ThomX

History: Properties and interests in Compton scattering
Applications
Monochromatic X-ray imaging ➔ ThomX project
Machine Characteristics
Technology. Laser systems for Compton scattering
➔ Use of Fabry-Perot optical resonator
   Optical R&D
Properties and interests in laser-electron Compton scattering
Properties of Compton scattering

Dynamics of the process

- **Thomson Scattering** (at ‘low energy’)
  - Electron+plane wave scattering
    - Jackson, *Classical Electrodynamics*
- **Compton Scattering** $\gamma (\text{laser}) + e \rightarrow \gamma' + e'$
  - Photon(laser)+electron scattering
    - Fano, JOSA39(1949)859;

We are interested by using the scattered photon

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

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

Tolhoek, Rev.Mod.Phys.28(1956)277

Independent of polarisations

Polarisation of the 4 particles are observed
Interests in Laser electron Compton scattering

1\textsuperscript{st} interest: the energy boost
(no polar. are observed)

Energy distribution $\sim$ flat
with
\[ \omega_{f,\text{max}} = 4\gamma^2 \omega_{\text{laser}} \]
with $\gamma \sim 100$ ($E_{\text{electron}} = 50\text{MeV}$)

\[ \omega_{f,\text{max}} = 45000\text{ev} \text{ if } \omega_{\text{laser}} \sim 1\text{eV} \]

Compton scattering is the most powerful mechanism to boost photon energies

Sprangle et al. JAP\textbf{72}(1992)5032
2nd interest: the angular energy correlation

Compton scattering
Photon_laser+e→photon+e’
is a
2 body process \( \omega_f = f(\theta) \)

\[ \gamma = \frac{E_{\text{electron}}}{m_e c^2} \]

~monoenergetic beam by selecting Backscattered photons at \( \omega_f,_{\text{max}} \)

Sprangle et al. JAP72(1992)5032
3rd interest: incident electron and laser polarisation effects
(2 polar. are ‘observed’)

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

\[ \frac{d\sigma}{d\omega_f} = A_0(\omega_f) - P_e S_3 A_1(\omega_f) \]

\( A_0, A_1 \): 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
\( \Rightarrow \) 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
(3 polar. observed: incident e & laser, final photon)

\[ (P_e, S_{3, \text{laser}}) = (0, 1) \]

Compton scattering acts as a mirror for circular polarisation at low energy if highest values of \( \omega_f \) are selected (i.e. backscattered photons are selected)

\( S_{3f} = 1 \) for \( \omega_f = \omega_{f, \text{max}} \) & \( S_{3, \text{laser}} = 1 \)

\[ \gamma \gamma \text{ collider (} E_{\text{electron}} \approx 250-500 \text{ GeV)} \]
Ginzburg et al. NIM219(1984)5

\[ \rightarrow \text{Polarised positron source (} E_{\text{electron}} \approx 1 \text{ GeV)} \]
Compton polarised positron source for the ILC
Alternative solution
Araki et al. arXiv:physics/0509016

The e+ are longitudinally polarised

Experimental proof at ATF
• Omori et al. PRL 96(2006)114801
Applications of Compton scattering: quasi monochromatic X/γ ray beam

γ ~100 MeV

γ ~ 1 MeV

X ray ~10-100 keV

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
- γγ collider

- Polarised positron source

LAL Accelerator group has now projects in the low & high energy domains
Motivations for a compact Compton X-ray source

• What has been done with synchrotron light that we would like to do in a museum, hospital or lab. room
  – examples taken from results at the ESRF synchrotron machine (http://www.esrf.eu/news/spotlight/)
    • Paleontology
    • Painting analysis
    • Resonant radiotherapy
Paleontology application

Piece of amber
100 millions years BC (France/Charentes)

~30keV monochromatic X-rays from ESRF

¬ non destructive 3D imaging of elements contained inside the ambre since more than 100M years
(Synchrotron Rad. 16(2009) 43-47)
‘K edge imaging’

- 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 $\rightarrow$ blanc, Hg $\rightarrow$ vermilion...) of a Van-Gogh’s painting

But $\sim$30k€ insurance for 2 days
→ Compact machine inside Le Louvre museum (was !) decided ...
→ This was the original motivation of ThomX

