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Bunch Deformation of a Multi-Bunched Beam in TRISTAN Accumulation Ring

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Abstract

A remarkable bunch deformation has been observed in the TRISTAN Accumulation Ring (AR) during multi-bunch operations. When two bunches that have different populations are stored in the ring, the bunch length of the smaller current bunch is larger than that of the larger one. In some cases, longitudinal distributions of electrons exhibit two peaks. These phenomenon can be explained by an effect of wakefields due to higher order modes of accelerating cavities. We tried to determine the frequency of the mode and the strength of the wakefield that is responsible for the phenomenon with a test bunch method.

I. Introduction

When an electron storage ring is operated in a single bunch mode, the current dependence of the bunch length is explained by the potential well distortion and the microwave instabilities. These theories were successfully applied to the bunch lengthening in the AR [1]. On the other hand, a remarkable bunch deformation was observed when several bunches were stored in the AR [2]. In some cases the longitudinal distributions of electrons exhibit two peaks or tabletop-like shape in four bunch or eight bunch mode operations. These phenomena were explained qualitatively with the potential well distortion due to the long range wakefield, however, its source has not yet been determined.

In this paper, the bunch deformation when two bunches are stored in the ring is discussed. Because the deformation of each bunch was stable over the synchrotron oscillation period, it is quite natural to think that the deformation is caused by the potential well distortion due to high-Q components in the ring. In the AR, the higher order modes (HOMs) of the accelerating cavities are one of the candidates. We tried to determine the frequency of the HOMs and the strength of the fields which induce the bunch deformations.

The machine parameters and the experimental conditions are listed in Table I.

II. Observation of Bunch Shape

There are two RF sections in the AR. Each section contains four APS (Alternating Periodic Structure) type cavities, each of which has 11 accelerating cells. It is reported that the maximum beam current is limited by the coupled bunch instabilities which arise from higher order modes (HOMs) of the cavities [3], we therefore drove only one RF section to avoid the instabilities.

The longitudinal distributions of electrons were observed by focusing the visible light on a streak camera. Synchrotron radiation (SR) from a bending section is led to an optical stage located on a ground level and splitted into two lines. One line of them is used for the streak camera or a high speed photodiode, and the other is for a photon counting system. In the multi-bunch operation, a streak camera detects the bunch shape while the photon counting system measures the population of each bunch. In the photon counting method, the flux of SR is attenuated down to a level at which the output of the photon detector corresponds to one photon detection. The time differences between the arrival time of a photon at the detector and the timing signal synchronized to the bunch revolution are digitized and collected numerically.

Table I
Main Parameters of the AR

Beam energy	E	2.5 GeV
Momentum compaction factor	α	0.01289
Harmonic number	h	640
RF voltage	V_0	1.0 ($\sim$ 2.0) MV
RF frequency	f_{RF}	508.5808 MHz
Energy loss	U_0	0.1458 MeV/turn
Natural bunch length	σ_0	1.4943 cm
number of total cavity		8
number of operating cavity		4

Figure 1 shows an example of longitudinal beam profile of two bunches observed by the streak camera (Hamamatsu C1587 with M1955 synchroscan unit). The vertical axis represents the longitudinal distribution and the horizontal axis shows the vertical distributions of the bunches in successive revolutions.

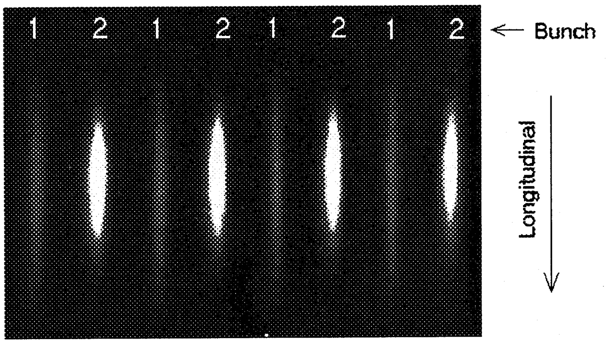

Figure. 1. Longitudinal line density of two bunches. The bunch current of number 1 and number 2 is 10 mA and 15 mA, respectively.

III. Determination of the Higher Order Mode

A. Principle of Test Bunch Measurement

We found that longitudinal bunch shapes of the multi-bunched beam resembled a bunch shape with a double

RF system proposed for the suppression of the longitudinal coupled bunch instabilities [4]. We consider a simple model in which the bunch shape is determined by the accelerating rf and a higher order mode of a cavity. The voltage seen by the beam is expressed as

$$V(\phi) = V_0 \left\{\sin(\phi + \phi_s) + k \sin(n\phi + n\phi_n)\right\}, \qquad (1)$$

where ϕ_s is the synchronous phase, ϕ_n the phase of the HOM field, kV_0 the peak voltage of the HOM, $n\phi$ the phase of the HOM which has the frequency nf_{RF}. For any RF waveform, the electron line density is given by [5]

$$i(\phi) \propto \exp\left\{\frac{-eV_0 Y^2(\phi, \phi_s)}{2\pi h \alpha \beta^2 E \left(\frac{\sigma_p}{p}\right)^2}\right\}, \qquad (2)$$

and

$$Y^2(\phi, \phi_s) = \frac{1}{V_0}\int_0^{\phi} \left\{V(\phi) - V_r\right\} \mathrm{d}\phi \qquad (3)$$

where $\left(\frac{\sigma_p}{p}\right)$ is the rms momentum spread of the bunch and eV_r is the energy loss per turn mainly due to the synchrotron radiation.

