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The Potential for Extending the Spectral Range Accessible to the European X-ray Free Electron Laser in the Direction of Longer Wavelengths

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Abstract

The baseline specifications of European XFEL give a range of wavelengths between 0.1 nm and 2 nm. This wavelength range at fixed electron beam energy of 17.5 GeV can be covered by operating the SASE FEL with three undulators which have different period and tunable gap. A study of the potential for the extending the spectral range accessible to the XFEL in the direction of longer wavelengths is presented. The extension of the wavelength range to 6 nm would cover the water window in the VUV region, opening the facility to a new class of experiments. There are at least two possible sources of the VUV radiation associated with the X-ray FEL: the "low (2.5 GeV) energy electron beam dedicated" and the "17.5 GeV spent beam parasitic" (or "after-burner") source modes. The second alternative, "after-burner undulator" is the one we regard as the most favorable. It is possible to place an undulator as long as 80 meters after 2 nm undulator. Ultimately, VUV undulator would be able to deliver output power approaching 100 GW level. A beam from this device could be run in pump-probe mode with the X-ray FEL.

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1 Introduction

Baseline design of present European XFEL project [1] assumed only standard (SASE FEL) mode for production of radiation. Recent developments in the field of FEL physics and technology form a reliable basis for perspective extensions of the XFEL facility. In [2] we proposed a concept of XFEL laboratory which will allow to implement perspective features from the very beginning of operation. These extra features include delivery of X-ray pulses in the attosecond regime, increasing of the FEL power (up to sub-TW level), simultaneous multi-undulator capability. A photon beam distribution system based on movable multilayer X-ray mirrors can provide an efficient way to organize a multi-user facility. Distribution of photons is achieved on the basis of pulse trains and it is possible to partition the photon beam among a few tens independent beamlines thereby obtaining many users working in parallel.

The further development discussed in this paper concerns the expanded photon energy range. The baseline specifications of European XFEL give a range of wavelengths between 0.1 nm and 2 nm. It would be extremely interesting to extend this range into so-called "water window", i.e. the range between the K-Absorption edges of carbon and oxygen at 4.38 nm and 2.34 nm, respectively. This paper explores ways in which the wavelength of output radiation can be increased well beyond the XFEL design. It will be shown that the flexibility of the XFEL design proposed in [2] allows a considerable expansion in reachable FEL photon energy in the direction of longer wavelengths. The wavelength range 0.1-6 nm at fixed electron beam energy of 17.5 GeV can be covered by operating the SASE FEL with four undulators which have different period and tunable gap. In proposed ("after-burner") scheme it will be possible to provide in parallel hard (around 0.1 nm) and VUV radiation for two photon beamline. The extension of the wavelength range to 6 nm would cover the water window, opening the facility to a new class of experiments. For example, in some modes of operation, VUV FEL radiation could be used with X-ray FEL radiation to do pump-probe experiments with precise intervals between the sources.

2 VUV radiation from the European XFEL

This study will consider two possibilities: the first is based on "electron switchyard" technique. Figure 1 shows the schematic layout of the switchyard and the undulator beamlines togeter with the accelerator. The electron beam (at energy of 2.5 GeV) is extracted from the main linac and enters transport line, which guides it to the VUV undulator located near the experimental hall. The beam distribution system consists of two transport lines. The first beamline (2.5 GeV) directs one bunch train, coming to the "water window" undulator.

