Operational Experience with the CEBAF Beam Loss Accounting System†

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Abstract. Continuous Electron Beam Accelerating Facility (CEBAF) is a new generation particle accelerator for basic research in nuclear physics. After a successful commissioning period, we started delivering beam to first experiments in November 1995, with beam availability of better than 70 %. In this paper we present specifications, design and discuss operational experience with the personnel safety and machine protection implementation of CEBAF's beam loss accounting system (BLA). The diagnostics section of this system uses low Q TM_{010} stainless steel cavities as beam current monitors to sample beam current throughout the beam path. The associated RF front end and analog signal conditioning electronics output signals proportional to beam current or beam loss, depending on the implementation. The personnel safety and the machine protection systems then use this current or loss information to turn off the beam when hazardous conditions occur. This system, implemented in its final configuration in January 1996, was developed in one year and is performing to specifications.

INTRODUCTION

In the CEBAF accelerator, superconducting cavities operating at 1497 MHz accelerate electrons to 4 GeV energy in five passes. This unique facility is capable of delivering continuous wave (CW) electron beams with currents that span 1 nA to 200 µA range, energies between 800 MeV to 4 GeV, to facilitate nuclear physics research at the quark level.

An errant beam can produce hazardous amount of radiation in areas where personnel may be present. This is the domain of the Personnel Safety System (PSS). An errant beam with such high power density can also damage the machine components considerably. This is the domain of the Machine Protection System (MPS). CEBAF's Beam Loss Accounting system provides protection in these two domains.

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† Supported by DOE Contract #DE-AC05-84ER40150

Personnel Safety Specifications

The PSS protects people from exposure to prompt beam-induced radiation [1]. During normal operations, the PSS issues an active permission signal, which is a 625 kHz square wave. When a fault occurs, the PSS withdraws the permission, causing the removal of the beam at the electron gun. As a second level protection, kicker magnets deflect any beam to a water cooled aperture on PSS faults. Figure 1 shows the location of the Beam Current Monitors (BCMs) assigned to the PSS. These BCMs serve the following functions:

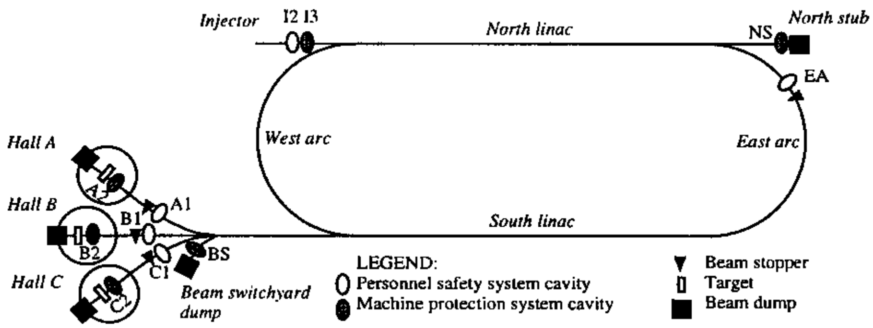

FIGURE 1. BCM cavities location along the CEBAF beamline.

1. Beam stoppers near the entrance to the experimental halls protect personnel from the beam during access to the experimental areas. When the stoppers are in place, de-energized magnets prevent the beam from going in their direction. Should this safety feature fail, it is conceivable that a beam of high power density may tunnel through the stoppers. The BCMs (EA, A1, B1 and C1) protect the stoppers by causing the termination of the beam when they detect a beam current greater than 1 μA.
2. CEBAF's contractual requirement imposes an operational limit on the beam current. The BCM (I2) ensures that the beam current in the injector does not exceed 190 μA. Hall B BCM (B1) sets a 1 μA limit to prevent the possibility of errant beam going up towards the counting house.

Machine Protection Specifications

The MPS protects the accelerator and end station equipment from beam related damage. During normal operations, the MPS issues an active permission signal, which is a 5 MHz square wave. When a fault occurs, the MPS withdraws the permission, causing the removal of the beam. Figure 1 shows the locations of the BCMs for machine protection. The BLA system performs the following functions.

