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A HIGH-RESOLUTION, LOW-LATENCY, BUNCH-BY-BUNCH FEEDBACK SYSTEM FOR NANO-BEAM STABILIZATION

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Abstract

A low-latency, bunch-by-bunch feedback system employing high-resolution cavity Beam Position Monitors (BPMs) has developed and tested at the Accelerator Test Facility (ATF2) at the High Energy Accelerator Research Organization (KEK), Japan. The feedback system was designed to demonstrate nanometer-level vertical stabilization at the focal point of the ATF2 and can be operated using either a single BPM to provide local beam stabilization, or by using two BPMs to stabilize the beam at an intermediate location. The feedback correction is implemented using a stripline kicker and the feedback calculations are performed on a digital board constructed around a Field Programmable Gate Array (FPGA). The feedback performance was tested with trains of two bunches, separated by 280 ns, at a charge of ~1 nC, where the vertical offset of the first bunch was measured and used to calculate the correction to be applied to the second bunch. The BPMs have been demonstrated to achieve an operational resolution of ~20 nm. With the application of single-BPM and two-BPM feedback, beam stabilization of below 50 nm and 41 nm respectively has been achieved with a latency of 232 ns.

INTRODUCTION

Accelerator Test Facility

The ATF (Accelerator Test Facility) [1] is a 1.3 GeV electron beamline at KEK, Japan. The facility is a test-bed for the technologies required for a future linear electron-positron collider and comprises a linear accelerator, damping ring (DR) and final focus system (Fig. 1). The focal point of the ATF2 beamline is designated as the interaction point (IP) (Fig. 2). The primary goals of the ATF2 are to achieve a beam size of 37 nm and vertical beam position stabilization to the nanometer level at the IP [2].

The Feedback On Nanosecond Timescales (FONT) group [3] have developed prototype beam stabilization feedback systems which have been tested at the ATF2 [4–6]. Here we report the performance of a low-latency feedback system, located at the ATF2 IP (Fig. 2), demonstrating stabilization of the beam waist to the nanometer-level.

FONT IP Feedback System

The FONT IP feedback system includes three C-band cavity BPMs [7] around the IP (IPA, IPB and IPC), shown in Fig. 2. The signals from the BPMs are digitised on a FONT5A board [5] and the feedback calculation is performed on an FPGA mounted on the board [8]. An analogue correction signal is output from the board, amplified using a custom power amplifier with a fast rise-time (35 ns) [9] and used to drive a stripline kicker, IPK (Fig. 2). Feedback is performed bunch-to-bunch, so that the offset of the first bunch is measured and the second bunch is corrected. This requires a high position correlation between the two bunches.

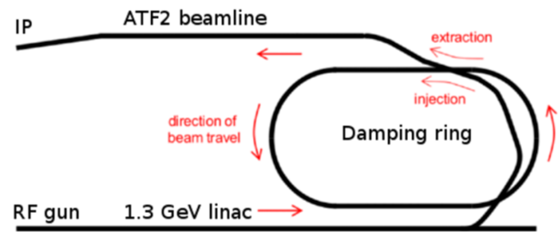

Figure 1: Schematic of the ATF2 layout, with the focal point indicated as the IP.

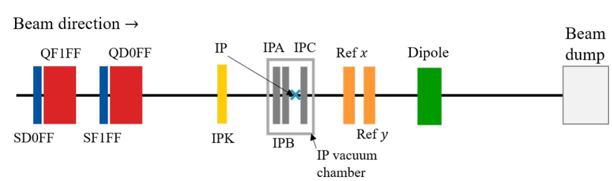

Figure 2: Schematic of the ATF2 IP region, showing dipole cavity BPMs IPA, IPB and IPC, reference cavity BPMs Ref x and Ref y, and stripline kicker IPK.

As a charged bunch passes through a cavity BPM it excites the cavity's electromagnetic eigenmodes. Separate cavities are designed for the extraction of the signal from the monopole and dipole modes, called 'reference' and 'dipole' cavities respectively; IPA, IPB and IPC are dipole cavities. The monopole signals are proportional to the bunch charge and the dipole signals depend on the bunch offset and charge. The dipole cavity BPMs are mounted on piezo-mover systems allowing for the alignment of the BPMs with the beam [10].

Position Calculation

Two stages of frequency down-mixing are used [11, 12] to produce baseband signals which can be digitized by the FONT5A board (Fig. 3). In the first stage, the cavity signals

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are down-mixed using a common 714 MHz Local Oscillator (LO). In the second stage, the down-mixed reference and dipole signals are mixed in-phase and in-quadrature to produce I and Q signals, respectively (Fig. 3). These signals are orthogonal components which together include the full amplitude and phase information of the BPM waveform.

