PERFORMANCE OF NANOMETRE-LEVEL RESOLUTION CAVITY BEAM POSITION MONITORS AND THEIR APPLICATION IN AN INTRA-TRAIN BEAM POSITION FEEDBACK SYSTEM

N. Blaskovic Kraljevic, T. Bromwich, P. N. Burrows, G. B. Christian, C. Perry, R. Ramjiawan,
John Adams Institute, Oxford, UK
D. R. Bett, CERN, Geneva, Switzerland
T. Tauchi, N. Terunuma, KEK, Tsukuba, Ibaraki, Japan
S. Jang, Dept. of Accelerator Science, Korea University, Sejong, South Korea
P. Bambade, LAL, Orsay, France

Abstract

A system of three low-Q cavity beam position monitors (BPMs), installed in the interaction point (IP) region of the Accelerator Test Facility (ATF2) at KEK, has been designed and optimised for nanometre-level beam position resolution. The BPMs have been used to provide an input to a low-latency, intra-train beam position feedback system consisting of a digital feedback board and a custom stripline kicker with power amplifier. The feedback system has been deployed in single-pass, multi-bunch mode with the aim of demonstrating intra-train beam stabilisation on electron bunches of charge ~1 nC separated in time by c. 220 ns. The BPMs have a demonstrated resolution of below 50 nm on using the raw measured vertical positions at the three BPMs, and has been used to stabilise the beam to below the 75 nm level. Further studies have shown that the BPM resolution can be improved to around 10 nm on making use of quadrature-phase signals and the results of the latest beam tests will be presented.

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 (Fig. 1). In addition, a pulse-to-pulse feedback system is envisaged for optimising the luminosity on timescales corresponding to 5 Hz.

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]. Demonstration of an upstream closed-loop feedback system that meets the ILC jitter correction and latency requirements is described in [3], together with results demonstrating the propagation of this correction along the ATF2 line. The ultimate aim is to attempt beam stabilisation at the nanometre-level at the ATF2 IP.

In order to achieve the required BPM resolution, three low-Q cavity BPMs have been developed, installed and optimised in the ATF2 IP region. We report here the BPM resolution measured with the ATF2 beam and the results achieved using one of these cavity BPMs to drive local feedback correction at the IP.

EXPERIMENTAL SET-UP

An overview of the ATF2 extraction and final focus beamlines, showing the positions of the system components in the IP region, is given in Fig. 2. The IP region contains the three C-band cavity BPMs IPA, IPB and IPC, operated on an x, y mover system [5], with IPB being used in the single-loop IP feedback system described below. The cavity BPM design quality factors are shown in Table 1. The IP feedback correction is applied using 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. The offset of the QF7FF magnet can be used to change the pitch of the beam trajectory through the IP region.

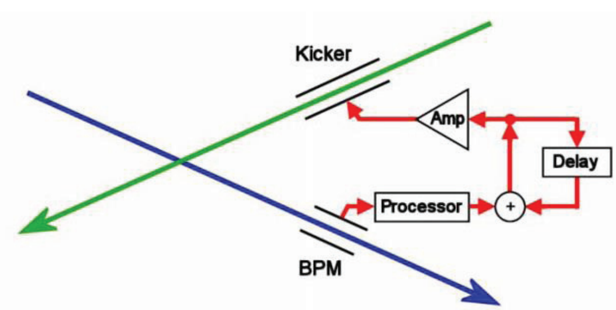

Figure 1: Schematic of IP intra-train feedback system with a crossing angle.

Table 1: Cavity BPM Design Quality Factors [6]

Quality factor	y dipole mode
Loaded quality factor, Q_L	579
Internal quality factor, Q_0	3996
External quality factor, Q_{ext}	677

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A schematic of the IP feedback system is given in Fig. 3. 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 [6]. The signals are down-mixed to baseband using a two-stage down-mixer [7], 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. 4) and normalised by the beam bunch charge; the charge is deduced from the amplitude of the reference cavity signal using a diode detector. The charge-normalised I and Q signals are calibrated against known beam position offsets (by moving the BPM mover), allowing the IPB vertical beam position to be known in terms of a linear combination of charge-normalised I and Q.

