ISBN: 978-3-95450-220-2 ISSN: 2673-5474 doi: 10.18429/JACoW-FEL2022-MOP22

SIMULATION STUDIES FOR THE ASPECT PROJECT AT EUROPEAN XFEL

J. W. Yan*, G. Geloni, C. Lechner, S. Serkez, European XFEL, Schenefeld, Germany
Y. Chen, M. Guetg, C. Heyl, E. Schneidmiller
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

Intense attosecond pulses generated by x-ray free-electron lasers (XFEL) are promising for attosecond science, for example, to study the quantum mechanical motion of electrons in molecules. This paper presents numerical simulations of the generation of attosecond soft and hard x-ray FEL pulses with the chirp-taper and the enhanced self-amplified spontaneous emission methods, based on the parameters of the European XFEL. To overcome the coherence time barrier, a modification of the chirp-taper scheme is used in the case of soft x-rays. The results show that several hundred attosecond pulses can be obtained at both 700 eV and 6 keV photon energies.

INTRODUCTION

As a new generation of light sources, x-ray free-electron lasers (XFELs) are indispensable tools for a wide range of research fields. The demand for attosecond XFEL pulses is increasing rapidly in recent years. Several methods have been proposed to shorten the FEL pulse duration [1]. Many of these schemes employ an external laser to modulate an electron beam and let only a short part of the electron beam lase effectively, such as the chirp-taper [2, 3] and the enhanced self-amplified spontaneous emission (ESASE) schemes [4].

In the chirp-taper scheme, an electron beam is modulated through the interaction with a few-cycle intense laser in a few-period wiggler, and a strong energy chirp is introduced, which inhibits lasing. Reverse taper is used to compensate this effect in a short part of the electron beam, the one with the strongest energy chirp. In addition to the energy modulation, the ESASE scheme relies on the creation of high-current spikes in short parts of the electron beam, with the help of a dispersive section (a chicane) following the energy modulator. Due to the high current levels, in the ESASE scheme, space-charge interactions play a particularly important role. We are currently setting up a project dedicated to the generation AttoSecond Pulses with eSASE and Chirp-Taper schemes (ASPECT) at the European XFEL [5]. ASPECT will initially serve two of the three SASE line at the European XFEL, SASE1 and SASE3, which are respectively specialized in the production of hard and soft x-rays.

The schematic layout of the ASPECT project is shown in Fig. 1. The energy modulation section is placed before SASE1, where external laser and electron beam interact in a two-period wiggler. The energy-modulated beam can be transported to both SASE1 and SASE3. The ESASE scheme is enabled by the two chicanes located, respectively, before SASE1 and SASE3.

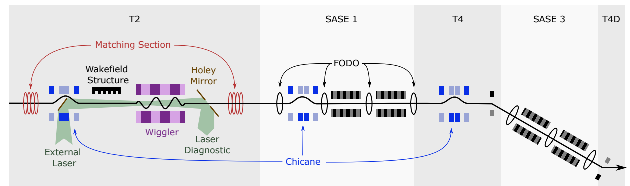

Figure 1: Schematic layout of the ASPECT project.

CHIRP-TAPER SCHEME

We analyze the performance of the chirp-taper scheme for two case studies covering the generation of hard (6 keV) and soft (700 eV) x-ray radiation. A 14 GeV electron beam with a flat-top current of 2500 A is used in both simulations. The electron beam is modulated by a laser with a wavelength of 1030 nm, a pulse energy of several mJ (see below) and an FWHM pulse duration of 4 fs in the two-periods wiggler with a period of 0.7 m. The simulations for the hard and soft x-ray cases are respectively based on the parameters of SASE1 and SASE3 [5], made up of 5 m-long segments, respectively with 40 mm and 68 mm period, followed by 1.1 m-long intersections.

Hard X-Ray Case

In the hard x-ray case, the pulse energy of the laser is selected as 4 mJ. The energy modulation induced by the laser is calculated by theoretical analysis [6] and three-dimensional numerical analysis [7, 8]. As shown in Fig. 2, the two methods yield very similar results. An energy modulation amplitude of around 30 MeV can be obtained.

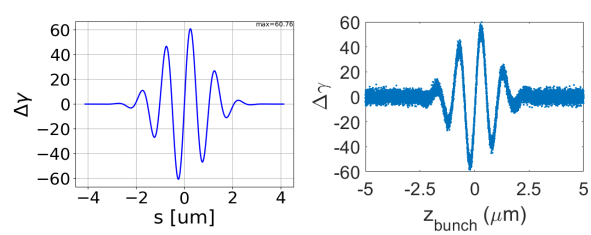

Figure 2: Energy modulation induced by the laser, obtained by theoretical analysis (left) and three-dimensional simulation (right). The bunch head is to the right.