1. The BLA system limits the beam current in the injector to 180 μA. This ensures that the MPS will trip before the PSS in all cases.
2. If i(I3), i(NS),.., represent the beam current values in BCMs at I3, NS,..., the BLA system calculates the beam loss by computing i(I3)-i(NS)-i(BS)-i(A2)-i(B2)-i(C2). If this CW loss exceeds 2.5 μA, the system will terminate the beam.

3. In case of an instantaneous beam loss, the BLA system will terminate the beam such that the integrated beam loss does not exceed 25000 μA-μs.[2,3].

DESIGN OVERVIEW

The Cavity

The BCM is a stainless steel pill box cavity with an intrinsic Q of 3100, operates in the TM_{010} mode at 1497 MHz (Fig. 2). This cavity has a larger bandwidth and a better temperature stability than a copper or other high Q cavity. A micrometer stub tuner adjusts the resonant frequency of the cavity.

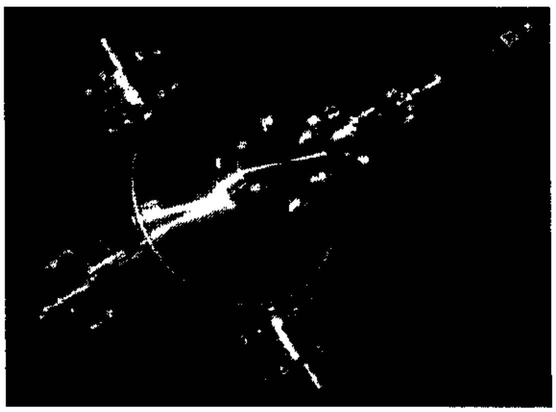

FIGURE 2. a. The CEBAF beam current monitor pill box cavity, three port configuration.

Table I. Cavity specifications

Mode	TM 010
Frequency	1497 MHz
Q_0	3100
R/Q (cavity center)	93 Ω *
Cavity Radius	7.74 cm
Cavity Length	7.50 cm
Beam Pipe Radius	1.75 cm
Material	304 Stainless Steel

* $R=V^2/2P$

The cavities in the MPS system have two couplers per cavity, whereas the cavities in the PSS system have three couplers per cavity. The three coupler cavity provides a redundant output channel, which is a PSS requirement. Magnetic field loops situated around the cavity accomplish the coupling in and out of the cavity. The loops mount on a 2.75" rotatable conflat flanges.

In the MPS cavity, port 1 has the large area loop and port 2 has the small area test loop. Rotating the large area loop facilitates critical coupling and the resulting loaded cavity Q is approximately 1550. Adjustment of the small area test loop sets the insertion loss between the two ports to 13.5 dB.

In the PSS cavity, ports 1 and 2 have the large area loops and port 2 has the small area test loop. By carefully adjusting the large area loops, it is possible to make the two loops identically undercoupled, while the combination results in critical coupling and a loaded cavity Q of 1550.

Standard Electronic Modules

The 'standard' electronic modules are the downconverter, a test source, RMS to DC converter, an equalizer and an integrator. Figure 3 shows the 'standard' configuration.

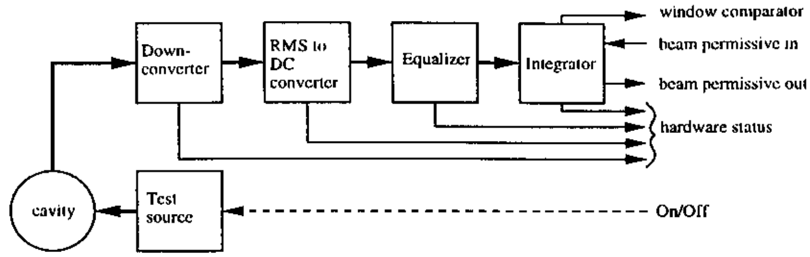

FIGURE 3. Standard modules and their configuration.

