EXPERIENCE OF QUASI-ISOCRONUS OPERATION AT NEWSUBARU

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Abstract

quasi-isochronus operation is one of the operation modes of NewSUBARU, a 1.5 GeV VUV storage ring. NewSUBARU has six invert bending magnets to control the momentum compaction factor. The aim of this research is to explore the extreme reduction of electron bunch length by reducing the momentum compaction factor. We experimentally reduced the momentum compaction factor from 0.0014 down to less than 10^{-5}, keeping the beam in the ring. The second-order momentum compaction factor was adjusted to almost zero, while keeping the third-order momentum compaction factor positive. The ring was operated at 1.0 GeV. Using a streak camera, the shortest bunch length we observed was 4 ps FWHM.

1 INTRODUCTION

NewSUBARU [1] is a 1.5 GeV synchrotron radiation ring at the SPRing-8 site. Laboratory of Advanced Science and Technology for Industry (LASTI) at the Himeji Institute of Technology is in charge of its operation, collaborating with SPing-8. A bending cell in the ring is a modified DBA with an 80° invert bend between two 34° normal bends. This facilitates the control of the linear momentum compaction factor ($\alpha_1$) while keeping the cell achromatic and with only a small change of natural emittance.

The bunch length was measured with a streak camera as a function of $\alpha_1$. The idea of bunch shortening is derived from a well-known expression that the equilibrium bunch length is proportional to $\sqrt{\alpha_1}$. It was demonstrated in some facilities in 1990s [2]. Recently M. Abo-Bakur et al. reported that in BESSY the bunch length decreased to 1 ps (FWHM) according to the $\sqrt{\alpha_1}$ law, but with stored current of less than 1 µA per bunch [3]. On the other hand, Y. Shoji et al. theoretically predicted the intrinsic bunch-shorting limit came from longitudinal radiation excitation [4]. At NewSUBARU, that was 0.144 ps (FWHM) at 1.0 GeV. Approaching this limit is one of the goals of the bunch-shortening study. We report some experiences of quasi-isochronous operation at NewSUBARU up to the present.

2 EXPERIMENTS

We define the linear and non-linear momentum compaction factors ($\alpha_i$) as

$$L = L_0(1 + \alpha_1 \delta + \alpha_2 \delta^2 + \alpha_3 \delta^3 + \ldots).$$

Here $L$ is a circumference and $\delta$ is a relative energy displacement defined by $E = E_0(1 + \delta)$. In this report symbols with suffix "0" denote the values of the reference electron.

2.1 Control of $\alpha_1$

We control $\alpha_1$ by changing two quadrupole families at the dispersive sections as shown in Fig.1. The measurement of the synchrotron oscillation frequency $f_S$ confirmed a shift of $\alpha_1$. It is known that when we keep the RF acceleration voltage $V_{RF}$ constant, $f_S^2 \propto \alpha_1$. The shift of $f_S^2$ to the $\alpha_1$ of the lattice model is shown in Fig.2. Our linear lattice model had energy dependence and was not good enough for the accurate calculation of $\alpha_1$. The $\alpha_1$ was estimated at one set-point from two kinds of independent measurements [5]. We estimated $\alpha_1$ at the other set from measured $f_S$ assuming that $f_S^2 \propto \alpha_1$.

Figure 1: Calculations of dispersion function of NewSUBARU in one bending cell. The solid line is for $\alpha_1=0.0014$ and the broken line for $\alpha_1=0$.

Figure 2: Measured $f_S^2$ vs. set value of $\alpha_1$ (calculation using the present model). The solid line was measured at the stored energy of 0.7 GeV and the broken line at 1.0 GeV.
2.2 Control of $\alpha_2$

The second order momentum compaction factor $\alpha_2$ was controlled by changing one sextupole family SF at the dispersive section. The smallness of $\alpha_2$ was confirmed by measuring $f_S$ varying $\Delta f_{RF}$. Fig. 3 shows $f_S$ vs. $\Delta f_{RF}$ at $\alpha_1=7.5 \times 10^{-6}$.

When $\alpha_2$ was not small enough for a small $\alpha_1$ there existed a two stable buckets in one RF period. A beam in one bucket was transferred to another bucket by changing $f_{RF}$ as shown in Fig. 4.

Figure 3: Synchrotron oscillation frequency ($f_S$) vs. the shift of RF frequency ($\Delta f_{RF}$). Circles are measured and the line is a calculated assuming that the circumference is proportional to the function: $1+7.5 \times 10^{-6} \delta +0.9 \delta^3 -180 \delta^4 +1000 \delta^5 +6.4 \times 10^6 \delta^6 -6 \times 10^{-8} \delta^7$. During this measurement the RF acceleration voltage ($V_{RF}$) was set at 114 kV.