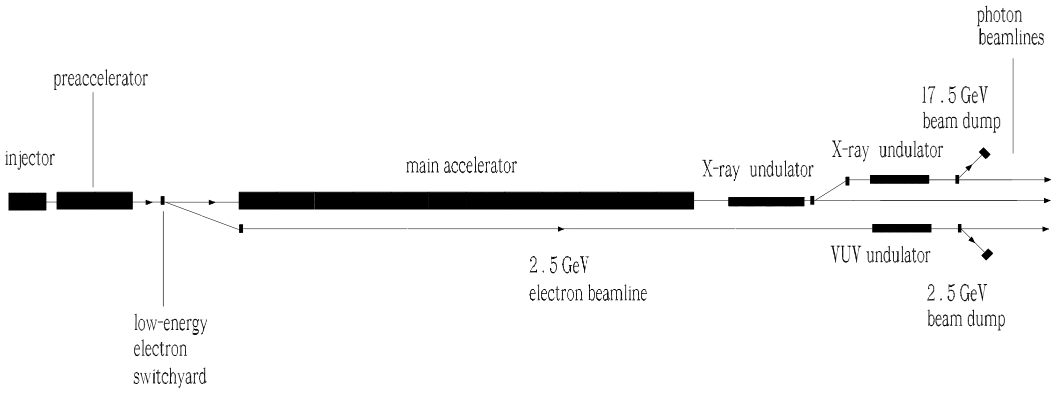

Fig. 1. Schematic layout of the first possible strategy for VUV radiation. This scheme is based on the "electron switchyard" technique

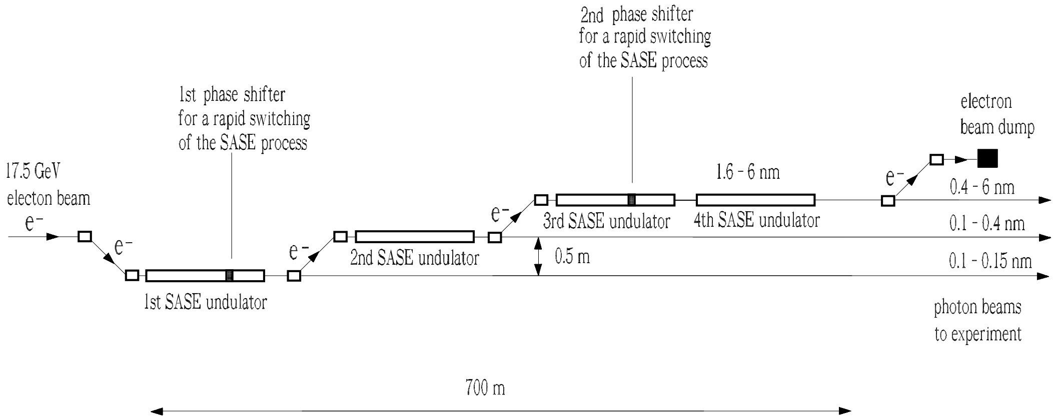

Fig. 2. Schematic layout of the most favorable strategy for VUV radiation. In this scheme it will be possible to provide simultaneously hard X-ray and VUV radiation beams ("after-burner" mode of operation)

The second beamline (17.5 GeV) takes every other bunch train and delivers it to X-ray undulators.

Figure 2 illustrates the second (baseline energy) option. This alternative is the one we regard as most favorable. The second option holds the energy at the baseline value (17.5 GeV) and chooses the undulator period length to match the water window wavelengths. Tables 1 and 2 present optimized parameters of undulator and FEL performance applied to "water window" wavelength range with the electron energy of 2.5 GeV, and for the case of the maximum available

