Overview of Self-Seeding at X-ray FEL Facilities
Gianluca Geloni, European XFEL
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- A short introduction to self-seeding
- Working Self-Seeding installations
  - LCLS (SXRSS and HXRSS)
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- Outlook and Conclusions
A short introduction to self-seeding

Method first introduced for soft x-rays [J. Feldhaus, E. Saldin, J. Schneider, E. Schneidmiller, M. Yurkov, Optics Comm. 140, 341 (1997)]: basically an active filter in frequency

First part: usual SASE pulse in the linear regime
Chicane needed for:
- Creating an offset 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

Independently of Self-Seeding:
- Chicane for 2 colors...
- Chicane for autocorrelation...
- Chicane for DD scan...

Challenging: compensating the optical delay from the mono within a compact setup
A short introduction to self-seeding

Method made “easy” for HXR
Single-crystal mono

A short introduction to self-seeding

![Graphs showing Abs[T] and Arg[T] vs. λ [nm] and Abs[FT(T)] and Arg[FT(T)] vs. s [μm].]
A short introduction to self-seeding

Note: notch-shape changes the profile, but not principal

A short introduction to self-seeding

Reflection self-seeding at SACLA

Ichiro Inoue1, Taito Osaka1, Takahiro Inagaki1, Shunji Goto1,2, Toru Harai, Yuichi Inubushi1,2, Ryota Kinjo1, Haruhiko Ohashi1,2, Takashi Tanaka1, Kazuaki Togawa1, Kensuke Tono1,2, Hitoshi Tanaka1, and Makina Yabashi1,2

Recent reflection-based mono at SACLA

A micro channel-cut crystal X-ray monochromator for a self-seeded hard X-ray free-electron laser

Taito Osaka1, Ichiro Inoue1, Ryota Kinjo1, Takashi Hirano1, Yuki Morioka1, Yasuhiro Sano1, Kazuto Yamauchi1 and Makina Yabashi1,2

Averaged spectrum of the seed measured with a Si(220) channel-cut crystal. The number of accumulation at each point is 100 shots. The central photon energy is 10 keV
A short introduction to self-seeding

Nominal energy range: 500 eV - 1000 eV

930 eV
4.3 GeV
Self-Seeding installations: SXRSS at the LCLS

LCLS Parameters:
- Electron energy: up to 14 GeV
- Undulator length: 33 segments x3.4m magn. length
- Undulator period: 30 mm
- Peak current: 2-4kA
- Spectral reach: 280eV-12.8keV

Best SASE reaches a maximum average brightness of ~90k counts on this scale, Best Seeded with a large SASE pedestal reaches an average brightness of ~150k on this scale.

Thanks to A. Lutman for data, slides and discussions
Self-Seeding installations: SXRSS at the LCLS

1\textsuperscript{st} Undulator section makes SASE, that gets monochromatized in the SXRSS chicane
2\textsuperscript{nd} Undulator section amplifies the seed, should not reach saturation to have second color
3\textsuperscript{rd} Undulator section makes SASE at a different color.

Developed for stimulated resonant inelastic x-ray scattering (sRIXS) experiment (Rohringer July 2015)

Thanks to A. Lutman for data, slides and discussions
Overview of self-seeding at x-ray FEL facilities

HXRSS mode between 4.5 keV and 11 keV
Pulse energy < 400 µJ (average), up to 30 fs
XTCAV allows diagnosing e-beam long. Phase space
E-beam manipulation impacts on seeded pulses

First experimental verification at the LCLS (Jan 2012): J. Amann, Nature Photonics 6, 693 (2012)

Thanks to A. Lutman for data, slides and discussions
Self-Seeding installations: HXRSS at the LCLS

Multiple colors (within SASE BW)

Combination with fresh bunch

Still B increase for usual self-seeding is 12.5/2.4 = 5.2

And FBSS can be used at low rep-rate

Comment: could be problematic at high rep-rate (crystal heat-load)

A.A. Lutman et al., PRL 113, 254801 (2014)

C. Emma et al, APL, 2017

Thanks to A. Lutman for data, slides and discussions
Self-Seeding installations: HXRSS at the LCLS

Comparison best seed vs. best SASE ever (6mJ scaled) after a mono with rectangular 1eV BW response function

