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SIMULATION STUDIES FOR ATTOSECOND SOFT X-RAY FEL PULSE GENERATION AT PAL-XFEL

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Abstract

Pohang Accelerator Laboratory X-ray Free-Electron Laser (PAL-XFEL) is currently developing a method to generate attosecond soft X-ray FEL pulses using the Enhanced Self-Amplified Spontaneous Emission method. This involves manipulating the electron beam to generate a current spike and optimizing the undulator tapering based on the slippage length. By doing so, it is possible to obtain an attosecond soft X-ray FEL pulse with a duration of several hundred attoseconds at the resonant wavelength of 1 nm from the PAL-XFEL soft X-ray undulator line.

INTRODUCTION

PAL-XFEL has initiated a project to generate attosecond soft X-ray FEL pulses, and Fig. 1 depicts the schematic layout for this purpose. Currently, PAL-XFEL comprises two undulator lines: a hard X-ray undulator line with a maximum electron beam energy of 11 GeV and a soft X-ray undulator line that branches off after the L3A section and employs an electron beam with a maximum energy of 3.15 GeV. The soft X-ray undulator line is equipped with seven undulator segments that are currently used for user service. To manipulate the electron beam for generating attosecond soft X-ray FEL pulses, additional components such as an external laser system, chicane, and wiggler will be installed upstream of the undulator segments, which are the initial sections of the FODO lattice for the soft X-ray undulator line.

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CURRENT SPIKE GENERATION

Self-Amplified Spontaneous Emission method (E-SASE) method [1] is employed to generate current spikes in the electron beam. When the electron beam interacts with an external laser pulse in the wiggler, energy modulation can be induced, as depicted in Fig. 2(a). Subsequently, when the electron beam passes through a dispersive section like a chicane, the energy-modulated electrons can be compressed due to the path length difference that is dependent on their energy, as shown in Fig. 2(b).

The compressed part of the electron beam has a locally higher peak current, which is referred to as the current spike, as illustrated in Fig. 3(a). However, as the peak current increases, the slice energy spread also increases, as shown in Fig. 3(b), which can be an obstacle to FEL lasing [2]. To achieve such a current spike, the parameters listed in Table 1 are used in the simulation. The peak current of the current spike is approximately 6 kA, and its width is approximately 480 nm, as shown in Fig. 4.

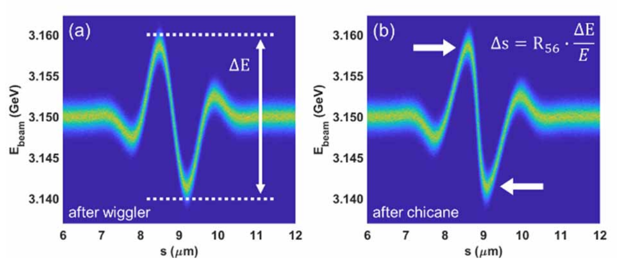

Figure 2: Energy distribution of the electron beam (a) after wiggler and (b) after the chicane in the E-SASE section.

