FEASIBILITY STUDY OF A COMPACT XFEL*

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Abstract

This paper discusses feasibility of a compact XFEL in the future. It gives theoretical argument how a compact XFEL can be realized. For that purpose, the energy dependence of parameters is discussed. It is shown that a much improved electron gun with an extremely low emittance and very small energy spread is an essential tool for the realization of a compact XFEL.

INTRODUCTION

X-ray free electron laser (XFEL) based on self amplified spontaneous emission (SASE) [1, 2] is considered the next generation light source. It is supposed to give highly bright photon beam in a sub-pico second pulse. Furthermore, the radiation is transversely coherent. However, it is highly doubtful that this magnificent tool of science will be as easily accessible as the third generation light sources, because the XFEL machine is so huge and generally costs very high. The Linac Coherent Light Source (LCLS) that is under construction consists of a long linear accelerator of 14.35 GeV electron beam energy and a long undulator of 112 m [3], while the European XFEL that is under proposal will be even bigger [4]. Therefore, it is a natural attempt to find the possibility of reducing the size of an XFEL machine to a reasonably modest size without degrading the radiation quality [5, 6].

This paper shows that the reduction of XFEL in size and energy is realizable only by an improved electron gun with lower emittance and smaller energy spread. This result may look obvious, but this paper shows it quantitatively and analytically. The needed improved gun does not seem to exist at the moment. However, recent development of technology makes it a realistic goal in the near future. 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) [7]. Its emittance is expected to be around $\epsilon_n = 0.6$ mm mrad, although this goal is not achieved yet [8]. 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 [9]. It is still at the very beginning stage. However, its R&D plan has a concrete schedule and goal, because the PSI-XFEL (the new XFEL project of PSI) relies upon the gun development. Besides these new type of guns, conventional photo-cathode guns are still under progress toward a low emittance [10, 11]. 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 [10].

In this paper, we study the feasibility of a compact XFEL machine, although its practical construction is in the future. Note that ϵ_n here refers to the theoretical normalized emittance used in the FEL physics, that is, the slice emittance. We will show that ϵ_n and $\delta E/E$ are the key parameters for the success of a compact XFEL.

ENERGY DEPENDENCE OF PARAMETERS

We want to find the energy dependence of an XFEL design. It is most clearly shown by ρ, the FEL parameter, defined by

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

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

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

K is the undulator parameter defined by

$$K = 0.934 B_0[\text{Tesla}]\lambda_u[\text{cm}], \tag{3}$$

where λ_u is the undulator period and 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

$$B_0 = 3.694 \exp\left[-5.068\frac{g}{\lambda_u} + 1.520\left(\frac{g}{\lambda_u}\right)^2\right] \tag{4}$$

with g denoting the undulator gap. The undulator peak field is not in wide range but usually restricted to between 1 and 1.5 Tesla. Hence, in this paper, we will fix g/λ_u to keep B_0 unchanged.

Since ρ roughly describes the SASE FEL efficiency as in

$$\rho \sim \frac{\text{generated field energy}}{\text{electron kinetic energy}}, \tag{5}$$

a high ρ is preferred in the XFEL design. The reason why XFEL needs high electron energy and low beam emittance is that they are necessary to make ρ high enough.

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In Eq. (1), 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

$$\beta_{opt} = 11.2\left(\frac{I_A}{I_{pk}}\right)^{1/2} \frac{\epsilon_n^{3/2}\lambda_u^{1/2}}{\lambda_r K[JJ]}. \quad (6)$$

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

$$\rho = \frac{1}{2}K[JJ]\left(\frac{I_{pk}}{I_A}\frac{\lambda_u}{\epsilon_n}\right)^{1/2}\left(\frac{\lambda_r}{89.6\pi^2\epsilon_n\gamma^2}\right)^{1/3}, \quad (7)$$

Apparently, ρ has the E dependence of $E^{-2/3}$. But, this is wrong because λ_u is also dependent on E. We find it from the undulator resonant condition,

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right), \quad (8)$$

Note that Eq. (8) is a cubic equation for λ_u for given λ_r and B_0. Arranging Eq. (8) for λ_u gives

$$\lambda_u^3 + \frac{2}{a^2}\lambda_u = \frac{4\lambda_r\gamma^2}{a^2}, \quad (9)$$

where $a = 0.934B_0$. Solving this cubic equation, we obtain λ_u as a function of γ (or E). To obtain a rough dependence of λ_u on E, we see in Eq. (8 that when $K > \sqrt{2}$, which is usually the case, Eq. (9) is roughly approximated to

$$\lambda_u^3 \approx \frac{4\lambda_r\gamma^2}{a^2}. \quad (10)$$

Then, we can derive the rough dependence of λ_u on E as

$$\lambda_u(E) \propto E^{2/3}. \quad (11)$$

The graph of λ_u versus E for $\lambda_r = 1.5$ Å is shown in Fig. 1 for later use. As a boundary condition, we used the LCLS values, $E = 14.35$ GeV, $\lambda_u = 3$ cm, $B_0 = 1.32$ T, which means that g/λ_u is fixed to 0.217.

