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Storage Ring Based X-ray FEL Oscillator

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Abstract. As the linac-based X-ray FEL oscillator is actively pursued recently, feasibility of a storage ring based X-ray FEL oscillator is examined. Conditions of the required storage ring parameters such as beam emittance and machine parameters are investigated. Also, the performance and advantages and disadvantages of a storage ring based X-ray FEL oscillator is compared with those of other X-ray FEL sources.

INTRODUCTION

Production of X-ray laser has been the focus of the synchrotron radiation research for the past decade. Here, X-ray laser means longitudinally (temporally) and transversally (spatially) coherent intense X-ray beam. Currently, X-ray laser can be emitted not by bound electrons but only by free electrons that are moving through undulators after being accelerated by accelerators and that is why it is called the "free-electron laser (FEL)" [1]. The wavelength spectrum of the free-electron laser is wide from microwave to hard X-ray, but generating intense hard X-ray requires very high quality electron beam with high electron energy, very small electron beam emittance and energy spread. As the linear accelerator is able to provide smaller beam emittance, smaller energy spread, higher peak current and shorter bunches than the the storage ring, all X-ray free-electron laser (XFEL) facilities operational adopted the linear accelerator. Particularly, all those facilities make use of the FEL amplifier scheme based on self amplified spontaneous emission (SASE) [2]. The linac-based SASE XFEL scheme has been successful, but it has the following technical limitations;

- The X-ray output fluctuates from shot to shot because of the shot-to-shot fluctuations of electron bunches coming out of linear accelerator.
- Its temporal coherence is not perfect at all and is, in fact, much poorer than that of conventional laser while the spatial coherence is good enough. For refinement of temporal coherence, secondary processes such as self-seeding are required.

The recently proposed X-ray FEL oscillator (XFELO) [3] scheme has no these limitations in principle but has long been ignored because proper X-ray mirrors were not found. This scheme has recently been revived by adopting Bragg mirrors [4]. However, SASE or XFELO, linac-based XFEL is basically limited to a single or few user machine, not a multi-user facility like a storage ring.

Recently, installing an XFEL facility in a straight section of a storage ring light source without spoiling its multi-user facility character is considered by adopting the XFELO scheme. Technical developments necessary to overcome the limitation of the storage ring, relatively large beam energy spread, was made by introducing transverse gradient undulators (TGU) [5]. Note that XFELO is better suited to the storage ring than SASE XFEL not only because it does not require electron bunches as short as in SASE XFEL but also because it gives full temporal coherence capability, at the hard-X ray regime, to the storage ring. The storage ring radiation has partial transversal coherence and completely no temporal coherence and that is why monochromators are used. While bandwidth of a monochromator is usually limited to 10^{-4}, that of XFELO would even reach 10^{-7}. Therefore, combination of XFELO and a storage ring is very effective and meaningful. On the other hand, transversal coherence exists in the storage ring but the degree of coherence depends on the beam emittance with respect to the wavelength. Diffraction limited beam emittance given by $\epsilon_D = \lambda/(4\pi)$ is required to obtain full transversal coherence. Only in storage rings with sufficiently high energy and extremely low emittance, such as PEP-X and PETRA-IV to be constructed, full transversal coherence would

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be obtained. Actually, studies were done on inserting XFELO machine into PEP-X [6] and PETRA-IV [7] on the basis that XFELO in such facilities will provide intense hard X-ray beam fully coherent both longitudinally and transversally. However, this paper suggests that even ordinary third generation light sources with modest energy and beam emittance can accommodate and utilize XFELO, if full transversal coherence is given up. Below, this paper describes briefly the high-gain SASE FEL scheme and low-gain XFELO scheme to compare the two. Then, how TGU can help XFELO work in the storage-ring is explained. Finally, it is pointed out that third generation light sources with XFELO may be a very useful facility.

