Comments on the Tevatron BLM System

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Introduction

The Tevatron beam loss monitor (BLM) system was designed in 1981 primarily to assist in turn-on and commissioning of the Tevatron. It also included features to provide general radiation monitoring during normal beam operation, to warn the operators in case of excessive beam loss, and to trigger the beam abort system within 1 turn whenever there was danger of magnets being quenched by beam.

The BLM system was designed as an add-on to the Tevatron beam position monitor (BPM) system, in that the BLM chassis, into which up to 12 BLM detectors could be plugged, was read out into the BPM multibus chassis by way of a simple parallel digital databus at rates of 100 to 1000 Hz. The BLM chassis is a dedicated rack-mount chassis that could easily be read out into another purely digital readout system. A good overview of the BLM (and BPM) system is given in [1].

Detector

The detector is an argon-filled glass cylindrical ion chamber with nickel electrodes. The design was chosen to be extremely rad hard. The gas is 1 atm pure argon, active volume about 110 cm^3. No CO_2 was used, because CO_2 could eventually dissociate under ionizing radiation and affect the response. Furthermore, ion chambers are extremely stable (no long-term drift or voltage dependence) and have uniform unit-to-unit gain (e.g., coulombs per rad). Other ion chamber designs such as PLICs (long gas-filled heliax coax cables) were rejected because the outgassing of the polyethylene dielectric poisoned the gas unless the gas was continuously circulated. This would have been a maintenance headache. (Fred Hornstra had problems with this design, and with the paint can BLMs, on the old main ring).

The ion chamber design was a compromise of high gain, fast response (electron collection time), size, and low cost. The design included placing the anode (center electrode, signal output) and cathode (outer electrode, negative high voltage) feedthroughs at opposite ends of the glass "bottle" with a guard ring on the glass envelope to minimize the dark current leakage (roughly 100 pA at -2500V). Pulsed-beam measurements at ANL (by Larry Coulson et al.) showed that it could detect an instantaneous radiation dose (in 1 or 2 microseconds) of about 10 rads with less than 20% charge loss. This large amount of space charge (about 700 nC) severely modifies the electric fields in the gas as the ions and electrons drift toward the electrodes, leading to both recombination losses and gas multiplication. For comparison, the interelectrode capacitance was about 2 pF, leading to a displacement charge on the electrodes of about 5 nC at -2500V.

Log Integrator Circuit (The daughter card)

The BLM signal goes directly into the log integrator daughter card in the BLM chassis. A simplified block diagram of the daughter card is shown in [2]. Functionally, the daughter card includes a) a combined cable termination/low pass filter with RC= 20 us, b) a leaky charge integrator with RC = 1/16 s, and c) a 4-decade logarithmic amplifier. The input signal connection to the daughter card is a direct-connect flying lead to minimize ground current leaks. Two matched NPN transistors in a trans-diode connection are used in the feedback loops of two op-amps to create a logarithmic response amplifier. Because the current across the base-emitter junction is exponentially related to the forward junction voltage, the amplifier has a logarithmic response. A shortcoming of diode-junction based log amplifiers is that at low currents, the dynamic resistance is very high, leading to poor bandwidth (ask Bob Webber about this). Nowdays one would buy a logamp chip from Analog Devices. The log integrator gain was set to provide about a 4-decade operating range (from 1 nA to 10 uA) with no gain switching. (Note: although I refer to the circuit as a log integrator, the (leaky) integration should be done <u>before</u> the logarithmic amplifier, while the signal is still linear.)

With the 1/16 s leaky integration at the input, the output voltage was a rough indication of the probability of quenching a dipole magnet. Magnet quench threshold measurements made in the left bend of the extraction line to the Meson Area (by Roger Dixon?) showed that a superconducting dipole magnet could be quenched by roughly 0.5 mJ/gram (fast pulse), or 8 mJ/gram-s (slow loss) of radiation in the superconductor[3]. The ratio, 1/16 s, is the "time constant" of the superconducting cable. (reminder: 1 rad = 100 ergs per gram).

The complete log integrator daughter card included another trans diode pair to protect against reverse bias operation (which could happen when the BLM high voltage is ramped down), which would blow the base emitter junctions. It also included a dc leakage input bias current (offset) of about 0.5 nA, to provide a non-zero voltage output even when there was no radiation present, to indicate that the log integrator circuit was alive and working. This is seen in as a slight voltage offset in the BLM display [4].

The 4-decade dynamic range requirement came from considering that one wanted to be able to sense high radiation levels that could lead to magnet quenches, and at the same time sense low radiation levels that would be indicative of off-normal operation. This is a difficult calculation to do, and depends on what constitutes "off-normal" operation. (reminder: 3E7 MIPS (minimum ionizing particles) per cm^2 is equivalent to 1 rad). As one example, during commissioning in 1983, the BLM system detected a low radiation loss in F sector, which later turned out to be the circulating beam hitting a kim-wipe left inside the beam tube.

