RAD-HARD LUMINOSITY MONITORING FOR THE LHC*

J. F. Beche, J. M. Byrd, K. Chow, P. Denes, W. Ghiorso, H. S. Matis, M. Monroy, A. Ratti, S. de Santis, W. C. Turner, LBNL, Berkeley CA, USA
E. Bravin, CERN, Geneva, Switzerland
P. F. Manfredi, W. Vandelli, Univ. di Pavia, Pavia Italy

Abstract

Luminosity measurements at the high luminosity points of the LHC are very challenging due to the extremely high radiation levels in the order of 180 MGy/yr. We have designed an ionization chamber that uses a flowing inorganic gas mixture and a combination of metals and ceramics. With such a choice, an additional challenge is achieving the necessary speed to be able to resolve bunch-by-bunch luminosity data. We present the design, analysis and experimental results of the early demonstration tests of this device.

INTRODUCTION

The LHC beam luminosity monitor is a gas ionization chamber that observes minimum ionization particles (MIPs) near the shower maximum in the zero degree neutral particle absorbers (TAN) of IPs 1 and 5. The shower energy, measured by suitable detectors in the absorbers is proportional to the energy flux of neutral particle collision fragments from the IPs and, therefore, to the luminosity. The principle lends itself to a luminosity measurement on a bunch-by-bunch basis. While simple in principle, the system must comply with extremely stringent requirements. On one side, its speed of operation must match the 40 MHz bunch repetition rate of LHC. On the other, the detector must stand extremely high radiation doses.

In order to cope with these requirements, we have designed a multi-gap, flowing gas ionization chamber, where no active and only few passive components will be installed on the main path of the shower. The gas ionization chamber with an Ar plus N_2 mixture was chosen because of its radiation resistance.

To preserve the speed of the signal, we need to install the front end analog amplifiers in the LHC tunnel close to the ionization chamber. A low noise active termination properly prevents signal reflections and is integrated in the front end amplifier, together with a driver to transmit the analog signal back to the counting building, where the signal is shaped and digitized.

SYSTEM REQUIREMENTS

CERN has defined the system requirements for luminosity monitors, which are referred to as Beam Rate of Neutrals (BRAN) [1]. The highlights of these specifications are a relative luminosity signal stable to 1%, bunch-by-bunch measurement capability, crossing angle measurements and 'reasonable integration times', where several tens of seconds is considered acceptable.

CONCEPTUAL DESIGN

The extreme radiation levels seen by the detector determine the technical approach of using a gas ionization chamber. In this case, we are only allowing ceramics, metals and passive components to be in the path of the hadronic shower. Flowing the gas further ensures radiation hardness.

The number of gaps is chosen by trading off between signal strength, proportional to the number of parallel gaps, and speed, which is negatively affected by the larger capacitance shown by the parallel gaps. The final compromise, supported by MAGBOLZ modeling, is to use 6 gaps of 1mm each. Table 1 summarizes the baseline parameters of the device.

To allow for crossing angle calculations, the LUMI detector is segmented into four electrically isolated chambers, so that a rough position measurement of transverse position of the IP can be made. As the ionization chamber is designed to operate with the pressure in the range from one to ten atmospheres, a pressure vessel encloses the full detector.

Table 1 – Ionization chamber main parameters

Quadrant area,mm^2	1600
Gap between plates,mm	1.0
No. of gaps in parallel	6
Gas	Ar(94%),N_2(6%)
Gas pressure, atmos abs	6
Ioniz pairs/mip-mm	58.32
E/p, V/mm-atm	200
Gap voltage, V	1200
Electron drift velocity, mm/μsec	45.0
Amplifier/Shaper gain, μV/e-	0.16
rms noise,mV	1.24

The gas mixture must feature an adequately high electron drift velocity, without using organic molecules that may polymerize under the effect of radiation. We opted for a mixture of Argon with a few percent of Nitrogen. The charge yield in the shower detection can be raised to the desired value by acting on the pressure of the filling gas. The nominal gas mixture is 94% Ar + 6% N_2 at a pressure of 6 atmospheres. At this pressure, the HV

*This was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Department of Energy, under Contract No. DE-AC02-05CH11231

bias on the ionization chamber plates will be 1.2 kV and vary linearly with pressure to maintain a constant ratio of electric field to pressure – E/p = 200 V/mm-atm.

