Status of the European XFEL Accelerator

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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

European XFEL Users‘ Meeting

25 – 27 January 2017
DESY, Hamburg and XFEL.EU, Schenefeld, Germany
One Kilometer of Cold Linac
With almost 800 Superconducting Cavities
3 stage bunch compression: flexible and less sensitive to noise from RF system

4 accelerator modules

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

3rd harm.
module

R56 = 40 mm
dogleg

12 accelerator modules

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

bunch compression
c Chicane

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

$\sigma_\sigma = 0.02 \text{ mm}$
$I_{\text{peak}} = 5 \text{ kA}$
$\sigma_E = 0.3 \%$
$E = 2400 \text{ MeV}$

harmonic system

bunch compressor

beam diagnostics
Injector in Operation – First Beam in 12/2015
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

- Transverse Deflecting System operated
- **Slice emittance measurements give 0.5 mm mrad for 500 pC**; also over bunch train
- Laser heater commissioning started
Full Bunch Train Operation

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

- All girders were pre-assembled in clean rooms
- Tunnel installation required local clean rooms
A real top-view of the Dogleg Section
Warm Beam Line Sections
Bunch Compressor Sections – Challenging Installation
Bunch Compressor BC1
The BC2 TDS RF station is installed and successfully commissioned.

TDS structure commissioning is part of the linac commissioning.
Both Bunch Compressors BC1 / BC2 include Commissioning Beam Dumps
The accelerator tunnel (XTL) houses three cold linac sections separated by bunch compressors.

Down to approx. 50 m behind the last module 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.
Accelerator Module on its Way to the Tunnel

- 1st module July 1st, 2014 – last module August 1st, 2016
The First and the Last Module

- In total 96 modules in 103 working weeks
- The initially projected rate was 1 acc. module per week.
- Variation in coupler availability was compensated by additional efforts at CEA / Irfu wrt. assembly rate.
- Gained experience with module testing was used to shorten test duration of module 40+.
The last Process Line Welding on Sep 9, 2016
The End of Main Linac Section L3
Module performance well above specs. and visible improvement with time

- Tunnel installation used sorting of modules based on AMTF performance
- XM98 as scavenger module

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

<table>
<thead>
<tr>
<th>N_{cavs}</th>
<th>Average</th>
<th>RMS</th>
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<tbody>
<tr>
<td>VT</td>
<td>815</td>
<td>28.3 MV/m</td>
</tr>
<tr>
<td>CM</td>
<td>815</td>
<td>27.5 MV/m</td>
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</table>
Waveguide Tailoring was done for all Modules
European XFEL Accelerator Status

Energy Reach of European XFEL Modules

maximum energy reach

- after tunnel installation and
- according to accelerator module test

<table>
<thead>
<tr>
<th></th>
<th>Installed (GeV)</th>
<th>Module (GeV)</th>
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<tbody>
<tr>
<td>CS1</td>
<td>1.00</td>
<td>1.05</td>
</tr>
<tr>
<td>CS2</td>
<td>3.89</td>
<td>4.06</td>
</tr>
<tr>
<td>CS3</td>
<td>6.29</td>
<td>6.72</td>
</tr>
<tr>
<td>CS4</td>
<td>8.91</td>
<td>9.49</td>
</tr>
<tr>
<td>CS5</td>
<td>11.38</td>
<td>12.09</td>
</tr>
<tr>
<td>CS6</td>
<td>13.92</td>
<td>14.76</td>
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<tr>
<td>CS7</td>
<td>16.63</td>
<td>17.62</td>
</tr>
<tr>
<td>CS8</td>
<td>19.42</td>
<td>20.44</td>
</tr>
<tr>
<td>CS9</td>
<td>21.09</td>
<td>22.23</td>
</tr>
</tbody>
</table>

the maximum energy during FEL operation needs to respect the bunch compressor (BC) working points

- 2.4 GeV nominal BC2 energy leads to approx. 19.5 GeV
- higher BC2 energy (e.g. 3.3 GeV) allows for > 20 GeV

increased max. energy assures higher availability

European XFEL Users’ Meeting – January 2017
Hans Weise, DESY
During the 2\textsuperscript{nd} production year AMTF module testing was performed without any delay.

During the end of production the major non-conformity was overheating at the 70k coupler window; all respective warm coupler parts were exchanged.

Waveguide tailoring was done for all modules.

Successfully repaired modules were retested at AMTF when needed.

Not installed are

- XM8 (leaky cryogenic line)
- XM46 & XM50 (inacceptable cav. performance)
- XM99 (leaky beam line)
- XM100 spare module & replaced by XM-2
Optimized global process steps and sequence & daily improvements

- Cryo-String
- RF
- Signal Cables
- LWL
- Ethernet
- Prep Cond
- P.I.
- TÜV
- Improved process management and repetitive tasks helped to speed-up the installation.

- All groups worked with the goal to close the tunnel around mid October.

- Some work will remain to be done on maintenance days / weeks.

- Full operation incl. CS1 – CS8

- CS9 cabling etc. to be done during maintenance periods (two RF stations only)
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
Beamline Installation close to XTL Tunnel End

- All beam lines are suspended from the ceiling
- Engineering of ‘hanging’ system took long but result is very satisfying
- Installation work finished beginning of Q4/2016
- Commissioning finished also.
All beam dumps available and XS1 as well as main dump installed

Special vehicles to exchange activated dumps
Installation on Top of XS1 Dump Cave

- XS1 installation includes transport towards XTDs
- The safety magnet is installed at the upstream end
Shielding and personnel interlock finished in Q4/2016.

