ESTIMATION OF NON-LINEAR RF BUCKET OF NEWSUBARU

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Abstract

Linear and higher order terms of the momentum compaction factor of NewSUBARU were estimated from the measurements. The linear term was estimated from the shift of horizontal COD to the RF frequency. Higher order terms were estimated from the shift of synchrotron oscillation frequency to the RF frequency. The RF bucket in the user operation was calculated from these data. The bucket is not symmetric for dE/E>0 and for dE/E<0 because of the non-linearity of the momentum compaction factor.

1 INTRODUCTION

The synchrotron radiation facility NewSUBARU [1] is a VUV and Soft X-Ray light source 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 SPring-8. The ring has two operation modes for users. In the 1.5 GeV mode, the beam is accelerated to 1.5 GeV and stored, while in 1.0 GeV top-up mode, the beam current is kept at 250±0.15 mA by an occasional injection with the gaps of undulators closed.

The injection efficiency of NewSUBARU is lower than 80% when the undulator gaps are closed, although at the present this is acceptable because NewSUBARU has no in-vacuum undulator. The understanding of the real RF bucket is required to improve the injection efficiency, which is sensitive to the electron energy from the linac.

The accurate estimation of the momentum compaction factor (α) has a special importance at NewSUBARU, which has invert bending magnets to control the linear momentum compaction factor. Some trials by A. Ando *et al.* were not successful [2]. A dependence of the synchrotron oscillation frequency on the RF acceleration voltage (V_{RF}) did not give enough accuracy to the estimation α because of the uncertainty of V_{RF}. The analysis of non-linear dispersion function did not agree with the calculation. This report gives a reliable measurements of linear momentum compaction factor (α_1) with an accuracy of few %.

2 MEASUREMENT AND ANALYSIS

2.1 Formula of momentum compaction factor

We define the linear and non-linear momentum compaction factors (α_n) as

$$L=L_0(1+\alpha_1\delta+\alpha_2\delta^2+\alpha_3\delta^3+\ldots) = L_0\,[1+\alpha_1 A(\delta)]. \quad (1)$$

Here L is a circumference and δ 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. The function $A(\delta)$ represents the non-linear part of the momentum compaction factor.

The synchrotron oscillation frequency for a small oscillation amplitude (f_S) is given by the well-known equation,

$$f_S = [\,(\alpha f_{RF}^{\,2}\, eV_{RF} \cos\phi_S)/(2\pi hE)]^{1/2}. \quad (2)$$

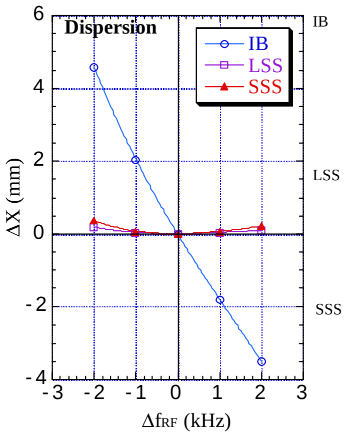
Here e, h, f_{RF} and ϕ_S are elementary charge, harmonic number, RF frequency and synchronus phase. Using $A(\delta)$, the α in Eq.(2) is written as

$$\alpha= (dL/dE)(E/L) = A'(\delta)\,(1+\delta)/[\,1+ \alpha_1 A(\delta)]. \quad (3)$$

The measurement of f_S gives good information about α.

2.2 Estimation of α_1 from dispersion

The α_1 was estimated from the shift of horizontal COD (ΔX) to the shift of f_{RF} (Δf_{RF}). Eighteen beam position monitors were grouped into three, six at the dispersive sections:"IB", four at the non-dispersive long straight sections: "LSS", and eight at the non-dispersive short straight sections: "SSS". We got $d(\Delta X)/d(\Delta f_{RF})$ for each group by fitting the data with polynomial functions as shown in Fig.1. The results are the listed in Table 1.



