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Scheme for simultaneous generation of three-color ten GW-level X-ray pulses from baseline XFEL undulator and multi-user distribution system for XFEL laboratory

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Abstract

The baseline design of present XFEL projects only considers the production of a single photon beam at fixed wavelength from each baseline undulator. At variance, the scheme described in this paper considers the simultaneous production of high intensity SASE FEL radiation at three different wavelengths. We present a feasibility study of our scheme, and we make exemplifications with parameters of the baseline SASE2 line of the European XFEL operating in simultaneous mode at 0.05 nm, 0.15 nm and 0.4 nm. Our technique for generating the two colors at 0.05 nm and 0.15 nm is based in essence on a "fresh bunch" technique. For the generation of radiation at 0.4 nm we propose to use an "afterburner" technique. Implementation of these techniques does not perturb the baseline mode of operation of the SASE2 undulator. The present paper also describes an efficient way to obtain a multi-user facility. It is shown that, although the XFEL photon beam from a given undulator is meant for a single user, movable multilayer X-ray mirrors can be used to serve many users simultaneously. The proposed photon beam distribution system would allow to switch the FEL beam quickly between many experiments in order to make an efficient use of the source. Distribution of photons is achieved on the basis of pulse trains and it is possible to distribute the multicolor photon beam among many independent beam lines, thereby enabling many users to work in parallel with different wavelengths.

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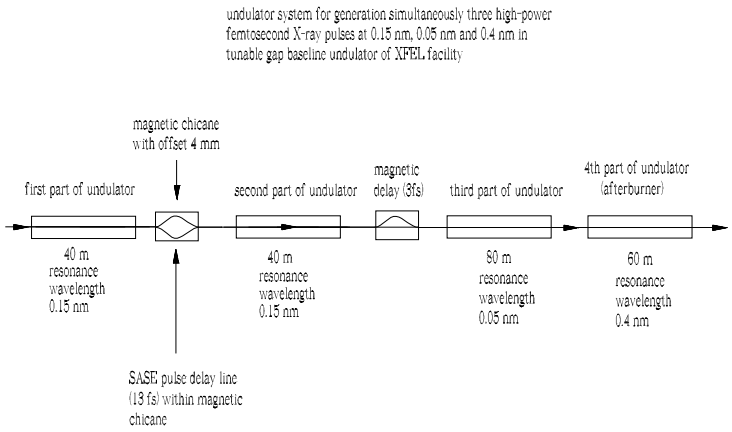

Fig. 1. Design of undulator system for high-power three-color femtosecond X-ray pulse generation.

1 Introduction

Two recent papers of us [1] and [2] discuss the exploitation of the high-performance beam-formation systems available for XFEL facilities. Recent results at LCLS [3, 4] demonstrate that they can work as in the ideal operation scenario. In particular, at LCLS, the small electron-beam emittance achieved (0.4μm with 0.25 nC charge) allows saturation within 20 undulator cells, out of the 33 available.

This optimal scenario should be exploited to provide users with the best possible fruition opportunities. Based on the fresh bunch technique [5]-[7], we suggested a method [1] to use the extra-undulator length available to provide two short (sub-ten fs), powerful (ten GW-level) pulses of coherent x-ray radiation at different wavelengths [2] for pump-probe experiments at XFELs, with minimal hardware changes to the baseline setup. In the following paper [2] we considered a similar approach for extending the spectral range accessible to the European XFEL down to 0.05 nm, by creating simultaneously two ten-fs, ten-GW pulses at 0.15 nm and 0.05 nm. We presented feasibility studies and we made exemplifications with the parameters of the SASE2 line of the European XFEL. In the present paper we extend the method in [2] to include simultaneous operation at three colors, 0.05 nm, 0.15 nm and 0.4 nm, and we subsequently describe a multi-user distribution system based on multilayers, which is proposed as an efficient way to distribute radiation to many users.

The extension of the method proposed in [2], described in section 2, is sketched in Fig. 1, and is justified by the length of the SASE2 undulator (see Table 1), which is about a hundred meters longer than what is needed to

[2] Within the full range of tunability of SASE2, i.e. from 0.1 nm to 0.4 nm.

