ANL/ASD/CP-99801

# Circular Polarization with Crossed-Planar Undulators in High-Gain FELs*

RECEIVED
OCT 12 1999
OSTI

**Kwang-Je Kim**

*Accelerator Systems Division, Advanced Photon Source,*

*Argonne National Laboratory, 9700 S. Cass Avenue,*

*Argonne, IL 60439 U.S.A.*

*Phone: 630.252.4647, FAX: 630.252.7369, E-mail: kwangje@aps.anl.gov*

We propose a crossed undulator configuration for a high-gain free-electron laser to allow versatile polarization control. This configuration consists of a long (saturation length) planar undulator, a dispersive section, and a short (a few gain lengths) planar undulator oriented perpendicular to the first one. In the first undulator, a radiation component linearly polarized in the x-direction is amplified to saturation. In the second undulator, the x-polarized component propagates freely, while a new component, polarized in the y-direction, is generated and reaches saturation in a few gain lengths. By adjusting the strength of the dispersive section, the relative phase of two radiation components can be adjusted to obtain a suitable polarization for the total radiation field, including the circular polarization. The operating principle of the high-gain crossed undulator, which is quite different from that of the crossed undulator for spontaneous radiation, is illustrated in terms of 1-D FEL theory.

*Keywords:*

*Classification Codes:*



*Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

## DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

# 1. Introduction

Among several possible designs for the next generation of light sources, the most exciting is the one based on self-amplified spontaneous emission (SASE) [1]. SASE is intense, coherent radiation generated by amplifying the initial spontaneous emission via an extremely high free-electron laser (FEL) gain process [2],[3]. The Linac Coherent Light Source (LCLS) is a proof-of-principle demonstration project for production and use of a 1-Å SASE based on the SLAC linac [4]. The R&D preparing for the conceptual design of the LCLS is underway as a multi-laboratory collaboration in the U.S. In Europe, a next-generation light source facility based on a continuous wave (CW) superconducting linac is being pursued by the DESY group [5].

The discussion of x-ray SASE has been usually based on planar undulators producing linearly polarized x-rays. However, it is anticipated that the demand for circular polarization or arbitrarily adjustable polarization will be significant in the future. Circular polarization could be obtained by employing a helical undulator. However, switching the polarization between two opposite helicities is difficult for a helical undulator.

In this paper, we propose an undulator configuration for high-gain FELs that allows easy control of polarization.

# 2. The Principle

The configuration is based on a pair of planar undulators in a crossed position, as illustrated schematically in Fig.1. The first undulator $\mathcal{U}_x$ is sufficiently long such that the SASE process for linearly polarized radiation in the x-direction is amplified to saturation level. The electron beam develops density modulation (micro-bunching) with the periodicity of the radiation wavelength. In the second planar undulator $\mathcal{U}_y$, which is rotated 90 degrees relative to the first undulator, the x-polarized radiation component does not interact with the electron beam and thus propagates freely. However, a new y-polarized radiation component is generated by the density-modulated electron beam and rapidly reaches saturation within a few gain lengths. These two radiation components have a definite relative phase, which is determined by the delay of the electron beam travelling through a dispersive section $\mathcal{D}$ between the two undulators. The delay, and therefore the net polarization, can be adjusted by adjusting the strength of the dispersive section. For example, the delay corresponding to a $\pi/2$ ($-\pi/2$) relative phase will give rise to right- (left-) circular polarization as indicated in the figure.

Except for the unequal length of the two undulators (one saturation length for the first and a few gain lengths for the second undulator), the scheme discussed here may appear to be similar to the crossed undulator scheme for spontaneous radiation [6]. However, the operating principles of the two cases are quite different. In the crossed undulator for spontaneous radiation, each electron generates two radiation pulses as it passes through the two undulators in sequence. Since they are separated in time, the two pulses cannot interfere with each other if left alone. They do interfere, however, after passing through a monochromator since each radiation pulse is stretched in the monochromator. The monochromator, therefore, is an important part of the operation of the spontaneous crossed undulator. The degree of polarization in this case is very sensitive to the electron beam emittance and energy spread, which induce phase smearing and depolarization.

In the high-gain crossed undulator proposed here, on the other hand, the interference occurs due to the overlap of two radiation components in the second undulator, and the degree of polarization is nearly 100% as long as the slippage (the distance within which a photon travels past an electron) in the dispersive section is negligible compared to that in the first undulator.

# 3. Analysis

We will now use the 1-D FEL theory in linear approximation as formulated in Ref. [2] to analyze the physical process in a high-gain crossed undulator. Consider the electric field amplitudes $A_x(z)$ and $A_y(z)$, where x and y are the polarization indices, as functions of z, the distance along the undulator axis. We also consider perturbation in the electrons' distribution function $F(\delta,z)$. Here $\delta$ is the scaled variable for momentum:

$$\delta = \frac{p - p_0}{p_0 \rho}, \tag{1}$$

where p = electron momentum, $p_0$ = reference momentum, and $\rho$ = the Pierce parameter of FEL interaction [1]. The function $F(\delta,z)$ is the microbunch distribution in the momentum space.

