APPLICATIONS OF STRIPLINE AND CAVITY BEAM POSITION MONITORS IN LOW-LATENCY, HIGH-PRECISION, INTRA-TRAIN FEEDBACK SYSTEMS

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Abstract

Two low-latency, sub-micron, beam position monitoring (BPM) systems have been developed and tested with beam at the KEK Accelerator Test Facility (ATF2). One system (upstream), based on stripline BPMs, uses fast analogue front-end signal processing and has demonstrated a position resolution as low as 400 nm for beam intensities of 1 nC, with single-pass beam. The other (IP) system, based on low-Q cavity BPMs and utilising custom signal processing electronics designed for low latency, provides a single pass resolution of approximately 100 nm. The BPM position data are digitised by fast ADCs on a custom FPGA-based feedback controller and used in three modes: 1) the upstream BPM data are used to drive a pair of local kickers nominally orthogonal in phase in closed-loop feedback mode; 2) the upstream BPM data are used to drive a downstream kicker in the ATF2 final focus region in feedforward mode; 3) the IP cavity BPM data are used to drive a local downstream kicker in the ATF2 final focus region in closed-loop feedback mode. In each case the beam jitter is measured downstream of the final focus system with the IP cavity BPMs. The relative performance of these systems is compared.

INTRODUCTION

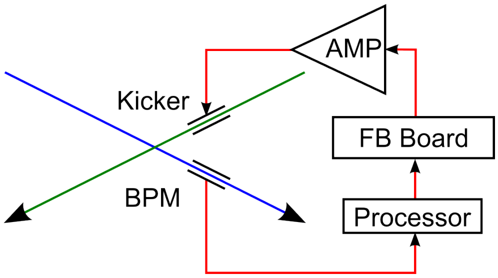

Figure 1: Schematic of IP intra-train feedback system with a crossing angle.

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 (Fig. 1). In addition a pulse-to-pulse feedback system is envisaged for optimising the luminosity on timescales corresponding to 5 Hz. Slower feedbacks, operating in the $0.1 - 1$ Hz range, will control the beam orbit through the Linacs and Beam Delivery System. The key components of each system are BPMs for measuring the beam orbit; fast signal processors to translate the raw BPM pickoff signals into a position output; feedback circuits, for applying gain and taking account of system latency; amplifiers to provide the required output drive signals; and kickers for applying the correction to the beam. Previous results [2], [3] have demonstrated an upstream closed-loop feedback system that meets the ILC jitter correction and latency requirements.

We report the latest development and beam testing results from the Feedback on Nanosecond Timescales (FONT) project. We have extended our ILC prototype systems, incorporating digital feedback processors based on Field Programmable Gate Arrays (FPGAs), to provide feedback and feedforward correction systems for sub-micron-level beam stabilisation at the KEK Accelerator Test Facility (ATF2). The ultimate aim is to attempt beam stabilisation at the nanometer-level at the ATF2 IP [4]. Initial achievements in this new area were reported in [5].

FONT5 DESIGN

An overview of the extraction and final focus beamlines at the ATF, showing the positions of the FONT5 system components, is given in Fig 2.

The upstream feedback system (Fig. 3) incorporates two stripline BPMs (P2, P3) which are used to provide vertical beam position inputs. Two stripline kickers (K1, K2) are used to provide fast vertical beam corrections. A third stripline BPM (P1) is used to witness the incoming beam conditions. Each BPM signal is processed by a front-end analogue signal processor; the analogue output is then sampled, digitised and processed by the digital feedback board. Analogue output correction signals are sent to a fast amplifier that drives each kicker.

The IP feedback system (Fig. 7) comprises two C-band cavity BPMs (IPA, IPB) and a 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. A high speed cable is strung along the beamline connecting the upstream and downstream systems and allowing a feedforward signal to be transmitted to the IP region.