In order to determine the frequency and the strength of the wakefield, we thought up a test bunch measurement method. We inject a large current bunch which generates a wakefield and also inject a sufficiently small current bunch whose wakefield is negligible. The shape of the small current bunch is deformed due to the wakefield, we therefore can estimate the frequency of the mode by selecting the distance between the two bunches. In the following part of this paper, we call the large current bunch the main bunch, and the small current bunch the test bunch.

If we assign TM020 mode as a HOM field which affect the bunch shape, f_{HOM} = 1210 MHz and $n = 2.381$ is obtained. We assume $\phi_n = 0$ to maximize the effect of the HOM and assume $k = 0.1$ as an example. Figure 2 shows calculated bunch shapes of the test bunch in successive 10 rf buckets after the main bunch. The bucket number 0 means the position of main bunch and the bucket number 1 means the bucket is just after the main bunch, and so on.

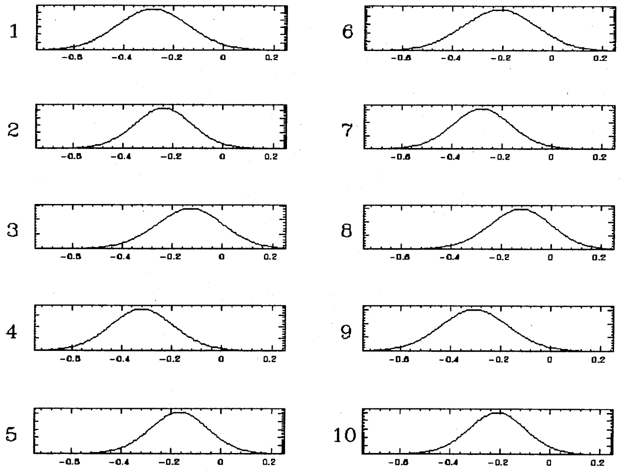

Figure. 2. Simulation of the bunch shapes of the test bunches with the bucket number 1 to 10. The bunch shapes are normalized with $\int i(\phi)\mathrm{d}\phi = 1$. The abscissa shows longitudinal position in units of radians.

There are two method to estimate the HOM frequency. One of them is to measure the peak position of the bunch, and the other is to measure the bunch length. In both methods, the Fourier transform of the obtained data gives us an information of the frequency of the mode. According to the sampling theorem, the highest frequency we can determine is half of the rf frequency, and the higher frequency than that causes an aliasing. Therefore, we have to determine the real frequency by any means.

We chose to measure the peak position of each bunch because the simulation suggests that the effect of the HOM appears more sensitively in the peak position than in the bunch length.

B. Experimental Setup

In the test bunch measurement, a large dynamic range is required and the streak camera is not appropriate for this purpose. We used a high speed PIN photodiode (AR-S2, Antronics Research) which has a rise time of 35 ps and the photosensitive area of 0.01 mm^2. The output of the photodiode was fed to a digitizing sampling oscilloscope (Hewlett Packard HP54121T). The trigger signal synchronized to the bunch revolution was generated by a circuit which divides the RF signal by the harmonic number of the ring. The time jitters of the divider were measured to be about 3 ps in standard deviation with a histogram function of the oscilloscope . We also used a photon counting system to measure the bunch shape, however, it has an disadvantage that it needs long time about three minutes in the measurement.

We injected the main bunch first, and injected the test bunch into a selected bucket. The beam current of each bunch is 20 mA and 1 mA, respectively. To avoid the coupled bunch instabilities, both bunches were dumped by a stopper whenever before the measurement of the next bucket. Because it is very time-consuming to measure all buckets in AR, we only measured the successive 20 buckets in 8 places in the ring.

IV. Results and Discussion

Figure 3 shows the peak position of the test bunches. The abscissa shows the bucket number from 1 to 640 and the ordinate represents the peak position in units of picoseconds. The peak positions vary depending on the bucket number due to the transient beam loadingeffect of the main bunch. The calculated difference in the synchronous phases between just after and before the main bunch was 128 ps which is consistent with the measurement.

We subtract the offset due to the beam loading and calculated the Fourier transform of the variations of the peak position. Peak positions of the unmeasured buckets were assumed to be zero. The result is shown in Fig. 4. There are sharp peaks in every 6.36 MHz. These peaks arise from the fact that we could not measure the all buckets but only eight places were measured.

