

# BASELINE PARAMETERS OF THE EUROPEAN XFEL

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## Abstract

We present the latest update of the baseline parameters of the European XFEL. It is planned that the electron linac will operate at four fixed electron energies of 8.5, 12, 14, and 17.5 GeV. Tunable gap undulators provide the possibility to change the radiation wavelength in a wide range. Operation with different bunch charges (0.02, 0.1, 0.25, 0.5 and 1 nC) provides the possibility to operate XFEL with different radiation pulse duration. We also discuss potential extension of the parameter space which does not require new hardware and can be realized at a very early stage of the European XFEL operation.

## BASELINE PARAMETERS

The European XFEL is driven by a superconducting accelerator with a maximum energy of electrons of 17.5 GeV [1, 2]. It operates in the burst mode with 10 Hz repetition rate of 0.6 ms pulse duration. Each pulse brings train of up to 2700 electron bunches (up to 4.5 MHz repetition rate). Three undulators are installed in the first stage of the project: SASE1, SASE2, and SASE3 (see Table 1). SASE3 undulator is placed sequentially after SASE1 undulator in the same electron beamline. All undulators

have similar mechanical design. The length of the undulator module is equal to 5 meters. The length of the undulator intersection is equal to 1.1 m. The undulators of SASE1 and SASE2 are identical: period length is 40 mm, number of modules is 35, the range of the gap variation is 10 to 20 mm. SASE3 undulator consists of 21 modules, the period is 68 mm, the gap tunability range is 10 to 25 mm [3]. Tunability range of the undulators has been corrected on the base of magnetic measurements [3], and in terms of undulator parameter is 1.65 - 4 and 4 - 9 for SASE1/SASE2 and SASE3, respectively. The tunability range in terms of  $\lambda_{\max}/\lambda_{\min}$  is 3.5 for SASE1/2 and 4.6 for SASE3.

Requirements of users are summarized and analyzed in a proper way to provide maximum opportunities for every instrument and experiment simultaneously [4–7]. The tunability ranges of the undulators are not sufficient to cover the required wavelength ranges at one fixed electron beam energy, and four electron beam energies have been defined: 8.5 GeV, 12 GeV, 14 GeV, and 17.5 GeV [4, 5]. Five operating points for the bunch charge has been fixed: 20 pC, 100 pC, 250 pC, 500 pC, and 1 nC (see Table 3). The beam formation system is designed to produce peak beam current of 5 kA with nearly Gaussian shape. Electron bunches with different bunch charges will generate radiation pulses with different radiation pulse duration. Figure 1 shows an overview of the main photon beam properties of the European XFEL for the bunch charge 1 nC. The left and right columns in these plots correspond to the SASE1/SASE2 and SASE3 undulators, and allow visual tracing of the operating wavelength bands, pulse energy, and brilliance as function of the electron energy. The general tendency is that operation with higher charges provides higher pulse energy and higher average brilliance, nearly proportional to the bunch charge.

Properties of the radiation from SASE3 are presented in Fig. 1, we assume that the electron beam is not disturbed by FEL interaction in the SASE1 undulator. Decoupling of SASE3 and SASE1 operation can be performed with an application of the betatron switcher [7, 9]. Feedback kickers can be used to test and operate this option at the initial stage. In case of positive results dedicated kickers need to be installed [6]. Operation of SASE3 as an afterburner of SASE1 is also possible, but with reduced range of accessible wavelengths and reduced power [7]. General problem is that tuning of SASE1 to higher pulse energies leads to higher induced energy spread in the electron beam, and to degradation of the SASE3 performance. For instance, operation of SASE3 at the energy of 17.5 GeV is impossible at any wavelength if wavelength of SASE1 is longer than 0.1 nm, and radiation power of

Table 1: Undulators at the European XFEL [3]

	Units	SASE1/2	SASE3
Period length	cm	4	6.8
Maximum field	T	1.11	1.66
Gap range	cm	1 – 2	1 – 2.5
$K$ range	#	3.9 – 1.65	9.0 – 4.08
Length of module	m		5
Length of intersection	m		1.1
Number of modules	#	35	21
Total magnetic length	m	175	105

