Beam Loss Detection

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1 Abstract

A review of Beam Loss Monitor Systems (BLM systems) used in accelerators since about 1960 is given, with emphasis on systems suitable for measuring and localizing beam losses over an entire accelerator. Techniques presented include: Long and Short Ionization Chambers, Scintillation Counters, Electron Multipliers, Cryogenic Calorimeters and PIN Photodiodes.

2 Introduction

2.1 Uses of BLM systems

The usual goal of particle accelerators is to deliver high luminosity to experiments. The information from BLMs helps in the tuning of the machines for the high beam currents and long lifetimes necessary for improved luminosity.

Beam loss may result in damage to accelerator components or the experimental detectors. A task of the BLM system is to avoid such damage; in some accelerators it is an integral part of the protection system, signaling a beam abort system to fire if a certain loss rate is exceed (Ref. 1, 2, 3). This is of vital importance to the Generation of superconducting accelerators, for which beam losses in the superconducting components may lead to a quench, resulting in a shut-down of accelerator operation during the quench recovery procedure, as well as possible damage to the components. Another task of BLM systems is to identify of the position (and time) of unacceptable losses. This often indicates the source of the problem in the machine. A BLM system provides a fast way to determine the position of aperture restrictions and semitransparent obstacles in the accelerator, and helps to keep the radiation level in the accelerator and its surroundings as low as possible.

2.2 Principles of loss detection

In case of a beam loss, the BLM system has to establish the number of lost particles in a certain position and time interval[1]. All BLM systems discussed here are mounted outside of the vacuum chamber, so that the detector normally observes the shower caused by the lost particles interacting in the vacuum chamber walls or in the material of the magnets. The number of detected particles (amount of radiation, dose) and the signal from the BLM should be proportional to the number of lost particles. This proportionality depends on the position of the BLM in respect to the beam, type of the lost particles and the intervening material, but also on the momentum of the lost particles, which may vary by a large ratio during the acceleration cycle. Together with the specification for acceptable beam losses as a function of beam momentum, this defines a minimum required sensitivity and dynamic range for BLMs. Additional sensitivity combined with a larger dynamic range extend the utility of the system for diagnostic work.

One has to distinguish between two types of losses:

FAST LOSSES:

Total beam loss during one or very few turns. In most cases there is no need of a BLM system to localize the error in the machine. Often it is a easily detectable error like a closed vacuum valve, a broken power supply, a

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[1] I exclude from my talk beam current monitors, which give the amount of losses but not the position

fired (or not fired) kicker, etc. Nevertheless it could be dangerous for accelerator components (especially superconducting components) and a BLM system may warn if an intolerable dose occurs.

SLOW LOSSES:

Partial beam loss over a time (circular machines) or distance (LINAC, transport lines) interval. In storage-rings, the lifetime is defined by slow losses. There are many reasons for these losses and a BLM system is very helpful for finding out what is happening in the machine. In superconducting accelerators a BLM system may prevent from beam loss induced quenches caused by slow losses.

In addition measurements of injection-, ejection- or collimator- efficiencies can be performed using BLMs (e.g. Ref. 4), as well as background measurements in the detectors (e.g. Ref. 27, 28). This survey concentrates on BLM systems which cover the entire accelerator.