Table 1
Parameters for the short 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	Short pulse mode
Undulator period	mm	47.9
Undulator length	m	256.2
Segment length	m	6.1
Number of segments	-	42
K parameter (rms)	-	2.513-4.300
β	m	17
Wavelength	nm	0.15 - 4.0
Energy	GeV	17.5
Charge	nC	0.025
Bunch length (rms)	μm	1.0
Normalized emittance	mm mrad	0.4
Energy spread	MeV	1.5

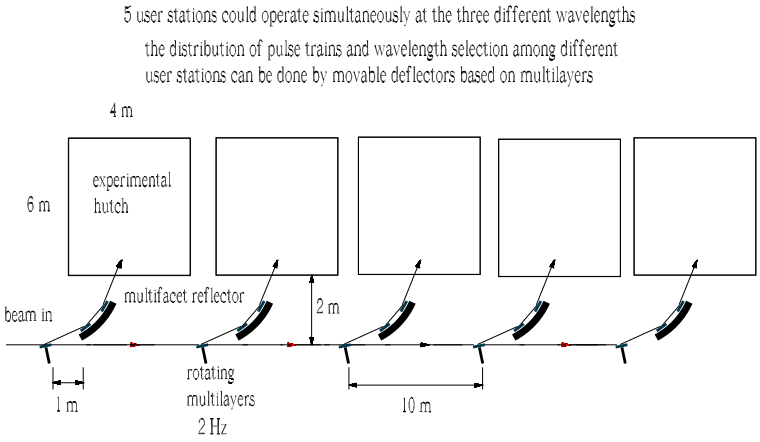

Fig. 2. Proposed SASE undulator beam line. A photon beam distribution system based on movable multilayer X-ray mirrors can provide an efficient way to obtain a multi-user facility. Distribution of photons is achieved on the basis of pulse trains and it is possible to serve simultaneously 5 user stations with (train) repetition rate 2 Hz at three different wavelengths.

implement the technique [2]. The basic idea is to exploit this extra-available length in the "afterburner" mode by letting the spent electron beam emit SASE radiation at a longer wavelength, 0.4 nm, for which the electron beam quality is still good enough to lase. In this way, three superimposed high-intensity pulses of radiation are produced.

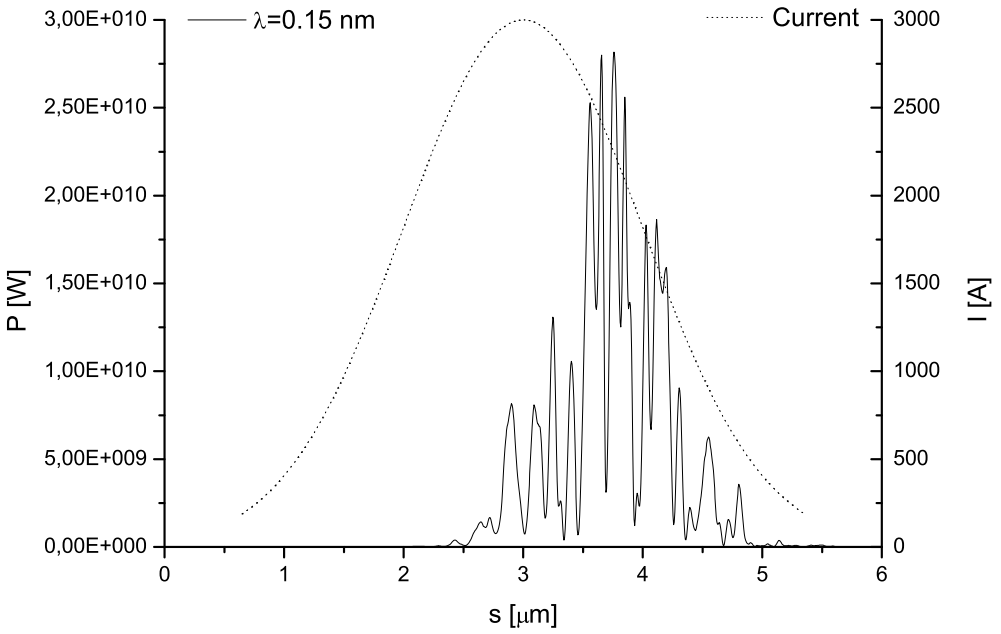

Fig. 3. Beam power distribution at the entrance of the third stage, after the magnetic delay, at 0.15 nm.

