THE DIAGNOSTIC SYSTEM AT THE EUROPEAN XFEL: COMMISSIONING AND FIRST USER OPERATION*

D. Nölle†, DESY, 22603 Hamburg, Germany
on behalf the European XFEL Diagnostic Team

Abstract

The European XFEL is now commissioned and user operation has started. Long bunch trains up to 500 bunches are established. The role of and experience with the electron beam diagnostic will be reported. Highlights, problems and their solutions will be discussed

INTRODUCTION

The European XFEL (Fig. 1) is an X-ray free-electron-laser based light source with soft and hard X-ray beamlines that will finally provide intense radiation from about 0.25 to 25 keV at TW level with pulse durations of a few 10 fs [1].

The length of the facility is about 3.5 km and the accelerator tunnel is crossing below inhabited areas in the city of Hamburg. It offers 5 photon tunnels ending in a big experimental hall. In the current configuration two hard X-ray FELs and one soft X-Ray FEL are in operation. The FELs are driven by a superconducting accelerator based on TESLA technology [2] with up to 17.5 GeV electron beam energy. The long RF pulse of 650 µs allows to accelerate up to 2700 bunches per RF pulse. With a repetition rate of 10 Hz this corresponds to up to 27000 X-ray pulses per second that can be distributed between the different undulator lines to allow for simultaneous operation of experiments.

Only 9 months after the cool down of the superconducting accelerator and initial beam commissioning first user experiments started. The total operation time in 2017 was about 7000 h. Currently the facility is mainly operated at 14 GeV with 1 – 60 bunches per RF pulse and photon energies around 9.3 keV, based on the users demands.

Up to now two photon beamlines served by the hard X-ray FEL device SASE1 are in operation and have started their user program. The soft X-ray FEL SASE3 driven by the spend electron beam of SASE1 is lasing routinely at photon energies around 900 eV and the commissioning of the photon beamline is in an advanced state. The user program of this beamline will start in fall 2018. The second hard X-ray FEL SASE2 is also lasing. Even lasing with all 3 devices in parallel was already demonstrated.

During special tests a photon energy range of 7.2 to 19.3 keV was easily achieved by tuning the gaps of the variable gap undulators. In test runs an average power of the X-ray beam of up to 6 W, running a bunch train of 500 bunches per RF pulse, as well as the design energy of 17.5 GeV have already been demonstrated.

LAYOUT OF THE FACILITY

The accelerator has an injector located in a separate vault. It consists of the normal conducting gun, one accelerating module of the TESLA type and a 3.9 GHz module [3] for phase space linearization, a laser heater system [4], followed by a diagnostic section. 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 [5, 6].

From the injector the beam is fed to the main accelerator tunnel. The accelerator is laid out with a 3 stage bunch compression and bunch compressors B0 at 130 MeV, B1 at 700 MeV and the final stage B2 at 2.4 GeV. The stages are separated by the LINAC systems L1 and L2, consisting of 4 and 12 accelerator modules, respectively. At 700 MeV and 2.4 GeV the compressors include diagnostic sections; the high energy one is equipped with a transverse deflecting system (TDS) for longitudinal phase space diagnostics [7]. After bunch compression to a few 10 fs, the beam is accelerated in the main LINAC build out of 80 accelerator modules. The RF system is designed such, that one RF station serves four modules.

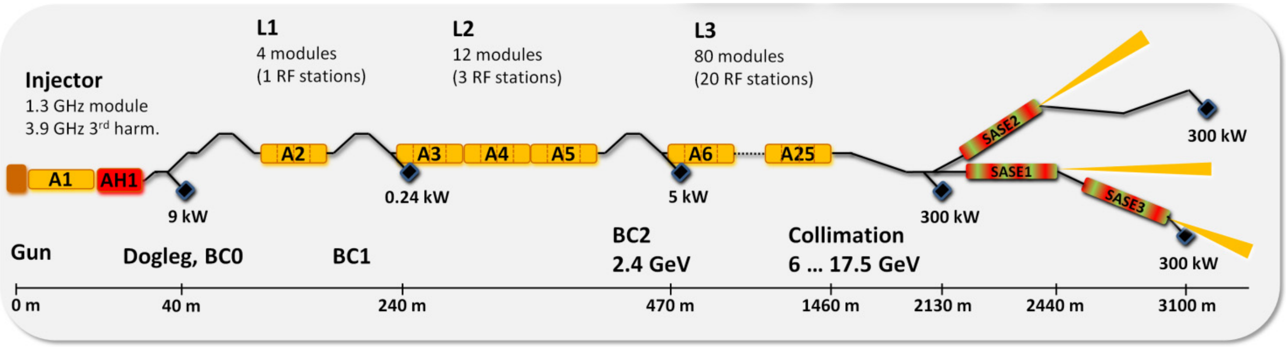

Figure 1: Block Diagram of the EXFEL.

