# Diagnostics of Sub-picosecond Electron Pulse Using the Fluctuation Method

K. Nakamura, T. Watanabe, T. Ueda, K. Yoshii, M. Uesaka
Nuclear Engineering Research Laboratory, University of Tokyo,
22-2 Shirakata-Shirane, Tokai, Naka, Ibaraki 319-1188, Japan

*Abstract*

Diagnostics of longitudinal bunch length of subpico- and picosecond electron beams by the fluctuation method has been carried out at the S-band twin linear accelerators at Nuclear Engineering Research Laboratory (NERL), University of Tokyo. The diagnostics method utilizes a statistical analysis of shot-noise-driven fluctuations in incoherent radiation. Experiment was performed on Cherenkov light emitted from 1.0 ps (FWHM), 20 MeV bunch. As a result, the fluctuation method indicated pulse duration four times longer than that by the streak camera. Its discrepancy attributes a spatial effect neglected in the theory. Thus, numerical analysis is extended to 2-dimensional one.

## 1 INTRODUCTION

Measurement of the longitudinal bunch distribution of a relativistic electron beam is of great importance in advanced accelerators, for example, X-ray FEL, linear collider, and laser-plasma cathode. So far, the femtosecond streak camera has been the most reliable tool for the measurement [1-3]. However, new techniques for the generation of ultrashort electron pulse (~10 fs), such as the plasma cathode [4-6], have been proposed. In order to diagnose such a short pulse, we have to use an alternative method, since the time resolution of the streak camera, 200 fs, is not enough. At NERL, the coherent transition/diffraction radiations (CTR/CDR) emitted at the wavelengths longer than or equal to the bunch length were used for the diagnostics of subpico- and picosecond electron pulses [1-2]. Recently, a new novel technique was proposed by M. S. Zolotorev, et al [7]. The method is based on observing the intensity and spectral fluctuations of incoherent radiation.

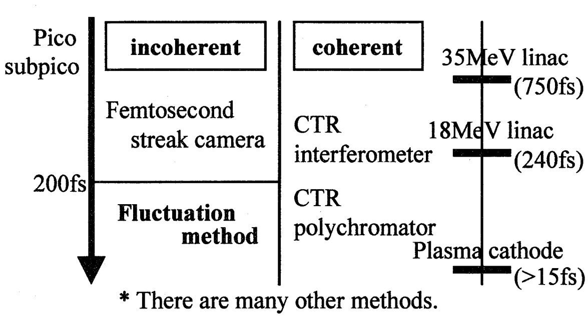


Fig. 1 Diagnostics schemes and their time resolutions

In the paper, the measurement of fluctuations in the picosecond time domain is performed, and the reliability of the method is discussed. As showed in Fig. 1, it is important to try alternative methods based on different physics and check their precision.

## 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 $\tau_{coh}$,

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

The pulse is consists of $N$ independent coherent parts as shown in Fig. 2. $N$ can be described as follows,

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

where $\tau_b$ 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 $\sigma$ 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 $\tau_b$ is acquired.

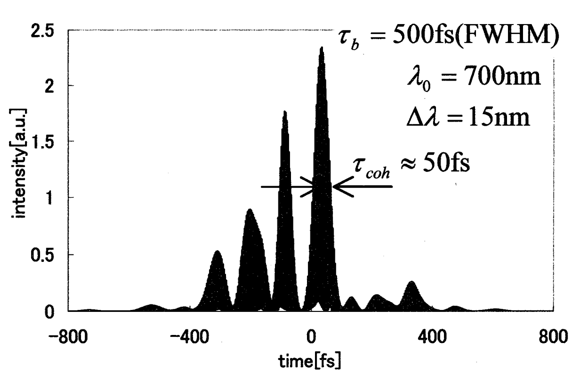


Fig. 2 Intensity of radiation through the BPF

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,

$$\tau_b = 1/\delta\omega. \tag{5}$$

Figure 3 shows the simulation result of the power spectrum of incoherent radiation.

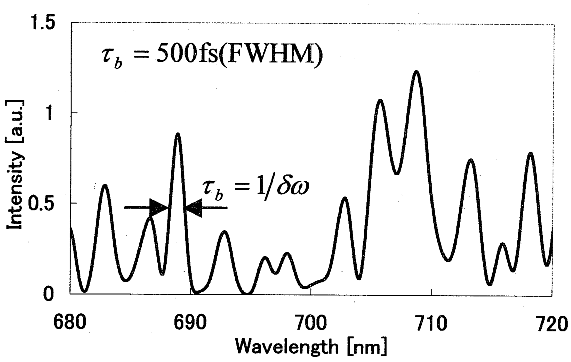


Fig. 3 Power spectrum of incoherent radiation

Equation (5) indicates that the width of the spike become wider as the pulse length is shorter. It is worth noticing that wider one is easier to be observed on the detector. Fourier transform of the power spectrum gives the correlation function, which can be defined as Eq. (6),

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

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

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

where the angular brackets denote the ensemble average. The simulation results of the measurement of $d_\Gamma(\tau)$ is shown in Fig.4. 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.

