COMMISSIONING OF THE EUROPEAN XFEL*

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on behalf of the European XFEL Commissioning Team

Abstract

The European X-ray Free-Electron Laser (EUROPEAN XFEL) in Hamburg, Northern Germany, was built to produce X-rays in the range from 0.25 up to 25 keV out of three undulators that can be operated simultaneously with up to 27,000 pulses per second. The EUROPEAN XFEL is driven by a 17.5 GeV superconducting linac. This linac is the worldwide largest installation based on superconducting radio-frequency acceleration, using the so-called TESLA technology which was developed for the superconducting version of an international electron positron linear collider. The construction of the European XFEL has been finished at the end of 2016 and commissioning has been started. Meanwhile the entire facility, driving 3 Free-Electron-Lasers in the hard and soft X-ray regime, is in operation. This contribution will report on commissioning and the transition to user operation.

INTRODUCTION

The European XFEL aims at delivering X-rays from 0.25 to up to 25 keV out of three SASE undulators [1, 2]. The FELs are driven by a superconducting linear accelerator based on TESLA technology [3]. The accelerator operates in 10 Hz pulsed mode and can deliver up to 2,700 bunches per RF-pulse. Electron beams can be distributed to three different beamlines within a RF-pulse allowing for simultaneous operation of three FELs.

Construction of the European XFEL started in early 2009. The beam commissioning of the facility began end of 2015 with a ½ year long operation of the injector [4]. End of 2016 the installation of the main linac was ready, and commissioning started with the cool-down of the superconducting accelerator. Now, 23 months after the first beam was injected in the beginning of 2017, the accelerator is operational, all three FELs are lasing and the experimental program has started for one hard X-ray beamline with the experimental stations FXE and SPB [5, 6]. The other two photon beamlines are in the commissioning process, and will start operation within a few months.

FACILITY LAYOUT

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 is installed at the lowest level of a 7 stories underground building whose downstream end also serves as the entry shaft to the main linac tunnel. Next access to the tunnel is only about 2 km downstream, at the bifurcation point into the beam distribution lines. The beam distribution provides space for in total 5 undulators - 3 being initially installed. Each undulator is feeding a separate beamline so that a fan of 5 almost parallel tunnels, separated each by about 17 m, enters the experimental hall located 3.3 km away from the electron source. The schematic layout of the accelerator is shown in Fig. 1.