BPM RESOLUTION RESULTS

The resolution of the system of three BPMs was measured as follows. Firstly, each BPM was calibrated, allowing the position of the beam to be calculated using:

$$y = \frac{I'}{qk} = \frac{I\cos\theta_{IQ} + Q\sin\theta_{IQ}}{qk} \tag{1}$$

where q is the charge measurement, and k and θ_{IQ} are constants obtained from the calibration. Note that this particular linear combination of the orthogonal I and Q terms is referred to as I'. A linear combination orthogonal to I' exists, and is referred to as Q':

$$I' = I\cos\theta_{IQ} + Q\sin\theta_{IQ}; \tag{2}$$
$$Q' = -I\sin\theta_{IQ} + Q\cos\theta_{IQ}. \tag{3}$$

Secondly, a 300-pulse data set was taken. The beam position measured at the first two BPMs is used to predict the beam position at the third using one of two methods. In the geometric method, the position at IPC is predicted using:

$$y_{\mathrm{IPC}} = a_1 y_{\mathrm{IPA}} + a_2 y_{\mathrm{IPB}}. \tag{4}$$

where a_1 and a_2 are obtained from the beam propagation transfer matrices. In the fitting method, linear regression is performed to find the fit coefficients c_1, c_2,…. in an equation of the type:

$$I'_{\mathrm{IPC}} = c_1 I'_{\mathrm{IPA}} + c_2 I'_{\mathrm{IPB}} + c_3. \tag{5}$$

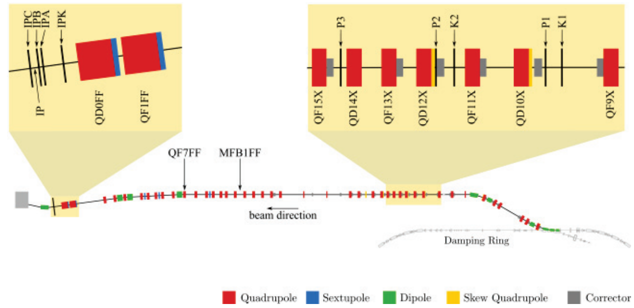

Figure 2: Layout [4] of the ATF2 extraction and final focus beamline with the FONT regions shown in detail.

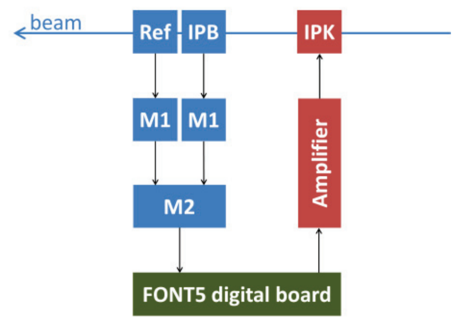

Figure 3: Schematic of IP feedback system showing the cavity BPM (IPB), reference cavity (Ref), first and second down-mixer stages (M1 and M2), FONT5 digital board, amplifier and kicker (IPK).

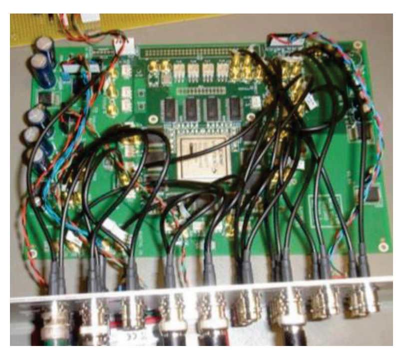

Figure 4: FONT5 digital feedback board.