At LHC's total design luminosity of 10^{34} $cm^{-2}s^{-1}$ and 3.6×10^{30} $cm^{-2}s^{-1}$ per bunch, we estimated an average of 6,800 minimum ionizing particles (MIPs) incident on the ionization chamber. At the operating gas pressure, the mips will produce a mean ionization electron charge $2.4 \times 10^6 e^-$.

MARS modeling

Extensive modeling has been done at FNAL to study the radiation levels on both interaction regions using the MARS code [2]. We received tremendous benefits from the results of such studies, as they guided several technical decisions on material choices, radiation damage studies of materials as well as the location of the front end electronics. These simulations show how the peak power density reaches 22.5 mW/g or 180 MGy/yr at shower maximum at 17 cm in the core, as well as 1kGy/yr at the surface of the TAN, where our electronics will be located.

MECHANICAL DESIGN

Detector design

The ionization chamber is designed with a single ground plane electrode in a four-quadrant comb structure. Four independent signal combs interleaved with the ground plane comb provide six 1-mm gaps each. A precision-machined housing made of mica-glass composite structurally supports the ground plane comb and signal combs.

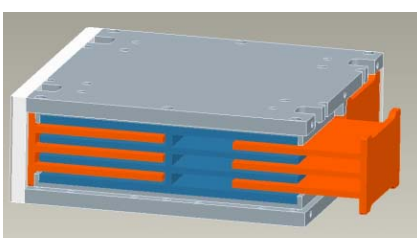

Fig. 1 – Detector ceramic housing and copper plates

Detector housing

The ionization chamber is mounted onto the end of a 605 mm long copper bar with a stainless steel end flange, and subsequently inserted into a stainless steel pressure case. The complete assembly is almost exactly the size of one of the copper bars in TAN, with all of the electrical and gas feedthroughs on the top flange.

The argon and nitrogen gas mixture is directed to the ionization chamber from the assembly top flange by way of a tube and holes in the ionization chamber walls. For a gas flow rate of 1 liter per hour (at 10 atmospheres), the flow is laminar and the pressure drop between the inlet and outlet of the assembly is less than 0.2 psi. This gas flow rate yields 1 volume change per hour inside the full assembly.

Gas supply

Gas is supplied to the luminosity monitor assembly from premixed gas bottles residing in a locked cage at the bypass tunnel area. A change-over panel and a gas distribution rack provides uninterrupted gas supply and remote control of pressure and flow rate to the monitor. The gas bottles require replacement once every 1 to 2 months. Although the gas distribution rack is about 150 meters from the monitors, the total pressure drop is less than 0.1 psi due to the low flow rate.

TAN installation

The luminosity monitor assembly is mounted to TAN using the same mounting holes as used by the copper absorber bars. Ceramic spacers are used to isolate the monitor assembly, and the complete assembly is also plasma coated with ceramic. Fig. 2 shows the detector housing and front end electronics in the TAN.

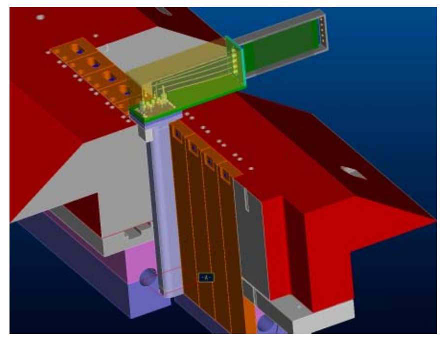

Fig. 2 – TAN installation

ELECTRONICS DESIGN

The electronics readout comprises two separate parts, the analog processing electronics installed in the tunnel, connected to the analog shaper and the digital backend, installed in the USA15 and US55 service areas.

Front end pre-amplifiers

The detector signal is a current pulse with a fast rise time and a long linear decay time [3]. The analog electronics performs a charge measurement by integrating that pulse. The LHC tunnel installation requirements impose the use of rad-hard cables between the detector quadrants and the electronics readout channels. The front-end stage is made of a charge sensitive preamplifier implementing a cold-termination technique. The time constant associated with the quadrant's capacitance and the preamplifier's input impedance is the dominant pole of the system. The main challenge of the front-end stage is to maintain a peaking time shorter than the 25ns bunch period to avoid pile-up effects that could not be compensated for. The preamplifier is built around a classic folded cascode stage followed by a gain and buffer stage to send the signal to the shaping amplifier.

