GUN EMITTANCE AND COMPACT XFEL *

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Abstract

Role of gun emittance is discussed to build a compact XFEL machine. It is shown that low gun emittance plays the critical role of reducing the XFEL machine size.

INTRODUCTION

X-ray free electron laser (XFEL) based on self amplified spontaneous emission (SASE) [1, 2] is considered the next generation light source. However, the XFEL machine is so huge and generally costs very high. It is a natural attempt to find the possibility of building an XFEL machine of lower electron energy and a reasonably modest (compact) size, without degrading the radiation quality. The difficulty of designing a compact and low electron energy (E) XFEL can be summarized as following.

1. As E is lowered, the FEL parameter ρ is also lowered depending upon E. However, since the relative electron beam energy spread σ_E/E gets lager, the lasing condition $\sigma_E/E < \rho$ is hardly met. As a result, the radiation power and quality are poor.

2. The linac size decreases as E decreases. However, the needed undulator length does not decrease as fast as E, as will be shown below.

3. In a low electron energy XFEL, the undulator gap tends to be small. The undulator wakefield problem is more serious.

We will show, in this paper, that these problems can be solved by using a low emittance gun [3, 4]. A normalized beam emittance (ϵ_n) of 1-1.2 mm mrad has been a widely used number for a photo-cathode RF gun. However, recent development of technology makes it a realistic goal in the near future to generate even lower gun emittance. There are a few schemes under intensive R&D. A well known example is the single crystal thermionic gun that is going to be used in the SPring-8 Compact SASE Source (SCSS) [5]. Its emittance is expected to be around $\epsilon_n = 0.6$ mm mrad, although this goal is not achieved yet [6]. Furthermore, a field emitter array gun that is now under development in Paul Scherrer Institute (PSI) is expected to achieve a lower emittance even down to $\epsilon_n = 0.1$ mm mrad [7], although it is still at the very beginning stage. Besides these new type of guns, conventional photo-cathode guns are still under progress toward a low emittance [8, 9]. For example, the slice emittance of the LCLS photo injector was recently measured to be 0.9 mm mrad with 1 nC charge, a promising result [8].

Therefore, it is now a good time to study the impact of a low emittance gun on the XFEL machine, although its practical application is in the future. In this paper, we study the feasibility of a compact XFEL machine with variable ϵ_n down to nearly 0.1 mm mrad and also variable gun current. Note that ϵ_n here refers to the theoretical emittance used in the FEL physics, that is, the slice emittance.

E-DEPENDENCE OF PARAMETERS

The method of energy scaling in XFEL is to lower the electron beam energy (E) while keeping the undulator resonant condition,

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

where λ_r is the resonant wavelength, $\gamma = E/(mc^2)$ is the Lorentz factor, and K is the undulator parameter defined by

$$K = 0.934 B_0[\text{Tesla}]\lambda_u[\text{cm}]. \quad (2)$$

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

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

with g denoting the undulator gap. To build a compact XFEL, B_0 should never be decreased, otherwise the saturation length and thus the undulator length would increase. We will fix g/λ_u to keep B_0 unchanged and will adjust λ_u in Eq. (1) to keep λ_r unchanged, while lowering E from the LCLS energy 14.35 GeV. The LCLS wavelength, $\lambda_r = 1.5$ Å, will be kept and $\lambda_u = 3$ cm, $g = 0.65$ cm will be adjusted with the ratio kept. To find out how λ_u should be changed to keep $\lambda_r = 1.5$ Å and B_0 at the energy scaling, note that Eq. (1) is a cubic equation for λ_u for given λ_r and B_0. Arranging Eq. (1) for λ_u gives

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

where $a = 0.934B_0$. Solving this cubic equation, we obtain λ_u as a function of γ (or E). The graph of λ_u versus E is shown in Fig. 1. Since $B_0 \approx 1$ T, we see that $a \approx 1$ cm^{-1} and $\lambda_u > a^{-1}$ for $\lambda_u > 1$ cm, which is usually the case. Equation (4) can then be roughly approximated to

$$\lambda_u^3 \approx \frac{4\lambda_r\gamma^2}{a^2}, \quad (5)$$

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from which we can derive the rough dependence of λ_u on E

$$\lambda_u \propto E^{2/3}. \quad (6)$$

Hence, as E decreases from the LCLS energy in the graph, λ_u decreases almost linearly. Since g/λ_u is fixed to 0.217, $g = 0.217\lambda_u$ also decreases making an in-vacuum undulator the inevitable choice at lower electron energies. E versus λ_u is shown in Fig. 1.

