Bunch Lengthening Observed using Real-Time Bunch-Length Monitor in the TRISTAN AR

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Abstract

A new type of a bunch length monitor, detecting two frequency components of a beam spectrum, has been installed in the TRISTAN Accumulation Ring (AR). Calibration of the monitor was carried out with the calculated natural bunch length at a low beam current. Bunch lengthening was measured as a function of the beam current. When the beam current increased, a sudden blowup of the bunch length was observed together with strong coherent oscillations. It was also observed that the blowup exhibited hysteresis when the beam current decreased, which suggested a strong nonlinear force in the bunch lengthening process.

1. INTRODUCTION

Bunch lengthening is one of the most important issues in electron/positron rings from the aspect of beam dynamics. In the AR, bunch lengthening actually occurs. It is expected that the bunch length should be measured dynamically to understand the bunch lengthening. The bunch length has been measured using the synchrotron light by a streak camera, whereby an rms bunch length is obtained from a stored logitudinal profile. This method has an advantage of detecting a charge distribution. However, it is difficult to follow dynamical change of the bunch length. Therefore, a real-time bunch-length monitor has been developed in the AR.

The AR has only one electron or positron bunch. The main parameters of the AR are listed in Table 1.

Table 1 Main parameters of the AR

Beam energy	E = 2.5 GeV
RF frequency	F_{rf} = 508.58 MHz
Harmonic number	h=640
Average radius	R=60 m
Number of buches	B=1
Maximum beam current	I_b=40 mA
Accelerating voltage	Vc=0.5 - 4.0 MV
Natural rms bunch length	σ_{l0} =0.8 - 2.0 cm
Synchrotron tune	ν_{s0}=0.025 - 0.050
Momentum compaction factor	α=0.0129
Energy spread	$\Delta E/E=4.40\times10^{-4}$

2. BUNCH LENGTH MONITOR (BLM)

A bunch is picked up by a stripline electrode with a length of L=30 cm. The pulse is divided into two paths. One is for detecting the 250 MHz component and the other for the 1620 MHz component. The two signals are detected and mixed again. An analog calculator unit (AD538) generates a signal proportional to the bunch length. An imbalance of the gain between the two channels produces an offset at the output of the monitor and is compensated by a variable attenuator inserted in one channel. Details of the electronics are seen in ref.[1].

Calibration of the monitor has been performed using a low-current bunch. When the beam current is sufficiently small, the longitudinal distribution should be Gaussian, and its rms bunch length approaches the natural bunch length (σ_{l0}). The bunch length is controlled by the accelerating cavity voltage (V_c). The bunch length was measured at a beam current of I_b=0.3 mA or N=2.4×10^9 particles. This current is within the effective range of the monitor. The bunch length at that current will be equal to the natural bunch length from the experiences so far. The measured bunch length is adjusted by using the variable attenuator with a step of 0.25 dB so as to set the measured value by the calculated bunch length. After fixing the attenuation, the bunch length was measured as a function of Vc. Vc was changed from 0.6 to 3.2 MV, which corresponded to the natural rms bunch length of 1.88 to 0.79 cm. Fig. 1 shows the measured bunch length agrees with the caluculated natural bunch length within ±10 %.

This monitor has the following features:

(1) It has high resolution, and can distinguish a difference of 0.1 mm for 20 mm bunch length, which corresponds time resolution of 0.3 ps.
(2) It has the wide dynamic range, minimum detectable current is 0.2 mA with an accuracy of ±10%.
(3) It has wide bandwidth of 150 kHz, and can detect coherent oscillations including higher modes, if excited.
(4) It automatically displays the bunch length.
(5) Easy to handle and maintain.

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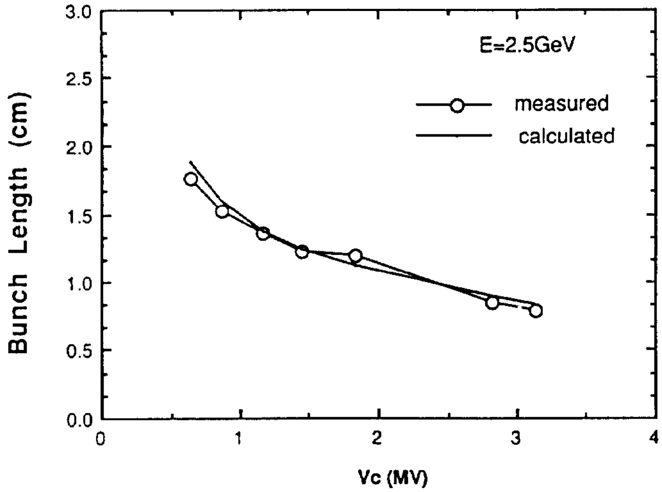

Fig. 1 Measured and calculated bunch length.

