The Time-of-Flight Trigger at CDF

G. Bauer M.J. Mulhearn Ch. Paus P. Schieferdecker S. Tether

Massachusetts Institute of Technology,
Department of Physics, Laboratory for Nuclear Science,
Bldg. 26-505, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, U.S.A.

J.D. Lewis, T. Shaw

Fermi National Accelerator Laboratory,
PO Box 500, Batavia, IL 60510-500, U.S.A.

D. Acosta J. Konigsberg A. Madorsky

University of Florida,
Department of Physics, P.O. Box 118440, Gainesville, FL 32611-8440, U.S.A.

Abstract

The Time-of-Flight (TOF) detector measures the arrival time and deposited energy of charged particles reaching scintillator bars surrounding the central tracking region of the CDF detector. Requiring high ionization in the TOF system provides a unique trigger capability, which has been used for a magnetic monopole search. Other uses, with smaller pulse height thresholds, include a high–multiplicity charged–particle trigger useful for QCD studies and a much improved cosmic ray trigger for calibrating other detector components. Although not designed as input to CDF's global Level 1 trigger, the TOF system has been easily adapted to this role by the addition of 24 cables, new firmware, and four custom TOF trigger boards (TOTRIBs). This article describes the TOF trigger.

Key words: Time-of-Flight, Trigger, CDF, Highly Ionizing Particle
PACS: 07.50.-e

1 Overview

The Collider Detector at Fermilab (CDF) is used to study $p\overline{p}$ collisions at $\sqrt{s} =$ 1.96 TeV. Beam crossings occur at 396 ns intervals, but the CDF electronics are based on a 132 ns clock cycle to accommodate a possible accelerator upgrade. At this rate, recording every event is impossible, so CDF uses a deadtimeless trigger to select the most useful events. The trigger is a three tiered system, as shown in Figure 1. The readout electronics for each detector component holds the event data in a digital pipeline, awaiting a global Level 1 trigger decision. The Level 1 decision is based on a small subset of the event data processed rapidly by custom electronics. A Level 1 accept directs the data to one of four Level 2 buffers, buying additional time for the Level 2 trigger decision, which is based on a larger subset of the event data. A Level 2 accept is followed by a readout of the whole event data from the Level 2 buffer. The data from all the detector components is assembled by the event builder and sent to a PC farm. At this stage, nearly complete event reconstruction is available for the Level 3 decision. Level 3 accepted events are written to tape.

In addition to tracking, calorimetry and muon systems, the multipurpose CDF detector [1] includes a Time-of-Flight (TOF) detector [2] to aid in particle identification. The TOF detector, composed of scintillator bars oriented parallel to the beam line, forms a cylinder just outside the tracking system and inside the 1.4 T solenoidal magnetic field (see Figure 2). In order to adequately distinguish pions and kaons, 100 ps timing resolution is required. As one step in reaching this resolution, the TOF system makes a charge measurement to correct discriminator threshold effects on the timing measurement. This charge measurement, proportional to a particle's ionization, has been used to provide three new physics triggers for the CDF global Level 1 trigger. The highly ionizing particle (HIP) trigger checks for abnormally large pulses, a signature of magnetic monopoles. The minimum ionizing particle (MIP) trigger requires that the total number of normal sized pulses is within a specified range. The TOF cosmic trigger requires two nearly back-to-back MIP hits in the TOF system.

An overview of the TOF trigger hardware is presented in Figure 3. The TOF scintillators form a cylinder around the tracking region; each 15° wedge contains nine TOF scintillator bars. The bars are instrumented on both ends with photomultiplier tubes (PMTs) and dual range pre-amplifiers. The pre-amplifiers make the PMT signal more robust for transmission and extend the dynamic range. An initial linear region at high gain is followed by a short non-linear transition region, then a second linear region at lower gain. The high gain region is intended for typical pulses from ordinary particles, the second low gain region is to avoid saturation for highly ionizing particles.

The digitization of the pre-amplified PMT pulses is done by TOF Transition (TOMAIN) and ADC/Memory (ADMEM) boards, as described in Section 2. Field Programmable Gate Arrays (FPGAs) in the ADMEMs set trigger bits for pulse heights larger than MIP and HIP thresholds.

Additional logic is performed by the special purpose TOF trigger board (TOTRIB), which collects data from TOF ADMEMs and checks for coincidences of pulses above HIP and MIP thresholds on both the east and west sides of TOF scintillator bars. The full coincidence data has five bits per nine TOF scintillator bars, but by combining multiple channels, coincidences are calculated at coarser granularity for Level 1 track matching and the TOF cosmic trigger. The TOTRIB also counts the number of MIP coincidences.

Using dedicated channels in the muon trigger system, HIP east-west coincidences from the TOTRIB can be matched to rapidly reconstructed drift chamber tracks found by the XFT track processor [3]. The high density of inputs to the muon trigger requires the use of serial fiber optic links, prepared by Muon Transition Cards (MTCs). The TOTRIB simplifies the muon match card (Matchbox) programming by providing coincidence data at the same granularity as the extrapolation (four bits per 30°).

At present, some features of the HIP trigger are not needed to control the rate. The extrapolation bits are always high, to override the track matching requirement. This means that any HIP coincidence causes the trigger to fire. Also, although the muon match cards report the full granularity coincidence data to the global Level 2 trigger, no special Level 2 trigger is needed. A Level 1 TOF HIP trigger causes an automatic Level 2 and Level 3 accept.

At CDF, each trigger component uses specially programmed Level 1 interface cards, called PreFRED cards, to set the global Level 1 trigger bits appropriately. Because the TOF HIP trigger uses the Muon system, the TOF HIP trigger bit is set by the Muon PreFRED. Data for the two TOF MIP triggers are processed in a PreFRED card shared with the forward detectors.

2 TOMAIN and TOF ADMEMs

The signal from TOF PMTs is digitized on ADC/Memory (ADMEM) modules [1]. The ADMEM's versatile design has allowed it to work for many subsystems at CDF, mainly calorimeters. In order to work for TOF, a specially designed transition card (TOMAIN) performs analog services on the PMT signals: converting the time interval between the PMT pulse arrival time and a common stop to an output voltage and converting the integrated charge of the PMT pulse into an output current pulse.

On the ADMEM, the current pulse digitization is normally made using the standard ADC cards (Cafe cards). The measurement is made with 10-bit precision, with additional range information making a wide 17-bit dynamic range after linearization. This precision is adequate for the TOF charge measurement, but not for the timing measurement, and so a replacement card is needed. Because the replacement 12-bit ADC requires neither the wide dynamic range or linearization features of the Cafe card, it is called the Decaf card.