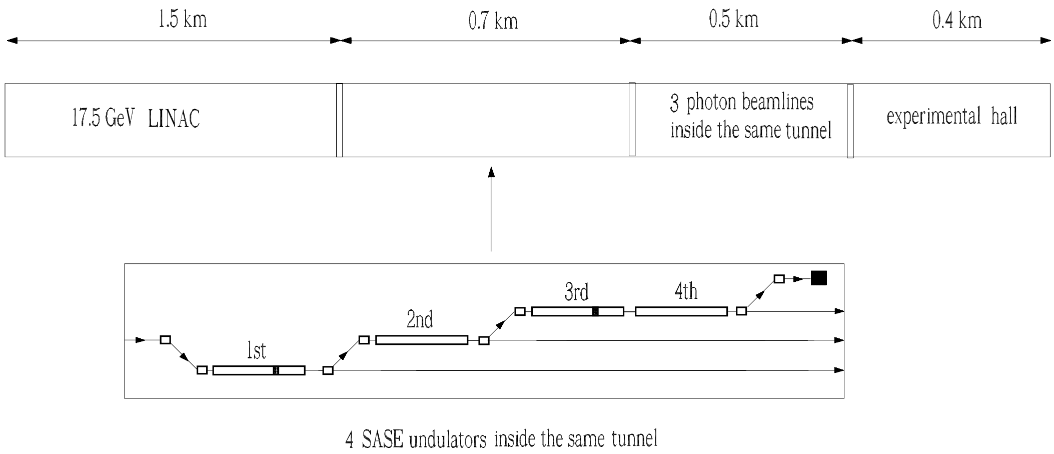

Fig. 3. The schematic layout of XFEL

Table 1
Specification of soft X-ray undulators for XFEL laboratory

	Energy	λ_{u}	gap	B_{u}	K_{rms}	β_{f}	L_{u}
	GeV	mm	mm	T		m	m
Nominal option	17.5	110	19-37	0.7-1.6	5.7-12	10-20	80
Low energy option	2.5	38	10-20	0.4-1	1-2.7	6	35

Table 2
Specification of soft X-ray FELs for XFEL laboratory

	Units	Nominal*	Low energy**
Energy	GeV	17.5	2.5
Wavelength range	nm	1.6/6.4	1.6/6.4
Peak power	GW	100/100	10/20
Average power	W	400/400	40/80
Photon beam size (FWHM)	μm	60/90	90/90
Photon beam divergence (FWHM)	μrad	11/27	11/30
Saturation length	m	70/80	18/32

*Operation in after-burner regime with rms energy spread of 8 MeV
**Operation with nominal energy spread of 1 MeV

energy (17.5 GeV). If the electron energy is that of the upper limit of the range of the baseline design (17.5 GeV) the undulator period length increases, for the resonant wavelength of 6 nm, from 4 to 11 cm. The FEL peak power is a factor of 10 higher for baseline energy (17.5 GeV). The saturation length of "water window" undulator at 17.5 GeV is 80 m, against the 30 m of the low energy undulator.

The second option is the simplest way to obtain VUV radiation from the European XFEL. This is XFEL parasitic mode. All electron bunch trains will be guided into one electron beamline and dump. The wavelength range 0.1-6 nm at fixed electron beam energy of 17.5 GeV can be covered by operating the SASE FEL with four undulators which have different period and tunable gap. These SASE undulators can be placed behind each other assuming that the subsequent undulator radiates at longer wavelength. It is a great advantage that accelerator and electron beam transport line in this scheme operate at fixed parameters and that a fast "electron switchyard" is not required. In order to avoid the need for a costly additional tunnels and shafts, the XFEL source is designed such that accelerator, all four SASE undulators, electron beam line, and photon transport beamlines are installed inside the same (5 m diameter) tunnel (see Fig. 3).

The electron beam transport line takes every bunch train and deliver it to the first SASE undulator. The two bending magnets with a 10 mrad bending angle provide a parallel shift of the beam axis by a distance of 0.5 m, then the electron beam reaches the entrance of the 2nd (3rd) SASE undulator. To bend the beam into the undulator, magnets operate in a DC mode. The photon beams of the 1st and 2nd (2nd and 3rd) SASE undulators have to be separated by the distance of 2 m in the experimental hall, which is realized by a deflection angle of about a mrad. After passing all four undulators, the electrons are stopped in the beam dump.

Although the electron beam leaving the 1st SASE undulator has acquired some additional energy spread (8 MeV), it is still a good "active medium" for the 3rd (4th) SASE undulator at the end. In this scheme it will be possible to provide in parallel hard (around 0.1 nm) and soft X-rays or VUV radiation for two photon beamlines (after-burner mode of operation). Normally if a SASE FEL operates in saturation, the quality of the electron beam is too bad for the generation of SASE radiation in a subsequent undulator which is resonant at a few times longer wavelength. On the other hand, to operate XFEL at the requested radiation wavelengths (0.1 nm - 6 nm) four undulators are needed. The new method of SASE undulator-switching based on the rapid switching of the SASE process proposed in the paper [2] is an attempt to get around this obstacle (see Fig. 4).

