COMMISSIONING STATUS OF THE EUROPEAN XFEL PHOTON BEAM SYSTEM

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Abstract

The European XFEL located in the Hamburg region in Germany, has finished its construction phase and is currently being commissioned. The European XFEL facility aims at producing X-rays in the range from 260 eV up to 24 keV out of three undulator beam lines that can be operated simultaneously with up to 27000 pulses/second. The FEL is driven by a 17.5 GeV linear accelerator based on TESLA-type superconducting accelerator modules. The accelerator has finished its first commissioning phase and is currently delivering photon beam to the experimental areas for commissioning in view of the user operation. This paper presents the status of the photon beam system from the undulators to the three experimental areas, as well as the status of the instruments.

INTRODUCTION

The European XFEL accelerator, operated by the DESY staff, has lased after 6 months of commissioning time [1, 2] and has reached the first set of design parameter as described in [3]. This success allows for the official start of the operation phase of the European XFEL. Although the machine would benefit of more time for a thorough commissioning of all its subsystems; the accelerator must provide x-ray (XR) laser type beam to the two instruments FXE (Femtosecond X-ray experiments) and SPB/SFX (Single Particles, clusters and Biomolecules /Serial Femtosecond Crystallography) located in the SASE 1 branch (see Fig.1). The technical commissioning of these two instruments, with and without beam, is in full swing in order to be ready to receive their first users in September 2017. The tight schedule allows a start of the exploitation phase with external users with a set of limited parameters for the electron and for the XR photon beams. The two other photon beamlines SASE 2 and 3 should be ready to receive beam in early 2018 and the instruments located at their end for user operation sometimes in late 2018.

ACCELERATOR OPERATION STATUS

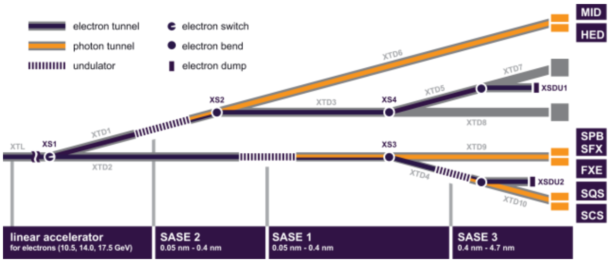

Figure 1: Photon beam system layout underlined by the orange color for the X-ray optics, diagnostics and beam transport

The layout of the entire superconducting based Linear accelerator, including the 3 undulator sections and their respective electron beam dumps can be found in Figure 3 in the following reference [1]. Some of the design parameters of this machine and the value achieved at the beginning of August 2017 are given in Table 1. The normalized slice emittance measured with a bunch charge of 500 pC was 0.6 mm/mrad. The machine is now providing and tunning around a photon energy of 9.1 keV hence adjusting the gap of the undulators according to needs based on the electron energy.

Table 1: European XFEL Design Parameters and Target Parameters Achieved at the Beginning of August 2017 [1].

Parameter		**Design**	**Achieved**
Energy	GeV	17.5	14.6
Bunch Charge	pC	20 - 1000	100-500
Macro Pulse Repetition Rate	Hz	10	10
Macro Pulse RF length	μs	600	600
Inner pulse bunch frequency		1-2700	1-30
Max. beam power at LINAC end	kW	473	1.8
Peak Current	kA	3-5	5
Compression Factor		200-2000	200
Operating Temperature	K	1.9	1.9

It must be mentioned that the injector itself which finished its commissioning in 2016 could produce and drive to the injector dump (160 MeV) 2700 bunches per train at 10 Hz. The complex pattern of the European XFEL is reproduced in Fig.2 .The warm RF gun could produce bunches with a charge varying from 20 pC to 1 nC [1].

In order to qualify the European XFEL facility to be ready to enter the operation phase, a set of parameters had to be achieved:

1. Photon Wavelength: < 0.2 nm
2. Peak brilliance: > 10^{30} photons/s/mm^2/mrad^2/0.1 % BW
3. Dimension at sample: < 1 mm^2 (FWHM)
4. Positional stability: < 50% of beam size (RMS)
5. Photon energy stability: < 0.1%
6. Shot-to-shot intensity fluctuation: < 10%

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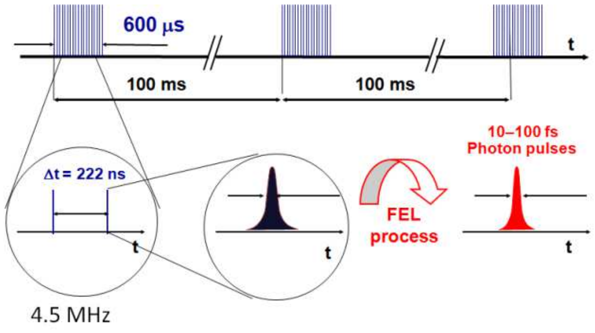

Figure 2: Electron beam pattern and FEL pulse length per bunch.

