THE SOFT X-RAY SELF-SEEDING SYSTEM DESIGN FOR SXFEL USER FACILITY*

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Abstract

X-ray free electron laser driven by SASE probes the evolution of the new generation light source in high brightness, transverse coherence. However, since SASE achieves lasing from random shotnoise, poor longitudinal coherence and relative wide bandwidth of SASE FEL limit the operation of many type experiments. Self-seeding as a promising scheme produces longitudinal coherence and even narrower bandwidth radiation by a monochromatic seeding instead of external seeding. The self-seeding system design based on the grating monochromator is carried out for SXFEL user facility across the photon energy from 800-1200 eV. The grating monochromator with a resolution power of 10^{-4} can provide a monochromatic seeding pulse to the seeding undulator. The layout design and simulations of the scheme are presented. It is showing that the self-seeding system for SXFEL user facility is able to improve SASE FEL longitudinal coherence significantly.

INTRODUCTION

Radiation driven by SASE presents well characteristics of remarkable brightness and complete transverse coherence [1], however, since starting from random electrons beam shotnoise, spikes exit on the temporal domain as well as spectrum domain. Therefore, the improvement of SASE FEL is practical important for an applications of broader areas. External seeding which improve longitudinal coherence apparently can't be a reliable scheme at photon energy beyond a few hundred eV. An alternative approach to SASE FEL, self-seeding, original proposed at DESY in combine with SASE and external seeding, can provide free electron laser of longitudinal coherence [2]. Since Soft X-ray and hard X-ray experimental results have been observed in 2012 [3] and 2015 [4] at LCLS separately, self-seeding FEL can be regarded as a promising scheme to improve the properties of SASE FEL longitudinal coherence for SXFEL user facility.

The self-seeding scheme consists of two undulators separated by a monochromator and a four-dipole chicane [5]. The two undulators are resonant in the same frequency to ensure the photon beam interacts with the electrons beam completely, finally, the output radiation on the end of the seeding undulator will be longitudinal coherent when FEL saturation. The SXFEL system design which is preliminarily designed at photonics energy of 1000 eV will achieve energy across the range of 800-1200 eV finally. The self-seeding system design consists of three portions: 1) The physics design uses the parameter of the proposed SXFEL user facility at the 1.6 GeV electron energy, 2) The four-dipole chicane delays the electrons beam as well as washes out the bunching in order to recombine the monochromatic photon beam, 3) The grating monochromator selects out a monochromatic photon beam from first undulator as the seed of the second undulator. The layout of SXFEL system design is shown on Figure 1.

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FEL PHYSICS CALCULATION

The SASE undulator is split into SASE undulator and seeding undulator to insert monochromator and chicane. The system design uses the parameters shown on Table 1 as SXFEL user facility. Based on the Genesis simulation, the saturation power is on the order of 10^9 W whose magnification factor is about 10^8. To ensure the seed pulse power dominate over the shot noise power at the beginning of seeding undulator, the magnification factor need to be at least 10^5 on SASE undulator corresponding to a length of 25 m SASE undulator concluding from Genesis simulation. The seeding pulse power is 1000 times of shot noise considering that the monochromator efficiency is 0.2, the bandwidth of SASE FEL $(\Delta\lambda/\lambda)_{SASE} = 0.2\%$ and the resolution power of the grating monochromator is $(\Delta\lambda/\lambda)_m$=0.01% .

GRATING MONOCHROMATOR

The grating monochromator is composed of a toroidal VLS grating monochromator, two plane mirror, a slit and a spherical mirror [6].

Table 1: FEL Physical Design Parameters

parameter	value
E(GeV)	1.6
L_b(fs)	100
δ_γ	0.01%
ε_N(mm-mrad)	1
λ_u(m)	0.015
I_{peak}(A)	800
E_{photon}(eV)	1000
L_{ray}	100
K	1.118

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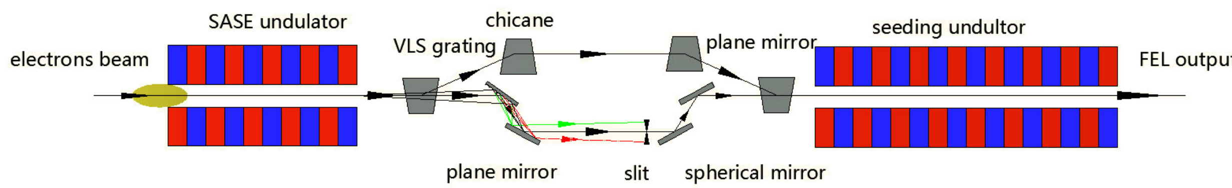

Figure 1: The side view of SXFEL systems design.

