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Implementation of Beam-Loss Monitor Systems for the SSC

R. G. Johnson

Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave.
Dallas, TX 75237 USA

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Abstract

Beam-Loss Monitors (BLM) are used with each accelerator in the Superconducting Super Collider complex. The primary purpose of these detectors is to protect the accelerators from damage due to the loss of protons. Although the range of primary beam energies to be covered is very large, 20 MeV to 20 TeV, we plan to maintain commonality of detectors and electronics as much as possible. In this report the plans for developing and implementing BLM systems for each of the accelerators will be discussed. Possible solutions to problems that have been identified are presented..

1.0 INTRODUCTION

The conceptual design of the Superconducting Super Collider (SSC) includes beam loss monitors (BLMs) for all the accelerators in the chain.¹ In Table 1 some of the parameters of the SSC accelerators, including the number of BLMs, are listed. As can be inferred from this table the BLM subsystem must encompass a large range of primary proton energies and as is the case for many systems in the SSC the sheer numbers are daunting.

The primary purpose of the BLM system is to protect equipment from damage due to loss of protons from the beam. This is especially critical for the superconducting machines (HEB and collider rings) where excessive losses may induce magnet quenches. Although the magnets are designed to handle quenches, operation will be severely affected. Higher beam loss can induce excessive residual radioactivity, produce immediate damage from heating, and produce long-term damage from radiation.

Secondarily, the BLMs can be used as an aid in tuning the accelerators. The BLMs produce information complementary to that of the beam-position monitors (BPM). The BLMs are sensitive to the beam periphery while the BPMs are sensitive to the beam centroid. Consequently, the BLMs may provide the first indication of large emittance growth, a large beam halo, mistuning of focusing elements, *etc.*

In the remaining sections of this report the requirements set for the BLM system will be discussed; and elements of a system satisfying these requirements will be presented. Much of the discussion will be centered on the lowest and the highest energies, *i.e.*, on the Linac where a BLM system must be installed first and on the collider rings where the requirements on the BLM system are the most stringent. In the areas where options are still open those options will be identified and the steps being taken to choose a single solution will be stated.

In general, instrumentation for all the accelerators has undergone a Physics Design Requirements Review. Consequently the requirements for the BLM systems are relatively well established.

Table 1. SSCL Accelerator Parameters.

Parameter	Linac	LEB	MEB	HEB	Collider
Injection Energy	35 keV	600 MeV	11.1 GeV	200 GeV	2 TeV
Extraction Energy	600 MeV	11.1 GeV	200 GeV	2 TeV	20 TeV
Circumference - Length	148.2 m	570 m	3.960 km	10.80 km	87.12 km
Harmonic Number	—	114	792	2160	17 424 x 6
Particles/Bunch*	—	$1 - 5 \times 10^{10}$	$1 - 5 \times 10^{10}$	$1 - 5 \times 10^{10}$	0.75×10^{10}
Total Particles*	—	$1 - 5 \times 10^{12}$	$0.8 - 4 \times 10^{13}$	$0.2 - 1 \times 10^{14}$	1.3×10^{14}
Rotation Time	—	2.3 - 1.8 μ s	13.2 μ s	36.0 μ s	290 μ s
Cycle Time*	0.1 s	0.1 s	3 - 4 s	4.3 min	—
Mono - Bipolar	—	Mono	Mono	Bi	2 Rings
Superconducting -Normal	Normal	Normal	Normal	SC	SC
Peak Field	—	1.2 T	1.7 T	6.7 T	6.6 T
No. of BLMs	32	90+	206+	636+	1936+

* Collider - test beam operation.

2.0 GENERAL REQUIREMENTS

Since there are over 2500 BLMs spread over a linear distance of over 100 km, the BLMs and their electronics must require little or no maintenance. The expected life of the detectors should be at or beyond the expected lifetime of the accelerators, 25 years. Any calibrations should be implemented through the control system. The detectors and electronics should perform diagnostics automatically on power up and continuously keep track of critical parameters. The ability to remotely mask out of the system any detector that is not working properly should be provided.

The BLM system performs a vital function for the accelerators and thus its reliability must be very high. As pointed out in the previous paragraph the detectors should require little maintenance and have a long life expectancy. However detectors will breakdown. In this regard the possibility of placing detectors in the cryostat has been rejected because it would decrease reliability and make replacement of defective detectors very difficult. Also, if the detectors are placed outside the cryostat, they can be easily repositioned.

An additional method of insuring system reliability is to provide redundancy. Where a detector performs a critical function a backup (with perhaps reduced effectiveness) should be available.

3.0 DETECTOR

The prototypical detector used in the conceptual design study was the gas ionization chamber² developed for the Fermi National Accelerator Laboratory (FNAL) Tevatron and used extensively for the other accelerators at FNAL. Details of the detector are presented in Table 2 and shown in Figure 1. This detector has many desirable properties for the application as a BLM. It is compact and rugged, requires little or no maintenance, has a predictable response with small sensitivity to variations in high voltage, has very low leakage current, and is relatively inexpensive. However, this detector has a rather low sensitivity that may not be adequate for all the accelerators.

Table 2. Parameters of the FNAL Ionization Chamber.

