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TECHNICAL REPORT

Layout of the X-Ray Systems at the European XFEL

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Th. Tschentscher

for the European XFEL project team

European X-Ray Free-Electron Laser Facility GmbH

Albert-Einstein-Ring 19

22761 Hamburg

Germany

Contents

Preface

This technical note provides an overview of the design considerations and the general layout of the X-ray instrumentation of the European XFEL X-ray sources, beam transport systems, and instruments. Updated free-electron laser (FEL) radiation parameters are provided. This document is an update of the X-ray systems layout and FEL radiation parameters described in the corresponding technical design report (TDR) in 2006 [1] and should be used in the future for reference purposes. This technical note describes the European XFEL in its startup configuration with three self-amplified spontaneous emission (SASE) undulators, three photon beam transport systems, and six scientific instruments.

The revised layout presented here is based on the recent results obtained at the Photo Injector Test Facility Zeuthen (PITZ) and at the SLAC Linac Coherent Light Source (LCLS) at Stanford University, demonstrating that a much smaller electron beam emittance can be achieved than previously assumed. Variation of the electron bunch charge from tens of pC to 1 nC enables further flexibility in providing very small emittances and ultrashort pulse durations. The new layout further includes updated requirements for the scientific instruments as a result of the user workshops held in 2008–2010.

This document does not include detailed information for the X-ray beam transport systems and the scientific instruments. These details will be provided in the respective conceptual design reports (CDRs).

This document will be updated regularly to reflect the evolvement of X-ray beam transport and instrument designs.

Introduction

Experimental results at the PITZ facility and at LCLS have demonstrated that the emittance of the electron bunches can be significantly improved if bunches with a smaller charge are generated in the injector. Furthermore, the transport and acceleration of electron bunches from the injector to the undulators does not dilute the emittance as much as previously expected. To obtain shorter electron bunches at the undulator, and respectively shorter X-ray pulses, a higher compression can be applied to electron bunches with a reduced charge compared to the 2006 design value of 1 nC.

Based on these findings, new baseline parameters for the electron beam have been defined and are listed in Table 1. These parameters have been used for the simulation of FEL radiation parameters and saturation lengths of the SASE undulators. Herein we identify the electron beam parameters by bunch charge and electron energy.

Table 1: *Electron beam properties as a result of s2e simulations of the electron beam and photon beam properties (W. Decking, M. Dohlus, T. Limberg, I. Zagorodnov, 2010).*

Parameter	**Unit**	**Value**					**TDR-06**
Bunch charge	pC	20	100	250	500	1000	1000
Peak current	kA	4.5	5.0	5.0	5.0	5.0	5.0
Norm. slice emittance (undulator)	10^{-6} m rad	0.32	0.39	0.6	0.7	0.97	1.4
Bunch length (undulator, FWHM)	fs	2.8	15	39	72	180	188
Slice energy spread (laser heater, undulator, rms)	MeV	4.1	2.9	2.5	2.2	2.0	1.0

In contrast to the TDR in 2006, we are applying a new definition for the saturation point of the FEL amplification process [2, 3]. In this new definition, saturation is reached at the magnetic length at which the FEL radiation attains maximum brilliance. Parameters for FEL radiation are simulated for a magnetic length that corresponds to the production of a photon beam of maximal transverse coherence. Beyond the saturation point, the FEL operates in an oversaturated mode where more energy can be extracted from the electron beam at the expense of FEL parameters, including bandwidth, coherence time, and the degree of transverse coherence.

In 2008–2010, the European XFEL organized a series of workshops dedicated to the prioritized scientific instruments, their science cases, and instrumentation. As a result of these workshops, the requirements for the instruments have been updated, as shown in Table 2. Furthermore, the continued, strong request by the user community for a variable polarization SASE3 source has been recognized. This request contrasts with an initial decision from 2008, taken due to a limitation of resources, to delay the implementation of a variable polarization SASE3 source. A working group therefore investigated optimized schemes for the generation of variable polarization FEL radiation [4–9]. It was concluded that an optimized solution consists of initially adding short helical or crossed-planar undulators operating at the second harmonic and on axis of the full length planar SASE3 undulator [8]. The realization of these helical undulators as permanent magnet or electro-magnet devices requires further investigation. In the long term, the construction of a much longer helical device operating at the fundamental harmonic will provide the best conditions for experiments [9].

Table 2: *Updated photon beam delivery requirements by the scientific instruments.*

Scientific instrument	**Photon energy [kev]**	**Bandwidth $\Delta\omega/\omega$**	**Tune [%]**	**Beam size [µm]**	**Special optics**
SPB	3–16	natural[1]	N/A	0.1–10; <1000	Extreme focussing
MID	5–20; 25–36	natural; 10^{-4}–10^{-5}	N/A	1–100; <1000	High-resolution mononochromator; beam split and delay unit
FXE	3 – ~20	natural; 10^{-4}–10^{-5}	±3	1–100; <1000	Beam split and delay unit
HED	3–16; 25–36	natural; 10^{-4}–10^{-5}	±3	<1–100; <1000	Beam split and delay unit
SQS	<0.28–3.0	natural; 10^{-4}	±3	<1–100; <1000	Beam split and delay unit
SCS	<0.28–3.0	10^{-3}–10^{-5}	±3	<1–100; <1000	High-resolution monochromator; beam split and delay unit

[1] The “natural” bandwidth corresponds to the line width of the FEL. This value is typically 10^{-3} in the hard X-ray range and 5×10^{-3} in the soft X-ray range.