---

* Work supported by the respective funding agencies of the contributing institutes; for details please see http:\\www.xfel.eu

† dirk.noelle@desy.de

ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-TUOA01

The main LINAC is followed by a collimation section providing both collimation of transverse phase space to about 60 σ and energy down to 2% relative energy deviation. Between collimation and beam distribution the Intra-Bunch-Train-Feedback System (IBFB) [8] for fast trajectory feedback within the bunch train is located.

The beam distribution system [9] is built from two switchyards, based on a kicker system in combination with a Lambertson septum. The first system allows to kick single bunches out of the train into the first 300 kW main dump line (TLD) at the end of the accelerator tunnel. The bandwidth of the kicker system allows to remove single bunches out of the train, even at 4.5 MHz bunch repetition rate. The second system uses a high precision kicker, having a rise time on 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. Both beam lines are terminated by another 300 kW electron beam dump each. In the SASE1/3 branch, the electron beam first passing the hard X-ray FEL SASE1, is also send to the soft X-ray FEL SASE3. The initial planning was to use the spent beam from SASE1 in SASE3, but it turned to be more efficient to suppress lasing in one of the FELs by means of a kicker [10]. This scheme called "soft-kick" or "fresh bunch technique" provides a decoupling of the two FELs by sending parts of the bunch train to different orbits in the same beamline. The other branch currently contains the hard X-ray FEL SASE2 only, but the tunnel system has space for up to 2 more FELs. Corresponding to the 5 possible photon sources five tunnels for photon beamlines are available (3 beamlines are already installed.). Each beamline can serve up to 3 experiments. The beam distribution system allows providing beam to all FELs simultaneously, thus serving experiments for real simultaneous operation.

COMMISSIONING HISTORY AND OPERATIONAL HIGHLIGHTS

The commissioning of the EXEL started with the operation of the injector in December 2016. Within a half year run all relevant beam parameters of the injector have been demonstrated [5]. Furthermore the injector run provided the possibility to commission devices from almost all diagnostic systems [6].

Commissioning of the main LINAC started in January 2017, immediately after the 3 weeks cool down of the superconducting accelerator [11]. Beam commissioning was started in parallel to the commissioning of the RF systems. This was possible due to the flexibility of the timing system [12] that allows shifting single RF stations away from the arrival time of the electron beam. After recommissioning of the injector, first beam was achieved in B1 on January 15th and first accelerated beam on January 19th. Beam up to B2 was possible on February 2nd. On February 22nd for the first time an accelerated beam of 2.5 GeV was produced up to B2. With this energy the beamline through the main linac up to the TLD beamline was set up, and first beam at the end of the main linac tunnel was demonstrated on February 24th. While final assembly and technical commissioning work in the SASE1/3 tunnels were continuing, the RF stations in L3 were commissioned in parallel to beam operation, so that the beam energy could be increased in steps up to 12 GeV. On April 27th the operation permission for the SASE1/3 branch was granted, and in the evening a 10.5 GeV beam was transported up to the dump in the SASE1/3 beamline. 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 [13]. After this successful but rather empirical first lasing attempt, a systematic program for photon beamline and diagnostics started. Beam based alignment (BBA) of SASE1 was resulting in position corrections of the movable quadrupoles of the undulator intersections. 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 the 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, just 10 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 pulse numbers between 1 and 120 pulses per RF pulse with up to 1.5 mJ/pulse and a photon energy range from 7.5 to 14 keV can be provided. The pulse number is limited by safety aspects of the experiments. With the shutters of the experiments closed, the machine was running 500 bunches per RF pulse (5000 pulses/s) at a repetition rate of 4.5 MHz with an average SASE pulse energy of 1.3 mJ/pulse, thus more than 6 W of average power.

