The CEBAF Beam Loss Sensors*

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Abstract

The CEBAF beam can burn through the vacuum wall in approximately 100 μs. We have developed an inexpensive beam loss sensor that will unambiguously detect a true beam loss and shut off the beam within this time without tripping on moderate interference from other sources. We have incorporated a full system test into the system, with provision for direct replacement of faulty sensors without adjustment.

We describe the sensors, the signal processing design, system test results, and characterization procedures.

I. INTRODUCTION

The CEBAF beam will carry 200 μA of current in its 100 μm diameter, enough to burn through the accelerator vacuum wall in time of the order of 100 μs [1, 2]. The beam loss monitors (BLM's), as the last resort for protection of the accelerator, must operate much faster than this time to allow time for the fast shutdown system [3] to shut the beam off before damage occurs. The time scale allocated to the BLM system is 10 μs. The size of the CEBAF accelerator (7/8 mile circumference) means either that many BLM's must be installed or that each must protect a large area.

II. SENSORS

The speed requirement ruled out most ion chamber configurations quite early in the process. Although several labs have designed ion chambers to operate in this time range, we felt that photosensitive devices offered a more likely direction for highly sensitive, low-cost beam loss sensing. Geoffrey Stapleton presented the possibility of darkened photomultipliers, which were known to be sensitive to cosmic ray pulses. The mechanism is scintillation and Cherenkov radiation in the glass envelope of the tube [4, 5], and extension to beam loss monitoring by detection of the radiation shower from beam interaction with nearby matter was highly successful.

Extensive testing showed that for beam loss monitoring one of the least expensive photomultipliers, the venerable 931B, was preferable, as it is among the highest in electron gain available. Since we did not need the features which make photomultipliers expensive, such as transparent or high-efficiency photocathodes, or large size, we selected this tube as the basis of our sensor.

The variation of tube gain with cathode voltage is convenient because it allows us to shift the detection range (discussed later) to suit various conditions. The disadvantage is that the high-voltage system hardware that we selected cost more than all the rest of the hardware together. We are investigating alternative high-voltage supplies for the needed expansion of the system as the rest of the accelerator comes on line.

The tubes are built into a housing made of ABS plastic, which has proved to be a consistently effective, inexpensive light barrier which does not impose much shielding even from lower-energy x-rays. Electrical interference is occasionally present when we must route the cabling near a fluorescent lamp, but even here we lose at most only the lowest decade (5 nA–50 nA) of the system's signal.

Since an undetected beam loss event could cause burn through of a cavity costing several hundred thousand dollars to repair reliability is a critical consideration. We incorporated into the control module [6] a test command signal which drives a light-emitting diode in the sensor. This tests the entire beam loss channel from high-voltage supply through the sensor and signal conditioning to the fault detect circuit.

The LED's within the sensor heads are calibrated precisely against reference tubes; then each tube to be used as a BLM is checked for current output at a specific cathode voltage when it is installed into the sensor head (figure 1). The light generates a current corresponding to about 80% of the four decade logarithmic scale (10% of the equivalent linear scale) of the sensor. This is well within the normal operating range of the sensors.

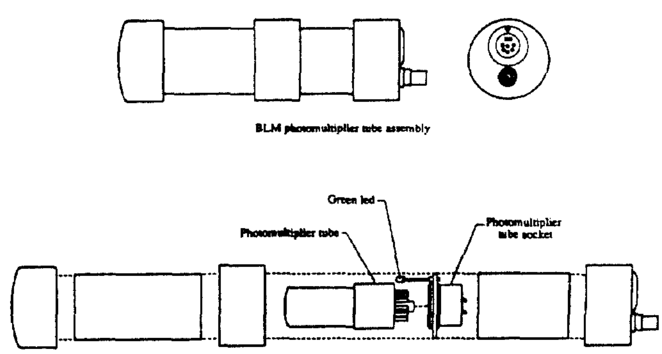

Figure 1. BLM Sensor

In extensive testing we found the best location to be well away from the beam line, since shielding by the many magnets of the CEBAF beam transport system is worst near the beamline. This gives the further benefit of reducing activation of the metallic parts of the sensor (discussed later). In the accelerator segments we attach the sensors to the cable tray, approximately five feet above the beam line, and in the recirculation arcs we attach them to the ceiling about eight feet to one side of the beam lines.

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III. SIGNAL PROCESSING

Since the photomultiplier is a very low noise device under normal conditions, and the radiation environment at CEBAF during normal running is rather low, the large dynamic range available from the tube (<5 nA to >100 μA) gave us the possibility of using the full range of the tube to survey a much larger area of the accelerator than is reasonably possible with linear signal conditioning. For this reason, we incorporated logarithmic signal conditioning, using $V_{\text{out}} = k \log (I_{\text{in}})$ to measure the radiation level signal.