Finally, we speculate to optimize the fruition of the three color pulses by installing a photon beam distribution system based on multilayer X-ray mirrors, as sketched in Fig. 2 and discussed in section 3 [8]. With the help of this technique, many user stations can be fed at the same time with the same high-quality photon beam.

2 Feasibility study

The starting point for the feasibility study of the three-color technique is the arrival point of reference [2], where we simulated the simultaneous production of two ten-fs, ten-GW pulses at 0.15 nm and 0.05 nm. We sum up these results in Fig. 3-4 and Fig. 5-6, which show respectively the beam power and spectrum distribution at 0.15 nm at the entrance of the third stage, and the beam power and spectrum distribution at 0.05 nm at the end of the third stage of Fig. 1.

At the entrance of the fourth stage of Fig, 1, the electron beam is spent, and its quality is deteriorated by the lasing process. This fact can be seen by inspecting Fig. 7, where we show the induced energy spread and the energy loss accumulated from the previous FEL interactions. Therefore it is

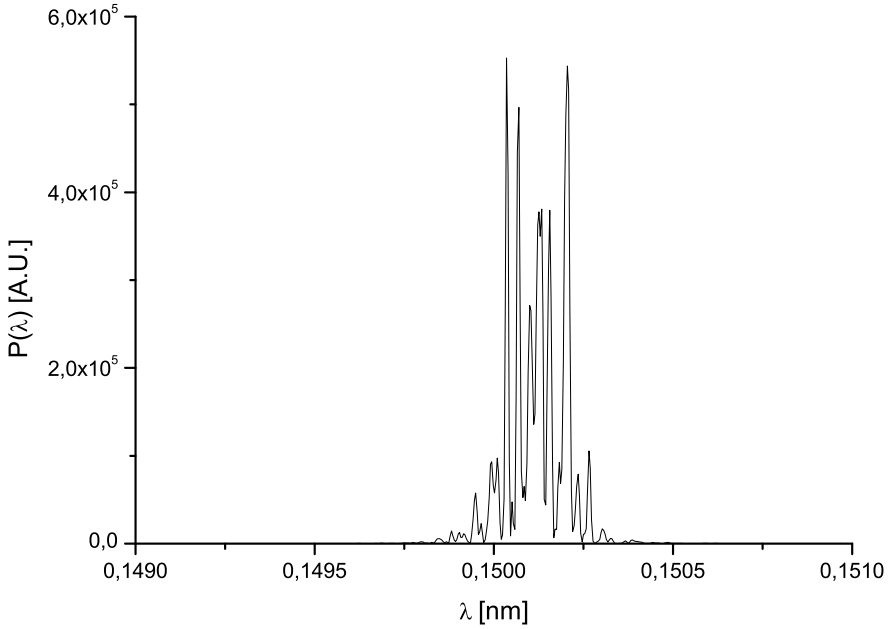

Fig. 4. First harmonic beam power spectrum at the entrance of the third stage.

not possible to lase at the same short wavelengths as in the previous stages. However, requirements on the beam quality for lasing are relaxed going to longer wavelength. This is essentially the "afterburner" concept [13]. Using as before Genesis 1.3 [14] we generate an electron bunch with energy loss and energy spread distributions as in Fig. 7, and we simulate the SASE process in the fourth stage of Fig. 1.

The result of this simulation is shown in Fig. 8 and Fig. 9 in terms of power and spectrum distribution respectively. We stop the simulation after 9 cells, as we obtain a power level comparable with those in Fig. 3 and Fig. 5. However, extra undulator length is available, and the output power of the third color may in principle be increased far beyond 10 GW.

