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SUPPRESSION OF LONGITUDINAL COUPLED BUNCH INSTABILITY BY HARMONIC CAVITY IN UVSOR ELECTRON STORAGE RING

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Abstract

In the UVSOR electron storage ring [1], which is dedicated for a VUV synchrotron radiation light source, a longitudinal coupled bunch instability (LCBI) is observed in multi-bunch operation. To suppress the LCBI, we routinely operate a third harmonic cavity (HCV) in a passive mode. By properly tuning the HCV, the instability is almost completely suppressed. Because of the lower beam energy (750 MeV) and brilliant beam emittance (17.5 nm-rad), the Touschek effect becomes severe in the UVSOR. To guarantee enough beam lifetime, we also apply the HCV for lengthening the bunch. The suppression of the instability and increasing the beam lifetime are crucial benefits by the HCV for the UVSOR. However, not only the origin of the LCBI but also the Landau damping effect by the HCV has not been understood systematically yet. We have noticed that one of the HOMs at the HCV itself could cause the LCBI and observed the behavior of the instability, which strongly depends on the beam current. From the experiment we have discussed the cause of the instability with the HOM theory. We have also tried to observe synchrotron tune spread and discussed a competition between the Landau damping and the instability growth.

INTRODUCTION

The UVSOR electron storage ring (UVSOR) is a VUV and soft X-ray synchrotron radiation light source which is mainly used for molecular and atomic science. The UVSOR has started the beam operation on 1983 as a second generation synchrotron light source, and since then, through twice major upgrade and replacement of the accelerator complex, now the UVSOR has been operated as a third generation light source and been continuously operated stably to deliver high quality synchrotron radiation to the users. Not only the upgrade of the storage ring which is used for the light source, but also for the top-up operation the UVSOR facility had an upgrade to a booster synchrotron which is operated as an injector for the storage ring. Due to the upgrade of the injector, now the UVSOR has kept enough stability for the beam current. However, the beam lifetime is still one of the main issue; its lower beam energy (750 MeV) and small emittance (17.5 nm-rad) make the condition of the Touschek lifetime severe. Moreover, at present the UVSOR has a longitudinal coupled bunch instability (LCBI) in daily multi-bunch operation for users.

To guarantee enough stability on the stored beam, we have routinely operated a third harmonic cavity (HCV) in passive mode to lengthen the bunch and to suppress the LCBI with Landau damping. The frequency of the main rf accelerating cavity is 90.1 MHz, so the operation frequency for the HCV is 270.3 MHz. In UVSOR, we have routinely operated the HCV system since 1994 [2] to suppress the LCBI. Because of several large upgrade and replacement of the accelerator components, it is supposed that the condition of the coupling impedance in the storage ring has largely changed from the initial condition, however, still we have observed a LCBI after the upgrades. Even though we can suppress the LCBI by operating the HCV with proper tuning condition, we have not yet had enough understanding for the origin of the LCBI in the upgraded UVSOR.

Because over 20 years have passed since the fabrication of the HCV, sometimes we have minor troubles in the HCV because of its aging problem. Now we have started a plan to fabricate a new HCV system for the replacement. In the design process, it is necessary to investigate how much Landau damping effect the new HCV must have for enough suppression of present LCBI. In the consideration, we have tried to make clear the origin of the main source of the LCBI in the UVSOR by systematic beam diagnostics measurements, a theory of the coupled bunch instability and the Laudau damping theory.

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Cause of Longitudinal Coupled Bunch Instability

To observe a dependence of the LCBI on the beam current, we have stored electron bunches in all of the RF buckets (uniform filling) at the beam current of 300 mA which is equal to that in users operation. The HCV has been operated as a passive mode which is the same as in the users operation, and after tuning the HCV properly to suppress the LCBI, we have decreased the beam current intentionally by a beam scraper under the same tuner condition. By decreasing the beam current we have observed the longitudinal beam motion by a visible streak camera with a setup to observe the LCBI. Figure 1 shows a typical result in the experiment in

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3 beam current conditions. As seen in the figure, when the beam current is large enough (300 mA) the LCBI is almost completely suppressed and the beam becomes stable. In the moderate beam current (100 mA), the LCBI starts and the beam becomes unstable. In the small beam current (7.4 mA), the LCBI stops and the beam becomes stable again. This behavior suggests a balance between the growth rate of the LCBI, Landau damping effect and the radiation damping rate. In larger beam current condition, the rf voltage inside the HCV is high enough to Landau-damp the LCBI because of the non linear rf field. When the beam current is smaller, the Landau-damping effect becomes no more sufficient and the LCBI starts. In much smaller beam current the growth rate of the LCBI becomes smaller than the radiation damping rate.

