The SASE3 Undulator Line Status and Plans

Joachim Pflueger,
Undulator Systems, European XFEL
Overview

- Status and Plans for Undulator Systems and SASE3
- New development: Afterburner
  - Principle
  - Reverse Tapering
  - Intensities
  - Proposal for Realization
- Afterburner Design
  - Apple-X design
  - Parameter Choice
  - Mechanical Design
- Afterburner Time Schedule
- Summary
Status of SASE3
The XFEL Undulator Systems in Tunnels XTD1, XTD2 and XTD4

<table>
<thead>
<tr>
<th></th>
<th>SASE1/2</th>
<th>SASE3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_0$ [mm]</td>
<td>40</td>
<td>68</td>
</tr>
<tr>
<td>Operational Gap Range [mm]</td>
<td>10-20</td>
<td>10-25</td>
</tr>
<tr>
<td>K-Range</td>
<td>3.9–1.65</td>
<td>9.3–4</td>
</tr>
<tr>
<td>Radiation Wavelength Range [nm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ 17.5 GeV</td>
<td>0.147-0.040</td>
<td>1.22-0.27</td>
</tr>
<tr>
<td>@ 14.0 GeV</td>
<td>0.230-0.063</td>
<td>1.90-0.42</td>
</tr>
<tr>
<td>@ 12.0 GeV</td>
<td>0.310-0.0828</td>
<td>2.44-0.621</td>
</tr>
<tr>
<td>@ 8.5 GeV</td>
<td>0.625-0.171</td>
<td>5.17-1.15</td>
</tr>
<tr>
<td># of Segments</td>
<td>35</td>
<td>21</td>
</tr>
<tr>
<td>System Length [m]</td>
<td>213.5</td>
<td>128.1</td>
</tr>
</tbody>
</table>

“Naked“ Undulator System

With Air Conditioning Enclosures
### SASE3 Parameters

<table>
<thead>
<tr>
<th>SASE3</th>
<th>$h\nu = 260 - 3000\ eV$</th>
<th>$P = 0.2 - 11.0\ mJ$</th>
<th>Lin./Circ. Pol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T = 2 - 100\ fs$</td>
<td>Coherence: 0.96</td>
<td>Split &amp; Delay</td>
<td></td>
</tr>
</tbody>
</table>

**High repetition rate:**

$< 27000\ pulses/\ sec$

**High data collection rate**

Multi-particle **coincidences**

- **Carbon 1s:** 284 eV
- **N 1s:** 410 eV
- **O 1s:** 543 eV
- **P 1s:** 2145 eV
- **S 1s:** 2470 eV

**Electron energy sets**

- **17.5 GeV**
  - 0.26 – 2 keV
  - 1.02 – >3 keV
- **14.0 GeV**
  - 0.48 – 2.2 keV
  - 0.65 – ~2.9 keV
- **12.0 GeV**
  - 3 keV
- **8.5 GeV**
  - 12.4 keV
  - 20 keV
  - 3.0 – >15 keV
  - 4.0 – >15 keV
  - 5.4 – >20 keV
  - 8.4 – >25 keV

M. Meyer, XFEL UM2016
SASE1: Hardware installed & Aligned
Control System operational
Air Conditioning commissioned
All 35 gaps closed to 10.000mm
The system is almost operational

SASE3: Hardware installed 50% Aligned
Control System operational
Air Conditioning commissioned
Gap not yet closed
Limits switches not yet adjusted

Plan:
SASE1 and SASE3 undulators will be fully operational by the end of March 2017
Operational Modes

Base Line Operation @ Day 1:
- **Static** operation at fixed gap. All Air Coils and Phase Shifters synchronized via look-up tables.
- Operation at fixed photon energy; Fine tuning for optimum performance
- Cross check and refinement of look-up tables

Advanced, dynamic Modes follow later
- All Air Coils and Phase Shifters synchronized **dynamically** via look-up tables
- Lasing „On the Fly“ for:
  - Photon Energy Scans
  - Synchronization with external devices (monochromators) via EtherCAT
- Gap speed limited by:
  - Transient eddy currents. Trend: The slower the better!
  - Scan speed of the monochromator
- Needs R&D: Synchronization of \( \approx 210 \) axes.
- Within hardware capability; Needs manpower, minor cost
- First R&D already started
- Time line estimate: Day 1 + \( \geq 1 \) year
Synchronization: Tolerable Gap Following Error

