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FEL OPERATION AT THE EUROPEAN XFEL FACILITY*

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Abstract

The European XFEL is a SASE FEL based user facility in the metropole region of Hamburg providing hard and soft X-ray photons with extremely high brilliance. The three FEL lines are operated simultaneously and are powered by a superconducting LINAC based on TESLA technology. Average power levels of up to several W have been demonstrated as well for soft and hard X-rays and can be requested by user experiments on day by day basis. This paper will report on the operation within the last two years. Typical operation conditions for parallel operation of 3 SASE lines will be discussed. The perspective for the operation with an extended photon energy range, as well as for full power operation with up to 27000 pulses per second will be presented.

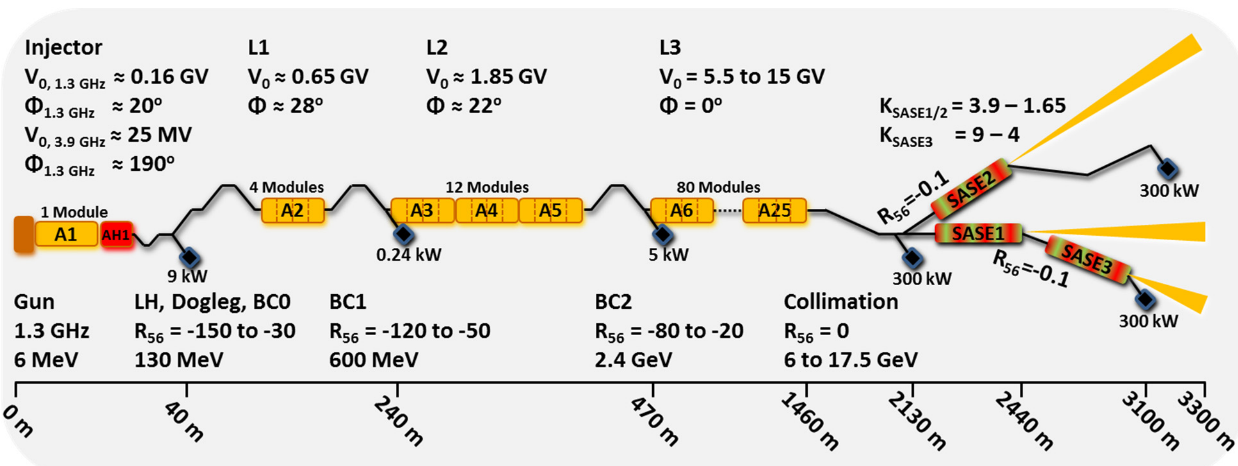

Figure 1: Schematic overview of the European XFEL accelerator. Single RF stations are named An and feed either one module (A1) or 4 accelerating modules (A2-A25). R56 ranges for the bunch compressors are given in mm, and the phases of the different linac sections refer to typical compression set-ups. 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.

INTRODUCTION

The European XFEL aims at delivering X-rays from 0.25 to up to 25 keV out of three SASE FEL lines [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: the two FEL branches and a dump line. The switching is done within the RF-pulse allowing for simultaneous operation of three FELs.

Construction of the European XFEL started in early 2009. Commissioning of the facility began end of 2015 with a ½ year long injector run [4]. End of 2016 the commissioning of the superconducting accelerator started. 9 month later in Sept. 2017 the instruments at SASE1 started with photon energies of 9.3 keV. In spring 2018 within one year from the first lasing of SASE1 parallel lasing in all 3 FELs was established [5, 6]. Distribution of the electron beam to the different sources with almost arbitrary bunch pattern is done by the flexible beam switchyard [7]. While SASE1 is in operation since fall 2017 SASE3 and SASE2 served first users at the end of 2018 and beginning of 2019. All experiments are far advanced on their way from first to standard user operation.