All photon beamlines can be operated in parallel. Using electromagnetic phase shifter in a SASE undulator it is possible to rapidly switch the FEL photon beam from one SASE undulator beamline to the other, providing simultaneous multi-undulator capability. Our approach focuses on the development of electromagnetic phase shifter embedded in the other components needed in-

Fig. 4. Photon pulse train patterns for the X-ray SASE FEL

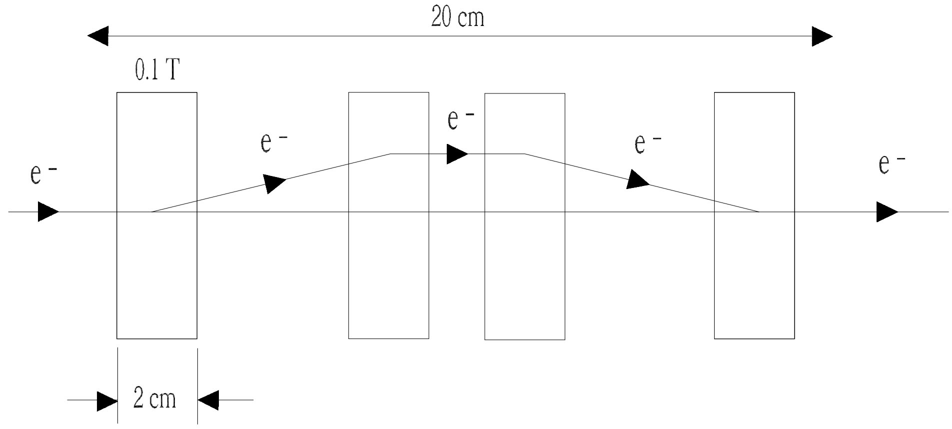

Fig. 5. Electromagnetic phase shifter for a rapid switching of the SASE process in the 0.1 nm undulator

side the undulator insertion. The technique of using a phase shifter as a switch relies on the fact that dependence of the FEL gain on the phase between the electron beam modulation and the radiation field, acting on the electrons is very strong. Optimal suppression is obtained when phase shift is such that most of electrons fall into accelerating phase and after passing through the phase shifter the electrons start to absorb power from electromagnetic wave. For the purpose of phase shifting, electron beam has to be slightly delayed (about of radiation wavelength) as compared to the radiation beam. This is done by suitably designed magnetic chicane called a phase shifter (see Fig. 5). It consists of three horizontal magnets. The length of the central one is doubled because it needs twice the strength. The total length of 0.1 nm phase shifter is about 20 cm. It uses electromagnets at an excitation level which

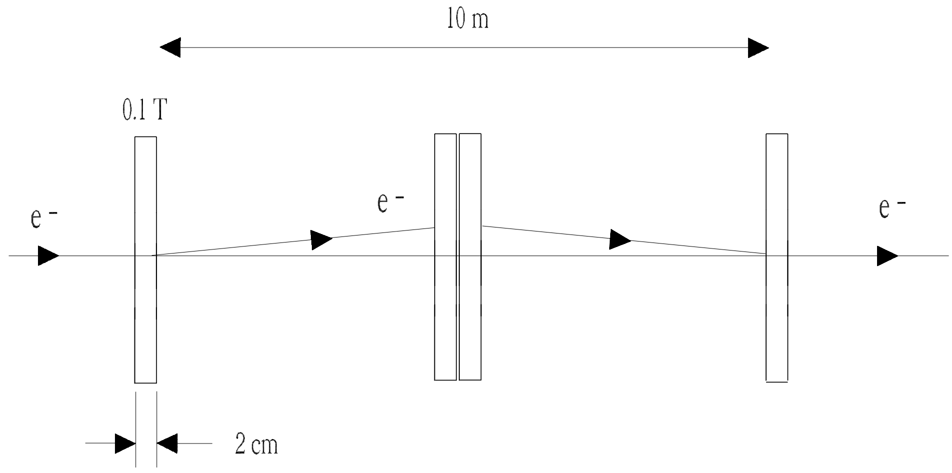

Fig. 6. Electromagnetic phase shifter for a switching of the SASE process in the 3rd (0.4-1.6 nm) undulator

