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OPTIMIZATION FOR THE TWO-STAGE HARD X-RAY SELF-SEEDING SCHEME AT THE SCLF*

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Abstract

Self-seeding mode has been demonstrated a great advantage for the achievement of a high brightness X-ray with a pure spectrum. Single-bunch self-seeding scheme with wake monochromators is adopted for the realization of the hard X-ray FEL at the Shanghai Coherent Light Facility (SCLF). Limited by the heat-loading of the monochromator, the two or multiple stages self-seeding scheme is required. In this contribution, we present a basic two-stage scheme design and optimization for the generation of the photon energy range of 3 keV to 15 keV at the line FEL-I of the SCLF. Simulation results show the peak power and pulse energy each stage, which illustrates the loaded energy required of the crystal monochromator as a pointcut of its following thermal analysis. The electron beam energy used in the study is 8 GeV and the central photon energy is 12.4 keV.

INTRODUCTION

Hard X-ray self-seeding scheme based on a single crystal monochromator was proposed for the generation of a narrow bandwidth radiation [1]. The forward Brag diffraction principle allows the crystal to delay out a monochromatic wake field narrower than Fourier-transform-limited from the SASE radiation, and the small-scale chicane feasible. The scheme has been demonstrated firstly at the LCLS [2], which reduced the bandwidth of the photon beam in the range 2-2.5% of the SASE operation. Currently, like LCLS-II, European XFEL, SACLA, Swiss FEL and PAL-XFEL, more and more FEL facilities are working on such self-seeding scheme.

The Shanghai Coherent Light Facility (SCLF) is currently under construction [3], in which the hard X-ray self-seeding setup is adopted for the hard X-ray pulse with the energy of 3-15 keV for the line FEL-I and 10-25 keV for the line FEL-III. In addition, the line FEL-II is a soft X-ray undulator line based on an external seed laser or a grating monochromator. The SCLF is a high repetition rate FEL facility, in this case, in order to decrease the heat-loading of the monochromatic-used crystal and maintain a rich signal-to-noise ratio between seed signal and initial SASE signal simultaneously, two stage monochromators are reliable combined with two chicanes, as shown in Fig. 1.

In this contribution, we study on the generation of a FEL pulse with energy of 12.4 keV based on an electron beam with energy of 8 GeV. The basic parameters are listed in Table 1. During the whole undulator transport, we simulate an about 20 m average betatron function and choose the C004 reflection of a 100 μm-thick C004 symmetric diamond crystal. In Fig. 1, the electron beam generates SASE radiation lack of temporal coherence through the SASE undulator stage. The first crystal monochromator filters a monochromatic wake from such radiation and then the wake interacts as a seed with the electron beam refreshed by chicane. In order to reduce the heat-loading, we shorten the SASE undulator length, which as a side effect, makes the signal-to-noise ratio poor. Even so, the monochromatic wake seed still can be amplified earlier than the SASE noise, and the bandwidth is narrower than the SASE case. Such generated radiation will be sent into the second crystal monochromator for filtering further. The filtered radiation will finally be amplified to saturation in the final undulator stage.

Table 1: The Basic FEL-Related Parameters Used for 12.4 keV Simulation at the SCLF.

Parameter	Value	Unit
Electron beam energy	8	GeV
Slice energy spread	0.8	MeV
Total charge	100	pC
Peak current	1.5	kA
Normalized slice emittance	0.45	mm·mrad
Photon energy	12.4	keV
Undulator parameter K	1.33	
Undulator period	2.6	cm
Repetition rate	0.66	MHz
Delay of chicane	5-100	fs

SIMULATION AND OPTIMIZATION

According to the parameters in Table 1, we simulate FEL process by GENESIS code [4] and calculate the crystal transmissivity by XOP 2.4 [5].

General Simulation Results

We firstly adopt the two-stage scheme, where the SASE, the first seeded and the second seeded undulator stages are 10 cells, 8 cells and 12 cells, respectively. Both of the monochromators choose the C004 symmetric diamond crystals with thickness of 100 μm. These two chicanes will delay the electron 25 μm and 15 μm, respectively. The simulation results are shown in Fig. 2-4. For comparison, we also present the results of the single stage self-seeding scheme shown in Fig. 5.

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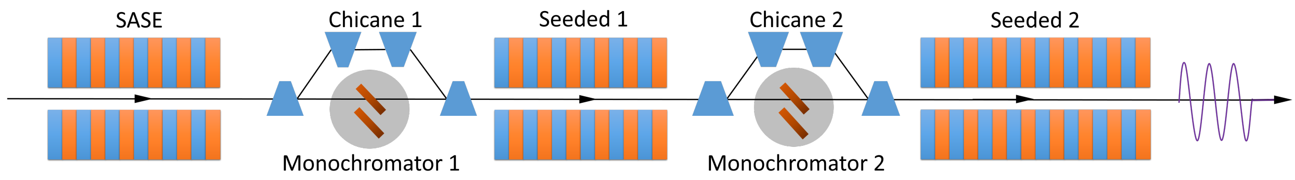

Figure 1: Layout of the two-stage hard X-ray self-seeding scheme at the SCLF.

