FIRST EXPERIENCE WITH THE STANDARD DIAGNOSTICS AT THE EUROPEAN XFEL INJECTOR

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Abstract

The injector of the European XFEL started beam operation in December 2015. Besides the gun and the accelerating section, containing a 1.3 and a 3.9 GHz accelerating module, it contains a variety of standard diagnostics systems specially designed for this facility. With very few exceptions, all types of diagnostics systems of the whole XFEL are installed in the injector. Therefore the injector operation allows validating and proving of the diagnostics performances for the entire facility. Most of the standard diagnostics have been available from the very beginning of the beam operation and have been used for the monitoring of the first beam. In the following months the diagnostics have been optimized and used for improvements of beam quality. In this contribution, the first results and the operation experience of the standard beam diagnostics of the European XFEL are reported.

INTRODUCTION

The European X-ray Free-Electron Laser (E-XFEL) [1] is the 3.4 km long international facility, running from DESY in Hamburg to the town of Schenefeld (Schleswig-Holstein) in Germany. To construct and operate the E-XFEL, international partners agreed on the foundation of an independent research organization – a non-profit limited liability company under German law named the European XFEL GmbH. DESY is leading the accelerator construction consortium and will be in charge of the accelerator operation.

The accelerator is based on superconducting TESLA Radio-Frequency (RF) technology. Within one RF pulse of up to 600 μs length, a train with up to 2700 bunches will be generated. This results in a bunch minimal spacing of 222 ns. The repetition rate of the RF pulses is 10 Hz, so that a maximum number of 27000 X-ray pulses per second can be produced. The operation charge varies from 20 pC to 1 nC to provide different characteristics of the output radiation, i. e. the average power or the bunch length, as requested by the users. Therefore diagnostics components have to monitor the beam properties within this dynamic range.

Beam operation of the photocathode gun started already in February 2015, the complete injector became operable in December 2015. In this first accelerator part of the facility, several diagnostics systems are installed, commissioned and have been optimized for the measurement of the electron beam properties. This paper focuses on standard electron beam diagnostics for the E-XFEL injector. Special and higher-order mode diagnostics systems are described in [2–8].

STANDARD DIAGNOSTICS FOR THE EUROPEAN XFEL

The standard diagnostics contains a variety of position, charge and loss monitors and screen stations. It is also planned to use wire scanners at positions with high electron energies. The full list of monitoring systems is given in Table 1. A description of the different systems with results of their laboratory and beam tests can be found in [9–24].

Table 1: Diagnostics System Numbers for the Complete E-XFEL and for the Gun with Injector

System	Total number	Gun and injector
BPMs	~460	14
Charge monitors	~50	10
Screens	~70	11
Wire scanners	12	0
Loss monitors	~490	20

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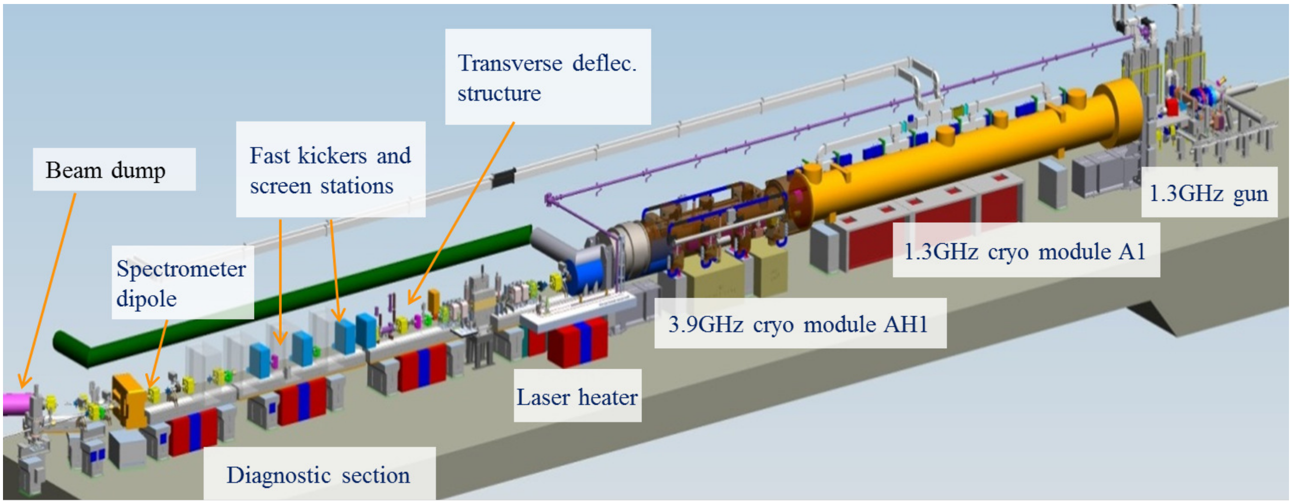

