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DEVELOPMENT OF A LOW-LATENCY, HIGH-PRECISION, BEAM-BASED FEEDBACK SYSTEM BASED ON CAVITY BPMs AT THE KEK ATF2

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Abstract

A low-latency, intra-train feedback system employing cavity beam position monitors (BPMs) has been developed and tested at the Accelerator Test Facility (ATF2) at KEK. The feedback system can be operated with either position information from a single BPM to provide local beam stabilisation, or by using position information from two BPMs to stabilise the beam at an intermediate location. The correction is implemented using a stripline kicker and a custom power amplifier, with the feedback calculations being performed on a digital board built around a Field Programmable Gate Array (FPGA). The addition of indium sealing to the BPMs to increase the cavities' Q-values has led to improvements to the BPM system resolution, with current measurements of the resolution of order 20 nm. The feedback performance was tested with beam trains of two bunches, separated by 280 ns and with a charge of ~1 nC. For single- (two-)BPM feedback, stabilisation of the beam has been demonstrated to below 50 nm (41 nm). Ongoing work to improve the feedback performance further will be discussed.

INTRODUCTION

The ATF2 [1] at KEK, Japan, consists of a 1.3 GeV electron accelerator with a prototype final focus system designed to demonstrate the beam size and nanometre-level beam stabilisation required for the International Linear Collider (ILC) [2]. The low-emittance beam is focussed to a virtual Interaction Point (IP), at which the Feedback On Nanosecond Timescales (FONT) IP feedback system acts to stabilise the beam waist, with the goal of demonstrating nm-level beam stabilisation. The feedback system contains three C-band cavity BPMs (IPA, IPB and IPC) which are used to measure the beam orbit. They are mounted on piezo-mover systems to facilitate the horizontal and vertical alignment of the BPMs with the beam, as well as the adjustment of the BPM pitch. The feedback calculation is performed on a 'FONT5A' digital board [3] and the correction is implemented using a stripline kicker, IPK (Fig. 1).

The FONT project has developed prototype feedback systems suitable for future single-pass colliders and demonstrated their performance with beam at the ATF2. An upstream FONT feedback system which utilises stripline BPMs, and meets the stabilisation and latency requirements for the ILC, is described in [4]. Stabilisation to 74 nm [5] has been achieved with the FONT IP feedback system, using a single cavity BPM to drive local feedback correction. Initial work towards stabilisation using two BPMs to drive the feedback correction is described in [6], for which 83 nm beam stabilisation has been demonstrated.

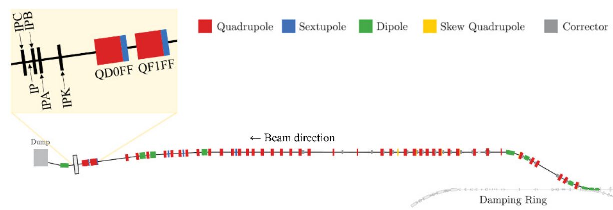

Figure 1: Schematic of the layout of the ATF2 extraction line and final focus [1], with the FONT IP region enlarged.

FONT IP FEEDBACK SYSTEM

ATF2 Accelerator Setup

The layout of the ATF2 extraction line and final focus is given in Fig. 1. The ATF2 is configured such that two bunches per train are extracted from the damping ring at 3 Hz, with a bunch separation of 280 ns. This separation has been found to provide a high degree of correlation between the vertical positions of the two bunches. This is essential for intra-train feedback operation as the system acts to stabilise the second bunch based on position measurements of the first bunch. The latency of the feedback system must then be less than the limit set by the bunch spacing and, for the system described here, a latency of 235 ns has been demonstrated.

IP Feedback System

The FONT feedback system contains one reference cavity BPM, for which the dominant mode of excitation is the monopole mode [3], and three dipole cavity BPMs, for which the monopole mode is filtered and the most strongly extracted mode is the dipole mode. The addition of indium sealing to the dipole cavity BPMs has increased the decay time of the cavity signals, which means a longer period of the BPM waveform at an optimum signal level and, consequently, an improved resolution [8]; this is discussed further in [7].

For vertical bunch position measurements, the signals from the BPMs are processed using a two-stage system (Fig. 2). The monopole and y-port dipole modes, both of 6.4 GHz, are frequency down-mixed to 714 MHz using a common 5.7 GHz Local Oscillator (LO) signal, thus retaining their relative phases [8]. For each of the BPMs, the

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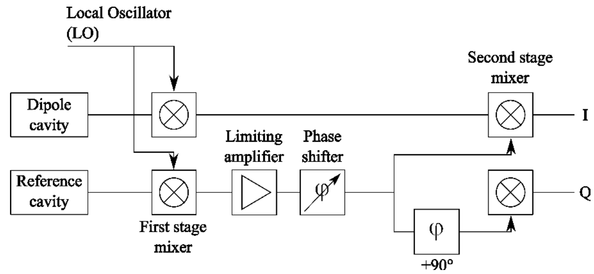

Figure 2: Simplified schematic of the FONT processing electronics [3].

monopole mode is then limited, split and mixed both in-phase and in-quadrature with the dipole signal, producing orthogonally-phased baseband I and Q signals [3]. These are digitised at 357 MHz by Analogue-to-Digital Converters (ADCs) on the FONT5A board.

