MEASUREMENT OF BUNCH LENGTHENING EFFECTS USING A STREAK CAMERA WITH REFLECTIVE OPTICS

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Abstract

For precise measurements of the bunch length, the incident optics of a streak camera should be free from optical path differences induced by chromatic effects. A reflective optics system was designed and installed on a camera: its performance was compared with the original refractive optics. Since reflective optics can employ white light of the synchrotron radiation, bunch length measurements at very low beam currents can be performed. We measured the bunch length as a function of the beam current and estimated the longitudinal coupling impedance of the PF-Ring.

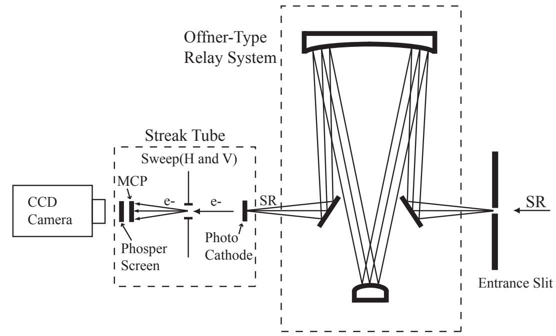
INTRODUCTION

A streak camera is a powerful tool for the instantaneous measurement of the bunch length. It converts the temporal structure of the input light into a spatial distribution. For the bunch length measurement using synchrotron radiation (SR), visible SR is focused to form an image of the beam profile on the entrance slit of the streak camera. The optical relay system transfers the image of the slit onto the photocathode of the streak tube. The built-in optical relay system comprises a compound lens system. Usually, streak cameras are used in the laser applications, where quasi-monochromatic incident light is used. Normally, a monochrometer, such as the band-pass filter, is used for bunch length measurements in order to reduce dispersion effects (e.g., chromatic aberrations.) in the lens system. However, the band-pass filter will reduce the intensity of the incident SR by more than 1/10. This loss in the incident intensity often introduces difficulty in measuring the bunch length for very low currents. To avoid this loss in the incident intensity, we designed and installed an optical relay system with reflective optics with no dispersion effects such as chromatic aberrations. In addition, Newtonian objective optics is employed to form the first image of the beam profile onto the entrance slit. By using these reflective-optics systems, we can measure the bunch length down to 0.1 mA. The results of the bunch length measurement are described in this paper. Bunch lengthening in the PF-ring is also discussed.

REFLECTIVE OPTICS

Streak Camera with Offner-type Relay System

We used a Hamamatsu model C5680-01 streak camera equipped with a dual sweep unit. The streak camera converts the temporal information of the SR into two-dimensional spatial information on a CCD. Fast scan is performed along the vertical direction on the screen with the highest resolution of 2ps. By using the dual time-base unit, a slow scan is performed along the horizontal direction; the bunch shape in successive revolutions can be measured.



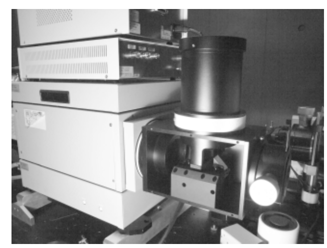


Figure 1: Schematic drawing (top) and a photo (bottom) of the Offner's relay system installed in the streak camera. (The figure is not to scale)

In front of the streak tube, an optical relay system is employed to form an image of the entrance slit onto the photocathode of the streak tube. Conventional streak cameras use lens systems with refractive optics, which induce certain dispersive effects (e.g., optical path differences (OPD)) in the bunch length measurement. On the other hand, reflective optics is free from dispersive effects because the light does not pass through the inside of glass material. The Offner's relay system, comprising two nearly concentric spherical mirrors, yields images with one-to-one magnification at a high resolution and low distortion [1, 2]. We designed and constructed an Offner-type relay system for the streak camera, as shown in Fig.1. A photograph of the system is also shown in this figure.

Effect of Incident Optics

The dispersion effects were compared by replacing the incident optics of the streak camera. Monochrometers such as band-pass filters were not used in the measurement. Figure 2 shows the bunch lengths measured by using reflective optics and refractive optics. Both these measurements were performed by storing a single bunch in the ring. The symbol in the figure denotes the average

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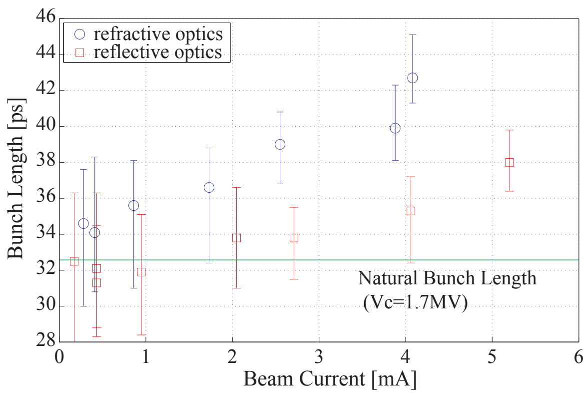

