BUNCH BY BUNCH FEEDBACK SYSTEM REVIEW *

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Abstract

Bunch-by-bunch feedback (BBF) is a system designed to control the betatron or synchrotron oscillation of each bunch independently. It not only serves as a tool to dampen these oscillations, primarily for the suppression of beam instabilities, but also to excite individual bunches independently and to record their position or timing on a bunch-by-bunch, turn-by-turn basis. This paper reviews the applications of BBF presented at the I.FAST Workshop 2024 on Bunch-by-Bunch Feedback Systems and Related Beam Dynamics.

INTRODUCTION

Bunch-by-bunch feedback system (BBF) is a system that controls horizontal/vertical betatron oscillations (“transverse”) or synchrotron oscillation (“longitudinal”) for each bunch individually, with the bunch separation down to a few nanoseconds. The BBF has a wide variety of applications, not only for the suppression of beam instabilities. We will review these various applications based on presentations at the I.FAST Workshop 2024 on Bunch-by-Bunch Feedback Systems and Related Beam Dynamics [1], held at The Karlsruhe Institute of Technology, Germany.

BUNCH-BY-BUNCH FEEDBACK

The block diagram of a typical BBF system [2] is shown in Fig. 1. In the figure, both transverse and longitudinal BBF are shown, however, horizontal/vertical/longitudinal BBF can be installed and operated independently.

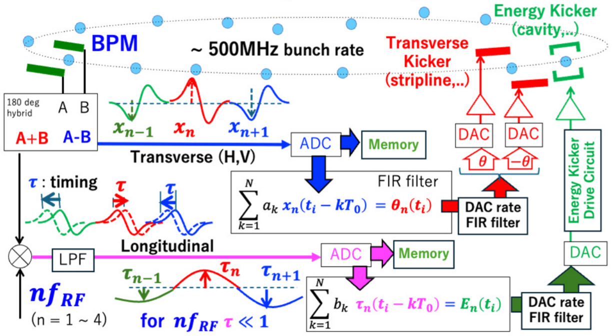

Figure 1: Block diagram of a typical BBF system. Both transverse and longitudinal BBFs are shown.

In a BBF, the two signals generated on the two electrodes of a beam position monitor (BPM) as an electron bunch passes between them are sent to a 180-degree hybrid, which produces their difference and sum signals. The difference signal has a voltage proportional to the transverse position and is used for a transverse BBF, while the sum signal contains bunch arrival timing information and is used for a longitudinal BBF. This timing information is converted to a voltage by mixing it with the carrier frequency, which is usually a multiple of the bunch rate or the acceleration RF frequency. These position and timing signals are sampled by an ADC and converted to digital data. This digital data is then sent to an FIR filter where the kick signal is calculated, and the resultant kick is sent to a DAC, which converts the digital kick data into an analog signal that drives a kicker system.

FIR FILTER

Each bunch has its own FIR filter, where the input is the turn-by-turn position history of the bunch, and the output is the kick signal required to damp betatron (transverse) or synchrotron (longitudinal) oscillations, as shown in Fig. 1.

An FIR filter has the form of

$$\theta_n(t) = \sum_{k=N_D}^{N_D+N_T-1} a_k \; x_n(t - kT_0)$$

where x_n and θ_n are the position and kick of n-th bunch, respectively, as illustrated in Fig. 2, T_0 is the revolution period of the bunch, and N_D is the number of turn (delay) required to prepare the kick at a kicker. The number of input data points, N_T , is called the “number of taps”. The tune response of the FIR filter is given by:

$$G(\nu)e^{i\psi(\nu)} = \sum_{k=N_D}^{N_D-1+N_T} a_k \, e^{-ik\,2\pi\nu}$$

where $G(\nu)$ and $\psi(\nu)$ are real numbers representing the gain and the phase shift at tune ν, respectively, as s illustrated in Fig. 3.

