IMPROVEMENT IN THE BEAM PERFORMANCE BY AN RF PHASE MODULATION AT THE KEK PHOTON FACTORY STORAGE RING

S. Sakanaka, M. Izawa, T. Mitsuhashi, M. Tadano, and T. Takahashi
KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki, 305-0801 Japan

Abstract

In the Photon Factory storage ring at KEK, we found that a longitudinal coupled-bunch instability was remarkably suppressed by applying a small phase modulation on the rf accelerating voltage at a frequency of 2 times the synchrotron frequency. At the same time, a considerable increase in the beam lifetime was observed. This paper reports on these experimental results and discussions.

1 INTRODUCTION

The 2.5-GeV Photon Factory (PF) storage ring[1] at KEK is a dedicated synchrotron light source which has been operating since 1982. The principal parameters of the ring are given in Table 1. A long beam lifetime and high beam stability are critical for such light sources.

It has been reported[2-4] that the beam quality in the light sources was improved, or predicted to be improved, by applying a small phase modulation to the rf accelerating voltage. The first one[2] reports on a certain suppression of a longitudinal coupled-bunch instability by modulating an rf phase at the synchrotron frequency. The second one[3] reports on a significant increase in the beam lifetime by modulating an rf phase at 3 times (or 1, 2, and 4 times) the synchrotron frequency, and gives a theoretical explanation on this effect. We found in the PF storage ring that such improvements in the beam quality were most effective when we modulated an rf phase at the frequency of 2 times the synchrotron frequency. We obtained both remarkable suppression of the longitudinal coupled-bunch instability and a considerable improvement in the beam lifetime[5]. This paper reports on these experimental observations and discussions.

Table 1: Principal parameters of the PF storage ring.

Parameter	Symbol	Value
Beam energy	E	2.5 GeV
rf frequency	f_{rf}	500.1 MHz
Harmonic number	h	312
Momentum compaction	α	0.0061
Radiation loss per turn	U_0	399 keV
Total cavity gap voltage	V_c	1.7 MV
Synchrotron frequency[1]	f_s	23.7 kHz
Natural bunch length	σ_τ	31 ps

[1] Under actual operation. Calculation: 22.7 kHz.

2 EXPERIMENTS

2.1 Longitudinal coupled-bunch instability

In the PF storage ring, four 500-MHz rf cavities are used to produce an accelerating voltage of 1.7 MV. A fast phase shifter following the master oscillator allows us to modulate all phases of the klystron output rf waves at the same time. Although excellent damped accelerating cavities[6] are used, there arises many spectrum lines in a button-type monitor (BPM) signal at high currents due to a longitudinal coupled-bunch instability. Since these spectrum lines do not correspond to any frequencies of the cavity higher order modes, the observed longitudinal instability is considered to be induced by some resonant structures in the vacuum components. Since the amplitudes of these oscillations fluctuate with time, it causes a harmful fluctuation in the brightness of the synchrotron radiation.

When the longitudinal coupled-bunch oscillation of a mode number μ arises, the following spectrum lines appear in the BPM signal[7]:

$$f_{\mu,n}^{\pm} = n \cdot f_{rf} \pm (\mu \cdot f_r + f_s) \qquad (1)$$

where n is an arbitrary integer, f_r the revolution frequency, and f_s the synchrotron frequency. We surveyed the longitudinal coupled-bunch oscillations by scanning the signal level at every frequency of the upper sideband ($f_{\mu,n}^{+}$) in the range of 0.5-1 GHz (i.e. the range of μ = 0-

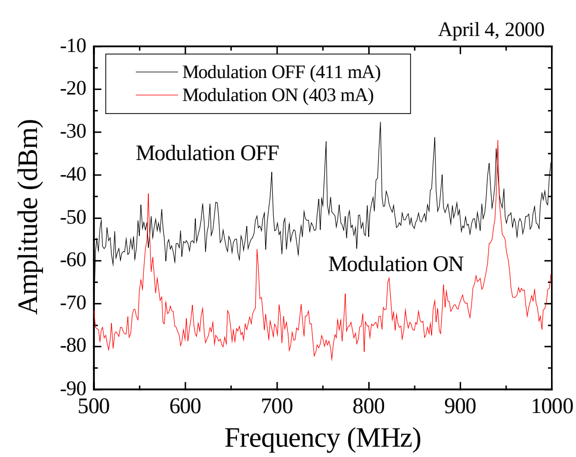

Figure 1: Measured spectra of the longitudinal coupled-bunch instability with and without applying phase modulation.

