PHASE SHIFTER DESIGN FOR ISASE

S.D. Chen, K. Fang, L.Zhu, H.-D. Nuhn, C. Pellegrini, J. Wu, SLAC, CA 94025, USA
S.D. Chen, C.S. Hwang, NCTU, Hsinchu 30076, Taiwan
C.S. Hwang, NSRRC, Hsinchu 30076, Taiwan

Abstract

A phase shifter to generate an additional phase advance of the spontaneous light versus the electron beam was designed for the iSASE scheme. The iSASE mechanism is for reducing the bandwidth further from SASE FEL process. A large phase advance about 1600*2Pi as the FEL operating at wavelength 0.8 nm was needed according to the simulation of iSASE process. Since the iSASE is thought to implement into LCLS II project, the space limitation causing by LCLS II should be considered when designing the phase shifter. An optimized three-pole electric phase shifter with 7.3 mm gap has the center field of 1.8 T . The vanadium steel was considered as pole material and the magnet physical length is 260 mm, meanwhile the water-cooling type copper coil was adopted. The temperature increment, force analysis, low field operation mode concept, and preliminary tolerance study were discussed.

INTRODUCTION

Improved SASE (iSASE) [1,2] was proposed to reduce the SASE bandwidth. In iSASE scheme, several phase shifters with large phase delay are inserted to increase the coherence length. In this scheme, the phase shifters should be placed in linear growth region, for example in our layout: five phase shifter was inserted into LCLS-II lattice, and the phase shifter for phase matching at local place [3, 4] will be replaced.

In our case, five phase shifters divide the linear growth region into six sections. Looking into the details of how the mechanism works: as electron beam passing through the first section, the electric field (light field) grows up and contains the informations of structure of local electron beam; after going through the first phase shifter, the electric field got a further phase advance and located at a new position inside the electron bunch; in the second section, the electric field can stimulate the new local electrons as a seed; in the following sections, same thing happens that the electric field will be placed at a new position by large phase delay caused by phase shifter and works as a seeding stimulating local electrons at new position. The coherence length was hence increased.

The scheme was first studied by a fundamental set up of five phase shifter with 100, 200, 400, 800, 1600*2pi phase delay, at wavelength 0.8 nm. The largest phase shifter, 1600*2pi, which is the hardest one to be achieved, was first designed and presented in this paper. Restricted by the space limitation from LCLS-II undulator hall, the length of phase shifter should be less than 260 mm, which forces the magnetic field high as 1.8 T to generate such a large phase delay. A permanent magnet can not afford the requirement; an electric magnet with pole material of the vanadium steel, which has a high saturation field of 2.4 T, was chosen. Meanwhile the water-cooling type copper coil was adopted to eliminate the Joule heat from copper wire.

This paper was organized as following: the specifications of magnet were first presented, then the water cooling system and evaluation of phase delay were described; the requirement of fringe field and remanence field were also discussed; the preliminary tolerance study was mentioned; the conclusion was in the end.

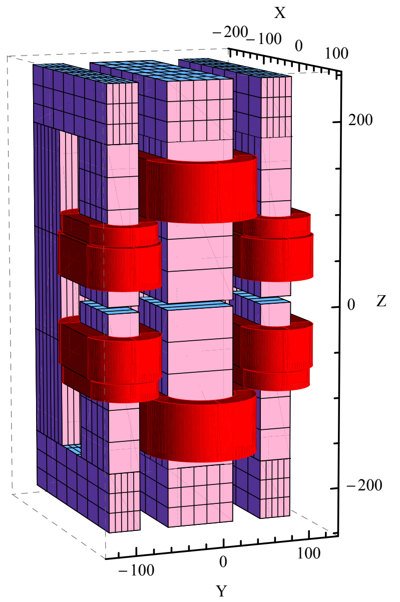

Figure 1: Magnet model plotted by Radia.

DESIGN OF THE MAGNET

The model displayed herein is a preliminary design, but can be the proof of the feasibility of producing 1600*2pi phase delay under space limitation, which is that physical length is less than 260 mm, gap is 7.3 mm, and physical height is less than 500 mm. To make the model practical, the details of manufacturing of the magnet and the effects on neighber magnets as inserting into undulator hall were integrally considered. The model was designed by Radia associated with Mathematica; the diagram of model is in Figure 1 and the specifications were in Table 1. The pole will be sliced and glued to prevent strong eddy current and reduce the charging time. The minimum bending radius of copper wire is considered. The transverse good filed region is now 10 times larger than requirement, however the saturation

