SUPPRESSION OF TRANSVERSE INSTABILITIES BY CHROMATICITY MODULATION*

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Abstract

The first demonstration of suppression of transverse instabilities with modulating chromaticity at a synchrotron frequency was performed at the NewSUBARU electron storage ring. This method introduces the betatron tune spread within a bunch and produces Landau damping of coherent transverse oscillations. The enhancement of the damping of the coherent betatron oscillations, suppression of a transverse multi-bunch beam instability, and the increase in the bunch current limited by a single-bunch mode-coupling instability were observed with this method.

INTRODUCTION

Transverse beam instabilities of storage rings are the ones of the most serious limiting factors of the average and bunch current. Active feedback [1] and Landau damping by introduction of betatron tune spread [2] are widely used for suppression of those instabilities. For feedback for high frequency instabilities, the precise tuning of the system is required and the kicker efficiency becomes lower as the frequency increases. For synchrotrons of low-velocity particles, it is difficult for feedback to synchronize to the varying revolution period during the acceleration. For a ring with various bunches in bunch current, the system to compensate the bunch position signal level which has a dependence on the bunch current is necessary. And feedback can only act on the motion of the center of the mass of bunches and not on the higher-order motion.

Landau damping methods are free from the above disadvantages of feedback. Octupole magnets are used at many rings [3] to introduce the amplitude dependent tune shift which produces the tune spread with in a bunch through a beam emittance. For a low emittance ring, strong octupole is necessary, and it seriously reduces the dynamic aperture of the ring, which results in the reduction of the injection efficiency and the beam lifetime. The static chromaticity produces instantaneous tune shift of a particle. However, for bunched beams, the time-averaged tune shift over the synchrotron period is zero and the damping effect is not high [4].

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The chromaticity modulated with a synchrotron frequency also produces the tune spread within a bunch and, is expected to have wider dynamic aperture than with octupole magnets. This method was first proposed by one of the authors [5] and later its effect on the head-tail instabilities was analyzed [6,7].

We demonstrated the suppression of transverse instabilities [8] with the chromaticity modulation method at the NewSUBARU electron storage ring [9]. With the chromaticity modulation, we observed the strong enhancement of the damping of coherent betatron oscillations, the suppression of a transverse multi-bunch instability, and the increase in the bunch current which was limited by a single-bunch mode-coupling instability.

CHROMATICITY MODULATION

We first summarize the principle of the chromaticity modulation method (CM). The chromaticity modulated with a synchrotron frequency, and the relative energy shift of a particle by a synchrotron oscillation can be written as

$$\xi(t) = \xi_0 + \xi_1 \cos \omega_s t \tag{1}$$

$$\delta(t) = \tilde{\delta} \cos(\omega_s t + \varphi) \quad , \tag{2}$$

respectively, where ξ_0 and ξ_1 are the DC chromaticity and the amplitude of the AC chromaticity, respectively, and ω_s is the angular synchrotron frequency. The time averaged tune shift of this particle is now non-zero and is

$$\overline{\Delta\nu(t)} = \overline{\xi(t)\delta(t)} = \frac{1}{2}\xi_1\delta(0), \tag{3}$$

therefore its distribution is the same as that of the energy spread and the rms tune spread of a bunch is

$$\sigma_\nu = \frac{1}{2}\xi_1\sigma_\delta \tag{4}$$

where σ_δ is the rms relative energy spread. If the energy distribution is Gaussian as in high-energy electron storage rings such as the NewSUBARU ring, the Landau damping rate by the tune spread [2] is

$$\frac{1}{\tau_L} = \sqrt{\frac{2}{\pi}}\omega_0\sigma_\nu = \sqrt{\frac{2}{\pi}}\omega_0 \frac{1}{2}\xi_1\sigma_\delta \tag{5}$$

where ω_0 is a angular revolution frequency of the ring. An instability is suppressed if this damping rate exceeds the growth rate of the instability. The suppression of a multi-bunch instability with CM was confirmed by a simulation [5,10].

AC SEXTUPOLE AND NewSUBARU RING

To modulate the chromaticity, we developed an AC sextupole magnet (ACSM) [11] and a special lattice [12] to introduce finite dispersion at the ACSM as show in Fig. 1. The parameters of the NewSUBARU ring at the experiment and of the ACSM are listed in Tables 1 and 2, respectively. In this report, we use amplitude, not rms values, for the values of ACSM parameters. The Landau damping time according to Eq. (5) is now $\tau_L[\mathrm{ms}] = 0.34/\xi_1$ or

$$\tau_L[\mathrm{ms}] = \begin{cases} 53/I_{ACSM}[\mathrm{A}] & \text{for horizontal} \\ 69/I_{ACSM}[\mathrm{A}] & \text{for vertical} \end{cases} \quad (6)$$

where I_{ACSM} is a amplitude of the drive current of the ACSM.