The ADMEM receives the analog output signals from the TOMAIN card through the J3 connector of the VME backplane (see Figure 4.) Digitized charge measurements from the Cafe cards and time from the Decaf cards are sent to FPGAs on the ADMEM, which hold the results in the Level 1 pipeline awaiting a Level 1 accept, and in Level 2 buffers awaiting a Level 2 accept. The ADMEM contains 5 FPGAs for this purpose, each handling 4 input channels. In TOF ADMEMs, each FPGA handles two charge and two time measurements, except the last FPGA, which handles a single charge and time measurement, because the TOF ADMEM serves the nine bars of a 15° wedge.

These FPGAs also perform trigger logic. Because the TOF trigger logic is different from the Calorimeter trigger logic, new firmware was written to check whether the two charge measurements are greater than adjustable HIP or MIP thresholds. To limit costs, a single HIP output bit is set if either of the charge measurements exceeded its HIP threshold (and likewise for the single MIP output bit.) The logical `OR` is implemented in the ADMEMs trigger lookup table.

The ADMEM contains an additional FPGA which controls the VME interface for the board (see Figure 4.) Although the five trigger FPGAs require new firmware, it is desirable to leave the VME firmware unchanged. The trigger FPGAs require separate HIP and MIP thresholds for each channel, four values per FPGA, which need to be easily set through the VME interface. This is accomplished by co-opting the already existing single pedestal register on each FPGA; the trigger FPGAs interpret four successive writes to the pedestal register as the four thresholds.

The ADMEM trigger outputs, one for each of the ADMEM's five trigger FPGAs, were designed to output 10-bit calorimeter energy sums. The TOF trigger uses only 2 bits, a HIP and a MIP bit, from each 10-bit connector. Each 20 channel TOF trigger cable takes the output from two ADMEMs (10 connectors). To avoid ground loops, the shield is connected to the housing of the first connector on the first ADMEM only.

3 TOF Trigger Board

The TOTRIB is a 9U single wide VME board (see Figure 5). Low Voltage Differential Signal (LVDS) input, sent by the TOF ADMEMs, is taken from front panel connectors (A0-2, B0-2) and received on three coincidence unit FPGAs where the trigger logic is performed (see Figure 6). Each FPGA performs a bitwise `AND` on its corresponding east and west data; the resulting coincidence data is output through the J3 backplane connector in TTL. To allow for possible future extensions, it is also output to board mounted connectors C0 and C1 in LVDS.

The TOF cosmic trigger looks for back-to-back MIP hits in the TOF detector. This selects events where cosmic rays have passed through the center of the detector, useful for calibration and performance studies. The cosmic trigger uses 15° granularity MIP data, which is calculated on the TOTRIB from the full coincidence data with appropriate bitwise `OR`s and output on the front panel connector (A3) in LVDS.

The TOF multiplicity trigger requires the total number of MIP hits in the entire TOF to be within a specified range, usually just a lower limit. Each coincidence unit FPGA counts the MIP hits in its share of the data and the partial counts are combined on the central FPGA. This is accomplished using the same firmware on all three FPGAs by providing the outer two FPGAs with logical input counts that are permanently set to zero. The outer FPGAs send their output counts to the inner FPGA, which sends its output count to the front panel (B3) in LVDS.

The two MIP triggers share a Level 1 interface card (PreFRED) with several other detectors. Because the card has a limited capacity to synchronize inputs, the TOTRIB coincidence unit FPGAs use digital pipelines to delay the MIP output on the front panel a variable number of clock cycles. The original PreFRED firmware was extended to include the two MIP triggers. For the MIP multiplicity trigger, it adds the MIP counts from all four TOTRIBs and requires that the sum falls in a specified range. For the cosmic trigger, it checks the MIP scatter pattern for hits in opposite sides of the TOF detector.

The TOTRIB sends the HIP and MIP coincidence data to the transition card in TTL format through the backplane J3 connector. It is sent on the clock cycle immediately after the data is latched. All CDF VME crates share the 132 ns CDF clock, `CDF_CLK`, broadcast on the J2 backplane of each crate. To ensure that the rising edge of the clock sent to the transition card does not come while the data is invalid, the differential PECL `CDF_CLK` used by the TOTRIB is taken from the J2 connector, converted to TTL, given a programmable delay, and sent to the J3 connector.

The CDF bunch zero signal, CDF_B0, indicates that the first of 36 bunch crossings is occurring. Because the data takes several clock cycles to arrive at the TOTRIB, the CDF_B0 signal is not synchronized with the data. The TOTRIB latches it, applies a programmable integer delay, and sends it to the transition card along with the coincidence data. When the CDF_B0 bit is high, the corresponding data is from the first bunch crossing.

To handle problems with the data acquisition, additional control signals are used to halt and recover: CDF_HALT and CDF_RECOVER. The Muon Transition Card uses the period after a CDF_RECOVER is issued to calibrate the fiber optic serial links that transmit data to the Muon Matchbox, so the TOTRIB latches the CDF_RECOVER signal and extends it for a variable length of time. The CDF_HALT signal is merely latched on the TOTRIB. Both modified signals are sent to the transition card through the J3 connector.

The TOTRIB has an additional FPGA dedicated to VME services, using the J1 backplane connector according to the VME specifications. Most of the board parameters are set through the VME interface:

- TOTRIB_CLKDELAY : The phase delay of the clock signal sent to the transition card.
- TOTRIB_B0DELAY : Number of clock cycles to delay the CDF_B0 signal for data synchronization.
- TOTRIB_RCVRLNG : Number of clock cycles to extend the CDF_RECOVER signal sent to the transition card.

Other board parameters are implemented as IEEE 1149.1 boundary scan (JTAG) registers. The VME interface allows access to the JTAG chain connecting the coincidence unit FPGAs to the VME FPGA. This requires the driver code to apply the appropriate steps to use the JTAG state machine: resetting the state, writing the instruction register a read or write command, then reading or writing the data register. The JTAG data mask register specifies input channels to ignore in case of hardware failure. The JTAG control register contains board parameters needed by the coincidence units:

- TOTRIB_PIPELENGTH: The length of the Level 1 digital pipeline.
- TOTRIB_MIPDELAY : Number of clock cycles to delay the MIP output.