The log converter was designed as a dual converter followed by a differential amplifier (figure 2). The first converter is biased at 5 nA, the maximum dark current (specified at 1000 V) for the 931B, and converts to voltage the input current from the tube plus the 5 nA bias. The second converter has a variable bias to allow us to offset the baseline output and thermal drifts of the first converter. The log conversion elements (the base-emitter junction of a high-gain, low-noise transistor) are thermally connected so that thermal drifts are well compensated.

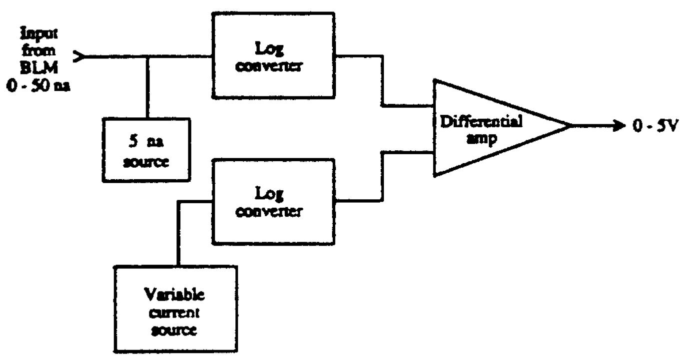

Figure 2. Signal Conditioner Block Diagram

Finally, the differential amplifier shifts the difference between the two converter outputs to a zero baseline, and amplifies the output to scale four decades of current (5 nA–50 μA) to the 0–5 V level for the fault detect and data acquisition circuitry. The output amplifier is slowed to a 4 μs rise time to avoid triggering on the short pulses characteristic of cosmic radiation.

IV. EXPERIENCE

In setting up the BLM's for operation, we set up the beam for 1 μA beam current in a 100 μsec wide pulse; this was deemed a completely safe condition for a beam driven directly into any component of the accelerator. We then drove the beam out of the beam line in all directions at many locations, concentrating on locations and angles our operations experts considered likely and/or particularly sensitive targets of errant beam. We set the cathode voltage and trip levels for reliable trip on the smallest signals found.

We tried first for fully redundant coverage of the accelerator. This proved to be impossible in some areas of the accelerator with the present density of BLM's. Where it was not possible, we tried for full coverage, and succeeded in all areas except the injector: here, we are forced to depend upon a correctly set up beam passing through protected locations before it can arrive at an unprotected location. This is generally considered a safe assumption.

The BLM's were initially attached to the beam line. Early tests showed two problems: first, local beam loss completely saturated the sensors even with very low cathode voltages of 100 V, and second, distant loss events were completely shielded by the many magnets and other equipment in the transport system. We could not fully protect the cryomodules with their expensive superconducting cavities.

We solved these problems by moving the sensors well away from the beam line as described above. Experience has shown that CEBAF's running radiation levels are below the threshold of the BLM system's detection; we could therefore take advantage of the property of a true loss event which generates a long pointed ellipsoid of high-level radiation downstream of the loss event. Since the log conditioners allow us to work effectively with the full range of the photomultipliers, we are able to detect the lower signal levels characteristic of distant beam loss events and still not damage the tubes with overloading due to strong local loss signals. Figure 3 shows a plot of the signal versus angle of loss at a BLM in the vicinity of an accelerator cryomodule.