IB

y = m1*M0+m2*M0^2+m3*M0^3	value	error
m1	-1.8825	0.023784
m2	0.13645	0.0042929
m3	-0.034341	0.0065965
kai^2	0.0012532	NA
R	0.99998	NA

LSS

	value	error
m1	0.0024128	0.0031993
m2	0.035857	0.00057746
m3	-0.0059828	0.00088731
kai^2	2.2675e-05	NA
R	0.99949	NA

SSS

	value	error
m1	0.0082891	0.0066535
m2	0.071558	0.0012009
m3	-0.011812	0.0018453
kai^2	9.8073e-05	NA
R	0.99944	NA

Figure 1: Horizontal COD displacements to RF frequency change (Δf_{RF}) for three beam position monitor groups, IB, LSS and SSS.

In order to estimate α_1 we adjusted the strengths of two quadrupole families of the model lattice at the dispersive sections so that the lattice model would be consistent with the data. A lattice with α_1=0.001417 gave the best matching as is listed in Table 1. The result was $\alpha_1=(1.417\pm0.023)\times10^{-3}$.

Table 1: Measured (fitting result) and calculated (assuming that α_1=0.001417) $d(\Delta X)/d(\Delta f_{RF})$.

BPM group	$d(\Delta X)/d(\Delta f_{RF})$ (mm/kHz)	
	measurement	calculation
IB	-1.883±0.024	-1.883
LSS	+0.0024±0.0032	+0.0037
SSS	+0.0083±0.0067	+0.0070

2.3 Estimation of α_1 from synchronus phase

This result was confirmed by the measurement of ϕ_S and f_S varying V_{RF}. The equation (2) is rewritten as

$$f_S = [(\alpha_1 f_{RF0}^2 U_O \cot\phi_S)/(2\pi h E_0)]^{1/2}. \qquad (4)$$

Here U_O is an average of energy loss of the reference electron per revolution. V_{RF} does not appear in this equation and is not used in the analysis. We measured the phase difference between the RF clock and the beam signal ($\Delta\phi_S$) and f_S varying V_{RF}. A strong non-linearity between f_S and ϕ_S gives α_1 with enough accuracy.

The data and the fit is shown in Fig. 2. The result of the calculation was $\alpha_1=(1.452\pm0.013)\times10^{-3}$, which agreed with the measurement of dispersion function within the error of about 3%.

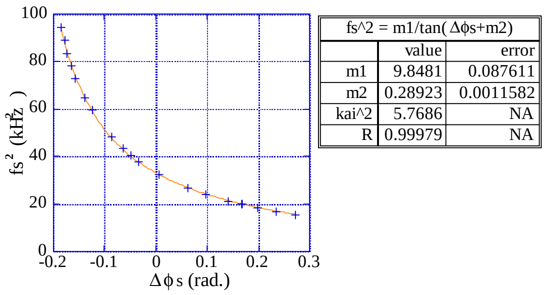


Figure 2: Square of the synchrotron oscillation frequency (f_S) vs. the shift of the synchronus phase($\Delta\phi_S$). The crosses are data points and the line is a fitted function.

2.4 Estimation of higher order terms

The non-linear momentum compaction factor was obtained from the measurement of the shift of f_S to Δf_{RF}. Using Eq.(2) and Eq.(3) f_S is simply written as

$$f_S = f_{S0}\, A'(\delta)^{1/2} \ . \qquad (5)$$

Here we kept V_{RF} constant and ignored a small dependence of f_{RF}, f_S, L and E on δ. The $A'(\delta)$ means $dA(\delta)/d\delta$. From the definition of A(δ), the inverse function of $A(\delta)$ is written as

$$\delta = A^{-1}([L/L_0-1]/\alpha_1) \approx A^{-1}(-\Delta f_{RF}/f_{RF0}/\alpha_1)\ . \qquad (6)$$

Here u is a parameter defined by $u=-\Delta f_{RF}/f_{RF0}/\alpha_1$. Considering that $A'(\delta)=1/A^{-1}{}'(u)$, Eq.(5) is rewritten as

$$1/f_S^2 = (1/f_{S0}^2)\, A^{-1}{}'(u). \qquad (7)$$

The measurement of f_S for various Δf_{RF} gives the function $A^{-1}{}'$. Integrating $A^{-1}{}'$ and taking the inverse, we reached to the function $A(\delta)$.

