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Upgrade of the DØ Luminosity Monitor Readout System

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***Abstract*— We describe upgrades to the readout system for the DØ Luminosity Monitor. The DØ Luminosity Monitor consists of plastic scintillation detectors with fine-mesh photomultiplier readout that cover the pseudorapidity range $2.7 < |\eta| < 4.4$. The detector is designed to provide a precise measurement of the rate for non-diffractive inelastic collisions that is used to calculate the TeVatron luminosity at DØ. The new readout system is based on custom VME electronics that make precise time-of-flight and charge measurements for each luminosity counter. These measurements are used to identify beam crossings with non-diffractive interactions by requiring in-time hits in both the forward and backward luminosity counters. We have also significantly increased signal/noise for the photomultiplier signals by developing a new front-end preamplifier and improving the grounding scheme.**

***Index Terms*— D-Zero, TeVatron, Luminosity, Preamplifier, VME.**

I. INTRODUCTION

THE DØ Luminosity Monitor (LM) measures the TeVatron luminosity by identifying beam crossings containing non-diffractive inelastic proton-antiproton collisions [1]. The LM consists of two arrays of scintillation counters located on the inside face of the end-cap calorimeters, 140 cm from the center of the DØ detector along the z direction (beam axis), and arranged symmetrically about the beam pipe. The detector covers the pseudorapidity range $2.7 < |\eta| < 4.4$, providing an acceptance of 98% for non-diffractive inelastic collisions. Each of the LM arrays consists of 24 identical 1.6 cm thick BC-408 scintillator [2] wedges, with Hamamatsu HPK R7474 [3] 1" diameter fine-mesh photomultiplier tubes (PMTs) mounted directly on the face of the scintillator (Fig. 1).

The LM readout system is designed to:

(i) Identify non-diffractive inelastic p-$\bar{p}$ collisions,
(ii) Identify beam crossings with beam halo, and
(iii) Provide trigger input terms for the Level 1 Trigger.

Inelastic p-$\bar{p}$ scattering and beam halo can be distinguished by time of flight (TOF). In the north (south) LM array, particles from (anti-)proton halo showers hit the LM counters ~ 9.5 ns earlier than particles from inelastic p-$\bar{p}$ interactions, allowing beam crossings with halo to be identified by TOF. To measure the TeVatron luminosity, scalers in the Level 1 Trigger Framework are used to count the number of detected inelastic p-$\bar{p}$ interactions, with each beam bunch having its own scaler. These scalers are used to calculate the measured rate for beam crossings that do not have an inelastic p-$\bar{p}$ interactions, and the luminosity in each beam bunch is calculated using Poisson statistics. This approach avoids the difficulty in counting multiple p-$\bar{p}$ interactions in a single beam crossing.

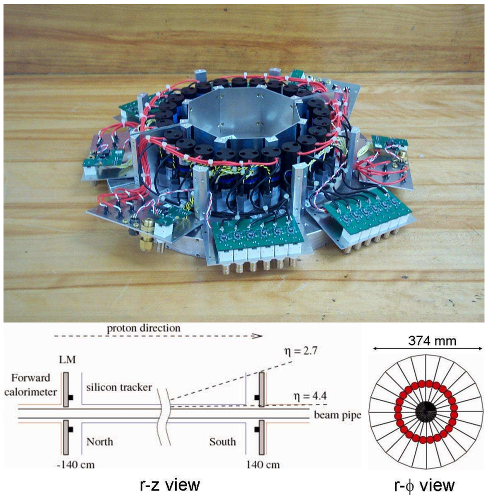

Fig. 1. Top: Photograph of the Luminosity Monitor detector (single side, 24 counters). The PMT and HV divider assembly is visible behind the preamplifier boards. Bottom: rz and $r\phi$ view of Luminosity Monitor detector.