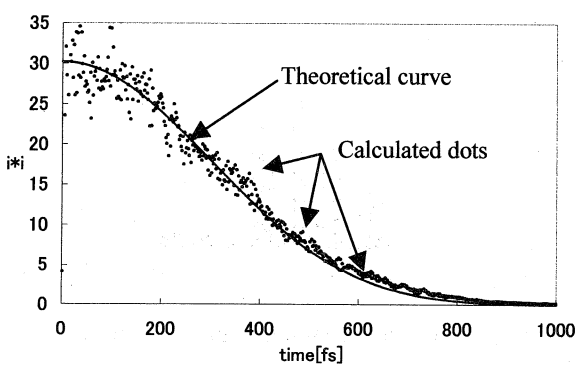


Fig. 4 Simulation result of measurement of pulse shape

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

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

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),

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

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

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

The result is shown with $N_e = 500$ in Fig. 2.

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

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

We assume a standard spectrometer with dispersion of about 2.3nm/mm and a CCD with 1100 channels of about 24 micrometers. The simulation result of measurement and pulse shape acquirement are shown in Fig. 3 and 4.

## 3 EXPERIMENT

The experimental setup is shown in Fig. 5. 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

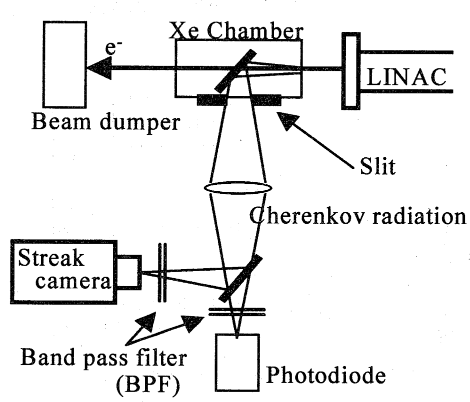


Fig. 5 experimental setup

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. 6. 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.

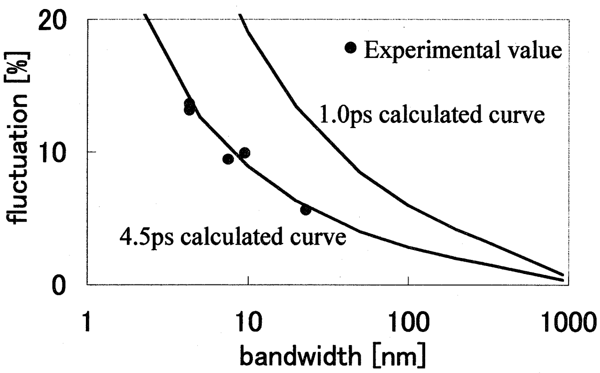


Fig. 6 experimental result

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

To take into consideration the transverse spatial effect in calculation, the simulation code is upgraded to 2-dimensional one. The transverse distribution is assumed to be Gaussian. The radiation from each source spreads spatially. The radiation intensity has spatial distribution on the detector. Only averaged signal on the detector can be acquired. The calculated model is shown in Fig. 7.

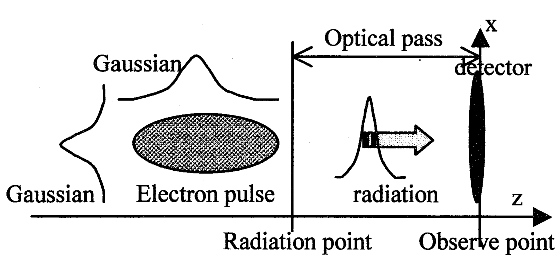


Fig. 7 Two-dimensional calculation model

Electric field of radiation is given as the function of x on the detector. The calculation is done following Eq. (12),

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

where, $l_k$ is the length decided by the transverse electron position.

The 2D-simulation of fluctuation is performed and shown in Fig.8. It is shown that the fluctuation is suppressed as the transverse bunch size is enlarged, as expected.

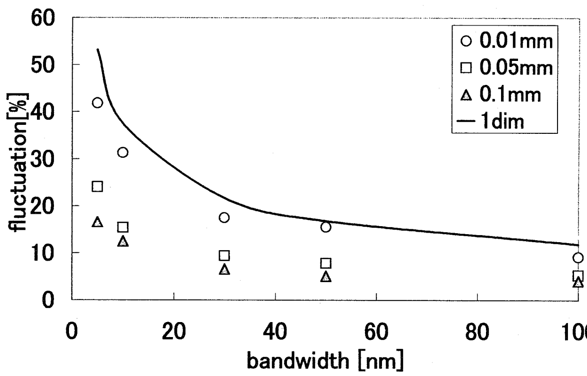


Fig. 8 Simulation results of 2-dimensional fluctuations

## 5 SUMMARY

The 1D-simulation of the fluctuation method was achieved. 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. The influence of the transverse beam size upon the fluctuation has to be taken into consideration. The simulation is upgraded to 2-dimensional one. It is shown that the fluctuation is suppressed as the transverse bunch size increases.

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

## REFERENCE

[1] M. Uesaka et al., Nuclear Instruments and Methods A 406 (1998) 371.
[2] T. Watanabe, et al., Nuclear Instruments and Methods A 437 (1999) 1.
[3] T. Watanabe, et al., Nuclear Instruments and Methods A (in press).
[4] D. Umstadter, et al., Science. 273 (1996) 472.
[5] E. Esarey, et al., Nuclear Instruments and Methods A 331 (1993) 545.
[6] H. Nasr, et al., Nuclear Instruments and Methods A 455 (2000) 148.
[7] M. S. Zolotorev and G. V. Stupakov, SLAC-PUB-7132, (1996).