EXPERIENCE WITH THE SNS LOSS MONITORING AND MACHINE PROTECTION

A. Zhukov, ORNL, Oak Ridge, TN, USA

Abstract

The Spallation Neutron Source (SNS) is a megawatt-class hadron accelerator. Beam loss monitoring is essential for machine protection, residual activation control and machine tuning. We discuss all parts of our beam loss monitoring system including its detectors, electronics, machine protection system (MPS) interface and its role in the accelerator tuning process. The system was designed more than 10 years ago, so we are now addressing obsolescence problems by designing a new FPGA based replacement. The plans for this next generation Beam Loss Monitor (BLM) system are presented.

INTRODUCTION

At SNS a 1ms long H^- beam (macro-pulse) consisting of ~1000 mini-pulses (700 nS pulse and 300 nS gap) is accelerated from 2.5 MeV to 1 GeV in a linac and then converted into H+ by a stripping foil for injection into a storage ring. The mini pulses are accumulated and the resulting, ~700 nS, accumulated beam pulse is extracted and then hits a mercury target. This process runs at 60 Hz and delivers up to 1.4 MW of power to the target. Average beam current is ~24 mA over 1 ms [1].

The SNS BLM system consists of 378 radiation detectors measuring secondary radiation due to beam loss. BLMs are used as MPS devices to shut down the current beam pulse if the integral loss is above threshold and to limit average loss to be under 1 W/m. The MPS system has to be software and timing independent to increase reliability.

Since the beam parameters are different in different parts of the machine, the nature of the losses are also very different.

DETECTORS

The BLM system is used as an MPS device as well as a beam tuning diagnostics. The same detectors are playing two roles and so have to combine reliability for MPS and flexibility for beam diagnostics. SNS uses ionization chambers (IC) as its main BLM device. This is due to their simple design and immunity to radiation damage. In addition to ICs we use several type of photomultiplier tube (PMT) based detectors. The neutron detectors (ND) are neutron sensitive detectors that are useful in low energy part of the linac (where ICs lack sensitivity). The ICs are not fast enough to provide macro-pulse structure to physicists so the PMTs can be used for such diagnostics purposes. Also all PMT devices can adjust their sensitivity significantly (factor of ~100-1000) by changing their HV bias.

Detector Distribution

BLMs are evenly distributed along the accelerator with a typical distance to the beam line of 0-90 cm. In addition to fixed detectors we found moveable detectors to be very useful for investigating unexpected activation patterns.

Table 1: BLM Distribution

Detector	DTL	CCL	SCL	HEBT	Ring	RTBT
IC	11	50	79	59	71	40
ND	12	8	23			
PMT	6	6	3			
DBLM		2	5			3

Figure 1 shows moveable BLMs placed in the transition area between warm and superconducting linacs.

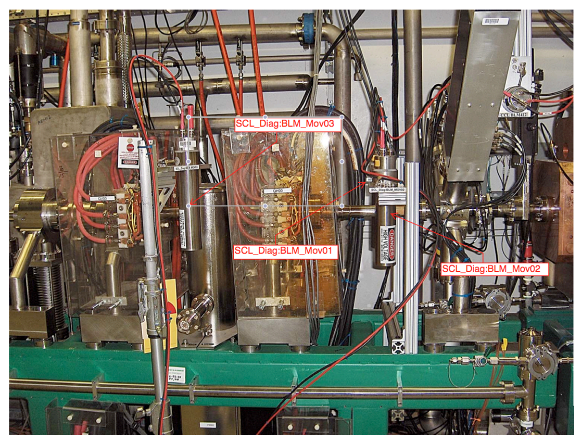

Figure 1: BLM placement for investigation of hot spot.

Detector Parameters

Most important detector parameters are shown in Table 2. Ionization chambers use daisy-chained HV lines since all of them have the same bias applied. All scintillator-based devices have dedicated HV power supply. In addition to signal and HV connections scintillator detectors have a test cable connected to an LED inside the detector. This connection allows testing and bias calibration for these detectors.

