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

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***Abstract*-- On the CMS experiment for LHC collider at CERN, the drift tube chambers (DT´s) are responsible of muon detection and precise momentum measurement. In this paper it is described the first level of the read out electronics for these DT chambers, that will be located inside the muon barrel detector in the so-called Minicrates (MC), attached to the chambers. The Read Out Boards (ROB) are the main component of this first level data acquisition system, and they are in charge of the time digitalization related to Level 1 Accept trigger of the incoming signals from the front-end electronics, following a consequent data merging to next stages of the data acquisition chain. Its architecture and functionality has been exhaustively tested, as well as its capability of operation beyond the expected environmental and radiation conditions inside the CMS detector. The satisfactory results obtained have allowed to proceed with ROB final production and its assembly in the MC´s. A total amount of 250 MC´s and around 1500 ROB´s are being produced and tested thoroughly at CIEMAT (Spain), including burn-in tests for guaranteeing ten years of limited maintenance operation. An overview of the system and a summary of the different results of the tests performed on ROB´s and MC will be presented. They include acceptance tests for the production chain as well as some validation tests that insured proper operation of the ROB´s beyond the CMS detector conditions.**

I. INTRODUCTION

CMS (Compact Muon Solenoid) is a general purpose detector that will be installed on the LHC (Large Hadron Collider), the new proton-proton collider that is being built at CERN and will become operative by 2007. Both luminosity (10^{34} cm^{-2} s^{-1}) and energy (14 TeV) frontiers are to be achieved in this deep exploring into matter, where muon tracks reconstruction at highest luminosity is an important aim that is central to the concept of CMS [1].

CMS consists on a large superconductor solenoid of 3 meters of ratio and 13 m length, which generates a magnetic field of 4 T. Inside the solenoid, several subdetectors are located, organized in layers around the beam vacuum tube.

The solenoid is surrounded by a large iron structure that serves as returning yoke for the magnetic field and that allocates the muon detector. The muon system uses three different technologies to trigger and measure muons: drift tubes (DT) in the barrel region, cathode strip chambers (CSC) in the endcap region and resistive plate chambers (RPC) in both the barrel and endcap regions.

Drift tube chambers are located inside the five wheels of iron yoke of the CMS barrel. Each wheel is organized in four concentric layers around the beam axis, namely MB1 to MB4, with each layer subdivided in 12 sectors, as can be seen on Fig.1. Therefore, the total amount of chambers is 250.

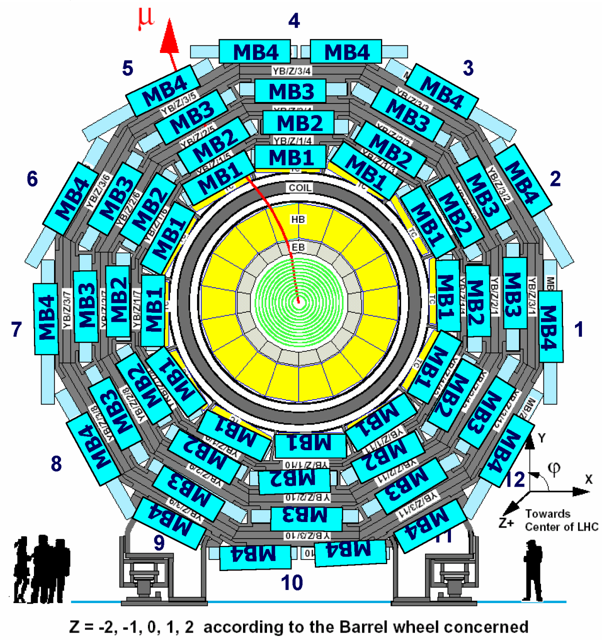

Fig. 1. Transversal view of the barrel region of the CMS detector.

A DT chamber consists on three superlayers, each with four layers of drift cells, separated by an aluminum light structure called the honeycomb. The two outer superlayers perform muon φ coordinate measurement (angle on the bending plane), meanwhile the inner one measures θ coordinate (angle in the non-bending plane). The single wire resolution of each cell is less than 200 µm, and as the drift velocity is ~55 µm/ns, timing resolution of the read-out electronics has to be better than 1 ns with a maximum drift time of 400 ns.

