Commissioning of the HPRF System for the European XFEL

Stefan Choroba, DESY
for the XFEL WP HPRF

CWRF2018
Hsinchu, Taiwan, 28/06/2018
Outline

- European XFEL
- RF System Overview
- System and Components, Status and Commissioning
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
# 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>
Superconducting Cavities
One Kilometer of Cold Linac
X-ray Beamlines for Different Wavelengths with Different Time Structures

- **LINAC**: 17.5 / 14 / 10.5 GeV
- **SASE 1**: 3 – 24 keV
- **SASE 2**: 3 – 24 keV
- **SASE 3**: 0.26 – 3 keV

- 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

- **Electron Tunnel**
- **Photon Tunnel**
- **Undulator**
- **Electron Switch**
- **Electron Bend**
- **Electron Dump**

Experiments:
- HED
- MID
- FXE
- SPB
- SQS
- SCS

European XFEL

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The Suite of Instruments

SASE 2
U 2
U 1
SASE 1
SASE 3

MID
HED

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
European XFEL Layout

- Undulator/Photon Tunnels
- Experiment Hall in Schenefeld
- Linear Accelerator 1.9 km - 17.5 GeV
- Injector at DESY campus
**XFEL High Power RF Requirements**

- Number of sc cavities: 800 total for **17.5GeV**
- Power per cavity: **122 kW**
- Gradient at 17.5GeV: **23.6 MV/m**
- Power per 32 cavities (4 cryo modules): **3.9MW**
- Power per RF station: **5.2MW** (including 10% losses in waveguides and circulators and a regulation reserve of 15%)

- Number of RF stations: **26** (orig. 27), active **25**
- Number of RF stations Main Linac: **25**, active **23**
- Macro beam pulse duration: **650µs**
- RF pulse duration: **1.38ms**
- Repetition rate: **10Hz (25Hz)**
- Average RF power per station: **72kW (150kW)**
XTL RF Station Overview

HV Pulse Cable

Modulator Hall XHM

RF Waveguide Distribution

HV Pulse Cable

Pulse Transformer

Klystron

XFEL Tunnel XTL

Racks and Water Distribution

European XFEL
RF Station in XTL
XTL RF Station Details
XTL Status
He-Line Collapse at End 2016
Status RF System

- 2 Injector RF stations in operation since 2014 (RF Gun)
- Installation and commissioning of RF stations in XTL until end of 2016 on RF loads
- Operation of RF stations on SC cavities since beginning of 2017
- 24 XTL RF stations in CS1- CS9 are in operation
- 22 XTL RF stations on beam
- 2 XTL RF stations in CS9 could only been finished and commissioned spring 2018 due to incident with the He transfer line end of 2016. The line collapsed during pressure test und damaged the waveguides of 5 stations in CS8 and 9. CS9 could not be finished in time.
- XFEL in operation for users: typ. 14GeV
**XFEL Injector RF Station**

- **RF Gun RF station:**
  - typ. 5MW up to 6.5MW at RF Gun (~7MW generated by the Klystron max. 10MW), 680µs, 10Hz (taking into account losses in waveguide distribution system)

- **Cryomodule RF station:**
  - 1.3MW, 1.38ms, 10Hz (as for main linac, but one quarter of RF power)

- Klystrons, pulse transformers, racks for the injector are on the 3rd underground floor of the injector building. RF power is transmitted in waveguides to the 7th underground floor.
RF Station Commissioning
Multi Beam Klystron

- RF Frequency: 1.3GHz
- Cathode Voltage: < 120 kV
- Beam Current: < 140 A
- Max. RF Peak Power: 10MW
- RF Pulse Duration: 1.5ms
- Repetition Rate: 10Hz
- RF Average Power: 150kW
- Efficiency: 63%

7 (6) pcs Toshiba E3736H

22 (20) pcs Thales TH1802
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Graph showing the cathode voltage (U cathode) for different RF stations (A1 to A25) over two different periods (Dec 2017 and May 2018). The graph compares the cathode voltage for these periods, with a focus on the range from 75 to 115 kV.
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Numbers of events