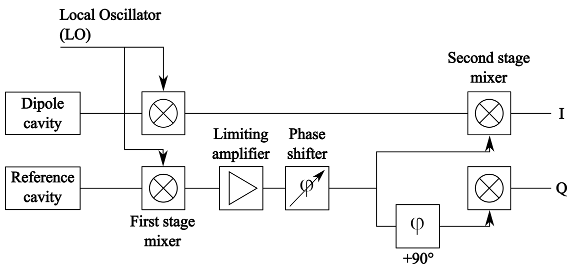

Figure 3: Simplified block diagram of the two-stage down-mixing process of the dipole and reference cavity signals [11].

The I, Q and charge, q, signals are digitized at 357 MHz by nine 14-bit analogue-to-digital converters (ADCs) on the FONT5A board. The sampling window consists of 164 samples and both bunches of a train can be digitised within a single window. Determination of the bunch position, y, is performed on the FPGA using the I, Q and q, signals as

$$y = \frac{1}{k}\left(\frac{I}{q}\cos\theta_{IQ} + \frac{Q}{q}\sin\theta_{IQ}\right), \quad (1)$$

where k and θ_{IQ} are determined through calibration. Each BPM is calibrated by scanning the beam (by changing the position of quadrupole QD0FF (Fig. 2)) and measuring the corresponding BPM response [7].

Feedback Calculation

The signal sent to the kicker, V, is converted from the position offset, y (μm), by using kicker calibration constant M (μm/DAC):

$$V = -G\frac{y}{M} + c, \quad (2)$$

where the feedback gain, G, is selected based on the bunch-to-bunch position correlation. A constant offset, c, can be added to adjust the transverse stabilization location. This system is designed to provide feedback correction in the vertical plane in which the beam is focused to nanobeam size.

BPM RESOLUTION

The resolution of the BPM system can be estimated using measurements of the bunch trajectory through all three BPMs. The bunch follows a straight-line trajectory which can be characterized with measurements from only two BPMs. Measurements from the third BPM can then be used to infer the resolution of the system. The resolution of the position measurement can be improved by integrating over multiple samples of the I and Q signals as this increases the signal level and averages over noise. With the current firmware, integration of up to 15 samples is possible with a latency of 232 ns. Figure 4 shows the resolution as a function of the number of samples integrated. The data were taken at a bunch charge of 0.5×10^{10} and with a dipole attenuation of 10 dB. The BPM resolution was improved by better than a factor of two, to 20 nm, by integrating at least ten samples.

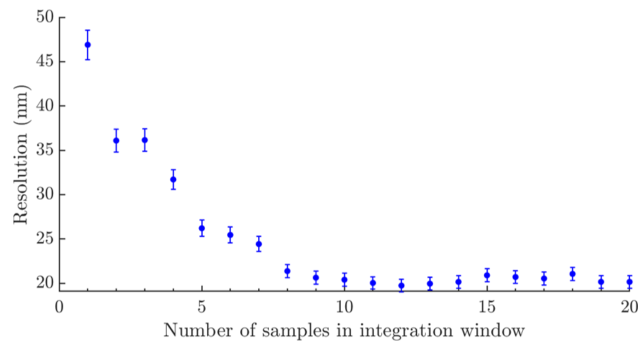

Figure 4: Dependence of the resolution on the number of samples integrated. The errorbars show the statistical uncertainty on the resolution.

Detailed studies have been performed to optimise the experimental setup to improve the resolution [13, 14]. The attenuation of the signals were studied, with the optimum setup having 10 dB attenuation on the down-mixed dipole signal so that the signal-to-noise ratio is as high as possible without saturating the second-stage mixer. Studies of the resolution as a function of BPM position and angle offset with respect to the beam identified that the offsets should be kept < 4 μm and < 1 mrad. The resolution was seen to be constant for position offsets within this range. With an angular offset, y', an additional term, $\propto y' \times \delta_{IQ}$, is introduced to Eq. (1), where δ_{IQ} is the deviation from the nominal θ_{IQ} caused by jitter on the phase delay introduced by the limiting amplifier (Fig. 3). For an offset of 2.1 mrad the resolution was seen to degrade to 80 nm [13] and the calibration constant, k became inconsistent with the nominal value suggesting non-linear behaviour.

BUNCH-BY-BUNCH IP FEEDBACK

Feedback was operated in 1-BPM mode, with stabilization at IPC, and in 2-BPM mode, with measurements at IPA and IPC to provide stabilization at IPB; these feedback loops are depicted in Fig. 5. Feedback was applied to alternate bunch trains to allow a direct comparison between the data with feedback 'off' and 'on'. The ATF was configured with trains of two bunches separated by 280 ns. The limited dynamic ranges of the BPMs necessitated the good alignment of the BPMs with the beam and the minimization of the beam jitter.

1-BPM IP Feedback Results

1-BPM feedback was operated with beam position measurements and stabilization of the beam waist at IPC. The stabilization achieved with 1-BPM feedback is illustrated in Fig. 6 and the values are given in Table 1. A 10 sample integration window was used, which was optimized empirically.

