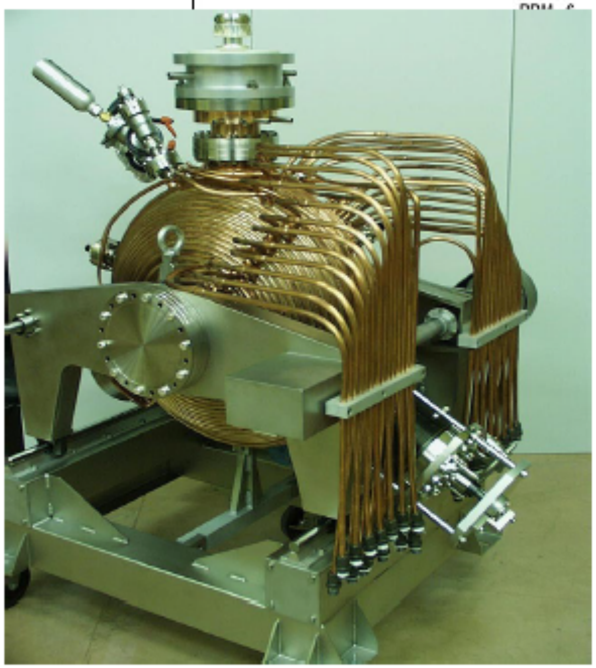
January 2016 - Start of the magnet measurements at ALBA.

Mai 2016 - Start of the magnet measurements at LAL.



