Longitudinal Beam Dynamics in Operation with Negative Momentum Compaction Factor on the UVSOR Electron Storage Ring

Masahito HOSAKA, Jun-Ichiro YAMAZAKI, Toshio KINOSHITA and Hiroyuki HAMA
UVSOR Facility, Institute for Molecular Science, 38 Nishigo-Naka, Myodaiji, Okazaki 444, Japan

Abstract

To investigate variations of the bunch length and the energy spread of the electron beam on a storage ring, we have measured longitudinal electron distributions and spectra of spontaneous radiation from an optical klystron on the UVSOR storage ring operated with both signs of negative and positive momentum compaction factors. Significant differences in the bunch lengthening and the increase of the energy spread with the beam current have been found between two operations.

1 Introduction

In general, the single bunch dynamic behavior such as lengthening of the bunched beam circulating in a storage ring is governed by the electromagnetic interaction between the impedance of the vacuum chamber. On the way of development of third generation synchrotron radiation sources, they have made effort to reduce the ring impedance employing very smooth connections of vacuum pipes along with development of a lattice for the very low beam emittance.

A longitudinal single bunch instability including increase of the energy spread of the beam due to high frequency impedance of many parts of the vacuum chamber, i.e., cavity, sudden change of pipes, groove, low Q cavity-like structure, etc., is well known as *microwave instability* [1]. On old machines, which were designed without deep consideration for the impedance, both longitudinal and transverse single bunch instability were often observed. However as far as recent reports on relatively new machines, there have been no clear evidence observed for the onset of microwave instability [2]. On the UVSOR ring, we have also observed no significant single bunch instability up to the maximum beam current can be stored at present. Based on a low Q resonator impedance model, Fang et. al. recently pointed out a possibility of which the threshold current for microwave instability would be high and the bunch lengthening would be not significant when a storage ring is operated with a negative momentum compaction factor [3].

Table 1 Basic Parameters of the UVSOR Storage Ring for Negative α Experiment.

Energy	E = 600 MeV
Circumference	C = 53.2 m
Bending radius	ρ = 2.2 m
Betatron tune	ν_x = 3.16 (horizontal)
	ν_y = 1.44 (vertical)
Momentum compaction α	α = |0.033|
Harmonics	h = 16
Main cavity RF frequency	f_{RF} = 90.107 MHz
Main cavity RF voltage	V_{RF} = 50 kV
Energy spread	σ_E = 0.23 MeV
Natural emittance	ε_0 = 230 π nm rad
	90 π nm rad (positive α)

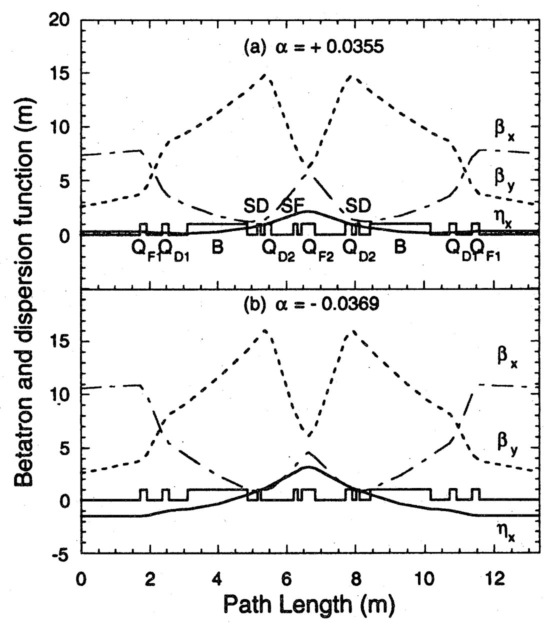

Fig.1 Calculated Twiss parameters for one unit cell at positive a (a) and negative a (b) operations.

2 Development of Lattice for Both Positive and Negative Momentum Compaction Factors

Table 1 shows basic parameters of the UVSOR storage ring for the negative α experiment. In the nominal operation for users of synchrotron radiation (SR), a bit of a positive dispersion remains in straight sections to minimize the effective emittance, and then the momentum compaction factor α is estimated to be + 0.035. For the experiment with negative α, we developed a new operating point, where α can be tuned smoothly from positive to negative without change of the betatron tunes. This operating point has been also optimized to use of the helical optical klystron with small gaps [4].

Calculated Twiss parameters of the lattice at positive and negative α operations are shown in Fig. 1a and 1b, respectively. At the positive α lattice, the dispersion function is positive in the bending magnet. On the other hand, at the negative α lattice, the dispersion function alters from negative to positive in the bend and a large negative dispersion function makes the integral of the dispersion in the arc negative.