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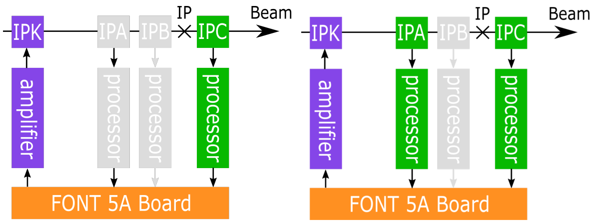

Figure 5: Diagrams of feedback loops with cavity BPMs (IPA, IPB and IPC) and a stripline kicker (IPK) for (a) 1-BPM feedback with beam stabilization at IPC and (b) 2-BPM feedback, with position measurements at IPA and IPC, for beam stabilization at an intermediate location.

As the correction was only applied to the second bunch, the position jitter of the first bunch was unchanged. The jitter of the second bunch was reduced with feedback and the mean position was brought closer to zero. The bunch-to-bunch position correlation was reduced to $-26.0^{+9.8}_{-8.8}$ suggesting the gain was set slightly too high. The remaining mean bunch-2 offset stems from the initial offset between bunch-1 and bunch-2 and can be trivially adjusted using the constant offset functionality of the feedback firmware.

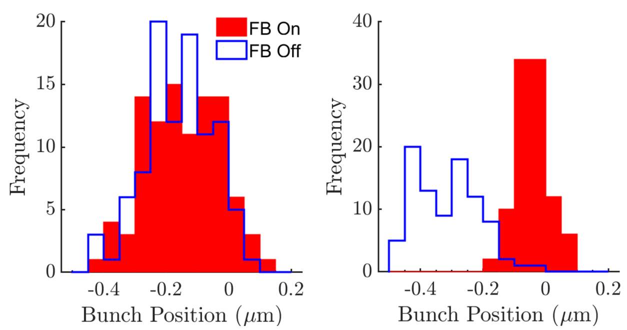

Figure 6: Bunch positions measured at IPC, for bunch-1 (left) and bunch-2 (right) with feedback off and on.

Table 1: Position Jitters and Bunch-to-Bunch Position Correlation with Feedback Off and On, for 1-BPM Feedback

FB	Position jitter (nm)		Corr. (%)
	Bunch-1	Bunch-2	
Off	109 ± 11	119 ± 12	$85.1^{+2.5}_{-3.5}$
On	118 ± 12	50 ± 5	$-26.0^{+9.8}_{-8.8}$

2-BPM IP Feedback Results

In order to operate three BPMs simultaneously, optics with a β_y^* of 1000 times the nominal value were used, with the beam waist at IPB. With IPA and IPC being used for feedback, IPB could be used as an independent witness of the feedback performance. Sample integration was used with a window of only five samples because of the higher signal levels with this BPM configuration.

The results from operating 2-BPM feedback are presented in Fig. 7 and Table 2. The beam stabilization demonstrated (41 ± 4 nm), is in excellent agreement with the beam stabilization expected (40.1 nm) given the bunch jitter and correlation. The mean bunch-2 position was shifted by ~2 µm which derives from the transverse offsets between the BPMs and can trivially be removed. Feedback was operated with a gain of 0.8 but the feedback-on correlation of $41.3^{+9.1}_{-12.3}$% suggests that the system under-corrected and with a higher gain the performance may be improved. The resolution measured for these data was 31.2 nm which was poorer than the best achieved resolution of 20 nm (Fig. 4). With a 20 nm resolution the predicted feedback performance would be stabilization of up to ~ 25 nm.

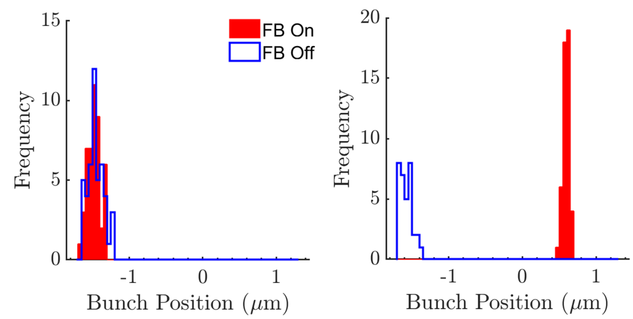

Figure 7: Bunch positions measured at IPB, for bunch-1 (left) and bunch-2 (right) with feedback off and on.

Table 2: Position Jitters and Bunch-to-Bunch Position Correlation with Feedback (FB) Off and On, for 2-BPM Feedback

FB	Position jitter (nm)		Corr. (%)
	Bunch-1	Bunch-2	
Off	106 ± 11	96 ± 10	$91.6^{+1.8}_{-3.1}$
On	100 ± 10	41 ± 4	$41.3^{+9.1}_{-12.3}$

CONCLUSIONS

A prototype feedback system for nano-beam control has been described, employing cavity beam position monitors with a demonstrated resolution of up to 20 nm within a latency of 232 ns. With 1-BPM feedback, stabilization to 50 ± 5 nm has been demonstrated and with 2-BPM feedback, 41 ± 4 nm stabilization was achieved. Studies suggest that with this setup and firmware stabilization to 25 nm would be possible.

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