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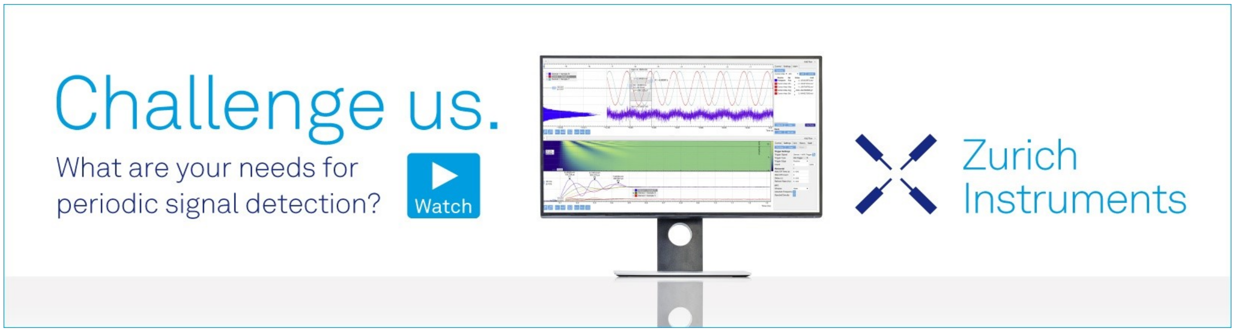

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First Photon Diagnostics Commissioning at the European XFEL

Jan Grünert[1,a)], Marc Planas Carbonell[1], Florian Dietrich[1], Wolfgang Freund[1], Andreas Koch[1], Naresh Kujala[1], Joakim Laksman[1], Jia Liu[1], and Theophilos Maltezopoulos[1]

[1] European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany

a) Corresponding author: jan.gruenert@xfel.eu

Abstract. The European X-ray Free Electron Laser (European XFEL) is a new user facility in the metropolitan area of Hamburg, Germany. It offers ultra-short (femtosecond) and intense (GigaWatt) transversely coherent x-ray laser beams in the soft to hard x-ray domain at MHz repetition rate. Up to 2700 pulses per train will be delivered at 10 Hz train repetition rate. The x-ray diagnostics [1-4] serves the electron machine to achieve lasing by Self-Amplified Spontaneous Emission (SASE), supports the SASE tuning, and assists to align and commission the photon beam transport. Finally, it delivers non-invasive online beam diagnostic data to the users at the experimental end-stations. In May 2017 the first undulator beamline, SASE1, was successfully commissioned with beam, and First Lasing was detected. This presentation describes the contribution of photon diagnostics during the distinct commissioning phases: Pre-beam checkout, first light from the bending magnets, x-rays from single undulator segments, SASE tuning with many undulator segments, First Lasing, optics alignment for FEL beam transport through the tunnel up to the experimental hutches, and finally beam delivery to first users. Assessed beam properties included per-pulse intensity, beam position, shape, lateral dimensions, and spectral properties. During this period, the machine provided up to 0.1 nm wavelength at up to 1.5 mJ pulse energy, up to 300 FEL pulses per train, and up to 4.5 MHz intra-bunch train repetition.

OVERVIEW

The first light, generated by the electrons passing through the undulator, is spontaneous undulator and bending magnet radiation with a wide spectrum from visible into very hard X-rays, determined by the high electron beam energy of 6 to 17.5 GeV and the magnet characteristics like undulator period length (40 mm in SASE1) and on-axis field strength (1.1 T at 10 mm in SASE1). Initial commissioning was started at an electron energy of 6 GeV, increasing step-by step to the nominal operation energy of 17.5 GeV.

A minimum number of photon system devices are required to prepare and observe First Lasing: it is mandatory on one hand to insert a scintillator into the photon beam to measure beam shape, spot size, and position as well as intensity. The optical system must be sensitive enough to detect already the spontaneous radiation of single undulator segments, much weaker - by 6 to 8 orders of magnitude - than the full FEL beam in saturation. Additionally and simultaneously, this photon beam absorbing measurement is complemented with a non-invasive, transparent intensity and beam position measurement with a gas-based device like the X-ray gas monitors (XGM).

