ELECTRON BEAM DIAGNOSTICS USING DIFFRACTION RADIATION*

Bibo Feng†, William E. Gabella,
FEL Center, Vanderbilt University, Nashville, TN 37235, USA
Tamas R. Sashalmi, Steven E. Csorna,
Dept. of Physics, Vanderbilt University, Nashville, TN 37235, USA

Abstract

Diffraction radiation emitted from electron bunches has the potential application as a non-intercepting electron beam diagnostic. The electron longitudinal distribution in a bunch can be obtained from the coherent diffraction radiation spectrum; the transverse beam properties, such as beam size, divergence and emittance, can be measured through the analysis of the angular distribution of the coherent diffraction radiation. The design study and initial experimental results at the Vanderbilt FEL facility are presented.

INTRODUCTION

Diffraction radiation (DR) is a promising technique for electron beam diagnostic. DR technique can be developed as a low cost, compact, and non-intercepting monitor which can be very useful for free electron lasers and linear colliders. Electron bunch profile measurements have been conducted using coherent synchrotron radiation (CSR), coherent transition radiation (CTR), as well as coherent diffraction radiation (CDR)[1, 2, 3].

Diffraction Radiation is generated when a relativistic electron passes through an aperture in a metallic plate. DR intensity for N electrons can be described by

$$I_{total}(\omega) = I_1(\omega)[N + N(N-1)F(\omega)], \qquad (1)$$

where $I_1(\omega)$ is the DR intensity at frequency ω from a single electron, and $F(\omega)$ is the bunch form factor. DR, like transition radiation, is emitted in the forward direction along the electron path, and in the backward direction along the direction of specular reflection from the metal screen.

CDR has a fixed phase relative to the electron bunches, and the measurement of the coherent radiation gives the longitudinal bunch form factor $f(\omega)$, thus providing information about the longitudinal bunch distribution function $S(z)$. The electron distribution in a bunch can be obtained from the inverse Fourier transformation of the form factor. CDR is a better choice for monitoring the electron beam bunch shape as CDR perturbs the electron beam less than CTR and CSR.

The use of diffraction radiation for measuring the transverse beam dimension is a new non-invasive technique. There are a few experimental investigations at the present time [4, 5, 6] . DR intensity is proportional to the square of γ, and is distributed in angle as $1/\gamma$, where $\gamma = E_{beam}/m_e c^2$ is the normalized electron energy; thus, both the intensity and the angular distribution can be used to deduce the beam energy[7]. DR has the potential capability to diagnose multiple beam parameters such as longitudinal and transverse beam sizes, energy, position, divergence and emittance. DR technique can also be developed as a single shot measurement.

Using the DR technique, one measures the spectrum and angular distribution in the frequency domain. High spatial and time resolution are potentially possible, hence DR is able to satisfy the requirements of a linear collider facility. In addition, the angular distribution of the DR from an electron passing through a slit in a metal foil has polarization properties because of the interference effects between the two half-planes of the radiator. The polarization shows different properties with the electric field parallel and normal to the plane of the slit. The electron beam transverse dimension can be measured through the analysis of the angular distribution of the diffraction radiation.

In this paper, we present our initial results of bunch length measurements using coherent diffraction radiation from a slit. Following this introduction, we give a description of the diffraction radiation from a slit and we show the method of extracting the bunch length from the CDR interferogram in the time domain. We measured spectrum of CDR from the slit and extracted the bunch length. As an application, we investigated the effects of changing linear accelerator parameters such as phase and cathode heating on the electron bunch length.

EXPERIMENTAL SETUP AND RESULTS

DR experiments were carried out at the Vanderbilt FEL Center on a Mark III type linear accelerator. The electron beam energy is variable between 25 and 45 MeV. The electron beam macropulse duration is about 8μs, and the average beam current is about 150 mA. The pulse contains 23,000 bunches, each with approximately 50 pC and a bunch length of approximately 1 ps.

The CDR experimental setup is shown in Fig. 1. A diffraction radiator is mounted at an angle of 45° to the electron beam. The gap of the radiator is adjustable, when closed it operates as a transition radiator. DR or TR is emitted as the electron beam passes through the radiator. This radiation passes through a quartz window and is reflected by a parabolic mirror and a couple of flat mirrors into an

* Work is supported by the NSF and DOD through the MFEL program under award No. F49620-01-1-0429.

† Corresponding author. Tel.:+1-615-343-6446; fax: +1-615-343-1103. Email: bibo.feng@vanderbilt.edu

interferometer to measure the radiation spectrum. The experimental system was aligned using a HeNe laser injected upstream into the beam line.