FIGURE 1. Aerial view of PAL-XFEL, a SASE FEL facility, together with PLS-II, a third generation facility, at the Pohang Accelerator Laboratory (PAL)

XFEL SCHEMES

Free-electron laser is basically the undulator radiation the wavelength of which is given by

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

where λ_u is the undulator period, $K = eB\lambda_u/(2\pi mc)$ is the undulator constant and γ is the relativistic factor. As this formula shows, the undulator radiation spectrum depends heavily on the energy spread of the free electrons. Large beam energy spread gives wide radiation spectrum. FEL selects a narrow portion of the wavelength spectrum and coherently amplifies it. Therefore, as the electron beam energy spread is smaller, the output FEL radiation is stronger. This is why the beam energy spread is so important and should definitely be small. Physically, there are two schemes for the coherent amplification, high-gain amplifier scheme based on self amplified spontaneous emission (SASE) and low-gain XFEL oscillator (XFELO) scheme. Each scheme has its advantages and disadvantages. The high-gain amplifier is a single-pass machine that each electron bunch generates an XFEL output pulse, whereas the low-gain oscillator is a multi-pass machine that each XFEL output pulse is contributed by a number of electron bunches.

In SASE, electrons in each bunch are regrouped into many micro bunches spaced in the wavelengths of the undulator radiation through the interaction between electrons and their radiation, and the radiation emitted by the micro bunches add up to become the intense FEL radiation. As this spontaneous process is random, the output XFEL radiation shows fluctuation from pulse to pulse because of the shot-to-shot fluctuations of electron bunches coming out of the linear accelerator and the temporal coherence is far from perfection and much poorer than that given by conventional laser. The temporal coherence of a SASE machine can be improved by secondary processes such as self-seeding. If the electron energy spread is too large, lasing would fail in the SASE FEL scheme. Theoretically, relative energy spread (σ_γ/γ) should be less than ρ the FEL parameter. Typically, 0.01% relative energy spread is required but the storage ring can typically give 0.1% energy spread while the linear accelerator can give 0.01% energy spread. In addition to small energy spread, the electron peak current should be high enough (a few kA) and this can also be given by the linear accelerator through bunch compressors. Therefore, the SASE XFEL scheme is well suited to the linear accelerator. As for the electron beam emittance required for transversal coherence, the SASE requirement is a little relaxed compared to that of XFELO. It is not necessarily required to be as low as ϵ_D but a more or less higher emittance is enough for lasing thanks to the so called "optical guiding". Hence, SASE XFEL is the transversal coherence oriented scheme. The XFEL facilities that are currently operating or under construction all adopted the SASE scheme. Being a high-gain scheme, SASE FEL is advantageous in achieving high power X-ray radiation.

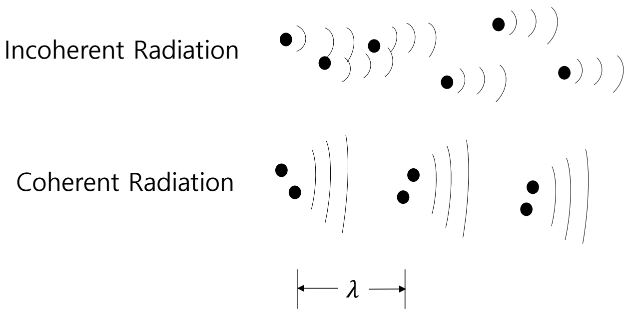

FIGURE 2. Schematic figure of coherent and incoherent radiation by free electrons. Coherent emission is the mechanism of FEL amplifier

