BETATRON TUNE MEASUREMENT AND AUTOMATIC CORRECTION SYSTEMS AT NEWSUBARU STORAGE RING

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Abstract

At the NewSUBARU electron storage ring, two different kinds of systems for betatron tunes have been developed: a high-precision tune monitor and a real-time measurement and automatic correction system. The high-precision tune monitor has the resolution of 0.0002 and uses frequency analysis methods such as SRSA, zoom FFT, in addition to usual FFT. Fluctuations of tune due to a slight difference of filling pattern in the top-up operation and tune shifts due to the decrease of stored current in the decay operation can be observed with this monitor. The tune monitoring and automatic-correcting system has been developed to compensate tune shifts during the energy ramp from 1.0 to 1.5 GeV. This system can measure and correct betatron tunes every 0.5 sec to keep tunes to the optimal values. The system also has a tune survey function that can automatically measure the beam lifetime in a tune diagram to find the optimal operating point experimentally.

INTRODUCTION

The NewSUBARU synchrotron radiation facility [1,2] of University of Hyogo [3] is located in the SPring-8 site and has a 1.5 GeV electron storage ring. Synchrotron radiation in the soft X-ray regime is applied to industrial purposes such as EUV Lithography, LIGA, the development of new materials, and the generation of gamma ray by Compton scattering. Electron beams are injected from 1.0 GeV Linac of SPring-8. The ring operates in the top-up mode at 1.0 GeV and the decay mode at 1.5 GeV. The main parameters of the ring are shown in Table 1.

Table 1: Main Parameters of the NewSUBARU Ring

Beam energy	1.0 – 1.5 GeV
Circumference	118.7 m
RF frequency	499.955 MHz
Stored Current	500 mA (max.)
Harmonic Number	198
Synchrotron Frequency	6 kHz
Betatron Tune	6.28 (H) / 2.22 (V)
Operation mode in user time	220 mA Top-up @1.0GeV 350 mA Decay @1.5GeV

One of the problems on machine operation is a betatron tune shift during user time. Tune shifts were observed in the following cases: (1) current dependence in the decay mode operation, (2) dependence on a slight difference of filling pattern in the top-up operation, (3) during energy ramping from 1.0 to 1.5 GeV. In our ring a stripe-line kicker shakes electron beams vertically to enlarge the Touschek lifetime. Thus horizontal and vertical tunes can be usually observed even during user time.

In this paper we introduce two different kinds of systems concerning betatron tunes, the one is for precise measurement and the other is for real-time tune correction.

BETATRON TUNE MONITOR

To measure betatron tunes with a high resolution we developed a precise tune monitor. Although the update rate is relatively slow, the monitor has the resolution of 0.0002 and can measure a slight change of tune or its fine structure.

Hardware

Signals from four electrodes of a Beam Position Monitor are analyzed using a BPM signal processing circuit (bergoz LRBPM). The output signals representing horizontal and vertical beam positions are digitized by a digital oscilloscope (NI PXI-5102) in a PXI chassis. The digitizer has 15MHz bandwidth and 20MS/s sampling speed. The PXI system was connected to a PC through Ethernet. The digitized waveform data in time domain, whose typical number of samples per channel is 25600, was transferred to the PC. The application software developed by National Instruments (NI) LabVIEW performs frequency analysis from the position data. The PC runs as a virtual machine on a host machine using VMware workstation.

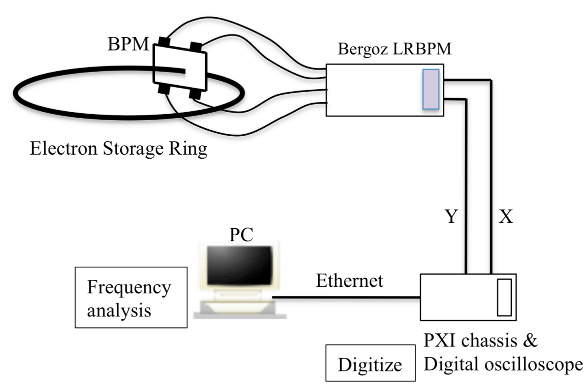

Figure 1: Layout of the precise tune monitor.

Frequency Analysis

The advantage of performing frequency analysis at the PC is that resources of high-performance PC can be used for the frequency analysis requiring a huge amount of

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calculation and that various methods of frequency analysis can be used. As frequency analysis methods, we used zoom FFT, SRSA (Super-Resolution Spectral Analysis) in addition to FFT which is the most popular frequency analysis method. Zoom FFT analysis [4] is an efficient computation on a subset of frequencies of interest, and can save an amount of processing power and time compared to computing the FFT for entire frequencies. SRSA is a model-based analysis method. It needs smaller datasets of sample points and prior knowledge of the input signal, that is, an estimate of the number of sinusoidal components in the input signal.

