HYSTERESIS PHENOMENA IN BUNCH LENGTHENING AT THE KEK ACCUMULATION RING

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ABSTRACT

The bunch length was measured using a real-time monitor based on the beam spectrum at the KEK Accumulation Ring (AR). The bunch length has showed hysteresis phenomena as functions of the beam current and of the cavity voltage. It was found that an impedance combination between cavities and unshielded bellows causes the hysteresis using a computer simulation. Moreover, both an observation and the simulation suggest a rather lower threshold current than that previously predicted by the mode-coupling theory in a longitudinal instability.

1 INTRODUCTION

Longitudinal effects of a bunch are discussed with the potential-well distortion[1] and the turbulent instability[2] in electron storage rings. The turbulent instability is excited together with bunch lengthening and energy spreading when the beam current reaches a threshold. The turbulent bunch lengthening is usually evaluated by using the scaling parameter ξ of Chao and Garete[3] or G of P.Wilson[4]. However, some curious phenomena related the turbulent bunch lengthening have been observed. First, the scaling parameter G showed a wiggle as a function of the bunch length when the length is 2cm at SPEAR[4]. The bunch length cannot be determined by only the parameter in this case. Next, a sudden blowup and a slow calmdown in the bunch length were repeated like a sawtooth as a function of time at the damping ring of SLAC[5]. The reason on the sawtooth phenomena is not yet clear. The turbulent bunch lengthening has also been measured at the AR[6]. A discontinuity in the bunch length was noticed as a function of the parameter ξ. The threshold of the instability was tried to explain with the mode-coupling theory[7]. However, coherent synchrotron modes did not couple even when the beam current reached the threshold current of 7mA[8]. Bunch lengthening with turbulence is still in a puzzle in electron storage rings.

2 MEASUREMENT

A single bunch was stored at the injection energy of 2.5GeV of the AR. The bunch length was measured using a bunch-length monitor[9] which compared two frequency components of the beam spectrum. The monitor can automatically measure not only the bunch length in real time but also coherent synchrotron oscillations. The measurement was carried out as a function of the beam current (Ib) under a constant cavity voltage Vc=1.18MV. As the beam current increased, a sudden increase of the bunch length was observed with accompanying coherent synchrotron oscillations from <B>to<C> as shown in Fig.1. An increase of the horizontal beam size was also noticed from the synchrotron light corresponding to the jump. When the current decreased, however, the bunch length did not return to the same path. The bunch length went down from <D>to<A> at a lower current and exhibited hysteresis. The bunch length has two values in the current region between two jumps of <A>-<D> and <B>-<C>. The hysteresis region where two bunch lengths exist depends on the cavity voltage. As Vc increases or the bunch length is shorter, the current region becomes larger. The bunch length was also measured as a function of Vc under a contant Ib. The bunch length did not change as $1/\sqrt{Vc}$ as is expected, but drawed a hysteresis curve when Vc increased and decreased. A bunch has an unstable band of the bunch length at Ib$\approx$5mA.

A longitudinal profile of a bunch was measured from the synchrotron light using a streak camera[10]. Two profiles of shorter and longer bunch lengths in the hysteresis region were obtained. They show a little asymmetric distribution with a shoulder at the shorter bunch length and a rather symmetric one at longer bunch length. A bunch did not indicate a two-peak distribution in the hysteresis region.

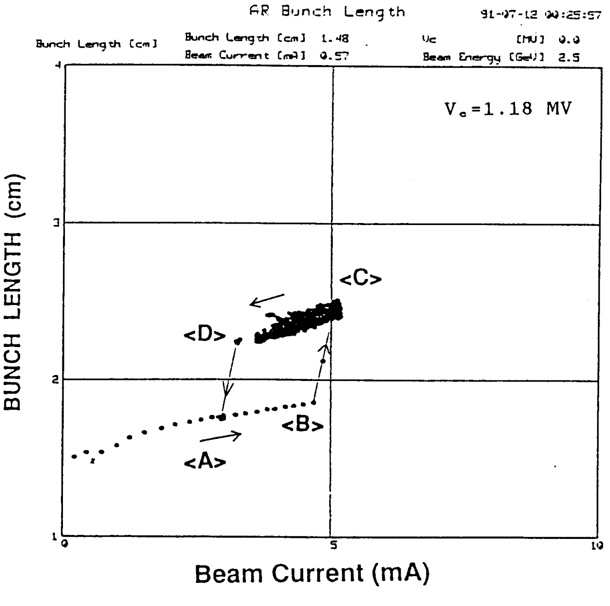

Fig.1 Hysteresis in the bunch length as a function of the beam current at Vc=1.18MV.

