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OPTIMIZATION OF A COHERENT UNDULATOR BEAMLINE FOR NEW ADVANCED SYNCHROTRON LIGHT SOURCE IN KOREA

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Abstract

Recently, the demand for a new advanced synchrotron light source in Korea is rapidly growing. Six local governments in Korea would like to host the new synchrotron light source project in their own provinces. The new advanced synchrotron light source will be the Diffraction-Limited Storage Ring (DLSR), which is based on the Multi-Bend Achromat (MBA) lattice. For the new synchrotron light source, we would like to build a special 60-m long coherent undulator beamline, which can deliver high-intensity coherent radiation at the hard X-ray region. To design the coherent undulator beamline, we have performed numerous beam dynamics simulations with GENESIS and SIMPLEX codes. In this paper, we report design concepts and those simulation results for the coherent undulator beamline.

INTRODUCTION

PLS-II, the third generation light source at Pohang in Korea, has been well utilized so far. Since the recent annual growth of PLS-II users is about 600, and its total users are about 7,000 in 2018, PLS-II is close to facility saturation, and the demand for a new advanced synchrotron light source is growing. In addition, due to the suddenly changing international situation between Korea and Japan, Korean government is planning to develop and produce advanced materials in Korea. To do this, the Korean government is also considering to build new advanced synchrotron light sources and has already allocated $1.2M budget to design a new advanced synchrotron light source in 2020.

Currently, several studies have been conducted for a new advanced synchrotron light source in Korea, and one of them is ongoing by Future Accelerator R&D Team in Korea Atomic Energy Research Institute (KAERI). The blueprint of the new advanced synchrotron light source in Korea is shown in Fig. 1, which consists of three parts; a CW SRF injection linac, a small UV & soft X-ray storage ring [1], and a main Diffraction-Limited Storage Ring (DLSR) with a Multi-Bend Achromat (MBA) lattice [2]. As shown in Fig. 2, we would like to use long drift spaces between the superperiods for coherent beamlines with many undulators. By injecting high quality electron beam from the injector linac continuously, the 60-m undulator beamline in the main storage ring can generate coherent high-brightness X-rays during the tens-of-turn operation mode. In this study, we present the design concepts and the simulation results of the coherent undulator beamline to generate hard X-ray at a wavelength of 0.1 nm with the Self-Amplified Spontaneous Emission Free Electron Laser (SASE FEL) concept [3, 4]. The beam dynamics and the radiation along the beamline are simulated with GENESIS and SIMPLEX codes [5, 6].

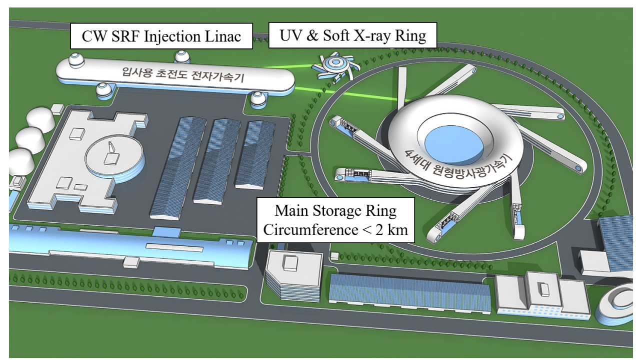

Figure 1: The blueprint of a new advanced synchrotron light source in Korea. The large round building on the right is the MBA-based main storage ring [2].

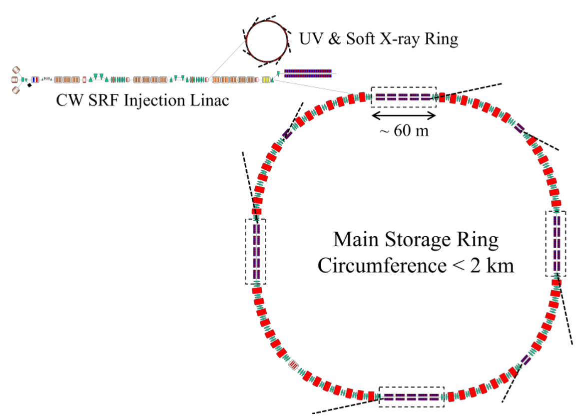

Figure 2: The layout of the new advanced synchrotron light source in Korea. Boxed sections are the coherent undulator beamlines [2].

DESIGN OF UNDULATOR BEAMLINE

Design Parameters

Although the design of the accelerator is ongoing, several key properties of the accelerator are already determined. The energy of the electron beam under consideration is 6 GeV for

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the main storage ring with 60-m long drift spaces between the superperiods. The maximum four coherent undulator beamlines can be installed at those drift spaces to deliver high intensity coherent hard X-rays.