When a charged particle goes through the cell volume, a signal (hit) is generated in its anodic wire, and after discrimination and adequation in the front-end system [2] it is

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injected in the read-out electronic. Time measurement of these hits related to a L1 Accept trigger allows later reconstruction of the particle track and momentum measurement.

As the maximum drift time is much larger than the LHC bunch crossing period (25ns), a read-out system that manages overlapping triggers is required. Even though the high bunch crossing frequency, the complex CMS trigger system [3] will reduce first level trigger (L1 Accept) rate to a maximum of 100KHz, having a L1Accept latency of around 3.2μs.

There are other several requirements for the read-out electronics imposed both from the functional operation of the LHC system and from the environmental conditions expected in the CMS detector. Accordingly, read-out electronic has been designed to accomplish with these requirements.

II. READ-OUT BOARDS AND THE HPTDC

The Read-Out Boards (ROB), developed at CIEMAT, perform the time digitalization of the incoming chamber signals. ROB´s are built around a 32-channels ASIC HPTDC (High Performance Time to Digital Converter) developed by CERN/EP Microelectronics group [4] and produced in IBM 0.25 μm CMOS technology. Each ROB has four HPTDC´s, i.e., 128 channels. This number was chosen in order to accommodate the amount of channels per chamber while minimizing the multiplication of common components. In the MB1 chamber the space available was so reduced that a smaller ROB had to be produced with only one HPTDC: ROB-32.

HPTDC time digitalization is based on the Delay Locked Loop (DLL) principle, having a Phase Locked Loop (PLL) that allows different resolution modes. In our case, we are using the low resolution mode of 0.78125 ns per bin, which is more than enough for the 1 ns required precision. Actually, 260ps RMS time resolution has been measured, and cross-talk tests show deviations below 350 ps between ROB channels [5].

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

Moreover, the different buffers that it contains are large enough to cope with hit rates of ~2 MHz and ~1 MHz trigger rate [4], much larger than the expected L1 trigger rates of maximum 100KHz and hits rates of 10KHz per read-out channel.

A clock synchronous token-ring scheme connects the four HPTDC´s in a ROB, with one of them configured as master to control the token of the read-out data chain. An Altera CPLD manages the handshake read-out protocol for merging data into an LVDS serializer for transmission through a 20 m copper link to the ROS boards (Read-Out Server). These ROS boards are located in racks in the periphery of the CMS detector and forward data 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 to avoid over-consumption that may be generated not only by electrical failures but also by SEE´s (Single Event Effects) due to the environmental radiation. In the CMS barrel region the expected neutron fluence is of 10^{10}cm^{-2}, the charged particle flux is 10 cm^{-2} s^{-1} and the expected ten year integrated dose is about 1 Gy. As radiation hard devices are not going to be employed, some irradiation tests were performed to the ROB´s and the results obtained indicated a MTBF (SEU) of ~3 days for all the HPTDC´s and Altera CPLD´s in the whole detector [5].

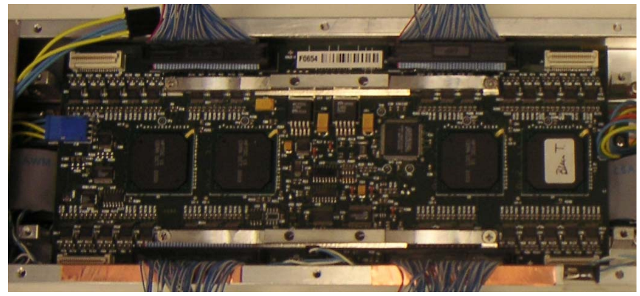

Fig. 2. Picture of a 128 channels Read-Out Board assembled on a Minicrate.

III. DESCRIPTION OF A READ-OUT MINICRATE

In order to minimize the large amount of cables needed for chamber signals, the read-out electronic will be located inside the CMS wheels, in an aluminum structure attached to the honeycomb of the chambers, the so-called Minicrates (MC´s). This aluminum structure will provide not only tightness to the boards that will be screwed there but also thermal conduction for refrigerating 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.

Read-Out electronics, mainly conformed by the ROB (Read Out Boards), is integrated in a complex system sharing with the muon trigger electronic: wire chamber signals, Timing and Trigger Control (TTC) signals [6], power supplies, cooling and mechanics.

