Measurement technology for the CMS experiment

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Abstract
The CMS experiment at CERN is a general-purpose collider detector designed to explore physics in new energy domains. It has to overcome different challenges in measurement technology. New techniques have often to be used to identify particles and to determine their energies, momenta and trajectories. Detector response times have to be small due to the high collision rate at the Large Hadron Collider. Many particles are produced in each collision; therefore a high number of detector and readout channels is necessary, which in turn leads to huge numbers of data to be stored and analysed. The dynamic range of the measuring devices needs to be large. In addition, the radiation environment is harsh. The solutions CMS has adopted to address these challenges with its devices for tracking, calorimetry, muon detection and triggering are described.

Keywords: CMS, CERN, particle physics, measurement technology, tracking, calorimetry, muons, trigger

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Large-scale high-energy physics projects such as the Compact Muon Solenoid (CMS) [1] experiment at the Large Hadron Collider (LHC) of CERN, the European Organization for Nuclear Research in Geneva, have to meet special challenges in measurement technology. Their ultimate goal is to explore new physics in the form of yet undiscovered particles such as the Higgs boson. Many detectors need to operate in concert to achieve this goal. The LHC accelerates protons or heavy ions in bunches, which collide every 25 or 125 ns, respectively. The particles produced in the collisions have to be identified. Their physical quantities such as energy, momentum, electric charge and location have to be measured. Furthermore, the bunch crossing from which they originated has to be determined.

The CMS subdetectors (figure 1) are located inside and outside a superconducting solenoidal magnet coil with a flux density of 4 T, which allows the momenta of charged particles to be determined from the curvatures of their trajectories measured in the inner tracker. The latter consists of a silicon pixel precision vertex detector close to the beam pipe and a silicon strip tracker surrounding it. Energies are measured in the calorimeters. The homogeneous electromagnetic calorimeter is made of lead tungstate crystals; the sampling hadronic calorimeter is made of brass and scintillator plates in the barrel and endcap regions. The very-forward region is also equipped with a hadronic calorimeter made of quartz fibres embedded in a steel absorber matrix. An iron return yoke interleaved with muon chambers surrounds the coil.

The specific challenges for the CMS experiment are manifold. Detectors using different technologies are therefore needed. They have to be operated simultaneously during physics data taking, but must also be able to work independently during commissioning and testing. Complex control and monitoring systems are therefore essential. The collision rate of 40 MHz for protons, with up to 20 interactions superimposed at the design luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$, leads to a high number of produced particles, which requires high-granularity detectors with about $10^8$ frontend electronics channels. A two-level trigger system is necessary to select only the most interesting events for permanent storage and off-line analysis. Nevertheless, raw data volumes are of the order of a petabyte per year. The detectors need to have fast response times, between 25 and 75 ns, in order not to integrate over too
many bunch crossing intervals. Since new particles are likely to be only rarely produced, a good background rejection and high signal-to-noise ratios are necessary. The energy spread of the produced particles requires devices with large dynamic ranges. A high measurement precision is also required, which necessitates frequent, sophisticated calibration and alignment procedures. The physical dimensions of CMS require electrical signals, gas, power and cooling water to be transported over large distances. Radiation levels can locally be very high. The annual dose rate at the highest LHC luminosity can in certain areas reach $10^6$ Gy, and neutron fluxes can approach $10^{15}$ cm$^{-2}$. Detectors and their associated electronics need to survive at least a few years before having to be replaced. Furthermore, most of them have to be able to operate inside a large magnetic field.

2. Tracking

The inner tracking system [2] serves to reconstruct trajectories of charged particles, to measure their momenta and to determine the primary collision vertex and possible secondary vertices. It is composed of a pixel precision vertex detector close to the interaction region and a silicon strip tracker surrounding it.

