Inverse Compton Scattering X-ray source

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Current lab X-ray sources

- Broadband with few characteristic lines
- Large photon flux but limited brilliance

Liquid gallium anode:
2.6×10^{10} \text{ photons s}^{-1} \text{ mm}^{-2} \text{ mrad}^{-2}
Brilliance

Synchrotron bending magnet (DUBBLE @ ESRF)

Brilliance (phot/s/mm²/mrad²/0.1%)

X-ray energy (keV)
Brilliance

Synchrotron bending magnet (DUBBLE @ ESRF)

liquid Ga K\textsubscript{\alpha} (Excillum)

rotating anode W K\textsubscript{\alpha}

Brilliance (phot/s/mm\textsuperscript{2}/mrad\textsuperscript{2}/0.1\%)

X-ray energy (keV)
Brilliance

- Synchrotron bending magnet (DUBBLE @ ESRF)
- Inverse Compton Scattering (Smart*Light)
- liquid Ga K$_\alpha$ (Excillum)
- rotating anode W K$_\alpha$
Inverse Compton Scattering
(Smart*Light)

Brilliance (phot/s/mm²/mrad²/0.1%)

X-ray energy (keV)

Synchrotron bending magnet (DUBBLE @ ESRF)

Inverse Compton Scattering (Smart*Light)

liquid Ga Kα (Excillum)

rotating anode W Kα
Inverse Compton Scattering (ICS)

\[ x = \frac{0}{4} \left(1 + \frac{2}{2} \right)^2 \]

- X-rays emitted in narrow cone, half angle \( \gamma^{-1} \)
- X-ray energy dependent on emission angle
- 1% energy spread if \( \theta < 0.1 \gamma^{-1} \)

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<thead>
<tr>
<th>Electron energy</th>
<th>Lorentz factor ( \gamma )</th>
<th>X-ray wavelength</th>
<th>X-ray energy</th>
<th>Emission angle 0.1 ( \gamma^{-1} )</th>
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<td>9 mrad</td>
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ICS sources: Lyncean
first commercial ICS source

Hard X-ray phase-contrast imaging with the Compact Light Source based on inverse Compton X-rays

Journal of Synchrotron Radiation
ISSN 0909-0495

Received 6 September 2008
Accepted 23 October 2008

Martin Bech,a,* Oliver Bunk,b Christian David,b Ronald Ruth,c,d Jeff Rifkin,c Rod Loewen,c Robert Feidenhansˈl,a and Franz Pfeiffer,b,e,*
ICS sources: Lyncean

*first commercial ICS source*

- 80 μm source size
- 15-36 keV x-ray energy
- $4 \times 10^9$ ph/s flux in 3% BW

Monochromatic computed tomography with a compact laser-driven X-ray source

K. Achterhold¹, M. Bech¹, S. Schleede¹, G. Potdevin¹, R. Ruth², R. Loewen³ & F. Pfeiffer¹

Published 21 February 2013

absorption computer
tomography of a mouse
ICS sources: ThomX

Electron machine under construction

- 10-20 ps
- 4 mm, mrad
- 70 mm
- 20 MHz Rep.
- 50-70 MeV
- 1 nc/bunch, 50 Hz inj.

- X-ray beam

- Injector + Linac
- Accelerating section 50-70 MeV
- Ring (20 mA)
- Ring (20 mA)
- Users

- X-ray torus

- FP cavity
- 4-mirrors + laser

- Optical cavity amplifieration
- Optical cavity amplifieration

- Pulsed laser: ps, ~10^6 average

- ICS stored inside the cavity

- E = 1 MeV

- 2 MW/pulse

- Gain 10^6

- (20-30 mJ/pulse)
ICS sources: ThomX
under construction

- 2017: installation & commissioning
- 2018: first X-ray users
LINAC-based ICS sources: why?