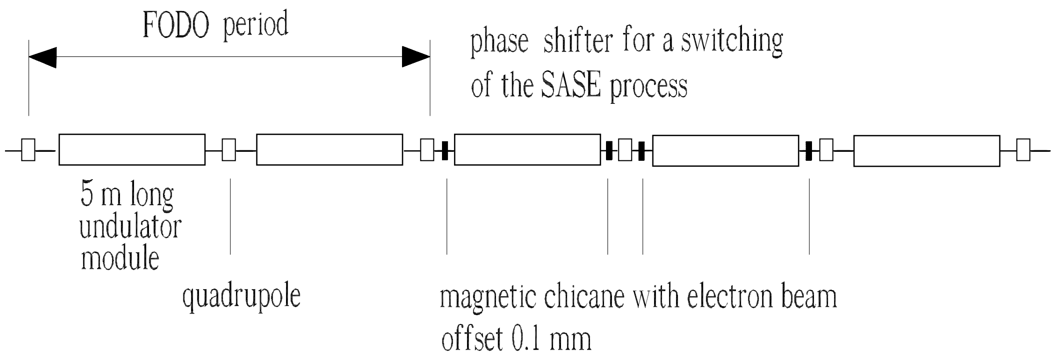

Fig. 7. Installation of an phase shifter in the 3rd SASE undulator

is low enough, so that water cooling is not needed. For trapezoidal mode a frequency of 1 Hz is specified with a switching time of less than 10 ms. This kind of insertion device can be embedded between two neiboring undulator segments.

The electromagnetic phase shifter can also be configured for longer undulator radiation wavelengths (see Fig. 6). The second phase shifter is a magnetic chicane designed to introduce the electron beam delay needed to suppress SASE process in the 3rd undulator. It is also composed of the three low current dipoles. Because of large delay, the total length of the second phase shifter increases from 20 cm to 10 m. There is no problem to insert small (a few cm long) dipole magnets at a 1 m spacing between two neiboring undulator segments (see Fig. 7).

The photon beam transport system will deliver the FEL radiation to the experiments. It is desirable to perform experiments relatively far (at the distance of several hundred meters) from the source. Therefore a long VUV beamline is planned, with experimental hall beginning about 500 m from the 4th (VUV) undulator exit (see Fig. 3). One of the principal design goal of the photon transport system is to contain the main photon beam entirely within the beamline vacuum pipe under all conditions. Because of its comparatively small divergence (about 30 μrad at 6 nm wavelength), this goal is not difficult to achieve without limiting the passage of the VUV FEL beam.

3 Operation of FEL source at longer wavelength

Present concept of an XFEL facility assumes to cover continuously wavelength range from 0.1 to 6 nm at a fixed (17.5 GeV) energy of the electron beam. This is achieved with four undulators installed in a series in one electron beamline as illustrated in Fig. 2. Optimization of undulator parameters has been performed for the electron beam parameters presented in [1]: peak current 5 kA, rms normalized emittance 1.4 mm-mrad, and initial energy spread of 1 MeV. All undulators are planar, variable-gap devices with an identical mechanical design. Optimized parameters of the undulator for both cases are presented in Table 1. Calculations of the FEL characteristics are performed with time-dependent FEL simulation code FAST [3].

In this section, some examples will be given that shed light on the differences between the undulator applied to the VUV wavelengths with the electron energy of 2.5 GeV and an undulator that is modeled for the baseline energy 17.5 GeV (after-burner undulator). The build-up of the radiation pulse energy along the undulator is shown in Fig. 8. Requirements for FEL saturation at the shortest wavelength (1.6 nm) defines the undulator length: 35 m for dedicated 2.5 GeV option, and 80 m for 17.5 GeV after-burner option. Intensity distributions of the radiation in the far and near diffraction zones are shown in Fig. 9. Typical temporal and spectral structure of the radiation pulse from the VUV FEL operating at saturation are presented in Figs. 10 and 11. For both options these structures are very similar, while peak power is much larger for the after-burner option.

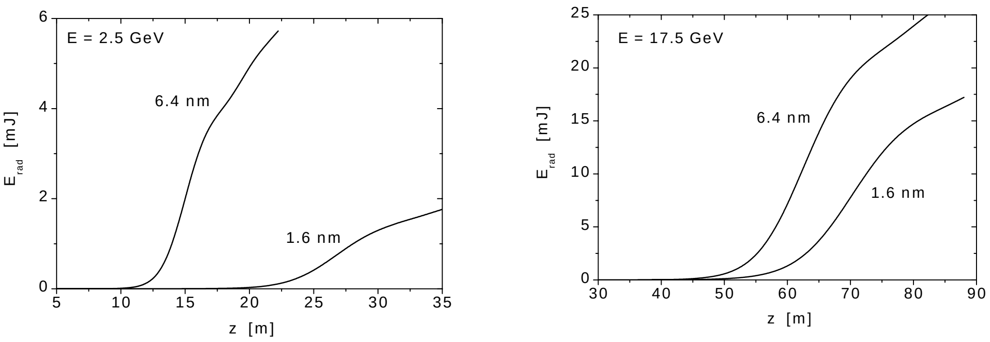

Fig. 8. Energy in the radiation pulse versus undulator length. Left plot: low energy option (2.5 GeV). Right plot: nominal energy option (17.5 GeV)

