The TOTEM electronics system

The Totem collaboration

G. Anelli [a], G. Antchev [a*], V. Avati [b], P. Aspell [a], V. Berardi [c], U. Bottigli [d], M. Bozzo [e], E. Brücken [f],
A. Buzzo [e], F.S. Cafagna [c], M. Calicchio [c], F. Capurro [e],M.G. Catanesi [c], P. Chalmet [g], M.A. Ciocci [d],
M. Csanad[h*], T. Csorgo [h], S. Cuneo [e], C. Da Viá [m], M. Deile [a], E. Dimovasili [a], K. Eggert [a], F. Ferro [e],
A. Giachero [e], F. Garcia [f], V. Greco [d], J. Hasi [m], F. Haug [a], J. Heino [f], T. Hilden [f], P. Jarron [a],
J. Kalliopuska [f], J. Kaplon [a], J. Kaspar [i], C. Kenney [l], T. Kiss [h], K. Kloukinas [a], A. Kok [m], V. Kundrat [i],
K. Kurvinen [f], S. Lami [d], J. Lämsä [f], G. Latino [d], R. Lauhakangas [f], E. Lippmaa [j], J. Lippmaa [f],
M.Lokajicek [i], M. LoVetere [e], D. Macina [a], M. Macri [e], G. Magazzu [d], M. Meucci [d], S. Minutoli [e],
A. Morelli [e], H. Mugnier [g], P. Musico [e], M. Negri [e], H. Niewiadomski [a], E. Noschis [a], E. Oliveri [d],
F. Oljemark [f], R. Orava [f], M. Oriunno [a], K. Österberg [f], R. Paoletti [d], S. Parker [l], E. Pedreschi [d],A.L. Perrot [a],
J. Petaejaejaervi [f], E. Radermacher [a], E. Radicioni [c], S. Reynaud [a], E. Robutti [e], L. Ropelewski [a],
G. Ruggiero [a], A. Rummel [j], H. Saarikko [f], G. Sanguinetti [d], A. Santroni [e], S. Saramad [a], F. Sauli [a],
A. Scribano [d], G. Sette [e], J. Smotlacha [i], W. Snoeys [a], A. Soter [h] , F. Spinella [d], A.. Ster [h], J. Sziklai [h],
C. Taylor [b], F. Torp [k], A. Trummal [j], N. Turini [d] , N. van Remortel [f], L. Verardo [e], P. Vichoudis [a], S. Watts [m],
J. Whitmore [k]

[a] CERN, 1211 Geneva 23, Switzerland [*] also INRNE-BAS, 1784 Sofia, Bulgaria,
[b] Case Western Reserve University, Dept. of Physics, Cleveland, OH, USA,
[c] INFN Sezione di Bari and Politecnico di Bari, Bari, Italy, [d] Università di Siena and Sezione INFN-Pisa, Italy
[e] Universita di Genoa and Sezione INFN Genova, Italy, [f] Helsinki Institute of Physics HIP and Department of Physical Sciences, University of Helsinki, Helsinki, Finland, [g] C4I Le Salève Site d'Archamps 74160 France,
[h] MTA KFKI RMKI, Budapest, Hungary [*]also from the ELTE University, Budapest, Hungary,
[i] Academy of Sciences of the Czech Republic (ASCR), Institute of Physics, Praha, Czech Republic,
[j] Estonian Academy of Sciences, Tallinn, Estonia, [k] Penn State University, Dept. of Physics, University Park, PA, USA
[l] U of Hawaii, HI, USA, [m]Brunel University, Uxbridge, UK

walter.snoeys@cern.ch

Abstract

TOTEM is an LHC experiment around the same interaction point as CMS. It contains cathode strip chambers (CSC) and gas electron multiplier detectors (GEM) in the CMS cavern and 24 Roman Pots with silicon strip detectors in the LHC tunnel. TOTEM should run both standalone and together with CMS, and should be fully compatible with CMS. All three sub-detectors provide level one trigger building signals and use the same chips: VFAT2 providing both tracking data and fast trigger generation signals, the programmable Coincidence Chip, and the LVDS repeater chip. The same counting room hardware receives and handles both trigger building and tracking data.