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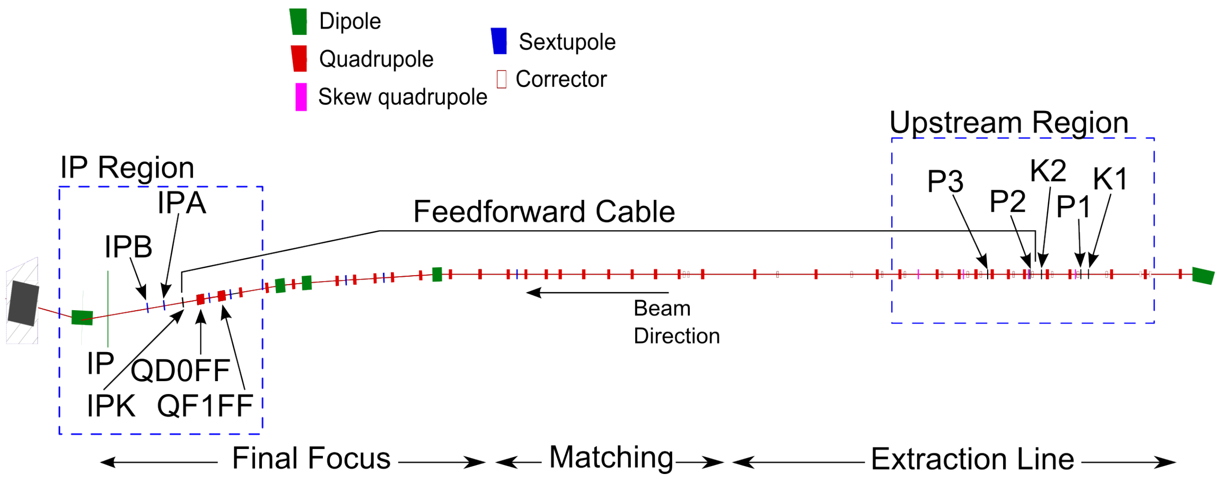

Figure 2: Layout of the ATF extraction and final focus beamline with the FONT regions marked.

The ATF can be set up to provide an extracted train that comprises two bunches separated by an interval selectable within the range $140-300$ ns. We have previously demonstrated bunch-by-bunch feedback in the extraction line with a latency below 140 ns, meeting the ILC minimum bunch spacing specification of around 150 ns. For the beam tests reported here the latency was relaxed so as to allow for several different experimental setups. For these purposes two custom digital feedback processor boards were installed at ATF, one upstream and one at the IP (Figs. 3, 5, 7). On each board there are nine analogue signal input channels digitised using ADCs with a maximum conversion rate of 400 MS/s, and two analogue output channels formed using DACs, which can be clocked at up to 210 MHz. The digital signal processing is based on a Xilinx Virtex5 FPGA. The FPGA is clocked with a 357 MHz source derived from the ATF master oscillator and hence locked to the beam. The ADCs are clocked at 357 MHz. The analogue BPM processor output signals are sampled on peak to provide the input signals to the digital processor. The gain stage is implemented via a lookup table stored in FPGA RAM. The digital output is converted back to analogue and used as input to the kicker amplifier. A pre-beam trigger signal is used to enable the amplifier drive output from the digital board.

The driver amplifier was manufactured by TMD Technologies [6] and provides ±30 A of drive current into the kicker. The rise-time is 35 ns from the time of the input signal to reach 90% of peak output. The output pulse length was specified to be up to 10 µs.

BPM PROCESSORS

Upstream Stripline BPM Processor

Stripline BPM processors have been designed and constructed in-house [2]. The top and bottom (y) stripline BPM signals are added with a resistive coupler and subtracted using a hybrid, to form a sum and difference signal respectively. The resulting signals are band-pass filtered, down-mixed with a 714 MHz local oscillator signal which is phase-locked to the beam, and low-pass filtered. The hybrid, filters and mixer were selected to have latencies of the order of a few nanoseconds to yield a total processor latency of 10 ns. Recent results have demonstrated position resolution of order 0.4 µm [7], [8].

IP Cavity BPM Processor

The cavity BPM processing scheme [9] consists of a two-stage downmixing system, the first downmixing the cavity signal to 714 MHz and the second to baseband. The baseband signal is then digitised in a local digital processor.

BEAM TEST RESULTS

We report the results of beam tests of the FONT5 system in the spring 2013 running period; earlier tests were reported in [2], [3] and [5]. The system was operated in three experimental modes: upstream feedback, feedforward, and IP feedback. The effects of each mode on the beam in the IP region were measured.

Accelerator Setup

The ATF facility 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 and feedforward 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/feedforward correction was toggled on and off on alternate machine pulses; the feedback/feedforward 'off' pulses thereby provide a continual 'pedestal' measure of the uncorrected beam position. For the purpose of recording data with BPM IPA or IPB the longitudinal location of the beam waist in the IP region