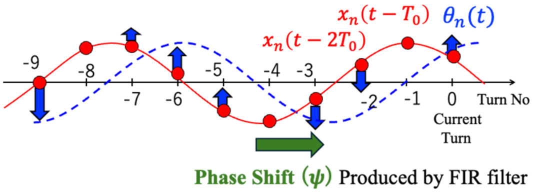

Figure 2: FIR filter for each bunch, converting the turn-by-turn position history into kick by producing phase shift.

For the transverse BBF, the phase shift is adjusted so that the relative phase between the position and kick oscillations at the kicker is -90 degrees, w achieving maximum feedback damping. If this relative phase is set to 0 degrees or -180 degrees with an FIR filter, the feedback acts as a defocusing or focusing quadrupole, respectively, introducing tune shift. Therefore, by controlling the phase shift with the FIR filter, the BBF can simultaneously produce damping/anti-damping and a tune shift of the betatron or

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synchrotron oscillation. One method for calculating coefficients of FIR filter is shown in Ref. [3]

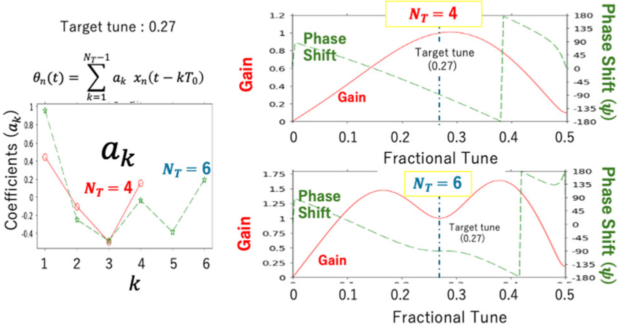

Figure 3: Examples of FIR filters and their tune response. With a 6-tap FIR filter, two more data points than a 4-tap filter are used to flatten the response near the target tune.

SUPPRESSION OF INSTABILITIES

The primary function of BBF is the suppression of beam instabilities using negative feedback. Here, we present the related topics.

Grow-Damp Experiment

The grow-damp experiment involves observing the growth of instabilities when the BBF is turned off, and their damping when the BBF is turned on. This experiment allows us to understand the growth rate, frequency, and characteristics of the instabilities, as well as the damping capability of the BBF. Figure 4 shows the results of the grow-damp experiment [4], performed at the SuperKEKB HER of the e+e- collider at KEK, analysing the bunch-by-bunch, turn-by-turn position history recorded by a BBF.

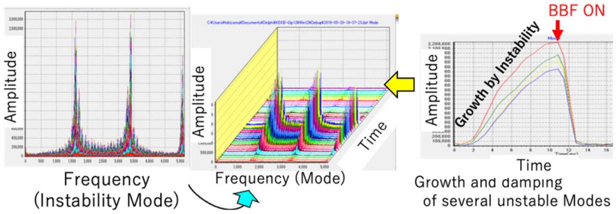

Figure 4: Grow-damp experiment at SuperKEKB HER.

Due to the fractional tune being around 0.5 at SuperKEKB, there are periods when the BPM signal and kick efficiency are low. To compensate for these periods, two BBFs were installed at locations shifted by 90 degrees in betatron phase [4], covering each other as shown in Fig. 5.

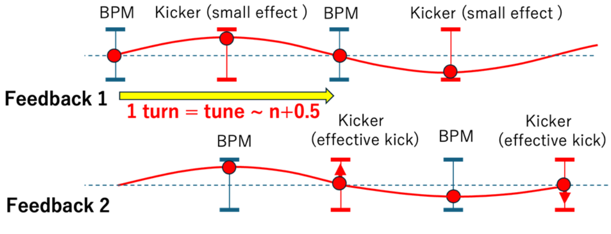

Figure 5: Two BBFs cover low kick efficiency and low BPM signal each other for fractional tune ~ 0.5.

