Design, Commissioning and Operational Results of Wide Dynamic Range BPM Switched Electrode Electronics*

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Abstract. The Continuous Electron Beam Accelerator Facility (CEBAF) is a high-intensity, continuous wave electron accelerator for nuclear physics. Total acceleration of 4 GeV is achieved by recirculating the beam through two 400 MeV linacs. The operating currents, over which the linac beam position monitoring system must meet specifications are 1 μA to 1000 μA. A system was developed in 1994 and installed in the spring of 1995 that switches four electrode signals at 120 kHz through two signal conditioning chains that use computer controlled variable gain amplifiers with a dynamic range greater than 80 dB. The system timing was tuned to the machine recirculation period of 4.2 μs so that components of the multipass beam could be resolved in the linacs. Other features of this VME based system include long term stability and high speed data acquisition, which make it suitable for use as both a time domain diagnostic tool and as part of a variety of beam feedback systems. The computer interface has enough control over the hardware to make a thorough self-calibration and verification-of-operation routine possible.

INTRODUCTION

The CEBAF accelerator linacs are designed to operate with linac currents ranging from 1 μA to 1 mA. The beam position monitoring (BPM) system is required to detect the beam with a relative accuracy of 100 μm for a position range of ± 5 mm. It must maintain this accuracy during both pulsed and CW operation. It was also required that the system have the capability of distinguishing the position of each of the five beamlets during pulsed operation for machine tune-up. Additionally, a technique to determine the position of the 5 beamlets during CW operation was desired.

The original BPM electronics [1] which were used for commissioning the machine did not have sufficient dynamic range to operate at total currents outside of a range between 10 μA and 100 μA. This four channel system suffers from differing drifts in the gain between the plus and minus channels for each beam axis. Additionally, there are no provisions for detecting multipass beam. The switched electrode electronics beam position monitoring (SEE BPM) system described in this paper overcame problems encountered with the previous BPM system by employing a single amplifier-detector chain for each of the two X and Y channels. Many of the features of the system described in this paper have been used in similar systems developed at other laboratories.[2, 3, 4, 5] The significant feature of this systems is its pulsed multipass detection scheme which is achieved by tuning the SEE timing to match the machine recirculation period of 4.237 μs. This along with operating the machine with 4.2 μs pulsed beam allowed us to resolve the components of a multipass beam. This same type of operation can be used to detect the difference in the beam centroid when an inverse snake (a reduction in beam current for 4.2 μs) is applied to the CW beam.

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SYSTEM REQUIREMENTS AND PERFORMANCE

The design team started with the requirements summarized in table 1. The dynamic range is defined as the range of currents for which the system operates within all other specified limits. At the end of the design phase the performance of the hardware was measured on the bench and to a lesser extent in the machine. The high current end of the dynamic range will be tested on the machine when it is operated at rated currents. Laboratory testing indicates that the lower end of the dynamic range is limited by thermal noise. The high end is limited by signal compression in the electronics. The current dependence, beam position range and rms fluctuation measurements are also based on laboratory measurements which have not been refuted by operating experience.

Table I. Requirement and performance specifications

	Requirement specification	**Performance specification**
Dynamic range	1 - 1000 μA	0.4 - 2000 μA
Nominal measuring rate out of control system	1 meas./s	1 meas./s
Beam position range	|x|, |y| ≤ 5 mm	|x|, |y| ≤ 5 mm
Resolution (rms. fluct. at nominal meas. rate)	≤ 0.1 mm	≤ 0.1 mm
Current dependence	≤ 0.1 mm	≤ 0.1 mm
Multipass capability	some kind	"snake" pulse
Measuring bandwidth	10 – 100 kHz	120 kS/s

SYSTEM DESCRIPTION

The installed linac SEE BPM system consists of six VME crates each controlling seven to ten BPM channels (56 channels total). These crates are located in the service buildings approximately 10 meters above the beam line. Each channel consists of a BPM detector, an RF module located in the tunnel and an IF module located in the VME crate. Each crate has a timing module which is used to synchronize the system to the accelerator and generated specific timing signals required by the IF, RF and data acquisition modules. The VME crate also contains three commercial data acquisition modules and a single board microcomputer which are used to acquire and process the position signals prior to transmitting them to the machine control system.