We built in each SASE beamline a so-called K-monochromator system in order to have a backup strategy if immediate lasing would have failed, for improvement of adjustment, for regular undulator measurements tracking for deterioration by radiation damage, and for FEL scans. The K-monochromator system consists of a crystal-based monochromator in combination with a filter chamber, a sensitive imager and a photodiode. This system can be applied to determine the magnetic field of single undulator segments, and therefore the undulator K-value, very precisely in-situ with photon beam-based methods without removing the undulator to the magnetic measurement lab.

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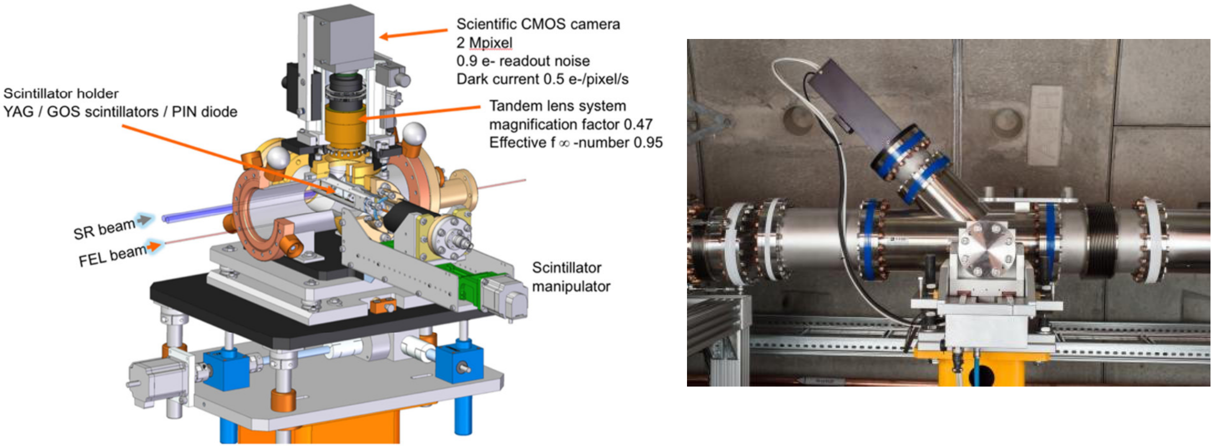
The overall layout of the European XFEL facility, in particular of the photon systems, is described in [1-4]. The commissioning of the European XFEL photon system is performed in the sequence SASE1 – SASE3 – SASE2. Most construction tasks and all commissioning steps followed this sequence, starting from hardware installation of vacuum chambers, cables and electronics, technical commissioning of controls, as well as finally the commissioning with photon beam. In the tunnels, all these activities culminated in First Lasing in each of the three undulator beamlines, and subsequent photon commissioning of the downstream X-ray optics, diagnostics, beam transport, and instruments.

Commissioning with Beam in SASE1

An obvious however not trivial prerequisite for commissioning with photon beam was the technical commissioning of the vacuum system with full remote control, including the first opening of the famous “V0-valve” which defines the boundary towards the upstream accelerator vacuum system. As soon as this valve was opened and electrons were sent to the main dump (T4D) of the Northern tunnels - still at entirely open undulator gaps - this provided transition radiation at the exit of the SASE1 undulator, and bending magnet radiation which originates from the dipole magnets that bend the electron beam in horizontal direction towards the SASE3 undulator, just downstream of the SASE1 undulator.



(a) (b)

FIGURE 1. (a) CAD model of the spontaneous radiation imager (IMGSR). (b) Photo of IMGPII45, one of the many pop-in monitors which monitor the beam position along the beam transport for alignment purposes.