II. LM READOUT SYSTEM

The LM readout system consists of two parts, the front-end electronics mounted on the detector and the readout electronics located in the Moving Counting House (MCH). At the front-end, the LM scintillators are read out using Hamamatsu fine-mesh photomultiplier tubes, which have a gain of $\sim 10^4$ in the local 1 T magnetic field and produce a 10 ns long current pulse. Preamplifiers with 50 ohm input and output impedance further amplify this signal by a factor of 60.5, and are described in Section III below. The resulting signal is then sent to the MCH on high-quality LMR-400 cable, with shorter segments of the more flexible LMR-240 (RG-58) on the detector (MCH) ends. The total cable length is about 200 ft. In the MCH, a patch panel passively divides the signal, with 10/11 of the signal going to VME-based electronics and 1/11 of the signal going

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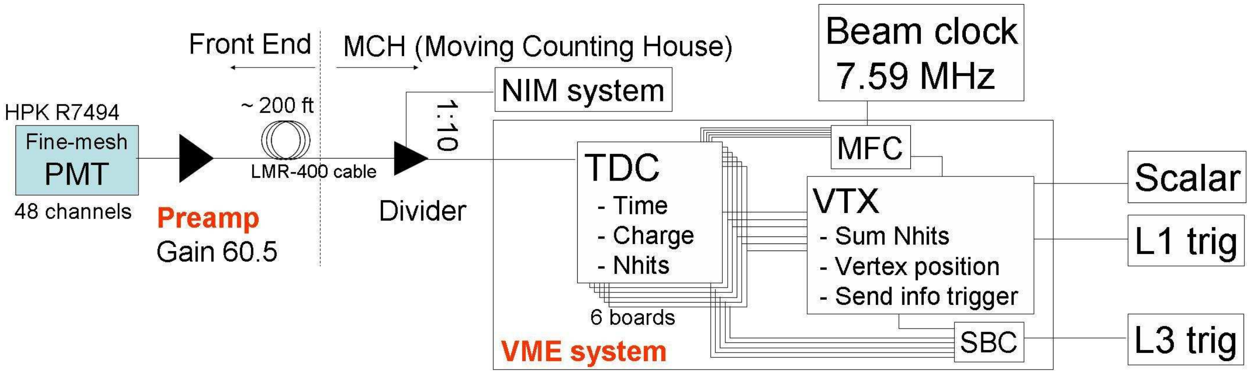

Fig. 2. Overview of the LM readout system.

to the NIM-based electronics. Thus, the VME (NIM) signal is amplified by a factor of 55 (5.5) relative to the PMT output.

In the NIM-based system, the 24 PMT signals in each luminosity detector are are summed by linear Fan-In/Fan-Out modules and discriminated by a constant fraction discriminater. A cut on the time difference between the discriminater outputs for the two detectors is used to identify inelastic collisions. There are some disadvantages in NIM based system: (i) the very large dynamic range of the analog sum signal leads to saturation for large signals and inefficiency for small signals, (ii) beam crossings where one or more particles hit the luminosity counters early in time fail the timing cut, introducing deadtime in the luminosity measurement, and (iii) the lack of charge and time measurements for each PMT did not allow extensive system monitoring. Use of the NIM-based system as the primary luminosity measurement for the DØ experiment was discontinued on 20 October 2005 in favor of the VME-based system described in Section IV below.

III. NEW PREAMPLIFIER MODULE

During the March $\sim$ May 2006 TeVatron shutdown, the preamplifier boards in the LM detectors were replaced. The new preamplifier has two non-inverting stages, each with a gain of 11, and is based on the fast low-noise operational amplifier, AD8099. The preamplifier is back-terminated to minimize signal reflections and provides a net gain of 35.5 dB at 48 MHz and a -3 dB bandwidth of 243 MHz. The output noise level is $\sim$100nV/$\sqrt{\text{Hz}}$, as shown in Fig. 3. An offset adjustment circuit allows the nominal DC offset voltage to be zeroed, with a residual temperature dependent offset of 140 μV/$^\circ$C at the preamplifier output, which is small compared to the 30 mV discriminator threshold.

A. Comparison with old preamplifier

The old preamplifier was based on AD8009 in a single-stage non-inverting configuration. The net gain was 5.5, with no offset adjustment made at the preamplifier. At the MCH, the signal was equally divided between the NIM and VME systems, and commercial NIM linear fan-in/fan-out and x10 amplifier modules in the MCH were used to remove the DC offset voltage and increase the net gain to 27.5. Figure 4 shows that the pedestal width for a 132 ns integration time is 1.6 pC for the old system and 0.4 pC for the new system. Taking into account gain differences (x27.5 vs x55), the noise level of new system is a factor of 8 lower than the old system. This improvement is due to minimizing the impact of downstream noise sources (such as cable pickup) by increasing the front-end gain, eliminating the commercial NIM modules, and improving the detector grounding scheme.

