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The potential for extending the spectral range accessible to the European XFEL down to 0.05 nm

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Abstract

Specifications of the European XFEL cover a range of wavelengths down to 0.1 nm. The baseline design of the European XFEL assumes standard (SASE) FEL mode for production of radiation i.e. only one photon beam at one fixed wavelength from each baseline undulator with tunable gap. Recent developments in the field of FEL physics and technology form a reliable basis for an extensions of the mode of operation of XFEL facilities. This paper explores how the wavelength of the output radiation can be decreased well beyond the European XFEL design, down to 0.05 nm. In the proposed scheme, which is based on the use "fresh bunch" technique, simultaneous operation at two different wavelengths possible. It is shown that one can generate simultaneously, in the same baseline undulator with tunable gap, high intensity radiation at 0.05 nm at saturation, and high intensity radiation around 0.15 nm according to design specifications. We present a feasibility study and we make exemplifications with the parameters of SASE2 line of the European XFEL.

1 Introduction

Three X-ray Free-Electron Lasers (XFELs), LCLS [1], SCSS [2], and the European XFEL [3] are currently under commissioning or under construction. These machines are based on the Self-Amplified Spontaneous Emission (SASE) process [4]-[7]. Lasing at wavelength as short as 0.15 nm has been recently demonstrated at LCLS [8], together with operation with electron bunch durations of less than 10 fs [9]. Also, at LCLS saturation has been reached within 20 undulator cells, out of the 33 available. This result has

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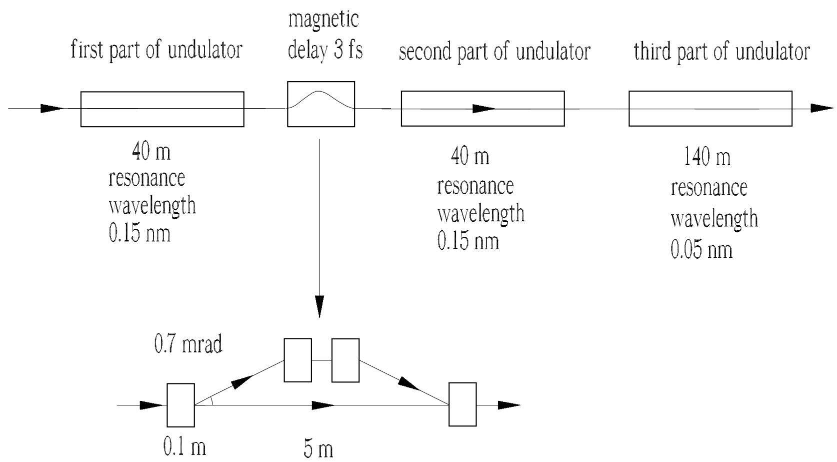


Fig. 1. Design of the undulator system for the generation of high power femtosecond SASE pulses at 0.05 nm. The scheme is based on the use of a fresh bunch technique. The FEL amplification process at 0.05 nm starts up from shot noise. As a result, the third part of the undulator must be relatively long, but the hardware is simpler compared to the self-seeding option discussed in this paper.

been enabled by the high-performance beam-formation system at LCLS, which works as in the ideal operation scenario.

This optimal scenario should be exploited to provide users with the best possible fruition opportunities. Elsewhere [10] we suggested 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 for pump-probe experiments at XFELs, with minimal hardware changes to the baseline setup.

In principle, the scheme proposed in [10] can be easily extended to generate radiation down to 0.05 nm. The scheme is illustrated in Fig. 1. The first two parts of the undulator generate radiation at 0.15 nm, based on a fresh bunch technique according to the method illustrated in [10]. The heading half of the bunch is seeded by the radiation produced in the first part of the undulator, and saturates in the second part, while the rear part of the bunch enters the linear regime in the SASE mode. As a result, the rear part of the electron bunch is still suitable for the SASE process in the third undulator part. After the second part we still have about 160 m of undulator available for SASE2, so that we can reach a high power level at a different wavelength, in our case 0.05 nm. In particular, our calculations are performed for SASE2 assuming that the third part of the undulator is 26 modules-long, corresponding to 158.6 m. Results are shown in Fig. 2, which include the radiation pulse at 0.15

