Undulator Systems for the European XFEL

Joachim Pflüger, European XFEL
12 Countries:
- Denmark
- France
- Germany
- Greece
- Hungary
- Italy
- Poland
- Russia
- Slovakia
- Spain
- Sweden
- Switzerland

Announced:
- China
- Great Britain

XFEL GmbH is officially founded!
Overview

- XFEL Basics, Choice of Parameters
- Undulator Systems Design
  - Undulator Segments
    - Mechanics
    - Magnetic Measurements
  - Intersections
    - Phase Shifter
    - Mover
  - Control System
- Tunnel Layout
- Time Schedule
Overview, Choice of Parameters
Overall layout: three above ground sites
Overall layout: three above ground sites
Conservative design assumptions:

- 1Å has to be reached safely
- FEL specifications to be fulfilled safely
- Permanent Magnet Technology (NdFeB)
- Avoid risks like SC undulators (technology), mini gap undulators, ultra small vacuum chambers (wake fields, radiation damage)

Strict standardization for drive mechanics, intersections, tuning procedures

Preparation for Large Scale Production

Synergy with PETRA III
TDR 2006  Saldin, Schneidmiller, Yurkov

Saturation length $\varepsilon_n = 1.4 \text{ mm mrad}$

Diffraction Parameter
($\rightarrow$ Coherence, Number of Modes)

Min Undulator gap

Gap 6 $\rightarrow$ 10mm would only save 20% on length

17.5 GeV for $B=100$

\[ \varepsilon_n = 1.4 \text{ mm mrad} \]

**Saturation length dependence on chosen wavelength for SASE1, SASE2 and SASE3**

**Photon pulse power as a function of magnetic undulator length**

\[ \lambda_R = \frac{\lambda_0 \left(1 + 0.5K^2(g_{ul})\right)}{2\gamma^2} \]

Lengths of undulator systems

SASE1    SASE2
## Undulator Systems for the European XFEL

### Baseline Design Parameters

#### Accelerator

<table>
<thead>
<tr>
<th>Type</th>
<th>SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>17.5 GeV</td>
</tr>
<tr>
<td>$\Delta \gamma / \gamma$</td>
<td>$1.25 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\varepsilon_n$</td>
<td>1.4 $\mu$m</td>
</tr>
<tr>
<td>$\varepsilon$ (17.5 GeV)</td>
<td>0.034 nm</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>1 nC</td>
</tr>
<tr>
<td>Bunch length</td>
<td>80 fsec</td>
</tr>
<tr>
<td>$I_{\text{Peak}}$</td>
<td>5000 A</td>
</tr>
<tr>
<td>Rep Rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Pulse train</td>
<td>1 - 3250</td>
</tr>
</tbody>
</table>

#### Undulator Systems

<table>
<thead>
<tr>
<th>Unit</th>
<th>SASE 1</th>
<th>SASE 2</th>
<th>SASE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>GeV</td>
<td>17.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Wavelength</td>
<td>nm</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Photon energy</td>
<td>keV</td>
<td>12.4</td>
<td>12.4</td>
</tr>
<tr>
<td>Peak power</td>
<td>GW</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Average power</td>
<td>W</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Photon beam size (FWHM)</td>
<td>$\mu$m</td>
<td>70</td>
<td>85</td>
</tr>
<tr>
<td>Photon beam divergence (FWHM)</td>
<td>$\mu$rad</td>
<td>1</td>
<td>0.84</td>
</tr>
<tr>
<td>Coherence time</td>
<td>fs</td>
<td>0.2</td>
<td>0.22</td>
</tr>
<tr>
<td>Spectral bandwidth (%)</td>
<td>%</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>fs</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Photons per pulse #/s</td>
<td></td>
<td>$3.0 \times 10^{16}$</td>
<td>$3.0 \times 10^{16}$</td>
</tr>
<tr>
<td>Peak brilliance</td>
<td>B</td>
<td>$5.0 \times 10^{23}$</td>
<td>$5.0 \times 10^{23}$</td>
</tr>
<tr>
<td>Average brilliance</td>
<td>B</td>
<td>$1.6 \times 10^{32}$</td>
<td>$1.6 \times 10^{32}$</td>
</tr>
</tbody>
</table>

**Table 5.2.2** XFEL radiation parameters for SASE 1 – SASE 3 as the result of simulations. Brilliance B is given in units of photons/0.1%bw/s/mm²/mrad².
Undulator Design
**Startup Scenario**

