Electronics for the CMS Muon Drift Tube Chambers: The Read-Out Minicrate

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***Abstract*—On the Compact Muon Solenoid (CMS) experiment for large hadron collider (LHC) at CERN laboratory, the drift tube chambers are responsible for muon detection and precise momentum measurement. In this paper the first level of the read out electronics for these drift tube chambers is described. These drift tube chambers will be located inside the muon barrel detector in the so-called minicrates (MCs), attached to the chambers. The read out boards (ROBs) are the main component of this first level data acquisition system, and they are responsible for the time digitalization related to Level 1 Accept (L1A) trigger of the incoming signals from the front-end electronics, followed by a consequent data merging to the next stages of the data acquisition system. ROBs' architecture and functionality have been exhaustively tested, as well as their capability of operation beyond the expected environmental conditions inside the CMS detector. Due to the satisfactory results obtained, final production of ROBs and their assembly in the MCs has already started. A total amount of 250 MCs and approximately 1500 ROBs are being produced and tested thoroughly at CIEMAT (Spain). One set of tests, the burn-in tests, will guarantee ten years of limited maintenance operation. An overview of the system and a summary of the different results of the tests performed on ROBs and MCs will be presented. They include acceptance tests for the production chain as well as several validation tests that insure proper operation of the ROBs beyond the CMS detector conditions.**

***Index Terms*—Data acquisition, detectors, electronic equipment, particle measurement, time measurement.**

I. Introduction

COMPACT Muon Solenoid (CMS) is a general purpose detector that will be installed in the large hadron collider (LHC), the new proton-proton collider that is being built at CERN and will be operational by 2007. Both luminosity ($10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) and energy (14 TeV) frontiers are to be reached in this deep exploration into matter, where muon tracks reconstruction at the highest luminosity is an important goal that is central to the concept of CMS [1].

CMS consists of a large superconductor solenoid with a radius of 3 meters and a length of 13 m, which generates a magnetic field of 4 T. This large magnet allows all of the tracking devices and calorimetry to be placed inside the coil of the solenoid, while the muon system will be located outside the coil, in the return yoke of the magnet.

The muon system employs three different technologies to trigger and measure muons: drift tubes in the barrel region, cathode strip chambers in the endcap region and resistive plate chambers in both the barrel and endcap regions.

Drift tube chambers are integrated in the five wheels of the return yoke of the magnet. Each wheel is organized in four concentric rings around the beam line, namely MB1 to MB4, with 12 sectors per ring to allocate each station as can be seen in Fig. 1. As sectors 4 and 10 of ring MB4 contain two chambers each, the total amount of chambers, and therefore, of MCs, is 250.

A drift tube chamber consists of three superlayers, each of which have four layers of drift cells, staggered by half a tube width. The average number of channels per layer is 64, which leads to a total number of channels of 172 200 cells in the whole detector. The two outer superlayers perform muon φ coordinate measurement (angle on the bending plane), meanwhile the inner measures θ coordinate (angle in the nonbending plane). An aluminum structure is glued in between the superlayers to provide the required stiffness to the chamber. This structure, the honeycomb plate, gives also a place for attaching the MCs to the chambers.

Any charged particle track going through a cell volume will generate a signal (hit) in its anodic wire that will be processed by the front-end system [2] before being injected in the read-out electronics. Time measurement of these hits related to an Level 1 Accept (L1A) trigger, which is the main goal of the read-out electronic, allows later reconstruction of the particle track and momentum measurement.

As the single wire resolution of each cell is less than 200 $\mu\mathrm{m}$, and the drift velocity is $\sim 55\ \mu\mathrm{m/ns}$, a timing resolution below 1 ns is considered to be adequate.

Also, a read-out system that manages overlapping triggers is required, due to a maximum drift time (400 ns) that is much larger than the LHC bunch crossing period (25 ns).

In spite of the high bunch crossing frequency, the complex CMS trigger system [3] will reduce first level trigger (L1A) rate to a maximum of 100 KHz. Moreover, the L1A latency due to this trigger system will be of around 3.2 μs; therefore, memories must have sufficient capacity to store hits until matching to the L1A can be accomplished.