311 for n=1), using a spectrum analyzer HP8566B and a computer. The upper trace in Fig. 1 shows thus obtained spectrum at a beam current of 411 mA with 280 bunches; many spectrum lines due to longitudinal coupled oscillations were observed. The spectrum changed as shown in the lower trace of Fig. 1 when an rf phase was modulated sinusoidally at a frequency of 46.7 kHz[1] (about 2 times the synchrotron frequency) with an amplitude of 4.6° p-p. It can be seen that most of the spectrum lines, except for several strong ones, were largely suppressed.

We carried out a similar investigation by setting the modulation frequency at about 3 times the synchrotron frequency ($3f_s$). Then, we observed a similar suppression effect, but it was less effective than in the previous case, even though we increased the modulation amplitude up to 14.4° p-p and scanned the modulation frequency slightly. One of the possible reasons is that the modulation frequency (about 69.7 kHz) was larger than the bandwidth (42 kHz) of our cavities, and thus, the cavity field did not respond well to the modulated rf. In addition, phase modulation at a frequency of the synchrotron frequency resulted in only a slight suppression of the longitudinal instability.

2.2 Improvement in the beam lifetime

We reported[5] that the beam lifetime in the PF storage ring could be increased by applying phase modulation at the frequency of 2 times the synchrotron frequency ($2f_s$). Recently, we could obtain further improvement in the lifetime by adjusting the modulation conditions. Figure 2 shows the measured beam lifetimes with and without applying phase modulation. The frequency and the amplitude of modulation were 46.7 kHz with a slight frequency modulation (see footnote in this page) and 4.6° p-p, respectively. The beam was filled almost equally in 280 bunches among 312 rf buckets. Table 2 gives a summary of the result. The lifetime was improved by a factor of about 2.1 by applying phase modulation.

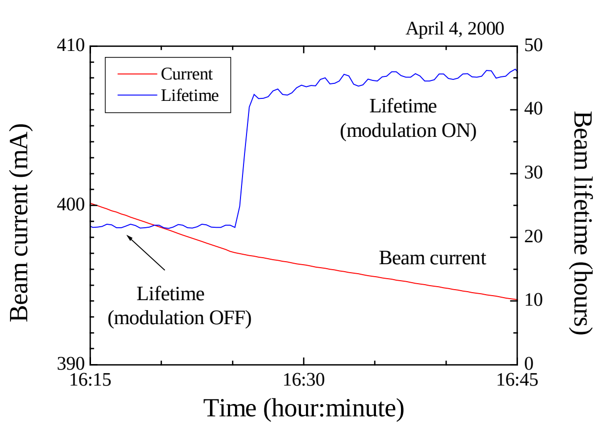

Figure 2: Measured beam lifetimes with and without applying phase modulation at the PF storage ring.

[1] In this experiment, this frequency was further modulated at a frequency of 300 Hz in a range of 800 Hz p-p since this seemed to give stable effect on the instability.

Table 2: Improvement in the beam lifetime by applying phase modulation at a frequency of $2f_s$.

Phase modulation	**On**[a]	**Off**
Beam current (mA)	396	399
Beam lifetime (h)	44.8	21.7
Average pressure [b] (Pa)	7.0×10^{-8}	

[a] Frequency: 46.7 kHz, amplitude: 4.6° p-p.
[b] Estimated pressure on the beam path.

Table 3: Improvement in the beam lifetime by the phase modulation at a frequency of $3f_s$.

Phase modulation	**On**[a]	**Off**
Beam current (mA)	386	385
Beam lifetime (h)	30.0	22.2

[a] Frequency: 69.7 kHz, amplitude: 14.4° p-p.

We also tuned the modulation frequency at a frequency of $3f_s$. The result is shown in Table 3; the lifetime was improved only by a factor of 1.4, even though we increased the modulation amplitude up to 14.4° p-p. Additionally, the phase modulation at around a synchrotron frequency resulted in little improvement in the lifetime. The above results showed that the beam lifetime was most improved when the phase modulation was applied at the frequency of $2f_s$, at least, in the PF storage ring.

2.3 Observation of longitudinal bunch profiles

In order to observe longitudinal profiles of the stored bunches under phase modulation, we detected a visible synchrotron light using a streak camera. The result is shown in Fig. 3. The measured bunch profiles under phase modulation suggested that the bunches were lengthened due to a quadrupole mode of longitudinal oscillation, and that the longitudinal coupled-bunch oscillation was reduced.

