

Control of the amplification process in baseline XFEL undulator with mechanical SASE switchers

Gianluca Geloni,^{a,1} Vitali Kocharyan^b and Evgeni Saldin^b

^a*European XFEL GmbH, Hamburg, Germany*

^b*Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany*

Abstract

The magnetic gap of the baseline XFEL undulators can be varied mechanically for wavelength tuning. In particular, the wavelength range 0.1 nm - 0.4 nm can be covered by operating the European XFEL with the SASE2 undulator. The length of the SASE2 undulator (256.2 m) is sufficient to independently generate three pulses of different radiation wavelengths at saturation. Normally, if a SASE FEL operates in saturation, the quality of the electron beam is too bad for generation of SASE radiation in the subsequent part of undulator which is resonant at a few times longer wavelength. The new method of SASE undulator-switching based on the rapid switching of the FEL amplification process proposed in this paper is an attempt to get around this obstacle. Using mechanical SASE shutters installed within short magnetic chicanes in the baseline undulator, it is possible to rapidly switch the FEL photon beam from one wavelength to another, providing simultaneous multi-color capability. Combining this method with a photon-beam distribution system can provide an efficient way to generate a multi-user facility.

1 Introduction

The recent achievement of LCLS [1, 2] relies on a high-performance beam formation system, which works as in the ideal operation scenario described in the conceptual design report [1]. In particular, the small electron-beam emittance achieved allows saturation within 20 undulator modules, out of the 33 available. A similar scenario is also foreseen for the European XFEL. One has, then, the possibility of taking advantage of a long, unused part of the SASE undulators to upgrade the facility.

¹ Corresponding Author. Tel: ++49 40 8998 5450. Fax: ++49 40 8998 1905. E-mail address: gianluca.geloni@xfel.eu

undulator system for generation in parallel high power X-ray
pulses at 0.1 nm, 0.15 nm, and 0.2 nm in baseline undulator
long pulse (60 fs) mode operation

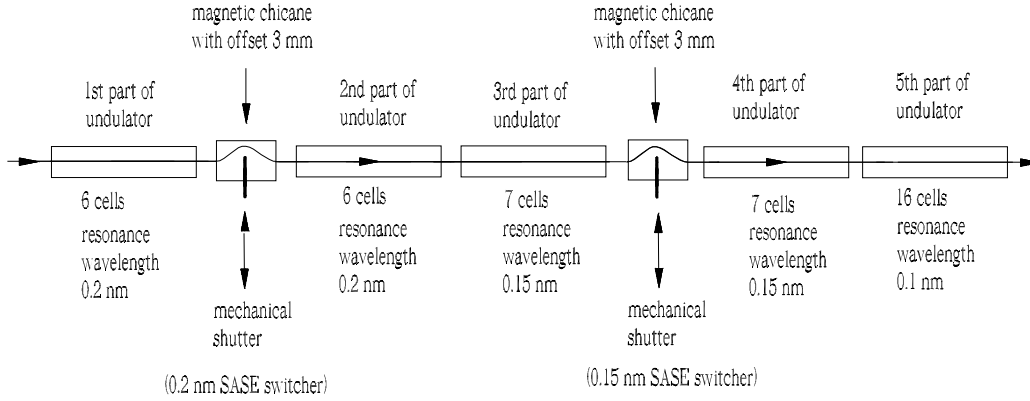


Fig. 1. Design of the undulator system for the three color X-ray source in the case of a long-pulse (60 fs) mode operation. Wavelength selection is based on the use of two mechanical SASE switchers. Each SASE switcher consists of a short magnetic chicane and a SASE shutter. The magnetic chicane generates an offset for the SASE shutter installation and additionally washes out the electron beam modulation. The extra path-length is much smaller than the radiation pulse length.

In this paper we describe a method for providing simultaneous multi-color capability at three different wavelengths. For the sake of exemplification we will consider radiation around 0.2 nm, 0.15 nm and 0.1 nm, produced by an electron beam with $0.4 \mu\text{m}$ normalized emittance and 0.25 nC charge. After integration with a photon-beam distribution system, this method can lead to an efficient multi-user facility.

In its essence, the method is based on controlling the amplification process in the baseline XFEL undulator with the help of SASE switchers constituted by mechanical shutters to be installed at the position of a weak magnetic chicanes at specific locations down the SASE undulator. A sketch of the setup is presented in Fig. 1. Three different modes of operations are foreseen, based on a long (60 fs) pulse, depending on what shutters are off and on (see Fig. 2). In the first part of the undulator the beam undergoes the SASE process in the linear regime. After that, it passes through the first switcher, which consists of two devices. First, a weak magnetic chicane creating a transverse offset for the electrons and washing out the electron beam modulation. Second, a mechanical shutter, which has two positions: "on" when absorbing SASE radiation and "off", when SASE radiation from the first undulator passes unperturbed to the second undulator. The electron bunch passes through the magnetic chicane, and the beam modulation is washed out. Note that in the chicane, the electron bunch is also delayed with respect to the radiation