The VME interface allows readout of diagnostic data by the CDF data acquisition system; the required CDF-specific signals are received on the J2 backplane connector. At each clock cycle the data calculated by each coincidence unit is placed in a digital pipeline, with a length specified by TOTRIB_PIPELINE. The data emerging from the pipeline is synchronized with the Level 1 Accept (L1A) signal; upon receipt of a L1A, the data is stored in one of four Level 2 buffers. Upon a Level 2 Accept, the readout of the data commences. The VME interface presents a virtual L2 VME buffer according to the CDF standard. As each word in the L2 buffer is requested, the VME FPGA assembles it from 8-bit installments extracted from the real buffers contained in the coincidence unit FPGAs. This somewhat slow approach is possible because the TOTRIB contains relatively little data; the readout time is dominated by other detectors with much larger buffers.

4 Calibration

The TOF HIP trigger thresholds have been adjusted to ensure that the total trigger rate operates at less than 0.5 Hz and every channel contributes equally to the rate.

Because the trigger requires a large pulse in both sides of a TOF bar, the east and west thresholds cannot be determined separately, but must be chosen simultaneously to control the rate democratically for the east and west. The east and west charge distribution (Q_e and Q_w) of a typical bar for minimum bias data is shown in Figure 7. It is divided into regions of

$$Q_{sym} = \sqrt{Q_e Q_w}$$

and the center of gravity for each region is found (circular markers). Requiring the choice of trigger thresholds to be along lines connecting center-of-gravity points ensures that the trigger requirement is not too far to the east or west. With this constraint, it is just a counting exercise to determine the rate at each point from data.

There is not enough minimum bias data to determine the low rate thresholds, so an iterative procedure is used. Data is taken with a high rate threshold, gathering data in the high charge region beyond the reach of the original sample, and a new lower rate threshold is chosen. More iterations are performed until the desired 0.5 Hz rate is achieved.

The rate requirement determines the operating point of the TOF trigger, but a calibration is needed to understand the trigger response to physics processes.

The TOF's response in the low charge region is calibrated using ordinary particles. The light L arriving at a PMT depends on the tracks path length in the bar s and the position relative to the center of the bar z:

$$L = L_0 \cdot s \cdot exp(\pm z/\lambda) \cdot exp(z^2/k) \ .$$

L_0 is the normal light output per path length in the bar for a particle striking at $z = 0$, λ is the attenuation length in the bar, and the $\pm$ refers to east or west PMTs. The z^2/k term is an observed effect suggesting reflections at the ends of the bar. By accounting for these effects and adding contributions from multiple tracks the response to a range of input light intensity can be measured. We define the effective path length, s_{eff}, by summing contributions from all the tracks hitting a single bar:

$$s_{\text{eff}} = \sum_{tracks} s \cdot exp(\pm z/\lambda) \cdot exp(z^2/k) \ .$$

The light yield is a Landau distribution around $L_0 \cdot s_{\text{eff}}$. Plotting the measured charge versus s_{eff} measures the response function of the TOF. This is shown in Figure 8. The charge distributions in slices of s_{eff} are fit to a Landau distribution; the most probable values are the points, and the line is a linear fit. One MIP corresponds to a single track passing straight through the 4 cm bars, at z=0. The charge versus effective path length plot reveals a linear response of the TOF from 0 to 4 MIPs.

The effect of the dual range pre-amplifier cannot be measured in the low charge region. To extend the calibrated region, we use the TOF's laser calibration system, which injects laser light into the TOF bars through optical fibers. The optical coupling to the laser varies from bar to bar, but is constant with laser intensity. For the calibration, a strongly coupled bar is paired with a weakly coupled bar, and the intensity of the laser is varied. The weakly coupled bar remains in its linear region and is used as a linear scale. The strongly coupled bar is in its linear region for low intensities, passes through a quadratic transition region, and returns to linearity at a lower gain (see Figure 9).

Because the optical coupling varies from bar to bar, and the TOF laser calibration system is only partially instrumented, the complete bi-linear response can only be measured for a few channels. The variation in the bi-linear effect for these few bars is extremely small, as expected from test stand measurements of the pre-amplifiers. For this reason, we expect the bi-linear response of all PMTs to be similar.

The calibrated HIP trigger thresholds are shown in Figure 10. The TOF HIP trigger is intended to search for magnetic monopoles, which would produce light in excess of 500 MIPs [4,5]. The thresholds are far below the expected response to magnetic monopoles, ensuring highly efficient operation.

5 Conclusion

The TOF trigger was commissioned at the beginning of 2003, and physics quality data was being taken by the end of the summer. For validation, we emulate the triggers response to the TOF ADMEM charge measurements, read from the TOF ADMEMs during real data taking, and compare with the actual response of the trigger. The trigger has been shown to be in perfect agreement with the emulation. The TOF HIP trigger has been used in a recent search for Dirac Magnetic Monopoles [6].

References

[1] R. Blair, et al., *The CDF-II Detector: Technical Design Report*, FERMILAB-PUB-96-390-E (1996).

[2] C. Grozis, et al., *A time-of-flight detector for CDF*, Int. J. Mod. Phys. A16S1C (2001) 1119–1121.

[3] E. J. Thomson, et al., *Online track processor for the CDF upgrade*, IEEE Trans. Nucl. Sci. 49 (2002) 1063–1070.

[4] G. Giacomelli, L. Patrizii, *Magnetic monopole searches*, hep-ex/0302011 (2003).

[5] M. Ambrosio, et al., *Final results of magnetic monopole searches with the MACRO experiment*, Eur. Phys. J. C25 (2002) 511–522.

[6] M. J. Mulhearn, *A Direct Search for Magnetic Monopoles*, Ph.D. thesis, Massachusetts Institute of Technology, Boston (Sept 2004).

[7] R. Brun, F. Rademakers, Root: An object oriented data analysis framework, Nucl. Instrum. Meth. A389 (1997) 81–86.