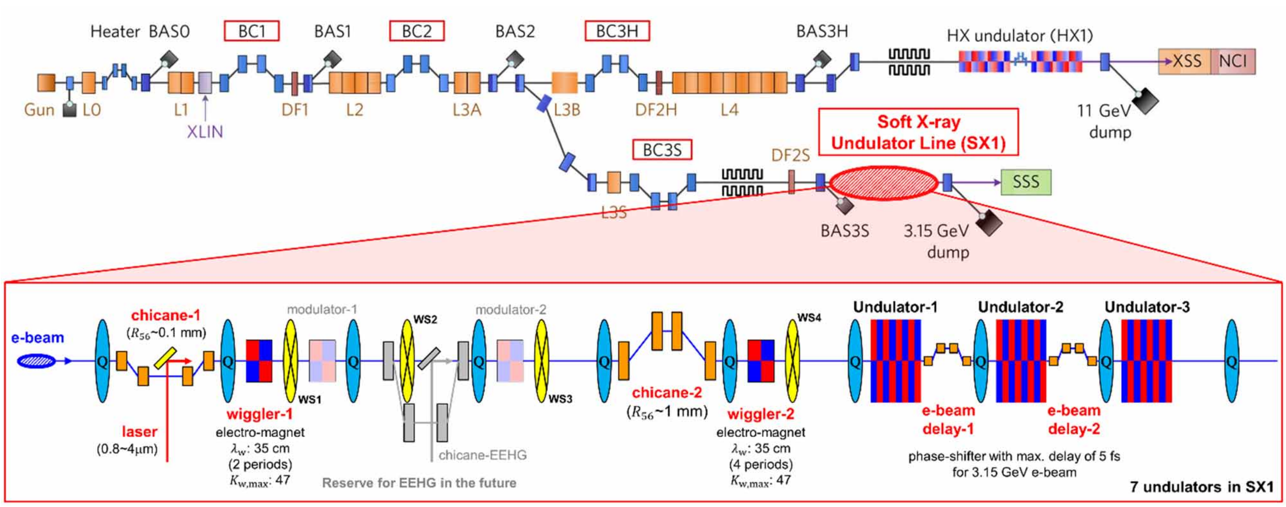

Figure 1: The schematic layout of PAL-XFEL and a detailed layout of the E-SASE method for generating attosecond soft X-ray FEL pulses.

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Table 1: Main Parameters Used in Simulations

Parameter	Value	Unit
Electron beam at the end of linac		
Energy (E_{beam})	3.15	GeV
Base current (I_{base})	3	kA
rms slice energy spread (σ_E, at 3 kA)	1.02	MeV
rms normalized slice emittance (ϵ_n)	0.4	µm
E-SASE section		
Wavelength of modulation laser (λ_{mod})	1.6	µm
K_w	26.32	
Wiggler period (λ_w)	35	cm
Amplitude of energy modulation (ΔE)	20	MeV
Momentum compaction factor (R_{56})	39.3	µm
Undulator section		
Resonant wavelength (λ_r)	1	nm
Resonant photon energy (E_{ph})	1240	eV
Undulator period (λ_u)	35	mm
Undulator length (L_u)	4.97	m

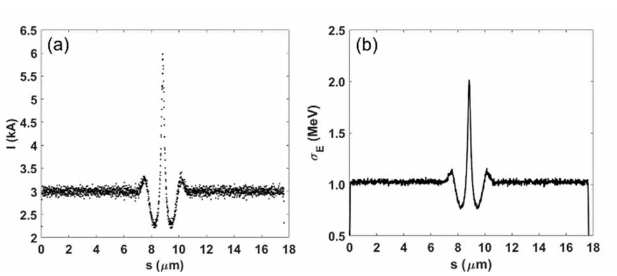

Figure 3: Profile of (a) the current and (b) the slice energy spread of the electron beam after chicane in the E-SASE section.

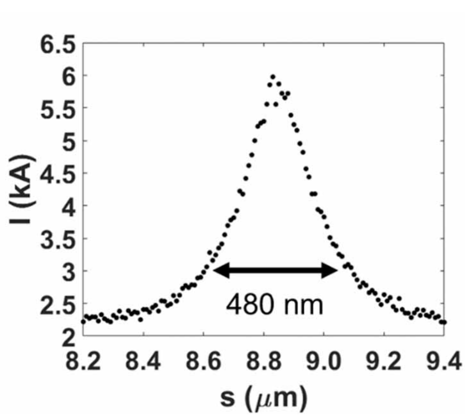

Figure 4: Expanded view of the current spike in Fig. 3(a).

FEL SIMULATION

At PAL-XFEL's soft X-ray undulator line, each undulator consists of 142 undulator periods, and the slippage length in each undulator is approximately 140 nm for a resonant wavelength of 1 nm. In this case, the amplified FEL pulse from the current spike will escape after only 3~4 undulators. Therefore, the undulator tapering must be optimized to compensate for the slippage length and continuously amplify the power of the FEL pulse. Such optimized tapering can also reduce the pulse duration and suppress the background radiation from other parts of the electron beam, except for the current spike [3].

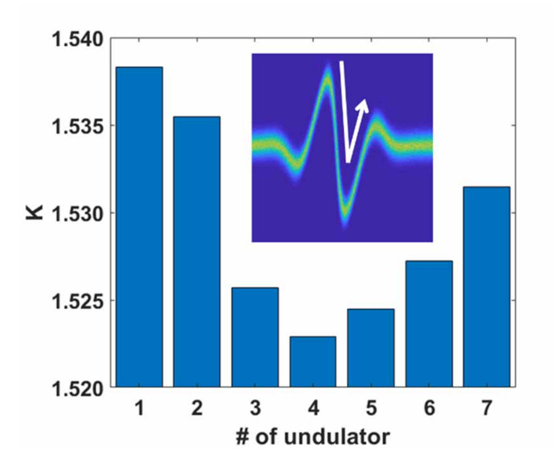

Figure 5: Undulator tapering based on the slope of the energy of the electron beam around the current spike to compensate for the slippage length of the FEL pulse.