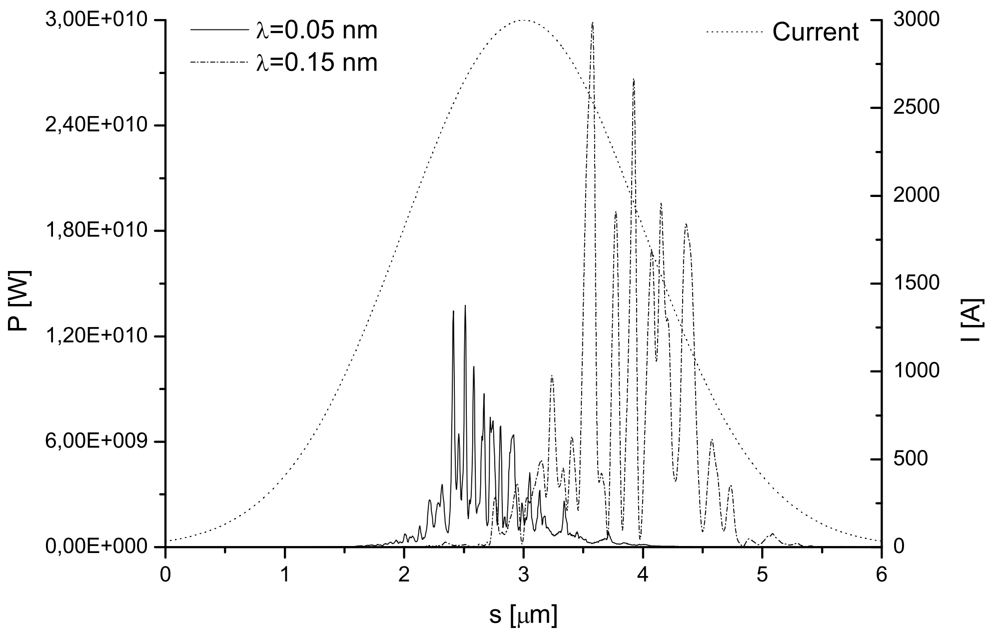


Fig. 2. Superimposed radiation pulses at 1.5Å and 0.5Å. The bunch current is also shown.

nm, as discussed in [10] and the short wavelength emission at 0.05 nm. Fig. 2 demonstrates that two femtosecond, ten GW level pulses of coherent x-rays with two different colors at 0.15 nm and 0.05 nm can be generated with this method. The advantage of this method is in the simple hardware required (only a short magnetic chicane) and in the possibility of independently tuning the wavelengths of both pulses. However, a fairly long undulator is needed. Note that the LCLS is equipped with a shorter undulator than SASE2. Therefore, for LCLS the requirement of a shorter undulator is of crucial importance, while for SASE2 this option can be practically realized.

In this paper we propose a scheme for the simultaneous generation of two maximal-power pulses of radiation around 0.1 - 0.15 nm and at 0.05 nm, using an undulator which is about 100 m shorter than the nominal SASE2 length, so that the extra-available undulator length can be kept for other purposes. This scheme is especially important for shorter undulators like for SASE1 and LCLS, which have fixed gap and can operate at fixed wavelength only. Technically, the gap of these undulators can be tuned to 0.05 nm and fixed once and for all. For this kind of undulators our scheme gives the possibility to tune and fix the gap so to keep the design mode operation at 0.1 - 0.15 nm and add an extra operation-mode at 0.05 nm. By this, we answer the interest of the scientific community towards shorter operation wavelengths, which would e.g. enable better spatial resolution in elastic x-ray scattering experiments, providing at the same time less photoelectric

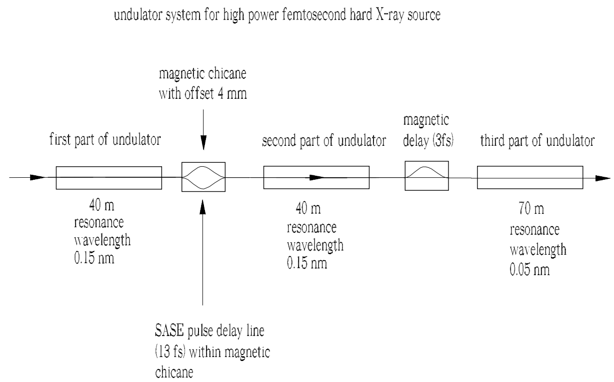


Fig. 3. Undulator system for generation high power femtosecond SASE pulse at 0.05 nm

absorption, longer penetration depth, less damage and larger scattering volume [11].

The overall idea is sketched in Fig. 3. In the first part of the undulator, SASE radiation is produced at 0.15 nm in the linear regime and in the short-bunch operation mode, according to the parameters in Table 1, and described in more detail in [10]. At the next step, the electron beam passes through an optical-delay stage composed by a mirror chicane and a magnetic chicane. The optical delay-stage delays the photon beam with respect to the electrons of about half of the bunch length. The magnetic chicane performs two actions. First, it allows for the installation of the mirror chicane. Second, the strength of magnetic chicane as dispersion section is sufficient for suppression of the beam bunching [10]. As a result, the amplification process in the second undulator section starts with a "fresh" electron beam, and with radiation produced by the first undulator section. This is the essence of the "fresh bunch" technique which was introduced in [12]-[14]. Subsequently, in the second part of the undulator the seeded half of the electron beam saturates within a short distance, while the non-seeded half of the electron beam lases in the linear regime only and remains unspoiled. Superimposed to the main first-harmonic pulse there is a percent-level (100 MW-level) third-harmonic pulse at 0.05 nm. The third-harmonic component is superimposed to the non-seeded half of the electron beam by delaying the electrons with respect to the photon beam with the help of a magnetic chicane between the second and the third part of the undulator. Then, the fresh bunch half of the bunch is fed into the third undulator part together with the first and the third harmonic pulse, Fig. 3. The third undulator part is tuned at 0.05 nm, so that the first harmonic pulse is not resonant, while the 100 MW-level third-harmonic pulse acts as seed and enables production of a 10 GW-level pulse at 0.05 nm at the exit of the third undulator part.