The read-out electronics have been developed to fulfil these, as well as other, requirements imposed both from the functional operation of the LHC system and from the environmental conditions expected in the CMS detector. One of the requirements comes from its location inside the CMS wheels, as the system has to operate during 10 years of limited maintenance. Moreover, the presence of high magnetic fields and the remnant radiation had to be taken into account during the design of the system. In the region where the electronics will be allocated, the

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Digital Object Identifier 10.1109/TNS.2005.852698

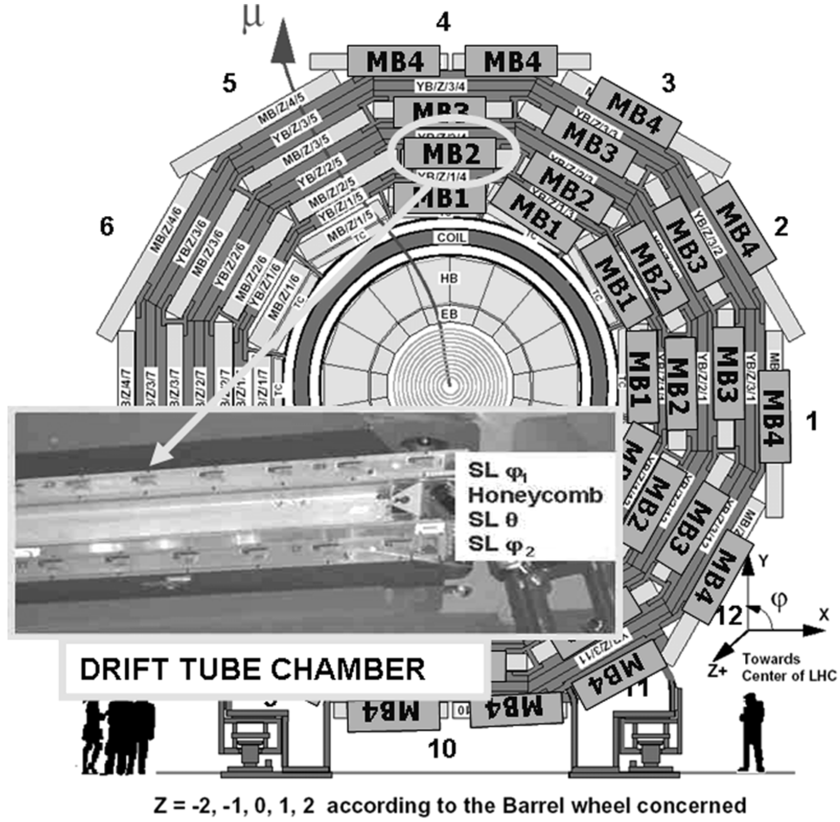

Fig. 1. Transversal view of one of the wheels in the CMS detector barrel region. A picture of a drift tube chamber inserted on the wheel is shown.

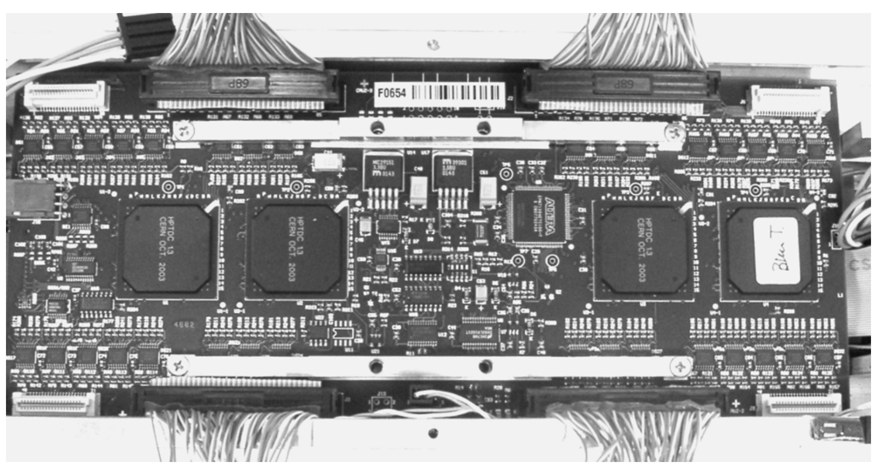

Fig. 2. Picture of a 128-channels ROB assembled on a MC. The two horizontal aluminum pieces that screw the ROB to the MC behave as thermal relieves for heat dissipation.

expected neutron fluence is $10^{10}\ \mathrm{cm}^{-2}$, and the charged particles fluence is $10\,\mathrm{cm}^{-2}$. The integrated dose during the 10 years of operation will be ~1 Gy.