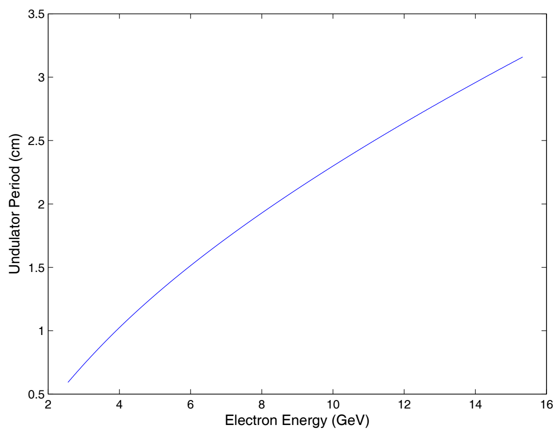

Figure 1: λ_u as a function of E to keep the resonance condition for 1.5 Å hard X-ray in the energy scaling. The undulator peak field B_0 is fixed in the scaling.

The rough dependence of λ_u on E is used to derive the rough E dependence of other parameters. First of all, the FEL parameter ρ that is defined by

$$\rho = \frac{1}{2\gamma}\left[\frac{I_{pk}}{I_A}\frac{\lambda_u^2 K^2 [JJ]^2}{8\pi^2\sigma_x^2}\right]^{1/3}, \quad (7)$$

where $I_A = 17.045$ kA is the Alfen current, I_{pk} is the peak current, σ_x is the cross sectional beam size, and $[JJ]$ is defined as

$$[JJ] = J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right). \quad (8)$$

In Eq. (7), note that $\sigma_x^2 = \beta\epsilon_n/\gamma$ where β is the betatron function. β is an independent parameter we can choose freely. It is usual to choose the optimal β that gives the shortest saturation length. The optimal β was evaluated in [12] and is given by

$$\beta_{opt} = 11.2\left(\frac{I_A}{I_{pk}}\right)^{1/2}\frac{\epsilon_n^{3/2}\lambda_u^{1/2}}{\lambda_r K[JJ]}. \quad (9)$$

Using β_{opt}, ρ is completely described by the known parameters as in

$$\rho = \frac{1}{2}K[JJ]\left(\frac{I_{pk}}{I_A}\frac{\lambda_u}{\epsilon_n}\right)^{1/2}\left(\frac{\lambda_r}{89.6\pi^2\epsilon_n\gamma^2}\right)^{1/3}. \quad (10)$$

Since K has the same E dependence as λ_u, it is easy to see the rough dependence of ρ as

$$\rho \propto \left(\frac{E}{\epsilon_n}\right)^{1/3}\left(\frac{I_{pk}}{\epsilon_n}\right)^{1/2}. \quad (11)$$

When ϵ_n is fixed to 1.2 mm mrad, the E-dependence of ρ is shown in Fig. 2. For the beam peak current, we used the LCLS value $I_{pk} = 3.4$ kA. ρ decreases as E decreases. This degrades the machine performance and the radiation quality. The requirement $\sigma_E/E < \rho$ gives a severe restriction. The LCLS initial value of σ_E/E is approximately 0.01% [10], which means $\sigma_E \approx 1.4$ MeV. Obviously, the lower E is, the larger σ_E/E is. As E decreases in the scaling, σ_E/E increases while ρ decreases. Figure 2 shows that σ_E/E is comparable to ρ at around $E = 4.5$ GeV, where the lasing barely happens.

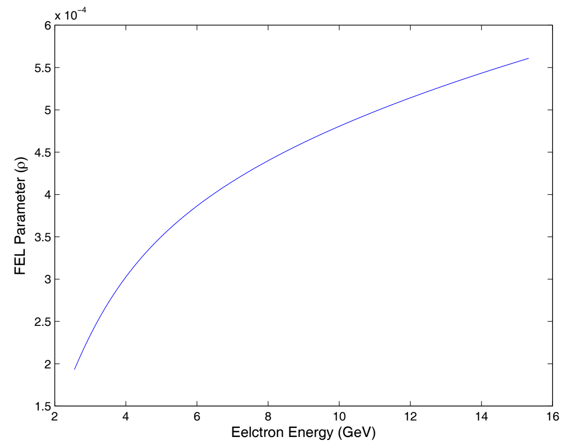

Figure 2: FEL parameter ρ as a function of E with $\epsilon_n = 1.2$ mm mrad.

