Bunch Lengthening caused by HOM in HiSOR electron storage ring

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Abstract

Bunch lengthening phenomena have been observed in HiSOR. Longitudinal coherent bunch oscillation is observed and a HOM about 1.3GHz is excited in the rf cavity when bunch is lengthened. A calculation by the computer code MAFIA and HOM survey using low power rf on the cavity show that the HOM of 1.3GHz actually exists in the cavity and causes coupled bunch instability. Detailed measurements show that the HOM causes the bunch lengthening through the coupled bunch instability. Simulation calculation in which fundamental mode voltage and HOM voltage are assumed indicates that 1.3GHz HOM can cause bunch lengthening.

1 Introduction

HiSOR is a dedicated ring for VUV/soft X-ray SR source. One feature of this ring is employing low energy injection, another is a racetrack type compact ring consisting of two 180° bending sections and straight sections. A RF cavity of the type of re-entrant is employed and operated at 191.244MHz. Main parameters of HiSOR are listed in Table 1.

Energy	E	150MeV (@injection) 700MeV (@storage)
Circumference	C	21.194m
RF frequency	f_{RF}	191.244MHz
Harmonic number	h	14
Momentum compaction factor	α	0.136
Synchrotron frequency (typical)	fs	70kHz (@150MeV) 120kHz (@700MeV)
Cavity voltage (typical)	Vc	10kV (@150MeV) 210kV (@700MeV)

Table 1 Main parameters of HiSOR

To achieve more intense or high quality beam, it is essential to investigate and take proper measures against beam instabilities.

We have measured current dependence of bunch length in single and full bunch operation at 150MeV and 700MeV. The results are shown in Figure 1[1].

At 150MeV, bunches are lengthened significantly from low current for both single and full bunch. On the other

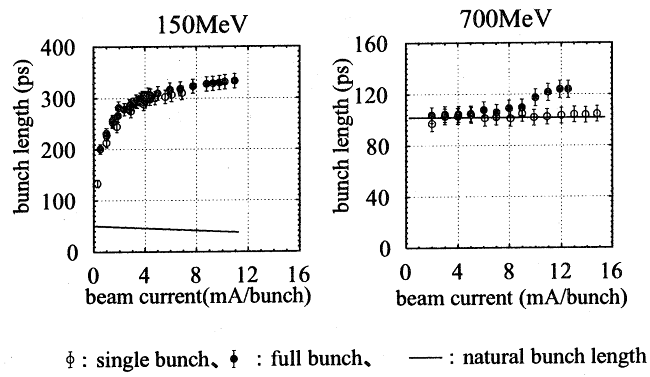

Figure 1 bunch lengthening in HiSOR

hand, at 700MeV, bunch lengths are almost equal to natural bunch length up to about 7mA/bunch for both single and full bunch. But above that threshold current, bunch length for full bunch largely lengthen while single bunch's is almost constant. It is remarkable that bunch makes coherent oscillation and HOM of about 1.3GHz is excited in cavity, when bunch is lengthened in any operation mode.

From these results, it has been considered that coupled bunch instability dominates bunch lengthening.

In order to reveal the effects of the coupled bunch instability, we have measured the relation among the bunch lengthening, the amplitude of the coherent bunch oscillation and the HOM excitation around the threshold current of the bunch lengthening in the 700MeV full bunch operation.

2 Measurement

Experimental setup is shown in Figure 2. The charge distribution in a bunch was measured by observing the synchrotron light with a streak camera (HAMAMATSU : C1370-01). The bunch length was defined as a RMS of the charge distribution in a single shot of the streak camera. The frequency analysis of the bunch oscillation was made by feeding the signal from the button electrode of the beam position monitor to a spectrum analyzer (HP8543E), which also detected the HOM in the rf cavity. From the frequency analysis of the bunch oscillation, it is clarified that the coherent oscillation of the bunch, when it is appeared, is a type of mode12 ($nf_{RF}\pm(12f_{rev}+f_s)$). It is also clarified that the HOM frequency ($=6f_{RF}+12f_{rev}+f_s$) corresponds to the mode of the coherent bunch oscillation. The frequency analysis of the bunch also gave the bunch length in addition to the measurement by the streak camera.

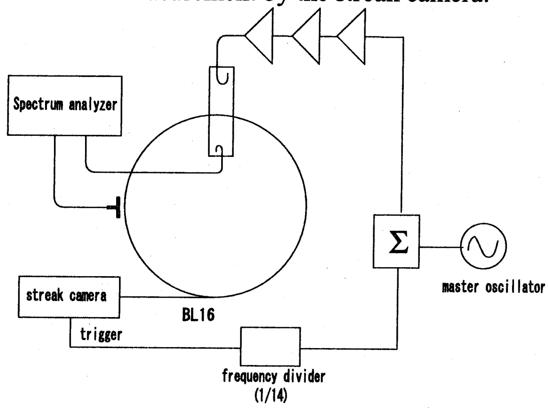

Figure 2 Experimental setup

3 Results

The results of the measurement are shown in Figure 3, where (a) the bunch length, (b) the HOM strength and (c) the amplitude of the mode12 coherent oscillation of the bunch are shown as a function of the beam current. In Figure2 (a), the bunch lengths measured by the spectrum analysis are plotted together with those measured by the