3 Measurement of Bunch Lengthening

A dual-sweep streak camera is a powerful tool to observe the electron distribution in the bunch and its variation in a certain time range [5]. Since a slow-sweep axis can be expanded up to 100 ms from the one turn period, we can not only observe the corrective longitudinal oscillation with the synchrotron frequency of about 15 kHz (see Table 1) but also detect instabilities of which the electron distribution is slowly varied.

Current dependent bunch lengthening has been measured up to ~ 100 mA with the single-bunch mode for the almost same absolute values of the positive and the negative momentum compaction factors ($|\alpha|$ = 0.033). RMS bunch lengths were deduced from spectra averaged over many turns in the two-dimensional dual-sweep images of SR from a bending magnet. Figure 2 shows variations of the bunch length at a wide range of the single bunch current. For the case of the positive α, the bunch lengthens monotonously, which is in agreement with our pervious measurements [6]. Based on potential-well distortion theory with a broad band impedance model [7], the bunch length σ_b at the average beam current I is expressed as

$$\left(\frac{\sigma_b}{\sigma_{b0}}\right)^3 - \left(\frac{\sigma_b}{\sigma_{b0}}\right) = \frac{e\,\alpha\, I\,[Z/n]_{eff}}{\sqrt{2\pi}\,\nu_s^{\,2}\,E}\left(\frac{R}{\sigma_{b0}}\right)^3, \qquad (1)$$

where σ_{b0} is the zero current (natural) bunch length and $[Z/n]_{eff}$ is the effective longitudinal coupling impedance. By fitting the data for the positive α with eq. (1), we obtained the effective impedance of 1.6 Ω, where we assumed no frequency dependence for $[Z/n]_{eff}$. As shown in Fig. 2, the fitting quality is not so bad that there seems to be no significant frequency dependence for $[Z/n]_{eff}$ at the narrow region of which the bunch length observed.

Since the bunch lengthening due to potential-well distortion does not accompany increase of the energy spread, the *Keil-Schnell* criterion for the threshold condition of longitudinal microwave instability is able to be modified by replacing the peak current of the lengthened bunch [8].

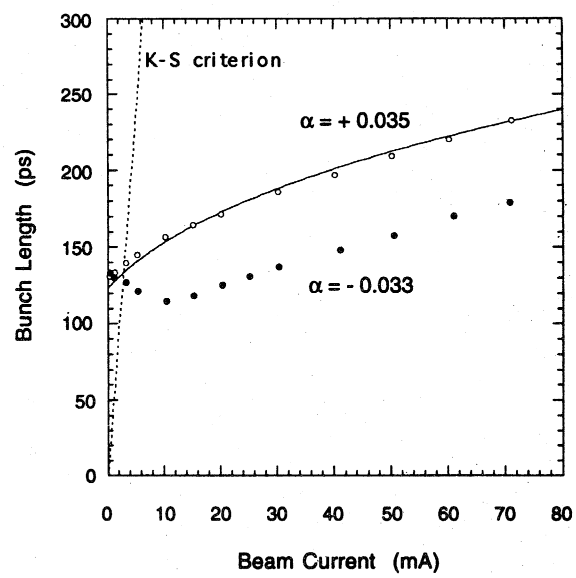

Fig. 2 Measured bunch lengths plotted as a function of the beam current.

The peak current for the Gaussian particle distribution is written as $IC/\left(\sqrt{2\pi}\,\sigma_b\right)$, the *Keil-Schnell* stability criterion is rewritten as

$$\sigma_b \geq \frac{C\,[Z/n]_{eff}\,I}{F\sqrt{2\pi}\,E\,|\alpha|}\left(\frac{\sigma_E}{E}\right)^{-2}, \qquad (2)$$

where σ_E/E is the relative energy spread of the beam, respectively. A form factor of the particle distribution in the momentum space F is approximately the unity for bell-shape distributions. Using the ring parameters shown in Table 1 and the deduced value of 1.6 Ω for $[Z/n]_{eff}$, a threshold bunch length for microwave instability estimated from eq. (2) is approximately 47 ps/mA. The beam with the bunch length below this line would be longitudinally unstable. However this threshold condition is obviously over estimated, because we have not observed clear evidence of instability even at the higher beam current of 100 mA with the positive α. Since the *Keil-Schnell* stability criterion is for the worst case and the threshold condition should be varied by a combination of actual resistive and reactive impedances.

The bunch lengthening with the negative α was drastically changed. As one can see, the bunch shortening was observed up to ~ 15 mA, and then the bunch lengthened with the current. We confirmed the point of discontinuity around 15 mA as an onset of longitudinal microwave instability by the 2-dimensional streak camera image.

The bunch shortening can be simply explained assuming the wake field generated by an inductive (L)

impedance as $V_{wake} = -L\left(dI/dt\right)$. Since the synchronous phase of the beam with the negative α is the opposite side of the slope of the accelerating RF field, a combined field with the RF field and the wake field becomes steep if the other is gently-sloping.