Another potential problem is the undulator wakefield, which is inversely proportional to the undulator gap. The undulator wakefield creates relative energy spread between the slices, the rms of which is given by [10]

$$\sigma_w = -\frac{e^2 N L (W_z)_{rms}}{E}, \quad (12)$$

where L is the undulator length, and $(W_z)_{rms}$ is the rms of the wakefield over a bunch. For a Gaussian bunch, we have [10]

$$(W_z)_{rms} \approx 1.02\frac{\Gamma(3/4)}{2\sqrt{2}\pi^2}\frac{c}{\sigma_z^{3/2} g}\left(\frac{Z_0}{\sigma}\right)^{1/2}. \quad (13)$$

L is obviously almost equal to L_{sat}. Since σ_w is inversely proportional to E, it is supposed to grow and give more power reduction for lower E. This is one of the difficulties to make a compact XFEL. However, using Eq. (19) and the fact that eN is proportional to I_{pk}, we can find the rough dependence of σ_w under the energy scaling as

$$\sigma_w \propto \left(\frac{\epsilon_n^2}{E}\right)^{2/3}\left(\frac{I_{pk}}{\epsilon_n}\right)^{1/2} g^{-1}. \quad (14)$$

ROLE OF GUN EMITTANCE

Equation (11) clearly shows that the reduction of ρ at a lower energy can be compensated by using lower emittance gun. ρ also depends on the ratio I_{pk}/ϵ_n, which measures the effectiveness or performance of a low emittance gun, although I_{pk} is determined by not only the gun performance but also the bunch compression. The higher the ratio is, the more effective the gun is in reducing the machine size. We will use f to denote the ratio as in

$$f = \frac{I_{pk}}{\epsilon_n}. \quad (15)$$

For a given f, low I_{pk} can be allowed if ϵ_n is low enough. ρ can be kept unchanged in the scaling if we decrease ϵ_n as obtained by solving Eq. (10),

$$\epsilon_n = \left[\left(\frac{K[JJ]}{2\rho_0}\right)^6 \left(\frac{I_{pk}}{I_A}\lambda_u\right)^3 \left(\frac{\lambda_r}{89.6\pi^2\gamma^2}\right)^2\right]^{1/5}, \quad (16)$$

where ρ_0 is the constant value of ρ. When ρ_0 takes the LCLS value, 5.5×10^{-4}, and this ϵ_n is used in the energy scaling, we have the same ρ and thus comparable radiation quality and power as LCLS at lower electron energies. ϵ_n as given in Eq. (16) is plotted in Fig. 3. If even lower ϵ_n is used at each energy, ρ will be even larger. It is possible to recover what was lost in working at a lower energy by using a lower gun emittance solving the first problem mentioned in the introduction.

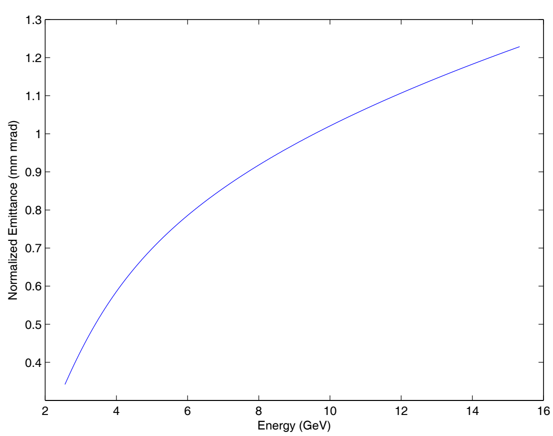

Figure 3: Graph of ϵ_n that cancels the E dependence of ρ and makes it constant in the energy scaling.

To build a compact XFEL, not only the linac size but also the undulator size should be reduced. Actually, the energy scaling reduces the undulator size, too. This is easily seen by the behavior of the one dimensional gain length defined by

$$L_G = \frac{\lambda_u}{\sqrt{3}\pi\rho} \quad (17)$$

or more accurately of the saturation length given by

$$L_{sat} = L_G(1+\eta)\ln\left(\frac{P_{sat}\lambda_r}{2\rho^2 Ec}\right), \quad (18)$$