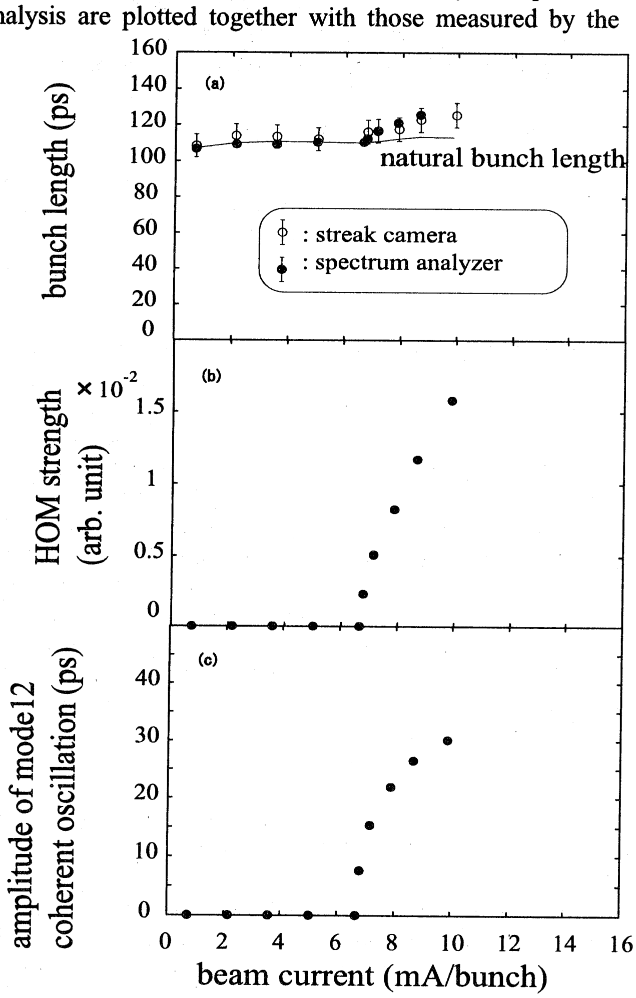

Figure 3 Current dependence of (a) bunch length, (b) HOM strength and (c) amplitude of coherent oscillation at 700MeV full bunch

streak camera, which are consistent with each other. They clearly show a threshold at 6.8mA. The natural bunch length shown in the figure is usually given from the rf field. The rf field of the HiSOR, however, is not constant, and then we have got it by measuring the synchrotron oscillation and by using the formula [2]

$$\sigma_0 = \frac{\gamma\alpha}{2\pi f_s}\sqrt{\frac{C_q}{J_\varepsilon \rho}} \tag{2}$$

where γ is the relativistic factor of the electron, C_q is a quantum coefficient and J_ε is a damping partition number that is 2 for HiSOR. The amplitude coherent bunch oscillation of the mode 12 was calculated using following equation.

$$\begin{aligned} I(t) = 1 &+ 2\sum_{l=1}^{\infty}(-)^l J_l(lM\delta l \cos(lM\omega_0 t) \\ &+ 2\sum_{n=1}^{\infty} J_0(nh\delta n\cos(nh\omega_0 t) \\ &+ 2\sum_{n,l=1}^{\infty}\{J_l((nh-lM)\delta)\cos(n\omega_0 - lM\omega_0)t \\ &\qquad + (-)^l J_l((nh-lM)\delta)\cos(n\omega_0 - lM\omega_0)t\} \end{aligned} \tag{1}$$

where J_l is bessel function, l is oscillation mode, M is coupled bunch mode, ω_0 is revolution angular frequency and δ is amplitude of coherent oscillation.

It is clearly seen that the HOM excitation and coherent oscillation of the bunch occurs at exactly the same threshold of the bunch lengthening, and they grow stronger as the bunch length becomes longer. These experimental results show that the bunch lengthening is caused by the coupled bunch instability.

4 HOM evaluation

Characteristics of the cavity HOM is required to estimate the threshold of coupled bunch instability. We have made two approaches to reveal the HOM characteristics: (1) computer code MAFIA (2) low power measurement on the real cavity and the model cavity.

2.1 Computer Code by MAFIA

The calculation by MAFIA shows the HOM with a frequency 1.3GHz is like a TM022 mode, which generates a longitudinal electric field at the cavity axis and can affect the electron bunch. Other calculation results for this mode are given in Table 2.

Mode	TM022 like (Longitudinal)
R/Q (defined as $V_c^2/\omega U$)	15.8Ω
Q	40000
Resonant frequency	1.297GHz

Table2 calculation result about 1.3GHz HOM

2.2 Low Power Measurement

Network Analyzer (HP8573E) was used to measure the resonant mode of cavity. Actual resonant frequency was measured on the real cavity from S11 of L-coupled loop, and Q-value was done on the model cavity which made from Aluminum with S21 from C-coupled cable to L-coupled loop considering electric conductivity. As a result, we got the resonant frequency and Q-value of HOM at 700MeV condition to be 1.312GHz and about 30000, respectively.

