DIAGNOSTICS OF SUB-PICOSECOND ELECTRON PULSE BY THE FLUCTUATION METHOD

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Abstract

Simulations and experiments of subpico- and picosecond electron pulse diagnostics by the fluctuation method were performed at Nuclear Engineering Research Laboratory (NERL), University of Tokyo. The method is based on the observation of the shot-driven-noise fluctuations of incoherent radiation and was proposed by M. Zolotorev et al. [1]. Here we focus our consideration on the influence of the transverse beam size upon the measurement of fluctuations. Two-dimension numerical analysis has been done and compared with the experimental results on the power fluctuation of incoherent Cherenkov radiation. Consequently, the suppression of the fluctuation caused by the finite transverse beam dimension is observed both in the numerical analysis and the experiment.

1 INTRODUCTION

Diagnostics of the ultrashort pulse is of great importance in advanced accelerator science and technologies. At NERL, the femtosecond streak camera has been the most reliable tool for the diagnostics so far [2-4]. However the ultrafast pulseradiolysis [5] and plasma cathode experiments [6-8], which are under development, require the new pulse diagnostic techniques, since the pulse duration that is necessary for their experiments is shorter than the time resolution of the streak camera. Therefore we have developed the diagnostic system making use of the coherent transition/diffraction radiations (CTR/CDR) emitted at the wavelengths longer than the bunch length [6,7]. It has been recently proposed that longitudinal properties of an electron pulse can be obtained through measurements of the fluctuation of incoherent radiation [1,9] and then achieved by using of spontaneous emission from undulator at the Accelerator Test Facility at Brookhaven National Laboratory (ATF/BNL) [10] and Argonne National Laboratory (ANL) [11]. In the paper, the measurement of power fluctuations of Cherenkov radiation from the picosecond electron pulse was performed, where the discrepancy between the fluctuation method and the streak camera was found. Then we introduced 2D simulation in order to evaluate the influence of transverse beam size on the discrepancy.

2 THEORY AND 1D-SIMULATION

The fluctuations in both the time domain and the frequency domain allow us to obtain the longitudinal bunch length. In case of the measurements in the time domain, by using the band pass filter (BPF) with bandwidth $\Delta\omega$, the incoherent radiation has coherence time τ_{coh},

$$\tau_{coh} \propto 1/\Delta\omega. \quad (1)$$

The pulse consists of N independent coherent parts as shown in Fig. 1. N can be described as follows,

$$N = \tau_b / \tau_{coh}, \quad (2)$$

where τ_b is bunch length with full width half maximum. In the experiment, the detector measures the time-integrated intensity of incoherent radiation as,

$$I = \int |E(t)|^2 \, dt, \quad (3)$$

where $E(t)$ is the electric field of radiation. Since each coherent part has random amplitude and phase, the value of the Eq. (3) would show fluctuations from one pulse to another with the relative variation of the order of $N^{-1/2}$. The pulse-to-pulse fluctuation σ can be expressed as,

$$\sigma[\%] = 1/\sqrt{N} \propto 1/\sqrt{\tau_b \Delta\omega} \quad (4)$$

Making use of a certain band pass filter, the bunch length τ_b is acquired.

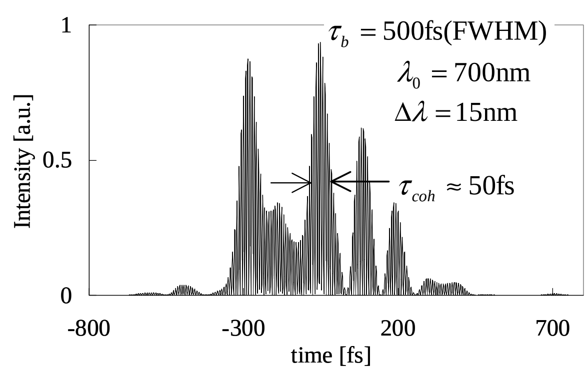

Fig. 1 Intensity of radiation through the BPF

In case of the frequency domain measurement, the pulse length can be deduced by a single shot from the spike width of the spectrum of incoherent radiation $\delta\omega$ by,

$$\tau_b = 1/\delta\omega. \quad (5)$$

Figure 2 shows the simulation result of the power spectrum of incoherent radiation. Equation (5) indicates that the width of the spike become wider as the pulse length is shorter, it follows that shorter pulse is easier to perform the measurement. Fourier transform of the power spectrum gives the correlation function, which can be defined as Eq. (6),

$$\Gamma(\tau) = \int_{-\infty}^{\infty} E(t)E^*(t-\tau)dt. \qquad (6)$$

Finally, from the dispersion of the correlation function, the longitudinal bunch distribution can be acquired as follows,

$$d_\Gamma(\tau) = \left\langle \left| \Gamma(\tau) - \langle \Gamma(\tau) \rangle \right|^2 \right\rangle$$
$$= \int_{-\infty}^{\infty} |K(\xi)|^2 d\xi \times \int_{-\infty}^{\infty} dt I(t) I(t-\tau), \qquad (7)$$

where the angular brackets denote the ensemble average. Only the averaged beam distribution can be obtained as the convolution of the radiation intensity by Eq. (7). It should be noticed that the infinitesimal diameter of beam is assumed throughout the above theory.