Parallel to the ongoing user program of SASE1, commissioning work of the soft X-Ray FEL and beamline as well as the completion of the second branch with the SASE2 hard X-ray FEL have been done. 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. Instead of just using the spend beam of SASE1 for lasing in SASE3, a scheme using fast kickers to send individual bunches on different lasing orbits in SASE1 and SASE 3 was established. This scheme called "soft kick" or "fresh bunch technique" allows decoupled hard X-ray operation in SASE1, while "SASE3 bunches" produce up to 7 mJ pulse energy in the soft X-ray regime.

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 attempt for SASE2 had to

ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-TUOA01

be delayed. After some initial BBA first lasing of SASE2 was achieved on May 1st 2018, less than one year after SASE1. In the following days simultaneous lasing in all 3 FELs was demonstrated making use of the flexible distribution system (Fig.2).

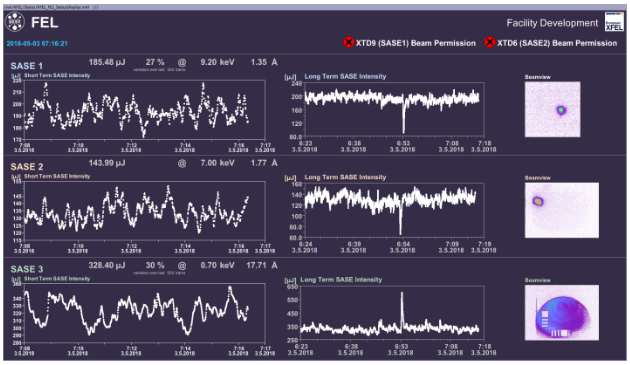

Figure 1: Screenshot of the SASE level display of European XFEL with all 3 SASE lines in operation. On the right hand side images of screens in photon beamlines can be seen.

Finally in July 2018 the two last RF stations have been ready and put to the beam for the first time. With all RF stations on beam the accelerator was run at the design energy of 17.5 GeV. Further detail improvements and advanced commissioning steps even promise exceeding 17.5 GeV in the near future. Nevertheless, the next user runs will use 14 GeV beam energy for SASE delivery.

The user program of SASE3 is planned to start in fall 2018, SASE2 will take up user operation in spring 2019.

ELECTRON BEAM DIAGNOSTICS AT EUROPEAN XFEL

Due to the size of the facility the number of diagnostic devices is large. Back bone systems like BPMs or BLMs consist of 500 or more installed devices (see Table 1). Therefore, the commissioning and administration of these devices needs to be very effective. Furthermore, all devices must deliver data from the beginning of the commissioning. Therefore, robust timing mechanisms like self-triggering or sufficiently big timing windows were required.

This design goal turned out to be very successful, since all basic systems provided data from the first electrons in a newly commissioned beamline. Already during the first beam adjustments, switching from self-triggering to timing mode has been done in the background. The net demand of time for diagnostics commissioning was almost zero.

Table 1: Diagnostic Devices in the European XFEL

System	Number
BPM System	*453*
Button BPMs	303
Cavity BPMs	126
Re-entrant Cavity BPMs	24
Charge Monitors	*51*
Faraday Cups	4
Dark Current Monitors	10
Toroids	37
Beam Size Measurements	*79*
Screens	52
Off Axis Screens	12
Dump Window Camera	3
Wire Scanners	12
Loss Monitors and Dosimetry	*1104*
Beam Loss Monitors	470
Beam Halo Monitors	4
RadFet Dosimeters	630
Longitudinal Diagnostic Systems	*16*
Bunch Compression Monitors	4
Bunch Arrival-Time Monitors	7
Electro-Optical Diagnostics	3
Transverse Deflecting Structures	2

BPM System

The BPM system of the European XFEL was constructed within a collaboration of PSI, CEA and DESY [14]. Three basic types of BPMs are part of this system. The standard BPMs are button BPMs with different beam pipe diameters. 30% of the BPMs in the cryostats of the accelerator modules are re-entrant cavity BPMs supplied by CEA, which are expected to have better performance at very low charge [15]. For precision measurement on µm or sub µm level cavity BPMs are installed. Two variants are available; the undulator type with 10 mm beam pipe and a type suited for the standard 40.5 mm beam pipe diameter. While DESY was concentrating on the pickups [16, 17], except for the re-entrant cavity BPM, PSI build the electronics [18, 19], except the RFFE of the re-entrant cavity BPM.