Parameter	Value
Construction	Sealed Glass
Volume	110 cm ³
Gas Fill	100% Argon
Pressure	725 torr
Electrodes	Nickel
Leakage Current	< 100 fA
Response	70 nC/rad
Risetime	< 10 μ s
Minimum Response	1.0 mrad; 10 mrad/s

TIP-05881

Figure 1. FNAL Ionization Chamber.

At FNAL the gas ionization detectors are used successfully in the booster, the p -bar rings, and the main ring in addition to the Tevatron. This experience indicates that the same detectors or very nearly the same detectors could be used from ~ 100 MeV in the Linac through the Low Energy Booster (LEB) and Medium Energy Booster (MEB) accelerators.

One of the principal design objectives for the Tevatron gas ionization chamber was longevity; hence the use of a glass envelope, Ni electrodes, pure A gas, and careful cleaning (specified in the construction documents).³ Operational experience at FNAL has confirmed that this objective has been met.⁴ The detector was also designed to minimize the leakage current.

Although the detector met its design goals, it has only moderate sensitivity, *i.e.*, 70 nC/rad. With the electronics used with the detector, the lower limits to the response are a factor of 100 less sensitive than that required for the SSC superconducting magnets. In order to increase the sensitivity, several possibilities are being considered.

The first set of options involves modification to the detector and electronics. An increase in volume and/or pressure combined with minor improvement in the electronics could provide the required sensitivity. Alternately, the detector could be modified to operate in the proportional region. However, it is more difficult to design a proportional counter that has the required longevity.

A second option is to add a preamplifier to the detector. Although a current preamplifier is preferred to maintain the dynamic range, charge sensitive hybrid preamplifiers that have demonstrated radiation hardness to 10 Mrad and 10^{13} n/cm² are available.⁵ Another possibility is the use of a tube-type preamplifier.

The final option is the use of solid-state ionization chambers. HERA has used Si-PIN diodes for this purpose.⁶ However, Si diodes are sensitive to radiation damage. GaAs strip detectors are being developed;⁷ but, they have a relatively high leakage current for use as ionization chambers. There are several exotic solid-state materials,^{8,9} *e.g.*, HgI₂, CdTe, and PbI₂ that show promise as ionization detectors with low leakage current and good radiation hardness.

4.0 SPECIFIC REQUIREMENTS

4.1 Linac

The requirements that have been established for the Linac¹⁰ impose some unique properties on the BLM system because the Linac is unique in the accelerator chain. In terms of the response times of detectors, *i.e.*, μ s, the Linac is the only accelerator for which the pulse structure of the beam is important. The Linac also spans the largest relative energy range and, of particular importance to the BLM detectors, the energy starts near zero. Finally, since the secondary radiation from beam loss is directed forward it is somewhat more difficult to detect in a linear as opposed to a circular accelerator.

For the lowest energy part of the Linac the protons do not carry enough energy to produce radiation outside the accelerator structure. In fact the lowest energy required for the BLM detectors is 13.6 MeV, *i.e.*, at the end of the DTL tank 1 and here a relaxed sensitivity, 0.1% loss, is specified. From DTL tank 2 (30 MeV) and above the required sensitivity is a 0.01% loss.

The requirements for the BLM system are listed in Table 3.

Table 3. Linac BLM Requirements.

Property	Value
Sensitivity (E = 13.6 MeV) (E > 30 MeV)	0.1% (1.5×10^{10} p/s) 0.01% (1.5×10^9 p/s)
Dynamic Range	10^4
Spacing - DTL	After each tank
Spacing - CCL	After each module
Pulse Rise Time	<10 μ s (1 μ s at 0.1% sensitivity)

At low energies the major secondary radiation from beam loss will be neutrons. Consequently, to obtain sensitivity at these low primary energies some relaxation of other requirements have to be made. To detect fast neutrons with high efficiency a hydrogen containing scintillator must be used. The choice is a plastic scintillator (2.5 cm in diameter and 10 cm in length). Either a PIN diode photo detector or a photomultiplier tube can be used with the scintillator. The use of a PIN diode provides possible advantages in that it has a good dynamic range, an insensitivity to bias voltage, and it is mechanically rugged. Another feature of the Linac allows us to keep a good signal-to-noise ratio. Since the Linac has a low duty factor, the detector can be gated on only during a pulse which reduces background. The problem with a plastic scintillator - PIN diode detector is that it is sensitive to radiation damage (damage threshold at 10^{13} n/cm²). Another option is to use HgI₂ photodetectors that can also reduce the radiation damage sensitivity.

Prototype detectors as described above have been ordered, received, and tested, primarily for signal to noise. A description of the results is included in Appendix A. The major conclusion of these studies is that the superior signal-to-noise ratio of the photomultiplier tube makes it the best choice.

Detectors should be placed after each DTL tank and each CCL module as close to the beam line as possible. For the DTL-CCL matching section detectors should be placed after Q2 and Q4, again close to the beam line. Module 3 of the CCL brings the beam energy over 200 MeV so that the total number of detectors of the type described here is nine.