The slow response time of the neutron detector is caused by a polyethylene moderator that is needed to slow the neutrons down and increase cross section of neutron capture inside scintillator. Lead shielding around the scintillator helps to suppress sensitivity to x-rays (Fig. 2).

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Table 2: BLM Parameters [2]

Detector	IC	ND	PMT
Type	Ionization chamber	Neutron sensitive plastic scintillator + PMT	plastic scintillator + PMT
Detector medium	Gas Ar, 113 cm^3	Polyethylene moderator, ZnS(Ag) scint	EJ-208 scintillator
Typical HV Bias, V	-1000	-700	-700
Typical Sensitivity	70 nC/Rad	80 pC/n/cm2	2 mA/R/hr
Response time	~2 uS	~50 uS	~10 nS
Connectors	Sig (BNC), HV (SHV)	Sig (BNC), HV (SHV), Test (BNC)	Sig (BNC), HV (SHV), Test (BNC)

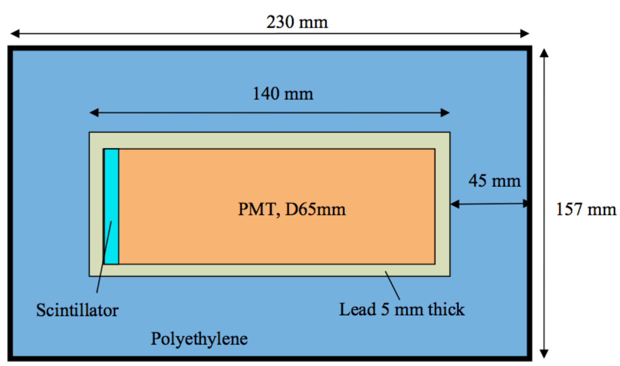

Figure 2: ND internals [2].

Detector Calibration

All ion chambers were calibrated with a gamma source. While that provided absolute calibration in terms of Rads per C of charge being measured, it was not very useful for estimating the fraction of beam being lost. For NDs we used a calibration with faraday cups imitating a full loss [3]. It agrees with simulation but doesn't emulate a real distributed loss.

In the SCL we were able to calibrate BLMs with a laser wire profile measurement device. The laser strips off an electron from the H^- and H^0 is subsequently lost. Knowing the number of H^0 created and measuring additional loss we concluded that SCL loss is around several 10^{-5} [4].

MACHINE PROTECTION AND CONTROLS

Front End Electronics

All detector types are effectively current sources and are interfaced to the same 8-channel analog front end (AFE) electronics that features transconductance amplifiers with jumper-settable gains (620, 6.2E3, 62E3 [Ohm]). The amplified signal is split between an MPS circuit (leaky integrator to integrate the total loss), a "view" circuit where the "fast" signal leaves the AFE and goes to a VME hosted ADC card where it is sampled at 100 kS/s (signal BW is 35 kHz) and the "slow" signal that is smoothed (BW 1 kHz) and also goes to a separate ADC channel [5]. Typical signals produced inside the AFE are shown on Fig. 3.

Hardware leaky integrators provides protection without relying on software or timing information. The system allows a shutdown of the macro-pulse within 15 uS of the integrated value exceeding a threshold. Software based integration over one second is used to limit average loss to stay below 1W/m and maintain residual activation of under 100 mRem/hr in the most parts of the tunnel.

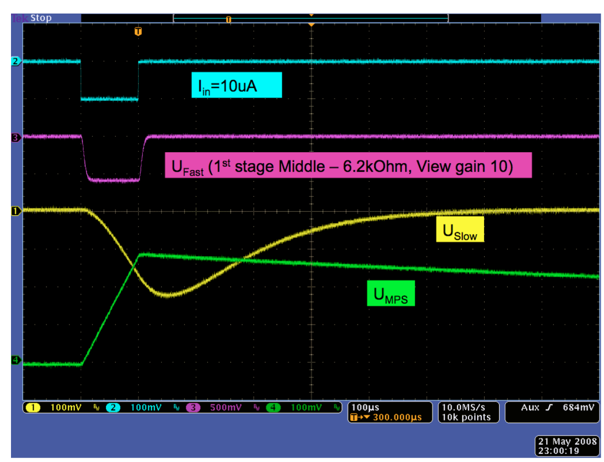

Figure 3: Signals in BLM AFE. Green shows MPS leaky integrator output.

