A Two-Bunch Beam Position Monitor Performance Evaluation

Robert Traller, Evgeny Medvedko, Steve Smith, Roberto Aiello

Stanford Linear Accelerator Center
Stanford, CA 94309

Abstract. New beam position processing electronics for the Linear Accelerator allow faster feedback and processing of both positron and electron bunch positions in a single machine pulse. More than 30 electron-positron beam position monitors (epBPMs) have been installed at SLAC in various applications and have met all design requirements. The SLC production electron bunch follows the positron bunch down the linac separated by 58.8 nS. The epBPM measures the position of both bunches with an accuracy of better than 5 μm at nominal operating intensities. For SLC, the epBPMs have measured the position of bunches consisting of from 1 to 8×10^{10} particles per bunch.

For PEP-II (*B* Factory) injection, epBPMs have been used with larger electrodes and several BPMs have been combined on a single cable set. The signals are separated for measurement in the epBPM by timing. In PEP-II injection we have measured the position of bunches of as little as 2×10^{9} particles per bunch. To meet the demands of SLC and PEP-II injection, the epBPM has been designed with three triggering modes:

1. As a self-triggering detector, it can trigger off the beam and hold the peak signal until read out by the control program.
2. The gated mode uses external timing signals to gate the beam trigger
3. The external trigger mode uses the external timing signals offset with internal vernier delays to precisely catch peak signals in noisy environments.

Finally, the epBPM also has built-in timing verniers capable of nulling errors in cable set fabrication and differences in channel-to-channel signal delay. Software has made all this functionality available through the SLC control system.

INTRODUCTION

The epBPM is a single-width standard CAMAC module functionally very similar to older processors used in the SLAC Linear Collider (SLC) but with many improvements and modern components. Beam signals are taken from four orthogonal striplines in a circular vacuum chamber, connected via double-shielded 50 Ω coax. The pulse doublet seen at the inputs goes through a 40 Mhz low-pass filter before being sent to both the internal trigger generator and the “sample and holds” (S/H). After filtering and amplification, each stripline signal goes to two S/Hs. Thus the four stripline inputs culminate in two sets of four S/Hs, with each set independently triggerable. In effect, the epBPM is like two processors connected to a single beam line device. The epBPM uses eight 14-bit ADCs (13 bits plus sign).

TABLE 1. Differences between epBPMs and Old Linac BPMs

Function	epBPM	Old linac processors
Measurements per pulse	2	1
Programmable Delay Triggers	2	1
Calibration	internal calibrator	beam
Bandwidth	40 Mhz	20 MHz
Ultimate resolution	5 μm	~30 μm
Trigger modes	3	2
Packaging	single width CAMAC	double width CAMAC

To form the trigger, each stripline signal is amplified and summed with the other three before the trigger is derived from the zero crossing of the summed wave form. The heart of this internal trigger generator is an Analog Devices AD891 Data Qualifier chip originally designed for recovering data from hard disk drives. The Data Qualifier produces an ECL-level pulse adjusted in our application to about 30 ns duration. In the self-triggered or gated modes this becomes the hold signal for the S/Hs. After generation of one pulse, the Data Qualifier is ready for another zero crossing event.

The ungated, self-triggered mode is not currently used by any epBPM installation. Gating the internal trigger with the distributed SLC timing system has enabled us to accurately measure any two of three bunches in the linac separated by approximately 60 ns. The need for a third trigger mode was anticipated for areas where signal might be weak and the pulses and/or reflections on cables might come in quick succession. Such is the case in PEP-II injection. The solution was to employ internal delay verniers which make it possible to use the distributed timing system to trigger the S/Hs at the precise peak of the signal.

Analog Devices AD 9500 digitally programmable delay generator has proven to be simple, effective and monotonic in providing a 10 ns vernier in 40 ps steps; six are used. One vernier is used for each of the two external timing signals brought in as a gate or trigger. In addition, in all trigger modes the hold signal for X+, X–, Y+ and Y– goes through additional AD9500s to compensate for any differences in internal signal path or mismatch of the cable set.