Figure 1: Scheme of the E-XFEL injector and its subsystems. The beam starts at the gun on the right and is stopped in the injector beam dump on the left. Total length of the shown section is 41m.

All sub systems are installed and used in the E-XFEL injector, except wire scanners. Therefore the commissioning and validation of the diagnostics systems in the real environment is possible before the commissioning of the entire facility.

THE INJECTOR

The E-XFEL injector consists of a normal conducting photocathode RF-gun followed by a standard 1.3 GHz XFEL superconducting module, as shown in Fig. 1. The module contains 8 Niobium cavities and accelerates the beam to about 150 MeV/c. Between gun and module, a first section with gun diagnostics is installed, containing 3 Beam Position Monitors (BPMs), a Toroid, a dark current monitor, 3 screen stations, 4 Faraday cups and beam loss monitors. The 1.3 GHz module is followed by a superconducting 3.9 GHz module, which is used to optimize the longitudinal phase space [25,26]. In the standard setting it decelerates the beam by 20 MeV, so that the final electron energy from the injector is 130 MeV. In each module a *cold* BPM is installed. The *cold* section is followed by a diagnostics section, see Fig. 1. The diagnostics section allows measuring the complete 6-dimensional phase space properties of the electron bunch. More details of the injector can be found in [27].

Chronological Order of Beam Commissioning

The operation of the photocathode RF-gun started in the end of 2013 with a conditioning process. On usual working days the installation of the gun diagnostics and following components continued. The first standard diagnostics system of the E-XFEL, which has detected field-emitted electrons along the RF pulse in 2014, was the dark current monitor (DaMon) [17]. Also the screen stations could identify the dark current. The first beam operation started February 2015, with operating the Toroid and the BPM systems, such that the charge and the position of the beam could be monitored immediately. The beam was transmitted to a dispersive section that provides a dump in the gun area, with screen station, BPM and Faraday cup to measure the beam momentum.

In 2015, the installation of the injector continued with the cooling down of the modules and it accomplished on December 15th, with all accelerator cavities tuned to resonance on December 18th. On the same day, the beam was transmitted to the injector dump within few hours. Even this first transmission was detected by the diagnostics systems, with the Toroids and the BPMs available from the first shot. Three days later the first emittance measurement was performed with the screen stations. Until July 2016, the operation continued for the full characterization and optimization of the beam properties. Currently the injector is switched off and is warmed up to prepare the cryo system for the cooling down of the entire facility.