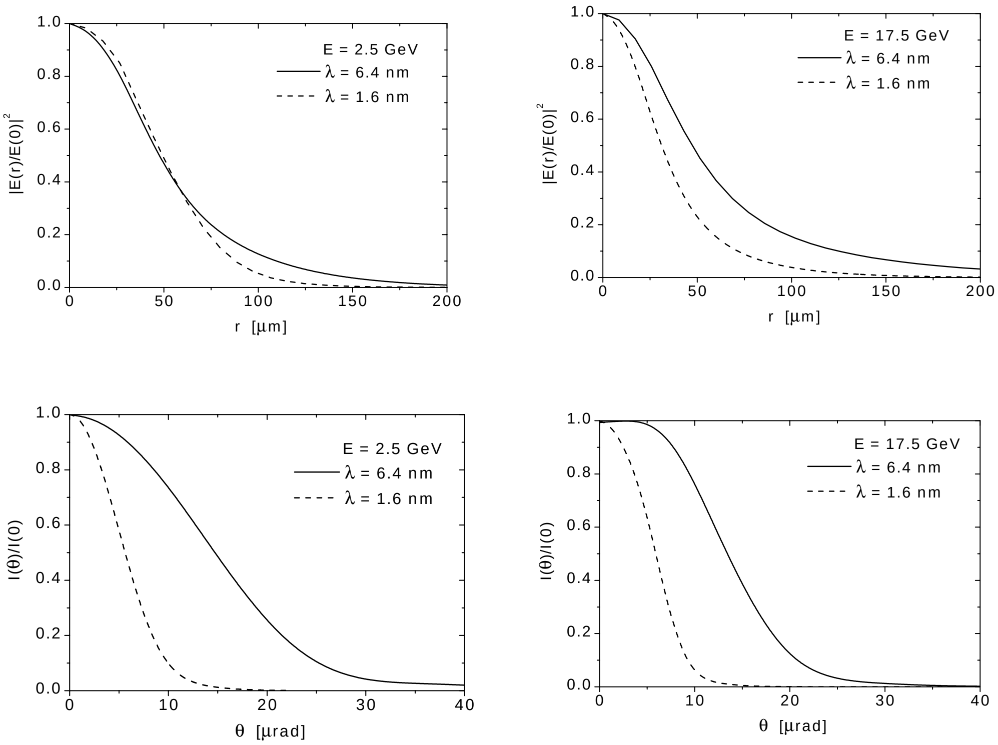

Fig. 9. Intensity distributions of the radiation in the near and far zone in saturation regime. Solid and dashed lines correspond to the radiation wavelength of 6.4 and 1.6 nm, respectively. Left column: low energy option (2.5 GeV). Right column: nominal energy option (17.5 GeV)