Determination of the bunch position, y, is performed on the FPGA using the I, Q and charge, q, signals,

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

where k refers to the position calibration constant and θ_{IQ} to the IQ phase angle [3]. Each BPM is calibrated by vertically scanning the beam through a known range and measuring the corresponding response of the BPM. The beam is steered vertically by moving the final quadrupole, QD0FF (Fig. 1) [9].

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

$$V = G\frac{y}{M}, \tag{2}$$

where the feedback gain, G, is set to 1 for a beam with 100% bunch-to-bunch correlation. If the bunch positions are not fully correlated, the gain should be scaled accordingly.

We have recently improved the firmware so that multiple samples of the I and Q waveforms can be integrated during the feedback calculation (within the latency constraint) so as to improve the signal-to-noise ratio and, thus, the resolution. A resolution of 20 nm has been achieved by integrating 12 samples [7].

The expected level of stabilisation for a given beam setup can be computed from the bunch jitter and the incoming bunch-to-bunch correlation. The corrected bunch-2 position, Y_2, in terms of the uncorrected bunch-1 and bunch-2 positions, y_1 and y_2, is

$$Y_2 = y_2 - y_1 + c, \tag{3}$$

where c is a constant offset which may be applied in order to shift arbitrarily the mean position of the stabilised bunches. Taking the variance of Eq. 3 gives

$$\sigma_{Y_2}^2 = \sigma_{y_1}^2 + \sigma_{y_2}^2 - 2\sigma_{y_1}\sigma_{y_2}\rho_{12}, \tag{4}$$

where ρ_{12} is the bunch-to-bunch correlation and σ_{Y_2}, σ_{y_1} and σ_{y_2} represent the jitters on positions Y_2, y_1 and y_2 respectively. The best performance is achieved with $\rho_{12} = 1$ and $\sigma_{y_1} = \sigma_{y_2}$, and when these conditions are fulfilled, the limit to stablisation depends on the BPM resolution, $\sigma_{\text{res.}}$:

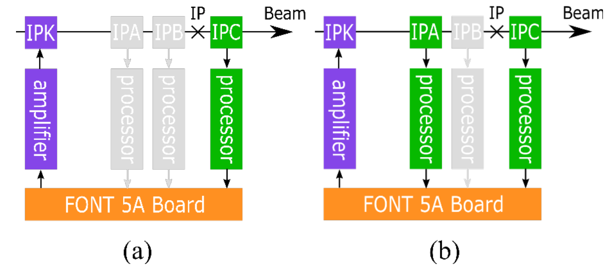

Figure 3: Diagrams of feedback loops with cavity BPMs (IPA, IPB and IPC) and a stripline kicker (IPK) for (a) single-BPM feedback with beam stabilisation at IPC and (b) two-BPM feedback, with position measurements at IPA and IPC, for beam stabilisation at an intermediate location.

$$\sigma_{Y_2} = \sqrt{2}\sigma_{\text{res.}}. \tag{5}$$

For two-BPM feedback, bunch position measurements at IPA and IPC are interpolated so the beam can be stabilised at an intermediate location. If the beam is stabilised at IPB then the feedback BPMs, IPA and IPC, contribute in a ratio 32:68, as determined from their distances from IPB. The resolution of the interpolated measurement is then

$$\sigma_{\text{res. int.}} = \sqrt{0.32^2\sigma_{\text{res.}}^2 + 0.68^2\sigma_{\text{res.}}^2} = 0.75\sigma_{\text{res.}}. \tag{6}$$

Feedback is performed in an interleaved mode, whereby consecutive bunch trains alternate feedback off and on, allowing for a comparison between the two batches of data.

RESULTS

Single-BPM IP Feedback

The latest results from operating single-BPM feedback at IPC are shown in Fig. 4 and Table 1, and were achieved with integration over 10 samples. The data were collected with the beam waist close to IPC, where the longitudinal position of the beam waist can be shifted by varying the strengths of QD0FF and QF1FF (Fig. 1) [9].