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
Length of undulator segment	m	5.0
Length of intersection	m	1.1
Total number of undulator cells	-	42
K parameter (rms)	-	1.201-2.513
β	m	17
Wavelength	nm	0.05 - 0.15
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

2 Feasibility study

In the following we describe the outcomes of computer simulations using the code Genesis 1.3 [16].

2.1 First stage

In the first undulator part, which is 7 cells long, each consisting of a 5m-long undulator segment and a 1.1m-long intersection, for a total length of 42.7 m. The beam power distribution is shown in Fig. 4. The electron beam energy loss and the induced energy spread are shown in Fig. 5. A short (sub 10 femtosecond) pulse of radiation is produced in the linear regime (100 MW level). Calculations are identical to the first stage of the pump-probe scheme reported in [10].

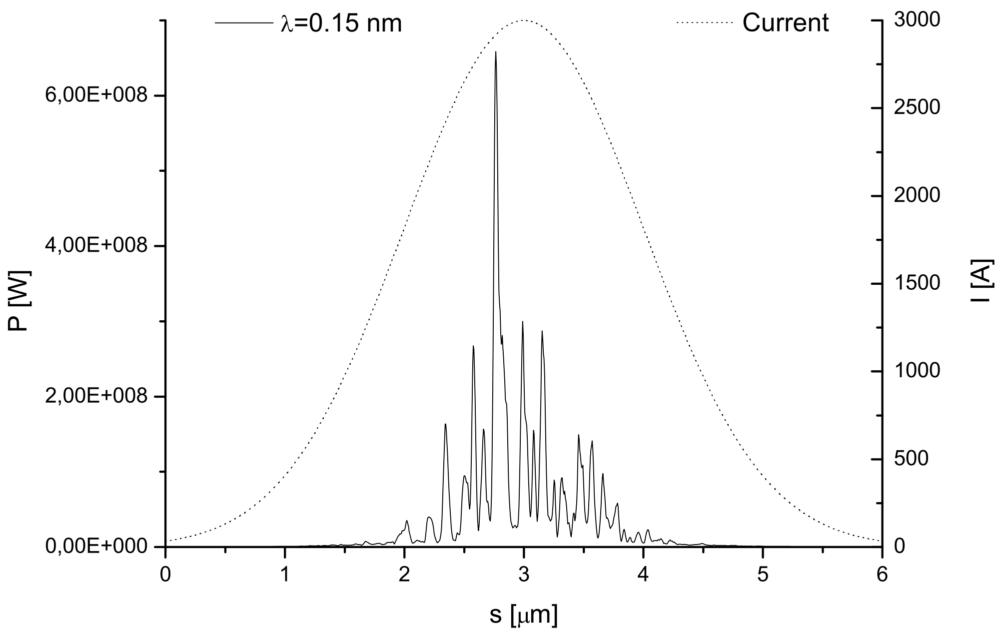


Fig. 4. Beam power distribution at the end of the first stage after 7 cells (42.7 m).

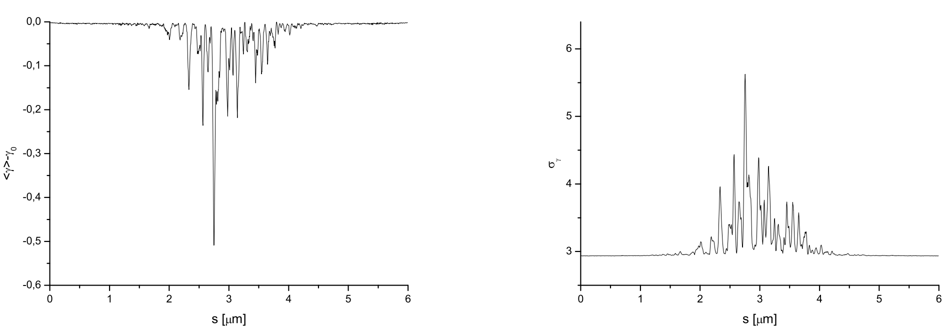


Fig. 5. Electron beam energy loss (left) and induced energy spread (right) at the end of the first stage after 7 cells (42.7 m).

2.2 *Optical delay*

At variance with respect to the pump-probe scheme in [10], the present scheme uses from the very beginning an optical delay stage. This choice is justified by the larger glancing angle for the radiation at 0.15 nm, which is about 2 mrad, with respect to that at 0.05 nm, which is 1 mrad only. The idea is to install a mirror chicane between the first and the second part of the undulator, as shown in Fig. 6. Issues concerning heat load and size of the mirror have already been discussed in [10].