Horizontal tune spectrums at the 1.0 GeV top-up operation obtained by the three methods are shown in Fig. 2. Peak frequency of 726 kHz corresponds to fractional tune of 0.287. The resolution of the FFT is 0.0002 in tune. In both sides of the main lobe sidebands are observed which are separated by a synchrotron frequency of 6 kHz from the main peak. The elapsed times for computing one waveform are 15.4 ms in FFT, 4.5 ms in zoom FFT and 10.0 ms in SRSA. Magnification of the zoom FFT is about 80. The zoom FFT has relatively lower resolution than the FFT but smaller elapsed time for computing. SRSA can the peak frequency but it is hard to obtain fine structure and need computing time longer than the zoom FFT.

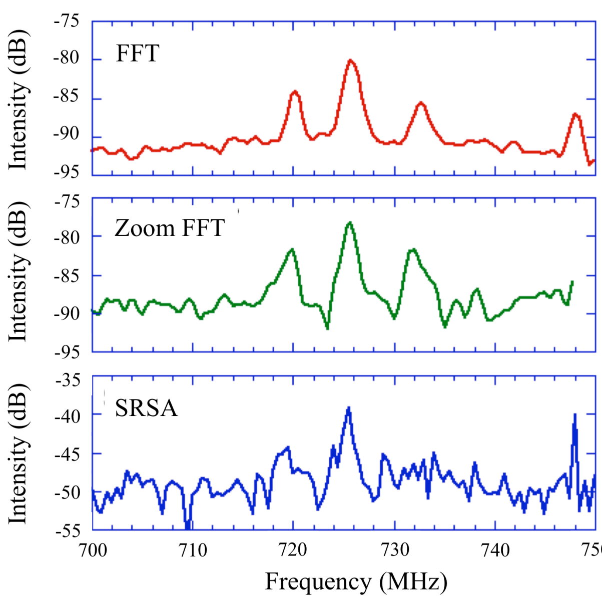

Figure 2: Horizontal tune spectrums analyzed by FFT (upper), zoom FFT (middle) and SRSA (lower).

Measurement Results

Temporal changes of horizontal and vertical tunes during top-up operation, where the stored beam current of 220 mA is kept constant for eight hours, are shown in Fig. 3. In our ring the number of harmonic number is 198 and “70+70 over Full-Fill” filling pattern, which means two 70 bunch trains plus fulfilling, is used in usual user time [5]. The ratio of bunch charge between a bunch in 70 bunch trains and the full-fill part is about 3 to 1. The beam from the linac can be injected in the order of bucket address or to a selected bucket which charge is smallest compared to the other bunches [6]. When beams are injected in the order of bucket address, observed tunes are fluctuated as shown in Fig. 3 due to a slight and relative variation of a filling pattern. When the address of an injected bunch is selected, no fluctuation was observed, but slow drifts of tunes in both horizontal and vertical were observed. These drifts may arise from a temperature drift such as magnets, vacuum chambers. Our facility stops machine operation at night and starts to operate power supplies in morning for energy saving everyday.

The dependence of tune on the stored current is shown in Fig. 4. Tune slowly decreases according to the decrease of the current for ten hours of the 1.5 GeV decay mode operation.

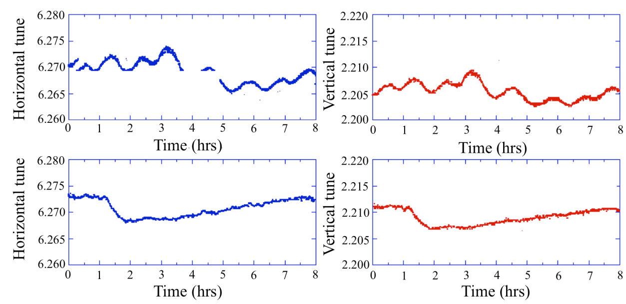

Figure 3: Measured tune variation during user-time in horizontal (left) and vertical (right). Bunch selection is OFF (upper) and ON (lower).

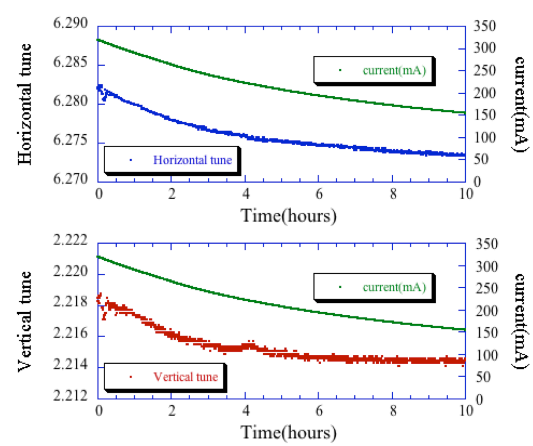

Figure 4: Horizontal (upper) and vertical (lower) tunes during 1.5 GeV decay mode.