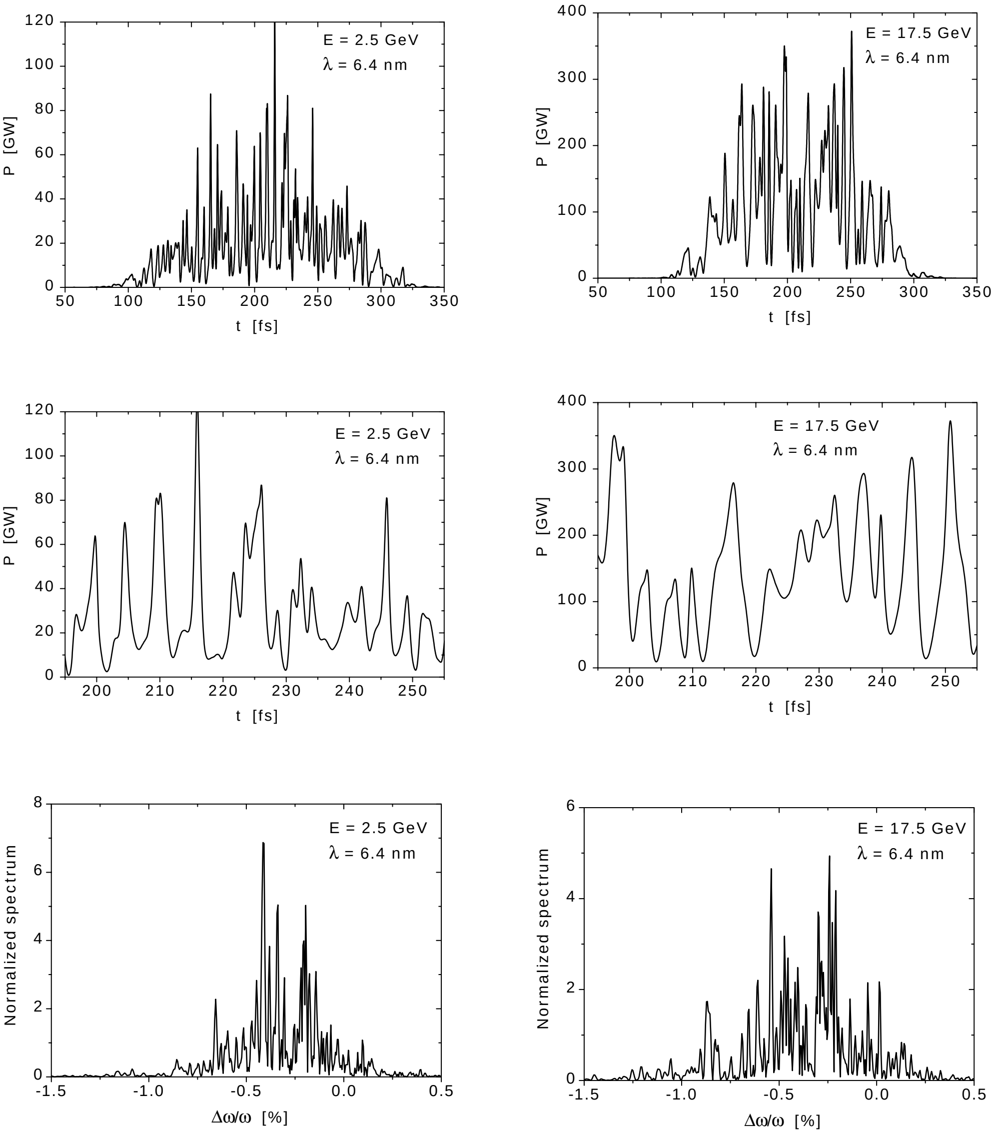

Fig. 10. Temporal and spectral structure of the radiation pulse in saturation regime. Radiation wavelength is 6.4 nm. Left column: low energy option (2.5 GeV). Right column: nominal energy option (17.5 GeV)

