Development of Fast Micron-Resolution Beam Position Monitors for Linear Collider Beam-Based Feedback Systems.

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***Abstract*–We present the design of prototype fast beam position monitor (BPM) signal processors for use in inter-bunch beam-based feedbacks for linear colliders and electron linacs. We describe the FONT4 intra-train beam-based digital position feedback system prototype deployed at the Accelerator test facility (ATF) extraction line at KEK, Japan. The system incorporates a fast analogue beam position monitor front-end signal processor, a digital feedback board, and a fast kicker-driver amplifier. The total feedback system latency is less than 150ns, of which less than 10ns is used for the BPM processor. We report preliminary results of beam tests using electron bunches separated by c. 150ns. Position resolution of order 1 micron obtained.**

I. INTRODUCTION

The international linear collider (ILC) requires a fast interaction point (IP) feedback system [1], operating on a bunch by bunch level, to maximize luminosity at the point of collision. This system is required to reduce bunch to bunch jitter, caused by external influences, therefore ensuring alignment of the incoming electron and positron bunches for collision.

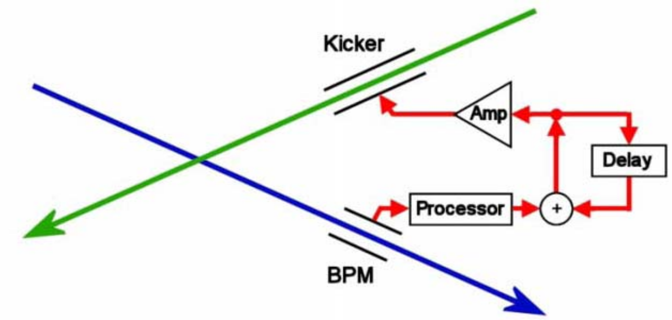

Fig. 1.Representation of an IP intra-train feedback system for an interaction region with a crossing angle [2]. The position of the outgoing beam is measured using a BPM and a correcting kick applied to the incoming opposing beam.

It is the aim of the FONT (Feedback on Nanosecond Timescales) group to develop such a system to operate on the nanosecond level. The major components of the system are as follows:

1. Stripline BPMs
2. Analogue BPM processors
3. Digital feedback circuits
4. Kicker magnets
5. Drive amplifiers

A representation of the feedback system setup for a small crossing angle (14mrad at ILC) is shown in figure 1.

For the development and beam testing of fast, single bunch resolution, analogue BPM processors the extraction line of the accelerator test facility (ATF) at KEK, Japan was used. A diagram of the feedback setup can be seen in figure 2. The typical beam properties at ATF have dimension approximately 7µm in y and 70µm in x with energy 1.28 GeV and ~1×10^{10} particles per bunch for single bunch operation [3]. The FONT system occupies a low emittance region of the accelerator.

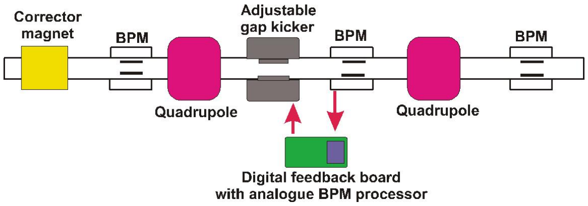

Fig. 2. Outline of the FONT 4 setup at ATF, detailing the major components of the system and the surrounding beamline. The quadrupoles shown were switched off during calibration to simplify beam optics calculations.

II. PROCESSOR DESIGN

The FONT system uses 12cm long stripline BPMs to measure the position of the incoming beam. The major requirement of the BPM processing electronics is micron level resolution with the major limiting factor being latency. It is for this reason that the processors are analogue in design, and stripline type BPMs are chosen. For this system the advantage of striplines over buttons and cavities is that; button BPMs have very short pulses, making processing more difficult; cavities have a period of ring down of the signal after the bunch passes through, this may increase the latency of the system.