From 200 MeV and above the switch to an ionization chamber or a proportional counter can be made. These detectors will be able to meet the requirements above this energy. The exact choice of detector is loosely tied to the choice of detector for the higher energy accelerators with an interest in maintaining compatibility, *i.e.*, choosing the same detector if possible.

4.2 LEB and MEB

The requirements for the LEB¹¹ and MEB synchrotron rings are very similar. In general BLM detectors will be placed at each quadrupole magnet of the accelerator, *i.e.*, where the beam envelope is at a maximum. For the proton energy range covered by these accelerators, the radiation generated by beam loss increases as $E^{0.8}$. With a minimum response of 10 mrad/s for the BLM the minimum loss rates are approximately 1.0×10^9 p/s to 1.0×10^7 p/s (1 m from a point loss at a shallow angle) from injection into the LEB to extraction from the MEB.

Although losses have been expressed per unit time with the assumption that these are continuous losses, the opposite extreme of instantaneous losses can be considered. This will become important for the cold machines where the quench characteristics depend on the loss time scale. The detector electronics have a ~ 0.1 s integration time built in to match these quench characteristics. Consequently the instantaneous response of the detectors is ten times (10x) more sensitive.

The BLM requirements for the LEB and MEB are shown in Table 4.

Table 4. LEB and MEB BLM Requirements.

Property	LEB Value	MEB Value
Sensitivity (Injection) (Extraction)	1.0×10^9 p/s 1.0×10^8 p/s	1.0×10^8 p/s 1.0×10^7 p/s
Dynamic Range	10 mrad/s – 100 rad/s	10 mrad/s – 100 rad/s
Spacing	~ 6 m	~ 19 m
Pulse Rise Time	<10 μ s	<10 μ s
Integration Time	100 ms	100 ms

4.3 HEB and Collider Rings

The most severe requirement on the BLM system will be at the top energy of the collider rings (20 TeV). At this energy the magnets are operating with the least margin and the energy carried by each proton is, of course, a maximum. In Table 5 the expected tolerable beam losses for a variety of effects are summarized.

Table 5. Projected Beam Losses for the Collider Rings.

Purpose	Beam Loss	Comments
Quench Protection	3×10^6 p/m-s	Slow loss (3 mW/g)
	3.5×10^6 p/p	Fast loss (0.5 mJ/g) - Reserve Enthalpy
Radiation Damage	1×10^4 p/m-s	Dose <1000 Mrad for 25 years
Cryogenics	1×10^5 p/m-s	Over a few magnets (<4 W per magnet)
	1×10^4 p/m-s	Over whole machine (<0.4 W per magnet)
Radiation Safety	1×10^4 p/m-s	For both slow and accidental losses
Beam-Gas Interaction	4×10^3 p/m-s	At design current and vacuum

Of prime importance in this table are the expected quench levels. For an instantaneous loss, *i.e.*, no heat flow, <1.0 ms, the quench level depends on the reserve enthalpy in the superconducting coils. A correction for the fact that the maximum energy deposition in the coils (along the horizontal plane) is not where the maximum magnetic field occurs has been included in the value calculated.¹² The quench level for a continuous loss depends on the cooling of the coils. This calculation is in progress for the SSC magnets. The value listed is based on extrapolation from measurements and calculations for the Tevatron magnets.¹³

Another slow response limit on beam loss is placed by the cooling capacity of the cryogenics system. The limits shown in Table 5 apply to an overload in one sector, *i.e.*, heating in a few magnets, and an overload of an entire ring. These limits are also important in determining the radiation dose limits that need to be considered.

From Table 5 the requirements on the BLM system can be specified. The range of losses is about 10^4 ; thus a dynamic range of this magnitude has been specified. The minimum sensitivity is selected by requiring that abnormal losses from beam gas scattering be observable and that the quench levels be near the top of the dynamic range. Thus, thresholds of 10^4 p/m-s for continuous losses and 10^3 p/p for fast losses have been established.

Calculation of the radiation dose (rate) outside the cryostat has been done using the MARS12¹⁴ high-energy hadron and electromagnetic cascade code. This code provides a detailed simulation in 3-D geometry, including the magnetic field, of the collider lattice for both rings. Beam loss has been simulated in three half standard cells (270 m) for the case of a continuous loss and an accidental loss at the beginning of a dipole. The energy deposition at positions just outside the cryostat as a function of distance along the ring for a continuous loss has been calculated (see Appendix B). Positioning a BLM on the horizontal plane at or near the downstream interconnect for each quadrupole is the most advantageous and leads to a dose rate of 0.1 to 0.3 mrad/s for a loss of 10^4 p/m-s. For a fast beam loss at the beginning of a dipole the maximum energy deposition is 6×10^{-4} GeV/g per proton. For a loss of 10^3 p the dose is 0.01 mrad.

A summary of requirements for the HEB and the Collider Rings are listed in Table 6.

Table 6. HEB and Collider Ring(s) BLM Requirements.

