GENERATING A SINGLE-SPIKE SASE PULSE IN THE SOFT X-RAY REGIME BY VELOCITY BUNCHING*

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Abstract

A bright ultrashort X-ray pulse emerges as a valuable tool for many fields of research nowadays. The single-spike operation of X-ray FEL is one way of making a bright ultrashort X-ray pulse. It requires extreme bunching and a magnetic chicane is a conventional compressor. In a low charge range, a magnetic chicane can be replaced by the velocity bunching technique. In this paper, we present the result of particle tracking simulation generating a single-spike soft X-ray SASE pulse without a magnetic chicane.

INTRODUCTION

XFEL based on SASE principle generates a fully coherent radiation in the transverse plane because the transverse emittance of the electron beam is usually tailored to smaller than the diffraction-limited emittance. In the longitudinal plane however, the coherence is rather poor because radiation starts from the shot noise. Therefore, efforts have been made to improve the SASE FEL's longitudinal coherence. One of the methods which is rather straightforward to implement is to create a single-spike radiation pulse on the order of a few hundred attosecond, two orders of magnitude shorter than the pulse length from a typical SASE FEL so that great enhancement of the longitudinal coherence is achieved.

In this regard, there are two different schemes to obtain an attosecond XFEL. The first scheme is to manipulate an initially long electron bunch and achieve lasing only part of the bunch in the longitudinal axis which is short enough for single-spike radiation. The other scheme is to enhance the bunching process to make an ultrashort electron bunch. As mentioned above, the radiation of SASE FEL has temporal fluctuation; it is a stream of many coherent pulses which separate each other. Single coherent pulse or single spike has space of $2\pi L_{c,1D}$ in between, which is given by

$$2\pi L_{c,1D} = \frac{\lambda_r}{2\sqrt{3}\rho}, \tag{1}$$

where $L_{c,1D}$ is called the cooperation length and λ_r is the radiation wavelength, and ρ is the pierce parameter. Making ultrashort electron bunch for single-spike operation has advantages in the clearness of single spike but making ultrashort bunch is technically difficult. Low charge is preferred to shorten the electron bunch but it also increases difficulties in the beam diagnosis.

The velocity bunching (VB) [1] is a technique to achieve bunching of electrons in the longitudinal direction which is effective when the electron speed is not close to the speed of light. Therefore, the VB process can take place between the rf gun and main accelerating cavities. VB can be an alternative of the magnetic chicane usually employed in the SASE FEL and is effective especially when the bunch charge is low. Therefore, it will be a very interesting question if one can achieve a desirable bunch length to generate a single spike radiation pulse in SASE FEL with a very small charge of a several pico-Coulombs. One may also anticipate that even VB can eliminate the need for magnetic chicane or at least minimize the use of chicane. The aim of this report is to propose the use of VB combined with a low charge of picocoulomb order for a single spike generation of SASE soft X-ray FEL.

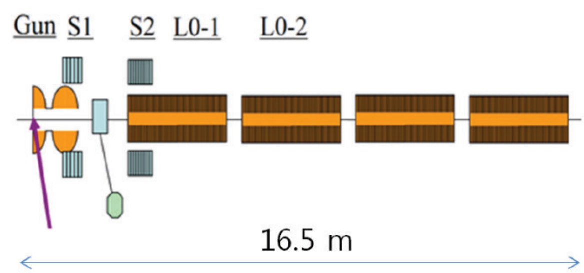

Figure 1: Layout of the injector lattice for the Soft X-ray FEL design.

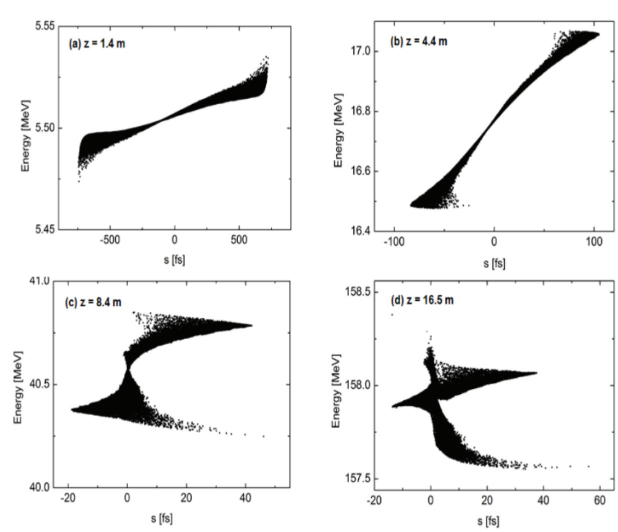

Figure 2: Longitudinal phase space distribution in the injector.

INJECTOR AND LINAC

We designed the injector linac similar to the LCLS injector [2] which is consists of a photo-cathode gun, two solenoids, and two 3-m long S-band accelerating sections L01 and L02. 200,000 particle tracking in the injector linac was performed with ASTRA [3]. Optimization for parameters was carried out through the Multi-Objective

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Genetic Algorithm (MOGA) [4]. The optimized parameters for the injector linac are listed in Table 1. The ranges of the laser parameters and initial beam parameters for optimization are determined from simple scaling of LCLS 20-pC operation parameters [5]. When charge is decrease from 20 pC to 5 pC, beam and laser length parameters are scaled as $\propto Q^{1/3}$ [6].

