FEATURES OF THE PAL-XFEL DESIGN*

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Abstract

PAL-XFEL, the new XFEL project of Pohang Accelerator Laboratory, aim to emit hard X-ray of $1 - 1.5$ Å, although its beam energy is only 3.7 GeV. To achieve the goal, coherent third harmonic radiation will be utilized. This paper discusses schemes of hard X-ray generation with 3.7 GeV electron beam and concludes that use of the third harmonic is the only possible way.

INTRODUCTION

The storage ring based third generation light source has spread all over the world in the last twenty years and is now a useful and common facility for scientific research. However, even more advanced X-ray source, the XFEL facility, is not likely to be so. Apparently, the X-ray FEL (XFEL) is achievable only by a high energy electron beam. To make $1 - 1.5$ Å hard X-ray FEL, the electron energy has been chosen 14.35 GeV for the Linac Coherent Light Source (LCLS) in SLAC [1] that is under construction and 17.5 GeV for the European XFEL in DESY [2] that is approved. Not only the linear accelerator but also the undulator in XFEL is long; the LCLS undulator is 112 m long and the European XFEL undulator is even longer, 260 m. We may have to conclude that hard X-ray FEL is too expensive to be available in most countries. Is it possible to reduce the machine size? The SPring-8 Compact SASE Source (SCSS) project in Japan tries to reduce the whole facility size by using an in-vacuum undulator and the new technology of C-band linear accelerator [3]. It is going to need only 8 GeV electron beam to generate hard X-ray. However, building and maintaining an 8 GeV electron machine still costs a lot even with the new technology. A natural question is how compact an XFEL facility can be.

PAL-XFEL, the new XFEL project of Pohang Accelerator Laboratory (PAL) [4], tries to achieve the goal by utilizing the third harmonic SASE radiation. It will uses 3.7 GeV electron beam. Below it will be shown that $1 - 1.5$ Å hard X-ray FEL can not be achieved by 3.7 GeV electron energy, if we insist to use only the fundamental SASE radiation. Therefore, PAL-XFEL may be the lowest energy hard X-ray FEL machine. The only defect is that the transverse coherence of the PAL-XFEL third harmonic radiation would be far from perfect. Basic parameters of the PAL-XFEL are listed in Table 1 for unfamiliar readers.

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Table 1: 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	0.01 %	
Full bunch length	270	fs
Undulator Parameters		
Undulator period	1.5	cm
Segment length	4.5	m
Full undulator length	80	m
Peak undulator field	1.19	T
Undulator parameter, K	1.49	
Undulator gap	4	mm
Average β-function	10	m
FEL Parameters		
Radiation wavelength	3	Å
FEL parameter, ρ	5.7×10^{-4}	
Peak brightness	5×10^{31}	1)
Peak coherent power	1	GW
Pulse repetition rate (Max.)	60	Hz
1D gain length	1.2	m
Saturation length, L_{sat}	45	m

1) photon/(sec mm^2 mrad^2 0.1%BW)

BEAM ENERGY DEPENDENCE OF XFEL FACILITY SIZE

To find the possibility of using low electron beam energy for an hard X-ray FEL, we need to know its beam energy dependence. To find out the beam energy dependence of an hard X-ray FEL, recall that the resonant wavelength of an undulator is given by

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right), \tag{1}$$

where λ_r is the resonant wavelength, λ_u the undulator period, γ the Lorentz factor, and K the undulator parameter. K is defined by

$$K = 0.934 B_0[\text{Tesla}]\lambda_u[\text{cm}], \tag{2}$$

where B_0, the undulator peak magnetic field, depends not only on the undulator gap and period but also on the magnet material. If we consider a hybrid undulator with vanadium permendur, it is given by

$$B_0 = 3.694 \exp\left[-5.068\frac{g}{\lambda_u} + 1.520\left(\frac{g}{\lambda_u}\right)^2\right] \tag{3}$$

