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PROGRESS TOWARDS ELECTRON-BEAM FEEDBACK AT THE NANOMETRE LEVEL AT THE ACCELERATOR TEST FACILITY (ATF2) AT KEK

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Abstract

Ultra-low latency beam-based digital feedbacks have been developed by the Feedback On Nanosecond Timescales (FONT) Group and tested at the Accelerator Test Facility (ATF2) at KEK in a programme aimed at beam stabilisation at the nanometre level at the ATF2 final focus. Three prototypes were tested: 1) A feedback system based on high-resolution stripline BPMs was used to stabilise the beam orbit in the beamline region c. 50m upstream of the final focus. 2) Information from this system was used in a feed-forward mode to stabilise the beam locally at the final focus. 3) A final-focus local feedback system utilising cavity BPMs was deployed. In all three cases the degree of beam stabilisation was observed in high-precision cavity BPMs at the ATF2 interaction point. Latest results are reported on stabilising the beam position to below 100 nanometres.

INTRODUCTION

A number of fast beam-based feedback systems are required at future single-pass beamlines such as the International Linear Collider (ILC) [1]. For example, at the interaction point (IP) a system operating on nanosecond timescales within each bunch train is required to compensate for residual vibration-induced jitter on the final-focus magnets by steering the electron and positron beams into collision. The deflection of the outgoing beam is measured by a beam position monitor (BPM) and a correcting kick applied to the incoming other beam. In addition, a pulse-to-pulse feedback system is envisaged for optimising the luminosity on timescales corresponding to 5 Hz.

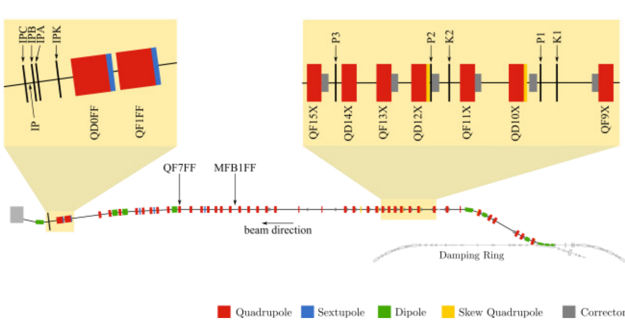

Figure 1: Layout [7] of the ATF extraction and final focus beamline with the FONT regions zoomed in.

The Feedback on Nanosecond Timescales (FONT) project has developed ILC prototype systems, incorporating digital feedback processors based on Field Programmable Gate Arrays (FPGAs), to provide feedback correction systems for sub-micron-level beam stabilisation at the KEK Accelerator Test Facility (ATF2) [2]. Previous results [3], [4] have demonstrated an upstream closed-loop feedback system that meets the ILC jitter correction and latency requirements. Furthermore, results demonstrating the propagation of the correction obtained using the upstream stripline BPM feedback system at ATF2 are reported in [5]. The ultimate aim is to attempt beam stabilisation at the nanometre-level at the ATF2 IP [6]. We report here the latest developments and beam testing results from the FONT project using a cavity BPM [7] to drive local feedback correction at the IP.

FONT5 SYSTEM DESIGN

An overview of the extraction and final focus beamlines at the ATF, showing the positions of the FONT5 system components in the IP region, is given in Fig. 1. The IP feedback system comprises a C-band cavity BPM (IPB) [7] and a short stripline kicker (IPK). The final focus magnets (QF1FF, QD0FF) can be used to steer the beam by introducing a position offset or to move the x and y beam waists longitudinally along the beamline. The offset of the QF7FF magnet can be used to change the pitch of the beam trajectory through the IP region.

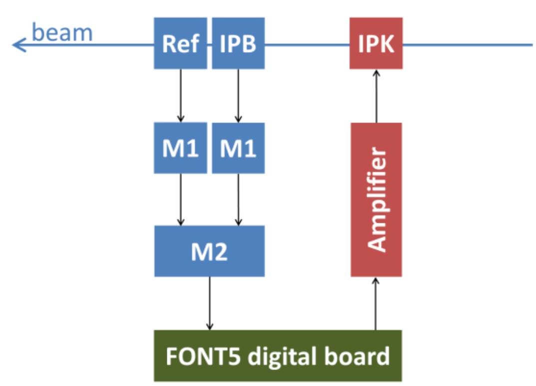

Figure 2: Schematic of IP feedback system showing the cavity BPM (IPB), reference cavity (Ref), first and second down-mixer stages (M1 and M2), FONT5 digital board, amplifier and kicker (IPK).