Property	HEB Value	Collider Value
Sensitivity (Continuous) at Low E (Instantaneous)	1×10^6 p/m-s 1×10^5 p/p	1×10^5 p/m-s 1×10^4 p/p
Sensitivity (Continuous) at High E (Instantaneous)	1×10^5 p/m-s 1×10^4 p/p	1×10^4 p/m-s 1×10^3 p/p
Dynamic Range (Cont.) (Inst.)	1.0 mrad/s – 10.0 rad/s 0.1 mrad – 1.0 rad	0.1 mrad/s – 1.0 rad/s 0.01 mrad – 0.1 rad
Spacing*	~ 32.5 m	~ 90 m
Pulse Rise Time	<10 μ s	<10 μ s
Integration Time	100 ms	100 ms

* Distance between quadrupoles

The SSCDR assumes a spacing of 30 m between detectors. This spacing was based on providing nearly uniform coverage. The simulations indicate that a spacing of 15 m is actually needed to provide uniform coverage, *i.e.*, the radiation from a point loss falls off an order of magnitude each 15 m. Fortunately, by careful consideration of loss scenarios, it has been realized that uniform coverage should not be required. The actual spacing between detectors should be determined by where the beam envelope is a maximum, *i.e.*, at the quadrupoles.

In Appendix B the considerations that control the required sensitivity and spacing of the BLMs are discussed in more detail.

5.0 ELECTRONICS

A block diagram of the proposed electronics for the BLM system is shown in Figure 2. This system is similar to that used at FNAL and also to that proposed for the LHC.¹⁵ Data would be digitized on a few μ s interval to track the time development of beam loss. On approximately 0.1 s time interval data would be sent to the central control system. Locally the latest 32-k data points would be retained and could be transferred to the central computer on request. The data in local memory will wrap around.

The electronics system for the BLMs will be implemented in a standard format, VXI or VME. The former is preferred because it has been designed to handle analog signals, includes a ± 24 V supply, electronic shielding, and larger board space. In fact the digital portion of a Beam Position Monitor electronics board has been designed and a prototype board built¹⁶ in the VXI format. This board, with very few changes, could be the digital portion of a BLM electronics board. The board has four individual ADCs with 32k words of memory for each channel.

It is expected that the control system will monitor the status of the crates that contain the electronics. This monitoring would include over and under voltage on all the standard voltages, over temperature, reduced air flow, and crate control status. These status parameters should be read on a nearly continuous basis, *i.e.*, 10 Hz. In addition a set of status and control registers are on each BLM board. These registers include the results of power up tests, module identification, and default parameters that need to be read only after a restart. Other registers that contain the current status will need to be monitored on a continuous basis.

Since the BLM system provides machine protection, the abort channel is a separate system that for the HEB and collider rings will be connected directly to the abort kickers. The design goal is to provide abort decisions in a time much less than the time for a single turn.

The warning and abort levels will be set digitally. These levels should be read back and compared to the requested levels to insure proper operation. Comparison at the digital level should be sufficient and would not add additional circuitry. These tests should be made on a near continuous basis. Tests of the abort system should be made prior to filling the accelerator. Ramping the detector bias supply will induce signals in the detector. The rate can be adjusted to trigger both the warning and abort levels. This procedure tests the BLM system and the abort chain. (Actual firing of the abort kickers could be inhibited or they could be fired at a lower level.)

In addition to the data acquisition board most detectors will require a HV bias supply. A design that provides eight channels of high voltage on a triple width VME card has been produced.¹⁷ A version of the design could be modified for VXI.

Figure 2. Electronics Block Diagram.

6.0 SUMMARY

Most of the requirements for the BLM system for the SSC accelerators have been established. Although the FNAL gas ionization chambers will be adequate for the accelerators up to the HEB, the sensitivity needs to be increased by 100 for the superconducting machines. Several options for providing this increased sensitivity have been listed. A single option will be selected so that final designs can be performed.

A conceptual design for the electronics system has been completed. The design of a prototype board is underway. As that design is completed the remaining options will be closed.

APPENDIX A

BLM Detector for the Linear Accelerator Proton Energy Less Than 200 MeV

A.1 INTRODUCTION

Since the first BLM system to be installed is that for the linear accelerator, the design effort for that system is much farther along. As discussed in the main text, for energies less than 200 MeV, the principle radiation outside the accelerator structure is neutrons. In the discussion below the research and development in designing the BLM system for this case is described. Although the detector will be specific to this case, the electronics will have a more universal character.

A.2 NEUTRON PRODUCTION

The neutron production in terms of the number of neutrons per incident proton for thick targets of various materials has been summarized by Tesch.¹⁸ The results (as obtained from Reference 19) are shown in Figure 3. To determine the number of neutrons that will interact with a BLM detector per lost proton requires definition of the particular geometry of the loss, the angular distribution, and the neutron production rate.

To guide the development of the BLM detector assume a proton loss in a thick target of Cu or Fe 1.0 m upstream of the detector (*i.e.*, near 0°). Assume no shielding between the loss point and the detector. The angular distribution for the (p,n) reaction is forward peaked. Typical enhancement over an isotropic distribution for the number of neutrons/sr in the forward direction is about 10. Thus the right hand scale in Figure 2 assumes that enhancement.

Figure 3. Neutron Production for Thick (Stopping) Targets of Several Materials. The left hand scale is the number of neutrons per incident proton. The right scale is the fluence at a distance of 1.0 m, near 0° , and for a current of 1.0 μ A.