II. The Read-Out Boards

The read-out boards (ROBs), developed at CIEMAT, perform the time digitalization of the incoming signals from the chamber front-end electronics. ROBs are built around a 32-channels application-specific integrated circuit, the high performance time to digital converter (HPTDC). The HPTDC was developed by CERN/EP Microelectronics group [4] and produced in a commercial 0.25 $\mu\mathrm{m}$ process. Each ROB has four HPTDCs; therefore, 128 channels. This number was chosen in order to accommodate the amount of channels per chamber while minimizing the multiplication of common components. An image of a 128-channels ROB can be seen on Fig. 2. The dimensions of a ROB are 9.8 cm × 22.6 cm.

The time digitalization of the HPTDC is based on the delay locked loop (DLL) principle, and uses a phase locked loop (PLL) to provide different resolution modes. The low resolution mode (0.781 25 ns per bin) is being used in the ROBs, as it is more than sufficient to meet the 1 ns required precision.

Actually, 260 ps RMS time resolution has been measured, and cross-talk tests show deviations below 350 ps between the time measurements of different ROB channels [5].

One of the main advantages of the HPTDC is its large programmability. Besides, an efficient trigger matching and hits reject mechanism allows managing of overlapping triggers.

Moreover, its several buffers are large enough to cope with hit rates of ~2 MHz and ~1 MHz trigger rate [4]. These rates are much larger than the expected 100 kHz maximum L1A trigger rate and 10 kHz hit rate per read-out channel.

The architecture of a ROB is based on a clock synchronous token-ring scheme that connects four HPTDCs in a ROB, where one of them is configured as master and controls the token of the read-out data chain. An Altera programmable device manages the handshake protocol to merge data into a low voltage differential serializer, which will transmit data through a 30 m twisted pair link to the read-out server (ROS) boards. These ROS boards, located in racks in the periphery of the CMS detector, collect the data corresponding to one full sector for subsequent transmission to the CMS data acquisition system.

Other features of the ROB include power supply, current and temperature monitoring and also a power supply protection circuitry with fast shut off capability to avoid over-currents. These over-currents may be generated, not only by electrical failures, but also by radiation induced errors of diverse severity. As radiation hard devices are not going to be employed, irradiation tests were performed on the ROBs and the results obtained indicated that only single event upsets, where the data is damaged but not the devices, occurred. In the Altera programmable device a triple redundant logic was implemented. Meanwhile, irradiation tests showed that the estimated mean time between failures was ~3 days for all the HPTDCs in the whole detector [5]. No other significant effect was observed.

III. The Read-Out Minicrate Operation

A read-out MC consists of a chamber control board (CCB) and the necessary number of ROBs according to the corresponding chamber. Nevertheless, within a MC, the read-out electronics is integrated in a complex system together with the muon trigger electronics. They share wire chamber signals, timing and trigger control (TTC) signals [6], power supplies, cooling and mechanics.

The MC trigger system consists of a layer of trigger boards (TRB) and a server board (SB). The TRBs are mounted on top of the ROBs to share chamber signals for selecting best muon candidates; meanwhile, the SB collects data from all the TRBs in a chamber and performs further track selection according to its quality. Additional details on the trigger system can be found in [3].

The CCB manages the electronics configuration, control, monitoring, and test functions. Part of the control electronics are hosted on the SB, connected on top of the CCB in the centre of the MC as can be seen in the MC scheme of Fig. 3. CCBs communicate via a dedicated optical fiber link with the CMS detector control system.

At power up, the CCB executes a BOOT program to check general MC status, e.g., the power supplies, memories status,

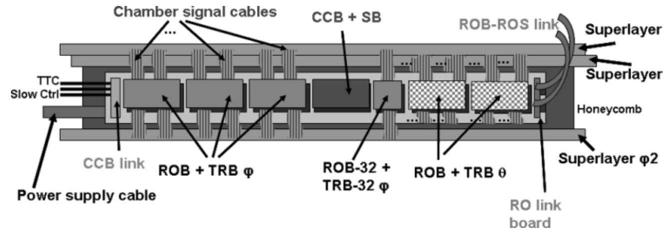

Fig. 3. A schematic drawing of an MB1 MC attached to a chamber is presented in this figure. The three superlayers of the chamber, as well as the honeycomb structure are shown. The different boards and the main connections are indicated.

etc. Upon completion of this task, it runs, by default, a MC configuration program stored in a nonvolatile memory.

ROB configuration consists mainly of loading the HPTDC set-up bits and performing the initialization of the PLL and DLL through a JTAG interface. Independent address capability is a basic feature of each element in the MC.