At the injector design, we need to maximize the VB to make the soft XFEL without a magnetic chicane. We added another two rf cavities to the hard Xray FEL injector design to maximize the VB and increase electron energy at the matching section between injector rf cavities and the linac rf cavities. We expected that it helps suppressing the current reduction caused by the LSC effect. The total length of the injector system is now 16.5 m (Fig. 1). Among the four cavities, the first and second cavities are used to VB and the last are used to acceleration and energy spread compensation.

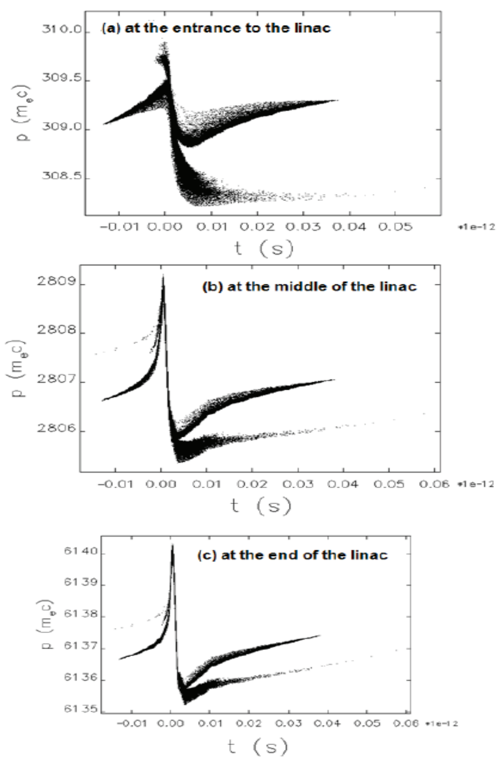

Figure 3: Longitudinal phase space distribution in the linac.

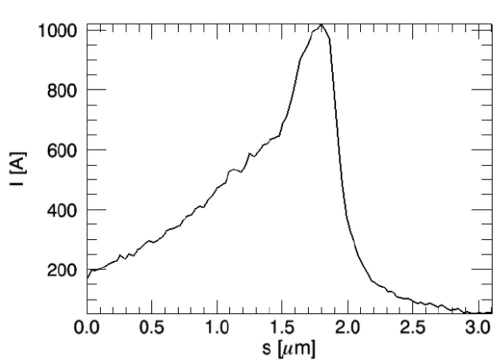

Figure 4: Longitudinal phase space distribution in the linac.

The change of the longitudinal phase space distribution at the injector is plotted in Fig. 2. The coordinate z is the position starts from the cathode and the z = 1:4 m at the start of the first rf cavity. Length of the one rf cavity is 3.0 m. From Fig. 2(a) to Fig. 2(c), electron bunch length is decreased by VB process. Figure 2(d) is at the injector end and it evolves to Fig 3(a) which is at the entrance to the linac rf cavities. Fig 3 shows that the shape of the longitudinal phase space distribution is preserved at the linac. The code Elegant [7] was used for the linac simulation. The current distribution at the end of the linac is presented in Fig. 4. Peak current is 1 kA and rms bunch length of current peak is 0.2 μm which is equivalent to 0.67 fs.

Table 1: FEL Parameters for the Single-Spike Mode 1 nm XFEL

Parameter	Unit	Value
Electron energy	GeV	3.136
Rms bunch length (of current peak)	fs	0.67
Peak current	kA	1
Undulator period	cm	3
Magnet full gap	mm	11.04
Undulator parameter K		1.7395
Average betatron function	m	30
Rms energy spread $\sigma_{\Delta\gamma}$		1.0
FEL (pierce) parameter ρ		0.00088
Cooperation length	fs	1.25/2π
Radiation wavelength	nm	1.00086
Peak saturation power (untapered)	GW	2
Saturation length	m	35

SINGLE SPIKE 1 NM FEL

FEL parameters for the single-spike mode 1 nm FEL is presented in Table 1. Electron energy has been lowered to 3.136 GeV from the hard X-ray XFEL design which is 5 GeV because the longer FEL wavelength loosen the parameter requirements. With the fixed current and undulator parameter, the Pierce parameter ρ is proportional to $(\gamma\lambda^2)^{1/3}$. Rms bunch length of the current peak is shorter than 2πLc but there is long low current tail where from s = 0 μm to s = 1.5 μm in Fig. 4. We need to suppress the lasing of that part of the electron bunch. Other FEL parameters are chosen considering the physical limit and optimization of FEL performance. For an untapered case, we expect a peak saturation power is 2 GW and a saturation length is 35 m. GENESIS 1.3 code [8] was used to perform FEL simulation.