Table 1: The Position Jitters of the Bunches with Feedback Off and On, for Single-BPM Feedback

Feedback	Position jitter (nm)		Correlation (%)
	Bunch-1	**Bunch-2**	
Off	109 ± 11	119 ± 12	$84.0^{+2.5}_{-3.5}$
On	118 ± 12	50 ± 5	$-26.0^{+9.8}_{-8.8}$

To account for the imperfect incoming bunch-to-bunch correlation, the feedback gain, G (Eq. 2), was set to 0.95, which was optimised empirically. Bunch-2 was stabilised to 50 nm, and from Eq. 4, given the jitter and correlation

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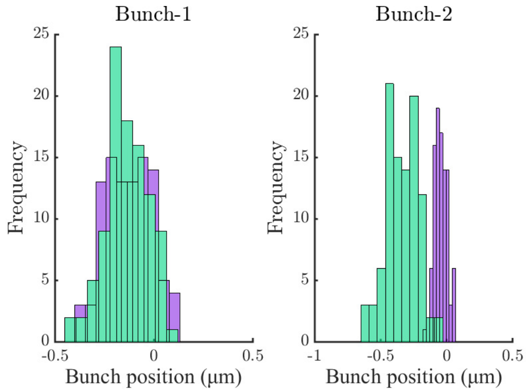

Figure 4: Distribution of bunch positions measured at IPC, with single-BPM feedback off (green) and feedback on (purple). The position jitters are given in Table 1.

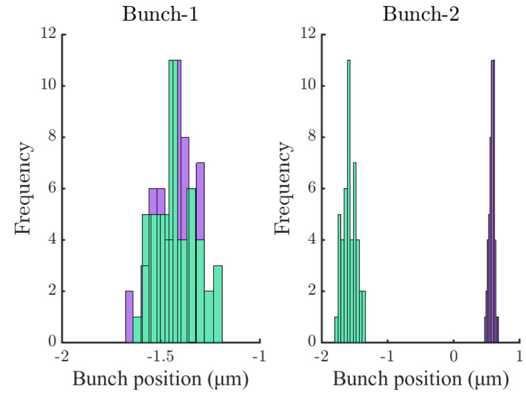

Figure 5: Distribution of bunch positions measured at IPB, with two-BPM feedback off (green) and feedback on (purple). The position jitters are given in Table 2.

of the uncorrected bunches, the feedback was predicted to stabilise the beam to 65 nm. The actual performance exceeds the predicted level of stabilisation, suggesting the measured incoming bunch-to-bunch correlation is considerably lower than the true correlation, possibly as a result of the resolution introducing an uncorrelated component to the position measurements. Demonstration of stabilisation to 50 nm is significantly better than the best result collected with single-sample single-BPM feedback of 74 nm [5].

Two-BPM IP Feedback

The firmware was also upgraded so as to allow two-BPM feedback with multiple-sample operation. This was tested for IPB using optics with a β_y^* which was 1000 times the nominal value. This reduces the position jitters at IPA and IPC, making it possible to align the beam within the dynamic ranges of all three BPMs simultaneously. Feedback was performed with integration over 5 samples as this empirically optimised the resolution; the best single-sample resolution achieved was ~41 nm, which was improved to ~31 nm by integrating 5 samples. The feedback results achieved in this configuration are shown in Fig. 5 and Table 2. Given the incoming bunch jitter and bunch-to-bunch correlation, the predicted stabilisation (from Eq. 4) was 40 nm, in excellent agreement with the measurement.

The mean position (Fig. 5) of the stabilised bunches is an arbitrary location which is determined by the relative positions of the feedback BPMs with respect to IPB; this can be removed by using the constant offset, c (Eq. 3).

Table 2: The Position Jitters of the Bunches with Feedback Off and On, for Two-BPM Feedback

Feedback	Position jitter (nm)		Correlation (%)
	Bunch-1	Bunch-2	
Off	106 ± 11	96 ± 10	$91.6^{+1.9}_{-3.2}$
On	106 ± 11	41 ± 4	$41.3^{+9.1}_{-12.3}$

The feedback was operated with a gain, G, of 0.8, for which the bunch-to-bunch correlation has not been fully removed (Table 2). This suggests that the gain was not fully optimised and that, with a higher gain value, the feedback performance could be improved further.

CONCLUSION

Modifications were made to the feedback firmware to allow for the use of integration over multiple samples of the BPM waveforms. This has been shown to improve the BPM system resolution [7] and, consequently, the feedback performance, where stabilisation to 50 nm was demonstrated with single-BPM feedback and 41 nm with two-BPM feedback.

OUTLOOK

Further work towards improving the system resolution will include the effect of minimising the pitch of the beam with respect to the BPM. Previous studies have suggested the pitch might degrade the resolution by coupling jitter on θ_{IQ} into the position measurement [3].

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