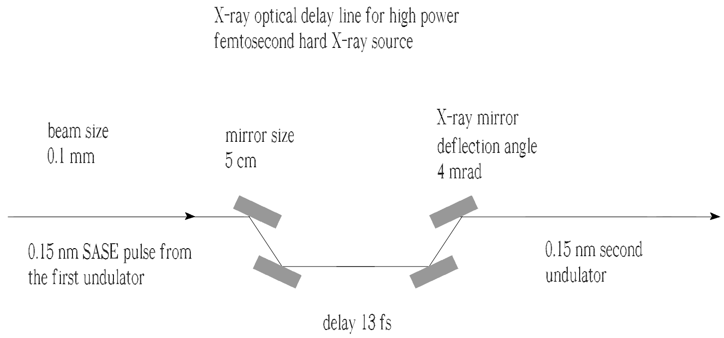


Fig. 6. X-ray optical delay line for high power hard X-ray source.

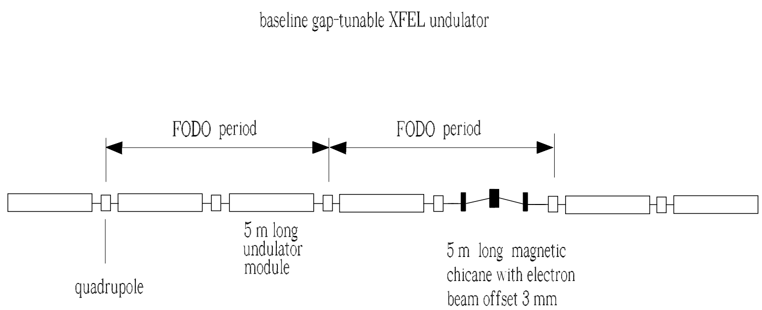


Fig. 7. Installation of a magnetic delay in the baseline XFEL undulator.

Of course, in order to install the mirror chicane one needs to first create an offset for the electron trajectory, meaning that a magnetic chicane should be inserted at the position of the mirror-chicane, Fig. 7. Such chicane has also the function of washing out electron beam density modulations on the 0.15 nm-scale. Issues concerning this possibility have also been discussed in [10].

The mirror chicane can be built in such a way to obtain a delay of the SASE pulse of about 13 fs. This is enough to compensate a bunch delay of about 10 fs from the magnetic chicane, and to provide the temporal shift in the range 3 fs, as shown in Fig. 8. It should be noted that the distance between quadruples in FODO lattice is 6.1 m, while in our scheme the length of chicane is 5 m only, so that the focusing system is not perturbed.

As a result of the passage through the magnetic chicane, the photon beam is delayed with respect to the electron beam of about 1 μm. The electric field fed into the simulation of the second part of the undulator is shown in Fig. 9. The electron beam used is generated according to the energy spread and

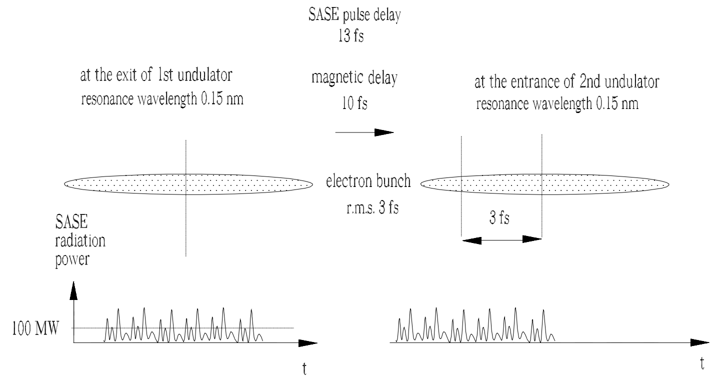


Fig. 8. Sketch of high power 0.05 nm X-ray pulse generation in the baseline XFEL undulator. First stage: "fresh" bunch technique.