Diagnostics Setup and Experience from the Injector Commissioning and Optimization

Beam Position Monitors Button and cavity BPMs [10–15] with single-bunch detection are used, such that each bunch with 222 ns spacing can be measured. Button BPMs with an aperture of 40.5 mm are the *working horse* along the E-XFEL beamline. Variants with apertures between 34 mm and 200 mm are used to adapt to the adjacent beam pipes. Cavity BPMs are used in the undulator intersection with 10 mm aperture and at dedicated positions where a better resolution is requested, e. g. for the intra-bunch feedback system [28], with the standard 40.5 mm aperture. Inside of each superconducting module, BPMs with aperture of 78 mm are installed, where 30 % of these *cold* BPMs are of reentrant type [14], and the others are button BPMs. The complete BPM system including electronics is an in-kind contribution of CEA Saclay, DESY and PSI [29]. The pick-ups are developed at DESY (buttons and cavities) and CEA (reentrant cavities); the electronics, firmware and software for all BPMs is developed at PSI, except for the reentrant front-end electronics provided by CEA. The information

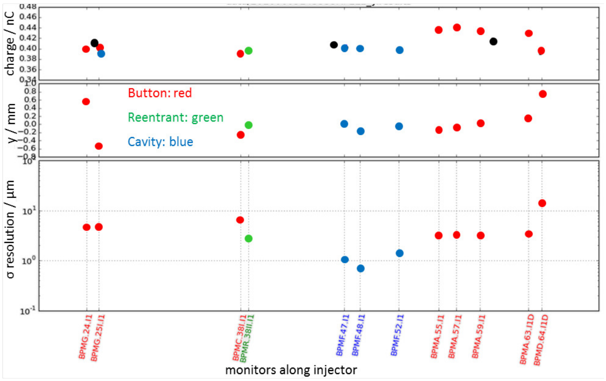

Figure 2: Measured charge values, positions and single bunch position resolution of the BPMs along the E-XFEL injector. The gun is on the left and the dump on the right side. The resolution was obtained by correlating the readings for 1000 bunches; the error bars are covered by the symbols. Therefore, a very stable operation is observed. Beam pipe apertures: BPMG 34 mm; BPMC, BPMR 78 mm; BPMF, BPMA 40.5 mm; BPMD 100 mm. The BPMG signals are attenuated by 6 dB remnant needed to protect the electronics during early gun tests.

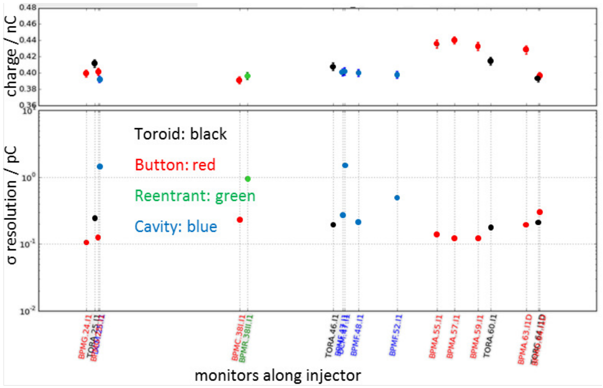

Figure 3: Measured charge values and single bunch charge resolutions from non-destructive charge monitors along the E-XFEL injector, the gun is on the left and the dump on the right side. The resolution was obtained by correlating the readings for 1000 bunches; the error bars are covered by the symbols. The data from cavity BPMs and DaMons are shown in blue.

about the position and charge from a BPM system is read by µTCA crates via a FPGA-to-FPGA bridge using optical fibers. The timing signals are connected by optical fibers as well. For the first beam the BPMs are used in self-trigger mode: if the ADC amplitude exceeds a given threshold, the data is treated as signal and the bunch is detected. In this mode, the first beam can be monitored independently of the timing system. Once the delay between beam and timing signal is measured (by the BPM electronics itself), the externally-triggered mode is used to improve the performance of the BPMs. Cavity BPMs need more adjustment for better performances (phase matching between signals from reference and dipole resonators). A pre-calibration of the front ends is made beforehand in the laboratory, and for cavities also by beam measurements at FLASH, such that all BPM are well-configured and operational before the first beam appears [10, 12, 15]. The BPM performance has been verified by cross correlation of each BPM to all the others, as depicted in Fig. 2, for details see [30]. In this example at a charge of about 0.4 nC, the position resolution is below 7 μm for button BPMs (except the last one in the dump line with larger aperture of 100 mm), for the reentrant BPM it is about 3 μm and for the cavity BPMs the resolution reaches about 1 μm.

