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SRF OPERATION AT XFEL: LESSONS LEARNED AFTER MORE THAN ONE YEAR

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Abstract

The European XFEL is the largest high-field SRF installation in the world and has now been in operation more than a year. It serves as a "prototype" for other facilities being constructed or in the planning stage. Performance of the operation of the SRF system over this period of time and the lessons learned will be discussed.

INTRODUCTION

The Eu-XFEL [1, 2] machine layout is presented in Fig.1. The linear accelerator is built in several sections starting with an injector section I1. I1 is composed of the normal conducting 1.5-cell photo-injector with one accelerating cryo-module (CM) A1 and 3rd harmonic (3.9 GHz) module AH1. CMs are grouped into the RF-stations A1 to A25, where stations A2 to A25 have 4 CM each (see Fig.2). An RF-station is connected to one RF source, a 10-MW multibeam klystron. The main linac is built in the XTL tunnel. The bunch compressor (BS) chicanes split the main linac into sections L1, L2 and L3. Linac sections are split into cryo-strings (CS), where section L1 has one RF-station in the CS and all other CS in L2 and L3 have three. General numbers are as follows:

- Length of accelerator: 1500 m
- Length of facility: 3400 m
- 101 CM (97 installed now)
- 8 SRF 9-cell cavities per CM

Four CM (one RF-station, A26) are not installed yet, because two CM must be repaired before the installation. Repair is ongoing (one CM done). It is planned to install these four CM later.

Currently three undulator sections SASE1, 2 and 3 are in the operation. Main beam parameters are listed in Table 1. The linac operation generates no beam losses.

Table 1: Eu-XFEL Main Beam Parameters

Parameter	Units	Value
Max. beam energy	GeV	17.5
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 duty factor	%	0.65
Energy jitter over bunch train		$<10^{-4}$
Average accelerating gradient	MV/m	23.6

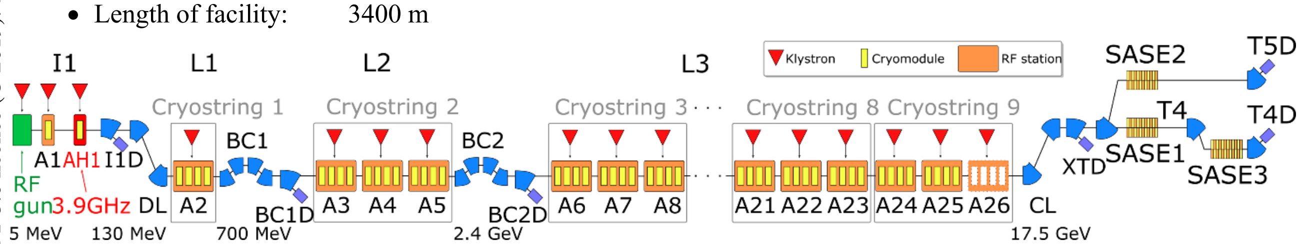

Figure 1: European-XFEL layout.

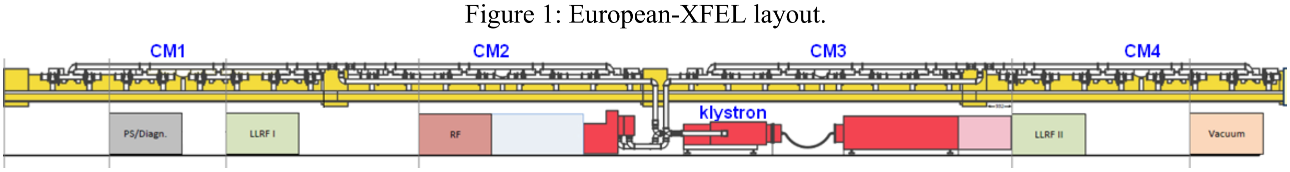

Figure 2: RF station layout (A2 – A25).

SRF Technology

Eu-XFEL accelerator is built on TESLA SRF technology with 8 accelerating cavities per CM (Fig. 3, Table 2).

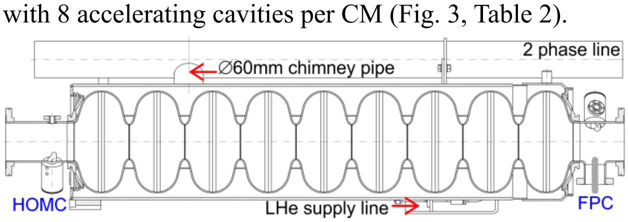

Figure 3: 9 cells TESLA type SRF cavity.

