Operation with the Low Momentum Compaction Factor on an Electron Storage Ring

H. Hama, J. Yamazaki, E. Nakamura and G. Isoyama
UVSOR Facility, Institute for Molecular Science
Myodaiji, Okazaki 444, Japan

Abstract

We have studied quasi-isochronous operation with the low momentum compaction factor to reduce the bunch length of the electron beam on the UVSOR storage ring. The momentum compaction factor α was reduced by changing the dispersion function in the bending magnets. Though effect of the second order α becomes dominant in the very low α region, we could compensate it by reducing strength of the focusing sextupole magnets. The momentum compaction factor was reduced to less than one hundredth with respect to the ordinary value. Using a streak camera, we measured the very short bunch, and confirmed the storage ring was operated nearly isochronously. The beam current dependence of the bunch length was also measured. The bunch lengthening was interpreted by potential-well distortion theory with a constant value of the effective longitudinal coupling impedance over the wide range of α.

Introduction

A concept of the isochronous ($\alpha = 0$) electron storage ring was introduced to measure the speed of light with high accuracy by Robinson in 1966[1]. Deacon proposed to use the isochronous ring as a driver for a free electron laser (FEL)[2] with high output power. Recently Pellegrini and Robin presented theoretical study of the single particle and collective dynamics of a quasi-isochronous ring to reduce the bunch length and increase the peak current mainly for colliders[3].

Since the beam bunch is very short when the storage ring is operated nearly isochronously, various applications can be foreseen in experimental study with synchrotron radiation. For example, the study region of time resolved experiment will be extended, and the gain of the FEL will be enhanced because of the high peak current of the short bunch. Coherent enhancement of synchrotron radiation[4] in the wavelength region of far infrared is possibly detected, if the bunch length shorter than a few mm is realized.

The fractional elongation of path length $\Delta l / l$ for an off-momentum particle is written as

$$\frac{\Delta l}{l} = \alpha \frac{\Delta p}{p}, \tag{1}$$

Table 1. Basic parameters of the UVSOR ring at the regular operating point for the beam energy of 600 MeV.

Circumference	C	53.2 m
Bending radius	ρ	2.2 m
RF frequency	f_{RF}	90.115 MHz
Harmonic number	h	16
Peak RF voltage	V_{RF}	46 kV
Momentum compaction factor	α	0.0354
Synchrotron frequency	f_s	14.8 kHz
Natural bunch length	σ_0	258 ps
Betatron tune	Q_x	3.16
	Q_y	2.62

where α is calculated by a formula

$$\alpha = \frac{1}{C}\int \frac{\eta}{\rho}\, ds, \tag{2}$$

and C, η and ρ denote the circumference of the ring, the dispersion function and the bending radius, respectively. The longitudinal natural bunch length σ_0 is proportional to the fractional energy spread σ_ε / E_0 and to the square root of the momentum compaction α, and inversely proportional to the square root of the slope of the RF field $\dot{V}_{RF}$;

$$\sigma_0 = \sqrt{\frac{\alpha E_0}{f_{rev}\, e\, \dot{V}_{RF}}}\, \frac{\sigma_\varepsilon}{E_0}. \tag{3}$$

Since the synchrotron frequency f_s is also proportional to the square root of α as

$$f_s = \frac{1}{2\pi}\sqrt{\alpha f_{rev} \frac{e\dot{V}_{RF}}{E_0}}, \tag{4}$$

it is a good index for α as far as the RF voltage is kept constant.

Experimental

The UVSOR storage ring[5] consists of four units cells of the Chasman-Green lattice, and is operated at an energy of 600 MeV for the beam injection. The beam is accelerated up to 750 MeV for user experiment after the injection. The momentum compaction factor is 0.035 at the regular operating point for 600 MeV and the natural bunch length is approximately 8 cm. The dispersion function η of this type of lattice can be varied while betatron wave numbers are maintained at constant values.