Table 1: Parameters of the NewSUBARU ring for the experiment. Suffixes H and V indicate that values are for horizontal and vertical, respectively.

Energy at experiment	E	1 GeV
Energy spread (rms)	σ_δ	4.7×10^{-4}
Momentum compaction factor	α	0.0018
Revolution frequency	$f_0=\omega_0/2\pi$	2.53 MHz
Synchrotron frequency	$f_s=\omega_s/2\pi$	5 kHz
Radiation damping time	$\tau_{\beta,H}$, $\tau_{\beta,V}$	22ms
Lattice parameters at AC sextupole		
Beta functions	β_H / β_V	17m / 13m
Dispersion	η	0.73 m

Table 2: Parameters of AC sextupole magnet (ACSM)

Drive frequency		4 – 6 kHz
Effective length		0.175 m
Number of turn		1
Rated values (amplitude, not rms)		
Drive current	I_{ACSM}	300A
Field strength	B''	36 T/m^2
AC chromaticity	$\xi_{1,H}$ / $\xi_{1,V}$	1.9 / 1.5
Landau damping time	$\tau_{L,H}$ / $\tau_{L,V}$	0.18ms / 0.23ms

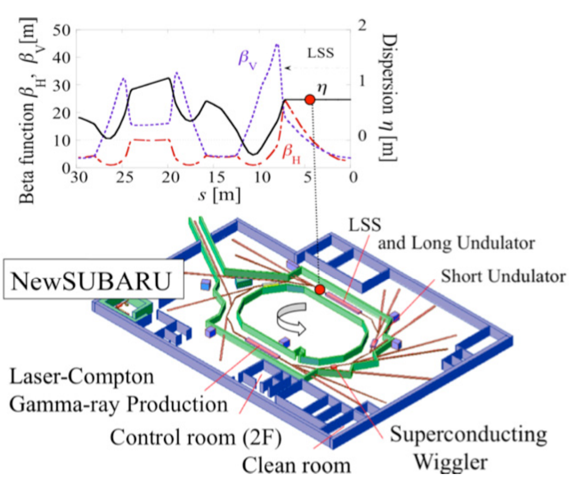

Figure 1: Lattice functions for the experiment and the location of the AC sextupole magnet (red dot at long straight section (LSS)) at the NewSUBARU ring.

If the closed orbit of a beam shifts from the center of the ACSM, the beam feels AC dipole and quadrupole fields which drive the closed orbit oscillation, the synchrotron oscillation and tune oscillations. The amplitude of them can be small enough if the shift is kept less than 0.5mm and with minimization of the excited synchrotron oscillation amplitude with the horizontal beam steering.

The coherent synchrotron frequency was maintained around 5 kHz with adjusting the acceleration voltage. However, by beam loading, the coherent synchrotron frequency has the current dependence and shifted from the incoherent synchrotron frequency to which the ACSM frequency had to be adjusted. The final adjustment of the ACSM frequency was performed with observing its effect on coherent betatron oscillations or instabilities.

The power supply for the ACSM was an LC resonant type with switchable capacitances for variable frequency. A ceramics beam pipe was installed for its AC magnetic field. The beam was injected with a nominal lattice, then the optics was gradually shifted to the lattice for the experiment because of its low injection efficiency.

DAMPING TIME MEASUREMENT

The observation of the enhancement of damping of the coherent betatron oscillations with CM was performed. The horizontal and vertical betatron oscillations were excited by sinusoidal kicks of which frequency was tuned to those betatron frequencies. Then the damping after turning-off of the excitation force was observed. The results are shown in Fig. 2. The enhancement of the damping was observed as increase in I_{ACSM} as predicted with Eq. (6).