3. MEASUREMENT OF BUNCH LENGTH

The measurement was carried out during an injection process under constant Vc. The bunch length was also measured using a streak camera (SC). Bunch lengthening was observed below 1 mA without a clear threshold. No coherent oscillation was observed below 3 mA. On the other hand, the transverse profile obtained from the synchrotron radiation showed a vertical instability [2]. The vertical profile was expanded intermittently, which was not dipole oscillations. The vertical instability is stronger for higher Vc and for shorter bunch length. However, the vertical instability seems to be settled to above 4.0 mA. When the beam current was around 3.2 mA, the monitor showed coherent oscillations with a quadrupole synchrotron frequency ($2f_S$) on a spectrum analyzer. Suddenly, the bunch length increased by 20 to 40%, when the current was 4.8 mA. This jump was also confirmed by the streak camera. A jump of the bunch length makes the pattern of the oscillations different. Though only quadrupole oscillation was excited before a jump, strong oscillations were excited with higher order modes after a jump as seen in Fig.2(a) and Fig.2(b). The synchronous phase angle also jumped by about 2 deg. together with the jump of the bunch length.[3]

A jump in the bunch length exhibited hysteresis as a function of the current as is shown in Fig. 3. When the current was decreased from point <C> after a jump, the bunch length did not return at the same current of 4.8 mA, where the jump-up occurred when the current was increased. The bunch length pursues line <C>-<D>. The pattern of oscillations on line <C>-<D> was the same as that observed at point <C>. While the bunch length was on line <C>-<D>, no vertical oscillation was observed. The longer bunch length on line <C>-<D> fluctuates due to the coherent oscillations as seen in Fig.2(b). As the current was further decreased, jump-down occurred from point <D> to <A>. At the same time, no coherent oscillation was observed, and the bunch length hysteresis disappeared.

There are two jumps in the bunch length, one corresponds to line <B>-<C> and the other <D>-<A>. The current for the jump depends on Vc. A lower Vc or longer bunch length makes the jump-up and the jump-down occur at a lower current. The region between the two jumps is called the hysteresis region, where two bunch lengths are possible. Fig. 4 shows the jump-up and the jump-down values of the current as a function of Vc. The hysteresis region increases as Vc increases.

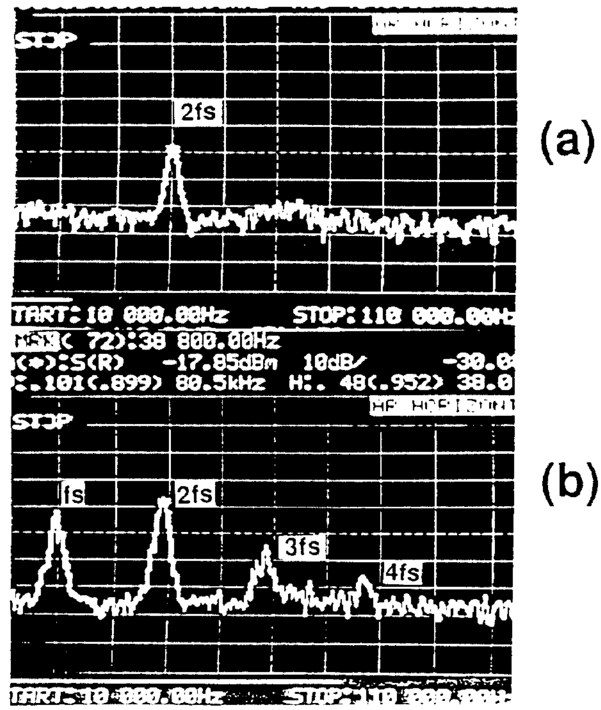

Fig. 2 Coherent oscillations at a shorter bunch length before a jump-up (a), and a longer bunch length after a jump-up (b) at Ib= 4 mA, and Vc=1.18MV. The frequency span is 10 to 110 kHz. The vertical scale is 10 dB/div.

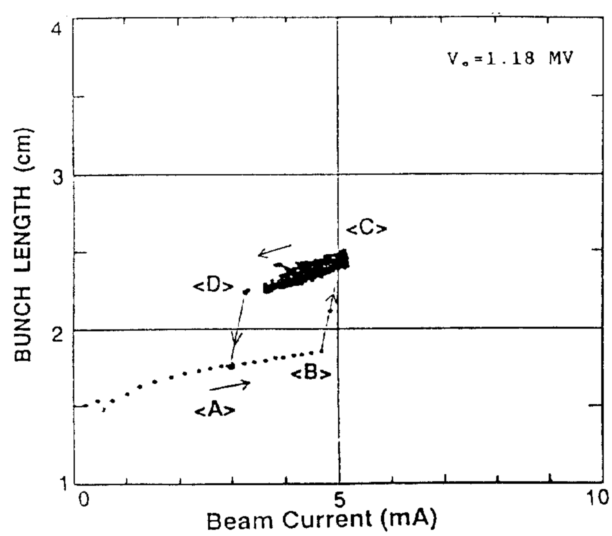

Fig. 3 Hysteresis of a jump in the bunch length as a function of the current at Vc=1.18 MV.