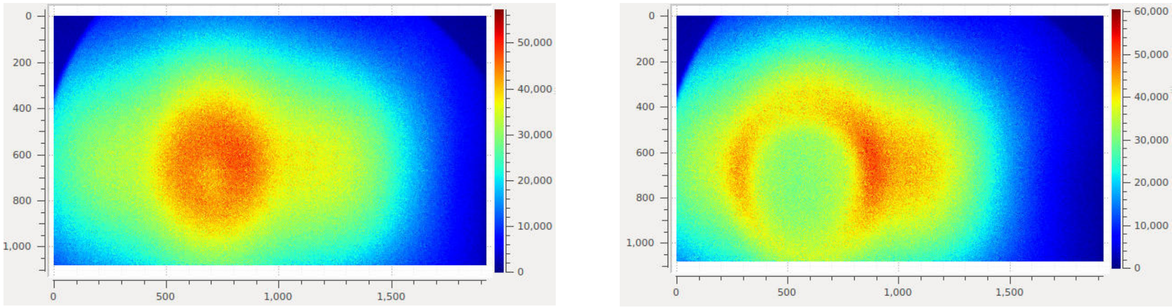
The photon system commissioning-with-beam started with these first photons which allowed for initial tests: the spontaneous radiation imager (IMGSR, see Fig.1) was inserted to the beam for imaging. It contains various scintillators: the most efficient is Gd_2O_2S:Pr (GOS) which was used for spontaneous radiation, while Ce:YAG was later used for FEL beam imaging. On the same manipulator there is a photodiode (Hamamatsu S3590-09, 10x10 mm active area) which detects photons at low intensities (below the lasing threshold) and which is used in combination with the K-monochromator. IMGSR was designed for highest photon sensitivity to detect faint radiation from single undulator segments at large distances (> 400m). It uses high numerical aperture optics and low-noise SCMOS camera, details in Fig.1a and dedicated device publications.

Upstream of IMGSR, a filter chamber (FILT) allows inserting various thin metal filters, see Tab.1: an aluminium foil to blocking visible light, and three other metal foils for basic spectroscopy of the spontaneous radiation and for spectral calibration for the K-monochromator. At the absorption energy edges (K-edges) of these metals, the significantly increased absorption of photons with only slightly higher energy leads to a clear signature e.g. in images of the spontaneous radiation, because the photons on the central beam axis have higher photon energy.

Therefore, when the beam energy is set just below an absorption edge, a circle of lower scintillation intensity will appear in the center of the image, see Fig. 2 as an example at 8.65 GeV electron beam energy, undulator Gap = 23 mm, Cu filter. This allows for a first photon energy determination. The effect is more pronounced when some undulator segments are closed, effectively still producing spontaneous radiation but with sharper resonances and higher intensity. The absorption circle grows with increasing undulator gap which leads to higher photon energies.

TABLE 1. Metal foils in the filter chamber

Metal foil material	Foil thickness	Absorption K-edge
Aluminum (light blocker)	2.5 µm	(1560 eV)
Copper	10 µm	8979 eV
Nickel	5 µm	8333 eV
Molybdenium	20 µm	20 keV



(a) (b)

FIGURE 2. Spectroscopy of the spontaneous radiation of a single undulator segment with an inserted copper foil. The undulator gap is (a) at 22.7mm and (b) at 23.0mm with electron beam energy 8.65 GeV. X/Y-units are camera pixels (~14µm per pixel), intensity in ADC units with 16-bit resolution. At the larger gap value, the spectrum shifts to higher photon energies (here 8987 eV) beyond the K-edge of copper which reduces the detected intensity in the beam center.

This technique was also one option to determine the SR beam pointing of each of the 35 individual SASE1 undulator segments separately, a supplementary information to the optimization of the electron beam orbit in the undulator which was mainly achieved by beam-based alignment, an iterative adjustment of the undulator intersection quadrupoles at different electron beam energies to finally obtain dispersion-free steering, i.e. no orbit changes for different electron beam energies, one of the requirements for successful X-ray lasing.

