The European XFEL

Presented at the CERN Accelerator School (CAS)
Free Electron Lasers and Energy Recovery Linacs
June 7th, 2016
Hans Weise

with many pictures from Dirk Noelle
Superconducting Cavities
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

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>17.5 GeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.02 - 1 nC</td>
</tr>
<tr>
<td>Peak current</td>
<td>2 - 5 kA</td>
</tr>
<tr>
<td>Slice emittance</td>
<td>0.4 - 1.0 mm mrad</td>
</tr>
<tr>
<td>Slice energy spread</td>
<td>4 - 2 MeV</td>
</tr>
<tr>
<td>Shortest SASE wavelength</td>
<td>0.05 nm</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Bunches per pulse</td>
<td>2700</td>
</tr>
<tr>
<td>Pulse length</td>
<td>600 µs</td>
</tr>
</tbody>
</table>
3 stage bunch compression: flexible and less sensitive to noise from RF system

3rd harm. module

diagnostics

magnet chicane

bunch compression

diagnostics

4 accelerator modules

12 accelerator modules

R56 = 40 mm

R56 = 60-120 mm

R56 = 30-100 mm

\( \sigma = 2 \text{ mm} \)
\( I_{\text{peak}} = 50 \text{ A} \)
\( \sigma_E = 0 \% \)
\( E = 130 \text{ MeV} \)

\( \sigma = 1 \text{ mm} \)
\( I_{\text{peak}} = 100 \text{ A} \)
\( \sigma_E = 1.5 \% \)
\( E = 130 \text{ MeV} \)

\( \sigma = 0.1 \text{ mm} \)
\( I_{\text{peak}} = 1 \text{ kA} \)
\( \sigma_E = 1 \% \)
\( E = 600 \text{ MeV} \)

\( \sigma = 0.02 \text{ mm} \)
\( I_{\text{peak}} = 5 \text{ kA} \)
\( \sigma_E = 0.3 \% \)
\( E = 2400 \text{ MeV} \)
X-ray Beamlines for Different Wavelengths with Different Time Structures

- **SASE 1**: tunable, planar, 3 – 24 keV
- **SASE 2**: tunable, planar, 3 – 24 keV
- **SASE 3**: tunable, planar, 0.26 – 3 keV

- 2 hard x-ray undulators and beam transport with 4 instruments
- 1 soft x-ray undulators and beam transport with 2 instruments
Electron bunch trains at 10 Hz repetition rate (with up to 2700 bunches per train, 0.1–1 nC)

Δt = 222 ns

4.5 MHz

10–100 fs Photon pulses

FEL process
The Suite of Instruments

- **SASE 2**
  - MID
  - HED

- **U 2**

- **U 1**

- **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)
Organization of the European XFEL Project

In-kind Contributions

Accelerator Consortium
Institutes from D, F, I, CH, PL, ES, RU, CN, SE...

Coordinator: DESY

Other In-kind Contributors

European XFEL GmbH

Council

Management Board
Managing Directors
M. Altarelli, Chair
C. Burger, Admin. Director
Scientific Directors
S. Molodtsov
A. Schwarz
T. Tschentscher

Advisory Committees
SAC
MAC
AFC
IKRC + Det. AC
Lasers AC

CERN Accelerator School (CAS) on FELs and ERLs – June 2016
Hans Weise, DESY
Organigram of the XFEL Construction Project

Project Board (PB)
Accelerator Consortium Coordinator – ACC
Administrative Director of the XFEL GmbH – ADG
Civil Construction Coordinator – CCC
Cold Linac Coordinator – CLC
Machine Layout Coordinators – MLC

Photon Systems Coordinator – PSC
Project Office Leader – POL
Technical Coordinator – TC
WP Representatives – WPRs
XFEL Project Leader – XPL

Staff Functions

WP²-Group 1
WP²-01* RF System
WP²-02* Low Level RF
WP²-03* Acc. Modules
WP²-04* S.C. Cavities
WP²-05* Power Couplers
WP²-06* HOM Couplers
WP²-07* Frequency Tuners
WP²-08* Cold Vacuum
WP²-09* Cavity String Assem.
WP²-11* Cold Magnets
WP²-46* 3.9 GHz System