Revised X-ray systems layout

This section describes the X-ray system layout designed to best fulfil the updated requirements of the instruments and reflecting the new set of electron beam parameters.

Undulator systems

The four hard X-ray instruments require the option to select photon energies in a broad range with an emphasis on photon energies from 6 to 12 keV. This requirement presents a change with respect to the estimate of early 2008, when the prioritized instruments and their placing at FELs were proposed. This new requirement leads to the need to adapt the photon energy ranges provided by the hard X-ray FEL undulators SASE1 and SASE2.

ⓘ *X-ray systems layout:* SASE1 and SASE2 will use identical magnetic structures, thus providing the same photon energy range and gap tunability.

In addition, the requirements for even lower (>3 keV) and higher photon energies (~20-25 keV) have been accepted. The lower emittance enables the provision of saturation of the FEL radiation for a given magnetic length of an undulator at significantly higher photon energies than the previously anticipated 12 keV. The high electron energy of the European XFEL offers the opportunity to provide FEL radiation in the the fundamental harmonic at energies possibly reaching beyond 25 keV. It has been confirmed that the photon energy accessible at the SASE3 instruments should cover the range from the carbon K-edge at 284 eV to an intermediate photon energy of 3 keV. To optimize the undulator parameters with respect to delivered photon energies, it was decided to provide the full photon energy range by a combination of gap and electron energy tunability. The optimization has been performed for 14 GeV electron energy. This electron energy enables a very good performance for hard X-ray FEL radiation (at SASE1 and SASE2) and, simultaneously, the smallest accessible photon energy in the regime of the water window, below 540 eV (at SASE3).

As a result, the undulator period for SASE1 and SASE2 should be 40 mm. The period for SASE3 of 68 mm remains unchanged because longer periods would lead to higher forces and would require a major redesign of the undulator's mechanical structure. The minimum magnetic gap was reviewed and confirmed to be 10 mm in order to avoid both additional energy spread due to wake fields and unsafe operation for the high average power (up to 300 kW) electron beam. All undulators will provide gap tunability.

X-ray systems layout: The magnetic period of SASE1 and SASE2 has been set to 40 mm. The SASE3 period remains at 68 mm. The smallest magnetic gap will be 10 mm.

Table 3 provides an overview of photon energies as a function of gap settings for the two undulator periods and three electron energies.

Table 3: *Photon energy in keV as a function of magnetic gap and electron energy. Numbers in grey indicate gap settings that are unlikely to provide saturation.*

	Electron energy					
	SASE1 and SASE2 (λ_u=40 mm)			**SASE3 (λ_u=68 mm)**		
Magnetic gap	**10.5 GeV**	**14 GeV**	**17.5 GeV**	**10.5 GeV**	**14 GeV**	**17.5 GeV**
10 mm	2.3	4.1	6.4	0.26	0.47	0.73
12 mm	3.4	6.9	9.3	0.34	0.54	0.84
15 mm	5.5	9.8	15.3	0.45	0.80	1.25
20 mm	10.5	18.7	29.2	0.95	1.68	2.63
24 mm	14.9	26.5	41.4	1.5	2.6	4.1
28 mm	18.6	33.1	51.7	2.2	3.9	6.1

Variation of the electron energy to 17.5 GeV allows for the optimization of radiation properties at photon energies of >20 keV, while for 10.5 GeV the smallest photon energy at SASE3 is below the carbon K-edge. Presently, three operating points—at 10.5, 14, and 17.5 GeV electron energy—are defined. The respective photon energy ranges overlap to a large extent, thus facilitating the user operation of the European XFEL facility, as shown in Figure 1.

X-ray systems layout: Three electron energy working points at 10.5, 14, and 17.5 GeV have been defined.

