ELECTRON SIGNAL DETECTION FOR THE BEAM-FINDER WIRE OF THE LINAC COHERENT LIGHT SOURCE UNDULATOR*

Juhao Wu†, P. Emma, R.C. Field, SLAC, Menlo Park CA 94025, USA

Abstract

The Linac Coherent Light Source (LCLS) is a SASE x-ray Free-Electron Laser (FEL) based on the final kilometer of the Stanford Linear Accelerator. The tight tolerances for positioning the electron beam close to the undulator axis calls for the introduction of Beam Finder Wire (BFW) device. A BFW device close to the upstream end of the undulator segment and a quadrupole close to the down stream end of the undulator segment will allow a beam-based undulator segment alignment. Based on the scattering of the electrons on the BFW, we can detect the electron signal in the main dump bends after the undulator to find the beam position. We propose to use a threshold Cherenkov counter for this purpose. According to the signal strength at such a Cherenkov counter, we then suggest choice of material and size for such a BFW device in the undulator.

INTRODUCTION

In order to ensure the lasing of the LINAC Coherent Light Source (LCLS) [1], the undulator has to be aligned with a tight tolerance, and the electron beam should be positioned to the undulator axis to a high precision. A Beam Finder Wire (BFW) is plan to be installed upstream of each undulator segment and fiducialized so that its horizontal and vertical wires will have a fixed and known position with respect to the undulator axis. When the BFW is to be used, the electron beam will collide with two wires (one horizontal and one vertical), one at a time. The amount of beam hitting the wire will be measured by detecting scattered particles downstream of the wire. A detecting device can be placed in the main dump line after the undulator. Such a device can be a threshold Cherenkov counter with a Photo Multiplier Tube (PMT) and a Gated Analogous Digital Converter (GADC). A schematic plot is shown in Fig. 1. Since there are 33 undulator segments, we plan to install 33 BFW labelled as BFW01 to BFW33 in the plot. The electron beam hits the BFW, and passes through the strong vertical bend dump line [BYD1(,2,3)]. We then plan to install a threshold Cherenkov counter (TCC) in the main dump line to detect the halo electrons. In the following, we report a feasibility study of such a scheme.

* Work supported by the U.S. Department of Energy under Contract No. DE-AC02-76SF00515.

† jhwu@SLAC.Stanford.EDU

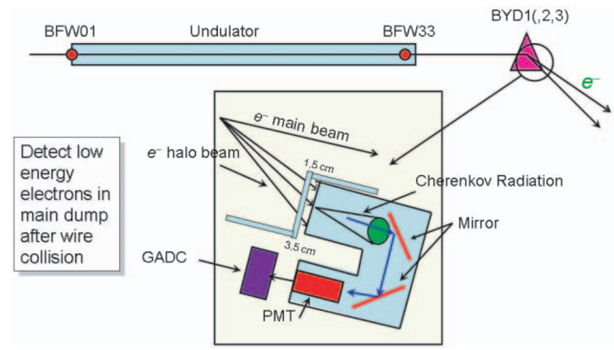

Figure 1: Layout of the threshold Cherenkov Counter in the main damp line after the undulator.

ELECTRON-WIRE SCATTERING MODEL

Number of Scattered Electrons

Assuming a square wire with a width of d and the electron beam has an rms transverse size of σ_x, the fraction η of electrons scattered by the wire parallel to the y-axis is

$$\eta = \int_{\infty}^{\infty} \int_{-d/2}^{d/2} \frac{1}{2\pi\sigma_x\sigma_y} e^{-\frac{(x-x_c)^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}} dxdy \approx 0.4 \frac{d}{\sigma_x} e^{-\frac{x_c^2}{2\sigma_x^2}}, \quad (1)$$

for $d \ll 2\sqrt{2}\sigma_x$. Similar situation can be found for the BFW parallel to the x-axis. For cylindrical wire with radius r, we can simply take $d_{\rm eff} \approx 1.8r$. For $d = 10$ μm and $\sigma_x = 35$ μm, we have $\eta \sim 10\,\%$.

