PHYSICS REQUIREMENTS OF PLS-XFEL UNDULATOR *

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Abstract

Pohang Accelerator Laboratory(PAL) is planning a 0.3 nm SASE (Self Amplification of Spontaneous Emission) XFEL based on 3.7 GeV linear accelerator. For shorter saturation length, application of SPring8 type in vacuum undulator is needed. This reflects the experiences from SPring8 SCSS project. The end structures were designed to be asymmetric along the beam direction to ensure systematic zero 1st field integral. The thickness of the last magnets were adjusted to minimize the transition distance to the fully developed periodic field. This approach is more convenient to control than adjusting the strength of the end magnets. The final design features 4 mm minimum pole gap, 15 mm period, peak effective field of 1.09 Tesla. In this article, the physical design of the undulator, the design of the end structure, and the physics requirements of the undulator system will be presented

INTRODUCTION

Pohang Accelerator Laboratory (PAL) is planning to build a X-ray FEL based on SASE (self amplified spontaneous emission) process[1]. The machine is named as PAL-XFEL and will utilize the upgraded injector linac for PLS (Pohang Light Source) electron storage ring. Current electron beam energy of the linac is 2.5 GeV and it needs to be upgraded to at least 3.7 GeV for 0.3 nm FEL radiation. The SASE XFEL offers unprecedented opportunity for X-ray users. SASE XFEL radiation is supposed to be at least ten orders of magnitude brighter than the 3rd generation synchrotron light sources. The SASE XFEL is transversely coherent and the pulse length is very short, femto-second level, which also privides users with chances for new scientific research.

On the other hand, the SASE XFEL is quite a scientific challenge, as is well known; the generation of an extremely low emittance electron beam through a photo-cathode RF gun, bunch compression to an extremely short length, maintaining the low emittance to the end of the linac, and keeping the beam orbit as straight as possible in the undulator. The PAL-XFEL adds a few more scientific difficulties because it is targeting relatively short radiation wavelength (0.3 nm) with lower electron beam energy (3.7 GeV). Therefore, the PAL-XFEL requires very short period undulator with minimum possible gap. This implies the use of in Vacuum undulator developed at SPring8 is essential to the project. In this paper, the magnetic design of the periodic part, the magnetic design of the end part and other physics requirement of the PAL-XFEL undulator will be described. The major design parameters of the PAL-XFEL are summarized in Table 1.

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Table 1: Major design parameters of PAL-XFEL

Beam Parameters	**Value**	**Unit**
Electron energy	3.7	GeV
Peak current	3	kA
Normalized slice emittance	1	mm mrad
RMS slice energy spread	0.02	%
Full bunch duration	270	fs
FEL Parameters		
Radiation wavelength	3	Å
FEL parameter ρ	5.7×10^{-4}	
Peak brightness	1×10^{32}	Pts/sec/mm^2/mrad^2/0.1%BW
Pulses repetition rate (Max.)	60	Hz
1-D gain length	1.2	m
Saturation length, L_{sat}	45	m

MAGNETIC FIELD REQUIREMENTS

A few kinds of technologies are considered for SASE XFEL undulators. For higher magnetic field at smaller magnetic period, superconducting (SC) undulator looks promising. But they believe that the technology is not mature yet and there is higher risk factor that hinders many laboratories to adopt SC technologies for SASE-FEL undulator. Helical undulator has advantage in getting polarized radiation with shorter saturation undulator length. But it has difficulty in manufacturing and error control. Therefore, many laboratories prefer Halbach type hybrid undulator or PPM (Pure Permanent Magnet) type undulator which can be in vacuum or out vacuum type. A lot of experiences are accumulated in this kind of planar undulator for error control and tuning procedures. It achieves comparatively higher flux density and it is believed that the tight SASE-XFEL undulator requirements can be comfortably met.

The basic magnetic structure of the undulator will be a Halbach type hybrid structure that use strong rare earth high performance magnets and ferromagnetic poles. This type can produce higher flux density and the field is mostly dominated by the mechanical manufacturing accuracy instead of less controllable material property of the magnets. Due to these advantages, the ambitious TESLA-FEL at DESY and SLAC LCLS (Linac Coherent Light Source) projects are planning to use the Halbach hybrid type undulator.