RF Module

The detector in the system is a four wire stripline antenna system previously described [6]. It is connected to a four-input (X+, Y+, X-, and Y-) two-output (X and Y) RF module, which is located about 1 m off of the beam line axis. The RF module switches between the plus and minus channels; amplifies the signal by 23 dB if necessary; down converts the 1497 MHz RF signals to 45 MHz; and transmits them to the IF module via coaxial cables. The range of input signals for the RF module is –77 dBm to –11 dBm (1 μA to 1 mA, off centered 5 mm). The conversion gain in the high gain mode is 25 ± 0.2 dB and 1.5 ± 1 dB in the low gain mode. The RF module is also capable of injecting a calibration signal of variable amplitude into any of the four electrodes for calibration purposes. Communication with and control of the RF module is done via the IF module using a two way, RS-485 serial link. The TTL level control signals for the attenuator RF switch and the RF boards are produced on the RF logic board which is located in the RF module. To improve radiation hardness of the system, the RF logic board design was implemented using bipolar logic.

The RF switching, amplification, down conversion and IF amplification were implemented on the RF board. A simplified schematic is shown in Figure 2. In this diagram the X+ channel is being switched through a pair of GaAsFET switches (Mini Circuits, YSWA-2-50DR) to the input of an isolator. At the same time the Calibration switch and the X– switch are connected to double the isolation between the channels. From the output of the isolator, that was used to keep the input impe-dance constant throughout the dynamic range, the signal passes through a 75 MHz bandwidth crystal filter which rejects unwanted beam induced harmonics. The filter is followed by a pair of switches which allow one to switch in a pair of 11.5 dB amplifiers (Mini Circuits, MAR-6) that provide gain during low (<100 μA) current operations. The signal is then down converted to 45 MHz, low pass filtered and amplified. The variable gain IF amplifier (Analog Devices, AD603) was adjusted during the module calibration procedure such that the output gain of all of the RF modules provided 25 dB of conversion gain when operated in the high gain mode. The most difficult part of the design was to reduce the VSWR of the input in all modes of operation to a value below 1.2. This was accomplished by using a line transformer which was further tuned during production by adding capacitive stubs to the input traces located between the RF inputs and the first RF switches. This resulted in VSWR values between 1.03 and 1.19 at all RF inputs.

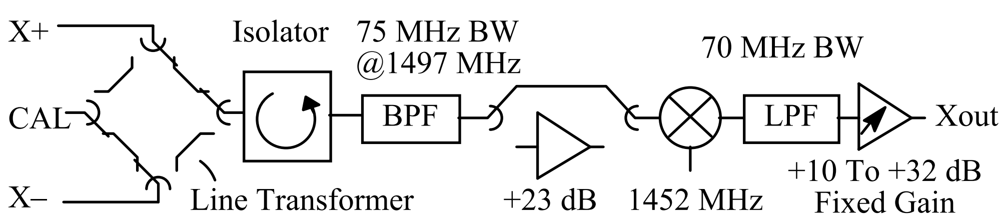

Figure 1. Switched electrode electronics RF chain schematic diagram.

IF Module

The function of the IF module is to amplify the IF signal generated by the RF module and down convert it to a baseband signal that can be digitized with a commercial data acquisition module. A simple schematic drawing is shown in figure 2. The input range of the IF module is -59 dBm to -27 dBm. The first bandpass filter is an LC filter that reduces the broad band noise. It is followed by a pair of variable gain IF amplifiers (AD603) which have 84 dB of dynamic gain control. To further reduce the noise level, the IF bandwidth is limited to 1 MHz using a commercial LC filter. This is followed by a single stage amplifier whose gain is adjusted at the time of calibration. The 45 MHz signal is down converted to base band using a low level video detector (Motorola, MC1330). The base band signal is buffered and filtered by using an 860 kHz low pass filter followed by gated integrating filter which integrates the signal for 2.9 μs of the 4.2 μs cycle time. A sample and hold amplifier maintains the signal level at the end of the integration period while the signal is multiplexed with the signal from the Y channel. This produces a series of X+, Y+, X-, Y- signals which are applied to the input of a commercial, 12-bit, high speed data acquisition module (VMIC-3115).