Unlike earlier SLC BPM processors, the epBPM has a built in calibrator. A CAMAC command causes the generation of an ECL pulse which is split. One of the pulses is then delayed 4 ns before both are applied logic gates to produce two narrow pulses of opposite polarity slightly staggered in time. An e^+/e^- select signal toggles a switch to determine which pulse is applied to the inverting and which to the non-inverting amplifier inputs. The result is a facsimile of an e^+ or e^- doublet which passes through a programmable attenuator before connecting to the regular signal input path via combiners. During calibration a pedestal measurement is made by internally generating a hold signal when no beam or calibration pulse is present, then the calibrator is triggered at three separate attenuator settings to accurately determine the difference in gain between channels.

The heart of the digital portion of the epBPM is the Xylinx field programmable gate array. All decoding of CAMAC commands, generation of calibrate and pedestal pulses, ADC control and handling of the serial bit stream from the eight ADCs takes place here.

B FACTORY INJECTION LINES

The completion of the first production epBPMs coincided with commissioning of the PEP-II (*B* Factory) injection. Before any beam reached these BPMs, the installation was used to test the epBPM displays and software and to insure proper calibration and response to all CAMAC functions. During this period we discovered a problem with low drop-out voltage regulators in the epBPMs which required minor modification. Subsequently it was discovered that the CAMAC power supplies purchased for PEP-II would oscillate when loaded with certain modules, including epBPMs. Vendor modifications were implemented (BiRa Systems).

The PEP-II injection lines require long cable runs to connect the BPMs to the closest CAMAC crate. Cable sets of from 200' to 500' of RG214 were used. The BPMs themselves are spaced 8 to 10 meters apart on the beam line. A series of 10 dB couplers were mounted on cable trays above the BPMs and linked with RG214. The BPMs were connected to the couplers with 10' sets of RG223. Up to six BPMs were connected in this way with an additional two BPMs added to the end of the line with a power combiner. This results in a train of eight beam pulses separated by approximately 75 ns.

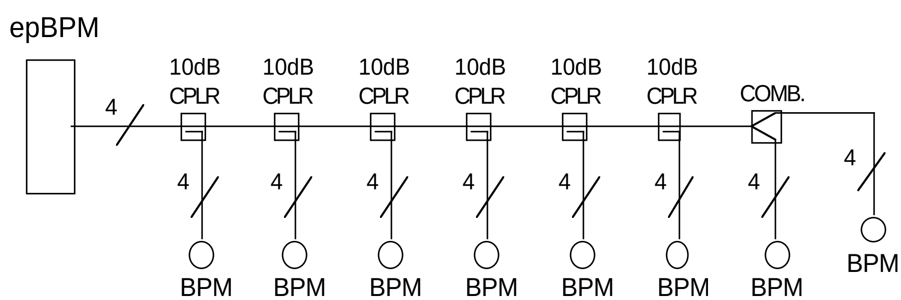

FIGURE 1. Typical section of *B* Factory injection BPM system.

Before the installation was complete, a test was devised using the epBPM as part of a TDR. We output a strong fast pulse (~35 volts peak, ~2ns) into a TEE. One side went to the BPM cable plant, the other side of the TEE went to a four-way power splitter and into the epBPM. Thus, the epBPM saw the pulser output and its reflections off the BPMs and couplers. Sweeping the timing in increments on 1 ns or less while reading the ADCs gave a picture very much like the view seen using a 400 Mhz oscilloscope.

Timing

The distributed timing signals for PEP are different from SLC. SLC distributes 119 MHz to its CAMAC via programmable delay units (PDU) and the control system can program triggers in delay steps of 8.4 ns. PEP’s timing is based on 476 MHz and PEP’s programmable delay units (PPDU) provide steps of 2.1 ns. The epBPM software and timing diagnostics must recognize which system it is using and increment the internal timing verniers to provide consistent timing steps with either delay unit. In fact, the entire handling of timing at SLAC had to be modified so that everything was referenced to nanoseconds instead of 8.4 ns “ticks” as was the previous practice.