Table 1: Parameters for the BFW and the electron bunch. Notations are explained in the text.

d (μm)	X_0 (cm)	σ_x (μm)	E_b (GeV)	E_1 (MeV)
10	20	35	14	1

Number of Photons

Let us now estimate the number of photons. Assuming the radiation length of the BFW is X_0, which is the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung. For Carbon wire, we have $X_0 = 20$ cm. The electron loses energy as [2]

$$\Delta E = E_b \left(1 - e^{-d/X_0}\right) \approx \frac{d}{X_0} E_b, \quad (2)$$

with E_b being the nominal electron beam energy. For 10-μm diameter round Carbon wire and $X_0 = 20$ cm, we have

$\Delta E/E_b \approx 4.5 \times 10^{-5}$. With N_e electrons, the total energy lost is $\Delta E \eta N_e$. We assume a $1/E$ spectrum, then the emitted γ-ray has an average energy of

$$\langle E_\gamma \rangle \equiv \frac{\int_{E_1}^{E_b} \frac{E}{E} dE}{\int_{E_1}^{E_b} \frac{1}{E} dE} = \frac{E_b - E_1}{\ln\left(\frac{E_b}{E_1}\right)} \approx E_b / \ln(E_b/E_1), \quad (3)$$

where E_1 is the cutoff energy. For $E_b = 14$ GeV and $E_1 = 1$ MeV, we have $\langle E_\gamma \rangle \approx 1.5$ GeV. Hence, $\langle E_\gamma \rangle / E_b \approx 10$ %. As we will find late in this paper, the exact value of the cutoff energy E_1 does not come into the final result. Hence, it is relatively arbitrary. The total number of γ-ray photons, *i.e.*, the total energy divided by mean energy per photon, is

$$N_\gamma = \frac{\Delta E \eta N_e}{\langle E_\gamma \rangle} \approx 4.4 \times 10^{-5} N_e, \quad (4)$$

where parameters are assumed same as in the previous estimates in Table 1. Since we have $d/X_0 \approx 4.5 \times 10^{-5}$, we assume single emission process. This means that the number of electrons emitting γ-ray is equal to N_γ.

ELECTRONS AT THE BREMSSTRAHLUNG WINDOW: *Elegant* SIMULATION

We use *Elegant* [3] to simulate the beam line shown in Fig. 1. The twiss parameters are shown in Fig. 2. The beam line consists of the undulator with 5-mm(vertical)×12-mm(horizontal) aperture limit, the undulator termination section, and the dump line. Since we simulate electrons with very large energy spread, the elements in the beam line are all canonical elements in the *Elegant* simulation.

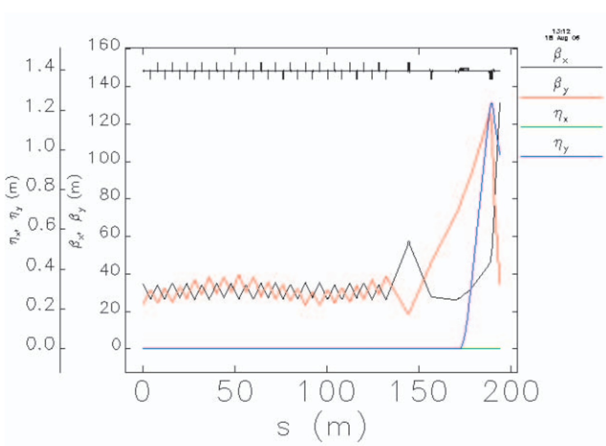

Figure 2: Twiss parameters for the undulator and the main beam dump line.

We simulate the electron-wire interaction according to the above described model. The emitted γ-ray has a spectrum of $1/E_\gamma$. Assuming single emission, the scattered electron has a spectrum of $f(E) = 1/(E_b - E_\gamma)$. The angular spread is [2]

$$\theta_0 \approx \frac{13.6\text{MeV}}{\beta c p} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \log\left(\frac{x}{X_0}\right)\right], \quad (5)$$

where p, βc are the momentum and velocity of the incident electron, and x is the thickness of the scattering medium. Because of the dispersion in the beam line and also the large energy spread, the chromatic angular spread is much large than the angular spread in Eq. (5) from the initial electron wire scattering. However, *Elegant* can simulate the scattering more precisely to include multiple scattering events.