AUTOMATIC TUNE CORRECTION SYSTEM

The second system is the tune measurements and automatic correction system. In the NewSUBARU storage ring, horizontal and vertical tunes drift or

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fluctuate during energy ramping in addition to the filling patterns and the stored current as mentioned above. Tune shifts during the ramping come from asynchronous ramping speeds among magnets, eddy currents and an inadequate reproducibility of magnetic field strength. It is desired to compensate tune shifts in real-time for a stable operation.

Tune Measurement for Correction

The layout of the tune correction system is shown in Fig. 5. To measure both horizontal and vertical tunes simultaneously, beam signals from diagonally displaced two electrodes of a BPM are used. The intensity and phase of the two signals are adjusted using attenuators and phase shifters. And subtracted signal is generated by 180-degree hybrid. After being amplified, this signal is frequency analyzed by the spectrum analyzer (ADVANTEST U3751). The spectrum data is transferred to a PC through GPIB and Ethernet. In the PC raw spectrum data is analyzed and tunes are evaluated in real-time using the application software developed by LabVIEW.

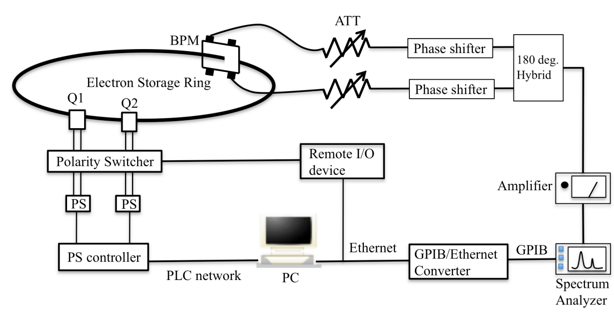

Figure 5: Layout of the automatic tune correction system.

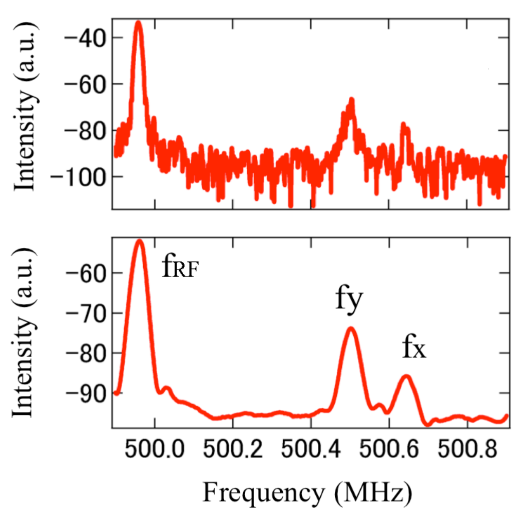

Figure 6: Spectrum waveform before (upper) and after (lower) ten times averaging and a smoothing.

In Fig. 6 measured spectrum waveforms are shown. The raw data from the spectrum analyzer is very noisy, so the estimation of signal peaks is difficult. After ten times averaging and a smoothing, the processed waveform becomes clear and suitable for peak detection. In the software the peaks are carefully analyzed so that there is no detection error, taking into account that the beam signal intensity varies according to the stored beam current and a spectrum is largely disturbed in top-up operation if the timing of measurement is overlapped with a beam injection.

Tune Correction

A flow chart for the tune correction scheme is shown in Fig. 7. The PC detects two peaks of tunes in the spectrum waveform and determines that it should be corrected if the measured tunes are largely shifted from the desired ones. The PC calculates correction amount of tune and corresponding currents for power supplies (PS).

To adjust tunes we attached the additional windings to quadrupole magnet Q1, Q2 families. For the additional winding, power supplies that can be controlled separately from the main power supplies for Q1 and Q2 are provided. The PC sends current setting for Q1 and Q2 windings to the PS controller, which controls the PS through Programmable Logic Controller network. The control loop speed is 0.5 sec.

Because these power supplies are monopolar from the point of view of cost, a simple polarity switcher that can be controlled by external high/low voltage from the remote I/O device (NI compact Fieldpoint) is used. To avoid an over-correction due to measurement errors, in case of tune shifts larger than 0.02 in one cycle, the correction is not performed.

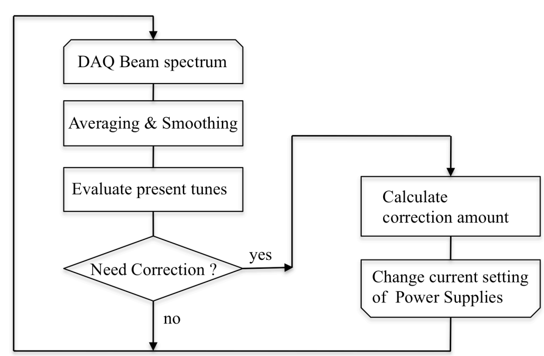

Figure 7: Scheme of tune correction.