Vanadium permendur is popular material for ferromagnetic pole due to its higher saturation. For rare earth magnetic material, higher remanence and higher coercivity is required. Higher remanence is important for higher undulator field. Higher coercivity is preferable for stronger resistance to the radiation damage. Experimental studies show that higher coercivity is very helpful for less degradation in magnetic performance after radiation damages[2]. Also, operating temperature of the magnet should be high enough taking in to account the higher (about 120 ^{o}C) baking temperature of the IVUN type undulator. A good compromise would be Neomax35EH class permanent magnets. It features operating temperature of 160 ^{o}C with remanence of 1.17 T to 1.26 T and coercivity of 11.0 kOe to 12.0 kOe. The intrinsic coercivity reaches up to 25 kOe meaning high resistance to demagnetization. The Neomax 35EH is well verified in SPring8 IVUN undulators.

PERIODIC MAGNETIC STRUCTURE

The key features of PAL SASE-XFEL can be summarized as achieving most promising 0.3 nm wavelength FEL radiation using lower e-beam energy. To achieve this goal, all parameters are set to be very aggressive. For undulators, achieving smallest possible magnetic gap is helpful in achieving smallest possible undulator period. Therefore, PAL-XFEL undulator system will positively use IVUN which is actively developed and used by SPring8 ID team. Since the advent of SPring8's success in implementing IVUN in their storage ring, the adoption of IVUN in synchrotron radiation sources became popular in all major synchrotron radiation laboratories. The IVUN technologies are well established by SPring8 and SSM(Sumitomo Special Metals) Inc. and we assume that we can fully utilize their expertise. This strategy that uses well established commercialized undulator can reduce risks and speed up the development period. In this context, we mostly concentrate in the physics design of magnetic structures and the detailed mechanical engineering should be elaborated with eligible undulator supplier. In this report, the undulator which will be used for 0.3 nm SASE-XFEL with 4 mm magnetic gap and 15mm magnetic period will be treated.

To estimate the minimum undulator pole width, we need to know the required transverse roll-off. Pierce parameter is a key parameter in FEL theory and it determines the gain length and the spectral bandwidth. And it naturally gives requirements for undulator field accuracy. For 0.3 nm PAL SASE-XFEL case, the undulator period is 15 mm and $\rho \approx 4.3\times10^{-4}$.

The transverse uniformity of the field should satisfy $\Delta B_z / B_z(x=0) \le \rho$ for sufficient wide range. Although the rms e-beam radius is about $r \approx 36\mu m$, we require good field region of ±1 mm for expected operating magnetic gap of 4 mm~6 mm. This redundancy will alleviate alignment requirements and other tolerances with small increase in pole width. The maximum gap is set to 6 mm arbitrarily as the upper limit of the operation since the field will be small for gap larger than 6 mm and there will be no chance of saturated SASE-FEL lasing.

To estimate the required pole width, the transverse roll-off is calculated using ANSYS[3] while varying the pole width with 15 mm period and 6 mm maximum operating gap. From the calculation, it is seen that we can safely achieve required tolerance of $\Delta B / B_0 < 1.0\times10^{-4}$ for ±4 mm at pole width of 30 mm. The pole width 30mm is good enough allowing wide good field region. To optimize the pole thickness, the effective peak field is calculated while varying the pole thickness. The pole height was set to 25 mm with sufficient overhang. The effective peak field is calculated from the fourier component along the longitudinal direction. The maximum effective field occurs when the pole thickness is 2.4 mm. From this pole thickness can be preliminarily decided to be 2.4 mm. Same kind of calculation is repeated while varying the pole height. The block size is also increased to maintain constant vertical overhang of 4 mm. For pole height larger than 20 mm, the increase of the effective peak field slows down rapidly suggesting 25 mm pole height is reasonable first estimate for the pole height. Therefore, the final magnetic geometry for periodic part could be described as 30 mm pole width, 25 mm pole height, 2.40 mm pole thickness. The magnet is 38 mm wide and 29 mm high and 5.10 mm thick.

Table 2: Major parameters of SASE-XFEL Undulator. The effective peak field at 4 mm is slightly higher than the target field (B_0=1.0573, K_{eff}=1.4812). This difference can be used as a engineering margin.

