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STATUS OF THE EUROPEAN XFEL

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Abstract

The European XFEL is a Hard X-ray Free Electron Laser based on superconducting accelerator technology. In operation since 2017, it now serves 3 FEL beamlines simultaneously for user experiments. We will report on the present operation of the linear accelerator, the beam distribution to the various beamlines and the performance of the FEL radiators.

FACILITY LAYOUT

The European XFEL aims at delivering X-rays from 0.25 to up to 25 keV out of 3 SASE undulators [1]. The radiators are driven by a superconducting linear accelerator based on TESLA technology. The linac operates in 10 Hz pulsed mode and can deliver up to 2700 bunches per pulse. Electron beams are distributed to the 3 different beamlines within a pulse, thus being able to operate three experiments in parallel.

The complete facility is constructed underground, in a 5.2 m diameter tunnel about 25 to 6 m below the surface level and fully immersed in the ground water. The 50 m long injector occupies the lowest level of a 7 story underground building that also serves as the entry shaft to the main linac tunnel. Next access to the tunnel is about 2 km downstream at the bifurcation point into the beam distribution lines. The beam distribution provides space for 5 undulators (3 being initially installed), each feeding a separate beamline so that a fan of 5 almost parallel tunnels with a distance of about 17 m enters the experimental hall 3.3 km away from the electron source.

The European XFEL injector consists of a normal-conducting 1.3 GHz photo injector followed by a standard superconducting 1.3 GHz accelerating module and a 3rd harmonic linearizer, consisting of a 3.9 GHz module – also superconducting – containing eight 9-cell cavities. A laser-heater, a diagnostic section and a high-power dump complete the injector.

A three-stage bunch compression scheme is used to reduce both micro-bunching and the required 3.9 GHz voltage. All magnetic chicanes are tuneable within a wide range of R_{56} to allow for flexible compression scenarios, for instance balancing peak current and arrival time stability with LLRF performance. Diagnostic stations are placed after the second and third compression stage.

The superconducting linear accelerator consists of 96 TESLA-type accelerator modules. Always 4 modules are fed by one 10 MW multi-beam klystron. The accelerator modules are suspended from the ceiling, while the complete RF infrastructure (klystron, pulse transformer, LLRF electronics) is installed below the modules.

After the linac a collimation section protects downstream hardware in case of component failure and collimates halo particles [2].

Almost 2 km of electron beam line distribute the beam to the SASE undulators SASE1 and SASE3 ('North Branch') or SASE2 ('South Branch').

The electrons are distributed with a fast rising flat-top strip-line kicker in one of the two electron beamlines. Another kicker system is capable of deflecting single bunches in a dump beamline. This allows for a free choice of the bunch pattern in each beamline even with the linac operating with constant beam loading. Figure 1 summarizes the accelerator layout.

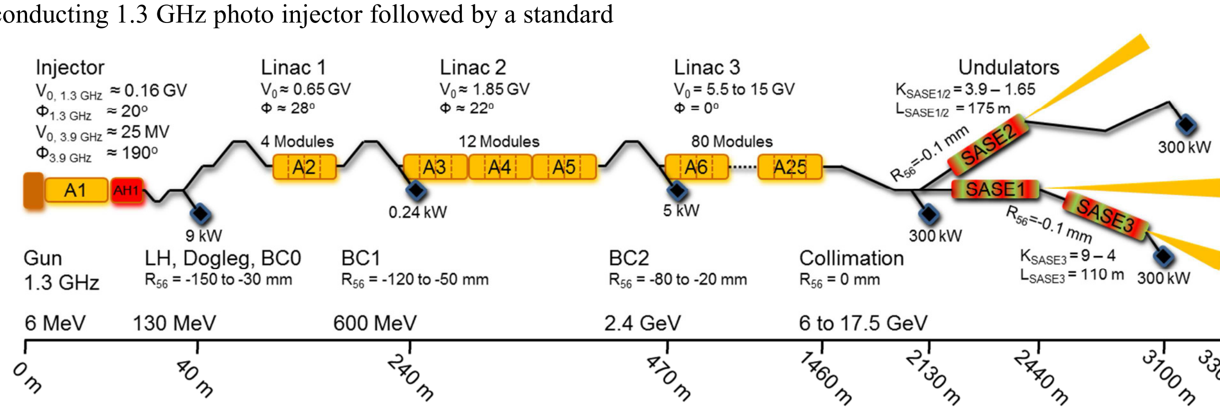

Figure 1: Schematic overview of the European XFEL accelerator, switch yard and undulator beam lines.