2.3 Coupled Bunch Instability threshold

We estimated the threshold current of coupled bunch instability caused by the 1.3GHz HOM, assuming at threshold current growth rate of coupled bunch instability is equal to radiation damping rate. Radiation damping rate was calculated from synchrotron frequency using fundamental formula and to be 2.1ms. Growth rate was calculated using following equation [3].

$$\tau^{-1} = \frac{N r_0 \alpha}{2\gamma T_0 \omega_s} \sum_{p=-\infty}^{+\infty} (p\omega_0 + \omega_s) \mathrm{Re} Z_0''(p\omega_0 + \omega_s) \quad (3)$$

The results of estimation are listed in Table3. It is suggested that at 150MeV coupled bunch instability is dominant from low current for both single and full bunch. It is also suggested that at 700MeV, the threshold current for single bunch is much higher than the threshold current for full bunch. Although these situations strongly depend on the HOM frequency, these estimations are consistent with the instabilities observed in HiSOR.

Beam condition		threshold current
150MeV	Single	30(μA)
	full	1.2(μA/bunch)
700MeV	single	140(mA)
	full	5(mA/bunch)

Table 3 Estimation of the coupled bunch instability threshold for each operation mode.

5 Simulation

To investigate the mechanism of bunch lengthening, we performed tracking simulation. We simulated two situations : (1) coupled bunch instability is not occurred and (2) coupled bunch instability is occurred. For the case of (1), only the fundamental mode (191.244MHz=f_{RF}) voltage affects particles are affected, while For the case of (2) not only fundamental mode voltage but also HOM (1.311GHz=$6f_{RF}+12f_{rev}+f_s$) voltage induced by the coherent bunch oscillation affect. For simplicity no interaction

	(1)	(2)
Acceleration voltage	190kV	
HOM voltage	0V	1kV
Amplitude of mode 12 coherent oscillation	0ps	30ps
fs sideband at 1.3GHz	0A	4mA
Natural bunch length	115ps	

Table 4 parameters used in simulation for each condition : (1) coupled bunch instability is not occurred and (2) coupled bunch instability is occurred.

between beam and cavity impedance was considered. Damping mechanism is also not considered. In this simulation 10^4 particles contained in a bunch and the bunch length is defined as RMS of the particle distribution. Parameters used in simulation are listed in Table4. Fundamental mode voltage was calculated from synchrotron frequency. HOM voltage was estimated from amplitude of coherent oscillation of bunch.

Simulation results are shown in Figure 4 for the case of (1), i.e. without HOM voltage, bunch length is almost equal to natural bunch length. For the case of (2), bunch length become longer than natural bunch length.

Although absolute value of the bunch length is not in concern since so simple, the simulation results suggest that HOM voltage induced by bunch coherent oscillation cause bunch lengthening.

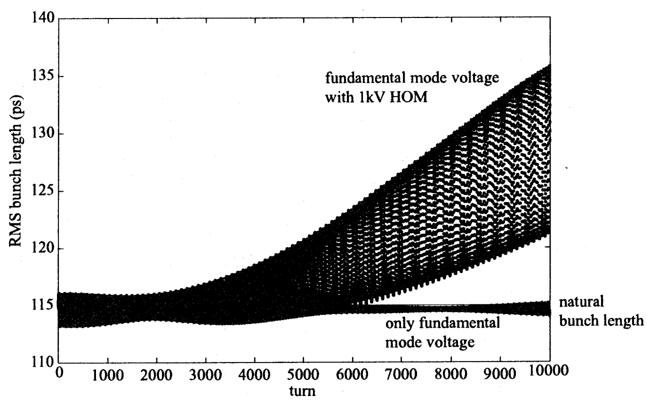

Figure 4 simulation result on bunch lengthening for with and without HOM voltage. Solid line is natural bunch length.

6 Summary

We studied the characteristics of 1.3GHz HOM and the correlation between coupled bunch instability and bunch lengthening those were excited above 7mA/bunch under 700MeV full bunch operation at HiSOR. Investigation about cavity using MAFIA and low power measurement reveal that Longitudinal HOM exists around 1.3GHz in cavity and can cause coupled bunch instability which has been observed. Measurement indicated that there was correlation between amplitude of coherent oscillation and bunch length. Simulation in which acceleration voltage and HOM voltage were assumed was performed. Simulation result indicated that HOM voltage could cause bunch lengthening.

7 References

[1] T.Fujita, K.Umemori et al., "Bunch lengthening in compact SR source HiSOR", Nucl. Instr. Meth. A 467-468, pp.95-98 (2001)

[2] R.F.Stiening and J.E.Griffin, "Longitudinal instabilities in the FERMILAB 400-GeV Main Accelerator", IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June, 1975

[3] A.W.Chao, Physics of Collective Beam Instabilities in High Energy Accelerators (Wiley, New York, 1993)