A schematic of the IP feedback system is given in Fig. 2. Determining the position of the beam at IPB requires both the dipole mode signal of IPB and the monopole mode signal of a reference cavity (Ref). The cavities were designed such that the y-port frequency of both signals is 6.426 GHz [8]. The signals are down-

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mixed to baseband using a two-stage down-mixer [9], as follows. The first stage down-mixer (M1) takes the 6.426 GHz reference and IPB signals and mixes each with an external, common 5.712 GHz local oscillator (LO) to produce down-mixed signals at 714 MHz. The second stage down-mixer (M2) mixes the IPB 714 MHz signal using the reference 714 MHz as LO, giving two baseband signals: I (IPB and reference mixed in phase) and Q (IPB and reference mixed in quadrature). The I and Q signals are subsequently digitised in the FONT5 digital board (Fig. 3) and normalised by the beam bunch charge; the charge is deduced from the amplitude of the reference cavity signal. The charge-normalised I and Q signals are calibrated against known beam position offsets (by moving the beam using QD0FF), allowing the IPB vertical beam position to be known in terms of a linear combination of charge-normalised I and Q.

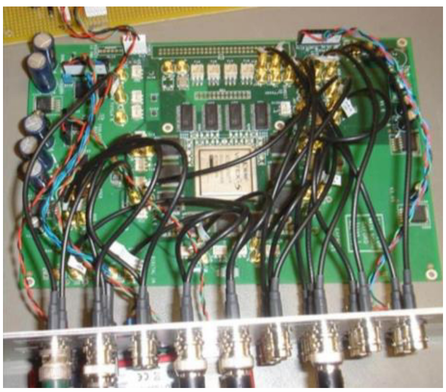

Figure 3: FONT5 digital feedback board.

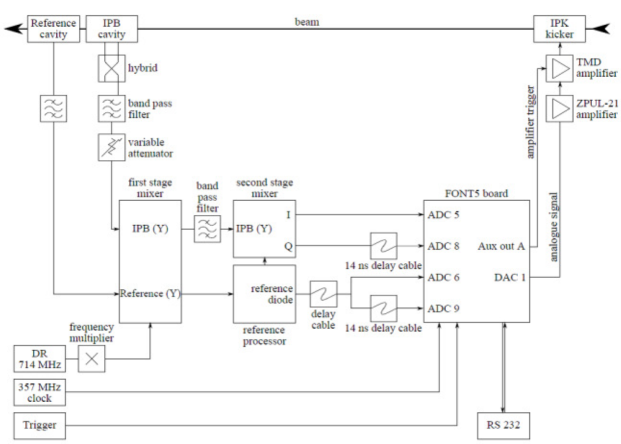

Figure 4: Schematic of configuration of IP feedback system.

BEAM TEST RESULTS

We report the results of beam tests of the FONT5 system in the 2014 running period; earlier tests were reported in [10,11,12]. A detailed schematic of the hardware configuration is given in Fig. 4.

Accelerator Setup

The ATF was set up to provide two bunches per pulse of beam extracted from the damping ring, with a bunch separation of 274.4 ns. This separation was found typically to provide a high degree of measured vertical spatial correlation between the two bunches. The feedback tests therefore involve measuring the vertical position of bunch one and correcting the vertical position of bunch two. The system was typically operated in an 'interleaved' mode, whereby the feedback correction was toggled on and off on alternate machine pulses; the feedback 'off' pulses thereby provide a continual 'pedestal' measure of the uncorrected beam position. For the purpose of recording data with BPM IPB the longitudinal location of the beam waist in the IP region was adjusted by varying the strengths of the two final focus magnets QF1FF and QD0FF. For the results reported here the beam waist was typically set near the position of IPB.

IP Feedback

The IP feedback system latency was measured and found to be 134 ns; however this could be reduced if, for example, a greater effort was made to optimise cable lengths.

The performance of the feedback system was measured using IPB. Figure 5 shows the vertical position of bunch two recorded in IPB. The IP feedback reduced the vertical beam jitter from an r.m.s. deviation of 410 nm to 67 nm. The time-sequence of the data from the same run is shown in Fig. 6.

In order to study the feedback operation a scan was performed of the beam waist longitudinal position around the nominal centre of IPB by varying the current in the QD0FF magnet (Fig. 1). As the focal point is moved longitudinally away from the centre of IPB, the vertical beam jitter measured in IPB increases (Fig. 7b). Also, due to their slightly different incoming beam trajectories, this scan had the effect of changing the vertical position of bunch 2 w.r.t. bunch 1 (Fig. 7a). Both changes allow a test of the feedback performance. The range of vertical position change of bunch 2 was roughly +-4 um w.r.t. nominal centre, and the incoming beam jitter varied up to about 400 nm. Figure 7b shows that the feedback reduced the incoming beam jitter at all scan points. The expected bunch 2 feedback-on jitter can be computed using the feedback-off jitter and bunch 1-2 position correlation measurements; this is shown in Figure 7b, and agrees remarkably well with the measured bunch 2 jitter.