3 Multi-user distribution system based on multilayers.

The typical layout of a SASE FEL is a linear arrangement in which the injector, accelerator, bunch compressors and undulator are nearly collinear, and in which the electron beam does not change the direction between accelerator and undulators. However, it is desirable that an X-ray FEL laboratory could serve tens of experimental stations which should operate independently according to the needs of the user community. In this section we

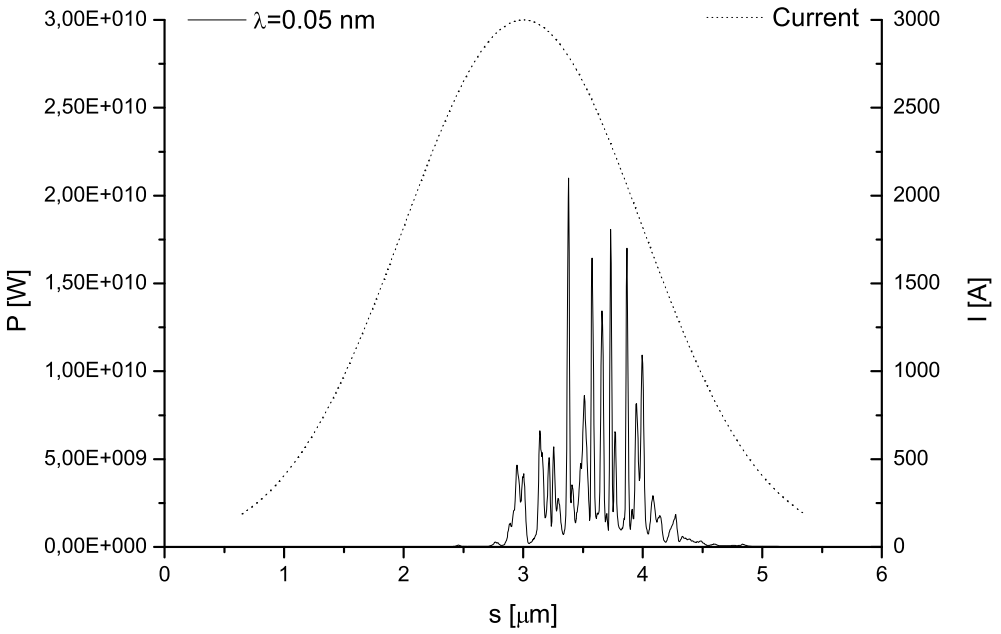

Fig. 5. Beam power distribution at 0.05 nm at the end of the third stage, which is 11 cells-long (67.1 m).

describe a beam distribution system, sketched in Fig. 2, which may allow to switch the FEL beam quickly between many experiments in order to make an efficient use of the source. Many applications require only very high peak brilliance. Experiments for which the average brilliance is not critical could operate simultaneously at the three different radiation wavelengths available.

The technical approach adopted in this variant of the XFEL laboratory design makes use of movable multilayer X-ray mirrors. Layered structures with usually composed by two alternating materials with low and high density respectively. These structures play an important role in synchrotron X-ray optics [9]-[12]. Typical multilayers used as optical elements at third generation synchrotrons provide a spectral bandwidth of 1% to 5%. Typical glancing angles are of the order of a degree and thus lie between the mrad-wide angles of X-ray mirrors and the much wider 10 degree-wide Bragg angles of single crystals. The angular acceptance of X-ray multilayer mirrors is of the order of a mrad (for a bandwidth 1%). As a rule, from 100 to 400 layers (each about 10 nm-thick) participate in the effective reflection in such mirrors. About 90% peak reflectivity was achieved for wavelengths around 0.1 nm. Computer simulations are in very good agreement with experimental results in all cases, so that efficiencies can be safely predicted.