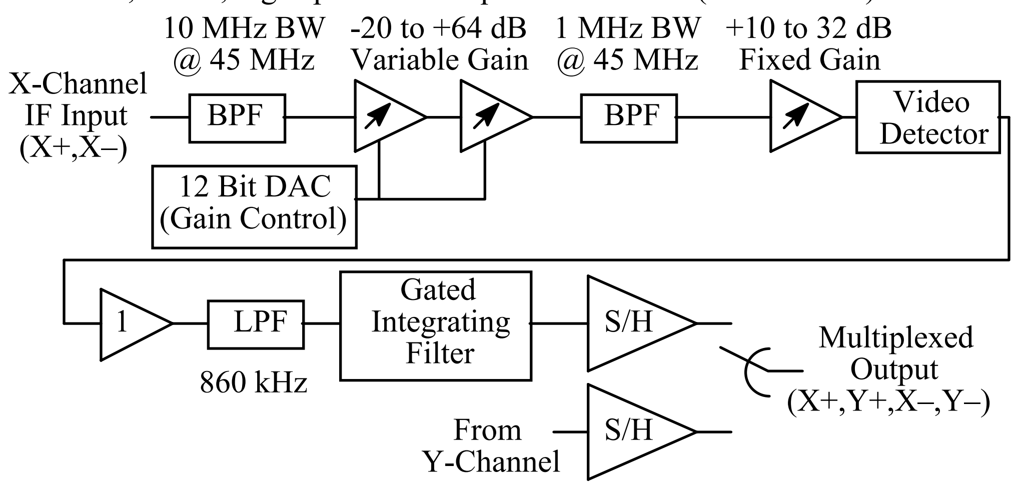

Figure 2. SEE IF module analog chain schematic diagram.

In addition to attention to cross talk and low level noise issues associated with the design and layout of the IF module printed circuit board, there are two subtle details associated with the design of the IF Module. The signal levels at each stage in the IF chain were calculated and the fixed gain IF amplifier was adjusted such that none of the earlier stages saturate prior to reaching the maximum gain. The final critical item was the timing of the gated integrated filter, switch clock, data clock and the multiplexer. Cable transient times and beam delay along the linac (because several channels share the same clock) had to be calculated so that the gated integrating filter was charging only when there was valid data present at the IF module. Additionally, the falling edge of the data clock signal was timed to occur when there were no other digital transitions occurring on the IF card. For this reason, communication between the local VME computer, the timing module, and the IF modules is done using the two bidirectional data ports on one of the VMIC-3115 modules. The advantage of this is that there was control of all of the logical signals on the IF module which insured that the transitions generated by the bussed control, data and address signals did not interfere with the low level 45 MHz signals.

Timing Module

System timing and synchronization is controlled by the timing module which produces the timing signals for all of the IF modules in a given VME crate, the acquisition clock for the data acquisition modules, the delays required for multipass operation and the pulse count per acquisition trigger. The clock on the timing module was selected such that the system operates at the revolution time of the machine (4.237 μs) to within 0.02%. The delay control, which was required for multipass operation, allowed a variable control between 109 ns and 27 μs in 109 ns steps. The timing module is a straight forward digital design implemented with a combination of PLDs and discrete logic.

Operational Software

During normal operations the data is synchronously acquired at a 248 kHz rate and processed locally by a Motorola MV162 single board VME computer (68LC040 based). This computer runs a custom-written data acquisition task under VxWorks, which processes the raw digital data into beam position. This task also implements a digital gain control loop so that the video detectors operate in their linear range. The X and Y beam positions that this task computes are passed to an EPICS [7] network database, which also runs on the local computer. From there, the beam position is made available over ethernet to high level applications and displays that run on Unix host computers.