Having obtained the fit coefficients, Eq. (5) is used to calculate the predicted I' values at IPC, which can then be converted to predicted positions using Eq. (1). Additional fit parameters (such as Q' or q) can be added to Eq. (5). The residual of the measured and predicted positions at the third BPM is calculated, and the standard deviation δ of the residuals is computed. The resolution is then calculated by scaling δ by a geometric factor [7]:

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$$\text{Resolution} = \frac{\delta}{\sqrt{1+a_1^2+a_2^2}}. \tag{6}$$

The results in Table 2 show that a base resolution of around 50 nm can be achieved using the geometric method. Transitioning to fitting brings the resolution down by a factor 3, and including the Q' term to the fit brings the resolution down further to the order of 10 nm.

Table 2: Resolution of the Triplet Cavity BPM System Using Geometric and Fitting Methods. Statistical Errors are Shown

Method	**Resolution (nm)**
Geometric	49.5 ± 2.0
Fitting I' & constant	16.4 ± 0.7
Fitting I', Q' & constant	14.1 ± 0.6
Fitting I', Q', q & constant	13.4 ± 0.6

FEEDBACK RESULTS

We summarise here the results of beam tests of the FONT5 feedback system. Further results are reported in [8, 9].

The accelerator was set up to provide two bunches per pulse of beam extracted from the damping ring, with a bunch separation of 215.6 ns. This separation was found typically to provide a high degree of measured vertical bunch position 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.

The IP feedback system latency was measured and found to be 212 ns [10]. The performance of the feedback system was measured using IPB; Fig. 5 shows the vertical position of both bunches with feedback off and on. The IP feedback reduced the vertical beam jitter from an r.m.s. deviation of 420 nm to 74 nm (Table 3). Fig. 6 shows the bunch 2 position versus bunch 1 position for this data set. The feedback removes the correlated component between the bunches, reducing the bunch-to-bunch position correlation from 98.2 % to approximately zero (Table 3).

Table 3: Position Jitter of Bunch 1 (σ_{y_1}) and 2 (σ_{y_2}) and Bunch-to-bunch Position Correlation ($\rho_{y_1 y_2}$) with and without Application of the IP Feedback Correction

Feedback	σ_{y_1} **(nm)**	σ_{y_2} **(nm)**	$\rho_{y_1 y_2}$ **(%)**
Off	412 ± 29	420 ± 30	$+98.2^{+0.3}_{-0.4}$
On	389 ± 28	74 ± 5	-13 ± 10

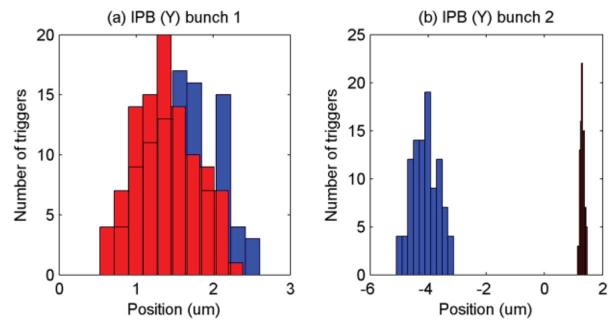

Figure 5: Distribution of the vertical position of (a) bunch 1 and (b) bunch 2 in IPB with (red) and without (blue) application of the IP feedback correction.

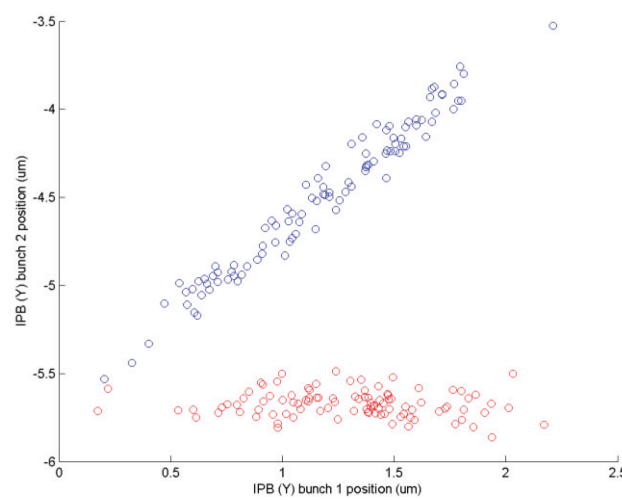

Figure 6: Vertical position for bunch 2 versus bunch 1 in IPB with (red) and without (blue) application of the IP feedback correction.