Simultaneous Damping of Two Tunes

At the Beijing Electron-Positron Collider II (BEPCII), the coherent horizontal betatron oscillation with the "pi" mode: yaw like oscillation of a bunch, is excited by beam-beam interaction. Simultaneously, the "sum" mode: center of mass oscillation of a bunch, is excited by a beam instability. Therefore, a BBF must suppress both modes simultaneously [5]. The tunes and required phase to damp them are

- $\psi(\nu = 0.508) = -140\,degree$ for sum mode
- $\psi(\nu = 0.519) = -50\,degree$ for pi mode

with $G(\nu = 0) = 0$, and with $G(\nu = 0.508)$ and $G(\nu = 0.519)$ are ~1.

Because of the separation of the tunes is $\Delta\nu \sim 0.01$, the uncertainty principle of wave: $2\pi \lesssim \Delta\omega\Delta t = 2\pi f_0 \Delta\nu \times N_T T_0 = 2\pi\, \Delta\nu\, N_T$ requests $1/\Delta\nu = 100 \lesssim N_T$.

Then, replacing the previously used 16-tap FIR filter, several 32-tap FIR filters were generated and one of them met the requirements as shown in Fig. 6. With this FIR filter, the oscillations of "pi" mode and "sum" mode are simultaneously suppressed.

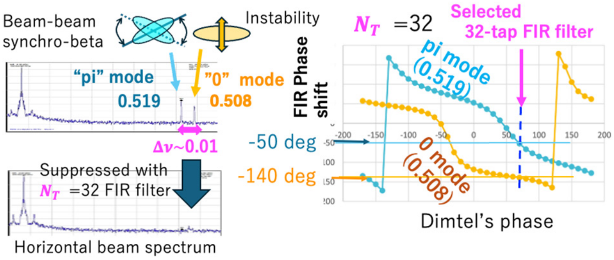

Figure 6: Suppression of two betatron oscillation modes at different tunes with a single FIR filter and BBF with it.

BBF for High Contrast Bunch Current Filling

Fillings with high bunch current singlet(s) and low bunch current train(s) are requested by users in several light sources. For a BBF for such filling with high contrast in bunch current, the system [6] illustrated in Fig. 7 was developed with the collaboration of SPring-8, SOLEIL and PLS-II and are in operation at them.

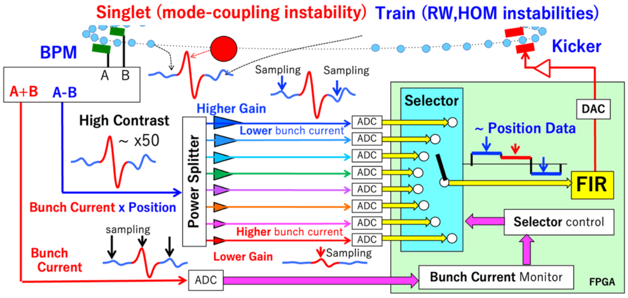

Figure 7: BBF for high contrast bunch current. Sets of different gain front-ends and ADCs are prepared and switched based on the measured bunch current.

Correction of Amplifier/Kicker Response

For the digital kick signal, an FIR filter with a sampling rate of the DAC (Fig. 1) is sometimes used to compensate for the response of the kicker and its power amplifier, as shown in Fig. 8.

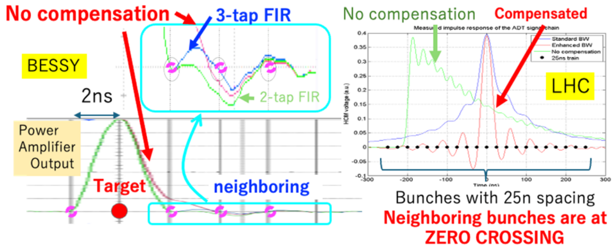

Figure 8: Compensation with FIR filter of DAC sampling rate. Left: BESSY: compensation with 3-tap FIR to reduce the kick at neighbouring bunches [7]. Right: LHC: With compensated kick, neighbouring bunches are placed at zero crossing timing of kick [8].