Copyright © 2014 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-133-5

Table 1: Specifications

Items	Value	Unit
Physical length	258.9	mm
Physical height	487.3	mm
gap	7.3	mm
Magnetic field center/side	1.795/-1.780	T
$\triangle B/B$ along X	$<$ 0.2%in 15 mm	-
wire type	5.6mm x 5.6mm copper, rectangular ϕ3mm hollowed	-
Main current	273	A
Material of pole	vanadium steel	
temperature increase on coil	1.87 / 1.86	°C
Vertical force Center/Side	0.77 / 0.35	tons
1st Integral field	-20.0	µTm
2nd Integral field	-1.5	µTm^2

issue is the priority of optimizing the transverse width of poles. The temperature increase on the surface of magnet is required to be lower than 2°C, so the 2-in-2-out cycling water circuit is adopted to the coil of main pole (detailed in next section.) The field along the beam trajectory is in Figure 2. The saturation analysis inside the pole is plotted in Figure 3. It shows the corner of the pole material is highly saturated; More design work on the shape of pole can improve the efficiency of this magnet. The total force between upper and bottom part was analyzed and is about 1.4 tons. Considering the strong force and the assembling of magnet, the C-frame design should be replaced by H-frame.

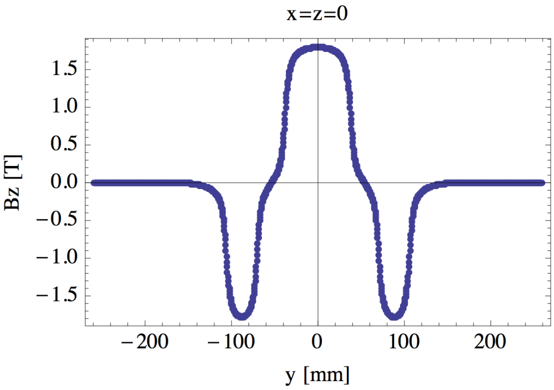

Figure 2: Field along the beam trajectory.

TRANSVERSE GOOD FIELD REGION

The required horizontal good field region is mainly determined by beam dynamic. It should be wider than wiggle amplitude as the electron beam passing through phase shifter. The maximum value of second integral of magnetic field is 4600 µTmm^2. The amplitude can be calculated by $\int\int B_z d^2y/\bar{B}\rho$, where $\bar{B}\rho$ is beam rigidity. With beam energy 4 GeV, the maximum amplitude is calculated as 345.1 µm. Beam size should be also considered; for β-function equal to 20 m, $\sigma_x = \sqrt{\epsilon\beta}$ is around 20 µm. The jitter from shut to shut increases the required width too. It is about 10 % of beam size and is 2 µm. The field error from the misalignment of phase shifter should be prevented. To be safe, the quantity of misalignment is estimated about 0.5 mm. Combining all mentioned issues, the horizontal good field region is around $\pm 1mm$, of which the field variation is $6.2 * 10^{-5}$.

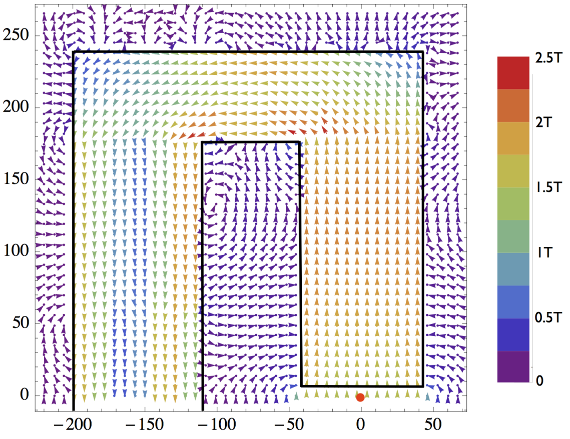

Figure 3: Field inside the pole.

WATER COOLING SYSTEM

There are 4 Side-Coil and 2 Center-Coil, and it is 1-in-1-out for side coil and 2-in-2-out for center coil. Waterways of all 8 coil sections are in parallel connection. The water pressure is at 5 atm, and the required total flow rate is 27 Liter per minute. The temperature raise on magnet is under 2°C by the design in Table 2, however, the flow velocity is too high; empirically 2.5~4 m/sec is proper number to have better efficiency. More optimization work were needed for cooling system. On the other hand, the cooling water itself of cooling system in LCLS-II has a temperature vibration about 2°C. This will be considered in following work.

