Totem Trigger System

Josef Kopal[1,2]
on behalf of the TOTEM collaboration
[1]Department of Applied Electronics and Telecommunication, West Bohemia University in Pilsen
Univerzitní 26, Pilsen, 306 14, Czech Republic
Email: jkopal@zcu.cz
[2]CERN
Geneva 23, Geneva, CH-1211, Switzerland
Email: josef.kopal@cern.ch

***Abstract*—This paper describes the TOTEM Trigger System that is in function at the LHC since 2009. The TOTEM experiment is devoted to the forward hardronic physics at collision energy from 2.7 TeV to 14 TeV. It is composed of three different sub detectors that are placed at 9, 13.5, and 220 m from an interaction point.**

A fast electronic system is needed to review collisions and to select the relevant ones to be stored by the Data Acquisition (DAQ). This electronics is called the Trigger system of the TOTEM experiment.

The TOTEM has a large collaboration. This is reflected in the paper. The first part contains a brief introduction to the entire project. The second part describes the work on the Trigger system.

I. Introduction

The Large Hadron Collider [4] is the largest hadronic particles collider. It is build to study fundamental corner stones and laws of the universe. It was designed and constructed under the aegis of the European Organization for Nuclear Research - CERN [1]. It is located on Swiss - French border. Its perimeter is 27 km.

Colliding protons and heavy ions (lead ions) are used to study the sub atomic particles and the interactions in between them. Currently, the energy 4 TeV per proton is used. In the future, the accelerator is foreseen to reach energy 7 TeV per proton.

When two protons collide at high energy their partons (quarks and gluons) exchange momentum and new particles can be created. The exiting angle of the trajectory of the produced particles is related to the momentum loss. Some of the out-coming particle's trajectories are perpendicular (or contain large angles) to the axis of the beam pipe: So called Central Region is covered by large detectors (ATLAS [5] and CMS [6]).

On the other hand, there is a complementary area to the central region: So called Forward Region covers collisions with a low momentum loss. In such case, it can be that at least one of two colliding protons is preserved and it continues under a small angle with respect to the original trajectory, thus it can be detected at a large distance from the interaction point.

The TOTEM experiment [3] is situated around the Interaction Point 5 (IP5). The experiment focuses mainly on the forward region. The configuration is radically different with respect to the large general-purpose experiments (like ATLAS). The TOTEM detectors are small in size, but are very close to the beam axis and are situated up to 220 m far from the IP5 (in both directions, following the beam pipe). Special demands for the detectors also imply limitations and challenges for the mechanical construction and detectors design (precise movable parts, edge-less silicon detectors).

The TOTEM physics program covers the following phenomena and measurement:

- total cross section,
- elastic scattering,
- single diffraction,
- double diffraction,
- central diffraction,
- hard diffraction(with CMS).

There are examples of possible measurements in Figure 1. The first example is the elastic scattering. If there is no energy transfer between particles during a collision, but only impulse transfer, then the event is elastic. Both protons are preserved and they continue in flight under extremely small angles (tens of μrads) to the previous trajectory and are detected by dedicated detectors (Roman Pots RP) far from an interaction point.

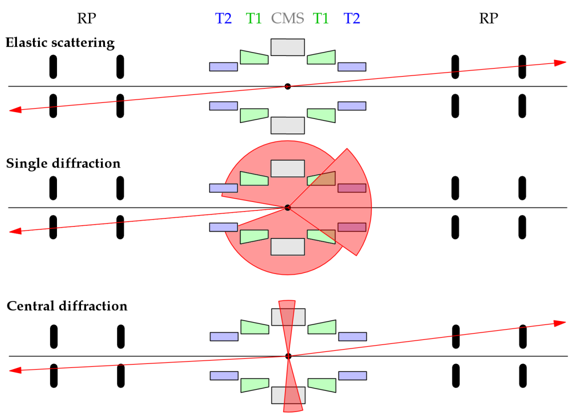

Fig. 1. Measurement principles

As the exchanged momentum grows, the probability of the proton destruction grows as well. The process when only one proton survives the collision is called single diffraction (Figure 1). In such a case, new particles are created and detected by dedicated inelastic-detectors called T1 and T2.

The directions of the new particles are related to the amount of the momentum loss of the surviving proton. In some events the tracks can reach also the central region. This means that for TOTEM and CMS, it is very important to integrate the data from both experiments.