With the K-monochromator, filter chamber and SR imager we had built a dedicated set of instrumentation for the photon-based in-situ measurement of the magnetic field of individual undulator segments. This in principle [2] allows to set the individual undulator gaps such as to achieve a K-parameter variation less than $\Delta K/K = 1E\text{-}4$ which is required for SASE lasing. This technique and our measurement results are described in another contribution to this conference in detail [6]. These data are also used for long-term undulator radiation damage studies.

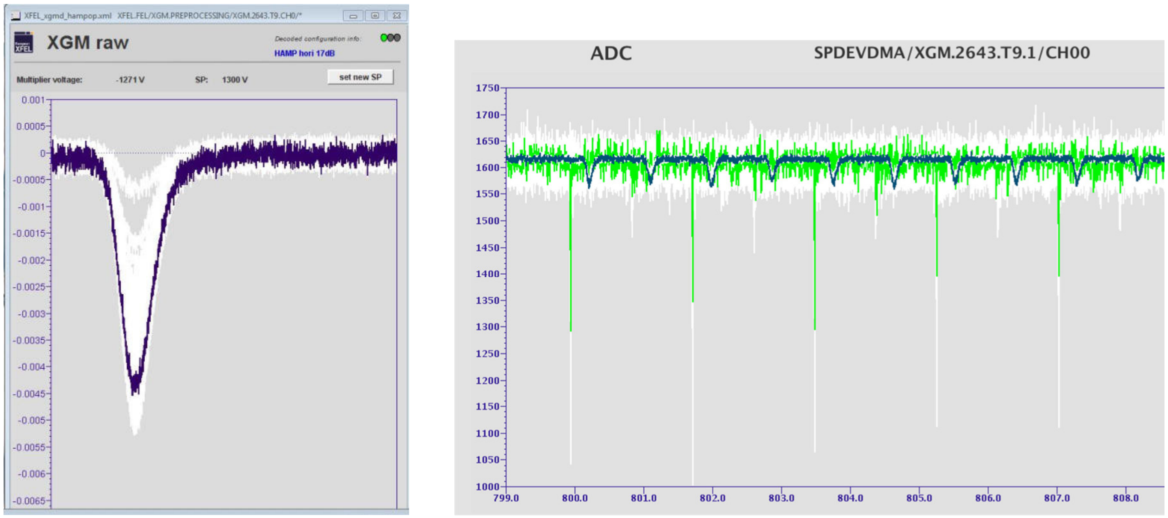
When the electron machine was prepared for the First Lasing attempt, the following photon diagnostics devices required for lasing detection were activated:

1. The X-ray gas monitor (XGM): Faraday cups collect photo-ions and -electrons generated by the X-ray beam passing through a rare gas at low partial pressures. During commissioning we typically applied Xenon at 5E-5 mbar. The photocurrents are monitored by Keithley picoammeters.
2. The Huge Aperture Multiplier (HAMP) is another detector inside the XGM package. Its main purpose is to yield sufficient signal towards the upper hard X-ray energy limit of the facility beyond 20 keV, where the photoemission cross-sections with rare gases are much decreased. Both effects dramatically reduce the integrated photoemission current, thus requiring a larger collection area. HAMP operates with high repulsion fields up to 20 kV to separate the electron and ion signals. Each XGM package contains two

HAMPs, one each for x- and y-direction since the HAMPs also deliver beam position information in one dimension.

3. Simultaneously with the XGM, the FEL imager (IMGFEL) is operated which is an imager downstream of the XGM. Unlike IMGSR, this imager is optimized for high optical intensities as expected from FEL radiation converted to visible by scintillators. Nevertheless it turned out to be sufficiently sensitive for imaging down to spontaneous level below the lasing threshold.

Figure 3 shows a typical signal trace of the HAMP detector during single-bunch beam delivery. It is on one hand a standard tool for the electron beam operators for tuning from spontaneous radiation to SASE saturation, and on the other hand it delivers shot-to-shot intensity data to the users. In particular, the HAMPs shall allow for operation with hard X-rays beyond 12 keV, which was however not yet commissioned.