The coupled Maxwell-Vlasov equation for $z \geq z_1$ can be solved given the initial functions $A_x(z_1)$ and $F(\delta,z_1)$. The solution is especially simple after a distance of a few gain lengths, i.e.,

$$2\,k_u \rho \lambda_I (z - z_1) > 1\,. \tag{2}$$

Here $\lambda_I$ is the imaginary part of $\lambda$, which is the solution, with the largest imaginary part, of the dispersion relation

$$D(\lambda) \equiv \lambda + \int d\delta \frac{V'(\delta)}{\lambda+\delta} = 0\,. \tag{3}$$

Here $V(\delta)$ is the unperturbed momentum distribution function and $V' = dV/d\delta$.

The solution is

$$A_x(z) = \frac{1}{D'} e^{-2ik_u\lambda\rho(z-z')} \left[ A_x(z_1) - \frac{i}{\kappa} \int d\delta \frac{F(\delta,z_1)}{(\lambda+\delta)} \right], \tag{4}$$

$$F(\delta,z) = -\frac{\kappa i A_x(z) V'(\delta)}{(\lambda+\delta)}\,. \tag{5}$$

In the above, $k_u = 2\pi/\lambda_u$, $\lambda_u$ = undulator period, $\kappa$ is a constant and

$$D' = \frac{dD}{d\lambda} = 1 - \int d\delta \frac{V'(\delta)}{(\lambda+\delta)^2}\,. \tag{6}$$

Let $z = 0$ be the entrance of the first undulator, where $A_x(0) = 0$. At the exit of the first undulator $z = L$,

$$A_x(L) = -\frac{i}{\kappa D'} e^{-2ik_u\lambda\rho L} \int d\delta \frac{F(\delta,0)}{\lambda+\delta}, \tag{7}$$

$$A_y(L) = 0, \tag{8}$$

$$F(\delta,L) = -\kappa i \frac{A_x(L) V'(\delta)}{\lambda+\delta}\,. \tag{9}$$

In the above, $F(\delta,0)$ is the bunching present in the discrete noise of the initial electron beam.

The length of the first undulator L should be chosen to be the saturation length in order to obtain the maximum radiation power. Therefore, Eq. (6), which was derived using the linear theory, is an approximate expression. However, the approximation is adequate for the purpose of illustrating the principle of the high-gain cross undulator device.

In passing through the dispersion section of length d

$$A_x(L+d) = A_x(L), \tag{10}$$

$$A_y(L+d) = 0, \tag{11}$$

$$F(\delta, L+d) = F(\delta,L)\, e^{i(\Delta\theta + \mathscr{D}\delta)}, \tag{12}$$

where

$$\Delta\theta = -(k_u d)\left[\frac{1+K_D{}^2/2}{1+K^2/2} - 1\right], \tag{13}$$

$$\mathscr{D} = 2\rho k_u d\left(1+K_D{}^2/2\right)/\left(1+K^2/2\right), \tag{14}$$

$$K_D{}^2 = \frac{2}{d}\left(\frac{e}{mc}\right)^2 \int_0^d \left[\int_0^z B(z')dz'\right]^2 dz\,. \tag{15}$$

In the above, K is the undulator deflection parameter, e = electron charge, m = electron mass, c = speed of light, and B(z) is the magnetic field strength in the dispersive region.

In the second undulator, the field component $A_x$ remains unchanged. However, the field component $A_y$ will grow as in Eq. (4) but $A_x$ is replaced by $A_y$. At the end of the second undulator $z = z_f$ we find

$$A_x(z_f) = A_x(L), \tag{16}$$

$$A_y(z_f) = \xi\, A_x(z_f), \tag{17}$$

$$\xi = -\frac{e^{-2ik_u\lambda\rho\ell + i\Delta\theta}}{D'} \int d\delta \frac{V'(\delta)\, e^{i\mathscr{D}\delta}}{(\lambda+\delta)^2}\,. \tag{18}$$

In the above, $\ell$ is the length of the second undulator.

Equations (17) and (18) are the basic design equation for the high-gain crossed undulator. For example, circular polarization will result if

$$|\xi| = 1\,, \tag{19}$$

$$\mathrm{Arg}(\xi) = \pm\,\pi/2. \tag{20}$$

The condition (19) can be satisfied by a proper choice of $\ell$. Since the factors in Eq. (18) are all of order unity, the length of the second undulator $\ell$ need only be a few gain lengths. The phase of $\xi$ can clearly be adjusted by changing the phase $\Delta\theta$, or by varying the strength of the dispersion magnet B.

For an illustration, consider the case of the vanishing momentum spread $V(x) = \delta(x)$. In this case, $D(\lambda) = \lambda + 1/\lambda^2$, the imaginary part of the leading eigenvalue is $\lambda_I = \sqrt{3}/2$, $D'(\lambda) = 3$, and Eq. (19) becomes $\ell = \ln(1.5)/2k_u\lambda_I\rho$. (Strictly speaking, since the resulting $\ell$ is less than a gain length, the approximation of retaining the leading eigenvalue is not accurate. However, it is straightforward to generalize the derivation to take into other eigenvalues.)

