TUNE TRACKING RFKO BUNCH PURIFICATION WITH BUNCH-BY-BUNCH FEEDBACK AT SPRING-8

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Abstract

The bunch purification of a singlet bunches for the SPring-8 storage ring is performed at the booster synchrotron, by clearing out electrons in neighbouring RF buckets by RF kick (RFKO). The injection period to the storage ring at top-up operation is tens seconds and is not fixed; however the booster is currently running at 1 Hz to stabilize the booster machine parameters. To save energy and the operation cost, we intend the on-demand operation of the booster at injection, however the large tune drift was observed in the on-demand operation and this drift drives the tune to off-resonance of the RFKO frequency. To overcome this tune drift, we are developing a tune tracking RFKO bunch cleaning system with transverse bunch-by-bunch feedback. In this system, the betatron oscillation of the main bunch is excited by positive feedback and the signal from the feedback excites the RFKO system, thus the frequency of the RFKO system is locked to the tune.

INTRODUCTION

The purity of a singlet bunch (the ratio of the current of the satellite bunches and the main bunch) of the SPring-8 booster synchrotron without the bunch purification is the order of 10^{-6} because the dark current of the injector linac are simultaneously injected from the linac to the booster and form satellite bunches. This purity level is not sufficient for the singlet bunch users at the storage ring and the bunch purification system is routinely operated at the booster to clear out the electrons in the satellite bunches to keep the purity of the order of 10^{-11} level [1]. The bunch purification is performed with RFKO method for vertical betatron oscillation at the injection energy of 1GeV, during 250ms after the injection and before the acceleration. The booster is continuously operated with 1 Hz to stabilize the field of the magnets of the booster to keep the vertical tune stable for RFKO. On the other hand, the injection period at the top-up operation of the SPring-8 storage ring is not fixed and around tens seconds, hence if we perform on-demand operation of the booster for the injection to the storage ring, we can reduce the power consumption and the electricity cost. At the on-demand operation of the booster, the drift of the vertical tune is observed, thus we need to tune the RFKO frequency to the vertical betatron frequency by some method. For this purpose, we are now testing the tune tracking RFKO system with the SPring-8 bunch-by-bunch feedback processor [2].

TUNE TRACKING RFKO SYSTEM

The block diagram of the tune tracking RFKO system is shown in Fig. 1, and the parameters of the booster are listed in Table 1. The vertical betatron oscillation of the main bunch is continuously excited by the positive feedback loop and the excitation signal is send to the RFKO system to excite the electrons in satellite bunches.

Table 1: Parameters of the SPring-8 Booster Synchrotron

parameters	symbol	value
Revolution frequency	f_{rev}	757 kHz
RF frequency	f_{RF}	509 MHz
Vertical fractional tune	$\Delta\nu_y$	0.78
Vertical betatron frequency	$f_y = (1-\Delta\nu_y)\, f_{\mathrm{rev}}$	167 kHz