A reverse step-taper is applied in SASE1, and the dimensionless undulator parameter K increases by 0.0013 in each undulator segment. Figure 3 shows the evolution of the

* jiawei.yan@xfel.eu

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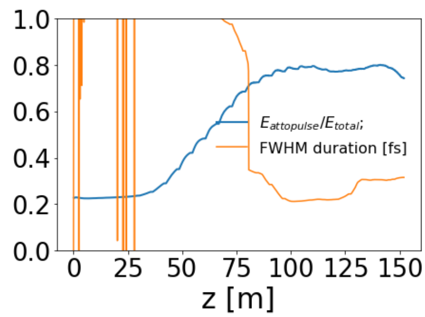

Figure 3: The change of pulse duration and contrast along the undulator.

pulse duration and contrast along the undulator. Figure 4 presents the power profile of the FEL pulse at the position of 130 m down the SASE1 undulator, where the peak power, FWHM duration, and contrast of the pulse are 86 GW, 278 as, and 78%, respectively.

A stability analysis of the FEL performance related to the carrier-envelope phase (CEP) [9] of the optical laser is shown in Fig. 5. Each point in Fig. 5 represents the average value of 10 simulation runs (referring to different shot noise initial conditions) with a certain CEP change. For most applications, we estimate that pulses are satisfactorily stable within ± 0.2 pi phase change.

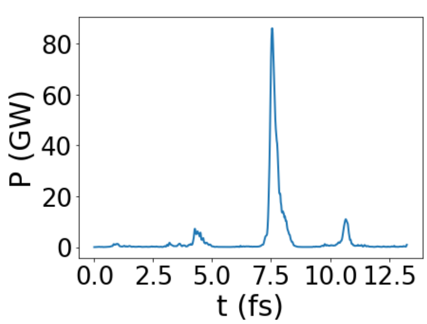

Figure 4: Power profile of the 6 keV FEL pulse at the position of 130 m.

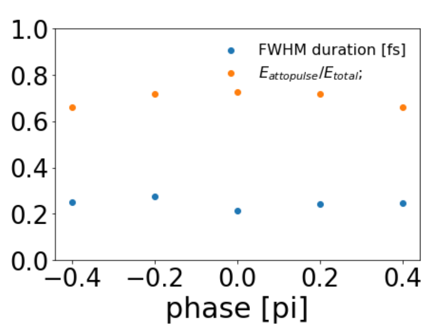

Figure 5: CEP stability analysis of the chirp-taper scheme at 6 keV.

Soft x-ray case

The radiation coherence time increases with the target wavelength. In the soft x-ray range it becomes longer than the lasing window, and poses a limit to the obtainable pulse duration. Here, we employ a modified chirp-taper scheme [3] to ease this performance limitation at 700 eV. As shown in Fig. 6, in the modified chirp-taper scheme, a first stage of the SASE3 undulator with an excessive reverse taper is used to suppress lasing, while obtaining a strong bunching. A second stage composed of one or two undulator segments is works as radiator with decreased slippage. Intense, short FEL pulses can be obtained at the second stage through careful optimization of the undulator strength.

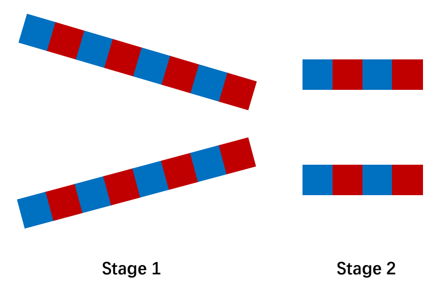

Figure 6: Schematic layout of the modified chirp-taper scheme at SASE3.

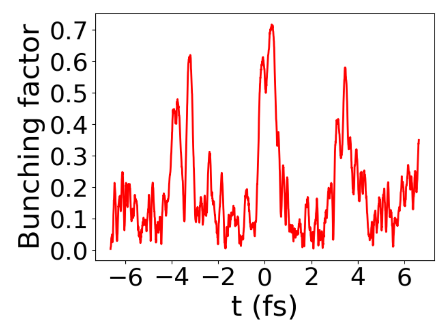

Figure 7: Bunching factor distribution at the exit of the first stage.

Here the pulse energy of the laser is chosen as 5 mJ. An energy modulation amplitude of 34.7 MeV can be obtained in this case. The K in the first stage increases by 0.0122 in each undulator segment to ensure a suitable excessive taper. The bunching factor distribution of the beam at the exit of 10 undulator segments is shown in Fig. 7.

Then the electron beam is sent to the second stage, which consists of one undulator segment. Fig. 8 shows FEL pulse duration, peak power, and contrast at the exit of the second stage as a function of the K parameter of the second stage. The value $K = 9$ is selected as a balanced solution. As presented in Fig. 9, an FEL pulse with a peak power of 22.6 GW, an FWHM duration of 446 as, and a contrast of 81.6% can be obtained. The CEP stability analysis shown in Fig. 10 indicates that the modified chirp-taper scheme holds similar stability compared to the normal chirp-taper scheme.