- **SASE1**: Full
- **SASE2**: Shortened by 5 Seg
- **SASE3**: Linear

<table>
<thead>
<tr>
<th></th>
<th>$\lambda_R$</th>
<th>$\lambda_0$</th>
<th>Gap</th>
<th>$B_0$</th>
<th>$K$</th>
<th>$\beta_0$</th>
<th>$L_{Sat}$</th>
<th>$N_{Tot}$</th>
<th>$L_{Tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SASE 1</strong></td>
<td>1</td>
<td>35.6</td>
<td>10</td>
<td>1.0</td>
<td>3.3</td>
<td>32</td>
<td>174</td>
<td>33</td>
<td>201.3</td>
</tr>
<tr>
<td><strong>SASE 2</strong></td>
<td>1-4</td>
<td>48</td>
<td>19-10</td>
<td>0.63-1.37</td>
<td>2.8-6.1</td>
<td>46-15</td>
<td>174 - 72</td>
<td>37</td>
<td>225.7</td>
</tr>
<tr>
<td><strong>SASE3</strong></td>
<td>4-16</td>
<td>65</td>
<td>23-10</td>
<td>0.66-1.76</td>
<td>4.0-10.7</td>
<td>15</td>
<td>$\approx$100</td>
<td>21</td>
<td>128.1</td>
</tr>
</tbody>
</table>

* Planar Hybrid Undulator
** 1st Harmonic of Spontaneous Emitters
+ Net saturation length with no contingency for field errors
++ Number of 5m undulator segments including 20% contingency
+++ Total system length includes 1.1m long intersection after each undulator segment

Later Upgrade to full TDR 2006 Scope is possible
Undulator Systems for the European XFEL

Schematic of Undulator Systems

Undulator System in Tunnel

Cell Structure
Undulator Segments
Synergetic XFEL – PETRAIII design. Ongoing since 2004
- Fulfill XFEL (and PETRAIII) requirements
- Suited for Serial Production
- Cost optimized

2 Generations of Prototypes to test and develop XFEL Technology

Construction of 13 planar PETRA III undulators using this technology

Results:
- Relaxed Tolerances: Girder Material AlMg
  
- High Precision Drive System
- Cost optimized
- Ready for Tendering
2. Generation Support Mechanics

Special Attention:  
1. Shear deformation vs. compressive deformation  
2. Material pairing; Bimetallic bending  
3. Four point support of girders  
4. Four Motors, electronic gears  
5. Forced girder guiding  
6. Precision gap control with accuracy $\pm 1\mu m$
Girder guiding by Support Guide Way

Problem: The intermediate girder deforms under magnetic forces

Solution:
- Girders have a rotational degree of freedom of low friction
- Alignment through the support guide way, adjustable via screws
- Total Girder Tilt \( \approx \leq \pm 100 \, \mu \text{rad} \)
Required Accuracy $\pm 1\mu m$

Problem: Forces of Measurement

Best Result at present: $\pm 1\mu m$

G. Naulin, G. Nawrath
Prototyping History

1. Generation
   5m U29 Petra III /XFEL
   Pre-Series 5m U35/48/68 XFEL
   New
   2006

2. Generation
   2m U29 PETRA III
   New
   2006-2007

Pre-Series 5m U35/48/68 XFEL
2006
2m U29 PETRA III
2007-Present
Magnetic
Design & Measurements
Magnet Structure I

Based on FLASH Experience

- Structure clamped on girder.
- Same Material for girder and Magnet support structure: AlMg
All XFEL relevant field errors can be tuned by adjustment screws

Magnetic Structure III: Pole Height Adjustment

Measurement Bridge

Reading Accuracy: ±1μm
Requirement: ±5μm

Double Bridge in Use

Direct view
Simple, easy to use
preferred Method
Magnetic Structure IV: Pole Height and Tilt Adjustment

Pole Height Adjustment

U29A1 Trajectory Optimization $B_y$

- Status Ante RMS: 27.6 Tmm
- 1st Iteration RMS: 20 Tmm
- 2nd Iteration RMS: 10.1 Tmm

\[ I_{2,RMS} = \frac{B_{\text{Peak}}}{\sqrt{2}} \left( \frac{\lambda_0}{2\pi} \right)^2 \]

