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FEL PERFORMANCE ACHIEVED AT EUROPEAN XFEL

M. Scholz*, DESY, Hamburg, Germany
on behalf of the European XFEL operation team

Abstract

The European XFEL has achieved first lasing by mid-2017 and first user experiments started by the end of that year. This invited talk describes the status of this facility, presenting highlights from the construction and commissioning, outlining experience from early operation, and discussing potential future developments.

INTRODUCTION

The European XFEL aims at delivering X-rays from 0.25 to up to 25 keV out of 3 SASE undulators [1,2]. The radiators are driven by a superconducting linear accelerator based on TESLA technology [3]. Parts of the linac as well as the first out of three bunch compressors are shown in Fig. 1. The linac operates in 10 Hz pulsed mode and can deliver up to 2700 bunches per pulse. The foreseen electron beam energies for SASE runs are 8–17.5 GeV. Electron beams can be distributed to 3 different beamlines within a pulse, thus being able to operate 3 experiments in parallel. Further tunnels provide space for two additional undulator beamlines. The European XFEL is being realized as a joint effort by 12 European countries. The accelerator of the European XFEL and major parts of the infrastructure are contributed by the accelerator construction consortium, coordinated by DESY. DESY is also responsible for the operation, maintenance and upgrade of the accelerator. Construction of the European XFEL started in early 2009; and the commissioning of the linear accelerator began end of 2016. The first SASE pulses could be achieved in May 2017 and the first user runs started mid September 2017.

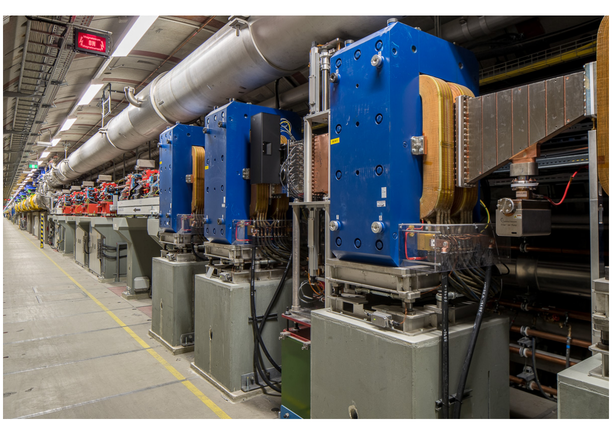

Figure 1: The first bunch compressor and parts of the European XFEL's main linac in the background on the left hand side. The grey tube in the upper part of the picture is a helium transfer line feeding the cryostats of the cold linac.

A layout of the European XFEL including the injector, the bunch compressors, the acceleration sections, the undulator beamlines as well as the beam dumps is shown in Fig. 2. The north branch of the photon beamline fan houses two undulators, SASE1 (for hard X-rays) and SASE3 (for soft X-rays). A further hard x-ray undulator beamline, called SASE2, is located in the south branch.

EUROPEAN XFEL COMMISSIONING

Injector

The commissioning of the European XFEL's injector started already in December 2015 [4] and the beam was dumped in a dedicated beam dump at the end of the injector. The installation of components in the linac and in the subsequent sections was still ongoing during this time. The injector commissioning started with the conditioning of the normal conducting L-band photoinjector [5, 6] followed by the cooldown of the first two superconducting RF modules located in the injector hall. All types of diagnostic devices [7] that are installed in the European XFEL are also part of the injector beamline and could be tested and optimized there. Also high-level control tools as well as diagnostics middle layer servers etc. [8, 9] could be commissioned and adapted before the electrons entered the main linac for the first time. Studies and optimizations of the electron beam emittances were carried out. Especially emittance and beam mismatch studies along the long electron bunch trains, a unique feature of the European XFEL, could be successfully performed [10]. Up to 27000 bunches per second were accelerated successfully. The injector commissioning ended in July 2016 to connect the cryogenic distribution boxes, feeding the cryostats of the main linac, to the cryo-infrastructure.

Linac

A step by step commissioning of the beamline sections downstream the injector started after the shutdown in December 2016 with the cooldown of the complete cold linac. This could be achieved with no cold leaks occurring. Regulation loops were optimized in the following weeks, and the pressure of the 2 K circuit can now be kept constant well below the requirement of ± 1% [11]. As of spring 2018, 22 of the 24 RF stations in the linac are available and a maximum electron beam energy of 14.9 GeV was reached so far. Further energy reach is expected due to ongoing fine-tuning of the regulations loops together with explicit verification of the individually tailored waveguide distributions. In combination with the two additional RF stations, it is expected to reach the maximum planned electron beam energy of about 17.5 GeV by summer 2018 [12].