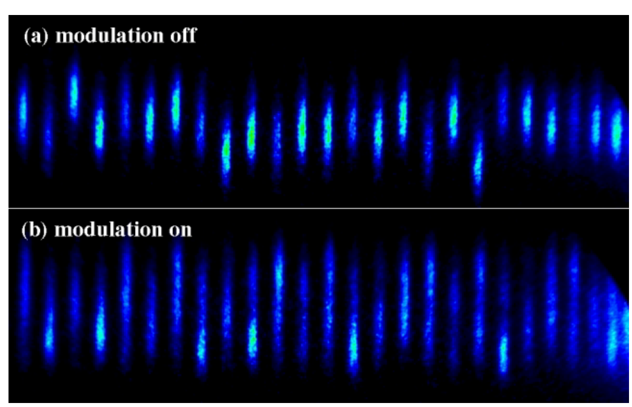

Figure 3: Measured longitudinal profiles of the bunches from a dual timebase measurement[5]. Vertical full scale: 400 ps, horizontal full scale: 200 ns. (a) Under no phase modulation, beam current: 399 mA. (b) Under phase modulation (48.1 kHz, 3.2° p-p), beam current: 388 mA.

3 DISCUSSIONS

When the phase modulation is applied at the frequency of $2f_s$, longitudinal oscillations of the stored electrons are excited by a parametric resonance process[5]. A small amplitude motion of a single electron under this modulation is approximately described by a similar equation to the Mathieu equation. It can be shown that the electrons in a bunch tend to oscillate in one of the two states of oscillation, and thus, they tend to gather in two groups which oscillate out of phase to each other. Then, each bunch executes a quadrupole mode of longitudinal oscillation. Since the bunch length is elongated on the average, this results in a longer Touschek lifetime.

The motion of a bunch under phase modulation can be predicted by a multiparticle tracking simulation. We modeled a single bunch by using 1000 macro particles, and took account of the radiation excitation, the cavity response to modulated rf, and the beam loading effect. It was shown that the beam loading is very important to understand the bunch motion at high currents.

The result of the tracking simulation under phase modulation is shown in Fig. 4. Both the condition of phase modulation and the beam current were chosen to be very similar to those in the experiment (in Table 2). It can be seen that the particles form two subbunches which oscillate out of phase. Then, the bunch length oscillates at the frequency of $2f_s$ with an average rms bunch length of 48 ps, that is, about 1.55 times longer than the natural bunch length (31 ps). As a result, the Touschek lifetime will be improved about the same factor. Since we do not consider detailed particle distribution, this gives only a rough estimate of the Touschek lifetime.

We can consider that the beam lifetime in the PF storage ring is determined by both the Touschek effect and the beam-gas scattering process. The estimated beam lifetimes under the experiment are given in Table 4. The estimated beam lifetimes agreed considerably with the experimental result. The predicted increase (a factor of 1.4) in the total beam lifetime roughly agreed with that (a factor of 2.1) from the experiment as well.

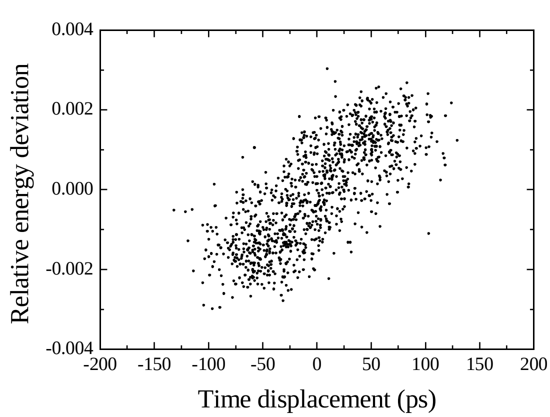

Figure 4: Simulated distribution of particles under phase modulation (f_{mod}=45.36 kHz, 4.6° p-p) at a beam current of 400 mA. Distribution after about 30 000 turns.

Table 4: Estimated beam lifetimes under the experimental conditions in Table 2.

Phase modulation	**On**	**Off**
Lifetime due to gas scattering (h)	206	206
Touschek lifetime (h)	65	42
Total beam lifetime (h)	49	35

On the other hand, the suppression of the coupled-bunch instability due to phase modulation was partly discussed in ref. [5]. One of the possible mechanisms of this suppression is that the phase modulation introduces a prevention or promotion of the oscillation of each bunch according to its phase of the coupled-bunch motion. This effect can disturb the coherence of the coupled oscillation.

4 CONCLUSION

We have shown experimentally that the longitudinal coupled-bunch instability was remarkably suppressed by applying rf phase modulation at a frequency of 2 times the synchrotron frequency. At the same time, the beam lifetime was improved by a factor of 2.1 under multiple (280) bunch operation. These effects were less effective when the modulation frequency was tuned at about 1 or 3 times the synchrotron frequency, at least, in the PF storage ring. By using the above technique, the beam performance in the PF storage ring has been largely improved in both lifetime and stability since May, 1999.

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