ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT061

EUROPEAN XFEL UNDULATORS - STATUS AND PLANS

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Abstract

European XFEL has three undulator lines based on permanent magnet technology: two for hard and one for soft X-rays. The planar undulators can be tuned to cover the acceptance in terms of photon beam energy of the respective photon beamlines: 3.6-25 keV (SASE1/2) and 0.25-3 keV (SASE3) by changing the electron energy range between 8.5 GeV and 17.5 GeV and/or the undulator gap. In order to obtain different polarization modes, as required by the soft X-ray beamlines, a helical afterburner consisting of four APPLE X undulators designed by PSI has been installed at the downstream end of the present SASE3 undulator system. The European XFEL plans to develop the technology of superconducting undulators, which is of strategic importance for the facility upgrade. In order to extend the energy range above 30 keV a superconducting undulator afterburner is foreseen to be installed at the end of SASE2. This contribution presents the current status and the planned upgrades of the undulator lines at European XFEL.

INTRODUCTION

European XFEL has three undulator lines: two for hard and one for soft X-rays. The two hard X-ray lines SASE1 and SASE2 consist of 35 undulators cells each, while the soft X-ray line SASE3 of 21. The undulator system as built and commissioning of SASE1 are described in Ref. [1]. By changing the electron energy between 8.5 GeV and 17.5 GeV and/or the undulator gap, the undulator lines can be tuned to cover the acceptance in terms of photon beam energy of the respective photon beamlines: 3.6-25 keV (SASE1/2) and 0.25-3 keV (SASE3). The undulators have been specified and characterized to work in the range of the undulator parameter K values indicated in Table 1.

All undulators installed in the tunnel are planar and generate horizontally polarized radiation. In order to obtain different polarization modes, as required by the soft X-ray beamlines, a helical afterburner consisting of four APPLE X undulators has been installed downstream with resepct to the present SASE3 undulator system [2].

In all undulator lines it is in principle possible to extend the photon energy range of the fundamental to harder X-rays by further decreasing the undulator parameter K. In SASE1/2 it is possible to reach about 70 keV by working at larger undulator magnetic gaps up to 40 mm (K~ 0.33) and at 17.5 GeV. At this working point, the efficiency of the FEL is low because the coupling strength between electron beam and the emitted photons is proportional to the undulator parameter K. It is therefore foreseen to exploit these higher photon energies by increasing the FEL process efficiency and energy per pulse output with a superconducting undulator (SCU) afterburner [3]. This is planned to be installed after the present SASE2 line, which is already built with an X-ray optics transporting up to about 65 keV photon beams. The photons per pulse produced by the SCU afterburner ($\gtrsim 10^{10}$ for photon energies above 30 keV) are expected to be more than two orders of magnitude higher than the ones available at the diffraction limited storage rings as ESRF-EBS and APS-U, in pulses more than 5000 times shorter.

PLANAR PERMANENT MAGNET UNDULATORS

The main parameters of the planar permanent magnet undulators (PMUs) in the three lines are shown in Table 1. All installed planar PMUs are made of neodymium-iron-boron (NdFeB) and cobalt-iron poles. They all have the same support structure and mechanical drive. The beam vacuum chamber is made of extruded aluminium-magnesium and has an elliptical beam stay clear of 15 mm (horizontal) and 8.6 mm (vertical). The outer vertical height of the beam vacuum chamber is 9.6 mm. The undulator lines must be segmented. Each undulator is 5 m long. This is a compromise to maximise the number of periods along the line, by still having economic manufacturable lengths of the support structure to keep the magnetic forces and reasonable measurement benches.

Table 1: Main Parameters of the Planar Permanent Magnet Undulators [1]

	SASE1/2	SASE3
Period length (mm)	40	68
Operational K range	1.65–3.9	4–9
Magnetic length (mm)	4980	4998
Max. phase jitter (°)	≤ 8	≤ 8
Max. $I_{1x,y}$ (T mm)	±0.15	±0.15
RMS $I_{2x,y}$ (T mm^2)	< 100	< 210(y)100(x)

Each undulator is followed by a so-called intersection. This is 1.1 m long, equipped with air coil correctors, a quadrupole, an absorber to screen the following undulators from synchrotron radiation, a phase shifter, a cavity beam position monitor (BPM) with sub-micrometer resolution [4], and a beam loss monitor [5]. Air coil correctors at the entrance and exit of each undulator are used to compensate the vertical and horizontal first and second field integrals, so that the undulators are transparent to the electron beam. The maximum values of the first field integrals reported in Table 1 are to be further reduced with the air coil correctors to $I_{1x,y} < 0.02 - 0.03$ T mm, where the lower value refers to an electron beam energy of 10 GeV and the higher