Figure 1 shows beam optics calculated with the computer code LATTICE[6] for an extreme case close to $\alpha = 0$. The dispersion function changes its sign in the bending magnet. The integral in eq. (2) cancels out, so that α becomes zero.

The experiment was performed at the energy of 600 MeV, and the single bunch mode was employed. The

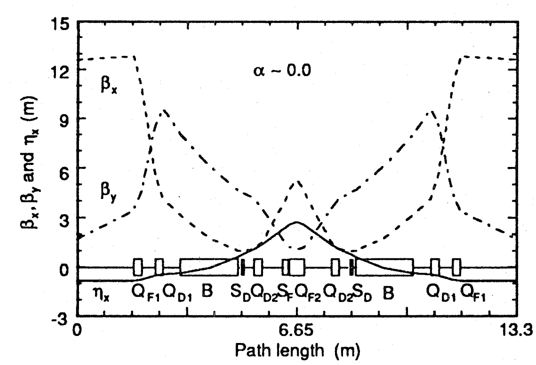

Fig. 1. Calculated betatron and dispersion functions in a unit cell for the extreme point of $\alpha \sim 0$. The horizontal and the vertical betatron wave numbers are maintained at 3.16 and 2.62, respectively.

preliminary results and the experimental details are reported in ref. 7. Results of further investigation are described in the followings.

Compensation of α_2

We gradually reduced the momentum compaction α from the injection point using an accelerator control software[8]. The same procedure for the beam acceleration was employed to synchronously change excitation currents of the Q-magnets but the bending field was maintained. In the region of α below 0.01, the effect of the second order term α_2 became dominant for the off-momentum particle.

Taking into account a chromatic effect of the Q-magnet for the dispersion function as

$$\eta = \eta_1 + \eta_2 \frac{\Delta p}{p}, \quad (5)$$

the momentum compaction factor should be redefined as

$$\frac{\Delta l}{l} = \alpha_1 \frac{\Delta p}{p} + \alpha_2 \left(\frac{\Delta p}{p}\right)^2. \quad (6)$$

As reported previously[7], the strength of the focusing sextupole magnets for the chromaticity correction results in over correction for α_2. Experimental values of α_2 were

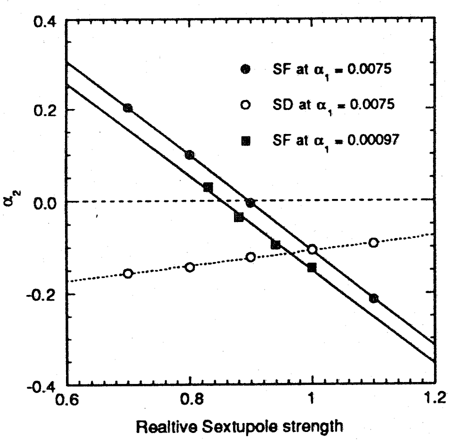

Fig. 2. Magnitude of α_2 as a function of the relative strength of sextupoles for operation points of different α_1. Strengths of sextupoles are normalized to that for the chromaticity correction.

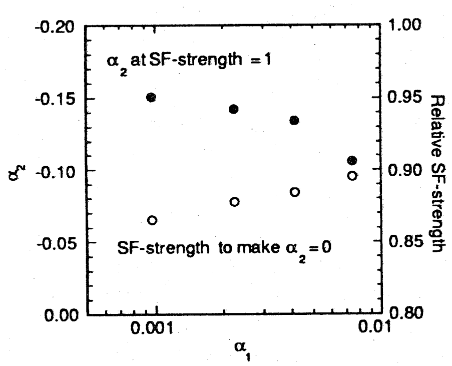

Fig. 3. Relative strength of SF-magnets to make $\alpha_2 = 0$ for various operating points. Measured values of α_2 at the SF-strength for the chromaticity correction are also plotted.

derived from the RF frequency dependence of the measured synchrotron frequency fitted with an analytical formula[7] of f_s including α_2 term. The magnitude of α_2 has linear dependence of the strength of sextupoles as shown in Fig. 2. Since the value of η at the focusing sextupoles (SF-magnet) is much larger than that at the defocusing ones (SD-magnet), the SF-magnet is more effective to compensate α_2.