CMS has chosen an all-silicon solution [3] for its inner tracking detectors. Silicon detectors fulfil the requirements of good spatial resolution, high speed and radiation tolerance. Radiation damage is largely due to bulk and surface damage. Bulk damage mainly affects the sensors, altering the effective carrier density by the removal of donor atoms and the creation of acceptor atoms, which leads to type-inversion and consequently to a change in depletion voltage. The bulk leakage current and thus the noise increase as the detector is irradiated. Surface damage mainly affects the front end chips through the trapping of holes in the silicon oxide layer, which leads to additional space charges that can alter the properties of MOS structures. Ionizing particles can also generate single event upsets (SEU) in the readout electronics. For all these reasons the CMS readout chips are manufactured in a 0.25 $\mu$m CMOS technology which leads to good radiation tolerance due to the thin gate oxide layer. Nevertheless, the whole tracker volume will be operated at about $-10$ $^\circ$C, in order to limit noise, reverse annealing and thermal runaway. The life expectancy for the silicon strip tracker and the outer layers of the pixel detector is about ten years of LHC operation. The innermost layer of the vertex detector will have to be replaced after one to two years.

The vertex detector is a hybrid pixel detector consisting of three cylindrical barrel layers at radii of 4.4, 7.3 and 10.2 cm, and 2 × 2 endcap discs at ±34 cm and ±46 cm from the collision vertex. The pixel size was chosen to be $100 \times 150$ $\mu$m in order to obtain occupancies below 1% at the highest LHC luminosities and to achieve a spatial resolution better than 20 $\mu$m. The sensors are manufactured in an n-on-n technique consisting of n$^+$ pixel implants on n-bulk silicon. Drift angles for electrons are three times greater than those for holes due to a large Lorentz drift in the magnetic field. Therefore charge sharing across pixels occurs, which can be used to optimize position resolution by a 'centre-of-gravity' method. The sensor pixels are bump-bonded to 0.25 $\mu$m CMOS readout chips, which amplify the charge generated by a traversing ionizing particle and deliver analogue signals, which are transported through optical links to the frontend drivers in the underground control room located at a distance of the order of 100 m from the experimental cavern. The drivers receive and convert the optical signals, digitize them and send them to the data acquisition after formatting. Capton high density interconnect boards glued on top of the sensors distribute the signal and power lines throughout a detector module.

The silicon strip tracker (SST) surrounds the pixel detector, occupying the region with radii between 20 cm and 1.10 m. The sensors are single-sided p-in-n type microstrips. A crystal orientation of (100) was chosen, after irradiation tests showed that the interstrip capacitance increase was smaller than for more conventional (111) orientations. The barrel part of the SST is made of four cylindrical layers (TIB) of thin strips (320 $\mu$m) and six layers (TOB) of thick strips (500 $\mu$m) oriented parallel to the beam. Strip capacitance increases with length. To compensate for higher noise levels of longer strips, the TOB uses the thicker strips yielding larger signals, in order
to keep the signal-to-noise ratio well above 10. The forward parts are each made of three discs with radii of 55 cm (TID) and nine discs with radii of 1.10 m (TEC). Their strips are oriented radially, perpendicular to the beam. The TID and the four inner discs of the TEC have thin sensors, the outer discs of the TEC have thick sensors. Module sizes vary between 10 cm × 80 µm and 25 cm × 180 µm, depending on the expected strip occupancy. Both single-sided and double-sided modules are used. The double-sided modules, with a stereo angle of 5.7°, provide the measurement of a second coordinate. In figures 2(a) and (b) a silicon sensor module and a partly assembled TOB layer are shown. The frontend hybrids are wire-bonded to the sensors. They contain APV (analogue pipeline voltage) ASIC readout chips, which each serve 128 strips and consist of charge-sensitive amplifiers, shapers and a 192 bunch crossings deep analogue pipeline memory that stores the signals until the level-1 trigger accept (L1A) decision is made. Upon a positive decision the data from multiplexed pairs of APVs are transmitted along optical fibres through laser driven opto-hybrids connected to the frontend hybrids. They are received in the underground control room by frontend driver boards that perform digitization and zero-suppression before sending them to the data acquisition. The frontend hybrids also contain detector control chips to survey hybrid and sensor temperatures, low voltage and leakage currents, and PLL chips to decode clock and trigger signals.