3 Long Ionization-Chambers

In 1963, Panowsky (Ref. 5) proposed for SLAC a BLM system consisting of one long (3.5 km) hollow coaxial cable. It is an industrial RG-319/U cable with a diameter of 4.1 cm, filled with Ar (95%) + CO_2 (5%) and used as an ionization-chamber (Panowski's long ionisation chamber, PLIC). It is mounted on the ceiling along the LINAC, about 2 m from the beam.
Position sensitivity is achieved by reading out at one end the time delay between the direct pulse and the reflected pulse from the other end. The time resolution is about 30 ns (≈ 8 m), for shorter PLICs about 5 ns are achieved. This BLM system has been working for more than 20 years and was upgraded for the SLC (Ref. 6). Nearly the entire SLC is covered with a few PLICs
This principle of space resolution works for one-shot (-turn) accelerators (and transport lines) with a bunch train much shorter than the machine and with relativistic particles. For particles travelling significantly slower than the signal in the cable (≈0.92c) the resolution of multiple hits in the cable becomes difficult. In this case and for circular machines it is necessary to split the cable. Each segment has to be read out separately, with spatial resolution approximately equal to the length of the unit. This was done in the BNL 200 MeV LINAC, where 30 cables, each 7-9 m long, are used (Ref. 7). They are installed at 1.5 - 3 m from the beam.
In the AGS ring, Booster and transport lines about 200 monitors with a length of about 5 m are installed (Ref. 8, 9). To improve the sensitivity of the BLM system in the AGS ring for ion acceleration the cables were moved from a position below the magnets to the median plane on the open side of the magnets (Ref. 10). The dynamic range of the BLMs is about 10^3.
In the KEK-PS 56 air-filled cables with a length of about 6 m are installed. Using amplifiers with a variable gain, a dynamic range of 10^4 is archived (Ref. 11).

4 Short Ionisation Chambers

Short ionization chambers are used in many accelerators. They are more or less equally spaced along the accelerator with additional units at special positions such as aperture restrictions, targets, collimators, etc. An early example of an Air filled Ionisation Chamber is the AIC proposed in 1966 in Ref. 12 (Fig. 1). 100 AICs were installed in the CERN-PS. Each chamber had a volume of about 8000 cm^3 and used a multi-electrode layout to reduce the drift path, and hence the recombination probability, of the ions and electrons, with the goal of improved linearity. A dynamic range of 10^3 was obtained.
The idea of AIC was renewed in 1992 in Ref. 14. The authors propose an AIC with a 2π geometry around the beam pipe. The goal is to measure the loss in the vacuum wall independent of azimuth angle and with high sensitivity.
The TEVATRON relies on 216 Argon filled glass sealed coaxial ionization chambers to protect the superconducting magnets from beam loss induced quenches (Ref. 1). The volume of each chamber is 190 cm^3 (Fig. 2). Most are positioned adjacent to each superconducting quadrupole. An Ar-filled chamber has the advantage of a better linearity because of a lower recombination rate than in AICs. A dynamic range of 10^4 has been reached.

A new idea is proposed in Ref. 15 for the UNK superconducting magnets. The ionization chamber is an integral part of the magnet and uses the liquid Helium as an ionization medium. A 2π geometry close to the beam pipe is foreseen, with predicted dynamic range of 10^5, but additional investigations are necessary to determine the linearity in this range, which may be restricted by the recombination rate.

5 Scintillation counters

In case of losses in a machine without a, BLM system, a temporary installation of plastic scintillator with photomultiplier readout is often made. This counters have a well known behavior but the strong radiation damage of the plastic scintillator restricts their long term use. Liquid scintillators avoid this damage and were installed in some accelerators, e.g. Ref. 16, 17. Fig. 3 shows the device at LAMPF with a dimension of 500 cm^3. A photomultiplier (PM) inside a oil filled paint can detects the scintillation light from the oil. This BLM is very fast, the pulse rise time is about 10 ns and a dynamic range of 10^5 was obtained. The gain of the photomultipliers varies within a factor of 10. Therefore a careful intercalibration of the BLM sensitivities was necessary by adjusting the high voltage (HV). The drift of the gain is a well known behavior of PMs. A stabilized HV-source and continuous monitoring of the photomultiplier gain over the run period keep the calibration error small.