In normal operation mode, at an L1A trigger arrival, the HPTDCs match buffered hits according to a programmable time window, generating 32-b words with the time measurement and channel identification. This information is enclosed between a header and a trailer generated by the master HPTDC, specifying the L1A event number, the beam bunch crossing identification and the number of data words sent.

Chip internal errors as well as buffer overflows are reported to the CCB like other system faults, but they are also included within the read-out data flow.

In the ROB, the readout is performed at an effective bandwidth of 200 Mbps, with an estimated throughput of 16 Mbps. This throughput value is well below the ROB-ROS link bandwidth, which is very unlikely to be reached unless MHz noise coming from a malfunctioning chamber channel. In such a case, independent channel disabling can be performed.

The reliability of the ROB-ROS link has been measured and the tests showed a bit error rate of less than 10^{-15}.

Besides individual channel disabling, an HPTDC bypassing mechanism has also been implemented in the ROB and of course, a whole ROB could be disconnected when needed without interfering with the rest of the MC operation. In summary, the electronics have been designed so that a failure in one component does not cause failure in other elements of the system.

A special operation mode called test-pulse will be used to test and calibrate the drift tubes electronic chain by the emulation of vertical artificial tracks. In this mode, ROBs are responsible for enabling groups of four channels in each event, according to a particular pattern sequence. This sequence is controlled by the Altera programmable device that receives the test-pulse control signals from the CCB.

These MC operation modes have been successfully tested in the laboratory and also in several beam tests at CERN. In 2003 one fully-equipped chamber and the attached MC were exposed to a secondary muon beam with a 25 ns structure similar to the one foreseen in LHC. In 2004 two chambers were operational. No significant error was found in the read-out chain during these tests, confirming the results obtained in previous beam tests where the functionality of a stand-alone ROB was validated [7].

IV. Description of the Read-Out Minicrate

Placing the read-out electronic inside the CMS wheels created some restrictions to their maintenance, but it drastically minimized the large number of cables otherwise needed and, consequently, the overall cost. Accordingly, it was decided that the MC will be hosted in the available space of the C profile of the chambers honeycomb. This space is limited, mainly for MB1, with only 1.7 m length and more than 650 channels, so a smaller ROB had to be produced with only one HPTDC: the ROB-32.

The aluminum structures of the MC, as well as the complex boards support structures, have been designed not only to provide sound construction, but also thermal conduction for refrigeration through a water cooling system. As a fan based refrigeration system is not possible due to the presence of a 0.08 T magnetic field in the MC region, the electronics are cooled by water flowing in tubes extruded in the MCs' aluminum profile along the full length of the MC.

As stated before, ROB and TRB configuration and monitoring is accomplished through the CCB, which is connected to the ROBs through a fine-pitch 40 lines parallel bus, so-called ROBUS. This bus carries signals such as: JTAG interface for configuration and monitoring, TTC signals, ROB addresses, power up lines, test-pulse control signals and a 1-wire interface for voltage, current and temperature on board monitoring.

Read-out clock is obtained from the LHC 40.08 MHz bunch crossing clock that is distributed to every system by the TTC interface through an optical link. At MC level, the CCB is responsible for decoding the TTC signals to extract the L1A trigger, the bunch and event counters resets, the clock signal and the corresponding test-pulse commands. All these signals are transmitted to the ROBs through the ROBUS except for the clock, which is distributed using differential signals on twisted pair point-to-point cables.

Besides ROBs and CCBs, other elements are lodged inside a read-out MC, i.e., power supply filters, a ROB-link board that serves as a patch panel for the ROB-ROS link connections, a CCB-link board that communicates with the TTC, and CMS control system and the different cables that interconnect all of the MC items.

In Fig. 3, a scheme can be seen of the different items that constitute an MC and its main external connections. An image of a partially assembled read-out MC under test can be found in Fig. 4.

With a total number of 250 MCs, there are up to 20 types of read-out MCs. Depending on the station type and sector, the number of ROBs varies from 3 to a maximum of 7. Also, the position of the service side leads to left and right MCs, and finally, due to the CMS structure, some MCs have special features.

MC lengths vary from 1 to 2 m, with a fixed width of 10.5 cm and height of 5.5 cm. The average weight of a read-out MC is approximately 8 Kg.

In principle, the MC power supply sources will be CAEN modules A3050 for 3.3 V and A3009 for 5 V MC power supply.

