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BUNCH LENGTHENING AND PURITY MEASUREMENTS OF SINGLE-BUNCHED BEAM BY PHOTON COUNTING METHOD IN KEK-PF

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Abstract

A photon counting system was installed in beamline 21 in the Photon Factory at the KEK in order to measure the bunch time structure in the single bunch mode. Large dynamic range and high time resolution of the system enables us to measure the single bunch impurity precisely and the bunch length. From the bunch lengthening measurement, the coupling impedance of $|Z/n| = 1.2\ \Omega$ was obtained. The resolution of 10^{-5} was achieved in the impurity measurement.

Introduction

A photon counting method is suitable for measuring the time structure of positrons (electrons) in bunches of a positron (electron) storage ring. In this method, a photon emitted from a positron in a bunch is detected individually and the events are counted digitally. An excellent dynamic range is obtained when enough events are collected. Moreover, high time resolution is achieved because the timing at which the event occurs can be detected precisely with a fast photomultiplier and a constant fraction discriminator.

Large dynamic range of the system gives us precise measurement of the single bunch impurity which is defined as a ratio of positron number in unwanted bunches to that in the main bunch. And high time resolution enables us to measure the bunch length precisely.

It is important to estimate the longitudinal coupling impedance of a storage ring because it determines the longitudinal performance of the ring. The impedance is calculated from the beam current dependence of the bunch length, i.e. bunch lengthening. The relationship between the bunch lengthening and the ring impedance has been investigated by several authors[3,4,5,6].

We have installed a photon counting system in beamline 21 in the Photon Factory at National Laboratory for High Energy Physics (KEK-PF)[2]. The bunch length was measured as a function of the beam current and the experimental data were fitted with a theoretical formula in order to estimate the longitudinal coupling impedance. In addition, growth of the single bunch impurity was measured. Related parameters of the KEK-PF is shown in Table 1. They are used in the following sections without further definition.

Table 1: Main Parameters of KEK-PF-Ring

Energy	E	2.5	GeV
Revolution Frequency	f_{rev}	1.6	MHz
Synchrotron tune	ν_s	0.0227	
Harmonic number	h	312	
Radio frequency	f_{rf}	500	MHz
Momentum compaction factor	α	0.0157	
Peak RF voltage	V	1.7	MV
Natural bunch length	σ_{s0}	50	ps
Ring average radius	R	29.8	m

Experimental

The photon counting system is shown in Fig. 1 schematically. Photons emitted in a bending section run through a vacuum pipe and hit a mirror. Photons in the range of the visible light are reflected with the mirror, and are extracted through a view port into the atmosphere. We chose a water cooled SiC mirror with good heat resistance in order to avoid the heat damage by the synchrotron radiation. A Pb-acrylic glass is used on the view port to reduce the scattered X-ray. With ND filters and a precise variable slit, the photon flux is attenuated down to the level of single photon detection per a few hundred revolutions of a bunch, and led to a microchannel-plate type photomultiplier (MCP-PMT, Hamamatsu Photonics R2809U). The PMT has a high time resolution and a small transit time spread (TTS=55ps).

The block diagram of the electronics is shown in Fig. 2. The output signal from the PMT is amplified by two-stage wideband amplifiers with a total gain of 49 dB. A constant fraction discriminator (CFD, Ortec 582) discriminates the pulses and generates the timing signals with constant pulse height. The RF signal divided by 312 (harmonic number) is used as a time reference synchronized to a bucket. The time interval between these two signals is converted to the amplitude of a pulse by a time-to-amplitude converter (TAC, Ortec 467). The pulse from the TAC is amplified by a DC-amplifier with a gain of 14 dB. A multichannel analyzer (MCA, EG&G 7800) analyzes the pulse height distribution in proportion to the time structure of positrons in the storage ring. The longer measuring time gives the larger dynamic range if the change of the condition in the storage ring is small.

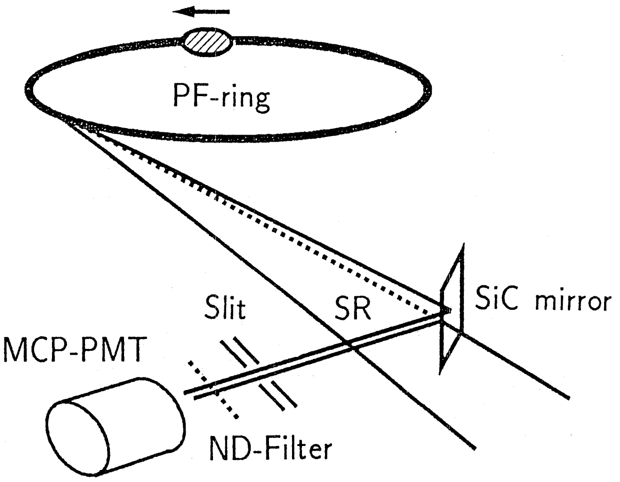

Figure 1: The photon counting system. Photons are detected by a microchannel plate type photomultiplier (MCP-PMT).