In the Central Diffraction, both protons are preserved but new particles are created and are detected only by the CMS and Totem inelastic detectors (Roman Pots). For this type of measurement, the joint operation of the TOTEM and CMS detectors gives the maximum physics coverage.

II. Trigger purpose

All detectors use 40 Mhz clock source and generate enormous amount (several MBytes) of data every single clock cycle. It is not possible to read-out and store detectors data continuously. An electronics has to buffer, monitor and analyze all events and to trigger the buffer data read-out when certain criteria are met.

To do this, all detectors send (in real time) simplified information about their state and dedicated electronics has to evaluate every collision and to execute the data acquisition (DAQ). This part of the experiment is called the Trigger system.

The Trigger:

- is the first step in the data analysis and is critical for the consecutive offline data analysis (the data that are not triggered on and stored by DAQ are lost),
- optimizes the usage of the available data bandwidth.

The Trigger system requires a precise timing calibration and one clock cycle time resolution.

III. Detectors

In TOTEM, there are three sub-detector types. Each detector type is designed accordingly to the physics requirements. Therefor detectors vary in size, mechanics and in sensor types. On the other hand, all detectors share components and technologies for the read-out, data-transmission and control.

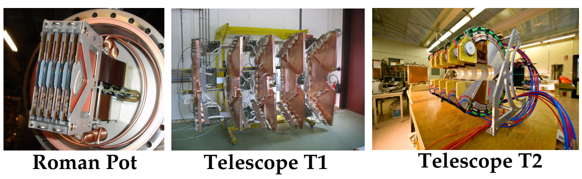

Fig. 2. Detectors used in TOTEM

A. Roman Pots - RP

The Roman Pot detectors [10](Figure 2) are located 220 m (in both directions following a beam pipe) from the IP5 and they detect surviving protons from the interactions. Used silicon sensors have to reach a position very close to the LHC beam (hundreds of μm). LHC beam dimensions depend on LHC operation. Thus Roman Pot detectors are constructed as movable devices. The movement and proximity to the beam requires a special and very precise mechanical construction. Once the LHC beam reaches nominal values, The Roman Pot detectors can leave a safe position and reach the beam with a 5 μm step precision.

B. Telescopes T1 and T2

Those detectors [10](Figure 2) are situated inside the CMS detector at 9 and 13.5 meters from the IP5 in both directions along the beam axis.They are designed to detect new particles created in interactions. Both detectors are based on gas chambers. The T1 detector uses the Cathode Strip Chambers (CSC). T2 uses Gas Electron Multipliers (GEM).

IV. Electronics related to the Trigger

A. System block diagram

The TOTEM trigger logic is located on several different places and it is realized in a tree structure. This reduces the amount of transmitted data. The first reduction takes place already in the front-end part of detectors. The reduced data are transmitted to the Trigger rack situated in the Counting room (inside the Service cavern) where the final part of the Trigger electronics is installed (the tracking data are send in the Counting room as well). The complete block diagram is in Figure 3.

This diagram is common for all detectors (up to small details). In general, there are four parts:

- **Detecting Part** - integrating the sensors and analog read-out electronics,
- **System control** - configuration of registers, activation of the read-out, distribution of the Trigger signal, clock and synchronization signals,
- **Data Transfer** - transmission of the tracking and trigger data,
- **Data Processing** - storing the tracking data, analyzing the trigger data and providing the Trigger signal in real-time.

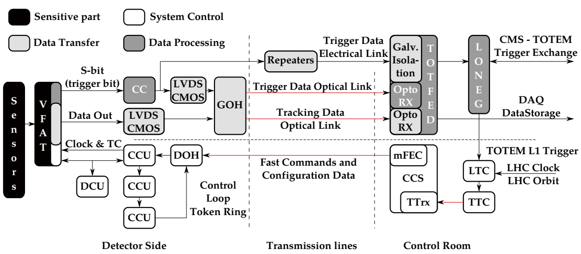

Fig. 3. Block diagram of the TOTEM electronics

B. Relevant electronics components

1) VFAT: VFAT [7] is a tracking front-end chip. It was designed by the CERN microelectronics group as a read out chip of sensors in the TOTEM experiment. It is one of the corner stones of our system. The main functionalities of the VFAT chip are to:

