Performance of the CEBAF Arc Beam Position Monitors*

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Abstract

The first three quarters of the first CEBAF arc have been instrumented with beam position monitors. Thirty-seven monitors (of 450) have been installed and their noise measured. Resolution of 100 μm was obtained at the lowest operating current of 1 μA. The update time of the system is 1 sec, limited by computer interfacing, with a potential bandwidth of greater than 10 kHz.

I. INTRODUCTION

The basic requirements for the beam position monitor system are dictated by the properties of the beam. In the accelerator arcs, the range of currents that should be accurately detected is from 1 μA to 200 μA. The beam size in these regions is approximately 100 μm rms. Therefore a system with 100 μm position resolution is appropriate. The BPMs should be useful both in CW mode, the standard operational mode for CEBAF, and in a pulsed low-power tune-up mode in which, for machine safety, the beam pulses are limited to about 100 μsec. The BPMs provide primary signals for feedback stabilization purposes.

A basic schematic of the system is shown in Fig. 1 [1]. Starting on the beam line, the fundamental frequency of the beam is induced on each of four BPM wires and transmitted to a B0005 chassis, better known as the arc tunnel electronics. Here the signal is amplified and down-converted to 1 MHz for transmission to detection circuitry in the service buildings upstairs. Each of the 1 MHz signals from the B0005 box is sent to a separate channel of a B0007 board resident in a CAMAC crate upstairs. In the B0007 board, the amplitude of the 1 MHz signal is detected and digitized. The digitized voltage levels are then conveyed to the computer where the beam position is computed.

If there were no errors in the system, and if $X_\pm$ and $Y_\pm$ were proportional to the amplitude of the beam generated signal on each wire, the beam position before rotation could be calculated as

$$X' = k\frac{X_+ - X_-}{X_+ + X_-},$$

and likewise for Y', where k is the sensitivity of the BPM at 1500 MHz.

Because of errors in the system, two software corrections are made. The first deals with the fact that the amplitude gains in the different channels might be different. The second deals with the offsets that exist in the amplitude detector. The modified computation of the unrotated positions is

$$X' = k\frac{(X_+ - X_{\mathrm{off}+}) - \alpha_X(X_- - X_{\mathrm{off}-})}{(X_+ - X_{\mathrm{off}+}) + \alpha_X(X_- - X_{\mathrm{off}-})},$$

and likewise for Y', where α_X, α_Y, $X_{\mathrm{off}\pm}$, and $Y_{\mathrm{off}\pm}$ are measured by the automatic calibration circuitry as follows:

- Using the zero wires facility in the software, measure the offset voltages $X_{\mathrm{off}\pm}$ and $Y_{\mathrm{off}\pm}$ with both the beam and calibration signal off,
- calibrate the X channels with a calibration signal on y_-, and
- calibrate the Y channels with a calibration signal on x_-.

The word "calibrate" means to find the relative gain ratios α_X and α_Y for the X and Y channels respectively. This is done by measuring the amplitude ratio when the beam is off and the calibration signal is on:

$$\alpha_X = \frac{X_+ - X_{\mathrm{off}+}}{X_- - X_{\mathrm{off}-}},$$

and likewise for α_Y.

The beam position, after rotation by 45°, is

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}\left[\begin{pmatrix} X' \\ Y' \end{pmatrix} - \begin{pmatrix} X'_{\mathrm{off}} \\ Y'_{\mathrm{off}} \end{pmatrix}\right],$$

where the offsets X'_{off} and Y'_{off} are used to save particular orbits as discussed below.

II. HARDWARE DESCRIPTION

A. Mechanical

The beam position monitors that are used in the CEBAF arcs are two models of the same basic design. They consist of four thin-wire quarter-wave pickup antennas, symmetrically placed at the corners of a square that is perpendicular to the beam and centered on the beam axis [2]. The pickups are parallel to the beam. The monitors in the first of the five beam passes must be accommodated to a larger beam pipe than the others, nominally 4.7 cm (the M20 monitor) as compared with 3.5 cm (the M15 monitor). The diameter of the outer shell is fixed by the requirement that the impedance be 200 Ω. Up to the present, most beam tests have been performed with M20 monitors; there is no evidence that the M15 monitors give substantially different results.

The pickup wires are approximately positioned in the manufacturing process. They are then individually positioned with the aid of an optical comparator to within 75 μm. When this process is completed, their electrical response is individually measured with a network analyzer to ensure that it is within acceptable limits. The monitors are

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then cleaned and slow-baked, and finally are leak-tested. If accepted, they are released to be installed on the accelerator beamline. The BPM sensitivity k is measured for every monitor; the values usually are within 1% of 18.5 mm.