Storage Ring RF system

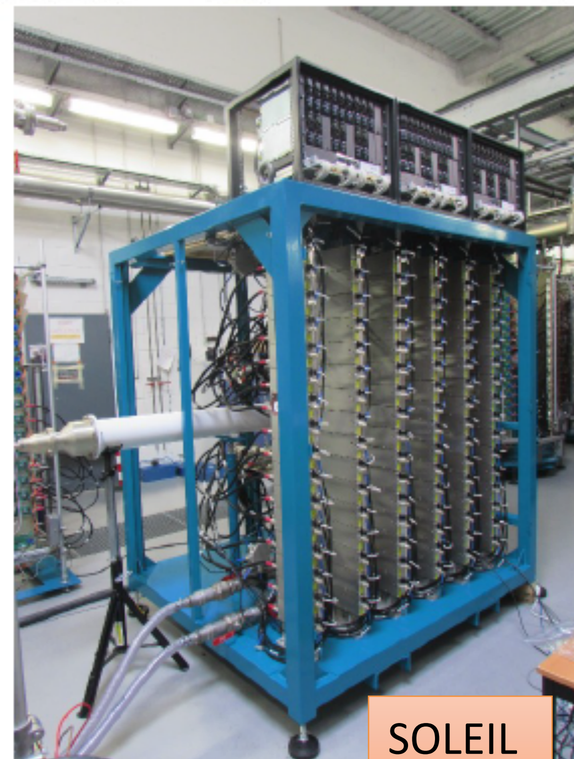




- ELETTRA type cavity

500 MHz

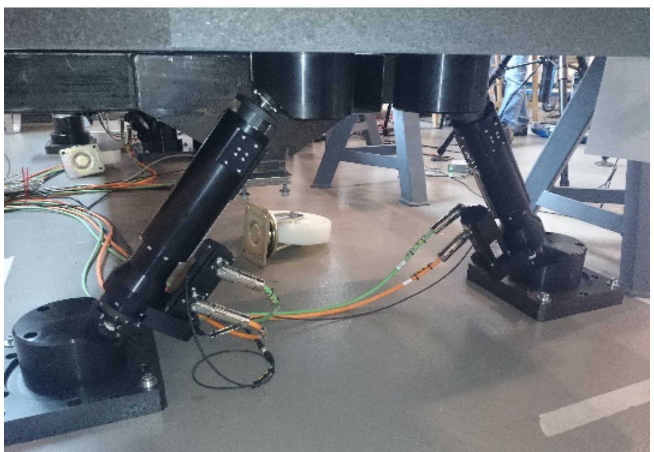
50 kW CW



Solid state amplifier

Granit table reception at LAL

Cavity vacuum vessel installation at LAL

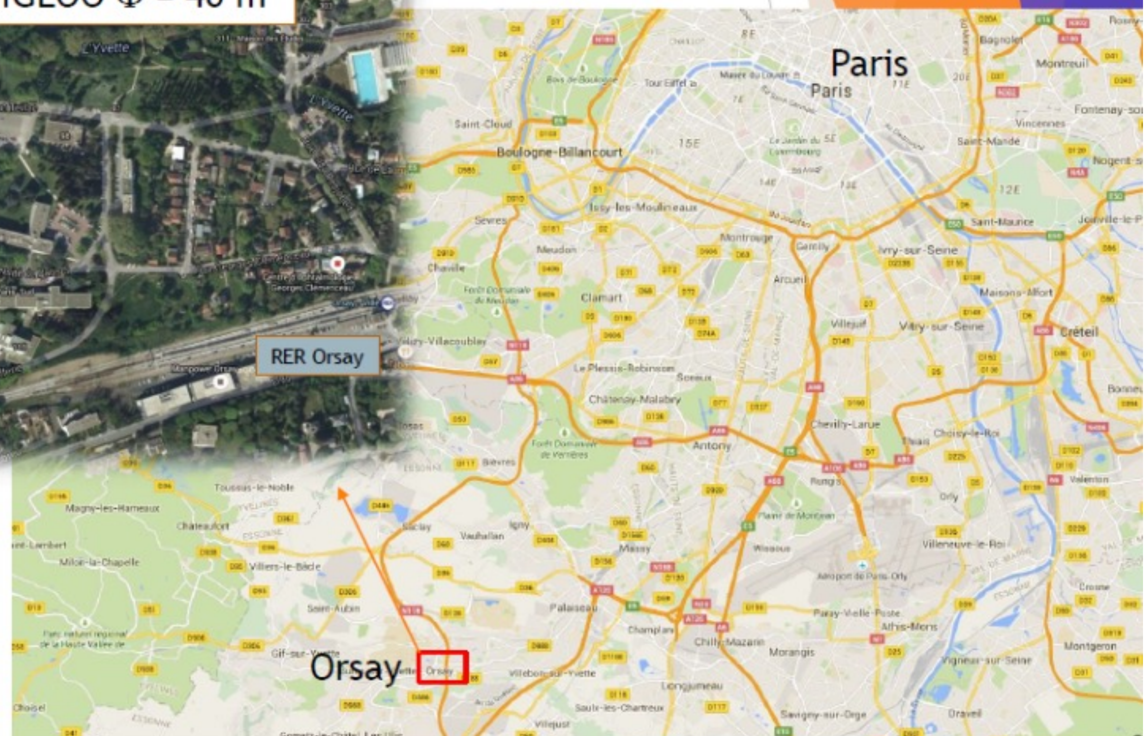


Hexapode feets

Cheikh,Pierre, Themis, Xing office

ThomX implantation : Igloo

Université Paris-Sud
Laboratoire Accélérateur Linéaire



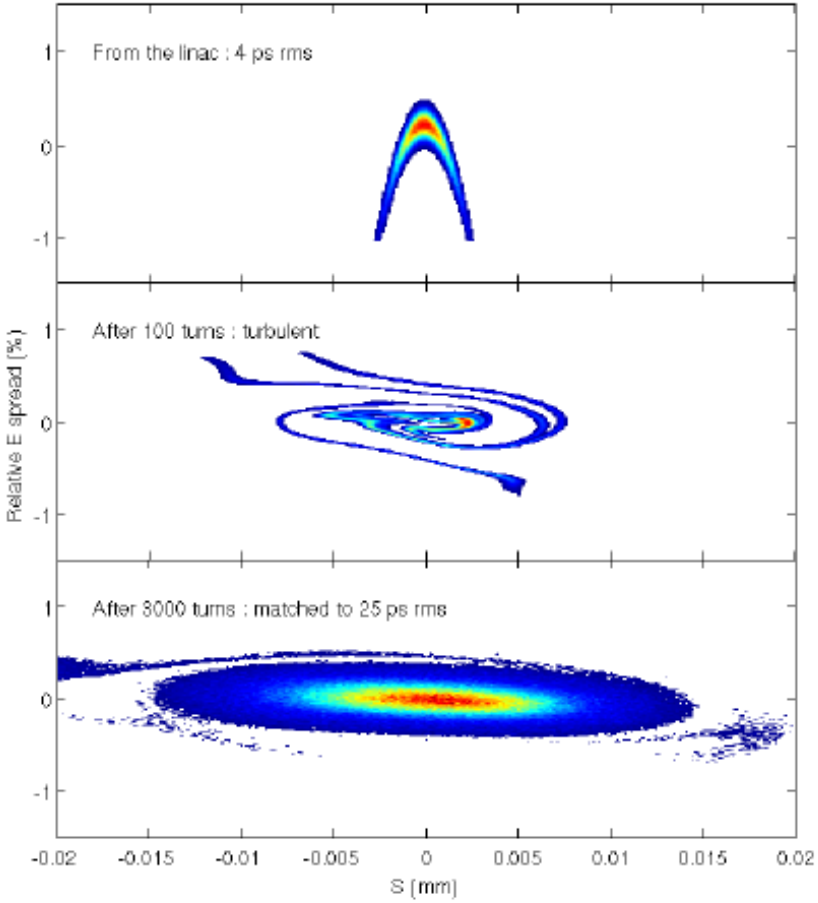
Avancement du chantier

2 Thomx issues :

- ✓beam dynamics
- ✓Laser/cavity technology

Storage Ring beam dynamics
First turns …

1 nC – 50 MeV



Typical longitudinal shape from the linac

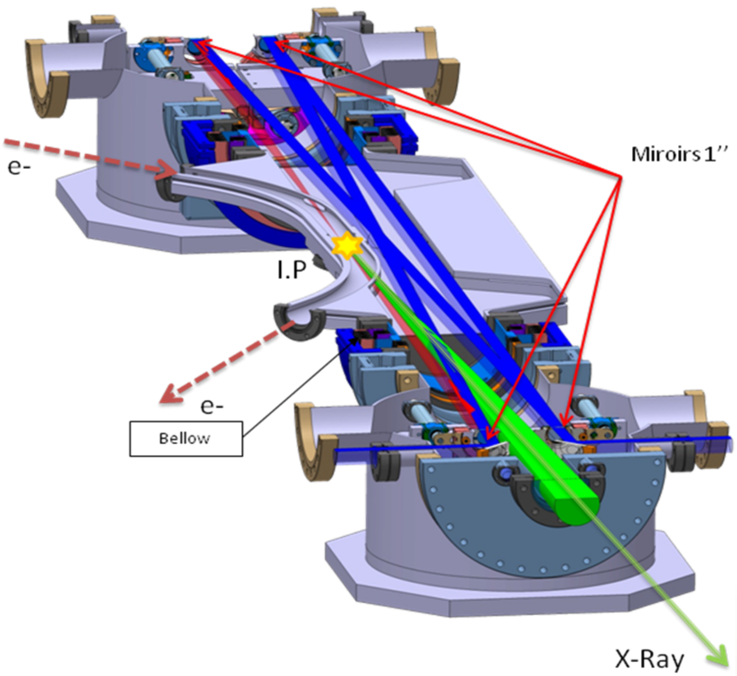
Strongly mismatch in the ring
Undergoes "turbulent" dynamics
Strong collective effects
➔Coherent rad. Synch.