Time-of-flight calculations were made to estimate initial delays to enter into database timing variables. We were able to estimate the timing of all the BPMs in a string quite accurately, relative to the first BPM in that string. The arrival time of beam at the first BPM was a bit harder to determine.

Although the external timing mode was designed largely with PEP injection in mind, we chose to leave the processors in "gated" mode for initial commissioning. We reasoned that even if some BPM readings were polluted by noise or reflections, timing in the gated mode would be less critical and it would be easier to find the first beam. We only had to get a beam signal within a 35 ns window rather than accurately find the correct peak out of a string of eight doublets. As it turned out, PEP injection worked so well that beam reached a profile monitor at the far end of the injection line before any other instrumentation was required to do its job. Nevertheless, several BPMs did read some signal and the timing diagnostics enabled us to insure that we were selecting the correct BPM signal.

For the most part, PEP injection continued working in the gated mode without problems. Only when we attempted to inject at intensities much below 2×10^9 particles per bunch did triggering become a bit erratic in gated mode. Eventually all PEP injection epBPMs were set to external trigger mode.

LINAC FEEDBACK SYSTEMS

Unlike *B* factory injection, commissioning of epBPMs for linac systems consisted of replacing units in working systems. Program managers are not anxious to shut down for wholesale replacement of critical feedback components. Even during scheduled downtimes, the fear is that good running configurations will be difficult to recover if critical systems are changed.

The linac BPM system consists typically of eight BPMs in each 100-meter section of linac. These BPMs are cabled to processing electronics in three CAMAC crates, thus two or three BPMs are processed in each crate. When the system was originally designed, an attempt was made to limit the need for programmable triggers. The original BPM processors were designed with a "hard-wired" connection to the same trigger in each crate. The cable sets were fabricated in lengths that insured all BPM signals arrived at a crate simultaneously. This has worked well enough but constrains modifications. Signal paths must remain the same for every processor in a crate unless independent triggering is available. Without independent triggering for the electronics, any timing adjustments must be made the same for all the units in a crate. If one BPM has noise or cross-talk from the other beam pulse, the trigger (gate) cannot be moved independently to find a time frame free of the unwanted signal.

Collimator Feedback System

Near the end of the linac is an area of collimators and a feedback system involving 12 BPMs with 24 processors to measure the position of both e^+ and e^- on each machine pulse. The 24 processors would be replaced by 12 epBPMs. We began the upgrade in stages, installing two or three epBPMs at a time and testing them before the next phase. In the collimator feedback area of the linac there are enough triggers for each epBPM to get two triggers: one for each set of S/Hs. However, these same two triggers apply to all epBPMs in a crate. For only about 1/3 of the units were there enough triggers to independently trigger each epBPM. Furthermore, where there are not enough triggers available to independently trigger the epBPMs, we cannot combine them with old linac processors in the same crate, as the internal delays are quite different for the two.

In the lab we used the built-in calibrator to find values for the internal timing verniers which would compensate for differences in signal delay from channel to channel. These are stored in a PROM and assume a perfectly matched cable set. On-line diagnostics were developed to scan a range of values for the verniers and select the optimum setting for the installation. We could not just scan the vernier delays for X^+, X^-, Y^+, Y^- and read the ADCs for a peak value as this could be polluted by position offsets. Since the BPM is symmetric, we assumed $X^+ + X^- = Y^+ + Y^-$. Therefore, since $X^+ = Y^+ + Y^- - X^-$, we calculated the ratios:

$$\frac{X^+}{Y^+ + Y^- - X^-}$$

$$\frac{X^-}{Y^+ + Y^- - X^+}$$

$$\frac{Y^+}{X^+ + X^- - Y^-}$$

$$\frac{Y^-}{X^+ + X^- - Y^+}$$

The vernier delays at which these ratios peak are the optima. The software allows one to write these values directly into the module and store them in the database. The database also stores the difference between the module's pre-programmed values and those calculated using the on-line utility. These then are the site-specific cable offsets will be added to values stored in module memory should the module be changed for maintenance reasons.