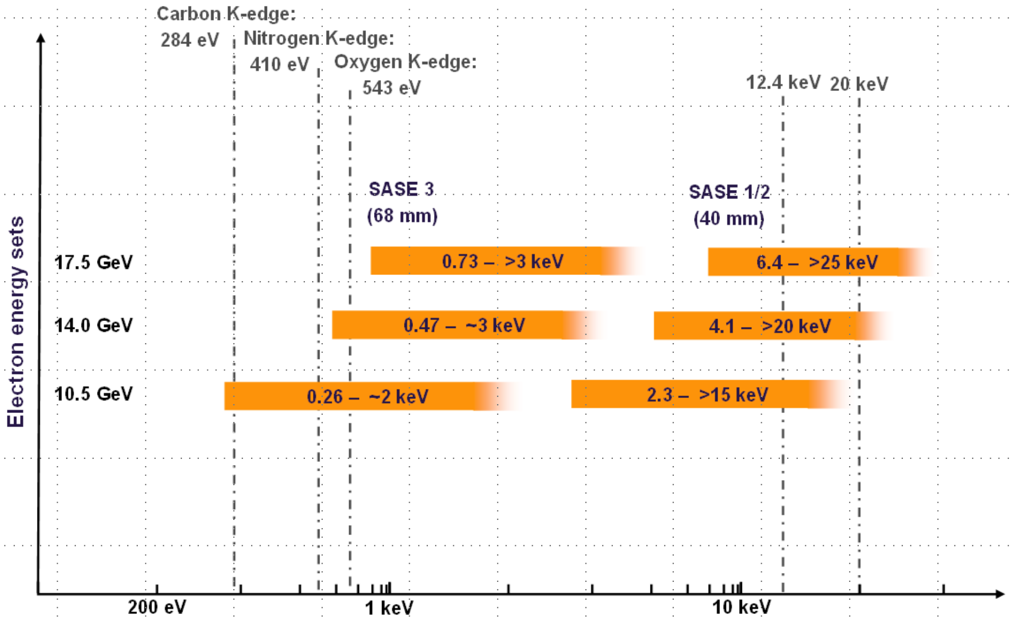

Figure 1: *Photon energy ranges of SASE1, SASE2, and SASE3 undulators for the electron energies 10.5, 14, and 17.5 GeV. While the low energy cut-offs are fixed (compare with Table 3), the highest accessible energies are determined by the electron beam parameters and the magnetic length of the undulators.*

Figures 2 and 3 show simulated values for the saturation lengths as a function of bunch charge for selected pairs of photon–electron energy. Operation of the FEL in oversaturated mode with undulator tapering offers the possibility of providing higher pulse energies, but requires the availability of additional magnetic length. This regime is not discussed in this paper.

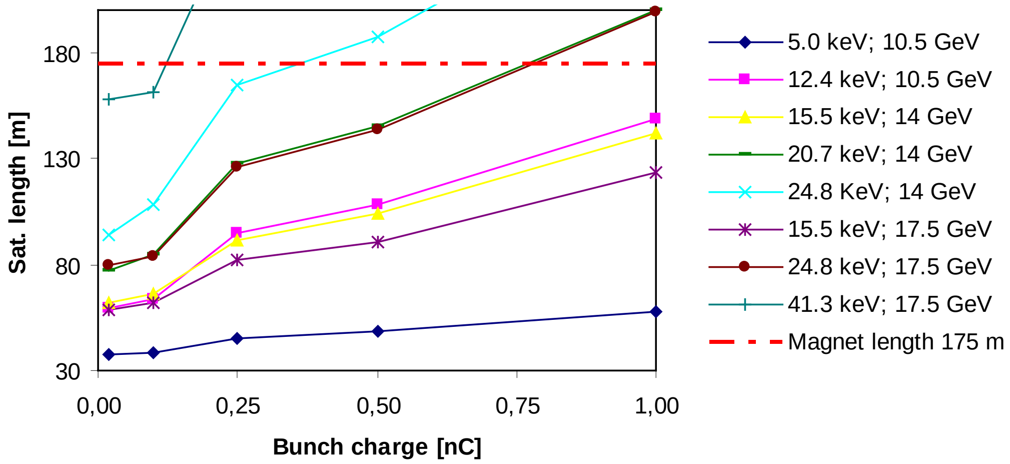

Figure 2: *Saturation length for hard X-rays (SASE1 and SASE2) as a function of bunch charge. Several curves indicate values for selected pairs of photon–electron energy.*

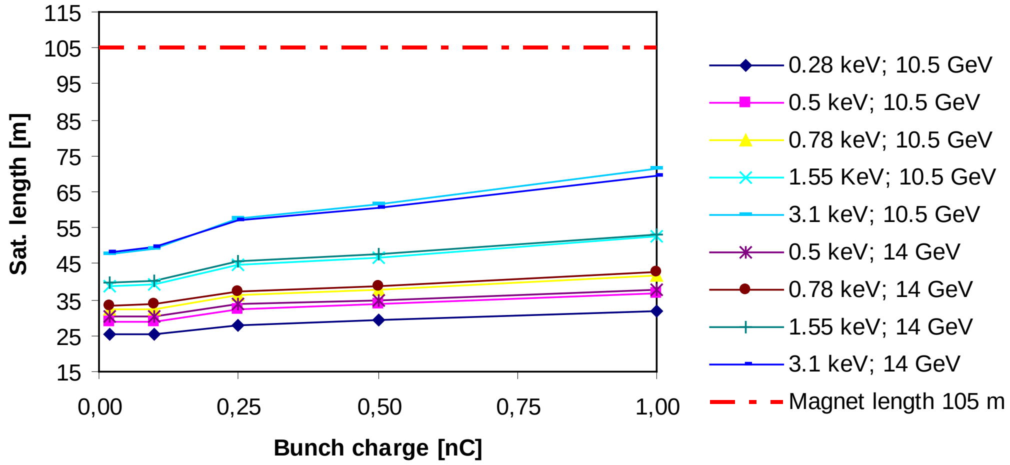

Figure 3: *Saturation length for soft X-rays (SASE3) as a function of bunch charge. Energy spread corresponds to the "fresh-bunch" mode of operation. Several curves indicate values for selected pairs of photon–electron energy.*

SASE1 and SASE2 should both have a magnetic length of 175 m. This length allows saturation up to photon energies of 25 or 30 keV for electron energies of 14 or 17.5 GeV, respectively.