A.3 PROTOTYPE DETECTOR(S)

For the low energy BLM detectors a plastic scintillator with dimensions of $2.8 \times 2.8 \times 10 \text{ cm}^3$ has been used as a prototype. There are several options for scintillator and photodetector under study. They are:

Scintillator

Bicron HF
Nuclear Enterprises NE108

Photodetector

PIN Diode
HgI₂ Photodetector
Photomultiplier Tube

The combination of the NE108 and a HgI₂ photodetector is preferred because of its radiation hardness. However, the price and availability of the HgI₂ photodetector are not known at this time; also, leakage currents may limit the efficiency of solid state photodetectors, so all combinations will be tested and rated.

The efficiency of a recoil proton neutron detector is given by:

$$\epsilon = \frac{N_H \sigma_H}{N_H \sigma_H + N_C \sigma_C} \{ 1 - \exp [- (N_H \sigma_H + N_C \sigma_C) d] \}$$

where roughly $\rho = 1.0 \text{ g/cm}^3$, $N_H = N_C = 4.5 \times 10^{22} \text{ molecules/cm}^3$. For example at a neutron energy of 2.0 MeV, $\epsilon = 31\%$. The efficiency as a function of neutron energy is shown in Figure 4. Two curves are shown the so-called biased efficiency that applies to counting experiments in which a threshold is set on the pulse height. The second curve is the unbiased efficiency that would apply to current monitoring systems. Although Monte Carlo programs exist for calculating these efficiencies, the equation above is within a factor of 2 of the more complicated result.

Most of the details on neutron detectors discussed in this section can be found in Reference 20.

Typical plastic scintillators produce approximately 10^4 photons/MeV for electrons and 10^3 photons/MeV for protons. Typical photodetectors have quantum efficiencies of 20 to 80%. Assuming a preamp gain of 200, the expected minimum current at 30 MeV during the Linac pulse (at 1.0 m and 0° from the loss point) is

$$\begin{aligned} i_{\max} &= (i_{\text{loss}} \cdot \mu\text{A}) (\phi_n \cdot \text{cm}^{-2} \text{s}^{-1} \text{m}^2 \mu\text{A}^{-1}) (N_\gamma \cdot \text{photons/MeV}) (E_p \cdot \text{MeV}) \\ &\quad \times (qe) (Q_p \cdot C) (G) (\epsilon) (A \cdot \text{cm}^2) (f) \\ i_{\max} &= 2.5 \cdot 5 \times 10^6 \cdot 10^3 \cdot 1.0 \cdot 0.4 \cdot 1.6 \times 10^{-19} \cdot 200 \cdot 0.31 \cdot 28 \cdot 0.17 \\ i_{\max} &= 240 \cdot n\text{A} \end{aligned}$$

where A is the area of the detector and f is a rough estimate of the photon collection efficiency that depends on the geometry, the reflectivity at the surfaces, and the absorption of the scintillator. Over the 35- μs Linac pulse the total charge is 8.4 pC.

Figure 4. The approximate neutron efficiency of a $2.8 \times 2.8 \times 10 \text{ cm}^3$ plastic scintillator. The result of applying the equation in the text to a simplified model of plastic, *i.e.*, $H/C = 1.0$ and $\rho = 1.0 \text{ g/cm}^3$. The biased efficiency is estimated using a 0.5 MeV threshold.

Although using a preamp at the detector is undesirable for several reasons, it probably will be necessary to obtain the needed sensitivity if solid state photodetectors are used. Firstly, Si is sensitive to neutron radiation but with a limit of about 10^{16} neutrons/cm² before damage (for the preamps selected). At the same loss rate as above the expected lifetime of a preamp is sufficient. In addition the preamp will probably be the limiting factor in the dynamic range. Care will be needed to maintain the required dynamic range. Note that lifetimes for Si-PIN diodes are less than 10^{12} n/cm².

A.4 DETECTOR ELECTRONICS

The output of the detector will be sent over a long RG-58 cable (up to 100 m) to an electronics module. The front end of that electronics could consist of a passive integrator with a time constant of about 100 μs and a logamp. The logamp will produce an output that is proportional to the log of the ratio of the current with respect to a fixed current, *e.g.*, about 1 nA. Another possibility being considered is replacing the logamp with a linear amplifier and using a few μs integration time. If the output is sampled at a rate greater than 500 kHz the dynamic range can be maintained by summing the samples over the Linac pulse.

The digital electronics is based on the VXI card that was designed for the BPM system. The card has four channels each with an ADC, an averaging circuit (in a FPGA), and 32 kwords of memory. An area of the card that can be separately shielded has been left for the analog electronics. For the BLM system the passive integrators and logamps would occupy this same area. The ADC and memory would serve the same purpose as for the BPM but the averaging circuit would be modified to do digital comparisons.

In the higher energy machines the BLM system will be used to abort the beam, if beam losses become excessive. Although the Linac does not have an abort channel, warnings should be issued if the beam loss is too high. The electronic board will allow two levels to be sent to it. These levels will be compared to the beam loss as measured and signals sent if the beam loss exceeds the preset levels and for a preset number of comparisons, *e.g.*, three in succession. The comparison will be made digitally in the FPGA.