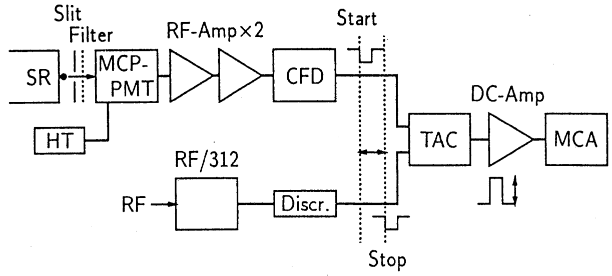

Figure 2: The block diagram of the electronics. MCP-PMT: Microchannel plate-type photomultiplier, CFD: Constant fraction discriminator, TAC: Time to amplitude converter, MCA: Multichannel analyzer, RF/312: Trigger signal synchronized to revolution frequency.

We selected a measuring time of 300 seconds to optimize the dynamic range under condition changes. An example of the measurements is shown in Fig. 3. The abscissa shows the channels of the MCA and the ordinate shows the number of counts in each channel in log scale. Time flows from right to left in this figure. The largest peak corresponds to the main bunch and smaller peaks are unwanted bunches. The time interval between bunches corresponds to the period of the RF system, therefore we can easily calibrate the channel separation; it is 5.05 ps per channel. The width of the main peak and the total area of unwanted peaks correspond to the bunch length and the single bunch impurity, respectively. The broad peak between the third and fourth peaks seems to be caused by internal reflections in the PMT.

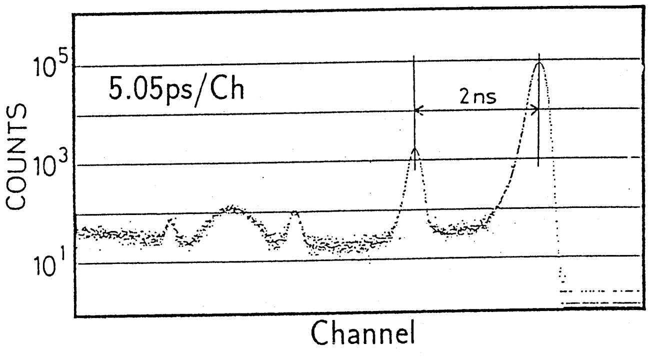

Figure 3: Time-structure of bunches in log scale.

Bunch Lengthening

When the beam current is small, bunch lengthening occurs owing to the RF potential well distortion

$$\left(\frac{\sigma_s}{\sigma_{s0}}\right)^3 - \left(\frac{\sigma_s}{\sigma_{s0}}\right) - \frac{I_b \alpha e|Z/n|}{\sqrt{2\pi}E\nu_s^2}\left(\frac{R}{\sigma_{s0}}\right)^3 = 0, \qquad (1)$$

where $|Z/n|$ is the longitudinal coupling impedance, I_b is the beam current, σ_s is the bunch length and e is the positron charge. When the beam current is high, the bunch length does not follow eq. (1). This phenomenon is interpreted as the longitudinal microwave instability, and the relation between the bunch length and the beam current is described by the Chao - Gareyte scaling law[4]

$$\sigma_s^a \propto \xi, \qquad \xi = \frac{\alpha I_b}{E\nu_s^2}, \qquad (2)$$

where ξ is called as the scaling parameter. Note that the bunch length is proportional to the one-third power of ξ if $|Z/n|$ has no frequency dependence. Assuming the same frequency dependence, we can estimate the longitudinal coupling impedance from the threshold current,

$$I_{th} = \frac{F'}{\sqrt{2\pi}e}\frac{\nu_s^2 E}{\alpha|Z/n|}\left(\frac{\sigma_{s0}}{R}\right)^3, \qquad (3)$$

where F' is the bunch form factor which is close to the value of 8 for a Gaussian distribution[5].

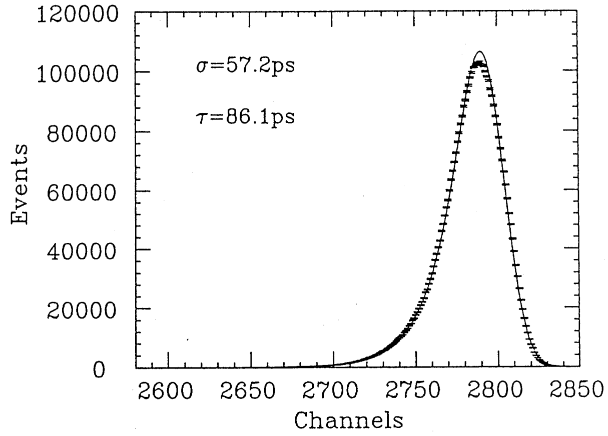

Figure 4: The shape of the main bunch in linear scale. The beam current was 10mA.