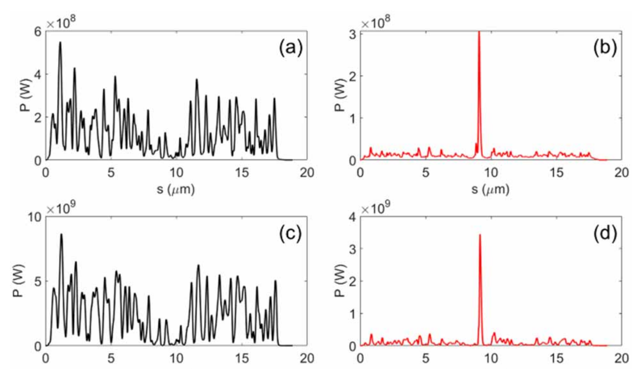

Figure 6: Temporal profile of the FEL pulse at the end of (a, b) the 4th undulator and (c, d) the 5th undulator. Figures with a black line (a, c) represent the case without undulator tapering, while figures with a red line (b, d) represent the case with undulator tapering.

To verify the effect of undulator tapering, FEL simulations were carried out for two cases: with and without undulator tapering. The undulator tapering used in the simulation is shown in Fig. 5. FEL simulations were performed using the GENESIS code [4], and the radiation profiles at the end of the 4th and 5th undulators for both cases are shown in Fig. 6. Without undulator tapering, the growth of the background radiation is dominant, and the FEL pulse from the current spike cannot be distinguished. However,

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the FEL pulse from the current spike is clearly visible, and the background radiation is also effectively suppressed when undulator tapering is employed. The radiation profile of the FEL pulse from the current spike and the spectrum of the radiation pulse at the end of the 4th and 5th undulators are shown in Figs. 7 and 8, respectively. By securing a wide bandwidth of several electron volts, attosecond soft X-ray FEL pulses with a duration of hundreds of attoseconds can be generated.

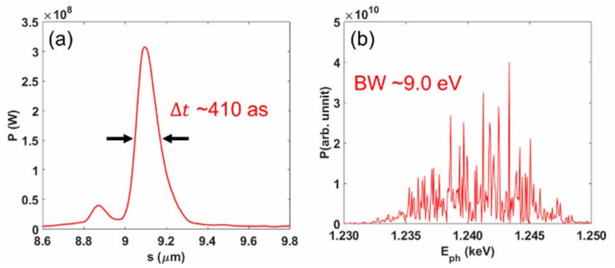

Figure 7: (a) Expanded view of the FEL pulse and (b) the spectrum at the end of the 4th undulator in Fig. 5(b).

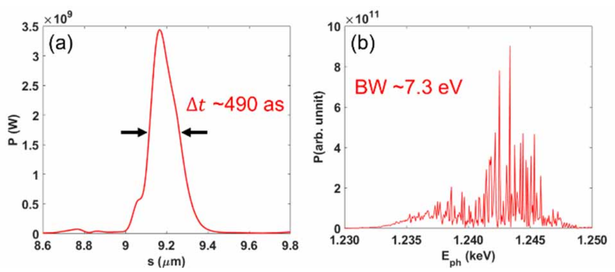

Figure 8: (a) Expanded view of the FEL pulse and (b) the spectrum at the end of the 5th undulator in Fig. 5(d).

DISCUSSION

Based on the preliminary simulation studies, it is feasible to generate attosecond soft X-ray FEL pulses at PAL-XFEL. However, further improvements are needed to suppress the background radiation and enhance the signal-to-noise ratio of the FEL pulse. Longitudinal space charge effect from the wiggler-2 in Fig. 1 will be investigated to induce time-energy correlation in the current spike, and optimize undulator tapering to suppress the growth of background radiation. Additionally, a phase shifter with a maximum delay of 5 fs for 3.15 GeV electron beam will be developed and installed between undulator segments to investigate cases for multi-current spikes with electron beam delay to increase the peak power of the attosecond soft X-ray FEL pulse, despite the long slippage length. Furthermore, simulation studies using different wavelengths of the modulation laser will be conducted.

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