Table 2: Working Points and Tunability Ranges of the European XFEL

	SASE1/2	SASE3
Tunability, $\lambda_{\max}/\lambda_{\min}$	3.64	4.45
El. energy, GeV	Photon energy range, keV	
8.5	1.99 – 7.27	0.24 – 1.08
12.0	3.97 – 14.48	0.48 – 2.16
14.0	5.41 – 19.71	0.66 – 2.94
17.5	8.45 – 30.80	1.03 – 4.59
	Photon wavelength range, nm	
8.5	0.171 – 0.622	1.15 – 5.10
12.0	0.086 – 0.312	0.57 – 2.56
14.0	0.063 – 0.229	0.42 – 1.88
17.5	0.040 – 0.147	0.27 – 1.20

Table 3: Properties of the Electron Beam at the Undulator Entrance [6]

Bunch charge	nC	0.02	0.1	0.25	0.5	1
Peak beam current	kA	4.5	5	5	5	5
Normalized rms emittance	mm-mrad	0.32	0.39	0.6	0.7	0.97
rms energy spread	MeV	4.1	2.9	2.5	2.2	2
rms pulse duration	fs	1.2	6.4	16.6	30.6	76.6

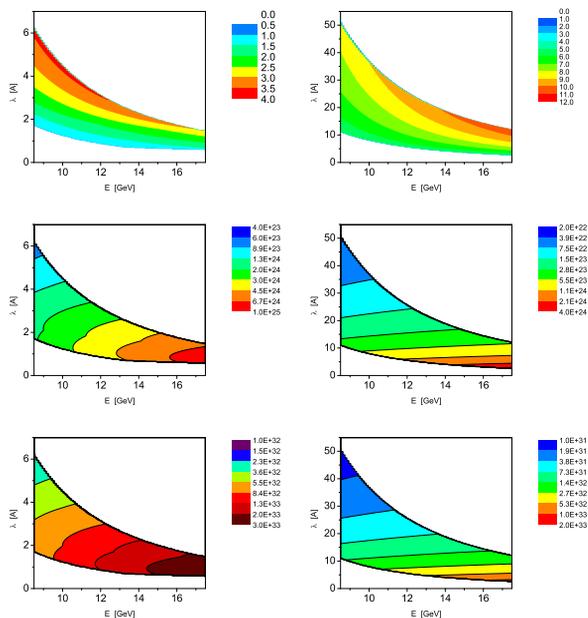


Figure 1: An overview of photon beam properties of the European XFEL for SASE1/2 (left column) and SASE3 (right column). Contour plots present pulse energy (top row), peak brilliance (middle row), and average brilliance (lower row). Units for the pulse energy and brilliance are mJ and photons/sec/mm<sup>2</sup>/rad<sup>2</sup>/0.1% bandwidth, respectively. Bunch charge is equal to 1 nC. Calculations have been performed with FEL simulation code FAST [8].

SASE1 is tuned by a factor of 1.5 above saturation power [7].

Full description of the baseline parameters is presented in a dedicated report [10]. It contains an overview and detailed saturation tables, and reference physical information for users.

The best way for planning user experiments is performing start-to-end simulations tracing radiation pulses from its origin (undulator) through a beamline (mirrors, monochromators, etc.) to a target, simulation of physical processes of the radiation interaction with a sample, and simulation of detection process of related debris (photon, electrons, ions, etc.) by detectors. We present an XFEL photon pulses simulation database (XPD) accessible through public web-server that allows the access to the data produced by time-dependent FEL simulation code FAST [8]. A web application allows for picking up selected photon pulse data in the hdf5 format for any given XFEL operation mode (electron energy, charge/photon pulse duration, active undulator range, etc.) suitable for statistical analysis, propagating through the op-

tical system, interaction with the sample, etc. The pulses post processing data, including the gain curve, time structure, source size and far field angular divergence are also provided. Detailed parameters of the radiation together with 3D field maps are being compiled in the photon data base of the European XFEL [10, 11]. Currently this data base is used for optimization of the photon beam transport and imaging experiment [12, 13]. Official web page of the European XFEL photon data base XPD is <https://in.xfel.eu/xpd/> [11].

## POTENTIAL EXTENSIONS BEYOND BASELINE OPTION

There are several potential extensions beyond the baseline option which can be realized at a very early stage of the European XFEL operation without additional hardware, or by means of extension of the functions of the present hardware. Some solutions are pretty old, and some other appeared just recently. Some proposals rely on parameters of the electron beam beyond the baseline option. Several groups perform theoretical and simulation studies of different options. There is also experimental activity at FLASH and LCLS on verification of advanced concepts. Here we briefly highlight several extensions related to the European XFEL with references to the most fresh publications.

