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

Photon laser + e $\rightarrow$ photon + e' is a 2 body process $\Rightarrow W_f = f(q)$

$g = \frac{E_{\text{electron}}}{m_e c^2}$

PRL138(1965)B1546

Quasi monochromatic X/\gamma ray beam

$w_f, \text{max} = 4 g^2 w_{\text{laser}}$

$w_f (\text{keV})$

$q (\text{mrad})$

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 feet
Located in the old LURE igloo at Orsay

Phase of manufacturing and tests at SERAS and ESRF

Table 1 - Continuous monitoring

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

Working zone X-hutch (exp & control)

X-ray cone emission ~10mrad
Transfer Line - Storage Ring

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

Granit table reception at LAL

Cavity vacuum vessel installation at LAL
Cheikh, Pierre, Themis, Xing office

ThomX implantation : Igloo

Site ThomX
IGLOO $\Phi = 40$ m

Université Paris-Sud
Laboratoire Accélérateur Linéaire

ThomX Status avril 2016
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

⇒ Laser oscillator rep. rate & CEP locking @ Dn/n \(\sim 10^{-12}\)
Illustration of one issue: the laser cavity feedback

Cavity finesse $F = \text{gain} \times p$

$F = G \times p = \frac{p}{(1-R)} \approx 10^4 \times p$

Optical path length: $L \approx 7.5 \text{ m}$

Cavity resonance frequency linewidth $D_n = \frac{c}{LF} \approx 1.3 \text{ kHz}$

$D_n/n = \frac{l}{LF} = \approx 10^{-12}$

Same numbers as in metrology!!!

M. Oxborrow

Ultra-Low Expansion (ULE) Glass:

- Typical length: 10 cm
  - Free spectral range $\approx 1.5 \text{ GHz}$

- Typical finesse: 300,000
  - Linewidth $\approx 5 \text{ kHz}$
  - Power enhancement $\approx 10^5$

*Applied power (CW): 1 mW
Intracavity power (CW): 100 W*

- Mirrors optically contacted to spacer

Linewidth 1.3 kHz $\Rightarrow F = 10^6...$
Besides
In metrology experiments:

The hyper stable small cavity is ‘hyper’ temperature stabilised

Put on an hyper stabilised optical table

Into an hyper isolated room

Put on an hyper isolated table

For Compton machines
✓ ‘Geant’ mechanical structure
✓ Noisy accelerator environment
✓ Pulsed laser beam regime
✓ $\geq 1$kHz linewidth oscillator
✓ ‘Huge’ average & peak power!

M. Oxborrow
ThomX Laser amplification system: CELIA Lab. (Bordeaux)

Laser and Amplifier

Yb doped gain media
Used for « high Average Power »

33MHz ~200fs

Goals: stack as much average power as possible in an optical resonator ➔ 1MW
Present optical cavities performances
Non-planar cavity

Circular polar mode

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
State of the art table top

Cavity average power = $670\text{kW} @ 10\text{ps}$

$400\text{kW}@250\text{fs}$

Laser + amplifier: $420\text{W} @ 250 \text{ MHz}$

Cavity enhancement factor $\sim 2000$

Careful choice for mirror substrate materials & coating

$\Rightarrow$ Test with high finesse cavity undergoing

To further increase circulating power

$\Rightarrow$ Reduce fluence on the mirrors

To increase luminosity

$\Rightarrow$ reduce mode waist & aberrations (astigmatism)

Optical cavity developments

- reduce damage threshold
- reduce aberrations

Cavity with parabolic mirrors


Bessel-Gauss beam cavity with toroid


Non-planar cavity
- circular polar mode

- Klemz et al. NIMA564 (2006)212

“External” cavity “inside” the laser oscillator

- Uesugi et al. arXiv1509.05840

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 vermilion...)
of a Van-Gogh’s painting

But ~30k€ insurance for 2 days
➤ Compact machine inside Louvre museum was foreseen ($E_x \sim 10-100\text{keV}$)...
➤ 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)

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.

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

**Requested fluxes:**

- **Radiotherapy**: \( \sim 10^{13} \) photon/s within \( \text{DE/E}=10\% \) and \( E_x=50-90\text{keV} \)
  - Would provide flux closed to ESRF trial (Jacquet et al. Phys. Med. 31(2015)596)
  - X-rays produced in a cone \( \sim 10\text{mrad} \)
  - \( \sim 500\text{kW} \) 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 of 45-90 keV @ $10^{11} - 10^{13}$ s$^{-1}$
  • Imaging & radiotherapy studies planned
• Room for upgrading performances
  • Beam dynamics
  • Laser power & optical cavity developments