Those parameters were demonstrated by the European XFEL commissioning team (European XFEL and DESY staff) and endorsed by the Machine and Scientific Committee Chairs.

This success is commendable but more work is still to come for the machine in order to reach the nominal design parameters as displayed in Table 1. In addition the machine will enter 2 modes of functioning, an operating mode to serve users and a commissioning mode to finish its own commissioning but also provide a stable beam to commission the photon systems and the remaining 4 instruments located in the SASE 2 and 3 tunnels and experimental areas. Finally the machine is expected to be fully commissioned in 2019 and to operate 5800 hrs with 4000 hrs reserved for user runs and 1800 hours reserved for Accelerator and X-Ray development.

PHOTON BEAM SYSTEM

The responsibility of the photon beam system (PBS) starts, and is shared at the undulator sections and ends inside the experimental hutches. The layout of these sections and the SASE (Self Amplified Spontaneous Emission) FEL radiation energy expected are shown in Fig. 1,3 [3].

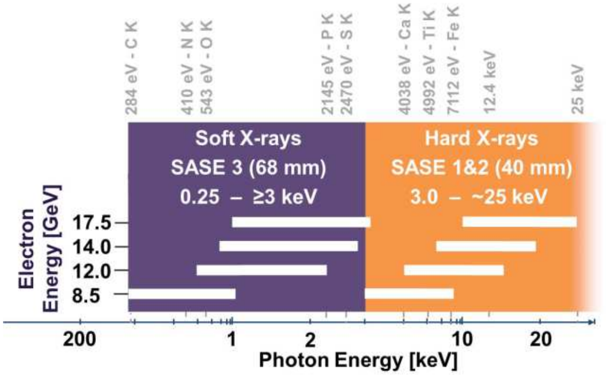

Figure 3: Photon Energy Range produced by the variable gap undulators depending on the electron beam energy

The first electron/photon and photon beam line to be commissioned is labeled SASE 1. It encompasses two series of tunnels XTD2 and XTD9 as represented in Fig. 1.

In XTD2 the electron beam and the FEL light will co-propagate and two control systems will be used to direct them to their respective end destination, either to XTD9 and the SASE 1 experimental area for the photons or in the SASE 3 section for the electrons. The DOOCS system is used to control the accelerator and the electron beam optics while Karabo [4, 5] is used for the photon beam system, the control of the instruments and to cope with the deluge of data the detectors, installed at the instruments Fig. 4, will produce. A bridge between the two control systems is still under development to, at term, authorize the control of the undulators by the users using the Karabo control system. With this bridge the machine will be able to read, in DOOCS, all the photon diagnostics installed in the tunnels but also installed in the experimental hutches, for better tuning. The control room is equipped with consoles running both systems.

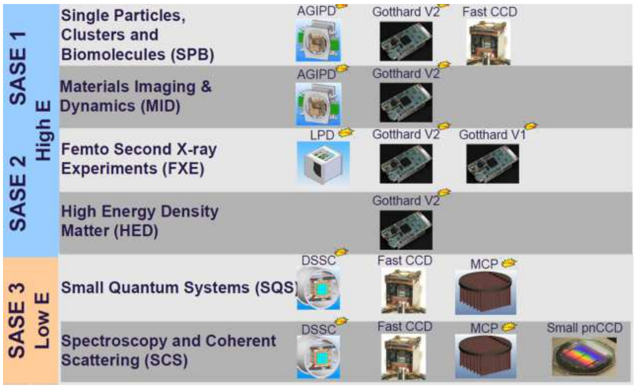

Figure 4: Various photon detectors needed at the soft and Hard X-ray beamlines. Most of them are capable of operating at the intra-bunch frequencies (4.5 MHz). A Gotthard type detector is also used by the diagnostic group as a photon arrival time monitor.