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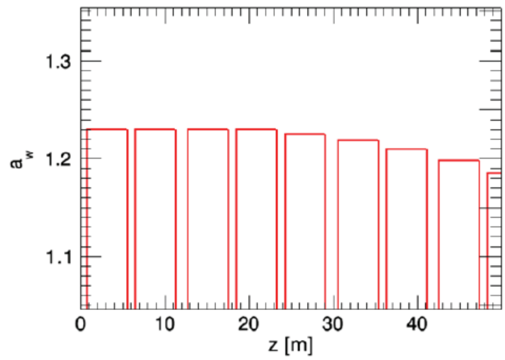

Figure 5: Stepwise tapering of the undulator parameter for the soft XFEL simulation.

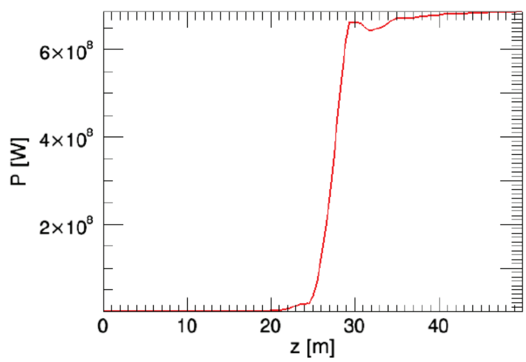

Figure 6: Average radiation power along the undulator position z.

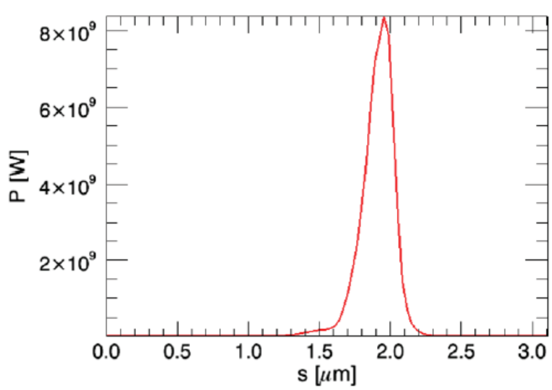

Figure 7: Temporal power profile at z = 30 m.

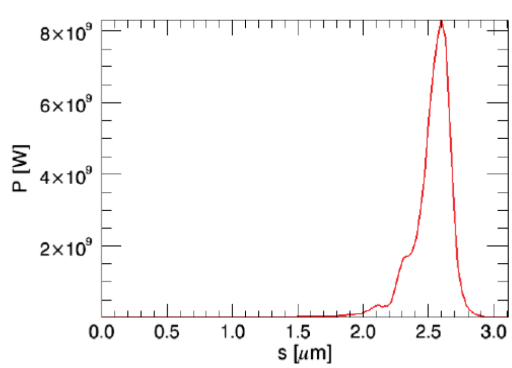

Figure 8: Temporal power profile at z = 50 m.

In order to suppress the lasing of the low current part of the electron bunch and increase the radiation power, we introduce the undulator tapering (Fig. 5). The current peak is lased prior to the low current part, strong undulator tapering after the saturation of the current peak will prevent the lasing of the low current part. The average radiation power along the undulator position z is presented in Fig. 6. The saturation length is 29 m and there is no power increase after 30 m because of the strong tapering. That cease of the power increase is express the suppression of the lasing of the low current part.

Figure 7 and 8 shows the temporal radiation power profile at z = 30 m and 50 m respectively. It shows the effect of the undulator tapering. There is small side peak after the main single-spike radiation but it is negligible. Peak saturation power is 8 GW and rms duration of the single-spike radiation is 0.1 μm or equivalently 0.33 fs. Figure 9 shows the spectral power density at z = 30 m. It has the relative bandwidth of 1.0×10^{-3}.

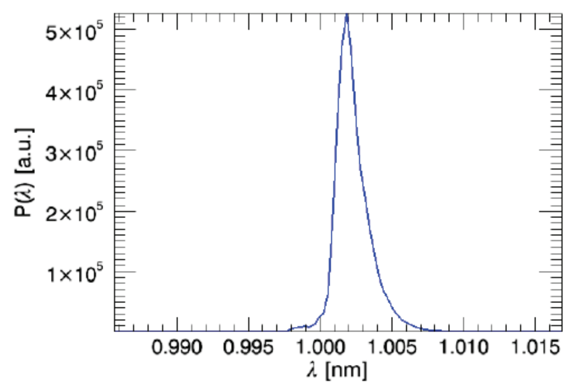

Figure 9: Spectral power density after the saturation.

CONCLUSION

We simulated XFEL design which generates single-spike radiation for the 1 nm FEL with 5 pC, 3.1 GeV electron beam. Velocity bunching technique was used to replace magnetic chicane and we obtained the single-spike radiation with 8 GW at z = 30 with 5 pC and 3.1 GeV electron beam with the help of strong undulator tapering. Because of the simplicity and compactness of the design, we expect it will be an economical soft X-ray light source. Error study is needed especially for the injector rf system and we will conduct in near future.

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