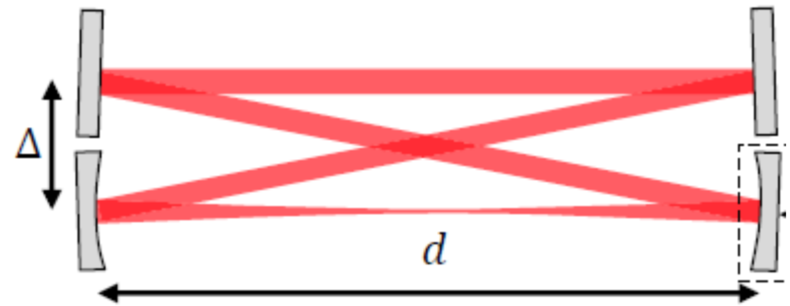
Strong Needs: Position feedback in the 3 planes
Side effects : Horizontal emittance increase
Main risk : To brake the bunch / losses

Finally reach a ring matched form
Still subject to some head tail effects

Simulations from I. Drebot

2nd issue: the Optical cavity





(a) Standard bow-tie (SBT) 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

➔ Laser oscillator rep. rate & CEP locking @ Dn/n ~10^{-12}

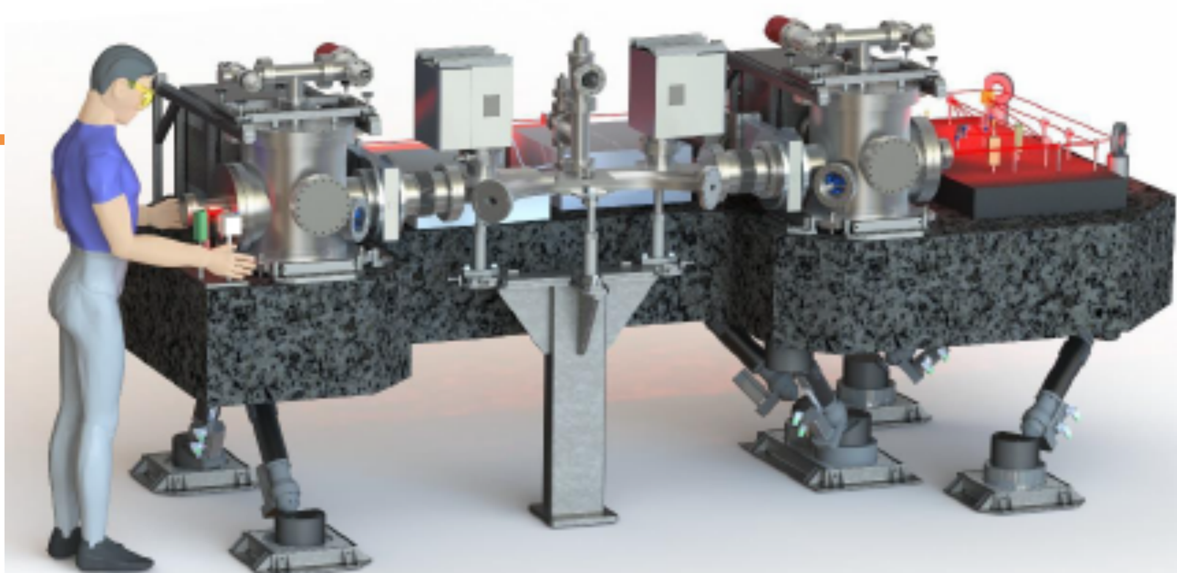


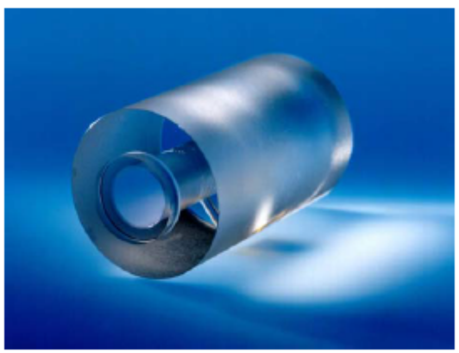
Illustration of one issue : the laser cavity feedback

Cavity finesse F=gain* p :
F=G × p = p/(1−R)~10^4 × p
Optical path length : L~7.5m

Cavity resonance frequency linewidth
Dn=c/(LF)~1.3 kHz !

Dn/n=l/(LF)=~10^{-12}
Same numbers as in metrology !!!

- Ultra-Low Expansion (ULE) Glass:

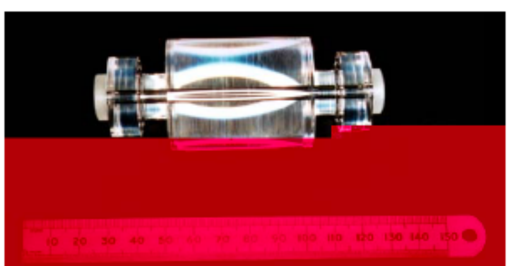


- Typical **length**: 10 cm
→Free spectral range ~ 1.5 GHz

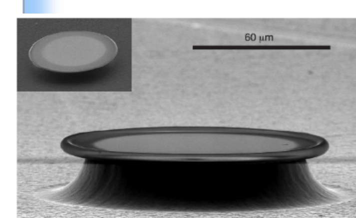
- Typical **finesse**: 300,000
→ linewidth ~ 5 kHz
→ **power enhancement ~10^5**
[applied power (CW): 1 mW
intracavity power (CW): 100 W]

Linewidth 1.3kHz
➔F=10^6…

- Single-crystal Sapphire (cryogenic: ~4 K)



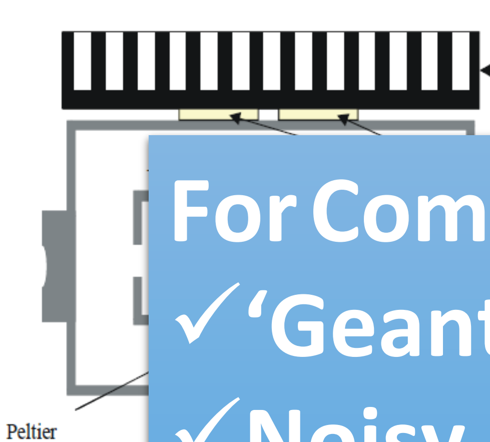
- Mirrors **optically contacted** to spacer