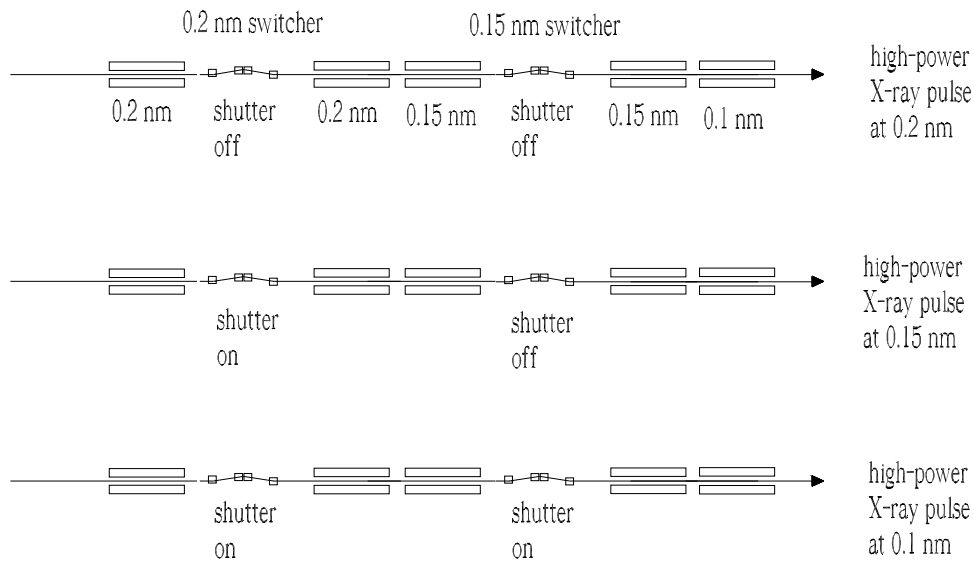


Fig. 2. The three modes of operation for the SASE shutters in the baseline undulator.

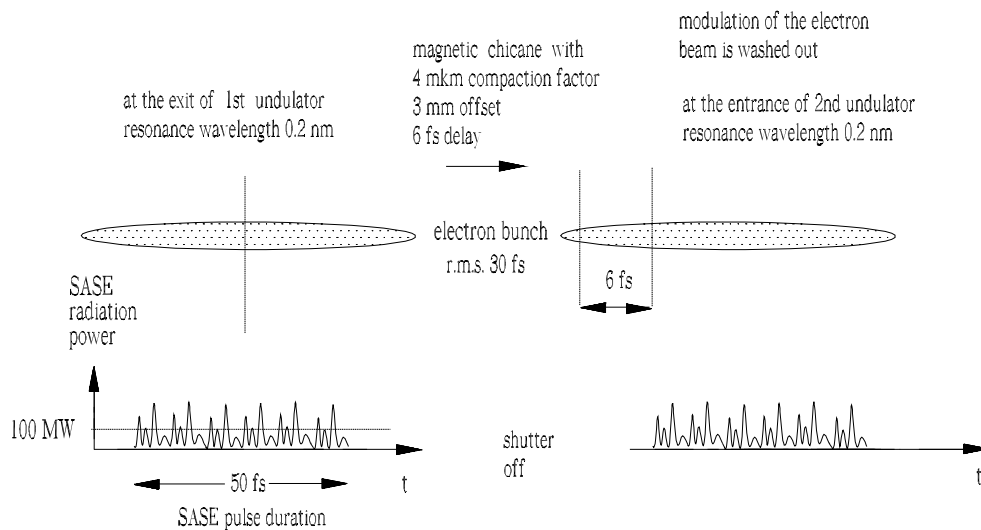


Fig. 3. Sketch of principle of multi-color X-ray pulse generation in the baseline XFEL undulator. Here the SASE shutter is off. Modulation of the electron beam due to the FEL process in the first undulator part is washed out in the magnetic chicane. In the second part of the undulator, the seeded main part of electron bunch reaches saturation with ten GW power level at 0.2 nm wavelength.

but the extra-path length can be chosen small enough to provide a shift of 6 fs, much shorter than the long electron bunch (30 fs rms). If the shutter is off (see Fig. 2 top and Fig. 3), at the position of the second undulator almost all the "fresh" (washed out) bunch is seeded by the radiation coming from the first part, and the seeded main part of electron bunch reaches saturation

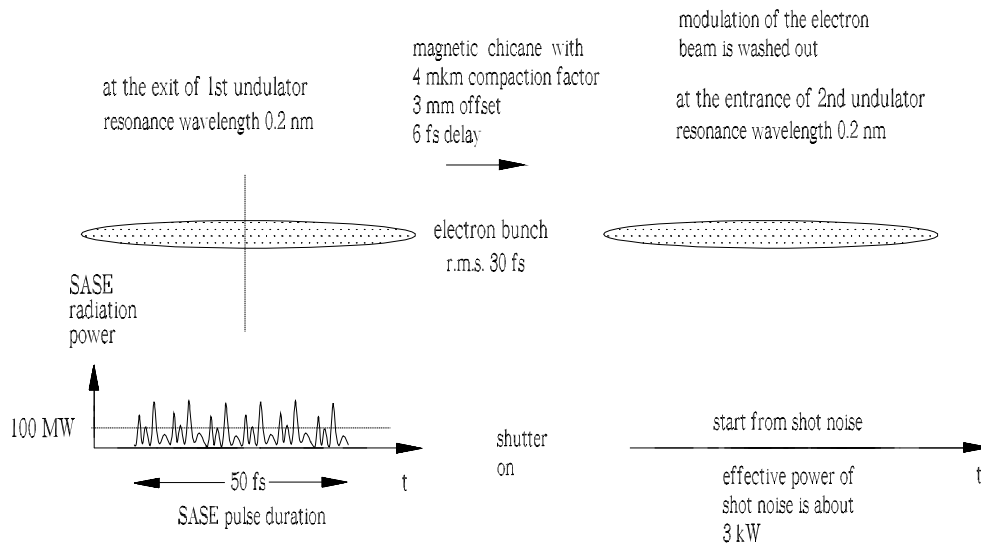


Fig. 4. Sketch of principle of multi-color X-ray pulse generation in the baseline XFEL undulator. Here the SASE shutter is on. Modulation of electron bunch due to FEL process in the first part of undulator is washed out in magnetic chicane. In the second part of undulator FEL amplification process start up from shot noise and reaches 0.1 GW power level only. As a result, energy losses and energy spread within the electron bunch are negligible and the electron bunch is still a good "active medium" for the next color pulse generation in the following undulator parts.