The HV bias is shared by several (usually four) ICs that are daisy-chained in the accelerator tunnel. The HV is supplied by a VME HV module.

In addition to integrated loss, software monitors MPS detector health: gain settings, HV bias set points and read back, and HV bias current (that will detect cable problems in HV circuit).

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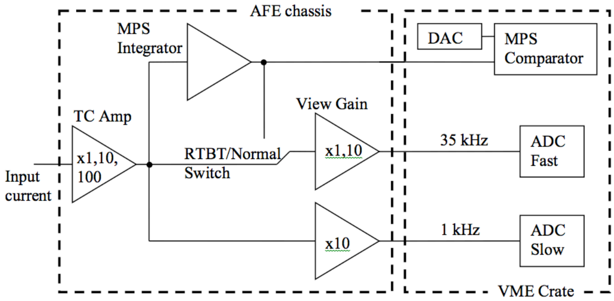

Figure 4: Analog front end [2].

Controls System [6]

The gain setting of the AFE is controlled and monitored by a VMIC VMIVME2510 64-bit digital IO module. The Machine Protection System (MPS) interface module compares AFE MPS loss to an MPS trip level and outputs the result to a separate MPS chassis. The MPS trip levels are set with the outputs of two Hytec8402 Industry Pack (IP) DAC cards (16 channels of 16-bit DAC each) residing on a GreenSpring VIPC616 IP Carrier board. There is a direct communication link from the Motorola MVME-5110 CPU board to the MPS Chassis through the PMC card attached to CPU board. Two ICS110B ADC cards read the AFE outputs of both the fast loss and slow loss signals. Each ICS110B card has 32 independent 24-bit Sigma-Delta ADCs. The ADC can sample up to 108 KHz (100 KHz is used). These data are then transferred and processed by the CPU board. The MVME-5110 features a 500MHz MPC7410 microprocessor, 512MB ECC SDRAM. The standard SNS timing configuration (V124S + V108S cards) provides a real-time data link of machine status as well as beam time synchronization and triggers. The VME crate used is an SNS-standard Weiner 21-slot crate.

The BLM IOC software is based on the Experimental Physics and Industrial Control System (EPICS) framework. Each programmable VME module in the crate has associated EPICS device driver software support which runs on the CPU board. For VME modules with common use at the SNS, beyond the BLM system (e.g. timing and MPS PMC), software is reused from the SNS standard software repository. Other BLM specific software drivers have been written for the remaining modules – the most significant and complex being that for the ICS110B ADC cards. The ICS110B driver is interrupt driven and relies on Direct Memory Access (DMA) for data transfer to the CPU card. It uses a specialized, hardware specific software driver. Alternating beam pulse data is captured by this ADC card into one of two internal “ping-pong” FIFO’s. As one FIFO fills, the other, containing the prior pulse’s data, is transferred via DMA to the CPU board and processed. For each 60 Hz beam pulse 400 samples (4 mS duration) are acquired for each fast and slow loss signal. Approximately 10 seconds of these data (600 pulses) are queued and internal to the system at any time. Various displays and display rates are available to visualize these data.

CAVITY X-RAYS

Beam loss is not the only source of radiation detected by BLMs. Significant x-ray background comes from RF cavities. To account for these x-rays, the SNS timing system generates a “blank” pulse every 10 seconds. During this blank pulse RF is switched on but there is no beam. The signal from the loss monitors is stored as a reference that is subtracted, in software, from the following normal pulses (with beam enabled). While this approach works, it cannot be used for fast protection because the leaky integrator cannot subtract the stored reference. This inherently compromises MPS because the loss limit set on the DAC has to include “losses” from x-rays.