Final internal check of the personnel interlock done Nov. 15/16.
- BINP and DESY teams have finished the mechanical vacuum work in the northern branch.
- Work in the southern branch is still ongoing.
SASE Undulator Sections with special air conditioning hutch
Linac Commissioning started from Accelerator Control Room (BKR)
First Linac Sections on the Control Screen
Work on Trajectory Response (here @ 600 MeV)

Measured responses to a change of GY146 L1 on the various BPMs:

- BPM 112.11:
  - $x$: $(0.002 \pm 0.019)$ mm
  - $y$: $(2.036 \pm 0.089)$ mm

- BPM 115.11:
  - $x$: $(0.012 \pm 0.021)$ mm
  - $y$: $(3.017 \pm 0.010)$ mm

- BPM 117.11:
  - $x$: $(0.016 \pm 0.028)$ mm
  - $y$: $(0.019 \pm 0.011)$ mm

- BPM 119.11:
  - $x$: $(0.001 \pm 0.020)$ mm
  - $y$: $(0.011 \pm 0.030)$ mm

- BPM 134.1.
  - $x$: $(0.003 \pm 0.076)$ mm
  - $y$: $(0.003 \pm 0.076)$ mm
The pannel shows the vector sum control settings.

Vector sum amplitude and phase are calculated from probe signals of all cavities.
Full Beam Transmission to BC1 Dump
19.01.17 – Linac L1 RF Commissioning

Cavities on resonance

A2.L1: finer frequency tuning
Still 19.01.17 – 493 MeV in BC1 Dump

Creating optimism but PLEASE give us time!
Overview of XFEL Cryogenic Equipment

Contributions
- LINDE
- DEMACO
- BINP

AMTF
- Warm He-Pumps

Shaft
- Cold Compressors CB44
- Distribution Box XLVB

Injector
- Distribution Box XIXV
- EC 3.9 GHz CM FC

Linac
- Distribution Box XLTL1
- FC CMS EC
- EC 3.9 GHz CM FC

Main Linac
- XLTL2
- XLTL3
- SCB CMS EC
- SCB CMS SCB

Overview of XFEL Cryo Plant (Building 54)
- SC Purifier
- Coldbox 41
- Coldbox 43
Overview of XFEL Cryogenic Equipment

- Expected **Heat Loads**: 2K: 1.9 kW  5/8K: 3.6 kW  40/80K: 24 kW
- 24 / 7 operation; 2 – 3 years operation w/o scheduled breaks
- Refrigerator availability > 99%
- Cold Compressors to reach operating temperature of 2K
Cryogenics is challenging

- **Complexity of cryogenic system** requires sufficient time to perform commissioning and establish / optimize operation procedures
- **Gain experience** with new machines, e.g. 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

**Remark to Cold Compressors (CC):**
CCs are used instead of warm He-pumps due to efficiency and operational cost reasons. Operation cost saving of ~ 2.5 Mio EUR per year. But each CC system is unique, CCs are very sensitive towards mass flow-, temperature- & pressure changes. Start up of CC can be very time consuming; operational experience required. We are *entering uncharted waters*…
First Cooldown of XFEL Linac (300K to 4K)

- 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!!!
2K Operation reached on January 6th, 2017
MANY THANKS to the Cryoteam !!!

BUT....

- We still need to learn a lot wrt. 2K operation (30.6 mbar)
- Set pressure is not yet reached automatically (many manual interventions are still necessary to avoid failures / CC shut downs)
- Set pressure is not yet reached exactly and pressure stability doesn’t reach the envisaged +/- 1% stability
- Different operating parameters for different operating modes still have to be established (mainly for cold compressors)
  - CC are not yet operated at their design values (e.g. driving frequencies, pressure ratios, etc.)
  - 2K return flow has to be stabilized to ensure stable operating conditions of cold compressors
- Pressure and mass flow of 2K return flow has to be stabilized

- We are still addressing reliability issues of the CC’s driving motors
Pressure at 2K System

... is definitely stable enough for all linac commissioning steps.
Linac commissioning

- Sequential commissioning of accelerator modules and beam lines
  - Injector at 130 MeV
    - pass on to BC1 beam dump
    - L1 commissioning (1 RF station until Feb 1\textsuperscript{st})
  - L1 at $E_{\text{final}} = 600$ MeV
    - pass on to BC2 beam dump for L2 commissioning
    - L2 commissioning (3 RF stations until Feb 15\textsuperscript{th})
  - L2 at $E_{\text{final}} = 2.4$ GeV
    - pass on to XTL dump for L3 commissioning
  - L3 up to $E_{\text{final}} = 17.5$ GeV (15-18 RF stations, April 15)

- Set-up bunch compression in parallel to linac commissioning
North Branch Commissioning

- Once Northern Branch is ready…
  - transport beam to main dump after SASE1&3 (April)
- First lasing in SASE1 (May)
- SASE1 photon systems and experiment commissioning follows

- First lasing in SASE3 (June) and following photon systems and experiment commissioning depends on operation priorities and systems readiness

- South branch (SASE2) commissioning depends on installation readiness and operation priorities, first lasing presently scheduled for November
The fascinating time of accelerator module production / testing / installation comes to an end

the **Tunnel is closed since beginning of 12/2016.**

The linac is cooled down to 2K.

Technical and beam commissioning started.

Based on injector experience and accelerator module performance we are looking forward to reaching all design parameters

**The milestone 'first lasing possible' is still scheduled 6 months after 'tunnel closure’**

The first few weeks of commissioning were very successful.

But give us the time we need. There will be surprises…no doubt.

**Full performance is expected approx. 1.5 years after first lasing**
Thanks to all Contributors to the European XFEL Accelerator

100 accelerator modules

800 accelerating cavities
1.3 GHz / 23.6 MV/m