Non-intercepting electron beam diagnostics using diffraction radiation

Personnel and Institution(s) requesting funding

B. Feng, W. E. Gabella, W. M. Keck Foundation Free-Electron Laser Center, and S. Csorna, Department of Physics and Astronomy, Vanderbilt University

Project Leader

Bibo Feng
bibo.feng@vanderbilt.edu
(615)-343-6446

Project Overview

The Linear Collider presents new challenges for beam instrumentation. Some of the beam dimensions are of the order of a few nm (at the i.p.), and to be able to reach these small sizes, the beams have to be tightly controlled and understood from their very inception onward. A number of different techniques are available in the arsenal of beam size and beam emittance measurements (e.g. transition radiation, metal wire, laser wire, laser interferometry, cavity BPM). Experiments of 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, 7]. Because the CDR perturbs the electron beam less than CTR, it is a better choice for monitoring the electron beam bunch shape. The use of diffraction radiation (DR) for measuring the transverse beam dimension is a new non-invasive technique, only partially investigated at the present time [4, 5]; for example transverse beam size and emittance measurements have not been performed even though it is apparently possible to make precision measurements of bunch length, emittance at low energies, and the transverse size. (A recent experiment at KEK, by a Japan-Russia collaboration, has presented vertical beam size measurements using optical diffraction radiation[9].

This collaborative effort involving physicists and facilities from Cornell and Vanderbilt is aimed toward a comprehensive investigation of the potential use of DR over the broad spectrum of energies to be found at the Linear Collider. A graduate student, Tamas Sashalmi, at Vanderbilt University has started on this project. He does his doctoral dissertation on this topic and we anticipated he will be done in about two years.

Diffraction radiation is emitted from relativistic electron bunches passing through an aperture in a metal screen. The simplest aperture is a circular hole or a slit. The DR, like the transition radiation, is in the forward direction along the electron path, and in the backward direction along the direction of specular reflection from the the metal screen. The DR intensity is proportional to the square of γ, and it is distributed in angle as $1/\gamma$, where γ is the electron energy factor ($E_{beam}/m_e c^2$); thus, both the intensity and the angular distribution can be used to deduce the beam energy [6]. The DR technique can be developed as a low cost, compact, and non-intercepting monitor which can be very useful for each element of the Linear Collider, starting with the injection linac, the damping rings and the main linac. DR has the potential capability to diagnose multiple beam parameters such as longitudinal and transverse beam sizes, energy, position, divergence and emittance. The DR technique also can be developed as a single shot measurement. As the DR technique measures the spectrum and angular distribution in the frequency domain, it has very high spatial and time resolution, and it is easy to satisfy the requirements of the Linear Collider facility. The goal in spatial resolution in this proposal is less than 1 μm in the longitudinal and transverse beam size measurement. From the analysis of measured data, the error on bunch length is estimated to be of the order of about 20%.

The coherent properties are included in the DR spectrum in which the radiation wavelength is nearly equal to the beam bunch length. In the case of the LC, 100 μm bunch lengths would produce radiation in the 0.1 mm wavelength region. The CDR has a fixed phase relative to the electron bunches, and the measurement of the coherent radiation gives the longitudinal bunch form factor $f(\omega)$ and hence provides information about the longitudinal bunch distribution function $S(z)$. Therefore, the electron distribution in a bunch can be obtained from the inverse Fourier transformation of the form factor. 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 electron beam transverse dimension can be measured through the analysis of the angular distribution of the diffraction radiation [4, 5].

Broader Impact

The budget for this project is mostly for a graduate student and two summers of undergraduate help. The graduate student has been invaluable in motivating experiments and data analysis. He is also being trained as an accelerator physicist with talents needed by many existing and planned particle beam machines. Vanderbilt University has a joint physics and astronomy training program with Fisk University, an historically black college. It is part of the plan to be more active in this collaboration and hire undergraduates from Fisk for summer work.

Results of Prior Research

The UCLC collaboration and NSF have kindly supported this effort over the last two years. First with seed money and most recently with a year of salary for a shared graduate student in the study of coherent diffraction radiation electron diagnostics. This and other linear collider efforts receive broad support from the FEL Center director Dr. David Piston, in the form of support staff, vacuum hardware, and other materials and supplies.