Table 2: Cooling Water System

Items	Value	Unit
Cooling water pressure	5	atm
sections per coil (Center/Side)	2/1	-
Flow velocity (Center/Side)	7.95/7.98	m/sec
Flow rate of each coil (Center/Side)	6.74/3.38	Liter/Min
Total flow rate	27.0	Liter/Min

Copyright © 2014 CC-BY-3.0 and by the respective authors

PHASE DELAY

Refer to the field along the beam trajectory in Figure 2, the phase delay can be integrated by formula

$$\mathrm{PI}=\int_{-\infty}^{\infty}\left(\left(\int_{-\infty}^{z} B_x\left(z'\right)\,dz'\right)^2+\left(\int_{-\infty}^{z} B_y\left(z'\right)\,dz'\right)^2\right)dz,$$

where B_x and B_y are the field of two transverse direction. The integrated PI along the beam trajectory is plotted in Figure 4. The number of phase delay can be calculated by

$$\Delta\varphi=\frac{\pi}{\lambda_\gamma}\frac{e^2}{\gamma^2 m_e^2 c^2}PI.$$

The total $\Delta\varphi$ is $1653 * 2\pi$, which is 3% more than expectation. The small amount excessive give more flexibility for engineering tolerance.

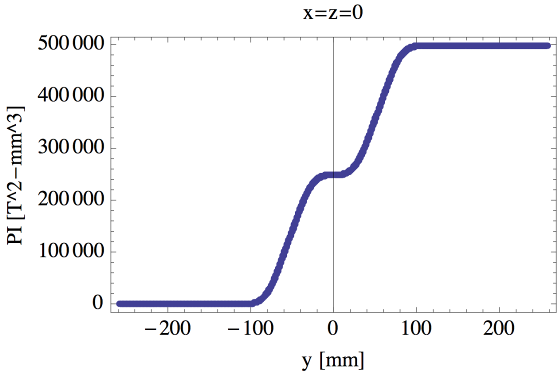

Figure 4: Phase delay.

FRINGE FIELD ANALYSIS

There are a undulator and a qudrupole at the downstrain and upstrain of phase shifter, respectively. The both two magnets are about 10 cm far from the side of phase shifter, so the fringe field on the transverse plane was analyzed and shown in Figure 5. The result shows that the fringe field is up to 75 Gauss, which is much higher than requirement, 0.5 Gauss. The magnetic shielding was needed to be inserted between phase shifter and neighbor magnets.

REMANENCE FIELD

In LCLS-II, iSASE scheme should be remain optional. Once the iSASE mechanism is turned off, the phase shifter should work as a normal phase shifter for phase matching between undulators. At such situation, few number of phase delay with high precision of around 3° was needed. However, it's hard for a magnet, which is optimized for such a large phase delay, to offer a small and precise magnetic field. The remanence field is the first priority problem. As long as the remanence field is low enough, there is a chance to operate this phase shifter for phase matching. Unfortunately, the actual remanence field and result of the degaussing process can only be discovered experimentally. So, it was planed to do the remanence field analyzation after the prototype constructed. If there are no chance to operate the phase shifter for phase matching, a moving stage carrying two phase shifter, one is for iSASE scheme and another is for phase matching, will be adopted to solve the problem.

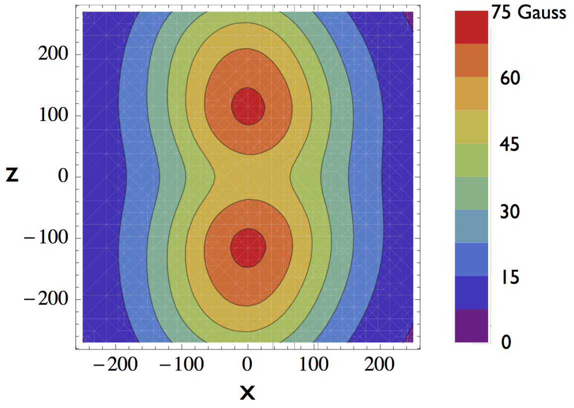

Figure 5: Fringe field at 10 cm far from phase shifter.

PRECISION OF POWER SUPPLY

The variation of power supply causes additional phase error on phase shifter. If the phase error is demanded lower than 10°, the power supply should have a precision of $3 * 10^{-5}$ for the largest phase shifter. Supposing the presented design is adopted for all 5 phase shifter, the current and the required precision of power supply were simulated and listed in Table 3; how the B-field various is plotted as a function of current in Figure 6. The designed phase shifter is optimized for the 1600*2π, and only one power supply was needed for all three poles. If this design is going to be adopting on other smaller phase shifter, the center and side poles should be charged by two different power supplies for compensating the 1st and 2nd integral field. The high precision of power supply is achievable when using proper power supply associated with 16-bit control system; the current facility in LCLS-II can match the requirement. However, the phase error of 10° is only a naive assumption; further tolerance study is needed.

Table 3: Precision of All Phase Shifter.