WP²-Group 2
WP²-12* Warm Magnets
WP²-14* Injector
WP²-15* Bunch Compression
WP²-16* Lattice
WP²-17* Stand. Diagnostics
WP²-18* Special Diagnostics
WP²-19* Warm Vacuum
WP²-20* Beam Dumps
WP²-21* FEL Concepts

WP²-Group 3
WP²-71 Undulators
WP²-72 Sim. of Photon Fields
WP²-73 Ray Opt. & Beam Tr.
WP²-74 X-Ray Diagnostics
WP²-75 Detector Development
WP²-76 Optical Lasers
WP²-77 Sample Environment
WP²-78 Advanced Electronics
WP²-79 IT & Data Management

WP²-Group 4
WP²-81 Scient.Instr. FXE
WP²-82 Scient.Instr. HED
WP²-83 Scient.Instr. MID
WP²-84 Scient.Instr. SPL
WP²-85 Scient.Instr. SQS
WP²-86 Scient.Instr. SCS
WP²-87 IT & Data Management
WP²-88 IT & Data Management

WP²-Group 5
WP²-28* Acc. Controls
WP²-35* Radiation Safety
WP²-36 General Safety
WP²-36* Personnel Interlock
WP²-36* EMC
WP²-37* Tunnel Installation
WP²-38* Survey & Alignment
WP²-39* Utilities
WP²-40* EPS

WP²-Group 6
WP²-31 Site & Civ Constr.
WP²-41/42/43 Site Lot 1-3
WP²-44 Site Engineering
WP²-45 AMSSF
WP²-47 Lots 4-7, 9
WP²-48 Lot 8

WP-monitoring by PB-member:

- CLC
- PSC
- CCC
- TC
- MLC
Figures and Facts

- 1.22 billion euro (price level 2005)
- Approx. 50% in-kind
  - [Link to in-kind contributions](http://www.xfel.eu/project/in_kind_contributions/)
- 11 countries
- XFEL company founded in 9/2009

- Construction time 2009 to 2016
- First electron beam / start injector operation in 12/2015
- Technical commissioning starts in 2016
- User operation with first beamline and two experiments starts in 2017
## Milestones

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>Starting TESLA R&amp;D aiming for large scale SRF electron beam accelerators, TESLA Test Facility (TTF) located at DESY.</td>
</tr>
<tr>
<td>2/2000</td>
<td>First lasing at TTF (today FLASH).</td>
</tr>
<tr>
<td>10/2002</td>
<td>XFEL TDR as supplement to TESLA TDR.</td>
</tr>
<tr>
<td>2/2003</td>
<td>Fundamental decision of the German Federal Ministry of Education and Research: <em>The X-ray laser laboratory is to be realized as a European project at DESY, and Germany will bear approximately half of the costs because of the advantage of location.</em></td>
</tr>
<tr>
<td>2003</td>
<td>TESLA Test Facility (TTF) is extended to a total length of 260 m and modified into the new VUV-FEL (later renamed FLASH).</td>
</tr>
<tr>
<td>2/2004</td>
<td>An international steering committee is established to concretize the participation of European countries in the project.</td>
</tr>
<tr>
<td>9/2004</td>
<td>MoU signed by first countries; and a state treaty provides a legal basis for the construction and operation of the X-ray laser.</td>
</tr>
</tbody>
</table>