\( \lambda_0 = 29 \text{ mm}, B_{\text{Peak}} = 0.682 \text{ T} \Rightarrow I_{2,RMS} = 10.3 \text{ Tmm} \)

\( \approx \pm 0.3 \text{ mm} \)

Pole Tilt Adjustment

U29A1 Trajectory Optimization $B_z$

- Status Ante RMS: 17.9 Tmm
- 1st Iteration RMS: 10.2 Tmm
- 2nd Iteration RMS: 8.2 Tmm
- 3rd Iteration RMS: 3.3 Tmm

\( \approx \pm 4 \text{ mrad} \)
XFEL Magnetic Lab
Undulator Systems for the European XFEL

XFEL Magnetic Lab with 0.1° C Stability

(C. Schulz)

Temporal Temperature Stability

0.06K

96 h

Local Temperature Stability

0.34K

96 h

EFST Workshop on Advanced Undulator Physics and Technology for Light Sources, Shanghai, Dec 3-4, 2009
J. Pflueger, European XFEL
Undulator Systems for the European XFEL

Field Measurements Results New Lab on PETRA III 2m

U. Englisch
Extension Plans in Building 36 (C. Schulz)

North

XFEL Area
Present Status

- Magnetic Measurements and tuning
  - Pole Height and Tilt Tuning is working well
  - Routinely used for PETRA III
  - Has the potential for fast tuning “perfect” undulators:
    - Phase Jitter $<< 2^\circ$
    - RMS trajectory walkoffs $<< 1\mu m$ ($2^{\text{nd}}$ Fieldintegral $\approx 2 \text{Tmm}^2$)
  - All basic Magnet Measurement and tuning Techniques needed for XFEL are available

- 1. New Magnetic Lab
  - Lab operational
  - Temperature Specs fulfilled
  - Control Software working
  - At present: Heavily in use by HASYLAB for PETRA III Devices…
  - Prototype for the new XFEL benches

- Extension of Lab in Bldg. 36 started
Intersections
Europa
XFEL
Intersection Overview

Undulator Systems for the European XFEL

SASE 1

Air Coll Correctors
Phase Shifter
Cavity BPM
SR Absorber / Pump
Support Base Plate
Loss Monitors
Adjustors
Concrete Pillar

SASE 2

Vacuum Chamber
Quadrupole
Quadrupole Mover

Phase Shifter

J. Pflüger

H. Lu, M. Wang, J. Zhuang

I. Moya, S. Sanz, P. Oriol
Phase Shifter: General

1. Prototype

Magnetic Design Principle

Intersection

Phase Shifter
Undulator Systems for the European XFEL

**Phase Shifter: Final Results**

*Lu Huihua, Zhuang Jian, Wang Motuo, J. Pflüger*

\[
PI \left( \frac{g_p}{g_U} \right) = \left( \frac{mc}{e} \right)^2 \left( \frac{\lambda U}{2\pi n} \right)^2 \left( 1 + 0.5 K \sqrt{2} \left( \frac{g_U}{U} \right) \right) \gamma^2 \left( \pi - L \right) = \left( \frac{mc}{e} \right)^2 \left( \frac{\lambda R}{\gamma^2} \right) \gamma^2 \left( \pi - L \right) \geq 0
\]

For more Details: H.H. Lu, Y. Li, J. Pflüger, NIMA 605 (2009) 399
Quadrupole Mover
Quadrupole Mover

Javier Munilla, CIEMAT
Quadrupole Mover Specifications

- **Movement Range:** ± 1.5mm
- **Accuracy better:** ± 1µm
- **Load Capacity:** ≈ 75kg

**Motion Control:**
- Linear actuators using stepping motors
- Absolute position measurement using LVDTs
- Closed loop feedback using Beckhoff control components (XFEL standard)

**Safety:**
- Precision switches
- Hard stoppers
Reentrant Cavity Beam Position Monitors
D. Lipka, D. Nölle WP17

D. Lipka, D. Nölle  XFEL Meeting 16.9.09

Based on Spring8 Design
Vacuum System (T. Wohlenberg WP19)

Vacuum components for the Intersections Intersection

XFEL Prototype Chamber built for the 4m Undulator for sFLASH
• Extruded Al Profile

