NONDESTRUCTIVE BUNCH LENGTH MEASUREMENT WITH COHERENT DIFFRACTION RADIATION

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Abstract

This paper presents the observation and use of coherent diffraction radiation generated by a 26 MeV beam of femtosecond electron bunches at the SUNSHINE (Stanford UNiversity Short INtense Electron source). The radiation is used to measure the bunch length in an autocorrelation technique. This bunch length measurement using coherent diffraction radiation has the great advantage of being nondestructive. Data analysis and limitations of the technique will be discussed.

1 INTRODUCTION

Diffraction radiation (DR) is emitted when a charged particle travels in the neighborhood of some inhomogeneity. The theory of DR was developed in the late 1950's [1,2], examining charged particles passing through simple structures including circular apertures and slits. In 1995, the first observation of coherent DR generated from a 150 MeV beam passing through a circular opening or iris was reported [3]. The experiment was set to observe the forward DR and used a mirror to deflect the diffraction radiation to the observer. The mirror was in the path of the electron beam and acted as a radiator of transition radiation (TR). The observed radiation was then the superposition of DR and TR.

In our experiments, we use backward radiation to avoid this superposition. The backward DR from a circular opening can be observed by rotating the iris 45° with respect to the beam trajectory. Since the perturbation by the radiation generation to the electron beam is relatively small, it is then possible to generate diffraction radiation at several experimental stations as the beam is travelling along the beam line. This also makes coherent DR of great interest for nondestructive bunch length measurements using the autocorrelation technique.

2 DR FROM A CIRCULAR APERTURE

The radiation intensity emitted from an electron moving with velocity $\mathbf{v}$ passing through a circular aperture radius r in an ideal conducting screen can be expressed as [1-3]

$$I_{DR}(\omega) = I_{TR}(\omega)\, D(\omega)\,, \qquad (1)$$

where $I_{TR}(\omega)$ is the spectral intensity of TR and $D(\omega)$ is the correction for DR.

$$D(\omega) = \left[\mathrm{J}_0\left(\frac{\omega r}{c}\sin\theta\right)\left(\frac{\omega r}{c\beta\gamma}\right)\mathrm{K}_1\left(\frac{\omega r}{c\beta\gamma}\right)\right]^2 . \qquad (2)$$

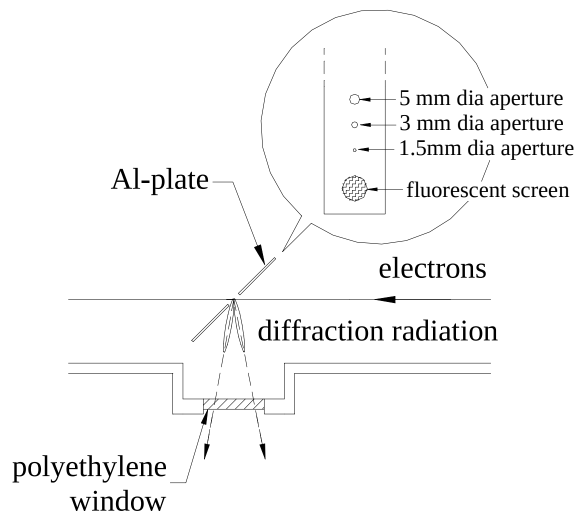

Figure 1: Schematic diagram of the setup to generate diffraction radiation. The target can be moved in the direction normal to the plane of the figure to select different apertures.

Here, θ is the observation angle with respect to the beam axis, $\boldsymbol{\beta} = \mathbf{v}/c$, γ is the Lorentz factor, J_0 is the Bessel function of the zeroth order and K_1 is the modified Bessel function of the first order. For backward DR, the angle θ is the angle between the radiation direction and $-\mathbf{v}$. The radiated intensity approaches that of the TR when the aperture radius decreases $(r \to 0)$.

3 COHERENT RADIATION

At wavelengths longer than or comparable to the bunch length, the radiation generated from the electron bunch is coherent. The coherent radiation intensity is proportional to the square of the number of electrons in the bunch and the radiation spectrum includes information of the particle distribution [4]. Reference [5] describes the generation of coherent synchrotron radiation and coherent transition radiation from femtosecond electron bunches at SUNSHINE.