An electronics block diagram is shown in Figure 2. The ADC is a 12-bit, 500-kHz to 2-MHz part and data would normally be taken at 0.5 to 2 μ s intervals for the up to the 35 μ s of the Linac pulse.

The HV supplies depend on the photodetector selected. For the PIN diode (~ 80 V) and the HgI₂ photodetector (~ 400 V) a single supply can provide for several detectors. For the PMT (~ 1000 V), where the gain depends strongly on the HV, individual supplies will probably be needed. The preamp power can be daisy chained to several detectors.

A.5 COMPARISON OF SCINTILLATOR/PHOTODETECTORS

As stated in the introduction there are three photodetectors and two scintillators that were to be evaluated. The photodetectors were a HgI₂ photodetector (20×20 mm²), a PIN photodiode (18×18 mm²), and a photomultiplier tube (PMT, 38-mm diameter, Burle 10 stage S83010E). The plastic scintillators (chosen for their radiation damage resistance) were Bicron 3HF and Nuclear Enterprises NE108, both $28 \times 28 \times 100$ mm³. Appropriate combinations of these scintillators and photodetectors were tested using gamma-ray sources (²²Na, ¹³⁷Cs, and ⁵⁷Co). (Not tested was the PMT/NE108 combination because of a mismatch in the sensitivity/emission spectra.)

The solid state photodetectors have high quantum efficiency (up to 80%) and low leakage current (~ 50 pA); however, they produce one electron-hole pair per detected photon, whereas the PMT has internal gain of $\sim 10^6$.

Tests of the detectors using gamma-ray sources lead to the following conclusions and to the preferred detector as a BLM for the low energy part of the Linac:

- HgI₂ has a quantum efficiency twice that of the PIN diode.
- For the HgI₂ photodetector, NE108 has 20% higher pulse height than 3HF.
- For the PIN photodiode and the HgI₂ photodetector the noise threshold is about 200 keV.
- The count rate for the PMT/3HF detector is 100 times that of the HgI₂/NE108 detector.

The last conclusion is critical for the choice of the neutron detector for the Linac. For the solid state photodetectors the effective noise threshold is so high that what is seen is a spectra that is due to two gammas detected at the same time. This noise threshold would be much too high for neutrons that produce a tenth the light of an equivalent gamma ray. Thus the preferred design for the Linac neutron detector is a 2.5-cm diameter, 10-cm long, Bicron 3HF plastic scintillator viewed by a ~ 10 -stage 32-mm or 38-mm diameter PMT.

Several other points concerning each of the detectors were considered in reaching the final choice. They are:

- Radiation hardness:
 - HgI_2 and the eV-Products preamplifier have good radiation damage resistance, 10^{15} n/cm^2 and 10^{16} n/cm^2 , respectively.
 - PIN photodiodes show increased leakage current at fast neutron fluxes of 10^{12} n/cm^2 .
 - PMTs are inherently radiation damage resistant but they will age and will require periodic recalibrations (~6 months).
- Power supplies:
 - The preamplifiers would require $\pm 12 \text{ V}$.
 - HgI_2 would require $+400 \text{ V}$ and the PIN photodiode $+80 \text{ V}$ (daisy chained in both cases).
 - The PMT will require -900 V , separately adjustable for each detector.

The results of the tests on the PMT/3HF detector using the radiation sources is shown in Figure 5. Plotted is the energy of the Compton edge vs channel. The pulse directly out of the PMT has a rise time of 10 ns , a FWHM of 20 ns , and a maximum pulse height of 150 mV for the 1060 keV edge from ^{22}Na . The HV was operated at -900 V , the gain on the Ortec 575A Amplifier was set at 400 (with a $1.5 \mu\text{s}$ shaping time), and the conversion gain on the MCA was 512.

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Figure 5. Pulse Height Channel vs Energy of the Compton Edge for the Characteristic Gamma Rays of the Calibration Sources.

A.6 DETECTOR

Based on the studies of the prototype detectors it was decided that a detector consisting of a BCF-60 scintillator and a low gain Hamamatsu 2060 photomultiplier tube would be used. The diagram of this detector is shown in Figure 6.

This detector is specified by Source Control Drawing ADA-2180821. A bracket for the detector has been designed, Drawing ADA-2180822.

Figure 6. Low Energy Linac BLM Detector.

A.7 ANALOG ELECTRONICS DESIGN FOR THE BLM SYSTEM

Since the pulse structure of the Linac is a maximum of 35 μ s, the use of a passive integrator (with a long time constant) and a log amplifier to extend the dynamic range is not very effective. Rather, to obtain the maximum information, a fast integrator (linear) with a time constant on the order of 1–2 μ s has been developed.

The circuit based on the AD-844 opamp is shown in Figure 5. The pulse from the PMT/3HF detector, after transmission through 100 m of RG-58A/U has suffered a 3.1 dB attenuation and has stretched to 60 ns. The measured noise after transmission through the cable is 0.5 mV pp.

Pulses at the output of the fast integrator have a rise time of 60 ns and a FWHM of 1.0 μ s. The peak voltage is the same as the input. Output noise has increased to 3 mV pp. (This is for the breadboard circuit. Noise should be less for the optimized circuit.)