with ten GW power level at 0.2 nm wavelength. In this case, energy losses and energy spread within the electron bunch are important, and the bunch cannot further be used for generation of high intensity SASE radiation at wavelength comparable to 0.1 nm. If the shutter is on (see Fig. 2 middle and bottom, and Fig. 4) instead, a fresh electron beam will enter the second part of the undulator, and will start radiate according to the usual SASE process. The second part of the undulator is short enough so that the SASE amplification process ends, once more, in the linear regime. In this case energy losses and energy spread within the electron bunch are negligible and the electron bunch is still a good "active medium" for the next color pulse generation in the following undulator parts. These parts are tuned to a different wavelength, namely 0.15 nm and 0.1 nm. When the second shutter is off (see Fig. 2 middle), the seeded SASE process reaches saturation at 0.15 nm. When the second shutter is on, instead, one has saturation in the final part of the undulator only at 0.1 nm (see Fig. 2 bottom). The distribution of photons can be achieved on the basis of pulse trains, thereby allowing many users working in parallel at different wavelengths. For the temporal structure of the radiation produced at the European XFEL [3], this means that we have no restrictive requirement on the switching time of the mechanical shutter, which should be simply shorter than 100 msec, a very

Table 1

Parameters for the pulse mode used in this paper. The undulator parameters are the same of those for the European XFEL, SASE2, at 17.5 GeV electron energy.

	Units	
Undulator period	mm	47.9
Undulator length	m	256.2
Undulator segment length	m	5.0
Intersection length	m	1.1
Number of segments	-	42
K parameter (rms)	-	1.97-2.96
β	m	17
Wavelength	nm	0.1 - 0.2
Energy	GeV	17.5
Charge	nC	0.25
Bunch length (rms)	μm	10.0
Normalized emittance	mm mrad	0.4
Energy spread	MeV	1.5

suitable condition for mechanical system.

In the next section we present a feasibility study of the method, and we make exemplifications with the parameters of the SASE2 line of the European XFEL (see Table 1). With the help of this scheme it will be possible to provide in parallel X-rays at three different wavelengths around 0.2 nm, 0.15 nm and 0.1 nm. In the following section we will see how, combining this method with a photon-beam distribution system, one can provide an efficient way to generate a multi-user facility.

2 Feasibility study

In the following we describe the outcomes of computer simulations using the code Genesis 1.3 [4].

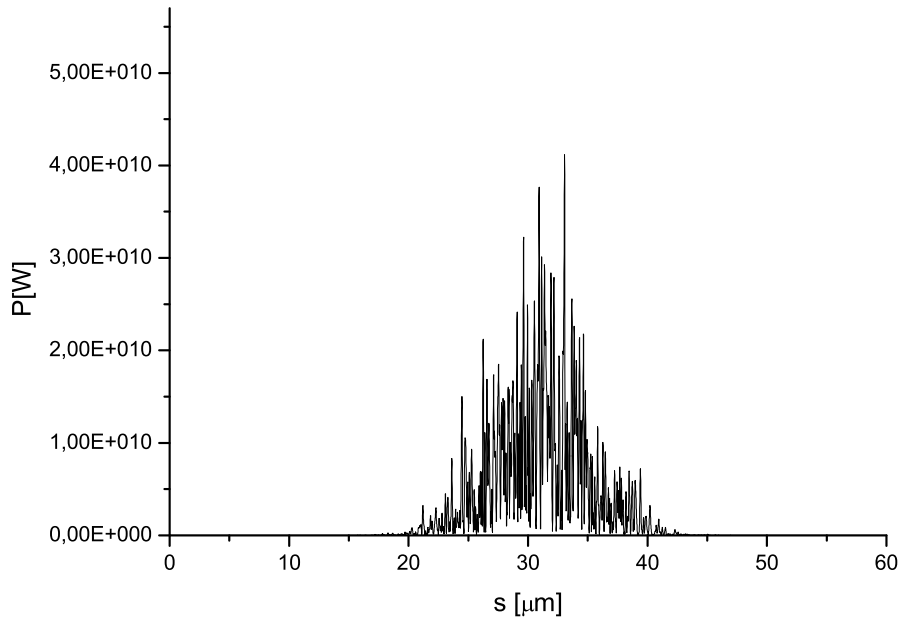


Fig. 5. Beam power distribution at the end of the second part of the undulator after 7 + 7 cells (42.7 m+42.7 m). The first shutter is off.

2.1 Both shutters off

First we consider the case when both shutters are off and the first and second parts of the undulator are tuned at 0.2 nm, Fig. 2 top.

The power and spectrum after the second part of the undulator are shown in Fig. 5 and 6.

In this case the SASE process reaches saturation in the second undulator part. The electron beam energy loss and induced energy spread are severe, and prevent the beam to undergo the SASE process again in the following undulator parts, Fig. 7.