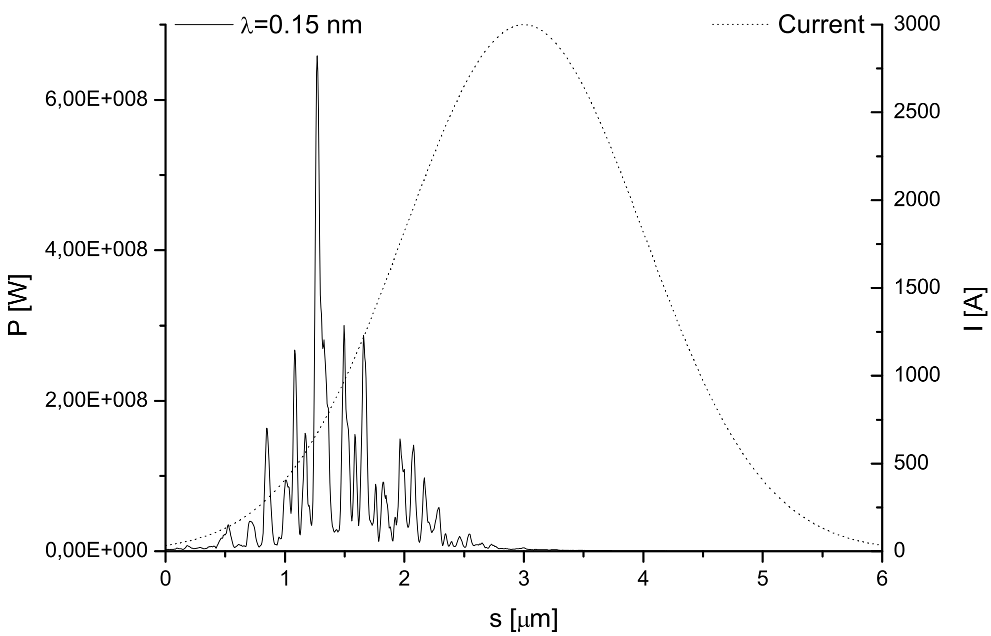


Fig. 9. Beam power distribution at 0.15 nm after the optical delay.

energy loss distributions in Fig. 5, similarly as done in [10].

2.3 Second stage

In the second undulator part, the seeded half of the electron bunch reaches saturation with ten GW power level. The second undulator part is taken to be another 7 cells long. The output power distribution and spectrum is

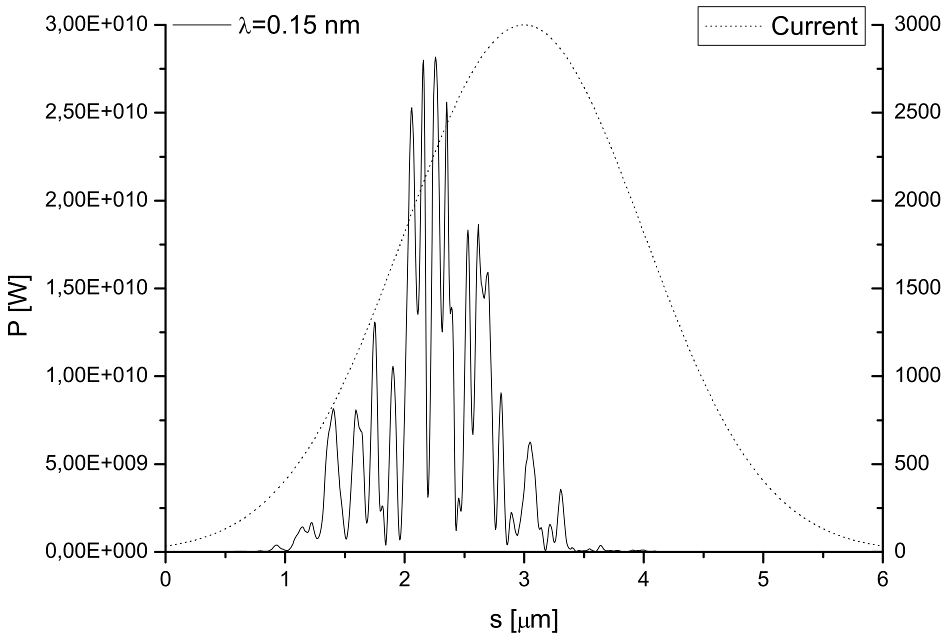


Fig. 10. Beam power distribution at the end of the second stage, 7 cells long (42.7 m).

shown in Fig. 10 and Fig. 11, while energy loss and energy spread are plotted in Fig. 12. The right part of the electron bunch produces SASE radiation in the linear regime only, which is negligible.

2.4 Magnetic delay

Together with the saturated first harmonic pulse, the radiation pulse produced by the seeded (left) half of the electron bunch also includes some percent-level third harmonic contents. Letting the bunch through a short chicane, we effectively let the radiation pulse slip forward [2] and seed the fresh (right) half of the electron bunch, Fig. 13. The effect of the chicane on the relative position between electrons and photons is shown in Fig. 14. First and third harmonic pulses will be superimposed, but if the third part of the undulator is resonant with the third harmonic only, the first harmonic will not be of interest as concerns the SASE process. As a result, in our simulations, we simulate the magnetic delay by extracting the third harmonic content and shifted it right with respect to the electron bunch. The result is shown in Fig. 15.

[2] In these simulations, the shift amounts to 1.5μm.