- receive raw signals from sensors (each VFAT has 128 inputs),

- process, amplify, shape and compare readout signals with threshold values to produce tracking and trigger data,
- buffer the tracking for the possible readout,
- transmit the tracking data from a selected time slot,

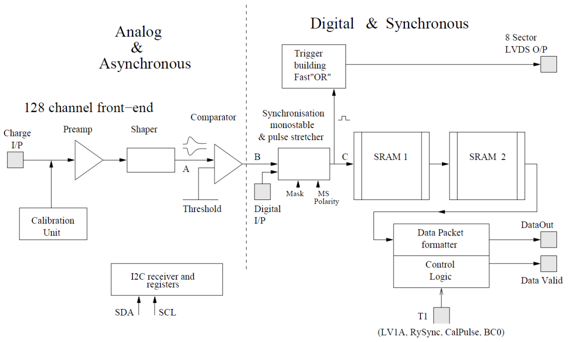

Fig. 4. VFAT chip block diagram

The VFAT block diagram is in figure 4. The internal part of the chip is divided into the analog and digital sections. The analog part amplifies the signal from the sensor and compares is with threshold values. The digital part propagates the tracking and the trigger information to the rest of the system. The chip contains two memory blocks, a control logic for the data readout and the a logic for the trigger. The tracking information is stored in FIFO (SRAM 1) and in parallel reduced trigger information is sent. The tracking data are stored in FIFO continuously. Once the read-out request is received the data from the FIFO are read and stored in a transmitter buffer (SRAM 2). The read-out pointer for the FIFO is programmable. This allows to compensate for different signal delays for individual detectors. The data in SRAM 2 are automatically sent into the data acquisition system.

2) Coincidence chip: In contrary to particles produced by a shower inside an LHC beam pipe, a trajectory of particles that collide in IP5 is almost perpendicular to sensitive planes of detectors (Figure 5). The coincidence of several planes helps to identify an origin of particles. It also helps to suppress a possible noise signal produced by individual channels. The Coincidence chip [14] is dedicated for this functionality. It is designed specially for the Trigger of T2 and Roman Pots and the chip is located in proximity of VFAT chips. If a desired number of bits related to the

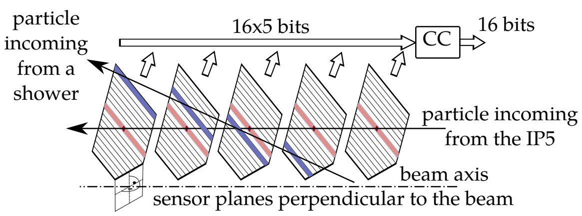

Fig. 5. Coincidence chip function

same position on sensor planes is activated then the Coincidence Chip propagates the Trigger signal. The coincidence reduces the transmitted Trigger bits by a factor of five for Roman pots and by a factor of ten for the T2.

3) GOL and GOH: The GOH [11] is a module developed by CERN for the optical data transmission. The GOH is based on an ASIC chip GOL [12] which is designed as the radiation hard 1 Gbit optical link transmitter. Therefore it can operate inside detectors where exposed to a high level of radiation. This chip uses 16 bit wide bus as a data input at 40 MHz. It uses 8 to 10 bit encoding to generate output frame at 1 Gbits^{-1}.

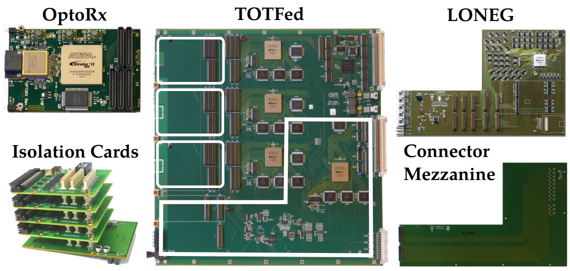

Fig. 6. Mezzanines cards overview for the TOTFed card

4) TOTFed: The TOTFed (Figure 6) is a board for a VME crate. It can host mezzanines that are used for the Trigger and data-acquisition system. It is based on four Stratix II GX FPGA chips. It also contains components(TTCRx and PLL25) related to the Trigger Timing Control [8] (TTC). Those components allow the board to share and distribute the common synchronous LHC clock, This is very important aspect of the trigger system which provide the precise timing of the clock.

