Developments of optical resonators and optical recirculators for Compton X/γ ray machines

Aurélien MARTENS for MightyLaser, ThomX, ELI-NP-GS

LAL, CELIA, KEK, LMA, INFN, Alsyom, Amplitude
Applications of Compton scattering: $e^- + h\nu \rightarrow e^- + X/\gamma$

Compton energy threshold for $\lambda_{\text{laser}} = 1\mu\text{m}$

Low energy applications
- Radiography & Radiotherapy
- Museology

~10-1MeV

High energy applications
- Nuclear physics
- Nuclear survey
- Nuclear waste management
- Compton polarimeter
- $\gamma\gamma$ collider
- Polarised positron source

~1MeV-100MeV

>100MeV
Examples of ICS sources

**LINAC solution**
- 😞 lower repetition rate
- but 😊 better beam quality (0.5% BW, $10^9$ ph./s)

**Ring solution**
- 😊 higher repetition rate
- but ☹ lower beam quality (few % BW, $10^{13}$ ph./s)
Storage ring solution

RF Gun \quad LINAC \quad Electron bunches

Laser

Compton photon

LINAC solution
\rightarrow \bigcirc \text{ lower repetition rate}
\rightarrow \text{ but } \bigcirc \text{ better beam quality (0.5\% BW, } 10^9 \text{ ph./s)}

RF Gun \quad LINAC

Electron bunch

Ring solution
\rightarrow \bigcirc \text{ higher repetition rate}
\rightarrow \text{ but } \bigcirc \text{ lower beam quality (few \% BW, } 10^{13} \text{ ph./s)}

Photon'15, Novossibirsk, Russia, 19/06/2015

Aurélien MARTENS
ThomX

~50 MeV ring, 1 nC
→ complicated electron dynamics
17.8 MHz repetition rate
4-mirror planar optical cavity

10^{11} - 10^{13} γ/s
1%-10% spectral bandwidth (w/ diaphragm)
10 mrad divergence w/o diaphragm
Oscillator phase-noise control is critical:

\[
\frac{\Delta \nu}{\nu_{\text{opt}}} = 3 \cdot 10^{-12}
\]

\[
\Delta \nu \sim 1kHz
\]

Choice of oscillator requires R&D:

- Commercial vs home made (CELIA) lasers

R&D on numeric feedback to lock the oscillator on:
- the optical cavity
- the accelerator RF
Three-stage CPA amplification R&D
→ micro-structured fibres
→ Ytterbium doped fibres
→ connections must be robust, stable, reliable
100W obtained regularly in output

State of the art, best effort:
ThomX R&D challenges

Optics R&D:
- Thermal effects in compressor (CVBG)
- Thermal effects in optical cavity:
  - substrate choice
  - Spatial mode matching (adaptive optics)

Thermal loading of the cavity takes few 100 ms ($P_{\text{trans}}$ reduces)

$P_{\text{trans}} \approx 0.4 P_{\text{trans}}$

H. Carstens et al., ASSL JTh5A (2013) 3

Photon'15, Novosibirsk, Russia, 19/06/2015
Aurélien MARTENS
Past results: MightyLaser

Results obtained at the KEK ATF: collaboration with KEK colleagues
1.08MHz collision rate, ~1nC beam charge, 1.3GeV damping ring

Finesse ~ 30000
~50W seed laser-power
~100 γ/crossing @ ~25MeV
$P_{\text{cavity}} > 100\text{kW}$ (transient regime)
40kW (continuous regime)

Photon yield as function of time measured with BaF2 scintillator block + PM
→ Observation of emittance evolution
→ Exhaustion of the electron beam

Optics being re-commissioned at LAL:
→ >10kW with 25W incident (finesse 3000 cavity)
→ x3 in coupling (better mode matching)
LINAC solution

→ 😞 lower repetition rate
→ but 😊 better beam quality (0.5% BW, $10^9$ ph./s)

Ring solution

→ 😊 higher repetition rate
→ but 😞 lower beam quality (few % BW, $10^{13}$ ph./s)
Tight constraints on photon beam:
→ divergence <0.2 mrad
→ beam spot at 10 m <1 mm
→ bandwidth (BW) <0.5%
→ av. spectral density @20 MeV: 8x10^3 (s.eV)^{-1}
→ brilliance 1x10^{22} / (s.mm^2.mrad^2.0.1%BW)

D. Habs et al., arXiv:1008.5336

Curtis et al. Optics Letters 36 2164 (2011)