Figure 2: Bunch length difference with refractive optics and reflective optics. At low beam currents, the bunch length is close to its natural value obtained in the reflective optics measurement.

value of the bunch length, and the error bar shows the minimum and maximum in several measurements. The natural bunch length is also shown in the figure. It is evident that the refractive optics exhibits a systematically larger bunch length as compared to reflective optics. With regard to the reflective optics, the measurement shows a good agreement with the calculated natural bunch length. For small beam currents, the intensity of the SR is also weak. As a band-pass filter decrease the intensity more than 1/10, the measurement for small beam currents became difficult. Reflective optics does not need a monochrometer and hence the precise measurement at very low beam currents becomes possible.

BUNCH LENGTHENING MEASUREMENT

Optical Layout

The optical layout of the bunch lengthening measurement is shown in Fig.3. To avoid the heat load because of the hard X-ray components of SR, a water-cooled mirror made of beryllium (Be) reflects the visible

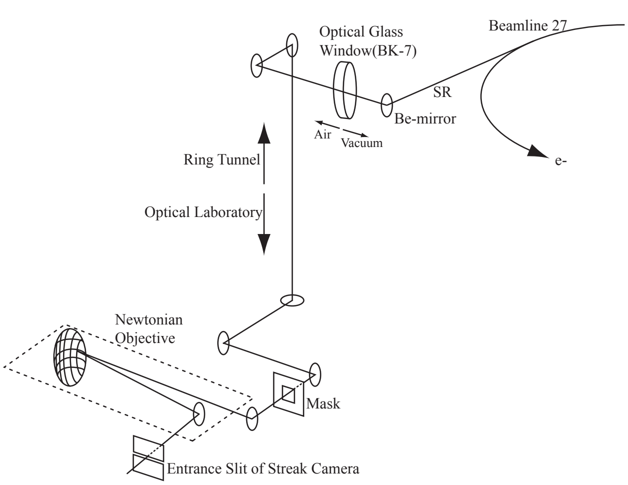

Figure 3: Optical layout of the bunch length measurement. The optical laboratory is located at the underground level of the storage ring.

light components of the SR. The light is extracted to the atmosphere pressure environment through a 20mm-thick quartz window and fed to the optical laboratory underneath the storage ring tunnel. The distance from the source point to the optical bench is approximately 8m, and the optical path is surrounded by pipes and boxes in order to avoid path fluctuations caused by air turbulence.

Usually, a converging lens is used to form a focus image of the beam profile on the entrance slit of the streak camera. The Newtonian objective, indicated as the dotted box in Fig.3, is used to avoid the dispersion effect of lens glass. The focal length of the parabolic mirror is 800 mm. The Newtonian objective system is used to create a focusing image directly on the entrance slit of the streak camera.

The bunch lengths at several cavity voltages were measured and the results are shown in Fig. 4. The beam currents were selected to be around 0.7 mA to avoid the bunch lengthening. The red line in the figure shows the theoretical calculation of the natural bunch lengths, which is in good agreement with the measured vaule.

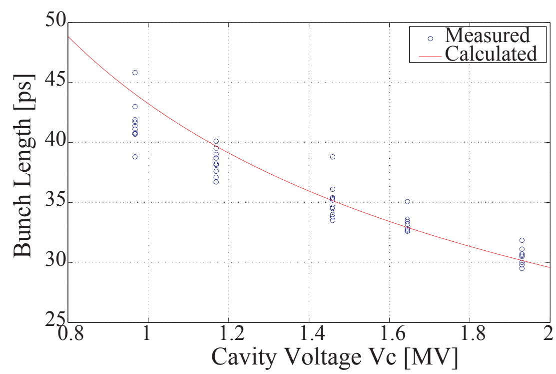

Figure 4: Bunch length as a function of cavity voltage at a beam current of 0.7mA. The solid line represents the calculated natural bunch length.

Potential Well Bunch Lengthening

In the low beam current region, the streak camera image exhibits a Gaussian distribution in the longitudinal *z* direction. Along with an increase in the beam current, the bunch shape became asymmetric: it can be characterized as[3],

$$I(z) = I_0 + I_1 \exp\left\{ -\frac{1}{2} \left(\frac{z-\bar{z}}{[1+\mathrm{sgn}(z-\bar{z})A]\sigma} \right)^2 \right\},$$

where I_0 and I_1 denote the pedestal and peak of the distribution, respectively. The term $[1+\mathrm{sgn}(z-\bar{z})A]$ is the asymmetric factor that characterizes the bunch shape, σ is the root-mean-square bunch length and $\bar{z}$ is the mean. The bunch length as a function of the beam current is shown in Fig.5. The bunch shape had tails longer than the heads, and the asymmetry factor A in the above mentioned equation increased with the beam current. This is caused by potential well distortion induced by the resistive impedance.