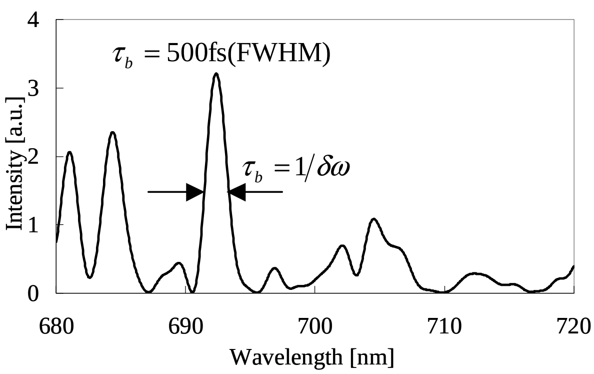

Fig. 2 Power spectrum of incoherent radiation

We have performed computer simulation of the pulse measurements based on the fluctuation method. In case of time region measurements, the code simulates the incoherent radiation with Eq. (8) is,

$$E(t) = \sum_{k=1}^{N_e} e(t - t_k) \quad , \qquad (8)$$

where N_e is the number of radiation sources, t_k the time of arrival of the *k*th particle at the observation point, and $e(t)$ electric field from one radiation source as in Eq.(9),

$$e(t) = \mathrm{Re}\left[\int e(\omega)\exp(i\omega t)d\omega\right], \qquad (9)$$

where $e(\omega)$ is decided by the transmittance of BPF, and assumed to have Gaussian distribution. It is assumed that the distribution of radiation sources has Gaussian distribution, and the average intensity of incoherent radiation is given by Eq. (10) as,

$$I(t) = I_0 \exp\left(-\ln 2 \frac{t^2}{\tau_b/2}\right) \quad . \qquad (10)$$

The result is shown with $N_e = 500$ in Fig. 1.

In case of the frequency region, the code generates the Fourier component of the electric field with Eq. (11),

$$E(\omega) = e(\omega)\sum_{k=1}^{N_e} \exp(i\omega t_k). \qquad (11)$$

We assume a standard spectrometer with dispersion of about 2.3nm/mm and a CCD with 1100 channels of about 24 micrometers.

3 EXPERIMENT

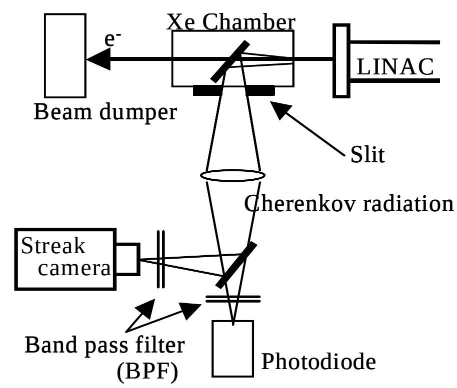

Fig. 3 experimental setup

The experimental setup is illustrated in Fig. 3. Cherenkov radiation emitted by the electron bunch in the Xe chamber was introduced to the photodiode and the streak camera through the band pass filter (BPF). The photodiode detects the time-integrated intensity of the Cherenkov radiation as stated in the theory, and the shot-by-shot fluctuations are evaluated. Time-variation of the electron beam intensity detected by the photodiode is automatically compensated by use of the Faraday cup. The fluctuations measured as a function of the bandwidth are shown in Fig. 4.

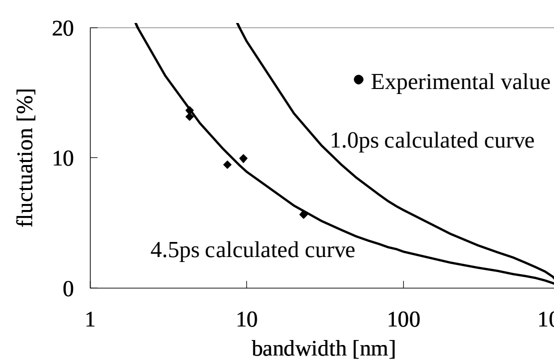

Fig. 4 experimental result

By fitting the experimental data with the calculated value from Eq. (4), the bunch length by the fluctuation method was estimated to be 4.5 ps, whereas the bunch length measured independently by the streak camera was 1.0 ps.