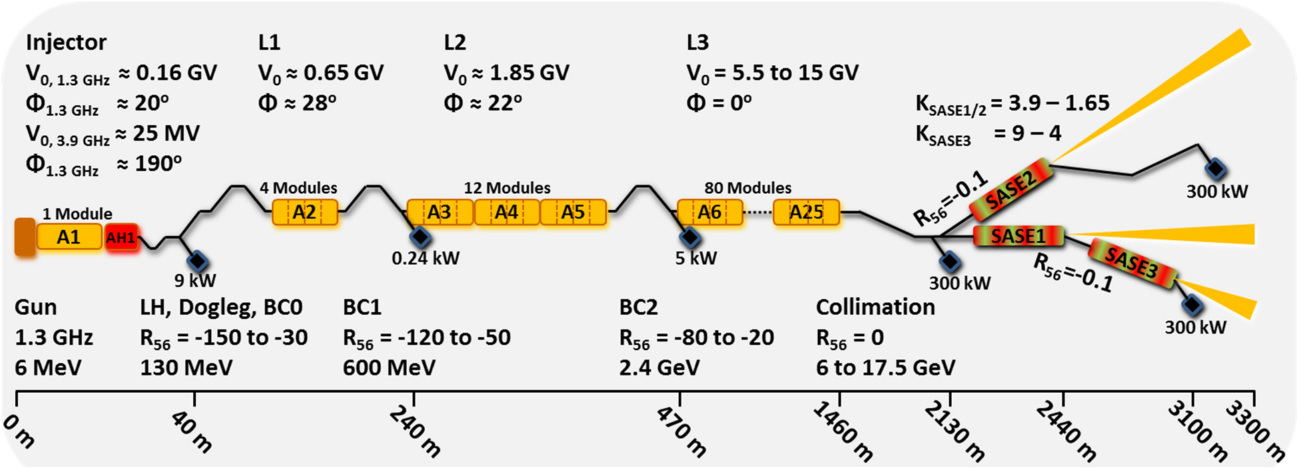

Figure 1: Schematic overview of the European XFEL accelerator. Single RF stations are named A*n* and feed either one module (A1) or 4 modules (A2-A25). R_{56} ranges for the bunch compressors are given in mm, and the phases of the different linac sections refer to typical compression set-ups. The maximum allowed beam power of the three commissioning dumps after the injector and the 2nd and 3rd bunch compressor (BC1 and BC2) as well as of the main dumps after the linac and each beam distribution line is given.

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The injector consists of the normal conducting gun, one TESLA type accelerating module and a 3.9 GHz module [7] for phase space linearization, a laser heater system [8], followed by a diagnostic section [9]. This installation was completed and commissioned one year before the main LINAC, so that most essential parts of almost all systems could be commissioned during this time [4, 10].

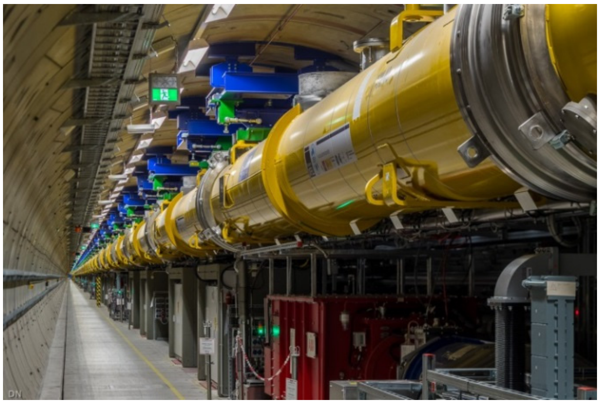

Figure 2: View into the linac tunnel with the accelerator modules suspended from the ceiling and the RF infrastructure placed below, on the floor.

From the injector the beam is fed to the main accelerator tunnel. The superconducting linear accelerator consists of 96 TESLA type accelerator modules [11]. The accelerator is grouped into 3 sections, intercepted by the 3 stage bunch compression. The first L1, consisting of 4 modules, the second L2 with 12 modules and the main linac L3 with 80 modules. The cryogenic installation is built as one continuous cryostat. Always 4 modules are fed by one 10 MW multi-beam klystron providing sufficient RF power for high gradients and regulation reserve. The accelerator modules are suspended from the ceiling (see Fig. 2), while the complete RF infrastructure (klystron, pulse transformer, LLRF electronics), except the modulator is installed below the modules. The modulators are placed in one single hall above ground, and the high-voltage pulse is fed to the pulse transformer by up to 2 km long cables.

Figure 3: First bunch compression chicane.

The bunch compressor B0 is located in front of L1 at 130 MeV and B1 before L2 at 700 MeV (Fig. 3). The final stage B2 at 2.4 GeV is located between L2 and the main linac. All magnetic chicanes are tuneable within a wide range of R_{56} allowing for flexible compression scenarios. Diagnostic stations are placed after the second and third compression stage, the later is equipped with a transverse deflecting system (TDS) for longitudinal phase space diagnostics [12].

After bunch compression to a few 10 fs, the beam is accelerated in the main linac to energies up to 17.5 GeV. The main linac is followed by a collimation section providing collimation of transverse phase space to about 60 σ and energy collimation for particles exceeding 2% relative energy deviation [13]. Between collimation and beam distribution section the Intra-Bunch-Train-Feedback System (IBFB) [14] for fast trajectory feedback within the bunch train is located. The beam distribution system is built from two switchyards [15] based on a combination of kicker and DC Lambertson septum. A fast kicker system allows to kick single bunches out of the train into the 300 kW dump line (TLD) at the end of the accelerator tunnel. The bandwidth of the kicker system allows removing single bunches out of the train, even at 4.5 MHz bunch repetition rate.

