Impedance Measurement Utilizing Bunch Lengthening Effect in ATF Damping Ring

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Abstract

The inductive component of the longitudinal impedance in the ATF damping ring was measured using the bunch lengthening effect with streak camera. The amount of inductance was evaluated to $L = 52.8$nH. It was consistent of the simulated value with TBCI and ABCI codes.

1 Introduction

The vacuum chamber in the ATF damping ring is designed to keep low impedance for avoiding a single bunch instability[1, 2]. The threshold of the single bunch instability is correlated to the absolute value of impedance $|Z_{\|}/n|$. It was reported that the purely resistive impedance generated a new type of longitudinal single bunch instability extremely[3], and the threshold of single bunch instability for the vacuum chamber of the inductive impedance was higher than the purely resistive one. On the other hand, the induced voltage by a single bunch passing through an inductive component of $Z_{\|}/n$ has the slope of the opposite sign of RF field, and it generates significant bunch lengthening. For intence, it was measured that the rms bunch length was increased by 60% at 3×10^{10} for old inductive vacuum chamber in SLC damping ring[4].

2 Inductive Impedance

2.1 Vlasov equation

The beam current distribution below the turbulent threshold, calculated with Vlasov equation[5], is given by

$$I(t) = K \exp\left(-\frac{t^2}{2\sigma_{t0}^2} + \frac{1}{\dot{V}_{RF}\sigma_{t0}^2}\int_0^t dt'\, V_{ind}(t')\right) \quad (1)$$

,where σ_{t0} and $\dot{V}_{RF}$ are the natural bunch length and the slope of the rf voltage at the position of the bunch. Furthermore, V_{ind}, the transient induced voltage with $t = 0$ the synchronous position for the low current beam, is given by

$$V_{ind}(t) = -\int_0^{\infty} dt'\, W(t')\, I(t - t') \quad (2)$$

with $W(t)$ a Green function of the longitudinal wakefield. The value of the normalized constant K in Eq.(1) is defined as the complete integral of $I(t)$ is equal to the total charge in bunch Q. If we know the Green function of the wakefield, Eq.(1) can be solved numerically to give the current distribution of the bunch in the present wakefields. By taking the derivate of both side of Eq.(1),

$$\frac{\dot{I}}{I} = -\frac{t}{\sigma_{t0}^2} + \frac{V_{ind}}{\dot{V}_{RF}\sigma_{t0}^2} \quad (3)$$

is derived as another formation of it.

2.2 Purely Inductive Impedance Model

In the ATF design[1], the amount of resisteive part is very small, so it can be ignored for the bunch lengthening. When the impedance of the ring is assumed to purely inductive one, namely the induced voltage is given by

$$V_{ind} = -L\,\frac{dI}{dt} \quad (4)$$

with a constant inductance L, Eq. (3) can be written as

$$\frac{dy}{dx} = -\frac{xy}{1+y} \quad (5)$$

with the variables of $x = t/\sigma_{t0}$, $y = LI/\dot{V}_{RF}\sigma_{t0}^2$. Here, it is possible to define the normalized charge Γ, the complete integral of y, as follows

$$\Gamma \equiv \int_{-\infty}^{\infty} dx\; y = \frac{LQ}{\dot{V}_{RF}\sigma_{t0}^3} \quad (6)$$

The numerical solution of Eq. (5) is shown in Fig. 1(a) for several values of Γ. The charge distribution for a perfect inductor is symmetric about $x = 0$ and it is almost the same as Gaussian distribution at low intensity regions. On the other hand, it is apparent that the solution of Eq. (5) is rather parabolic distribution than Gaussian distribution whenever $y \gg 1$. The σ_x values of Gaussian function for various Γ values is

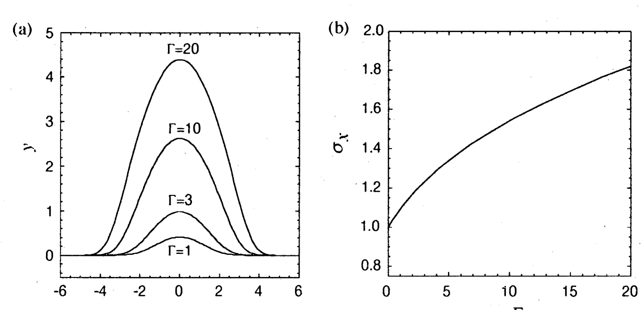

Fig. 1 (a) The bunch shape for several values of bunch charge, and (b) The bunch length variation as a function of bunch charge

Table 1
Main Parameter of Streak Camera

Vertical Sweep Unit	
streak time range	0.2ns to 50ns
resolution	1.5ps for 0.2ns range
repetition rate	max. 10 kHz
Horizontal Sweep Unit	
sweep range	100ns to 100ms
Sensitive Wavelength	400 to 900mm
MCP gain	max. 3000

shown in Fig. 1(b). Fig. 1(b) shows that σ_x varies like as linear for small current regions and roughly as $\Gamma^{\frac{1}{3}}$ for large current regions.