Photon source and beam transport

A thorough description of the capabilities of the undulators, the phase shifters, and the properties of the B_4C coated XR mirrors are available in [6–8]. All undulators have been installed allowing for the feeding of all the experimental stations in the three SASE areas, Fig.1. The transport mirrors, 2 offset mirrors (X,Y) and a distribution mirror, are installed on SASE 1 beam line. SASE 3 and 2 will have their mirrors installed by the end of this year.

The undulator parameters are summarized in Table.2 [7]. It has to be noted that the beam transport system does not allow the propagation of the 1.99 keV and 30.8 keV radiation in SASE 1 & 2 and the 4.6 keV radiation for SASE 3.

The commissioning of the SASE 3 & 2 photon systems will be happening during the first quarter of 2018.

In SASE 1, the undulator system and its control software is in general well operational. Amelioration of the control system is ongoing to be able to perform for example in a single click a photon energy scan. Such scans, using variable gap undulators, require that the gap of the undulators and the

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Table 2: FEL Undulator Source Parameters

Parameter	SASE1 SASE2	SASE3
Period length (mm)	40	68
Maximum B-field (T; @10 mm)	1.11	1.68
Number of poles per segment	248	146
Number of segments	35	21
Total system length (m)	205	121
Gap range (mm)	10 - 20	10 - 25
K-parameter range	1.65 - 3.9	4 - 9
Photon energy range (keV; @8.5 GeV)	1.99 - 7.2	0.243 - 1.08
Photon energy range (keV; @12 GeV)	3.97 - 14.5	0.485 - 2.16
Photon energy range (keV; @17.5 GeV)	8.44 - 30.8	1.031 - 4.6

phase shifters are moving in sync. The undulator group will test this implemented feature in a dedicated machine development run. The undulator group is also carefully monitoring the electron beam losses as radiation dosing will cause demagnetization of the permanent magnets (poles per segment as in Table 2) constituting each undulator. The wavelength of the photons (λ_{photon}) produced by the undulators is highly dependent on knowing reliably the K parameter of each undulator, it is given by:

$$\lambda_{photon} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \tag{1}$$

with

$$K = \frac{e\, B_{undulator}\, \lambda_{undulator}}{2\pi m_e c} \tag{2}$$

where $\lambda_{undulator}$ is the period of the undulator, $B_{undulator}$ is the magnetic field at a given gap, see Table 2, γ is the Lorentz factor, e the electron charge and c the speed of light. In the current absence of the K monochromator spectrometer, the machine relies on the K tables produced by the undulator group. The commissioning parameters, as described in the first section, reflects the care taken to protect the sensitive equipment.

As stated previously, the super polished mirrors have been installed in their vacuum chambers and can deflect the beam from the straight line to SPB/SFX to the FXE experimental station. The mirror can also be inserted half way such that both instruments can commission some of their uncritical elements with FEL beam. During installation it was found that a mechanical collision with the water cooling system of the mirrors existed. The cooling system has been removed allowing for the free translation of the mirror in or out of the beam. In consequence the mirrors cannot take, for the moment, the full load of the nominal parameters that the machine shall provide. To protect those long lead delivery items, the machine will run longer with reduced number of bunches and charge. An upper limit in term of heat load and deformation has already been evaluated by the optics group.

Photon Beam Diagnostics

The tuning and characterization of the SASE FEL beam (quality of the photon beam (wavefront), pulse energy, position, wavelength, spectrum and bandwith, polarization) depends on available XR diagnostics. A full set of invasive (imagers (or screens), K spectrometer ...) and online diagnostics (X-Ray gas monitor (XGM), high resolution x-ray spectrometer (HIREX)...) have been installed in the appropriate tunnels [6, 7]. The search for SASE and the tuning of the FEL energy was done first using the various imagers installed along the photon beamline. The energy of the photon beam was then measured using the calibrated XGM, Fig.5. A FEL energy of 1 mJ has been achieved at a wavelength of 1.5 Å. The energy of the photon beam provided by the XGM relies on the operation at a pressure of 10^{-5} mbar partial pressure of the following gases Xenon, Krypton, Neon, Argon or Nitrogen. Xenon is for the commissioning time the selected gas as it provides the largest signals thanks to its largest cross-sections in the hard X-ray domain. With both elements available (Imagers and XGM) one can first easily integrate the intensity of the light on a screen to provide a quick quantitative value for the XR beam energy. Those values can be cross calibrated using the XGM to produce an absolute photon beam energy using solely a screen. The XR photon diagnostics group is now concentrating its effort in commissioning the K spectrometer. The K spectrometer is now necessary in order to cross check the validity, after a few months of operation, of the K of the SASE 1 undulator beam line.