Since K has the same E dependence as λ_u, the rough E dependence of β_{opt} becomes

$$\beta_{opt} \propto E^{-1/3}\left(\frac{\epsilon_n}{I_{pk}}\right)^{1/2}\epsilon_n. \quad (12)$$

It is straightforward to see the rough dependence of ρ as

$$\rho \propto \left(\frac{E}{\epsilon_n}\right)^{1/3}\left(\frac{I_{pk}}{\epsilon_n}\right)^{1/2}. \quad (13)$$

LOW ENERGY

Equation (13) shows that ρ decreases as E decreases as $E^{1/3}$. This means the degraded machine performance and radiation quality. Fortunately, ρ depends on the ratio E/ϵ_n.

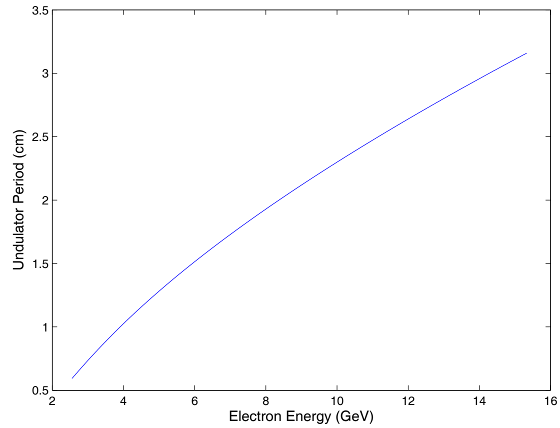

Figure 1: λ_u as a function of E for $\lambda_r = 1.5$ Å. The undulator peak field $B_0 = 3.694\exp[-5.068g/\lambda_u + 1.520(g/\lambda_u)^2]$ is fixed in the scaling.

Hence, if we want to build an XFEL machine at a lower energy than usual but with comparable machine performance and radiation quality, it shows that we should use a low emittance electron gun to recover ρ to its high energy value. Since ρ also depends on the peak current I_{pk}, the low emittance guns should also provide sufficient current in order to make high enough I_{pk}. However, in general, lower emittance guns give lower gun current and so lower I_{pk}. For example, in the PSI-XFEL project, I_{pk} is expected to be 1.5 kA, which is approximately half of the LCLS peak current with 1 nC charge. Fortunately again, ρ actually depends on the ratio I_{pk}/ϵ_n and the effect of low I_{pk} is successfully canceled by the low ϵ_n.

The low emittance is not all that we need from new and improved guns. Physically, ρ describes the upper bound of the allowed relative energy spread of the electron beam for the SASE process. The physical unit where the SASE process happens is not the whole bunch but each of many slices in a bunch. Let $\delta E/E$ denote the relative energy spread in a slice. The SASE process begins only when $\delta E/E < \rho$ and it stops (saturates) when $\delta E/E$ grows and reaches around ρ. Hence, a lower relative energy spread is preferred. For example, in LCLS, the initial $\delta E/E$ is 1×10^{-4} while ρ is 5×10^{-4} [3]. Note that δE, the energy spread, is determined by the electron gun while $\delta E/E$ is also determined by the electron energy. It increases simply when we use a low energy electrons. This is one of the reasons why the beam energy of an XFEL is so high. If we want to build an XFEL at a lower energy than usual, it is not enough to recover ρ to its high energy value by using low emittance. Due to the increased $\delta E/E$, the SASE process stops quickly and we would not have enough radiation power. We have to also reduce the gun energy spread δE to recover $\delta E/E$ to the high energy value. Therefore, not only the gun emittance (ϵ_n) but also the gun energy spread (δE) should be reduced to build a compact XFEL. Low energy

XFEL is realizable only by a much improved electron gun.

SHORT UNDULATOR

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

$$L_G = \frac{\lambda_u}{\sqrt{3}\pi\rho} \tag{14}$$

or more accurately of the saturation length given by

$$L_{sat} = L_G(1+\Lambda)\ln\left(\frac{P_{sat}\lambda_r}{2\rho^2 Ec}\right), \tag{15}$$

where Λ is the famous fitting formula by Ming Xie [13] and $P_{sat} = 1.6\rho IE/e(1+\Lambda)^2$ is the saturated peak power. Using Eqs. (11) and (13), we obtain the rough dependence

$$L_G \propto (E\epsilon_n)^{1/3}\left(\frac{\epsilon_n}{I_{pk}}\right)^{1/2}. \tag{16}$$