6 Aluminum Cathode Electron Multipliers

An enhanced sensitivity of photomultipliers to ionized radiation is archived by replacing the photocathode by an aluminum foil. This foil works as secondary electron emitter when irradiated. A BLM system consisting of this Aluminum Cathode Electron Multipliers (ACEM) was proposed in Ref. 18 and installed in the CERN-PS (100 units) and in the PS-Booster (48 units). They are located on top of the magnets behind each straight section plus 32 additional positions for specific applications (PS).The dimensions of the tube are 4 cm in diameter and 9 cm length plus the adjacent HV-divider (Fig. 4). This BLM is very fast; the rise time of the signal is about 10 ns. For the dynamic range a value of 10^6 was exceeded by adjusting the HV. An careful selection of the ACEMs had led to gain variations of 10 %, but intercalibration and gain monitoring was performed nevertheless. This BLM system is rather expensive because the ACEM is not a standard tube of PM-suppliers (Ref. 20).

7 Cryogenic Microcalorimeters

A new system called the Cryogenic Microcalorimeter was proposed and tested in 1992 for LEP (Ref. 21). It is designed to detect beam loss induced quenches in the superconducting quadrupoles of LEP. This detector is different from all the other BLMs presented here because it does not make use of the charge created by the lost particles. A carbon resistor thermometer measures the temperature rise of the liquid Helium in the cryostat produced by beam losses. It is a very small device with dimensions of about 3 x 3 x 1.5 mm (see Fig. 5). Its position is restricted to the cryostat of superconducting magnets.

No values for the linearity and the dynamic range are available up to now but first measurements indicate an easily detectable signal with a rise time of about 20 ms in case of a beam induced quench. The signal occurs well before the quench and it should give enough time for the quench protection system to take action. The dynamic range is limited by the critical (quench-) temperature of the liquid Helium and by the noise of the monitor. One can expect that, with a known correlation between losses and temperature, this detector will work in a BLM system for superconducting accelerators. For quantitative loss measurements the temperature increase due to synchrotron radiation has to taken into account.

8 PIN Photodiodes

Most of the existing BLM systems are installed in hadron accelerators or in Linacs. Circular electron accelerators emit hard synchrotron - radiation (SR). The radiation interacts with the BLMs and a separation between SR-background and the beam loss distributions using the traditional BLM techniques is practically impossible. HERA is an accelerator with an electron and a proton ring in the same tunnel, operating at the same time. Protection of the superconducting proton magnets from beam loss induced quenches must rely on a BLM system which sees only the proton beam losses and not the SR-background. The (hadronic) shower created by beam losses includes a large number of charged particles, in contrast to the photons of the SR. The HERA BLM system consists of two PIN Photodiodes, mounted close together (face to face) and read out in coincidence (Ref. 22). Thus charged particles crossing through the diodes give a coincidence signal, while photons interact in only one diode do not.

In contrast to the charge detection of most other BLM systems, coincidences are counted, with the count rate is proportional to the loss rate so long as the number of overlapping coincidences is small.

The Photodiodes (2 x 2.5 x 2.5 mm^3) and the preamplifier (5 x 5 x 5 cm^3) are shielded by a hat of 3 cm of lead (Fig. 6). The overall reduction of SR signals is about 10^4, resulting in a count rate of $\approx$ 1 Hz with 25 mA current at 30 GeV/c in the electron ring (Ref. 23). The system has very low noise, with a dark count rate of less than 0.01 Hz. The pulse length is adapted to the 96 ns bunch spacing in HERA, so that the maximum count rate is 10.4 MHz. Therefore a. dynamic range of more than 10^9 is available.

The radiation resistance of the BLMs is adequate for long term use in HERA. A dose of 5 x 10^5 rad leads to a small and tolerable reduction in gain (Ref. 24, 25), while the dose reaching the monitor below the lead shield will be about 10^4 rads/year. BLMs are mounted on top of each of the superconducting quadrupoles. At this position the showering of the lost protons give a count rate which is independent of the radial position of the loss, and, within 5 m, also of the longitudinal position (Ref. 23). Additional BLMs are mounted on collimators, and on some of the warm quadrupole magnets, for a total of 250 units.

The BLM system has been operating since the 1992 running period and their good performance is indicated by some measurements:

1) The loss rotes calculated from lifetime and measured by the BLMs agree to within 25 % (Ref. 26)[2].

