On behalf of the European XFEL Accelerator Consortium
work supported by the respective funding agencies of the contributing institutes; for details please see http://www.xfel.eu
First Lasing.

World's largest X-ray laser generates first laser light

17/05/04 · Press-Release

Biggest X-ray laser in the world generates its first laser light

In the metropolitan region of Hamburg, the European XFEL, the biggest X-ray laser in the world, has reached the last major milestone before the official opening in September. The 3.4 km long facility...

The super X-ray laser

More about the European XFEL in DESY's research magazine!
One Kilometer of Cold Linac
With almost 800 Superconducting Cavities
The European XFEL
Built by Research Institutes from 12 European Nations

Some specifications

- Photon energy 0.3 - 24 keV
- Pulse duration ~ 10 - 100 fs
- Pulse energy few mJ
- Superconducting linac 17.5 GeV
- 10 Hz (27 000 b/s)
- 5 beam lines / 10 instruments
  - Start version with 3 beam lines and 6 instruments
- Several extensions possible:
  - More undulators
  - More instruments
  - …….
  - Variable polarization
  - Self-Seeding
  - CW operation

SASE2

(= SASE1)

17.5 GeV

SASE1, \( \lambda_u = 40 \) mm

0.2 – 0.05 nm

SASE3, \( \lambda_u = 68 \) mm

1.7 – 0.4 nm
### Accelerator Complex with Challenging Parameter Set

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam energy</td>
<td>8/12.5/14/17.5 GeV</td>
</tr>
<tr>
<td>Macro pulse repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>RF pulse length (flat top)</td>
<td>600 μs</td>
</tr>
<tr>
<td># of bunches/second</td>
<td>27,000</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.02 – 1 nC</td>
</tr>
<tr>
<td>Electron bunch length after compression (FWHM)</td>
<td>2 – 180 fs</td>
</tr>
<tr>
<td>Normalized slice emittance*</td>
<td>0.4 - 1.0 mm mrad</td>
</tr>
<tr>
<td>Beam power</td>
<td>500 kW</td>
</tr>
<tr>
<td>Simultaneously operated SASE undulators</td>
<td>3</td>
</tr>
</tbody>
</table>

* normalized emittance: $\varepsilon_n = \gamma \varepsilon = \gamma \sqrt{\langle x^2 \rangle \langle p^2 \rangle + \langle xp_x \rangle^2}$
State of the Art 3 Stage Bunch Compression

3 stage bunch compression: flexible and less sensitive to noise from RF system

3rd harm. module

- 4 accelerator modules
- 12 accelerator modules
- dogleg
- bunch compression chicane
- diagnostis
- diagnostis
- $R_{56} = 60-120 \text{mm}$
- $R_{56} = 60-120 \text{mm}$
- $R_{56} = 30-100 \text{mm}$

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sigma_x$</th>
<th>$I_{\text{peak}}$</th>
<th>$\sigma_E$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>$2 \text{ mm}$</td>
<td>$50 \text{ A}$</td>
<td>$0 %$</td>
<td>$130 \text{ MeV}$</td>
</tr>
<tr>
<td>2nd</td>
<td>$1 \text{ mm}$</td>
<td>$100 \text{ A}$</td>
<td>$1.5 %$</td>
<td>$130 \text{ MeV}$</td>
</tr>
<tr>
<td>3rd</td>
<td>$0.1 \text{ mm}$</td>
<td>$1 \text{ kA}$</td>
<td>$1 %$</td>
<td>$600 \text{ MeV}$</td>
</tr>
<tr>
<td>4th</td>
<td>$0.02 \text{ mm}$</td>
<td>$5 \text{ kA}$</td>
<td>$0.3 %$</td>
<td>$2400 \text{ MeV}$</td>
</tr>
</tbody>
</table>

- harmonic system
- bunch compressor
- beam diagnostics
X-ray Beamlines for Different Wavelengths with Different Time Structures

- **SASE 2**: 3 – 24 keV
- **SASE 1**: 3 – 24 keV
- **SASE 3**: 0.26 – 3 keV

**LINAC**
- 17.5 / 14 / 10.5 GeV

- 2 hard x-ray undulators and beam transport with 4 instruments
- 1 soft x-ray undulator and beam transport with 2 instruments
- All undulators planar and tunable

**Experiments**
- HED
- MID
- FXE
- SPB
- SQS
- SCS
The Suite of Instruments

- **SASE 2**: MID, HED
- **SASE 1**: SPB, FXE
- **SASE 3**: SQS, SCS

- **FXE**: Femtosecond X-ray Experiments
- **HED**: High Energy Density Science
- **SPB**: Single Particle & Biomolecules
- **MID**: Materials Imaging & Dynamics
- **SQS**: Small Quantum Systems
- **SCS**: Spectroscopy & Coherent Scattering

