Physical design of a wavelength tunable fully coherent VUV source using a self-seeding free electron laser *

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Abstract: In order to meet the requirements of the synchrotron radiation users, a fully coherent VUV free electron laser (FEL) has been preliminarily designed. One important goal of this design is that the radiation wavelength can be easily tuned in a broad range (70–170 nm). In the light of the users' demand and our actual conditions, the self-seeding scheme is adopted for this proposal. Firstly, we attempted to fix the electron energy and only changed the undulator gap to vary the radiation wavelength; however, our analysis implies that this is difficult because of the great difference of the power gain length and FEL efficiency at different wavelengths. Therefore, we have considered dividing the wavelength range into three subareas. In each subarea, a constant electron energy is used and the wavelength tuning is realized only by adjusting the undulator gap. The simulation results show that this scheme has an acceptable performance.

Key words: wavelength range, self-seeding free electron laser, undulator gap, electron energy

PACS: 41.60.Cr **DOI:** 10.1088/1674-1137/38/5/058101

1 Introduction

Driven by scientific research demands of the synchrotron radiation users at Hefei Light Source (HLS), a 70–170 nm wavelength tunable fully coherent free electron laser is desired, which is a very broad range of wavelength for an FEL facility. In addition, it is also expected that the radiation intensity will gradually increase with the wavelength tuning, from short to long.

Last year, a similar source has been projected, named Dalian Coherent Light Source (DCLS) [1, 2], which applies a high-gain harmonic generation (HGHG) [3] scheme with an optical parametric amplification (OPA) seed laser and which is dedicated at the spectral regime of 50–150 nm. In the light of the users' requirements and our actual conditions, the self-seeding scheme is selected in this proposal as a preliminary research project.

The self-seeding FEL [4–9] is a promising approach to significantly narrow the self amplified spontaneous emission (SASE) [10] bandwidth. Generally, a self-seeding facility consists of two undulators separated by a photon monochromator and an electron bypass. The two undulators are resonant to the same radiation wavelength. The SASE radiation generated by the first undulator passes through the monochromator to create a transform-limited pulse, which is used as a seed laser in the second undulator. The electron bypass is normally a four-dipole chicane. The dispersion of the chicane smears out the electron bunch microbunching produced in the first undulator. The monochromatized laser pulse is amplified by interacting with the non-bunched electron bunch in the second undulator. The required seed power for the second undulator must dominate over the shot noise power within the gain bandpass. Usually, the self-seeding FEL requires a longer undulator. However, it does not need the OPA seed laser.

In this article we preliminarily design the 70–170 nm FEL using the self-seeding scheme. Particular emphasis is laid on the FEL physics. The wavelength tuning is implemented mainly by adjusting the undulator gap but not changing the electron energy. The reason for this is that, on one hand, as the electron energy is not very high here, the undulator natural focusing is considerable and the undulator length of self-seeding FEL is usually long, hence the focusing system and the bypass chicane should both be reset if the electron energy is changed. On the other hand, if the radiation wavelength is mainly tuned by adjusting the electron energy, it will bring difficulties to the design of the monochromator and the user beam line because of the great difference of the radiation power at different wavelength. Therefore, we consider using a constant electron energy and only adjusting the gap in

Received 4 June 2013

∗ Supported by Major State Basic Research Development Program of China (2011CB808301) and National Natural Science Foundation of China (11205156)

Section 2. Then, in Section 3 we divide the radiation wavelength range into three subareas and a constant electron energy is used in each one.

2 Using one constant electron energy

We select the NdFeB permanent magnet undulators with a remanence of $B_r=1.2$. Its peak magnetic intensity B_0 can be calculated by the empirical formula:

$$B_0=3.495e^{-4.885\frac{g}{\lambda_u}+1.41\left(\frac{g}{\lambda_u}\right)^2},0.07\leqslant\frac{g}{\lambda_u}\leqslant 0.7, \qquad (1)$$

where g and λ_u are the gap and period of the undulator, respectively. For a planar undulator, the normalized magnetic parameter is,

$$a_u=0.6605B_0[\mathrm{T}]\lambda_u[\mathrm{cm}], \qquad (2)$$

on the other hand, the two parameters are also constrained by the FEL resonance,

$$\lambda_s=\frac{\lambda_u}{2\gamma^2}(1+a_u^2), \qquad (3)$$

where λ_s is the resonant wavelength and γ is the normalized electron energy.