All BPMs feature a self-triggering mode, while the standard trigger is driven by the timing system. For each individual bunch within the bunch train, the BPMs deliver position and charge data. While button BPMs have no sign ambiguities, the sign of the displacement had to be set for the cavity BPM types during commissioning.

The BPM system was operating reliably from day one. During first beam steering the BPMs were showing beam intensities and positions along the beamline to be commissioned. Even signals at the 1 pC level from bunches almost lost along the beamline, have been detected and processed. With their self-triggering mode BPMs have served as the basic tool during initial beam steering. Already during the first hours of operation the trigger could be switched over to the timing system, sign ambiguities of the cavity BPMs could easily be fixed during initial steering. As soon as first beam was established in a beamline the BPM system was fully functional and operating to specification.

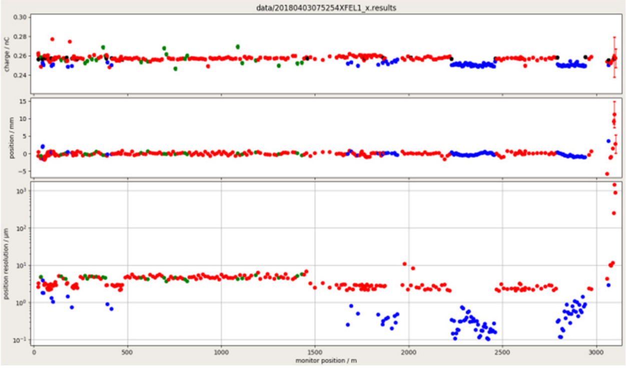

Figure 2: Plot of the horizontal BPM resolution versus longitudinal position in the accelerator. The upper two sub-plots show charge and position along the beamline. The lower sub-plot gives the position resolution of the BPMs in the horizontal plane. The colour code is red for button, green for re-entrant and blue for cavity BPMs. The first 6 cavity BPMs show higher resolutions due to an attenuation of the signals with 10 dB for safety. The 10 µm resolution for 2 button BPMs at about 2000 m position is due to a larger pipe diameter of 100 mm.

During the normal operation BPMs are a reliable backbone of operations. They provide a resolution superior to specification and work reliable even below 10 pC charge. As shown in Figure 3, BPM resolution is well below 10 µm even in the rather large 78 mm beam pipe of the cold LINAC, and about 5 µm for the 40.5 mm standard type. Cold button (red) and re-entrant cavity (green) BPM perform comparable. Cavity BPMs (blue) have a resolution below 1 µm The 10 mm type in the undulator sections turns out to be the best, as expected.

Charge Monitoring

European XFEL uses 3 kinds of monitors to measure the charge: In the gun region a destructive method with simple Faraday cups is used. The main working horse is the so called toroid, a type of current transformer commonly used at many DESY accelerators [20]. In addition the machine uses single cell stainless steel 1.3 GHz cavities, the so called dark current monitors [21]. Due to pile up in the resonator even the very small charge of dark current with 1.3 GHz repetition rate from the gun or field emission of the module produces a reasonable signal, allowing measurements down to the noise level at about 50 nA. In addition the charge signals from the beam can be measured. Depending on the settings of the electronics fC charge levels can be measured. This turned out to be useful, finding the first beam signals in the photo-injector, while phase and laser position on the cathode were still unknown. Such monitors are installed after the gun and around all 4 cold LINAC sections.

The toroid charge monitors have sensitivity of less than a pC and a resolution of about 100 fC at the usual operation charge of 250 pC. The high sensitivity together with the self-triggering mode has proven to be essential for the reliable beam detection during initial commissioning. The 37 monitors of this type are connected in a kind of chain by a fibre network. The electronics is based on a commercial ADC board with a FPGA. Fast digital data processing allows sending charge information of one monitor to the next upstream toroid via the fibre connections. Also branching of the beamlines is taken into account. Using this information a fast transmission interlock signal is implemented. The signals are used by the machine protection system (MPS) to stop the beam within a bunch train. Additional features are interlocks stopping the beam due to persisting poor transmission, or to stop beam production at certain integrated charge limits. A further useful feature is an alarm, if bunches are in the expected bucket. In addition an error margin of the timing error is provided, that can be used for corrective actions, e.g. to align the injector laser to the correct RF timing.

The digital backend of the toroids with a powerful Virtex 6 FPGA provides potential and flexibility for implementing new requirements to control transmission or global beam loss on various time scales and under different aspects. With their well-defined interface to the MPS system the toroids are very valuable and customizable sensors to protect the machine.

