MEASUREMENT OF ELECTRON BUNCH TIMING JITTER USING STROBOSCOPIC METHOD

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Abstract

The electron bunch timing jitter is measured by using a stroboscopic method. The method can be realized by a stroboscopic device such as a dissector. In the fast RF sweeping operation mode of the dissector without slow linear ramping, the voltage distribution of electron bunches is recorded on a digital sampling oscilloscope after signal amplifying and noise filtering by a differential amplifier. A quantitative analysis about the working principle of the dissector shows the relation between the bunch timing jitter and the rms value of the voltage distribution. We can calculate the bunch timing jitter after measuring a bunch length with the dissector. Finally, the timing jitter is compared with that measured by using a signal pick-up and a sampling oscilloscope.

1 INTRODUCTION

The timing jitter of electron bunches is inevitable in RF accelerators due to RF noise, high power supply ripple, synchro-betatron coupling, or even wakefields.[1,2] The timing jitter changes the phases of electron bunches entering the RF cavities and may induce beam quality degradation, different energy gain, and beam instability. Especially, in the application of accelerators to free electron lasers (FELs), the timing jitter of bunches can be a serious operation problem. For example, 1 ps of timing jitter corresponds to 150 μm of the dynamic cavity detuning in the FELs, and it can affect negatively both the gain and the power of the shorter wavelength FELs including infrared FEL.[3] Also, in the self amplified spontaneous emission (SASE) FEL, the peak current and the energy spread of electron beam depend on the timing jitter of electron bunches sensitively, which are closely related to brightness, gain, growth, and saturation at ultraviolet or x-ray wavelengths.[4,5] Thus, the measurement of the bunch timing jitter and its improvement are important for successful operation of the FELs.

In this paper, we present a new stroboscopic method for the measurement of electron bunch timing jitter. The stroboscopic method utilizes a slight temporal asynchronism between the bunch repetition and a RF phase. It is represented by a voltage distribution whose variance can be converted to the timing jitter of electron bunches by a theoretical analysis. We have tested the measurement method for an electron accelerator experimentally and compared the experimental result with that measured by using a wall current monitor and a sampling oscilloscope.[6]

2 MEASUREMENT THEORY

In order to realize the stroboscopic method, a stroboscopic device is required, which is composed of a pair of deflecting plates, a narrow slit, a photocathode, an anode, dynodes, etc. In addition, an OTR is also needed to deliver the temporal information of electron bunches to the stroboscopic device because it may be undesirable to use high energy electron beam directly. The periodic light pulses which are radiated from a surface of OTR screen by the periodic electron bunches enter the photocathode of the stroboscopic device, and generate the periodic photoelectron pulses. After a photoelectron pulse passes through the deflecting plates applied fast sweeping RF voltage, its pulse width is lengthen on a slit diaphragm. The slit plays the role of selecting a part of a whole pulse. If the photoelectron pulses and the RF deflecting voltage are strongly synchronized, then a stationary pulse profile appears on the plane of slit diaphragm.[7]

However, the complete synchronization between the photoelectron bunches and RF deflecting voltage may not be achieved since the electron bunches in RF accelerators have a period fluctuation, i.e., timing jitter as well as an amplitude fluctuation. Therefore, we should obtain a voltage distribution as a statistically accumulated output signal from the multi-bunches. For the quantitative analysis, as you see in Fig. 1, the current of the bunches can be expressed in time domain as

$$i(t) = \sum_{k=-\infty}^{\infty} i_k(t), \quad (k = \cdots, -1, 0, 1, \cdots), \tag{1}$$

where i_k is the current of k-th bunch, which can be expressed as

$$i_k(t) = Q_o(1 + A_k) f(t - kT_o - J_k), \tag{2}$$

where A_k and J_k are the normalized amplitude fluctuation and the timing jitter of k-th bunch respectively. Q_o is the average charge in a bunch and T_o is the period of the

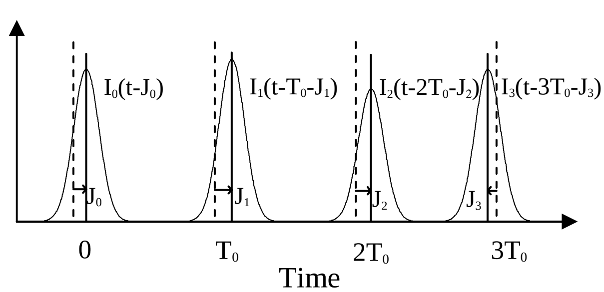


FIG. 1. Time structure of bunch current in the accelerators.

stationary bunches. Since the bunches in the accelerators can be expressed by a Gaussian distribution in a good approximation, f(t) is given by

$$f(t) = \frac{1}{\sqrt{2\pi}\,\sigma_b} \exp(-t^2/2\sigma_b^2)\ , \tag{3}$$

where σ_b is the bunch length.

