SRF Operation at XFEL: Lessons Learned After More Than One Year

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European XFEL – a great success story

17.5 GeV
27000 bunches/s
Outline

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Eu-XFEL: General Layout

Length of accelerator: 1500 m
Length of facility: 3400 m

101 Cryo Modules (97 installed now)
8 SRF 9-cell cavities per CM

Beam pulse length µs 600
Repetition rate Hz 10
Max. # of bunches per pulse 2700
Min. bunch spacing MHz 4.5
Bunch charge nC ≤ 1
Max. beam current mA 4.5
Nominal beam DF % 0.65
Average Gradient MV/m 23.6

650 µs long RF pulse in gun and accelerating modules
Operation energy 8 – 16.5 GeV
LLRF takes into account electron beam induced fields
Energy jitter over bunch train <10^-4
No beam losses
Eu-XFEL: SRF Technology

- Cavity type: TESLA
- Number of cells: 9
- Cavity length: 1.035 m
- Operating frequency: 1.3 GHz
- R/Q: 1030 Ω
- Accelerating Gradient: 20 – 31 MV/m
- Quality factor, $Q_0$: $\geq 10^{10}$
- $Q_{ext}$ (input coupler): $4.6 \times 10^6$ (10^6 – 10^7)
- Operating temperature: 2 K
Eu-XFEL: Timeline

Jan 13, 2017
Jan 15, 2017: 130 MeV
Jan 19, 2017: 600 MeV
Feb 2, 2017: 600 MeV
Feb 22, 2017: 2.5 GeV
Feb 25, 2017: 2.5 GeV
April 8, 2017: 12 GeV
Oct 23, 2017: 14.9 GeV
May 2-3, 2017
First lasing SASE1 @ 9 Å
April 27, 2017
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May 2-3, 2017: First lasing SASE1 @ 9 Å
April 27, 2017: First lasing SASE3 @ 1.3 nm
February 8, 2018
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  - Jan 15, 2017: 130 MeV
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- Feb 2, 2017: 600 MeV
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- Feb 25, 2017: 2.5 GeV
  - April 8, 2017: 12 GeV
  - Oct 23, 2017: 14.9 GeV

- March 13, 2018
  - First lasing SASE1 @ 9 Å

- May 2-3, 2017
  - First lasing SASE3 @ 1.3 nm

- April 27, 2017

- February 8, 2018
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Oct 23, 2017: 14.9 GeV
March 13, 2018
First lasing SASE1
@ 9 Å
May 1, 2018
First lasing SASE2
@ 1.8 Å
May 2-3, 2017
April 27, 2017
First lasing SASE3
@ 1.3 nm
February 8, 2018
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Oct 23, 2017: 14.9 GeV

May 1, 2018
First lasing SASE2 @ 1.8 Å

March 13, 2018
First lasing SASE1 @ 9 Å

May 2-3, 2017
First lasing SASE3 @ 1.3 nm

April 27, 2017

Flexible Beam Distribution
May - October, 2018
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Jan 13, 2017
Jan 15, 2017: 130 MeV
Jan 19, 2017: 600 MeV

Feb 2, 2017: 600 MeV
Feb 22, 2017: 2.5 GeV

Feb 25, 2017: 2.5 GeV
April 8, 2017: 12 GeV
Oct 23, 2017: 14.9 GeV

July 12, 2018: 17.6 GeV

March 13, 2018
First lasing SASE2
@ 1.8 Å
May 1, 2018

May 2-3, 2017
First lasing SASE1
@ 9 Å

April 27, 2017
First lasing SASE3
@ 1.3 nm

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Eu-XFEL: Timeline

Jan 13, 2017
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Jan 19, 2017: 600 MeV
Feb 2, 2017: 600 MeV
Feb 22, 2017: 2.5 GeV
Feb 25, 2017: 2.5 GeV
April 8, 2017: 12 GeV
Oct 23, 2017: 14.9 GeV
July 12, 2018: 17.6 GeV
Nov 2, 2018: 2699 bunches/RF pulse
March 13, 2018
First lasing SASE2
May 1, 2018
First lasing SASE1
@ 1.8 Å
May 2-3, 2017
First lasing SASE3
@ 1.3 nm
April 27, 2017
First lasing SASE2
@ 1.8 Å
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May 2-3, 2017
First lasing SASE3
@ 1.3 nm
February 8, 2018
Flexible Beam Distribution
May - October, 2018
Jan 15, 2017: 600 MeV
Jan 19, 2017: 600 MeV
RF Power Distribution