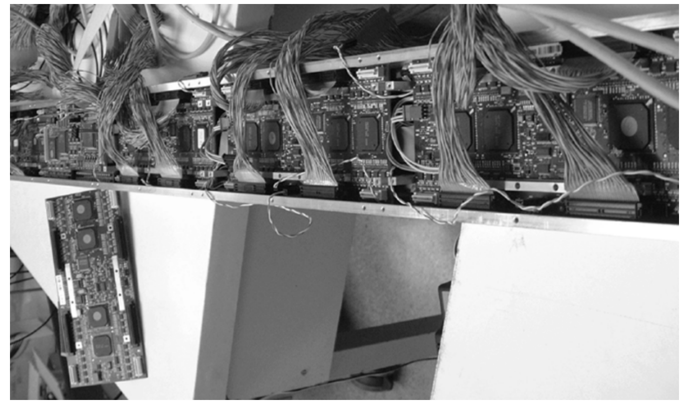

Fig. 4. View of a read-out MC under test.

TABLE I
Current and Power Consumption in Several Read- Out MC Types

MC Type	MB1	MB2/MB4	MB3	MB4(9/11)
Nº of ROBs	6+ROB-32	6	7	3
I(A) average 3.3V	7.7	8	9	5
I (A) average 5V	2.2	2.2	2.2	2.2
Power Consumption (W)	36.41	37.4	40.7	27.5

A total of 130 units of A3050 and 70 modules of A3009 will be positioned on the CMS barrel towers, at a distance of 10–20 m from their loads. Voltage sensors will be placed at the MC LV patch panel attached to the iron yoke to guarantee a nominal voltage of 4 and 6 V at MC input in order to power the low drop voltage regulators of the boards. Inside each MC, the 3.3 V power supply is distributed by two copper 25 mm^2 square bars to minimize voltage drops and simplify connections.

In Table I it is shown the average current and power consumption in some of the different types of read-out MCs, that is, including ROBs and CCB. Total MC power consumption, including TRBs and other chamber elements powered from the MC, can increase up to 130 W for MB3. This power will have to be dissipated through the cooling system as no heat emission is allowed inside the CMS cavern. Former tests with a cooling system similar to the one that will be present at CMS (water flow of 1.5 l/min at 20 $^\circ\mathrm{C}$) have shown a maximum temperature of 38 $^\circ\mathrm{C}$ on any board.

However, ROB behavior with temperature has been previously tested [5] during temperature cycling tests, between 0 $^\circ\mathrm{C}$ to 70 $^\circ\mathrm{C}$, where small variations on voltage, current and time shifts were shown. Besides, lifetime tests have been performed to a fully operational ROB at 105 $^\circ\mathrm{C}$ ambient temperature to find out failure mechanisms in an accelerated stress test. During 4 months no wrong operation was found, which will mean a worst case failure rate below 1 per ROB during 10 years of operation. This failure rate has been calculated considering a low activation energy failure mechanism, such as solder bonding (0.4 eV) [8].

Several prototypes of the MC mechanics and of the ROBs were developed to obtain a final design that has been approved at the 2003 Electronic System Review. Accordingly, production of 1500 ROBs and 250 MCs has already started at CIEMAT.

V. Minicrate Production

Full MCs production is shared by CIEMAT, INFN Legnaro, INFN Bologna, and RWTH-Aachen. Each of the institutes have manufactured part of the 250 plus spare aluminum extrusions; CIEMAT has designed and produced most of the mechanical pieces and cables, and then, boards assembly is performed in two stages:

First, at CIEMAT, the read-out elements are assembled, including mechanical pieces, low voltage items, links and clock cables, and all of the boards except for the TRBs.

A second stage is performed at Legnaro and Bologna, which includes assembly of the TRBs with its necessary mechanics and its cabling. The foreseen MC production rate is 16 MC/month.

Each of these steps, along with further installation on chambers at CERN, involves detailed and thorough tests of all the assembled items. Moreover, ROB production includes meticulous tests to verify its proper operation. ROBs have also undergone burn-in tests, attempting to screen for "infant mortality" of integrated devices. This burn-in tests consists of 48 powered and clocked boards inside a rack at 50 °C for 1 week. Considering an acceleration factor of 4, this will represent ~700 h of the ROB lifetime. At the moment this paper was written, 600 ROBs have been burned-in and no failures have been found.

VI. Read-Out MC Production Tests

A test system has been developed at CIEMAT to perform MC functional testing, and it is being used at present for read-out MC assembly validation.