I. THE THREE TOTEM SUBDETECTORS

TOTEM [1] is an LHC experiment in construction around the same interaction point as CMS [2] (figure 1). The cathode strip chambers (T1) and the GEM detectors (T2) are two gas detectors located within the CMS cavern at a distance of about 10 and 15 m from the interaction point, respectively (figure 2). T1 consists of 4 quarters each containing 15 cathode strip chambers. T2 consists of 4 quarters of 10 gem detectors. Four groups of six Roman Pots with silicon strip detectors are mounted in the straight sections of the LHC tunnel on both sides of the interaction point at 150 and 220 m distance.

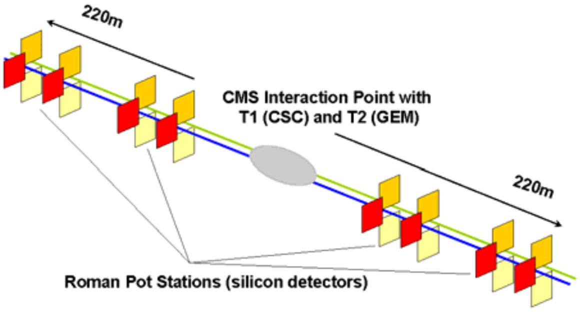

Figure 1: TOTEM with its Roman Pot stations in the tunnel and its gas detectors in the CMS cavern

TOTEM needs to operate both as a standalone experiment and as a subdetector of CMS. This requires full compatibility with CMS. All three sub-detectors need to participate in the trigger building with a high degree of flexibility.

Table 1. gives an overview of the three detectors with the main properties and constraints for the electronics. The number of front end chips (VFAT) is mentioned as well. The gas detectors generate more signal charge, distributed especially for T2 over a larger number of electrodes. The silicon strips generate positive charge, T2 negative, and T1 generates both polarities (anodes and cathodes). The large occupancy for T1 and T2 is due inelastic events where a large number of particles pass through the beam pipe (and interact) towards these two detectors. The high ionizing radiation dose expected for T2 precludes putting optical components on the detector.

Figure 2: Cross-section of CMS indicating the T1 and T2 location. T1 and T2 are respectively located at about 10 and 15 m from the interaction point (in the bottom left corner of the figure)

Table 1: Detector overview

	Roman Pots	T1	T2
Detector Type	240 Si strip detectors	60 Cathode Strip Chambers	40 Gas Electron Multiplier Detectors
No. of channels	122880	12540 an. 20900 cath	62400 pads 20480 strips
No. of VFATs	960	480	680
Input charge	~4fC	~50fC	~50fC
Occupancy	<1%	<10% an. <20% cath.	<5% pads <30% strips
Radiation dose	< 10 Mrad 10^{15} n/cm^2	< 50 krad 10^{15} n/cm^2	< 50 Mrad 10^{15} n/cm^2

II. SYSTEM OVERVIEW

Limited manpower, resources and time imposed significant standardization across subdetectors and reuse of existing components. The compatibility with CMS naturally imposed the use of several CMS components. Standardization was necessary across subdetectors for the integrated circuits development and the counting room hardware. This lead to similar systems for all three subdetectors: they work with the same front end chips but need printed circuit boards compatible with their specific channel segmentation and geometry.

Figure 3 shows an overview of the TOTEM electronics system. The on-detector electronics are electrically isolated from the counting room through the systematic use of floating power supplies and optical signal transmission or electrical transmission with optocouplers. The low voltage power supplies are located as close as possible to the detectors, a few meters for T1 and T2, but up to 70 m for the Roman Pots in the closest alcove in the tunnel. The high voltage power supplies are located in the counting room.

