DEVELOPMENT OF A FAST MICRON-RESOLUTION BEAM POSITION MONITOR SIGNAL PROCESSOR FOR LINEAR COLLIDER BEAM-BASED FEEDBACK SYSTEMS

R. Apsimon, P.N. Burrows, C. Clarke, B. Constance, H. Dabiri Khah, T. Hartin, C. Perry, J. Resta Lopez, C. Swinson, John Adams Institute, Oxford University, UK;
G.B. Christian, ATOMKI, Debrecen, Hungary; A. Kalinin, Daresbury Laboratory, UK

Abstract

We present the design of a prototype fast beam position monitor (BPM) signal processor 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 was obtained.

INTRODUCTION

A number of fast beam-based feedback systems are required at the International electron-positron Linear Collider (ILC) [1]. At the interaction point (IP) a very fast system, operating on nanosecond timescales within each bunchtrain, is required to compensate for residual vibration-induced jitter on the final-focus magnets by steering the electron and positron beams into collision.

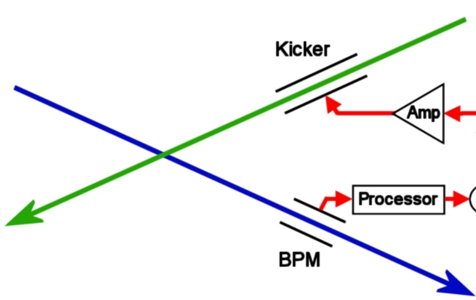

Figure 1: Schematic of IP intra-train feedback system with a crossing angle. The deflection of the outgoing beam is registered in a BPM and a correcting kick applied to the incoming other beam.

The key components of each such system are beam position monitors (BPMs) for registering the beam orbit; fast signal processors to translate the raw BPM pickoff signals into a position output; feedback circuits, including delay loops, for applying gain and taking account of system latency; amplifiers to provide the required output drive signals; and kickers for applying the position (or angle) correction to the beam. A schematic of the IP intra-train feedback is shown in Figure 1, for the case in which the beams cross with a small angle; the current ILC design incorporates a crossing angle of 14 mrad.

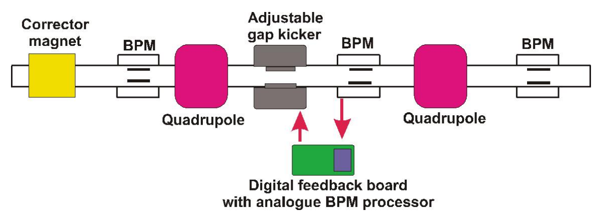

Figure 2: Outline of the FONT4 setup at ATF. The quads shown were switched off during calibration to simplify beam optics calculations.

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 include dimensions of approximately 7um in y and 70um in x, energy 1.28 GeV and ~$1x10^{10}$ particles per bunch for single bunch operation [2]. The FONT system occupies a low emittance region of the beamline.

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 ringdown of the signal after the bunch passes through, which may increase the latency of the processor system.

These tests implement y corrections and so the top and bottom stripline signals are input to the processor. These are subtracted using a hybrid, filtered and down-mixed using a 714MHz local oscillator signal that is phase-locked to the beam (Figure 3.). The total latency of the processor was measured to be 9.2ns [3,4].

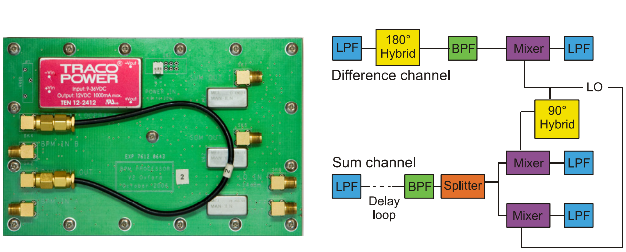

Figure 3: (a) Photo of analogue BPM processor. (b) Simple schematic of the processor, showing major components.

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 $0.9\text{x}10^{10}$ 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 were 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-processor 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 beam position (Figure 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 [5]. It is a generalized matrix inverse which satisfies the following;

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

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 distribution of residuals:

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

BEAM TEST RESULTS

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 (Figure 2). The beam was swept, in the vertical plane across the beampipe over a range of approximately

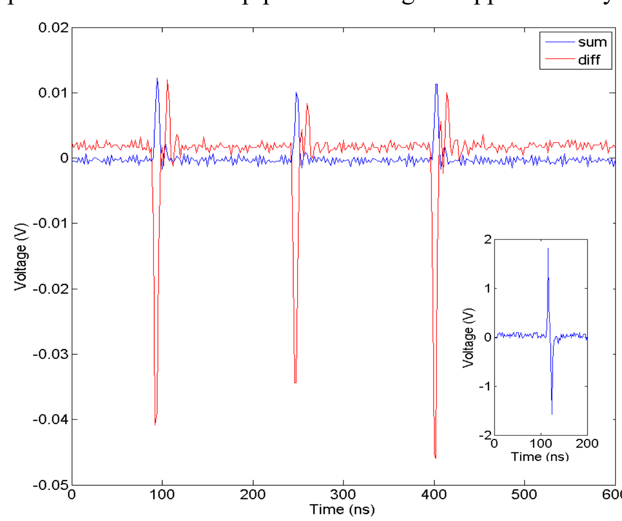

Figure 4. Processor sum and difference outputs with raw stripline signal inset. The low latency of the processors allows individual bunches to be resolved, and the latency of the whole system is less that the bunch spacing of 154ns therefore allowing bunch by bunch feedback.