These tests implement y corrections and so the top and bottom stripline signals are input to the processor. These are

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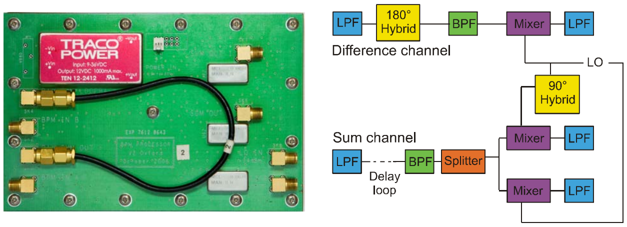
subtracted using a hybrid, filtered and down-mixed using a 714MHz local oscillator which is phase-locked to the beam (Fig. 3.). The total latency of the processor was measured to be 9.2ns.



(a) (b)

Fig. 3. (a) Photo of analogue BPM processor. (b) Simple schematic of the processor, showing major components. The raw BPM stripline signal goes from left to right.

III. BEAM-BASED RESOLUTION DETERMINATION

Calibration of the BPMs along with resolution measurements were done on the beamline. At ATF an electron beam of a single bunch per train with 0.9×10^{10} electrons per bunch was used. The BPM was calibrated using a corrector magnet (denoted ZV8X) situated upstream of the BPM. The beam was moved across the beampipe in the vertical plane and data taken at multiple positions. This allows us to get the change in processor output signal as a function of corrector current. The magnet current can then be translated into position values using calculated beam optics. This process was simplified by turning off all quadrupoles between the corrector and the BPM.

The resolution is determined using a three BPM system. This was done by splitting the output signal from a single stripline BPM and inputting it to three identical processors.

The resolution is then calculated using the calibration constant, which is the slope of the curve of BPM signal as a function of distance (Fig. 4). Since all three processors are connected to the same BPM the position as measured in one is related to those of the other two by a system of linear equations such that:

$$\mathbf{A}x = \mathbf{B} \quad (1)$$

Where **A** is the matrix containing the positions measured by the two other identical BPMs and **B** is a vector of position as measured by the BPM in question; x gives the position of the beam as predicted by the measurements from the two other BPMs. The solution is given by:

$$x = \mathbf{A}^{-1}\mathbf{B} \quad (2)$$

This solution may not be unique if the matrix **A** is a non-square matrix. This case requires the use of a method such as singular value decomposition or a generalized inverse; the Moore-Penrose matrix inverse, or pseudoinverse, ($\mathbf{M}^{+}$) is particularly suited to this situation [4]. It is a generalized matrix inverse which satisfies the following:

$$\mathbf{MM^{+}M} = \mathbf{M}$$
$$\mathbf{M^{+}MM^{+}} = \mathbf{M^{+}}$$
$$(\mathbf{MM^{+}})^{T} = \mathbf{MM^{T}}$$
$$(\mathbf{M^{+}M})^{T} = \mathbf{M^{T}M}$$

Multiplying both sides of (1) by the transpose of **A** gives a square matrix which can then be inverted to give:

$$\mathbf{A}^{T}\mathbf{A}x = \mathbf{A}^{T}\mathbf{B}$$

$$x = (\mathbf{A}^{T}\mathbf{A})^{-1}\mathbf{A}^{T}\mathbf{B}$$

$$x = \mathbf{A}^{+}\mathbf{B}$$

Once the predicted position has been determined the resolution is taken to be the standard deviation of the following:

$$\mathbf{Residual} = \frac{\text{measured position - predicted position}}{\text{calibration constant}}$$