Criterion “Lasing on the Fly“

\[ K(gap) = a \cdot \exp \{b \cdot gap + c \cdot gap^2\} \]

\[ \frac{\partial K}{\partial g} = K(g) \cdot \{b + 2c \cdot gap\} \]

\[ \frac{\Delta K}{K} \equiv \rho = \Delta g \cdot \{b + 2c \cdot gap\} \]

\[ \Delta g = \frac{\rho}{b + 2c \cdot gap} \]

<table>
<thead>
<tr>
<th>SASE1/2; ( \lambda_0=40\text{mm} )</th>
<th>( \rho )</th>
<th>( \Delta g ) [( \mu m )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap [mm]</td>
<td>10</td>
<td>( \leq 3 \cdot 10^{-4} )</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>( \leq 3 \cdot 10^{-4} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SASE3; ( \lambda_0=68\text{mm} )</th>
<th>( \rho )</th>
<th>( \Delta g ) [( \mu m )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap [mm]</td>
<td>10</td>
<td>( \leq 10^{-3} )</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>( \leq 10^{-3} )</td>
</tr>
</tbody>
</table>

Message: SASE1/2: \( \Delta g < 3-4 \ \mu m \) → Challenge
SASE3: \( \Delta g < 18-20 \ \mu m \) → doable
Synchronization: Gap Speed

Speed is set by the energy scan speed of the monochromator: \( \approx 1 \text{eV/sec} \)

\[
E1[\text{eV}] = 2.48311 \cdot 10^{-3} \frac{\gamma^2}{\lambda_0[\text{mm}] (1 + 0.5K^2)}
\]

\[
\frac{dE1}{d\text{gap}} = \frac{dE1}{dK} \cdot \frac{dK}{d\text{gap}} = 2.48311 \cdot 10^{-3} \frac{-\gamma^2K^2}{\lambda_0[\text{mm}] (1 + 0.5K^2)^2} \left\{ \frac{b}{\lambda} + \frac{2c \cdot \text{gap}}{\lambda^2} \right\}
\]

Assumption: Monochromator limited to \( \approx 1 \text{eV/sec} \)

<table>
<thead>
<tr>
<th>Gap [mm]</th>
<th>E1 [eV]</th>
<th>( \frac{dE1}{d\text{gap}} ) [ev/mm]</th>
<th>Speed [\text{\mu m/sec}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SASE1/2 17.5GeV</td>
<td>10</td>
<td>7301</td>
<td>-1295</td>
</tr>
<tr>
<td>20</td>
<td>30420</td>
<td>-2966</td>
<td>0.33</td>
</tr>
<tr>
<td>SASE3 8.5 GeV</td>
<td>10</td>
<td>780</td>
<td>-97</td>
</tr>
<tr>
<td>25</td>
<td>5287</td>
<td>-537</td>
<td>1.86</td>
</tr>
<tr>
<td>SASE3 17.5 GeV</td>
<td>10</td>
<td>1018</td>
<td>-109.6</td>
</tr>
<tr>
<td>25</td>
<td>4576</td>
<td>-417</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Measured minimum gap speed: \( \approx 0.76 \text{nm/s} \) (M. Yakopov, S. Abeghyan Report WP71/2016/05)
Afterburner Development
How to avoid contamination of CP radiation?

1. Spacial Filtering;
   Planar SASE radiation stopped by slit
   Geloni et. al. (2010)

2. Isochronous Bend;
   Beam bent out of linear SASE radiation by $< 1$ mrad, rotation of the microbunched beam
How to avoid contamination of CP radiation

3. Reverse Tapering:
**Suppress radiation by SASE3, but preserve microbunching**
M. Yurkov, E. Schneidmiller IPAC 2016, May 8-13, Busan Korea, MOPOW008, (FLASH results)

4. Modulated Electron Bunch with Amplitude Front Tilt,
**Beam bent out of linear SASE radiation by 100-200 μrad, micro bunching not rotated!**
Proposed: Afterburner Configuration at SASE3 using Reverse Tapering

- **5m SASE3 U68 Undulator Segment**
- **2m Apple-X Segment**
- **1.1m Standard Intersection without quadrupole**, with focusing, with defocusing quadrupole

- **Simplest Solution**, uses existing Intersections, Phase Shifters, Quadrupole Movers
- **XFEL intersection design** can be used; Problem: Replacement of In Kind Contributions
- **FODO Lattice continued**, mismatch negligible
- **No additional effort**: No bend, dogleg or spatial filters
Experimental Evidence
Undulators

<table>
<thead>
<tr>
<th></th>
<th>Period</th>
<th>Length</th>
<th>Gap Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLASH1:</td>
<td>2.73 cm</td>
<td>27 m (6 x 4.5 m modules)</td>
<td>fixed gap</td>
</tr>
<tr>
<td>FLASH2:</td>
<td>3.14 cm</td>
<td>30 m (12 x 2.5 m modules)</td>
<td>variable gap</td>
</tr>
</tbody>
</table>

E. Schneidmiller and M. Yurkov, Workshop on variable polarization at SASE3, European XFEL, Feb. 11, 2016
Reverse taper experiment at FLASH2 from M. Yurkov, E. Schneidmiller

Beam energy 720 MeV, wavelength 17 nm.