Beam Size Measurements

In total 67 screens and 12 wire scanners are distributed along the facility. Besides of screens for the rather big beam pipes before dumps and septa that are foreseen mainly for observation, European XFEL uses 2 types of precision screens for measurements.

The systems use scintillator crystals instead of OTR targets, which are oriented perpendicular to the beam axis. This geometry allows for spatial suppression of potential COTR effects on the crystal surface. Observation is under 45° and the optics features a depth of field extension using the Scheimpflug principle, either with 1:1 or 1:4 reproduction scales [22]. Initially LYSO was chosen as the screen material, but it turned out, that intrinsic quenching at high charge densities results in an overestimation of the beam size [23]. Therefore, other materials are under investigation. The currently most promising materials are YAG (Fig. 4) and YAP, which is now installed in the injector. Most of the screens are installed in groups of 4 at prominent locations in order to provide matching points for the optics with the 4 screen method, like in the injector and in the diagnostic sections after the bunch compressors. For the low energy sections the screen stations provide so called off axis screens, being smaller crystals leaving the beam axis uncovered. With dedicated kicker systems arbitrary single bunches are kicked out of the long bunch train and are hitting the screens [24].

In the high energy regime after the main LINAC, most of the screens have longer version of the vacuum chamber that allows integrating wire scanners, thus having two independent beam size measurements optically at one place. 4 matching sections after the main LINAC and before each SASE undulator are equipped with wire scanners [25].

The wire scanner type developed for European XFEL provides slow and fast scans. With the fast mode the wire is passing through the beam with a speed of 1 m/s, so that a profile can be taken within a single bunch train. Since long bunch trains are up to now not standard operation the scanners are used in slow mode. For the evaluation of new screen materials, the wire scanners are used as a reference measurement for the beam size [23]. Furthermore they turned out to be sensitive tools to study beam halo and its suppression in the collimation system [26].

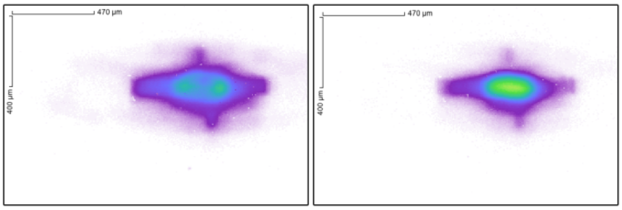

Figure 3: Comparison of LYSO (left) and YAG scintillators (right). The two scintillators are installed in the same screen station at 1650 m. The pictures are taken under the same conditions with a 14 GeV 250 pC beam. One can see for the LYSO a drop of intensity in the middle, so that the area of highest intensity looks like a "smoke ring" [23]. The YAG screen does not show such an artefact in the middle.

Beam Loss and Radiation Dose

In order to control beam loss in the machine a beam loss monitor (BLM) system with 470 monitors is installed [27]. The BLMs are based mainly on plastic scintillators read out by photomultipliers. At positions, where either high particle loss is expected, or hard X-ray synchrotron radiation would also trigger the BLM, the scintillators are replaced with quartz rods of the same dimensions. The use of Cherenkov radiation makes the BLMs sensitive to particle loss only. The BLM system can interrupt the operation via the MPS, acting on different time scales; there are single bunch alarms and multi-bunch alarms with different thresholds, as well as an integral alarm, sensitive to losses from dark current or field emission, emitted by the gun or the accelerating modules. In parallel to the digital data processing using an ADC and FPGA board, there is a simple analogue comparator circuit, able to generate alarms independent of timing or firmware issues.

Like for the toroids also the beam loss monitors firmware includes a kind of memory, if to many (configurable) events happen in a row, the bunch train is not only cut, but beam production is stopped via the MPS, and continues only after acknowledgment from the operator.

A difficult issue for BLMs is always how to calibrate the system. Even if BLMs would be calibrated to a given dose or loss rate, the location within the machine makes it difficult to judge the readings due to different loss and shielding situations of each BLM. European XFEL does not use individually calibrated BLMs, but makes use of the activation profile of the accelerator. The activation of the machine is measured on a regular level. If at certain positions the activation is judged to be too high, the alarm thresholds of the BLMs are tightened at these positions. On the other hand thresholds can be relaxed, as long as activation is reasonably low. Following this strategy, measurements even shortly after runs with up to 5000 bunches per seconds show a very moderate activation profile of the machine. Even at the collimators and in the dump regions the activation is currently well below 100 µSv/h. Of course it is expected that with increasing average power, BLM thresholds will get tighter and nevertheless activation at critical places of the machine will increase.

