TRANSVERSE COUPLED BUNCH INSTABILITY DRIVEN BY 792-MHZ CAVITY HOM IN NEWSUBARU ELECTRON STORAGE RING

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Abstract

The 792-MHz HOM of the RF cavity can drive horizontal coupled bunch instability in the NewSUBARU electron storage ring. Detailed characteristics of this instability were investigated by changing the HOM frequency, betatron tune, chromaticity and magnitude of the stored current at the energy of 1 GeV. The experiments were performed under the condition that the only one mode can be excited and the stored current was limited as ~ 3.4 mA/bunch to avoid catastrophic blow up. The measured results showed saw tooth oscillation and were compared with an analytical calculation using a rigid bunch model. The co-existence of the longitudinal modes ; l = 0 and l = ± 1 might produce complicated beam behaviour.

INTRODUCTION

The main parameters of the NewSUBARU storage ring [1] are summarized in Table 1. There is one HOM damped RF cavity with SiC absorber [2], but there still exists a strong HOM near 792 MHz which kicks an electron beam horizontally and drives transverse coupled bunch instability. This limited the maximum stored current at the initial operation even for the horizontal chromaticity (ξ_x) of ~ 3.5. This is now completely avoided by tuning HOM frequency with a HOM tuner as shown in Fig.1, where the tuner for the control of the main acceleration mode is shown as " FB Tuner ". It is very interesting for beam dynamics to know detailed behaviours of this instability because the driving mechanism is simple and well known.

Table 1: Main Parameters of NewSUBARU Ring

Circumference	118.7 m
Injection Energy	1.0 GeV
Maximum Energy	1.5 GeV
Harmonic Number	198
RF Frequency	499.955 MHz
Betatron Tune ν_x	~ 6.29
Synchrotron Tune ν_s	~ 0.002

MEASURING METHOD

Environment of Excitation

The following set up was approved to clarify the unstable oscillation. The position of the HOM tuner (HMP) was set at 7 mm easily to fit the resonance condition, $f_{HOM} = f_{ReV}$ (kM - μ - [ν_x] - $l\ \nu_s$) , where f_{HOM} and f_{ReV} are the frequencies of the HOM and the beam revolution, [ν_x] is the fractional part of the horizontal betatron oscillation tune, ν_s is the synchrotron oscillation tune, μ is the mode number, l is the longitudinal mode number, M is the number of equi-spaced bunches and k is integer (HMP is 10 mm for the ordinal operation). f_{HOM} was precisely adjusted by the FB tuner with setting the detuning angle suitably. The frequency change due to the FB tuner position (FBP) is estimated as - 87 kHz/mm from the different measurement by a network analyzer. M was selected as 6, then only μ = 4 could be excited because $f_{HOM} / f_{ReV} \approx 313.7 = 6*53 - 4 -$ [ν_x] . ξ_x was set at 0.52 and the bunch current (I_b) was set at ~ 3.4 mA to observe clear unstable but non-catastrophic oscillation. The beam energy is 1 GeV and the RF voltage is ~ 100 kV. The FB tuner is sometimes noted as " Tuner " in figure.

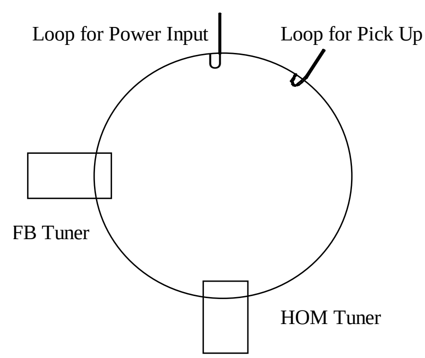

Figure 1: Cross section of the RF cavity.

Bunch Oscillation

The streak camera of Hamamatsu Photonics C6860 was used in dual sweep mode to measure relative horizontal position of each bunch. This also gave information about horizontal tilts of bunches.

Oscillation Growth

The output signal of Bergoz LR-BPM-500MHz circuit for one BPM were measured by the digital oscilloscope Lecroy WavePro 7300. (The output is calibrated by the closed orbit correction system.) This gave the oscillation amplitude of the bunch centre and its growth time.

~ 792 MHz HOM

The pickup signal of the RF cavity was fed to the real time spectrum analyzer : SONY Tektronix 3056 to measure the excited HOM power and frequency. The output signal of an ion-clearing electrode (ICE) was also fed to this analyzer to observe the beam oscillation itself in frequency domain.

MEASURED RESULTS AND COMPARISON WITH PERTURBATION CALCULATION

Mode number and Head - Tail Phase

The horizontal oscillation of bunches were measured by the streak camera at first. Deviation of the bunch centres from those in stable case and the tilts in 100 psec were fitted by sinusoidal functions. The mode number was confirmed as 4 and the head-tail phase was obtained as 0.65 (rad.) which agrees with the theoretical estimation of 0.64 (rad.).

Saw Tooth Instability

Oscillation of bunch centres showed a saw tooth shape as shown in Fig.2 and this pattern differed from a clear periodic one to a complicated one according to the detuning of f_{HOM} (distance from resonance). It showed random pattern at FBP = 6.5 ~ 6.7 (mm) and there was no equilibrium or steady-state.