3. Calorimetry

The calorimetry consists of three principal parts—the electromagnetic calorimeter, the preshower detector and the hadronic calorimeter. The electromagnetic calorimeter (ECAL) [4] is a homogeneous calorimeter made of close to 80 000 lead tungstate (PbWO₄) crystals. They allow us to build a fast, dense and highly granular, radiation hard detector with superior energy resolution. The highly granular preshower detector, only present in the endcap regions, serves mainly to reject background from neutral pions, which could mimic a Higgs boson decaying into two closely spaced photons. The hadronic calorimeter (HCAL) [5] serves to detect hadronically interacting particles in the form of jets and measure their energies. In addition, it plays a major role in determining energy sums and missing transverse energy, which originates from neutrinos and other predicted weakly interacting particles such as supersymmetric neutralinos. It has a central section consisting of barrel (HB) and endcap (HE) parts in the magnetic field volume, an outer section (HO) in the barrel region just behind the magnet coil, and two very-forward parts (HF) close to the beam on both sides of CMS.

3.1. Electromagnetic calorimeter

The task of ECAL is to identify electrons and photons and to measure their energies and locations. These particles lose practically all their energy in the crystals, which in turn produce scintillation light with a decay time of the same order as the LHC bunch crossing interval of 25 ns. Avalanche photodiodes (APD) and vacuum phototriodes (VPT) are used to detect this light in the barrel and endcap regions, respectively. These photodetectors have been selected according to their radiation and magnetic field tolerance properties. They have been specially developed for CMS. The APDs are insensitive to the high field in the barrel, but cannot survive a neutron fluence of 2 × 10¹⁴ cm⁻² and dose of 50 kGy, as required for the endcap regions. VPTs can withstand these radiation levels. As the light output of the crystals is rather low, the photodetectors need to have a gain, 50 for the APDs and 10 for the VPTs. However, this gain and also the light output are dependent on operating temperature and voltage. A temperature control of ECAL to 0.05 °C is therefore necessary.

Pairs of APDs or single VPTs are glued to the back of each crystal (figure 3). Groups of five crystals are connected to very frontend boards (VFE). The VFEs shape, amplify and digitize the signals. The first two steps are performed by a low-noise, large dynamic range pre-amplifier. It has three outputs with gains of 1, 6 and 12 respectively, which are each coupled to separate 40 MHz ADCs. The multi-gain preamplifier (MGPA) is an ASIC chip built in 0.25 µm technology, as are the four-channel 12-bit ADCs. An integrated logic selects the highest non-saturated signal and outputs the bits of the corresponding ADC together with the ADC number. A dynamic range from approximately 50 MeV to 2 TeV is thus achieved, according to the requirements for ECAL. The ADC values from five VFE boards are collected by a frontend (FE) board, on which the digitized data are stored during the level-1 latency, and energy sums of a 5 × 5 crystal matrix (supercrystal) are calculated for triggering purposes. From the FE boards optical links transfer the trigger information and, upon a positive level-1 accept decision, the readout data to the off-detector electronics.
3.2. Preshower detector

The preshower detector (PD) is a sampling calorimeter that consists of two layers, each of which has a lead radiator and a silicon microstrip detector behind it. The sensors, 320 μm thick, have 32 large strips, with a pitch of 1.9 mm. The orientation of the strips in the two planes is orthogonal. At normal incidence, a minimum ionizing particle (MIP) deposits a charge of about 3.6 fC. Each of the 4300 sensors is decoupled to the PACE (Preshower Analog CMS Electronics) chip, a frontend ASIC that preamplifies, shapes and samples the signals. The chip has two switchable gains, a low gain for standard physics running with a high dynamic range up to 200 fC for calibration and testing purposes. The readout is also similar. About 90% of the deposited energy in HO is contained in two consecutive charge samples. The signal-to-noise ratios are about three for a MIP in the first case, and ten in the second case. The PD does not participate in the level-1 trigger; therefore the readout data need to be stored until a level-1 decision occurs.