After further calculations [8], we can get a following relation;

$$\frac{1+(\sigma_J/\sigma_b)^2}{\sqrt{1+2(\sigma_J/\sigma_b)^2}} \exp(2B_2 - B_1) = \frac{1+\left(\sigma_V/\langle V_k\rangle\right)^2}{1+\langle A_k^2\rangle}\ . \tag{4}$$

In Eq. (4), the index, $2B_2 - B_1$, is relevant to a position and we can adjust it to zero. The peak current fluctuation, $\langle A_k^2 \rangle$, is measured as 0.5 % when the repetition rate of bunches is regular. Now, the timing jitter of bunch can be determined from rms and mean values of voltage distribution.

3 EXPERIMENT AND RESULT

An OTR and a dissector are used as a radiation source and a stroboscopic device, respectively. In the experiment, the OTR screen is placed at 45° with respect to the electron beam and the backward radiation is observed. The electron energy is 2 MeV, so the angle of the peak cone is 15°. The viewport line was inclined 15° with respect to the perpendicular direction of main beamline so that the peak optical light could enter the photocathode of the dissector. In order to prevent a viewport from cracking due to discharge caused by deposition of scattered electrons from the OTR screen, a large-angle bending magnet was installed between the OTR and the dissector. The focal length of the dissector lens was adjusted so that the dissector could receive the maximum peak of light emitted from a point-like lamp which was located at the same distance as the OTR screen was done from the dissector.

3.1 Bunch length measurement

As you can see in Eq. (4), the bunch length should be measured in order to calculate the timing jitter of electron bunch from the output voltage distribution. A little alignment error of a dissector should be corrected with a low DC voltage applied to the deflecting plates of the dissector, so that a signal of lamp-light ought to be detected without RF sweeping and linear ramping. The scanning of the bunch current is performed with both 90.2 MHz RF sweeping voltage and a low frequency ramping voltage applied to the deflecting plates simultaneously. Fig. 2 shows the measured signal of bunch length. The signal includes timing jitter as well as electron bunch itself. Therefore, the square of measured bunch length, σ_{bm}^2, is the sum of the square of pure bunch length and the square of timing jitter, i.e.,

$$\sigma_{bm}^2 = \sigma_b^2 + \sigma_J^2\ . \tag{5}$$

According to Zinin's calculation of bunch length, [9] the measured bunch length, σ_{bm} is 206.9 ps.

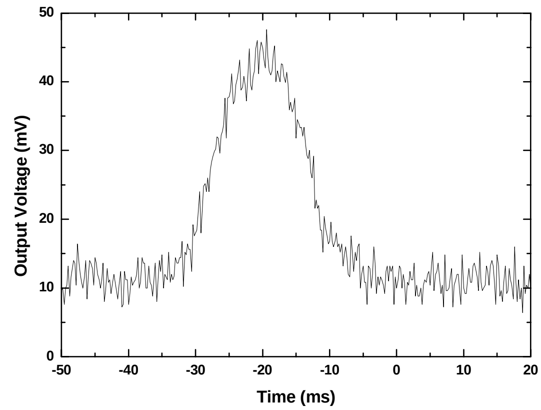


FIG. 2. The measured signal of bunch length using a dissector, which shows the full width at half maximum of bunch is 14.5 ms, which corresponds to 206.9 ps of σ_{bm}.

3.2 Voltage distribution measurement

A schematic diagram of the arrangement to measure bunch timing jitter is shown in Fig. 3.

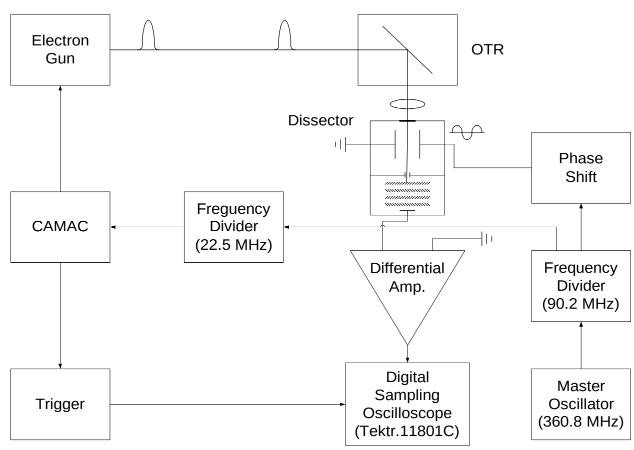
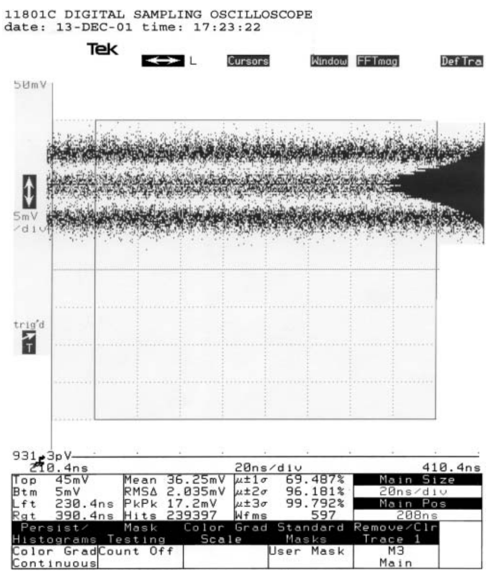