**Self-Seeded**

<table>
<thead>
<tr>
<th></th>
<th>Average Energy</th>
<th>Average Energy in 1.088 eV</th>
<th>Fluctuations</th>
<th>Fluctuations in 1.088 eV</th>
<th>Strongest Shot</th>
<th>Strongest Shot in 1.088 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 fs Full set</td>
<td>0.390 mJ</td>
<td>0.255 mJ</td>
<td>55%</td>
<td>58%</td>
<td>1.08 mJ</td>
<td>0.675 mJ</td>
</tr>
<tr>
<td>30 fs Full set</td>
<td>0.752 mJ</td>
<td>0.482 mJ</td>
<td>42%</td>
<td>54%</td>
<td>1.80 mJ</td>
<td>1.45 mJ</td>
</tr>
<tr>
<td>50 fs Bunch energy filtered</td>
<td>0.49 mJ</td>
<td>0.33 mJ</td>
<td>43%</td>
<td>43%</td>
<td>1.08 mJ</td>
<td>0.675 mJ</td>
</tr>
<tr>
<td>30 fs Bunch energy filtered</td>
<td>0.89 mJ</td>
<td>0.57 mJ</td>
<td>33%</td>
<td>45%</td>
<td>1.80 mJ</td>
<td>1.45 mJ</td>
</tr>
</tbody>
</table>

**SASE**

<table>
<thead>
<tr>
<th></th>
<th>Average Energy</th>
<th>Average in 1.088 eV</th>
<th>Fluctuations</th>
<th>Fluctuations in 1.088 eV</th>
<th>Average x 4 in 1.088 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7 mJ SET</td>
<td>3.7</td>
<td>0.25 mJ</td>
<td>9%</td>
<td>45-60%</td>
<td>1 mJ</td>
</tr>
<tr>
<td>6 mJ SCALED</td>
<td>6</td>
<td>0.4 mJ</td>
<td>9%</td>
<td>45-60%</td>
<td>1.6 mJ</td>
</tr>
</tbody>
</table>

Average x 4 is listed to generally take into account SASE fluctuation within bandwidth.

Thanks to A. Lutman for data and discussions

Thanks to A. Lutman for data, slides and discussions

Intensity on the spectrometer was saturated

Similar behavior is reported as concerns average and most intense shots
Self-Seeding installations: HXRSS at SACLA (transmission)

- Electron energy: up to 8.5 GeV
- Undulator length: 21 segments x5m magn. Length
- Undulator period: 18 mm (in-vacuum)
- Peak current > 3kA
- Spectral reach: 4 keV - 20 keV

Thanks to T. Tanaka and T. Osaka
Overview of self-seeding at x-ray FEL facilities

**Self-Seeding installations: HXRSS at SACLA (transmission)**


![Graph showing photon intensity and number of downstream IDs vs. photon energy.](image)

 Beam energy 7.8 GeV  
 Beam charge 340 pC  
 Undulator K-value 2.1  
 Photon energy 10 keV  
 Pulse repetition 10 pps

Spectral brightness was much lower than normal SASE...

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**Two problems:**

- **Broad SASE background**  
  Comparable transmitted SASE tail and monochromatic seed?  

- **Transmitted SASE makes the tuning difficult**  
  We cannot directly see the seed pulse, such as, intensity, profile, pointing etc.

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From I. Inoue *et al.*, talk at FEL19

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The electron bunch and XFEL pulse of SACLA has a tail.

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Thanks to T. Tanaka and T. Osaka
Self-Seeding installations: HXRSS at SACLA (reflection)

- Clean monochromatic seed w/o SASE contamination
- High conversion efficiency from SASE to seed
- Cooling capability

μ-Channel-cut monochromator

T. Osaka et al., J. Synchrotron Rad. (2019)

- Diffraction plane: Si(111) (ΔE/E ~ 1.3e-4)
- Channel width: 90 μm
- Energy range: >4.5 keV in design
- Optical delay: 120 fs @10 keV
- Beam offset: <180 μm
- Spatial acceptance: ~100 μm (V) x 500 μm (H)

Spatial acceptance is large enough for incident SASE beam (~50 μm FWHM)

Thanks to T. Tanaka and T. Osaka
Self-Seeding installations: HXRSS at SACLA (reflection)

Early commissioning results

Inoue, Osaka et al., Nat. Photon. (2019)

Accel. parameters (same as usual)

- E-beam energy: 7.8 GeV
- E-bunch duration: ~10 fs
- E-beam charge: 270 pC
- K-value: 2.1
- Photon energy: 9.85 keV