More about experiments: [http://www.xfel.eu](http://www.xfel.eu)
Project History

2000: First lasing at 109 nm at the Tesla Test Facility (TTF), now FLASH
2001: TESLA Linear Collider TDR with XFEL appendix
2002: TESLA TDR supplement with stand-alone XFEL
2006: European XFEL TDR

2009: Foundation of the European XFEL GmbH

Start of underground construction

2010: Formation of the Accelerator Consortium

16 accelerator institutes under the coordination of DESY

2012: End of tunnel construction

Start of underground installation

2016: Finish of accelerator installation

Start of commissioning
# Commissioning Plan

(include as many systems as early as possible)

<table>
<thead>
<tr>
<th>Date</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/16</td>
<td>Linac Cooldown</td>
</tr>
<tr>
<td>01/17</td>
<td>Injector at 130 MeV (3 RF stations)</td>
</tr>
<tr>
<td>01/17</td>
<td>L1 commissioning (+1 RF station)</td>
</tr>
<tr>
<td>02/17</td>
<td>L2 commissioning (+3 RF stations)</td>
</tr>
<tr>
<td>02 - 04/17</td>
<td>L3 commissioning (+15 RF stations)</td>
</tr>
<tr>
<td>05/17</td>
<td>Beam through SASE1 &amp; SASE3 undulator sections</td>
</tr>
<tr>
<td>end 05/17</td>
<td>Milestone “First Lasing Possible”</td>
</tr>
<tr>
<td>06 - 08/17</td>
<td>Commission SASE1 photon beamline and experiment</td>
</tr>
<tr>
<td></td>
<td>Consolidate FEL operation at 8-10 keV photon energy</td>
</tr>
<tr>
<td>09/17</td>
<td>First user experiments (total 800 hours)</td>
</tr>
<tr>
<td>2018</td>
<td>Continue facility commissioning + 2000 user hours</td>
</tr>
<tr>
<td>2019</td>
<td>Routine operation with 6 experiments + 4000 user hours</td>
</tr>
</tbody>
</table>
- Photoinjector conditioned and characterized at PITZ, DESY-Zeuthen
- Injector cool-down 12 / 2015
- First Beam on Dec 18\textsuperscript{th} 2015 - commissioning till Q2/2016
- Full bunch train length (27,000 bunches/s) reached for 20pC - 1000pC bunch charges
- Photocathode laser with excellent up-time (Yb:YAG laser from Max-Born Institute Berlin; 257 nm \leq 4 \, \mu J; 3 \, ps)
- 3.9 GHz system operational from day 2
- Laser heater commissioned
Cryo plant with cold compressors and extended distribution system

- Cooling capacity:
  - 2K : >1.9 kW
  - 5/8K : 4 kW
  - 40/80K : 24 kW

- Linac is one 1.5 km long cryo-string
First Cooldown of XFEL Linac during Dec 2016

- Start asymmetrical operation of two cold boxes to speed up cooldown
- Entry of cold return flows in cold boxes to enhance cryogenic capacity
- Fast cooldown at temperatures below liquid nitrogen (no more thermal stress)

No Cold Leaks!!!
Cryogenics is very challenging

- **Complexity of cryogenic system** asked for sufficient commissioning time; experts had to establish / optimize operation and to **gain experience** with new machines, especially the used cold compressors.

- **How to deal with…**
  - 671 control valves
  - >3,800 sensors (temperature, pressure, flow, level)
  - 433 regulation loops
  - >22,000 records and >220,000 properties
  - and last but not least … >300 tons of material to be cooled down

- **Required 2K pressure stability** of 2% peak from LLRF requirements (cavity detuning)

- Tedious adjustment of regulation loops

- Inner-system heaters to counteract dynamic processes
We cooled down all 96 accelerator modules.
All RF stations including CS7 are commissioned at moderate gradients.
Detailed measurements will show the path towards higher beam energies.
CS8 is meanwhile ready for LLRF commissioning; thanks to maintenance days.
The last two stations (CS9) require still longer tunnel access.
Commissioning milestones
- Initial checks (LLRF system ready for commissioning)
- Cold coupler conditioning (optional)
- Cavity Forward and Reflected RF signal integrity (cabling issues? signal saturation?)
- Frequency tuning (from parking position)
- Cavity Probe RF signal integrity (cabling issues? signal saturation?)
- Coupler tuning (target QL)
- Power-based gradient calibration (coarse)
- Cavity phasing (using waveguide phase shifters)
- Closed-loop operation (feedback, learning feedforward)
- Beam-based gradient calibration (fine)

Reached goals by now
- Handed over to operations and controlled via FSM
- Inner loop RF stability <0.01 deg, < 0.01%
- Preliminary measurements of beam energy jitter ≈ 10^{-4}
**European XFEL Status & Commissioning**