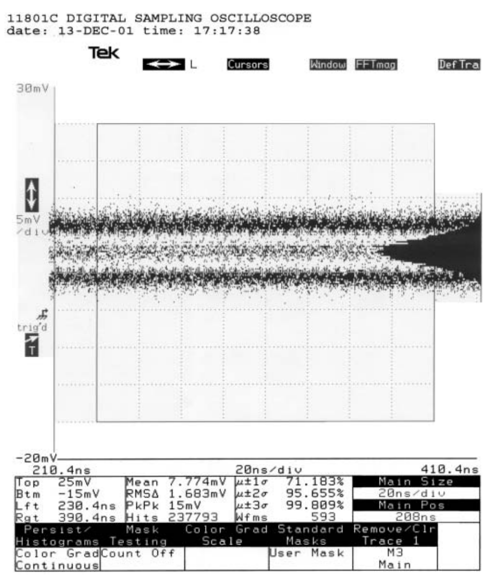
FIG. 3. The schematic diagram of the arrangement to measure bunch timing jitter.

The voltage distribution is measured by using a dissector and a data acquisition system. Unlike the bunch length measurement the dissector is operated with the RF sweeping voltage, but without a low frequency ramping on the deflecting plates. This operation mode allows us to measure the fluctuation of a relative phase difference between RF field and the electron bunches due to timing jitter. The fluctuation of the phase difference can be converted into a voltage distribution which results from the statistical accumulation of output voltages through a data acquisition system, which is composed of a differential amplifier and a digital sampling oscilloscope.

The differential amplifier amplifies a small signal through the narrow slit of the dissector and filters the low and high frequency noises. Since the digital sampling oscilloscope has a potential of 200 kHz sampling rate, it is possible to pick up signals from the electron bunches with 188 kHz repetition rate bunch by bunch. The measured voltage distributions are shown in Fig. 4.



(a)



(b)

FIG. 4. The measurements of voltage distributions (a) when the electron bunches interact with an OTR and (b) when the electron bunches are passing through a beamline without the OTR.

4 ANALYSIS AND CONCLUSION

We measured the bunch length, rms and mean values of voltage distribution with a dissector. Fig. 4 shows the measured voltage distributions of two cases. The one is a case when the electron bunches interact with an OTR and the other is a case when the electron bunches pass through a beamline without the OTR. The latter results from the background noises which may be caused by X-ray response of the photocathode and dark currents of the dynodes etc. Since the former includes the noises together with the signals of electron bunches, they should be removed from the signal distribution. If the two distributions are regarded as Gaussian, the pure standard deviation can be obtained easily. According to Fig. 4, the pure rms value of voltage distribution is given by 1.144 mV, and the mean value 28.476 mV. Therefore, we can determine the timing jitter with the help of Eqs. (4) and (5). The calculated timing jitter, σ_J, is 49.4 ps and the pure bunch length, σ_b, is 200.9 ps.

As for the timing jitter measurement with a dissector, the resolution depends on the adjustment error of beam centering and RF stabilities such as voltage fluctuations and phase jitter. Firstly, a resolution for centering of beam bunch depends on the size of a slit. According to the calculation, the smaller timing jitter is, the worse the resolution is. For the case of timing jitter, 49.4 ps, and a slit width, ±20 μm, it is about 0.3 ps. Secondly, a few percents of RF voltage fluctuation are tolerable in an order of subpicosecond. But the phase jitter of RF voltage will affect the resolution of a timing jitter measurement seriously.

Finally, the timing jitter measured by using a stroboscopic method of the dissector is compared with that measured by using a wall current monitor and a sampling oscilloscope. Unfortunately, the wall current monitor has not been installed near the OTR and we could not compare the measured jitters directly. However, we can estimate a value transformed to the same position by considering the effects of all components between them. The timing jitter which is measured behind a bunching cavity using a wall current monitor is 31.2 ps. But the different energy gain bunch to bunch due to timing jitter, 0.5 %, may make a path difference between trajectories in 180° bending magnet, and it induces the timing jitter spread about 20.6 ps. Therefore, the obtained timing jitter, 49.4 ps, can be accepted as a reasonable value.

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