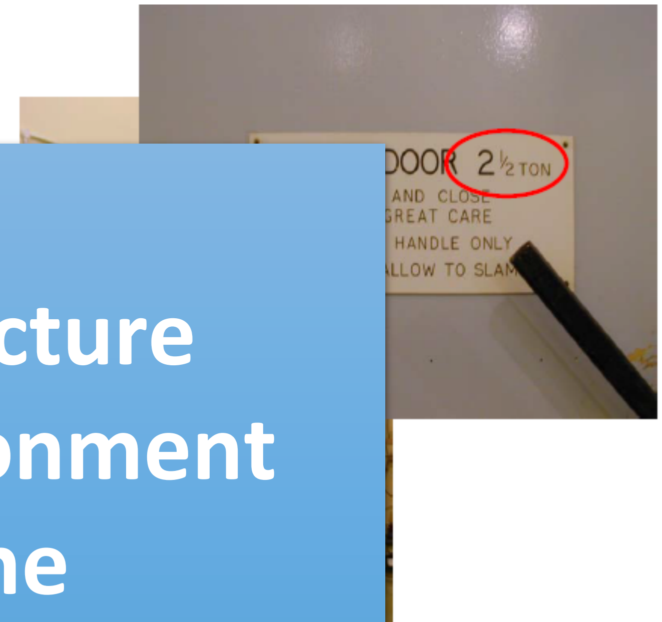
NPL M. Oxborrow

Besides
In metrology experiments :

The hyper stable small cavity is 'hyper' temperature stabilised



Into an hyper isolated room



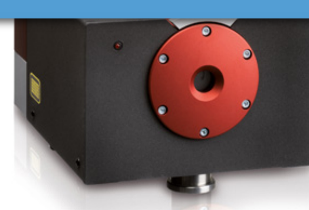
For Compton machines

- ✓'Geant' mechanical structure
- ✓Noisy accelerator environment
- ✓Pulsed laser beam regime
  - ✓∄ 1kHz linewidth oscillator
  - ✓'Huge' average & peak power !

Put on an

ser is used,

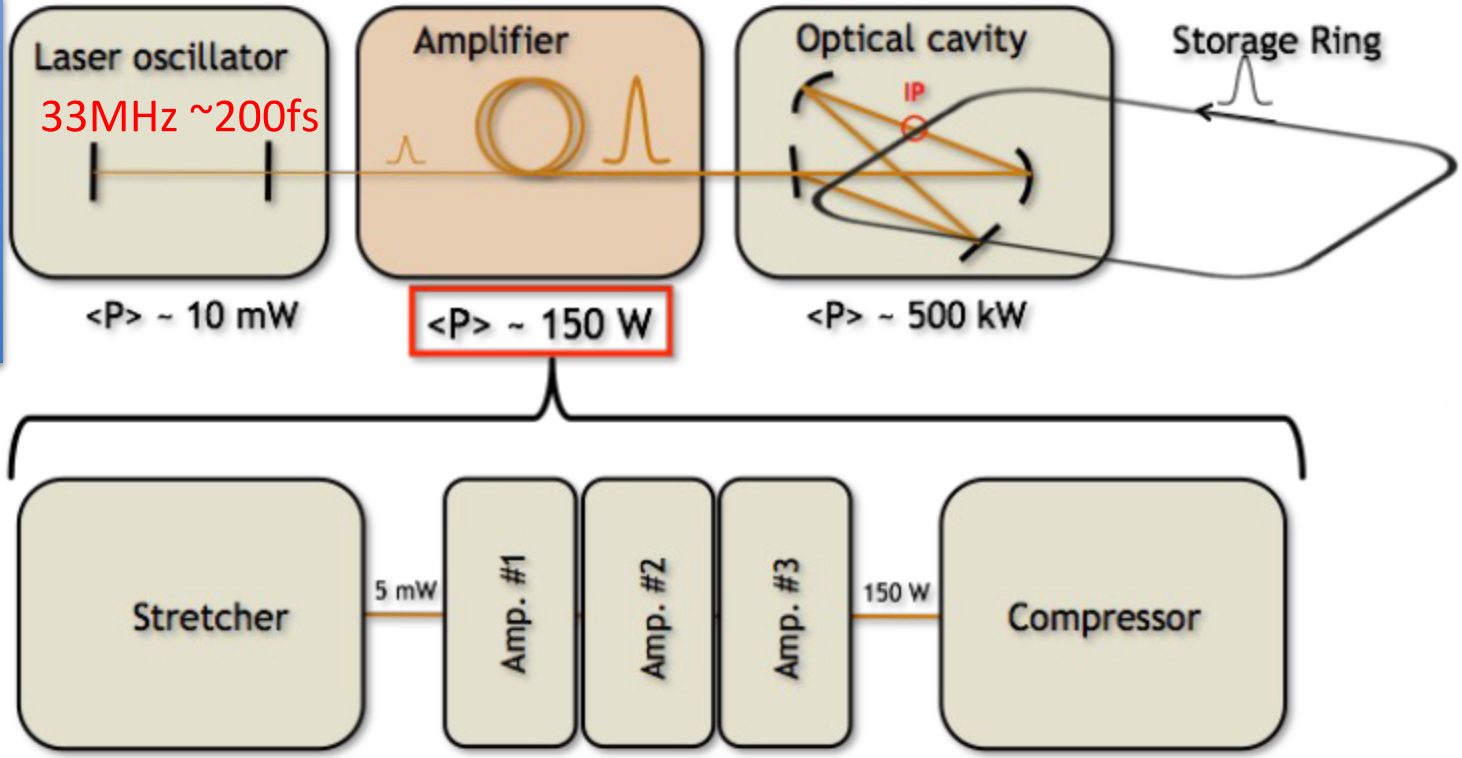
phisto



ThomX Laser amplification system: CELIA Lab. (Bordeaux)

Laser and Amplifier

Yb dopped gain media Used for « high Average Power »



Goals: stack as much <u>average power</u> as possible in an optical resonator→1MW