Beam halo monitors (BHM), a special kind of loss monitor, are located in the main dump lines (and in the injector) [28]. They are using 4 diamond and 4 sapphire detectors each and are working like solid state ionisation chambers. Due to their location around to the beam pipe after the last focussing element, they act like a virtual aperture. All trajectories passing the inside of this aperture will pass the dump window without losses. Due to the possible high average power of the beam the robustness of solid state detectors was necessary. The BHMs are connected to the MPS system and provide fast interlock signals to cut the bunch train within the RF pulse.

In addition to the fast acting loss monitors the European XFEL diagnostic suite also includes a dosimetry system [29]. It is based on about 630 RadFet sensors and delivers data on the integrated (gamma) dose at certain points inside the accelerator installation. The electronics of the RadFet sensors developed as an FMC board that can be installed and read out by any FMC interface. In addition to internal sensors the FMC board provides an interface to a custom made field bus providing access to external sensors.

The internal and external sensors are adapted for different purpose. Using a bias voltage and high sensitivity the internal ones are used for a dose survey in the electronics racks. Corresponding FMC boards are installed on the MPS electronics as well as in the BPM crates, creating a widespread measurement network in the tunnel infrastructure. Without bias voltage the sensors are less sensitive, but can measure higher dose levels. In this mode they are used as external sensors mainly in the undulator section, with two sensors installed on the undulator yoke close to the beam entrance. During commissioning it turned out, that the RadFet sensors, like the standard BLMs with plastic scintillator, are also sensitive to high energy X-rays. Therefore the dose readings in the last part of the undulators are dominated by spontaneous radiation. As a countermeasure 4 mm lead shields for the RadFet sensors are in preparation.

Longitudinal Diagnostics

Two S-band transverse deflecting structures (TDS) provide bunch length measurements with a resolution better than 200 fs in the injector and about 15 fs after the second bunch compressor. In order to use these systems with long bunch trains, the kicker systems and off axis screens are used [30].

In order to measure and later to feedback the arrival time of the beam, 7 beam arrival time monitors (BAM) are installed; the first in the injector, a pair around the chicane in B1 and B2 and a last station in front of the switchyard [31]. The arrival time jitter after the bunch compression is typically of the order of 30 fs. It is expected that this value improves, as soon as the intra-train arrival time feedbacks get operational.

The main working horse of the longitudinal diagnostics is the bunch compression monitor (BCM) [32]. Based on coherent diffraction radiation by a 5 or 7 mm aperture, the intensity of the coherent radiation in the far IR or terrahertz regime is measured. Assuming a decent working point for the compression the general shape of the beam is assumed to be rather constant. Therefore changes of the coherent intensity should reflect slight changes of the bunch length without significant changes of the beams form factor. This qualitative signal with bunch to bunch resolution is suited to feedback the RF systems to keep the compression constant. During SASE operation feedbacks using these signals on injector, L1 and L2 chirp or phase are used routinely.

MACHINE PROTECTION SYSTEM

With the large number of bunches, typical for the superconducting machines, strict and fast machine protection is mandatory [33]. The European XFEL uses a scalable distributed system. It is implemented as FPGA firmware on a µTCA board, that collects interlock data from many different sources and that acts on different actuators and combinations of them like the photo injector laser, the dump kicker as well as on RF systems. Inputs are provides by fast systems like BLMs and toroids as well as slow inputs like magnets or vacuum interlocks. Depending on the machine settings the system determines allowed beam destinations as well as allowed number of bunches, individual for the two SASE lines. If there is a magnet failure or BLM alarm in one branch, operation is only stopped for this branch. In case a screen is inserted the beam is only limited in this branch to single bunch.

The fast signals from BLMs and toroids are able to stop beam production within the long bunch train. The latency is dominated by signal travel and varies from less than 4 µs close to the injector to about 35 µs at the end of the SASE lines. With the highest repetition rate of 4.5 MHz this would correspond to more than 120 bunches, that would still be accelerated. Therefore the fast kickers of the distribution switchyard are also used to stop the beam in the SASE lines in order to reduce the latency to about 15 µs.