The next phase of the facility upgrade will include helical afterburner based on the reverse tapering.

### Efficiency Increase by Undulator Tapering

Undulator tapering will allow significant increase of FEL power. Many studies on this subject have been performed for the parameters of the European XFEL (see [1, 7, 14, 15] and references therein). Application of the undulator tapering has evident benefits for the SASE3 FEL operating in the wavelength range around 1.6 nm. It is about a factor of 6 in the pulse radiation energy with respect to the saturation regime, and factor of 3 with respect to the radiation power at the full length. General feature of tapered regime is that both spatial and temporal coherence degrade in the nonlinear regime, but more slowly than for the untapered case. Peak brilliance is reached in the middle of the tapered section, and exceeds the value of the peak brilliance in the saturation regime by a factor of 3. The degree of transverse coherence at the saturation for the untapered case is 0.86. The degree of transverse coherence for the maximum brilliance of the tapered case is 0.66, coherence time is reduced by 15%. At the exit of the undulator the degree of transverse coherence for the tapered case is 0.6, and coherence time is reduced

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by 20%. Radiation of the 3rd harmonic for both the untapered and tapered cases exhibit nearly constant brilliance and nearly constant contribution to the total power. Coherence time of the 3rd harmonic for the tapered case approximately scales inversely proportional to harmonic number, as in the untapered case.

### *Multicolor Mode of Operation*

A betatron switcher [9] can be used in long undulators for providing multi-color operation. Different parts of the undulator are tuned to different resonance wavelengths. Fast kicker and steerer force lasing of selected bunch in specific part of the undulator.

### *Harmonic Generation and Harmonic Lasing Self-Seeded FEL*

Contrary to nonlinear harmonic generation, harmonic lasing in a high-gain FEL can provide much more intense, stable, and narrow-band FEL beam which is easier to handle if the fundamental is suppressed [16]. At the European XFEL the harmonic lasing would allow to extend operating range ultimately up to 100 keV. Currently this option is studied for implementation in the MID instrument [17]. Dedicated experimental program on harmonic generation is ongoing at LCLS [18].

A concept of a harmonic lasing self-seeded FEL (HLSS) has been proposed recently [16]. A gap-tunable undulator is divided into two parts by setting two different undulator parameters such that the first part is tuned to a sub-harmonic of the second part. Harmonic lasing occurs in the exponential gain regime in the first part of the undulator, also the fundamental stays well below saturation. In the second part of the undulator the fundamental mode is resonant to the wavelength, which was previously amplified as the harmonic. The amplification process proceeds in the fundamental mode up to saturation. In this case the bandwidth is defined by the harmonic lasing (i.e. it is reduced by a significant factor depending on harmonic number) but the saturation power is still as high as in the reference case of lasing at the fundamental in the whole undulator, i.e. the spectral brightness increases. Application of the undulator tapering in the deep nonlinear regime would allow generation of higher peak powers approaching the TW level [19]. Modification of the HLSS scheme, named purified SASE - pSASE [20], is under consideration as well by [21].

### *Extended Range of Electron Beam Parameters*

Several options are under consideration for exploiting higher peak currents, and higher bunch charges to increase pulse energy and peak power (see [7, 22] and references therein). Dedicated activity of simulation, production, and characterization of high charge bunches in XFEL-type electron gun is ongoing at PITZ [23, 24]. Another direction of studies is production of ultrashort pulses. This activity also involves both, simulation studies for XFEL and experimental studies at FLASH (see [25–27] and references therein).

For instance, use of higher charges in combination with tapering will allow generation of sub-Joule energies in the radiation pulse [7]. Note that there can be some technical complications for operation with charges which are not in the gate of baseline parameters [6]. It is our experience of FLASH operation with small charges that limitations of the electron beam diagnostic are not stopovers, but they significantly complicate tuning, since some feedback system stop working because of noisy measurements.

### *“Pink” Photon Beam*

Some user application require a “pink” photon beam with a spectrum width of several percent. Two options to increase the spectrum range have been considered so far: formation of the energy chirp in the bunch train [6], and formation of the energy chirp within electron bunch [28].

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