For further details see [http://www.xfel.eu/overview/milestones/](http://www.xfel.eu/overview/milestones/)
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
</table>
| 1/2005 | The free-electron laser VUV-FEL (today known as FLASH) generates high-intensity, ultrashort laser pulses with a wavelength of 32 nm for the first time  
* shortest wavelength ever produced at a free-electron laser  
* properties of the radiation perfectly match the theoretical predictions |
| 4/2005 | Application for the XFEL public planning approval procedure |
| 7/2006 | Approval resolution ("Planfeststellungsbeschluss") for the construction and operation of the European XFEL |
| 6/2007 | The German Federal Minister of Education and Research Dr. Annette Schavan officially launches the European XFEL |
| 1/2009 | Start of construction |
| 11/2009 | Signing ceremony of the international convention in Hamburg. Five shareholders from the non-German partner countries join the European XFEL company (founded 9/2009) |
| 2017 | Start of user operation with first beamline and first 2 experiments |
Three construction sites

- 5.8 km tunnels (approx. 6 to 38 m below surface)
- 12,000 m² surface buildings
- 150,000 m³ of underground building volume
DESY Bahrenfeld – Injector Complex

Two injector tunnels and main transport shaft
Osdorfer Born Site

Distribution shaft from linac tunnel to undulator tunnels
Schenefeld Site

Distribution Shafts
Power, Water, Cooling Supplies
Experimental Hall
Office Building
Schenefeld Site – Experiment Complex

Laboratory and office building

experimental hall

photon tunnels
Inauguration of main building 6/2016
Laboratories and offices
An Accelerator Complex for 17.5 GeV

- 100 accelerator modules
- 800 accelerating cavities
  - 1.3 GHz / 23.6 MV/m
- 25 RF stations
  - 5.2 MW each
Contributors to the XFEL Accelerator

100 accelerator modules

800 accelerating cavities
1.3 GHz / 23.6 MV/m
Injector in Operation – First Beam in 12/2015

Dump

Transverse Deflecting Structure

Spectrometer  Diagnostic Section  Laser Heater  3.9 GHz Module  1.3 GHz Module  Gun
The first injector beam represented only …

\[ \approx 1\% \text{ of the total accelerator length} \]

\[ \approx 1\% \text{ of the final energy} \]

\[ \approx 1\% \text{ of the electrons/second} \]

… but all accelerator sub-systems were needed and functional.
Before and after Getting the First Injector Beam
XFEL RF Gun Installed in XTIN
4 waveguides connect to one 10 MW multi-beam klystron
RF Gun Waveguide Installation
one single RF window connects to the rf gun
RF Gun Commissioning

a short beam diagnostics section upstream of a standard XFEL 1.3 GHz accelerator module
3.9 GHz Module
supporting the longitudinal phase space gymnastics

- 3.9 GHz cavity string and module was assembled at DESY
- Common effort of INFN and DESY based on multitude of expertise like Ti welding, X-ray certification, frequency tuners, couplers, super insulation, vacuum... i.e. full expertise in s.c. cavities and modules was required
First cavity vertical test 26-Sep-14 and last 11-Feb-2015

Summary of all vertical tests of 3.9 GHz cavities

SPEC: 15 MV/m @ 10^8
Kickers and off-axis screens allow to measure emittances of single bunches during operation with long bunch trains.

- These measurements are fast and allow also to measure the emittance and mismatch evolution over the bunch train.
**XFEL Injector Status as of 6/2016**

- Injector installation finalized in Q4/2015
- 3.9 GHz module installed in 9/2015
- Injector cool-down started beginning of 12/2015
- First Beam on December 18th, 2015
- Successful commissioning during Q1/2016

- Emittance measurements done on a routine basis;
- Projected emittance as expected (1...1.5 mm mrad)
- Full bunch train length (2700 bunches) reached and beam stopped in injector beam dump

- Commissioning of Transverse Deflecting System started
- First slice emittance measurement showed 0.5 mm mrad for 500 pC
- Laser heater commissioning started
Full Bunch Train Operation

- A dedicated injector beam dump system allows for full bunch train operation
- **24/7 operation** is used to test many operation procedures
- **Operation crew** is getting trained
Warm Beam Line Sections
Dogleg & BC0 in Front of Linac L1

- installation started
- some remaining girders to be assembled in clean rooms
The accelerator tunnel (XTL) houses three cold linac sections separated by bunch compressors.

Down to the end of module XM100 the complete beam vacuum system is particle free.