The readout pipeline is 192 bunch crossings long. Data from the triggered bunch crossing and crossings before and after it are read out. The PACE chips are connected to motherboards through frontend hybrids. The motherboards contain 12-bit ADCs as well as electronics for control purposes. The digitized data are formatted, packaged and complemented with bunch crossing information by ASICs called K-chips. Optical links transfer the data to data concentrator cards, which forward them to the data acquisition.

3.3. Hadronic calorimeter

The hadronic calorimeter in the barrel and endcap regions is made of alternating plates of brass and plastic scintillator tiles read out by hybrid photodiodes (HPD) [6] through wavelength shifting optical fibres. The photosensors consist of a fibre-optic entrance window onto which a photocathode is deposited, followed by a gap of several millimetres over which a large electric field accelerates photoelectrons onto a silicon diode target. An additional fibre through which light from a laser or a LED can be injected is connected to each HPD for calibration and testing purposes.

The frontend modules of the barrel and endcap hadronic calorimeter contain charge integrator and encoder (QIE) chips to digitize the analogue signals from the photodiodes. They have two input amplifiers in order to be able to accept negative pulses from the HPDs and positive pulses from the photomultipliers used in the very-forward calorimeters. The required dynamic range is large—from about 200 MeV deposited by a muon to a few TeV. The QIE response is therefore designed to be highly nonlinear, and a multi-range technique is used. The input current is simultaneously integrated in four ranges. Comparators select the lowest non-saturated range, and the corresponding voltage is digitized by a flash-ADC. The latency is four bunch crossings. Optical links transmit the data to 48 HCAL trigger and readout (HTR) boards at a rate of 1600 Mb s⁻¹. At each level-1 accept the data are copied to a derandomizing buffer, from which they are linearized by look-up tables and filtered. Zero-suppression is also applied. The derandomizers can hold up to ten charge samples per bunch crossing. A charge sample can thus participate in more than one event. The logic that copies the data from the HTR pipeline must therefore be able to handle overlapping events. LVDS links transport the data to a data concentrator card, which contains the event building logic. Error detection and correction by a Hamming scheme are also performed before sending the data to the acquisition.

At least ten absorption lengths are necessary in order to prevent leakage from late developing hadronic showers. For this reason the region between the magnet coil and the first station of barrel muon chambers is instrumented by 10 mm thick Bicron scintillator plates. The coil doubles as an absorber. In the central wheel there are two layers of scintillator, separated by 15 cm of tailcatcher iron. In the outer wheels there is only one layer. The absorbers and the scintillators make up HO, which also plays a part in the trigger (section 5). Wavelength-shifting fibres and subsequent clear fibres transport the scintillation light to HPDs, as in HB and HE. The readout is also similar. About 90% of the deposited energy in HO is contained in two consecutive charge samples. The HPDs are operated at a typical gain of 2500.

HF, the two very-forward modules of HCAL located on both sides of the detector at distances of about ±11 m from the interaction point, has steel absorber plates sampled by quartz fibres due to their good radiation tolerance and fast signal response. The areas closest to the beamline will have experienced a dose of roughly 10⁷ Gy and a charged hadron flux of more than 10¹¹ cm⁻² after ten years of LHC operation. At worst optical transmission is expected to be degraded by about 50% after this time. The calorimeter is insensitive to low-energy neutrons. The HF readout is performed with conventional eight-stage photomultipliers, since the magnetic flux density in the very-forward regions is much lower than in the central part. Lightguides connected to fibre bundles transport the light to the photomultipliers.
4. Muon system