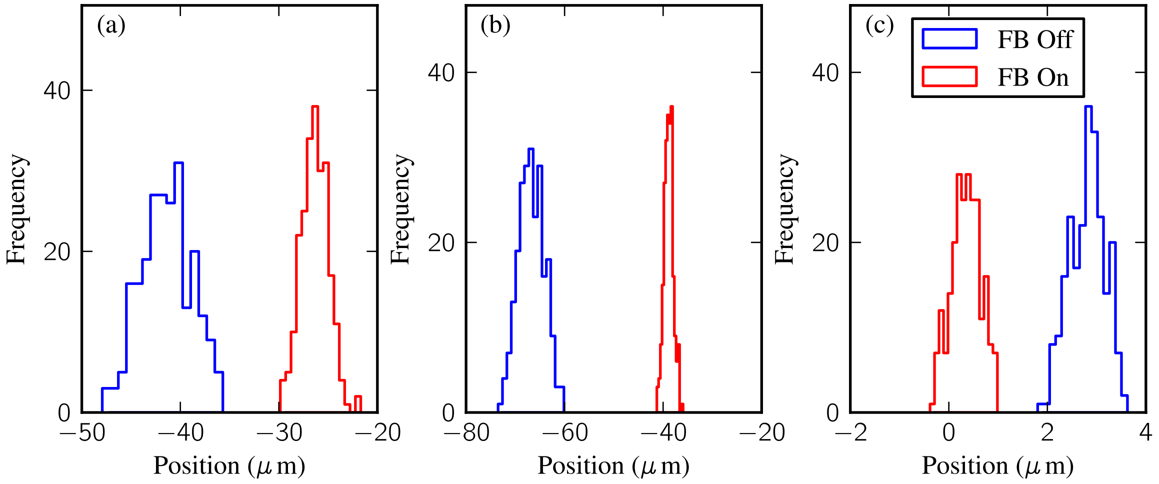

Figure 4: Distribution of the vertical position of bunch two in (a) P2, (b) P3 and (c) IPB with (red) and without (blue) application of the upstream feedback correction.

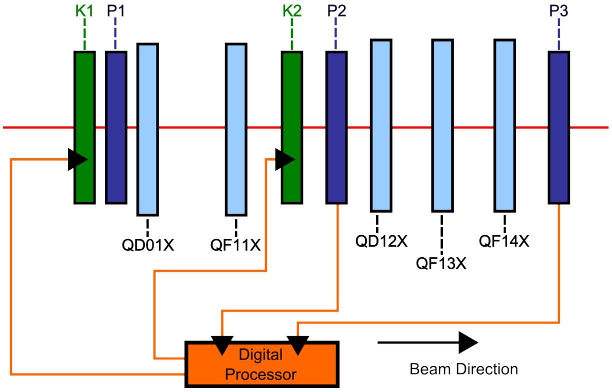

Figure 3: Schematic of upstream feedback system showing the relative locations of the kickers, BPMs and other elements.

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.

Upstream Feedback

In this mode (Fig. 3) the system records the measured beam position of bunch one in the two upstream BPMs P2 and P3 and calculates a coupled-loop feedback correction which is applied locally to bunch two using the upstream kickers K1 and K2. The latency of the upstream system has been measured previously and demonstrated to be less than 140 ns [3]. The impact of the upstream feedback correction was measured in the IP region using IPB. Figure 4 shows the vertical position of bunch two recorded in BPMs P2, P3 and IPB. In the upstream region the feedback reduced the incoming vertical beam jitter at P2 and P3 from 2.5 ± 0.1 to 1.4 ± 0.1 μm and 0.90 ± 0.04 μm respectively. The system was set up to centre approximately the beam at IPB, and Fig. 4(c) shows that the average beam position was corrected from 2.82 ± 0.02 μm to 0.34 ± 0.02 μm. However, the corresponding vertical beam jitter correction was from 0.36 ± 0.02 μm to 0.30 ± 0.01 μm. The system therefore successfully centred the beam at IPB, and did reduce the jitter, although the level of jitter correction was much smaller than that observed upstream. One possible explanation is that there are additional sources of vertical beam jitter between the upstream and IP regions; work is ongoing to understand this.

Feedforward

The feedforward system (Fig. 5) uses as input a linear combination of the bunch one vertical position recorded in the two upstream BPMs P2 and P3. This is used to generate a correction signal which is transmitted down the feedforward cable to the IP region, where it is amplified and used to deflect bunch two with a stripline kicker (IPK) placed just after QD0FF. Using this setup the effect of a correction based on the upstream beam position can be measured locally at the IP using IPB. Fig 6 shows the vertical position of bunch two recorded in BPM IPB. The effective latency of the feedforward system was measured and found to be 202 ns. The system was set up to centre approximately the beam at IPB; the mean vertical beam position was corrected from 2.40 ± 0.02 μm to 0.14 ± 0.01 μm. The corresponding vertical beam jitter was reduced from 0.30 ± 0.02 μm to 0.17 ± 0.01 μm. This is a significant degree of correction, and work is ongoing to interpret it in terms of a model of beam transport down the ATF2 beamline.