## 4. Generalization

The high-gain crossed undulator configuration discussed here can be generalized to other configurations. For example, a helical device for the first undulator and another helical device of opposite helicity for the second will give rise to linearly polarized radiation whose polarization direction could be arbitrarily adjusted.

It is also possible to bend the electron beam out of the radiation path after the first undulator, as shown in Fig. 2. In this case, the function of the first undulator is to induce microbunching, and the second undulator can be tailored to produce any desired radiation characteristics. Since the second undulator needs to be only a few gain lengths, the system is quite versatile. However, an additional complication is the fact that the bend must be isochronous to preserve the bunching.

## 5. References


[1] R. Bonifacio, C. Pellegrini, and L.M. Narducci, Opt. Commun. 50 (1984) 373.

[2] K.-J. Kim, Nucl. Instr. and Meth. A250 (1986) 396; K.-J. Kim, Phys. Rev. Lett. 57 (1986) 1871.

[3] J.-M. Wang and L.-H. Yu, Nucl. Instr. and Meth. A250 (1986) 484.

[4] LCLS Design Study Report, SLAC-R-51 (April 1998).

[5] Conceptual Design of a 500 GeV e+e- Linear Collider with Integrated X-Ray Facility, DESY 1997-048 (May 1997).

[6] K.-J. Kim, Nucl. Instr. Meth. 219 (1984) 425.

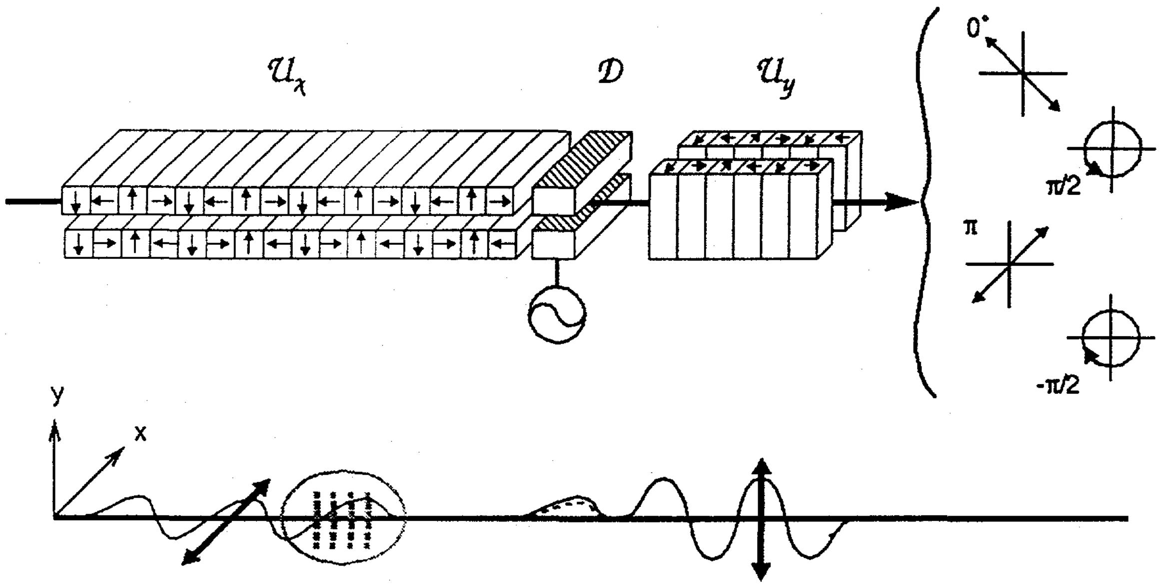


Figure 1. Operating principle of a high-gain crossed undulator.

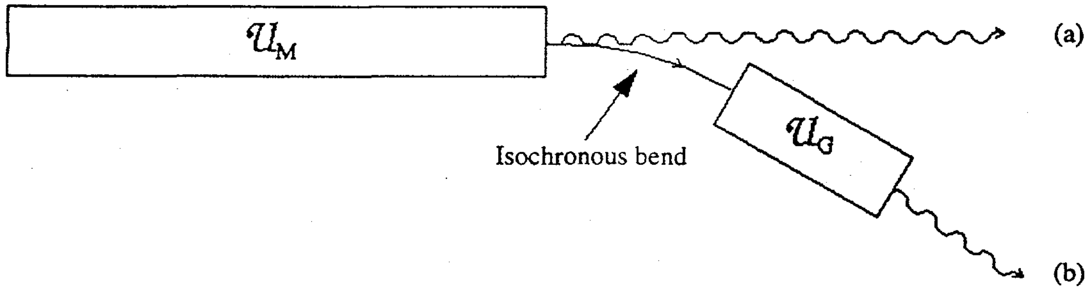


Figure 2. A buncher-radiator concept. The electron beam is bunched in the main undulator $\mathcal{U}_M$. The radiation properties at (b) are entirely determined by the short undulator $\mathcal{U}_G$.