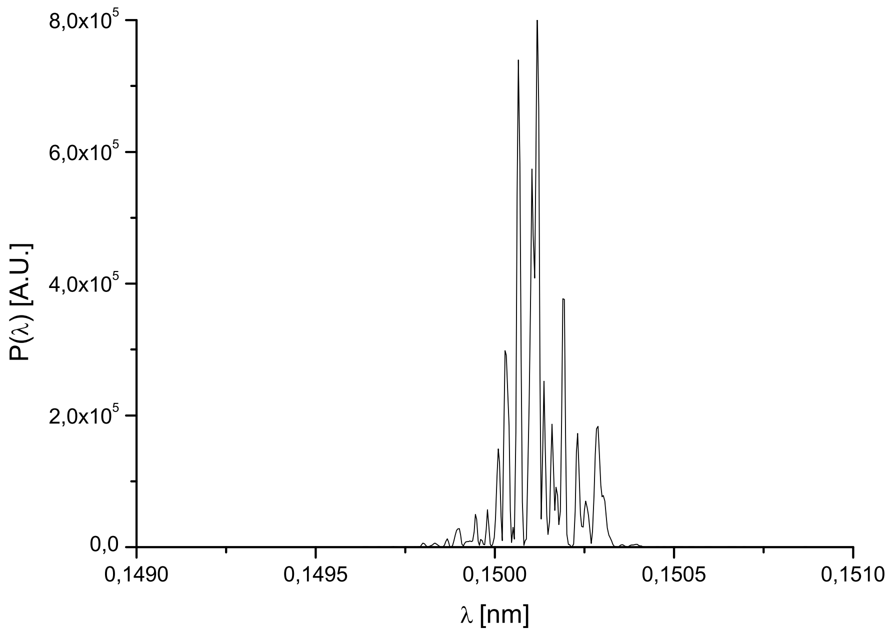
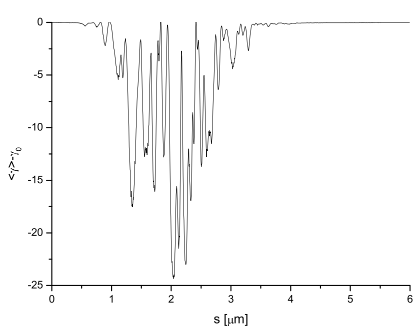


Fig. 11. Beam power spectrum at the end of the second stage, 7 cells long (42.7 m).



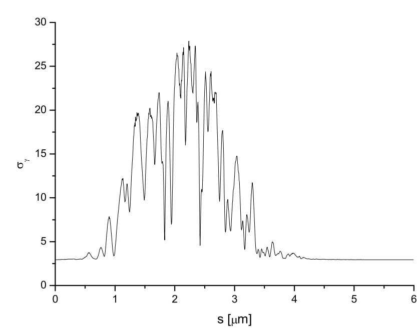


Fig. 12. Electron beam energy deviation (left) and induced energy spread (right) at the end of the second stage, 7 cells long (42.7 m).

2.5 Third stage

Following the optical delay, we model the third part of the undulator, which is 11 cells-long (67.1 m), by feeding the third harmonic seed in Fig. 15 into the simulation code. Similarly as before, the electron beam used is generated according to the energy spread and energy loss distributions in Fig. 12.

The output power distribution and spectrum is shown in Fig. 16 and Fig. 17, while energy loss and energy spread are plotted in Fig. 18.

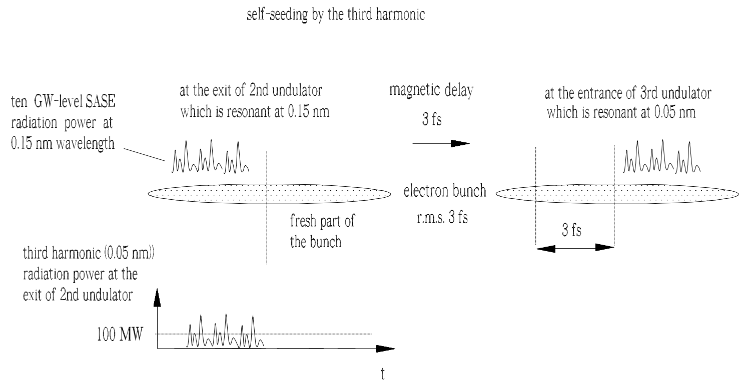


Fig. 13. Sketch of third harmonic amplification from second to third undulator. Ten GW-level on fundamental and third harmonic can be reached simultaneously by using combination fresh bunch technique and self-seeding technique.

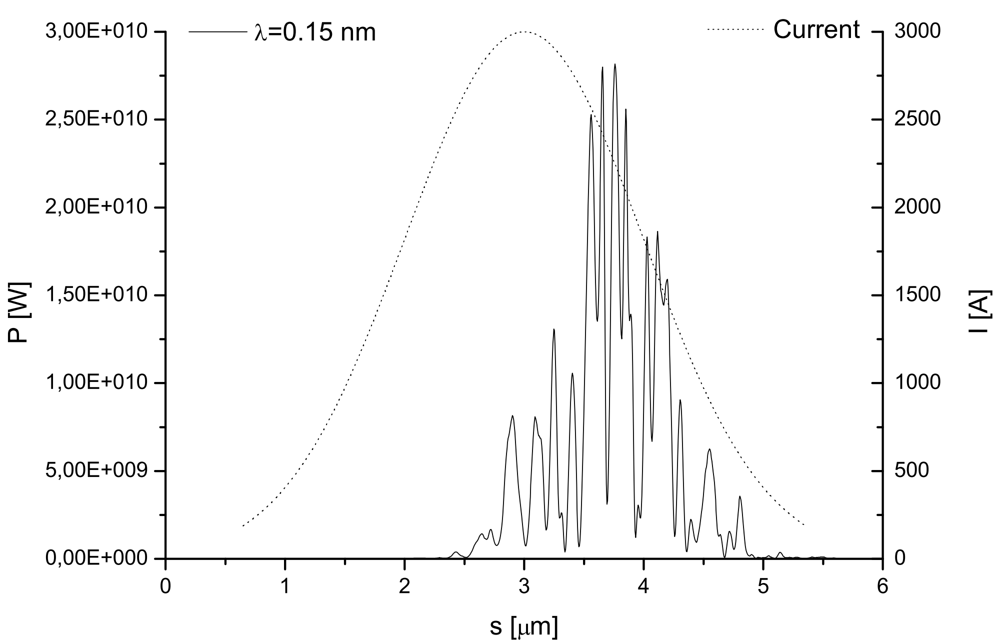


Fig. 14. Beam power distribution at the entrance of the third stage, after the magnetic delay, at 0.15 nm.

