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CONCEPTUAL DESIGN OF SUPERCONDUCTING TRANSVERSE GRADIENT UNDULATOR FOR PAL-XFEL BEAMLINE

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Abstract

Recently, the transverse gradient undulator (TGU) applications are suggested from laser plasma wake-field accelerator (LPWA) to ultimate storage ring (USR). Especially for X-ray FELs, TGU can be used to generate a large bandwidth radiation up to 10%. In this proceeding, a review of PAL-XFEL beam parameters and TGU requirements was done to apply a variable large bandwidth operation to the PAL-XFEL beamlines. Also, the conceptual design of TGU, based on superconducting undulator (SCU) was proposed, and B-field calculation results were introduced for large bandwidth operation modes of PAL-XFEL.

INTRODUCTION

The original TGU concept was introduced to overcome the large electron beam energy spread of an earlier stage of FEL development in the 1980s. The main parameter of TGU is the amount of K-value gradient in the transverse direction, defined by a parameter α. The α is defined as [1]

$$\alpha = \frac{\Delta K/K_0}{\Delta x} = \alpha_k/K_0. \tag{1}$$

Lately, the various types of TGU, canting pole geometry permanent undulator, and SCU were suggested and built for LPWA or USR to compensate the energy spread for compact FEL source development [2,3]. Other TGU applications are also suggested for X-ray FEL by using a small energy spread electron beam [4]. This application uses a TGU and an RF deflecting cavity to generate the large bandwidth X-ray radiation. A deflected electron beam sees different K-values of TGU and the bandwidth of X-ray FEL can be adjusted by changing the gradient amount of TGU, up to 10% order. By using this scheme, FEL beamlines can provide a variable X-ray FEL bandwidth to meet the requirements of users.

LARGE BANDWIDTH MODE OF PAL-XFEL

PAL-XFEL Beam Parameters

PAL-XFEL, an X-ray FEL user facility, has hard and soft x-ray beamlines based on Self Amplified Spontaneous Emission (SASE). The hard X-ray beamline uses a 10 GeV, 200 pC and 3.0 kA electron beam to provide 0.1 nm hard X-ray FEL by using twenty undulator units. For the soft X-ray beamline, seven undulator units are used to provide 1 nm soft X-ray FEL by using a 3.0 GeV, and 2.5 kA electron beam. Hard X-ray Undulator (HXU) and Soft X-ray Undulator (SXU) of PAL-XFEL are hybrid type undulators and Table 1 shows an undulator system parameters of each undulator systems.

Table 1: Undulator System Parameters of PAL-XFEL Beamlines

Parameters	HXU	SXU
Period	26.0 mm	35.0 mm
K	1.973	3.321
B_{eff}	0.812 T	1.016 T
gap_{min}	8.3 mm	9.0 mm
Length	5.0 m	5.0 m

The large bandwidth operation mode of PAL-XFEL requirements was calculated based on the suggested concept in Ref. [4] by using the PAL-XFEL beam and undulator parameters. The assumptions were used in this proceeding that a deflecting cavity is installed in front of the undulator beamlines and the TGU beamline, which can provide up to 10% bandwidth X-ray radiation, is installed. The deflected length of the electron beam was assumed as 1 mm for both the hard and soft X-ray beamlines for simple calculation. Table 2 shows a required K-value and gradient parameters to generate a 10% bandwidth radiation wavelength, λ_R, for the PAL-XFEL beamlines. For the calculation, the periods of the hard and soft X-ray TGUs were assumed as 26 mm and 35 mm, respectively.

Table 2: Undulator Parameters Required for 10% Large Bandwidth Operation of PAL-XFEL

Beamline	λ_R (nm)	K_0	$\alpha_K (m^{-1})$	$\alpha (m^{-1})$
Hard	0.1	1.973	99.6	50.5
Hard	0.06	1.239	95.2	76.8
Soft	3	3.321	130.8	39.4
Soft	1	1.531	109.9	71.8

Requirements for PAL-XFEL TGU

One of the important requirements of PAL-XFEL large bandwidth operation mode calculation was the variable bandwidth of X-ray FEL. To change the bandwidth of FEL, the TGU of PAL-XFEL can change the K-value and gradient by the user experiment requirements. Usually, the fixed gradient TGUs by using a canting pole geometry was proposed and built for the LPWA applications. These canting pole geometry TGUs can provide a fixed large gradient with a high K-value for short undulator periods. However, these canting pole geometry undulators are not proper for the PAL-XFEL large bandwidth operation mode.