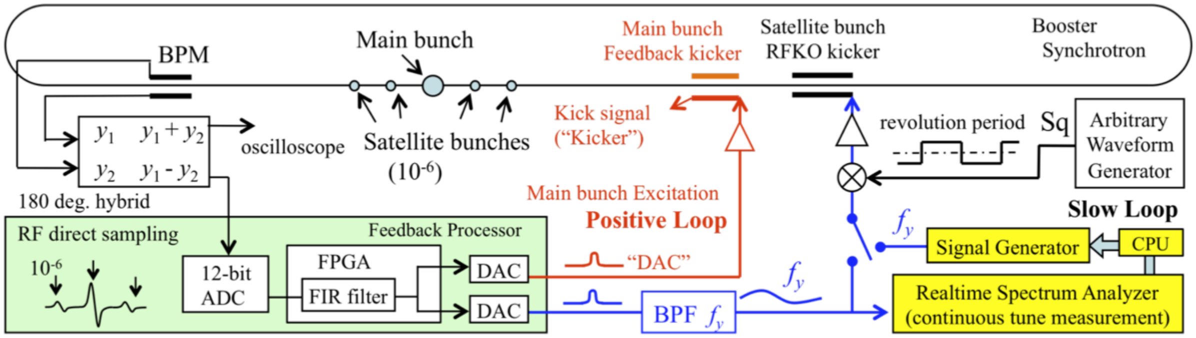


Figure 1: Tune tracking RFKO system. Position signal (y_1 - y_2) from BPM is digitized by ADC and processed by FIR filter to produce kick signal to excite betatron oscillation of the main bunch continuously (**Positive Loop**). The same signal is fed to RFKO system to excite and kick out satellite bunches. At RFKO system, the signal is modulated with the square wave of which period is one turn of the booster to avoid the excitation of the main bunch as in usual RFKO systems. The signal is also send to realtime spectrum analyzer for continuous measurement of the tune. The control of frequency of signal generator with measured tune frequency is a candidate of alternative scheme (**Slow Loop**).

The two RF signals from a vertical pair of BPM striplines are subtracted by an 180 deg hybrid to produce a difference signal $y_1 – y_2$, which is proportional to the product of the shift of the vertical position and the current of bunches. The purity (the ratio of the charge of satellite bunches and the main bunch) is the order of 10^{-6} before the clearing. Therefore, the difference signal of satellite bunches is so mall that feedback itself produces no gain on satellite bunches. In the booster, the striplines for a BPM and kickers for the feedback and for the RFKO kicker are all in the same straight section.

FIR FILTER

The difference signal is digitized by an ADC of a feedback processor with RF direct sampling scheme without a down conversion [3]. The digitized difference signal is processed by an FIR filter to produce the kick signal to excite the vertical betatron motion of the main bunch. The FIR filter produces the phase shift between the beam position and the kick at the kicker position. If the phase between them is set to 90 deg, the feedback can excite the betatron motion, and if the phase shift is set to 180 deg, the feedback can produce the positive tune shift, as shown in Fig. 2. The phase between 90 deg. And 180 deg. can produce both effects. The tune responses of possible 7-tap FIR filters for the system are shown in Fig. 3. The required time for the tracking by 7-tap is the order of ten revolution period ~ 10μs, which is enough short to track the tune drift, and to track the tune ripple driven by the ripple of the power supplies.

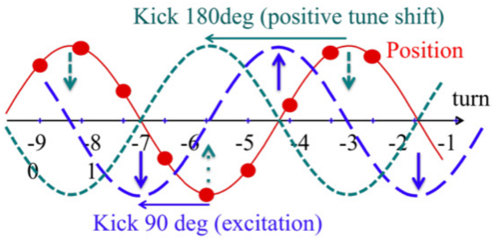


Figure 2: The turn-by-turn response of the FIR filter. The beam position and the kick at the kicker is shown. The input is the difference signal which is proportional to the bunch position (solid line with circles). The output is the kick to the beam. The phase shift of 90 deg. (dashed line) excites the oscillation and that of 180 deg. (dotted line) produces positive tune shift.

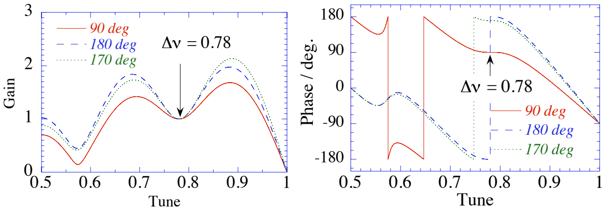
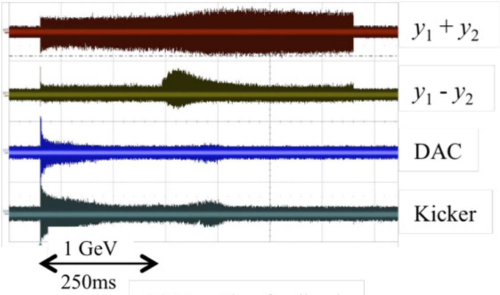


Figure 3: The tune response of the gain (left) and the phase (right) of FIR filters; the phase shift 90 deg (solid line) for excitation, 180 deg. (dashed line) for positive tune shift, and 170 deg. (dotted line) for both excitation and tune shift.