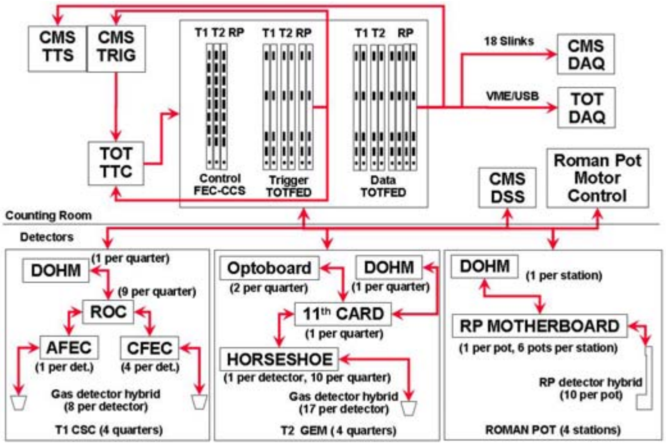

Figure 3: Overview of the full TOTEM electronics system

In the following the system will be described in more detail starting from the detector hybrids moving up to the counting room. The compatibility with CMS is further discussed as well. A separate section is dedicated to the newly developed TOTEM chips.

A. Detector hybrids

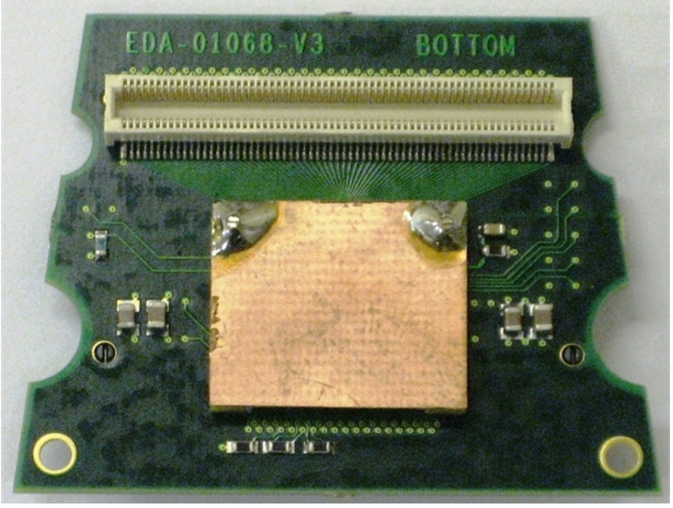

Figure 4: The TOTEM gas detector hybrid carrying one VFAT readout chip (under the cover).

For the gas detectors a common hyrid (figure 4) was constructed with one readout chip VFAT[3]. This hybrid is mounted on the detector as a mezzanine card with a connector carrying the input signals. A cable connector serves as the interface to the outside world. This mezzanine card also allows digital signals to be fed into the front end chip which for T1 offers the possibility to precondition the signals coming from the cathodes with CMS frontends. This lead for T1 to two types of Cathode Front End Cards (CFEC), one of which uses the analog VFAT front end and the other one the

CMS front end based on the Buckeye chip. The trigger building and tracking output signals are both in the VFAT format leading to full standardization of the rest of the readout and trigger chain. An Anode Front End Card (AFEC) is foreseen as well to interface the detector to this gas detector hybrid. The T1 detector needs 480 gas detector hybrids, and T2 680.

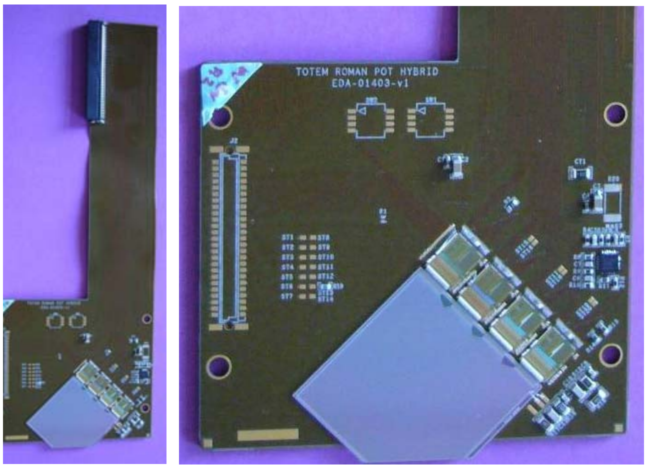

Figure 5: The TOTEM Roman Pot hybrid (left) carrying the silicon detector and its four VFAT readout chips (zoom in on the right)