2.3 Bunch length Measurement

For the bunch length measurements the streak camera (Hamamatsu C6860) was used in synchro-scan mode. The set up of the camera was explained in the other article [6]. The fast sweep frequency was 83.3 MHz, 1/6 of the RF frequency (500 MHz). The measured bunch shape was an accumulation of signals emitted for 1.0 second. The harmonic number of the ring was $198=6 \times 33$. We filled the ring with 33 bunch trains of five filled and one unfilled buckets in succession.

We reduced $\alpha_1$, keeping the $V_{RF}$ constant, to ensure that the theoretically expected bunch length was proportional to $f_S$. The stored beam current was about 1μA per bunch with stored energy of 1.0 GeV. Fig.5 shows the measured bunch length with respect to the measured $f_S$. The bunch length agreed with theoretical calculation in the range of $\alpha_1=1.2 \times 10^{-3}$ ~ $2.0 \times 10^{-4}$. Fig.6 shows the observed bunch shape at $\alpha_1=2.2 \times 10^{-3}$, which was fitted with Gaussian distribution. However at very small $\alpha_1$, the measured length was greater than the calculated one. As yet, we have not reached any conclusion about why this occurred.

We also observed a dependence on $V_{RF}$, keeping $\alpha_1$ constant, as shown in Fig.7. The bunch length was longer at the highest $V_{RF}$.

Figure 5: Bunch length vs. $f_S$. The circles are measured length and the line is a theoretical calculation. The RF acceleration voltage was kept constant ($V_{RF}=310 kV$) while changing $\alpha_1$. 

Figure 6: Observed bunch shape at $\alpha_1=2.2 \times 10^{-5}$, which was fitted with Gaussian distribution.

Figure 7: Observed bunch length with respect to $f_S$, keeping $\alpha_1$ constant. The bunch length was longer at the highest $V_{RF}$. 

Terms of higher order than $\alpha_2$ were not controlled because the ring has no element to control them. The $\alpha_3$ was always positive. This finite positive $\alpha_3$ was essential to keep the beam inside the ring aperture especially when the ring parameter was moving. The smaller the $\alpha_1$, the larger the energy displacement is, and the positive $\alpha_3$ reduced the energy displacement for a mismatch of the RF frequency ($f_{RF}$) to the ring circumference. Although a beam storage with smaller $\alpha_1$ value was not difficult, the synchrotron oscillation was no longer linear. At $\alpha_1=7.5 \times 10^{-6}$ an energy displacement of 0.048%, which is a standard deviation of a natural energy spread, increases the magnitude of $\alpha$ by about 10% because of the finite higher-order terms.
Figure 6: Measured bunch shape by the streak camera, including the resolution of the system. The line is a Gaussian distribution fitted to the data.

Figure 7: Bunch length vs. \( V_{RF} \). The circles are measured length and the line is a theoretical calculation.

2.4 Synchrotron Oscillation Amplitude

Coherent movement of the beam was detected via the pickup electrode in the storage ring, and timing fluctuations appeared as side bands of \( f_{RF} \) in FFT spectrum. The coherent synchrotron oscillation amplitude in time axis (\( \Delta t_s \)) can be estimated from the peak ratio of side bands (\( \sqrt{V[f_{RF} \pm f_S]} \)) to \( f_{RF} \) (\( \sqrt{V[f_{RF}]} \)) as

\[
\Delta t_s = \frac{1}{2\pi f_{RF}} \frac{\sqrt{V[f_{RF} \pm f_S]}}{\sqrt{V[f_{RF}]}},
\]

Fig.8 shows the measured \( \sqrt{V[f_{RF} \pm f_S]/V[f_{RF}]} \) when we varied \( \alpha_1 \). Two phase feedback loops of RF low level control reduced the RF phase noise at low frequency, which excited the synchrotron oscillation [7]. If the side bands were narrow, \( \sqrt{V[f_{RF} \pm f_S]}/V[f_{RF}]=-70 \) dB means \( \Delta t_s=0.1 \) ps.

However the synchrotron oscillation side band was broad at small \( \alpha_1 \).

We observed a dependence of the synchrotron oscillation amplitude on \( \Delta f_{RF} \) as shown in Fig. 8. The effective bunch length was long for large synchrotron oscillation amplitude as shown in Fig.9.

Figure 8: Dependence of the synchrotron oscillation amplitude on \( \Delta f_{RF} \). The sharp peak at the left is \( f_{RF} \).

Figure 9: Measured bunch length for three cases of Fig.8.

3 ACKNOWLEDGMENTS

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4 REFERENCES