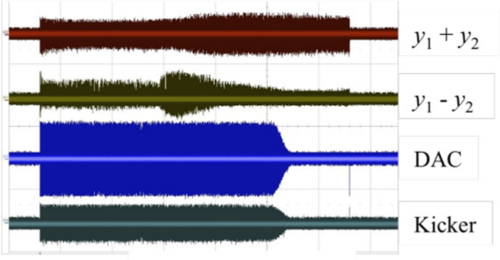
EXCITATION OF MAIN BUNCH

The beam test of the continuous excitation of the main bunch by the positive feedback was performed with the setup shown in Fig. 1. The RFKO kicker was turned off in this test. The tune response of the FIR filter used for the test is shown with the trace "*90deg*" in Fig. 3. We measured the response of the main bunch with positive and negative feedback by changing the polarity of the DAC output. The result is shown in Fig.4. The beam motion with negative feedback is shown in Fig. 4(a) ; the betatron oscillation seen in the difference signal of the BPM electrodes ($y_1 – y_2$) was damped by the feedback. The beam motion with positive feedback is shown in Fig. 4(b); the betatron oscillation was continuously excited by the feedback without the loss of the main bunch current seen in the sum signal of the BPM electrodes ($y_1 + y_2$). And the amplitude of the DAC (DAC) and the kicker field (Kicker) is constant because the DAC was saturated by the adjustment of the feedback gain.

Also we slightly change the timing of the signal "Sq" in Fig.1 to kick the main bunch by the RFKO system to excite its oscillation. This scheme can eliminate the amplifier and the kicker for positive feedback; however, the precise adjustment of the timing is necessary to keep the oscillation of the main bunch.



(a) Negative feedback



(b) Positive feedback

Figure 4: Response of a main bunch with negative feedback (a) and with positive feedback (b). As shown in Fig. 1, the traces "$y_1 + y_2$" and "$y_1 - y_2$" are the sum and the difference signals of the BPM electrodes, respectively, and those are proportional to the bunch current, and to the vertical position and the bunch current, respectively. The region shown by the arrow in Fig. 4a is "flat bottom" region where the energy is kept the injection energy 1 GeV. After the flat bottom, the beam is accelerated to 8 GeV and extracted from the booster to the storage ring. The increase of the "$y_1 + y_2$" signal in the middle of the time range is supposed to be due to the decrease of the bunch length by the acceleration.

With this operation of the system, we can continuously measure the tune of the main bunch with the realtime spectrum analyzer in Fig.1, which is enough to drive the another planed loop (slow loop in Fig. 1), with which the RFKO frequency is tuned to the betatron tune of the satellite bunches by an CPU controller connected to the realtime spectrum analyzer and a signal generator for RFKO.

Also we intend to switch the polarity of the feedback to damp the betatron motion of the main bunch after the purification, by inversion of the polarity of the DAC by an external gate signal to the feedback processor.

BUNCH CURRENT DEPENDENT TUNE SHIFT

Excitation with the Tune Shift

At 1 GeV in the booster synchrotron, we observed the bunch current dependent tune shift of $\Delta\nu = -0.002$ for the main bunch. The excitation tune of the tune tracking RFKO is locked to the tune of the main bunch and shifts this amount from the tune of the satellite bunches. This shift leads to the reduction of the kick efficiency for the satellite bunches. The simple calculation shows the amplitude of the satellite bunch excited by the RFKO with this tune shift is

$$\tilde{y} = \frac{\sqrt{\beta_{y,K}\beta_{y,A}}}{4\pi\Delta\nu}\tilde{\theta} \qquad (1)$$

where $\beta_{y,K}$ and $\beta_{y,A}$ are the vertical betatron functions at the kicker and at an vertical aperture limiting point, respectively, and $\tilde{\theta}$ is the kick angle amplitude. In this calculation, we assume that the resonance width by damping is negligible compared with the tune shift and radiation damping time at 1GeV is nearly one seconds.