Present optical cavities performances

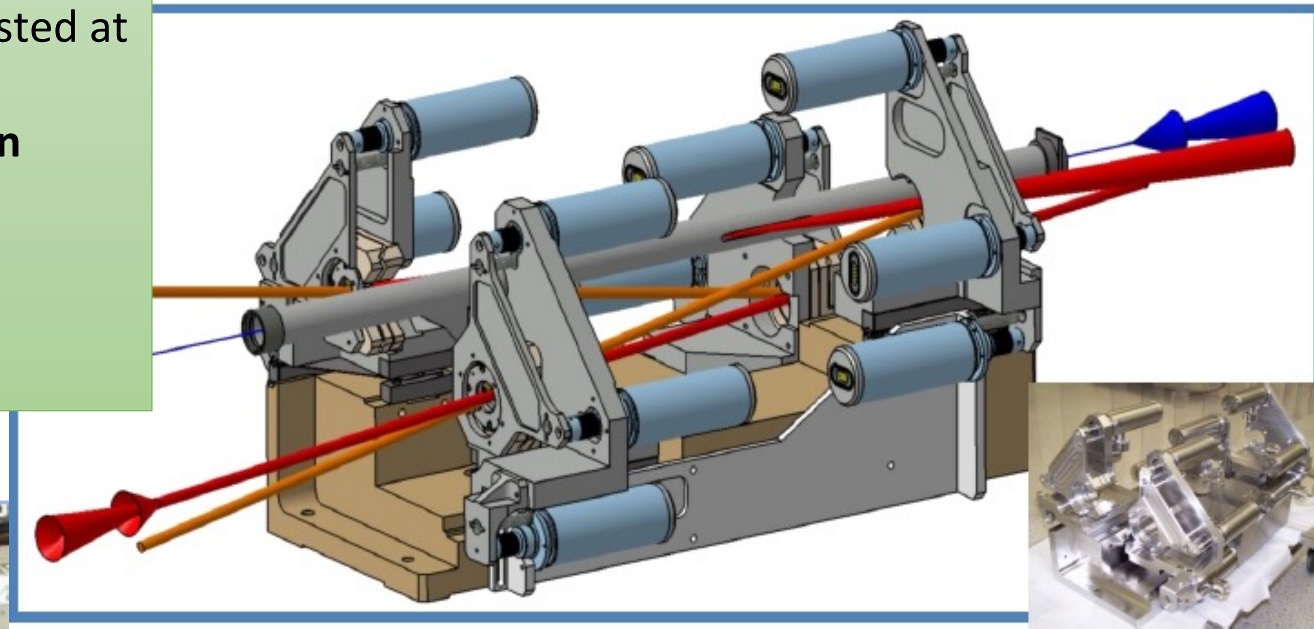
4-mirror high finesse cavity tested at KEK on ATF (1.3 GeV ring)

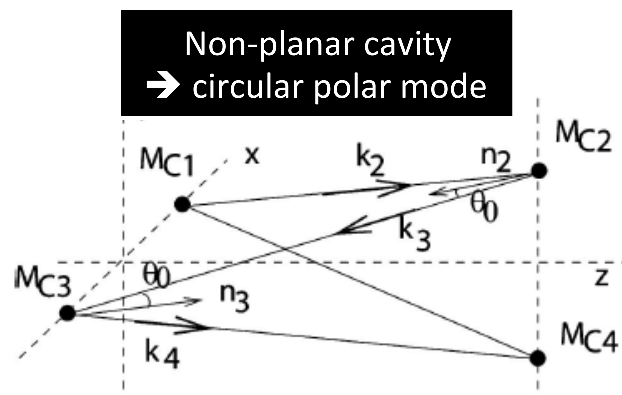
French-Japanese collaboration

➔100kW stored power
(before the earthquake)