The low level data acquisition task is also set up to acquire calibration data on demand: without beam, the calibration oscillator is turned on and routed to one of the electrodes, and the output signals from the other axis are recorded as a function of IF amplifier setting. This data is used to determine offset between electrodes, due to VSWR mismatch, cable differences, and detector imbalance. Finally, the system can be used to acquire a trace of beam motion for as much as 68 ms at the full 128 kS/s data rate. In one case, five BPM's in one crate have been simul-taneously sampled in this mode, providing complete characterization of the beam properties (current, x, x', y, y', E) with a measurement bandwidth of 60 kHz.

LABORATORY RESULTS

Figure 3a shows the beam position as a function of beam current, measured under laboratory conditions. The beam was simulated by using a power splitter with a 4.5 dB attenuator inserted in the X+ line. The input power was varied from –100 dBm to –10 dBm; the AGC circuit in the IF module was controlled and the data was acquired using a VMIC-3115 module controlled by a Macintosh computer running LabVIEW®. Approximately 2000 position readings were acquired for each data point on the graphs. The thermal noise and bandwidth of the system limit the low current operation within the specified ± 100 µm to 400 nA in high gain mode and 5 µA in low gain mode where the high and low gain refer to the gain setting in the RF module. Below these values the video detector in the IF module is not capable of reliably locking into the 45 MHz IF signal because of the level of the broad band noise. Figure 3b shows the standard deviation of the position as a function of beam current. This indicates that signal averaging must be employed at currents below 10 µA (high gain) and 100 µA (low gain) to insure reasonable data. At the high current end of the operations the IF module gains saturate at 125 µA and 2.5 mA depending on the gain setting of the RF module.

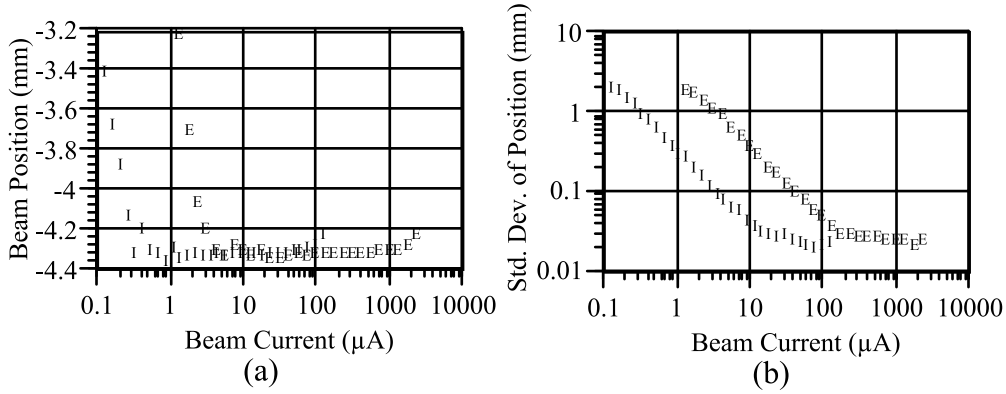

Figure 3. (a) Beam position and (b) standard deviation of beam position as a function of beam current in a laboratory setup which includes a SEE RF module, a SEE IF module and a SEE timing module. An “X” indicates RF module high gain operation and an “O” indicates RF module low gain operation. The data on (b) is position data taken at 124 KS/s.

OPERATIONAL EXPERIENCE

Figure 4 shows the measured beam position as a function of location for seven different currents ranging from 500 nA to 100 µA. These data were taken by varying the current of a single pass beam in the CEBAF accelerator while maintain-ing all other machine parameters fixed. 144 readings were averaged for each point shown. Figure 5, is another representation of the same data. In this figure each data point represents the difference between the recorded values and the average of all the points for which the current exceeded 10 µA at each machine position. With the exception of 1.7 % of the data, the drift of the position as function of beam current is < 100 µm when the beam current is > 1 µA. Additionally, only one data point is > 100 µm from the mean value when the current is > 10 µA.