Since the logarithm is insensitive to the variation of its variable, the behavior of L_{sat} under the energy scaling is mostly given by the behavior of L_G. The only possible correction comes from Λ, which is given by

$$\begin{aligned}\Lambda &= a_1\eta_d^{a_2} + a_3\eta_\epsilon^{a_4} + a_5\eta_\gamma^{a_6} + a_7\eta_\epsilon^{a_8}\eta_\gamma^{a_9} \\ &+ a_{10}\eta_d^{a_{11}}\eta_\gamma^{a_{12}} + a_{13}\eta_d^{a_{14}}\eta_\epsilon^{a_{15}} + a_{16}\eta_d^{a_{17}}\eta_\epsilon^{a_{18}}\eta_\gamma^{a_{19}},\end{aligned} \tag{17}$$

where the scaled parameters are defined by

$$\begin{aligned}\eta_d &= \frac{\lambda_u}{\sqrt{3}\pi\rho}\frac{\lambda_r}{4\pi\beta_{opt}\epsilon_n}, \\ \eta_\epsilon &= \frac{\lambda_u}{\sqrt{3}\pi\rho}\frac{4\pi\epsilon_n}{\beta_{opt}\lambda_r\gamma}, \qquad (18) \\ \eta_\gamma &= \frac{4}{\sqrt{3}\rho}\frac{\sigma_E}{E}, \qquad (19)\end{aligned}$$

and $a_1, \cdots, a_{19}$ are determined numbers. Although this correction to Λ is not critical because Λ often is smaller than 1, it can sometimes give non-negligible change to Λ. Note that Λ includes $\delta E/E$ in η_γ, which gets larger when E is lower than usual. This correction is easily removed if we use an improved gun with reduced δE.

Equation (16) shows that both working at a low energy and using the improved gun reduces the needed undulator length. Again, we see that ϵ_n and $\delta E/E$ are key parameters to realize a compact XFEL.

UNDULATOR GAP

The discussion so far may give the impression that the energy and size of an XFEL can be reduced to as small scale as the gun emittance and energy spread allow. However, this may not be true. A limitation for how compact an XFEL machine can be may come from the narrow undulator gap, no matter how low ϵ_n and $\delta E/E$ are. Recall that g/λ_u is fixed in this discussion to maintain the same undulator peak field. As λ_u decreases, g also decreases. Figure 1 shows that λ_u is only 1 cm at around $E = 4$ GeV, which means g is only around 2 mm. Since the electron beam size is so small ($< 100\mu m$), there is practically no lower limit of the undulator gap as far as beam passing is concerned. However, the narrower the undulator gap is, the tighter the alignment and beam control tolerances are.

An adequate g should be chosen by taking into consideration the above factors. In many cases, this chosen g may determine E and λ_u.

UNDULATOR WAKEFIELD

A potential problem in realizing a compact XFEL is the undulator wakefield, which is inversely proportional to the undulator gap. We saw above that the undulator gap can be very narrow in a compact XFEL. The undulator wakefield creates relative energy spread between the slices, the rms of which is given by [3]

$$\sigma_w = -\frac{e^2 NL(W_z)_{rms}}{E}, \tag{20}$$

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 [3]

$$(W_z)_{rms} \approx 1.02\frac{\Gamma(3/4)}{2\sqrt{2}\pi^2}\frac{c}{\sigma_z^{3/2}g}\left(\frac{Z_0}{\sigma}\right)^{1/2}, \tag{21}$$

where σ is the conductivity of the metal. It would be no problem to replace L by L_{sat} in Eq. (20). Since σ_w spreads energy between slices not within a slice, it does not prevent the FEL process from occurring but causes slices with large energy deviation radiate out of resonance. The final result would be simply the radiation power reduction.

Since σ_w is inversely proportional to E, it is supposed to grow and give more power reduction for lower E. Using Eq. (16) and the fact that eN is proportional to I_{pk}, we can find the rough dependence of σ_w as

$$\sigma_w \propto \left(\frac{\epsilon_n}{E}\right)^{2/3}\left(\frac{I_{pk}}{\epsilon_n}\right)^{1/2}\frac{\epsilon_n^{2/3}}{g}. \tag{22}$$

We see that the growth of σ_w by lowering E and g can be canceled by using a low emittance electron beam. There is no undulator wakefield problem in a compact XFEL.

CONCLUSION

It would be really great, if it is possible to build a LCLS-quality XFEL in a compact size at a lower energy. This paper has shown that a compact hard X-ray FEL can be constructed only by using a much improved electron gun with extremely low emittance and energy spread. The necessary technology for the improved guns is not at hand but under development. If these guns are realized in the future, a practical limit for how compact an XFEL can be may come from the undulator gap, which should not be too small considering the alignment and beam control difficulties. Finally, there will be no undulator wakefield problem in the compact XFEL.

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