Saturation length values for SASE3, as shown in Figure 3, have been obtained for “fresh-bunch”[2] operation, meaning an energy spread of the electron beam corresponding to undisturbed source parameters. In contrast, electron bunches that have been used for lasing in the preceding SASE1 undulator may accumulate additional energy spread exceeding 10 MeV. This “spent-bunch” operation mode allows for the utilization of the same electron bunch in both undulators, SASE1 and SASE3, and this capability of the facility will be maintained. For SASE3, a magnetic length of 105 m allows saturation in the “spent-bunch” mode (σ_e=15 MeV) up to ~3 keV for 14 GeV operation, as shown in Figure 4.

X-ray systems layout: SASE1 and SASE2 have a magnetic length of 175 m, SASE3 of 105 m.

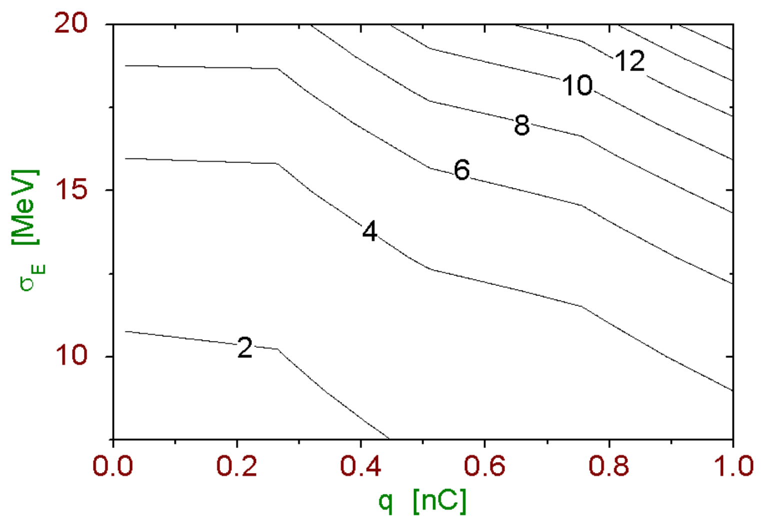

Figure 4: *Dependence of the shortest wavelength [in Å] for which SASE3 saturates at a magnetic length of 100 m as a function of energy spread and bunch charge.*

[2] “Fresh-bunch” corresponds to electron bunches not having acquired additional energy spread or emittance in the preceding SASE1 undulator. This could be achieved by providing selected bunches a betatron oscillation in the SASE1 area [10]. Likewise, the SASE process is suppressed and the electron bunch keeps its very small energy spread. The betatron oscillation is stopped before entering into SASE3. Using this scheme, it is possible to decouple operation of two of more FEL undulators within one electron beamline at the expense of the average brilliance or the number of FEL pulses provided.

X-ray optics and beam transport

For the X-ray beam transport systems, several constraints have to be considered in defining an optimized design. In order to provide highest performance while keeping the optical elements and the beam transport layout achievable, main photon energy ranges have been defined for each of the beam transport systems, as shown in Table 4. Extended photon energy ranges will be accessible at all beam transport systems, but with reduced performance.

ⓘ *X-ray systems layout:* Each beam transport system will have main and extended ranges of operation.

Table 4: *Photon energy ranges for the beam transport systems and the location of the instruments. Conditions are given for central (C) and side (S) lines of transport systems.*

Source	**Line**	**Instr.**	**Main [keV]**	**Extended [keV]**	**Compromises in extended photon energy ranges**
SASE 1	C	SPB	5 – 20	3 – 5	Cannot accept 4σ
	S	FXE	5 – 20	3 – 5	Cannot accept 4σ
SASE 2	C	MID	5 – 20	3 – 5	Cannot accept 4σ
				20 – 36	Metal-coated mirrors; risk of damage
				>36	By crystal monochromators only
	S	HED	5 – 20	3 – 5	Cannot accept 4σ
				20 – 36	Metal-coated mirrors; risk of damage
				>36	By crystal monochromators only
SASE 3	C	SQS	0.45 – 2.0	0.26 – 0.45	Cannot accept 4σ; risk of damage
				2.0 – 3.0	Special focussing optics
	S	SCS	0.45 – 2.0	0.26 – 0.45	Cannot accept 4σ; risk of damage
				2.0 – 3.0	Reduced resolution of monochromator

A particular requirement is to enable the transport of low and high photon energies. For the main energy ranges, low-Z coated mirrors are proposed. However, for low photon energies in the vicinity of the carbon K-edge and for high photon energies (>~20 keV), other coatings are required. In general, there is a concern that these coatings may get damaged.