J. Dik et al., *Analytical Chemistry*, 2008, 80, 6436
http://www.vangogh.ua.ac.be/
Laser–electron Compton scattering process should lead to compact X-ray machines

**Requested fluxes:**
- **Radiotherapy:** $\sim 10^{13}$ photon/s within $\Delta E/E=10\%$ and $E_X=35-80\text{keV}$
- **Imaging:** $\sim 10^{11}$ photon/s within $\Delta E/E=3\%$ and $E_X=6-90\text{keV}$

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

- No therapy for glioblastoms $\rightarrow$ new technique
  - Locate platinum (cisplatine) inside tumor cells (rat brains)
  - Shoot with 78keV X-ray (platinum K-shell) & chemotherapy
  - Observed $\sim 700\%$ increase of life time

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

[Image: Survival curves]

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]
The ThomX project: monochromatic high flux X-ray source for Low-energy applications

- Collaboration between:
  - LAL (A. Variola, project leader),
  - SOLEIL (Synch. Rad. machine, Saclay),
  - CELIA (Laser lab., Bordeaux)
  - NEEL (Instr. X, Grenoble)
  + C2RMF/CNRS (scientific lab. of Le Louvre museum, led by P. Walter)
  - at start (C.R. Physique 10 (2009)676)
  + New archeological Lab. in paris (P. Walter)
  + ESFR&INSERM (Grenoble, Synch. Rad. Machine, medical ligne group, A. Bravin)
  + Thales for industrial applications

- ThomX funded (EQUIPEX) with the ‘grand emprunt national’ ➔ ~10M€
The ThomX machine

Size ~10mx7m will be located at Orsay

~50MeV electrons

S-band (3GHz) LINAC

Optical resonator

X rays

Photo gun

Pixel det. ImXgam ➜ From ATLAS/CPPM
Higher flux than rotating anodes
But worse brilliance that Synch. Rad. Machines...
# ThomX machine parameters

<table>
<thead>
<tr>
<th>Source explored range</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X energy</td>
<td>6–92 keV</td>
</tr>
<tr>
<td>Flux</td>
<td>$10^{10}$–$10^{13}$ ph/s</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>3%</td>
</tr>
<tr>
<td>Divergence</td>
<td>&lt;2 mrad</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accelerator</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring and injector energies</td>
<td>~20–70 MeV</td>
</tr>
<tr>
<td>Charge</td>
<td>1 nC</td>
</tr>
<tr>
<td>Electron bunch length</td>
<td>20 ps r.m.s.</td>
</tr>
<tr>
<td>Electron energy spread</td>
<td>0.6% r.m.s.</td>
</tr>
<tr>
<td>Non-normalized electron beam emittance</td>
<td>$5 \times 10^{-8}$ π m rad</td>
</tr>
<tr>
<td>Electron beam waist sizes</td>
<td>70 μm r.m.s.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laser</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intracavity average power</td>
<td>&gt;100 kW</td>
</tr>
<tr>
<td>Laser pulse length</td>
<td>1 ps r.m.s.</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>1030 nm</td>
</tr>
<tr>
<td>Laser beam focus size</td>
<td>43 μm r.m.s.</td>
</tr>
<tr>
<td>Laser pulse energy</td>
<td>30 mJ</td>
</tr>
<tr>
<td>Compton $f_{rep}$</td>
<td>50–200 MHz</td>
</tr>
</tbody>
</table>
### Electrons characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_e$</td>
<td>Number of electrons / bunch</td>
<td>$6.25 \times 10^9$</td>
</tr>
<tr>
<td>$\sigma_{xe}, \sigma_{ze}$</td>
<td>Rms transverse size</td>
<td>$70 , \mu m$</td>
</tr>
<tr>
<td>$\sigma_{te}$</td>
<td>Rms longitudinal size</td>
<td>$6 , mm / 20 , ps$</td>
</tr>
<tr>
<td>$\alpha_{el}$</td>
<td>Angle between electron bunch trajectory and laser one</td>
<td>$0.035 , rad / 2^\circ$</td>
</tr>
</tbody>
</table>