- All CM were cold-tested in Accelerating Module Test Facility (AMTF)
- Cavity operational limits:
  - Quench
  - Field Emission (X-ray monitor threshold $10^{-2}$ mGy/min)
  - 31 MV/m – power limit (administrative)
- $E_{acc}$ measurement error ~10%

Cryomodule Waveguide Distribution System (WDS) tailored to match forward power to each cavity within practical limits

- Distribution of klystron output power to the superconducting cavities
- Protection of the klystron from reflected power
- Control of phase

Errors:
- WDS: 0.02 dB
- Klystron arm: 0.04 dB

Module ‘pairs’ balanced (power requirement)
- Module power balance adjusted to match max. voltage (up to 3dB)
Fundamental Power Couplers

- Main coupler design for the Eu-XFEL linac is well established and proven.
- All of 25 Eu-XFEL RF stations 776 couplers are conditioned except 4 FPCs were not conditionable and showing T70K overheating – shorted / disconnected from the RF source.
- Couplers operation stable since over two years of Eu-XFEL operation – no other shorted (not used) couplers.
- FPC cold window temperature (T70K) increase with high RF power on some couplers shows, that proper coupler cooling could be rather critical – currently it is not a problem for the operation.
- FPC conditioning (warm and cold) is important for the linac operation.

Eu-XFEL fundamental power coupler consists of warm, cold and waveguide main parts. Coaxial coupler is made of copper and copper plated (10/30µm) stainless steel with two alumina TiN coated ceramic windows.

Motorized antenna tuning (±10mm) allows for Q_{load} adjustment (10^6..10^7). Operating Q_{load} is 4.6×10^6.

All FPCs are pre-conditioned up to 1 MW pulsed RF power up to 400 µs RF pulse length and up to 500 kW with 1.3 ms pulse, repetition rate is 10Hz.
Reaching the Design Energy

Maximum Gradient Task Force (MGTF)
- start on 21.06.2017
- 20 of 20 stations in L3 investigated
- 1 of 3 stations in L2 investigated
- 40 investigations done

17.6 GeV at TLD on 12.7.2018
- With 2.6 GeV after BC2
- Further investigations followed

17.6 GeV at TLD on 18.7.2018
- With design energy of 2.4 GeV after BC2

Energy gain due to MGTF: 1.9 GeV
- Nearly 11% of final energy
- Equal to about 2.4 L3 RF stations
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Denis Kostin, May 20th, 2019

SRF Cavities: Performance

Reached an average of 93.6% of AMTF performance
SRF Cavities: Limits

- Quench (soft quenching)
- Field emission (500 µSv/h neutrons)
- Power / missing piezo operation
- Other limitations → solved
  - Waveguide sparking
  - Too low klystron power
  - Cryogenics
- In some cases, there are potential energy gains from further optimization of the WDS

Detuned cavities (31.01.2019)

<table>
<thead>
<tr>
<th>Reason of detuning</th>
<th>Number of cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td>After AMTF tests</td>
<td>5 (~0.6%)</td>
</tr>
<tr>
<td>After tests in XTL (coupler)</td>
<td>4 (~0.5%)</td>
</tr>
<tr>
<td>MGTF</td>
<td>12 (~1.5%)</td>
</tr>
<tr>
<td>Sum</td>
<td>21 (~2.7%)</td>
</tr>
</tbody>
</table>

- A6.M3.C1 cavity problem: high FE/X-rays (10MV/m limit)
- A6.M3.C5 MGTF: too much power to this cavity (higher V_VS without)
- A6.M3.C6 MGTF: too much power to this cavity (higher V_VS without)
- A7.M1.C7 MGTF: too much power to this cavity (higher V_VS without), degradation
- A7.M2.C3 MGTF: too much power to this cavity (higher V_VS without)
- A7.M2.C7 cavity problem: high FE/X-rays (11MV/m limit)
- A8.M4.C1 MGTF: too much power to this cavity (higher V_VS without)
- A8.M4.C4 MGTF: too much power to this cavity (higher V_VS without)
- A8.M4.C5 MGTF: too much power to this cavity (higher V_VS without)
- A12.M2.C2 MGTF: too much power to this cavity (higher V_VS without)
- A12.M3.C8 MGTF: too much power to this cavity (higher V_VS without)
- A14.M3.C5 MGTF: high cryo-losses (already at AMTF observed)
- A17.M3.C7 MGTF: too much power to this cavity (higher V_VS without)
- A18.M4.C4 wrong WG-distribution 31MV/m (FE limit at 23MV/m)
- A21.M4.C2 MGTF: too much power to this cavity (higher V_VS without), degradation
SRF Cavities: Operation