Two factors contribute to the uncertainty of the measurements with beam. The first is the number of readings taken. For the laboratory measurements, 2000 readings were averaged for each data point. This becomes more important as the beam current decreases below 1 μA where the standard deviation of the position readings is greater than 400 μm. The second factor is the uncertainty of the actual beam position stability during the 1 1/2 hours that it took to ramp the current and

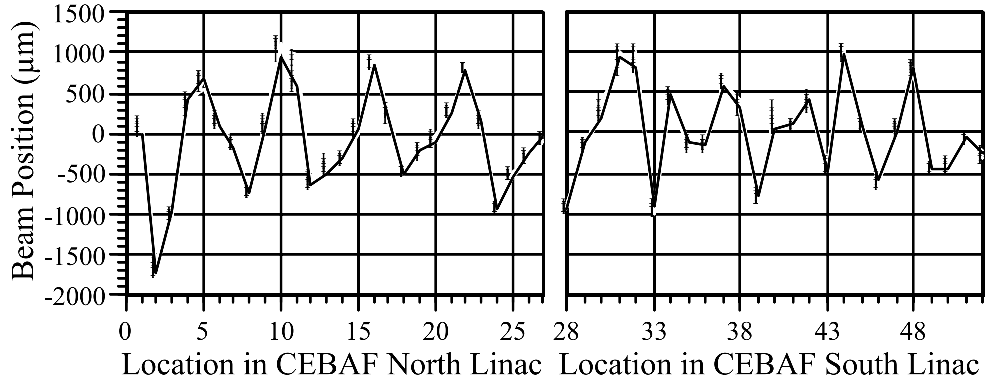

Figure 4. Measured Beam Position as a function of location in the CEBAF linacs for seven different values of beam current between 500 nA and 100 μA.

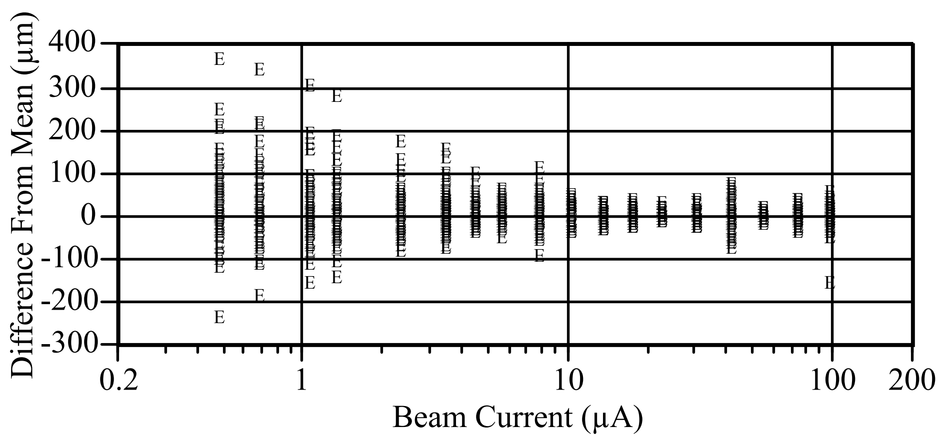

Figure 5. Difference from average of the beam position at each location when the current is > 10 μA as a function of beam current as measured in the CEBAF linacs.

take the measurements. Unfortunately this factor can not be quantified. However, further examination of the data shown figures 4 and 5 indicates that positions 10, 11, 32, 40 and 42 are the only positions in the machine for which the current dependence exceeds ±100 μm when the current is greater than 1 μA. The fact that the worst offenders are grouped geographically tends to indicate beam motion.

During normal operations 5 passes of continuous beam are present in the linacs. One machine parameter that has to be controlled is the re-injection properties of the second and subsequent passes (position and angle). The technique that was developed is known as sending a “snake” around the machine. A beam pulse just shorter than the single pass time for the machine, 4.2 μs, is injected into the machine. A beam synchronization pretrigger is applied to the timing module, and the delays on the SEE BPM system are set such that the beam pulse is captured on each of the five passes without overlap from the previous ones. Each beam pulse is acquired five times as it repeatedly passes through the BPM. Normally the sequence is X1+, X2–, X3+, X4–, X5+ on the first beam pulse followed by X1–, X2+, X3–, X4+, X5– on the subsequent beam pulse, were the number indicates the pass through the accelerator . Thus, data from two successive pulses must be combined before full multipass beam position can be computed. For the SEE system to be operated simultaneously with the 4-channel electronics, installed on the arcs, the actual beam pulse structure consists of a 250 µs pulse followed by a 100 µs pause, followed by a 4.2 µs snake pulse. This is now the normal tune-up mode of operation at CEBAF.