FACILITY LAYOUT

The complete facility is constructed in an underground tunnel up to 30 m below surface level. Access to the tunnels is possible in the injector area as well as through shaft buildings at the bifurcation points, where one tunnel splits up into two. The longest tunnel is the main accelerator tunnel with about 2 km length. Total length of the entire tunnel system is about 6 km. The distance of injector to experimental hall is 3.3 km. Besides of the three already installed FEL lines, the tunnels provide space for two more FEL sources [8]. The schematic layout of the accelerator is shown in Fig. 1.

The injector consists of the normal conducting gun, one TESLA type accelerating module and a 3.9 GHz module

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[9] for phase space linearization, a laser heater system [10], followed by a diagnostic section [11,12].

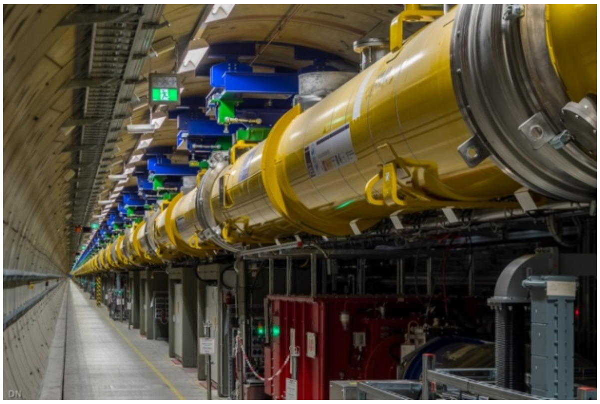

Figure 2: View into the linac tunnel with the accelerator modules suspended from the ceiling and the RF infrastructure placed below, on the floor.

From the injector the beam is fed to the main accelerator tunnel. The superconducting linear accelerator consists of 96 TESLA type accelerator modules [13] grouped into 3 sections, intercepted by the 3 stage bunch compression. The first section is named L1, consisting of 4 modules, the second is L2 with 12 modules and the main linac L3 consists of 80 modules. The cryogenic installation is built as one continuous cryostat. Always 4 modules are fed by one 10 MW multi-beam klystron. The accelerator modules are suspended from the ceiling (see Fig. 2), while the complete infrastructure, except the modulator is installed below. 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 special pulse 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 last stage B2 at 2.4 GeV is located between L2 and tL3. All magnetic chicanes are tuneable within a wide range of R56 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 [14].

After bunch compression to a few 10 fs, the beam is accelerated in the main linac L3 to energies up to 17.5 GeV. After the main linac a collimation section is providing cleanup of transverse phase space to about 60 σ and energy collimation for particles exceeding 2% relative energy deviation [15].

Between collimation and beam distribution section the Intra-Bunch-Train-Feedback System (IBFB) [16] for fast trajectory feedback within the bunch train is located.

The beam distribution system is built from two switchyards [17] based on a combination of kicker and DC Lambertson septum. The first makes use of a fast kicker system to send selected 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 even at 4.5 MHz bunch repetition rate.

The second switchyard is based on a high precision kicker with about 20 μs rise time and a precise flat top. This system is used to split the bunch train 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 both beam lines are also capable for 300 kW electron beam power, each. 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 not only providing beam to all FELs within the same RF pulse, but also – obeying some constraints - arbitrary bunch pattern. Thus experiments are served with beam for real parallel operation [7].

OPERATION OF THE XFEL FACILITY

With the transition from commissioning to operation phase the FEL operation is rapidly approaching the specified delivery time for X-rays of 4800 h/y. The annual operation time is about 6000 -7000 h/y, depending on the required shutdown periods for upgrade programs. In the following several aspects of the operation will be highlighted.

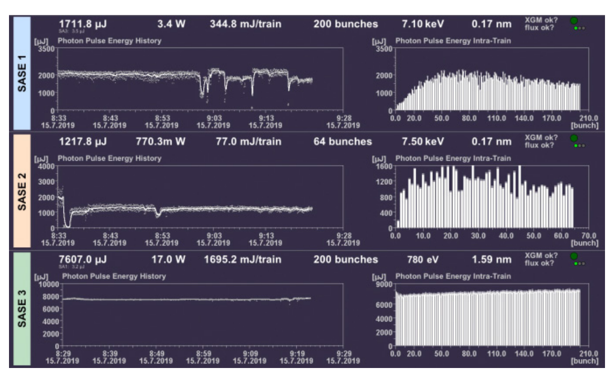

Figure 4: Screenshot of the FEL status panel, taken during a 4.5 MHz run with parallel multibunch operation in all 3 beamlines. Note the 2000 pulses/s produced in SASE1 and SASE3 correspond to 4000 bunches in the north branch of EXFEL.