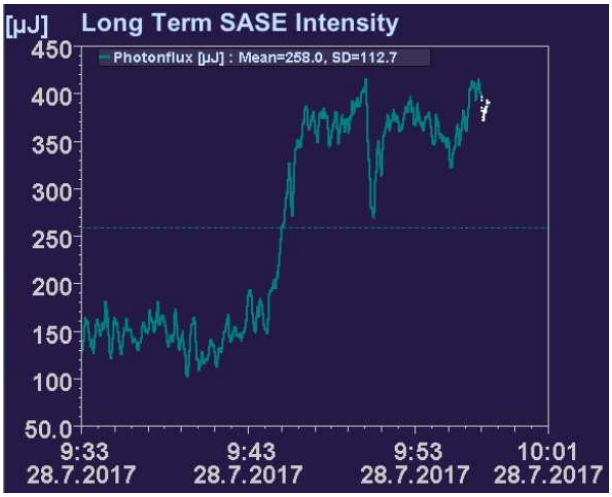

Figure 5: SASE intensity measured with the XGM during a 30 bunch operation per train (0.5 nc, 10 Hz, 12.7 GeV) at 8.27 keV (1.5 Å).

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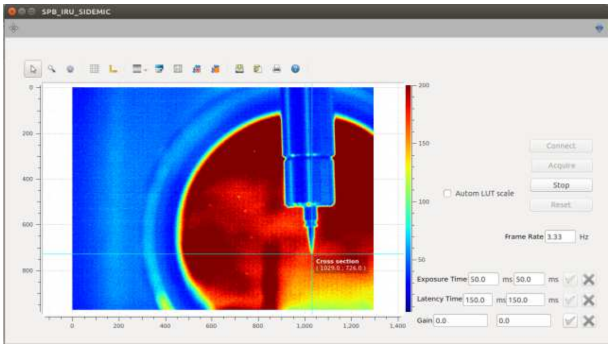
EXPERIMENTAL AREA

Past the photon beam shutter the XR will enter the experimental zones where the 6^{th} instruments are located, Fig.1. The science addressed by the instruments are summarized in Table 3.

The SASE 1 instruments are under commissioning while SASE 3 and SASE 2 instruments will be commissioned during the second and third quarter of 2018, respectively. The SASE 1 instruments (FXE and SPB/SFX) are scheduled to welcome their first users on 14^{th} of September 2017. Both instruments will carry out pump probe experiments and depends on the availability of the lasers [6]. Due to delays in the laser hutches and laser lab infrastructure the lasers will be available toward the end of 2017.

Readiness of SPB/SFX

The SPB/SFX instrument [7] is the most complex of the two instruments. SPB/SFX experiments are dependant of the in-vacuum detector AGIPD (Adaptive Gain Integrating Pixel Detector). The full performances of SPB/SFX will be achieved when its 4 Kirkpatrick-Baez (KB) mirrors and an additional 2 KB mirror systems for focusing the XFEL beam to micron-scale and 100 nm-scale focii, respectively, will be installed. For its first experiments the instruments has commissioned its focusing Beryllium compound refractive lenses (CRL). The first AGIPD detector is currently being installed on the beamline. The delivery sample system [6] is installed, see Fig.6. The whole experimental beamline including the optic hutch is now being commissioned with FEL type beam, Fig.7. The commissioning is done in shifts of 12 hours 24/7 over a few days. The beam alternates between the SPB/SFX instrument and the FXE instrument.



Frame Rate 3.33 Hz

Exposure Time 50.0 ms 50.0 ms ✓ ✕

Latency Time 150.0 ms 150.0 ms ✓ ✕

Gain 0.0 0.0 ✓ ✕

Figure 6: Liquid Jet delivery sample system in the SPB experimental chamber. Shot taken using Karabo.