IV. BEAM TEST RESULTS

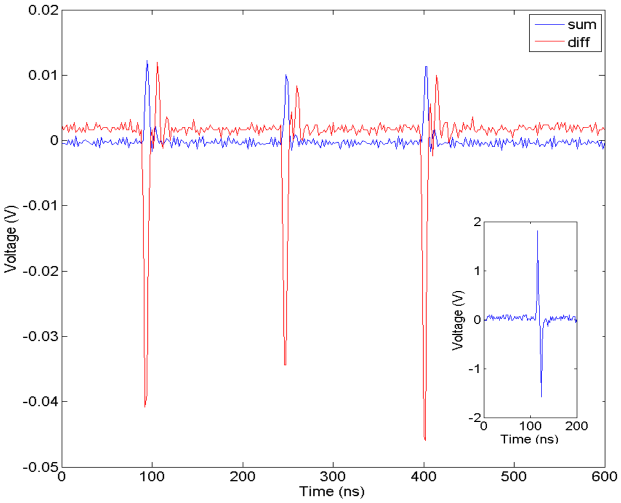


Fig. 4. Processor sum and difference outputs with raw stripline signal inset. The low latency of the processors allows individual bunches to be resolved, and the latency of the whole system is less that the bunch spacing of 154ns therefore allowing bunch by bunch feedback.

The output of the BPM processors comes in the form of two signals; one is the sum of the signal from opposing striplines (indicating charge) and the other is the difference between them which is proportional to the beam position. Figure 4 shows an example of the processor output for a three bunch train (that which is used to demonstrate feedback) illustrating the capability of single bunch resolution.

The first stage of the experiment was calibration of the BPMs which was done using an upstream corrector magnet (Fig.2). The beam was swept, in the vertical plane across the beampipe over a range of approximately 3mm (+-1.5mm from the centre of the beampipe). Using corrector magnet ZV8X, 4.06m upstream of the BPM, data was taken for 50 pulses of single bunch beam per current setting of -1.2A, -0.6A, 0.3A, 0.6A and 1.2A. The resulting difference signals were charge normalized and plotted as a function of position giving a calibration curve (Fig. 6.) which yielded a constant of -3.14mm^{-1}. Resolution data was taken for a magnet current of 0.3A, which is the current that placed the beam closest to the centre of the beampipe (i.e. the point at which the difference signal is minimized).

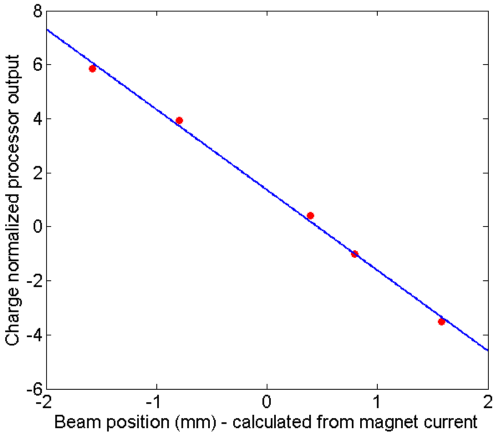


Fig. 5. Calibration curve with slope -3.14mm^{-1}. Each point gives the average position over 50 pulses of a single bunch per train beam.

To extract the calibration information from the data the area under each pulse was integrated and the baseline noise removed. This was then averaged over 50 pulses. During this process it was found that the calibration constant (and therefore the resolution) has a strong dependency on the portion of the waveform chosen for integration (fig. 7). Figure 6 shows an example waveform, indicating the choice of integration window. Here the window is taken to have a width of 26 samples centred on the peak, where the sample size is 200ps. It is thought that this phenomenon is caused by mis-optimization of the mixer used in the processing electronics which will be considered in the next generation of BPM processors.

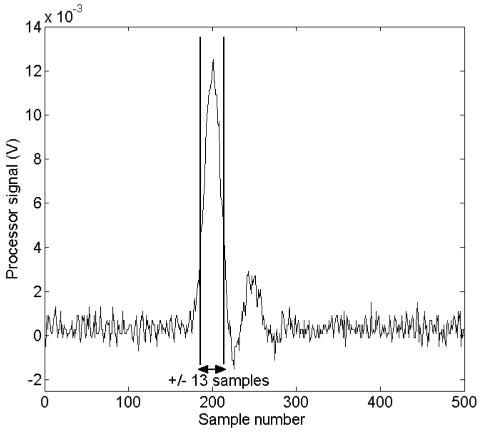


Fig. 6. This plot shows the window of integration used for translation into position. Each sample has size 200ps.