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ACCELERATOR OPERATION

Commissioning of the accelerator started in early 2017 [3], and by May 2017 first lasing in SASE1 was observed. First photon experiments followed in September 2017, whilst first lasing of SASE3 and SASE2 was achieved in February and May 2018, respectively [4].

The development of scheduled operation hours over the operation years 2017 – 2020 is displayed in Figure 2. Since the start of commissioning the accelerator has been operated for about 7000 hours/year. X-ray delivery has been ramped up over the years and is scheduled to reach 4000 hours/year in 2020. About 1000 hours/year are foreseen for development of both accelerator and photon systems. The increased complexity of the 3 beamline operation is reflected in the increase of scheduled tuning time. One should note that the time allocated in this category also includes short notice maintenance access and set-up after long shut-downs or configuration changes.

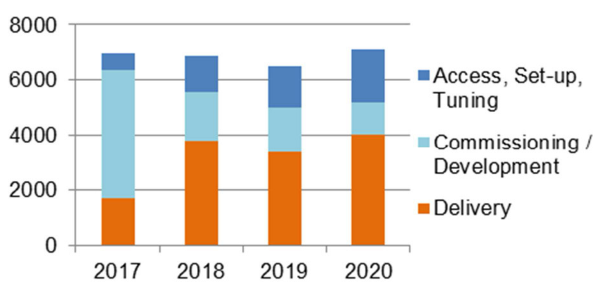

Figure 2: Development of scheduled operation hours.

Table 1: Accelerator Parameters

Parameter	Project Goal	Demon-strated	Routine
Energy [GeV]	17.5	17.5	10-16.5
Beam pulse length [µs]	600	600	550
RF pulse repetition rate [Hz]	10	10	10
Bunch repetition rate [MHz]	4.5	4.5	1.125
Bunch charge [pC]	20-1000	100-1000	250
Max. Beam Power [kW]	500	80	30
# of SASE FELs	3	3	3

The so-far demonstrated accelerator parameters are summarized in Table 1 and compared to the project goals and the routine operation parameters. The bunch repetition rate is presently restricted due to safety reasons at the photon beam stops, which can be severely damaged by the large obtainable X-ray power.

REACHING DESIGN PERFORMANCE IN THE LINEAR ACCELERATOR

The European XFEL linear accelerator consists of 24 RF stations, each powering four superconducting accelerator modules. Installed in the years 2012 to 2016, most of the RF stations have been commissioned in 2017. Installation work and technical commissioning of the last two stations was only finished in April 2018 during two scheduled maintenance periods.

Commissioning of the eight modules with beam followed in parallel to standard beam operation. In addition, all other RF stations were systematically investigated and acceleration voltage-limiting factors were identified and improved. Finally, electrons could be accelerated to the design energy of 17.5 GeV [5], [6].

Usually, the main linac L3 is operated with at least one RF station in reserve. This allows fast swapping of RF stations during operation. At 17.5 GeV no reserve station will be available and operation at this energy will only be possible at the expense of a somewhat reduced availability.

During most of 2018, the nominal operation energy was 14 GeV. This is also a good compromise in terms of reaching both high photon energies in SASE1 and SASE2, while at the same time allowing operating SASE3 at rather long wavelength.

One of the biggest advantages of superconducting technology is the possibility to accelerate many bunches within one RF pulse. In November 2018, the European XFEL successfully achieved its design value of (maximal) 2700 bunches with a 4.5 MHz spacing, accelerated by a 600 µs flat-top RF pulse with a 10 Hz repetition rate. Achieving these numbers posed various challenges:

- The RF pulses had to be sufficiently long, leading to increased average power, an issue mainly for the normal conducting photo-injector cavity.
- The RF flat-top had to be regulated over the complete pulse length with high precision also in the presence of beam loading.
- The 80 kW beam power electron beam has to be safely guided to the beam dump without losses and potential damage to surrounding equipment.