Fig. 10 shows the relevant photon beamline configuration. The distribution

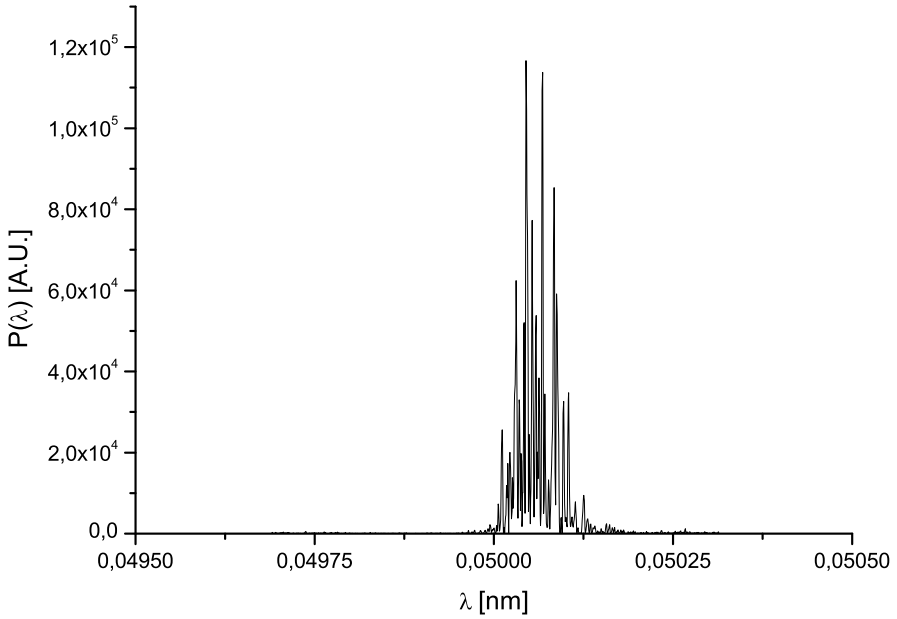

Fig. 6. Third harmonic beam power spectrum at the end of the third stage.

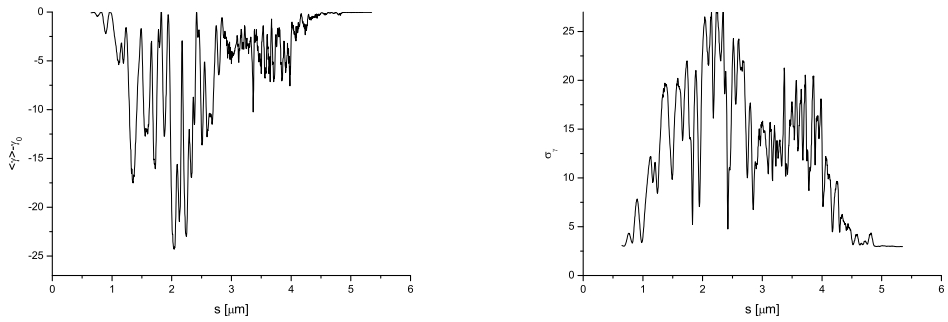

Fig. 7. Electron beam energy loss (left) and induced energy spread (right) at the end of the third stage, which is 11 cells-long (67.1 m).

of pulse trains among the different user stations can be done by movable deflectors. A schematic diagram of a movable deflector is shown in Fig. 11. Its key components include rotating multilayers and a multifacet reflector.

The advantages of using multilayer mirrors as movable photon beam deflectors are manyfold. First, multilayer mirrors are characterized by larger deflection angle compared to X-ray mirrors. As a result, the length of a multilayer mirror required for deflecting photon beam with transverse size order of fraction of mm is in the ten-cm scale. In contrast to this, X-ray mirrors performing the same function are in the meter-scale length. Second, the bandwidth of the multilayer reflectivity is much wider compared