Table 1: Design Parameters for the Coherent Undulator Beamline and Test Electron Bunch

Parameter	Value	Unit
Energy of Electron Beam E	6.0	GeV
Photon Wavelength λ_{ph}	0.1	nm
Undulator Period λ_u	15	mm
Undulator Parameter K	1.295	–
Undulator Module Length	3.96	m
Quadrupole Length (QF, QD)	0.18	m
Length of FODO Lattice	9.0	m
Number of Undulator Modules	10	–
Average β-function $\bar{\beta}_{x,y}$	15	m
Normalized Slice Emittance (rms) $\epsilon_{n,s}$	0.3	µm
Single Bunch Charge Q	200	pC
Bunch Length (rms) σ_z	9.0	µm
Peak Current I_{peak}	2.7	kA
Slice Relative Energy Spread (rms) $\sigma_{\delta,s}$	0.01	%

Design parameters for the coherent undulator beamline are summarized in Table 1. To achieve the saturation of the SASE FEL power at 0.1 nm within 60 m, numerous parameters of undulator and electron beam are optimized. The resonant wavelength of planar undulator is give by

$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right), \tag{1}$$

where λ_{ph} is the resonant photon wavelength, λ_u is the undulator period, γ is the energy of electron beam in units of electron rest mass energy, and K is the undulator strength parameter [4]. To get sub-nm photon wavelength, λ_u is set as 15 mm. From Eq. (1), K is calculated as 1.295. Those parameters can be achieved by using the in-vacuum undulator (IVU), which has already been installed at various synchrotron light sources [7, 8].

As shown in Fig. 3, β-functions and a layout of a single FODO lattice of the coherent undulator beamline are optimized with SIMPLEX code [6]. The FODO lattice consists of a focusing quadrupole, a defocusing quadrupole, and two undulator modules. Average β-functions are 15 m for both $\bar{\beta}_x$ and $\bar{\beta}_y$.

We set parameters of the test electron bunch for the coherent undulator beamline by using those of SwissFEL because energy of the electron beam (6 GeV) is close to that of SwissFEL (5.8 GeV) [7]. The single bunch charge Q of 200 pC with a uniform normalized slice emittance $\epsilon_{n,s}$ of 0.3 µm is distributed in Gaussian form in the longitudinal direction. The rms bunch length σ_z is 9.0 µm, and the peak current I_{peak} is about 2.7 kA.

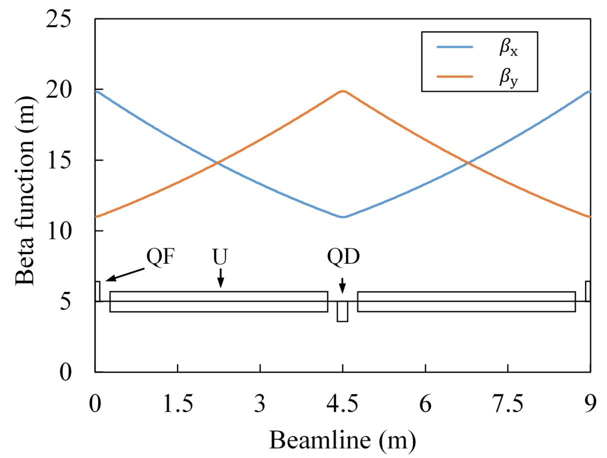

Figure 3: β-functions and a layout of the FODO lattice for the coherent undulator beamline.

Parameter Verification

Before the simulation, theoretical verification of the parameters is required to achieve the exponential growth of the radiation power within 60 m. For the verification, Pierce parameter ρ is defined as a following:

$$\rho = \left[\frac{1}{16}\frac{I_{peak}}{I_A}\frac{K^2\,[JJ]^2}{\gamma^2\epsilon_{n,s}\bar{\beta}_{x,y}k_u^2}\right]^{1/3} \tag{2}$$

Here, the Bessel function factor $[JJ] = [J_0(\xi) - J_1(\xi)]$ with $\xi = K^2/(4 + 2K^2)$, the Alfvén current $I_A \approx 17$ kA, and $k_u = 2\pi/\lambda_u$ [4]. With the parameters from Table 1, ρ is given by 4.887×10^{-4}.

To obtain the saturation of the SASE FEL power within the coherent undulator beamline, the saturation length L_{sat} should be shorter than 60 m. Typically, L_{sat} of SASE FEL [3] is given by

$$L_{sat} \approx 20L_G, \tag{3}$$

where the one-dimensional (1D) power gain length L_G [4] is given by

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho}. \tag{4}$$

From the design parameters, calculated L_G is 1.41 m, and L_{sat} is about 28.2 m, which is shorter than the 60-m drift section.