For the Roman Pots a dedicated hybrid (figure 5) was designed carrying one silicon strip detector and four VFAT chips. The VFAT2 inputs are directly bonded to the detector strips (pitch adapter is included on the detector). Strip direction is at a 45 degree angle (bottom left to top right). Components are concentrated on the right half (pads on left are for testing purposes only) so that when these hybrids are mounted face-to-face to obtain strips oriented in two perpendicular directions, space has to be provided for only one component height. Every of the 24 Roman Pots is equipped with 10 of these Roman Pot hybrids.

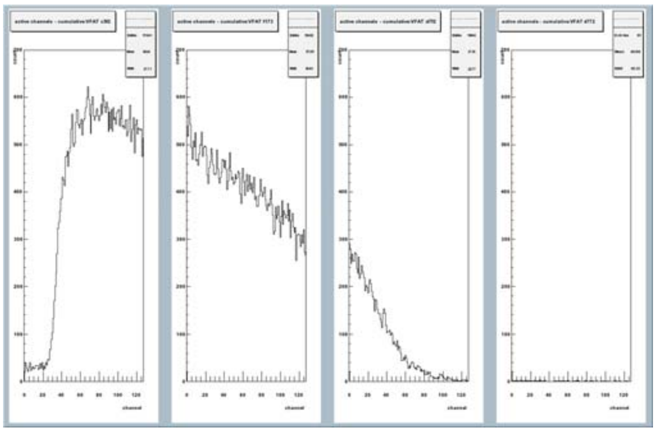

Figure 6: Source profile taken with a Roman Pot hybrid.

Figure 6 shows a cumulative plot of the data taken by a Roman Pot hybrid exposed to a radioactive source.

B. *On-detector electronics cards*

The detector hybrids need interfacing to the outside world and for this dedicated cards have been developed for each of the three subdetectors to address their individual geometrical and detector segmentation needs. They include the following functions:

1. Receive and transmit the Trigger Timing and Control (TTC) signals [4] from and to the DOHM module [5], standard for all three subdetectors, and provide and receive these signals to all on-detector chips through the CCUM mezzanine card [5]. This includes the regeneration of the clock and fast signals from the LV1 signal using the PLL25 chip [6] and further clock jitter reduction necessary for optical signal transmission using the QPLL[7].
2. Receive the LVDS tracking data signals from the VFAT readout chips, convert them to CMOS levels and present them to GOH hybrids, which serializes 16 of these in parallel and converts the result to an optical signal transmitted over a fiber to the counting room [8,9].
3. Receive the LVDS trigger building bits from the VFAT readout chips, put them into coincidence using the coincidence chip mezzanine card (only for the Roman Pots and T2, for T1 the VFAT trigger building bits are transmitted directly), convert the result from LVDS to CMOS, present it to the GOH hybrids, which serialize and optically transmit the result to the counting room.
4. Store the trigger building bits and include them in the readout data stream by means of the VFAT trigger mezzanine card. This mezzanine card also decodes the fast command signal to extract the Bunch Crossing Zero (BC0) signal to insert it in the trigger building signal stream for synchronization purposes.
5. Receive power from the power supply lines and provide them to the hybrids. For the Roman Pots also the HV supply is retransmitted to the hybrids via these cards.
6. Provide the necessary connectivity for monitoring signals (PT100, Radiation Monitor, Pressure, etc…)