In the booster, those values are $\beta_{y,K} \sim \beta_{y,A} \sim 13$ m, and $\tilde{\theta} = 7.5$ µrad, then, the amplitude is $\tilde{y} \sim 3$mm , which is not enough for the satellite bunches to be drive to hit the vertical aperture of the booster of 15 mm.

Compensation of Tune Shift by Feedback

As we mentioned earlier, the feedback can produce the tune shift and the excitation, simultaneously. If the feedback gain and phase is set so that the feedback produces the positive tune shift to cancel the negative current dependent tune shift of the main bunch, we can reduce $|\Delta\nu|$ in Eq.(1) and can increase the amplitude of the betatron motion of the satellite bunches. The required phase shift ψ of the FIR filter for the feedback growth time τ_{FB} and the tune shift $\Delta\nu$ is

$$\tan\psi = -\frac{1}{\omega_{rev}\tau_{FB}\Delta\nu} \qquad (2)$$

where $\omega_{rev} = 2\pi f_{rev}$ is the angular revolution frequency. And in this case, the phase ψ should be between 90 deg and 180 deg. If we set $\tau_{FB} = 0.6$ ms and $\Delta\nu = 0.002$, the required phase is $\psi = 170$ deg. The tune response of such FIR filters is shown in Fig 3.

TEST WITH RFKO FOR PURIFICATION

We performed the preliminary beam test of the purification of the main bunch by the tune tracking RFKO, with the RFKO kicker turned on. In some cases, the purity was improved from 10^{-6} to 10^{-8}, however, this purity level is not sufficient for user operation, and is not easily reproduced. And we sometimes observed the fluctuation of the betatron amplitude during the continuous excitation. For the increase of the purity and the stable operation, we are now developing automatic gain control block (AGC in Fig. 5) in the feedback processor by modifying the FPGA program of the processor. The signal level is detected with a mixer and low pass filter with a FIR filter FIR2, and the gain of the positive feedback loop is controlled by this signal level through the predefined function stored in a memory look-up table.

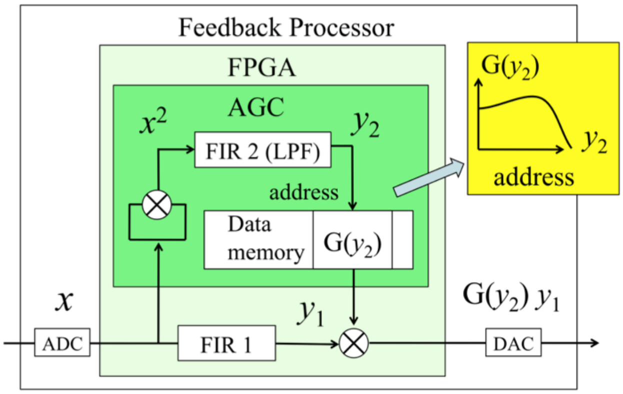


Figure 5: Automatic gain control (AGC) for the positive feedback loop in the feedback processor. The “AGC” block detect the amplitude of the oscillation and change the gain of the positive loop driven by “FIR 1” with the function stored in data memory for memory look up table.

SUMMARY

We performed the tune tracking RFKO bunch purification system based on the positive feedback loop driven by the SPring-8 feedback processor and obtained the improvement of the purity of the main bunch. To achieve higher level of the purification, we are now developing automatic gain control block in FPGA to control flexibly the excitation level of the betatron motion.

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