B. Electrical

The electronics portion of the arc BPM system is composed of a heterodyne front-end preamplifier located in the tunnel enclosure and a synchronous amplitude detector located in the service buildings.

The front-end B0005 electronics amplifies, and then downconverts each of the four position inputs from 1.5 GHz to 1 MHz. The 1 MHz signals are buffered and sent upstairs to be detected. An oscillator used in the calibration and testing of the BPM system is included in the front-end electronics; it is activated only during the calibration sequence. If both channels are working correctly the relative gain ratio should be approximately 1.

The B0007 detector card includes a programmable gain amplifier, synchronous detector, and analog-to-digital converter on each channel. The detection and conversion may be either internally (CW mode) or externally (pulse mode) triggered, selectable by the operator. The minimum detectable pulse width is governed by the synchronous detector and is on the order of 25 μsec.

The synchronous detector system is used to provide an amplitude-detected signal for each channel. The instantaneous dynamic range of the detected signal is governed by two factors. First, the detector has a minimum threshold below which it cannot phase lock the incoming signal. Second, the detected signal is digitized using an 8-bit analog-to-digital converter which limits the signal range to 256 states. For this reason a programmable gain amplifier is included in the detector front end. The gain, adjustable over a 30 dB range, is set according to the expected value of the operating current of the accelerator.

Because the arc BPM is a linear difference-over-sum system, special attention is given to ensure sufficient dynamic range and signal-to-noise ratio in the preamplifier and detector subsystems. The CEBAF peak beam current ranges from 1 to 200 μA, giving a signal level between -73 and -27 dBm on center. Care is taken to ensure sufficient signal-to-noise ratio through the detector. The front-end preamplifier establishes the system noise figure at approximately 4 dB.

III. SOFTWARE DESCRIPTION

The BPM software system, part of the TACL [3,4] control system, consists of an operator interface and software controls. The interface is comprised of three types of TACL display pages running on console computers. The software controls reside in user functions in TACL logic processed on front-end computers attached to CAMAC crates. Communication between the operator in the control room and the B0007 cards in CAMAC crates in the service buildings is managed by the software system.

The basic software organization is that one BPM user function accesses one B0007 card, but display pages may provide monitor and control capabilities for one or more BPMs. Various BPM operating modes, for example the calibration mode, are requested and monitored by the operator via display pages, and these requests are interpreted and passed by logic to the selected user functions. All signal and position information generated by the user function is calculated using ADC wire data acquired by logic from the B0007 card. Other CAMAC interactions required to initiate and terminate BPM operating modes are handled by the user function. The user function converts and calculates all of the data from the BPMs on the display pages.

The information from the BPM system is displayed in the control room in three ways. Beamline screens are used in daily operations and provide the relative position of the BPM on the beamline, the device name, and the calculated beam position in millimeters or the BPM status. Second, test screens provide the operational controls for the BPMs and display system information such as readbacks for wire signal values, position and wire offsets, calibration constants, and approximate beam current. Finally, "Red October" charts display all of the BPM positions in individual sonar-like displays.

During normal operations the user function converts filtered ADC wire values to positions. The normal mode of filtering collects one set of values at the same cycle rate as logic (3 to 8 Hz) and averages them continuously, giving position data that lag the machine state by 20 sec without degrading overall performance. This lag can be reduced to less than a second at the expense of front-end performance if logic reads the BPM crate many times per logic cycle and provides an averaged ADC value to the BPM user function. This second mode of filtering results in a reduction of overall front-end performance by a factor of three. Such filtering modes can be combined to achieve the best tracking response while minimizing the impact on performance. The normal filter mode can be applied globally to all the BPMs in the machine or can be specified for a subset of BPM modules. The CAMAC averaging scheme is specifically invoked for subsets of BPM modules. Because of the performance cost, it should be reserved for situations where tracking response time is a concern, as with automated optics setup software [5,6].

One of the capabilities of the user function is to define a "golden orbit" or position offset. The BPM electronics pick up noise from neighboring RF cavities and power sources as well as the beam signal, resulting in false or offset position readings. This can be eliminated by establishing an acceptable beam orbit and requesting the user functions to use the current positions as the zero reference. Once these offsets are recorded, they are subtracted from the calculated positions until a new "golden orbit" is defined. Currently, this option is used most with automated orbit correction algorithms which attempt to center positions in the BPMs [5].