The trigger system of a MC is basically composed of TRB´s (Trigger Boards), which are connected on top of the ROB´s to receive LVDS-TTL converted chamber signals, and a SB (Server Board), that collects TRB´s data.

ROB and TRB configuration and monitoring is done through the CCB (Chamber Control Board), which is connected to the ROB´s through a 40 lines parallel bus, so-called ROBUS, that carries signals such as: JTAG interface for configuration and monitoring, timing and trigger control signals, ROB addressing, power up lines, test pulse control and 1-wire interface for voltage, current and temperature on board monitoring.

Read-out clock is obtained from the LHC 40.08 MHz bunch crossing that is distributed to every system by the TTC interface through an optical link. At MC level, the CCB is responsible of decoding the TTC signal to extract L1 Accept trigger, bunch and event counters resets, clock and test pulse commands. All this signals are transmitted to the ROB´s through the ROBUS except for the clock, which is routed in a point-to-point connection by a twisted pair cable on the bottom of the MC.

Separated clocks with possible skews in 104 ps steps are provided for ROB´s and TRB´s. TRB´s clock phase will be adjusted on each MC to maximize trigger efficiency, meanwhile

ROB´s need a fixed phase with respect to the TTC signals to guarantee a simultaneous detection with respect to the 25 ns bunch crossing. Therefore, clock cable lengths have been adjusted to compensate ROBUS skews.

Other MC elements are power supply filters, a ROB-link board, which serves as a patch panel for the 20 m FTP cables of the ROB-ROS link, and a CCB-link board, that interfaces to the TTC and Slow Control systems.

In the following figure it can be seen an image of a read-out MC under test.

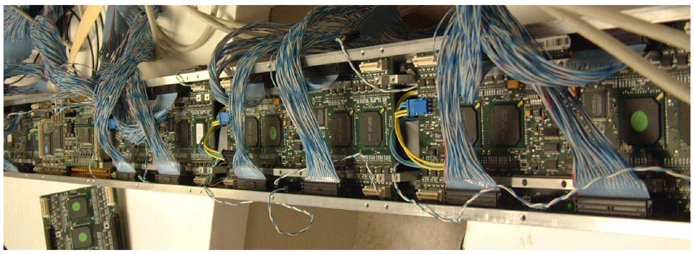

Fig. 3. View of a Read-Out Minicrate under test.

With a total amount of 250 MC´s, there are up to 20 types of read-out MC´s, depending on the station type and its amount of channels, i.e. number of ROB´s, from MB4(9/11) with 3 ROB´s to MB3 with 7, on the position of the service side in the different wheels and sectors, that leads to left and right MC´s, and on special size chambers for chimney location.

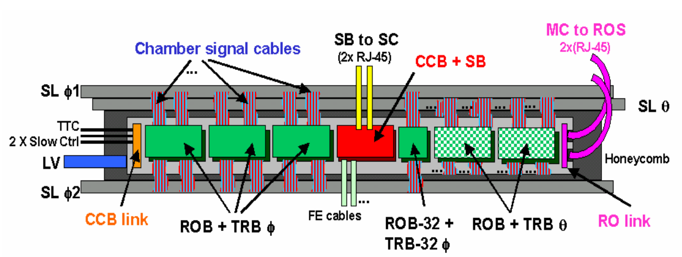

Fig. 4. An schematic drawing of an MB1 minicrate attached to a chamber is presented in this figure. The different boards and connections are indicated.

MC lengths vary from 2 m in MB3 to 1 m in MB4(9/11), with a fixed width of 10.5 cm. The average weight of a read-out MC is 8 Kg.

With respect to the MC power supply sources, they will be CAEN modules A3050 for 3.3V high current MC supply and A3009 for low current 5V of the CCB and also for analog front-end supply. A total of 130 A3050 and 70 A3009 modules will be standing 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 4V and 6V at MC input to power the low drop voltage regulators of the boards. Maximum current required is 42 A for 3.3V and 1.8 A for 5V. Inside each MC, the 3.3V power supply is distributed by two copper 25 mm^2 square bars to minimize voltage drops and simplify connections.

Power consumption of each ROB is around 3 W, and MC consumption, including TRB´s and CCB, is around 130 W. 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 water flow of 1.5 l/min at 20ºC show a maximum temperature of 38ºC on any board.

