Self-seeding techniques for hard X-ray FELs using a single-crystal monochromator

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Self-seeding techniques and their importance for XFELs

SASE pulses, baseline mode of operation: poor longitudinal coherence

$$\frac{\Delta \omega}{\omega} \sim 2 \rho \sim 10^{-3}$$

$$\left( \frac{\Delta \omega}{\omega} \right)_{\text{spike}} \sim \frac{1}{\sigma_T \omega} \sim 10^{-5}$$

- Hundreds of longitudinal modes
- A lot of room for improvement
- Self-seeding schemes answer the call for increasing longitudinal coherence

Figure 5.2.4 Temporal (top) and spectral (bottom) structure for 12.4 keV XFEL radiation from SASE 1. Smooth lines indicate averaged profiles. Right side plots show enlarged view of the left plots. The magnetic undulator length is 130 m.

Method historically introduced for soft x-rays in: J. Feldhaus et al., Optics Comm. 140, 341 (1997)
- Linearly amplified SASE is filtered through a grating monochromator
- Electron beam bypass washes-out beam microbunch, makes up for x-ray path delay by grating and allows for grating installation
- Demodulated beam is seeded in the output undulator

Grating monochromator substituted by crystal monochromator for applications to hard-x rays: [E. Saldin, E. Schneidmiller, Yu. Shvyd'ko and M. Yurkov, NIM A 475 357 (2001)]

Extra x-rays path due to monochromator ~1cm. Long electron bypass (tens of meters) needed
Double-bunch self-seeding with a four-crystal monochromator

Method based on production of two identical bunches separated by an RF period [see O. Grimm K. Klose and S. Schreiber, EPAC 2006, THPCH150, Edinburgh]

Developed independently in:
- G. Geloni, V. Kocharyan and E. Saldin, DESY 10-053
Self-seeding techniques with a single-crystal monochromator
First part: usual SASE → linear regime pulse

Weak chicane ($R_{56} \sim$ several $\mu$m) for:
- Creating a small offset (a few mm) to insert the monochromator
- Washing out the electron beam microbunching
- Acting as a tunable delay line

The photon pulse from SASE goes through the monochromator

Photon and electron pulses are recombined
The monochromator hardware is constituted by a single crystal in Bragg geometry. The forward diffracted beam is considered. Transmissivity (modulus and phase) can be calculated using the dynamical theory of X-ray diffraction.

Alignment can be performed with the help of a suitable detector. This fixes the central frequency of the filter transmittance.
The single-crystal monochromator principle: frequency vs. time

Temporal Window ~1μm
Feasibility study for LCLS (I)

LCLS baseline undulator (33 cells)

11 cells

SASE undulator

Weak chicane

9 cells/12 cells

Output undulator
(uniform)

12 cells/off

Output undulator
(tapered)

Self-seeded
X-ray pulse

electrons

Single crystal

100 GW-level
Fully-coherent
Self-seeded
X-ray pulse

4 \times 10^{11} \text{ photons}

5 \text{ fs (FWHM)}

at 0.15 \text{ nm}

low charge
(0.02 \text{ nC}) mode of
operation

105 cells

4m-long magnetic chicane

\text{R}_{56}=12 \mu \text{m}

Parameters for the low-charge mode of operation at LCLS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
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<tr>
<td>Undulator period</td>
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<td>K parameter (rms)</td>
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<td>Bunch length (rms)</td>
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<td>Normalized emittance</td>
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<td>Energy spread</td>
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<td>1.5</td>
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</tbody>
</table>

Gianluca Geloni, European XFEL Users’ Meeting, 26 January 2011
Feasibility study for LCLS (II)

After 11 cells

Efficient seeding mechanism
(monochromatic tail much larger than shot noise) is achieved

After the Diamond crystal
Feasibility study for LCLS (III)

Spectrum at saturation without tapering

Energy without tapering

Power distribution at saturation with no tapering

12 cells
Output
Undulator (no tapering)

12 cells
Output
Undulator (no tapering)
Feasibility study for LCLS (IV)

9 Uniform + 12 Tapered = 21 cells (84 m)

Energy with tapering

Spectrum at saturation with tapering

Power distribution at saturation with tapering
Feasibility study for the European XFEL (I)

5m-long magnetic chicane

$R_{56}=12\mu m$

Parameters for the short pulse mode of operation

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<td>mm mrad</td>
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<tr>
<td>Energy spread</td>
<td>MeV</td>
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</tbody>
</table>
About 30000 bunches/s vs. 10 bunches/s

→ Heat loading much more severe for European XFEL

→ Cannot increase length of first undulator part

→ Relevant SASE contribution
Three-undulator setup

Small SASE contribution: at the second filter BW nearly Fourier limited already
Tapering scheme

Similarly as for LCLS to increase output power/brightness
Feasibility study for the European XFEL

10 Uniform + 18 Tapered = 28 cells

Energy with tapering

Spectrum at saturation with tapering

Power distribution at saturation with tapering
Conclusions

- Solves the problem of poor longitudinal coherence for hard x-ray FELs
  - Bandwidth down to $10^{-4}$ for $Q=0.02$ nC

- Low cost
  - No need for long electron bypass
  - No need for special photo-injector setup
  - Only needs: 1 weak chicane + 1 crystal within a single segment

- Robust
  - Baseline mode of operation is not disturbed