We measured f_S through as wide Δf_{RF} as possible (-9 kHz ≤ Δf_{RF} ≤ 14 kHz) to cover the full RF bucket. Our measurement took place with low stored current (0.2mA multi-bunch) in order that the shift of f_S by the beam loading was negligible. At Δf_{RF} = -9.2 kHz the ring could not store the beam and at Δf_{RF} = 14 kHz the ring had very short beam life.

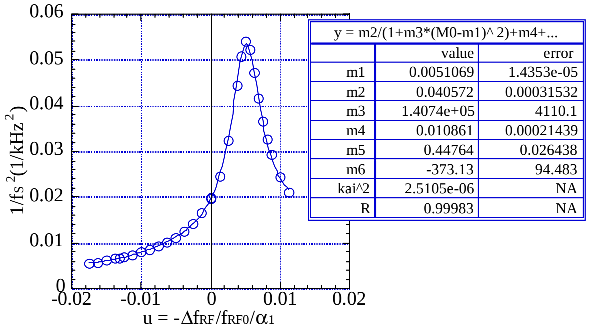


Fig.3 Fitting $1/f_S^2$ as a function of $u=-\Delta f_{RF}/f_{RF0}/\alpha_1$. Circles are data points and the line is a result of the fit.

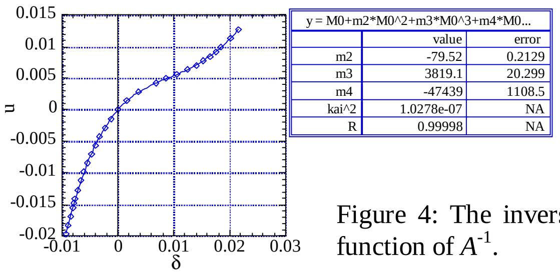


Figure 4: The inverse function of A^{-1}.

We fitted the measured data assuming the function form of $A^{-1}{}'$. A simple polynomial function did not work well. We needed Lorentzian function in addition to the polynomial function. The result of the fitting to $1/f_S^2$ as a function of u is shown in Fig.3 and Eq.(8).

$$(1/f_{S0}^2)A^{-1}{}'(u) = 0.010861+0.44764u-373.13u^3 + \frac{0.040572}{1+140740(u-0.005107)^2} \qquad (8)$$

Using f_{S0}=7.117kHz and integrate the function $A^{-1}{}'$(u) under the condition that $A^{-1}(0)=0$, we get

$$A^{-1}(u)=0.0055325 \tan^{-1}[187.58\,(2u-0.0102138)] + 0.006029+ 0.55561\,u + 11.450\,u^2 - 4772\,u^4. \qquad (9)$$

A simple 4th order polynomial function

$$A(\delta) = \delta - 79.5\delta^2 + 3820\delta^3 - 47400\,\delta^4\ . \qquad (10)$$

was a good enough approximation of the inverse of A^{-1} as shown in Fig.4. Finally we get the following.

$$L=Lo(1+0.00142\delta-0.1129\delta^2+5.423\delta^3-67.3\delta^4). \qquad (11)$$

2.5 Non-Linear RF Bucket

Using the Eq.(11), we calculated the typical RF bucket of NewSUBARU, with V_{RF}=113kV. The result is shown in Fig.5. The energy acceptance of the bucket was -0.9% ≤ δ≤ +1.7%. The measured area, corresponding to -0.9% ≤ δ≤ 2.2%, had covered the full bucket acceptance.

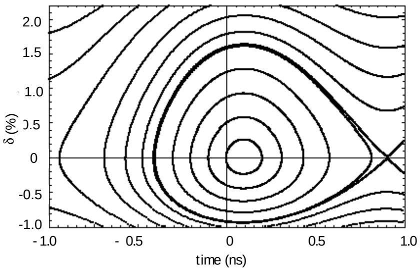


Figure 5: Typical RF bucket of NewSUBARU. The vertical axis is δ in %.