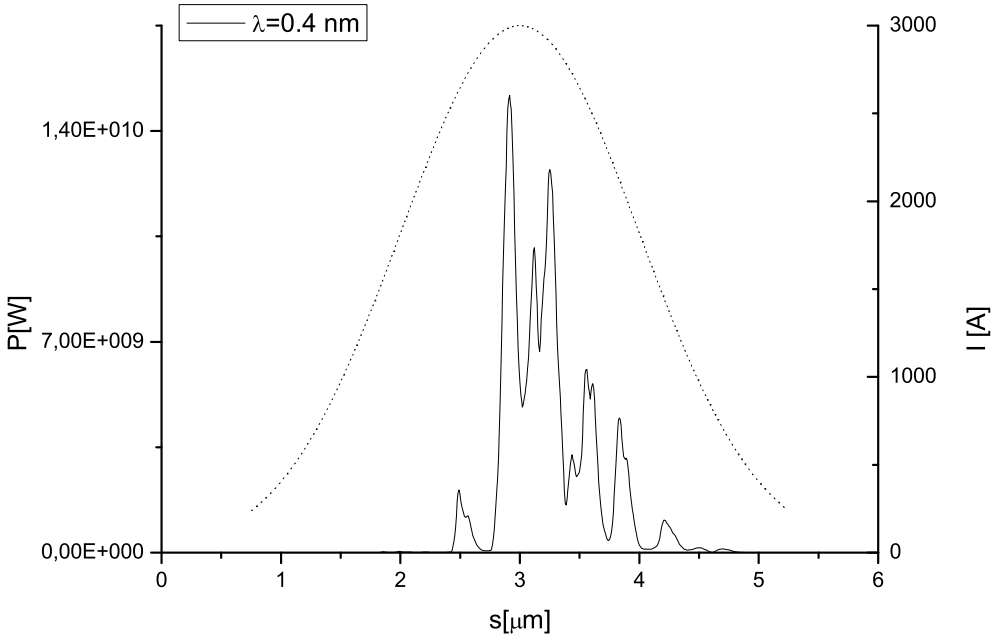

Fig. 8. Beam power distribution at 0.4 nm at the end of the fourth stage, which is 9 cells-long (54.9 m).

to crystals, and it can be possible to deflect the full spectrum of the SASE radiation pulse without perturbation. It should be noted that in the ideal case, multilayer mirrors keep the angular beam divergence constant. Third, the bandwidth of multilayer mirrors is much smaller than unity and there is a possibility in our case to deflect only a single color beam when we deal with multi-color pulse generation.

In order to achieve stable photon beam deflection the alignment accuracy of multilayer deflectors must be less than 0.1 mrad. It is believed that technology will enable rotating multilayers to satisfy these requirements. The initial photon beam will thus be transformed into 5 different beams. The switching mirrors need to rotate (for European XFEL laboratory case) at a frequency of 2 Hz such that each user actually receives two trains of pulses with a duration of 1 ms per second. Note that even if the photon beam is distributed among many users, the peak flux per user remains untouched (apart from the losses in the deflector system). All users will receive a photon beam of identical, high quality.

It should be noted that the deflection process happens only once during the pass of a given photon beam through the deflector unit. Also, the deflection process requires three multilayers mirror only, Fig. 11, so that the problem of absorption of the radiation in the distribution system does not exist. Another advantage of this method comes from the small (one to few