2.6 Results

Fig. 14 and Fig. 16 constitute our main results. Note that the two pulses at 0.15 nm and 0.05 nm are actually superimposed one on top of the other. Like in the case discussed elsewhere [10], one faces the task of transport and utilization of the two radiation pulses to the experimental station. Transport

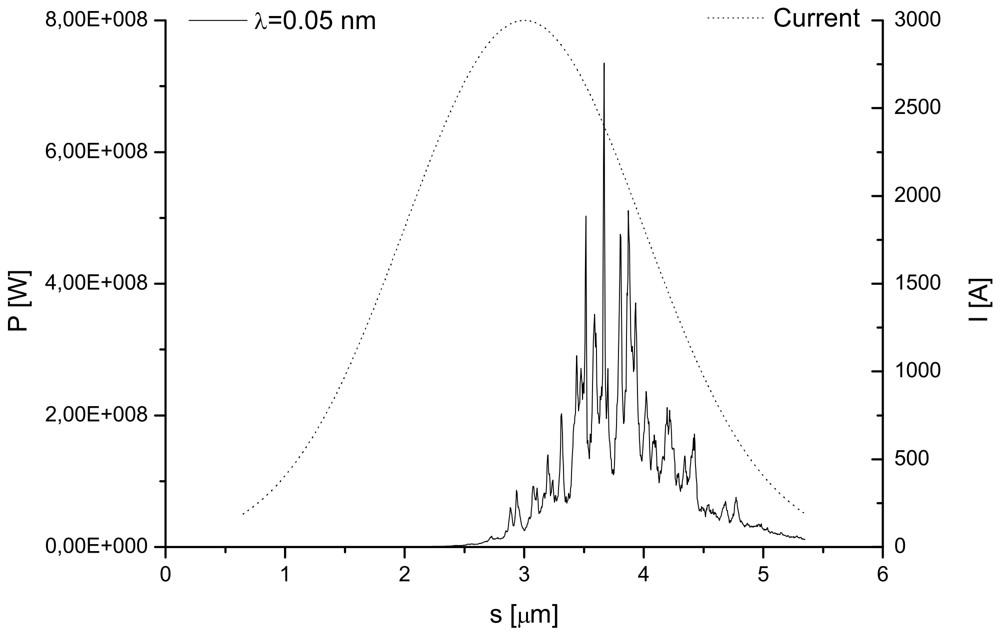


Fig. 15. Beam power distribution at the entrance of the third stage, after the magnetic delay, at 0.05 nm.

can be performed with the same optics without problems, but utilization of the two pulses implies the capability of separating the two pulses at the experimental station. Investigating this capability goes beyond the scope of this paper.

3 Conclusions

In this paper we propose a technique to extend the baseline wavelength range of the European XFEL up to 0.05 nm. Simultaneously, together with the short-wavelength pulse, a longer wavelength pulse of similar duration and power is produced at 0.15 nm.

Two recent developments in FEL physics have made our technique feasible. First, the lasing of LCLS and the possibility of working in the low-charge mode of operation [8, 9]. Second, the invention in [10] of a new kind of fresh bunch technique [12] allowing for the production of two color pulses with similar frequency, which relies on a single electron bunch passing two parts of the same undulator setup, separated with magnetic delay. Also the scheme proposed in this paper is based on letting the same electron bunch radiate in separate undulator stages separated with optical delays