ⓘ *X-ray systems layout:* The operation of the beam transport system in the main photon energy range makes use of low-Z coated mirrors. For extended ranges, other coatings and mirror settings may have to be applied.

Each photon beam transport system will initially serve one central line and one side line. The side line will make use of one additional mirror deflecting the beam such that, at the entrance to the experiment hall, a horizontal separation of 1.3 m between the central and side beam is achieved. Each line serves one instrument. Each beam transport system enables the future addition of a second side line, which would serve a third instrument. Figure 5 shows the conceptual layout of this photon beam transport. Details are described in the corresponding CDR.

ⓘ *X-ray systems layout:* Initially, each photon beam transport system will have one central and one side line with a correspondingly located instrument.

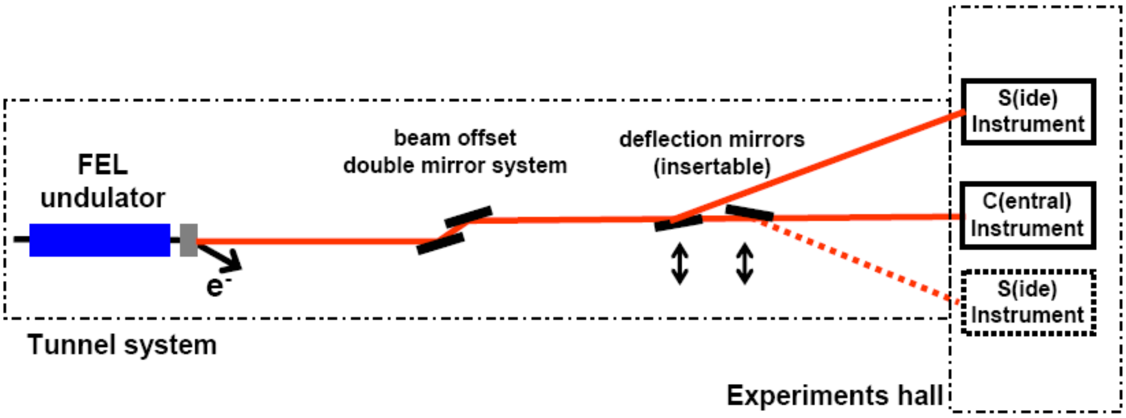

Figure 5: *Photon beam transport from the FEL undulator to the instruments. Guiding of the X-ray beam is achieved by X-ray mirrors. Initially, one central (C) and one side (S) instrument will be implemented, but provision for a second side instrument has been made.*

Each beam transport system has, as a first optical element, a double-mirror system for rejection of the on-axis Bremsstrahlung radiation. The offset of this system is set according to the reflection angle to fit the beam footprint on the mirror. Further collimation of the beam in the horizontal plane will be achieved by the second mirror. All mirrors reflect in the horizontal plane.

A critical FEL radiation parameter for the optics design is the divergence angle. Since FEL radiation has almost diffraction-limited divergence, reduction of the electron beam size (as a consequence of smaller emittances) results in the widening of the radiation cone with respect to the parameter space described in the corresponding TDR [1]. Another factor contributing to an increase of the angular divergence is a possible mismatch of the electron trajectories within the electron beam. This effect most probably defines roughly an extra 50% of the angular divergence at LCLS. From X-ray FEL beam propagation simulations, it is concluded that the optics should cover at least 4σ of the beam to avoid strong diffraction effects and a loss of intensity. To achieve high performance, we account in the simulations for larger electron beam phase space and use the upper-bound simulated values for the divergences as the parameter for the X-ray optics design. This critical parameter for the X-ray beam transport layout is discussed extensively in the corresponding CDR.

To further maximize the coverage of the FEL beam divergence, the distance between the end of the undulator and the first receiving X-ray mirror has been minimized. This change involved adjusting both undulator and mirror locations, at the same time keeping optional space behind the undulators for possible extensions.

ⓘ *X-ray systems layout:* The distance from the end of the SASE1 and SASE2 undulators to the first mirror is the same for both beam transport systems and equals ~250 m.