This has been the first time that a bunch train of such length has been accelerated in a long superconducting linear accelerator and several of the predicted beam dynamics aspects leading for instance to trajectory variations along the bunch train, could already be observed. In the future, operation at high beam power will be further consolidated. While standard operation in 2018 has been with about 300 bunches per RF pulse, up to 600 bunches and photon pulses are foreseen for user times in 2019.

OPERATING THREE SASE FELS IN PARALLEL

The SASE1 undulator and its photon beamline had been commissioned in 2017 and pioneering experiments could be performed at the two experimental stations. The operation of SASE1 has been further consolidated and

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photon pulse intensities of up to 4 mJ have been achieved. Typical photon energies range between 9 and 14 keV, and lasing could be demonstrated up to 19.3 keV. An average X-ray power of up to 10 W has been reached during test runs with up to 5000 photon pulses/s. Nominal user operation is presently restricted to beam power below 2.5 W.

First lasing in SASE3 was observed in February 2018. Due to the relaxed tolerances at long photon wavelength and high electron energies, tuning is comparably easy and up to 10 W of X-ray power was obtained. Both SASE3 experimental stations were able to host first users by the end of the year. SASE3 operates behind SASE1 in the same electron beamline. The quality of an electron beam that lased in SASE1 has suffered significantly, so that the lasing in SASE3 is affected. Even if SASE3 still delivers sufficient intensity the coupling in SASE1 and SASE3 performance appears to be not acceptable for user operation. A way out is the so-called "fresh-bunch" technique, in which betatron oscillations are excited for individual bunches. At betatron amplitudes of several 10 µm lasing in SASE1 is hampered and thus a fresh bunch can lase in SASE3 with optimal performance. This technique has been implemented on the fly by intentionally 'misusing' one of the fast beam distribution kickers. A remaining challenge is the unavoidable spontaneous synchrotron radiation, and eventual residual SASE background of kicked bunches that still have to be transported through all the undulators.

The last undulator SASE2 was put in operation after a very swift commissioning of the 1000 m long electron beam transport from the switchyard to the beam dump. First lasing was observed at the beginning of May 2018, and only a day later all three SASE FELs were operated in parallel by using the beam switchyard that allows distributing bunches into the different beamlines within the RF pulse. In the course of 2018 this scheme has been further developed and today users can actually change the number of photon pulses they are getting for their experiment themselves. This unique feature is widely used and allows the full exploration of the bunch train capability of the European XFEL.

Table 2 summarizes the SASE FEL parameters.

Table 2: SASE FEL Parameters

Parameter	SASE1	SASE2	SASE3
Demonstrated Photon Energy Range [keV]	6-19	6-19	0.5-2.8
Typical Photon Energies [keV]	7-14	7-12	0.7 -2.0
Typical Pulse Energies [mJ]	1.5	1.0	4
Maximum Pulse Energies [mJ]	4	2	10

Figure 3 shows a screen shot of the public status display of European XFEL. At that time the accelerator was operated with 460 bunches / RF pulse at a nominal energy of 14 GeV. 10 bunches each had been distributed to the SASE1-3 undulators while 430 bunches are dumped into the beam dump after the linac. This is a typical operation mode for beamline and experiment commissioning and adjustment. So far only about 15% of the accelerated charge of more than 11 Coulomb has been used for X-ray production.

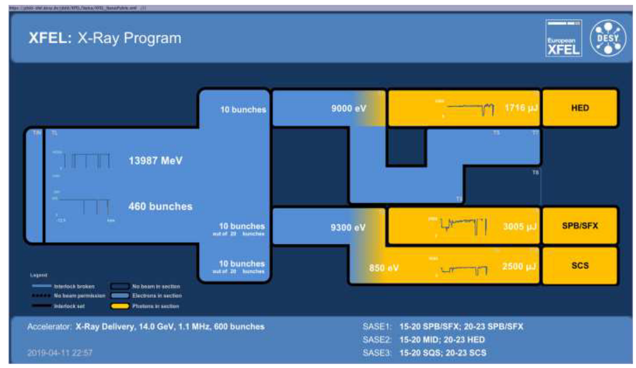

Figure 3: Screen shot of the public status display showing the parallel operation of all 3 SASE FELs [7].

CONCLUSION

The European XFEL is in operation for almost 2 years. During this time all commissioning and development milestones for the accelerator have been met and all three SASE FELs are in operation for X-ray delivery.

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