with g denoting the gap. In LCLS, for $\lambda_r = 1.5$ Å, the beam energy is 14.35 GeV, $\lambda_u = 3$ cm, and $g = 0.65$ cm. If we want to use lower beam energy, we have to use shorter λ_u and smaller K that depends on λ_u and B_0. Since B_0 depends on g/λ_u, we have two parameters (λ_u and g/λ_u) to be controlled to compensate for the decreasing beam energy. Hence, we fix g/λ_u (and thus B_0) and use only λ_u. Solving Eq. (1) for λ_u while keeping the LCLS value of the ratio $g/\lambda_u = 0.217$, we can determine λ_u that gives 1.5 Å hard X-ray at a lower electron energy. First, arranging Eq. (1) for λ_u, we obtain a cubic equation

$$\lambda_u^3 + \frac{2}{a^2}\lambda_u = \frac{4\lambda_r\gamma^2}{a^2}, \qquad (4)$$

where $a = 0.934B_0$. Solving this cubic equation, we obtain λ_u as a function of γ or E, the electron energy. The graph of λ_u versus E is shown in Fig. 1. As E decreases from the LCLS energy, λ_u decreases almost linearly. Since g/λ_u is fixed, $g = 0.217\lambda_u$ also decreases making in-vacuum undulator an inevitable choice at lower electron energies. Figure 1 may imply that hard X-ray FEL is achievable by using very low energy electrons if the undulator period is properly short. However, the undulator gap g should also be very small, which causes serious problems. Hence, both λ_u and g can not be arbitrarily small and electron energy can not be very low.

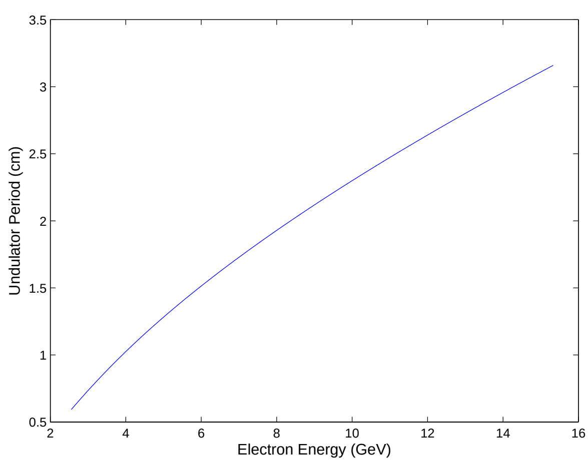

Figure 1: Graph of λ_u that gives 1.5 Å radiation as a function of E. The ratio g/λ_u is fixed to 0.217, the LCLS value.

To build a compact XFEL, we also have to reduce the undulator length. To estimate the SASE saturation length, L_{sat}, and find its energy dependence, a key parameter is the FEL parameter ρ defined by

$$\rho = \frac{1}{2\gamma}\left[\frac{I}{I_A}\frac{\lambda_u^2 K^2[JJ]^2}{8\pi^2\sigma_x^2}\right]^{1/3}, \qquad (5)$$

where $I_A = 17045$ A is the Alfen current, I is the beam peak current, σ_x is the cross sectional beam size, and $[JJ]$ is defined by

$$[JJ] = J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right). \qquad (6)$$

Note that ρ roughly defines the upper bound of the electron energy spread σ_E/E in a slice. The SASE process begins only when $\sigma_E/E < \rho$ and it stops (saturates) when σ_E/E grows and reaches ρ. Hence, ρ should not be too small for successful power growth.