Scientific instruments

The placement of the hard X-ray instruments has been determined for their revised requirements and the new X-ray layout. On the SASE1 and SASE2 undulators, distribution for the central and side beam transport lines is proposed. Decisive parameters for the placement are the requirements to access high photon energies, possibly beyond 25 keV, and for minimized wavefront distortion, beneficial for sub-µm focussing. To enable photon energies of 25 keV or higher, metal-coated mirrors are required. One consequence of metal coatings is a significant increase in the background radiation level at the instruments in the experiment hall due to high-energy Bremsstrahlung radiation. This increased background leads to the need for increased hutch shielding in the experiment hall. Instruments with this requirement will be located at the same beam transport system. The latter requirement is most important for the Materials Imaging and Dynamics (MID) and High-Energy Density (HED) science instruments, which should therefore be located at the same undulator. The two coherence instruments, Single Particles, Clusters, and Biomolecules (SPB) and MID, will be placed on the central lines to minimize the number of required optical elements that could lead to beam distortions. In the case of soft X-ray instrumentation, the Small Quantum Systems (SQS) instrument needs high-flux radiation, whereas the Spectroscopy and Coherent Scattering (SCS) instrument requires a monochromatized beam. These conditions define the positions of the SQS and SCS equipment at the pink (central) and monochromator (side) branches, respectively.

ⓘ *X-ray systems layout:* The location of the instruments is proposed to be SPB (C) and FXE (S) on SASE1, MID (C) and HED (S) on SASE2, and SQS (C) and SCS (S) on SASE3.

X-ray FEL radiation parameters

Using the updated electron beam parameters and the revised undulator parameters, a full simulation of the SASE FEL radiation properties has been performed [11]. Most important parameters of FEL radiation for selected settings are listed in Table 5 and Table 6 for soft and hard X-ray FEL radiation, respectively. The results for the pulse duration are shown in Table 7. The saturation length data was used for the determination of the undulator magnetic lengths. For details, see “Undulator systems” on page 9. Full data sets are provided in an overview report [11].

Tables 5 and 6 provide an overview of simulated FEL radiation parameters at the saturation point for several photon energies from 0.28 to 25 keV and for several bunch charge settings. Average values correspond to 27 000 pulses per second. The X-ray source parameters partially follow the electron beam settings, which are optimized as a function of emittance, electron, and photon energy. The *FEL source size* varies between 30 and 60 µm (FWHM). The *FEL beam divergence* varies from 3.9 to >30 µrad in the soft X-ray regime, being largest for the lowest photon energies and the smallest bunch charge. For hard X-rays, values range from 0.6 to 2.3 µrad. The divergence increases by ~40%, going from a 1nC to a 20 pC charge. These values refer to an ideally matched electron beam. The LCLS experience indicates that mismatching can result in an extra 50% increase in the measured angular divergence. For details, see “X-ray optics and beam transport” on page 11.

Table 5: *Soft X-ray (SASE 3) FEL radiation parameters for selected settings.*

Parameter	**Unit**	**Value**											
Photon energy	keV	0.28			0.496			1.55			3.1		
Radiation wavelength	nm	4.43			2.50			0.80			0.40		
Electron energy	GeV	10.5			14			14			14		
Bunch charge	nC	0.02	0.25	1	0.02	0.25	1	0.02	0.25	1	0.02	0.25	1
Peak power	GW	105	106	94	118	119	105	90	86	72	73	66	51
Average power	W	5	67	273	5	75	304	4	54	209	3	41	147
Source size (FWHM)	µm	51	65	79	43	56	68	39	50	60	36	46	56
S. divergence (FWHM)	µrad	33.9	29.6	26.0	23.1	20.0	17.5	9.7	8.1	6.9	5.6	4.6	3.9
Spectral bandwidth	1E-3	6.9	6.4	5.7	5.8	5.3	4.7	4.4	3.9	3.3	3.6	3.1	2.5
Coherence time	fs	1.49	1.63	1.83	1.01	1.11	1.25	0.43	0.49	0.57	0.26	0.31	0.38
Coherence degree		0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.91
Photons/pulse	1E11	39	547	2240	25	347	1420	6	81	312	2	31	109
Pulse energy	mJ	0.2	2.5	10.1	0.2	2.8	11.3	0.2	2.0	7.8	0.1	1.5	5.4
Peak brilliance	1E31*	7	7	7	16	17	17	49	54	53	98	104	93
Average brilliance	1E21*	3	46	212	7	109	498	22	338	1520	44	654	2680

* In units of photons/(mm^2 $mrad^2$ 0.1% bandwidth s)

Table 6: *Hard X-ray (SASE1 and SASE2) FEL radiation parameters for selected settings.*