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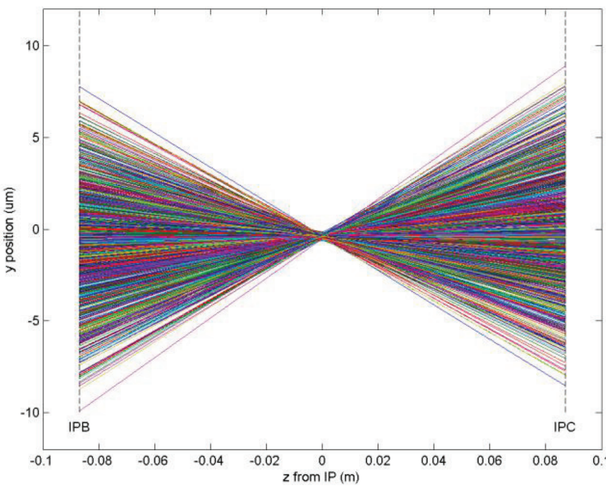

Figure 7: Vertical bunch position y, obtained for each trigger by linearly interpolating the measured beam positions at IPB and IPC, versus longitudinal distance z from the IP.

The jitter that can be attained with feedback on (σ_{Y_2}) can be calculated from the feedback off values for the jitter of the two bunches (σ_{y_1}, σ_{y_2}) and their correlation ($\rho_{y_1 y_2}$):

$$\sigma_{Y_2}^2 = \sigma_{y_1}^2 + \sigma_{y_2}^2 - 2\sigma_{y_1}\sigma_{y_2}\rho_{y_1 y_2} \geq 2\sigma_r^2 \quad (7)$$

where σ_r is the BPM resolution [11]. The above equation yields an expected jitter with feedback on of $\sigma_{Y_2} = 79.4$ nm, which agrees with the measured value of 74 ± 5 nm. Furthermore, Eq. (7) sets an upper limit to the resolution of $\sigma_r \lesssim 50$ nm, which agrees with the resolution measurements presented above.

OUTLOOK

Future plans consist in using two IP BPMs in order to stabilise the beam at a location between them. Preliminary measurements have been taken simultaneously at BPMs IPB and IPC, located equidistantly either side of the IP. Given the absence of magnetic fields in the IP region, the beam trajectories can be calculated by linearly interpolating the positions measured at the two BPMs as shown in Fig. 7. The results show that, under typical operating conditions, the position jitter is ~3 µm at IPB and IPC. The beam waist can be clearly reconstructed at a location 0.3 mm downstream of the nominal IP with an interpolated position jitter of 82 nm.

In addition to the benefit of stabilising the beam at a location other than the BPM itself, the use of two BPMs to perform the measurement has the potential of improving the position resolution available to the feedback system. In the configuration where IPB and IPC are used to stabilise the beam at the IP, the vertical position at the IP would be taken as the average of the vertical positions measured at IPB and IPC. Thus, the error on this mean position would be $\sigma_r/\sqrt{2}$ where σ_r is the resolution of either BPM [11]. The challenge in this mode of operation results from the requirement of a large BPM dynamic range of over 10 µm whilst preserving the BPM resolution.

CONCLUSIONS

Three low-Q cavity BPMs have been developed, installed and optimised in the ATF2 IP region. A BPM resolution of below 50 nm has been achieved on using the raw measured vertical positions with the expected beam propagation. Fitting the beam transport, and making use of the BPM quadrature-phase signal Q’, brings the resolution down to around 10 nm.

Beam stabilisation using one of these cavity BPMs has been demonstrated successfully. Vertical beam position stabilisation to below the 75 nm level has been achieved using a local IP feedback system. The system has a demonstrated latency of 212 ns. Work is ongoing to improve the resolution of the cavity BPMs and to work towards operating a feedback system using the inputs from two IP BPMs.

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