Discussion

Figure 4 shows the shape of the main bunch in linear scale. An asymmetry is noticeable. We think this asymmetry is caused by the TTS of the PMT and we deconvoluted the data with the following equations. We fit the data to the Gaussian distribution $\rho(t)$ of a bunch and the exponential response $\psi(t)$ of the TTS of the PMT :

$$\rho(t) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{(x-h-\mu)^2}{2\sigma^2}\right), \qquad (4)$$

$$\psi(t) = \frac{a}{\tau}\exp\left(-\frac{h}{\tau}\right). \qquad (5)$$

The time constant τ and the standard deviation σ are estimated by the least square fitting. We employ the computer code MINUIT assuming there is a statistical error of $\sqrt{N+1}$, where N is the number of events. The fitted result is shown with the solid curve in Fig. 4. The fitting is not very good around the peak. Two possible reasons are considered to explain this deviation. One is the synchrotron oscillation of the bunch. In the beam spectrum we observed a peak which correspond to the synchrotron oscillation of which mechanism has not been resolved in the PF-ring. The other is the difference of the distance between the point where a photon is emitted and the face of the PMT. We took into account both of these effects in the fitting, but the deviation around the peak still remained. However, because their contributions to the bunch length is small, there are no problem to the bunch length measurements. On the other hand, we investigated the asymmetry of the bunch at various beam current. However, no apparent systematic difference was found.

The measured data and the natural bunch length are shown by crosses and dotted lines, respectively, in Fig. 5. Even if the beam current is sufficiently small, the measured bunch length is not equal to the natural bunch length. The difference is about 4ps or less. We fitted these data with eqs. (1) and (2), and we obtained the threshold current I_{th} of 28 mA from the crossing point of the two curves. From eq.(3), we estimated the longitudinal coupling impedance of the PF-ring to be 1.2Ω. This value is consistent with other data[2].

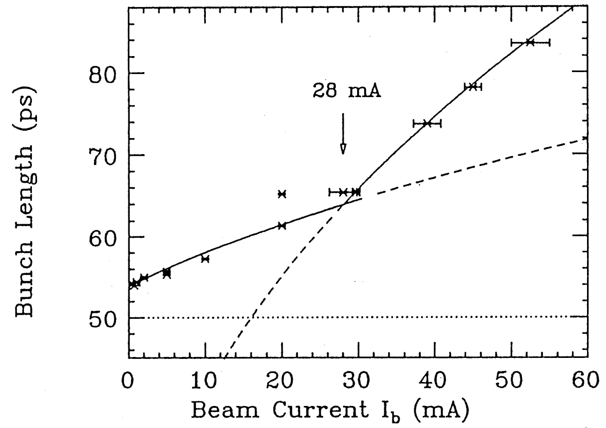

Figure 5: The bunch lengthening in the PF. The threshold current is 28 mA.

With the photon counting system, we obtained a resolution of the impurity measurement of the order of 10^{-5}, which is small enough to observe the change in impurity. The impurity of the KEK-PF-ring becomes worse at a rate of 10^{-4} per hour as shown in Fig. 6.

During injection of the single bunch mode, positrons must be injected only into one bucket. Nevertheless, in some cases, positrons accumulate in other buckets. In addition, the positrons which gain momenta larger than the bucket height by the Touschek effect may be captured by buckets following the main bucket. Therefore unwanted bunches form and grow gradually. The increase in population of positrons in the first unwanted bunch is shown in Fig. 6. The solid curve in the figure is the preliminary results of a theoretical calculation[7]. In the calculation, we adopted the most preliminary theory that positrons are thrown out from the bucket due to the Touschek effect and some of them are captured. An estimated Touschek lifetime of 700 minutes was used. In spite of the crude assumption, the estimation agrees with the measurement well.

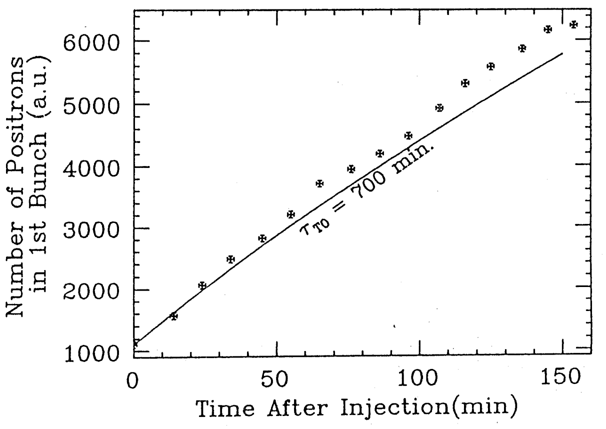

Figure 6: The increase in the positron number in the first unwanted bunch (a.u.). The initial number of positron (26mA) in the main bunch was 1.4×10^7 in the same unit.

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