QUASI-ISOCHRONOUS OPERATION AT NEWSUBARU

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Abstract

A quasi-isochronous 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 (α). The aim of this research is to explore the extreme reduction of electron bunch length by reducing α. We experimentally reduced linear α from 0.0014 down to less than 10^{-5}. The second-order α was adjusted to almost zero, while keeping the third-order α positive. The ring was operated at 1.0 GeV. Using a streak camera, the shortest bunch length we observed was less than 1.5 ps (standard deviation). The higher order α became to be a limitation to the bunch shortening.

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 University of Hyogo is in charge of its operation, collaborating with SPring-8. The beam is injected from the SPring-8 linac with 1.0 GeV of electron energy. A bending cell in the ring is a modified DBA with an 8° invert bend between two 34° normal bends. This facilitates the control of the linear momentum compaction factor (α_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 α_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 and recently by M. Abo-Bakr *et al*. [2]. They reported that in BESSY-II the bunch length decreased to 1.5 ps (in this report the bunch length is expressed by means of standard deviation) according to the $\sqrt{\alpha_1}$ law. On the other hand from the theoretical side, we have reported two limitations expected at ideally low beam current. One is the intrinsic bunch-shortening limit came from the longitudinal radiation excitation [3]. At NewSUBARU, that is 0.06 ps at 1.0 GeV. Another is the bunch lengthening by a horizontal emittance [4]. That depends on a location in the ring, and is 0.2 ps at the light source point for the streak camera. Approaching these limits is one of the goals of the bunch-shortening study.

For the followings we define the linear and non-linear momentum compaction factors (α_n) as

$$\Delta L/L = \alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3 + \ldots \quad (1)$$

Here L is a circumference and δ is a relative energy displacement defined by $\delta = \Delta E/E$.

EXPERIMENTAL SETUP

Streak Camera

For the bunch length measurements we used the streak camera (Hamamatsu C6860) setup at BL6 (beam line for bending magnet radiation). The camera's static resolution, determined by the width of the slit, was σ= 0.3 ps. We operated the camera in synchro-scan mode. The measured bunch shape was an accumulation of signals emitted for 1/30 second.

The fast 83.3 MHz sweep-voltage for the camera was produced from the 500 MHz master oscillator signal divided by six. The harmonic number of the ring is 198 = 6×33. We filled the ring with 33 bunch trains of five filled and one unfilled buckets in succession. Details of the system were reported in SRI'03 [5].

Control of α_1

We control α_1 by changing two quadrupole families at the dispersive sections. A small dispersion change at the invert bends changes α_1, as shown in Fig.1. The α_2 was set to almost zero by adjusting strength of one sextupole family at the dispersive sections. Terms of higher order than α_2 were not controlled because the ring has no element to control them. At a low α_1, we estimated α_3 by measuring the synchrotron oscillation frequency (f_S) shift with respect to the RF frequency shift (Δf_{RF}), as shown in Fig.2. This finite positive α_3 was essential to keep the beam inside the ring aperture especially when the ring parameter was moving.

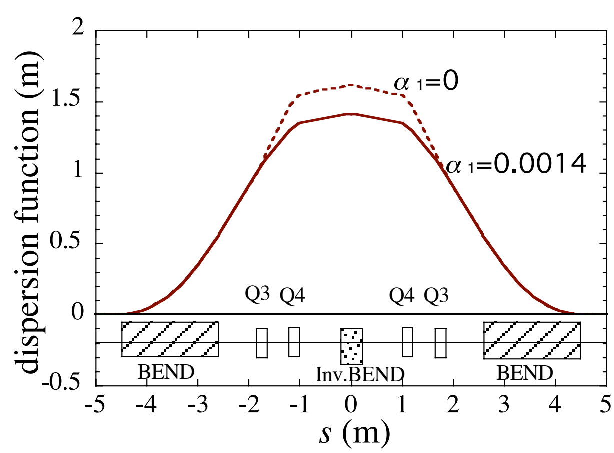

Figure 1: Calculations of dispersion function of NewSUBARU in one bending cell. The solid line is for α_1=0.0014 and the broken line for α_1=0.

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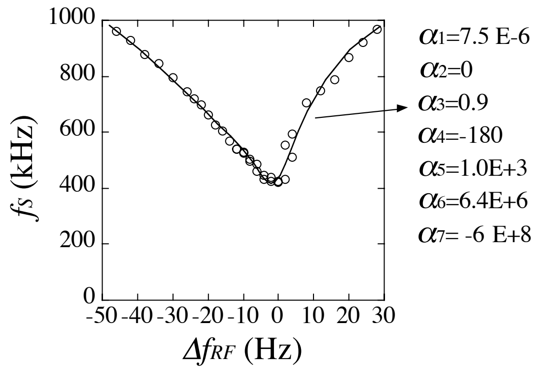

Figure 2: Synchrotron oscillation frequency (f_S) vs. the shift of RF frequency (Δf_{RF}). Circles are measured and the line is a calculation assuming the listed factors.