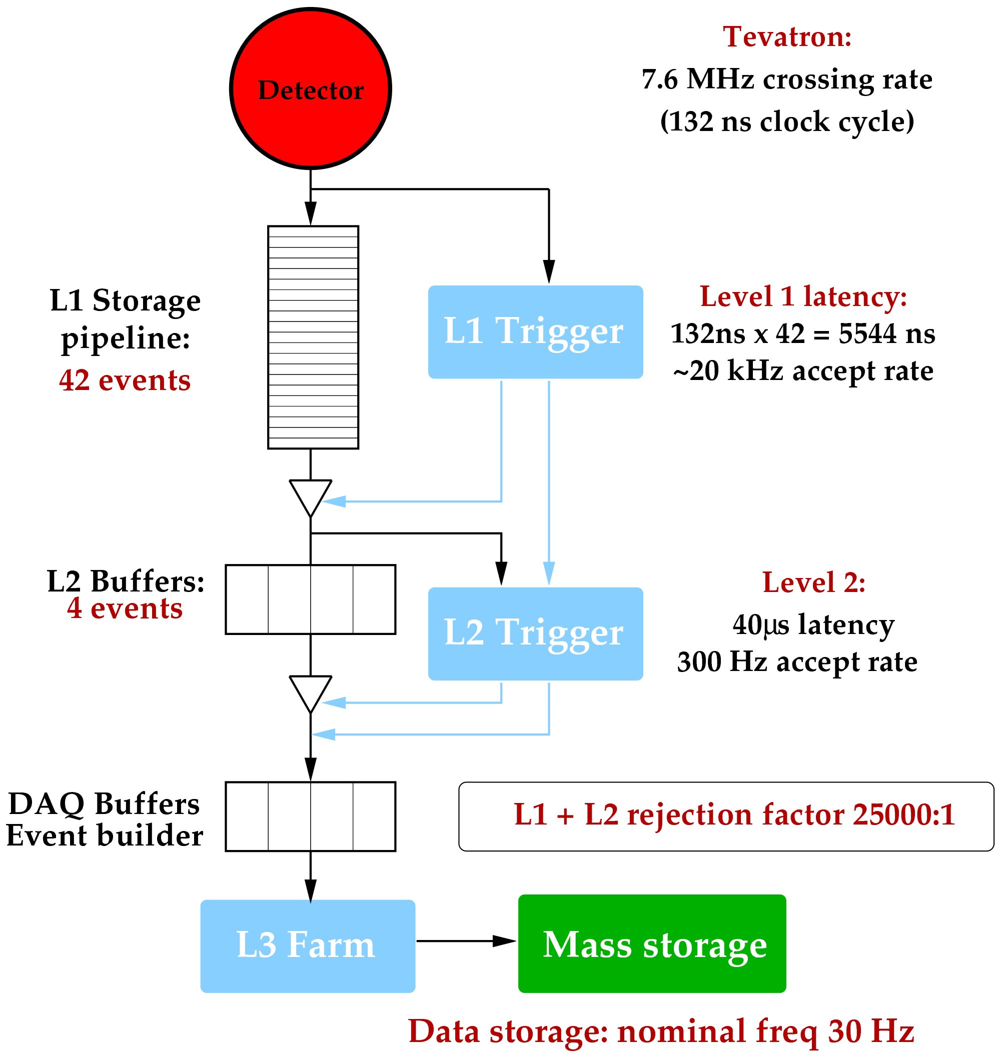

Fig. 1. The CDF data acquisition uses a three level deadtimeless trigger. The first two triggers are implemented with custom hardware and the third trigger uses a PC farm.

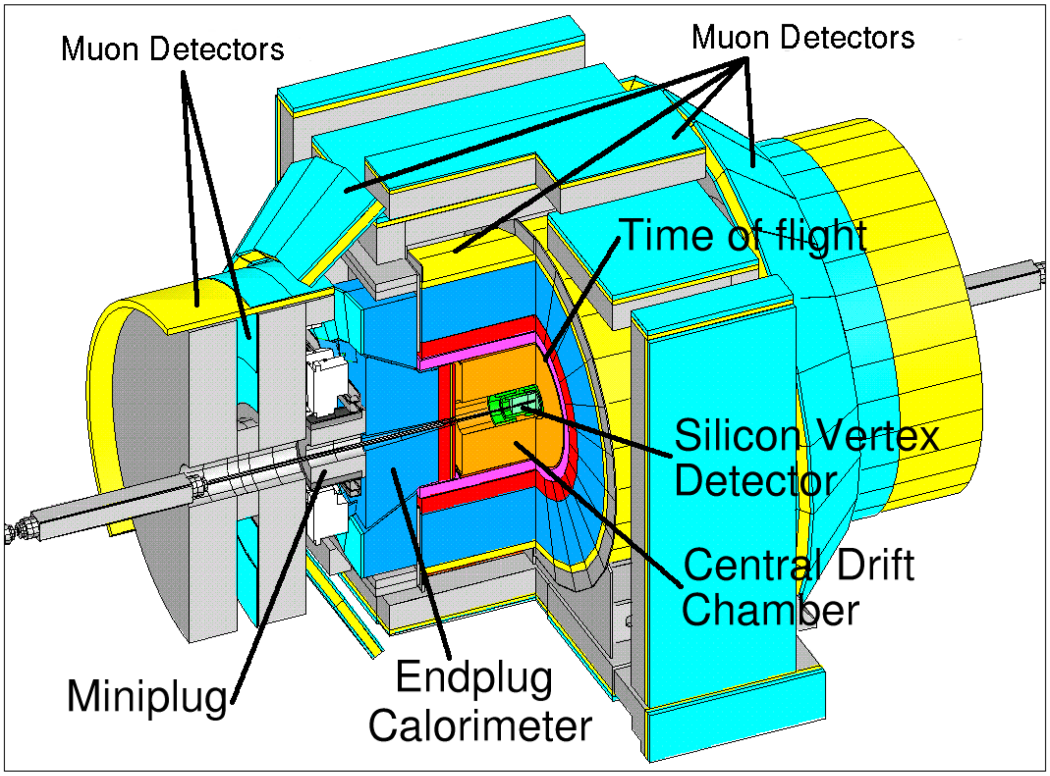

Fig. 2. The CDF detector, with a quadrant removed to reveal the inner sub-detectors.