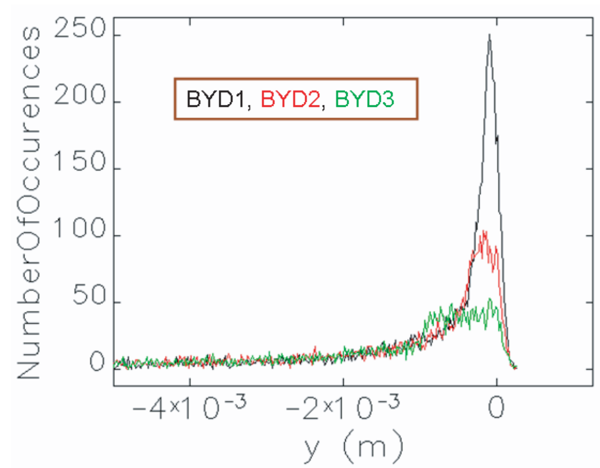

Figure 3: The histogram of the electron vertical position at BYD1, BYD2, and BYD3.

As an example, we simulate the BFW01, *i.e.*, the very first BFW in the undulator. The electron distribution is shown in Fig. 3 right after the three bending magnets [BYD1(,2,3)]. It shows that the electrons spread more in the y-direction when they travel down the beam line. We assume to put the detector right after BYD3, the last bending magnet in the dump line. At BYD3, the vertical dispersion is $\eta_y = 0.209$ m. Assuming one klystron fails, hence there is an energy drop of 235 MeV. The worse case will happen when we are running the low energy operation mode, in which at BYD3 the beam nominal energy is 4 GeV, so that one klystron failure means about $\delta = 5$ % relative energy drop. Translating this into the vertical movement, it is $\eta_y \delta \approx 1$ cm. Hence, for safety reason, we set beam stay clear distance as 1.5 cm. Therefore, as shown in Fig. 1, we expect the detector will receive halo electrons passing through the Stainless Steel thin pipe wall for an offset distance of 1.5 cm to 3.5 cm from the beam axis. Since we assume a thin wall, the cascade shower is ignored. Assuming the wall is 2 mm thick, then the detector aperture is from 1.7 cm to 3.5 cm, which corresponding to $\delta \in (8.13, 16.75)$ %. Hence the halo electrons pass this bremsstrahlung window is

$$N_d \equiv \frac{\int_{8.35\% E_b}^{16.75\% E_b} \frac{1}{E} dE}{\int_{E_1}^{E_b} \frac{1}{E} dE} N_\gamma \approx 3.6 \times 10^{-6} N_e = 2 \times 10^4, \quad (6)$$

assuming all the above parameters as in Table 1. By comparing Eqs. (3), (4), and (6), we readily find that the exact value of E_1 is irrelevant. The *Elegant* simulation gives $N_d \approx 2.5 \times 10^4$, very similar to the estimate in Eq. (6). Furthermore, the *Elegant* simulation shows that this number is almost the same for BYD1, BYD2, and BYD3.

SIGNAL STRENGTH OF THE THRESHOLD CHERENKOV COUNTER

In the visible range, the number of Cherenkov γ-ray per electron per meter track is about [4]

$$\begin{aligned} & N_{C-\gamma}(\text{per } e^- \text{per m}) \approx 5 \times 10^4 \, [\sin{(\theta_C)}]^2 \\ \approx \quad & 10^5(n + \beta - 2) \approx 10^5(n-1), \end{aligned} \tag{7}$$

where n is the refractive index of the material.

Table 2: Parameters for the threshold Cherenkov counter.

l_t (m)	$n-1$ (air)	T	Q_E	G
0.1	2.73×10^{-4}	50 %	0.15	2×10^5

Let us now describe some details and introduce notations. The track length is l_t in units of m. The Cherenkov γ-ray has a transmission rate T from birth place of the γ-ray to the PMT. The PMT has a quantum efficiency Q_E and gain G, then the charge after the PMT is

$$Q_{\text{PMT}} = eN_{C-\gamma}N_d l_t T Q_E G. \tag{8}$$

For example, if the threshold Cherenkov counter is filled with air, and assuming the track length is 0.1 m and other parameters in Table 2. We then have $Q_{\text{PMT}} = 120$ pC. We can use a typical Gated Analogous Digital Converter (GADC) such as $LRS2249W$, which has a sensitivity of $S_{\text{GADC}} = 4$ counts/pC. Hence, for the above estimated $Q_{\text{PMT}} = 120$ pC, we will have about 500 counts.