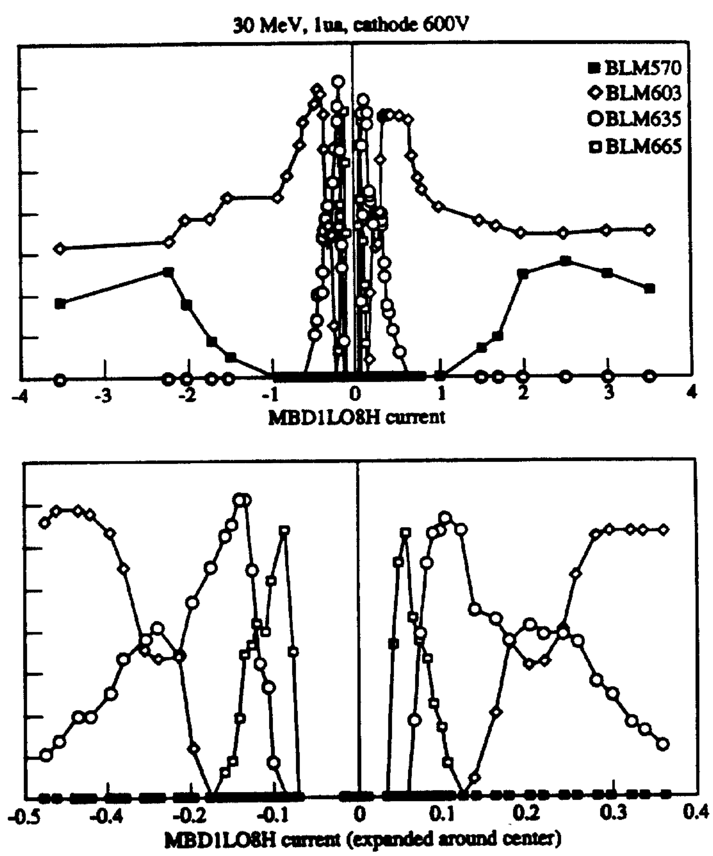

Figure 3. Beam Loss Signal vs. Corrector Magnet Current

The upper plot shows the reduction of signal level as the beam is directed at very large angles away from the beam line and the sensors. BLM 570 is actually upstream of the magnet being tested: in this 30 MeV test, one may observe that there is rather little backscatter.

The lower plot is expanded around the center of the upper plot. BLM #665 is 30 M downstream and one can see that it is effective for very small angles of loss, where the beam is lost far downstream of the disturbing magnet. BLM #635 is the next nearer BLM. Note that both BLM #635 and BLM #603 show the effect of magnet shielding at +0.2A and -0.3A. Note also that sensing overlaps from one sensor to the next at approximately midscale, which corresponds to 1% of an equivalent linear full scale. It would be impossible to protect the accelerator fully with linear signal conditioning.

Later tests showed an increasing pulse noise at the lower end of the sensors' range which limited sensitivity for higher voltages. This noise has been of concern since it was first noticed in late 1992. The photomultipliers were originally of very low noise, showing few pulses above the 15 nA level. The 70 that were in the accelerator have shown increasing spurious pulse levels up to 400 na that required that they be moved to the higher-energy sections of the accelerator and replaced with new tubes for the lower-energy sections.

It is not yet clear whether the pulse noise derives from activation of the tubes or from helium contamination due to residual helium in the accelerator tunnel. For several months, they were attached to the beam line, and subject to direct irradiation from errant beam. Further, our superconducting accelerator requires great quantities of helium for its operation, and a certain amount of that helium is always present in the tunnel atmosphere. Helium is suspect because it diffuses into the tube through the glass envelope, corrupting the vacuum.

We are testing a number of tubes for both possibilities. We have already determined that after the sensors were moved away from the beam line in February 1993 they generally showed a marked decrease in spurious pulse level and frequency; this argues for radioactive interference from the metallic elements of the photomultiplier tube. We have in fact confirmed that the worst offenders are contaminated with ^{57}Co and ^{58}Co, among other radioactive isotopes. We are having a set of the tubes tested for helium contamination.

V. CONCLUSIONS

In the accelerator the BLM sensors have so far performed adequately. They reliably detect beam loss at distances exceeding 20 m when energy is above 100 MeV at 1 μA current; at reduced energy (i.e., reduced beam loss radiation power level), pulse noise from the photomultipliers causes spurious trips if the tubes are not selected for low pulse noise. Recent tests show a diminution of this pulse noise that augurs well for the future when BLM's are placed away from the beam line.

At the low energies of the injector, the present BLM's are inadequate: careful selection of photomultipliers and placement of sensor assemblies are required to get even partial coverage of critical locations. We are actively exploring methods of completing the coverage of the injector.

The concept of using darkened photomultipliers has proved to be an inexpensive, effective method of detecting beam loss in the higher-energy segments of the CEBAF accelerator.

III. REFERENCES

[1] P. K. Kloeppel, "On the Temperature Effects of High Current, Low Emittance Beams," CEBAF-TN-85-018, Nov. 1985.

[2] C. K. Sinclair, "Time Response Requirement for the BLM/FSD System," CEBAF-TN-92-046, Oct. 1992.

[3] J. Perry, E. Woodworth, "The CEBAF Fast Shutdown System," CEBAF-PR-90-015, or, *Proceedings of 1990 Linac Conference*, p. 484, Sept. 1990.

[4] A. T. Young, "Cosmic Ray Induced Dark Current in Photomultipliers," *Review of Scientific Instruments* **37**, p. 1472, Nov. 1966.

[5] S. N. Makeev *et al.*, "Variation of Photomultiplier Anode Current for Continuous and Pulsed Gamma Radiation," transl. in *Instrum. & Exp. Tech.* (USA), Vol. 29, No. 1, pt. 2, Jan.–Feb. 1985, pp. 182–185.

[6] J. Perry, E. Woodworth, "The Beam Loss Monitors at CEBAF," CEBAF-PR-90-022, October 1990, or, *Proceedings of the Second Annual Accelerator Instrumentation Workshop, p. 294, October 1990*