Table 2: SRF Accelerating Cavity Parameters

Parameter	Units	Value
Operating frequency	GHz	1.3
Cavity length	m	1.035
R/Q	Ω	1030
Accelerating gradient	MV/m	20–31
Quality factor, Q_0		$\geq 10^{10}$
Q_{ext} (input coupler)		4.6×10^{6}
Operating temperature	K	2.0

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Timeline

Important Eu-XFEL milestones are listed in Table 3.

Table 3: Eu-XFEL Timeline

Milestone	Date
injector operation in tunnel	Jan 13, 2017
600 MeV to the BC1 dump	Jan 19, 2017
2.5 GeV to the BC2 dump	Feb 22, 2017
12 GeV to the XTD dump	Apr 08, 2017
First lasing SASE1 at 9 Å	May 03, 2017
14.9 GeV to the XTD dump	Oct 23, 2017
First lasing SASE3 at 1.3 nm	Feb 08, 2018
First lasing SASE2 at 1.8 Å	May 01, 2018
17.6 GeV to the XTD dump	Jul 12, 2018
2699 bunches/pulse	Nov 02, 2018

REACHING THE DESIGN ENERGY

In the last two years, after the Eu-XFEL machine was built, the effort was taken to reach the project goals and to obtain the linac performance parameters up to the module tests results achieved previously [3-7]. All CM were cold tested in the Accelerating Module Test Facility (AMTF) before the installation. Each CM got an individual RF power distribution – Cryomodule Waveguide Distribution System (WDS, see Fig.4) tailored to match forward power to each cavity within practical limits: E_{acc} measurement error of ~10%, WDS error of 0.02 dB and klystron arm error of 0.04 dB [8].

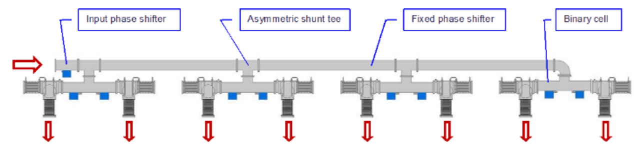

Figure 4: CM waveguide distribution system.

In order to reach the project design beam energy of 17.5 GeV the Maximum Gradient Task Force (MGTF) was formed. The MGTF started its activities on June 21st, 2017. Since then all 20 RF-stations in L3 and one in L2 were investigated at least once (40 investigations in total). The beam energy of 17.6 GeV was reached in July 2018 with energy gain due to MGTF equal to 1.9 GeV or 11% of the final energy (see Fig. 5). Figure 6 shows a comparison of the RF-station performance in the L3 section: an average of 93.6% of AMTF performance was achieved.