However, ROB behaviour with temperature has been previously tested [5] in temperature cycling tests, between 0ºC to 70ºC, were small variations on voltage, current and time shifts were shown. Also, lifetime tests have been performed to a fully operational ROB at 105ºC ambient temperature to find out failure mechanisms in an accelerated stress test. During 4 months no wrong operation was found, which will mean, for a low activation energy failure mechanism, such as solder bonding (0.4eV), a worst case failure rate <1 per ROB during the ten years of CMS operation.

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

IV. The Read-Out MC Operation

At power up, the CCB executes a BOOT program to check general MC status, e.g. the power supplies, memories status, etc. Afterwards, if no BOOT command is received, the CCB runs a configuration program stored in the CCB flash memory.

ROB set-up consists mainly in loading the HPTDC configuration bits and PLL and DLL initialization protocol through the JTAG chain to each addressable ROB.

In normal operation mode, after a L1Accept and when the HPTDC receives the read-out token, it provides 32 bits words with the time information of the corresponding hits and the HPTDC and channel number that received the hit. Time information is enclosed between a header and a trailer from the HPTDC master, which includes information about the number of data words and about the event number and the bunch crossing identification that corresponds to that L1Accept. Chip internal errors as well as buffer overflows are reported to the CCB and also within the internal data flow.

ROB read-out is performed at an effective bandwidth of 200Mbps, with an estimated throughput of 16Mbps. This throughput value is well below the ROB-ROS link bandwidth, and in order to reach it, each HPTDC would have to transmit ~1.5 Mbps, which is very unlikely with a 100KHz trigger rate unless MHz noise comes from a broken chamber channel, which will be soon disabled. The ROB-ROS link reliability has been measured using a 30 m cable, and the BER obtained is 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. Therefore, a failure in one of the component will not propagate to other elements of the system.

A special operation mode called Test-Pulse will be used for testing and calibration of all the DT electronic chain. Artificial tracks are emulated at Front-End level representing vertical tracks on the chamber. ROB´s are in charge of enabling particular groups of 4-channels at the LVDS receivers level in each event, according to a particular pattern sequence controlled with test-pulse signals coming from the CCB.

These MC operation modes have been successfully tested at laboratory and also in the 2003 and 2004 beam tests at CERN. One and two chambers, respectively, with its MC´s attached were exposed to a SPS secondary muon beam with a 25 ns structure similar to the one foreseen for LHC. No significant error was found in the read-out chain during these tests, as it happened on other beam tests in October 2001 where ROB and HPTDC functionality was validated [7].

V. MINICRATE PRODUCTION

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

Firstly, at CIEMAT, where the read-out part is assembled, including mechanical pieces, low voltage, ROB-link, CCB-link and ROB and TRB clock cables, and all the boards except for the TRB´s.

A second stage is performed at Legnaro and Bologna, which includes assembly of the rest of the pieces, TRB´s and trigger cabling. The foreseen MC production rate is 12 to 16 MC/month.

Each of these steps, plus installation on chambers at CERN, involves detailed and thorough tests of all the items assembled. Besides, ROB production, which will be soon finished, also includes meticulous tests of its operation, as well as burn-in tests making an attempt to screen for “infant mortality” of integrated devices. This burn-in consists on 48 powered and clocked boards in a rack at 50ºC for 1 week. Considering an acceleration factor of 4, this will represent ~700 hours of the ROB lifetime. At this moment, 600 ROB´s have been burned-in and no failure has been found.

VI. READ-OUT MC PRODUCTION TESTS

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

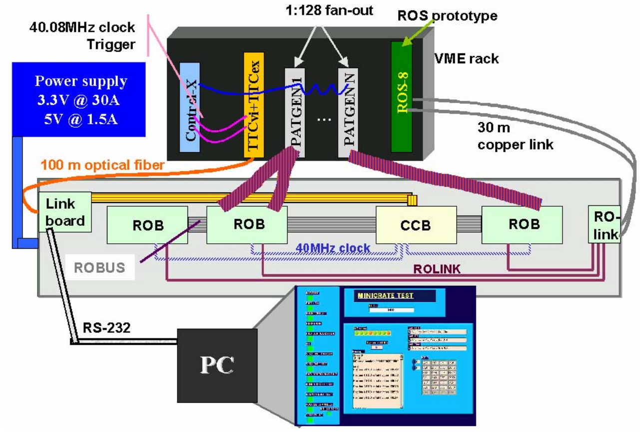

Fig. 5. Diagram of the RO-MC test jig.