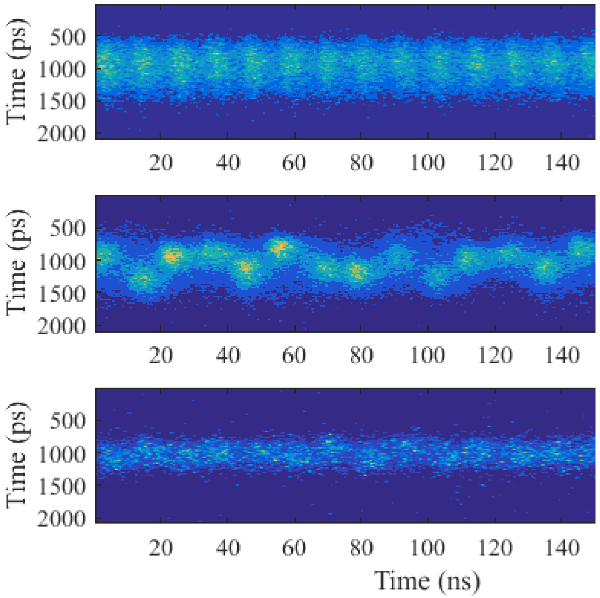

Figure 1: The streak camera images at the beam current of (upper) 300 mA, (middle)100 mA and 7.4 mA. The HCV has been operated in passive mode and the tuning condition of the HCV has been fixed.

To evaluate this, firstly we tried to find the origin of the LCBI in the UVSOR. In the consideration we have found possibility that TM020 mode at the HCV itself could cause the LCBI. From the simulation by Superfish code, we have estimated the frequency of TM020 as 780 MHz, on the other hand we have measured higher order mode (HOM) of the HCV by a network analyzer and found that one sharp resonance at 782.6 MHz. This resonance could be the TM020 mode and couple with a longitudinal mode number of 11 in the UVSOR. From the measurement by the network analyzer and the calculation by Superfish, we have concluded the loaded Q and the shunt impedance of TM020 in the HCV are 6500 and 270 kΩ; which is not negligible for the stability of the beam.

To evaluate the origin of the LCBI, we have estimated a growth rate of TM020 inside the HCV at the beam current of 7.4 mA. From a theory of the longitudinal coupled bunch instability [3] the growth rate is estimated to be 24.4 s^{-1} at the longitudinal mode number of 11. On the other hand, the radiation damping rate of the UVSOR is 60.4 s^{-1} which has the same order of the magnitude as the instability growth rate. Figure 2 shows a spectrum data for the beam modes when the instability occurs. As seen in the figure, the mode 11 (and mode 5 because the harmonic number of the UVSOR is 16) is clearly enhanced in another mode spectral peaks. These results strongly imply that one of the causes of the LCBI in the UVSOR is HOM in the HCV itself. Here we emphasize that the HCV, though it could be one of the causes of the LCBI, is very helpful to lengthen the bunch stably and can be used for improving the beam lifetime.

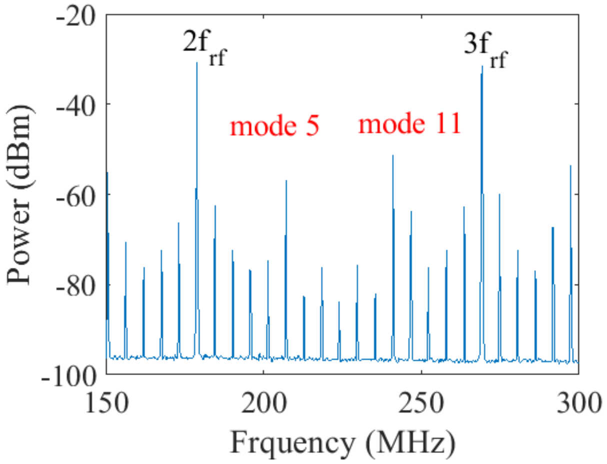

Figure 2: Result of the mode spectrum under the longitudinal coupled bunch instability. Mode number 11 and 5 are enhanced in another mode spectral peaks.

Landau Damping by Harmonic Cavity

We have observed that the LCBI ceases when the beam current is larger than 280 mA, which implies that the synchrotron tune spread increases due to the non linear field of the HCV and Landau damping becomes effective to suppress the LCBI. To evaluate the effect due to the HCV field on the synchrotron tune spread, we have tried to measure the synchrotron tune spread by using rf phase modulation method. We have applied phase modulation whose modulation pattern is pure sinusoidal wave to the main rf accelerating cavity which has operation frequency of 90.1 MHz. We have adjusted the modulation frequency near from the synchrotron oscillation frequency with proper modulation phase amplitude. Under the condition we have observed synchrotron sideband spectrum around a higher harmonics of the revolution frequency. By changing and scanning the modulation frequency, we have observed a dependence of the beam response on the modulation frequency; this frequency distribution contains information for the synchrotron tune spread. Strictly, the frequency distribution depends on the beam response against the modulation, therefore, it does not

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mean directly the tune spread itself. Here, however, as one of the benchmark for the tune spread, we have performed the measurement of the frequency response against the phase modulation. Figure 3 shows a result of the frequency response due to the phase modulation for the synchrotron oscillation frequency. We have observed the frequency response for various beam current and analyzed the peak width of the response. Figure 4 shows a summary of the FWHM for each response peak. As seen the figure, it is clearly seen that the width of the response peak tends to increase with the beam current. Because the HCV has been operated with the passive mode, the width increases with the beam induced harmonic voltage inside the HCV.