The FEL oscillator makes use of a mirror system that selects a target wavelength out of the undulator radiation from an initial bunch and makes the selected radiation oscillate back and forth in the mirror system for continuing interaction with subsequent electron bunches. The mechanical work done to the radiation by the bunches gives amplification until it reaches saturation. As the number of passes (oscillations) increases, the radiation power grows. While growth rate is an important parameter for the SASE FEL, the 'gain' per pass is an important parameter in the FEL oscillator. Even in the case of small gain, the output radiation can reach high enough if the number of passes is sufficiently high. The saturated FEL radiation passes through the mirror system. As subsequent bunches do not spoil the temporal coherence of the initial radiation, the FEL oscillator maintains excellent temporal coherence. However, on the other hand, the oscillator mechanism does not particularly guarantee transversal coherence, which should be assured independently by that the electron beam emittance satisfies $\epsilon \leq \epsilon_D$. Extension of the FEL oscillator scheme to the hard-X-ray regime had long been ignored because good X-ray mirrors were difficult to find. The current XFELO scheme has been enabled by adopting the diamond Bragg crystal as the necessary X-ray mirror. Wavelength is selected by the Bragg's law $\lambda = 2d\cos\theta$. Hence, XFELO is a temporal coherence oriented scheme and very stable from pulse to pulse. Being a low-gain and multi-pass machine, XFELO should be operated in a high repetition rate (typically MHz order) to be able to compete with SASE XFEL for output power. This is why energy recovery linacs are often considered for driving an XFELO machine.

Advantages and disadvantages of the two schemes are compared in Table 1 below. The oscillator scheme is complementary to the SASE scheme in the sense that its advantages correspond to disadvantages of SASE scheme and vice versa. SASE XFEL's strength over XFELO would be its fs scale short bunches and it would be particularly useful in such fields as femto-second dynamics, and XFELO's strength over SASE XFEL would be its temporal coherence and it would be particularly useful in such fields as resonance in-elastic X-ray spectroscopy.

TABLE 1. Comparison of SASE XFEL and XFELO.

	SASE XFEL	**XFELO**
Temporal Coherence	Poor	Good
Band Width ($\Delta\omega/\omega$)	10^{-3}-10^{-4}	10^{-7}
Spatial Coherence	Good	Good
Photons/pulse	10^{12}	10^{9}
Pulse-to-Pulse Stability	Poor	Good
Pulse Duration	10-100 fs	0.1-1 ps

STORAGE RING BASED XFELO

On the other hand, the idea of installing an XFELO machine in a straight section of a storage ring with proper conditions has grown. There may be several reasons for this idea but one of them is certainly to integrate XFEL function into a multi-user facility. To accomplish this goal, there are the following technical requirements and difficulties:

- High beam energy is required for generation of sufficiently many hard X-ray photons. In general, the higher, the better. But, 3 GeV electron beam would work with the help of in-vacuum undulators.
- Low beam emittance is required to obtain transversal coherence. The “ultimate storage ring”s based on multi-bend achromatic (MBA) lattice can have this emittance.
- The effect of the 0.1% level relative beam energy spread on the radiation wavelength spectrum must be mitigated. The recent idea of transverse gradient undulator (TGU) can do this as explained below. This is a crucial idea for realization of XFELO.

Transverse Gradient Undulator

The basic idea of TGU is to give constant transversal gradient to the undulator field so that $B(x)$ and correspondingly $K(x)$ become increasing functions of x with $x = 0$ denoting the horizontal undulator center as in the figure below. Then, for an electron experiencing the field $B(x)$ at x with energy $\gamma(x)$, we have $x = D\delta\gamma/\gamma_0$, by definition, where D is the dispersion of the straight section, $\delta\gamma = \gamma - \gamma_0$, $\gamma_0 = \gamma(0)$ and betatron oscillation is ignored. This definition can be rewritten as

$$\gamma(x) = \gamma_0\left(1 + \frac{x}{D}\right). \tag{2}$$

And, as $B(x) = B_0 + \kappa x$ where $B_0 = B(0)$ and κ is the constant gradient of the field, the undulator constant K can be written as