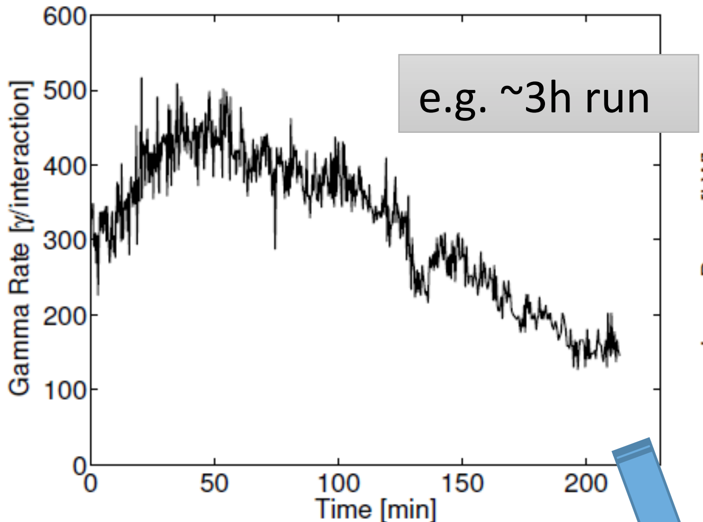
Mirror surfaces degradation

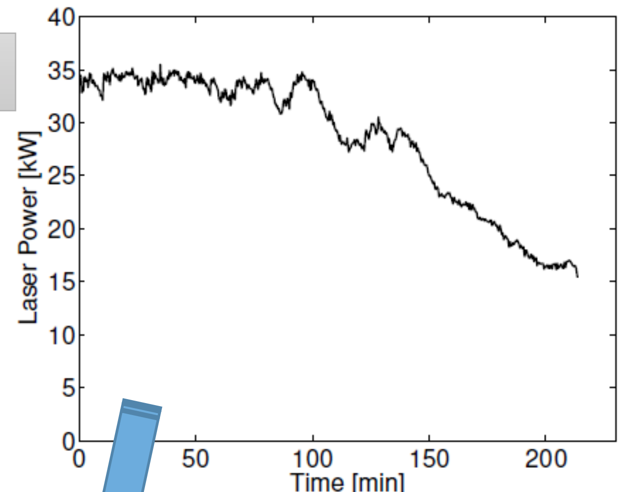
➔runs with 45kW at most



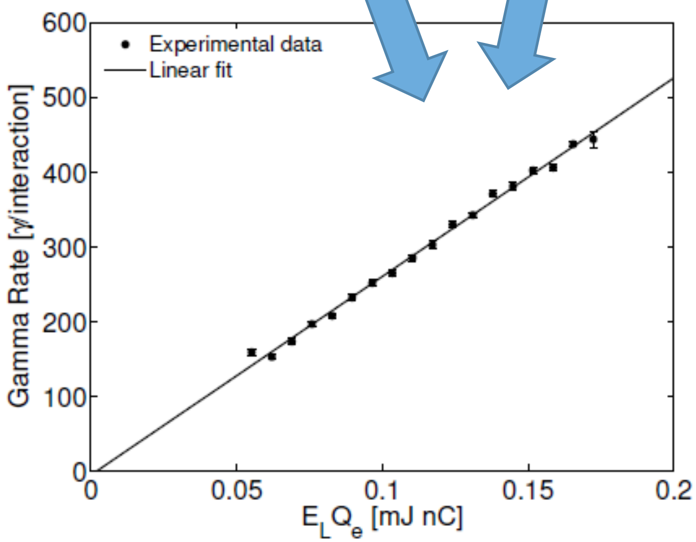


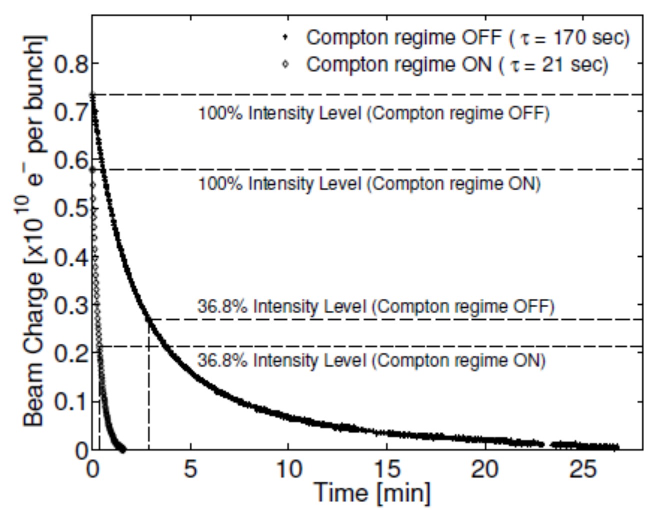
‘Huge’ average power must be stored inside the optical cavity
➔mirror thermoelastic deformations & damage





Stable >500kW average power needed for ThomX
➔goal 1MW

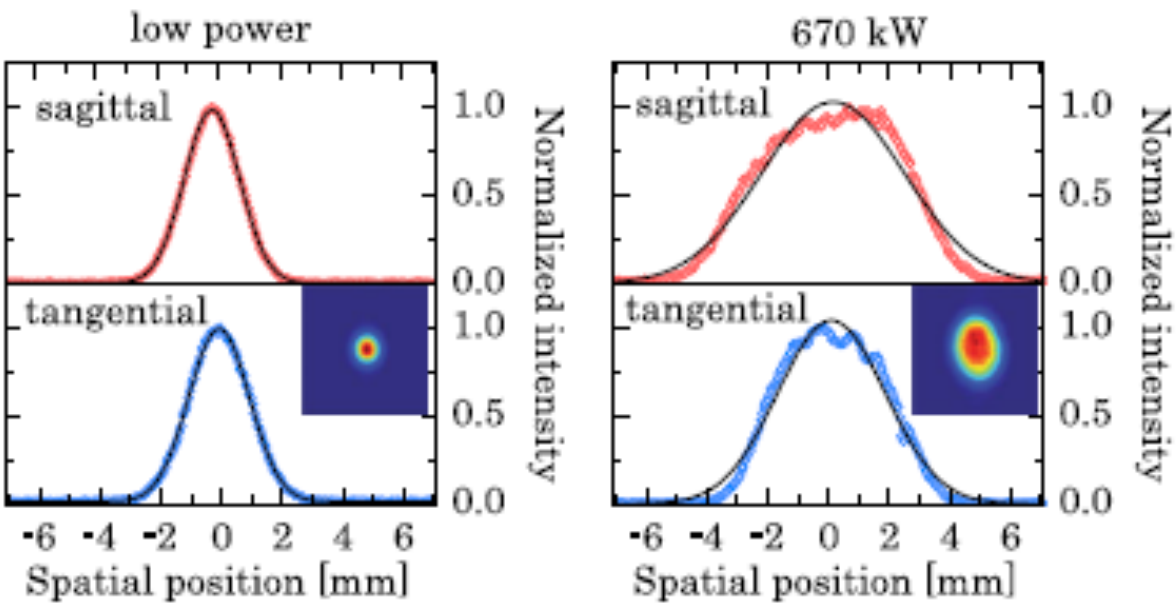




Chaikovska et al.

State of the art table top

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



Carstens et al. Opt Lett 39 (2014) 2595

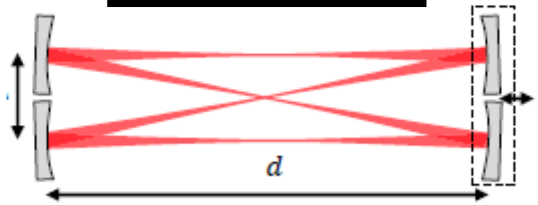
Careful choice for mirror substrate materials & coating
➔ Test with high finesse cavity undergoing

To further increase circulating power
➔ Reduce fluence on the mirrors

To increase luminosity
➔reduce mode waist & aberrations (astigmatism)

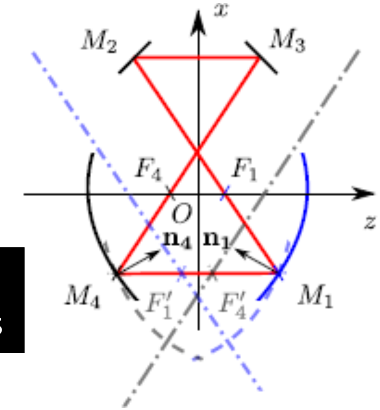
Optical cavity developments
➔ reduce damage threshold
➔ reduce aberrations