It is a PC-based system with a slow control connection to the CCB and a 6U VME rack module where four kind of boards are employed: a TTCvi + TTCex module that generates global clock and connects to the MC CCB link board for TTC commands transmission; up to 7 PATGEN (Pattern Generators) boards that perform a 1:128 fan-out for injecting hits patterns into the MC, simulating chamber signals; a ROS prototype for ROB´s 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 the test jig is presented.

LabView software has been developed to perform the different tests. Besides visual inspection, the following tests are performed:

- Check that all the boards on the MC turn on with their corresponding power-up address and that the short-circuit flag line works properly, as well as the ROB error flag line.
- Insure proper configuration of all the ROB´s and verification of set-up mismatches, HPTDC´s idcodes, PLL and DLL lock and buffers status. These routines allow checking the JTAG chain and the ROB addressing mechanism, and also, operation of the ROB reset signal is checked.
- Besides, 2.5V and 3.3V voltage levels, current and temperature are monitorized on every ROB, insuring proper operation of the 1-wire protocol, where there is a unique identification number for each sensor.
- Furthermore, there are several tests in which the read-out chain is checked, in all of them some parameters are always verified: as the consecutive event number on each trigger, the common event and bunch crossing number among all the boards, the word count number, the 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 jig, 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, and secondly, every HPTDC channel disabling mechanism is checked, and finally, operation with all channels enabled is also tested. It is guaranteed that each ROS channel is receiving data from the proper corresponding ROB.
- Loading a MC configuration without activation of the reset signal, allows testing of the event and bunch crossing counters reset signals, verifying that event and bunch counter values are only common to all the boards after a reset.
- Finally, test pulse sequences are performed to check all the control lines involved and the proper disabling of channels at ROB LVDS-TTL converters level.

With these tests, every cable and connection is checked, as well as boards operation, guaranteeing proper MC assembly. In addition, a purpose designed board has been developed at CIEMAT for quality control of the manufactured cables before their assembly on the MC [8].

VII. Conclusions

We conclude that the RO-MC design and configuration works properly and covers satisfactorily the different CMS requirements that derive from the location of the electronics inside the CMS wheels, as shown the different tests performed to the MC and to the ROB´s, which includes operation in the test beams, 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 has been launched and first 39 read-out MC´s have already been assembled and satisfactorily tested. A versatile and complete test jig, has been developed at CIEMAT for testing thoroughly the RO-MC´s before shipping to the next assembly stage. With this test jig, functionality of every device and assembly of every element 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.

VIII. References

[1] CMS Collaboration. (1997, Dec.). CMS. The Muon Project. Technical Design Report. CERN/LHCC 97-32.

[2] F. Gonella, M. Pegoraro. "The MAD, a full custom ASIC for the CMS Barrel Muon Chambers Front End electronics," in Proc. 7th Workshop on Electronics for LHC Experiments, 2001, pp. 204.

[3] CMS Collaboration. (2000, Dec.) CMS. The TriDAS Project. Technical Design Report. Volume I. The Trigger Systems. CERN/LHCC 2000-38.

[4] J. Christiansen. (2002, Jul.) High Performance Time to Digital Converter. Version 2.2. CERN/EP-MIC. Switzerland. [Online]. Available: http://micdigital.web.cern.ch/micdigital/hptdc.htm

[5] C. F. Bedoya, J. Alberdi, J. Marin, J.C. Oller, C. Willmott. "Design and Performance Testing of the Read-Out Boards for the CMS-DT chambers," in Proc. 8th Workshop on Electronics for LHC Experiments, 2002.

[6] B. G. Taylor. "Timing, Distribution at the LHC." in Proc. 8th on Electronics for LHC Experiments, 2002, pp.63.

[7] M. Cerrada et al, "Test Beam Analysis of the First CMS MB2 Drift Tube Muon Chamber," CERN, Switzerland, CMS NOTE 2003/007, Jan. 2003.

[8] C. Fernández Bedoya, M. Montero and C. Willmott, "Desarrollo de un Sistema de Pruebas para el Cableado de los Minicrates de la Electrónica de Lectura de las Cámaras de Deriva de CMS." CIEMAT, Madrid, Tech. Rep. 1037. Feb. 2004.