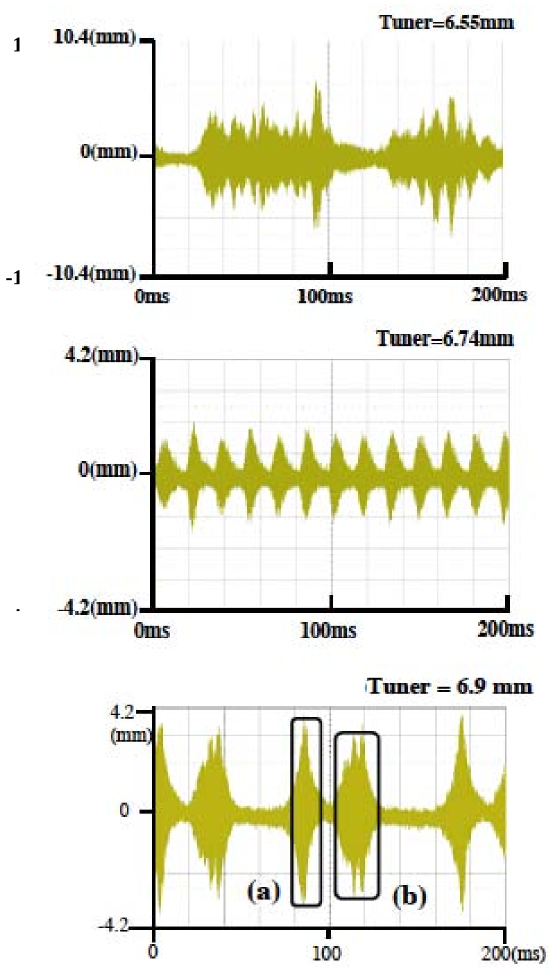

Figure 2: Outputs of the Bergoz circuit. These shows typical oscillation patterrn of bunch centres.

Growth Time

The true growth time (τ_G) was estimated from the measured rise time by subtracting the radiation damping time (τ_R, 22 ms) and is shown in Fig.3 in comparison with perturbation calculation [3]. (The following parameters were used. R_{sh} : 7.8 MΩ/m, Q = 2845, Bunch length : τ (psec) = 60 (I_b < 0.88 mA) & 71.8 $I_b^{1/3}$(mA) - 8.76 (I_b > 0.88 mA), β_x : 11 m) The smallest value was approved for random patterns. We assumed that FBP = 6.59 (mm) for f_{HOM} = 313.71*f_{ReV}. Growth time is essentially explained by the calculation (l = 0 mode).

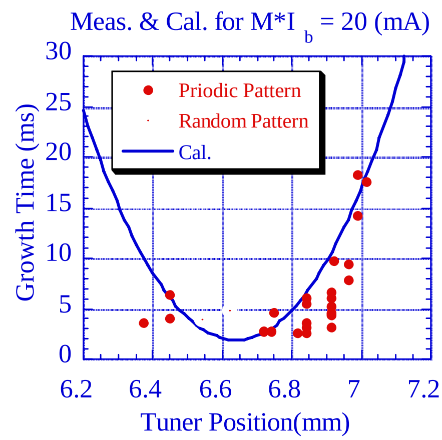

Figure 3: True growth time. Circles; measured, line ; calculation (l = 0 mode).

Damping Time

The damping was assumed due to Landau damping and then the observed damping time is given by $1/\tau_{MD}=1/\tau_R+1/\tau_{DC}$ where τ_{DC} is the decoherence time due to a tune spread. It should be noted that a tune spread due to chromaticity and momentum spread does not contribute because these produce oscillation of tunes and results in the head-tail phase shift.

Tune Spread and Horizontal Emittance

The amplitude dependent tune shift ($\Delta\nu$) was estimated from the spectrum shift of HOM signal of the cavity and the corresponding Bregoz signal. Assuming β_x = 10 (m) and the same mechanism works on tune spread ($\delta\nu$), we had $\delta\nu = 4.5 \times 10^{2}\ \varepsilon$ where ε is the horizontal beam emittance (natural emittance is ~ 40 nm). These are estimated as shown in Fig.4 (we use $\delta\omega_\beta = 2\pi / \tau_{DC}$). Here we suppose that a drastic blow up of emittance occurs at the maximum oscillation.

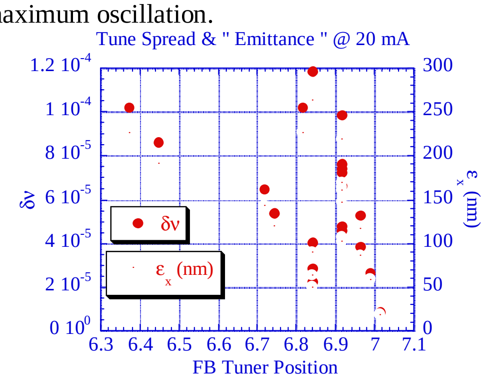

Figure 4: Estimated tune spread and emittance for Landau damping. Closed circle: tune spread, open: emittance.