Cavity with
4 concave mirrors



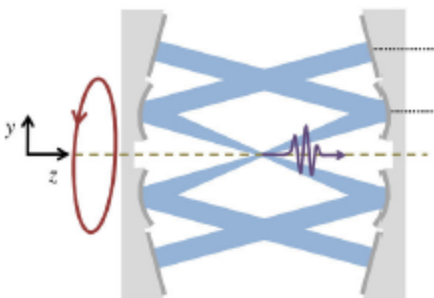
(b) All-curved-mirror (ACM) cavity
Carstens et al. Opt Expr 21(2013)11606

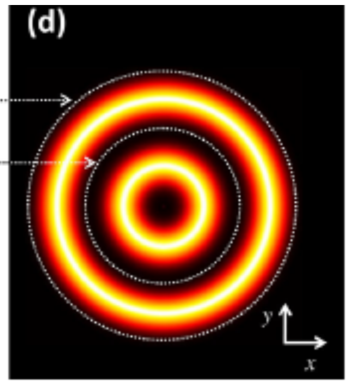
Cavity with
parabolic mirrors



Dupraz et al., Opt. Comm. 353 (2015)178

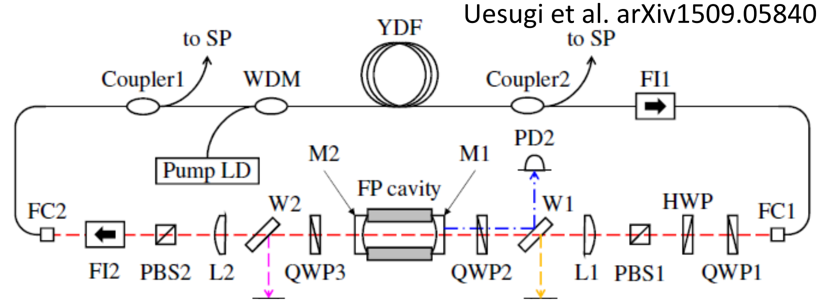
Bessel-Gauss beam
cavity with toroid





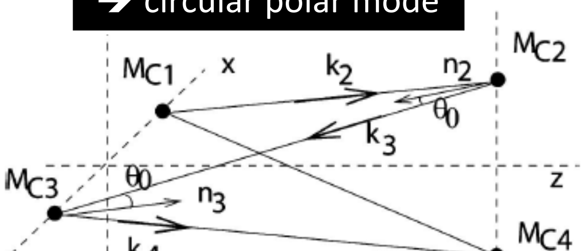
Putnam et al. Opt. Exp. 20(2012)24429

Uesugi et al. arXiv1509.05840



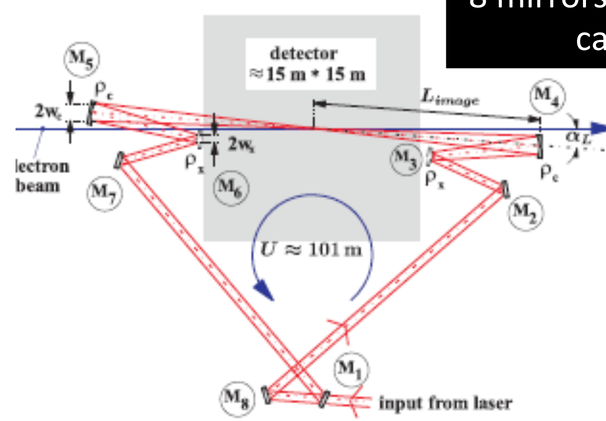
"External" cavity "inside" the laser oscillator

Non-planar cavity
➔ circular polar mode



Apl Opt 48 (2009) 6651

8 mirrors telescopic cavity



Klemz et al.
NIMA564
(2006)212

ThomX APPLICATIONS

Quasi monochromatic 40-90keV X-ray beams

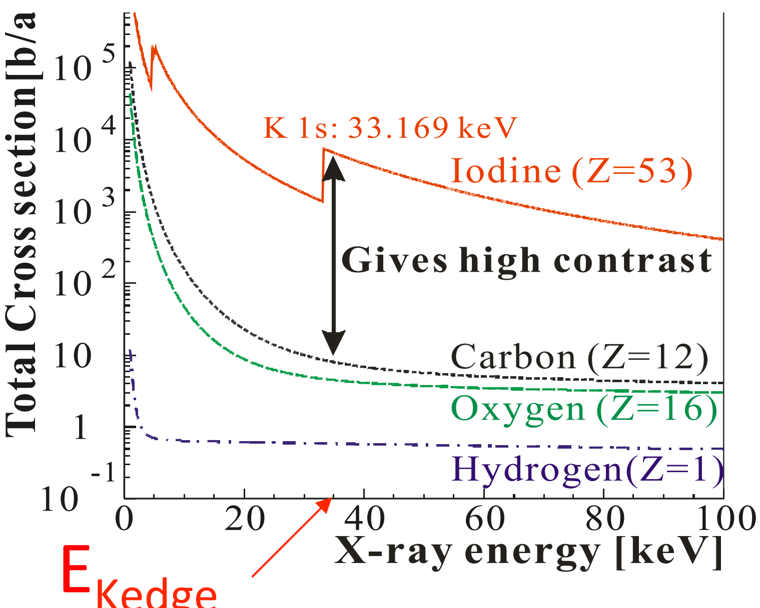
Painting / archeology analyses

'K edge imaging' (see Hayakawa-san's talk)

- Heavy chemical elements are contained in painting pigments
  - Characterised by K absorption edges