BUNCH LENGTH MEASUREMENT

Reduction of α_1

We reduced α_1, keeping the RF voltage (V_{RF}) constant, to ensure that the theoretically expected bunch length was proportional to $\sqrt{\alpha_1}$. Fig. 3 shows the results for two kinds of V_{RF} settings (120kV and 300kV) at two bunch current (1.8 μA/bunch and 0.24 μA/bunch). The α_1 was estimated from the measured f_S. However at $\alpha_1 < 1\times10^{-5}$, because the f_S was not easy to be identified, we used an extrapolation of the magnet current vs. α_1 plot.

The bunch length became longer than that expected from the $\sqrt{\alpha_1}$ law before reaching to the predicted limits. It looked as if it took the minimum at $\alpha_1 \approx 1\times10^{-5}$. We observed no current dependence with such a weak beam.

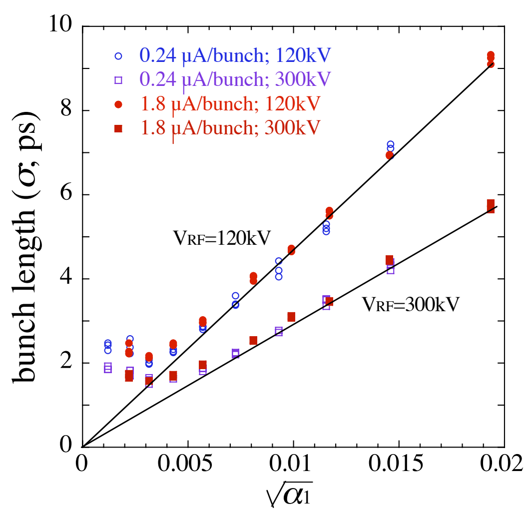

Figure 3: Bunch length vs. $\sqrt{\alpha_1}$. The symbols are measured length and the lines are theoretical calculation. The RF acceleration voltage was kept constant at 120kV or 300kV while changing α_1. The open symbols and the shaded symbols are the results with stored beam current of 1.8 and 0.24 μA/bunch, respectively. The resolution of the camera was not corrected.

Dependence on V_{RF}

V_{RF} dependence of the bunch length at $\alpha_1=1\times10^{-5}$ is shown in Fig. 4. The difference between the measured and the theoretical prediction, $\sqrt{(\sigma_{MEASURED}^2-\sigma_{THEORY}^2)}$, was roughly 1.3 ps and slightly decreased with V_{RF}.

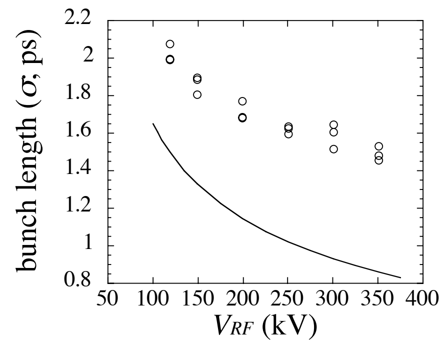

Figure 4: V_{RF} dependence of bunch length measured at $\alpha_1 = 1.0\times10^{-5}$ with stored beam current of 0.24 μA/bunch. The circles are measured length. The line is a calculation using a simple linear model.

Dependence on δ

The bunch length was not always shortest at the smallest f_S. It strongly depended on the energy displacement δ(or Δf_{RF}) at small α_1. Fig.5 shows the beam shape and FFT spectrum of a beam signal at different f_{RF}. The beam signal was picked up from an electrode on the beam pipe

At $\delta > 0$ ($\Delta f_{RF} < 0$) the amplitude of coherent synchrotron oscillation was large and the observed bunch was long. On the other hand at $\delta < 0$ ($\Delta f_{RF} > 0$) the coherent synchrotron oscillation almost disappeared and the observed bunch length became shorter. That beam behaviour was not observed at higher α_1 (1×10^{-4}) with the same δ (that meant a large Δf_{RF}). We have no clear explanation on why the synchrotron oscillation was enhanced at $\delta > 0$.

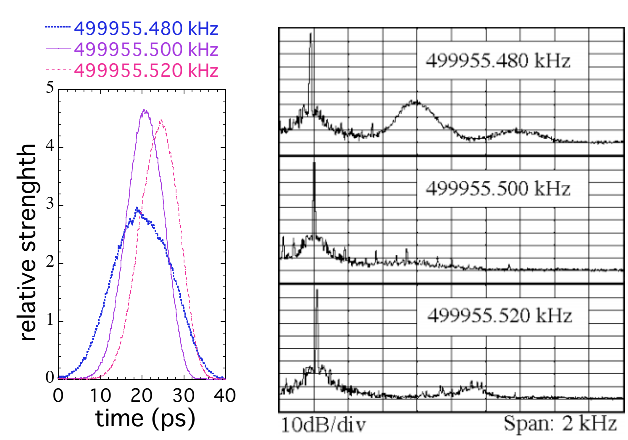

Figure 5: Dependence of coherent oscillation on the RF frequency (or δ displaced by Δf_{RF}) at $\alpha_1 = 1.0\times10^{-5}$. Left: bunch shape. Right: FFT spectrum of the beam signal. The highest narrow peak was the RF frequency.