where η is the famous fitting formula by Ming Xie [11] and $P_{sat} = 1.6\rho IE/e(1+\eta)^2$ is the saturated peak power. Since the logarithm is insensitive to the variation of its variable, the behavior of L_{sat} under the scaling is mostly given by the behavior of L_G. Using Eqs. (6) and (11), we obtain the rough dependence

$$L_{sat} \propto (E\epsilon_n)^{1/3} f^{-1/2}, \quad (19)$$

where f is the previously defined ratio of I_{pk} to ϵ_n. Equation (19) shows that the saturation length (thus the undulator length) decreases, as E decreases, only as $E^{1/3}$. However, it also shows that L_{sat} can also be reduced further by using low gun emittance. For example, if ϵ_n varies as in Fig. 3, L_{sat} decreases almost as linearly as E decreases as shown in Fig. 5. Hence, a low gun emittance solves the 2nd problem.

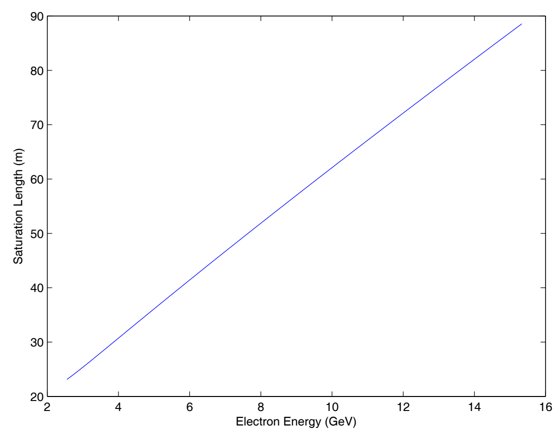

Figure 4: Saturation length in the energy scaling when ϵ_n moves as in Fig. 3.

Finally, we see from Eq. (14) that the growth of σ_w by lowering E can be canceled by using a low emittance gun. The equation also shows that even the growth of σ_w due to the small undulator gap can be canceled by ϵ_n low enough. Another critical role of ϵ_n to realize a compact XFEL. It solves the third problem.

OPTIMAL GUN EMITTANCE

As far as ϵ_n is concerned, it is not true that the lower, the better. ϵ_n should be chosen to give the maximal transverse coherence to the XFEL radiation. The XFEL degree of transverse coherence was obtained as a function of $z = 2\pi\epsilon_n/(\lambda_r\gamma)$ [12]. According to this result, the maximal transverse coherence is achieved at around $z \approx 1$. For LCLS, $z = 1.8$ is close enough to 1, but as the energy is scaled down z grows substantially and the transverse coherence of the radiation degrades. This degradation at a low energy can be prevented or the transverse coherence can even be improved by using a gun emittance low enough. In terms of ϵ_n, the condition $z = 1$ becomes

$$\epsilon_n = \frac{\lambda_r}{2\pi}\gamma. \quad (20)$$

For given λ_r and γ, this may be called the optimal ϵ_n. This optimal ϵ_n versus E is plotted in Fig. 5 for two hard X-ray wavelengths, 1 and 1.5 Å.

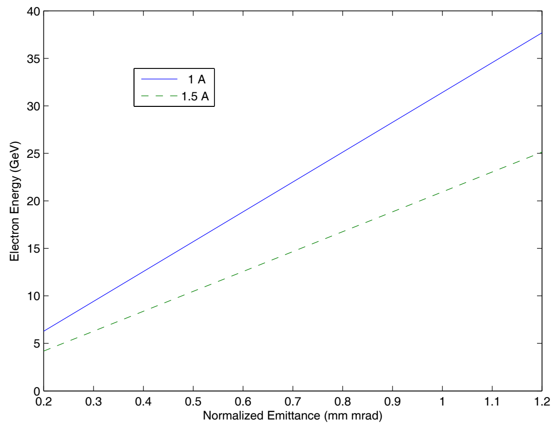

Figure 5: E and ϵ_n that gives the maximal transverse coherence for two different wavelengths, 1 and 1.5 Å.

CONCLUSION

Simply scaling down the LCLS energy degrades the machine performance and the radiation quality. Specifically, it reduces the radiation power, deteriorates the transverse coherence, and increases the power reduction due to the undulator wakefield. However, the performance and the radiation quality can be recovered or even be improved by using a gun emittance low enough. Furthermore, the low gun emittance reduces the undulator length. And, it also reduces the undulator wakefield effect. This paper has shown that a compact hard X-ray FEL can be constructed only by adopting a lower emittance gun. The necessary technology for the low emittance gun is not at hand but under development.

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