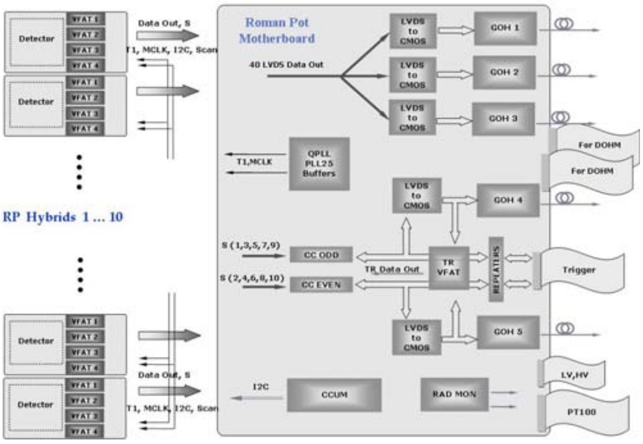

Figure 7: Schematic overview of the Roman Pot Motherboard

For the Roman Pots these functions are implemented in the Roman Pot Motherboard (figure 7 for a schematic overview including the motherboard and the 10 detector hybrids depending on it). This card is glued into the flange closing the space containing the detector hybrids. This space has to be under secondary vacuum to protect the primary machine vacuum in case of mechanical failure of the thin window separating the detectors from the primary beam. Therefore this card serves as the feedthrough of more than 700 signals between the detectors in this secondary vacuum and the atmospheric outside world.

The trigger building signals of the five hybrids in one Roman Pot with the same strip orientation are put into coincidence resulting in 16 bits per Roman Pot transmitted to the counting room for each of the two strip orientations. To meet the latency requirement for these trigger building signals the possibility to transmit these bits electrically in LVDS format has been foreseen. This requires the insertion of repeaters about every 70 m along the cable.

For T1 these functions are taken care of by the ReadOut Card (ROC), each of which serves 1 or 2 detector chambers. As mentioned T1 does not use the coincidence function provided by the coincidence chip as its detector geometry renders this coincidence too complicated. The number of trigger bits generated by each chamber has been kept to a minimum of only 16 only to arrive at a reasonable total of 960 bits transmitted to the counting room with more available processing resources.

The high radiation levels in T2 (see table 1) precluded the use of optohybrids on the detector itself. Therefore optoboards will be put in a rack nearby the detector but outside of the shielding. They receive the readout and trigger building signals in LVDS format and take care of the conversion to CMOS and subsequent serialization and optical transmission to the counting room. On the detector two cards were necessary for the previously mentioned functions: the horseshoe card (named after its physical shape) regroups the signals from and to the 17 VFATs reading out one GEM detector and acts therefore mainly as a connector. The 11th card performs the mentioned functions for the 10 horseshoe cards (and 10 GEM detectors) corresponding to one quarter of the GEM detector.

C. Counting Room Hardware

The counting room hardware has been fully standardized across detectors and the same hardware is used for data readout and trigger signal generation:

The HOST board equipped with opto-receiver (optoRX) mezzanines is called TOTFED: it receives both trigger building and tracking data[10]. This was a shared development: the CMS preshower designed the opto-receiver mezzanine and TOTEM the HOST board. The fully CMS compatible system is equipped with SLINK64, USB and VME interface. The level 1 trigger generation is also carried out by HOST boards. Trigger building signals can be sent to the CMS global trigger or a level 1 trigger signal can be generated directly for TOTEM standalone operation. 8 HOST boards are needed for the tracking data and 6 for the trigger system.

The CMS FEC-CCS [11] and TTCci cards [12] are used to provide the on-detector electronics with Trigger, Timing and Control signals (TTC). Slow control data can also be read back from the detectors. 3 FEC-CCS cards are needed for TOTEM.

TOTEM can run in standalone mode where it provides data to its own data acquisition only, and generates a trigger itself, it can also run as a subdetector of CMS. This is further detailed in the following section.

D. Compatibility with CMS

Several CMS systems/solutions were adopted for TOTEM:

The TTC system was adopted with the CMS specific TTCci card. The slow control system of CMS tracker/ecal is used with the CMS FEC-CCS card and the CCU token ring. This system includes the Digital Opto Hybrids (DOH) which receive and transmit the optical TTC signals from and to the FEC-CCS card and perform the on-detector conversion from and to electrical signals. All programmable chips on the TOTEM detector have been equipped with an I2C interface which can be connected to the CCU. TOTEM occupies one TTC partition out of 32 for CMS.

TOTEM uses the same digital optical link for data transmission as CMS: this includes the GOH optohybrid, the fanouts, the fiber ribbon and the optical receiver.