The second switchyard is based on a high precision kicker with a rise time of the order of 20 µs and a precise flat top. With this system the bunch train is split into two parts, one going straight to the SASE1/3 branch, and the other being kicked into the SASE2 branch. The beam dumps at the end of these beam lines are capable for another 300 kW electron beam power. In the SASE1/3 branch, the electron beam first passes the hard X-ray FEL SASE1 followed by the soft X-ray FEL SASE3.The other branch currently contains the hard X-ray FEL SASE2 only, but the tunnel system has space for up to 2 more FELs. The beam distribution system allows providing beam to all FELs within the same RF pulse, thus serving experiments for real parallel operation.

The fully commissioned facility will operate electron bunch charges from 20 pC to 1000 pC, with resulting bunch length after compression ranging from 3 fs to 150 fs FWHM [16]. With three different linac energies (8.5, 14, and 17.5), and the variable gap undulators, photon energies from 0.25 keV to 25 keV will be covered.

COMMISSIONING RESULTS

Injector Commissioning

The injector is operated in a separate radiation enclosure, well separated from remaining tunnel installations. The beam dump at the end of the injector allows injector operation up to full beam power.

The superconducting accelerator of the injector was cooled down in December 2015 and first electrons were accelerated to 130 MeV on Dec. 18th. Also at that early stage the 3rd harmonic lineariser was commissioned and from then on operated at the design gradient throughout the complete run [7]. The injector commissioning ended in July 2016, to connect the cryogenic distribution boxes of the main accelerator to the cryo-infrastructure.

Within this commissioning most of the design parameters of the European XFEL injector could be reached or even exceeded [4]. Long bunch trains were produced and the measured slice emittance at 500 pC was between 0.4 and 0.6 mm mrad, depending on the measurement technique. Extensive emittance studies were made possible by a 4-off-axis-screen measurement stage. This enabled fast parameter scans and the study of the emittance evolution along long bunch trains [9]. Combined with a transverse deflecting structure, slice properties along the bunch train were measured.

Main Accelerator System

The commissioning of the XFEL accelerator started mid of January 2017, immediately after successful cool down of the superconducting accelerator [17]. The effort was planned such, that beam transport to subsequent sections can be achieved as early as possible.

Two tasks were performed in parallel; commissioning of the RF stations and establishing beam transport. Due to a feature of the timing system [18], the RF pulse of individual RF stations can be shifted in timing away from the beam arrival. This allows working on these stations without any influence of the beam.

While the RF commissioning team was working on the first linac section L1, consisting of only 1 RF station, the beam operation team was establishing the beam transport, using the 130 MeV beam from the injector without further acceleration. As soon as the RF station was operational, the timing shift was removed, and the beam was accelerated. With moderate bunch number of 30 bunches, the initial phasing of the RF system was optimized. After one week of operation, 600 MeV beam was available up to the dump before L2.

This strategy was continued with L2 and its 3 RF stations, so that on Feb. 22nd 2.4 GeV could be transported to the BC2 dump in front of the main linac L3. Using this 2.4 GeV beam the electron beamline up to the TLD dump was commissioned. First beam up to about 1950 m could be achieved on even on Feb. 22nd, full transmission to the TLD dump was demonstrated on Feb. 25th. Using the principle of shifting RF stations of the beam, the RF commissioning was continued parallel to beam operation.

The RF commissioning went extremely smooth. Multipacting was observed at almost all RF stations at an accelerating gradient of 17-18 MV/m but could be conditioned in all cases with an effort of a couple of hours per station. The phase and amplitude stability was measured inner loop to be better than 0.01° and 0.01%. Preliminary beam energy jitter measurements give an upper limit for the RMS relative energy jitter of 3e-4 after BC1 and 1e-4 after BC2.