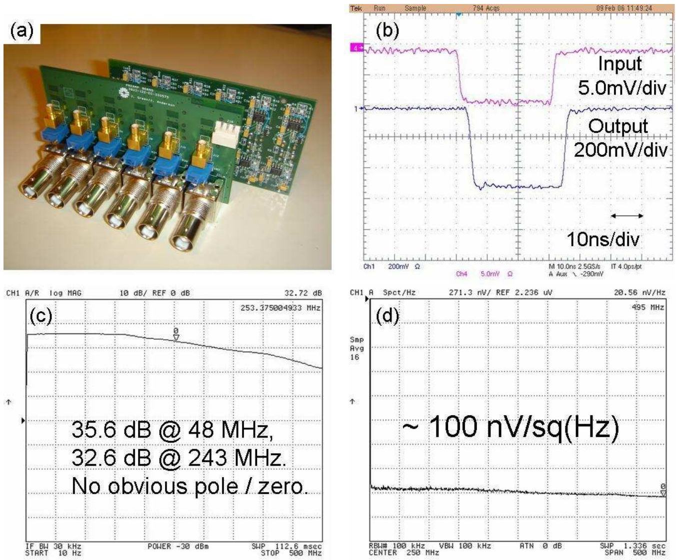

Fig. 3. (a) Photograph of new preamplifier. Input connectors are SMB and output connector are BNC. (b) Pulse shape. The vertical scale is 5 mV/division (200 mV/division) for the input (output) pulse. The horizontal scale is 10 ns/division. (c) Frequency dependence of gain. No obvious pole or zero is seen. (d) Frequency dependence of Noise. No obvious peak is seen

IV. LM VME READOUT SYSTEM

Two types of readout boards are needed for the LM electronics: the LM Timing (TDC) board and the LM Vertex (VTX) board. The TDC board digitizes and processes eight PMT signals. A total of six TDC boards are used to readout the LM, three each for the north and south arrays. A single VTX board processes the signals generated by the TDC boards and

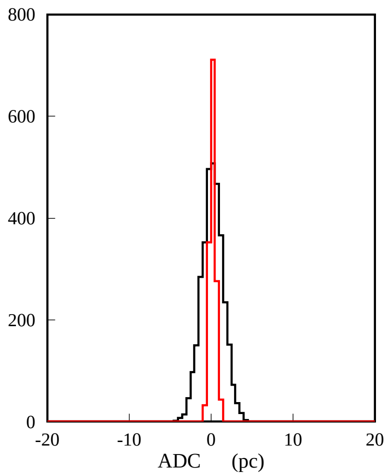

Fig. 4. Pedestal distribution of new (red) and old (black) system.

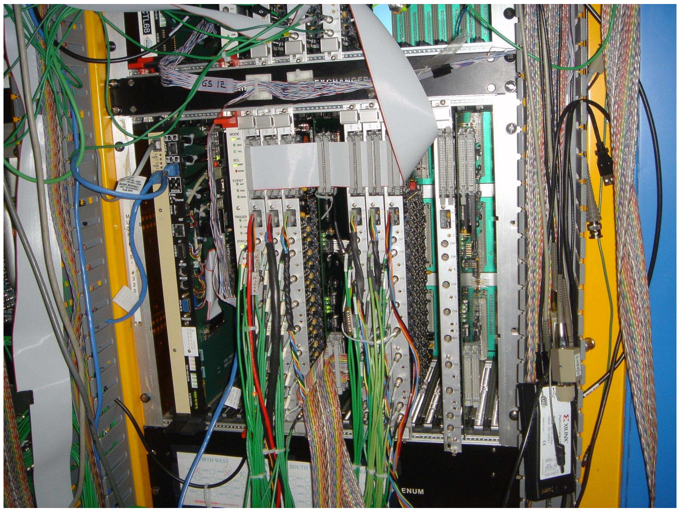

Fig. 5. Photograph of LM VME crate. From left to right are the PowerPC, SBC, MFC, three LM TDC board for the north (-z) detector, LM VTX board, and three LM TDC board for the south (+z) LM detector.