Three FPGA are dedicated to the corresponding mezzanine slot (called Main 1, Main2 and Main 3). The fourth FPGA (Merger) is dedicated to combine three 64 bit-wide-buses from the Main FPGA. The Merger and the S-link slot is used to merge the trigger information and for the propagation of the trigger signal into the LONEG card. The VME interface is realized using the cyclone FPGA.

5) OptoRX: The OptoRX module (Figure 6) was designed as a TOTFed card mezzanine. The main functionality is to receive the optical data stream from up to 12 independent GOH modules that are transmitting at 1 Gbits^{-1}. The card holds a Stratix II GX FPGA for this purpose. This FPGA contains 12 dedicated hardware receivers. Each receiver allows a reception of a data frame with structure of the 8 to 10 encoding.

The FPGA chip is also used for the data processing for the DAQ and the Trigger as well. In the FPGA are programmable FIFOs for a local data storage and control registers. All the relevant information is read out and controlled trough a VME interface.

6) Isolation Card: Roman Pots situated at 220 m from the IP5 may have different ground potential in comparison to the Counting Room. Thus a galvanic isolation has to be provided. It is designed as a stack of the Isolation Cards (Figures 6 and 7).

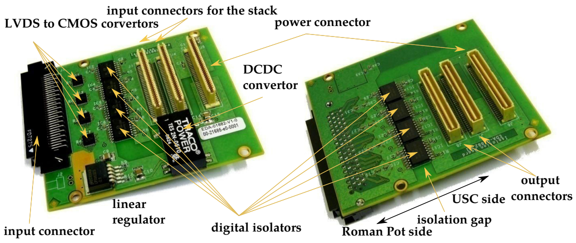

Fig. 7. Isolation Cart for galvanic isolation of the RP and USC side

7) LONEG: The LONEG mezzanine card(Figure 6) is developed specially for the TOTEM Trigger. It is a Stratix II FPGA based board. It is the last stage of the Trigger System and it combines the Trigger information from all detectors and it allows the exchange of trigger with CMS.

8) Repeater: Repeater Cards (Figure 8) are designed to reshape incoming LVDS signals. The signal pre-emphasis is applied to transmit a signal over 70 m long metallic lines. The pre-emphasis is realized by a low pass RL filter.

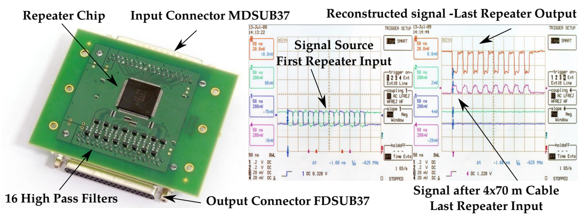

Fig. 8. Signal quality measurement for the signal repeater

V. Trigger Data Paths

A. Optical Trigger

Main components of the Optical Trigger path are the GOH and OptoRx modules. A 16 bit wide parallel bus outgoing from the CC are converted into the 1 Gbit Optical link by the GOH module. The data are transmitted over fibers up to 300m long and received in an OptoRX module. Each OptoRx module can handle up to twelve optical fibers. The OptoRx FPGA is used to synchronize data on the individual detectors level and it is processed accordingly to the detector type. The firmware (Figure 9) is common for T2 and RP. There is a slightly different firmware for the T1. Once trigger data are pre-processed, they are send into the LONEG card that contains the final Trigger logic.

B. Electrical Trigger

The Electrical Trigger infrastructure (Figure 10) has been installed during the March 2012. It is installed for the RP 220 m stations. Data transmission lines (270 m long) are segmented in approximately 70 m long fragments and the Repeater Cards are inserted between those segments.