Seed Money for Non-Intercepting Electron Beam Diagnostics
Award: NSF PHY-0303702
Award period: September 15, 2003 to August 31, 2004
Award amount: $11,020

This was awarded by the NSF for UCLC work and is administered as a sub-contract with Cornell University. The money was used to purchase a Golay cell detector(QMC Instru. Ltd, Model OAD-7). The detector was received in July 2004 and is planned to measure the coherent diffraction radiation in the Center. The grant also paid for the very valuable trips to the 2004 Beam Instrumentation Workshop and the 2004 Free Electron Lasers Conference, where we published our initial experiment results [7]. It was very helpful to see the state of the international research.

Non-Intercepting Electron Beam Diagnostics
Award: NSF PHY-0355182
Award period: September 1, 2004 to August 31, 2005
Award amount: $9,040

This is also an award by the NSF for UCLC work and is administered as a sub-contract with Cornell University. The money is being used to pay a graduate student. He is shared with Dr. W.E. Gabella and is working on electro-optic and diffraction radiation diagnostics.

Recently, we have accomplished several of our research tasks. We designed and built a DR radiator, modified a Martin-Puplett type interferometer, and carried out preliminary electron bunch length measurements using coherent diffraction radiation from a slit. As an application, we investigated the effects of changing linear accelerator parameters such as phase and cathode heating on the electron bunch length. The research results were published on the 26th International Free Electron Laser Conference [7].

The CDR 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 diffraction radiator is mounted at an angle of 45° to the electron beam. 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 $75 \times 50 mm^2$. 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 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 interferometer to measure the radiation spectrum. The experimental system was aligned using a HeNe laser injected upstream into the beam line.

The interferometer is a wire grid Martin-Puplett type. 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.). A second Golay cell detector (ODA-7, QMC Instrument ltd) was purchased but is not currently functioning; it will be repaired and tested. 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. 1. 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 transverse 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. 2. 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.

A simpler technique to extract the electron beam bunch length from the CDR interference spectrum was introduced in reference [8]. 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

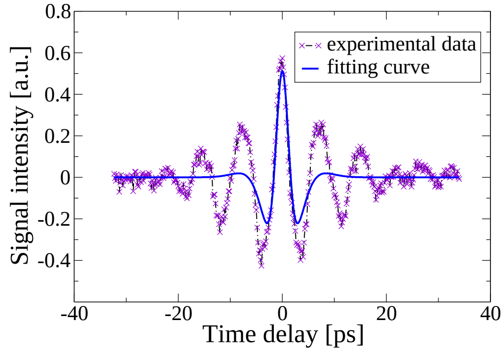

Figure 1: Typical CDR interferogram and time domain fit.

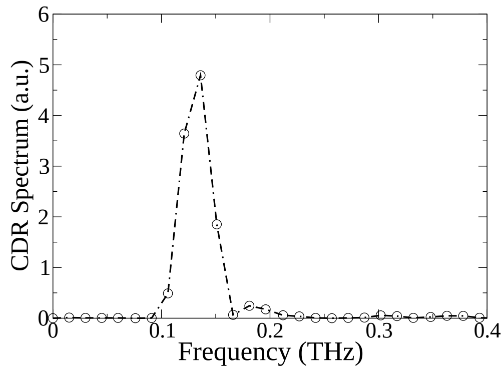

Figure 2: CDR spectrum corresponding to interferogram in Fig. 1.

$$S(t) = e^{-\frac{t^2}{4\sigma^2}} - \frac{2\sigma e^{-\frac{t^2}{4(\sigma^2+\xi^2)}}}{\sqrt{\sigma^2+\xi^2}} + \frac{\sigma e^{-\frac{t^2}{4(\sigma^2+2\xi^2)}}}{\sqrt{\sigma^2+2\xi^2}}. \qquad (1)$$

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. 1,which gives the electron bunch length $\sigma \simeq 0.87$ ps.