FAST INTRA BUNCH TRAIN FEEDBACK

Besides of slow orbit feedbacks to stabilize the electron beam orbit at essential points of the machine, there is a fast system to stabilize the orbit also within the bunch train. The IBFB, installed between the collimation section and the switchyard, is an in kind contribution from Switzerland [8]. Using 4 cavity BPMs with sub-micron precision, a set of two stripline kickers and fast FPGA logics the system, the system is able to stabilize the electron orbit along the train and to correct for pulse to pulse jitter of the incoming train. Adaptive feedforward algorithms and feedback reduce the bunch by bunch orbit deviations along the bunch train, as well as the pulse to pulse position deviation to the level of a few µm. The time constant for the initial stabilization is on the order of a 10 µs, the latency for bunch to bunch stabilization is on the order of 1-2 µs.

The initial part of the bunch train, needed for fast feedbacks to start regulation, can be kicked into the dump system before the SASE lines.

CONCLUSIONS

Commissioning and the onset of standard operation of the European XFEL have been very successful. The superconducting accelerator is operating according to specs. Within one year first lasing of all three FELs from soft to hard X-rays could be achieved. First user operation started on schedule 9 months after the first beam. This effective turnover from construction to operation was strongly supported by the diagnostic systems; almost all have been available from t_0. Therefore, the goal to commission the beam with diagnostics and not the diagnostics with beam was fully reached. In the current phase of “early operation” the diagnostics provide reliable and precise systems for further optimisation and improvement of the facility.

AKNOWLEDGEMENTS

Construction and commissioning of the diagnostics for European XFEL was the effort of a bigger team. Therefore, the author would like to thank all colleagues, who have participated in the work to set up the diagnostic system for the European XFEL. These thanks especially include the BPM collaboration, together with PSI and CEA, and also the colleagues from IHEP, Protvino, who have participated in the construction of the BLMs.

REFERENCES

[1] M. Altarelli *et al.* Ed., “The European X-Ray Free-Electron-Laser – Technical Design Report”, DESY, Hamburg, Germany, Rep. DESY 2006-097, July 2017.

[2] R. Brinkmann *et al.* Ed., “TESLA Technical Design Report – Part II: The Accelerator”, DESY, Hamburg, Germany, Rep. DESY 2001-011, March 2001.

[3] C. Maiano *et al.*, “Commissioning and Operation Experience of the 3.9 GHz System in the EXFEL Linac”, in *Proc. IPAC’17*, Copenhagen, Denmark, MOPVA059, pp. 999-1002.

[4] M. Hamberg *et al.*, “Electron Beam Heating with the European XFEL Laser Heater”, in *Proc. FEL’17*, Santa Fe, USA, WEP018, pp 450-451.

[5] F. Brinker, “Commissioning of the European XFEL Injector, in *Proc. IPAC’15*, Busan, Korea, TUOCA03, pp. 1044-1047.

[6] D. Lipka *et al.*, “First Experience with the Standard Diagnostics at the European XFEL Injector”, in *Proc. IBIC’16*, Barcelona, Spain, MOBL02, pp. 14-19.

[7] M. Hüning, "Bunch Length Measurements using transverse Deflecting Systems", to be presented at LINAC'18, Beijing, China, Sep. 2018.

[8] B. Keil *et al.*, "Status of the European XFEL Transverse Intra Bunch Train Feedback System", in *Proc. IBIC'15*, Melbourne, Australia, TUPN064, pp. 492-496.

[9] W. Decking and F. Obier, "Layout of the Beam Switchyard at the European XFEL", in *Proc. EPAC'08*, Genoa, Italy, WEPC073, pp. 2163-2165.

[10] E. A. Schneidmiller and M.V.Yurkov, "Baseline Parameters of the European XFEL", in *Proc. FEL'17*, Santa Fe, USA, MOP033, pp. 109 -112.

[11] T. Schnautz *et al.,* „First operation of the XFEL linac with the 2K cryogenic system", presented at CEC-ICMC 2017, Madison, USA.

[12] A. Aghababyan *et. al.*, "XFEL Timing System Specifications", Conceptual Design Report - Version 2.2, Hamburg, Germany, May 2013, `http://ttfinfo2.desy.de/doocs/Timing/CDRv2.2short.pdf`.