Parameter	**Unit**	**Value**																	
Photon energy	keV	7.75			12.4			15.5			20.7			24.8			24.8		
Radiation wavelength	nm	0.16			0.10			0.08			0.06			0.05			0.05		
Electron energy	GeV	14			14			14			14			14			17.5		
Bunch charge	nC	0.02	0.25	1	0.02	0.25	1	0.02	0.25	1	0.02	0.25	1	0.02	0.25	1	0.02	0.25	1
Peak power	GW	46	37	24	35	24	12	29	15	9	21	11	7	15	8	5	25	13	8
Average power	W	2	23	69	2	15	34	1	9	27	1	7	19	1	5	15	1	8	23
Source size (FWHM)	µm	31	39	46	29	37	49	29	35	54	28	39	60	27	42	64	25	36	55
S. divergence (FWHM)	µrad	2.8	2.3	1.9	1.9	1.5	1.3	1.5	1.3	1.0	1.2	1.0	0.8	1.0	0.8	0.6	1.1	0.9	0.7
Spectral bandwidth	1E-3	2.3	1.9	1.4	1.9	1.4	1.0	1.6	1.3	0.8	1.3	0.9	0.6	1.1	0.7	0.5	1.3	0.9	0.6
Coherence time	fs	0.16	0.20	0.27	0.13	0.17	0.23	0.12	0.15	0.23	0.11	0.16	0.24	0.11	0.17	0.26	0.09	0.13	0.20
Coherence degree		0.96	0.96	0.91	0.95	0.91	0.71	0.96	0.84	0.57	0.94	0.69	0.40	0.89	0.58	0.30	0.94	0.71	0.42
Photons/pulse	1E11	0.6	7.0	20.7	0.3	2.8	6.4	0.2	1.4	4.0	0.1	0.7	2.1	0.06	0.5	1.4	0.11	0.8	2.2
Pulse energy	µJ	76	864	2570	58	549	1260	49	347	991	35	248	708	26	196	558	42	302	863
Peak brilliance	1E33*	2.38	2.41	1.96	3.54	3.17	1.6	4.26	2.46	1.6	5.01	2.69	1.48	5.15	2.75	1.39	7.57	4.05	2.29
Average brilliance	1E23*	1.1	15.1	56.8	1.6	19.9	46.4	1.9	15.5	46.2	2.3	16.9	42.9	2.3	17.3	40.1	3.4	25.4	66.3

* In units of photons/(mm^2 $mrad^2$ 0.1% bandwidth s)