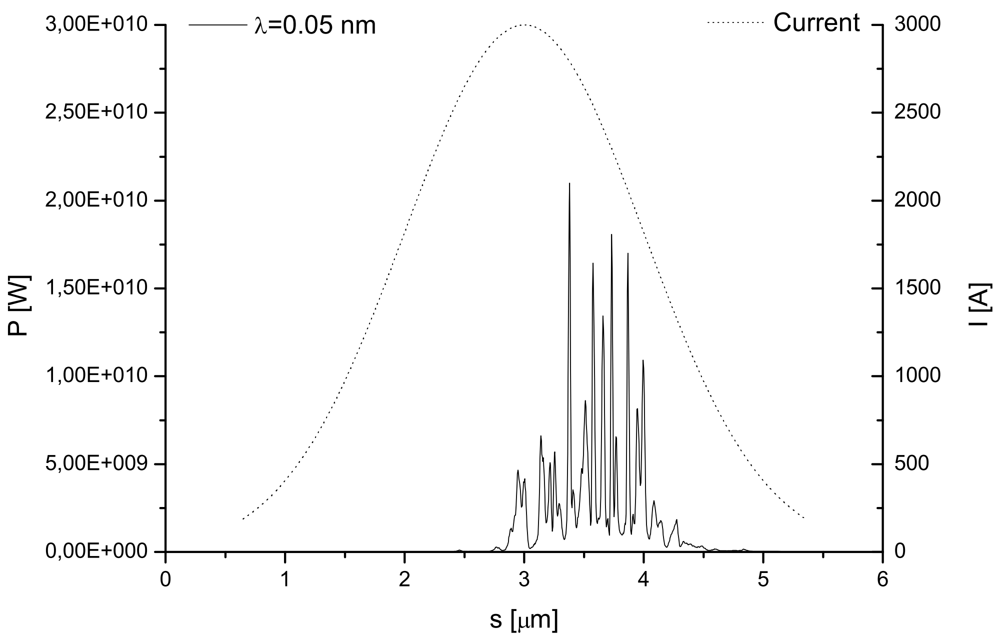


Fig. 16. Beam power distribution at the end of the third stage, which is 11 cells-long (67.1 m).

and magnetic chicane.

The technique itself is fairly straightforward. Following the first stage, where seed radiation is produced at 0.15 nm in the linear regime, an optical delay stage enables one half of the electron beam to interact with the seed. After saturation at the end of the second stage the third harmonic component of the radiation is further used as a seed in the third stage, which is resonant at 0.05 nm wavelength. This undulator is long enough (70 m) to reach saturation at the wavelength of 0.05 nm. In the third undulator the radiation at 0.15 nm plays no role and is diffracted out of the electron beam.

As the method in [10], 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. Even though we discuss the case of the European XFEL, our technique may be taken advantage of by other facilities as well.

4 Acknowledgements

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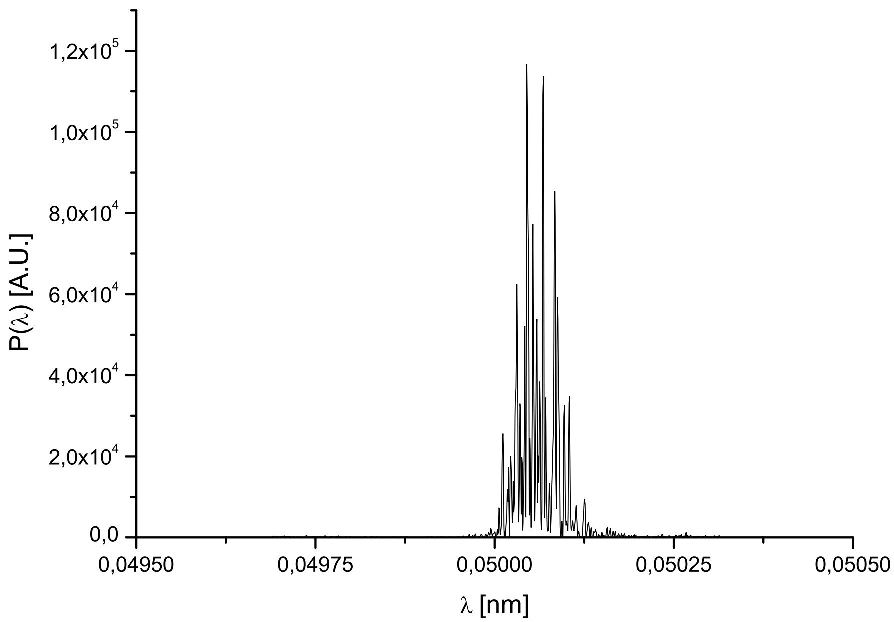

Fig. 17. Beam power spectrum at the end of the third stage, 11 cells-long (67.1 m).

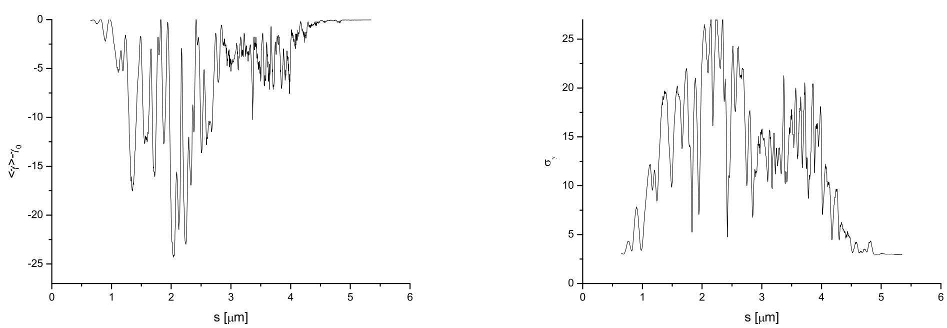

Fig. 18. Electron beam energy deviation (left) and induced energy spread (right) at the end of the third stage, which is 11 cells-long (67.1 m).

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