Timing Jitter and Longitudinal BBF Acceptance

At the BESSY booster, the bunch-by-bunch timing jitter of injected beam to the booster was produced by the booster cavity beam loading and the injector's klystron jitter. This timing jitter is almost comparable with the longitudinal BBF acceptance and is reduced with several tunings [9]. The possible method to increase of the timing acceptance is to lower the mixing frequency at the timing front-end mixer shown in Fig. 1, from 1.5GHz ($3 \times f_{RF}$) to 0.5GHz (f_{RF}); however, the sensitivity is reduced.

POSITIVE FEEDBACK TO SIMULATE BEAM INSTABILITIES

By inverting the BBF kick sign, the BBF provides positive feedback, causing exponential growth of an oscillation. The growth rate and tune shift can be controlled by the gain and phase shift of the FIR filter, allowing the BBF to simulate beam instabilities. Using this method, the stability diagram of Landau damping was measured and compared with theoretical predictions at the LHC (Fig. 9) [8].

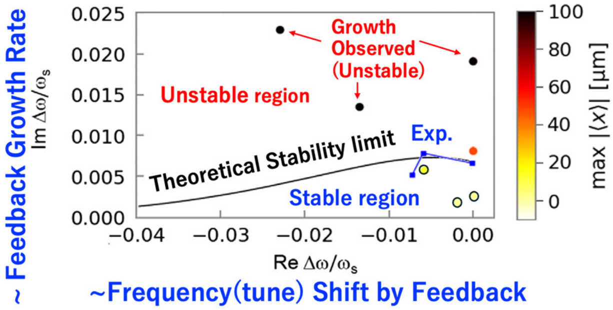

Figure 9: Direct Landau damping measurement with simulated beam instabilities with BBF.

BUNCH-BY-BUNCH EXCITATION

Tune Measurement, Cleaning of Buckets

BBF can excite just one bunch in a ring for tune measurement, which minimizes the effect on users. This bunch-by-bunch excitation function is used to clean up the bunches at the filling gap.

Tune Following Excitation

A tune-following beam response measurement was reported from BESSY [7]. In this method, a betatron oscillation of a pilot bunch is excited, and the tune frequency is tracked by measuring the phase difference between the excitation signal and the bunch oscillation signal. By exciting other bunches with a shifted frequency from the tracked tune frequency, the beam frequency response can be clearly measured even under tune jitter, as illustrated in Fig. 10.

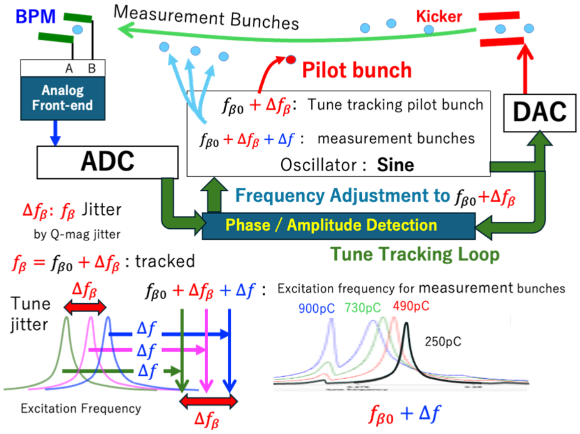

Figure 10: Tune following (tracking) excitation under tune jitter. Bottom right is the bunch current dependence measured with this method.

Emittance Feedback

In some light sources, vertical emittance must be stabilized to maintain the brilliance of synchrotron radiation for users. Emittance feedback with BBF was reported from SOLEIL [10] and DIAMOND [11], as shown in the block diagram in Fig. 11 The BBF method offers a faster response and simpler control than the x-y coupling control with a skew quadrupole.