Reverse taper (10%) was applied to the 10 undulator segments; the gap of the 11\textsuperscript{th} and 12\textsuperscript{th} segments was scanned.

Power ratio of 200 was obtained. For a helical afterburner it would be larger by a factor of 2.
Reverse taper experiment at FLASH2 from M. Yurkov, E. Schneidmiller

Simulations for SASE3

≈ 200 (x 2)

≈ 400

M. Yurkov, E. Schneidmiller, IPAC 2016, May 8-13, Busan Korea, MOPOW008, (FLASH results)
Afterburner

1. Nearly the same output power at equal number of periods
2. Output power of 8m long Afterburner comparable to SASE3 linear power
Apple-X Magnet Design
Boundary Conditions

- Modification of the Apple-X Design for the Undulator for the Athos Beamline at SwissFEL
- Use same mechanics; Length fixed to 2.0m
- Only magnetic part modified to match to the SASE3 operational range.

Specification:

- Right/left circular polarization
- Linear polarization with selectable polarization angle ±90° or:

\[
\lambda_{After} \left(1 + \frac{K_{After, Lin}^2}{2}\right) = \lambda_{SASE3} \left(1 + \frac{K_{SASE3}^2}{2}\right) \lambda_{SASE3} = 68\text{mm};
\]

over the full SASE3 range \( K_{SASE3} : 4 \ldots 9; \)
Parameter choice to match with SASE3
Original Idea: Delta Undulator like LCLS

DELTA

- Fixed gap
- Field change by longitudinal shift
- Compact, symmetric Design
- No lateral access for magnetic measurements
- Problem: Strong field gradients

Courtesy: H.D. Nuhn, SLAC
APPLE-X: Gap adjustable Delta Undulator

Crossed Undulator, Onuki 1986

Apple-X

Requires 8 Degrees of Freedom

H. Onuki, NIMA 246 (1986) 94
Large Aperture for Storage Rings
Pure PM structure

Apple-X is an improved Delta Undulator with improved field properties → no gradients
**Determination of $\lambda_0$**

**NdFeB: $B_r=1.25T$ (XFEL Grade)**

- **Example**

- $R_1=3.25\text{mm}$, $R_2=17.5\text{mm}$, slit=3mm

\[
\lambda_{After}(1 + \frac{K_{After,Lin}^2}{2}) = \lambda_{SASE3}(1 + \frac{K_{SASE3}^2}{2})
\]

<table>
<thead>
<tr>
<th>Undulator period $\lambda_u$(mm)</th>
<th>$R_2$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>38.8</td>
</tr>
<tr>
<td>85</td>
<td>29.2</td>
</tr>
<tr>
<td>90</td>
<td>24.6</td>
</tr>
<tr>
<td>95</td>
<td>21.6</td>
</tr>
<tr>
<td>100</td>
<td>19.5</td>
</tr>
<tr>
<td>105</td>
<td>17.9</td>
</tr>
</tbody>
</table>

More: WP71/2016/13
Apple-X
Mechanical Design
Time Plan Athos & XFEL

Order Prototype (long lead components 1st)
Order Series (long lead comp.)
Order Series Confirmation

<table>
<thead>
<tr>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>US 55 Undulators</td>
<td>design &amp; prototype</td>
<td>TEST USB</td>
<td>synchro production</td>
<td>commissioning</td>
</tr>
<tr>
<td>ATHOS RF stations</td>
<td>procurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF and photon beamlines and experiment procurement</td>
<td>design &amp; procurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S&amp;I procurement &amp; installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Completed (2D): Feb. 2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype produced and assembled: Sep. 2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype tested: Feb. 2018</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Units produced (19 Months): Sep. 2019</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 units for E-XFEL after Sep. 2019</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SASE3
Almost completed
Ready for electron beam: End of March 2017

Afterburner
- Helical / Linear ±90° Afterburner
- In collaboration with SwissFEL
- 4 x 2m segments
- Uses Reverse Tapering
- Intensity comparable to SASE3
- Ready Q1/2020
Acknowledgements: Cooperators

WP71, European XFEL:
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The End