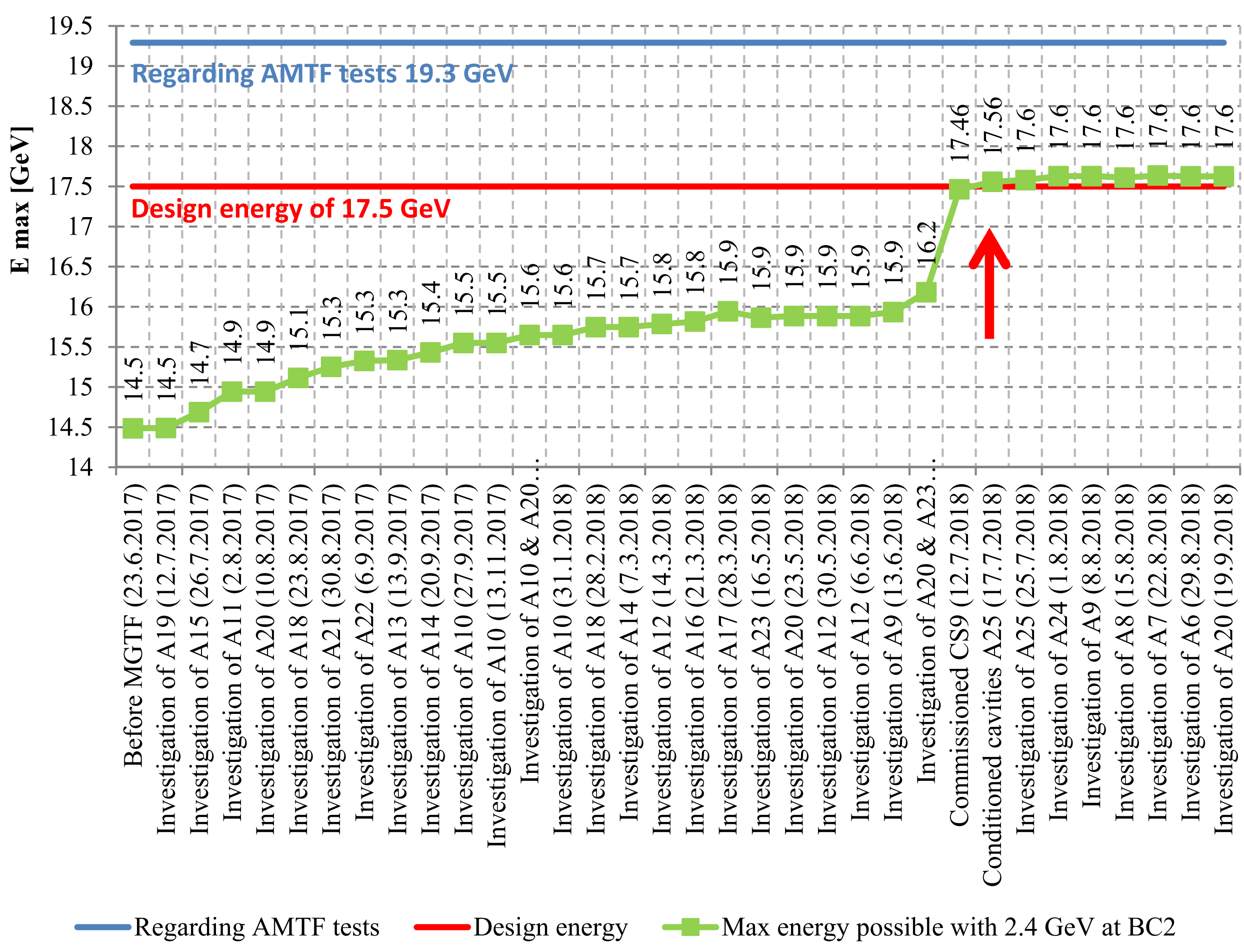

Figure 5: Reaching the design energy of the Eu-XFEL.

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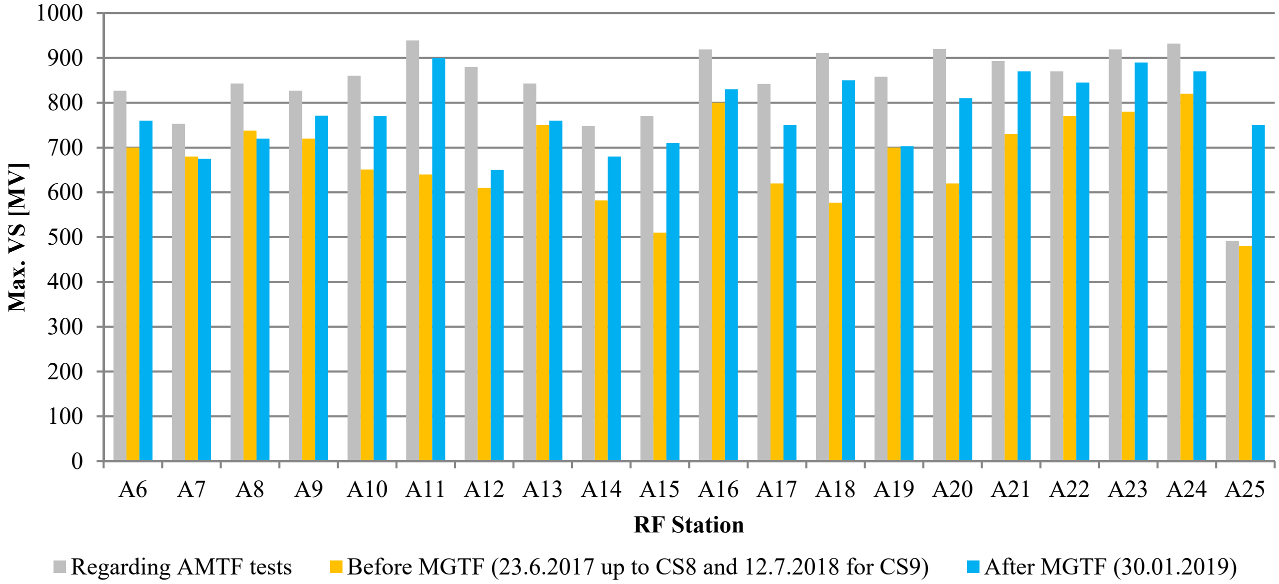

Figure 6: RF-stations performance in L3 section.