The Detector Safety System in CMS receives a certain amount of sensor data and controls rack power to switch off elements in case limit values on the sensors are exceeded. The TOTEM detector safety system is fully integrated into this system, because T1 and T2 are integrated within the CMS detector (and need to be powered off in case of severe problems also to protect the CMS detector). To not needlessly complicate things the detector part of the Roman Pots has been added.

The movement of the Roman Pots to optimally position the silicon detectors near the beam is controlled by the machine collimator control system, which includes a dedicated safety system. This way all movable parts in the machine are controlled by one uniform system, which is capable to dump the beam and prevent beam injection when not all conditions for safe machine operation are satisfied.

In addition to just adopting CMS systems TOTEM also needs to guarantee the transmission of tracking and trigger building data in the correct format from its own systems to CMS:

CMS has adopted the Slink64 format for transmitting data to the Data Acquisition system (DAQ), and uses a special mezzanine card to drive this link. TOTEM uses the same card and has made sure this card can be mounted on its counting room hardware.

TOTEM has to provide up to 16 trigger building signals to the CMS global trigger system for common runs. The most important constraint for this was that these signals have to be provided within a certain time after the event actually took place. This caused increased complexity especially for the

Roman Pots which are far removed from the interaction point (for more details see below).

The Trigger Throttle System (TTS) in CMS allows subdetectors to request less triggers in case of difficulty for instance with data buffering. Care has been taken to be fully compatible with this system.

III. INTEGRATED CIRCUITS

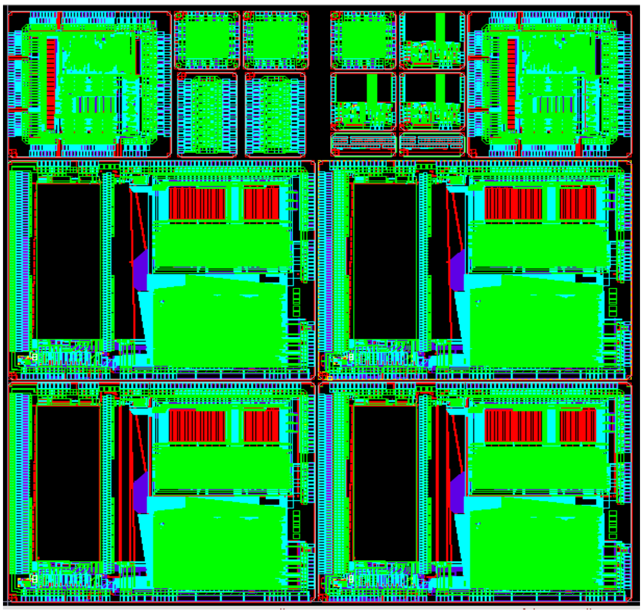

Figure 8: Layout of the production mask for the TOTEM chips.

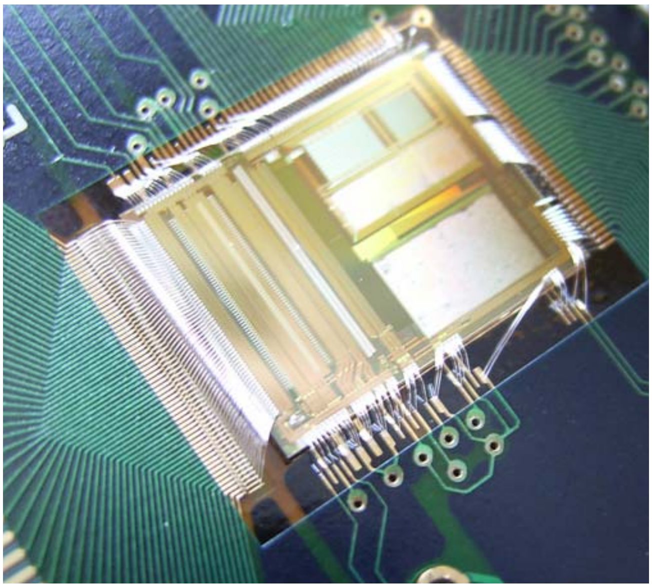

Figure 9: The VFAT2 chip

All three sub-detectors need to participate in the trigger building with a high degree of flexibility. To realize this, three new chips (the VFAT2, the Coincidence Chip and the LVDS repeater chip) were designed in a collaboration with C4i funded by the Departement de la Haute Savoie and produced in a single run (figure 8). All were designed using special layout techniques for total radiation dose tolerance, with additional measures for robustness against single event upsets. The maskset contains two times two copies of the VFAT2 chip, one with special protection against gas discharges, one without, two copies of the coincidence chip and two copies of the LVDS chip, and some additional test structures.