- Lower emittance beams ➔ higher X-ray coherence
- Easier alignment, *fast change of X-ray energy*

![Diagram showing LINAC-based ICS source]

- RF potogun
- Solenoid
- X-band LINAC accelerator
- Quadrupole focusing triplet
- Dipole bending magnet
- Beam dump

**Burst mode**
- Electron beam
- Recirculated pulsed laser beam
- X-ray beam
LINAC-based ICS sources: why?

- Deceleration option: strongly reduced shielding requirements
- Will fit into sea container

• Lower emittance beams \(\Rightarrow\) higher X-ray coherence
• Easier alignment, fast change of X-ray energy
Enabling technology: compact 12 GHz X-band LINAC

Developed by CERN, PSI and VDL-ETG collaboration

X-band test facility @ PSI

- 12 GHz accelerator structure
- 40 MeV/m average gradient

1 m long accelerator structure sufficient for generating up to ~100 keV monochromatic X-ray beams
Enabling technology: electron guns, pulsed lasers

5 MeV low-emittance RF photogun developed at TU/e

*Coherence X-ray beam ultimately limited by emittance electron gun*

Spectacular development industrial pulsed fiber laser technology

Commercially available compact, high-power, femtosecond fiber lasers
200 fs, 2mJ @ 10 kHz
Enabling technology: high-power optical circulator

FIG. 2. Isometric view of ELI-NP-GBS recirculator. The mirror $M_0$ is used to inject the incident laser beam. The mirror-pair system (structures positioned on a circular helix) and the laser beam paths (green lines) are located between two parabolic mirrors $M_1, M_2$. Two of the 32 recirculation passes (green lines) are drawn. The polarization vectors $s_{in}$ and $p_{in}$ related to the incoming laser beam are also shown. The 7 degrees of freedom for the mirror motions are sketched: two tilts for $M_0$; two tilts and three translations for $M_2$. The inset scheme shows the optical pass ordering.
LINAC-based ICS sources: CXLS

W.S. Graves et al., funded

TABLE I. Estimated performance at 0.1\% and 5\% bandwidth for 12.4 keV x rays from the compact source.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0.1% bandwidth</th>
<th>5% bandwidth</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy</td>
<td>12.4</td>
<td>12.4</td>
<td>keV</td>
</tr>
<tr>
<td>Average flux</td>
<td>$2 \times 10^{10}$</td>
<td>$5 \times 10^{11}$</td>
<td>phot/s</td>
</tr>
<tr>
<td>Average brilliance</td>
<td>$7 \times 10^{12}$</td>
<td>$2 \times 10^{12}$</td>
<td>photons/(sec mm$^2$ mrad$^2$ 0.1%)</td>
</tr>
<tr>
<td>Peak brilliance</td>
<td>$3 \times 10^{19}$</td>
<td>$9 \times 10^{18}$</td>
<td>photons/(sec mm$^2$ mrad$^2$ 0.1%)</td>
</tr>
<tr>
<td>rms horizontal opening angle</td>
<td>3.3</td>
<td>4.3</td>
<td>mrad</td>
</tr>
<tr>
<td>rms vertical opening angle</td>
<td>3.3</td>
<td>4.3</td>
<td>mrad</td>
</tr>
<tr>
<td>rms horizontal source size</td>
<td>2.4</td>
<td>2.5</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>rms vertical source size</td>
<td>1.8</td>
<td>1.9</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>rms pulse length</td>
<td>490</td>
<td>490</td>
<td>fs</td>
</tr>
<tr>
<td>Photons/pulse</td>
<td>$2 \times 10^{5}$</td>
<td>$5 \times 10^{6}$</td>
<td>...</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>100</td>
<td>100</td>
<td>kHz</td>
</tr>
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Compact x-ray source based on burst-mode inverse Compton scattering at 100 kHz

W. S. Graves,$^{1,*}$ J. Bessuille,$^2$ P. Brown,$^2$ S. Carbajo,$^3$ V. Dolgashev,$^4$ K.-H. Hong,$^1$ E. Ihloff,$^2$
B. Khaykovich,$^1$ H. Lin,$^1$ K. Murari,$^3$ E. A. Nanni,$^1$ G. Resta,$^1$ S. Tantawi,$^4$ L. E. Zapata,$^{1,3}$
F. X. Kärtner,$^{1,3}$ and D. E. Moncton$^1$
LINAC-based ICS sources: Smart*Light

starts in 2017
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5 MeV RF photogun
Q = 10–100 pC,
ε_n = 0.15–0.5 mm mrad
1 kHz RF pulses
100 bunches/RF pulse

5 MeV RF photogun
45 MeV
X-ray beam

burst mode
electron beam

recirculated laser beam

1 kHz, 10 mJ laser
100× recycled in optical cavity
⇒ 10^5 colliding pulses/sec
in 5 μm laser beam waist
X-ray photon flux and brilliance

Total number of X-ray photons produced:

\[ N_{x,\text{total}} = N_e N_0 \frac{\sigma_T}{2\pi w_0^2} \]