Table 3: Science Addressed by the Six Instruments at European XFEL

Scientific Instrument	nm-scale structures	Ultra-fast Processes	Extreme States
SPB/SFX: Single Particles, clusters and Biomolecules / Serial Femtosecond crystallography Structure determination of single particles: atomic clusters, bio-molecules, virus particles, cells	X	X	
FXE: Femtosecond X-ray Experiments Time-resolved investigations of the dynamics of solids, liquids, gases		X	
MID: Materials Imaging & Dynamics Structure determination of nano-devices and dynamics at the nanoscale.	X	X	
HED: High Energy Density Matter Investigation of matter under extreme conditions using hard X-ray FEL radiation, e.g. probing dense plasmas		X	X
SQS: Small Quantum Systems Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena	X	X	X
SCS: Soft x-ray Coherent Scattering/Spectroscopy Electronic and real structure, dynamics of nano-systems and of non-reproducible biological objects	X	X	

Readiness of FXE

The FXE beamline [7] depended for most of its components on an in-Kind Contribution (IKC) from Denmark through DTU. This IKC was very successful and all components were delivered in time. The main focusing elements for FXE are also a set of CRLs.

FXE first test with the FEL beam was done using calibrated LaB_6 powder. Fig.8 presents the diffraction rings from the LaB_6 powder recorded via Karabo on 2-tile prototype of the LPD, using 2 bunches per train with an unfocused XR beam. The LPD was set to measure 32 images and Fig.8 proves the single shot detection capability of LPD when running at 4.5 MHz and the performances of Karabo.

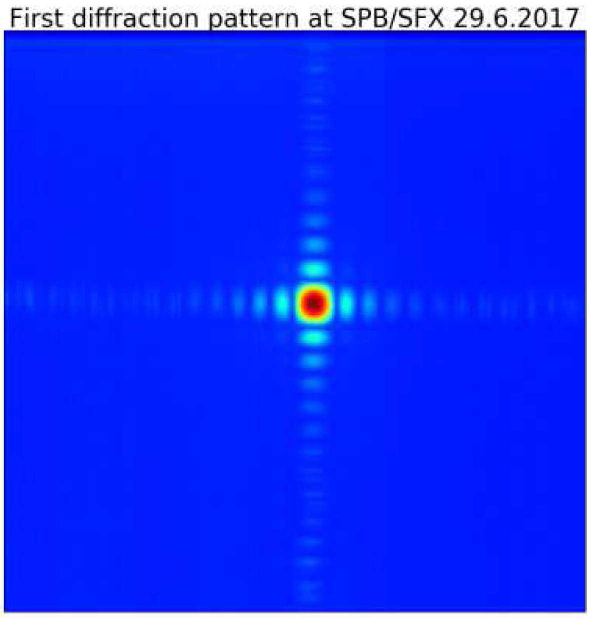


Figure 7: First Diffraction pattern recorded by SPB/SFX team, 1 bunch per train , 8.3 keV.

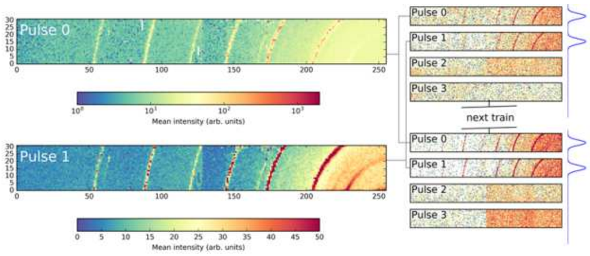


Figure 8: Diffraction ring pattern recorded via Karabo on 2 tiles of the LPD detector. LaB_6 calibration powder, 2 bunches per train , 8.3 keV, few hundred μJ FEL energy

Since then, three detectors are being commissioned, LPD Fig.9, the Van Hamos and Johan spectrometers. FXE strength lies in the so call pump-probe type experiments. As noted earlier, they depend strongly on the availability of a pump laser lasing in the IR, VUV regions, depending on the needs. The FXE team will use a Tangerine® laser [9] from Amplitude technology to ensure the first experiments by its users.

CONCLUSION

The European XFEL facility is finishing its first phase of commissioning which will allow for a first user run on the SASE 1 beam line from September 2017 on. In 2018 parallel operation of the 3 beamlines are foreseen. SASE 1 will see its second user run with the full availability of the pump-probe laser, while SASE 2 and 3 will commission their photon systems and their instruments. It is expected that a user run in the second semester of 2018 will be possible for SASE 3 and for MID (SASE 2). The sharing of the 6000 hours of machine run, between user runs, machine and XR system development in 2019, will have to be reviewed in due time.

Figure 9: Large Pixel Array detector in the FXE experimental hutch.

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