We systematically searched for suitable strengths of the SF-magnet for α_2 compensation at various operating points. When the natural chromaticities are corrected with the sextupoles, the magnitude of α_2 increases gradually as α_1 is lowered. However it can be seen in Fig. 3 that α_2 is able to be compensated by slightly reducing the SF strength.

Bunch length measurement

The lowest α so far achieved with compensation of α_2 was 0.0002, which is more than 150 times smaller than that of the regular operating point. The bunch length was measured using a streak camera at a low beam current less than 0.1 mA. The synchrotron frequency was also measured simultaneously to make sure of the reduction of α. Streak time and a response function of a focused image were calibrated using a semiconductor laser. Figure 4 shows typical temporal profiles of the bunch. When the bunch is very short, the bunch length was derived by taking into account the response function of the detector because the focused image on the screen of the streak camera has a finite width. The solid lines indicate de-convoluted shapes of the time profile, while the dotted lines are raw spectra of the measured bunch profile.

Using eqs. (3) and (4), the bunch length can be expressed

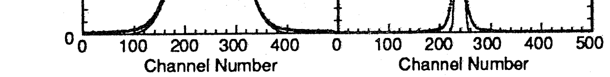

Fig. 4. Time profiles of the bunch measured by the streak camera at the injection point (left) and at the lowest α (right).

with the synchrotron frequency as

$$\sigma_0 = \frac{\sqrt{2}\,\pi\, E_0}{e\,\dot{V}_{RF}} \frac{\sigma_\varepsilon}{E_0} \frac{f_s}{f_{rev}}. \quad (7)$$

The bunch length is plotted as a function of the synchrotron frequency in Fig. 5. The bunch length is clearly proportional to the synchrotron frequency. The time resolution of the streak camera is estimated to be 15 ps, which is mainly due to streak trigger jitters. The shortest bunch length was 20 ps (6 mm) and a corresponding synchrotron frequency was 1.2 kHz which is approximately 1/12 of the normal value. Therefore the momentum compaction factor was lowered to be 0.0002. Though we could successfully reduce α to the very low value, we lost the beam current from ~ 0.1 mA down to a few μA during the operation to further reduce α from $\alpha \sim 0.001$. The reason is not clear at the moment whether the control of the quadrupoles and the sextupoles was inappropriate or some

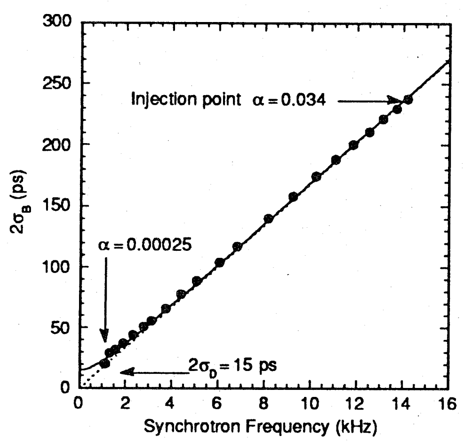

Fig. 5. Measured bunch length plotted as a function of f_s measured simultaneously. The solid line is a result of the fit including the detector resolution.

instability occurred.

Bunch lengthening

In a previous experiment, we observed the bunch lengthening due to the potential-well distortion which does not accompany with the increase of the energy spread[9]. This is also supported by the result of the current dependence of the measured FEL gain[10].