Cavities Limits

During the CM tests in AMTF, the operational gradient limit on individual cavities was in general limited by either hard quench, field emission (measured X-Ray threshold of 10^{-2} mGy/min) or to 31 MV/m (administrative power limit). During the MGTF studies, the performance of the RF stations was mostly limited by single cavity quench or in some cases by excessive radiation in the tunnel due to dark current (≤500 µSv/h), cryo stability (so-called soft quenching) or available klystron power. During the course of the studies, several other issues were identified which could later be fixed and have since been mitigated (e.g. waveguide sparking).

Some cavities must needed to be detuned in order to obtain a higher vector sum (VS) voltage in the RF-station with the remaining cavities with 32 cavities connected to one RF power source (see Table 4). Total lost beam energy due to MGTF detuned cavities is 242 MeV. Two cavities degraded their performance compared to the tests in AMTF. A full list of detuned cavities with the detuning reason is shown given in Table 5.

Table 4: Eu-XFEL Detuned Cavities

Reason of detuning	Number of cavities
After AMTF tests	5 (~0.6%)
After tests in XTL (coupler)	4 (~0.5%)
MGTF	12 (~1.5%)
Sum	**21 (~2.7%)**

Table 5: Detuned Cavities List

#	Cavity	Reason for detuning
1	**A4.M4.C4**	coupler: T70K overheating
2	**A6.M3.C1**	cavity: high X-rays (FE) (10 MV/m limit)
3	**A6.M3.C5**	MGTF: higher VS without
4	**A6.M3.C6**	MGTF: higher VS without
5	**A7.M1.C7**	MGTF: higher VS without: cavity degraded
6	**A7.M2.C3**	MGTF: higher VS without
7	**A7.M2.C7**	cavity: high X-rays (FE) (11 MV/m limit)
8	**A8.M4.C1**	MGTF: higher VS without
9	**A8.M4.C4**	MGTF: higher VS without
10	**A8.M4.C5**	MGTF: higher VS without
11	**A10.M1.C3**	cavity: low Eacc BD (no FE) (13 MV/m limit)
12	**A12.M2.C2**	MGTF: higher VS without
13	**A12.M3.C8**	MGTF: higher VS without
14	**A12.M4.C1**	coupler: T70K overheating
15	**A14.M3.C5**	MGTF: high cryo-losses
16	**A16.M2.C1**	coupler: T70K overheating
17	**A17.M3.C7**	MGTF: higher VS without
18	**A18.M4.C4**	wrong WDS setting: FE limit
19	**A20.M4.C1**	coupler: T70K overheating
20	**A21.M3.C4**	cavity: low Eacc BD (no FE) (14 MV/m limit)
21	**A21.M4.C2**	MGTF: higher VS without: cavity degraded

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Figure 7 presents a comparison between the cavity quench limits found in AMTF and in the linac (MGTF study).

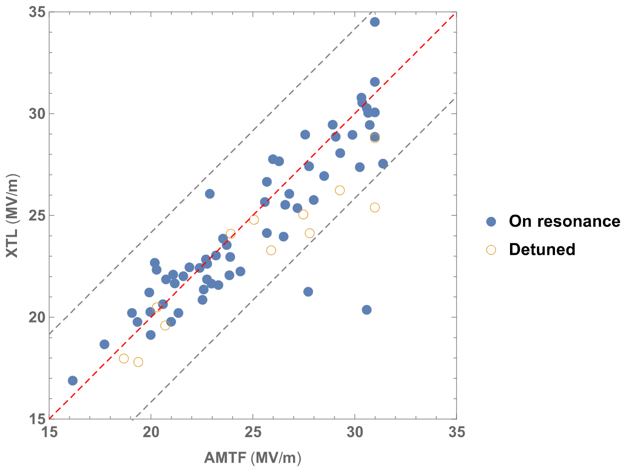

Figure 7: Cavity quench limits determined during MGTF studies compared to AMTF tests.

The following summarizes the results of the MGTF effort in reaching the Eu-XFEL project design beam energy:

- Possible to reach 17.6 GeV.
- Quench limits of 76 cavities were determined operationally (1 – 3 per CM), see Fig.7.
- 12 cavities are detuned to optimize the performance (max. energy), see Tables 4 and 5.
- 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.