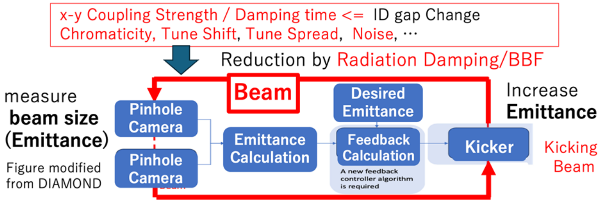

Figure 11: Emittance control loop [11].

The vertical emittance is measured with pinhole cameras, and the value is sent to a controller to determine the necessary kick and excite the vertical betatron oscillation with BBF. The excited coherent motion is converted to "pure" emittance (Fig. 12) through the phase mixing by the tune spread by chromaticity and amplitude dependent tune shift.

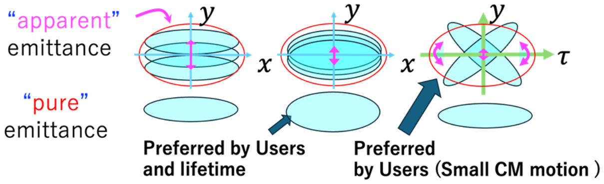

Figure 12: "Apparent" emittance and "pure" emittance.

At DIAMOND [11], the excitation precisely on the frequency of a synchrotron sideband of a betatron frequency is used to excite pitch like motion of bunches, keeping its center-of-mass motion small. The strong kick effect is required for this method; therefore, the excitation frequency is kept precisely on resonance using the tune-following method shown previously (Fig. 13).

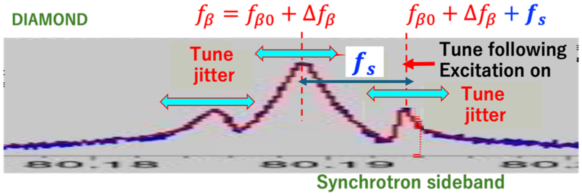

Figure 13: Resonant excitation of synchrotron sideband.

At SOLEIL [10], a random signal is used to excite betatron oscillation for vertical emittance feedback (Fig.14), and they show that wider random signal band creates more 'pure' emittance, as shown in Fig. 15, and reduces emittance jitter under the feedback. The 'pure' emittance was estimated from the bunch lifetime, which is proportional to the bunch volume.

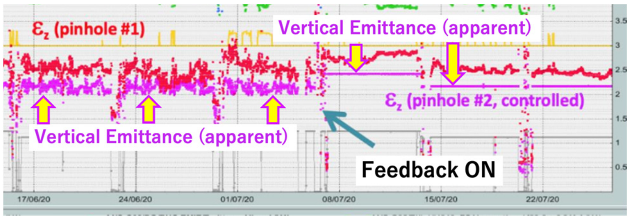

Figure 14: Vertical emittance feedback at SOLEIL.

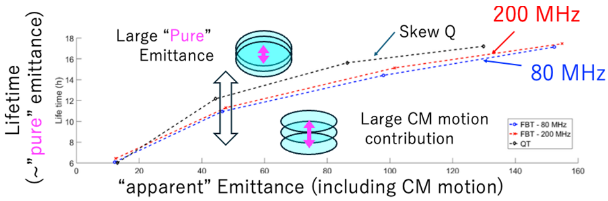

Figure 15: Comparison of "pure" emittance produced by skew quad and BBF with different frequency band ("200MHz" and "80MHz") of random signal.

Bunch Lengthening with BBF

At KARA, the longitudinal quadrupole mode is excited using a BBF to lengthen bunches to suppress beam instabilities, as shown in Fig. 16 [12].

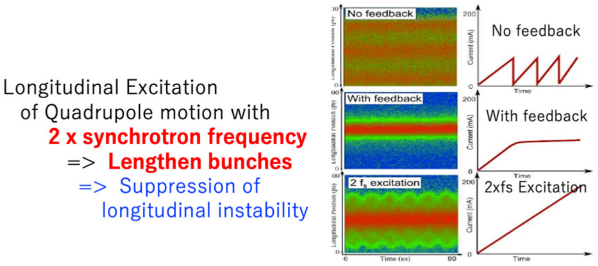

Figure 16: Lengthen bunch by excitation of quadrupole mode with $2 \times f_s$ frequency for suppression of instabilities.