2) The counts are integrated over a time period of 5.2 ms to match the cryogenic time constant of the superconducting magnets (>20 ms). The predicted coincidence rate corresponding to the critical loss rate for a quench at 820 GeV/c is about 860 counts/5.2 ms. The only beam induced quench of a HERA quadrupole in 1992 showed a count rate of 1258 counts/5.2 ms for the quenched quadrupole. A nearby quadrupole which did not quench showed a rate of 893 counts/5.2 ms. The critical rate must be somewhere in between and is not far away from the predicted one. The critical rate was detected about 100 ms before the magnet quenched.

3) A lifetime problem in the HERA electron ring was solved using the BLMs. All monitors were moved from the proton ring to the electron ring to find the problematic section. A high count rate, inversely proportional to the beam lifetime, was measured in one of the straight sections. The problem vanished after a part of the vacuum-chamber in this section was replaced. This result demonstrates that the BLM system is also useful in high energy electron rings. It is planned to install about 250 additional monitors in the HERA electron ring.

9 Summary

Some Beam Loss Monitors techniques for measuring losses along an entire accelerator have been presented.

A long ionization chambers using a single coaxial cable works well for one-shot accelerators or transport lines. To achieve spatial resolution of losses along an entire accelerator two conditions must be fulfilled: 1) The machine must be much longer than the bunch train, and 2), the particles must be relativistic.

The most common BLM now in use is a short ionization chamber. Whether a simple air filled chamber is adequate, or an Argon or Helium filled chamber, with superior higher dynamic range, must be used, depends on the conditions of the particular accelerator. Ionisation chambers are radiation resistant but respond to synchrotron radiation.

A very sensitive system for measuring beam losses is an electron multiplier in combination with a photocathode and scintillator or with an Aluminum cathode acting as secondary electron emitter. Because of the adjustable gain the dynamic range can be large, but the calibration of each device must be adjusted and monitored over time. These systems are also sensitive to synchrotron radiation and relatively expensive.

The Cryogenic microcalorimeter measures the temperature rise of the liquid Helium in superconducting magnets resulting from beam loss. The temperature rise corresponding to beam loss sufficient to cause a quench

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[2] Please note that the efficiency of the BLM to charged particles is about 20 time higher than previously assumed (Ref. 27). Correct the loss-rate in Ref. 26 by 1/20.

is readily observed. Some additional investigations must be made of the dynamic range and the linearity of this device but first measurements indicate its suitability for quench prevention and loss measurements. The temperature rise due to synchrotron radiation must be taken into account when using Cryogenic Microcalorimeters for loss diagnostics in electron machines. The application of the calorimeter is limited to superconducting magnets.

The combination of two PIN-Photodiodes in a coincidence counting results in a detector with very large dynamic range and extremely effective rejection of synchrotron radiation. The small dimensions permit simple shielding and easy installation at any position. The measured radiation resistance permits long term use also in high energy electron machines with a high radiation background. The monitor with its simple accompanying electronic is inexpensive, which may be of great importance in very big machines with a large number of loss monitors. A (present) limitation is the inability to distinguish overlapping counts, so that the response is linear only for losses for which there is significantly less than one count per coincidence interval.