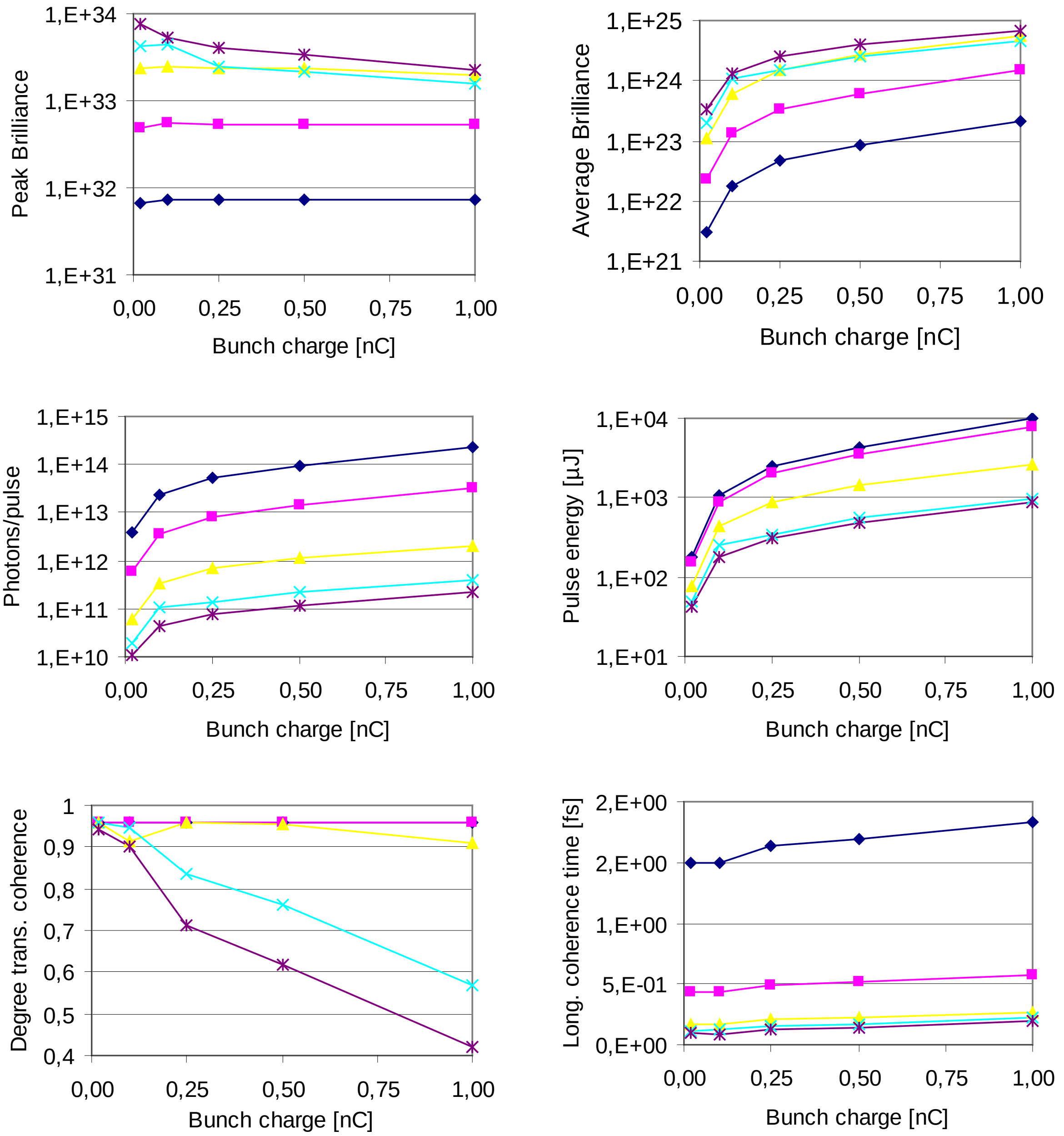

Figure 6: *FEL parameters as function of bunch charge for various photon energies. Dark blue, pink, yellow, light blue, and violet lines indicate 0.28, 1.55, 7.75, 15.5, and 24.7 keV, respectively.*

The *peak brilliance* depends mostly on photon energy, as shown in Figure 6. A dependence on bunch charge becomes visible only for the highest photon energies. Above 15 keV, it decreases slightly with increasing bunch charge. The *average brilliance* increases significantly with increasing bunch charge, as does the number of *photons per pulse*. Figure 6 shows how the average brilliance and the number of photons per pulse increase and decrease, respectively, with increasing photon energy. The *degree of transverse coherence* [3] varies between 0.3 and a maximum value of 0.96. Up to ~8 keV values >0.9 are provided for all bunch charges, corresponding to almost fully transversely coherent radiation. For higher photon energies, this value reduces significantly for higher bunch charges, while for 20 pC only a very small decrease is observed. Figure 6 indicates the variation of the degree of transverse coherence as function of bunch charge for several settings.

Table 7: *Photon pulse duration as a function of bunch charge. Values are independent of electron energy.*

Parameter	**Unit**	**Value**				
Bunch charge	pC	20	100	250	500	1000
Pulse duration (FWHM)	fs	2	9	23	43	107

The X-ray *pulse durations* listed in Table 7 depend only on the electron bunch length in the FEL undulator, respectively on bunch charge and compression. These numbers are valid for all photon and electron energies. The *FEL bandwidth* ranges from 0.5×10^{-3} to 7×10^{-3}, with a narrowing for higher photon energy and higher charge. The *longitudinal coherence time* varies from ~0.1 fs for highest photon energies and smallest charge to >2 fs for soft X-rays and large charge. For photon energies of 0.28 to 0.5 keV and a bunch charge of 20 pC, the coherence time approaches the pulse duration (the so-called "few spikes regime").

For 24.8 keV, a comparison of values obtained for electron energies of 14 GeV and 17.5 GeV indicate that, for the higher energy, the FEL power, photon flux, and brilliance increase by a factor of 1.5 to 2. The degree of transverse coherence improves from 0.89 to 0.94 in the low emittance settings.

References

[1] M. Altarelli et al. (eds.), 2006, *The European X-RayFree-Electron Laser Technical Design Report*, DESY Report 2006-097.

[2] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, 2008, *Coherence properties of the radiation from X-ray free electron laser*, Optics Communications 281 (2008), 1179.

[3] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, 2010, *Statistical and coherence properties of radiation from x-ray free-electron lasers*, New J. Phys. 12 (2010), 035010.

[4] Y. Li, B. Faatz, J. Pflueger, E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, 2008, *Study of Controllable Polarization SASE FEL by a Crossed-planar Undulator*, Proc. EPAC08, Genoa, Italy.

[5] B. Faatz, W. Decking, Y. Li, J. Pflueger, E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, 2008, *Study of Controllable Polarization of a SASE FEL Using a Crossed-planar Undulator*, Proc. FEL 2008, Gyeongju, Korea.

[6] Y. Li, B. Faatz, J. Pflueger, 2010, *Polarization properties of crossed planar undulators*, Nucl. Instrum. Meth. A 613 (2010), 163.

[7] Y. Li, W. Decking, B. Faatz, J. Pflueger, 2010, *Microbunch preserving bending system for a helical radiator at the European XFEL*, Phys. Rev. ST Accel. Beams 13 (2010), 080705.

[8] E.A. Schneidmiller, M.V. Yurkov, 2010, *An Option of Frequency Doubler at the European XFEL for Generation of Circularly Polarized Radiation in the Wavelength Range Down to 1 - 2.5 nm*, FEL 2010, Malmö, Sweden.

[9] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, 2009, *Expected Properties of the Radiation from a Soft X-ray SASE FEL (SASE3) at the European XFEL*, Proc. FEL 2009, Liverpool, UK.

[10] R. Brinkmann, E.A. Schneidmiller, M.V. Yurkov, 2010, *Possible Operation of the European XFEL with Ultra-Low Emittance Beams*, Nucl. Instrum. Meth. A 616 (2010), 81.

[11] E.A. Schneidmiller, M.V. Yurkov, 2011, *An overview of the photon beam properties from the European XFEL operating with revised set of baseline parameters of the electron beam and undulators: status of December 2010*, DESY Print TESLA-FEL 2011-01.

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