The muon system [7] serves to identify and to trigger on muons as well as to measure their spatial parameters and momenta, in collaboration with the inner tracker. It consists of three types of muon chambers. One type, the resistive plate chambers (RPC), is only used in triggering, the other two—the drift tube chambers (DT) in the barrel and the cathode strip chambers (CSC) in the endcaps—are used both for precision tracking and triggering. The barrel DT and endcap CSC chambers are arranged in four stations embedded in the iron yoke surrounding the magnet coil. Several layers of double-gap RPCs are mounted on the DT and CSC tracking chambers, six in the central region (two layers on the inside and outside of the two innermost muon stations, one on the inside of the two outermost stations) and four in the forward parts (one layer on the inside of each station). The DT and CSC deliver track segments, each of which is characterized by its position and its bending angle in the magnetic field. From these segments the precise transverse momentum \( p_T \) and the charge of a track can be reconstructed off-line. A coarser measurement is also available for triggering purposes. The RPCs deliver hit patterns, together with the bunch crossing number from which a muon candidate originated.

Each DT chamber consists of staggered planes of drift cells. Four planes are glued together and form a superlayer. The three innermost stations are made of chambers with three superlayers. The inner and outer superlayers measure the azimuthal coordinate \( \phi \) in the bending plane transverse to the LHC beams. The central superlayer, which is orthogonal to the two outer superlayers, measures \( \theta \), the coordinate along the beam direction. The fourth muon station has only \( \phi \)-superlayers. With eight track points in the two \( \phi \)-superlayers measured with a resolution of a single wire that is better than 250 \( \mu \)m, a chamber \( \phi \)-position resolution of about 100 \( \mu \)m is achieved.

The anode wire signals from the drift tubes are amplified by charge preamplifiers, shaped and transformed to LVDS-compatible signal levels suitable to drive twisted pair cables. These tasks are performed by 0.8 \( \mu \)m BiCMOS ASICs. The digitization of the drift times, based on a delay-locked loop principle, is performed by 0.25 \( \mu \)m 32-channel TDCs located on readout boards. The data collected on these boards, which are housed in minicrates [8] mounted on the chambers, are sent to dedicated readout server (ROS) boards located at an average distance of 30 m at one side of the experiment, from which they are forwarded to the data acquisition.

The CSCs are trapezoidally shaped multiwire proportional chambers, in which one cathode plane is segmented into strips and anode wires run perpendicular to them. They are designed for reliable operation at hit rates of up to 1 kHz cm\(^{-2}\) and in non-uniform magnetic fields. The chambers have six individual layers. Muon track segments, also called local charged tracks (LCT), consisting of positions, angles and bunch crossing information are first determined separately in the nearly orthogonal anode and cathode views. They are then correlated in time and the number of layers hit. The cathode electronics is optimized to measure the \( \phi \)-coordinate, the anode electronics to identify the bunch crossing with high efficiency. Figure 4 shows the layout of the CSC electronics.

Signals from the cathode strips are amplified and shaped on cathode front end boards (CFEB), each of which reads out a 16-strip by six-layer deep section of a CSC. To minimize pile-up effects due to high event rates, circuits to cancel the long tail of the chamber pulses due to ion drift are integrated into the shaper. Upon a level-1 accept signal 12-bit ADCs digitize the charge of the shaped pulses which have been stored in 50 ns time samples in a switch capacitor array. Depending on luminosity, eight or sixteen consecutive time samples per strip are digitized on each CFEB. Signals from groups of anode wires are amplified, shaped and discriminated on anode front end boards (AFEB). The discriminator bits are transmitted to the anode local charged track board (ALCT) where signals above threshold are stored as hits. Discriminator hits for up to five 25 ns time samples are stored for each event. The ALCT finds hit patterns in the six chamber layers that are consistent with having originated at the vertex, and determine the bunch crossing. An ALCT board reads out all AFEBs for a chamber. The data for a CSC are read out by a data acquisition motherboard (DMB) located in a peripheral VME crate on the outside of the iron yoke. Data from the CFEBs on the chamber are transmitted directly to the DMB. The ALCT data reach the DMB through the combined cathode local charged track board/trigger motherboard (CLCT/TMB), which is also located in the peripheral crate. The CLCT circuits look for strip hit patterns consistent with high-momentum tracks. The TMB circuits perform a time coincidence of cathode and anode LCT information. From the DMB optical fibres transport the data to the acquisition for readout.