There are two other requirements for the SASE FEL saturation within 60 m. The slice relative energy spread $\sigma_{\delta,s}$ of the electron must be smaller than the Pierce paramter ρ;

$$\sigma_{\delta,s} < \rho. \tag{5}$$

Also, the normalized slice emittance $\epsilon_{n,s}$ should satisfy a following condition;

$$\epsilon_{n,s} < \frac{\lambda_{ph}}{4\pi}\frac{\gamma\bar{\beta}_{x,y}}{L_G}. \tag{6}$$

The design parameters in Table 1 are good to satisfy both two conditions in Eqs. (5) and (6).

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SIMULATION OF UNDULATOR BEAMLINE

Table 2: Simulation Results of the Coherent Undulator Beamline

Parameter	Value	Unit
Photon Wavelength λ_{ph}	0.1	nm
Photon Energy E_{ph}	12.4	keV
Saturation Length	36	m
Bandwidth (rms)	0.138	%
Pulse Length (rms)	5.56	µm
Pulse Duration (rms)	18.5	fs
Radiation Power at Saturation	1.8	GW

To test the performance of the coherent undulator beamline, GENESIS code is used [5]. The main results of the simulation are summarized in Table 2, and the radiation power at the center of the single bunch along the coherent undulator beamline is shown in Fig. 4. Each line represents the radiation power with a different random seed. The radiation power is saturated around 36 m, corresponding to 8 undulator modules or 4 FODO lattices. The radiation power of core part in the single bunch is 1.8 GW at the saturation.

Note that the test electron bunch is ideal with uniform normalized slice parameters. Therefore the saturation length can be increased if we use a real 3D beam distribution. After the linac design, a new optimization with a realistic 3D electron beam distribution will be conducted.

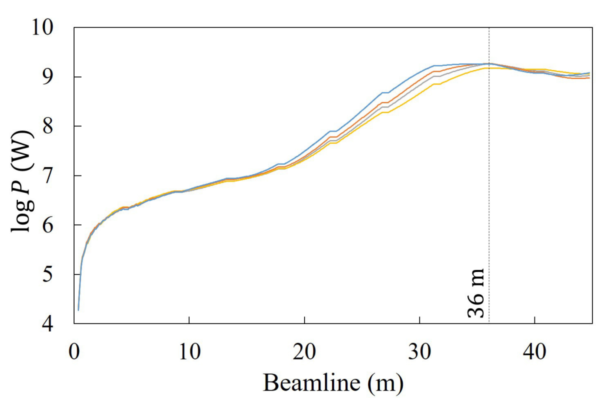

Figure 4: Radiation power of core part in the bunch along the coherent undulator beamline.

The single-shot radiation spectrum at the saturation length of 36 m is shown in Fig. 5. The bandwidth is 0.138% with respect to 12.4 keV. To reduce the bandwidth of the coherent beamline, tapering will be applied. We are also considering applying the self-seeding technology to get a narrower bandwidth and a higher intensity [9].

CONCLUSION

In this paper, by using the SASE FEL concept, we have designed the coherent undulator beamline for a new advanced synchrotron light source in Korea. Parameters of the electron beam and the coherent undulator beamline are determined to satisfy the SASE FEL lasing conditions for the hard X-rays at 0.1 nm. With the calculated parameters and GENESIS simulations, it was confirmed that the saturation of the SASE FEL power can be achieved within 60 m for an energy of 6 GeV electron beam.

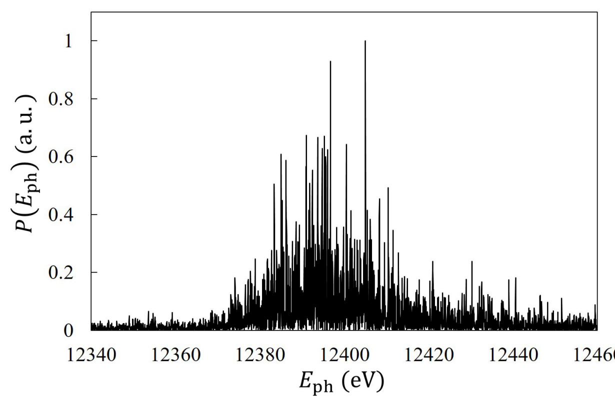

Figure 5: Radiation spectrum at 36 m.

For the next step, optimization with a realistic 3D electron beam distribution will be carried out in the near future. With the bunch, tapering will be applied to get a higher radiation power and a narrower bandwidth. Temporal structure is also an important property of coherent radiation. By applying the self-seeding technology, it can be possible to produce attosecond long hard X-rays with our design.

In addition, more deep research on beam quality degradation in the synchrotron is required. In our design, an electron bunch will be dumped after tens of turns because synchrotron radiation and other sources may increase the slice energy spread, which can destroy coherent FEL lasing. Therefore, optimization of our design and detailed operation conditions including the maximum circulation number of an electron bunch in the synchrotron should be studied further.

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