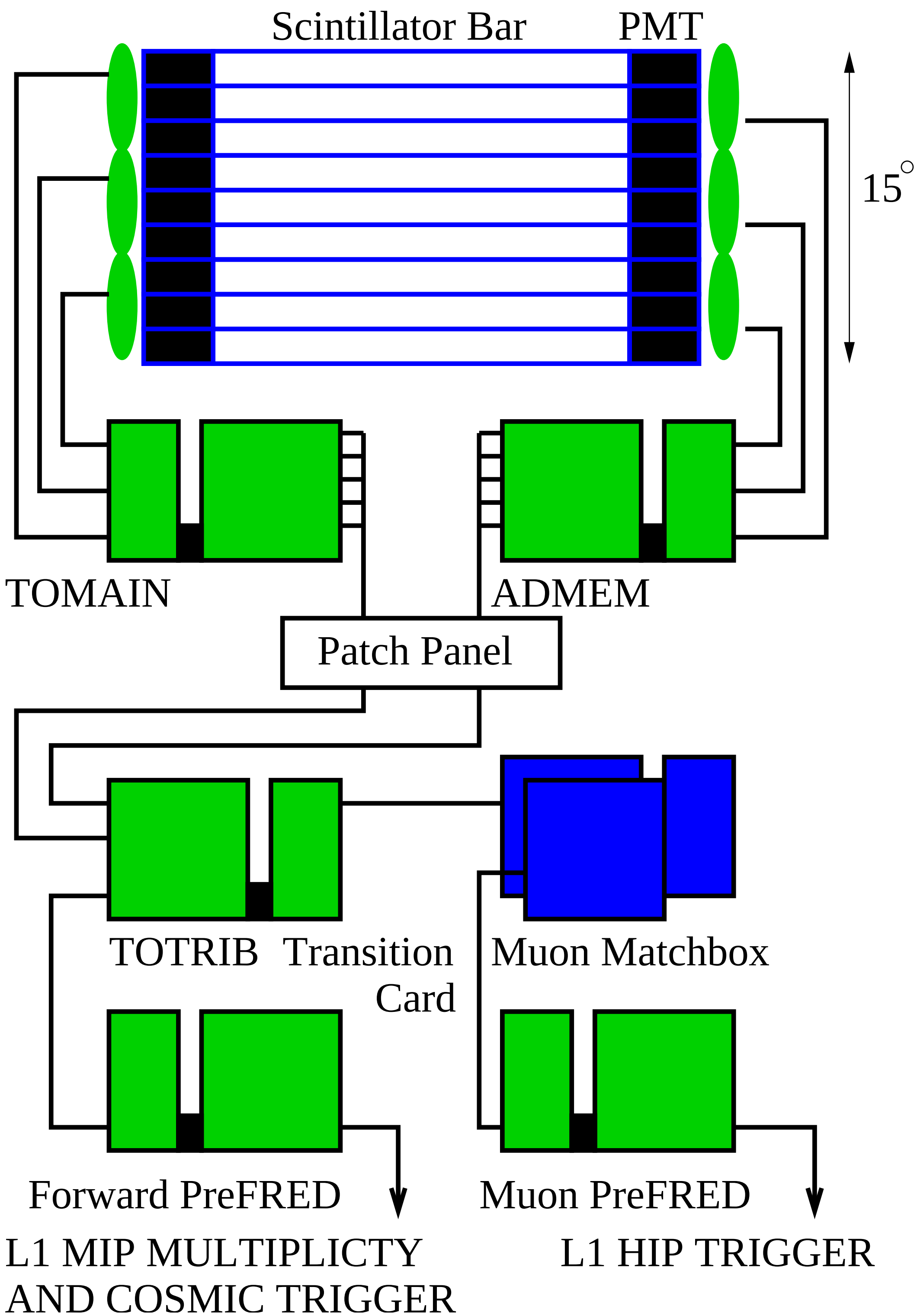

Fig. 3. The TOF Trigger Hardware extends the TOF system to provide a HIP trigger, a MIP multiplicity trigger and a cosmic trigger.

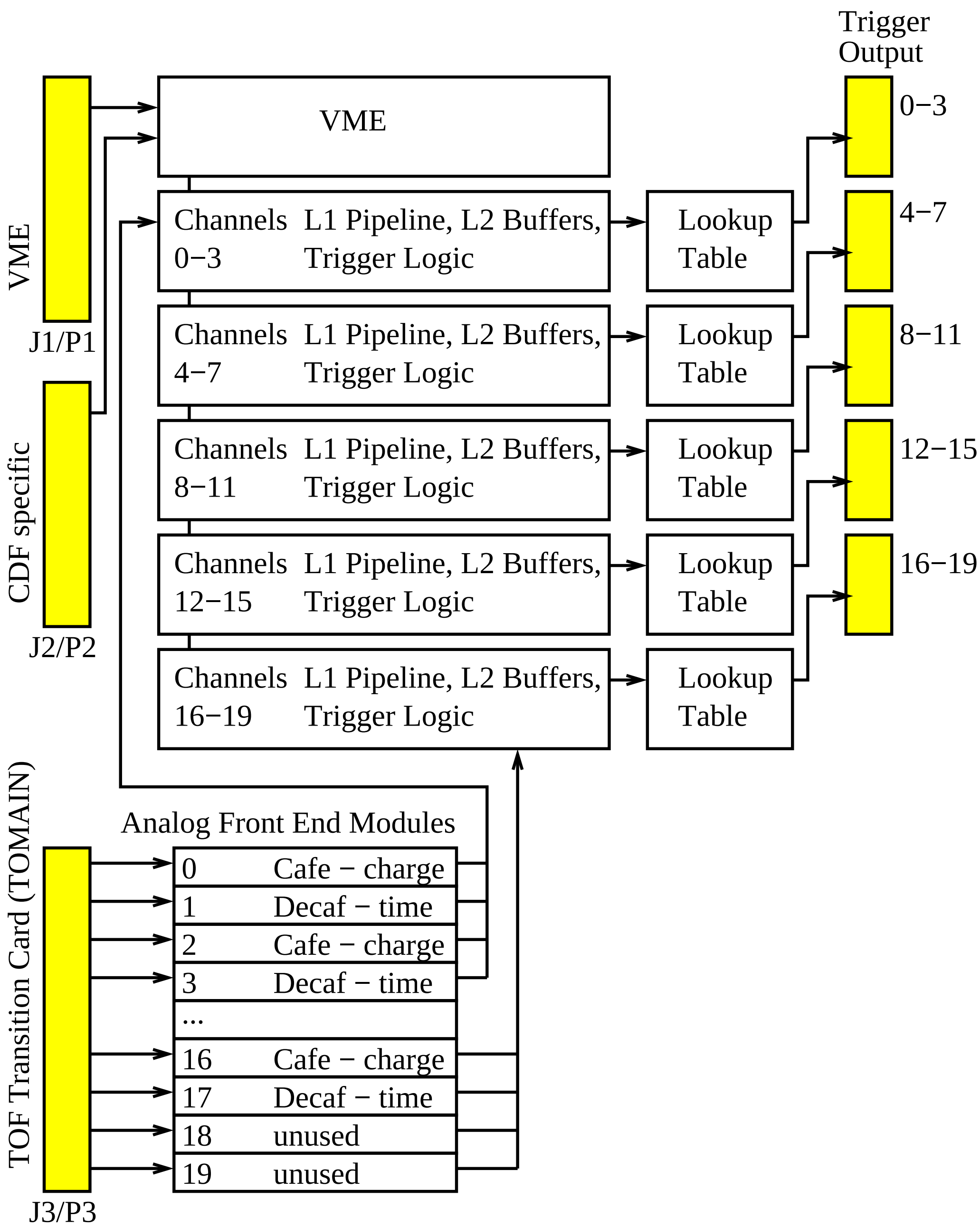

Fig. 4. The ADMEM trigger logic is performed on five trigger FPGAs. An additional FPGA provides VME services.