The grating monochromator consists of five parts: The toroidal VLS grating vertically focuses and disperses the radiation, then, a removable plane mirror M1 deflects the light to the slit tangentially, after that, a cylindrical mirror tangentially focuses the light to the entrance of seeding undulator, and finally another plane mirror M2 deflects the light to the second undulator. The mirror M1 need to rotate along axis of the red points on Figure 2 and the slit need to move back and forward when the system scan across a photo energy range of 800-1200 eV.

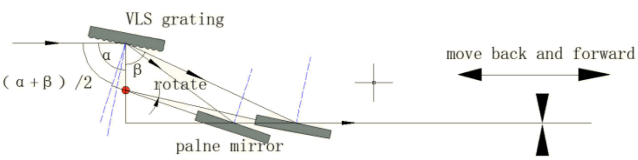

Figure 2: Mechanical scan across different photonic energy.

THE TOROIDAL VLS GRATING

The grating monochromator uses the vary-line space grating to reduce the optical aberration. Incidence angle is fixed 89° to reduce the mechanical difficulty. The incidence angle α and diffraction angle β satisfy the diffraction equation:

$$n\lambda = d(\sin(\alpha) - \sin(\beta))$$

The incidence angle to the M1 is (α+β)/2 to ensure the light is deflected to the horizon plane. The line intensity of VLS grating can be expressed as:

$$D(x) = D_0 + D_1 x + D_2 x^2 + D_3 x^3 + \ldots\ldots$$

The optical aberration coefficient can be expressed as corresponding to the D(x):

$$F = AP + PB + Nm\lambda = \sum_{j=0}^{\infty}\sum_{i=0}^{\infty} F_{ij}\omega^i l^j$$

F_{20}, F_{30}, F_{40} of F_{ij}[7] is defocusing aberration, coma and spherical aberration respectively. Grating monochromator parameters is shown on Table 2. b_2 ,b_3 ,b_4 can be calculated if let F_{20}=0, $F_{30} = 0$, $F_{40} = 0$ to eliminate the optical aberration. D_0, D_1, D_2, D_3 can be obtained by equation followed:

$$D_0 = \frac{1}{d_0}, D_1 = \frac{b_2}{d_0}, D_2 = \frac{b_3}{d_0}, D_3 = \frac{b_4}{d_0}$$

The M2 is cylindrical mirror and the mirror radius is 10.67 to focus the light to the entrance of the seeding undulator. The layout of the grating monochromator is shown on Figure 3.

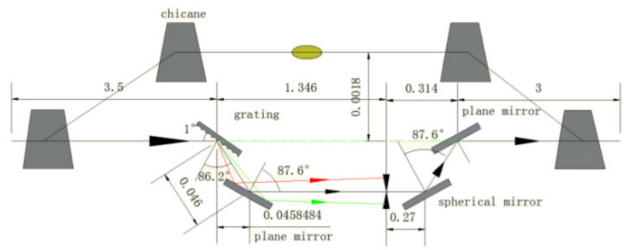

Figure 3: Devices distribution of SXFEL self-seeding design, the reference photonic energy is 1000eV.