01.01.2017 - 31.12.2017
01.01.2018 - 30.05.2018


XFEL RF station

European XFEL
**HV Pulse Modulator**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulator Pulse Voltage</td>
<td>9.6kV</td>
<td>12kV</td>
</tr>
<tr>
<td>Modulator Pulse Current Voltage</td>
<td>1.62kA</td>
<td>1.8kA</td>
</tr>
<tr>
<td>Klystron Gun Voltage</td>
<td>115kV</td>
<td>132kV</td>
</tr>
<tr>
<td>Klystron Gun Current</td>
<td>135A</td>
<td>150A</td>
</tr>
<tr>
<td>High Voltage Pulse Duration (70% to 70%)</td>
<td>1.57ms</td>
<td>1.7ms</td>
</tr>
<tr>
<td>High Voltage Rise and Fall Time (0 to 99%)</td>
<td>0.15ms</td>
<td>0.2ms</td>
</tr>
<tr>
<td>High Voltage Flat Top (99% to 99%)</td>
<td>1.37ms</td>
<td>1.5ms</td>
</tr>
<tr>
<td>Pulse Flatness during Flat Top</td>
<td>±0.2%</td>
<td>±0.3%</td>
</tr>
<tr>
<td>Pulse-to-Pulse Voltage fluctuation</td>
<td>±0.1%</td>
<td>±0.1%</td>
</tr>
<tr>
<td>Energy Deposit in Klystron in Case of Gun Spark</td>
<td>&lt;20J</td>
<td>20J</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>10Hz</td>
<td>10Hz (30Hz)</td>
</tr>
<tr>
<td>Pulse Transformer Ratio</td>
<td>1:12</td>
<td>1:12</td>
</tr>
</tbody>
</table>
**HV Modulator Status**

- We have 29 modulators, 26 modulators are required.

- Unexpected weak components have been detected after acceptance during long term commissioning. Many of the weak components have been improved or exchanged by the vendor already.

- A package of spare components has been ordered and delivered. Emphasis is on components which have long term delivery or might not be available in the future.

- Other spares might be required in the future.
Matching Network

Capacitor in matching network got fire. All capacitors were replaced.
RF Power Distribution

- Distribution of klystron output power to the superconducting cavities
- Protection of the klystron from reflected power
Module Waveguide Distribution
5.2MW, 1.37ms, 10Hz per RF station. Equal power to 32 cavities
Example for Module Measurement Results

Specification for Waveguide Distribution (WD) production

<table>
<thead>
<tr>
<th>WD number</th>
<th>WD type</th>
<th>Cryomodule name</th>
</tr>
</thead>
<tbody>
<tr>
<td>063</td>
<td>Left</td>
<td>XM70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cavity number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity gradient, MV/m</td>
<td>15.7</td>
<td>22.2</td>
<td>30.7</td>
<td>23.0</td>
<td>23.8</td>
<td>26.8</td>
<td>31.0</td>
<td>27.3</td>
</tr>
<tr>
<td>Cavity power, kW</td>
<td>59</td>
<td>118</td>
<td>225</td>
<td>127</td>
<td>136</td>
<td>172</td>
<td>230</td>
<td>178</td>
</tr>
</tbody>
</table>

$P_{WD} \approx 1.2$ MW

1. WD position in the RF station
2. Cavity number in the beam direction
3. The smaller number for a pair of cavities will be used
4. Cavity power is calculated by MHF-p based on accelerator parameters from XFEL TDR
5. Preliminary estimation of waveguide distribution power

Signed for and behalf of WP01

B. Yildirim

Date: 08.12.2015
Module Waveguide Distribution, Updated Requirements

Allow for adjustment of power for individual cavities and modules and for large spread of cavities (due to performance difference of SC cavities within a pair after module assembly, large spread).

- Asymmetric shunt tees with individual coupling factors
- Asymmetric shunt tees 3.0 dB, 4.77 dB, 6.0 dB
- Shunt tee
- Shunt tees with integrated phase shifters
- Fixed phase shifters
- Waveguide Bellow
- 350kW Ferrite Load
- 350kW Circulator
- Asymmetric shunt tees with individual coupling factors (induct. + cap. posts)
- Asymmetric shunt tee with individual coupling factor
WATF

- Acceptance, test and preparation of subsystems (waveguide components, cables, cooling system, supports), specification, assembly, test of waveguide distributions and connection
- 4 working places – Binary cell assembly and tuning, WD assembly and mechanical adjustment, LLRF and HPRF stand
- 12 specific test stands for tuning and adjustment of WD component (input geometrical control, air tightness test, step motor test, WG cleaning and drying, shunt tee tuning etc.)
- Measurement process is automated
- Storage place for 6 WD components plus 7 complete WD
- Production rate – 2 tailored WD per week
- Connection to modules in AMTF area
WD and Cryomodule at AMTF

WD connection to cryomodule with special 6 DoF (degree of freedom) setup at AMTF precision: +/-1.5mm, 0.2 degree at each coupler to avoid stress

The cryomodule itself is the support for the WD

WD Installation at cryomodule took about 7 hours
Power pattern for different WDs

High Power RF Test Results  \( \Delta = +250 \text{ MeV} \)  
Tailoring of waveguide distributions allows to reach nominal gradient with less RF stations