An RPC consists of two layers of two parallel plates made out of bakelite with a bulk resistivity of about \( 10^{10} \) \( \Omega \) cm, separated by a gas gap of 2 mm. The outer surfaces of the resistive material are coated with conductive graphite.

![Figure 4. Electronics of the cathode strip chambers.](image-url)
paint to form the high voltage and ground electrodes. The readout is performed by means of aluminum strips running in the gap between the two layers. Strip capacitance ranges between 160 and 400 pF. The rise time of the induced signals is about 1 ns, which is shorter than the time corresponding to a propagation delay of about 5.5 ns m$^{-1}$ along the strips. In order to avoid spurious hits due to reflections the strips are terminated. They are connected to frontend boards, which each contain two frontend eight-channel 0.8 $\mu$m BiCMOS ASIC chips consisting of amplifiers, discriminators, and monostable and differential line drivers. A one-shot monostable driver is necessary as after-pulses may occur for RPCs operated in avalanche mode. The charge sensitivity of the amplifier is around 2 mV fC$^{-1}$. The output jitter of the zero crossing discriminator has been measured to be less than 1 ns, which fulfils an important requirement for the accuracy of the bunch crossing determination. The frontend boards also contain a DAC to set thresholds, an ADC to read back the analogue threshold settings and various service components. Several boards are connected to a link board, which performs synchronization and data compression. It also contains an optical transmitter. Data from one link board are fanned out through a splitter board to two kinds of destinations, the trigger and the readout.

5. Trigger

At the nominal LHC design luminosity the event rate is almost 1 GHz. Since it is impossible to store and process the corresponding large number of data, a drastic rate reduction has to be achieved. This task is performed by the trigger system, which is the start of the physics event selection process. The rate is reduced in two steps called level-1 trigger (L1T) [9] and high-level trigger (HLT) [10, 11], respectively. The level-1 (L1) trigger consists of custom-designed, largely programmable electronics, whereas the HLT is a software system implemented in a filter farm of about one thousand commercial processors. The rate reduction capability is designed to be at least a factor of 10$^6$ for the combined L1T and HLT. The design output rate limit of the L1T is 100 kHz. The L1T uses coarsely segmented data from the calorimeters and the muon system. The tracker does not take part in the L1T. For reasons of flexibility the L1T hardware is implemented in FPGA technology where possible, but ASICs are also widely used where speed, density and radiation resistance requirements are important. A software system, the trigger supervisor [12], controls the configuration and operation of the trigger components. The L1T has local, regional and global components. Local triggers, also called trigger primitive generators (TPG), are based on energy deposits in calorimeter trigger towers, and track segments or hit patterns in muon chambers. Regional triggers combine their information and use pattern logic to determine ranked and sorted trigger objects such as electron or muon candidates in limited spatial regions. Subsequently, the global calorimeter (GCT) and global muon triggers (GMT) determine the highest-rank calorimeter and muon objects across the entire experiment and transfer them to the global trigger (GT), the top entity of the level-1 hierarchy. The latter takes the decision to reject an event or to accept it for further evaluation by the HLT. The L1T has to analyse every bunch crossing, necessitating a pipelined structure. The allowed latency between a given bunch crossing and the distribution of the L1A signal to the detector frontend electronics is 3.2 $\mu$s. The data flow of the L1T is shown in figure 5.