RFSoC FPGA FOR BBF PROCESSOR

RFSoC: FPGA with ADC, DAC inside, is now widely used in various applications. In SLS-2.0, a feedback processor with an AMD ZCU111 evaluation board (RFSoC: XCZU28DR-2) was tested for the horizontal plane. Their final goals are to control horizontal, vertical, and longitudinal directions with a single processor, and to directly drive a longitudinal feedback kicker at 1.875 GHz with a 280 MHz bandwidth using a 6.5 GS/s DAC on the RFSoC [13,14]. For PETRA-IV, a microTCA.4 board [15,16] with the candidate RFSoC: XCZU47DR-1 is being designed in collaboration with DESY, and the DAMC-DS5014DR is currently being tested. These developments were reported at the posters in this conference [14,16].

FEEDBACK NOISE

The emittance growth of LHC driven by the BPM noise through BBF was reported (Fig. 17) [8]. To reduce the noise, a low-noise BPM circuits is being developed.

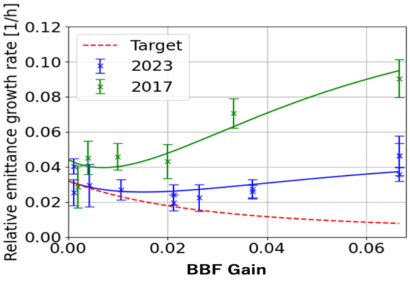

Figure 17: Emittance growth and BBF gain.

MEASUREMENT OF BUNCH MOTIONS

At ELETTRA, the variation of synchrotron tune and bunch timing within a bunch train was measured. This variation is produced by transient beam loading on the main and harmonic cavities driven by a filling with a train and a gap [17]. The results are shown in Fig. 18.

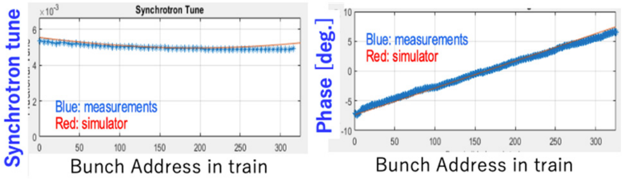

Figure 18: Synchrotron tune and phase of bunches in a train measured at ELETTRA with filling of a train and a gap.

BEAM SIMULATION UNDER BBF

Transverse Simulation for SOLEIL-II

An analysis of transverse beam instabilities for SOLIEL-II was reported [18], showing that head-tail single-bunch instability can be mitigated with low chromaticity and a BBF if a harmonic cavity is employed. Transverse coupled-bunch instabilities can be suppressed with the current BBF for SOLEIL, and the strength of beam-ion instability is reduced with multiple filling gaps, allowing the BBF to be effective.

Beam Longitudinal Dynamics (BLonD) Code

BLonD [19], introduced by CERN, is a Python code designed to simulate the longitudinal motions of a beam, including impedances, RF cavities with LLRF and tuner control, as well as RF noise and modulation. Several applications of BLonD, including bunch-to-bunch capture, optimization of RF power, and de-tuning and pre-tuning of the RF system, were demonstrated.

Longitudinal Simulation with Harmonic Cavity

From PSI, a longitudinal simulation [20] which includes transient beam loading of a harmonic cavity, was performed to estimate the shift of synchrotron tune and phase within a train, as the measurement at ELETTRA in Fig. 18. They also analysed the impact of the timing shift of bunches at the longitudinal kicker. All such effects are shown to be within feedback specifications.