The downconverter shifts the 1497 MHz spectral component of the cavities to 1 MHz. The downconverters and the 1497 MHz test source reside near the cavity in the accelerator tunnel. Such proximity minimizes cable attenuation drifts due to temperature variation. Low loss 10m long 0.5" Heliax cables connect the cavity to the downconverter and the test source. The same type of cable connects the downconverter to the electronics in the service buildings.

An RMS to DC converter converts the bandpass filtered 1 MHz signal to a baseband signal. This module uses the AD637 RMS to DC converter IC [4], which has excellent linearity and temperature stability.

An equalizer module compensates differences in cable losses. The output of the equalizer scales with the beam current.

All the above modules, except the equalizer, are calibratable in the laboratory and interchangeable with the same type in the field. The equalizer is specific to each BCM and its calibration is *in situ*.

The integrator monitors the average beam current or beam loss. When the beam current or beam loss exceeds a preset threshold, the integrator withdraws the permissions.

All modules conform to 3U eurocard standard. The interconnection among modules is through the back plane. Blindmate snap-on RF connectors carry the 1497 MHz signals, while 96-pin DIN connectors carry the baseband and digital signals. Keyed connectors on the modules and the backplane prevent insertion of the modules in the wrong place. Each module in the system is also equipped with a supervisory circuit to ensure safe operation. Upon detecting an error in its operation, a module will generate a fault signal, which prevents beam from leaving the injector.

Implementation of the PSS Part of the BLA System

The PSS part of the BLA system consists of 4 cavities at the beam stoppers and 1 cavity in the injector. The large area coupler connects to a downconverter. Figure 4 shows the PSS logic. The PSS permission from the electronics associated with the BCMs at EA, A1, B1 and C1 go to the injector. At the injector, these permission pass through logic associated with the BCM I2. The latter limit the beam current to 190 μA. For the stopper BCMs two modes of operation exist; one with beam stopper in place and the other without the stopper. For a given mode, faults occur if the beam current in any stopper BCM exceeds 1 μA when the beam stopper is in place. Occurrence of a fault results in the PSS permission going inactive and consequently in the removal of the beam.

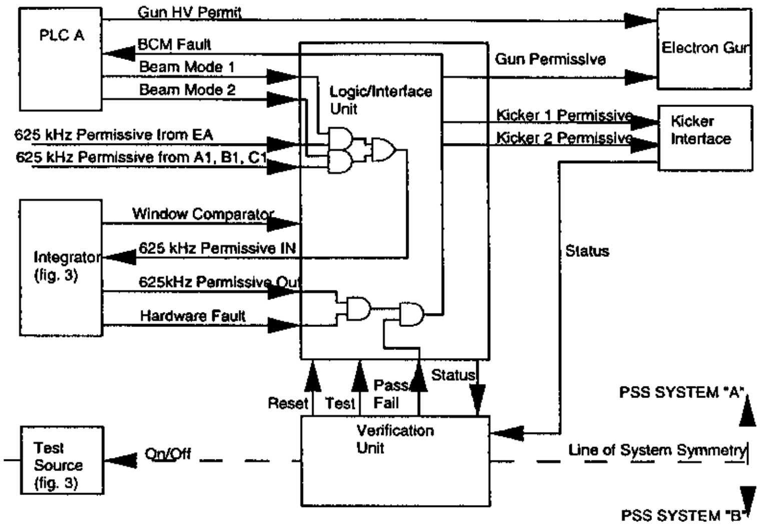

FIGURE 4. PSS BCM implementation block diagram.

The BLA system for the PSS also contains a verification unit, which is a time sequencing state machine. Through the control system interface to the verification unit, the operators can test the BLA system and remotely reset any BCM fault.

Implementation of the MPS Part of the BLA System

The MPS part of the BLA system consists of 6 cavities. The small area coupler connects to the test source and the large area coupler connects to a downconverter. Cables carry the signals from the downconverters to the beam switch yard service building (figure 5).