* matthias.scholz@desy.de

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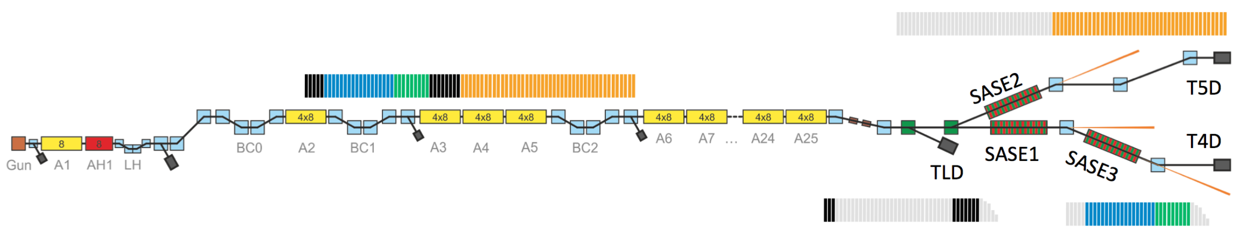

Figure 2: A schematic layout of the European XFEL. Also a possible bunch train distribution scheme is depicted. The beam can be distributed to the south branch (housing SASE2) and north branch (housing SASE1 and SASE3) as well as to a beam dump (TLD) upstream the switchyard. The color code depicts the different targeted dumps for the single bunches. The black marked bunches go to the TLD dump. Those marked in orange will be deflected towards the SASE2 undulator beamline in the south branch. The bunches marked in blue and green are supposed to lase in SASE1 respectively in SASE3.

Electron Beam Distribution

One of the European XFEL's key features are the long bunch trains with up to 2700 bunches per pulse @ 10 Hz repetition rate. The bunches in these pulses can be distributed either to a beam dump upstream the undulators or to one of the undulator beamlines. A possible beam distribution scenario as well as the location of the undulators and beam dumps are shown in Fig. 2. The dump kicker system for the beamline TLD is capable of deflecting single bunches out of the bunch train into the beam dump. The fast kickers deflect the beam only with a small angle and the main deflection is taken over by Lamertson type septa [13]. The fast kickers enable – inter alia – to reduce the repetition rate within a train and to generate a gap in the pulse train that is required to ramp the following distribution kickers. In addition, one of the fast kickers can be used to introduce a betatron oscillation for those bunches, that are supposed to lase in SASE3 but not in SASE1. The remaining electrons are distributed between the north and south branches with flat-top strip-line kickers. As for the dump beamline, the kickers introduce only a small kick and the main contribution to the deflection is realized with Lambertson-type septa. This setting with dump and distribution kickers allows for a free choice of the bunch patterns in each beamline even with the linac operating with a constant repetition rate and thus with constant beam loading. The triggers for the kickers of this system are distributed via the timing telegram that is broadcasted for each single bunch train. It contains – inter alia – encoded information about the targeted destination of every single bunch in the train [14, 15]. The first bunches in the dump of the north branch (named T4D as shown in Fig. 2) could be achieved by the end of April 2017. The second hard X-ray undulator beamline, SASE2, located in the south branch of the European XFEL, was still under construction when the north branch went into operation. First beam in the electron dump at the end of SASE2 could be achieved mid March 2018.

Figure 3 shows a real distribution of 75 electron bunches with an energy of 14 GeV to all three main dumps of the European XFEL. This was achieved for the first time shortly after the first bunches reached the dump of the south branch (housing SASE2). The same color scheme as in Fig. 2 was used to outline the targeted beam dumps. The fall time of the pulses in the flat-top strip-line kickers is about 10 µs and about a factor of 2 faster than the time required to raise and stabilize the kicker pulses. Thus, the 25 SASE2 bunches were at the beginning of the bunch train. 20 bunches were deflected towards the TLD dump beamline. That corresponds to a gap in the pulse of about 17 µs (with an intra bunch train repetition rate of 1.1285 MHz). The last 30 bunches were sent towards the dump of the north branch. This test could be finished successfully without losses at the septa and in both undulator beamlines above an intolerable level.

The fast intra bunch train orbit feedback (IBFB) [16] was commissioned successfully. It ensures that all bunches in a bunch train have the same orbit in the undulators. The required fast kickers are located upstream the switchyard for the undulator beamlines. The system uses beam position monitors to read the orbits of the single bunches either in the section of the kickers or located in the undulators. The IBFB is permanently in operation during SASE delivery.

SASE OPERATION

The first hard x-ray SASE photons were generated at the beginning of May 2017 [17]. The first soft x-ray SASE photons with an energy of 900 eV have been generated in SASE3 at the beginning of February 2018. The first SASE photons in the south branch (SASE2) are expected before summer 2018.