IP Feedback

IP feedback (Fig. 7) uses as input the bunch one vertical beam position measured in IPB. The IP digital processor evaluated a correction signal which was amplified and ap-

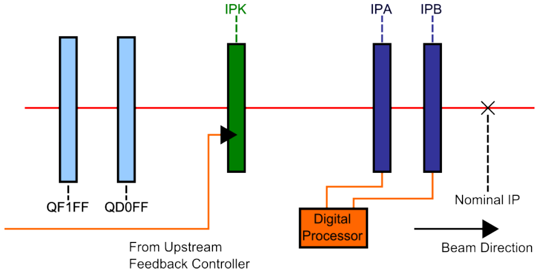

Figure 5: Schematic of feedforward system showing relative locations of the kickers, BPMs and other elements.

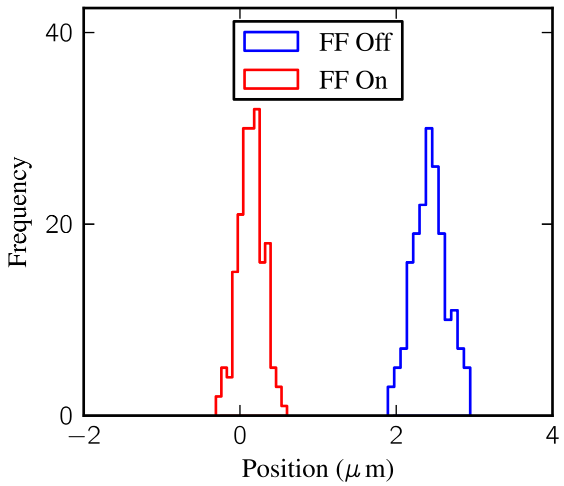

Figure 6: Distribution of the vertical position of bunch two in IPB with (red) and without (blue) application of the feedforward correction.

plied to bunch two using the IP kicker IPK. The IP feedback system latency was measured and found to be 134 ns; however this could be reduced if a greater effort was made to optimise cable lengths etcetera. The feedback algorithm used in the upstream system was utilised to a take as input the I and Q signals from the homodyne IPB processing system. The response of the system was measured using BPM IPB. Fig 8 shows the vertical position of bunch two recorded in IPB. The IP feedback reduced the vertical beam jitter from 168 ± 7 nm to 98 ± 5 nm. It also improved the average vertical position from 1.68 ± 0.01 µm to 0.81 ± 0.01 µm. The performance is consistent with a BPM resolution of somewhat better than 100 nm.

CONCLUSIONS

Three methods of beam stabilisation at the IP have been demonstrated successfully at ATF2. The best vertical beam position stabilisation, at the level of 100 nm, was obtained using a local IP feedback system. Feedback and feedforward correction schemes based on the beam position measured upstream and applied in the IP region achieved stabilisation at the level of 300 and 170 nm respectively. Work is ongoing to understand these results in terms of beam transport and jitter sources in the ATF2 beamline. During the summer 2013 recess the IP BPMs at ATF2 have been replaced; with a better understanding of the beam physics and improved BPMs it is hoped that improved results will be obtained in the next running periods.

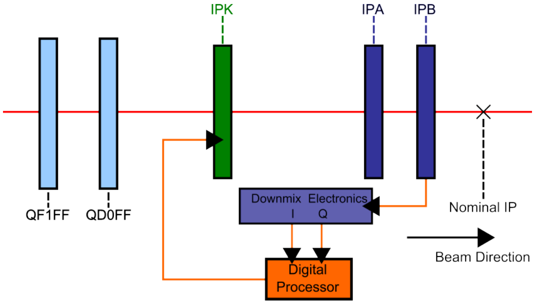

Figure 7: Schematic of IP feedback system showing the relative locations of the kickers, BPMs and other elements.

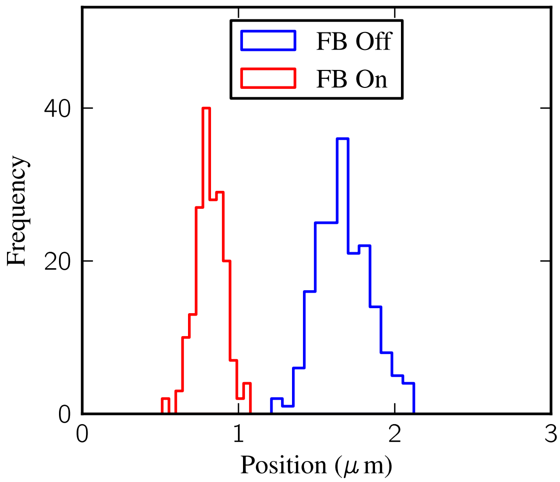

Figure 8: Distribution of the vertical position of bunch two in IPB with (red) and without (blue) application of the IP feedback correction.

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