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ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT061

to 17 GeV. Quadrupoles are needed to periodically focus the electron beam, keeping its dimensions small enough for the FEL process to occur. The quadrupoles can be steered (quadrupole movers) vertically and horizontally by ±1.5 mm with an accuracy of $\pm1\ \mu$m [6]. Together with the BPMs, the quadrupoles are used to perform beam-based alignment (BBA), which is needed to define a straight trajectory within the electron beam dimensions of $\approx$ 30 µm along the undulator line of $\approx$ 200 m [7]. A permanent magnet based phase shifter is implemented to compensate the phase advance of the emitted photons with respect to the electron beam [8]. For each K value, the end fields of the upstream and downstream undulators are used to determine the corresponding phase shifter gap [9]. The intersection after the last undulator downstream is not equipped with a phase shifter. A beam loss monitor using a photomultiplier tube as sensitive media is used together with integrating radiation sensors of the RadFET type (these last being not included in the intersection and closer to the magnets) to monitor and possibly reduce the radio-activation of the accelerator components, in particular a degradation of the magnetic performance of the undulators due to radiation damage of the magnets.

Two RadFET detectors are installed at the entrance of each magnetic array in each undulator at about 12-20 mm from the electron beam axis, depending on the magnetic gap. Presently, all RadFETs mounted on the top magnet array are unshielded, while the lower ones are shielded with 4 mm thick lead. This allows to discriminate between the low (< 100-200 keV) and high energy photons. The total accumulated radiation dose in all the three undulator lines since start of operation in 2017 is shown in Fig. 1. From the diagnostic undulators (DU) an initial limit of about 55 Gy for a 5×10^{-4} relative change in magnetic field has been estimated and taken as a limit looking at the shielded RadFETs (high photon energy dose) [10]. Figure 1 shows that for most of the PMUs the 55 Gy limit is not reached. Please note that in SASE1 during the first year of operation both RadFETs were unshielded. Measuring one of the SASE1 PMUs, exposed to 230 Gy during the first year of operation (all photon energies), it has been observed a relative change of 5×10^{-4} in magnetic field only near the upstream side [1]. Measurements of one of the PMUs with highest accumulated dose for low and high photon energies are planned to possibly identify higher threshold limits. The undulators have been mechanically tuned using the principle of mechanical pole adjustment [11] in presence of an ambient field, as the one measured in the corresponding tunnel. Average ambient vertical fields of 50 µT and horizontal of 15 µT for SASE1 and SASE2 and 20 µT for SASE3 have been observed. Nevertheless, two current windings have been installed along the undulator chambers and connected to power supplies which allow to superimpose a vertical magnetic field of up to about 500 µT along the complete cell length.

The magnetic axis of the undulators is determined with magnetic measurements with a precision of ±10 µm and its position is referenced to eight fiducials placed on the undulator support structure. The alignment of the undulators in the tunnel has been performed with a laser tracker. The undulators magnetic planes are aligned within ±250 µm with respect to each other [1]. After BBA, the magnetic axis of the undulators of the hard X-ray lines is determined by moving each undulator vertically and obtaining the minimum K value through spectral measurements [12]. Then all undulators magnetic axis are aligned along the BBA straight line orbit with an accuracy < 10 µm. This method cannot correct for yaw, pitch and roll misalignments. Since the vacuum chamber cannot be easily realigned, the drawback of this procedure is that the minimum magnetic gap of the undulators increases of few 100 µm from the nominal value of 10 mm. The determination of the magnetic axis with spectral measurements is not made on the soft X-ray undulator line, since lasing at smaller photon energies is in this respect less demanding. Therefore, the minimum magnetic gap of 10 mm in the soft X-ray undulator line is unchanged, allowing to reach the smallest photon energies.

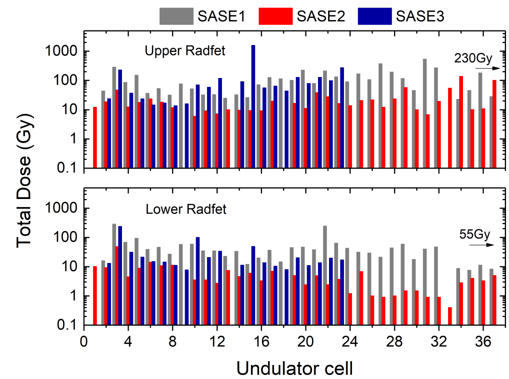

Figure 1: Total dose absorbed during five years of operations.

After lasing of all three undulator lines was demonstrated, three magnetic chicanes have been implemented: two in SASE2, and one in SASE3. In order to keep the FODO lattice, the magnetic chicanes occupy the same length as an undulator, and are followed by an intersection with all the elements as the others except for the phase shifter. The removed undulators are located upstream with respect to the corresponding undulator line. In SASE2, at the same position of the magnetic chicanes, diamond crystals are installed with the possibility to insert them to monochromatize the photon beam and allow Hard X-ray Self Seeding [13].

APPLE X UNDULATORS

The APPLE X undulators, designed by PSI, consist of four arrays built with NdFeB magnets. They are installed downstream with respect to the SASE3 undulator line. Each array can be independently moved longitudinally and radially. This allows a full flexibility in the choice of the polarization of the emitted photons. The main parameters of the APPLE X undulators are shown in Table 2. A more detailed desctription is given in Ref. [2]. PSI has provided EuXFEL also with a SAFALI system to magnetically characterize the undulators and two robots for shimming. The magnetic mea-

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT061

surements have been carried out at EuXFEL [14]. The vacuum chamber is made of extruded aluminium-magnesium and has a circular beam stay clear of 8 mm. The outer vertical diameter of the beam vacuum chamber is 12 mm [15].