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On the other hand, a normal planar undulator or an APPLE-X type EPU can provide a variable gradient for a specific K-value. The normal planar undulator can change the K-value and the gradient by changing the offset between the center of the vacuum chamber and the undulator magnet structure. The APPLE-X type EPU, suggested by Swiss-FEL, can change the K-value and gradient by changing the magnet structure phase or breaking the symmetry between the four magnet arrays. However, the available K-value and gradient of these two types of undulators are decided by the mechanical magnet array movement range. Also, in case of the APPLE-X type EPU, it is hard to provide enough K_0 value when $\lambda_U = 26$ mm, the PAL-XFEL hard X-ray beamline case.

CONCEPTUAL DESIGN OF TGU

As introduced in the previous section, the normal planar undulator or APPLE-X type EPU can be a candidate of TGU for a large bandwidth operation of PAL-XFEL. However, in case of normal planar undulator, it needs to keep the offset between the electron beam and the magnet structure center to maintain the K-value and gradient. To do that, the electron beam position in the vertical direction needs to be kept constant, and the vertical positions of the multiple undulator segments need to be also kept along the long beamline of about 100 m for the hard X-ray beamline case. For the high gradient region, the tolerance of the offset between an electron beam and the undulator magnetic center needs to be tight for keeping the K-value and gradient of the normal planar undulator. On the other hand, the APPLE-X type EPU undulator can change the K-value and gradient by moving the four magnet arrays. For the linear polarization mode, the K-value difference between the right and left magnet arrays induces the gradient of K-value at the center of the vacuum chamber. To achieve a maximum gradient of APPLE-X type undulator, one magnet array needs to be set as a minimum gap and the other as a maximum gap. Also, the APPLE-X type undulator is a pure permanent magnet (PM) undulator, and the maximum field is also decided by the types of the magnet material.

Design Parmeters

The conceptual design of a TGU for a large bandwidth operation of PAL-XFEL was done under the several considerations. The first consideration of the design was minimizing the mechanical part. Another consideration was adopting the concept of an APPLE-X type undulator to generate the gradient. By using these two conditions, the design of a TGU for the PAL-XFEL beamline was done as shown in Fig. 1 based on a superconducting undulator (SCU). This design has two planar SCU magnet arrays, and the steel pole is placed between these two magnet arrays to concentrate the B-field at the center. The gradient of K-value is induced and changed by the current difference between the right and left coils. This SCU concept was used to replace the mechanical part of planar or APPLE-X type undulators. Also, the magnetic gap was set to be larger than the 6.7 mm vacuum chamber height of PAL-XFEL by considering an SCU insulator thickness of about 2 mm. Figure 2 and Table 3 show the design parameters and value of the TGUs for the hard and soft x-ray beamlines. The maximum current density of the design was estimated by using the scaling law of SCU [5].

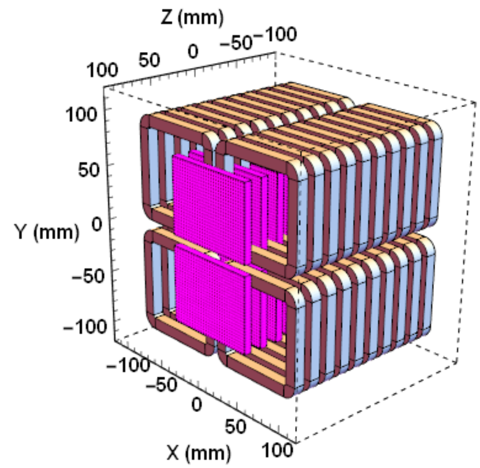

Figure 1: Dual superconducting TGU model for PAL-XFEL soft x-ray beamline.