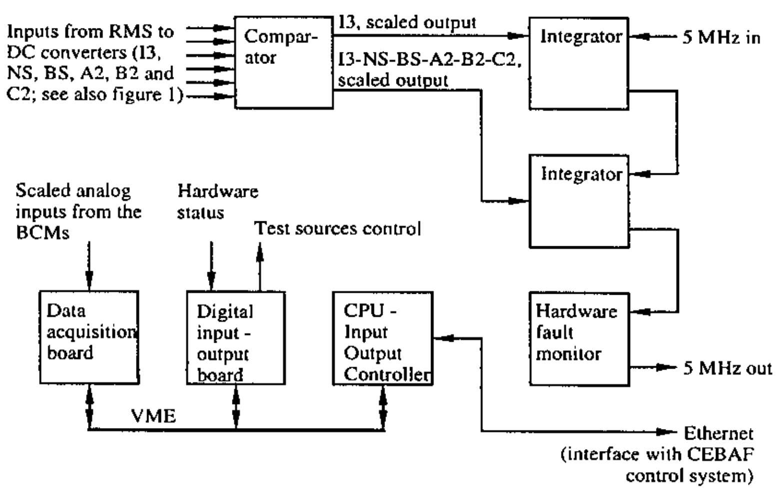

FIGURE 5. MPS BCM implementation block diagram.

RMS to DC converters process the signals. The MPS implementation requires a slight modification to the standard configuration of figure 3. This modification results in a comparator board that consists of 6 equalizers and a circuit that calculates the difference between the injector signal and the sum of the other 5 BCM signals. The comparator board has two outputs, each of which goes to an integrator. One output is for the case the beam current in the injector exceeds 180 μA. The other is for the case the average beam loss exceeds 2.5 μA or the instantaneous beam loss (above 2.5 μA) exceeds 5000 μA-μs. Both outputs force the integrators to withdraw MPS permissions.

A 1 inch thick layer of thermal insulation around the cavities along with heating tapes, thermocouples, and controllers maintain their temperature at 110 °F. This minimizes frequency de-tuning due to ambient temperature change.

The MPS BLA software continuously monitors the current readings, identifies failed hardware devices and permits system testing and verification. The user interface consists of two components. The overview screen is a diagram of the accelerator with bar charts and readbacks showing the current reading on each BCM. Operators use this screen during normal operation of the machine. Additional information, namely, the hardware status readbacks are available on the expert screen.

CALIBRATION METHOD

Calibration of the BLA system was a two step process. The first step was to tune the cavities using a network analyzer. The second step was to calibrate the system. At the cavity end of the cable, (where the cavity connects to the downconverter), we connected a 1497 MHz source of a known signal level. We then adjusted the DC signal level at the equalizer (PSS System) or the comparator (MPS System) to obtain an output that scales with the beam current.

PERFORMANCE

The BLA began operation in January 1996. One of the conditions to extend the contractual requirement of CEBAF's operational envelope from 120 kW to 800 kW was to demonstrate the reliability of the BLA system under normal operations. An independent panel of experts tested and verified the PSS system. Following is the summary of the operational experience during the first three months.

PSS System

We verified all the system requirements during acceptance testing. A Faraday cup in the injector provided a reference for absolute current measurement. Initial calibration showed an average of 13 % difference between PSS BCMs and the Faraday cup measurements. After calibrating the injector PSS BCM with the beam, we investigated the cause of the discrepancy. Since we did not consider VSWR mismatch between the cavity ports and the 50 Ω transmission system during our calculations, we hypothesized that this mismatch was the source of the error. If this hypothesis is correct, then this error should be common to all PSS

BCMs. In order to test this idea we applied to all PSS BCMs, the same amount of gain offset applied to the injector BCM. With these corrections, the measured maximum absolute error between the Faraday cup and the BCMs was <1 %.