### Laser characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_l$</td>
<td>Number of photons/pulse</td>
<td>$1.6 \times 10^{17}$</td>
</tr>
<tr>
<td>$\sigma_{xl}, \sigma_{zl}$</td>
<td>Rms transverse size</td>
<td>$40 , \mu m$</td>
</tr>
<tr>
<td>$\sigma_{l}$</td>
<td>Rms longitudinal size</td>
<td>$1.5 , mm / 1 , ps$</td>
</tr>
<tr>
<td>$\lambda_{l}$</td>
<td>Wavelength</td>
<td>$1.06 , \mu m$</td>
</tr>
</tbody>
</table>

### Compton Back Scattering (CBS) radiation characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{th}$</td>
<td>Thomson cross section</td>
<td>$6.66 \times 10^{-29} , m^2$</td>
</tr>
<tr>
<td>$F_c$</td>
<td>Initial flux</td>
<td>$1.2 \times 10^{13} , photons /s$</td>
</tr>
<tr>
<td>$\Delta E_l$</td>
<td>Energy loss per electron and per turn</td>
<td>$2.3 , eV$</td>
</tr>
<tr>
<td>$E_x$</td>
<td>Maximum/mean energy of CBS radiation</td>
<td>$50/25 , keV$</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Period</td>
<td>$48 , ns$</td>
</tr>
<tr>
<td>$\tau_{xcbs}$</td>
<td>Transverse damping time</td>
<td>$2.1 , s$</td>
</tr>
<tr>
<td>$\tau_{scbs}$</td>
<td>Longitudinal damping time</td>
<td>$1.1 , s$</td>
</tr>
<tr>
<td>$\sigma_{ecbs}$</td>
<td>Energy spread</td>
<td>$1.8%$</td>
</tr>
<tr>
<td>$\varepsilon_{xcbs}$</td>
<td>Normalized emittance</td>
<td>$6.9 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

### Synchrotron Radiation (SR) characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E_0$</td>
<td>Energy loss per electron and per turn</td>
<td>$1.6 , eV$</td>
</tr>
<tr>
<td>$E_{rs}$</td>
<td>Critical energy of SR radiation</td>
<td>$0.8 , eV$</td>
</tr>
<tr>
<td>$\tau_{xrs}$</td>
<td>Transverse damping time</td>
<td>$3.1 , s$</td>
</tr>
<tr>
<td>$\tau_{srs}$</td>
<td>Longitudinal damping time</td>
<td>$1.5 , s$</td>
</tr>
<tr>
<td>$\sigma_{ers}$</td>
<td>Energy spread</td>
<td>$7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\varepsilon_{xrs}$</td>
<td>Normalized emittance</td>
<td>$1.5 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

### Equilibrium values of both SR and CBS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_x$</td>
<td>Transverse damping time</td>
<td>$1.2 , s$</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>Longitudinal damping time</td>
<td>$0.6 , s$</td>
</tr>
<tr>
<td>$\sigma_e$</td>
<td>Energy spread</td>
<td>$1.4 %$</td>
</tr>
<tr>
<td>$\varepsilon_x$</td>
<td>Normalized emittance</td>
<td>$6.5 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Table 9: SR and CBS characteristics in the ThomX ring.
Injection system: LINAC @ 1 nC

New photoinjecteur

| Energy (MeV) | 50.4 |
| Normalized emittance (π mm.mrad) | 4.2 |
| Transverse size (mm) | 1.2 |
| Bunch length (ps) | 4.5 |
| Energy spread (%) | 0.68 |

| Energy (MeV) | 70.4 |
| Normalized emittance (π mm.mrad) | 4.5 |
| Transverse size (mm) | 0.9 |
| Bunch length (ps) | 4.5 |
| Energy spread (%) | 0.57 |

50 MeV => ~40 keV

70 MeV => ~80 keV
Injection and transport line
Also if it is a leptonic accelerator...
It has a memory (transient mode, no damping)
### Caractéristiques de l’anneau