State of the art laser systems required

ELI-NP-GS in a nutshell
Start-to-end simulation → optimize geometry to maximize spectral density \((\text{ph}/(\text{s.eV}))\) averaged over the number of passes \((N=32)\)

\[ K. \text{ Dupraz et al, Phys. Rev. ST Accel. Beams 17 033501 (2014)} \]
Tight constraints on alignment & synchronisation:

- Transverse spread of IPs $\sim 3 \, \mu m$, typical divergence $< \text{few} \, \mu \text{rad}$
- Synchronisation $< 200$fs

ELI-NP-GS alignment, synchronisation

100μm, 100μrad alignment 
NOT ACCEPTABLE

Dedicated alignment 
procedure required

Demonstration of the synchronisation:
→ few 100fs for 1 pass with a 3 ps laser
→ Experimental setup being updated with a few 200fs laser
→ Robustness to environmental fluctuations required

Beam quality depends strongly on:
→ Parabola optical micro-structure
→ Avoid peaks in surface PSD
→ Constrain PSD shape
→ $\sigma_{\text{RMS}} < 10\text{nm}$
→ Good polishing company required

Original solution for high spectral density ICS source
→ Proof-of-principles and detailed simulations show it is feasible
→ Detailed prototype studies to be done in the autumn
→ Main challenges related to optics quality, synchronisation, alignment

Active R&D on high average flux ICS source
→ Few 10kW operations routinely demonstrated in an accelerator (KEK)
→ Naive scaling  few 100kW are reachable
→ Requires understanding and mitigation of thermal effects, and new effects that could dominate in the ~MW regime

What is the limit of the technology for high finesse cavities in pulsed regime?
Backup slides

- two separate optical ring cavities and two laser beams
- optical path requires vacuum beam pipes
- geometry based on the TESLA detector

Mechanical stability ☹
Optics breakdown fluence ☹ Surface quality for large optics ☹
Cannot cope with 30MW in cavity ☹ need to empty cavity between trains
Dedicated laser locking procedure in this regime
Laser phase noise must be controlled ☹
Another $\gamma\gamma$ collider design

Asner et al., hep-ex/0111056
Bogacz et al., arXiv:1208.2827

\[ \text{~150 bunches 10 trains at 100Hz rep. Rate} \]

\[ \text{~1J per pulse few ps} \]
\[ \text{~10-20}\mu\text{m laser focalisation} \]
\[ \text{200000 pulses/sec} \]

\[ \text{Optical recirculator or resonator required} \]

\begin{table}
\begin{tabular}{ | l | c | c | c |}
\hline
Variable & Symbol & CLICHE [3] & SAPPHiRE \\
\hline
\hline
Laser beam parameters & & & \\
Wavelength & $\lambda_L$ & 0.351 $\mu$m & 0.351 $\mu$m \\
Photon energy & $h\omega_L$ & 3.53 eV = $5.65 \times 10^{-19}$ J & 3.53 eV \\
Number of laser pulses per second & $N_L$ & 169400 s$^{-1}$ & 200000 s$^{-1}$ \\
Laser peak power & $W_L$ & $2.96 \times 10^{22}$ W/m$^2$ & $6.3 \times 10^{21}$ W/m$^2$ \\
Laser peak photon density & & $5.24 \times 10^{40}$ photons/m$^2$/s & $1.1 \times 10^{40}$ photons/m$^2$/s \\
\hline
Photon beam & & & \\
Number of photons per electron bunch & $N_{\gamma}$ & $9.6 \times 10^{9}$ & $1.2 \times 10^{10}$ \\
$\gamma\gamma$ luminosity for $E_{\gamma\gamma} \geq 0.6E_{CM}$ & $\mathcal{L}_{\gamma\gamma}^{\text{peak}}$ & $3.6 \times 10^{33}$ cm$^{-2}$s$^{-1}$ & $3.6 \times 10^{33}$ cm$^{-2}$s$^{-1}$ \\
\hline
\end{tabular}
\end{table}
GBS Collimation

Inside vacuum chamber

Bandwidth vs collimator gap @ 13 MeV

Counts

12.4 12.5 12.6 12.7 12.8 12.9 13

2.0 mm (0.7%) 1.5 mm (0.5%) 1.1 mm (0.4%) 0.6 mm (0.3%)
ELI-NP-GBS polarization

Photon'15, Novossibirsk, Russia, 19/06/2015

Aurélien MARTENS
Optics surface quality

Macrostructure

PSD