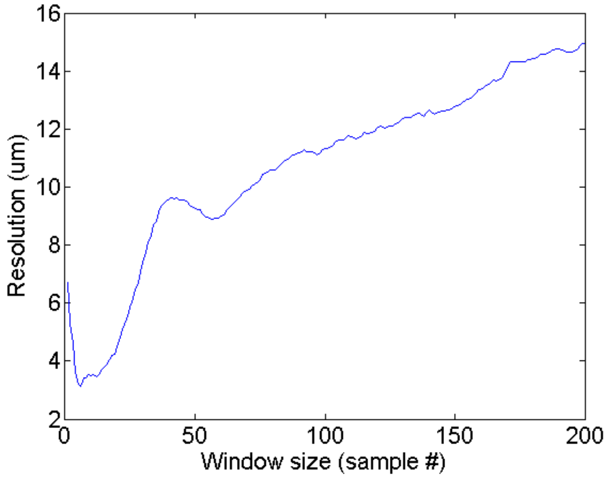


Fig. 7. Variation of integration window size vs. calculated resolution. Each sample = 200ps

The next stage of analysis was to determine the resolution of each processor. This is equal to the standard deviation of the spread of residuals for the 50 pulses of data taken multiplied by some geometric factor [5]. In this case the factor is one since all three processors are connected to one stripline (i.e. at the same point along the beamline). Figure 7 shows the distribution of residuals for 50 single bunch pulses. The resolution of the BPM is determined to be 3.15µm.

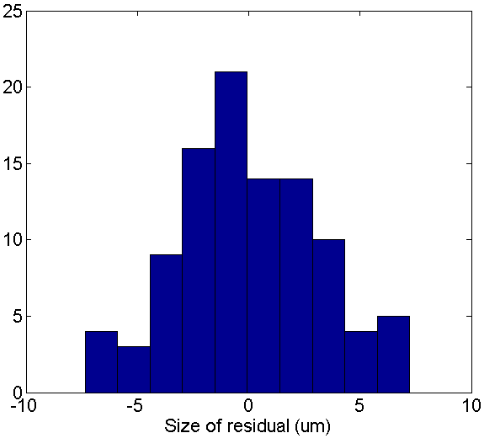


Fig. 8. Residual of difference between predicted and measured positions. The resolution is taken to be the standard deviation of this spread and was found to be 3.15um.

V. CONTINUING DEVELOPMENT

The next generation of BPM processors will be installed at the final focus test beam line, ATF2 at KEK [6] next year. It is hoped that improvements focusing on optimization of the mixer and improved data acquisition will allow achievement of resolution ~1µm, whilst maintaining the same short latency of <10ns that has been achieved here.

REFERENCES

[1] "International linear Collider Reference Design Report", Volume 3, 2007

[2] FONT4: P. N. Burrows et al, Proceedings PAC07, Albuquerque, NM, USA, June 2007, p.416

[3] http://www-atf.kek.jp/atf/introduction

[4] A. Ben-Israel, T. N. E. Greville "Generalized inverses: theory and applications", 1974

[5] S. Walston et al., "Performance of a nanometer resolution BPM system", Proceedings of EPAC 2006, Edinburgh, Scotland.

[6] B. I. Grishanov et al, "ATF2 Proposal", Vol. 1 and 2, August 2005.

[7] FONT 1: P. N. Burrows et al, Proceedings PAC03, Portland, Oregon, May 2003, p. 687

[8] FONT 2: P. N. Burrows et al, Proceedings EPAC04, Lucerne, July 2004, p. 785

[9] FONT 3: P. N. Burrows et al, Proceedings PAC05, Knoxville, TN, May 2005, p. 1359

[10] FONT 4: P. N. Burrows et al, Proceedings EPAC06, Edinburg, UK, June 2006, p. 849

[11] A. Kalinin, P.N. Burrows, Proceedings PAC07, Albuquerque, NM, June 2007, p. 416