Parameter	Value
Pole Gap (nominal)	4 mm
Period	15.00 mm
Pole Dimension (W × H × T)	30 × 25 × 2.40 mm^3
Magnet Dimensions (W × H × T)	38 × 29 × 5.10 mm^3
Effective Peak Field (B_{eff})	1.0917 Tesla
Undulator Magnetic Length (L_{und})	4500 mm
Effective K value (K_{eff})	1.529
Fundamental photon energy	3.996 keV
Fundamental photon wavelength	0.310 nm

MAGNETIC STRUCTURES AT THE TRANSITION REGION

To achieve maximum number of periodic field, the undulators need to reach the periodic field with minimum possible transition from the ends. A number of different schemes have been used in the past for this purpose. K Halbach calculated the correct excitation pattern for the transition poles that results zero offset. The scheme involves adjusting the strength of a few poles near the ends. APS[4] and LCLS undulator uses a pole recess and partial strength magnet for the last magnet. SPring8 uses a longitudinal gap for last magnet for smallest undulator orbit offset. ESRF has their own unique and smart transition sequence[5]. In our case, we modify APS scheme and try to use a recess in the last pole and thinner last magnet. This thinner magnet can avoid the difficult process of partial demagnetization of magnet block. And an asymmetric undulator configuration that have even number of poles are selected. In this scheme, the first pole and the end pole has different polarity and the residual field integral is systematically zero. A small residual field integral may exist that may result from manufacturing errors. These kinds of small errors are usually well manageable. This concept can reach the periodic field with shorter transition length and it is geometrically simple, and does not need flux shunts. The geometry of the end transition sequences are determined by varying the thickness of the last magnet, and the recess of the last pole. Varying the 2 parameters, the optimal geometries are optimized that results minimum orbit drift in the undulator for the operating gap range. The transition parts are simulated using RADIA[6,7]. Simulating the whole undulator is unpractical due to the limited computer resources. As a compromise, only 20 periods are calculated. Since integral contribution from the periodic part cancel each other, this 20 period modelling is not bad to estimate the orbit drift from the transition sequences. The typical calculated field profile, and orbit are shown in Fig 1 and Fig 2, respectively. It can be seen that the field is approaching to the periodic part in a minimum distance. In our case, the field is odd in z direction and the field is asymmetric. It is seen that the average slope in the body of the undulator is nearly zero and the residual offset is practically zero.

SUMMARY

In this report, the design efforts for the undulator for PAL-XFEL are summarized. The undulator has 15mm period with 4 mm minimum gap. The periodic magnetic structures are optimized and the details of the transition parts are elaborated. In the calculation, the RADIA code developed from ESRF, and ANSYS are mostly used. The major parameters are summarized in Table 1. Since the geometries are not implemented completely (tolerances etc) and the magnetic properties are approximate, there might be small differences between the calculation and the reality. This can results an error but the difference will be small. Our experiences show that the peak field agrees within 1% of the calculated values. Also these differences might show somewhat different behaviour in the gap dependence of the residual field. But hopefully, the final undulator after tuning the minor differences will agree with design and will meet all the design requirements.

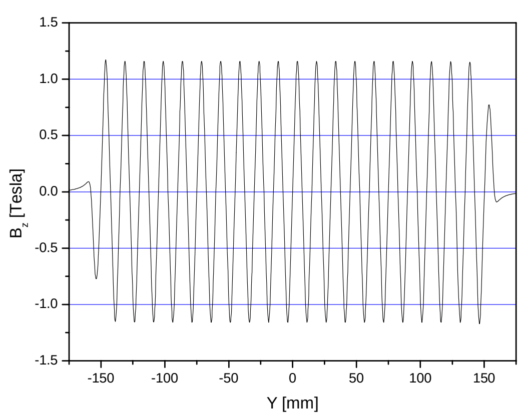

Figure 1: The calculated field profile.

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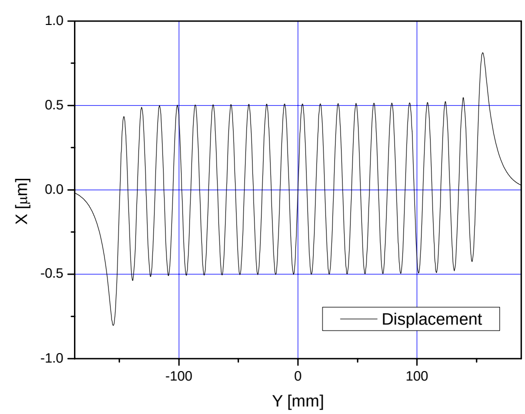

Figure 2: The calculated orbit based on the calculated field profile