Thanks to T. Tanaka and T. Osaka
Self-Seeding installations: HXRSS at SACLA (reflection)

Recent status of reflection self-seeding

- Smaller chirp in the e-beam
- Narrower BW with Si(220)

Thanks to T. Tanaka and T. Osaka
Self-Seeding installations: HXRSS at PAL

<table>
<thead>
<tr>
<th>Undulator Line</th>
<th>HX1</th>
<th>SX1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy [keV]</td>
<td>2.0 ~ 14.5</td>
<td>0.25 ~ 1.25</td>
</tr>
<tr>
<td>Beam Energy [GeV]</td>
<td>4 ~ 11</td>
<td>3.0</td>
</tr>
<tr>
<td>Wavelength Tuning</td>
<td>energy</td>
<td>gap</td>
</tr>
<tr>
<td>Undulator Type</td>
<td>Planar</td>
<td>Planar</td>
</tr>
<tr>
<td>Undulator Period / Gap [mm]</td>
<td>26 / 8.3</td>
<td>35 / 9.0</td>
</tr>
<tr>
<td>No. of undulators</td>
<td>20</td>
<td>7</td>
</tr>
</tbody>
</table>

**Main parameters**
- $e^-$ Energy: 11 GeV
- $e^-$ Bunch charge: 150 - 220 pC
- Slice emittance: < 0.4 mm mrad
- Peak current: > 3 kA
- Repetition rate: 60 Hz
- FEL photon energy: 2 ~ 14.5 keV (HX)
  - 0.25 ~ 1.25 keV (SX)
- FEL intensity: > 1 mJ (HX), > 0.2 mJ (SX)
- Duration: 5 ~ 35 fs
- SX line switching: DC magnet (to be changed to Kicker by 2020)

Small e-energy
Jitter: 0.012% rms
Configuration: 8+12

From Chang-Ki Min
Talk at FEL19
TUB03

Thanks to Heung-Sik Kang for data, slides and discussions
Self-Seeding installations: HXRSS at PAL  From Chang-Ki Min Talk at FEL19, TUB03

Seeding at 3.5 keV – 30µm crystal
Pitch angle: 89.5 deg [11-1]
FEL energy: 400 mJ seeded – 1 mJ SASE
BW (FWHM): 0.5 eV seeded (ave) – 6.5 eV SASE

Seeding at 14.4 keV – 100µm crystal
Pitch angle: 46.63 deg [440]
FEL energy: 400 mJ seeded – 1 mJ SASE
BW (FWHM): 1 eV seeded (ave) – 18 eV SASE

PAL seeds between 3.5 and 14.4 keV
LH improves spectral purity and brightness of seeded FEL
(increase up to a factor 3)

Courtesy H.-S. Kang
Self-Seeding installations: HXRSS at PAL

Courtesy H.-S. Kang

European XFEL

Thanks to Heung-Sik Kang for data, slides and discussions
Nominal electron energy points: 8.5 GeV, 12 GeV, 14 GeV and 17.5 GeV

HXR undulators (SASE1, SASE2)
- period: 40mm
- length: 35 segments x 5m magnetic length each
- Nominal Spectral reach: 3.0keV – 25keV (at different electron energies)
Overview of self-seeding at x-ray FEL facilities

G. Geloni, FUSEE Workshop, Trieste, December 2019

HXRSS at the European XFEL

Nominal reach: 3-25 keV (different e-energies) → Equipped with HXRSS

Long undulators (175m magnetic length at SASE2) → Tapering

High repetition-rate. Overall, more pulses but:
Larger heat-load. For example HXRSS:
→ ω-shift beyond Darwin width (conservative)
→ Spectrum broadening
Two sources:
→ SR
→ FEL-based: depends heavily on photon energy

Larger spectral density (seeded signal)
Compared to one-chicane

\[
\frac{S_2}{N_2} \sim \frac{S_1}{N_1} \frac{\sigma_{\text{SASE}}}{\sigma_{\text{seed}}}
\]
**HXRSS at the European XFEL**