<u>The Mother Board</u>

(The following is from my long-term memory, which is somewhat foggy). The real-time analog signals from up to 12 BLMs as I recall went to 3 separate circuits, an 8-bit digitizer and two analog comparators. a) Each log integrator output was digitized by a multiplexed 8-bit digitizer [5] and loaded into a dual port memory. b) Each output went to an analog comparator that compared the log integrator output to a preset downloaded digital value that was converted to a dc voltage by a DAC. If the preset value was exceeded between data readouts, an alarm bit was set, causing a Multibus interrupt, thus warning the operator that there was a beam loss. The BLM data digital readout allowed the operator to determine which BLM caused the alarm. As a precaution, each alarm bit was individually maskable to prevent Multibus interrupts in case of a malfunctioning BLM channel. c) Each output went to a second analog comparator that compared the log integrator output to another higher preset downloaded digital value that was converted to a dc voltage by another DAC. If the preset value was exceeded between data readouts, an abort bit was set. majority logic (when >=*N* abort bits were set) would send a prompt realtime abort trigger signal to the Abort System. Because the abort bit could be due to a malfunctioning channel, each individual abort bit could be masked off via the Control System. There were actually two digital alarm registers and two digital abort registers for each BLM channel, which were selectable by a Tev clock event broadcast to all BLM chassis. Thus for example, at injection, when beam losses are high and the magnets are unlikely to quench, the alarm and abort thresholds were set high. As the beam was accelerated and the magnets were much more likely to quench at a specific radiation level, the alarm and abort thresholds of all BLM channels were simultaneously switched.

The BLM detector high voltage supply, one per chassis, was a dc-dc converter that could be set by a downloaded 8-bit word via a DAC. The high voltage for all detectors on a particular BLM chassis was daisy-chained in the tunnel. By ramping the hv down, waiting 20 seconds, and ramping up under computer control (permitted only when the beam was off), a small amount of charge, about 4 nC at 2000V, could be injected into every BLM detector channel and digitized. This integrated system test checked cabling (both hv and signal), the BLM detector, and the analog and digital circuitry for every channel.

Because I may have overlooked some important features of the software or hardware, someone should review the mother board circuit design and the software control download functions before embarking on a new design. Also consult with John Larsen, Fred Krueger, Rich Meadowcroft, and Bob Webber, all of whom participated in the design, construction or operation of the BLM system.

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[1]. "The Tevatron BPM and BLM Systems," R. E. Shafer, R. E. Gerig, A.E. Baumbaugh, and C. R. Wegner, Proc. of the 12th Int. Conf. on High Energy Accelerators, pages 609-615 (Fermilab, 1983).

[2]. A simplified block diagram of the daughter card is shown in Fig. 2 of reference [1].

[3]. See page 226 of "Design Report, 1979 Superconducting Accelerator", F. Cole, R. Donaldson, D. Edwards, H. Edwards, P. Koehler, Eds. (May 1979)

[4]. See the bottom trace of Fig. 3 in ref [1].

[5]. An 8-bit (256 count) digitizer is sufficient to provide 4 decades of dynamic range with 5% resolution, with more than 50 counts to spare. Proof: $(1.05)^{200} = 17{,}293$.

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Editorial comments.

After 20 years of Tevatron operation, the experience gained by the operators, plus the new Tevatron operating conditions totally unforeseen in 1981, plus the new technology available certainly warrant a redesign of the BLM system. The modern trend is to minimize the analog circuitry and digitize immediately. I would caution about moving the digitization upstream of the log integrator, however. Doing this processing in a real-time analog circuit with a new logarithmic amplifier will compress a large amplitude BLM signal dynamic range (the BLM detector dynamic range is probably 6 decades) into a relatively small voltage dynamic range that can easily be handled with simple ADCs (e.g., 12 bits), simple analog comparators, and without range switching. Range switching is probably ruled out in order to preserve the 1-turn abort trigger real-time response requirement. To achieve 4 decades linear response with a single ADC, it probably should be a 16-bit (65,535 count) ADC.

The abort comparator should be real time, within 5 us or so. If the comparison is carried out using analog circuits, as was done in the original BLM system, this is true. If the comparison is done after digitization, then the ADC must sample each channel at roughly 200 kHz. If the ADC is multiplexed, then the ADC must run 12 x faster, or 2.4 MHz. So, if the BLM system is completely digital and the ADC is multiplexed, the ADC is probably16-bits @ 2.4 MHz.