Two large peaks are recognized at 189.1 MHz and 241.6 MHz. From a measurement of cavity higher order modes, several modes can be listed up as candidates. In the single bunch operation, we measured the beam spectrum of a cavity with a pickup located on its end plate. The resonant frequency of the TM020 mode is ranged from about 1206.3 MHz to 1211.9 MHz because the APS cavity has 11 cells in it. These frequency will be observed

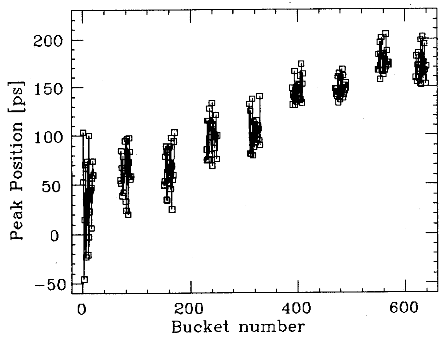

Figure. 3. Peak position of the test bunchs. The measured bucket number is 0±20, 80±10, 160±10, ⋯ , 480±10 and 560±10.

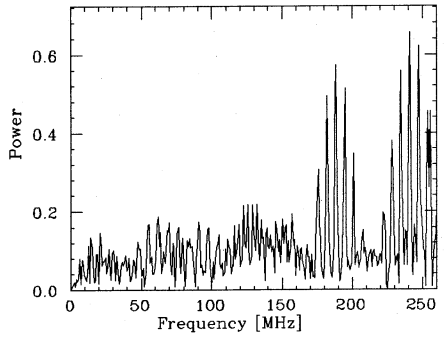

Figure. 4. Fourier transform of the peak position.

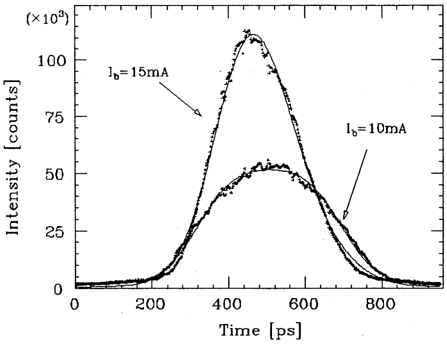

Figure. 5. Longitudinal line density of two bunches measured by the streak camera. The beam current of the large peak is 15 mA and the small peak is 10 mA, and the measured bunch length was 250 ps and 375 ps in FWHM, respectively. The total RF voltage was 2.3 MV.

from 189.1 MHz to 194.7 MHz which is consistent with the Fourier transform of the test bunch measurement. In the same way, TM022 mode which has the resonant frequency from 1788.8 MHz to 1798.3 MHz will appear as 236.0 MHz to 245.6 MHz. We have not measured the characteristics of the other seven cavities in detail, however, the two modes are thought to be the main source of the bunch deformation.

In the rest part of the paper, we will discuss the bunch deformation in the two bunch operation.

At first, we measured the bunch length under the single bunch condition. The bunch was lengthened in accompany with the increase of bunch current, which is well matched with the scaling low above threshold [6]. Next, we stored two bunches in the ring. When the bunch currents of the two bunches were equal, the bunch lengths were equal to each other and the length was slightly longer than that of the single bunch if we compare with the same bunch current. However, if the bunch currents are not equal, the bunch length of the smaller one becomes much longer than that under a single bunch condition, and the bunch length of the larger one becomes shorter as shown in Fig. 5. We fit the bunch shape using the eq. 2 with the least-squares method. The solid line in the figure shows the fitted result. We assumed that the field of two higher order modes, TM020 and TM022, affect the bunch shape. To estimate the strength of the long-range wakefield only, we used the bunch length of the single bunch condition instead of the natural bunch length in the equation. Rough estimation of the k value from the bunch shape was $k = 0.1 \sim 0.25$.

If we assume $k = 0.1$ in both modes, the maximum peak variation of the test bunch was calculated to be about 100 ps. This value is well matched to the measured peak variation in Fig. 3.

At last, we estimated the induced voltage of the HOMs by calculations and compared with the measurements. The impedance of the APS cavity was calculated with the computer code URMEL [7]. The higher order mode which has the highest shunt impedance is the TM012 mode that could produce a wake voltage of 34 kV at $I_b = 25.7$ mA. It corresponds to $k = 0.015$ and is ten times smaller than the measurement. If we consider the TM020 and TM022 modes, the difference of the calculations and the measurements are in the same order. However, the impedance is calculated for only one cavity in the AR. If we take eight cavities into account, the difference will become small.

V. Summary

The bunch deformation in the AR during the multi-bunched beam operation was measured and explained with the higher order modes of the cavities qualitatively. We thought up the test bunch measurement method and concluded that the two modes, TM020 and TM022, are candidates for the source of the deformation. The field strength estimated from the test bunch method is consistent with the strength which produces the deformation of the two bunches, however, the calculated impedance of a cavity is ten times smaller to explain it. Further analysis and measurements are now in progress.

Acknowledgments

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