• Clearance: Vertical: 8.6mm, Horizontal: 15mm

• 2 Water cooling Channels

• 2 additional Channels for Fiber Loss Monitors à la FLASH

• ≈300nm RMS inner Surface Roughness

• No Coating: The Beam sees Al

• Support on independent, external and adjustable prefabricated Frame made from AL profiles

Chamber Cross Section
Requirements

- Must keep magnetic center to better than ±2µm from 10 to 100% of rated excitation
- Extensive R&D called “New TQG” triggered by negative FLASH experience

Result: An economic Solution:

- Low coercive iron „Russian Relais Iron“ provided as IKC
- Thermal annealing at 850°C after machining mandatory
- In XFEL: Fiducialization and test of magnetic center stability
Quadrupole Center stability on „New TQG“

- Excitation is changed from 0 to 80A and back several times
- Center is determined using a rotating coil setup

Transfer of center position to Fiducials

Horizontal (X) Center Position

Vertical (Y) Center Position
Undulator Controls
Undulator Cell Local Control
- Motion Control of undulator segment, synchronization, limit movement, operational safety
- Air coil correction, synchronized with gap movement
- Temperature compensation
- Motion Control of Intersection synchronized with gap motion

Global Control System
- General Control of Undulator System
- Synchronize Undulator all Cells
- Operational Modes Taper, length control
- Operational Interface to machine, users, diagnostics, local
Tasks
• Provide fast Gap Control with micrometer accuracy
• Synchronization with low following error (less than ±10µm)
• Provide safe operation, failure detection, prevent damage........
• Limitation of movement, limit switches

- Local temperature measurement and gap correction
- Gap dependent Air Coil Correction
- Gap dependent Phase Shifter Setting
- Motion Control for Quadrupole Movers

BECKHOFF

virtual master axis

EtherCAT Technology Group
**Embedded PC:**
- Windows based, **realtime capable**
- Programmable Logic Controller (PLC)
- Numerical Control (NC)
- sever for machine control system (TCP/IP)
- HMI + IDE

**I/Os:**
- limit switches
- additional controls (eg. correctors)
- interlock signals
- Profibus terminal

**EtherCAT**
- servodrives
- linear encoders
- resolver feedback
- power
- motors

**Profibus**
**Undulator Systems for the European XFEL**

**Global Undulator System Control**

- **virtual master axis**
- **remote synchronization**

**TwinCAT based Soft-NC:**
- synchronization of Undulator cells
- communication to global control system
- also allows to move single cells

- **synchronous / collective** movement of all axes during operation
- **external synchronization** via EtherCAT – for example with monochromator
- **different operational modes:** tapering, diagnostic, local, maintenance ….

A. Schoeps
- Widely used in Automation Industry (Europe, China)
- Fast EtherCAT based communication
- TwinCAT based software with mighty diagnostic tools (ScopeView)
- Available off the shelf
- Wide variety of controls for Motion control (servos, steppers, ADCs (til 24 bit), DACs, encoders, I/O…)
- Economic : 240€ to include a 4A stepping motor such as Phase Shifter
- Growing scientific use: FLASH, PETRA III, EMBL, DESY Accelerators, XFEL, ELBE…
Near Future Plans

- Extension Magnetic Lab
  - Extension of Hall 5 in Bldg. 36 by 6/2010
  - CFT for 2 more benches by 6/2010
- Intersections
  - SASE2 / IHEP see presentation of Huihua Lu
  - SASE2 / XFEL Prototype Assembly Begin 1/2010
  - SASE1 Prototype Assembly Begin 1/2010
  - Test, Redesign
  - Production Readiness Review End of 2010
- Preseries Prototypes
  - 2 SASE3 U68 Prototypes (CELLS) until 9/2010
  - 2 SASE1 and 2 SASE2 (XFEL) until 9/2010
Global Time Schedule

- Extension Magnetic Lab until 19.3.2012

- Undulator Segments
  - Pre-Series Prototyping until 5.7.11
  - Serial Production 6.7.11 – 1.7.14 (last)

- Intersections
  - Prototyping Test Mockup until 7.2.11
  - Production 8.2.11 – 1.4.13 (last)

- SASE 1-3 Operational by late 2014
The End
Open Positions in WP71

- 2 Scientists for magnetic measurements S-022
- Controls engineer for a magnetic measurement lab E-013
- Mechatronics engineer (f/m) E-015
- Support engineer / hall engineer (f/m) E-016

More Positions at European XFEL:
http://www.xfel.eu/organization/job_offers/