3mm (+-1.5mm from the centre of the beampipe). Using corrector magnet ZV8X, 4.06m upstream of the BPM, data were 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 (Figure 6.) which yielded a constant of -3.14mm^{-1}. Resolution data were 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).

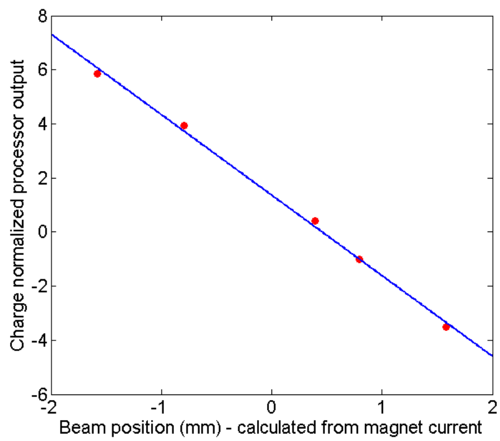

Figure 5: Calibration curve with slope -3.14mm^{-1}. Each point gives the average position over 50 pulses of a single bunch per train beam.

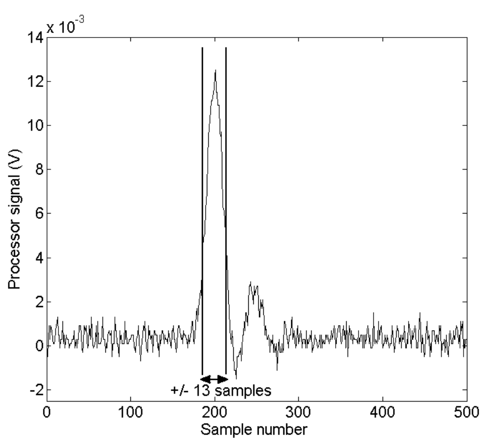

Figure 6: Window of integration used for translation into position. The samples are every 200ps.

To extract the calibration information from the data the area under each pulse was integrated and the baseline noise subtracted. This was then averaged over 50 pulses. During this process it was found that the calibration constant (and therefore the resolution) has a strong dependence on the portion of the waveform chosen for integration (Figure 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.

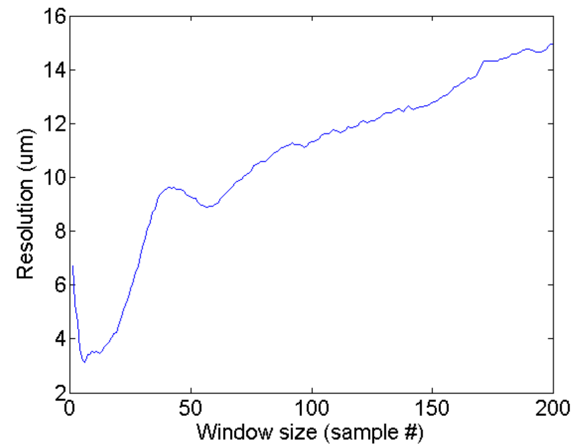

Figure 7: Variation of integration window size vs calculated resolution.

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 a geometric factor [6]. In this case the factor is on since all three processors are connected to one stripline (i.e. at the same point along the beamline). Figure 8 shows the distribution of residuals for 50 single bunch pulses. The resolution was determined, from the standard deviation of this spread, to be 3.2um.

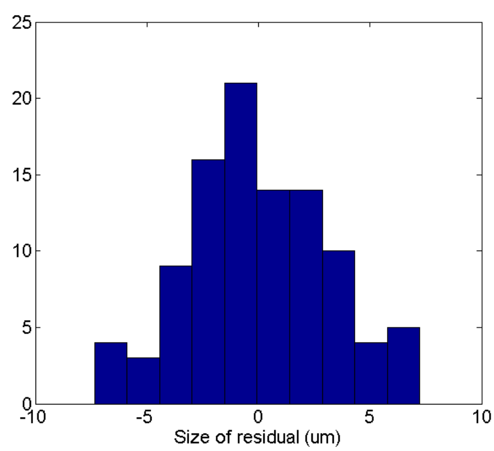

Figure 8: Residual of difference between predicted and measured positions.

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