$$K(x) = K_0\left(1 + \frac{\kappa}{B_0}x\right). \tag{3}$$

If these two equations are used in Eq. (1), we obtain for small x

$$\begin{aligned} \lambda &= \frac{\lambda_u}{2\gamma_0^2(1+2x/D)}\left[1 + \frac{K_0^2}{2}\left(1 + \frac{2\kappa}{B_0}x\right)\right] \\ &= \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right)\left[1 + \frac{K_0^2\kappa}{(1+K_0^2/2)B_0}x\right]\left(1 - \frac{2}{D}x\right) \\ &= \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right), \end{aligned} \tag{4}$$

if the undulator field gradient satisfies

$$\frac{\kappa}{B_0} = \frac{2 + K_0^2}{DK_0^2}. \tag{5}$$

Therefore, with TGU, λ is independent of beam energy spread up to $O(x)$.

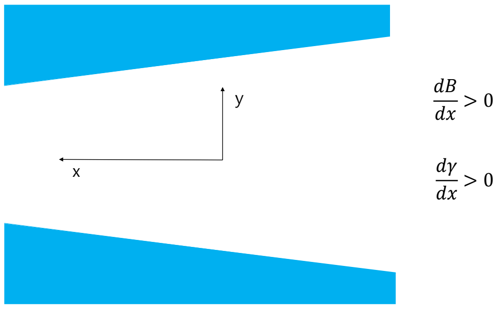

FIGURE 3. Schematic side view of a TGU.

Feasibility of XFELO for the Third Generation Light Sources

With TGU, it is possible to mitigate the effect of beam energy spread on the undulator radiation wavelength spectrum. The only other obstacle for the fully coherent XFELO inserted into a storage ring is to achieve the diffraction limited beam emittance, $\epsilon_{Dx,y} = \lambda/(4\pi)$. With this beam emittance, the storage ring based XFELO would give transversely and longitudinally coherent intense hard X-ray beam. For a typical hard X-ray photon of 12 keV, the corresponding emittance is approximately $\epsilon_{Dx,y} \approx 10$ pm. Among the many multi-bend lattices that are under construction, study or design, only few facilities including PEP-X and PETRA-IV are capable of this low emittance. With their high beam energies (4.5 GeV at PEP-X and 6 GeV at PETRA-IV), these two facilities are certainly adequate for incorporating XFELO competitive with existing SASE FEL machines.

However, a number of third generation light sources with 3 GeV beam energy and 1-10 nm beam emittance may also incorporate XFELO, giving up full transverse coherence and brightness as high as the linac-based XFEL machines. As pointed out above, XFELO is a valuable opportunity for the third generation light sources to have full temporal coherence. It would certainly expand the application scope of the third generation light sources and the cost would be relatively low. For an XFELO installed in a storage ring, the oscillator gain per pass with energy spread an TGU is approximately given by the i-dimensional theory as in [6]

$$G \approx 1.53\pi^3\gamma \frac{K_0^2[JJ]^2}{1+K_0^2/2}\frac{\lambda}{\lambda_u}\frac{N_u/\sigma_\eta}{D/\sigma_x + (5.46N_u)^2\sigma_x/D}, \qquad (6)$$