Shapers and signal distribution

The shaping amplifier's main function is to reduce the time occupancy of the preamplifier signal to less than 25ns. The shaper's design has evolved through several iterations to a two-pole shaper, benefiting from the well known pole-zero (PZ) cancellation scheme. The zeros cancel two poles, one associated to the detector capacitance and the preamplifier's input impedance and the other associated to the preamplifier's feedback network. The poles of the shaper implement a pseudo-gaussian function built using a Sallen-Key low-pass filter configuration. Proper pole-zero compensation is essential in order to optimize the return of the signal to the baseline and each zero is implemented with PZ compensation capabilities. The shapers will be implemented on a single board in the final system. The shaped signals from the quadrants will also be summed in an analog fashion to provide the total charge measurement and also partial sums and differences to compute the center of mass information. Once the signals for the individual quadrants are processed, they are buffered and distributed to the digitizers as well as to local diagnostic ports. We are also sharing such signals with the ZDCs of LHC's experiments, to cross calibrate our measurements.

Digitizers

The digitization of those analog signals will be performed using the IBMS board developed by the AB/BI group at CERN. The IBMS boards have been developed as mezzanine boards for the DAB64x, a VME64x Data Acquisition Board developed by TRIUMF for LHC beam instrumentation [4]. Such board provides a very flexible platform for signal processing combining a good amount of on-board memory with the flexibility and processing power of the Altera Stratix family of FPGAs. Dedicated firmware running on the DAB64x will be developed to control the instrument and to process the data from the Luminosity Monitor.

Once digitized and processed, the resulting values are shared and made available to the control room and the community through the LHC control system.

R&D PROGRAM

Due to the demanding requirements of the system, we completed an R&D program that included testing at CERN in the SPS, as well as at the ALS.

High speed demonstration

25 ns resolution is a very critical feature that has been demonstrated using a custom designed this housing and hard X-rays at a beamline at the ALS. This allowed us to validate the modeling as well as to demonstrate full signal processing within the desired 25 ns. Minor pileup still remains which so we'll have to deconvolve it [5].

Rad hardness studies

Due to the extreme levels of radiation, we have two radiation damage tests underway, one at BNL using the high intensity beam at the RHIC linac, and one at the CERN ISOLDE ion source facility. The results of these tests, due later this summer, will guide us towards a final materials choice for the detector elements.

RHIC experiments

Taking advantage of the present RHIC run, we have installed our prototype in the BNL collider, and are prepared to monitor collisions and compare them with the results of the nearby Zero Degree Calorimeters. This provides a test bed for the device in a hadron collider environment, allowing us to develop an understanding of the device and its performance in preparation for LHC commissioning.

CONCLUSIONS

The luminosity monitor is under construction and will be available for LHC operations. Great care has been taken to ensure the most suitable approach is chosen to cope with the extreme levels of radiation. While the basic R&D has demonstrated the feasibility of the system, an ongoing program continues to allow system development and ensure

ACKNOWLEDGMENTS

The list of collaborators across the community is too long to mention all. Selecting a few, the authors are particularly grateful for the help of N. Mokhov, who has provided all MARS modeling and helped us setup our own system. Similarly we are extremely thankful of N. Simos of BNL and R Catherall of CERN, who are independently testing our passive components in their rad damage test facilities as well as D. Bishop of TRIUMF for his support of the DABIV environment. The BNL CAD department has allowed us to install and test our detector in RHIC; these tests were done under the leadership of A. Drees.

REFERENCES

[1] "Measurement of the relative luminosity at the LHC" - LHC-B-ES-0004, Nov. 2003

[2]- N. Mokhov, et al., "Protecting LHC IP1/IP5 Components Against Radiation Resulting from Colliding Beam Interactions", FNAL TN –732, and updates at www/cern.ch/tan

[3] Initial Test results of an ionization chamber shower detector for an LHC luminosity monitor, P.S. Datte et al. IEEE Trans. on Nuclear Science Vol 50, 258 (2003)

[4]- "VME64x digital acquisition board for the LHC trajectory and closed orbit system" - LHC-BP-ES-0002, March 04

[5] J. Byrd, et al, "High speed measurements of the LHC luminosity monitor" – Beam Instrumentation Workshop, FNAL, May 2006