It consists of a PC-based system with a slow control connection to the CCB and a 6U VME rack module where four kinds of boards are employed: a TTC module that generates global clock and connects to the MC CCB link board for TTC commands transmission; up to 7 Pattern Generators (PATGEN) boards that perform a 1:128 fan-out to inject simulated chamber signals in every channel of the MC; a ROS prototype for ROBs' data acquisition; and finally, a Control-X board. The Control-X board generates the PATGEN inputs and a synchronous trigger that will be injected in the TTC module for transmission into the MC with proper latency. In Fig. 5, a diagram of this test system is presented.

LabView software has been developed to perform the different tests. Besides visual inspection, several tests are performed with different verifications that are indicated below.

Proper turn on of all the boards on the MC with their corresponding power-up lines is checked, as well as the short-circuit flag and the ROB error flag.

Operation of the logical addressing mechanism is insured and it is also verified that the ROBs are properly configured, including PLL and DLL locking and the status of the different buffers. The JTAG protocol and the ROB reset signals are verified with these routines.

Besides, 2.5 and 3.3 V voltage levels, current and temperature are monitored on every ROB, insuring proper operation of the 1-wire protocol. A unique identification number is provided by each of these sensors, allowing remote unmistakable identification of each ROB.

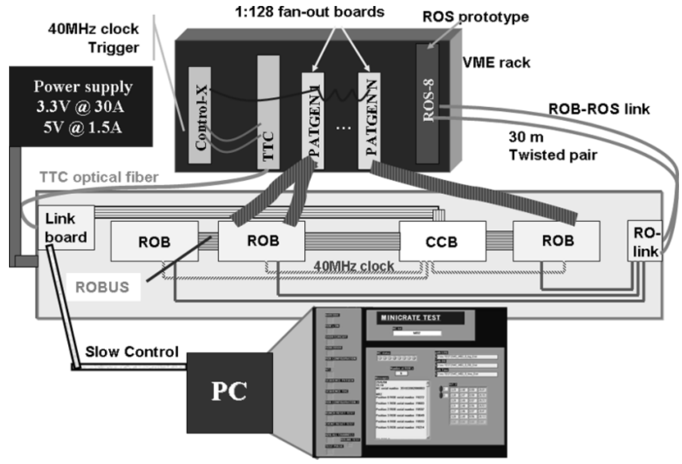

Fig. 5. Diagram of the read-out MC test system.

The read-out chain is checked through several tests. All of them verify some common parameters such as consecutive event number on each trigger, common event and bunch crossing number among all the boards, word count number, HPTDC master identification, any HPTDC or ROB error present, or possible unlock or parity error in a read-out channel.

Moreover, as the time difference between hits and triggers is fixed by the test system, leading, trailing and width time measurements of the hits signals of every channel are verified.

Every channel operation is checked in several ways: firstly, one hit at a time is sent to each channel, insuring its operation and discarding possible cross-talks. Secondly, every HPTDC channel disabling mechanism is checked, and finally, operation with all channels simultaneously receiving hits is also tested. It is guaranteed that each ROS channel is receiving data from the corresponding ROB.

Loading a MC configuration without activation of the reset signal allows testing of the event and bunch crossing counters reset signals. In this way, it is verified that the event and bunch counter values are common to all of the boards only after a corresponding type of reset.

Finally, test-pulse sequences are performed to check all of the control lines involved and also proper channels disabling mechanism at the ROB receivers according to the test-pulse logic.

With these tests, every cable and connection is checked, as well as every board functionality, validating proper MC assembly and guaranteeing later operation. It is worthwhile to say that a suitable system [9] for quality control of the manufactured cables before their assembly on the MC has been developed at CIEMAT.

VII. Conclusion

In conclusion, the read-out MC design works properly and satisfactorily covers the different CMS requirements, including the ones that derive from the location of the electronics inside the CMS wheels. This has been shown in the different tests performed to the MC and to the ROBs, which included operation in beam tests with conditions similar to the expected in the CMS detector.

Moreover, lifetime and burn-in tests have allowed the study of limited maintenance problems, which are in part minimized by the employment of independent functional units, monitorization, sensoring elements and other failure detection mechanisms.

As a result, ROB and MC production have been launched and the first 39 read-out MCs have been assembled and satisfactorily tested. A versatile and complete test system has been developed at CIEMAT for thoroughly testing the read-out MCs before they are shipped to the next assembly stage. With this test system, functionality of every device and proper assembly of every item is verified to guarantee its operation.

Therefore, we conclude that the design of the read-out system is reliable for operation beyond the expected CMS environmental conditions.

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