First lasing has been obsreved at 700 eV and 900 eV in different polarization modes with 14 GeV electron beam energy [2]. The APPLE X undulators can reach lower photon energies with respect to the planar ones. For example, at 14 GeV it is possible to reach 460 eV, while with the planar PMUs the minimum photon energy is 660 eV. This adds tunability to the undulator line, since it is possible, using frequency mixing [16], to now exploit these, up to now, forbidden photon energies. The radiation produced has lower energy per pulse, but can be offered with all polarizations. Presently, the commissioning of the APPLE X afterburner is paused because of the failure of a large number of linear and rotary encoders [2].

Table 2: Main Parameters of the APPLE X Undulators [2,14]

Period length (mm)	90
Operational mag. gap range (mm)	12.5–31.6
Operational long. shift range (mm)	±45
Magnetic length (mm)	1957.5
K_{eff} max. lin. h/v & circ.	9.4
K_{eff} max. lin. ±45°	6.62

SUPERCONDUCTNG UNDULATORS

The development and implementation of SCUs is part of EuXFEL facility development program. More details are described in Ref. [3]. The implementation of the SCUs has several advantages on a long term strategy. It opens the possibility to lase at very high photon energies towards 100 keV. In addition, in case of a possible upgrade to a CW mode, which implies a lower electron beam energy (7-8 GeV), SCUs can cover approximately the same photon energy range as avaliable with 17 GeV and the presently installed PMUs.

The SCU afterburner is planned to consist of six modules to be installed downstream with respect to the last PMU of SASE2. Each module is a cryostat about 5 m long containing two SCU coils 2 m long, superconducting (SC) correctors and a SC phase shifter. The length of the modules is chosen to be the same as the one of the presently installed PMUs. The intersections can use the same elements (i.e. phase shifter, quadrupole, etc...) as described in the section on planar PMUs. The length of the intesections will slightly increase, since they will host RF bellows. The RF bellows permits vertical and horizontal alignment of the SCUs with beam and length compensation for the thermal shrinkage of the SCU modules after cooldown. An RF valve will be placed in the intersection separating the last PMU and the first SCU. All modules will be cooled with cryocoolers. To reach this goal the following steps are foreseen: 1) two test stands are being developed: SUNDAE1 (Superconducting UNDulator Experiment) and SUNDAE2. SUNDAE1 is a vertical test stand in which SCU coils up to about 2 m length can be trained and characterized with a Hall probe mounted on a sledge moved along the magnetic axis [17]. The SCU coils are immersed in a liquid or superfluid helium bath with a fixed height of approximately 2.4 m. Measurements at 2 K have been foreseen to be open to possible future applications considering also complete SCU lines. Those would need a cryoplant and might use a similar cooling to 2 K as realized for the SRF cavities. SUNDAE2 is a horizontal test stand to characterize the magnetic field of the coils in their final cryostat [18]. Planned are a Hall probe and a pulsed wire system for the local field characterization [19] and the moving wire to measure the first and second field integrals. Both test stands are developed in collaboration with DESY and are located in the DESY campus. 2) a Superconducting undulator PRE-SerieS mOdule (S-PRESSO), which has been specified. The contract has been assigned to the company Noell GmbH. S-PRESSO will be installed and tested in SASE2. 3) An R&D activity on advanced SCU coils has started to build up know-how inside the facility. To this end a winding machine and an impregnation chamber have been specified and procured. Together with the experimental activity magnetic simulations are carried out.

The main parameters of the 2 m long SCU coils of the SCU afterburner are summarized in Table 3.

Table 3: Main Parameters of the 2 m SCU Coils [3]

Period length (mm)	18
Vacuum gap (mm)	5
K max.	3.06
Beam heat load (W)	10

The SCU afterburner can be operated by amplifying the first harmonic of the PMUs up to $\approx 40 - 50$ keV. To reach higher photon energies it is planned to use the bunching at the second harmonic generated on the electron beam in the PMUs and amplify it with the fundamental of the SCUs. From first estimations the number of photons per pulse is $\gtrsim 10^{10}$ up to ≈ 50 keV and $> 10^9$ at ≈ 60 keV. Further studies including wakefields, tapering and optimized electron beam parameters are ongoing [20].

CONCLUSION

Three undulator lines based on planar PMUs are in operation at EuXFEL: SASE1/2 for hard X-rays and SASE3 for soft X-rays. An APPLE X afterburner has been installed downstream with respect to the planar PMUs of SASE3 during the 2021/22 winter shutdown. An SCU afterburner is planned to increase the photon energy range of SASE2 towards harder X-rays. S-PRESSO, the first module, has been specified and the contract has been assigned to Bilfinger Noell GmbH.

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ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT061

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