One example for 17.5GeV 100pC electron beam

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**Stage 5**

**Segment 6**

- $Q = 9.13 \times 10^9$ pC
- $P = 3.0 \times 10^8$ W

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**C004 symmetric, 100um**

**Stage 1**

- 6 segments

**Stage 2**

- 6 segments

**Stage 3**

**Stage 4**

**Stage 5**

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**European XFEL**

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G. Geloni, FUSEE Workshop, Trieste, December 2019
HXRSS at the European XFEL
HXRSS at the European XFEL
HXRSS at the European XFEL

Installed during last winter shutdown
HXRSS at the European XFEL
HXRSS at the European XFEL
HXRSS at the European XFEL
HXRSS at the European XFEL

Position control range
- \( x \): -1.5/10 mm
- \( y \): +2/-10 mm
Position settability (rms)
- \( x \): <0.05 mm
- \( y \): <0.05 mm

Pitch angle
- Crystal pitch angle hard limit range: 42 - 98 deg
- Crystal pitch angle limit switch range: 45 - 95 deg
- Crystal pitch angle operation range: 47 - 93 deg
- Pitch angle settability (rms): <0.005 mrad

Yaw angle
- Crystal yaw angle control range: \( \pm 2.5 \) deg
- Crystal yaw angle settability (rms): <0.010 mrad
**HXRSS at the European XFEL**

Mono. #1:
- 105µm <100>
- 110µm <111>

Mono. #2:
- 105µm <100>
- 42µm <111>
Overview of self-seeding at x-ray FEL facilities

HXRSS at the European XFEL

Mono. #1:
105µm <100>
110µm <111>

Mono. #2:
105µm <100>
42µm <111>

G. Geloni, FUSEE Workshop, Trieste, December 2019

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C(004), 100um,
pitch ~59deg
8keV photon energy

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x position control range
y position control range
x and y position setability (rms)
crystal extraction position (approx).
crystal pitch angle hard limit range
crystal pitch angle limit switch range
crystal pitch angle operation range
pitch angle settabiliy (rms)
crystal yaw angle control range
crystal yaw angle settabiliy (rms)
HXRSS at the European XFEL

High Resolution hard X-ray single-shot spectrometer available

HI-bEX spectrometer at SASE1 from J. Gruenert et al, JSR 26, 1422 (2019)

A similar unit is available at SASE2
**HXRSS at the European XFEL**

**September: 8 keV, C(004), 100um. First HXRSS try (spectrometer available)**

First seeding indications, chicane around 25fs delay

- First observation of self-seeding at SASE2 in the linear regime
- Only a few microjoules
**HXRSS at the European XFEL**

Many people involved in different ways from different facilities...


...apologies if I forgot somebody...

...and special thanks to Alberto Lutman (SLAC) for making available his calibration tool.
**HXRSS at the European XFEL**

*October: 9 keV, C(004), 100um. Best seeded beam up to now*

Chicane at about 15fs delay

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Up to ~200 µJ

(XGM data after low-λ contamination check)

FWHM BW < 1eV

Pitch at 49.64 deg

1 pixel = 0.55 eV
**HXRSS at the European XFEL**

*October: 9 keV, C(004), 100um. Best seeded beam up to now*

A first attempt to go to higher rep-rate. 10 → 50 bunches/train (10 trains/second)
**HXRSS at the European XFEL**

**November: 9.3 keV, C(-3-33), 100um.**

Extremely bad SASE conditions: max 35uJ from XGM (run 211)

Si(440) mounted → better resolution: run 210 – FWHM = 0.6 eV; run 211 – FWHM = 0.8 eV

Runs @ 9.3 keV, averaged over 500 trains, actual transmission considered

Actual reflection at 47.24 deg

SASE level with 16 cells closed below XGM noise
Overview of self-seeding at x-ray FEL facilities

HXRSS at the European XFEL

Data analysis by V. Sleziona

Average XGM value ~ 7μJ
(still in the XGM noise for that day settings)

Average XGM value ~ 155μJ

Average XGM value ~ 33μJ
Outlook and Conclusions

- 1x operating SXRSS system (LCLS)
- 4x operating HXRSS system (LCLS, SACLA, PAL, EuXFEL)
- Did not discuss about systems under considerations
- ...Nor possible schemes e.g. for shorter wavelengths, seeding + harmonics

- These devices rely on magnetic length & e-beam quality extra-budget

- EuXFEL only started the commissioning
  - Robust (even with bad SASE), and clean pulses
  - Unicity of EuXFEL:
    - High rep rate
    - Second chicane
    - Long undulators → effective tapering possibilities
The End...

Thanks for your attention!