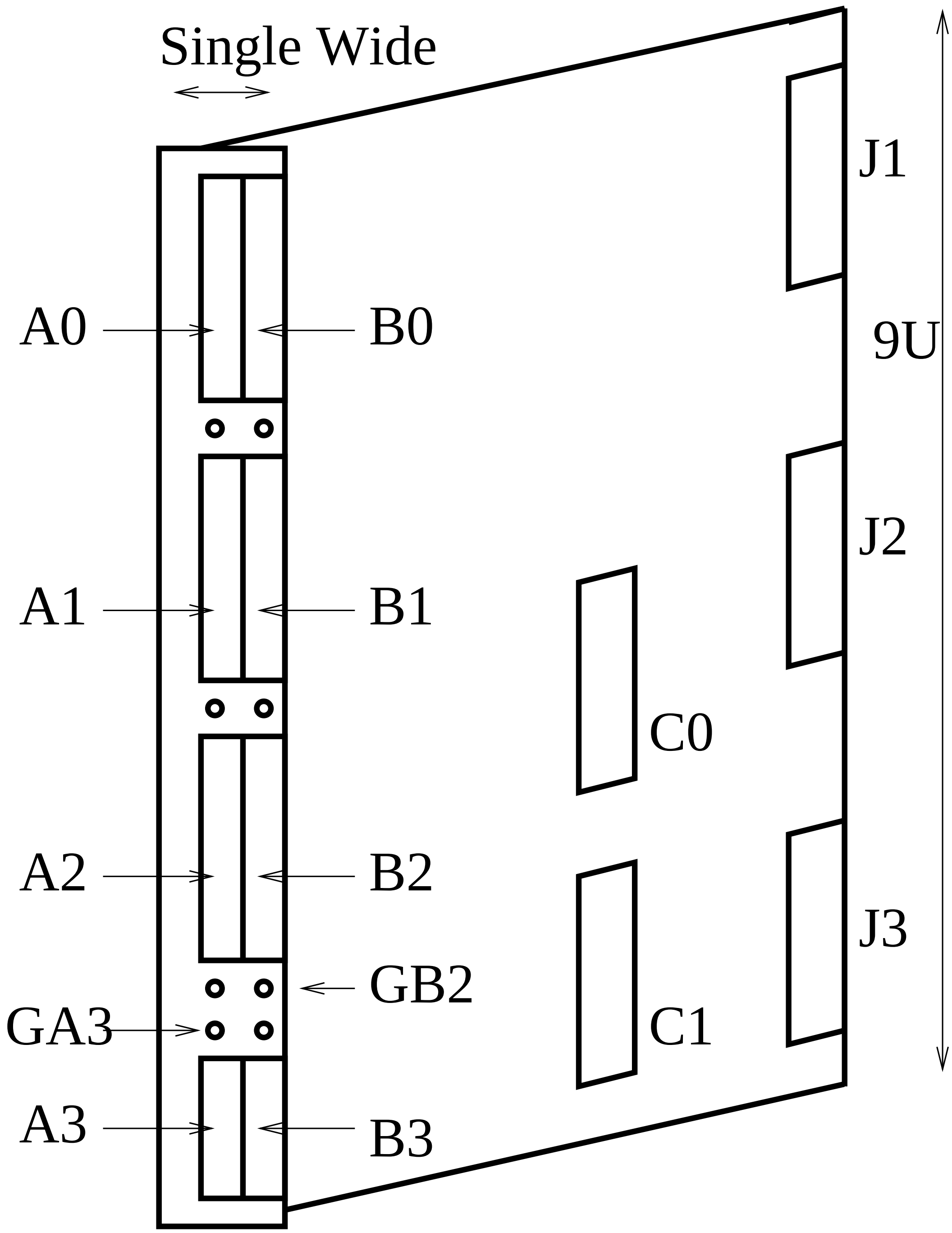

Fig. 5. The TOTRIB is a 9U single-wide VME card. Input is from front panel connectors A0-A2 and B0-B2. MIP output is sent to the front panel connectors A3 and B3. The coincidence data is ouput through the J3 backplane connector.

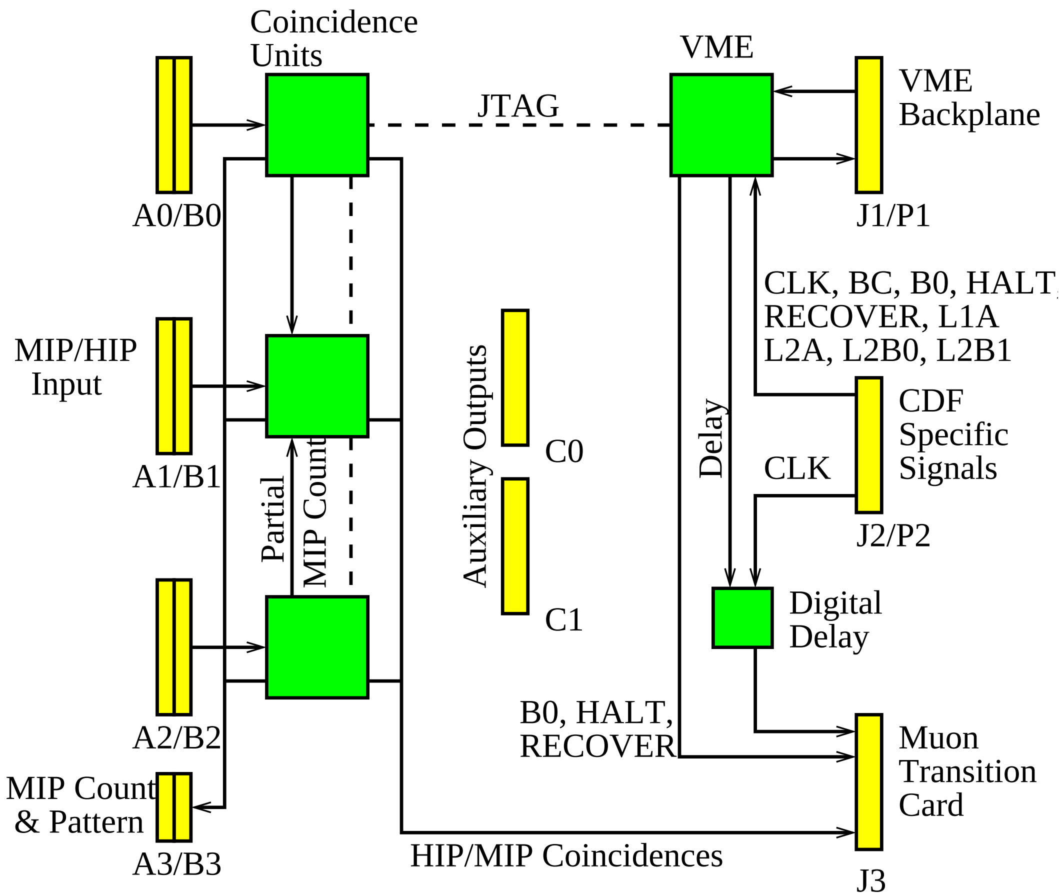

Fig. 6. The TOTRIB contains three FPGAs to perform coincidence logic, and an additional FPGA to provide VME services.