Figure 1 plots the curves of the undulator parameter au as functions of undulator period for Eqs. (2) and (3). Considering the construction technics of the undulator, we chose the electron beam energy to be 300 MeV and the undulator period to be 3.2 cm. In this case, when tuning the radiation wavelength from 70 nm to 170 nm, the undulator gap varies in a range of about 11.5–18 mm. The FEL power gain length and pierce parameter variation with the radiation wavelength are given in Fig. 2. One can find that the power gain length decreases from 0.65 m to 0.35 m and the pierce parameter grows from 0.0028 to 0.0047, with radiation wavelength tuning from 70 nm to 170 nm. This may result in a problem in that

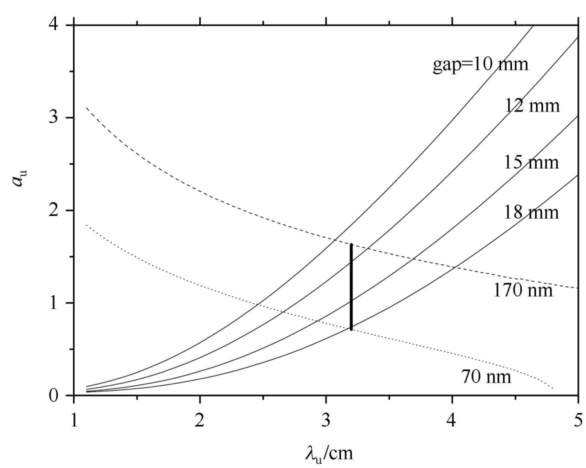

Fig. 1. The undulator parameter a_u as functions of the undulator period λ_u for Eq. (2) (line) and Eq. (3) (dot line). The electron beam energy is assumed to 300 MeV.

it is difficult to determine the length of the first section. If too short, the radiation intensity at the short wavelength will not be strong enough to seed the second section. Contrarily, if too long, the electron beam quality will degrade too much for the long wavelength because the gain length is shorter. As Fig. 3 shows, the 170 nm has a higher radiation power than 70 nm by three orders of magnitude around z=10 m.

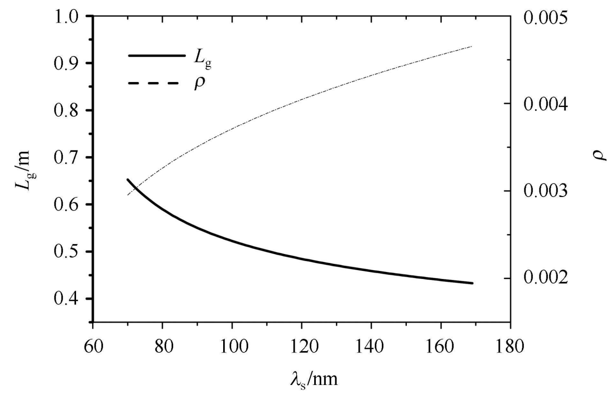

Fig. 2. The FEL power gain length and pierce parameter varying with the radiation wavelength.

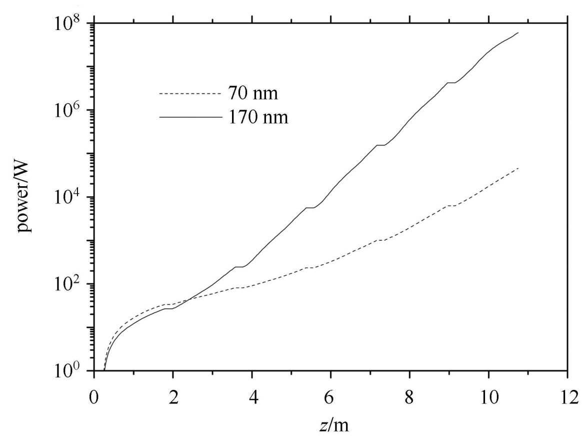

Fig. 3. The FEL power of 70 nm and 170 nm in the first section.