The potential well effect caused by the beam duct is estimated using simple model in ref. [4, 5], and the fitted result is shown as the solid line in Fig.5. Although the model is simple, the fitted result is not bad because the calculated natural bunch length in the PF-Ring is 22 mm in the FWHM, which is not too short as compared to the aperture of the vacuum duct. The typical size of the duct is 38 mm in height and 90 mm in width[6].

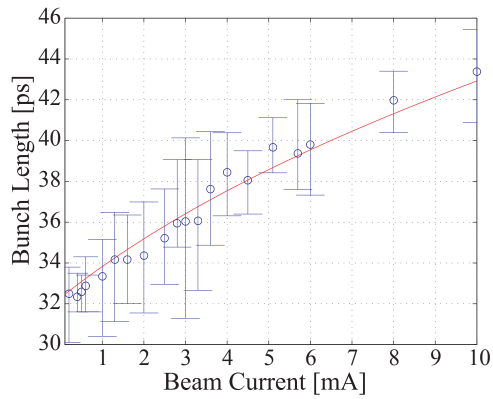

Figure 5: Bunch length at low beam currents. The solid line shows the fitted result with the potential-well distortion model.

Microwave Instability

In the high beam current region, namely, above the threshold current of microwave instability, the bunch shape starts to deviate from neither the Gaussian nor the asymmetric Gaussian shape. At the same time, the bunch shape became unstable and the change in the bunch length became large. We used the FWHM bunch length and calculated the standard deviation divided by the factor 2.355. Although this factor has no meaning when the bunch shape is not like the Gaussian distribution, we use this value as a rough estimation of the bunch length.

When the longitudinal broadband impedance exhibits frequency dependence with the form $Z(\omega) \propto \omega^a$, Chao-Gareyte scaling law holds above the threshold, which states that the bunch length is proportional to the power of the scaling parameter ξ as[7,8]

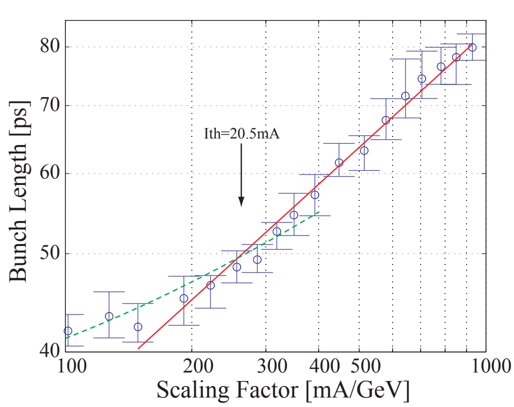

Figure 6: Bunch length above the threshold. The solid line and dotted lines denote the calculation using the scaling law and potential well distortion model, respectively.

$$\sigma \propto \xi^{1/(2+a)} = \left(\frac{\alpha I_b}{E \nu_{s0}^2} \right)^{1/(2+a)},$$

where I_b denotes the beam current, α the momentum compaction factor, E the beam energy, ν_{s0} unperturbed synchrotron tune, respectively. The result of fitting is shown with solid line in Fig.6, and the parameter a is determined to be 0.64.

Impedance Estimation

From the potential well model and scaling estimation, the threshold current of the microwave instability was determined to be 20.5 mA. The corresponding coupling impedance was to be approximately 0.5 Ω [5,9].

In 2005, the PF carried out major upgrade. The project aimed to introduce four new straight sections for short-gap undulators, and to enlarge the length of the existing straight sections[10]. Before the upgrade, the threshold current for microwave instability was 12 mA, and corresponding impedance was approximately 1.1 Ω. Threshold current has been improved because the old vacuum components such as unshielded bellows and small cavity-like structure in vacuum flanges have been renewed. We also plan to measure a change in energy spread to compare to this result.

CONCLUSION AND FUTURE PLAN

Incident optics with reflective optics was designed and installed for the streak camera. It is confirmed that dispersion effects induce a systematic error in ordinal refractive optics with white light. Reflective optics can use white light and is effective for measurements in small beam current. This incident optics is already used in the streak camera of KEK B-Factory and PF-AR.

The longitudinal coupling impedance of each vacuum component can be estimated from calculation using MAFIA or some computer codes: this estimation is in progress. The threshold of the microwave instability was estimated from the bunch length measurement, and the preliminary estimation of the longitudinal impedance was performed. Another Be-mirror will be installed in beamline 21 of the PF-ring. Measurement of the energy spread using two optical monitors will be done in 2007.

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