2.2 First shutter on

Subsequently, we studied the case when the first shutter is on and the second is off, corresponding to the situation in Fig. 2 middle. The presence of the shutter prevents the seeding process in the second undulator part. As a result the SASE process at 0.2 nm is far from saturation, and the beam can be used to produce radiation at 0.15 nm in the third (6 segments, 36.6

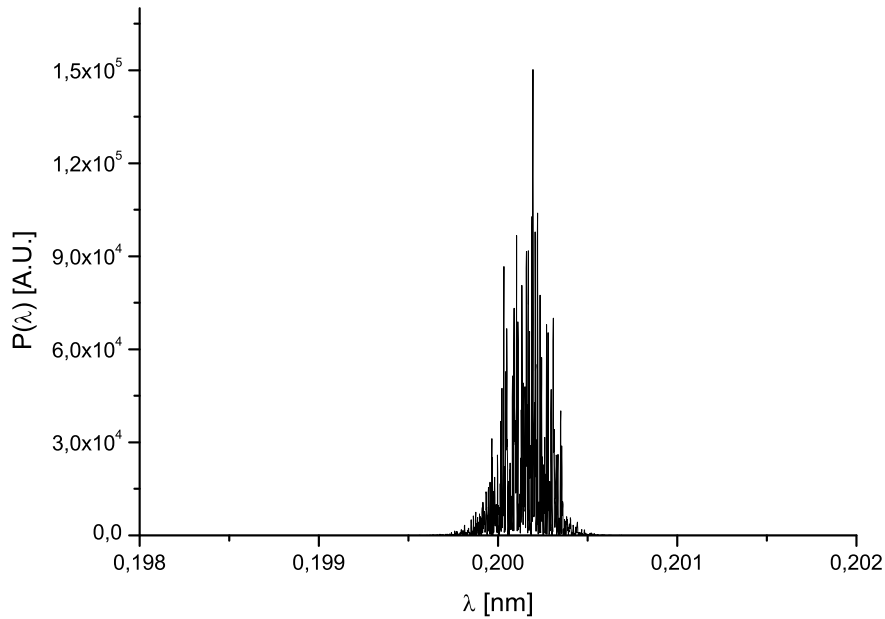


Fig. 6. Spectrum at the end of the second part of the undulator 7 + 7 cells (42.7 m+42.7 m). The first shutter is off.

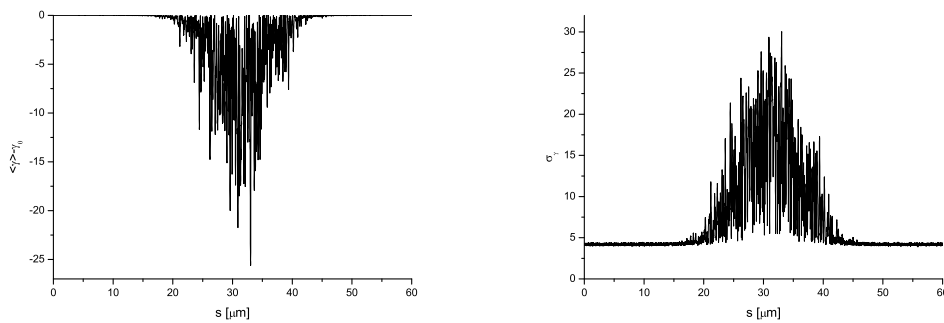


Fig. 7. Electron beam energy loss (left) and induced energy spread (right) at the entrance of the third part of the undulator. The first shutter is off.

m) and fourth part (6 segments, 36.6 m) of the undulator. In this case, the properties of the electron beam at the entrance of third part of the undulator are summarized in Fig. 8.

The power and spectrum after the fourth part of the undulator are shown in Fig. 9 and Fig. 10.

In this case the SASE process reaches saturation in the second undulator part. The electron beam energy loss and induced energy spread are severe, and prevent the beam to undergo SASE process again in the last undulator

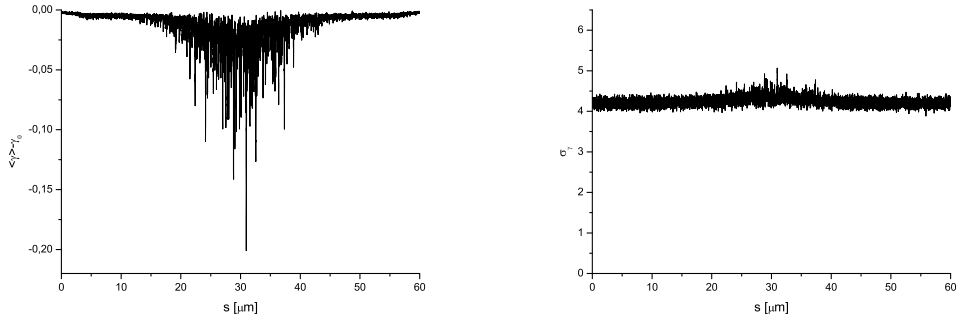


Fig. 8. Electron beam energy loss (left) and induced energy spread (right) at the entrance of the third part of the undulator. The first shutter is on.