The collimator feedback area is one of the most important for good position resolution. After commissioning the utilities for adjusting vernier delays in the epBPMs we were able to use orbit-fitting algorithms to calculate resolution in this area of about 4 μm with beam intensities of 3×10^{10} to 4×10^{10} particles per bunch.

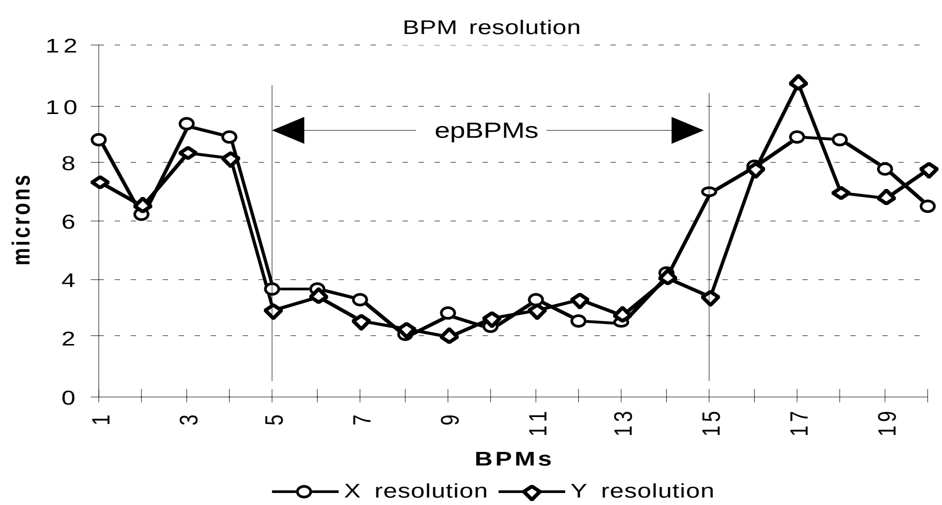

FIGURE 2. Resolution measured for 20 BPMs in the collimator section of the linac. Beam intensity is about 4×10^{10} electrons per bunch.

Ring-to-Linac Launch Feedback System

By the time the collimator feedback system was fully commissioned, the ’97 SLC run was well under way and beam currents were rising as systems got tuned up. The next feedback system to be upgraded was the area where all three bunches enter the linac from the damping rings. In the collimator region, only positrons and electrons destined for collisions are present. Here, production electrons, positrons, and the scavenger bunch bound for the positron target all converge from North and South damping rings.

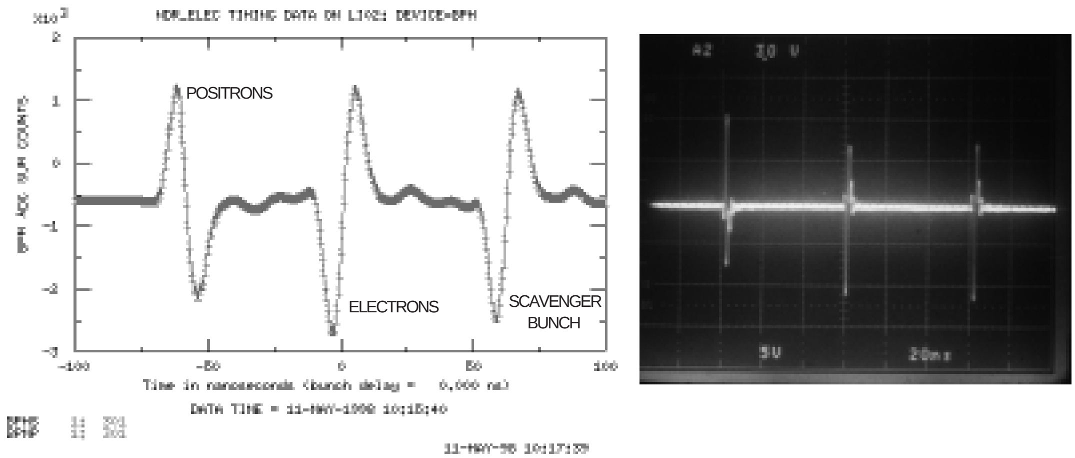

FIGURE 3. Left: plot made by reading ADCs while incrementing trigger in 500 ps steps. Right: 400 Mhz scope picture of input to epBPM