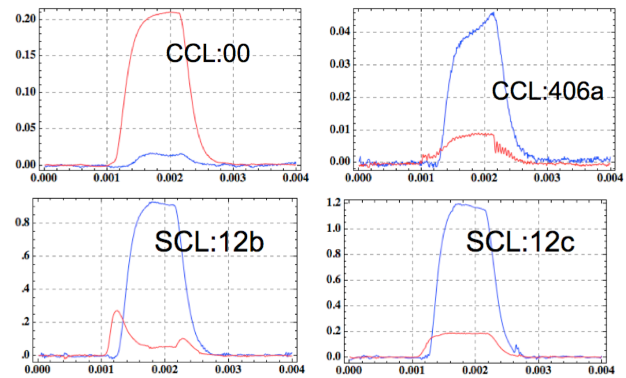

Figure 5: Loss waveforms showing Loss vs Time (s) in different locations. Red gives x-rays only signal (stored reference) and blue shows loss only signal (after subtraction of the reference).

As one can see in Fig. 5, the x-ray component is quite significant and can be even greater than the loss itself. A detector that is sensitive to neutrons and not sensitive to x-rays could be a possible solution. Unfortunately it is hard to create such a detector that would work in analog mode. We are currently experimenting with Dual BLM, which essentially consists of two scintillator-based detectors. One detector has increased sensitivity to neutrons and it measures neutrons and x-ray flux; the second detector measures x-rays only (its’ neutron sensitivity is much lower than the first one). Thus by subtracting the “x-ray signal” from “neutron plus x-ray signal” we can get the signal from neutrons only.

NEXT GENERATION OF BLM SYSTEM

This BLM system was designed around 1999. The major problem now is part obsolescence. The AFE boards are using obsolete, discontinued parts and several VME boards are discontinued including the ADC board. Instead of designing replacement boards, we are developing a new system that will significantly differ from the current one.

We plan to use FPGA technology to add flexibility to the MPS setup. MPS functionality will be moved from software to FPGA. We will still have analog integration, but its output will be fed into the FPGA as well. Beam abort decision will be made inside the FPGA and software will be used for communication purposes only. Instead of having just two limits for single pulse loss and one second average loss we will have arbitrary integration windows that could be different for various regions of the accelerator following similar approach used in LHC [7]. For example, since the SCL requires a faster reaction time to high loss, the beam will be tripped if a single digitizer's sample exceeds a threshold level instead of the integral over several samples.

The multichannel AFE boards will be replaced with single channel modules (Fig. 6) of different types to accommodate different detectors.

Key features of a single channel AFE module:

- Analog subtraction using fader IC [8]
- PGA gain
- HV power supply
- Own MPS integrator
- DAC for threshold settings, HV control, subtraction control, test signal control
- Analog front end can have several options
  - Maximum configuration for Dual BLM (already designed and being under test)
  - Only MPS integrator and fixed gain amplifier for ion chamber with shared HV supply

Figure 6: Single channel module with HV power supply and dual input for Dual BLM.

All modules will have amplified analog signals routed to the backplane and front panel for testing purposes. One chassis will host 8 (or 16) modules; analog signals in the same chassis will be digitized and processed in one FPGA (currently we consider cRIO system from National Instruments). This will add flexibility in defining trip conditions. We will be able to use the combination of losses from several detectors to determine if the beam is errant or not while having the MPS logic in hardware (FPGA). For example, the new system will be able to trip the beam if the weighted sum of losses exceeds a threshold; such testing can be performed on the fly on a point-by-point basis.

NON TYPICAL APPLICATIONS OF BLM

Fast BLMs for Beam Studies

We found it very useful to have fast BLMs (PMTs in Table 1). These devices are not connected to the MPS and are used for research only. They are fast enough to distinguish between mini-pulses of SNS beam. These detectors can be used as high time resolution devices for profile measurements. A PMT detects radiation caused by beam hitting a wire. Since it is not a beam line device it can be easily added anywhere in the tunnel. Another example where time resolution is essential is the injection area. Here PMTs can distinguish between loss from H^- hitting the foil and H^+ circulating in the ring.