The output of the fast integrator will be digitized by a 1–2 MHz, 12-bit ADC, *e.g.*, the Analogic ADS-112 or the ADS-117 is one of the parts that can be used on the BPM VXI board. The measured dynamic range for this ADC is 10.5 bits. To extend the dynamic range to the specified 10^4 , the data taken at 0.5 μ s intervals can be averaged over the full Linac pulse.

Figure 7. BLM Analog Electronics – Fast Integrator.

A.8 HIGH VOLTAGE POWER SUPPLIES

High voltage (HV) power supplies will be required for the photomultiplier tubes (PMT) used in the BLM system. The 9-to-11 stage PMTs will need less than 1500 V and less than 1 mA. Since the gain is sensitive to the HV, separate supplies will be needed for each PMT. For the same reason low ripple and stable supplies are required.

Note that since as far as possible equipment designs are to be used for the latter machines in the accelerator chain the requirements of other possible BLM detectors should be considered. The gain of a proportional counter is also sensitive to the HV; whereas an ionization chamber is not sensitive to the HV. Thus the proportional counter will require separate supplies for each detector, but several ionization chambers can be daisy chained to a single supply. These detectors may require HV up to 3000 V.

Several conceptual designs have been developed to provide the high voltage to the PMTs. All of these require very little hardware development. The designs are at most the mechanical assembly of a few modules. The concepts developed are:

- Use the eight-channel VME card (triple wide) developed at FNAL.¹⁷ This power supply card offers extensive controls including D/A setting of the voltage and current and A/D reading of voltage, current voltage limit, current limit, and voltage setting. The supply also has extensive safety trips including over voltage, over current, watch-dog timer, external interlock, and external trip.
- Develop a separate chassis with 4-to-12 commercially available HV modules powered by a single linear supply, *e.g.*, typical required voltage of +24 V. Use D/A and A/D VME modules to control and monitor the output of the HV modules. The digital measurement and control can come from one of several sources:
 - The Controls Department can supply D/A, A/D, and digital I/O channels.
 - Use commercially available VME cards, *e.g.*, the VMIC VMIVME-4512 16-channel analog I/O board (16 D/A and 16 A/D channels).
 - Develop a HV supply control card – probably VME based.
- Develop a VXI card similar to the FNAL VME card.

The FNAL eight-channel VME card is now available commercially from Bi Ra Systems (2404 Comanche N.E., Albuquerque, NM 87107) Model VME4877.

The specifications of most HV supplies designed for PMTs exceed the requirements for the BLM system. Examples of HV modules that could be used for the above designs are the Bertan High Voltage (121 New South Road, Hicksville, NY 11801) Model PMT-20C-P,Nnd Matsusada Precision Devices Inc. (745 Aojicho Kusatsu 525 Japan) Model HPMR-2P,N.

Specifications for these modules along with the Bi Ra Systems card are summarized in Table 7.

Table 7. Specifications of Typical HV Modules.

Manufacturer Model Number	Bertan PMT-20C-P,N	Matsusada HPMR-2P,N	Bi Ra Systems
Voltage	0 – 2 kV	0 – 2 kV	10 V – 2 kV
Current	0 – 2 mA	0 – 1.5 mA	0 – 3.0 mA
Ripple	2 mV	2 mV	100 mV
Power	+24 Vdc @ 400 mA	+24 Vdc @ 350 mA	+12 Vdc
Regulation:			
Line	±0.001% for ±1% change	±0.001% for ±1 V change	
Load	±0.001% for 0–2 mA	±0.001% for 0–1.5 mA	
Temperature Coefficient	50 ppm/C	50 ppm/C	
Stability	0.005% per hr	0.005% per hr	
	0.02% per 8 hr		
Price	\$255	\$316	\$315 per channel

APPENDIX B

BLM System for the Collider Rings

B.1 INTRODUCTION

The BLM System for the Collider Rings must be carefully considered. The requirements on the system are not only demanding from the standpoint of sensitivity; but, the majority of the BLMs are located here. Consequently the requirements of longevity and maintainability are particularly important. At the highest energy the superconducting magnets are operating with the least margin and each proton is carrying its maximum energy.

In this appendix some of the issues that determined detector sensitivity and spacing will be discussed. A preferred detector that meets the required sensitivity and also the required longevity has been selected. This choice will be discussed.

B.2 RADIATION CALCULATIONS

In the main text it was pointed out that the most important parameters in determining detector sensitivity are the expected quench levels of the superconducting magnets. For an instantaneous loss, *i.e.*, no heat flow, <1.0 ms, the quench level depends on the reserve enthalpy in the superconducting coils, *i.e.*, 0.5 mJ/g. A correction for the fact that the maximum energy deposition in the coils (along the horizontal plane) is not where the maximum magnetic field occurs has been included in the value calculated. The quench level for a continuous loss depends on the cooling of the coils. The estimated value is 3 mW/g. Another continuous loss is the limit on the cooling capacity of the cryogenics system. These limits apply to an overload in one sector (4 W per magnet), *i.e.*, heating in a few magnets, and an overload of an entire ring (0.4 W per magnet).