Phase Jitter

We tried a correction of coherent oscillations, like that conducted by Abo-Bakr *et al.* [2]. We analysed profiles of 22 measurements with 0.1 ms timing gate. They were shifted according to the peak position of each measurement and were added. The width of the sum of the profiles was 1.48 ps, which was slightly smaller than that of the simply added profile, 1.53 ps. The difference of length was $\sqrt{(1.48^2 - 1.53^2)} \approx 0.4$ ps. The bunch length measurement in 1 second resulted in longer bunch than that in 1/30 sec. Their difference, $\sqrt{(\sigma_{1S}^2 - \sigma_{1/30S}^2)}$, was 0.3-0.5 ps. A coherent oscillation did exist in the time rage of 0.1ms – 1s. However it was not large enough to explain the deviation from the $\sqrt{\alpha_1}$ scaling law.

ENERGY SPREDING

Because of the large α_3, as shown in Fig. 2, an energy spreading of beam (or shift of f_{RF}) effectively enlarges α.

Natural Energy Spread

Neglecting α_2 and the higher order terms than α_3, the shift of RF frequency and the momentum compaction factor are given by

$$\Delta f_{RF}/f_{RF} = -(\alpha_1\delta + \alpha_3\delta^3) , \quad (2)$$
$$\alpha = \alpha_1 + 3\alpha_3\delta^2 . \quad (3)$$

Using the natural energy spread of NewSUBARU (σ_{NE}= 4.7×10^{-4}) as δ and α_3=0.9, the contribution of α_1 and α_3 to a are comparative at $\alpha_1 = 6\times10^{-7}$. However we did not have reached to that small α_1.

Higher Order Effect of Betatron Motion

The higher order contribution of betatron oscillation to the circumference is given by the equation [5],

$$\Delta L/L = (1/4)\ \varepsilon_{CSI}\ (<\gamma> + <\beta/\rho^2>). \quad (4)$$

Here ε_{CSI} and ρ are Courant Snyder Invariant and curvature of radius, respectively. The γ and β are Twiss parameters of horizontal betatron motion. This shift of $\Delta L/L$ is cancelled out by an energy shift δ given by

$$(\Delta L/L) = -(\alpha_1\delta + \alpha_3\delta^3) . \quad (5)$$

Using parameters of NewSUBARU, $\varepsilon_{CSI}=3\times10^{-8}$m (natural emittance), $<\gamma>=1.4$m^{-1} and $<\beta/\rho^2>= 0.05$m^{-1}, $\Delta L/L$ is calculated to be 1.1×10^{-8}. This energy and orbit shift corresponds to a shift of Δf_{RF} =5.4Hz in Fig. 2. This effect pushed f_S up by some tens of %.

A shift of the synchronous phase ϕ_S is given by

$$\Delta\phi_S = \tan\phi_S\ [k\ \beta_{RF}\varepsilon_{CSI}/4 - (2+D)\delta\ ]. \quad (6)$$

Here D is the damping partition number and k is a factor, which represents the radial dependence of the RF acceleration field. When k is small, the contribution of $\Delta\phi_S$ to the bunch length is negligibly small.

COD Drift

A time dependent dipole error field fluctuates the beam energy. Horizontal COD of an electron storage ring, x, produced by an error kick θ_{ERR} is given by

$$x = [\sqrt{\beta}/2\sin\pi\nu]\ \sqrt{\beta_{ERR}}\ \theta_{ERR}\cos[\,|\psi-\psi_{ERR}|-\pi\nu] \\ -(1/\alpha_1)\ (\theta_{ERR}\ \eta_{ERR}/L_0)\ \eta\ . \quad (7)$$

Here ν, ψ and η are betatron tune, betatron phase and dispersion function. The parameters with suffix '$_{ERR}$' are values at the error kick location. The second term, which is proportional to the inverse of α_1, is produced from the change of the circumference,

$$\Delta L = \theta_{ERR}\ \eta_{ERR}\,. \quad (8)$$

In NewSUBARU this shift was measured to be $\Delta L/L \approx \pm3\times10^{-8}$. Its main frequency components were 60Hz, 120Hz and 180Hz. They are harmonics of the primary AC power line and are comparable to the longitudinal damping time (12 ms). This effectively enlarged α and probably prevented the bunch compression below $\alpha_1=1\times10^{-5}$.

CONCLUSION

We could not reduce the bunch length below $\alpha_1=1\times10^{-5}$. The combination of large α_3 and the fluctuation of energy by the dipole field fluctuation was one of possible reasons. We are planning to install a feed back system to stabilize the beam orbit using a fast BPM.

After the installation of the new system, we would soon face to the contribution of the horizontal natural emittance. Still we do not understand all and need more research.

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