AUXILLARY SYSTEMS

Some additional sub-system and cavity-performance-related measurements are discussed in this section.

Fundamental Power Couplers

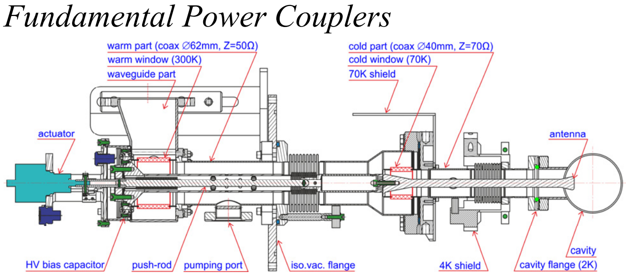

Figure 8: Eu-XFEL fundamental power coupler.

The Eu-XFEL Fundamental Power Coupler (FPC) consists of warm, cold and waveguide main parts (see Fig. 8). The coaxial coupler is made of copper and copper-plated (10/30 µm) stainless steel with two alumina TiN coated ceramic windows. Motorized antenna tuning (±10 mm) allows for Q_{ext} adjustment (10^6 – 10^7). The nominal operating Q_{ext} is 4.6×10^6. FPCs are able to be operated at up to 1 MW pulsed RF power up to 400 µs RF pulse length and up to 500 kW with 1.3 ms pulse, at a repetition rate of 10 Hz.

During the linac commissioning, four out of the total of 776 couplers showed over-heating on the 70 K cold window and could not be operated (conditioned), and have been shorted and disconnected from the RF source. The remaining FPCs have been operated stably since over two years. The FPC cold window temperature increase with high RF power on some couplers suggests that proper coupler cooling can be rather critical. In general, FPC conditioning (warm and cold) is important for successful linac operation.

Cryogenics

Eu-XFEL cryo-plant (4 K) is 2 years in operation since successful commissioning. The performance results comply within the error margin with the specification: 2 K cryo-losses set to ~5 W/CM, measured <6.3 W/CM at 17.5 GeV (see Fig.9).

Figure 9: 2K cryogenic heat load at 17.5 GeV (07.2018).

The 2K pressure stability is excellent: at 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 drastically affecting the pressure stability drastically.

There are some problems with bearings of the cold compressor motors: a new motor design is being developed, as well as other 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.

Tunnel Radiation

Radiation (gamma and neutrons) measurement is an important tool to understand the machine during operation. There are several different systems used in Eu-XFEL: RadFET; TLDs; BLMs; Gamma and Neutron Sensors, including a remote-controlled robot system (MARWIN). Radiation measurements show almost no dependence on the beam (only near the chicanes). Radiation is mostly caused by the CM dark current i.e. cavity field emission. Only three RF stations are limited by the radiation at maximal energy. No strong evidence of performance degradation has been observed during the last two years of operation. Radiation values do change with accelerating gradient and tuning, but this is expected behavior.

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OUTLOOK

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 [9, 10], at the cost of lower maximum photon energy.

As part of a future possible CW upgrade to complement Eu-XFEL's pulsed operation, the following CW beam parameters are being considered: 25 µA (100 pC and 250 kHz) with 8 GeV (CW) and 12 GeV (long-pulse: ~100 ms). This could be accomplished as follows:

1. Replace the front-end cryomodules (I1, L1, L2: 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 → 5 kW
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), with no further action required in L3 (>1 km).

The upgraded XFEL would be capable of short pulse, long pulse and CW operation. Several Eu-XFEL type CMs were successfully tested in CW and long-pulse mode in Cryo Module Test Bench (CMTB) at DESY [11-13].

SUMMARY

- European-XFEL operates since over two years – without major problems.
- Important project milestones – 17.5 GeV and 27000 bunches/s (not lasing) were achieved.
- Current beam energy: 8 – 16.5 GeV (for user operation).
- Initial achieved station voltages were consistent with production module tests projections including errors.
- MGTF carefully studied and tuned each station individually, eventually achieving >90% of projected estimate.
- Currently running with 21 cavities detuned – 12 detuned as a result of the MGTF studies.
- Tunnel radiation (dark current): currently considered safely within limits, but will continue to monitor/study.
- Cavity piezo drivers are being commissioned: electronics is installed, test operation is running with an effective Lorentz force detuning compensation and 1.1% less RF power with same VS.
- Focus now on maintaining identified max. limits operationally – root causes analysis of trips, etc.
- A possible CW operation upgrade is under study.

ACKNOWLEDGEMENTS

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