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At European XFEL variable gap undulators are used to tune photon energies within a given range. Overlapping photon energy ranges are realized by operating the machine at different energy working points. Up to now energy points at 11.5 GeV for low photon energy operation and 14 GeV for standard photon energy range are established. A 16.5 GeV working point easily reaching photon energies in the 20 keV range will be established soon. Nevertheless, the design energy of E-XFEL of 17.5 GeV was demonstrated up to the first dump in the TLD line [5].

The superconducting accelerator offers the possibility to run long bunch trains within an RF pulse compared to single or few bunch operation typical for conventional warm copper linacs. With a bunch repetition rate of up to 4.5 MHz and a 600 µs flat top of the RF pulse, 2700 electron bunches per RF pulse, or with 10 Hz operation 27000 electron bunches per second can be provided. Operation of the full train up to the first main dump has already been demonstrated [18]; as well a FEL operation with up to 200 bunches per FEL, or up to 6000 lasing pulses per second. (Fig. 4). The limit on the bunch numbers of 6000 bunches is a temporary limit due to safety constraints, since intense FEL ration drills to almost all absorbing materials. Plans to update the safety system will be presented [19].

Since the high bunch repetition rate of 4.5 MHz is still demanding for the instrumentation of the experiments, the machine usually runs with 1.13 MHz bunch repetition rate and 500 to 600 bunches per RF train. A typical bunch distribution within the train reflects the properties of the distribution system. At 1.13 MHz bunch rep rate a train starts with 10 pre bunches. These bunches are foreseen for fast feedbacks to catch and start stabilizing the entire train. Currently only the fast orbit feedback is active. It provides orbit stabilization within the bunch train to about 2 µm RMS [16]. The pre bunches are kicked by the fast kicker system in to the TLD dump line. The remaining bunch train is split into 2 parts of configurable length (within the limits of the flattop length), one directed straight on to the SASE1/3 FEL lines or by means of the slow kicker to the SASE2 line. The kicker fall time needs a gap in the bunch train of about 20 µs, realized using the fast kickers sending the corresponding bunches to the TLD dump line. In order to decouple the lasing of SASE1 and SASE3, using a common electron beam path, one of the dump kickers operated at low kick strength is used to suppress lasing of “SASE3” bunches in SASE1 and vice versa. The so called soft kick drives a betatron oscillation of kicked bunches in SASE1, suppressing lasing. In front of SASE3 a DC steerer compensates the kick for “SASE3” and send “SASE1” bunches to a non lasing betatron oscillation [19].

Due to the high bandwidth of the fast dump kickers, arbitrary bunch patterns can be realized by kicking all bunches not requested by users to the TLD dump line. Within a predefined number for the maximum number of bunches, users can change the bunch numbers by themselves. With support of the operators also complex bunch pattern can be “programmed”. This includes reduction of bunch rep rates to 560 or other subharmonics of the bunch rep rate, interleaved operation of SASE1 and SASE3, up to programming bit pattern into the bunch train. Even a complete bunch pattern can be swapped in and out at a 10 Hz rate [7]. This provides maximum flexibility for the experiments. On the other hand many not requested bunches are dumped in the TLD region. Therefore, currently only a little less than 20% of the 18 C charge accelerated was used to produce photons (Fig. 5). It shows that there is still a large of potential for increasing the number of photons at the experiments.