During the recent series of pre-commissioning tests, the BPMs were most useful in initial manual beam threading efforts. In the user function the wire currents are summed together, providing an approximate beam current seen by the BPM. By watching the beam current values and the position readback on the test display screens, it is easy to determine whether or not the beam is passing through a specific BPM.

IV. RESULTS

Initial tests of the tunnel electronics uncovered two problems which have subsequently been remedied. The first was that the components selected for the microwave front-end amplifier were not ideally suited for 1497 MHz operation. Second, the tunnel electronics were susceptible to radiated interference from external sources. Both problems were addressed by redesigning the tunnel electronics using surface-mount technology. Initial tests of the redesigned board show measurable improvements in gain, noise immunity, and stability.

In Fig. 2, a graph of beam position as a function of time demonstrates the ability of the monitors to respond to weak currents. The jitter in position is the result of both electronics noise and actual beam motion. It is in any case less than about 0.1 mm rms at 0.5 μA, and is smaller at high currents. For example, at 10 μA (not shown), the jitter is only about one-fourth as large. Whether the beam is diagnosed in CW or pulsed mode, the position fluctuation after averaging is the same.

Thirty seven complete systems were installed and operated simultaneously, extending throughout the spreader and the first three quarters of the east arc. In normal operations, the software provided quick and reliable information, especially when the block reads were successfully implemented. The BPM test screens, through the calibration options, provided especially useful diagnosis of hardware problems.

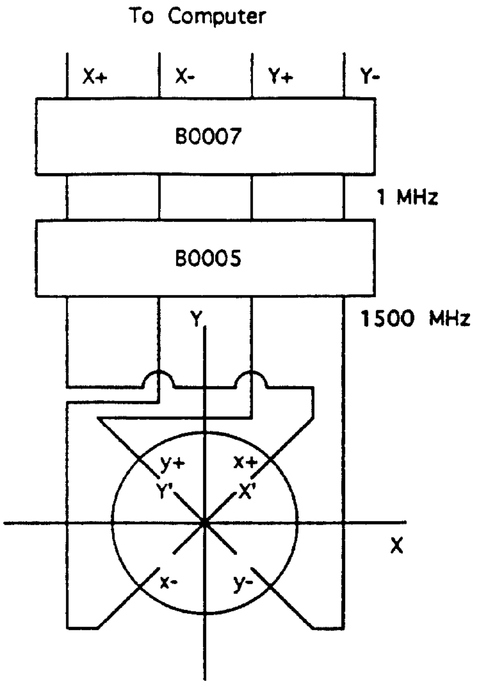

Figure 1. Block diagram of BPM electronics.

V. CONCLUSIONS

The CEBAF arc beam position monitors have been successfully used to diagnose the CEBAF beam in the first spreader and east arc of the CEBAF electron accelerator. The monitors are the only means of steering in a large section of the machine, and this section of the machine was traversed the first time with little additional difficulty. They have operated under a wide dynamic range in addition to the standard tune-up setting of about 10 μA beam current. Experiments reported in several other papers in this conference required functional BPMs. In particular, the automatic steering routines [5], east arc commissioning [6], and the energy correction hardware/software [7] relied on the arc BPMs.

VI. REFERENCES

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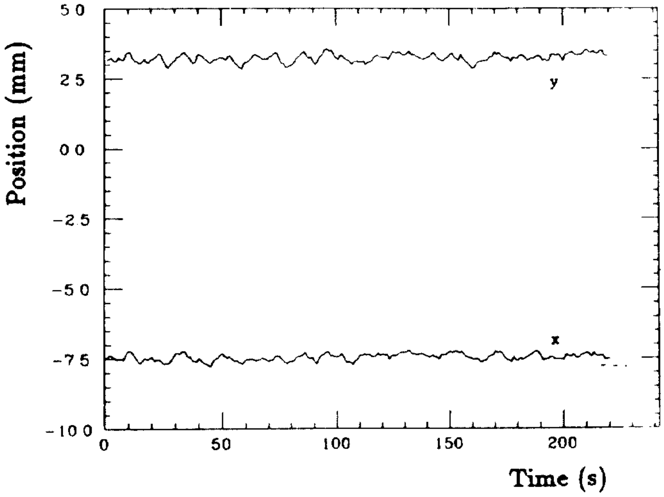

Figure 2. Position seen at 0.5 μA.