2.6 Measurements Using Streak Camera

We injected the short pulsed beam (10ps) into the RF bucket at various phases, using technique of RF synchronized injection [3]. Injected beam survived for more than 500 µs when the beam was injected at the timing from -43ns to 0.93ns in Fig.5. This experiment supported the estimation of bucket shown in Fig.5.

The synchrotron oscillation was excited by $2f_S$ phase modulation technique [4]. The observed non-linear synchrotron oscillation in time axis qualitatively agreed with the calculated one as shown in Fig.6.

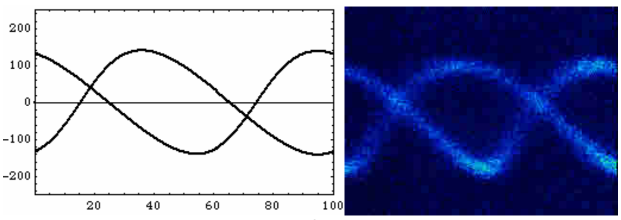


Figure 6: Simulation (left) and the observed (right) synchrotron oscillation. The horizontal and vertical full range are the same for the left and for the right.

2.7 Energy Acceptance

In section 2.5 we mentioned that there exists a hard limit at $\Delta f_{RF}\approx$ -9.2kHz ($\delta\approx$2%) and a soft limit at $\Delta f_{RF}\approx$14kHz ($\delta\approx$-0.9%) in energy acceptance of the ring. The measurement of ΔX and the betatron tune (ν_X and ν_Y) for Δf_{RF} gave possible solutions of what the limits were. According to the results of the measurements of COD (Fig. 7), the hard limit was possibly a mechanical aperture. The measurement of he betatron tunes (Fig.8) showed that the soft limit might be a horizontal normal octupole resonance ($4\nu_X$=25).

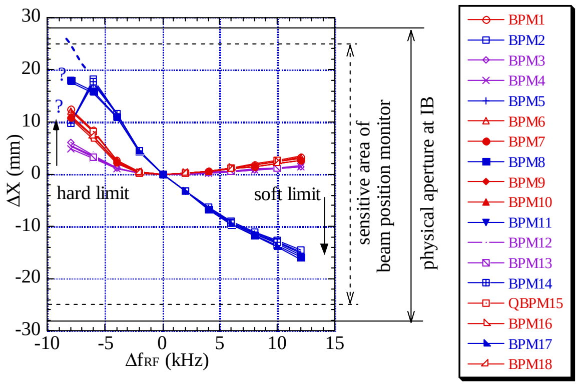
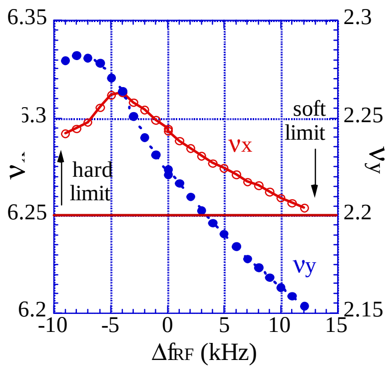


Figure 7: ΔX vs. Δf_{RF}. The BPM read out returns wrong position for ΔX>25mm [6].

Figure 8: Betatron tune vs. Δf_{RF}.



3 DISCUSSION

The estimated RF bucket was non-linear along the energy axis. This means that an appropriate control of the higher order momentum compaction factor [5] and the correction of the resonance would enlarge the energy acceptance of the RF bucket. The proof of this hypothesis and an expected elongation of Touschek life time will be the next step of this research.

4 ACKNOWLEDGEMENT

The authors wish to thank members of the SPring-8 accelerator division for their support on the machine operation, especially Dr. Y. Kawashima, Dr. T. Nakamura and Dr. S. Suzuki for their strong support on this research. We also thank Prof. A. Ando for his support on this work.

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