Figure 2 presents the FEL simulation results before and after the first monochromator. At the downstream of the SASE stage, one achieves an FEL pulse with peak power of 13 MW and FWHM bandwidth of 2e-4. The monochromator filters the central wavelength nearly 1.2398 keV, and the phase at the tail of the pulse becomes very pure that means a fully coherent wave field is generated with power of 10 kW order of magnitude, which can act as a seed laser instead of the initial shot-noise.

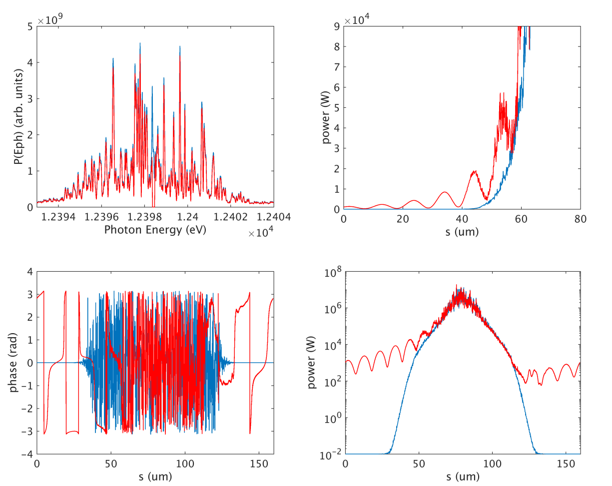

Figure 2: FEL radiation before (blue) and after (red) the first monochromator. Top-left: spectrum, top-right: power, bottom-left: phase, bottom-right: power at exponent coordinates system.

The filtered seed laser interacts with the electron beam refreshed by the first chicane in the first seeded stage. The simulation results are shown in Fig. 3, as well as ones after the second monochromator. Note that in Fig. 3(b) the power of the seed-amplified pulse has the same order of magnitude with the SASE pulse, and the central wavelength stands out from the SASE spectrum. The second monochromator filters the central wavelength again, and here the wake power is relatively high comparable to the seed-amplified pulse.

Finally the filtered wake by the second monochromator is sent into the radiator downstream, being amplified to saturation. In Fig. 4, the saturation power is up to 2.4 GW with several spikes in the time domain since several wake peaks are covered by the electron beam. In the frequency domain, a very rich signal-to-noise ratio is presented where the power of the central wavelength is thousands of times higher than the noise power. The spectral FWHM bandwidth is about 1e-6, two orders of magnitude less than the SASE one.

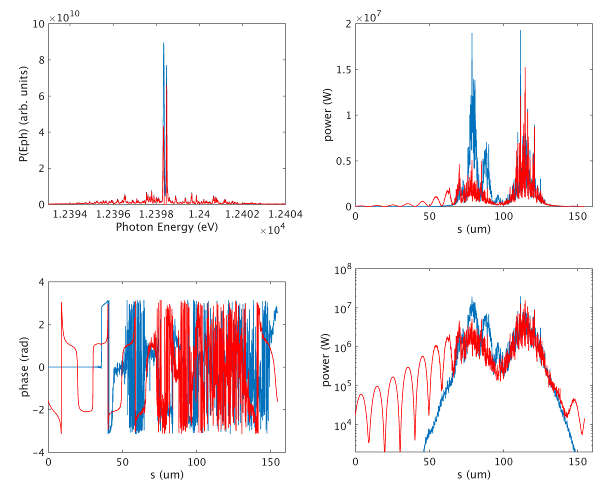

Figure 3: FEL radiation before (blue) and after (red) the second monochromator. Top-left: spectrum, top-right: power, bottom-left: phase, bottom-right: power at exponent coordinates system.

We consider the simulation results of the single stage self-seeding scheme for comparison, which is shown in Fig. 5. In order to increase the signal-to-noise ratio, we need lengthen the SASE stage where the scheme "13 cells+13 cells" is adopted. Before and after the monochromator, the FEL peak power is higher than 100 MW. At the exit of the radiation undulator, the saturation power is approximately equal to the two-stage one. While the spectral bandwidth is larger than the two-stage one, the signal-to-noise ratio is comparably poor and the power of the central wavelength is two orders of magnitude higher than the noise power.

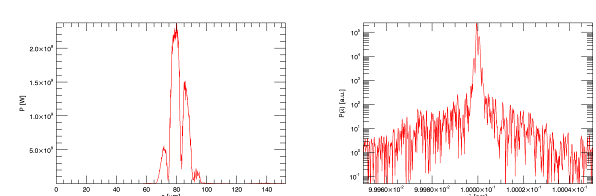

Figure 4: Saturation power (left) and spectrum (right).