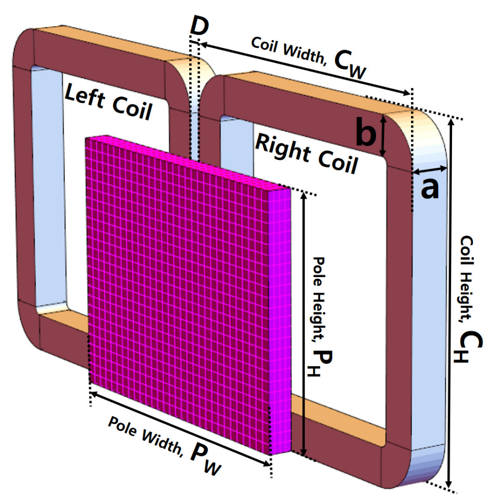

Figure 2: Parameters of superconducting undulator model design.

Magnetic Field of Superconcuting TGU

The field distribution of a superconducting TGU was calculated by using the RADIA [6] magnetic field calculation code. Figures 3 and 4 are calculation results of B-field distribution. In Fig. 3, the blue dotted line shows the B_y field when the left coil array current density, J_L, is 900 A/mm^2 and the right one, J_R, is 0 A/mm^2. The black dotted line shows B-field distribution when $J_L = 0$ A/mm^2 and $J_R = 900$ A/mm^2. The solid red line shows one when $J_L = J_R = 900$ A/mm^2 and the center position of vacuum chamber has maximum K-value and zero gradients.

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Table 3: Design and Simulation Parameter Values of Dual Superconducting Undulator for PAL-XFEL Beamlines

Parameters	Hard X-ray	Soft X-ray
a	7.5 mm	10.5 mm
b	7.5 mm	10.5 mm
C_W	30 mm	95 mm
C_H	31 mm	95 mm
D	2 mm	4 mm
P_H	58 mm	90 mm
P_W	16 mm	70 mm
J, Current Density	1200 A/mm^2	900 A/mm^2
Magnetic Gap	9.5 mm	10 mm

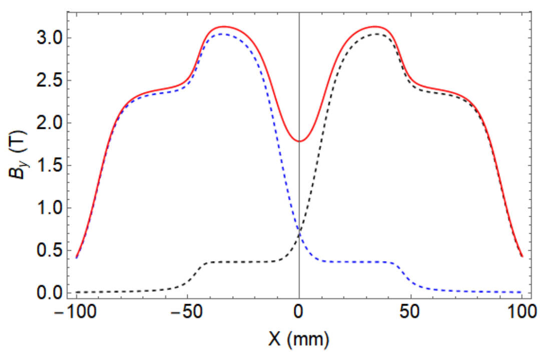

Figure 3: B-field distribution of dual superconducting TGU with $J_L = J_R = 900$ A/mm^2 for PAL-XFEL soft x-ray beamline.

On the other hand, Fig.4 shows a B-field distribution for $J_L = 900$ A/mm^2 and $J_R = -900$ A/mm^2. The gradient is the maximum value, and K-value is 0 for this case. By using the various combination of current density of two planar superconducting undulator coil, the gradient and K-value can be adjusted.

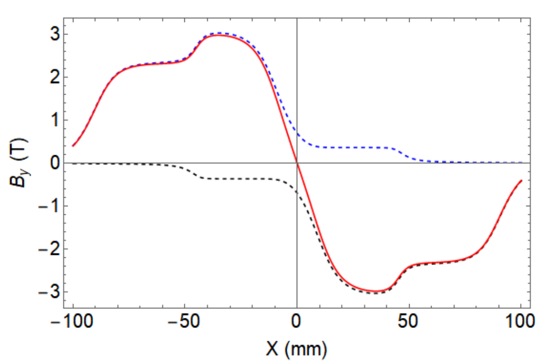

Figure 4: B-field distribution of dual superconducting TGU with $J_L = 900$ A/mm^2 and $J_R = -900$ A/mm^2 for PAL-XFEL soft x-ray beamline.