The chain ends in the same rack as the Optical Trigger where a Patch Panel is installed. The Patch Panel contains the last Repeaters. Those Repeaters are used to reshape signals and to convert heavy industrial

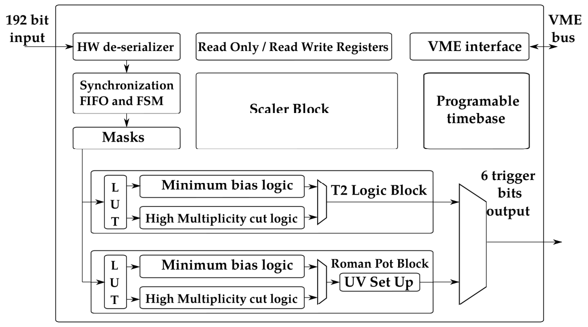

Fig. 9. OptoRX firmware block diagram

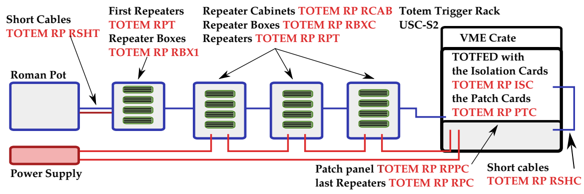

Fig. 10. Block diagram of the Electrical Trigger path

cables into more flexible and lighter ones. Then the Isolation cards are used to provide galvanic isolation between the RP side and Control Room electronics.

The power for the Repeaters is provided by Maraton power supplies situated in the protected cavern. This means that the power line has to use a huge power cables to eliminate the voltage drop over the long distance. The only exception is a set of the first Repeaters that are in proximity of the detectors. Those Repeaters use a detector power source.

The firmware (Figure 11) part is situated in the Main FPGA chips on the TOTFed Card and it is still under construction. There are two reasons. Firstly, the main focus is to calibrate the Roman Pots to achieve the one-clock-cycle precision in timing. The second reason is that possible measurements in collaboration with CMS have to be understood on physics level.

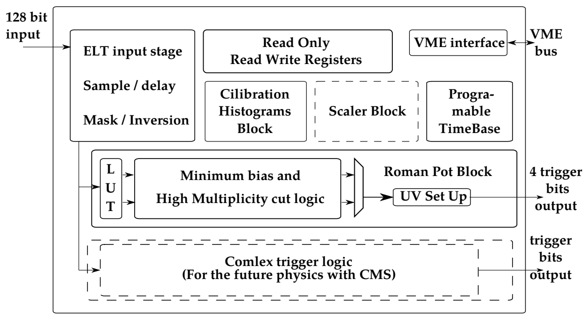

Fig. 11. Main firmware block diagram

The main challenge for the Electrical Trigger firmware is to calibrate the receiving part of the electronics to sample correctly all 384 incoming channels. The issue is that all the bits are represented by a parallel bus which is about 270 m long. The characteristic of our metallic cable is such that the propagation delay of 1 m is approximately (4.2 ± 0.1) ns. Also the cable length varies for individual cables. This means that the propagation delay of individual signals is different from channel to channel. Therefor every channel needs to be sampled and delayed separately to provide the time-synchronous output for the further logic. Also meta-stability states of the sampling logic have to be avoided.

This is accomplished by a programmable sampling stage (Figure 12). For the stage, it is possible to configure the signal sampling in steps of one quarter of the clock-cycle and delay the signal by up to 4 clock cycles. This is sufficient in the current environment.

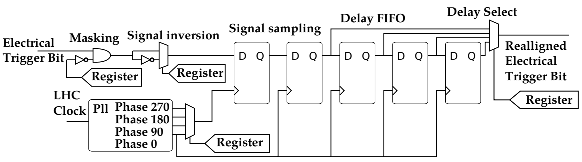

Fig. 12. Input Stage of the Electrical Trigger firmware

Of course, to determine correct configuration values is not trivial. For this purpose, we use the LHC beam structure and FPGA electronics. Accelerated particles inside the LHC accelerator are grouped in so called bunches. It is possible to observe these structures by creating a histogram of the events in the detector. For this purpose, there is a special block inside the firmware. This block uses the LHC synchronization signals and creates a 2 dimensional histogram (the 64 clock-cycles long and 384-bit-wide accordingly to the number of incoming bits). Figure 13 shows the histogram with default values.

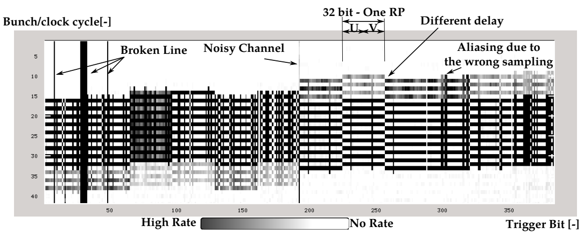

Fig. 13. Electrical Trigger calibration Histogram - Input stage uses default configuration values

To get the proper calibration values, we create histograms for each possible phase shift settings. Those histograms are analyzed. And correct set-up values are determined. Figure 14 shows the histogram that is created using the calculated set-up file. We can see that the train structure is now well aligned for each channel (and broken lines are masked). This means that incoming data are synchronized in time and sampled properly.