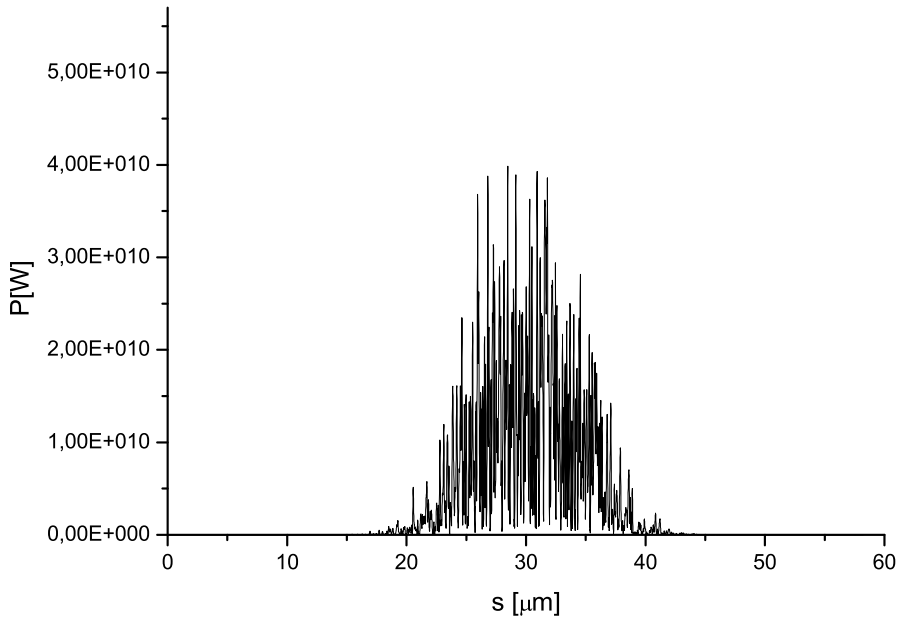


Fig. 9. Beam power distribution at the end of the fourth part of the undulator. The first shutter is on.

part.

2.3 Both shutters on

Finally, we study the case when both shutters are on, Fig. 2 bottom. In this case, the SASE process can start from shot noise in the fifth part of the undulator (16 segments, 97.6 m), at 0.1 nm, because the presence of both shutters prevent saturation before, and the beam quality is preserved up to

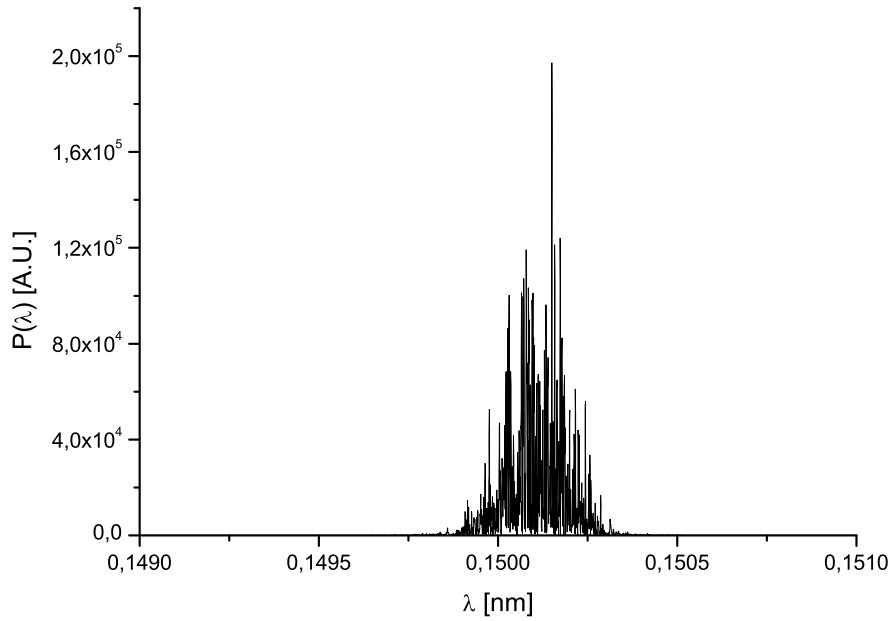


Fig. 10. Spectrum at the end of the fourth part of the undulator. The first shutter is on.

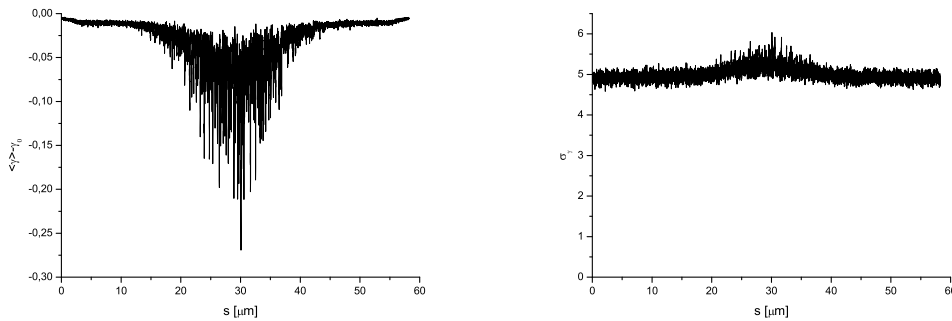


Fig. 11. Electron beam energy loss (left) and induced energy spread (right) at the entrance of the fifth part of the undulator. Both shutters are on.

the entrance of the last undulator part, see Fig. 11.

The power and spectrum after the fifth part of the undulator are shown in Fig. 12 and 13.

In this case the SASE process reaches saturation in the fifth undulator part.