Charge Monitors Thirty-five Toroids are distributed along the E-XFEL beamline, 4 of them are installed in the injector [16]. These are conventional current transformers, consisting of a ferrite core with windings around a ceramic gap in the pipe. The calibration is performed with additional windings and test signals; that can be used for self-test too. Like the BPMs the Toroids can run in self-trigger mode, and provide a measurement of the beam delay with respect to the timing system trigger. Like for the BPMs, first beam detection in self-triggered mode was successfully used. In addition, 9 dark current monitor (DaMon) systems [17] are distributed along the E-XFEL to measure the transmission of the dark current (2 of them in the injector); this device is able to detect the beam charge as well. Four destructive Faraday cups are installed in the gun diagnostics section. In Fig. 3, the resolutions of Toroids, BPMs and DaMons are shown. The reason of the charge difference is caused by non-perfect calibration of the devices. The resolutions are mostly below 1 pC, therefore these devices are capable to measure charges down to this level. Within the first half year of the operation in 2016, an integrated charge of 3 C was transmitted to the dump, mainly in some long bunch train runs, to test operation with 27000 bunches per second.

Beam Loss and Halo Monitors A beam loss monitor (BLM) is based on 4 scintillator pieces read out by photomultipliers [22]. The 490 BLMs are distributed along the electron beamline of the E-XFEL. These monitors are capable to detect the dark current and single bunch losses. In case the signal exceeds a threshold, an alarm is sent to the machine protection system (MPS). The analog signal processing and analog-to-digital conversion is performed in a rear transition module of a μTCA board. Various alarms are processed using fast digital signal processing in an FPGA AMC board that is connected to the MPS system. For safety reasons, an analog comparator based alarm is provided too. Fig. 4 shows an example of a BLM signal. The shown signals are mostly produced by dark current, one exceeds the threshold and indicates an (integration) alarm. Beam Halo monitor (BHM) consists of four diamond and four sapphire sensors operating as solid-state ionization chambers [23]. A BHM is installed in the injector dump section, three more

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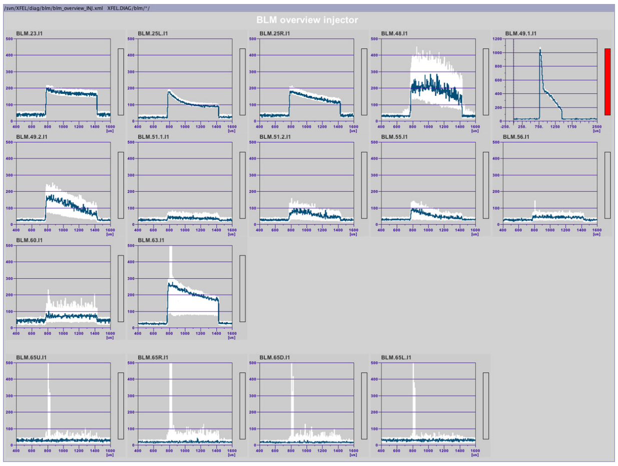

Figure 4: Display of the beam loss monitors during beam operation. Most of the monitors show the continuous dark current background, one BLM.49 produces an alarm (indicated in red). The BLMs in the dump line (bottom row) show in white color history data from previous trains.

BHMs are at the main dumps. They are capable to detect both beam losses on a bunch-by-bunch basis and dark current. Diamond sensors provide higher sensitivity, whereas sapphire sensors remain operational at higher intensities of impinging particles. The signal processing and electronics are similar to those of the BLMs.