4 modules / 32 s.c. cavities are connected to one 10 MW klystron.

12 modules form a cryogenic string.

At the XTL end a collimation and separation system is installed.
XFEL Accelerator Module with Tailored Waveguide System
## Contributions to the European XFEL Modules

<table>
<thead>
<tr>
<th>Institution</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BINP Novosibirsk, Russia</strong></td>
<td>• cold vacuum bellows</td>
</tr>
<tr>
<td></td>
<td>• coupler vacuum line</td>
</tr>
<tr>
<td><strong>CEA Saclay / Irfu, France</strong></td>
<td>• cavity string and module assembly</td>
</tr>
<tr>
<td></td>
<td>• cold beam position monitors</td>
</tr>
<tr>
<td></td>
<td>• magnetic shields, superinsulation blankets</td>
</tr>
<tr>
<td><strong>CIEMAT, Spain</strong></td>
<td>• Superconducting magnets</td>
</tr>
<tr>
<td><strong>CNRS / LAL Orsay, France</strong></td>
<td>• RF main input coupler incl. RF conditioning</td>
</tr>
<tr>
<td><strong>DESY, Germany</strong></td>
<td>• cavities &amp; cryostats</td>
</tr>
<tr>
<td></td>
<td>• contributions to string &amp; module assembly</td>
</tr>
<tr>
<td></td>
<td>• coupler interlock</td>
</tr>
<tr>
<td></td>
<td>• frequency tuner</td>
</tr>
<tr>
<td></td>
<td>• cold vacuum system</td>
</tr>
<tr>
<td></td>
<td>• integration of superconducting magnets / current leads</td>
</tr>
<tr>
<td></td>
<td>• cold beam position monitors</td>
</tr>
<tr>
<td><strong>INFN Milano, Italy</strong></td>
<td>• cavities &amp; cryostats</td>
</tr>
<tr>
<td></td>
<td>• contributions to frequency tuners</td>
</tr>
<tr>
<td><strong>Soltan Institute, Poland</strong></td>
<td>• Higher Order Mode coupler &amp; absorber</td>
</tr>
</tbody>
</table>
European XFEL requires 8 cavities & couplers to build 1 module per week.

Monthly average was to increased by approximately x30.
- Two cavity vendors were contracted to produce 400 cavities each.
- Slight variation in final surface treatment.
- All cavities are tested and partly re-treated / re-tested in collaboration of IFJ / DESY.
- Further assembly takes place at CEA Saclay / Irfu.
Linear Accelerator Buffer for all Sub-Components Established

string and module assembly relies on sufficiently filled buffers for all parts

- Cavities
- Couplers
- BQU (beam position monitor & quadrupole)
- Vacuum parts (bellows / gate valves)
- Cryostats
- Magnetic shielding
- Tuner
Niobium Material Bought and QC-ed by DESY

- All Nb / NbTi material (24,420 single parts!) was procured by DESY.
- Detailed quality inspection was developed and carried out.
- All material made available to cavity vendors.
- Special CE certified machines were developed and given to industry.
- Since accelerator cavities are delivered without performance guarantee, very detailed specifications are used.
- Many productions steps were supported and partly supervised by DESY & INFN.
- Several QC steps are established. Very detailed documentation.
Cavity Production (here at Company RI)

-all pictures courtesy Research Instruments
XFEL Cavities Ready for Testing at DESY
Vertical Test Cryostat at DESY
Production, Delivery and Test of > 800 cavities finished

- usable gradient well above specifications of 23.6 MV/m
- good stability of usable gradient over full production period
- the world-wide largest cavity production was finished 1/2016
800 Cavity Production Ended 1/2016
A total of 800 RF power couplers was produced at three different vendors.

The largest fraction was procured by LAL Orsay and produced by Thales / RI.

Approx. 20% were procured from CPI.

RF conditioning of all couplers was done at LAL Orsay at a rate of 10+ couplers/week.

Couplers were the by far the most challenging single items in the supply chain of the accelerator modules.