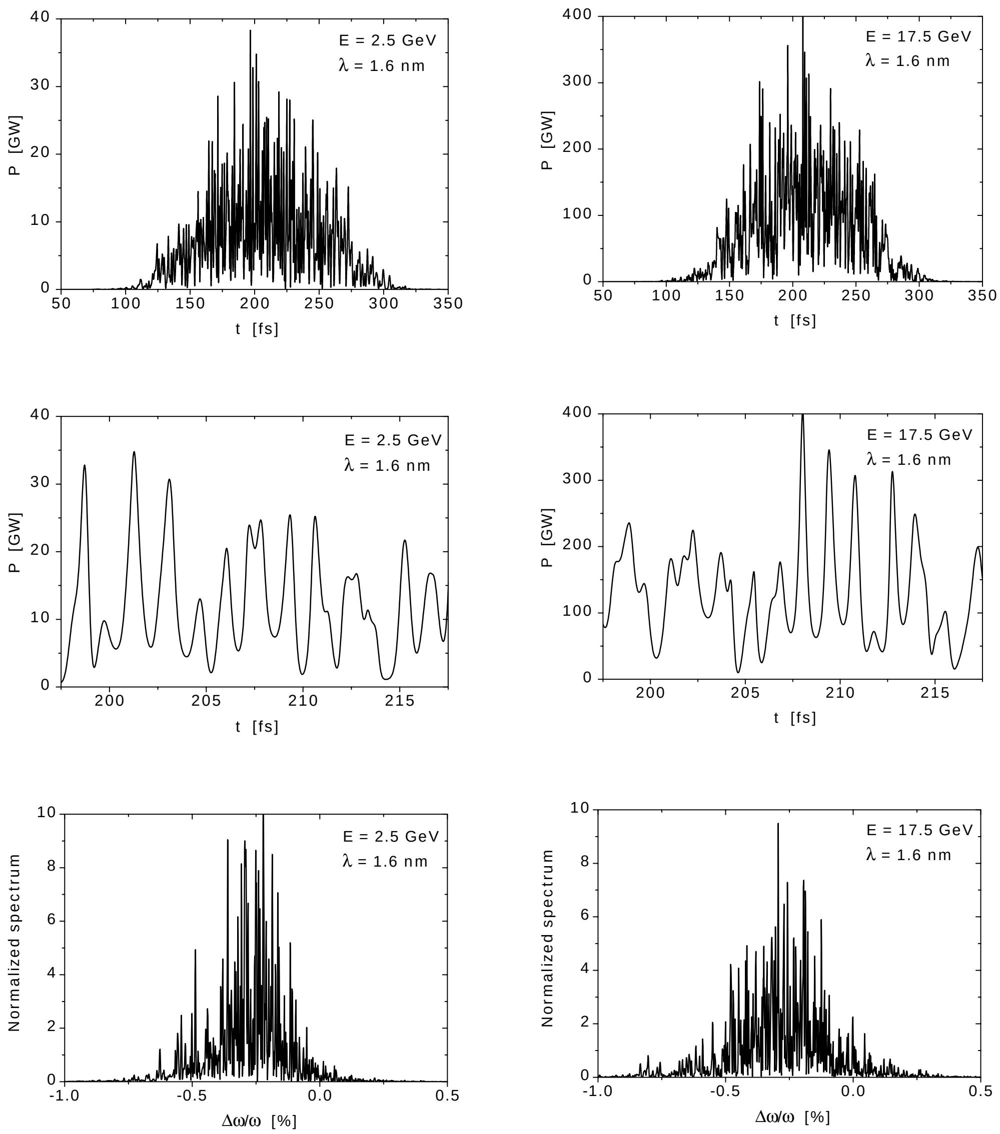

Fig. 11. Temporal and spectral structure of the radiation pulse in saturation regime. Radiation wavelength is 1.6 nm. Left column: low energy option (2.5 GeV). Right column: nominal energy option (17.5 GeV)

4 Conclusion

In this paper we performed direct comparison of two possible options to extend wavelength range of European XFEL towards 6 nm. The first option assumes to use electron beam extracted from the XFEL linac at the energy of 2.5 GeV. This beam is then transported via separate beam transport line, passes through the undulator, and is dumped into the beam dump. Extra expenses for this option are as follows. First, it requires to interfere XFEL linac in order to put extraction devices. Second, long beam transport line (of about two km long) is required. Third, it requires separate beam dump. These evident disadvantages can not be justified by relatively short undulator required (of about 35 meters). The second option, after-burner undulator is the one we regard as the most favorable. It uses electron beam with nominal energy of 17.5 GeV, and can be implemented in a parasitic mode of operation. It is possible to place an undulator as long as 80 meters after 2 nm undulator. Ultimately, VUV undulator would be able to deliver output power approaching 100 GW level (by an order of magnitude higher than for 2.5 GeV dedicated option). One should also keep in mind the problem of the overall efficiency of the XFEL laboratory, i.e. increasing the number of simultaneously working user stations. It is evident that 2.5 GeV option reduces the number of simultaneously working user stations: when electron beam is directed into the VUV branch, hard X-ray users need to wait. 17.5 GeV VUV option works in a parasitic mode: VUV pulse is produced by the electron bunch which was used for production of X-ray pulse in the previous undulator. Finally, in some modes of operation, VUV FEL radiation could be used with X-ray FEL radiation to do pump-probe experiments with precise intervals between the sources.

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