Longitudinal Simulation with Modelling of BBF

From DAFNE, a longitudinal simulation [21] includes an analog front-end, digital signal processing with ADC, FPGA, and DAC, kicker drive circuits, and longitudinal cavity kicker response was presented. However, discrepancies from the measurements were reported, which are supposed to be due to the actual feedback gain being smaller.

Wide Tune Acceptance Longitudinal BBF with Differentiator FIR Filter

For a filling with a bunch train and a gap, the synchrotron tune varies within the train as previously reported, and wide acceptance for the synchrotron tune is required for BBF. Dimtel Inc. proposed an FIR filter combining a differentiator and a low-pass filter [22]. The differentiator produces the 90 degree phase shift for all frequency, but its gain increases linearly with frequency. Therefore, a low-pass filter function is added, as shown in Fig. 19.

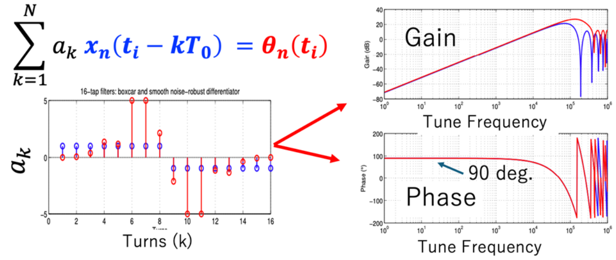

Figure 19: FIR filter with differentiator and low pass filter functions (red points in left) and its tune response (right).

Machine Learning BBF Optimization

From KARA, the application of machine learning for BBF parameter optimization was proposed (Fig. 20) [12]. It uses dedicated FPGA for machine learning, using the response of the system to a single kick of a beam.

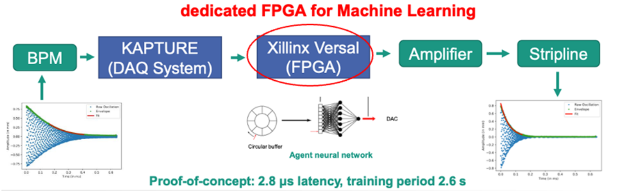

Figure 20: Proposal of optimization of BBF parameters with machine learning with response of bunch for kick.

Pitch/Yaw Monitor for picosecond Bunch and Pitch/Yaw BBF

From KEK, the test results of real-time pitch/yaw monitor [23] for picosecond electron bunch at the NewSUBARU ring ware reported (Fig. 21) and show the possibility of pitch/yaw BBF. The signals from standard button-type BPM electrodes were used and processed with simple RF circuits in the 1.5 GHz band. The monitor distinguishes the pitch/yaw signal by noting that it's shape is nearly the derivative of the center-of-mass signal shape.

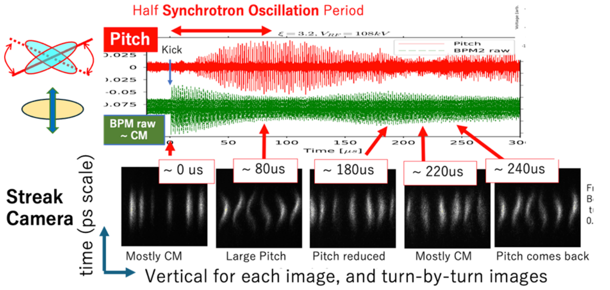

Figure 21: Test result of pitch/yaw real-time monitor.

COLLABORATIVE BEAM STUDY

The beam study was performed with the attendees of the workshop using the main ring and the booster of KARA.

The targets of the study is 1) to establish standard procedure for commissioning/tuning of BBF, 2) synchrotron sideband excitation with tune following for vertical emittance excitation, and 3) to find scheme to apply stripline kicker for longitudinal BBF. For 3), a stripline kicker was drove as drift-tube with high frequency longitudinal kick signal (250MHz for every two bunches and 1.35 GHz for every bunches). Also for 3), longitudinal BBF with the timing control with the transverse kick at dispersion was tested. All the study were successfully performed.

ACKNOWLEDGEMENTS

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