MPS System

Calibration of MPS cavities showed an average of 7 % difference with respect to the Faraday cup measurements. Relative accuracy, or match, between the injector and the end station BCMs is very important characteristic of the MPS part of the BLA system. In this regard, reproducibility of the calibration results is the key issue. First calibration failed due to yet unknown problem; the hall C BCM was off by 15 %. In the second attempt we obtained a relative accuracy between the injector BCM and the three end station BCMs that was better than 1.5 %. We believe that this is the maximum relative accuracy that one can obtain following the above described calibration method. However, in order to reliably operate the MPS system above 100 μA, the relative accuracy must be less than 1 %. The design team is currently evaluating an option to use the beam to "fine" calibrate the MPS BCMs, after a "coarse" calibration with the above procedure. Unfortunately, this method demands the confidence that we have 100 % transmission between the injector BCM and the BCM under calibration.

The first two months of operational experience gave us an opportunity to estimate the long term stability of the system. We used two methods to evaluate this. The first one relied on the operator performed weekly confidence tests. The operator turned on a test source associated with each cavity and measured the response. The disadvantage of this method is that any drift in the test source output appears as a drift in the BCM response. The purpose of this test is not to calibrate the system, but to verify that the BCM's response was within 5 % of the expected performance. The second method uses archived data for CW beam runs and compares readings from different BCMs. The uncertainty associated with this method is that we are never sure if we have 100 % transmission between the BCMs which response we want to compare.

TABLE II. Long-term stability data for the period March 13 to April 29, 1996.

Parameter	Drift	Method
Off-set (no-beam) drift	±0.1 μA	Beam off, test source off
PSS BCMs	±1.5 %	Regular tests using a test source
MPS BCMs	±1 %	Regular tests using a test source
MPS BCMs relative to each other	±0.7 %	CW beam

Analog signals proportional to beam current and loss are available in the control room. This diagnostic feature of the system proved to be very useful. Figure 6 shows waveforms for a typical operation of the system.

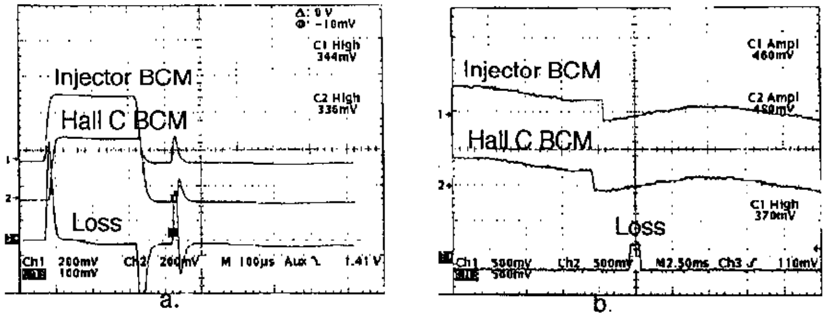

FIGURE 6. a. Machine operators use 250 μs long pulses to tune the machine. Spikes on the loss signal are due to delay between the BCM readings. The little pulse following the 250 μs one is a modulation pulse for multipass BPMs. **b.** MPS BLA detected loss and removed the beam at the gun. The injector and hall C BCM signals pick up 60 Hz noise on their way from the electronics to the control room (500 m). Transmission of the loss signal over commercial off-the-shelf AD-serial link-DA device is the reason for the absence of the 60 Hz noise on this signal. Scaling factor is 40 μA/V.

CONCLUSION

Both the PSS and MPS implementations of the beam loss accounting have met the performance goals required to safely operate the CEBAF accelerator and end stations at full design current. In addition, first few months of operational experience demonstrate that the system is reproducible and stable, and that it provides a useful diagnostic tool to machine operators.

ACKNOWLEDGMENTS

Many people helped shape this unique product. Realization of this complex system, within just one year, would not have been possible without the help from many persons. We thank T. Grummel, B. Smith and J. Coleman for technical support; J. Mammoser and D. Ouimette for valuable technical input during the review and acceptance phase; H. Areti for valuable input during the development phase of this project; machine operators for excellent support and feedback, during the implementation phase.

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