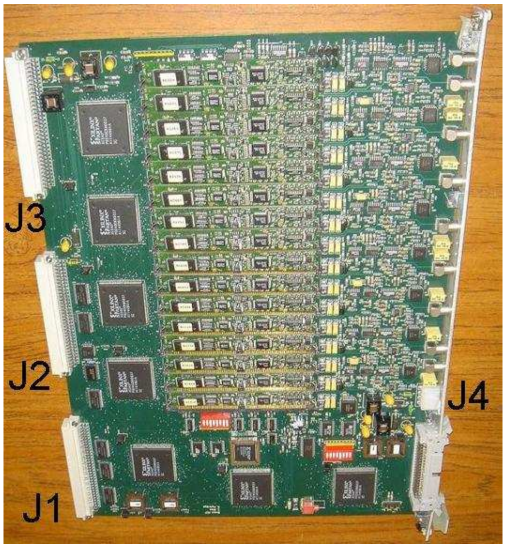

Fig. 6. Photograph of a LM TDC board.

sends the processed data to the Level 1 Trigger Framework. The processed data is also readout by the DAQ system for triggered events.

The TDC and VTX boards reside in a 9U 280 mm deep VME crate. The crate has a standard DØ muon backplane and contains a PowerPC crate processor, a Single Board Computer (SBC) that provides the DAQ readout, a Muon Fanout Controller (MFC) that distributes timing signals and provides readout control, six LM TDC boards, and one LM VTX board. The TDC and VTX boards are designed to emulate Muon Readout Cards (MRC) used by the muon system [4].

A. *TDC Board*

The TDC board accepts eight photomultiplier signals and a common stop signal via front-panel LEMO connectors. The primary role of the TDC board is to precisely measure the time a particle strikes the scintillator.

Time-of-flight measurement is performed on each channel using a Time-to-Charge converter based on switching on a current source when the PMT signal crosses a programmable threshold and switching off the current source when the common stop signal is detected. The charge from the switched current source is integrated and digitized using a CAFE card [5] developed for the CDF calorimeter readout. Each CAFE card includes a QIE multi-range pipelined charge integrator, a 10 bit ADC, and a lookup table with a 16 bit output. The lookup table for the Time CAFE is programmed to return a calibrated time measurement with a 50 ps lsb.

The integrated charge of the PMT signal is measured by a second CAFE card. The lookup table for the Charge CAFE is programmed to return a time-slewing correction and a multi-range charge measurement with 0.5 PC lsb for the most sensitive range. The time-slewing correction from the Charge CAFE is added to the time measurement from the Time CAFE to produce a slewing-corrected time-of-flight measurement.

The TDC board identifies both in-time hits and halo (early) hits by applying programmable cuts on the slewing-corrected time measurement. Currently, in-time hits are identified when the time is within 6.4 ns of the nominal value, while halo hits are those with earlier times. The TDC board also calculates several quantities used by the VTX board, including the number of in-time hits, the number of halo hits, and the sum of the slewing-corrected times for the in-time hits. These sums are calculated using a daisy chain approach, where each TDC board adds the value for it's own board to the sum from the previous board, and outputs the new sum onto a 40-conductor flat cable.

In order to realize these functions, the TDC board uses seven Xilinx Spartan FPGAs (Xilinx XCS40PQ240-3), as shown in Fig. 6. Four FPGAs provide the processing and readout buffering of the CAFE data (two channels per FPGA), one

FPGA is used to perform the sums used by the VTX board, one FPGA is used to handle synchronization and reaout buffering for the slewing-corrected times, and one FPGA provides the VME interface.

B. LM VTX Board

The VTX board receives the calculated quantities from the TDC boards via two 40 pin flat cables. One cable carries the information from the north (-z) LM detector and the other cable carries the information from the south (+z) LM detector. The most important role of the VTX board is to calculate the luminosity and halo signals that are sent to the Level 1 scalers, upon which the DØ luminosity calculation is based. The VTX board also calculates the position of the primary interaction vertex, generates input signals for the Level 1 trigger decision, and provides a histogramming facility for calibration and monitoring.