Therefore, we have considered dividing the whole wavelength range into several subareas.

3 Dividing the wavelength range into three subareas

We have investigated dividing the wavelength range into two subareas; however, the results imply that this is unable to solve the problem satisfactorily. Then, three wavelength subareas are considered. In each subarea, the electron energy is constant and the focusing settings can be fixed. The electron energy optimization is similar to that in Section 2. It has a upper limit corresponding to the minimum undulator gap. The detail is displayed in Table 1. The electron beam power is enhanced for the short wavelength, so as to achieve a comparative power for all wavelength at the exit of the first section. The main parameters for our proposal are listed in Table 2. The simulation is based on the code GENESIS 1.3 [11]. It should be pointed out that we do not scan the initial phase distribution of the electron beam as in normal SASE simulations because in this paper we have focused on how to reach the goal of broad wavelength range.

Table 1. The division of the wavelength range.

λ_s /nm	E_0/MeV	undulator gap/mm
70–100	360	12–14.5
100–130	315	12–13.75
130–170	275	12–13.8

Table 2. Main parameters for this proposal.

parameter	specification
E_0/MeV	<360
slice energy spread	0.01%
peak current/A	400
normalized emittance /(mm·mrad)	1.3
bunch length (FWHM)/ps	2.5
undulator period/cm	3.2
undulator section length/m	1.6

To determine the length of the first section, we first estimate the shot noise power at the beginning of the second section, which is in the order of several to tens Watts. Another important point is the design of the monochromator, which usually consists of a grating [4]. The monochromator in this proposal is traditionally composed of three mirrors and a rotational grating. The transport efficiency and bandwidth are given in Fig. 4. It can be found that the transport efficiency at short wavelength is higher than that at long wavelength, which can compensate the seed power in shorter wavelength to a certain degree. Based on these, the undulator length of the first section is selected to be 6.4 m. In this case, the time structure of the seed pulse for the second section at 70 nm and 170 nm is given in Fig. 5 by time-dependent simulation. Obviously, the power is high enough to seed the second section. we should indicate that we scan the wavelength in the nearby area when the radiation pulse generated in the first section passes through the monochromator, because the radiation at the target wavelength may be located in the trough between two spikes in the spectrum. However, in the experiment, it is impossible to scan the wavelength for every coming pulse. For this reason the output radiation of the second section will fluctuate, which is an inherent disadvantage of self-seeding scheme because the SASE process starts up from shot-noise.

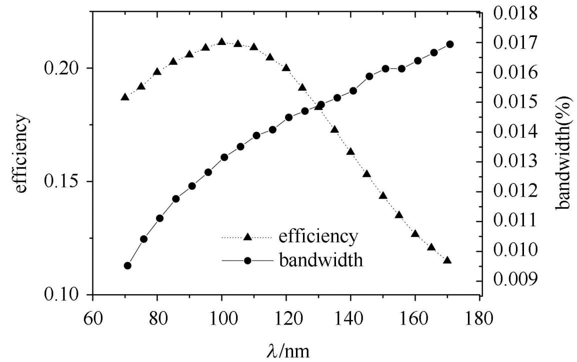

Fig. 4. The transport efficiency and bandwidth of the monochromator.