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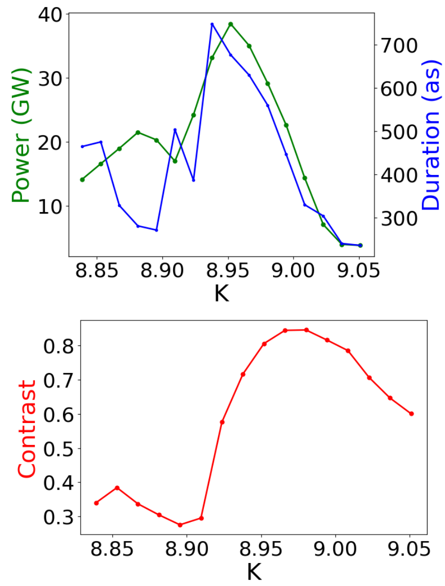

Figure 8: Scanning of the undulator strength of the second stage.

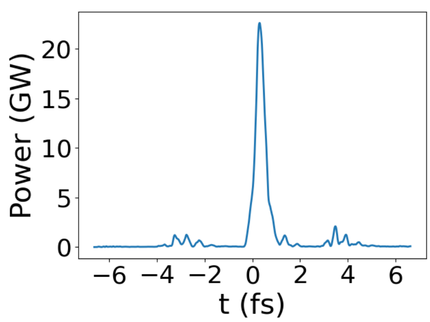

Figure 9: Power profile of the 700 eV FEL pulse at the exit of the second stage.

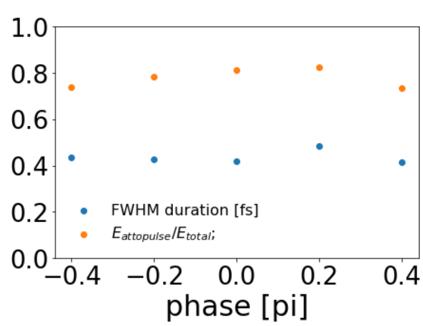

Figure 10: CEP stability analysis of the chirp-taper scheme at 700 eV.

ESASE SCHEME

We further analyzed the performance of the ESASE scheme at 700 eV. A 14 GeV electron beam with a flat-top current of 5000 A is used. Similar to the chirp-taper scheme, the laser is used to modulate the electron beam at the two-period wiggler. In this case, the pulse energy is selected as 4 mJ. The obtained energy modulation is the same as the one shown in Fig. 2.

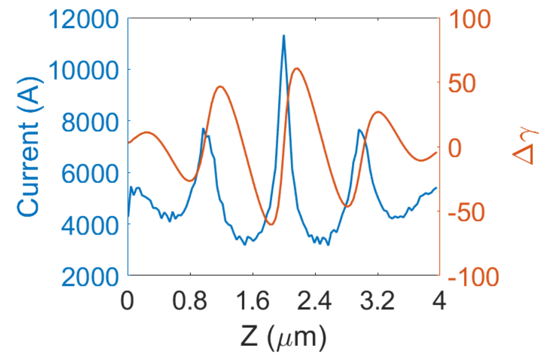

Figure 11: Energy modulation induced by the laser and current profile of the electron beam for the ESASE scheme.

The chicane and arc placed in front of the SASE3 are used to provide a total positive R_{56} of 40 µm. The electron beam is well compressed before passing through SASE3. The current profile of the electron beam after compression is presented in Fig. 11. Due to the high-current spike, the scheme benefits from a strong space charge effect in the SASE3 undulator section [10]. Preliminary analysis shows that intense FEL pulses with an FWHM around 200 as can be obtained at the position of 30 – 40 m. Figure 12 shows the obtained FEL power profile at 43 m, where the peak power is 27.3 GW and FWHM duration is 182 as.

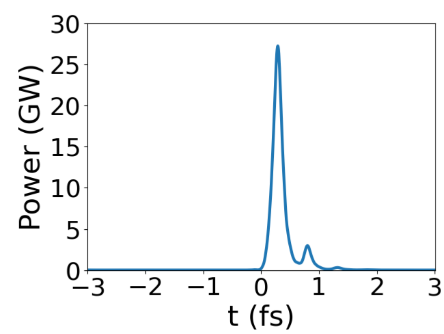

Figure 12: Power profile of the 700 eV FEL pulse obtained with the ESASE scheme.

CONCLUSION

In summary, the generation of attosecond XFEL at European XFEL with the chirp-taper scheme and ESASE scheme is analyzed. Preliminary simulation results show that both schemes are promising to provide several hundred attosecond XFEL pulses at both 700 eV and 6 keV photon energies. More systematically optimization based on start-to-end simulations is required to further improve the performance. Moreover, the possibilities of utilizing the self-modulation [11] in the wiggler to replace the external laser require further exploration.

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