The ECAL on-detector electronics boards, each serving 25 crystals, receive the ADC signals from the very frontend electronics located at the rear of the detector modules. The TPG pipeline is contained in six radiation-hard 0.25 $\mu$m CMOS ASIC chips. An off-detector trigger concentrator card (TCC) collects the primitives from the frontend boards through optical links. The TCCs finalize the TPG generation and encoding, store the trigger primitives during the L1 latency time and transmit them to the regional calorimeter trigger (RCT) upon reception of a L1A signal. Synchronization of the trigger data is performed by circuits that histogram the LHC bunch crossing structure. A data concentrator card (DCC) performs the opto-electronic conversion and deserialization of the serial input data streams and sends the readout data collected from the frontend boards to the DAQ.

As described in section 3.3, the HCAL trigger and readout boards linearize, filter and convert the input data to generate the HCAL trigger primitives. Energy values in trigger towers are summed and the bunch crossing number is assigned with a peak filtering algorithm. As for the ECAL, the primitives are sent to the RCT [13]. The RCT sums up energies in larger regions and determines electron/photon candidates from shower profiles. It also calculates regional energy sums. The serial input data are converted to 120 MHz parallel data, deskewed, linearized and summed before transmission on a 160 MHz custom monolithic backplane to the RCT boards, where different ASICs perform the algorithm calculations. The large number of data from the RCT crates is transmitted to the global calorimeter trigger through optical fibres. The core of the GCT processing is performed by leaf cards, which can be configured as electron or jet cards. Wheel cards perform sorting and data compression for jets and collect regional energy sums and jet multiplicities. A concentrator card finally collects the data from all electron leaf and wheel cards and performs the final sorting for electrons/photons, completes the jet finding in the boundaries between groups of three leaf
cards, sorts all jets, calculates the global energy and jet count quantities and sends the final results to the GT and the DAQ.

All three muon systems—the DT, the CSC and the RPC—take part in the trigger. The barrel DT chambers provide local trigger information in the form of track segments in the \( \phi \)-projection and hit patterns in the \( \theta \)-projection. The endcap CSCs deliver three-dimensional track segments. All chamber types also identify the bunch crossing from which an event originated. The regional muon trigger consists of the DT and CSC track finders (DTTF, CSCTF), which join segments to complete tracks and assign physical parameters to them. In addition, the RPC trigger chambers, which have excellent timing resolution, deliver their own track candidates based on regional hit patterns. The global muon trigger then combines the information from the three subdetectors, achieving an improved momentum resolution and efficiency compared to the stand-alone systems.

The electronics of the DT local trigger (figure 6) consists of four basic components: bunch and track identifiers (BTI), track correlators (TRACO), trigger servers (TS) and sector collectors (SC). The BTIs are interfaced to the frontend electronics of the chambers. Using the signals from the wires they generate a trigger at a fixed time after the passage of the muon. Each BTI searches for coincident, aligned hits in the four equidistant planes of staggered drift tubes in each chamber superlayer. The association of hits is based on a meantimer technique [14], which uses the fact that there is a fixed relation between the drift times of any three adjacent planes. From the associated hits track segments defined by position and angular direction are determined. The BTI algorithm is implemented in a 64-pin ASIC with CMOS 0.5 \( \mu \)m standard cell technology. The TRACO attempts to correlate the track segments measured in each of the \( \phi \)-superlayers. The TS performs a track selection. It has two components, one for the transverse projection (TS\( \phi \)) and the other for the longitudinal projection (TS\( \theta \)). The first one processes the output from the TRACO, whilst the second uses the output of the BTIs of the \( \theta \) view delivered by the \( \theta \) superlayers present in the three innermost muon stations directly. The TS\( \phi \) itself consists of two components, the track sorter slave (TSS) and the track sorter master (TSM). The TSS preselects the tracks with the best quality and the smallest bending angle based on a reduced preview data set coming from the TRACOs in order to save processing time. A select line in the TRACO with the best track is then activated and the TRACO is allowed to send the full data to the TSM. The output consists of the two tracks with the highest transverse momentum. In the longitudinal view the TS\( \theta \) receives two bits from each BTI, a trigger bit and a quality. A logic OR of groups of eight bits is applied. The output data consist of eight bits indicating the position of the muon and eight quality bits. The trigger and also the readout data from each of the 60 \( 30^\circ \)-sectors of CMS are sent to SC units, where the trigger information is coded and transmitted to the DTTF through high-speed optical links.