The main source of this discrepancy can be understood to be the influence of a large transverse size of the electron bunch. It is assumed throughout the theory that electron pulse has an infinitesimal diameter. From the experiment, we concluded that the spatial effect was not negligible in our experiment.

4 2D-SIMULATION

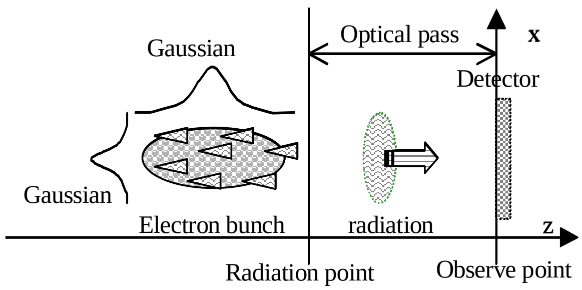

Fig. 5 Two-dimensional calculation model

To take into consideration the transverse spatial effect in calculation, the simulation code was upgraded to 2-dimensional one. The transverse distribution of electron is assumed to be Gaussian. The radiation from each source spreads spatially. The radiation intensity has spatial distribution on the detector. Figure 5 shows the numerical model. The calculation was performed by using Eq. (12).

$$E(t,x)=\sum_{k=1}^{N_e}\mathrm{Re}\left[\int e(\omega)\exp^{i\omega\left(t-t_k-\frac{x-l_k}{c}\right)}\right], \qquad (12)$$

where, l_k is the length decided by the transverse electron position. Electric field of radiation is given as the function of x on the detector. The transverse profile of time integrated intensity of radiation is calculated and shown in Fig. 6.

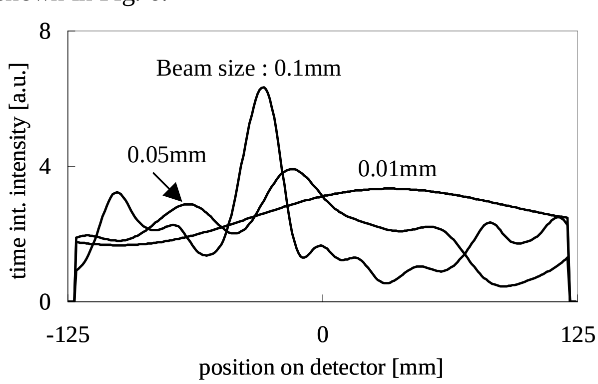

Fig. 6. transverse profile of time integrated intensity

The profiles of three different bunch sizes are shown. The number of the transverse modes [10] increases as the transverse bunch size increases. Practically, only averaged signal on the detector can be acquired. It means that the increase of the number of mode bring about the suppression of the power fluctuation. The 2D-simulation of fluctuation as a function of the band width is performed and shown in Fig. 7. It is shown that the fluctuation is suppressed as the transverse bunch size becomes larger, as expected.

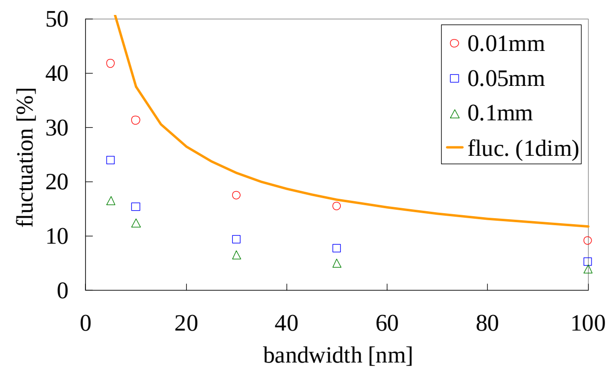

Fig. 7 Simulation results of 2-dimensional fluctuations

5 SUMMARY

The measurement of 1.0 ps electron pulses by the fluctuation method and the comparison with the streak camera have been done. There was a discrepancy of a few-ps between the two methods. We concluded that the influence of the transverse beam size upon the fluctuation has to be taken into consideration. Then the suppression of power fluctuation due to the transverse beam size was presented by introducing 2D simulation.

To achieve the quantitative comparison between calculation and experimental results and improve our analysis, we would develop the 3D simulation of fluctuation. We also plan to develop the calculation and perform the frequency domain measurement to obtain pulse shape information.

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