The photon beamlines of SASE1 (hard X-rays) and SASE3 (soft X-rays), including mirrors, screens, gas monitors etc. are largely commissioned. The first photon beams at the beam shutters of the two SASE1 experiments, SPB/SFX (Single Particles, Clusters and Biomolecules/ Serial Femtosecond Crystallography) [18] and FXE (Femtosecond X-Ray Experiments) [19], could be achieved 3 days after first lasing with hard X-rays in May, 2017. The first photons reached the inside of the experimental hutches by June 23, 2017. The photon commissioning team as well as the teams of the experiments did then start the commissioning of their devices. Calibrated gas monitors are in operation to measure the photon pulse energy as well as the positions of the FEL beam. The connection of Karabo [20], the control system used for the photon beamlines, to Doocs [21], the control

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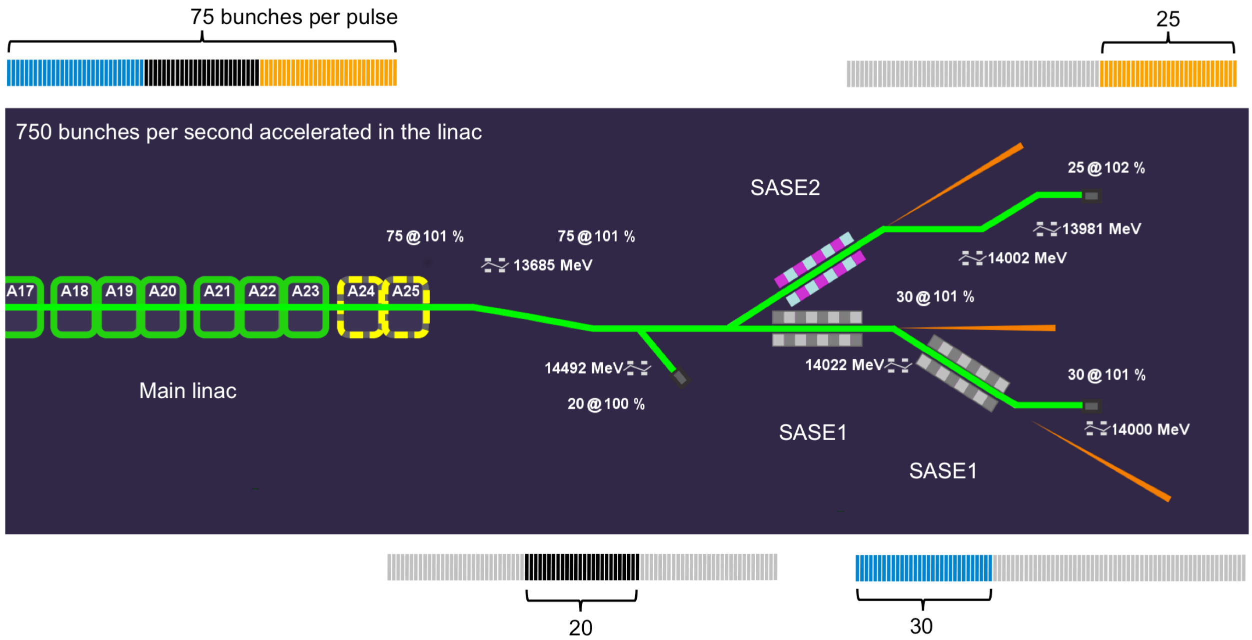

Figure 3: A control system screenshot during a test of the bunch distribution. 75 bunches per pulse (@ 10 Hz repetition rate) were distributed to all three main dumps of the European XFEL. 20 bunches (marked in black) are cut out of the bunch train's center using fast kickers. Those bunches are dump upstream the switchyard for the undulator beamlines. The resulting gap is required to decay (or launch) the pulse of the flattop kickers that deflect 25 bunches (marked in orange) towards SASE2. The remaining 30 bunches (marked in blue) are directed towards SASE1 and SASE3.

systems used for the accelerator, made progress. An increasing number of devices are accessible from Doocs, which allows better optimization of photon beam parameters.

The large number of photon bunches are challenging, especially from the machine protection and radiation safety point of view. Thus the number of bunches per pulse had to be increased incrementally over the last months. The maximum number of bunches during user runs was 300 bunches/second so far. However, SASE operation with up to 5000 bunches/second could be achieved already during test runs. It could be shown that the SASE level is about the same for all bunches within a bunch train. Furthermore, the average SASE pulse energy level did not change much when the number of bunches was increased.

Figure 4 shows an averaged spectrum of the hard x-ray beam as measured downstream the SASE1 beamline using the K-mono instrument [22]. The measured photon energy of 9.3 keV agrees well with the machine setup at that time. This photon energy was typically delivered during all user runs up to now.