where I is the peak current, $I_A = 17$ kA is the Alfen current, $[JJ] = J_0[K_0^2/(4+2K_0^2)] - J_1[K_0^2/(4+2K_0^2)]$, $\Sigma_{x,y}^2 = \sigma_{x,y}^2 + \sigma_{rx,y}^2$ where $\sigma_{x,y}$ is the horizontal and vertical beam size and $\sigma_{rx,y}$ is the horizontal and vertical radiation beam size, N_u is the number of undulator periods and σ_η is σ_γ/γ. Note that $\Sigma_{x,y} \approx \sigma_{x,y}$ for a third generation light source where the electron beam size is much bigger than the hard X-ray beam size whereas $\Sigma_{x,y} \approx 2\sigma_{rx,y}$ for the ultimate storage rings where the electron beam size is comparable to the radiation beam size. As $\sigma_{x,y}$ is much bigger than $\sigma_{rx,y}$ in a third generation light source, it is clear from this formula that gain would be much lower in a third generation light source than that in a MBA-based 4-th generation light source. An XFELO based on a 1 nm rad emittance third generation light source has gain about 100 times lower than that based on a 10 pm rad emittance ultimate storage ring. But, this can be compensated to some extent by the peak current I. In the ultimate storage ring, increasing bunch current is very difficult because it would blow up the beam emittance through intra-beam scattering. However, in the third generation light source, bunch current can be increased to a high value without emittance blowup. According to the PEP-X design, the peak current is 20 A, but 300 A peak current is usually achievable in a typical third generation light source. The hybrid mode in which one or a few single bunches filled with high bunch current circulate together with multi-bunched filled with low bunch current would raise the gain by 15 times. Also, as mentioned before, low gain can be compensated for by a high number of passes. From the past experience of operating storage ring based (VUV or soft X-ray) FEL oscillators, it is better to install an XFELO in a bypass line. Hence, in the XFELO hybrid operation mode, only the single bunches with high bunch current would be directed to the XFELO on a bypass line while other bunches just circulate on the conventional line. This can be done by using a fast kicker system.

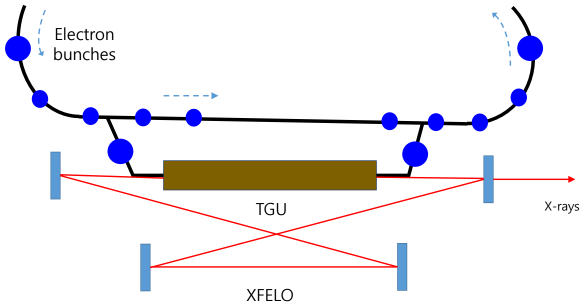

FIGURE 4. A schematic figure of a storage ring based XFELO on a bypass line. A hybrid fill pattern is assumed with bigger bunches denoting bunches with high bunch current.

To estimate the gain for a typical third generation light source, we examine the relation $\partial G/\partial D = 0$ to derive the optimal value of the straight section dispersion. From

$$\frac{1}{\sigma_x} - \frac{(5.46N_u)^2\sigma_x}{D^2} = 0, \tag{7}$$

we obtain the D value maximizing G as

$$D = 5.46N_u\sigma_x. \tag{8}$$

Note that σ_x is very small for the multi-bend ”ultimate storage rings” and so N_u has to be a high number. If D is too low, it would be difficult to make it accurately. However, for a typical value of $\sigma_x = 100\ \mu$m and $N_u = 300$, $D \approx 0.16$ m is obtained and this is a reasonable value for D. With this value of D and other typical parameter values of $\epsilon_x = 1.0$ nm rad, $I = 300$ A, K=1.0, $\sigma_\eta = 1.0 \times 10^{-3}$ and $\lambda_u = 0.02$ m, the gain per pass for the 12 keV X-ray FELO is given as $G \approx 0.1$. This is certainly lower than the PETRA-IV number of 0.3 [7], but it seems reasonably high enough for XFELO to be pursued.

CONCLUSION

The old FEL oscillator scheme can be used for producing hard X-ray laser by adopting diamond Bragg crystals for X-ray reflective system. This XFELO has the advantage of better temporal coherence and stable pulse-to-pulse stability over the widely used SASE XFEL. Particularly, XFELO may be put into a straight section of a storage ring and work as an XFEL source if transverse gradient undulators are used. If the storage ring is one of the so called ultimate storage rings with the diffraction limited emittance, XFELO would give fully coherent (temporally and spatially) intense hard X-ray beam. If it is merely a typical third generation light source, the spatial coherence would not be fully given but XFELO would still work as a valuable X-ray source with full temporal coherence that any storage ring cannot give by itself.

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