<table>
<thead>
<tr>
<th>Caractéristique</th>
<th>Valeur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
<td>16.8</td>
</tr>
<tr>
<td>Nominal energy (MeV)</td>
<td>50</td>
</tr>
<tr>
<td>Betatron tunes $v_x$, $v_z$</td>
<td>3.4 / 1.74</td>
</tr>
<tr>
<td>Betatron tunes max x,z (m)</td>
<td>11 / 11</td>
</tr>
<tr>
<td>Dispersion max (m)</td>
<td>0.9</td>
</tr>
<tr>
<td>Beta, dispersion @ IP (m)</td>
<td>0.2 / 0.2 / 0</td>
</tr>
<tr>
<td>Momentum Compaction Factor</td>
<td>0.0148</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
<td>500</td>
</tr>
<tr>
<td>RF harmonic</td>
<td>28</td>
</tr>
<tr>
<td>RF voltage (kV)</td>
<td>300</td>
</tr>
<tr>
<td>Period (ns) / Revolution frequency (MHz)</td>
<td>56.2 / 17.8</td>
</tr>
<tr>
<td>Natural chromaticities</td>
<td>-11.4 / -11</td>
</tr>
</tbody>
</table>
This is a priori a ‘transient ring’

Synch. rad. dumping time \( \sim 1.5 \text{s} \)
BUT
Compton Beam Scattering induces a damping time \( \sim 0.6 \text{s} \)

At 50MeV,
- Intra Beam Scattering
- Touschek effect
- Ion instabilities (\( \rightarrow \) limited vacuum)

are important and limits the beam life time

We expect that this machine will be tricky to run!
\( \rightarrow \) life time limited to 20ms for start (50Hz injection)
Dynamics: Compton + instabilities
Total flux

Wakefields

Stabilisation

C. Bruni, A. Loulergue
Commercial machine (Stanford)
http://www.lynceantech.com/

Tsinghua University/Beijing

Similar recent projects

MIT
Yb:YAG Oscillator
Yb: YAG Preamp
Yb:YAG Multi-pass amp

KEK/Japan

Compton program in KEK, J. Urakawa (KEK)
From 2011.9 to 2012.7 at STF

Super Cavity
Beam Dump
X-ray Detector

MIT

SRF photo-injector
Bunch compressor
RF amp
RF amp

1 mA, 25 MeV electron beam
6 m
1.5 m

Super Conduction Accelerator

Photo-cathode RF Gun
RF Gun Laser

x-rays
Mirror
Interaction Point
Septum
Kicker
RF cavity
Accelerator section
RF photocathode gun
UV laser
IR mode-locked laser
Laser systems for Compton scattering

Very simple in principle:

*One has to shoot and electron beam with a laser beam*

but much less easy in reality ...
Main drawback of Compton scattering: the flux

Compton/Thomson cross section $\sigma_T$ is very small

$$\text{Flux}_{cw} \propto \frac{\lambda P_L I_e \sigma_T}{\sqrt{\sigma_{\text{electron}}^2 + \sigma_{\text{laser}}^2}}$$

$I_e$: electron beam intensity  
$P_L$: laser power  
$\lambda$: laser beam wavelength  
$\sigma_{\text{electron}}$: electron beam size r.m.s  
$\sigma_{\text{laser}}$: laser beam size r.m.s
Experimental limitations: effect of e⁻ beam divergence

\[ \sigma^2_{\text{transverse}} = \varepsilon_{\text{transverse}} \beta^* \]

An example (ThomX), for fixed emittances energy distribution along the \( \theta=0 \) axis

For fixed emittances \( \varepsilon \):

- Decrease of the e_beam size
  - increase divergence (\( \beta^* \))
  - univocal energy-angle correlation lost
  - smearing of the energy\%angle distribution

\[ \sigma_{\text{transverse}} = \varepsilon_{\text{transverse}} \beta^* \]

High focalisation increases the flux but worsen the monochromaticity ...

The real issue to increase the flux while keeping monochromaticity is the laser beam power ...
A technical solution to reach high laser average power: Fabry-Perot cavity

Principle
Fabry-Perot cavity in pulsed regime

1ps Pulsed laser

Electron beam

Fabry-Perot cavity with Super mirrors

Difference between continuous and pulsed regime
Pulsed_laser/cavity feedback technique

Specificity ➔ properties of passive mode locked laser beams

Frequency comb ➔ all the comb must be locked to the cavity
➔ Feedback with 2 degrees of freedom: control of the Dilatation & translation

$$T = \frac{2\pi}{\omega_r}$$

$$\omega_n = n\omega_r + \omega_0$$

$$n \approx 10$$


State of the art (Garching MPI): ~70kW, 2ps pulses @78MHz, stored in a cavity
~20kW, 200fs pulses @78MHz