The fundamental length scale to determine the saturation length is the one-dimensional gain length defined by

$$L_{1D} = \frac{\lambda_u}{4\sqrt{3}\pi\rho}. \qquad (7)$$

In general, a large ρ is preferred not only for high gain, but also for a short gain length. In Eq. (5), note that $\sigma_x^2 = \beta\epsilon_n/\gamma$ where ϵ_n is the normalized emittance and β is the betatron function. The currently achievable value for ϵ_n is around 1.2 μ-rad and β is free to choose. The optimal β that gives the shortest saturation length is given by [5]

$$\beta_{opt} = 11.2\left(\frac{I_A}{I}\right)^{1/2}\frac{\epsilon_n^{3/2}\lambda_u^{1/2}}{\lambda_r K[JJ]}. \qquad (8)$$

Using β_{opt} in Eq. (5), we obtain

$$\rho = \frac{1}{2}K[JJ]\left(\frac{I}{I_A}\frac{\lambda_u}{\epsilon_n}\right)^{1/2}\left(\frac{\lambda_r}{89.6\pi^2\epsilon_n\gamma^2}\right)^{1/3}. \qquad (9)$$

Using the LCLS value $I = 3.4$ kA, the dependence of ρ on E as λ_u moves on the line of Fig. 1 is shown in Fig. 2. Note that ρ also decreases as E decreases. The requirement $\sigma_E/E < \rho$ gives a severe restriction for a compact XFEL source. The LCLS value of σ_E/E is approximately 0.01%, which means $\sigma_E \approx 1.4$ MeV. As the electron energy E is lowered, the relative energy spread σ_E/E increases while ρ decreases. At around $E = 4.5$ GeV, σ_E/E is comparable to ρ. Hence $E = 4.5$ GeV seems the lowest possible energy for 1.5 Å XFEL.

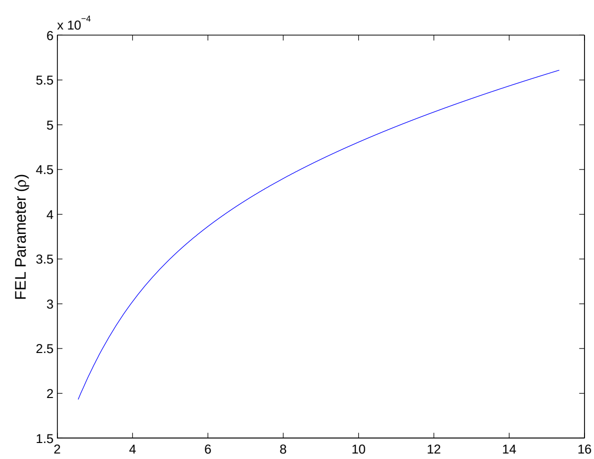

Figure 2: Graph of ρ as a function of E.

The three dimensional parameter L_{3D} is usually described as

$$L_{3D} = L_{1D}(1+\eta), \qquad (10)$$

where η measures the deviation from the one dimensional theory due to diffraction, emittance, and energy spread.

L_{sat} and P_{sat}, the saturated peak radiation power, are approximately given by

$$\begin{aligned} P_{sat} &= 1.6\rho\left(\frac{L_{1D}}{L_{3D}}\right)^2 \frac{I\gamma mc^2}{e}, \\ L_{sat} &= L_{3D}\ln\left(\frac{P_{sat}\lambda_r}{2\rho^2 Ec}\right). \end{aligned} \tag{11}$$

Certainly, L_{sat} is an important factor to determine the whole machine size. Using Eqs. (5) and (10) in Eq. (11), the E-dependence of L_{sat} is revealed and shown in Fig. 3. L_{sat} also decreases as E decreases from the LCLS energy and reaches the minimum at around $E = 5 - 6$ GeV. In Fig. 3, the part below $E = 4.5$ GeV is meaningless, because the energy spread exceeds ρ and there is no SASE process. The abnormal abrupt increase of the saturation length indicates the meaninglessness. P_{sat} is depicted in Fig. 4 on the logarithmic scale. Note that P_{sat} decreases slowly as E decreases from the LCLS energy to $E \sim 4.5$ GeV and drops rapidly outside of it. P_{sat} is still above 1 GW. Therefore, a compact XFEL does not sacrifice the radiation power. Overall, the shortest XFEL for 1.5 Å can be built at around $E = 4.5$ GeV.