As soon as new RF stations got available for operation, they were shifted to the beam to do the commissioning steps with beam. In the way the beam energy was raised step by step allowing for 12 GeV beam energy on April 8th.

In the shadow of the beam being send further and further down the accelerator, also the diagnostic systems have been taken into operation. Due to careful technical preparation, the availability of a self-trigger mode all charge monitors [19] and BPMs [20] were able to provide data for the initial steering. Due to the high sensitivity of these devices, even almost lost bunches on a pC level could be detected and used. All screens and the full beam loss monitor system have also been available from the very beginning [21].

The efficient commissioning work was well supported by the DOOCS control system. The newly developed MTCA.4 standard for the control crates provided stable and reliable access to all devices [22, 23]. A vast suite of high-level control software integrates and automates more complex tasks like emittance measurement and optics matching. The readiness of the control software upon start-up was one of the key preconditions for the fast success of the commissioning.

While the accelerator was reaching reasonable beam energies, the SASE1/3 branch was completed, and operation permission was given by the authorities on April 27th. Immediately operation was extended up to the undulators. Nevertheless the commissioning work on the main accelerator continues. Meanwhile all RF stations are available, advanced commissioning work was increasing the performance. The maximum beam energy achieved up to now is 17.6 GeV, with still some potential to increase [24]. Long bunch train operation with bunch spacings of 222 ns and 888 ns has been demonstrated. The intra-train feedbacks of the RF system as well as the fast intra-bunch-train orbit feedback IBFB [14] work well, and provide stable beam conditions. Even if standard operation is only up to 120 bunches per RF pulse due to safety restrictions of the photon beam lines, bunch trains up to 500 bunches have been operated without any problems. The demonstration of 2700 bunches per RF pulse is planned at the end of 2018.

SASE1/3 Branch Commissioning

Immediately after the permission of the authorities the beam was for the first time injected to the SASE1/3 beamline on April 27th. As in case of the main linac the diagnostics worked in self-triggered mode, so that steering to the main dump of this section and full transmission could be accomplished within one shift. Shortly after establishing first beam, the SASE1 undulator was closed and first SASE operation was demonstrated in the night from May 2nd to 3rd with a 6.4 GeV beam at 9 Å [25]. After this successful but rather empirical first lasing attempt, a systematic program for photon beamline and diagnostics commissioning started. Beam based alignment (BBA) of SASE1 was resulting in significant position corrections of the movable quadrupoles of the undulator intersections.

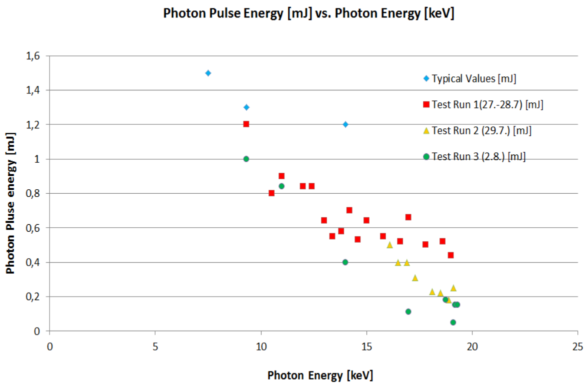

Figure 4: Photon pulse energy versus photon energy for dedicated test runs of the SASE1 FEL.