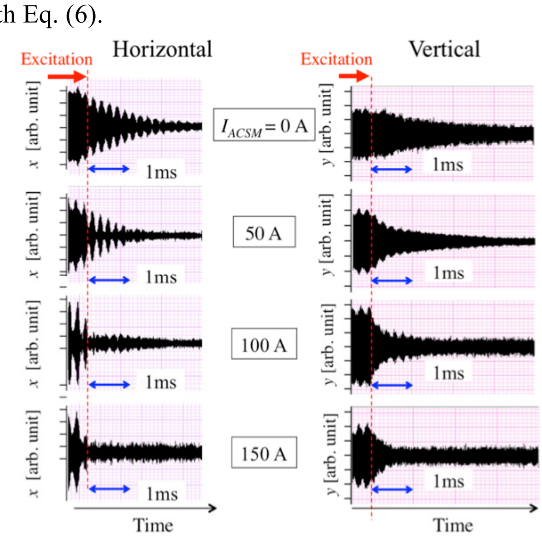

Figure 2: Damping of horizontal (left) and vertical (right) betatron oscillation by chromaticity modulation. The timing of the turning-off of the excitation force was shown in the figures. Increase of damping can be observed as increase in I_{ACSM}.

MULTIBUNCH INSTABILITY

To observe the effect of CM on the beam instabilities. a horizontal multi-bunch instability driven by a higher order mode (HOM) of a acceleration cavity was excited by tuning the HOM frequency to an instability resonance with an HOM tuner [13,14]. In the horizontal beam spectrum of a BPM electrode, the instability produced the horizontal betatron sideband peaks around the revolution harmonics. As I_{ACSM} increased, the instability peak height decreased, and eventually disappeared above I_{ACSM} = 100 A, and instability was suppressed. The effect of the CM on the instability is shown in Fig. 3 with switching CM on and off. Also we observed the shrink of the horizontal beam size in the profile monitor with CM turned on.

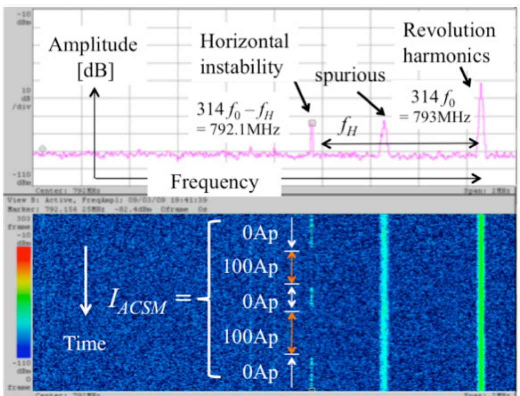

Figure 3: Suppression of the horizontal muti-bunch instability with CM seen in the horizontal beam motion spectrum in a signal of a beam position monitor electrode. The instability produced the betatron sideband peaks(right peak) separated by horizontal betatron frequency (f_H) from a revolution harmonics peak(left peak). The sideband peak disappeared by CM on (I_{ACSM} = 100A). A peak between two peaks is a spurious by the instrumentation.

SINGLE-BUNCH INSTABILITY

We also observed the effect of CM on a single-bunch instability. At the nominal lattice with low vertical DC chromaticity around 0.6, the threshold current of a vertical single-bunch mode-coupling instability was approximately 3mA/bunch: further injection was impossible above this current level. The injection and the shift of the optics to the lattice for the experiment were performed suppressing the instability with high vertical DC chromaticity. Then CM was turned on and the DC chromaticity was reduced gradually observing the instantaneous decrease of the bunch current. For the DC chromaticity more than 1, an increase in the current with CM was observed as shown in Fig. 4.

SUMMARY

In this paper, we report the first successful demonstration of the suppression of transverse beam instabilities by the chromaticity modulation method. With this method, we observed the enhancement of the damping of coherent transverse oscillations, the suppression of a multi-bunch instability, and the increase in the bunch current at low chromaticity, which is limited by a single-bunch mode-coupling instability. The chromaticity modulation method has several advantages over both the use of octupole magnets and feedback: wider dynamic aperture compared to that using octupole magnets, the effectiveness on higher-order motion within a bunch, easy application to a ring with various bunches in bunch current and synchrotrons of low-velocity particles.

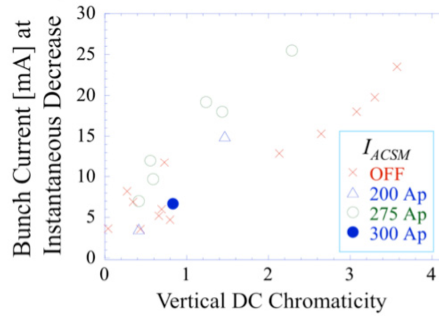

Figure 4 : The bunch current and DC chromaticity at the timing of instantaneous decrease of the current.

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