3 Bunch Lengthening in ATF Damping Ring

3.1 Experimental Apparatus

DC Current Transformer (DCCT)

The beam current was measured with DCCT located at straight section in the ATF damping ring. The characteristic of DCCT is not perfectly linear, but has some of deformation come from readout electronics. Thereby, we used the 3 dimensional polynominal calibration curve shown in Fig.2(a). It is found from Fig.2(b) that the displacement from calibration curve is 0.044% rms at the bunch population of 5×10^9 and the displacement is much smaller than the contribution of the thermal noise from readout electronics. The thermal is the main error source of this DCCT current monitor system, however the contribution, which is about 0.3% rms for 5×10^9 beam, is also small fraction of the error component in this measurement.

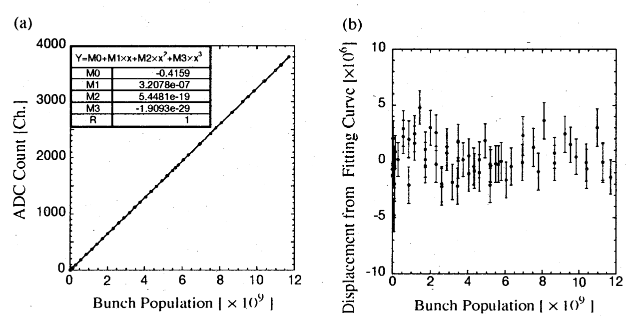

Fig. 2 The characteristic for DCCT : (a) Beam Current vs. ADC counts, and (b) The displacement from calibration curve

Streak Camera [6, 7]

The bunch length was observed by streak camera (Hamamatsu, C5680). Main parameter of the streak camera are given in Table 1. Horizontal and vertical ranges of 100ms and 1ns are adopted in this measurement, respectively. The resolution for this range is about 1.5mm caused by beam spot size at the streak tube. The contribution is subtracted from the longitudinal profile, then the bunch length is calculated as follows:

$$\sigma_z = \sqrt{\sigma_{meas.}^2 - \sigma_{spot}^2} \qquad (7)$$

with $\sigma_{meas.}$ the measured bunch length and σ_{spot} the contribution from the beam spot size at the streak tube. Furthermore, it is known that the effect of the measured pulse length increases with high intensity of incident light pulse, especially for short pulses[8]. It is called space charge effect inside the streak tube. For the preparation of the bunch length measurement, the effect was measured by inserting the ND filters of several transmission ratios at the entrance of the streak camera for the same bunch population of the beam(5×10^9). the results is shown in Fig.3. We chose the 15% ND filter, which enhansed the bunch length by 5% at the bunch charge of 5×10^9, for the bunch length measurement and we carried out the correction of the contribution for space charge enhancement with linear function. The correction factor is evaluated as follows:

$$f_{S.C.} = (8.72 \pm 0.81) \times 10^{-11} \quad \text{[mm/particles]} \qquad (8)$$

From Eq.(7),(8), the bunch length is evaluated with streak camera and 15% ND filter by

$$\sigma_z = \sqrt{\sigma_{meas.}^2 - \sigma_{spot}^2} - f_{S.C.} \times N_{bunch} \qquad (9)$$

with N_{bunch} the bunch population.

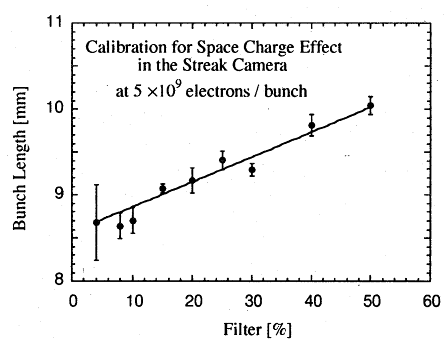

Fig. 3 The measured bunch length with streak camera by inserting the ND filters of several transmittion ratios.