<table>
<thead>
<tr>
<th>WD#</th>
<th>EXFEL WD</th>
<th>Estandard</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>247 MeV</td>
<td>192 MeV</td>
</tr>
<tr>
<td>55</td>
<td>222 MeV</td>
<td>143 MeV</td>
</tr>
<tr>
<td>61</td>
<td>195 MeV</td>
<td>150 MeV</td>
</tr>
<tr>
<td>63</td>
<td>201 MeV</td>
<td>130 MeV</td>
</tr>
</tbody>
</table>

RF Power
Zero suppressed
Phase

European XFEL
**XFEL Waveguide Distribution**

Max achievable linac energy is **22.2 GeV** (from module test).

Linac energy with specific waveguide distribution is **21.1 GeV** (installed) / **19.5 GeV** (BC2 energy 2.4GeV).

Linac energy with standard waveguide distribution would be **15.7 GeV**.
RF Performance

RF Performance as of 28.03.2018

L3 up to CS8

![Graph showing RF performance data for different RF stations, with maximum voltage vs. RF station.]

*Courtesy of M. Omet, DESY*
Reasons for deviation

- Some cavities and couplers deteriorated and had to be excluded.

- In some cases the cavity performance changed only slightly but the tailored waveguide distribution does not fit exactly to the changed parameter.

- Klystron arms produce different output power when reflected power (VSWR <1.2) is different in amplitude and phase for both arms.

- Waveguide sparks in klystron to module distribution, which could not be tested before in WATF.

- Total length of waveguide distribution ca. 1.55km, 5500 flanges, 55000 bolts and nuts.
RF breakdowns in WG systems (01/01/2017-30/05/2018)

Date of event

RF station

ARM1
ARM2

European XFEL
Waveguide Spark Detection

- Measurement of reflected power by installed directional coupler
- Measurement of sound by mobile sound detector system
Phaseshifter

There are \((32+5) \times 25 = 925\) movable phase shifters
In XFEL waveguide distribution
*Only One has been destroyed*
*Problem – was wrong washer (from steel instead plastic)*
Asymmetric Shunt Tee

There are $28 + 2 \times 25 = 750$ asymmetric shunt tees in XFEL waveguide distribution. 2100 post bolted connections. 
*Only One has been destroyed. Problem – was wrong torque of mechanical connection*
Waveguide Flange

There are about 5500 pairs of flanges in XFEL waveguide distribution. 55 000 (!) controlled bolted connections with torque 19±0.5 nm. 
Only two have been destroyed. Problem – non-flatness of flange. 
Such high reliability of flange connection was achieved due two factors - two level torque control of all bolted connection and flange design especially developed for XFEL waveguide distribution.
Two Level Waveguide Flange Control

There are about **55 000 controlled bolted connections** in XFEL waveguide distribution. To avoid mistakes during waveguide distribution assembly two persons with own labels bolted the flanges with torque 19±0.5 nm. Second person checked the torque once more.
Other Components and Spares

- Demand of spares of subsystem components has been estimated on FLASH experience.
- Urgent spares have been ordered for several subsystems: e.g. pulse transformers, power supplies in electronic racks, RF interlock system components.
- Additional spares will be required during operation.
Summary

- Installation of RF stations was done until end of 2016. 2 stations could not be finished due to He-line damage.
- Commissioning and operation of RF gun started already in 2014.
- Main linac commissioning and operation started beginning of 2017.
- XFEL is in operation for users.
- Last 2 stations (CS9) were commissioned in spring 2018.
- No severe problem was detected during commissioning.
- Capacitors in matching network had to be replaced.
- Some components in modulators are being replaced.
- Klystrons behave as expected.
- Small number of waveguide arcs in sections, which could not been tested outside XTL, diagnostic system has been developed.
- Waveguides might be re-tailoired between modules and at klystron output because of changed cavity performance.
Thank for your attention
Injector RF Station Overview

for 2. Injector (optional)

First RF Station for RF Gun of 1. Injector
RF Gun Waveguide Distribution

Klystron RF power 8MW
RF Gun RF power typ. 5MW, max 6.5MW, 680µs, 10Hz
Klystron has 2 output arms, RF power is split into 4 arms and transmitted in the shaft, finally combined into 1 arm and connected to the RF Gun window
3 stage bunch compression: flexible and less sensitive to noise from RF system

![Diagram showing 3 stage bunch compression]

- 3rd harmonic module
- Dogleg $R_56 = 30-100\text{mm}$
- Bunch compression chicane
- $3rd$ harm.

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

Harmonic system, bunch compressor, beam diagnostics