With these new settings and some basic photon diagnostics available, lasing at 2 Å or 6.2 keV with a 10.4 GeV beam was demonstrated on May 24th. Due to optimization of machine and undulator settings the SASE power could be increased to the mJ level within the next days. With ongoing commissioning work beam energy was further increased up to 14 GeV and a first standard working point at 9.3 keV was established with SASE levels of more than 500 µJ and up to 30 bunches/train. This working point was used for the commissioning of the photon beamlines, the initial commissioning of the two experimental stations of SASE1 and during the first user period, which was scheduled just 9 month after start of beam commissioning. The number of bunches per RF pulse is steadily increasing. For the first user period up to 30 bunches were provided. Currently up to 120 pulses with up to 1.5 mJ/pulse and photon energy ranging from 7.5 to 14 keV are provided during user operation. With the shutters of the experiments closed the machine was running 500 bunches at a repetition rate of 4.5 MHz with an average SASE pulse energy of 1.3 mJ, thus more than 6 W of average power. During development times the photon energy of SASE1 was varied over a wider range. Only with tuning the undulator gap and small adjustments of orbit and launch condition, the photon energy could be increased to 19.4 keV. After some tuning the pulse energy was still on the order of 150 µJ/pulse, so that with 30 bunches per pulse train mJ power levels could easily be produced at these photon energies. Figure 4 shows the photon pulse energy versus the photon energy during these test runs.

Parallel to the ongoing user program of SASE1, commissioning work of the soft X-Ray FEL SASE3 and the corresponding beamline has been done. As shown on the facility layout picture (Fig. 1) SASE3 is using the same beam as SASE1. As soon as the initial photon commissioning of the SASE3 beamline was ready, first lasing of SASE3 at 13 Å or 900 keV was possible on February 8th 2018, immediately reaching mJ pulse energies.

First operation was done with the spend beam from SASE1. As expected SASE1 and SASE3 photon pulse energies show a strong coupling. As expected [26] bunches lasing in SASE1 almost at saturation were producing a rather weak intensity in SASE3. But as soon as SASE in the hard X-ray gets disturbed, the intensity in SASE3 strongly increases.

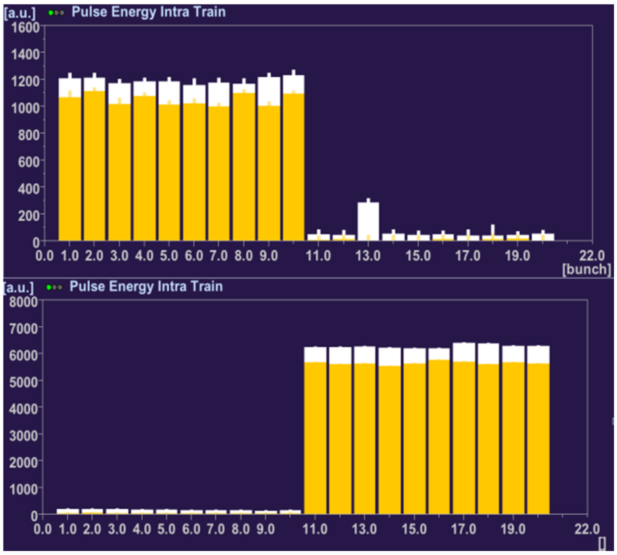

Figure 5: Fresh bunch operation of SASE1 (top) and SASE3 (bottom). Bunches foreseen to lase in SASE3 are kicked by a fast kicker in the switchyard, and put to SASE3 lasing orbit by a DC corrector. The y-axis is cross-calibrated with the XGM pulse energy measurement [27, 28], and thus gives the pulse energy in µJ.

In order to provide a sufficient decoupling of the two FEL sources fast kickers of the dump switchyard are used to send individual bunches to different trajectories in SASE1 and SASE 3. This scheme, called "soft kick" or "fresh bunch technique" [29], allows to suppress lasing of bunches foreseen to lase in SASE3 in SASE1, while bunches having lased in SASE1 produce much lower intensity in SASE3. Making further use of the different angle these bunches emit some FEL radiation in SASE3, their intensity can be further suppressed by apertures along the photon beam line. The decoupling of both lasers with SASE1 bunches delivering hard X-rays, while "SASE3 bunches" produce up to 7 mJ pulse energy in the soft X-ray regime has already been demonstrated. A picture showing the photon pulse energies during such an operation is shown in Fig. 5.