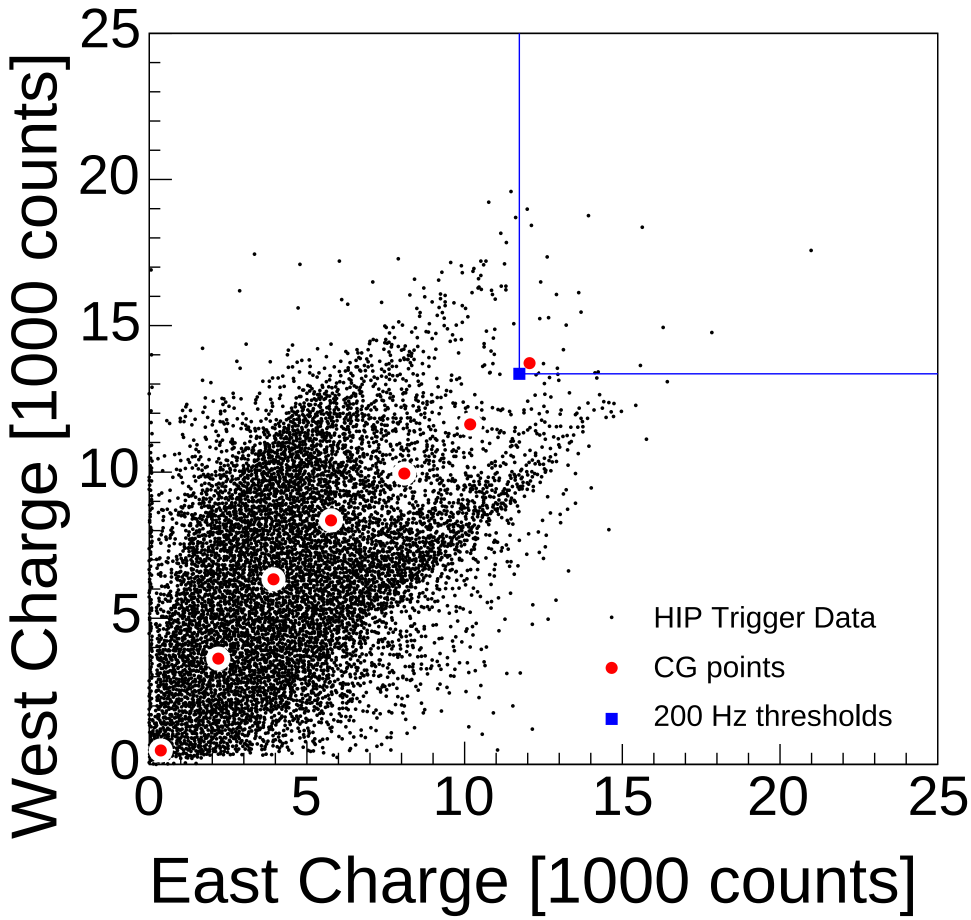

Fig. 7. The east-west charge distribution from minimum bias tracks is used to establish low rate trigger thesholds.

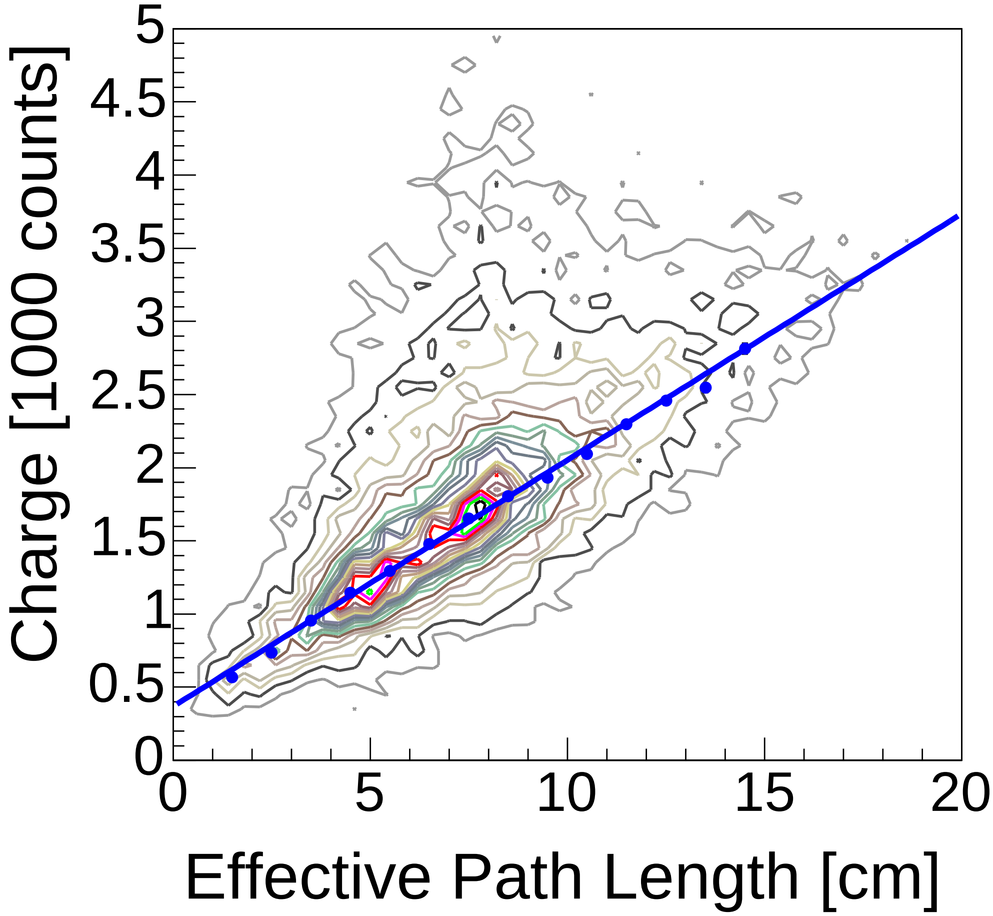

Fig. 8. The linear response of the TOF to ordinary particles is measured by comparing the measured charge to the sum of light contribution from ordinary tracks, accounting for attenuation effects.