Compare the radiation pulse energy for these two schemes, which effects on heat-loading of the diamond crystals. Listed in Table. 2, both of the single-stage and the two-stage are the

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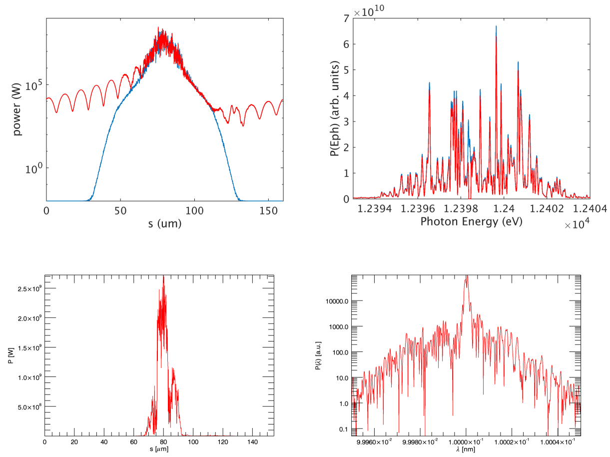

Figure 5: Single stage hard X-ray self-seeding scheme. Top-left: Radiation peak power before (blue) and after (red) monochromator. Top-right: Spectrum before (blue) and after (red) monochromator. Bottom-left: Saturation peak power at the end of the seeded stage. Bottom-right: Radiation spectrum at the end of the seeded stage.

nearly same saturation FEL power. While the pulse energy located in monochromators of the two-stage scheme are at the sub-μJ scale, one order of magnitude lower than the single-stage one, which increases the heat-loading capacity.

Table 2: FEL Pulse Energy of the Single-Stage Scheme and the Two-Stage Scheme.

Parameter	Single-stage	Two-stage
SASE stage	77 m	59 m
SASE power	180 MW/2.5 μJ	13 MW/0.23 μJ
1st seeded stage	77 m	47 m
1st seeded power	2.5 GW/77 μJ	19 MW/0.52 μJ
2nd seeded stage		67 m
2nd seeded power		2.4 GW/78 μJ

Optimization Next Step

From the general simulation results above, it is illustrated that such current two-stage self-seeding scheme can generate a very narrow bandwidth X-ray pulse with a higher signal-to-noise ratio, and meanwhile the heat-loading capacity can be increased significantly. It is noted that for the two-stage self-seeding scheme, it is necessary for optimization further. Firstly, decrease the length each of the undulator stages. The FEL bandwidth generated by an 100 kW wake seed is multi-ten times narrower than the SASE bandwidth according to the single-stage scheme. Consequently, one can properly reduce the power after the second monochromator, that means decrease the first seeded undulator length. The power at the exit of the first seeded stage presents a obvious signal-to-noise ratio although with side-band, therefore one can optimize the SASE undulator length to make sure the enough signal-to-noise ratio after the first monochromator. Optimization of these two undulator stages can reduce FEL pulse energy effecting on heat-loading of the crystals further. Next, more crystal reflection lattices might be adopted, such as C111, to improve the wake power, since the bandwidth filtered by lattice C004 is much narrower than the Fourier-transform-limited bandwidth. As a result, it is possible to decrease the pulse energy before monochromators. Besides, the crystal cutting surface effects on the radiation absorption of the crystal, which also should be considered. Further, in order to improve the FEL pulse energy, undulator tapering should be optimized in the future.

DOUBLE-CRYSTAL MONOCHROMATOR SYSTEM

The design of the double-crystal monochromator system (Fig. 6) is to cover the photon energy range of 3 keV to 15 keV. Preliminarily, the C111 and C004 crystal lattices will be chosen. The alignment and adjustment precision should be up to 3 μrad. Due to the high repetition rate of the beam, water cooling should be adopted to properly remove the heat-loading of the crystal. If necessary, liquid nitrogen cooling is also considered. Next step, more detail of the monochromator will be analyzed.

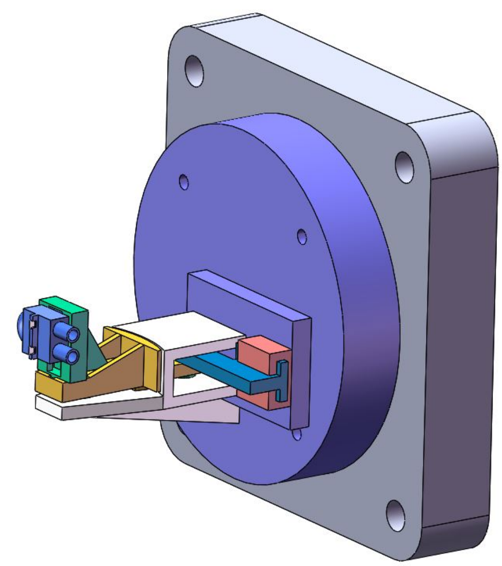

Figure 6: 3-D model for the diamond monochromator system

CONCLUSION

The scheme of the two-stage hard X-ray self-seeding is adopted at the SCLF, which is used to realize the generation of the fully coherent hard X-ray pulse in the range of 3-15 keV with 8 GeV electron beam. The forward Brag diffraction monochromator has been demonstrated the most effective method for hard X-ray self-seeding currently. The two-stage scheme also effectively reduces the heat-loading of the crystal. As the basic scheme at the line FEL-I of the SCLF, this work will be done more in-depth studies.

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