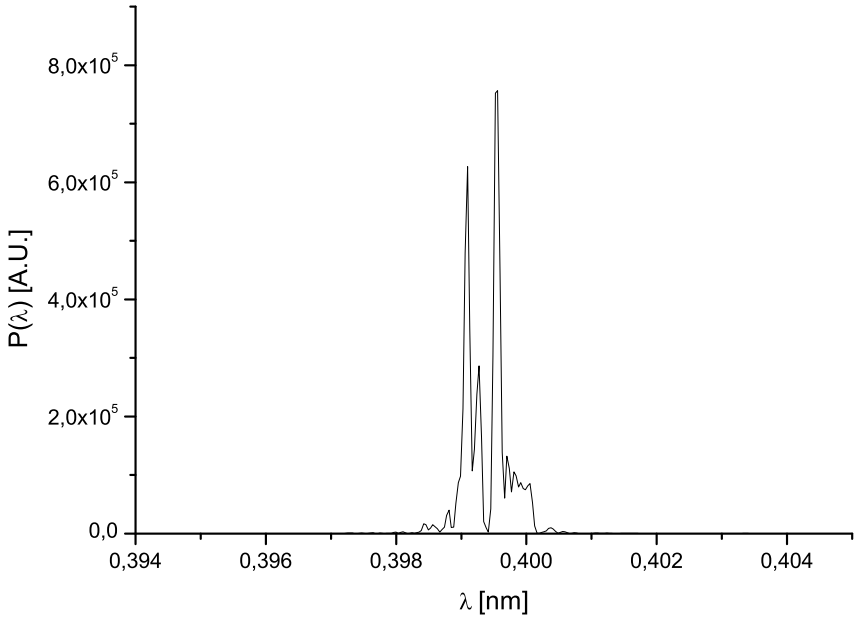

Fig. 9. Beam power spectrum around 0.4 nm, at the end of the fourth stage.

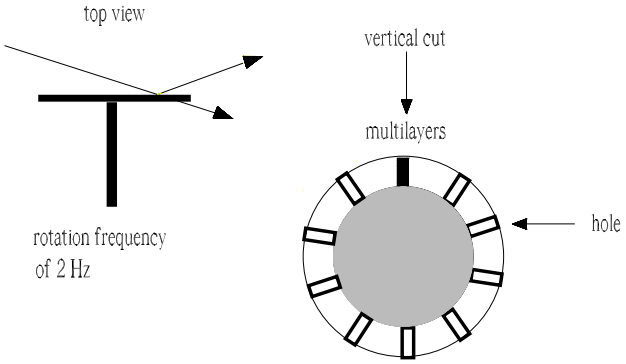

Fig. 10. Different views of a switching multilayer mirror.

microradians) angular divergence of the XFEL radiation. In fact, in an extended sequence of deflectors (say a few tens of meters), Fig. 2, the photon beam spot size remains unchanged. Finally, another attractive feature of the proposed photon distribution system is a high degree of flexibility: if some user will request a full photon flux for a given time, such request may be granted simply by ”freezing” the motion of the multilayer mirrors for a certain time, so that the full photon flux will be directed to a single, dedicated user station.

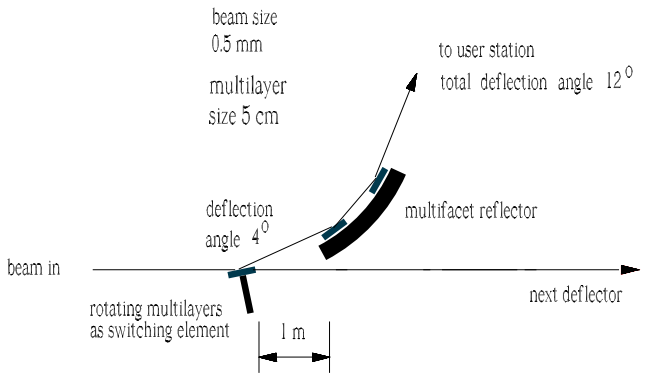

Fig. 11. Concept of the photon beam deflector based on multilayer X-ray mirror.

4 Conclusions

In this article we discuss the possibility of extending the technique in [2] to three colors. This is feasible due to the relatively short undulator length needed for the exploitation of the two-colors technique. The technique itself is fairly straightforward, and consists in the use of the remaining part of the undulator as an afterburner. We exemplified the proposed technique for the baseline parameters of SASE2 at the European XFEL. In particular, we showed how three sub-ten fs, 10 GW power level pulses can be simultaneously produced at 0.4 nm, 0.15 nm and 0.05 nm. As for the method described in [2], the present method requires very limited hardware too and is low cost. Moreover, it carries no risks for the operation of the machine in the baseline mode.

Subsequently, we speculate on how many users may simultaneously take advantage of these pulses in an effective way. In fact, the typical geometry of a SASE FEL where injector, accelerator, bunch compressors and undulator are nearly collinear, does not seem suitable for simultaneous operation of many users. However, a different concept of the XFEL laboratory allows one to simultaneously serve the need of multiple users. We propose to consider a multi-user distribution system based on multilayer X-ray mirrors, which allow many user stations to work in parallel with the same high-quality X-ray beams.

Finally, it should be noted that even if we discuss the case of the European XFEL, our technique may be taken advantage of by other facilities as well.

5 Acknowledgements

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