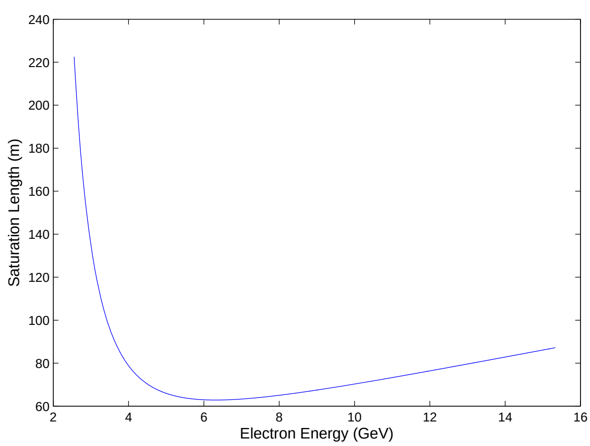

Figure 3: Graph of L_{sat} as a function of E.

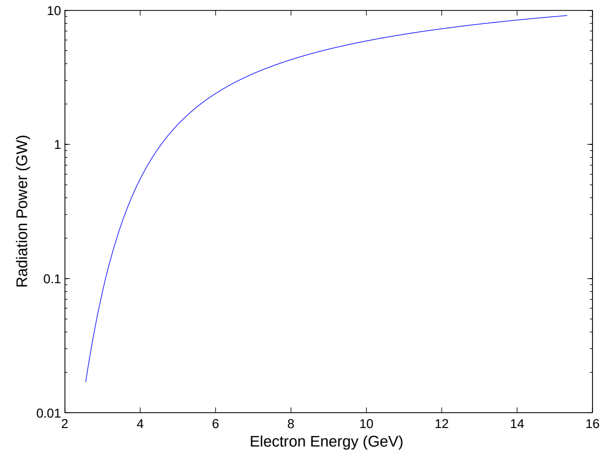

Figure 4: Graph of P_{sat} as a function of E.

TRANSVERSE COHERENCE

The condition for the transverse coherence is roughly given by

$$\frac{\epsilon_n}{\gamma} \sim \frac{\lambda_r}{4\pi}. \tag{12}$$

This rough condition claims that the beam energy has to be high enough to secure the transverse coherence for a very small λ_r (hard X-ray). Since Eq. (12) is an order of magnitude relation, accurate estimate of transverse coherence needs a computer. Especially, the degree of transverse coherence at the saturation was obtained as a function of $\hat{\epsilon} = 2\pi\epsilon_n/(\lambda_r\gamma)$ [5]. Converting this result to our purpose, we obtain Fig. 5, which shows clearly that the degree of transverse coherence for 1.5 Å hard X-ray decreases as the electron energy decreases. According to Fig. 5, the degree of transverse coherence of LCLS is approximately 0.83. At a lower energy and shorter undulator period, the transverse coherence would be worse. Therefore, we conclude that hard X-ray FEL is achievable at a lower electron energy but its transverse coherence may not be perfect.

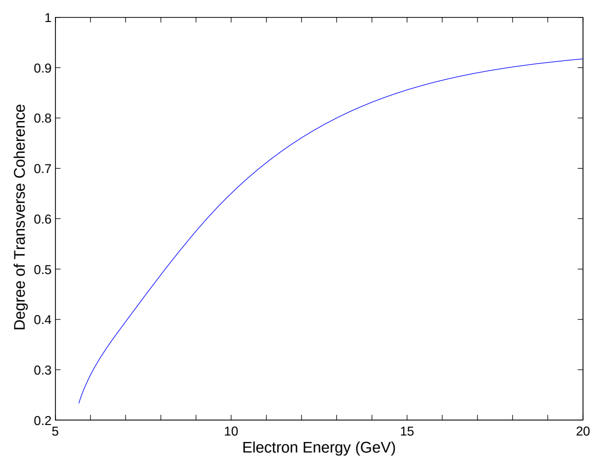

Figure 5: Degree of transverse coherence for 1.5 Å XFEL as a function of E.