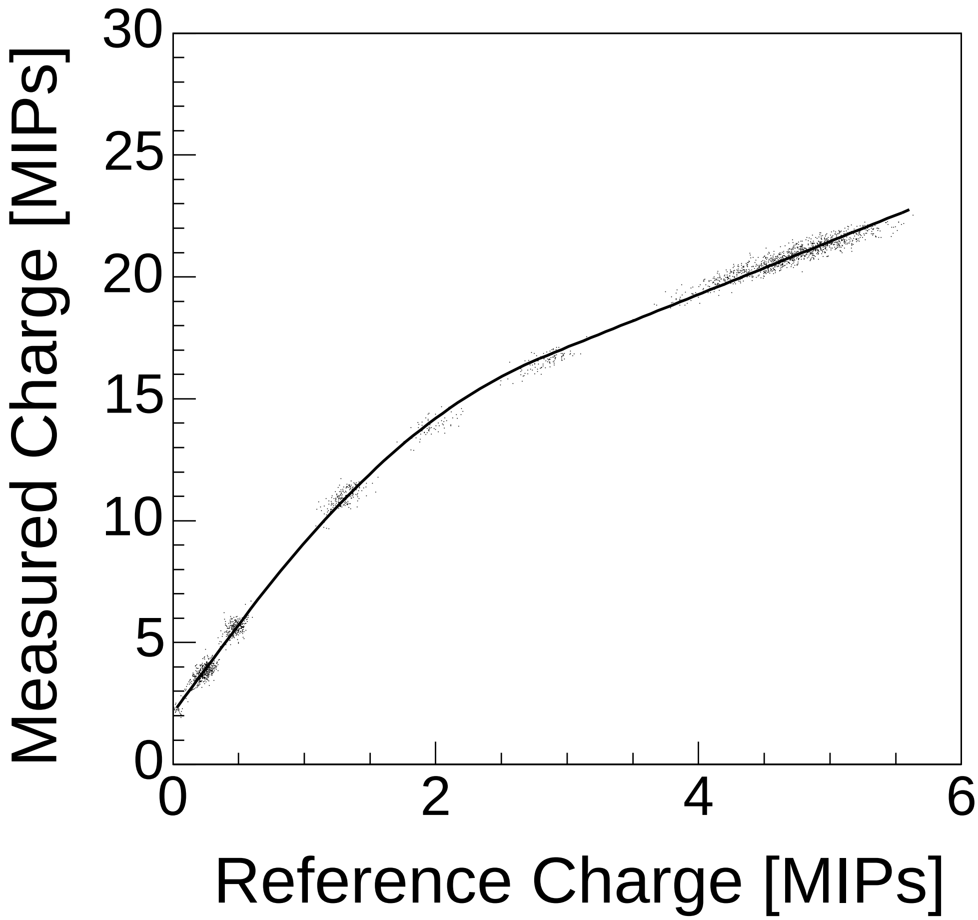

Fig. 9. A weakly coupled reference bar provides a linear scale to measure the charge response of the TOF to laser light of varying intensity.

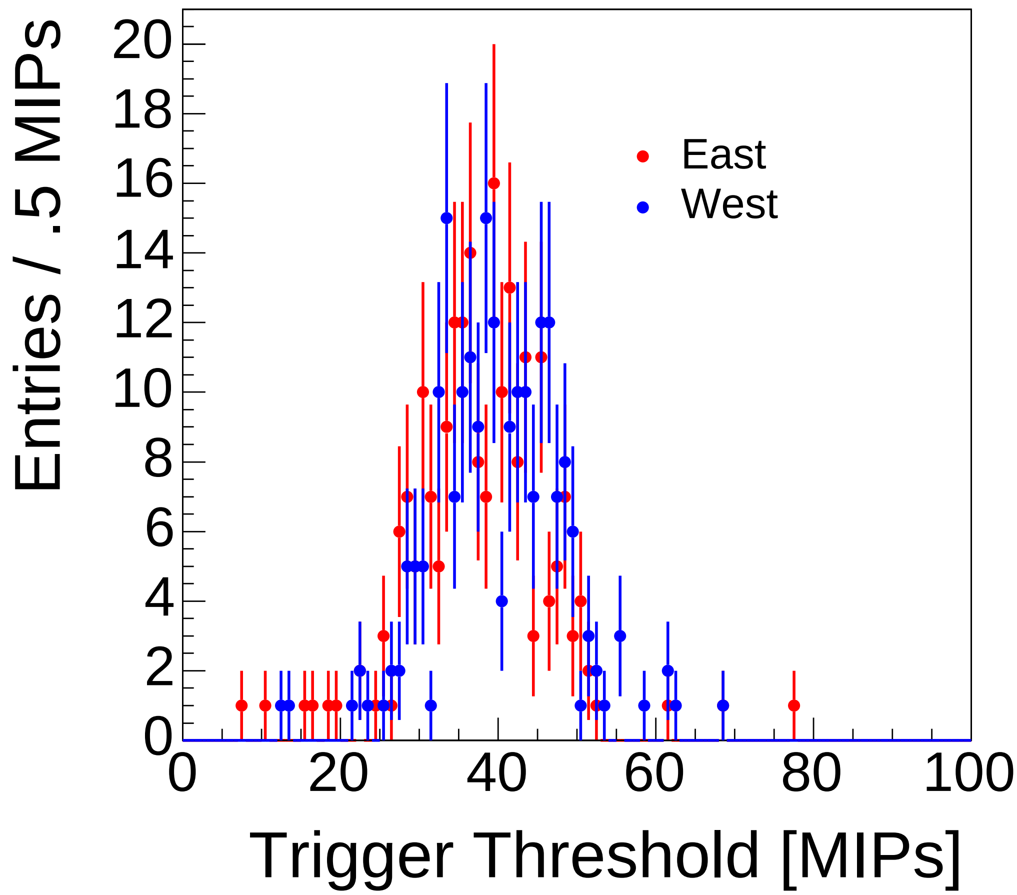

Fig. 10. Calibrated trigger thresholds.