Beam crossings containing halo particles are identified by placing a cut on the number of halo (early) hits found by the TDC boards. Proton (anti-proton) halo is currently identified by requiring at least three halo hits in the north (south) LM detector.

The interaction vertex position ($\mathrm{z_v}$) is calculated from the the time difference between hits in the north and south LM detectors. The average north (south) time T_N (T_S) is calculated by dividing the sum of the north (south) slewing-corrected times for in-time hits by the number of north (south) in-time hits. The vertex position is then calculated from the average times

$$\mathrm{z_v} = \frac{\mathrm{c}}{2}(\mathrm{T_N} - \mathrm{T_S}) \tag{1}$$

where c is velocity of light.

The DØ luminosity signal is asserted if there is at least one in-time hit in both the north and south detectors, the crossing is not identified as having proton or anti-proton halo, and the vertex position satisfies the cut $|z_v| < z_{cut}$ (currently, z_{cut} is set to 190 cm, effectively eliminating this cut). Beam crossings with either proton or anti-proton halo are vetoed in the luminosity measurement because only the first hit is measured by the LM TDC, so an early hit can mask the presence of an in-time hit in that counter. It is observed that some crossings have halo hits in all or almost all counters, producing a small deadtime in the luminosity measurement. At high luminosity $\sim 200e^{30}\mathrm{cm^{-2}s^{-1}}$, the fraction of beam crossings that satisfy the luminosity requirement is ~99.6%, so even a small deadtime can significantly change the measured luminosity if it is not properly accounted for. By explicitly vetoing beam crossings with halo, we can accurately account for and correct for this deadtime.

The VTX board has a single Xilinx Virtex FPGA, Xilinx XCV600E, that provides the processing for the LM VTX board (see Fig. 7).

C. Benefits of VME system

The VME-based luminosity system provides a number of advantages over the NIM-based system. Each PMT is individually discriminated, providing a much smaller dynamic range and that allows inelastic interactions to be identified with nearly 100% efficiency. The time-of-flight and charge measurements allow monitoring of the gain and timing on a channel-by-channel basis. Furthermore, the distribution for the multiplicity of counters with in-time hits has proven to be a valuable tool in developing an accurate MC model for the detector and determining the fraction of diffractive collisions present in our data. Figure. 8 shows the excellent agreement between MC and data that has been achieved.

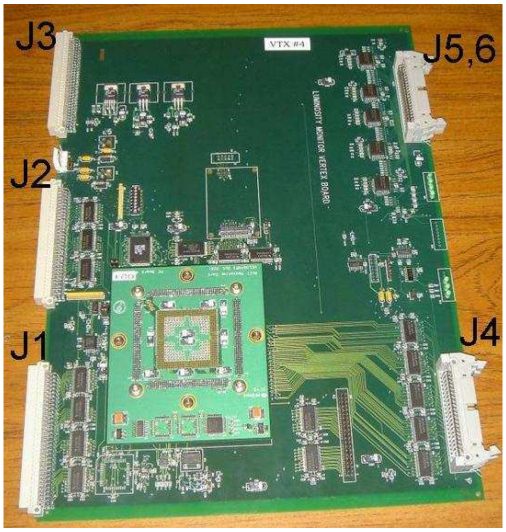

Fig. 7. Photograph of a LM VTX board.

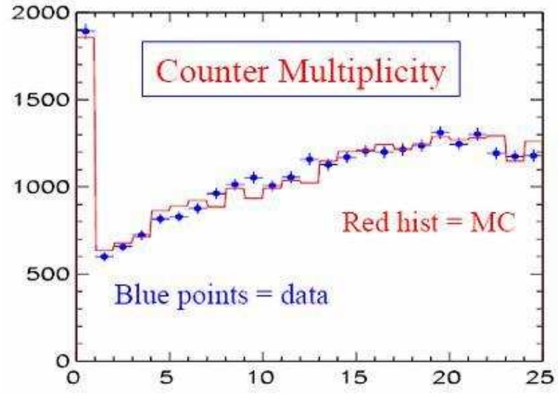

Fig. 8. Multiplicity distribution for the number of counters on the north side with in-time hits.

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