Facilities, Equipment and Other Resources

We propose the measurement of the coherent DR spectrum from a slit in a metal foil. The longitudinal profile will be evaluated from the fast Fourier transform of the autocorrelation function and the use of the minimal phase approximation. The results will be compared to that of intercepting CTR (Coherent Transition Radiation) and non-intercepting electro-optic measurement experiments conducted in the same environment.

In addition, we propose to measure the electron beam transverse dimension through the analysis of the angular distribution of DR. A simple CCD camera can measure the angular polarization of DR. The total intensity of angular distribution 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.

It should be noted that much more accurate angular information of DR can be obtained by placing two slits. We also propose to measure interference from the forward radiation off one slit as it interferes coherently with the backward radiation from the other. Analyzing the whole angular distribution in the normal plane and fitting it to the theoretical prediction allows us to determine the transverse dimension of electron beams, beam energy and emittance.

The bulk of the design and construction of the apparatus will be done at the Vanderbilt FEL Center, where there are available experienced scientists, mechanical and design engineers and where, importantly, a minimum of eight hours of beam time per week will be made available to this project. The undergraduate and graduate students at Vanderbilt University will also join to accomplish this project.

FY2005 Project Activities and Deliverables

In the first year, We will design and build a radiator as well as its housing chamber for the experiments. The two pieces of thin metal foils or aluminum coated silicon plates can be used as the radiator. The slit of the radiator should be moved to intercept the electron beam by an actuator. The slit width will be adjusted by moving the two half foils in the same plane. It emits transition radiation when the slit is closed, thereby allowing us to directly compare the results from DR and TR techniques.

We will also measure the DR angular distribution from the radiator to yield the beam transverse dimension according to the angular distribution theoretical calculation. We will measure the interference image from two DR screens with slits to obtain more detail information of the angular distribution of DR, and derive the electron beam properties such as beam transverse size, beam energy and beam angular spread.

The first year deliverables will be a DR radiator,a technical report describing the coherent DR and incoherent DR experimental results at Vanderbilt.

FY2006 Project Activities and Deliverables

During in the second year, we will carry out the beam property experiments using coherent DR and incoherent DR at the Cornell accelerator facility with higher electron beam energy. The device for measuring the angular distribution will be designed and built for accommodating different wavelengths and radiation bandwidths corresponding to different beam energy and slit width of the radiator.

The third year deliverables will be a technical report describing the coherent DR and incoherent DR experimental results at Cornell accelerator facility.

Budget justification

We expect that this year will be primarily devoted to studying the properties of the DR under varying beam conditions at Vanderbilt. The graduate student will have the primary responsibility for scheduling runs, acquiring data and doing a significant portion of the data analysis.

We expect that the second year will be primarily devoted to studying the properties of the DR under varying beam conditions at Cornell and Vanderbilt. Low energy running (50 MeV) can be efficiently performed at Vanderbilt, high energy running will be at Cornell (CESR). The graduate student will have the primary responsibility for scheduling runs, acquiring data and doing a significant portion of the data analysis.

A minimal amount of travel funds is included to cover collaboration meetings. We expect that on the basis of what we learn during this year, we will need to buy additional specialized equipment and electronics.

Two-year budget, in then-year K$

Institution: Vanderbilt University (Indirect costs are calculated at 52% rate for the first year and at 53% rate for the second year on total salaries, fringe benefits,travel, and materials and suplies)

Item	FY2005	FY2006	Total
Other Professionals	0	0	0
Graduate Students	20.5	21.2	41.7
Undergraduate Students	2.6	2.7	5.3
Total Salaries and Wages	23.1	23.9	47
Fringe Benefits	1.6	1.6	3.2
Total Salaries, Wages and Fringe Benefits	24.7	25.5	50.2
Optics Calib. System	8	0	8
CCD Camera System	0	7	7
Total Equipment	8	7	15
Tuition	6	6	12
Travel	4	4	8
Materials and Supplies	2	3	5
Other direct costs	0	0	0
Total direct costs	44.7	45.5	90.2
Indirect costs	15.9	17.2	33.2
Total direct and indirect costs	60.6	62.7	123.4

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