Total Cross Section of X-ray attenuation

for various elements



K-edge imaging
(Pb ➔ white, Hg ➔ vermillion…)
of a Van-Gogh's painting

But ~30k€ insurance for 2 days

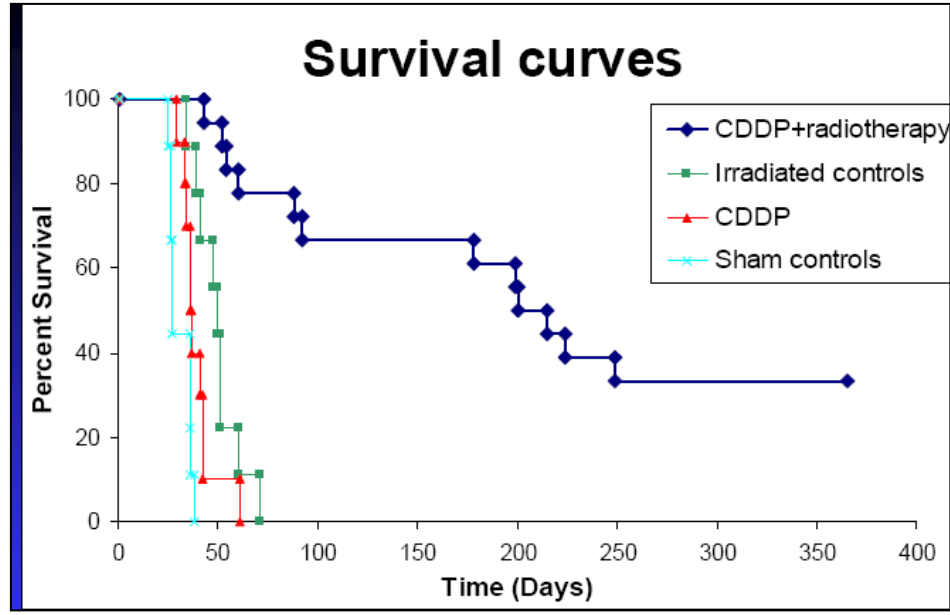
➔ Compact machine inside Louvre museum was foreseen (E_X~10-100keV)…

➔ This was the *original motivation* of ThomX with Le Louvre museum

A medical application at ESRF (ligne ID17): radiotherapy for brain tumors

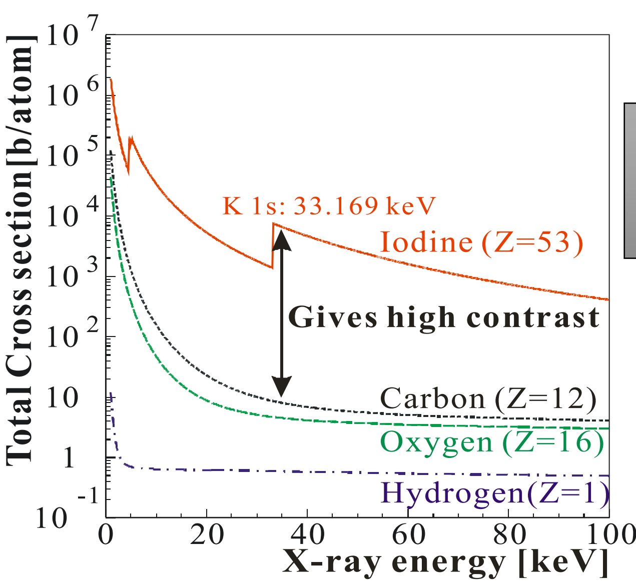
- **Search for glioblastoms therapy**
  - Locate platinum (cisplatine) inside tumor cells (rat brains)
  - Shoot with 78keV X-ray (platinum K-shell)
  - Observed ~700% increase of life time
  - Observed 34% survivals after 1 year …

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

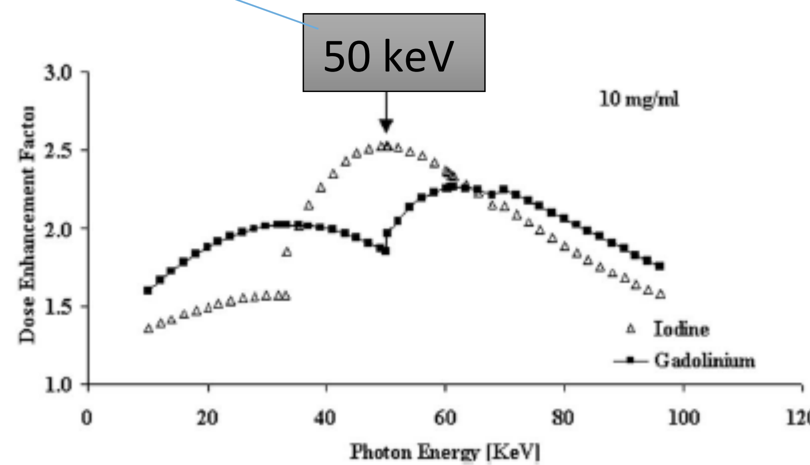


- **X-ray bandwidth need :**

e.g. iodine contrast agent (ongoing human trial at ESRF)



But relative to water absorption



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

Producing 50keV-80keV X-rays with a bandwidth of few %
➔can be done with Compton machines

> However, a routine use of synchrotron light for human treatment will necessitate the development of new X-ray monochromatic sources devoted to medical use. The next decade should be productive in developing such technology.

ThomX machine

[S. Corde et al. cancer reas. 63 (2003)3221]

Requested fluxes :

- **Radiotherapy: ~10^{13} photon/s within DE/E=10% and E_X=50-90keV**
  - **Would provide flux closed to ESRF trial (Jacquet et al. Phys. Med. 31(2015)596)**
  - **X-rays produced in a cone ~10mrad**

➔ ~500kW laser average power needed for ThomX

Summary

- Compact Compton Thomx machine under construction
  - Building construction in 2016
    at LAL-Orsay/Paris-sud university
  - Installation end 2016→2017
  - Commissioning end 2017→2018
- Expected performances g of 45-90 keV @ 10^{11} - 10^{13} s^{-1}
  - Imaging & radiotherapy studies planed
- Room for upgrading performances
  - Beam dynamics
  - Laser power & optical cavity developments