Table 2: Grating Monochromator Parameters of Constant Photonic Energy and Vary Photonic Energy

parameter	Value(1000eV)	Value(800-1200eV)
Incidence angle	89°	89°
Diffraction angle	86.2°	85.78°-86.5°
$D_0(mm)$	1646	1646
$D_1(mm^2)$	2.3481	2.3481
$D_2(mm^3)$	0.006298	0.006298
$R_m(m)$	111	111
$R_{sag}(cm)$	3.9	3.9
$f_{\mathrm{obj}}(m)$	3.5	3.5
$f_{\mathrm{imag}}(m)$	1.346	1.3429-1.3502
delay(fs)	851.45	782.6-945.5
M_2 radius	10.67	10.67

Based on the Shadow grating monochromator simulation using the photonic energy 1000 eV and 1000.02 eV, as shown in Figures 4 and 5, the different photonic energy photon beam can be distinguished apparently at the end of monochromator, we can summarize that the resolution power is on the order of 10^{-4}-10^{-5}which is far narrower than SASE FEL.

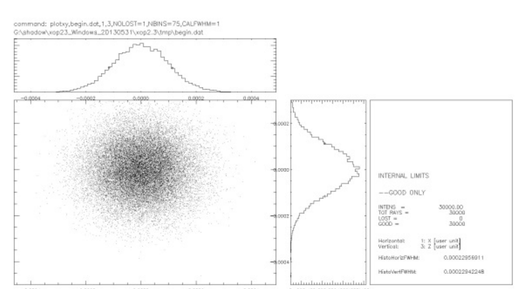

Figure 4: The photonic distribution before the grating monochromator by shadow simulation.

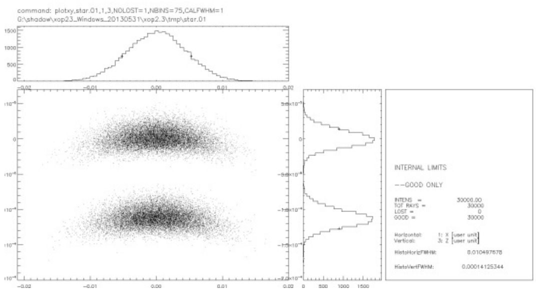
Figure 5: The photonic distribution after the grating monochromator by shadow simulation.

CHICANE MAGNETS

The chicane in the self-seeding section has three functions. 1) A transverse offset in the electrons beam is produced to offer space for the grating monochromator. 2) The chicane washes out the electrons bunching developed on the SASE undulator to ensure no enhanced SASE generate on the seeding undulator. 3) Time delay developed by optical pass is compensated by the chicane to recombine the electrons beam and photon beams. In our layout shown on Figure 6 the R_{56} is designed to be 372~446 μm to compensate the time delay.

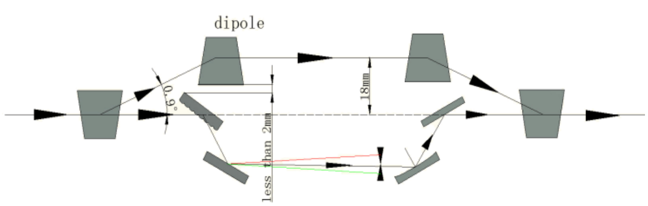

Figure 6: The layout of chicane of self-seeding section.

FEL SIMULATIONS

The seed power at the end of SASE undulator must dominate over shotnoise at the second undulator. Given the Genesis simulation parameters on Table 1, in order to ensure sufficient seed power incident into the second undulator, the length of SASE undulator has to be longer than 25 m, The frequency spectrum on the end of the first undulator shown on Figure 7 reveals that the bandwidth of SASE FEL is about 0.2-0.4%。

To achieve self-seeding, a monochromatic seed is required. In Genesis simulation, the output photon beam at the end of monochromator is used as the seed of seeding undulator and the electrons beam is reinitialized in the second undulator section [8]. The power evolution along the z-direction of Genesis simulation is shown on Figure 8. The spectrum at the end of the second undulator is shown on Figure 9. Based on the start-to-end Genesis simulation, the final output radiation has a bandwidth of about 0.02% which is 20 times smaller than that without seeding and the radiation power can reach saturation in the position of 40m in the seeding undulator.

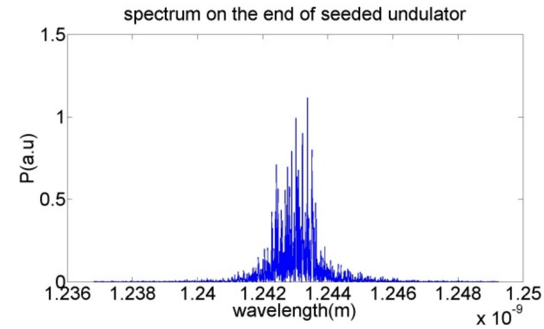

Figure 7: The spectrum on the end of SASE undulator.