Acknowledgements

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11 Figures

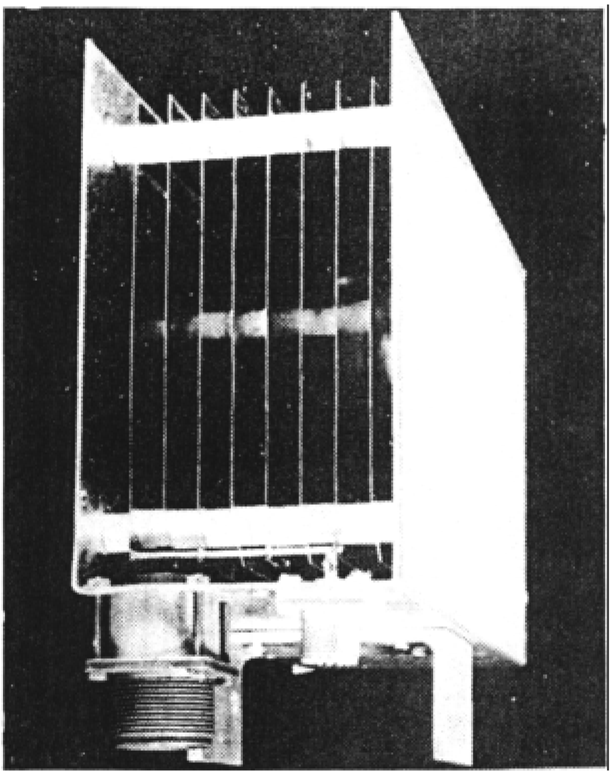

Figure 1: Air Ionisation Chamber at the PS (1968). The cover is removed (from Ref. 13).

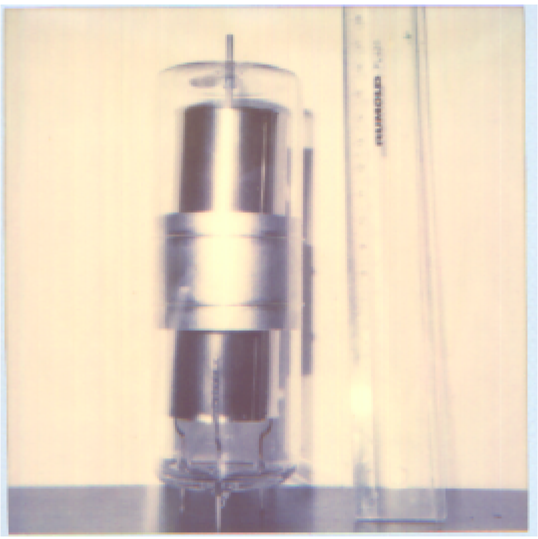

Figure 2: The TEVATRON Argon filled Ionization Chamber (1983)

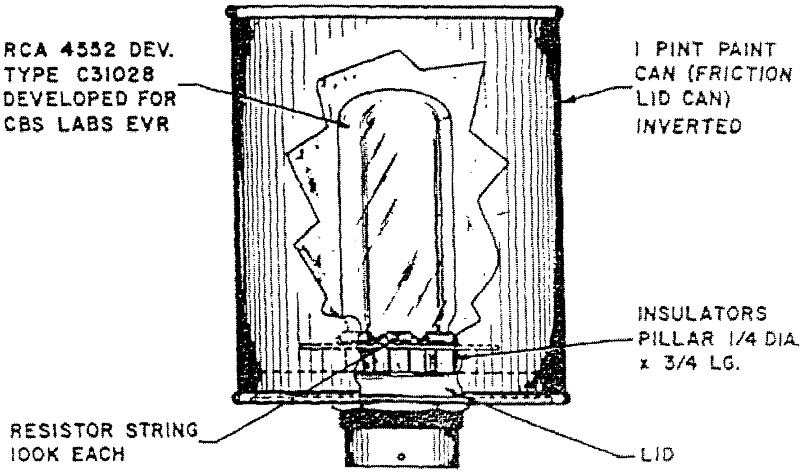

Figure 3: The Liquid Scintillator BLM at LAMPF (1971), (from Ref. 16)