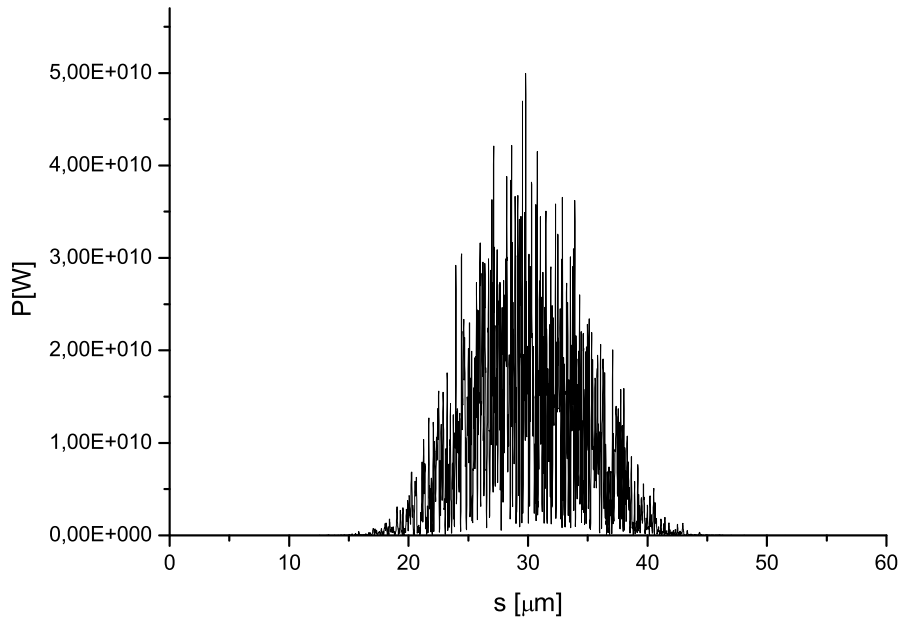


Fig. 12. Beam power distribution at the end of the fifth part of the undulator. Both shutters are on.

3 Photon distribution

As said before, the distribution of photons is done on the basis of pulse-trains. The two mechanical shutters need to operate at a frequency of 1 Hz for a single on-off-on cycle with switching time of less than 100 ms (the temporal delay between two consecutive trains). Consider a temporal interval of 1 second, i.e. 10 trains of electron bunches. During the first 400 ms, the first three trains of electron bunches are let through with both shutters off (see Fig. 2 upper part). Therefore, three trains of radiation at 0.2 nm are produced. Then, the first shutter is switched on in less than 100 ms, i.e. in the interval between the next two trains. During the next 300 ms, three trains of electron bunches produce radiation at 0.15 nm. Finally, the second shutter is switched on during the interval between the two following trains, and other four trains of radiation are produced during the final 300 ms, this time at 0.1 nm. Once separate color pulses are obtained in this way, they can be distributed to different users. Combining this method with a photon-beam distribution system based on movable multilayer X-ray mirrors, as discussed before in [5], can provide an efficient way to generate a multi-user facility. This option, exemplified in Fig. 14, is not specific for the European XFEL and may be applied for LCLS and other XFELs.

An option for the distribution of photons specific for the European XFEL

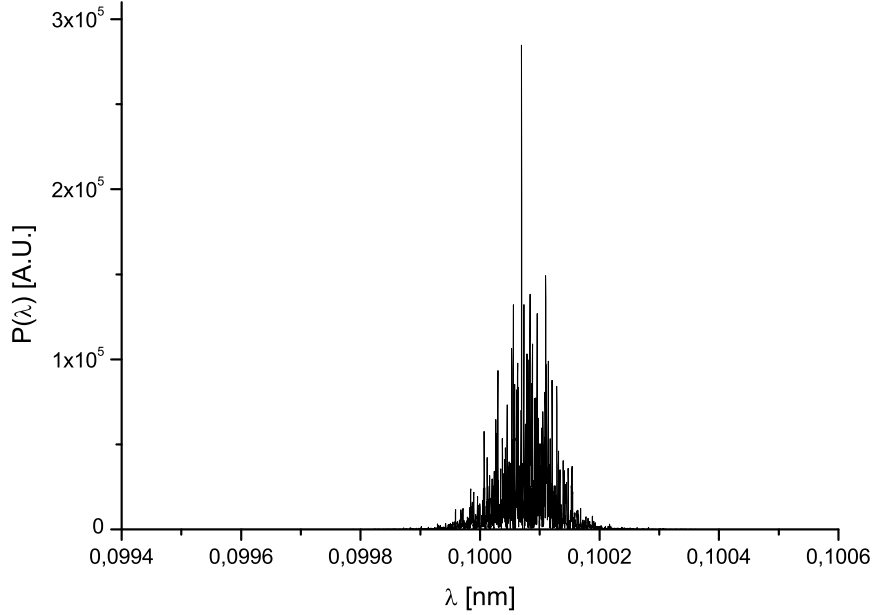


Fig. 13. Spectrum at the end of the fifth part of the undulator. Both shutters are on.

may also be considered. The original layout of the European XFEL includes two long undulators for spontaneous emission behind SASE2. These two undulators use the spent electron beam of SASE2. We speculate on the possibility of distributing the SASE2 undulator modules in three parts (14 cells, 12 cells and 16 cells), tuned at three different wavelengths as shown before, and of installing the second and the third part inside the U1 and U2 tunnels instead of the spontaneous emission undulators. The idea is sketched in Fig. 15. Combining this re-installation with mechanical SASE switchers for control of the FEL amplification process can provide an efficient way to generate a multi-user facility. The two mechanical shutters and the magnetic chicanes would be installed as shown in Fig. 15. Different colors may then be transported to different experimental halls. In principle then, at each experimental hall one may still take advantage of the multi-user scheme in Fig. 14.