3.2 Bunch Lengthening Measurement

The parameter of the ATF damping ring is listed in Table 2. The result of correlation plot for the bunch population and the bunch length is shown in Fig.4. The bunch lengths in Fig.4 are already made the correction by Eq.(9). Here, the normalized charge of Γ in Eq.(6)

Table 2
ATF Damping Ring Parameter at This Measurement

Beam Energy	1.299 GeV
Bunch Population	up to 5.5×10^9
RF Frequency	714 MHz
RF Voltage	220.6 kV
Harmonic Number	330
Momentum Compaction	1.96×10^{-3}
Synchrotron Frequency	8.95 kHz

can be evaluated by applying the curve of Fig.1(b), that is

$$\Gamma/N_{bunch} = (1.39 \pm 0.07) \times 10^9 \quad , \qquad (10)$$

$$\sigma_z = 6.83 \pm 0.05 \ \text{[mm]} \quad . \qquad (11)$$

From Eq.(6),(10),(11) and Table 2, the inductive component of the longitudinal impedance for the ATF damping ring can be evaluated as follows.

$$L = 52.8 \ \pm 1.3(S.C.) \ \pm 2.7(fit.) \ \text{[nH]} \qquad (12)$$

The fraction of error for "space charge" in Eq.(12) are evaluated by the slope error in Eq.(8) and the ratio of the slope for the bunch length enhancement of the space charge to the potential well distortion, "fitting" error comes from the contribution of the error in Eq.(10),(11). The inductance in Eq.12 corresponds to the longitudinal impedance of $|Im(Z_{\|}/n)| \approx 0.114\Omega$.

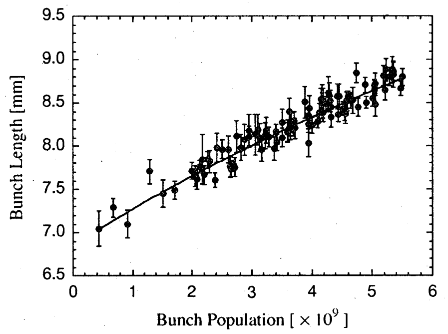

Fig. 4 The correlation plot for bunch population and the bunch length.

3.3 Effect of Intra Beam Scattering

There is another possibility for the bunch lengthening with increasing the beam current. It is called the intra beam scattering and the bunch length caused by the intra beam scattering is depends upon the volume of the bunch. The bunch lengthening calculated with SAD codes[9] for intra beam scattering is shown in Fig.5 for the various ratios of vertical emittance to horizontal one. Furthermore, it is reported that the dispersion ratio of vertical to horizontal is about 30%, which generates the vertical emittance of 30% for horizontal one, by the previous experiment in the ATF damping ring[10]. Hence, the vertical emittance of the beam in the ATF damping ring is evaluated larger than 30% compared to horizontal one. From Fig.5, it is estimated that the effect of the intra beam scattering for the longitudinal inductance is less than 6.7nH. The value of 6.7nH is, however, a little bit overestimated for the reason why the SAD calculation in Fig.5 is not included the effect of the bunch lengthening for potential well distortion.

4 Consideration

The measurement has good agreement with the simulation results for the designed impedance[1]. The inductive impedance sources are, however, not evaluated with actual geometories, but evaluated with approximate 2 dimensional geometories using TBCI and ABCI codes. Furthermore, the recent impedance of the ATF

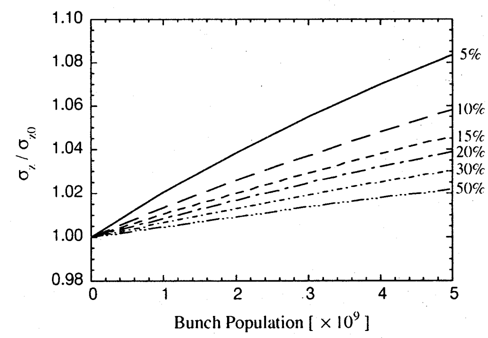

Fig. 5 The bunch lengthen caused the intra beam scattering for various emittance ratios of vertical to horizontal.

damping ring is small compared to the design for the reason why 2 RF cavities are only located in the ring, the cavities are, however, capacitive rather than inductive. The more precise calculation of the impedance for the ATF damping ring is in progress.

5 Summary

The inductive component of the longitudinal impedance in the ATF damping ring was measured using the bunch lengthening effect with streak camera. The amount of inductance was evaluated to $L = 52.8$nH. It was consistent of the simulated value with TBCI and ABCI codes. We plan to make certain of the inductive component of the longitudinal impedance and to measure the synchrotron phase shift, the spectral analysis of BPM electrodes and the phase shift to estimate the absoulte value of the longitudinal impedance $|Z_{\|}/n|$ and to investigete the single bunch instability.

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