Thomson cross section: \( \sigma_T = 6.6 \times 10^{-29} \text{ m}^2 \)

10 mJ laser pulse: \( N_0 = 2 \times 10^{16} \)

bunch charge \( Q = 10 \text{ pC} \Rightarrow N_e = 6 \times 10^7 \)

laser beam waist \( w_0 = 5 \mu\text{m} \)

\[ \Rightarrow N_{x,\text{total}} = 5 \times 10^5 \text{ photons per pulse} \]

**How many photons per second?**

- LINAC operates at 1 kHz rep rate
- amplified pulsed laser operates at 1 kHz
- 100 electron bunches per RF pulse
- recycle laser pulses 100 times in optical cavity
- \( \Rightarrow 10^5 \) pulses per second

\[ N_{x,\text{total}} = 5 \times 10^{10} \text{ ph s}^{-1} \]

**Few micron spot size, few mrad divergence**

\( \sim 10^{14} \text{ photons s}^{-1} \text{ mm}^{-2} \text{ mrad}^{-2} \)
X-ray photon flux and brilliance

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Few micron spot size, few mrad divergence
~10^{14} \text{ photons s}^{-1}\text{ mm}^{-2}\text{ mrad}^{-2}

Liquid gallium anode:
2.6\times10^{10} \text{ photons s}^{-1}\text{ mm}^{-2}\text{ mrad}^{-2}
X-ray photon flux and brilliance

Total number of X-ray photons produced:

\[ N_{x,\text{total}} = N_e N_0 \frac{\sigma_T}{2\pi \nu_0^2} \]

Number of photons per bandwidth:

\[ N_x = N_{x,\text{total}} \cdot \frac{12}{\pi} \frac{\Delta E}{E} \approx 0.004 \cdot N_{x,\text{total}} \text{ in } 0.1\% \text{ bandwidth} \]

Theoretically achievable brilliance:

\[ B \approx 10^{12} - 10^{13} \text{ ph} \cdot \text{s}^{-1} \cdot \text{mm}^{-2} \cdot \text{mrad}^{-2} \cdot (0.1\% \text{ BW}) \]

- Brilliance comparable to synchrotron bending magnet radiation (DUBBLE @ ESRF);
- Full calculation complicated due to interplay energy spread, emittance, pulse length, bunch length and Rayleigh length, etc;
X-ray photon flux and brilliance

Brilliance (phot/s/mm²/mrad²/0.1%)

Synchrotron bending magnet
(DUBBLE @ ESRF)

Inverse Compton Scattering
(Smart*Light)

liquid Ga Kα (Excillum)

rotating anode W Kα

X-ray energy (keV)
Two scenarios:

A

Optical mirror

few μm source size

Optical mirror

Laser beam

X-ray beam

sample

mm spots size

(μ-)XRD, (μ-)XRF

B

Phase Contrast Imaging

Electron beam

10 cm spots size

source size
Two scenarios:

A

Optical mirror

few μm source size

Optical mirror

Laser beam

X-ray focusing optics

sample

few μm spots size

(μ-)XRD, (μ-)XRF

B

Phase Contrast Imaging

Electron beam

10 cm spots size
Two scenarios:

(A): (μ-)XRD, (μ-)XRF; (B) Phase Contrast Imaging
A: Coherent & narrow-bandwidth pencil beam
GPT simulations 30 MeV beam

Source size:
- Source size: 7 μm
- Angular spread: 2.6 mrad

GPT simulations:
- $\text{Std}(x) = 3.57291$
- $\text{Std}(y) = 3.67496$
- $\text{Std}(B_x) = 0.0769206 \, \text{1/gam}$
- $\text{Std}(B_y) = 0.0731299 \, \text{1/gam}$
B: Coherent divergent beam
GPT simulations 30 MeV beam

Source size

Angular spread

6 μm
3 μm
30 mrad
64 mrad

std(x) = 2.876
std(y) = 1.47698

std(Bx) = 0.402683 1/gam
std(By) = 1.06582 1/gam
Summary

- Inverse Compton Scattering Source for tunable, monochromatic and highly coherent X-ray beams in a compact setup
- Required accelerator and pulsed laser technology available
- Achievable hard X-ray brilliance several orders of magnitude higher than current lab sources
- Achievable hard X-ray brilliance comparable to synchrotron bending magnet radiation (DUBBLE @ ESRF)