Quench limits vs AMTF data

Possible to reach 17.6 GeV.
Quench limits of 76 cavities were determined operationally (1..3 per CM).
12 cavities are detuned to optimize the performance (max. energy).
1 RF station (A14) is limited by the cryo-load.
3 RF stations (A6, A9, A12) are limited by the tunnel radiation.
Reached 93.6% AMTF test performance – within the error margins.
Tunnel Radiation

- Radiation (gamma and neutrons) measurement is an important tool to understand the machine operation.
- There are different techniques – Rad-FET, TLDs, BLMs, Gamma and Neutron Sensors – including a remote-controlled robot system (MARWIN).
- MARWIN measurement examples
- Radiation in the linac is almost entirely RF related (Field Emission / Dark Current).
- Radiation due to beam particle loss can be seen in collimation sections as expected
- Only three RF stations (A6, A9, A12) are limited by the radiation at max.energy.
- No degradation – radiation values do change with cavities accelerating gradient and tuning – understandable.
Cryogenics

Eu-XFEL cryo-plant (4K) 2 years in the operation since successful commissioning
- the performance results comply within the error margin with the specification: 2K cryo-losses set to ~5 W/CM, measured <6.3 W/CM at 17.5 GeV

The 2K pressure stability is excellent
- 0.6% peak-to-peak, 0.3% RMS
- The cascaded pressure regulation in combination with the automatic heat load compensation improved the pressure stability significantly
- Even dynamic procedures (power ramping, RF-shutdown, etc.) can be compensated quite well without affecting the pressure stability drastically

There are some problems with bearings of the cold compressor motors
- New motor design is being developed, improvements are being done as well
- The recovery effort after a cold compressor shutdown (e.g. bearing failure) is minimized by the automation and cryogenic system configuration

Eu-XFEL cryogenic system:
- 671 control valves
- 2647 temperature sensors
- 800 pressure sensors
- 212 flow sensors
- >100 level sensors
- 433 regulation loops
- > 22000 records
- > 220000 properties

2K cryogenic heat load at 17.5 GeV (July 2018)
Cavity Piezo Drivers

Test run at A24

- Piezo driver electronics installed at all RF stations
- Cable checking is scheduled now, then...
  - Cable fixing
  - Commissioning
  - AC/DC feedback operation
- Test operation at A24 since end of April
  - Less forward power required for same VS voltage (-1.1%)
  - Detuning kept stably around 0 Hz

Klystron forward power of arm1 and arm2

Vector Sum (VS)
Eu-XFEL: Current Operation

run with 1 or 2 RF-stations off-beam as a spare

Current beam energy: 14 GeV – 2 RF-stations off-beam (user operation).
Next planned beam energy: 16.5 GeV – 1 RF-station off-beam (user operation).
Possible CW Upgrade

Continuous Wave (CW) mode is the origin of the SRF accelerator technology. Eu-XFEL project was based on the Linear Collider (LC) technology (TESLA) operating in the pulsed RF power mode (10 Hz / 650 μs beam pulse). Many FEL user experiments will get an advantage (or become possible) with CW mode operation.

Possible beam parameters: 25 μA (100 pC and 250 kHz) with 8 GeV (CW) and 12 GeV (long-pulse: ~100ms).

Several CMs were successfully tested in CW and long-pulse mode in CMTB at DESY.

The Upgrade Plan:
1. Replace the front-end cryomodules (17x)
   - Larger cooling capability
   - CW optimized cavities
2. Install CW capable RF sources
   - 1× IOT per RF station
3. Double the cryo plant (cost driver)
   - 2.5 → 5kW
4. CW electron gun (preferred option: SRF gun).
5. The former front-end cryomodules can be installed at the end of the linac to lengthen L3 (+4 RF stations), no further action required in L3 (>1km).
6. The upgraded XFEL would be capable of short pulse, long pulse AND CW operation.
Summary

1. European XFEL operates since over two years – without major problems.
2. Important project milestones – **17.5 GeV** and **27000** bunches/s (no lasing) – achieved.
3. Current beam energy: 8 – 16.5 GeV (user operation).
4. Initial achieved station voltages were consistent with production module tests projections including errors.
5. MGTF carefully studied and tuned each station individually, eventually achieving >90% of projected estimate.
6. Currently running with 21 cavities detuned - 12 detuned as a result of the MGTF studies.
7. Tunnel radiation (dark current): currently considered safely within limits, but will continue to monitor/study.
8. Focus now on maintaining identified max. limits operationally - root causes analysis of trips, etc.
9. A possible CW operation upgrade is under study.
Acknowledgements

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Thank You!