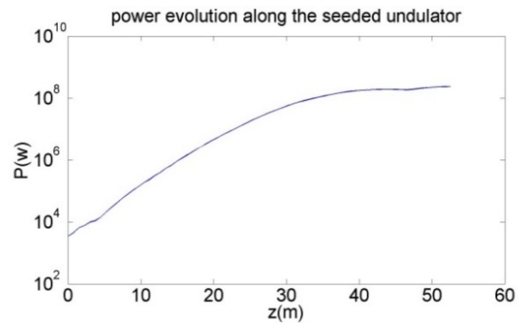

Figure 8: Power evolution along the seeding undulator.

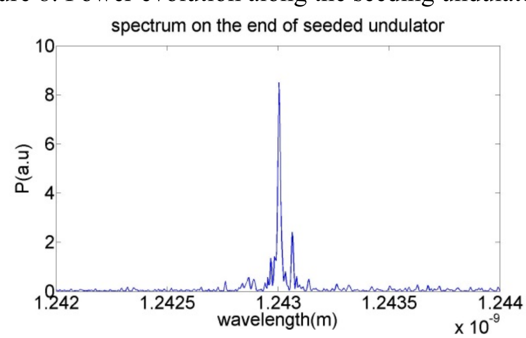

Figure 9: Spectrum on the end of seeding undulator.

CONCLUSION

A soft-x-ray self-seeding system is designed for SASE undulator line of Shanghai Soft X-ray FEL (SXFEL). The grating with a resolution power of 10^{-4} can ensure sufficiently narrow bandwidth seeding pulse at the second undulator. The seeding pulse can dominate shotnoise on the second undulator with a 25 m SASE undulator after monochromatic process. Genesis simulation shows that the self-seeding system can narrow the frequency spectrum bandwidth and improve the longitudinal coherence significantly. The current design is feasible to achieve self-seeding FEL and will be a probable scheme for SXFEL user facility.

Futher work will focus on improving the resolution power and transfer efficiency to generate more powerful seeding pulse at the second undulator. The electrons beam instability generated from the first undulator is under study to enhance the output stability.

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REFERENCES

[1] J. Andruszkow*et al.*, “First Observation of Self-Amplified Spontaneous Emission in a Free-Electron Laser at 109 nm Wavelength”, *Phy. Rev. Lett.*, vol. 85, no. 18, p. 3825, October. 2000.

[2] J. Feldhaus*et al.*, “Possible application of X-ray optical elements for reducing thespectral bandwidth of an X-ray SASE FEL”, *Optical. communications.*,vol. 140 p. 341-352, August. 1997.

[3] D. Ratner*et al.*, “Experimental Demonstration of a Soft X-Ray Self-Seeded Free-Electron Laser”, *Phy. Rev. Lett.*, vol. 114, p. 054801, Feb. 2015.

[4] J. Amann*et al.*, “Demonstration of self-seeding in a hard-X-rayfree-electron laser”, *nat. photonics.*, vol. 6, p. 693, Aug. 2012.

[5] Y. Feng *et al*, “System design for self-seeding the LCSL at soft x-ray energies”, in *Proc. Proceeding of FEL 2012*, Nara, Japan, 2012, paper TUOBIO1, pp. 205-212.

[6] Daniele Cocco *et al.*, “The Optical Design of the Soft X-ray Self Seeding at LCLS”, Pro of SPIE., vol. 8849, p. 88490A-1-88490A-8, Feb. 2014.

[7] Lijun Lu *et al.*, “Optimization of constant-length rowland-circle monochromator with a varied line spacing grating”, *Chinese optics letters.*, vol. 2, no. 11, p. 680-682, Nov. 2004.

[8] Svitozar Serkez *et al.*, “Soft x-ray self-seeding simulation methods and their application for the Linac Coherent Light Source”, *Phy. Rev. Special. topic.*, beams 18, 030708, Mar. 2015.