Test runs with higher photon energies showed that the European XFEL can deliver 14 keV photon energy with an electron beam energy of 14 GeV. Figure 5 shows a brief scan of the photon energy from 9.3 keV to 14 keV using the variable gap undulators. No further optimization was performed at the different energy steps. It was also possible to deliver bunch trains with special bunch patters on request of the XFEL users. Single bunches out of the bunch train were kicked either to the TLD dump, or a betatron oscillation was introduced to suppress lasing in SASE1. Both techniques increase the delay between two bunches, which was used to study the impact of the bunch repetition rate on the experimental sample.

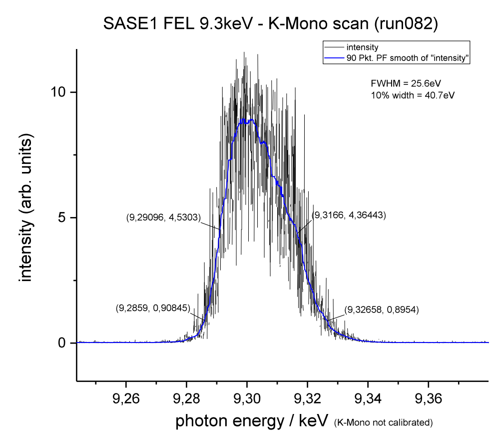

Figure 4: A photon beam spectrum averaged over several pulses measured with the K-Mono instrument installed downstream the SASE1 undulator. The measured wavelength of 9.3 keV agrees well with the machine configuration. The width of the spectrum was 25.6 eV (FWHM).

The parallel operation of SASE1 and SASE3 in the north branch could also be successfully tested. A betatron oscillation of the SASE3 bunches introduced by the fast kickers prevented them from lasing in the SASE1 undulator. That avoided an increase of the uncorrelated energy spread in the first undulator that would have reduced the ability to reach maximum photon pulse energies in the following undulator.

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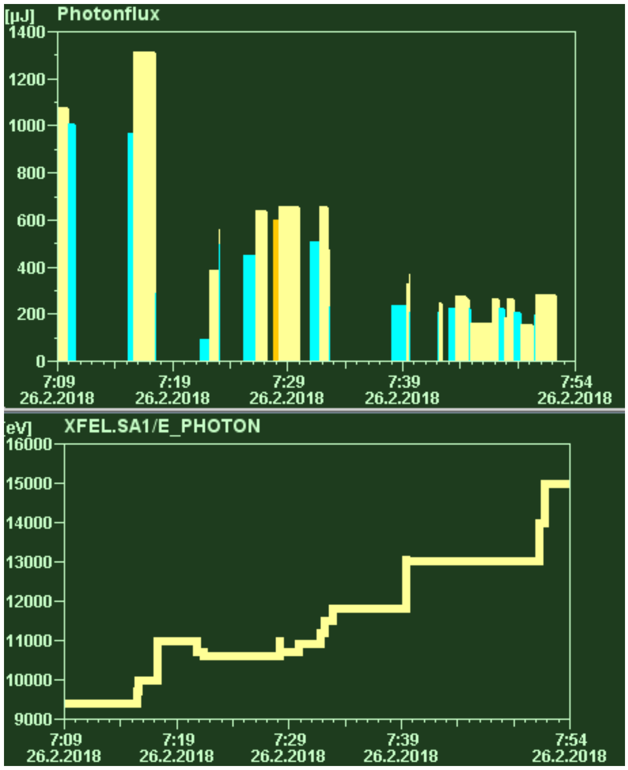

Figure 5: A photon energy scan showing that the European XFEL is capable of lasing with 14 keV photon energy driven by a 14 GeV electron beam. The upper plot shows the photon pulse energy and the lower plot depicts the chosen photon wavelength.

CONCLUSIONS AND OUTLOOK

The first beamlines of the European XFEL are in operation and the first user runs could be accomplished successfully. The cryo system as well as the cold linac have been in operation without larger problems. The maximum electron beam energy reached so far was 14.9 GeV and two more RF stations will come into operation soon. With further fine-tuning of all RF stations in addition, the maximum electron beam energy of about 17.5 GeV is expected be reached by summer 2018. 27000 bunches per second were already accelerated during the commissioning of the XFEL injector. Up to 5000 bunches per second have been accelerated up to 14 GeV and used for SASE operation during test runs.

The maximum number of pulses per second during the user runs in SASE1 have been 300 so far, typically delivered with an intra bunch train repetition rate of 1.13 MHz. The number of photon pulses will be increased step by step in the next months followed by radiation safety measurements in the experimental hutches. Parallel lasing of both beamlines in the north branch, SASE1 and SASE3, could be achieved earlier this year. The photon beamline commissioning in SASE3 is almost finished and first user periods are expected to start in autumn 2018. First SASE light in the south branch is expected before summer 2018.

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