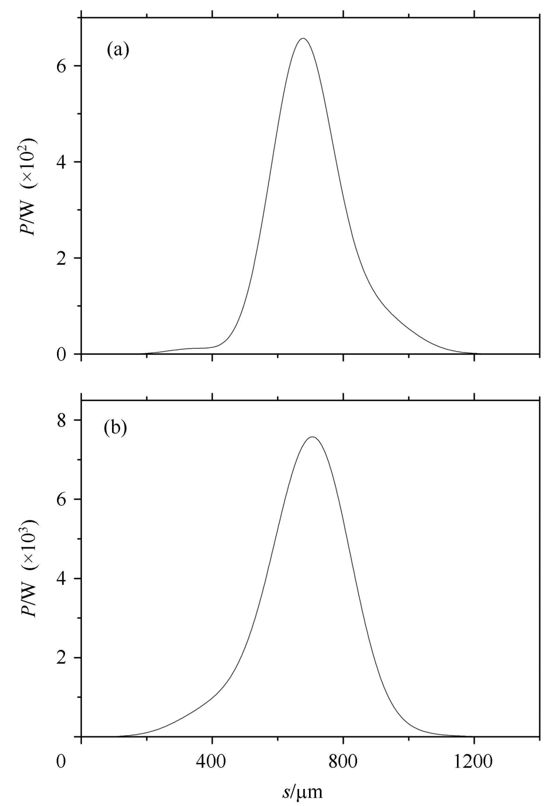

Fig. 5. The seed pulse for the second section at (a) 70 nm and (b) 170 nm.

In the second section, it still remains that the power gain length has a big variation range so that the saturation length is changed with the radiation wavelength. Thus, the undulator length is fixed by the saturation length of 70 nm radiation, which is about seven undulators. However, in the long wavelength range, the undulator length is longer than the saturation length. Consequently, the tapering technique is considered to enhance the radiation power in the long wavelength range [12–14]. In detail, the tapering starts from the undulator

Table 3. The radiation properties of several typical wavelengths.

λ_s/nm	L_{sat}/m	tapering start point/m	δa_u	E_{pulse} (no taper)/mJ	E_{pulse} (tapered)/mJ
70	12.352	No	–	0.245	—
85	12.352	No	–	0.274	—
115	10.752	9.152	1.5%	0.316	1.68
150	8.96	9.152	2%	0.337	2.14
170	8.352	7.328	3%	0.564	2.89

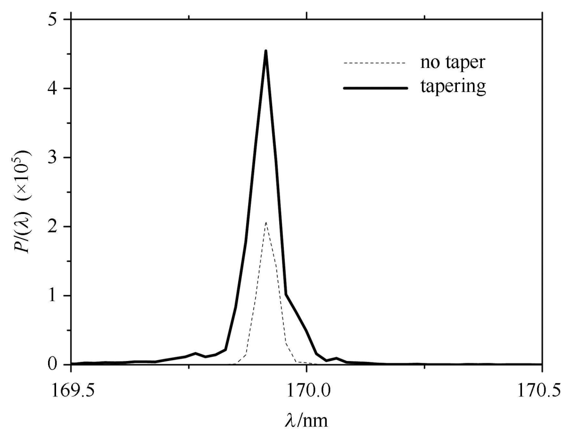

Fig. 6. The spectrum for 170 nm radiation at saturation point without taper (dashed) and at the end of the second section with taper (line).

that is closest to saturation point, and the tapering amplitude is first achieved by a rough calculation and then by a numerical scan. The radiation properties at several typical wavelengths are shown in Table 3. The pulse energy is basically stable when tapering does not open. When tapering is applied, the pulse energy of the long wavelength increases by several times. Fortunately, it meets the demand of the FEL users perfectly. We have also compared the spectrum with and without tapering, as Fig. 6 shows for the 170 nm case.

4 Summary

We have preliminarily designed a wavelength tunable VUV source using a self-seeding scheme. In this paper, emphasis was put on the global physical design but not on the detailed cell design. To reach the goal of a broad radiation wavelength range (70–170 nm), we divided the target wavelength range into three subareas, and in each subarea a constant electron energy is used and the transverse focusing system is fixed. Higher energy is used for shorter wavelengths to increase the beam power and compensate the longer gain length and lower FEL efficiency. The simulation results show that the scheme of dividing into three subareas has an acceptable performance. But, if more subareas be divided or the difference of electron energy of the each subarea be increased, a better performance may be achieved.

More work has to be done for the regular design, such as the bypass chicane design, studies of tolerance and stability, and so on.

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