In order to estimate the heating caused by the loss of protons and the radiation produced outside the cryostat, a Monte Carlo code was used. These calculations of loss induced heating and radiation dose (rate) outside the cryostat have been done using the MARS12 high-energy hadron and electromagnetic cascade code. This code provides a detailed simulation in 3-D geometry, including the magnetic field, of the collider lattice for both rings. Beam loss has been simulated in three half standard cells (270 m) for the case of a continuous loss and an accidental loss at the beginning of a dipole. The results of such simulations for the Collider arcs are shown in Figure 8.

Figure 8. Energy Deposition by (a) Continuous, Averaged over Each Element, and (b) Instantaneous Loss at the Beginning of a Dipole. Positions are just outside the cryostat; in and out refer to the center of the ring. QF and QD are focusing and defocusing quadrupoles, and SPR is the spool piece.

The energy deposition at positions just outside the cryostat as a function of distance along the ring for a continuous loss has been calculated. Positioning a BLM on the horizontal plane at or near the downstream interconnect for each quadrupole is the most advantageous and leads to a dose rate of 0.1 to 0.3 mrad/s for a loss of 10^4 p/m-s. For a fast beam loss at the beginning of a dipole the maximum energy deposition is 6×10^{-4} GeV/g per proton. For a loss of 10^3 p the dose is 0.01 mrad.

Additional simulations of beam loss have been performed for the interaction regions and the utility region (the location of the beam scrapers and beam abort systems). These simulations are used to predict the pattern of loss longitudinally in the various beam line elements. The radial and azimuthal distribution of radiation at selected points can also be obtained. Finally particle fluence and energy spectra can be predicted. These simulations will be used to help specify the placement of the BLMs and to predict their response under various loss situations. In these regions of the Collider, the BLM system becomes an important tool for tuning the machine in addition to its protective function. For example the scrapers are used to remove beam halo and that in turn improves the signal-to-background ratio in the large detectors. As the scrapers are moved into the beam the BLMs will provide information on the scraping rate. Also since the scrapers will likely be the limiting aperture any tuning problems may be evident by increased beam loss at the scrapers.

B.3 BLM SPACING

Initial SSC studies assumed a spacing of 30 m between detectors for the Collider. This spacing was based on providing nearly uniform coverage. The simulations indicate that a spacing of 15 m is actually needed to provide uniform coverage, *i.e.*, the radiation from a point loss falls off an order of magnitude each 15 m. Fortunately, by careful consideration of loss scenarios, it has been realized that uniform coverage should not be required. This is also the conclusion of similar studies for LHC.²¹

Several sources of beam loss have been considered. Losses can be caused by coherent beam motion such as multi-bunch instabilities, control problems and hardware errors during injection, ramping, and collisions. Losses may also be due to incoherent beam motion from transverse and longitudinal emittance growth in turn due to single bunch instabilities, power supply ripple, magnetic imperfections, elastic and diffractive protons from beam-gas, pp-collisions, and beam scraper and Lambertson interactions. In addition to loss of the primary beam secondaries can be produced from beam-gas and pp-collisions for example. These secondaries will then be lost elsewhere in the ring.

All these beam loss mechanisms are slow to develop as are any mechanical, vacuum, or magnet failures. Consequently with such an exceedingly stiff beam the first indication of beam loss will be at the limiting apertures, *i.e.*, first the scrapers then the quadrupoles.

The actual spacing between detectors should then be determined by where the beam envelope is a maximum, *i.e.*, at the quadrupoles. Although knowledge of which ring is at fault is not required for abort purposes, it is proposed that a BLMs be placed at the quadrupoles for each ring. These detectors can then provide increased reliability through redundancy and they can provide more complete diagnostic information on which ring caused the abort.

B.4 PROTOTYPE DETECTOR

As pointed out in the main text the FNAL ionization chamber is a factor of 100 less sensitive than required. The possible solutions for this problem were:

- Increase the volume and/or pressure.
- Use a gas proportional counter.
- Add a preamplifier at the detector.
- Use a solid state ionization detector (Si-PIN, GaAs, CdTe, PbI₂, HgI₂).

In order to achieve the requirements for the collider rings the preferred detector is a solid state ionization detector, HgI₂. A prototype detector with dimensions $20 \times 20 \times 3 \text{ mm}^3$ has been acquired and tested. The calculated sensitivity is $18 \mu\text{C}/\text{rad}$. The measured pulse rise time is about $2 \mu\text{s}$ at a bias voltage of +1.0 kV and the noise is very small. Previous radiation damage testing has shown that this material is very damage resistant (little fast neutron damage at $10^{15} \text{ n}/\text{cm}^2$). The primary question is whether the material will be available in sufficient quantity and at a reasonable cost.

These detectors would be rugged, radiation damage resistant, insensitive to HV variations, and have low noise. Since they are used as solid state ionization detectors, material and crystal quality may be relaxed, so that price can be controlled.

There are two probable sources for these detectors: (1) EG&G Nuclear Instruments (100 Midland Road, Oak Ridge, TN 37831), contact Richard Bly 615-483-2131; (2) Xsirius, Inc. (4640 Admiralty Way, Suite 214, Marina del Rey, CA 90292), contact Jan Iwanczyk 310-578-6655.

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