As one of the measure of the Landau damping, we have estimated a parameter ξ [3] which is estimated from the impedance value and gives a criterion for the stability of the beam by the Laudau damping. Generally, the efficiency of the Landau damping depends not only on the width of the frequency distribution of the beam but also the shape of the distribution. Here, we only have estimated the efficiency of the Landau damping by a simplified stability criterion:

$$|\xi| < \frac{1}{\sqrt{3}}\Delta\omega_{1/2}, \tag{1}$$

where $\Delta\omega_{1/2}$ represents a FWHM value of the frequency spread for any kind of the distribution. Because ξ can be calculated from the impedance and is proportional to the beam current, we can estimate the efficiency of the Landau damping against the LCBI in our case. According to the theory of the Landau damping, the $|\xi|$ from the impedance of the HOM in the HCV, it is estimated to be $\frac{|\xi|}{2\pi} = 8.5$ kHz/mA which corresponds to about 2.6 kHz at 300 mA. According to the beam diagnostic experiment, the LCBI ceases over 280 mA. The frequency width of the beam response under the effect of the HCV in Fig. 4 has almost the same value as the parameter of the stability criterion over 280 mA. This strongly implies that one of the cause of the LCBI in larger beam current condition is also the HOM in the HCV itself, and the HCV suppresses the LCBI with the Landau damping.

SUMMARY

As we have mentioned, the response of the beam due to the rf phase modulation could not reflect directly the frequency distribution of the beam; in our case, the particle distribution on the synchrotron oscillation frequency. Now we are proceeding some macroparticle simulation to evaluate the response of the beam on the rf phase modulation including a transient beam loading inside the rf cavities. Another simulation which can estimate the Landau damping effect under the condition of the HOM impedance from the HCV is also the next subject. We also plan to fabricate a new harmonic cavity in UVSOR storage ring. In its design phase, we take care not only to realize enough Landau damping effect by the HCV but also to avoid any critical HOM which can induce LCBIs.

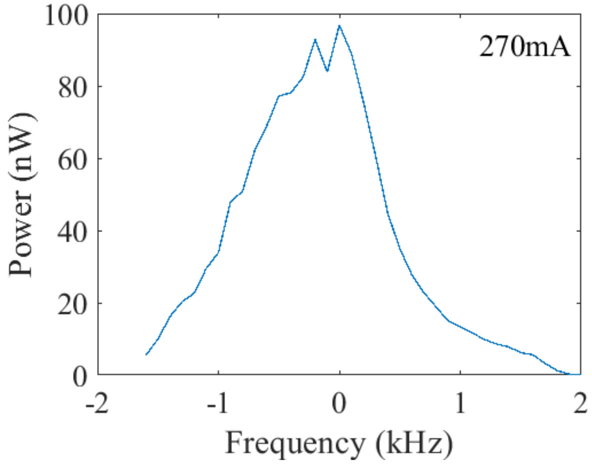

Figure 3: A result of a beam response against the rf phase modulation around the synchrotron oscillation frequency. The abscissa corresponds to frequency difference from the peak of the beam response.

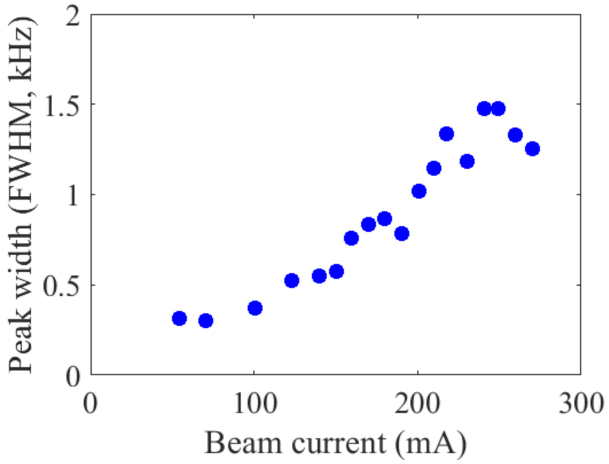

Figure 4: Dependence of the width of the beam response peak against the rf phase modulation on the beam current. The ordinate corresponds to FWHM value of the response peak.

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