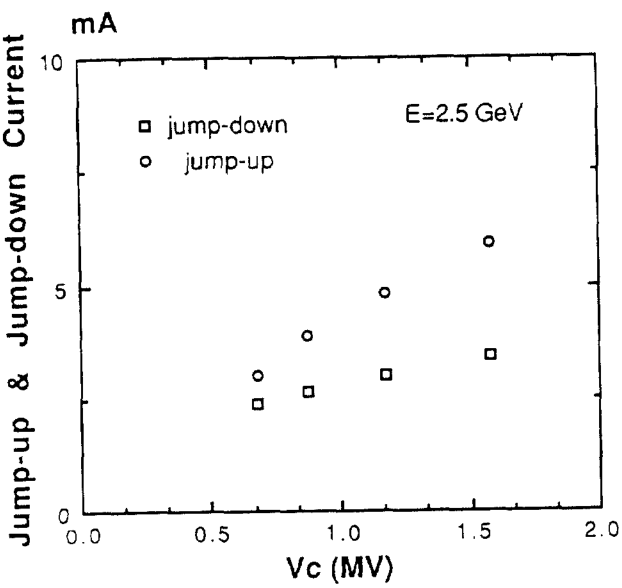

Fig. 4 Jump-up and jump-down currents in the hysteresis as a function of Vc.

4. DISCUSSION

Let's separate the bunch lengthening shown in Fig. 3 into two regions. At a low current region below 3 mA, no coherent oscillation is observed. The bunch length slightly increases. Bunch lengthening data are applied to the potential-well distortion model [4] expressed as

$$\left(\frac{\sigma_l}{\sigma_{l0}}\right)^3 - \left(\frac{\sigma_l}{\sigma_{l0}}\right) = \frac{I_b \cdot \alpha \cdot e}{\sqrt{2\pi} E \nu_{s0}^2} \left(\frac{R}{\sigma_{l0}}\right)^3 \left|\frac{Z(\omega)}{n}\right| \quad . \qquad (1)$$

Here, σ_l is the bunch length, e is the elementary electric charge and $|Z(\omega)/n|$ is the imaginary part of the effective impedance. The effective impedance can be estimated using eq. (1). The measured impedance is 0.9±0.1 and 1.7±0.2 Ω at Vc=1.18MV by the BLM and SC, respectively. The difference may be due to a deformation of the bunch shape.

At a higher current region above 3mA, a bunch is tumbling in the longitudinal phase space and is vertically expanded. One may consider the jump in the bunch lengthening is related to the turbulent instability.[5] The threshold current of the instability is given as

$$I_{th} \cong \frac{\sqrt{2\pi} E \alpha \left(\frac{\Delta E}{E}\right)^2 \sigma_l}{Re\left|\frac{Z(\omega)}{n}\right|} \quad . \qquad (2)$$

The bunch length and the impedance were measured by the two methods. Though there is a difference between their measurements, the threshold current can be estimated using each measured impedance. The calculated energy spread is used in eq. (2). Fig. 5 shows the estimated threshold current as a function of Vc. One may notice a big difference between Fig. 5 and Fig. 4. In Fig. 5, the threshold current decreases as Vc increases. On the contrary, The jump in the bunch length increases as Vc increases in Fig. 4. The reason of the difference is not clear. The vertical instability which occurs in the hysteresis region may play a mysterious role in this bunch lengthening. Further study is needed.

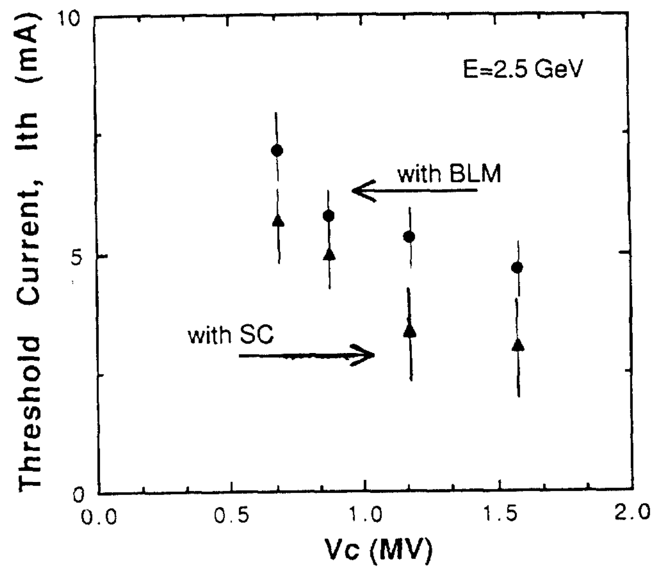

Fig. 5 Estimated threshold current of the turbulent instability using measured bunch lengthening data.

4. SUMMARY

1. The measured bunch length with the BLM agrees with the calculated natural bunch length within 10%. The bunch lengths measured by the BLM and by SC have a slight difference, which may be due to a deformation of the bunch shape.
2. A jump in the bunch length was observed together with coherent oscillations. This jump has hysteresis when the beam current increases and decreases, which suggests a strong nonlinear force in the bunch lengthening.
3. Considering the jumps as the threshold of the turbulent instability, the threshold current is estimated using measured bunch lengthening data. There is a difference between the measured and the estimated thresholds.

5. REFERENCES

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