Possibility of l = ± 1 mode

The horizontal beam size became wider by 2.5~3 times when the FBP = ~ 6.8 (mm) and the beam lifetime also became longer as seen in Fig.5. There was clear correlation between lifetime and a horizontal beam size obtained by the streak camera. But we could not find any saw tooth behaviour for the beam size. This might be the result of random trigger of the streak camera in our measurements.

There were two clear sidebands of synchrotron oscillation in both HOM signals from the cavity pickup and ICE. The relative power amplitudes of sidebands were about - 35 dB and independent on the FB tuner position. These signals just show synchrotron oscillation which is always excited by the RF control system in this order and can hide l = ± 1 mode signals.

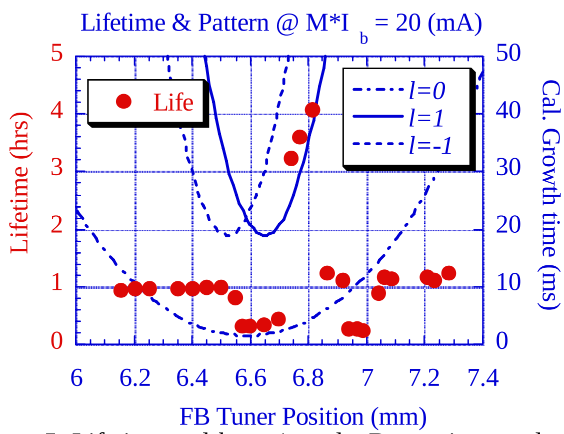

Figure 5: Lifetime and l = ± 1 mode. Beam size was large for long lifetime. Circles: lifetime, lines: growth time.

Although there were no clear signs of l = ± 1 modes in experiments, the calculation shows the possibility of these modes as shown in Fig.5, but no possibility of mode coupling. The maximum amplitudes of coherent oscillation are shown in Fig.6. From these figures and believing the calculation, we could expect that (1) co-existence of l = 0 and +1 modes (FBP : 6.7 ~ 6.9 mm) causes drastic blow up both of tune spread and emittance even for small oscillation of bunch centre and results in longer beam lifetime, (2) l = 0 and ±1 (FBP : 6.5 ~ 6.7 mm) does random saw tooth pattern and permits large coherent oscillation, (3) l = 0 and - 1 (FBP : 6.3 ~ 6.5 mm) does only blow up of tune spread (short lifetime).

DISCUSSION

Two types of saw tooth oscillation were clearly observed at FBP = ~ 6.9 (mm) as shown in Fig. 2 and the trend of the corresponding cavity HOM signal is given by Fig.7 (Every trace needed 2 msec to obtain spectrum).

(a) and (b) show the correspondence. The oscillation in region (a) could be explained by the perturbation theory and amplitude dependent tune shift. This would be l = 0 mode. But what happens in region (b)? Large oscillation amplitude but small tune shift. We suppose that this shows an interference between two modes ; l = 0 and +1. Periodical grow up of bunch centre oscillation would result in emittance blow up and longer lifetime, but this mechanism does not work under an interference between two modes ; l = 0 and -1.

The HOM signal at FTP = 6.5 ~ 6.7 (mm) shifted randomly corresponding to random saw tooth pattern, but did not stay at a fixed frequency (showed tune shift) like those as shown in Fig.7 (a). We suppose that this shows an interference among three modes ; l= 0, -1 and +1.

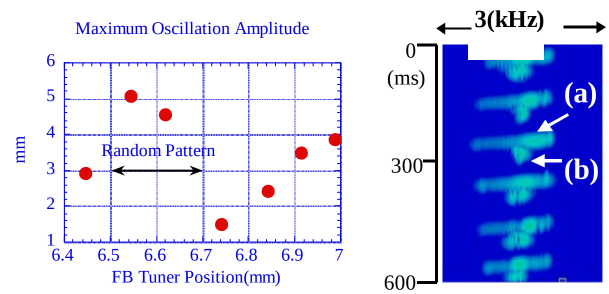

Figure 6: Maximum oscillation amplitude.

These suspicions are phenomenological on the basis of the perturbation calculation.

Damping would be caused by the tune spread which is the result of emittance blow up. This leads naive understanding of longer beam lifetime mentioned in (1) of the previous section. But this could not explain why the observed horizontal beam size was constantly large.

The chromaticity dependence was measured for ξ_x = 0.1 ~ 0.6 and MI_b = 1.5 (mA), The growth time agrees with calculation, but the measured damping time was constantly ~ 40 msec. This means that the growth time abruptly changed to ~ 49 msec when the oscillation reached at the maximum. The damping could be understood as the competition between instability growth and radiation damping, that is, damping mechanism must be completely different between MI_b = 20 and 1.5 (mA).

We just saw the phenomena but cannot understand the fundamental mechanism of saw tooth instability. The more investigation, in particular why there is no equilibrium of bunch centre oscillation, is needed to understand the beam behaviour driven by the TM110 mode in the cavity. We could only explain magnitude of growth time by the perturbation theory.

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