CHOICE OF PAL-XFEL

Although hard X-ray FEL is possible by using $E = 4.5$ GeV, note from Fig. 1 that the undulator period and thus the undulator gap is very small at the energy. The gap is around only 2.5 mm. This may not be an unreasonably small number. However, it causes not only beam handling difficulty but also severe wakefield effect that reduces the radiative power. If we try to choose a safer gap (maybe larger than 3 mm), the beam energy should be at least 6 GeV, which is not compact at all. Therefore, it may be concluded that hard X-ray FEL is not achievable by a compact XFEL machine of beam energy lower than 4 GeV. That is why PAL-XFEL chose to use the third harmonic radiation [8, 9, 10]. Then even smaller hard X-ray FEL facility is possible. If we generate 3 Å fundamental radiation at a even lower energy of 3.7 GeV, its 1 Å third harmonic radiation is usable. Since the needed undulator is shorter than using the fundamental radiation, the whole facility size is really compact.

The only problem is the output power. The output power of the third harmonic is much lower than that of the fundamental mode. The ratio of the third harmonic power to the fundamental power is given by [11])

$$\frac{P_3}{P_1} = 0.094 \times \left(\frac{K_3}{K_1}\right)^2. \quad (13)$$

K_1 and K_3, coupling factor of the fundamental and third harmonic respectively, are special cases of K_h defined by

$$K_h = K(-1)^{(h-1)/2}[J_{(h-1)/2}(Q) - J_{(h+1)/2}(Q)], \quad (14)$$

where $Q = hK^2/(4+2K^2)$. It is straightforward to compute $(K_3/K_1)^2$ as a function of K. As shown in Fig. 6, it increases from zero and becomes almost flat after $K > 2.5$ saturating to $(K_3/K_1)^2 = 0.22$, which gives the asymptotic value $P_3/P_1 \approx 0.02$. Hence, P_3 can not exceed 2% of P_1. With $K = 1.49$, the PAL-XFEL value, P_3 is approximately 1% of P_1. Parameters of the two harmonics are listed in Table 2. The peak power and peak brightness of the third harmonic radiation is still very high. Finally the degree of transverse coherence of the third harmonic radiation, obtained at this low energy, is also low.

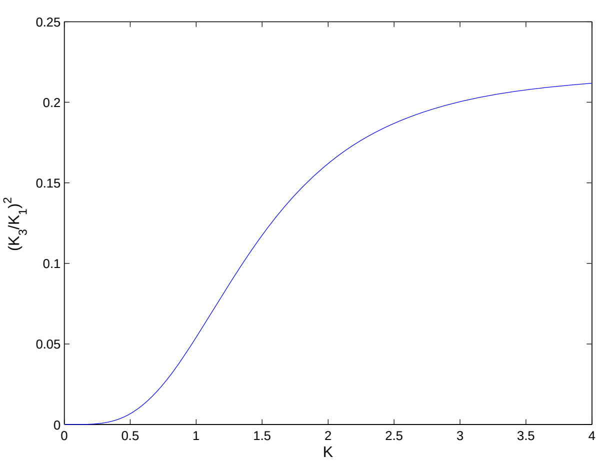

Figure 6: Graph of $(K_3/K_1)^2$ as a function of K.

Table 2: Parameters of the two harmonics

Parameters	Fundamental	Third harmonic
Wavelength (Å)	3	1
Peak power (GW)	1	0.01
Peak brightness [2)]	1×10^{32}	3×10^{29}
Photons/pulse	5×10^{11}	1.5×10^9

[2)] photon/(sec mm^2 mrad^2 0.1%BW)

SUMMARY

We have seen, in this paper, that it is possible to generate 1.5 Å hard X-ray FEL with lower electron energy (down to 4.5 GeV) and shorter undulator at the expense of reduced degree of transverse coherence. However, the facility size can be reduced even further by utilizing the third harmonic radiation whose power is less than 2% of the fundamental one and transverse coherence is also poor. PAL-XFEL is one such example. We can not build a compact hard X-ray FEL that has all three special properties. However, XFEL with incomplete transverse coherence is still very useful, because the majority of experiments do not need the transverse coherence.

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