C. Propagation delays of the electrical and optical line

The metallic transmission line for the RP 220 m is used, because the Optical Trigger suffers from a signal propagation delay penalty caused by:

- time needed to serialize and de-serialize the parallel bus (The Electrical Trigger uses parallel bus),
- the propagation delay of the used fiber is about 5 ns per meter (Used metallic wire has 4.2 ns per meter),

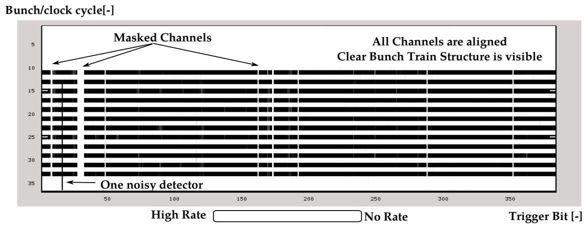

Fig. 14. Electrical Trigger calibration Histogram - Input stage uses correct configuration values

In Figure 15, there are two measurements. On the left side, there is a measurement of the signal delay of the optical and electrical setup in a laboratory. The test setup is similar to the final installation in the LHC tunnel. The only difference is that transmission lines are about two meters long. That means that the propagation delay comes mainly from the electronics. The difference between optical and electrical signal is about 400 ns.

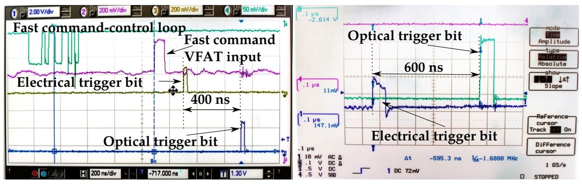

Fig. 15. Propagation delay measurement for the optical and electrical line

The second measurement (Figure 15 - right) is made on the final installation inside the LHC tunnel. The delay between the optical and electrical signal is about 600 ns. Concerning the laboratory measurement, it means that a delay contribution of the optical and electrical lines is about 200 ns. This is a crucial result for our experiment. The small difference gives us an opportunity to exchange the trigger information with CMS in time to commence the CMS data read-out.

D. LONEG firmware

The processed Trigger information from each detector is sent into the LONEG mezzanine card. At the moment, each detector is represented by a set of bits (related to the detector state). In the first step, the bits enter the programmable delay block to synchronize all trigger bits accordingly to the time frame (each detector has a different distance from the IP5 and the signals are delayed due to the cable length and the time of flight of the particles).

Then there is a mask for disabling the detectors. The last step is a programmable mono-stable. This allows to hold the trigger bit for up to 16 clock cycles. The default value of the mono-stable length is one clock cycle for the Roman Pots and four for the T1 and T2. This is related to the detector technology and the signal development that makes the signal to jitter for more than three clock cycles.

Once all bits are synchronized they enter the block dedicated to the selection criteria (related to the physics). Signals in each block go trough a combinational logic. For example, the elastic scattering requires

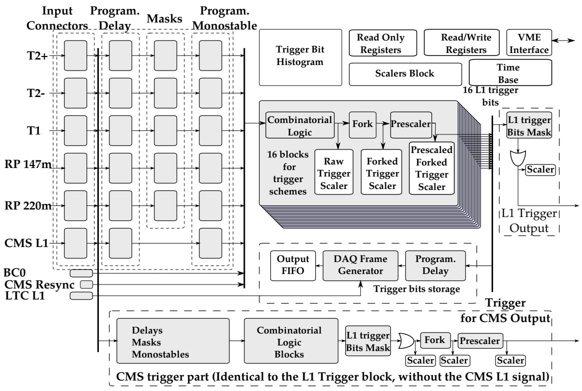

Fig. 16. LONEG firmware block diagram

one proton in a vertical Roman Pot in Sector 45 and one proton in a vertical Roman Pot in Sector 56. Then those signals are compared with so called "fork". It is a programmable gate following the beam scheme. It allows the signal to go through only in the time-slots with collisions and allows to select substructures of all the available bunches. At the end of the block, there is a pre-scaler which allows us to reduce the trigger rate.