4 EXPERIMENTAL SETUP

In this experiment, the DR is generated by a 26 MeV electron beam moving past a circular aperture in a 1.5 mm thick aluminum plate. The schematic diagram of the setup is illustrated in Fig. 1. Three aperture sizes, 1.5 mm, 3 mm

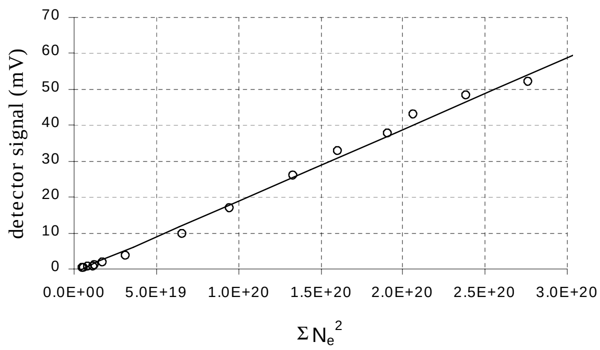

Figure 2: Diffraction Radiation intensity as a function of the sum of the number of electrons per bunch squared (the solid line represents a linear fit).

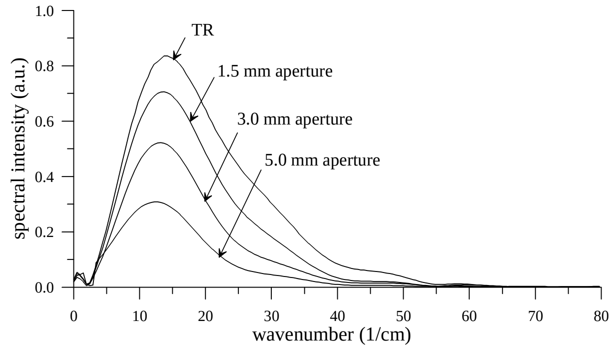

Figure 3: Spectral distribution of coherent transition radiation and coherent diffraction radiation generated at SUNSHINE.

and 5 mm in diameter, are available. The aperture size can be selected by moving the plate vertically to center the selected aperture on the beam trajectory. The Al-plate is tilted by 45° with respect to the beam path and the backward DR, emitted at 90°, exits through a 19-mm-diameter and 1.25-mm-thick polyethylene window. Also available on the Al-plate is a fluorescent screen which can be selected to monitor the beam position. The beam pro le is observed through a CCD camera (not being shown in the diagram) located on the opposite side of the polyethylene window. The beam is adjusted to pass through to the center of the screen by upstream steering magnets.

5 COHERENT DR INTENSITY

The intensity of coherent DR is expected to scale with the square of the number of electrons. To verify the coherence of DR, we measure the radiation intensity as a function of beam current. The DR is generated using the 5-mm-diameter aperture which is the largest one available in the setup. The beam current is measured through the current monitor located after the DR experimental station. By closing the high energy slit in the alpha-magnet to scrape off some electrons, the beam current can be varied. The sum of the number of electrons per bunch squared $\sum N_e^2$ is then evaluated [5]. The result is shown in Fig. 2 in which the radiation intensity scaling with $\sum N_e^2$ con rms the coherence of the DR.

6 COHERENT DR SPECTRUM

The spectral distribution of coherent DR generated by a 26 MeV beam at SUNSHINE is measured with a Michelson interferometer and is shown in Fig. 3. The backward DR is generated by the 1.5 mm, 3.0 mm, and 5.0 mm diameter apertures on an Al-plate while the backward TR is generated by the vacuum-aluminum interface. The low frequency suppression in the spectrum is due to thin lm interference effect in the 25-μm Kapton beam splitter [6]. The high frequency suppression is caused by the diffraction radiation spectral distribution expressed in (2) and becomes more severe as the aperture size increases.

7 BUNCH LENGTH MEASUREMENT USING COHERENT DR

The autocorrelation bunch length measurement technique retrieves frequency information of the bunch from the spectrum of coherent TR [7]. The coherent DR generated by the electron bunch also carries such frequency information. Moreover, generation of coherent DR can be done in a non-destructive way.

The spectral distribution of DR, however, has a frequency dependence. As shown in (1), the spectral distribution of DR from a circular aperture depends on the aperture sizes and beam energy. To use coherent DR in an autocorrelation bunch length measurement, we must consider this frequency dependence carefully.