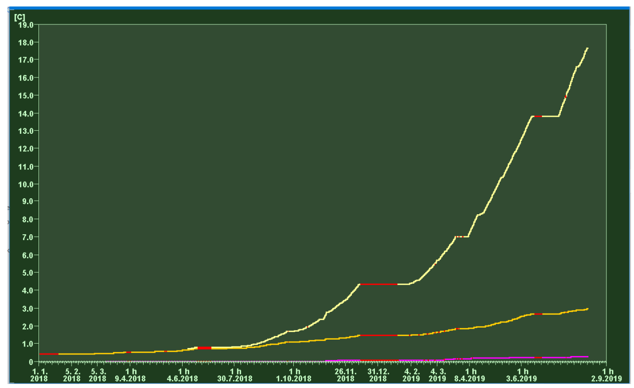

Figure 5: Integrated charge transported in the EXFEL. The bright yellow line shows the charge provided by the accelerator; dark yellow and pink give the amount of charge send through SASE1/3 and SASE2 respectively.

The SASE lines for E-XFEL are designed for different photon energy ranges. SASE1 and SASE2 are hard X-ray sources with design photon energies from 3 to 25 keV for electron beam energies between 8.5 and 17.5 GeV. SASE3 the soft X-ray line is able cover 0.4 to 3 keV at the corresponding electron beam energies.

The delivered photon energy range is driven by request of the experiments. Their demand is mostly 9.3 keV for hard X-rays and around 1 keV for soft X-rays. Both photon energy ranges are covered well at 14 GeV electron beam energy, making this energy the current standard working point of the facility. On user request the photon energies of the hard X-ray lines can be routinely tuned to energies between 6 and 14 keV at power levels of a least 1 mJ. With careful tuning up to 4 mJ in regime of 6-7 keV and 2-3 mJ at 9-10 keV are obtainable.

During machine development times an extended range of photon energies was checked for the hard X-ray regime. By simple gap changing and slight tuning of beam parameters and undulator orbit photon energies up to 20 keV could be demonstrated for SASE1 and SASE2.

SASE3 photon intensities turned out to be rather insensitive to gap changes. Without any further tuning changes within from 700 eV up to 2.5 keV show only a variation in pulse energy of about a factor of 2. Therefore, gap control on request is handed over to the experiments, allowing for precise tuning of resonances and scanning techniques.

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In fall 2019 the 16.5 GeV working point will be established, allowing for exploring the potential of EXFEL for high photon energies. In addition several weeks of beamtime are scheduled at 11.5 GeV to allow of experiments in the soft X-ray regime, e.g. at the oxygen edge.

CHALLENGES AND IMPROVEMENTS

While extending the operational range of the facility, some issues and problems have been found and are now going to be tackled.

As mentioned before, some initial bunches of the train, those sitting in kicker gaps and RF transition times and the parts of the bunch train not required in the FEL lines are removed with the fast kicker system. I turned out; that extensive use of these kicker had an influence even on bunches going straight. Investigation of the orbit showed, time dependent kick are present depending on the pulse pattern of the kicker magnets. These effects are expected to be due to eddy currents generated in the kicker. Since the observed shapes of the kick are highly repetitive, a feed forward system using spare kickers from the slow kicker system should be able to cope with this effect. Meanwhile a model to predict the effects of the fast kicker system was established and the preparation to run wave fronts instead of flat top current profiles was prepared. Tests in order to compensate the effect of the eddy currents will take place in near future [20].

More serious restrictions in the ramp up of the facility performance are given by safety restrictions. Intense FEL radiation focused to tiny spots easily creates plasmas, when hitting material. With the complex optics of an X-ray beamline the risk cannot be fully excluded, that focused beams can hit and thus can penetrate absorbers or shutters. Therefore, very shortly after first FEL light, tests were done, to verify the actual photon safety systems. This included not only testing the absorber materials under extreme conditions, but also investigating the beamline, determining potential critical settings. In order to ensure safe operation, operation restrictions were set to prevent performance levels of the machine, not safely within a tested envelope. With improving FEL performance the tested envelope was extended, so that currently, in the hard X-ray regime depending on photon energy between 0.8 and 8 W, average power, can safely be delivered. SASE3 is allowed to provide 30 W below 1.2 keV and 9 W higher than 1.2 keV. With typical values of the FEL performance these limits can be reached with between 40 to 400 bunches per train. From these results, it becomes clear, that a pure passive confinement system for FEL radiation will not be able to cover the full performance of EXFEL with up to 27000 pulses per second.