We use multiple scalers to monitor each step of the logic blocks. Those values help us to optimize Trigger rates.

The output bits from all Trigger blocks go in two different blocks. One block is used to store the Trigger bits together with the DAQ data for the offline analysis. The second block is used as an output stage generating the Trigger signal for the Data acquisition. This stage contain a mask for the masking individual Trigger schemes. Then there is an OR function to combine individual triggers. The output is connected to the control block and it drives directly the data read out request from all detectors.

For the purpose of the integration of TOTEM and CMS, the entire Trigger Block was duplicated. This allows to provide independent Trigger information to CMS. This information is processed by CMS consecutively returned to TOTEM and used for mutual triggering with a common event tagging, based on the Bunch and Orbit number, to synchronize the events of both experiments. The data merging is performed offline.

VI. Conclusion

A. TOTEM trigger and data-taking

The Trigger system has been improved during the 2009-2013 and since 2012 Totem shared it with CMS in special runs. The results of this run campaign has been published in the scientific journals:

- Measurement of proton-proton elastic scattering and total cross-section at sqrt s = 7 TeV (CERN-PH-EP-2012-239)
- Measurement of the forward charged particle pseudorapidity density in pp collisions at sqrt s = 7 TeV with the TOTEM experiment (EPL 98 (2012) 31002)
- First measurements of the total proton-proton cross section at the LHC energy of sqrt s = 7TeV (EPL 96 (2011) 21002)
- Proton-proton elastic scattering at the LHC energy of sqrt s = 7 TeV (EPL 95 (2011) 41001)

B. TOTEM and CMS trigger integration and common data-taking

Installation of the Electrical Trigger and lower signal latency due to the use of metallic transmission path allowed common data-taking of the TOTEM and CMS experiments. In the moment, the data from those runs are being analyzed.

References

[1] CERN
CERN official webpage. (March 2013).
Available online at:
http://www.cern.ch

[2] CERN
CERN pages for the staff and users. (March 2013).
Available online at:
http://user.web.cern.ch/user/Welcome.asp

[3] TOTEM
TOTEM official webpage. (March 2013).
Available online at:
http://totem.web.cern.ch/Totem/

[4] LHC
LHC official webpage. (March 2013).
Available online at:
http://lhc.web.cern.ch/lhc/

[5] ATLAS
ATLAS official webpage. (March 2013).
Available online at:
http://www.atlas.ch

[6] CMS
CMS official webpage. (March 2013).
Available online at:
http://cms.web.cern.ch/

[7] *VFAT2 - Operating Manual*. P. Aspell(July 2006).
Available online at:
http://totem.web.cern.ch/Totem/work_dir/electronics/totelwork_files/PDFgeneral/VFAT2Manual.pdf

[8] TTC
Timing, Trigger and Control (TTC) Systems for the LHC. (March 2013).
Available online at:
https://edms.cern.ch/cedar/plsql/cedarw.site_home/

[9] *LHC: the guide*. Lefevre, C.
Available online at:
https://cdsweb.cern.ch/record/989631?ln=en

[10] *The TOTEM Experiment at the CERN Large Hadron Collider*.
TOTEM collaboration
Available online at:
https://cdsweb.cern.ch/record/1129807/files/jinst8_08_s08007.pdf

[11] *Gigabit Optical Link Hybrid, description page*.
Available online at:
http://cms-tk-opto.web.cern.ch/cms-tk-opto/ecal/components/goh.html#spec

[12] *GOL Reference MAnual, Gigabit Optical Link Transitter Manual*.
P. Moreira, T. Toifl, A. Kluge, G. Cervelli, A. Marchioro and J. Christianses
Available online at:
http://totem.web.cern.ch/Totem/work_dir/electronics/RPMB/GOL.pdf

[13] *CERN accelerators description page*
Available online at:
http://public.web.cern.ch/public/en/research/AccelComplex-en.html

[14] *TOTEM Coincidence Chip Specification*
P. Chalmet, W. Snoeys
Available online at:
http://totem.web.cern.ch/Totem/work_dir/electronics/RPMB/CCSPECv2.pdf