Multiplier voltage: -1271 V

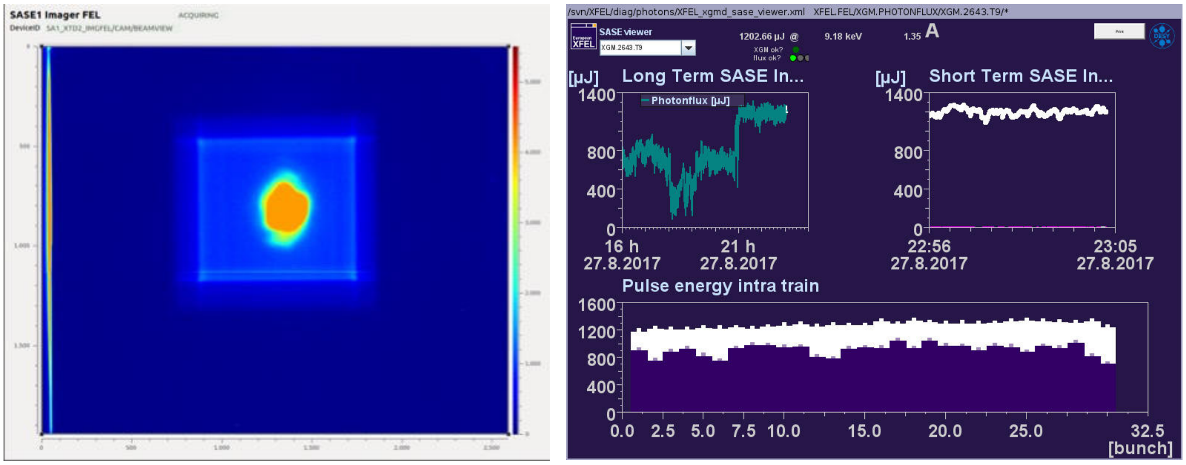
SP: 1300 V

(a)

(b)

FIGURE 3. (a) Typical signal from the horizontal HAMP detector as used during single-bunch mode tuning at 8.27 keV. Here Xenon at 5E-5 mbar was used with 1300 V multiplier voltage. The blue line is the HAMP ion current measurement, white lines are the persistence which indicates the shot-to-shot jitter. The calibrated intensity at this measurement (27.7.2017) was 479 µJ ±10% with an intensity variation SD = 33µJ per hour). (b) Ion signal (horizontal HAMP, blue trace) and electron signal (vertical XGMD, green trace) recorded at 1.12 MHz repetition rate. White lines again indicate the jitter.

During SASE search typically some spot can already be seen on the FEL imager before substantial lasing happens and is then detected by the XGM. To allow for this increased sensitivity below the lasing threshold, we had temporarily removed optical attenuators in the FEL imager optics. Once lasing is reached, the signal on the FEL imager clearly shows the sharply defined laser spot, see Fig. 4. The round FEL beam in the center was saturating the YAG scintillator already at this early stage so that X-ray attenuators had to be inserted for further beam analysis. The strong synchrotron radiation background stemming from the (at that time 10.3 GeV) electron beam was blocked outside the light blue rectangular area by the synchrotron radiation aperture (SRA) blades. Without this blocking, the gas-based diagnostics receives too much signal of the spontaneous radiation.



(a)

(b)

FIGURE 4. (a) Beam profile of the First Hard X-ray Lasing at 6 keV (0.2 nm) from the European XFEL undulator SASE1 as recorded by the FEL imager during the first hours after successful SASE tuning (24.5.2017). (b) Later during the commissioning pulse energies above 1 mJ as shown could be detected in multi-bunch mode with 30 bunches per train.

Commissioning of the photon diagnostics is a continuous process which depends on the progress in beam operation parameters. Whenever the electron machine reached a new milestone, typically the diagnostics devices could also be commissioned one step further out in the design parameter space. This again happened end of 2017 for the number of bunches, when for the first time more than 100 pulses per train at 10 Hz were produced and detected in SASE1. Since the mean pulse energy was on the order of 700 µJ, the delivered average power with 1200 pulses per second almost reached 1 Watt, see Fig. 5.