**XFEL RF System**

**INJECTOR**
- RF gun 3.9GHz
- A1 AH1
- 5 MeV
- 130 MeV

**LINAC1**
- cryostring 1
- DL BC1 A2
- A3 A4 A5

**LINAC2**
- cryostring 2
- BC2
- A6 A7 A8

**LINAC3**
- cryostring 3
- A20 A21 A22 A23
- A24 A25 A26
- 17.5 GeV

**CM1 (8 cav.)**
- KLYSTRON
- RF Wasserpflzhalter 3.5 m

**CM2 (8 cav.)**
- LLRF I
- Opt. Fibers 1.0 m

**CM3 (8 cav.)**
- LLRF II
- Vacuum

- **HV Modulators in surface hall**
- **Connected to pulse transformer via up to 2km long pulse cables**
**European XFEL Status & Commissioning**

**XFEL LLRF System**

**INJECTOR**
- A1
- AH1
- RF gun 3.9GHz
- 5 MeV

**LINAC1**
- cryostring 1
- DL
- BC1
- A2
- A3
- A4
- A5
- 130 MeV

**LINAC2**
- cryostring 2
- BC2
- A6
- A7
- A8
- 2.4 GeV

**LINAC3**
- cryostring 3
- A9
- A10
- A11
- A12
- A13
- A14
- A15
- A16
- A17
- A18
- A19
- A20
- A21
- A22
- A23
- A24
- A25
- A26
- 17.5 GeV

**CM1 (8 cav.)**
- Drift compensation
- Reference synchr. + distr.

**CM2 (8 cav.)**
- Clocks + local oscillator
- Main controller crate (MicroTCA)
- Piezo*
- Power supplies

**CM3 (8 cav.)**
- LLRF master

**CM4 (8 cav.)**
- LLRF slave

* not installed yet
Energy Reach of European XFEL Modules

- **Average accelerating gradient** after pre-installation module test and waveguide tailoring
  - 26 MV/m, (design 23.5 MV/m)
- Some additional gradient reduction due to tunnel waveguide distribution
- Excess energy reach will enhance operation reliability
After initial commissioning design gradient almost reached

Operation of RF stations “off beam” allows final commissioning of single stations parallel to XFEL lasing operation

Quite some RF cavities needed short multipactor processing around 16 to 20 MV/m.

So far 4 couplers were disconnected due to temperature rise at warm window; RF conditioning was not easily possible.
Warm Beam Line Sections
Bunch Compressor Sections – Challenging Installation
The BC2 TDS system is one important system to be used to verify short bunch lengths during linac setup.
Both Bunch Compressors BC1 / BC2 include Commissioning Beam Dumps
European XFEL Status & Commissioning

Post Linac Beam Lines upstream of XS1

- 200 m transport line (eq. to 4 + 12 modules)
- 200 m collimation

- 200 m beam distribution
- 100 m XS1 dump line
Transfer Lines at the End of the Main Linac Tunnel (XTL)

- All beam lines are suspended from the ceiling
- Engineering of ‘hanging’ system needed some effort but result is very satisfying
Warm Beam Line Sections
Transport Line to XS1 Beam Dump

- Three 300 kW main beam dumps
- Special vehicles to exchange activated dumps
Installation on Top of XS1 Dump Cave

- XS1 installation includes transport towards XTDs
Final Installation Activities
SASE2 Undulator Section

- Mechanical vacuum work in the southern branch almost finished.
SASE Undulator Sections with special air conditioning hutch
Installation of Photon Beamlines

1st and 2nd offset mirrors in XTD2
Fast valves and 500 m pipes in XTD9
Differential pump + XGM in XTD9
Photon Beam Diagnostics Status SASE1 – XTD9

XGM@XTD9

HIREX crystal chamber

Pop-in Monitors Type I and II-45

crystal chamber

grating chamber

HIREX diagnostic spectrometer system
XHEXP – SASE1 science instruments
SASE1 - Femtosecond X-ray Experiment (FXE)
Beamline Commissioning Progress

0m           30m                   230m                 480m         1430m    2100m           3100m

13/01* 15/01 @ 130 MeV 19/01 @ 600 MeV

02/02 @ 600 MeV 22/02 @ 2.5 GeV

27/04 Beam spot before dump

25/02 @ 2.5 GeV 19/03 @ 6 GeV 08/04 @ 12 GeV

* Beam permission on 13/01

27/04*

* Beam permission on 26/04

keen on lasing…
First signal from FEL radiation
02.05.17 - 03.05.17

- low energy 6.4 GeV working point for beam based alignment
- no undulator beam based alignment yet, no laser heater

Photon beam @ OTRC.2615.T9

some tweaking of compression and trajectory

\[ E = 6.4 \text{ GeV} \]
\[ K = 3.5 \]
\[ 9 \text{ Å} \]
Systematic approach towards short wavelengths

- After first lasing a systematic approach (BBA and commissioning of undulator ctrl) was chosen.
- Photon beam diagnostics was commissioned. Well prepared for lasing at short wavelength...
Lasing at 2 Angstroem

- orbit & compression feedback in operation
- transport to SASE1 exp area is next

Photon beam at the end of XTD9
Guest Scientists during commissioning

THANK YOU TO ALL CONTRIBUTORS TO THE EUROPEAN XFEL