To put everything together, we have

$$\begin{aligned} C(\text{counts}) \quad = \quad & 4 \times 10^4(n-1) l_t T Q_E G S_{\text{GADC}} \\ \times \quad & \ln\left(\frac{r_o}{r_i}\right) \frac{d^2}{\sigma_x X_0} Q e^{-\frac{x_c^2}{2\sigma_x^2}}, \end{aligned} \tag{9}$$

where r_o is the distance between the far edge of the bremsstrahlung window to the beam line axis ($r_o = 3.5$ cm here); and r_i is the distance between the near edge of the bremsstrahlung window to the beam line axis ($r_i = 1.7$ cm here); and x_c is the distance between the electron bunch centroid and the BFW; and Q is the charge per bunch.

EXAMPLES

Assuming the background is 100 counts, and assume the BFW is moving with a step of 30 μm, in Fig. 4, we show the simulation results of the detected signal when the BFW scans through the electron bunch.

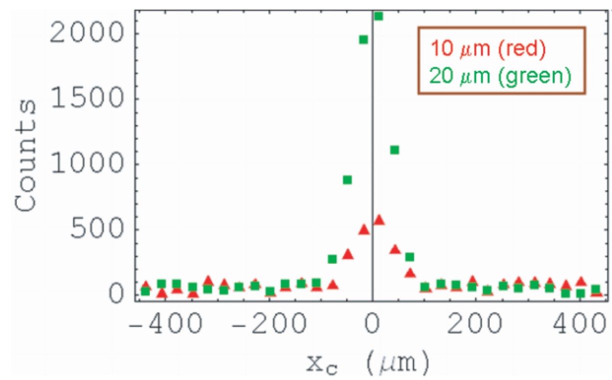

Figure 4: The signal strength for BFW with diameter of 10 μm (red) and 20 μm (green).

DISCUSSION

Based on the estimate in this paper, a Carbon BFW of $d = 10$ μm may already be sufficient. Along the undulator, the scattered electron hits the wall as shown in Fig. 5, hence they will damage the very precise magnetic field of the undulator. This calls for further detailed study. In Fig. 5, the horizontal axis is the distance along the undulator beam line, and the vertical axis is the scattered electrons remaining in the electron bunch. However, the absolute value on the vertical axis should be scaled to the real situation. Hence, we only want to indicate how much in fraction, the halo electrons get lost, and hit the undulator wall.

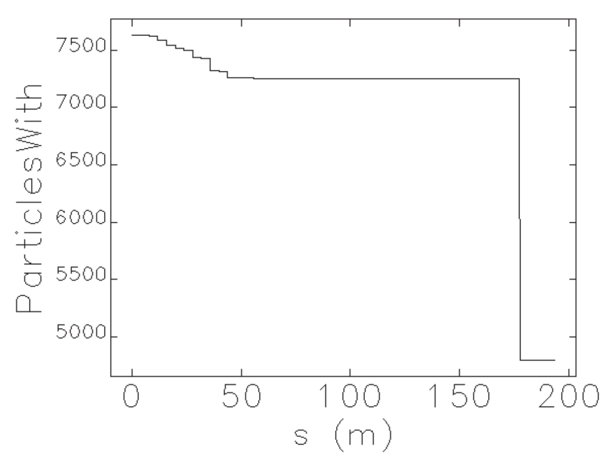

Figure 5: Halo electrons loss along the undulator.

REFERENCES

[1] J. Arthur *et al.*, SLAC-R-593, 2002.

[2] B. Rossi, High Energy Particles, (Prentice Hall, 1952).

[3] M. Borland, APS LS-287, Sep. 2000.

[4] R.M. Barnett *et al.*, Particle Physics Data Book, Phys. Rev. D **54**, 1 (1996).