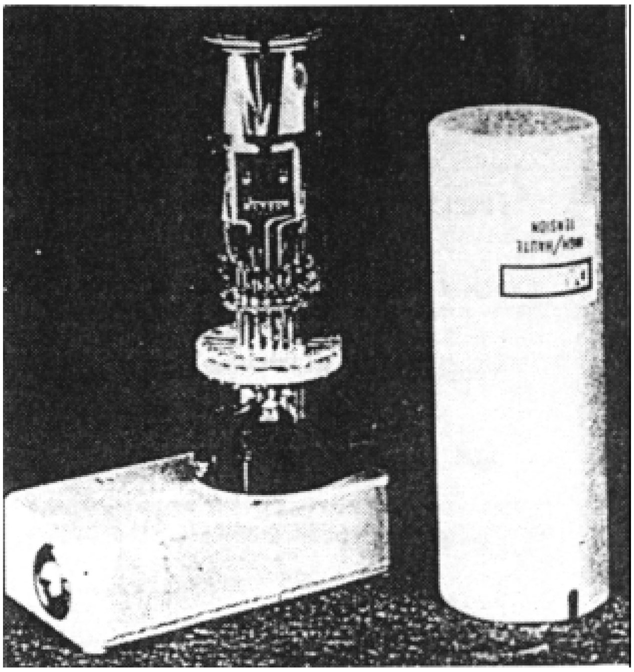

Figure 4: The Aluminum Electron Multiplier at CERN PS (1985), (from Ref. 19).

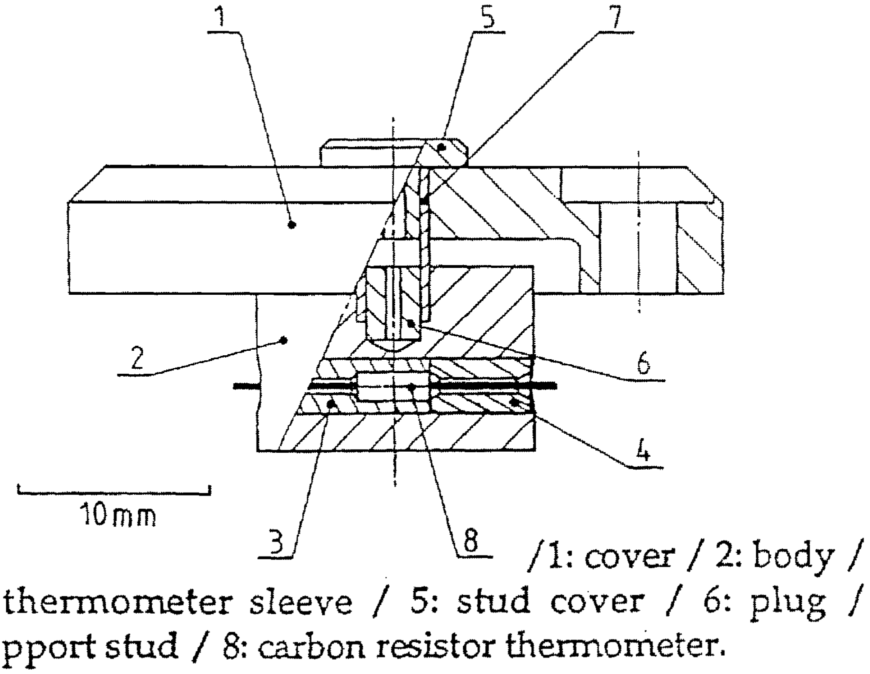

Figure 5: Cut-away view of the microcalorimeter (1992), (from Ref. 21).

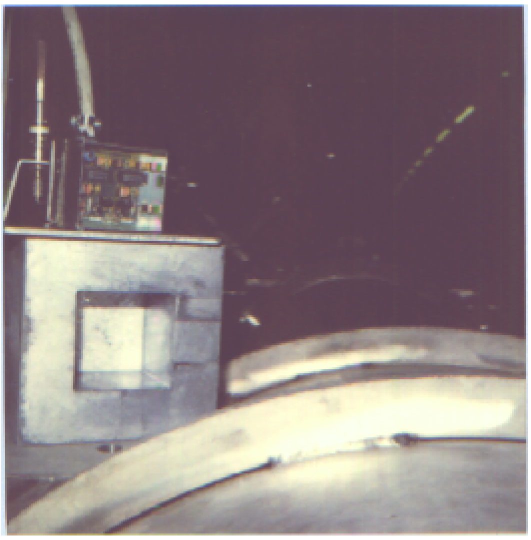

Figure 6: The PIN Photodiode BLM on top of a HERA magnet (1991). The lead hat is removed