Based on potential-well distortion theory[11], the bunch lengthening can be expressed as

$$I = (2\pi)^{-\frac{3}{2}} \frac{e\dot{V}_{RF}}{f_{rev} R^3} \frac{1}{[Z/n]_{eff}} (\sigma^3 - \sigma \sigma_0^2), \qquad (8)$$

where σ is the bunch length at the beam current I, R is the mean radius of the ring, and $[Z/n]_{eff}$ is the effective longitudinal coupling impedance. The bunch length was measured at various operating points at beam currents ranging from a few tens of mA to less than 0.1 mA. Figure 6 shows the bunch length measured for three different values of α and

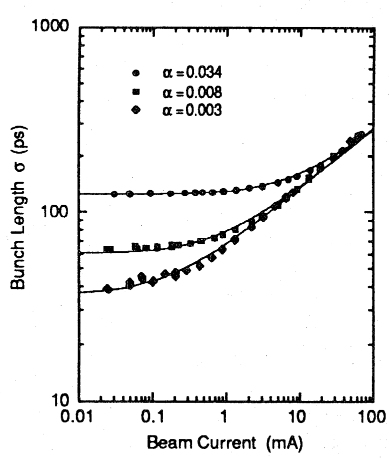

Fig. 6. Current dependence of the bunch length at three different values of α. The lines indicate the results of the fit with eq. (8).

results of the fit by eq. (8) with one free parameter of $[Z/n]_{eff}$. The bunch length measured at a very low beam current was used as the natural bunch length σ_0. One can see that the bunch length converges upon the single line at higher beam currents, which means the effective impedance is almost constant. The derived value of $[Z/n]_{eff}$ was approximately 2.5 Ω. The bunch lengthening is reasonably interpreted by potential-well distortion theory over the wide range of α. A similar result was obtained on the VUV-ring at NSLS[12].

Conclusion

We have successfully shortened the bunch length down to 20 ps by reducing the momentum compaction factor. The effect of α_2 was compensated to a certain extent by reducing the strength of the focusing sextupole magnets. The estimated lowest momentum compaction factor was approximately 0.0002, which is 150 times smaller than the value of the regular operating point. The measured synchrotron frequency was consistent with the bunch length, and confirmed that the storage ring was operated nearly isochronously.

The bunch lengthening was also measured at various values of the momentum compaction factor. Based on potential-well distortion theory, the effective longitudinal coupling impedance was derived to be approximately 2.5 Ω, which was almost independent of the bunch length and of the momentum compaction factor, over wide range of the beam current.

Acknowledgements

We are grateful to the staff of the UVSOR facility for their technical supports. One of the authors (H.H) wish to thank Dr. D. Robin for many variable discussions.

References

1) K.W. Robinson, Cambridge Electron Accelerator rep. CEAL-1032 (1966).
2) D.A.G. Deacon, Phys. Rep. 76 (1981) 349.
3) C. Pellegrini and D. Robin, Nucl. Instr. and Meth. A301(1991) 27.
4) T. Nakazato et al., Phys. Rev. Lett. 63 (1989) 1245.
5) G. Isoyama, Nucl. Instr. and Meth. A308 (1991) 31.
6) J. Staples, LATTICE, LBL rep. no. 23939 (Lawrence Berkeley Laboratory, Berkeley, 1987).
7) H. Hama, S. Takano and G. Isoyama, Nucl. Instr. and Meth. A329 (1993) 29.
8) N. Kanaya, H. Hama, J. Yamazaki, O. Matsudo and G. Isoyama, IEEE Trans. Nucl. Sci. (in press).
9) A. Lin, H. Hama, S. Takano and G. Isoyama, Jpn. J. Appl. Phys. 31 (1992) 921.
10) S. Takano, H. Hama and G. Isoyama, Jpn. J. Appl. Phys. 32 (1993) 1285.
11) B. Zotter, Proc. CERN Accelerator School, General Accelerator Physics. Paris, 1984 (CERN, Geneva, 1985) CERN 85-19, p. 415.
12) S. Krinksy et al., Storage Ring Development at the National Synchrotron Light Source, BNL rep. no. 46615 (Brookhaven National Laboratory, Upton, 1991).