On the other hand, when there is an offset in the x-direction, the superconducting TGU can provide a maximum gradient with a non-zero K-value. Also, as shown in Fig.3 or by adjusting the combination of two coil current density, the offset point can provide zero gradients with non-zero K-values. The offset point can be changed by the requirements of gradient and K-value. However, to maintain the radiation point of an FEL, changing the offset point is not proper for a large bandwidth FEL application. Thus, by considering the requirements of applications, the operation point of the superconducting TGU needs to be fixed.

TRANSVERSE GRADIENT AND K-VALUES

The calculated transverse gradient and K-value of the superconducting TGU and operation points are shown in Fig. 5 and 6. For the hard x-ray beamline, 1200 A/mm^2 was used

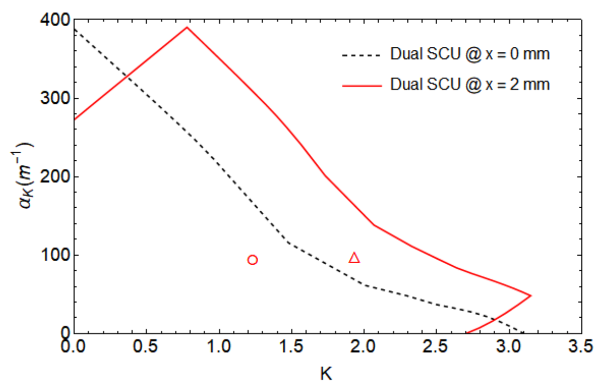

Figure 5: Gradient and K-value for PAL-XFEL hard x-ray beamline TGU.

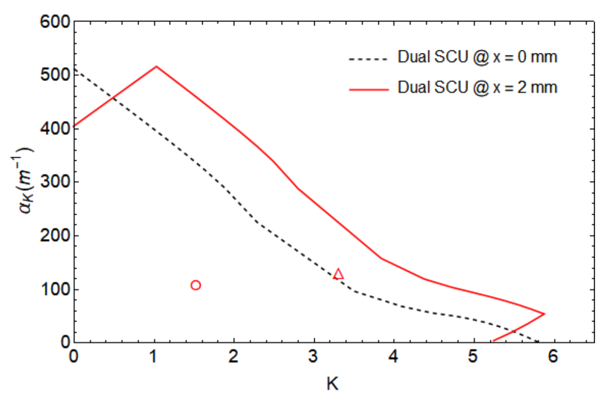

Figure 6: Gradient and K-value for PAL-XFEL soft x-ray beamline TGU.

as the coil maximum current density in this calculation. At the center position of the TGU, a 10% bandwidth operation for $\lambda_R = 0.06$ nm is possible. However, $\lambda_R = 0.1$ nm operation is hard to do at the center position due to the insufficient gradient. Instead, these two large bandwidth mode operations are possible by using the $x = 2$ mm offset point. Also, using the $x = 2$ mm point, a reduction of maximum current density can be expected to operate a large bandwidth mode at the hard x-ray beamline. Decreasing the maximum current density is beneficial for operating superconducting undulators.

For the soft x-ray beamline case, 900 A/mm^2 was used as a coil maximum current density for the calculation. At the center position of TGU, a 10% bandwidth operation for $\lambda_R = 1$ nm is possible. To meet the $\lambda_R = 1$ nm and $\lambda_R = 3$ nm operation requirements, a $x = 2$ mm offset point of the TGU is needed. Also, using the $x = 2$ mm point, a reduction of the maximum current density can be expected as for the hard x-ray beamline case.

CONCLUSION

In this proceeding, large bandwidth operation conditions of PAL-XFEL were calculated, and the conceptual design of a superconducting based TGU was carried out. The conceptual design consists of two normal planar SCUs. This superconducting TGU can change the K-value or gradient by changing the current density ratio between the two coils. By using a $x = 2$ mm offset point, the superconducting TGU can meet the requirements of the large bandwidth operation of PAL-XFEL. Also, using such an offset point, a reduction in the maximum current density, can be helpful for an SCU operation. Thus, this TGU type based on SCU can be an undulator option for an operation mode with a large bandwidth up to 10% at PAL-XFEL.

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