(O.L.35(2010)2052)
The ThomX Cavity demonstrator, MightyLaser

1. Our setup/goal
2. The ATF 4-mirror cavity
3. The optical scheme
4. The laser/cavity feedback
French Japanese Collaboration

F. Labaye, E. Cormier, CELIA CNRS Université Bordeaux 1, Bordeaux, France
T. Akagai, S. Miyoshi, S. Nagata, T. Takahashi, Hioshima University, Hiroshima, Japan
S. Araki, S. Funahashi, Y. Honda, T. Omori, H. Shimizu, T. Terunuma, J. Urakawa, KEK, Tsukuba, Japan
Y. Peinaud, V. Soskov, A. Variola, F. Zomer, LAL CNRS/IN2P3 Université Paris-Sud 11, Orsay, France
R. Flaminio, L. Pinaord, LMA CNRS/IN2P3, Lyon, France
STEP ONE: commissioning a 4-mirror cavity at ATF, done end 2010

STEP TWO: upgrade mirrors & laser power

Oscillator
\[ \bar{P} = 0.2 \text{W}, \ 1030\text{nm} \]
\[ \Delta t \approx 0.2 \text{ps} \]
\[ \text{frep} = 178.5\text{MHz} \]

Amplifier
photonic fiber
Yb Doped

4-mirror Fabry-Perot cavity
Gain \approx 1000 \rightarrow 10000

\[ \bar{P} \approx 5\text{W} \rightarrow 100\text{W} \]

STEP ONE (done end 2010)
With cavity laser/coupling \approx 50\%
\[ \Rightarrow \text{Power}_\text{cavity} \approx 2.5\text{kW} \]

STEP TWO
With cavity laser/coupling \approx 50\%
\[ \Rightarrow \text{Power}_\text{cavity} \approx 250\text{kW} \]

Numerical feedback

ATF clock

~7/\gamma/bunch-Xsing (E_{\text{max}}=28\text{MeV})

~1500/\gamma/bunch-Xsing

Final goal: to reach the MW average power
Cavity installation on the Accelerator Test Facility (ATF) at KEK

~ 54 m

Electron beam energy → 1.28GeV

Beam Size → 100μm × 10μm

Emittance → 1.0x10⁻⁹ rad.m
1.0x10⁻¹¹ rad.m (Ultra Low !!)

γ Detector (BaF2 Xtal)
-Stable solution: **4-mirror cavity** as in Femto laser technology

-BUT

- elliptical & linearly polarised eigen-modes which are instable because of vibrations at very high finesse

-Non-planar 4-mirror cavity

- Stable & circularly polarised eigenmodes (AO48(2009)6651) as needed for an ILC polarised positron source

Small laser beam size + stable resonator ➔ **2-mirror cavity**

Laser input

$e^-$ beam
Mirror positioning system

- 2 spherical mirrors
- 2 flat mirrors
- Invar base to ensure length stability
- 12 encapsulated Motors
- Mounting in class 10 room
- Gimbal mirror mounts for vacuum
- Laser
- E-
The laser amplification R&D

- We use Ytterbium doped photonic crystal fiber as amplifier

Ø core = 40 µm
Ø cladding = 200 µm

- We obtained 50W average power (~stable)
- 800W (11µJ/pulse) demonstrated with the same technique *Limpert, OL35(2010)94*
Numerical Pound-Drever-Hall feedback

Rétroaction on laser frequency

Clk = 100 MHz
8x ADC 14 bits
8x DAC 14 bits => Filtering => 18 bits / 400 kHz
FPGA Virtex II
Cavity locked \( (gain \sim 10000) \)

- Digital feedback (5k VHDL lines of code)
- Already \( \Delta f_{rep}/f_{rep} \sim 10^{-11} \) \( \Rightarrow \Delta f_{rep} \sim 7.6\text{mHz} \) for \( f_{rep} \sim 76\text{MHz} \)

We developed this feedback system to lock a Ti:sapph laser oscillator to a 30000 finesse cavity at Orsay.
We have also locked the 4-mirror ATF cavity at Orsay.
Only when the cavity is locked…Compton every turn.
Low power, next shift higher power…
• Thank you