4 Measurement of Energy Spread

Radiation spectrum from the optical klystron is very sensitive to the beam energy spread. A modulation factor, which indicates degree of interference between two radiations from undulators separated by a dispersive section, defined as $f_{mod} = (S_+ - S_-)/(S_+ + S_-)$, where S_+ and S_- are the maximum and the minimum intensities of a jagged-structure spectrum, respectively. Complete interference in both spatial and frequency demains makes $f_{mod} = 1$. An actual modulation factor may be separated into two terms as $f_{mod} = f_\varepsilon f_\gamma$, where f_ε and f_γ are the modulation factors originated from the emittance and the energy spread, respectively. The analytical formula of f_γ is written as

$$f_\gamma = \exp\left[-8\,\pi^2\left(N_u + N_d\right)^2\left(\frac{\sigma_E}{E}\right)^2\right], \qquad (3)$$

where N_u and N_d are the period number of one undulator and the interference order of the radiation.

We chose a resonant wavelength of 355 nm to measure the modulation factor, and N_d at the wavelength was 130. Results of the measurement of the energy spread are plotted as a function of the beam current in Fig. 3. One can apparently notice the threshold beam current around 15 mA exists for the increase of the energy spread in the negative α operation, which corresponds with the result of the bunch length measurement. Meanwhile there seems to be no clear indication of the onset of microwave instability in the positive α operation. Although there is a small discontinuity seen around the beam current of 50 mA, the increase rate of the energy spread at the higher beam current is slow. We have not identified whether microwave instability occurred in the positive α operation.

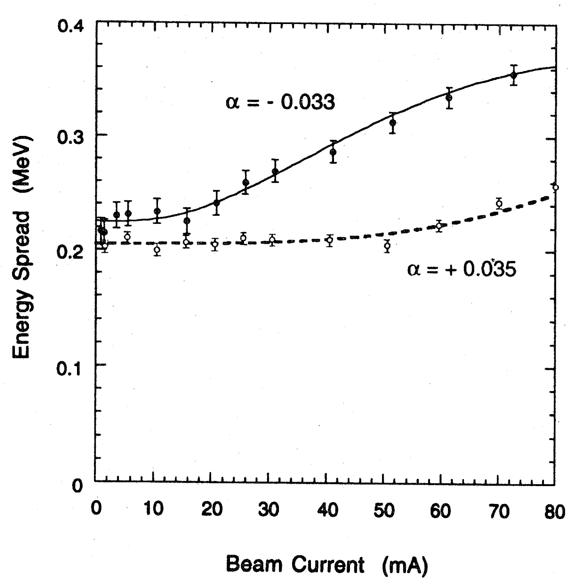

Fig. 3 Deduced energy spread from the modulation factor of the spontaneouse spectra. Lines are drawn by eyes.

5 Summary

The normalized effective longitudinal impedance of 1.6 Ω was deduced from the bunch lengthening with the positive α. The reason why the instability was occurred only in the negative α operation is that the potential-well distortion due to the impedance acts to shorten the bunch length for the negative α and the peak current reaches the threshold of instability at the lower beam current than the positive α. The averaged bunch length with the negative α is shorter than that with the positive α at the wide range of the beam current. Nevertheless the negative α operation has no advantage because of the lower threshold current of microwave instability. As far as the UVSOR ring, the suggestion of Fang et. al. is not realized. Probably the impedance model of a low Q resonator is not suitable for the UVSOR ring. As mentioned previously, the interaction between the electron bunch and the impedance of the chamber depends upon properties of the impedance, such as the combination of inductive and resistive components and the frequency dependence.

References

[1] for example; A. W. Chao, AIP Proc. No. 105 (American Institute of Physics, New York, 1983) 353.
[2] A. H. Lumpkin et. al., Proc. 18th Int. Free Electron Lasers Conf., Rome, Italy, 1996.
[3] S. X. Fang et. al., KEK Preprint 94-190 (National Laboratory for High Energy Physics, Tsukuba 1995).
[4] H. Hama et. al., Proc. 3rd Aisan Symp. on Free Electron Laser (IONICS Publishing Co. Ltd., Tokyo 1997) 17.
[5] H. Hama et. al., Nucl. Instr. and Meth. A375 (1996) 32.
[6] H. Hama et. al., Proc. 9th Symp. on Accelerator Science and Technology, Japan (1993) 468.
[7] B. Zotter, Proc. CERN Accelerator School, Paris 1984, CERN report 85-19 (CERN, Geneva, 1985) 415; J-L. Laclare, CERN Report 87-03 (CERN, Geneva, 1987) 264.
[8] E. Keil and W. Schnell, CERN report ISR-TH-RF/69-48 (CERN, Geneva, 1969).