Dosimetry The γ radiation is measured due to RadFets with rack-internal and external sensors [24]. The internal sensors are hosted on plug-in readout modules according to FPGA Mezzanine Card (FMC) standard. These modules are directly connected to the FMC carrier slots of the MPS μTCA electronics or the PSI BPM electronics. Online radiation monitors are distributed in critical sections along the accelerator. The external sensors are distributed at dedicated position along the E-XFEL and are connected via field bus system. The majority of sensors are installed in the undulator, where two sensors are fixed at the entrance of the magnetic structure. This system has the option of extension by Neutron dosimetry. During the E-XFEL injector operation, few sensors showed the integrated radiation at dedicated positions.

Screens The scintillating screen with 200 μm thick LYSO:Ce targets are oriented such that coherent optical transition radiation generated at the screen boundaries will geometrically be suppressed by an observation angle of 45 °. An additional feature is that the imaging optics operates in Scheimpflug condition, thus adjusting the plane of sharp focus with respect to the CCD chip. This significantly increases the apparent depth of field and the well-focused field of view. At each motorized station one full and one half filled screen (on- and off-axis) can be inserted. A grid for calibration is mounted on the screen mover too. Depending on the requirements, different optical systems are used for the screen stations. One provides 1:1 imaging, the other one reduces the screen image by a factor of two. Basler Aviator cameras are installed for good image resolution. The main system with 1:1 imaging reaches a resolution $\leq$10 μm [18]. In the following, measurements with these screen stations are described.

Highlights: Emittance along Bunch Train and TDS Operation

The emittance is measured through analysis of the beam images using the screen stations. Four stations within a FODO lattice with on-axis screens and quadrupole scans are used. Further, in order to perform the emittance measurements during long bunch train operation, a single bunch can be deflected from the train towards the off-axis screens by using fast kickers. This is demonstrated in Fig. 5. This offers additional possibility of emittance measurements during user operation, since a single bunch of one train and the train evolution can be investigated. The measurement can be performed at 2.5 Hz repetition rate. These measurements have been successfully performed routinely during the long bunch train operation of the injector.

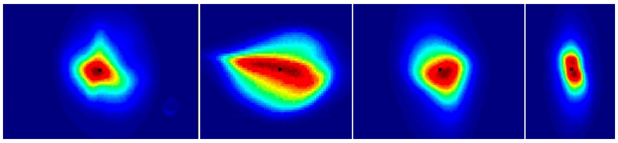

Figure 5: Four transverse images of kicked beams to off-axis screens for emittance measurements.

The main tool for longitudinal phase space diagnostics is the Transverse Deflecting Structure (TDS) [4]. A single bunch of a train is streaked and in the following kicked towards the off-axis screens. As a result, one axis on the image corresponds to the longitudinal dimension of the bunch. Several measurements were performed during E-XFEL injector operation in June and July 2016 such that the slice emittance could be measured and optimized.

SUMMARY

The standard diagnostics of the E-XFEL injector has been ready for beam property measurements since the first day of beam operation and the beam properties are investigated. All design values of the standard diagnostics could be achieved. BPMs and Toroids can be used in self-trigger as well as in externally-triggered mode for better performance. The resolution requirements are fulfilled. The dark current monitors are useful to measure both, dark current and beam charge. Online monitors of beam loss, halos and radiation dose are installed and operational. Screen stations are used with on- and off-axis screens. The latter one is useful during long bunch train operation to prove the beam properties during user operations by observing one bunch out of the whole train.

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OUTLOOK

The E-XFEL installation in the main accelerator tunnel is nearly finished. The electronics installation and technical commissioning of the linac should be finished in September 2016. BPMs and charge monitors are laboratory-calibrated and the results are compared with those in injector-operation. These devices will start in self-triggered mode to detect the first beam, with later usage in the triggered-mode to improve their performance. All screen stations are being installed and calibrated. BLM, BHM and dosimetry are ready for online monitoring using default thresholds. Cooling down of the superconducting modules is scheduled for October 2016, with first beam expected end of 2016. Remaining parts of the beamlines will be commissioned in the beginning of 2017. First lasing will be possible in April 2017.

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