Assuming that the FB performance is currently limited by the resolution of the cavity BPMs employed, the best position jitter stabilisation achieved, 67 nm, implies a BPM resolution of around 50 nm. This is consistent with direct estimates of the resolution determined using the system of three C-band BPMs at the ATF2 IP [8]. This is also consistent with fine scans of the longitudinal beam waist position at IPB, which yield a minimum measured beam jitter of around 50 nm (Fig. 8).

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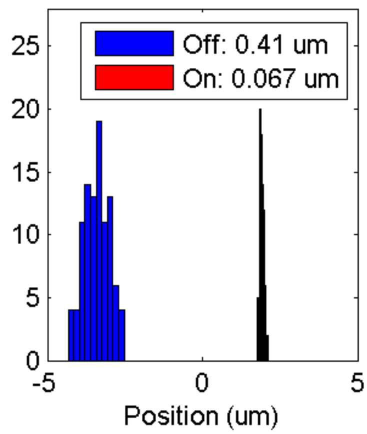

Figure 5: Distribution of the vertical position of bunch two in IPB with (red) and without (blue) application of the IP feedback correction.

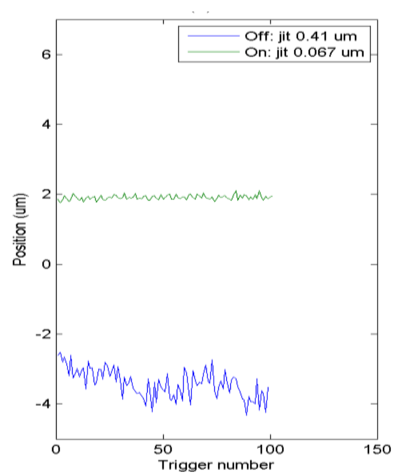

Figure 6: Time-sequence of the vertical position of bunch two in IPB with (green) and without (blue) application of the IP feedback correction.

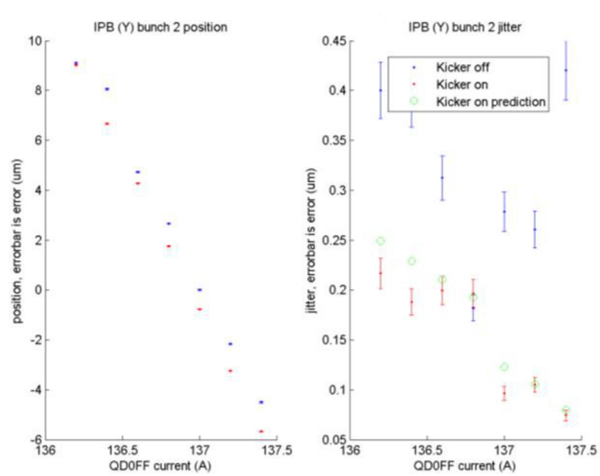

Figure 7: Bunch two mean position (a, left) and position jitter (b, right) with (red) and without (blue) application of the IP feedback correction. The green circles in (b) represent the predicted performance (see text).

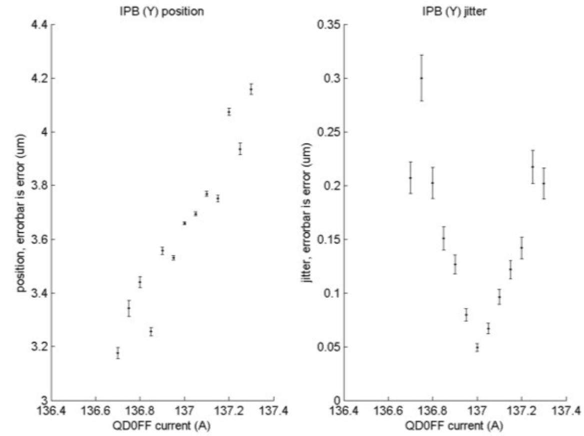

Figure 8: Bunch two mean position (a, left) and position jitter (b, right) vs. QD0FF current.

CONCLUSIONS

Beam stabilisation using cavity BPMs at the IP has been demonstrated successfully at ATF2. Vertical beam position stabilisation was achieved at the level of 67 nm using a local IP feedback system. The system has a demonstrated latency of 134 ns. Work is ongoing to improve the resolution of the cavity BPMs at the IP in order to obtain improved feedback results.

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