A. The VFAT2 readout chip

The VFAT2 front end ASIC (figure 8) provides tracking and trigger building data and can be configured to match the geometry of the three different sub-detectors. In its version for gas detectors it also contains a special circuit to protect itself against gas discharges [13]. The VFAT2 chip provides binary tracking data (1 bit per channel and per event). All data corresponding to a triggered event is transmitted without zero suppression: the occupancies vary to widely and are too large for some detectors (see table 1). The ~160 8 bit registers controlling the VFAT2 chip are programmable through its I2C interface. The VFAT2 includes a counter on its fast trigger outputs to monitor hit rates.

B. The Coincidence Chip (CC)

The Coincidence Chip provides on-detector coincidences to reduce the trigger data sent to the counting room. Figure 10 shows a block diagram. The chip has 80 LVDS inputs which can be grouped in 16 groups of 5 or 8 groups of 10 for either up to 5 or up to 10 overlapping detector planes. These groups correspond to detector sectors in a similar position on overlapping detector planes.

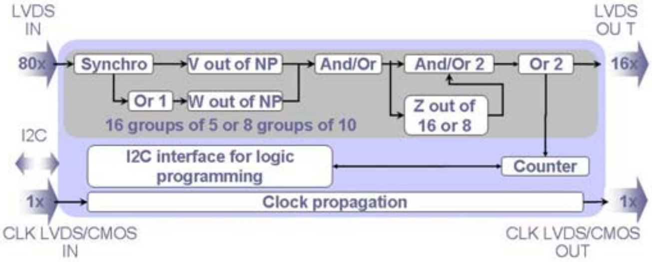

Figure 10: Schematic overview of the Coincindence Chip (CC)

A synchronization block is included to synchronize the pulses to the clock and to stretch the pulses over different clock cycles for detectors with an inherent timing spread larger than a single clock cycle. Asynchronous operation is also possible: a clock propagation path with a similar delay as the data path has been provided. For TOTEM only synchronized operation has been adopted.

Two coincidences can be performed, one on just one group (V hits out of NP number of detector planes), one which takes into account a programmable number of neighbouring groups (W hits out NP number of detector planes including X number of neighbouring sectors). The result of these coincidences can be logically combined in a programmable way (And/OR with possible inversion). The possibility to include neighbouring sectors or not allows a certain programmable selectivity on the direction of incoming particles.

The total number of positive coincidence results is checked (Z out of 8 or 16) and can be logically combined with the coincidence results (AND/OR2). This can be used to impose certain occupancy limits to for instance to prevent the generation of a trigger if a detector is completely filled with artificial hits due some interference. Finally signals can be grouped into a smaller number (OR2) to reduce overall signal count.

The parameters of the blocks on the Coincidence Chip can be fully configured through its I2C interface. The chip also includes counters on the fast trigger outputs to monitor hit rates.

C. LVDS REPEATER CHIP

Both trigger building and tracking data are optically transmitted to the counting room. However, the Roman Pots at 220 m from the interaction point are too far removed for the optically transmitted trigger data to arrive within the latency allowed by CMS and electrical transmission was adopted. The LVDS repeater chip is inserted at regular distances along the 270 m long cable and preserves the electrical signals.

IV. CONCLUSIONS

In conclusion, the TOTEM electronics system, fully compatible with CMS, became possible through standardization across its sub-detectors, adopting the same hardware for trigger building and tracking data, the collaboration with the CMS preshower group, and the support of the Departement de la Haute Savoie for the collaboration with C4i.

V. REFERENCES.

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