Continuing quality and delivery issues needed to be addressed.

Coupler delivery rate did not match the module assembly rate.
Module Assembly at IRFU / Saclay

- We have seen an assembly at a rate 1+/week
- XM 97 started as of May 24th, 2016
- We are still waiting for the last couplers

Based on extensive quality checks and test results, almost all accelerator modules were accepted for linac installation.

Number of non-conform modules steadily decreased; repair work of those modules (5%) was organized with the goal to repair as many as possible before the last delivery.

- XM100 expected for July 2016
The XFEL Village at IRFU / CEA Saclay

Warehouse
Alignment Area AL-WS1 & 2
Coupler Area CO-WS1 & 2
Cantilever Area CA-WS1
Roll-out Area RO-WS1 & 2
Reception Area REC-WS1
Clean room Area CO-WS1 & 2 SA-WS1 & 2
Shipment Area SH-WS1 & 2

the XFEL Village
AMTF Test Stand Infrastructure
Module performance well above specs. and visible improvement with time

Tunnel installation uses sorting of modules based on AMTF performance

Ramp-down impact to be avoided

Remark:
Clipping at 31 MV/m is done due to max. available RF power; limit given by waveguide distribution.

<table>
<thead>
<tr>
<th></th>
<th>N_{cav}</th>
<th>Average</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT</td>
<td>695</td>
<td>28.7 MV/m</td>
<td>2.9</td>
</tr>
<tr>
<td>CM</td>
<td>695</td>
<td>27.6 MV/m</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Three test benches were built to cope with 1 module per week.
Experience gained allowed for optimized procedures.
Testing rate drastically increased (10-12 days instead of >21 days).
All delivered modules can be immediately tested on one of the three benches.

Tailored waveguide distributions incl. cooling and cables are assembled, tested and connected.
Assembly rate increased to 1.5 per week by adding resources.
Module to Module Connection

- With time module to module connection rate was ramped up to approx. 1.5 connections per week
Status 30.06.2016
84 Modules installed
next 5 Modules in prep.
add. 6 Modules during assembly
1 RF-Station ready
6 RF-Stations commissioning
9 RF-Stations in preparation
One Kilometer of Cold Linac
Optimized global process steps and sequence & daily improvements

- Tunnel Installation Process

- Cryo-String
- RF
- Signal Cables
- LWL
- Ethernet
- P.I.
- Prep Cond
- TÜV
Warm Beam Line Sections
Bunch Compressor Section
Many beam line sections are suspended from the ceiling

Engineering of ‘hanging’ system took longer than anticipated, but very satisfying result

Installation of supports / mounts finished

Installation of magnets and vacuum components is ongoing at quite some pace

Planned to be finished mid 2016

Temporary beam line replacing 4 / 8 modules is in production
Warm Beam Line Sections
Transport Line to XS1 Beam Dump

- Several beam dumps
- Special vehicle to exchange activated dumps
**X-ray Beamlines**

- **SASE 1**
  - Electrons

- **SASE 2**
  - Electrons

- **SASE 3**
  - Electrons

**Experiments**

- SASE 1
- SASE 2
- SASE 3

**Equipment**

- SASE 1 undulator
- SASE 3
35 Undulator Segments in SASE1

courtesy of XFEL.EU
Optical Elements and Photon Diagnostics of the SASE1 Beamline

courtesy of XFEL.EU
Installation Activities
Photon Beam Lines

courtesy of XFEL.EU
SASE1 and SASE3 Hutches Installation
SASE1 stations FXE and SPB/SFX just prior to instrument installation
Summary and Outlook

- Accelerator module production / testing / installation comes to an end
- Based on injector experience and accelerator module performance we are looking forward to reaching all design parameters
- Tunnel closure is expected for end Q3/2016
- Technical commissioning continues after first cool-down
- The milestone 'first lasing possible' is scheduled 6 months after 'tunnel closure'
- User operation will start in 2017
- Full performance is expected approx. 1.5 years after first lasing

more than 1000 participants at the 2016 users’ meeting