In general, suppression of high frequency components of the coherent radiation results in a broader interferogram which leads to a seemingly longer bunchlength. To investigate the lengthening of measured bunch lengths in the autocorrelation technique based on coherent DR, we measure the bunch length using coherent DR generated in the experimental setup shown in Fig. 1. Interferograms have been taken with a Michelson interferometer in ambient air equipped with a 25.4-μm-Kapton beam splitter. Interferograms obtained from the radiation generated are shown in Fig. 4. displaying the lengthening of the apparent bunch length as the aperture size increases. The bunch length measured by TR is the most precise among all measurements since all the high frequency components are preserved. The theoretical value of the FWHM for each measurement can be estimated,

The effects of the DR spectral distribution on the interferograms can be demonstrated theoretically by simulations [6]. We apply the DR spectral distribution to the power spectrum of a known bunch distribution and use inverse Fourier transformation to retrieve a simulated in-

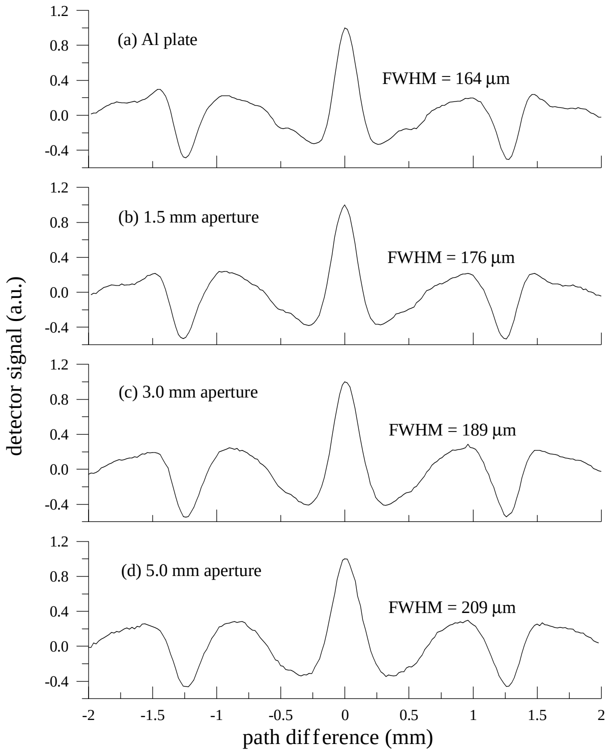

Figure 4: Interferograms of (a) coherent TR generated from Al-plate; and of coherent DR from (b) 1.5 mm, (c) 3.0 mm, and (d) 5.0 mm apertures on the Al-plate.

Radiation source	Measured FWHM (μm)	Theoretical FWHM (μm)
TR: 0 mm aperture	164	164
DR: 1.5 mm aperture	176	179
DR: 3.0 mm aperture	189	194
DR: 5.0 mm aperture	209	219

Table 1: Measured FWHM and theoretical estimate of FWHM for autocorrelation bunch length measurements with coherent transition radiation and coherent diifraction radiation.

terferogram of the coherent DR. Theoretical estimates of FWHM are shown in Table 1 along with the measured values. Although the angular spectral distribution of DR used in the model is valid for an in nitely thin beam passing through the center of a circular aperture, the theoretical and measured FWHMs show good agreement. The measured FWHM increases with a slower rate because some electrons in a nite beam width appear closer to the metallic boundary than the aperture radius thus reducing the high frequency suppression.

It has been shown that the accuracy of the autocorrelation bunch length measurement based on coherent DR depends greatly on preservation of high frequency components in the radiation spectrum. The spectral distribution

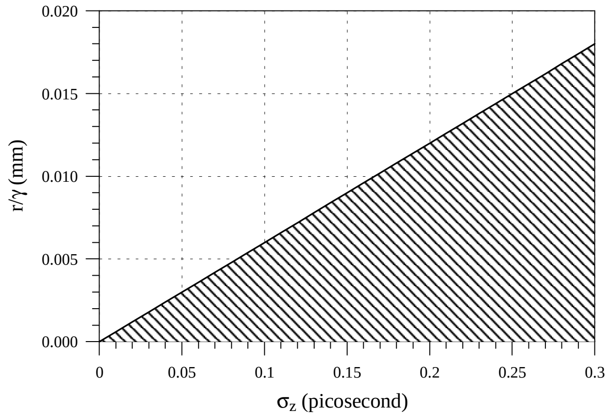

Figure 5: Bunch length σ_z, aperture radius r and beam energy γ in the autocorrelation bunch length measurement based on the coherent DR. On the curve, a measurement results in a measured bunch length with 5% longer than the measurement taken by the coherent TR.

of DR, determined by aperture sizes and beam energy, must be taken into account for the bunch length measurement.

Figure 5 shows a guideline to select the aperture radius r suitable for the beam energy in terms of γ and the bunch length in terms of σ_z. Simulations show that in the shade area, the error in the bunch length measurement by autocorrelation of coherent DR is $\leqslant +5\%$. Measurements aiming for higher accuracy should stay below the curve as much as possible. It is recommended that the bunch length is rst measured using coherent TR to calibrate the coherent DR bunch length measurement system.

8 ACKNOWLEDGEMENT

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