For the CSCs, the generation of LCTs has been described in section 4. The LHC timing reference, the L1A decision, the bunch crossing number and bunch counter reset signals are distributed by clock and control boards. Apart from the frontend boards and the ALCTs mounted directly on the chambers, the local trigger electronics is housed in 48 peripheral crates on the endcap discs. Except for the comparator-network ASIC implemented in the CLCT module the CSC trigger electronics is built in FPGA technology.

The RPC trigger is based on the spatial and temporal coincidence of hits in several layers. As opposed to the DT/CSC, there is no local processing on a chamber apart from synchronization and cluster reduction. The pattern comparator trigger (PACT) logic [15] compares strip signals of all four muon stations to predefined patterns in order to assign \( p_T \) and electric charge, after having established at least three coincident hits in time in four planes. Spatially the PACT algorithm requires a minimum number of hit planes, which varies depending on the trigger tower and on the \( p_T \) of the muon. Either 4/6 (four out of six), 4/5, 3/4 or 3/3 hit layers
are minimally required. For six planes there are typically 14,000 possible patterns. HO, the outer HCAL section, can also be taken into account by the RPC trigger in order to reduce rates and suppress background [16].

The DTTF [17] and the CSCTF [18] principles are based on extrapolation from a source track segment in one muon station to a possible target segment in another station according to a pre-calculated trajectory originating at the vertex. If a compatible target segment with respect to location and bending angle is found, it is linked to the source segment. A maximum number of compatible track segments in up to four muon stations is joined to form a complete track, to which parameters are then assigned. Both for the DTTF and the CSCTF the track finder logic fits into high-density FPGAs.

The global muon trigger [19] receives for every bunch crossing up to four muon candidates each from the DTs and barrel RPCs, and up to four each from the CSCs and endcap RPCs. DT and CSC candidates are first matched with barrel and forward RPC candidates based on their spatial coordinates. If a match is possible, the kinematic parameters are merged. Several merging options are possible and can be selected individually for all of these parameters. Cancel-out units reduce duplication of muons in the overlap region between the barrel and the endcaps, where the same muon may be reported by both the DT and CSC triggers. Finally, the muons are sorted by $p_T$ and quality, and the best four candidates are sent to the GT. The GMT electronics consists of three input boards and one logic board all using FPGA technology.

The global trigger [20] is a digital system that takes the decision to accept or reject an event at L1 based on algorithms applied to the trigger objects delivered by the GCT and the GMT. Most algorithms consist in applying thresholds to objects, but topological conditions are also possible. The maximum number of algorithms running in parallel is 128. In addition, the status of the subdetectors and the DAQ determined by the trigger control system (TCS) [21] is taken into account. The level-1 accept decision is communicated to the subdetectors through the timing, trigger and control (TTC) system [22]. The GT has five basic stages: input, logic, decision, distribution and readout. The corresponding electronics boards all use FPGA technology [23].

6. Conclusions

CMS has been designed to measure particle energies, momenta and trajectories with high precision in the presence of large event rates and a hostile radiation environment. A flexible trigger system contributes to maximize its physics potential. During summer 2006 the magnet, the principal subdetectors as well as the trigger and data acquisition were successfully operated together for the first time using cosmic rays [24], thus proving the adequateness of the design concept and the measurement technologies.

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