SASE2 Branch Commissioning

On March 13th the beam was send to the SASE2 branch for the first time. 100% transmission and stable beam conditions in the about 1 km beamline could be established within a single shift. Due to user program and shutdown work, the first lasing attempts for SASE2 had to be delayed. After some initial BBA first lasing of SASE2 was achieved on May 1st 2018, less than one year after SASE1. Meanwhile photon pulse energies of up to 900 µJ have been achieved at a photon energy of 7.5 keV with a 14 GeV beam.

The BBA results and also photon position data in the beamline indicate an issue with the initial alignment of the FEL and photon beamline, which is currently under investigation.

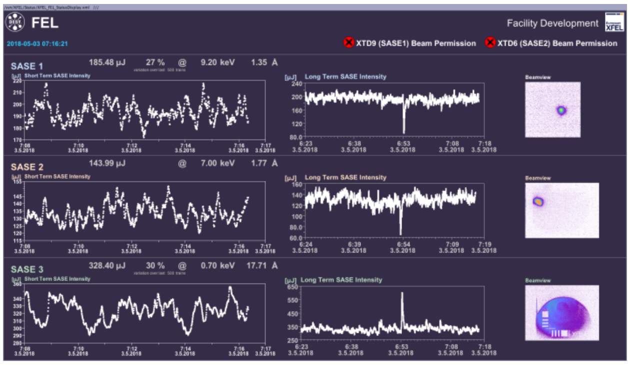

Figure 6: Screenshot of the SASE level display of EUROPEAN XFEL with all 3 SASE lines in operation. On the right hand side an image of a screen in photon beam line can be seen.

Simultaneous Operation of 3 FELs

Shortly after first lasing in SASE2, simultaneous lasing three FELs was demonstrated (Fig. 6), making use of the flexible distribution system. Even if this test was done under poor lasing conditions, it proofs the flexibility of EUROPEAN XFEL to operate the corresponding beamlines in parallel.

Operation Parameters

The current operation parameters of EUROPEAN XFEL as well as the design parameters and the parameters planned to be archived still in 2018 are summarized in Table 1.

Table 1: Parameter set of EUROPEAN XFEL, Comparing Project Goals, with Current Status Perspective for 2019

Quantity	Unit	Project Goal	Achieved	Routine
Beam energy	GeV	8-17.5	6 - 17.6	14
Rep Rate (intra train)	MHz	4.5	.58 – 4.5	0.58-4.5
Charge	pC	10-1000	10-500	250
Bunch length (FWHM)	fs	2-180	20, 50	20
Beam power	kW	500	18	1,8
Pulses/s	1/s	27000	5000	600
SASE1				
Photon Energy	keV	3-25	7.5-19.4	7.5-14
Pulse Energy	mJ		1.5	1.2
SASE2				
Photon Energy	keV	3-25	7.5	-
Pulse Energy	mJ		0.9	-
SASE3				
Photon Energy	keV	0.25 - 3	0.65–0.9	-
Pulse Power	mJ		7	

CONCLUSION AND OUTLOOK

The European XFEL accelerator has been put into operation. All major commissioning targets were achieved. The initial accelerator operation is smooth, the performance of the chosen superconducting technology is convincing. All 3 FEL sources had first lasing within 1 year and have been operated on mJ levels with up to 5000 pulses/s. The user program aiming to host highest quality user experiments with major impact on science has already started, 9 month after beginning of beam commissioning [5, 6].

The user program is going to be extended from hard to also soft X-ray experiments. First experiments at SASE3 are scheduled for November 2018. The second hard X-ray line served by SASE2 will start user operation in spring 2019. In parallel the accelerator will be further developed towards longer bunchtrains and higher beam power and flexible bunch patterns. After 840 hours of user operation in 2017 and 2000 hours in 2018, full operation with 4,000 user hours per year is foreseen in 2019.

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