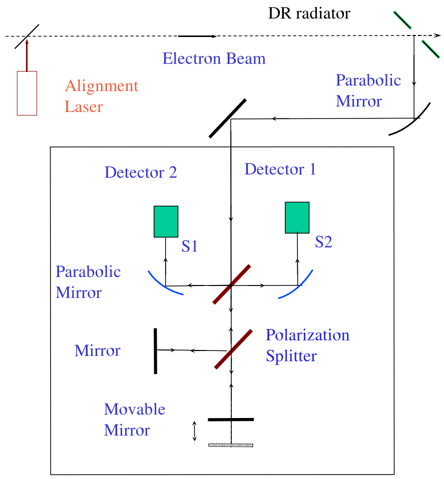

Figure 1: Schematic of the experimental setup.

The diffraction radiator consists of two separated screens and a stepping motor to adjust the width of slit. The resolution of the stepping motor is 5 μm per step. We select a polished silicon wafer as the screen because of its flatness. The thickness of screen is about 500 μm and its size is about $75 \times 50mm^2$. One of the silicon screens is mounted on an adjustable frame, so the reflection angle can be changed in order to keep both screens coplanar.

The interferometer is a wire grid Martin-Puplett type as shown in Fig. 1. The incident light is split onto orthogonal polarization components by a $45°$ tilted polarizing grid splitter. One component is reflected and focused onto a reference detector; the other is incident onto another vertical polarizing grid where the light is split into two beams, reflected by the roof mirrors, and finally recombined and focused onto a pyroelectric detector(P4-45,Molectron Inc.). Only one detector was used in this experiment because of another Golay cell detector malfunctioning. The frequency limitation of the interferometer is determined by the diffraction losses, the finite aperture of the detector and the grating constant of the wire grid. The frequency range is estimated between 2 cm^{-1} and 50 cm^{-1} (wavelengths of 5 mm to 200 μm).

A typical CDR interferogram is shown in Fig. 2. The electron beam had an energy of 25 MeV and an average macropulse current of 135 mA. It was focused and centered between the edges of the two screens. The beam size was about 2.5 mm and the slit width was set to 5 mm. The CDR spectrum is obtained by Fourier transformation of the interferogram as shown in Fig. 3. We observed relative strong power peak at the frequency of 0.13 THz (wavelength of 2.3 mm). The low frequency part of the spectrum is suppressed by the detector and the interferometer.

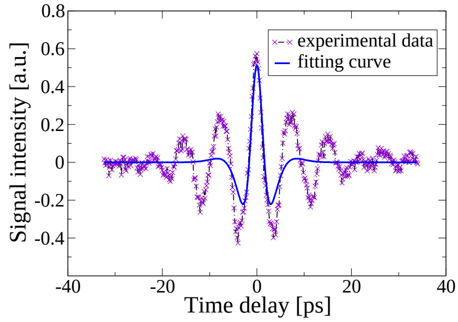

Figure 2: Typical CDR interferogram and time domain fit.

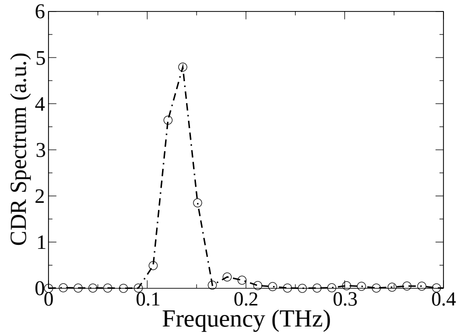

Figure 3: CDR spectrum corresponding to interferogram in Fig. 2.

A calculation of the coherent emission is shown in Eq. 1, giving the longitudinal bunch form factor $F(\omega)$ and hence providing information about the longitudinal bunch distribution function $S(z)$. Therefore, the electron distribution in a bunch can be obtained from the inverse Fourier transform of the form factor through the Kramers-Kronig relation [8].

A simpler technique to extract the electron beam bunch length from the CDR interference spectrum was introduced in reference [9]. Assuming a Gaussian longitudinal electron distribution of pulse length σ and the low frequency suppressed by the interferometer at cut-off frequency $1/\xi$, the time domain interferogram of the coherent radiation is described as

$$S(t) = e^{-\frac{t^2}{4\sigma^2}} - \frac{2\sigma e^{-\frac{t^2}{4(\sigma^2+\xi^2)}}}{\sqrt{\sigma^2+\xi^2}} + \frac{\sigma e^{-\frac{t^2}{4(\sigma^2+2\xi^2)}}}{\sqrt{\sigma^2+2\xi^2}}. \quad (2)$$

The bunch length σ can be obtained by fitting this two parameter formula to the time-domain interferogram. For example, a fit is shown in Fig. 2,which gives the electron bunch length $\sigma \simeq 0.87$ ps.

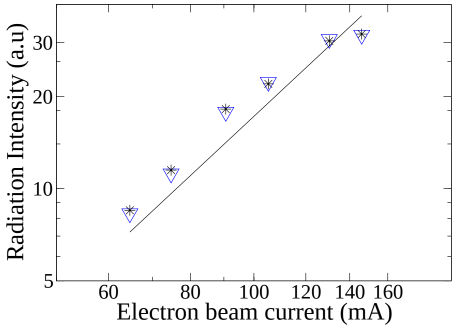

Figure 4: Dependence of CDR intensity on the electron beam current. Two measurement sets as symbols; solid line is $0.016I^2$, a fit to aI^2.