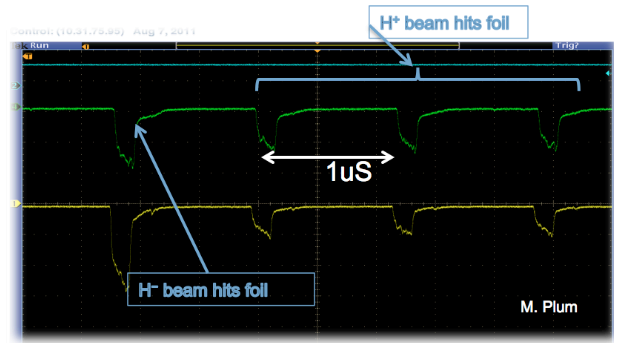

Figure 7: Fast BLM measurement revealing fine time structure of loss at injection area. One mini-pulse injected in the ring [9].

One of the main goals of the BLM system is controlling residual activation inside the accelerator tunnel. This is achieved by limiting one-second average loss. We also demonstrated that certain types of BLMs can be used to directly measure residual activation while beam is running. To achieve this we increase sensitivity of the scintillator-based detectors by ramping up their high voltage. Of course this causes saturation when beam is present (~ 1mS of 60 Hz period). But if we set the integration window to be well beyond the beam gate, the detectors are able to measure residual activation since there is no other radiation source when beam and RF are off. Figure 8 shows that one can see residual activation slowly decaying if beam is off for long time.

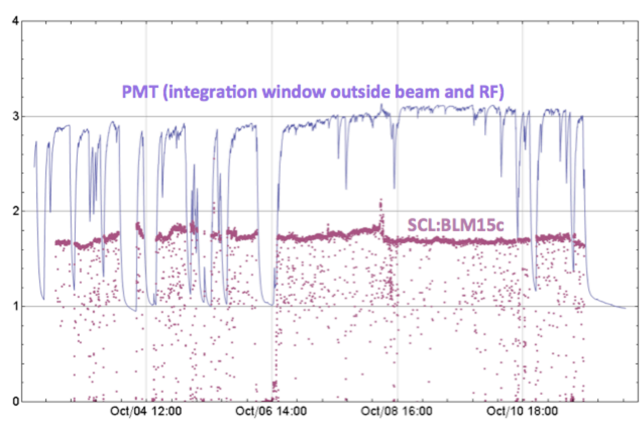

Figure 8: Residual activation in SCL measured by PMT vs. BLM (ion chamber) signal.

Installation of the new BLM system will make such residual activation measurement a standard procedure that will serve as additional guidance for tunnel surveys by radiation protection personnel.

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SUMMARY

The existing BLM system protects the SNS accelerator from beam related damage and controls residual activation by limiting average loss at specified 1 W/m level. The system covers all beam energies from 2.5 MeV to 1 GeV. The ionization chamber is the main detector used for MPS with dynamic range at least 10^5 and capable to measure down to 10^{-6} of fractional loss. It is capable to support beam power upgrades of at least doubling of beam power.

Low energy loss is hard to control with radiation detectors and other MPS devices are used in combination with the BLMs such as the differential BCM [10]. BLM systems are the main mechanism to trip errant beam; SCL downtime reduced by factor of six over last several years of operation by understanding causes of errant beam trips [1,10].

The system has proved to be quite reliable since SNS started operation in 2006. Total beam down time due to BLM malfunction is less than 12 hours; most of the downtime is related to software issues and VME power supplies failures.

Electronics obsolescence, including the ADC boards being discontinued, demands a system redesign. X-ray radiation from cavities presents an issue for hardware-implemented protection. Multi-channel AFE boards require beam shutdown for repair or troubleshooting. New FPGA-based [11] BLM system that will address the majority of these issues is currently under development.

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