Therefore an upgrade of the safety system is being implemented. Besides of the improvement of X-ray absorbers with a combination of diamond and B4C ceramics, active sensors of appropriate safety level, will be the major change. The so called burn through monitors will be located in the beam shutter system, between the radiation absorber and the main beam shutter. A sketch and a picture of the system are shown in Fig. 6. As soon as these monitors detect X-rays, meaning the absorber gets penetrated, they will trigger an emergency stop of the accelerator by means of the PPS system. Therefore, the main shutter has to persist the FEL beam only for the latency of the PPS system, being less or on the order of a second. Large area versions of this these detectors, also connected with the PPS system will be placed at critical places within the experimental hutches to ensure the integrity of the instruments area. The update will get active after the winter shutdown 2019/2020. Therefore, after restart in 2020 XFEL operation without limitations on the bunch numbers will be possible.

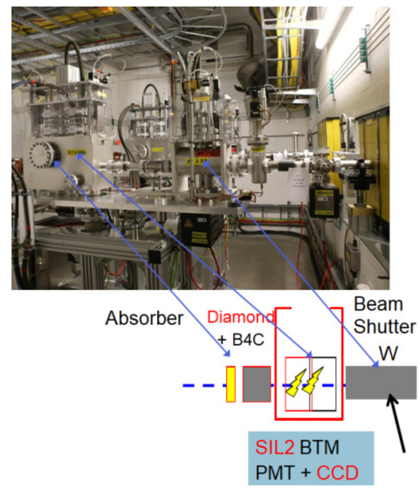

Figure 6: Layout of the beam shutter system with an absorber in front, followed by the active burn through monitor and the main beam shutter.

UPGRADES

While the machine in baseline setup is still ramping up performance, upgrade programs have already started. Both hard X-Ray FELs SASE1 and SASE2 will get self-seeding options; the corresponding chicanes are already available and installed in SASE2. Just recently the beam commissioning in SASE2 has started [21].

Other projects cover extending the photon properties in the soft X-ray regime. The installation of an afterburner system with variable polarization undulators [22] as well as a chicane system for two color operation modes [23] is being prepared, and will start installation within the winter shutdown 2019/2020.

A rather long term project is the extension of the facility with two more FEL sources. In the south branch there are still to sections available, capable for installation of recently long undulator systems. Technical possibilities and the science case for these additional sources is currently being explored [8]

The current operation parameters of EUROPEAN XFEL as well as the design parameters are summarized in Table 1.

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Table 1: Parameter Set of EUROPEAN XFEL, comparing project goals, with parameters already demonstrated and routinely delivered.

Quantity	Unit	Project Goal	Achieved	Routine
Beam energy	GeV	8-17.5	6 - 17.6	14
Rep Rate (intra train)	MHz	4.5	.14 – 4.5	0.14-4.5
Charge	pC	10-1000	10-500	250
Beam power	kW	500	95	35
Pulses/s	1/s	27000	27000	<13000
SASE1				
Photon Energy	keV	3-25	6-20	6-14
Pulse Energy	mJ		< 4	1-2.5
SASE2				
Photon Energy	keV	3-25	5.8-20	5.8 – 14
Pulse Energy	mJ		< 3	1-2
SASE3				
Photon Energy	keV	0.25 - 3	0.65–4.5	0.65-2.4
Pulse Power	mJ		10	4-8

CONCLUSION AND OUTLOOK

The European XFEL entered the operation phase. All major design parameters were demonstrated. Ramping up the facility performance to full range is well advancing. All 3 FEL sources have started the experimental program and the fraction of beam time with X-Ray delivery is continuously increasing. Unexpected issues compromising the performance envelope are tacked and removed. With the beginning of 2020 operation modes with up 27000/s can be provided on user request.

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