3 IMPEDANCE CALCULATION

In order to understand the hysteresis behavior in the bunch lengthening process, a longitudinal impedance of the AR was evaluated using a computer program of ABCI[11]. The ABCI solves the Maxwell equations directly in time domain when a bunch goes though an axisymmetric structure. Main components which may contribute to the impedance are estimated to be the APS cavity[12] and bellows. Eight APS cavities with 11 cells were installed. About 130 bellows with 12 convolutions are installed and the bellows are unshielded. Since the ABCI deals with an axisymmetric structure, crossectional shape of the bellows is modified from a racetruck to a circular type. The ABCI shows that frequency components of the wake of the cavity are mainly less than 2GHz within the beam spectrum. On the other hand, frequency components of the bellows have a peak at 7.5GHz which is higher than the cut-off frequency of the beam spectrum.

Total loss parameter can be obtained by summing up the loss of each component. The calculated wake sources are based on 29 cavities with 3-cell, 130 bellows with 12 convolutions and 6 circular collimators instead of 260 radiation masks. Fig.2 shows the calculated loss parameter as a function of the bunch length together with a measured value[13]. They agree with each other above the bunch length of 1.2cm. The loss parameter is almost governed by that of the cavity when the bunch length is longer than 1.5cm. The loss of the masks is negligiblly small. Though the loss of the bellows is much smaller than that of the cavity, its amplitude of the wake function is comparable with that of the cavity. Therefore, a bunch is strictly affected by these different types of wakes. The impedance of the AR cannot be modeled on a simple broadband impedance.

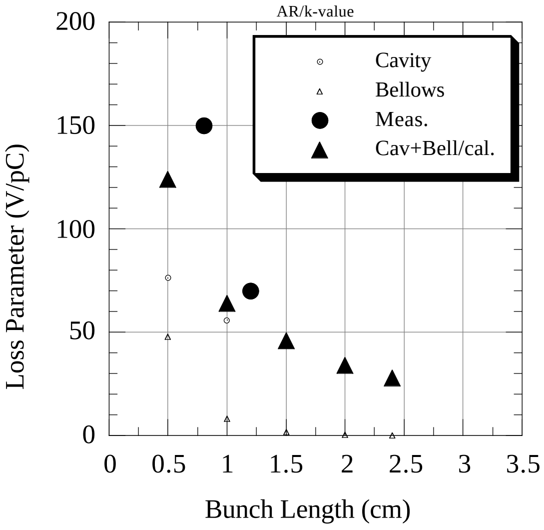

Fig.2 Total loss parameter vs. bunch length.

4 SIMULATION

A computer program[14] which deals with action angle variables (J,ϕ) in the phase space transformed from a Vlasov equation can solve a time-dependent distribution function. A time-dependent distribution function is written as

$$\Psi_1(t)=\sum_{nm}(C_{nm}\cos m\phi+S_{nm}\sin m\phi)\Delta J_n e^{-i\mu\omega_s t}\,. \qquad (1)$$

Here, m is the azimuthal mode number and ω_s is the angular synchrotron frequency. The wake function was calculated with a finite bunch length of 2mm with a step of 0.4mm. Since the wake data before the center of a bunch do not satisfy the causarity of the wake potential, these data are moved to just after the center and added to previous calculated data.

Fig.3 shows eigen frequencies in unit of the synchrotron frequency and its growth rate shown with a crossed bar as a function of intensity. Intensity of I=0.01 in Fig.3 corresponds to the beam current of Ib=1.25mA, where the natural bunch length is 1.5cm. Size of a crossed bar represents a magnitude of growth rate. One may find an instability with Re(μ)=1.0 occures at I=0.015. As the intensity increases further, a strong instability with Re(μ)=2.2 is excited above I=0.04. An instability with Re(μ)=3.2 is also excited. Threshold condition is given as

$$\mathrm{Im}(\mu)=\frac{1}{\tau_d\omega_s}, \qquad (2)$$

where τ_d is the damping time.

The calculated maximum growth rate at a fixed intensity is plotted as a function of the normalized energy spread (S=$\sigma_\varepsilon/\sigma_{\varepsilon 0}$) in Fig.4. One may expect that the growth rate usually weakens due to an effect such as the Landau damping as the energy spread increases. This phenomenon appears at I=0.02. However, the growth rate function changes at I=0.03. The growth rate is not a simple reducing function, but has a peak value as the energy spread increases. A local minimum growth occurs at S=1.05 and the maximum at S=1.15. This function suggests two stable regions of the energy spread or the bunch length at a fixed intensity. One is around the minimum at S=1.05, and the other is above the peak at S=1.30. Eigen frequencies between at S=1.05 and at S=1.30 are different. The maximum growth shifts to higher energy spread of S=1.25 at I=0.04. When the intensity increases to I=0.05, a peak did not appear.