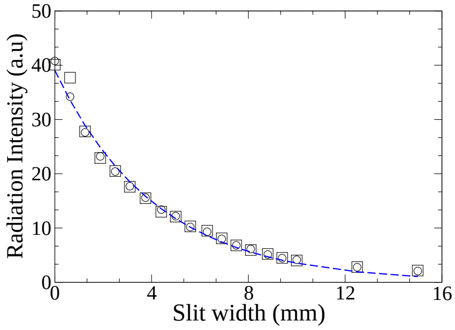

Figure 5: Dependence of CDR intensity on the slit width.

The experiment confirms that the CDR intensity is proportional to the square of the beam current (Fig.4). CDR is emitted from the slit with width of 5 mm, and using an electron beam size of 2.5 mm and energy of 39 MeV. As shown in the figure, the intensity is approximately proportional to the square of the beam current and therefore to the square of the electron number N in a bunch.

The dependence of the intensity on the slit width is shown in Fig.5. The electron beam has an energy of 29 MeV and a current of 154 mA. It has a diameter of 2.5 mm and it passes through the center of the slit. The CDR intensity decreases exponentially with increasing slit width.

The electron bunch length is affected by many parameters in the injection section and in the accelerator, including cathode heat, alpha magnet current, and accelerator phase. We observed the bunch length change while tuning these parameters. The accelerator was operating at 30 MeV, and the electron beam current was about 130 mA. The cathode needs to run within a certain temperature range to provide high current emission density and to keep the final electron beam current constant. Cathode heating in a RF gun affects the FEL efficiency. Fig. 6 shows the electron bunch length change while changing the cathode heat.

Alpha magnet strength is another important parameter for controlling the electron bunch length and optimizing a free electron laser. The alpha magnet acts both as both a momentum filter and a bunch compressor for the electron beam. Changing magnet strength selects a different energy partition of the electron beam. Fig.7 shows the dependence of electron bunch length on alpha magnet current. Electron beam bunch length decreases with respect to increasing alpha magnet current.

Changing the RF phase between the gun and the accelerator, we also observed the bunch length change. By increasing RF phase, the bunch length becomes longer as shown in Fig. 8.

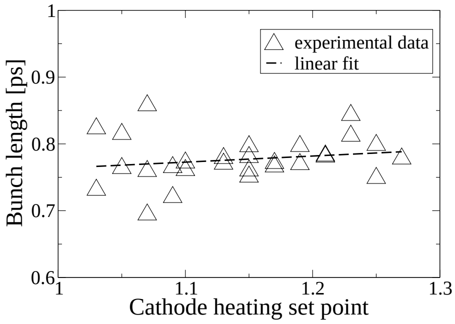

Figure 6: Bunch length vs. RF gun heating.

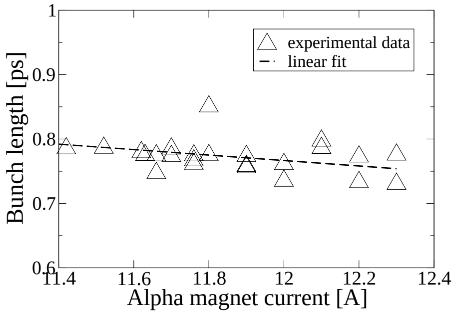

Figure 7: Dependence of electron bunch length on alpha magnet current.

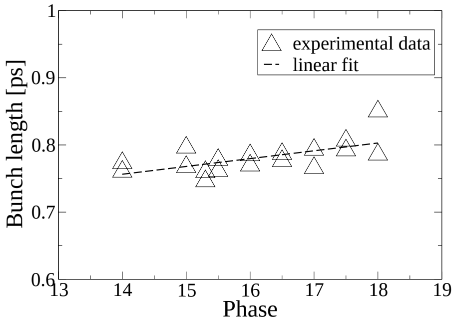

Figure 8: Dependence of electron bunch length on RF phase.

CONCLUSION

As a first stage of electron beam diagnostics using diffraction radiation, we have measured coherent DR spectrum from a slit of silicon wafer screens, and extracted the bunch length from the interferogram. We applied this diagnostic technique to the parameter study at Vanderbilt FEL linac.

We are planning to measure the electron beam transverse dimensions through the analysis of the angular distribution of incoherent DR. The total intensity of angular distribution in the normal plane has a minimum value when the beam passes through the center of slit. In practice, this property can be used to center the electron beam in the slit, and it may be a useful tool with which a cavity BPM can be centered on the beam. In order to get more accurate angular information, we plan to place two parallel slits to generate DR. The forward radiation from the first slit interferes coherently with the backward radiation from the second. Analyzing the whole angular distribution in the normal plane and fitting it to the theoretical prediction will allow us to determine the transverse dimension, the energy and emittance of the electron beam.

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