Finally, similarly as in [6] we remark that the main difficulty concerning the distribution of photons consists in the separation of the three colors. Once this task is performed, mirrors in the photon beam transport system can be used to distribute the three-color photon beam among three independent user beam lines. As in [6] we propose to separate the three colors already in the undulator with the help of x-ray mirrors. The idea is sketched in Fig. 16, Fig. 17 and Fig. 18. The three colors can be separated horizontally in two stages by installing the two-mirror setup sketched in Fig. 17 after the

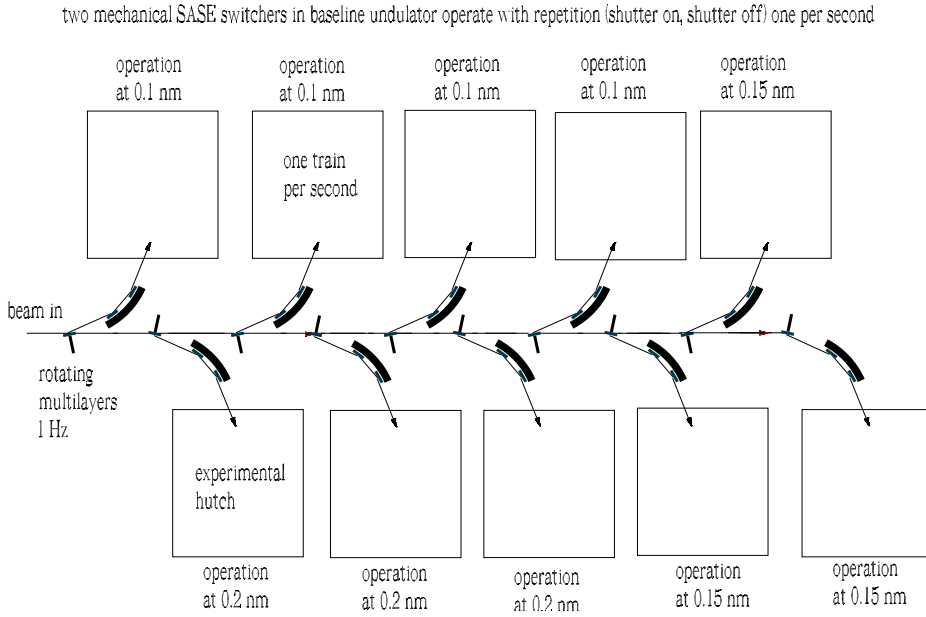


Fig. 14. Proposed SASE undulator beam line for multi-color mode operation. A photon beam distribution system based on movable multilayer X-ray mirrors. Distribution of photons is achieved on the basis of pulse trains and it is possible to serve simultaneously ten user stations with one train per second repetition rate at three different wavelengths. In this case each SASE shutter should be operated with one Hz repetition rate for a single on-off-on cycle only.

undulator parts producing a given color, as specified in Fig. 16. Note that the installation of these setups also requires the presence of a weak magnetic chicane in order to create an offset in the electron trajectory to accommodate the mirrors. The horizontal offset should be chosen small enough to account for the presence of the spontaneous radiation absorbers in the vacuum chamber, which limits the effective aperture to a circle of 9 mm diameter. The horizontal offset may be therefore chosen to be around 3 mm, which is enough for separating the two-color pulses: in fact, at the position of the optical station the FWHM beam size is less than a millimeter. Additionally, mirrors can also be used to generate a few μrad deflection-angle, which is not important within the undulator but will create further a small extra-separation of a few millimeters at the position of the experimental station, as shown in Fig. 18.

4 Conclusions

We presented a novel method to control the SASE amplification process in the baseline XFEL undulator with the help of mechanical SASE switchers. After the lasing of LCLS [2], a new scenario where the beam formation system works as in the ideal case has become reality. This allows for a

layout based on the use tunnels for two long spontaneous emission undulators (U1, U2) behind SASE2

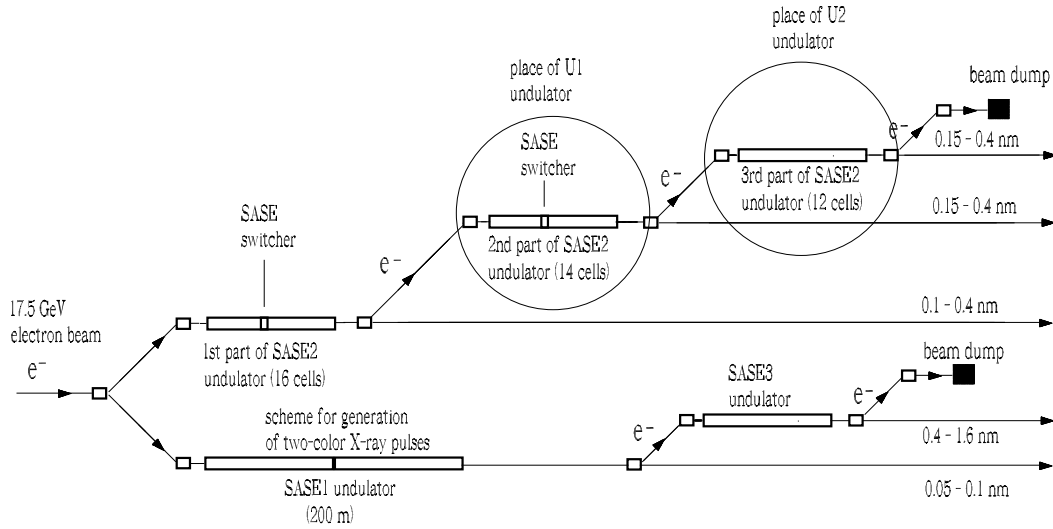


Fig. 15. Possible extension of the number of user stations which can operate simultaneously at three different wavelengths at the European XFEL. The present XFEL layout enables to accommodate two long undulators behind SASE2, for spontaneous emission in parasitic mode of operation. One may exploit these beamlines and distribute the undulator modules of SASE2 respectively inside the SASE2, U1, and U2 tunnels. Distribution of photons is achieved on the basis of pulse trains. Two mechanical SASE switchers in the first and second parts of the SASE2 undulator operate with repetition frequency of 1 Hz for a single on-off-on cycle.