In order to search which components contribute to the peculiar growth rate function, a number of the AR components was artificially varied in the simulation. First, a number of bellows was reduced from 130 without changing the cavity. The peak value of the growth rate function was increased. However, when all bellows were removed, a peak did not appear. On the contrary, when a number of the cavity was reduced from eight under fixed bellows, the growth rate was reduced. When a number of the cavity was four, the growth rate was a simple reducing function at I=0.03. These results suggest that main contribution is due to the cavity and contribution from the bellows is indispensable.

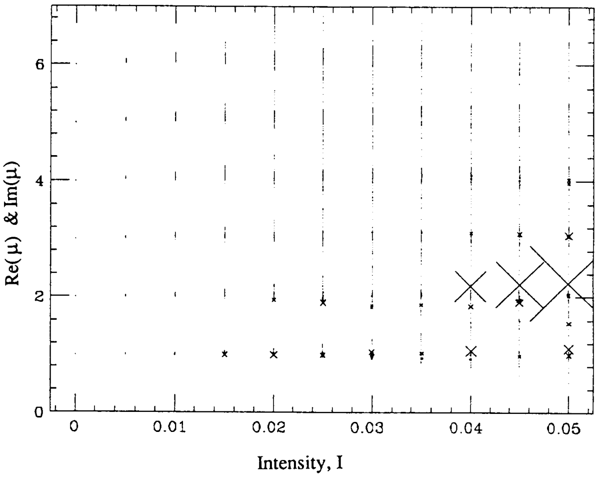

Fig.3 Eigen frequencies in unit of the synchrotron frequency as a function of intensity, I at the natural bunch length of 1.5cm. I=0.01 corresponds to Ib=1.25mA. Magnitude of crossed bars represents growth rate.

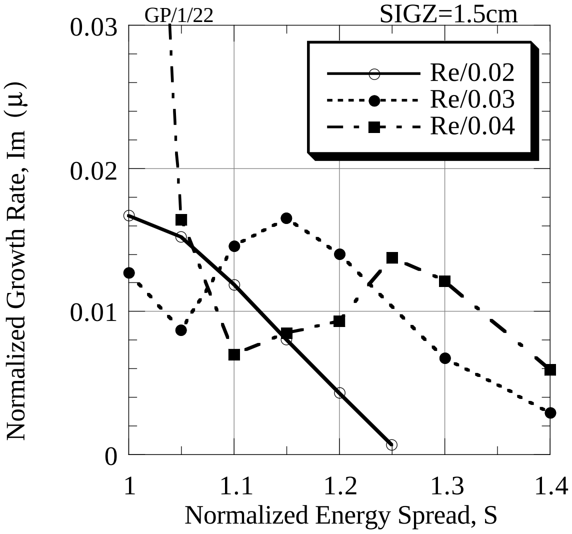

Fig.4 Normalized growth rate as a function of normalized energy spread at the natural bunch length of 1.5cm.

5 COMPARING MEASUREMENT WITH SIMULATION

The hysteresis region where two bunch lengths exist was found in the experiment. On the other hand, the simulation shows that the growth rate function has a peak. The hysteresis region corresponds to a region with a peak. Applying a measured damping time of 1ms to the simulation, two bunch lengths exist at both sides of the peaks in Fig.4. Since a bunch in the hysteresis region was observed with coherent oscillations, a stable condition may not be always required.

Both the measurement and the simulation indicate that twice the synchrotron frequency decreases by about 2.5% when the bunch length increases by 20%. The simulation never indicated a two-peak longitudinal distribution. The measurement and the simulation are consistent with each other from the results described above.

Assuming that the threshold of a longitudinal instability is an onset of coherent oscillations, the simulation predicts rather low threshold current of I=0.015 as shown in Fig.3. On the other hand, coherent synchrotron sidebands was measured at 4.25GHz using a spectrum analyzer. When the beam current was 1.8mA, a small sideband at fs appeared below the revolution harmonics by -40dB. The oscillation was weak with the amplitude of 2ps. When the current was 4mA, oscillations around twice the synchrotron frequency were observed as expected in the simulation. Threshold current of less than 4mA is lower than that previouly predivcted by the mode-coupling theory.

In conclusion, two remarkable impedance sources due to the multi-cell APS cavity with 88 cells and 130 unshielded bellows cause the hysteresis phenomena. The threshold current of a longitudinal instability is less than 4mA, which is lower than that previously predicted by the mode-coupling theory. The author would like to thank Dr.K.Oide for introducing the simulation and discussing the hysteresis. The author also acknowledges discussion on impedance calculation with Dr.Y.H.Chin.

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