To adjust the delays required for multipass operations, a single pass beam pulse of 4.2 µs is injected into the machine. The delay of each timing module is varied while the outputs of all of the channels in the same VME crate are recorded with the gain control held constant. Figure 6 shows the results of this operation for three of the eight channels in the first VME crate in the machine. Effectively, the charge control signal on the gated integrating filter (2.9 µs) is being convoluted with the beam pulse signal as it arrives at the IF module. The flat top of each of the curves represents the delay time when the integration time occurs coincident with the beam pulse. The difference in the relative position of the flat top is related to the

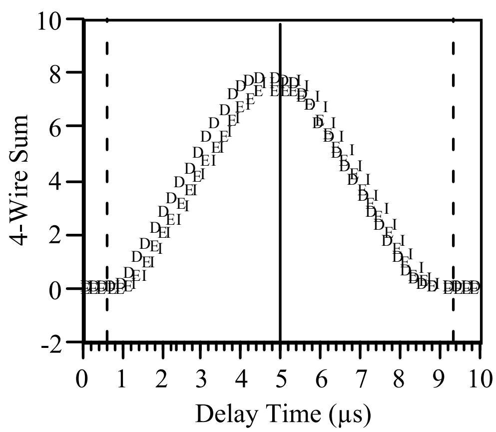

Figure 6. Four-wire sum as a function of delay time for three channels in the same VME crate. The solid line indicates the optimum delay time.

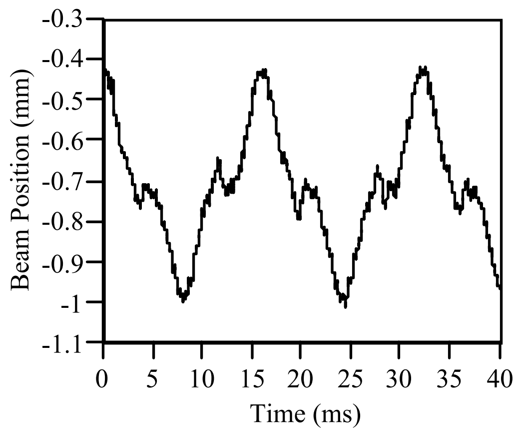

Figure 7. Beam position as a function of time in a dispersive region of the accelerator. The data was filtered using a 20-point running average. [8]

length of the IF module to RF Module cables (30 m to 150 m) and the relative position of the BPM on the beam line. The solid vertical line indicates the optimum delay for that group of channels. The dashed vertical lines indicate the time that next pass beam pulse would be present. Since both the beam pulse and the gated integrator have sharp time-domain cutoffs, cross talk between the passes is kept to a minimum.

Time domain beam position data has been taken using an EPICS based interface. The data shown in figure 7 was taken in a dispersive region of the machine in order to evaluate the need for a beam based fast feedback system. The raw position data, which was acquired at a 124 kHz rate, was filtered using a 20-point running average. The position data represents an energy variation ($\Delta E/E$) of $2X10^{-4}$ with major harmonic content at 60 Hz, 120 Hz and 180 Hz[8]. To reduce this energy fluctuation, a beam based fast feedback system is being implemented with the SEE BPM electronics.

CONCLUSION

The SEE BPM system installed in the linacs at CEBAF has been presented. The system provides ± 100 μm accuracy with a position range of ± 5 mm for currents between 400 nA and 2 mA. Beam tests with currents between 500 nA and 100 μA have been presented; they are consistent with laboratory results. The time domain data which has been presented demonstrates the usefulness of the system for the capturing beam motion with an acquisition rate of 124 kHz. Future enhancements to the system include its use in a beam based fast feedback system, increasing the dynamic range, and the lowering of the minimum specified current to levels below 200 nA.

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