[13] W. Decking and H. Weise, "Commissioning of the European XFEL Accelerator", in *Proc. IPAC'17*, Copenhagen, Denmark, MOXAA1, pp. 1-6.

[14] B. Keil *et al.,* "The European XFEL Beam Position Monitoring System", in *Proc. IPAC'10*, Kyoto, Japan, MOPE064, pp. 1125-1127.

[15] C. Simon *et al.*, "Design and Beam Test Results of the Reentrant Cavity BPM of the European XFEL", in *Proc. IBIC'16*, Barcelona, Spain, TUPG17, pp. 356-359.

[16] D. Lipka *et al.*, "Development of Cavity BPM for the European XFEL", in *Proc. LINAC'10*, Tsukuba, Japan, TUP094, pp. 629-631.

[17] D. Lipka *et al.*, "Button BPM Development for the European XFEL", in *Proc. DIPAC'11*, Hamburg, Germany, MOPD19, pp. 83-85.

[18] B. Keil *et al.*, "Production Tests, Calibration and Commissioning of Button BPMs for the European XFEL", in *Proc. IBIC'17*, Grand Rapids, USA TUPCF19, pp. 259-262.

[19] B. Keil *et al*, "Beam-based Calibration and Performance Optimization of Cavity BPMs for SwissFEL, E-XFEL and FLASH2", in *Proc. IBIC'14*, Monterey, USA WEPD11, pp. 665-669.

[20] M. Werner *et al.*, "A Toroid Based Bunch Charge Monitor System with Machine Protection Features for FLASH and XFEL", in *Proc. IBIC'14*, Monterey, USA WEPF02, pp. 521-524.

[21] D. Lipka *et al.*, "Dark Current Monitor for the European XFEL", in *Proc. DIPAC'11*, Hamburg, Germany, WEOC03, pp. 572-574.

[22] C. Wiebers *et al.*, "Scintillating Screen Monitors for Transverse Electron Beam Profile Diagnostics at the European XFEL", in *Proc. IBIC'13*, Oxford, UK, WEPF03, pp. 807-810.

[23] G. Kube *et al.*, "A Simple Model to Describe Smoke Ring Shaped Beam Profile Measurements with Scintillating Screens at the European XFEL", presented at IBIC'18, Shanghai, China, this conference.

[24] M. Scholz and B. Beutner., "Electron Beam Phase Space Tomography at the European XFEL Injector", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper MOPAP047, pp 196-198.

[25] T. Lensch and S. Liu, "Status and Commissioning of the Wire Scanner System for the European XFEL", in *Proc. IPAC'18*, Vancouver, Canada, WEPAF047, pp. 1919-1922.

[26] S. Liu *et al.*, "First Beam Halo Studies using Wire Scanners at the Wire Scanner System for the European XFEL", in *Proc. FEL'17*, Santa Fe, USA, TUP003, pp. 255-258.

[27] T. Wamsat, "The European XFEL Beam Loss Monitor System", presented at IBIC'18, Shanghai, China, WEOB03, this conference.

[28] A. Ignatenko *et al.*, "Beam Halo Monitor for FLASH and the European XFEL", in *Proc. IPAC'12*, New Orleans, USA, MOPPR018, pp. 816-818.

[29] F. Schmidt-Föhre *et al.*, "Commissioning of the new Online-Radiation-Monitoring System at the European XFEL Injector with first Tests of the High-Sensitivity-Mode for Intra-Tunnel Rack Surveillance", in *Proc. IBIC'15*, Melbourne, Australia, WECLA02, pp. 585-588.

[30] C. Gerth *et al.*, "Online Longitudinal Bunch Profile and Slice Emittance Diagnostics at the European XFEL", in *Proc. IBIC'17*, Grand Rapids, USA TUPCC03, pp. 259-262.

[31] M. Viti *et al.*, "The Bunch Arrival Time Monitor at FLAS and European XFEL", in *Proc. ICALEPCS'17*, Barcelona, Spain, TUPHA125, pp. 701-705.

[32] P. Peier *et al.*, "Coherent Radiation Diagnostics for Longitudinal Bunch characterization at European XFEL", in *Proc. FEL'14*, Basel, Switzerland, THP083, pp. 925-928.

[33] S. Karstensen, *et al.*, "XFEL Machine Protection System (MPS) Based On UTCA", in *Proc. Real Time Conference (RT) 2014 19th IEEE-NPSS*, Nara, Japan, May 2014, pp. 1-4.