reduction of the gain length in the SASE process and for exploitation of the extra-available undulator modules. In particular, we show how it is possible to accommodate three FELs, lasing at three different wavelengths within the foreseen undulator length for the SASE2 beam line at the European XFEL. The scheme makes use of mechanical switchers capable of switching on and off the SASE process at a given particular wavelength. Three possible configurations of two switchers allows for separate production of each of the three wavelengths. The switchers should work on the basis of a train of pulses, with a frequency of 1 Hz for an on-off-on cycle, and with a switching time of less than 100 ms. In this way, simultaneous operation at three different wavelength is possible. Distribution of the photons to different stations is discussed.

5 Acknowledgements

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three different radiation wavelengths can be horizontally separated in baseline undulator and serve three independent beam lines, thereby enabling many users to work in parallel

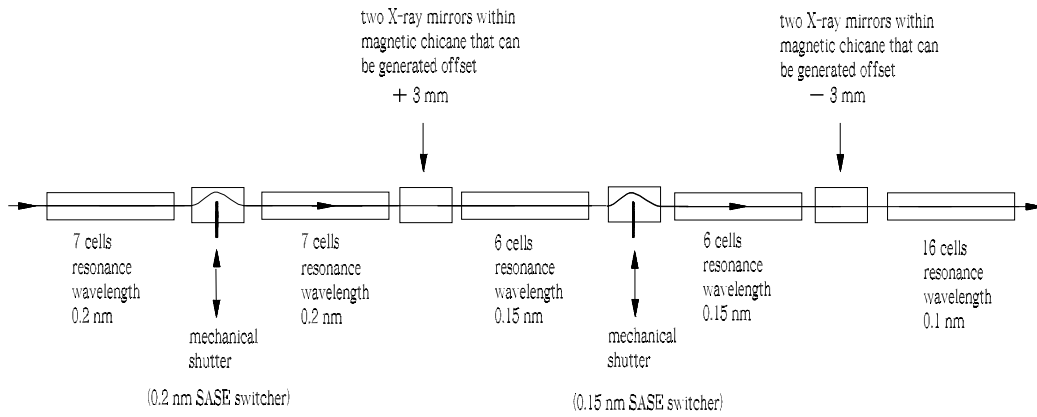


Fig. 16. Design of undulator system for generating in parallel three color X-ray pulses. Three different radiation wavelengths can be horizontally separated in baseline undulator and serve three independent beam lines.

first radiation wavelength can be horizontally shifted with respect to the other by two X-ray mirrors installed within additional magnetic chicane at the exit of 2nd undulator

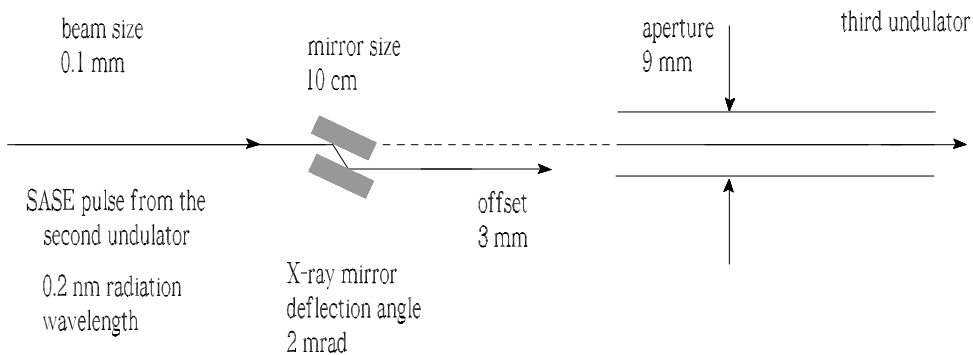
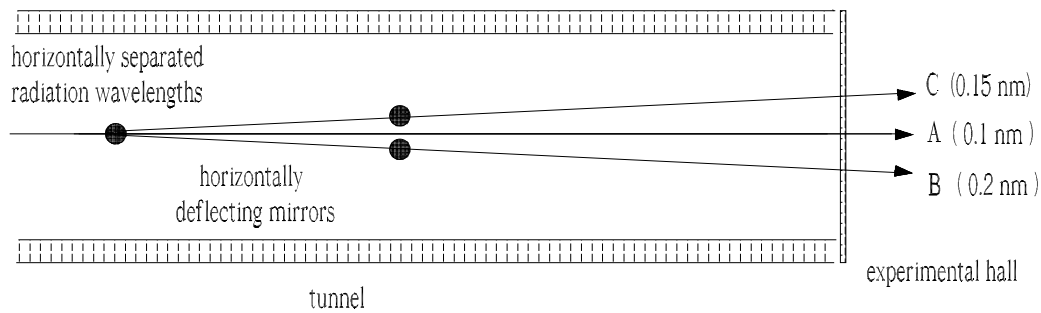


Fig. 17. Scheme for separating the first radiation wavelength with respect to the other within undulator system. Two X-ray mirrors can be installed within additional magnetic chicane at the second undulator exit.

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baseline layout of SASE 2 beam lines



it is possible to distribute the three color photon beam among three independent beam lines

Fig. 18. Baseline layout of the SASE 2 beam lines. It is possible to distribute the three-color photon beam among three independent beam lines. Distribution of photons is achieved on the basis of the horizontal separation of different colors in the baseline undulator.

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