The entire linac is a noisy environment with klystron modulators firing at 120 Hz. Throughout the history of BPMs at SLAC, we have battled noise with ferrite toroids, timing, filtering...whatever.

Triggering and Noise

At this stage in the commissioning of the epBPMs, it became apparent that we had some vulnerability to noise. The epBPM was designed with a 46 dB dynamic range. It was specified to be able to measure beam currents from 5×10^{8} to 1×10^{11}. This was achieved without the use of programmable attenuators, possibly a mistake. The ability of the internal trigger to fire down to 5×10^{8} also makes it vulnerable to noise and reflections caused by the larger signals coming in quick succession. We began to see noise interfere with calibrations as well as the ringing of one beam signal interfering with our ability to read the following pulse in the gated mode. We can read the pulses accurately in the external trigger mode, but independent triggering is not always available. Certainly, we must be able to get good calibration data. We had to raise the trigger threshold about 6 to 8 dB to get good calibrations and reliable readings in the gated mode of narrowly separated beam pulses.

FINAL FOCUS

On either side of the SLC interaction point (IP) there is a feedback system using BPMs to measure the energy loss from collisions at the IP. It is beyond the scope of this paper to describe the functioning of this system except to say it was originally seen as an area for using epBPMs. The system currently employs electronics designed for the Final

Focus Test Beam (FFTB) which works well but requires complicated wiring and occupies much CAMAC crate space. Considerable effort was made to use epBPMs but we were not able to achieve the necessary resolution. BPM diameters in this region are about three times that of the linac and the resolution demands are at least as stringent. Two epBPMs remain in the Final Focus replacing conventional electronics in less critical applications.

INJECTOR

Not part of our original upgrade plan, a feedback system using a single epBPM has been implemented at the very first BPM in the machine. This unit is less than one meter from the polarized electron gun. Here, a laser fires two quick pulses at the cathode producing the two bunches of electrons that will become the bunch destined for collisions at the SLC IP and the bunch used to create positrons. Machine physicists use an epBPM in externally triggered mode to monitor the two pulses and and keep their relative amplitudes the constant.

Once, after a brief maintenance downtime, we were asked to look at a problem with this unit. In this area there are a lot of beam losses. The two bunches might each have 6×10^{10} electrons right out of the gun and lose 20% within a few meters. The epBPM was showing a significant degradation from the level before the maintenance access. Using the epBPM timing verniers, I noticed the separation between the two bunches had changed by some 800 ps. The problem turned out to be timing in the laser system which had been recently modified. This demonstrates the use of the BPM as a timing diagnostic.

CONCLUSIONS

The epBPM has met all design specifications and has proven to be an accurate and versatile processor of BPM stripline signals. It can easily measure the position of pulses separated by less than 60 ns. Resolution better than 5 µm at 5×10^{10} particles/bunch using 25 mm diameter BPMs is easily achievable. Although resolution is dependent on the amount of signal, bunches 2×10^{9} to 8×10^{10} particles have been measured in the internally triggered mode.

In the lab better than 48 dB dynamic range was measured for the internal trigger. To use the internal trigger in noisy environments this dynamic range may have to be limited by raising the internal triggering threshold. In the external trigger mode, the trigger threshold is of no concern. The problem is merely the availability of stable distributed timing signals.

The internal timing verniers and the SLC/PEP timing system have proven to be more than stable enough for externally timing S/Hs. The long term stability of the timing has thus far remained within a few hundred picoseconds of original settings

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