Correction Results

Results of tune correction during energy ramping are shown in Fig. 8. Without corrections, horizontal and vertical tunes vary in the range of 0.01 to 0.02 during energy ramping. These changes come from discrepancy of magnetic field during energy ramping. The trajectory in a tune diagram during energy ramping is shown in Fig. 9. The large shift is one of reasons of a partial loss of beams or a beam abort.

With tune corrections, the range of tune shifts become be kept within 0.005 and stable ramping is possible. The tune trajectory with the correction in a tune diagram is also shown in Fig. 9.

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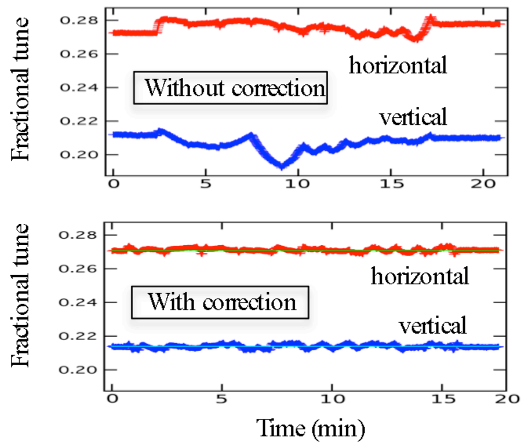

Figure 8: Time variation of horizontal and vertical tunes without and with correction.

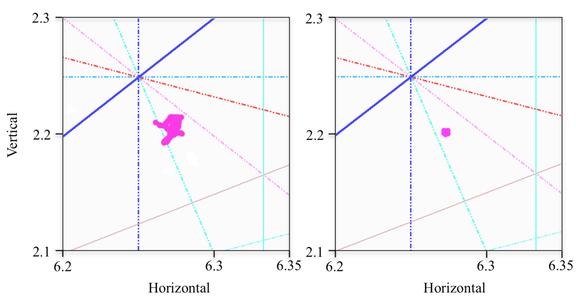

Figure 9: Tune trajectory during energy ramp from 1.0 to 1.5 GeV without (left) and with (right) tune real-time correction.

AUTOMATIC TUNE SURVEY

The tune correction system has an automatic survey function, which can measure automatically beam lifetime with varying operation points. Figure 10 shows the experimental results of tune survey of the beam lifetime at 1.0 GeV, 200 mA. Because of the insufficient number of windings and the lack of capability of power supplies, a survey area is divided into three parts. All data was taken within one hour. Some resonance lines and the usual operating point (6.28, 2.21) are also plotted. It is obvious that there are the decrease of lifetime due to resonances near $3\nu_x=19$ and $\nu_x - \nu_x=4$.

At the usual operating point, the product of current and lifetime Iτ is about 1000 mA hour. On the other hand, it is found that Iτ around $\nu_x=6.31$ increases about 40 %. This optimal area is relatively large but close to the strong resonance $3\nu_x=19$. Without tune corrections, ramping in this area may cause the reduction of lifetime or a beam abort, considering that tunes shift about 0.02 as shown in Fig. 8. Thus it is necessary for the stable operation to operate and ramp in this area with the tune correction.

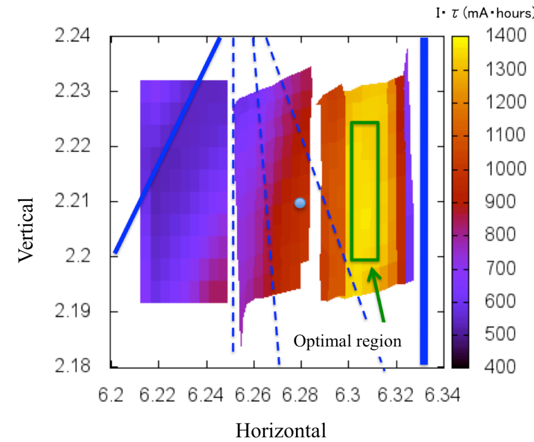

Figure 10: Contour plot of the measured beam lifetime in tune diagram. The circle denotes typical operating point.

CONCLUSIONS

In the NewSUBARU electron storage ring, the two kinds of betatron tune monitors have been used. The one is for the high-precision measurement and the other is for the real-time automatic correction.

Although the high-precision monitor is slow monitor, the resolution of tune measurements is 0.0002. In frequency analysis three methods such as FFT, zoom FFT, SRSA were compared. Small fluctuations of tunes during the top-up operation can be observed using this monitor.

The tune correction system can automatically compensates tune shifts every 500 ms, if measured values are shifted from the desired values. The automatic tune survey of the beam lifetime is useful for study of beam dynamics.

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