$\triangle\phi$	Current(A)	$\triangle$ I/I	ΔI (mA) for $\Delta\phi = 10°$
1600	272.92	$3 * 10^{-5}$	8.2
800	136.46	$3 * 10^{-5}$	4.1
400	71.48	$6.2 * 10^{-5}$	4.43
200	48.74	$8 * 10^{-5}$	3.9
100	38.01	$1.5 * 10^{-4}$	5.7

PRELIMINARY TOLERANCE STUDY

The physical requirement of how precise the phase shifter for iSASE scheme is preliminary studied. An modified GENESIS code [5] was developed to simulate iSASE scheme [6],

Copyright © 2014 CC-BY-3.0 and by the respective authors

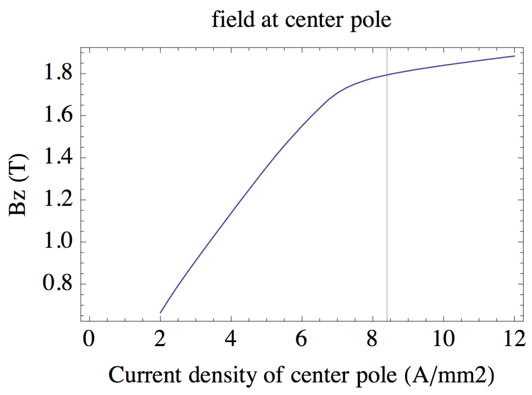

Figure 6: B-field various with exciting current.

and the phase error from phase shifter can also be simulated by the developed code. Various phase errors were adopted to the largest phase shifter, and the trend of variation of bandwidth was plotted in Figure 7. For each case of phase error, 20 cases of random seed were used for simulating the shot noise. The result shows that only in some few shots the bandwidth goes up. The trend of with different phase error tells that if the phase delay by the phase shifter is not an integer, the bandwidth does not affected. Note that this is only for the largest phase shifter with 1600*2π phase delay. So the tolerance of the largest phase shifter in this configuration is quit flexible.

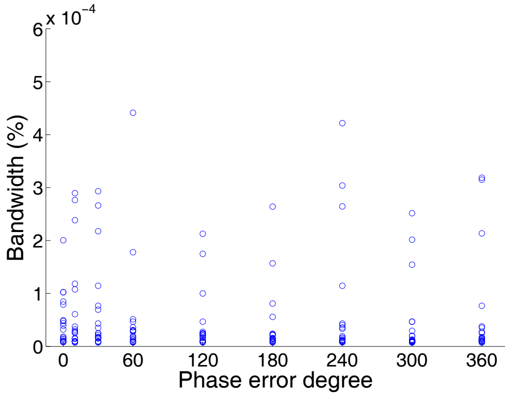

Figure 7: The phase error of 0°–360° were adopted to the 5th phase shifter, and the bandwidths were plotted.

CONCLUSION

A phase shifter for iSASE scheme with a large enough phase delay is proved achievable within space limitation by LCLS-II. The efficiency of this magnet, which is judged by saturation field analyzation, can be improved further. The magnetic shielding is needed for minimizing the cross-talk effect. Remanence field analyzation is hard topic, but an alternative method is planed if the remanence field is too high. There is only preliminary study for the tolerance about physical requirement; in the future, the fully tolerance study of physical requirement will be focused and the result is quite important to the study of iSASE scheme.

ACKNOWLEDGMENT

The authors would like to thank Amann, John W. and Wolf, Zachary R. of SLAC for many engineering discussions. The work was supported by the US Department of Energy (DOE) under contract DE-AC02-76SF00515 and the US DOE Office of Science Early Career Research Program grant FWP-2013-SLAC-100164. The work of K.F. was also supported by the US DOE grant DE-FG02-12ER41800 and National Science Foundation grant NSFPHY-1205431.

REFERENCES

[1] J. Wu et al., “Generation of longitudinally coherent ultra high power X-Ray FEL pulses by phase and amplitude mixing”, in *Proceedings of the 32th International Free Electron Laser Conference, Nara, Japan, 2012*, JACoW, p. 237 (2012).

[2] J. Wu et al., “X-Ray spectra and peak powr control with iSASE” in *Proceedings of the 4th International Particle Accelerator Conference, Shanghai, China, 2013* (JACoW), p. 2068 (2013).

[3] Heinz-Dieter Nuhn et al., “LCLS-II Undulator Phase Shifter-Physics Requirement Document”, SLAC Report, SLAC-I-060-103-083-00-R001 (2013).

[4] Wolf Zackary R. et al., “LCLS-II Undulator Phase Shifter-Engineering Specifications Document”, SLAC Report, SLAC-I-060-102-121-00-R000 (2013).

[5] S. Reiche, “GENESIS 1.3: a fully 3D time-dependent FEL simulation code”, Nucl. Instrum. Methods A, **429**, 243 (1999).

[6] K. Fang, “iSASE study”, TUPO029, Proceeding of FEL2014, Basel, Switzerland (2014).

Copyright © 2014 CC-BY-3.0 and by the respective authors