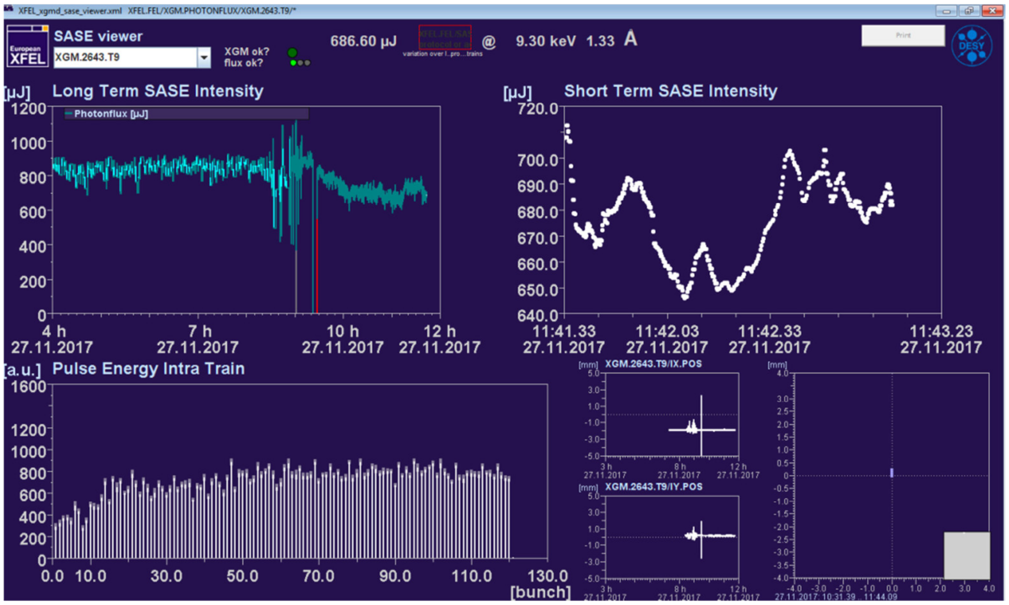


FIGURE 5. First detection of more than 100 pulses per train at SASE1. Here 120 pulses show an average of almost 1 Watt. The lower left plot shows the individual intensities of the individual pulses in the train, while the average pulse intensity per pulse is shown in the upper two plots. Since this was the first demonstration of 120 bunch mode, there was still some intensity inhomogeneity over the pulse train which was later reduced by improved feedbacks.

There are more diagnostics devices installed in the SASE1 tunnels which were commissioned but cannot be described here in detail. In particular this concerns the MCP-based detector for alternative high-rep rate intensity measurements and the spectral characterization of the FEL pulses: the HIgh-Resolution X-ray spectrometer (HIREX) delivers, on request, calibrated spectral beam data at single and multi-bunch operation. An important feature is that it functions also in parasitic mode. These two devices and their commissioning results will be described elsewhere, and also the first commissioning results of the online gas-based soft X-ray photo-emission spectrometer (PES) and other diagnostics devices particular to SASE3.

SUMMARY AND OUTLOOK

The commissioning of the European XFEL with photon beam has started, and all planned diagnostics devices were used to prepare, support, and detect first lasing, to commission the beam transport and optics and deliver beam to the experimental end-stations. This was achieved for the first undulator SASE1 in the hard X-ray domain. Subsequently comparable commissioning happened in the two other undulators SASE2 and SASE3, which will be described elsewhere in detail. Diagnostics of the photon beam continues in this commissioning phase with remarkable qualitative progress each time when the electron beam machine achieves new capabilities towards the design parameters, such as increasing the number of bunches per bunch-train, increasing the photon energy, and providing special on-demand bunch patterns. New capabilities of the installed SASE1 and SASE3 diagnostics were activated based on the actual machine operation status and data acquisition system availability. The online gas-based intensity diagnostics (XGM) operation is continuous 24/7 and almost entirely automated. It is also used to characterize individual pulses, so far with up to 500 pulses per train.

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