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Fernández, C.
Fouz, M.C.
Marín, J.
Oller, J.C.
Willmott, C.
Amigo, L.J.

Departamento de Fusión y Física de Partículas

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Fernández, C.; Fouz, M.C.; Marín, J.; Oller, J.C.; Willmott, C.; Amigo, L.J.

22 pp. 10 figs. 5 refs.

Abstract

Part of the readout system for the CMS muon drift chambers has been tested in test beams at CERN/GIF. Read Out Board (ROB) and HPTDC have been validated with signáis from a real muon beam, with an structure and flux similar to LHC operating conditions and using one of the chambers produced in CIEMAT already located in the test beam área under normal gas and voltage conditions.

Validación en el Test Beam del CERN/GIF de la Electrónica de Lectura de las Cámaras de Muones del Experimento CMS.

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Resumen

Parte de la electrónica que compone el sistema de adquisición de datos de las cámaras de muones del experimento CMS ha sido probada en un experimento con haz de muones real en el CERN/GIF. Se ha validado el funcionamiento tanto de la tarjeta de lectura de datos ROB como del asic HPTDC utilizando una de las cámaras de deriva de CMS fabricadas por el CIEMAT en condiciones normales de gas y tensión bajo un haz de muones con una estructura y flujo muy similar al del LHC.

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1. INTRODUCTION

The CMS experiment is one of the four large experiments that will be placed in the new accelerator LHC (Large Hadron Collider) that is being built at CERN. LHC will reach a proton - proton collision energy at the center – of - mass of 14 TeV, a luminosity of $10^{34}cm^{-2}s^{-1}$ and a beam cross frequency of 40 MHz. The ability to trigger on and reconstruct muon tracks at high luminosities is the central point of the Compact Muon Solenoid detector, as this will allow deeper exploring into matter, probing the Higgs mechanisms and other aspects of the Standard Model [1].

CMS is built around a large superconducting magnet located at one of the high luminosity crossing points of the beams. Tracks of the particles originated in the collision will be curved by the magnetic field and registered in the different subdetectors that conform CMS i.e.: electromagnetic calorimeter (ECAL), hadronic calorimeter (HCAL), tracker and muon detector. These systems are built with the aim of detecting different kind of particles and perform tracking and particle identification.

One of these moun subdetectors are the drift tube chambers (DT) located in the barrel of the detector. These chambers will provide a precise measurement of the position and momentum of muons going through them with a space resolution of 250 μm per cell, corresponding to 4.5 ns [1]. Their operation relies on the almost constant drift velocity of the electrons generated in the gas when a charged particle passes through the volume of one of the cells of the drift tube chambers. Accordingly the exact position of the particle track can be inferred from the arrival time when an electric pulse is received in the anodic wire of the drift cell.

These electric pulses are processed by the front-end electronics placed inside the chambers, and afterwards a digitalization has to be performed to obtain a time measurement that relates this pulses to a common trigger. This is the main task around which the readout electronics for the DT chambers has been implemented. Large levels of multiplexing follow this first level data acquisition, as 172.000 chamber channels have to be merged to be processed and obtain fine θ and ϕ position of muon tracks.

Due to the high rate of collisions expected in this experiment, processing of the information relative to one bunch crossing will be performed simultaneously with the acquisition of new events. There is a complex and dual trigger system in CMS with different levels of triggering that performs the task of extracting the valid information from the whole amount of received data, reducing by a factor of 10^4 the number of primary interactions to be processed by the Read Out system [2].

The developed system is committed to operate under certain constraints, as it is the high frequency of triggers or the enormous amount of data that requires fast processing. As a result of the products of the successive interactions a remnant radiation is expected in the detector area, including all the electronics located in the chambers. This forces the employment of radiation tolerant devices that will have to be tested. On the other hand the high magnetic fields created by the solenoid impose certain restrictions to the electronics, mainly to the power supplies and cooling systems.

The operation of the CMS detector is foreseen to last about 10 years and during this time the maintenance may be possibly restricted, moreover in the electronics located inside the detector wheel. Therefore a robust and reliable system is demanded, requiring the less intervention as possible.

The read out system has been developed according to these requirements and it is being tested to guarantee its performance. The test beams described in this document have demonstrated that the system can operate at a rate similar to the one at LHC and that it can manage a large amount of data without buffer overflowing, even in a noisy environment. This is a fundamental feature that validates the system design.

2. READ OUT SYSTEM DESCRIPTION

The read out system is staggered in several levels merging data from all chamber channels to the DAQ system in the control room. First of all the front-end electronics, placed in the gas volume inside the chambers, provide discriminated signals to the Read Out Boards (ROB). The fundamental task of digitalizing these signals is performed by the High Performance Time to Digital Converter (HPTDC) devices assembled in the ROB´s. Following, the digitalized information is sent to the Read Out Server boards (ROS) situated in the towers in the periphery of the detector and then to the Device Dependent Units which interface to the DAQ [4]. All this steps have to ensure a secure path from the chambers until the DAQ processing, guaranteeing transfer velocity large enough to assure merging of all the data according to the buffer sizes on each of the elements and including the necessary overhead to identify each measurement properly.

2.1. High Performance Time to Digital Converter (HPTDC)

The HPTDC is the 3rd generation of TDC´s developed by CERN/EP Microelectronics group [3]. This chip supplies the basic time elements to reconstruct muon tracks, that is, the relative time to a common trigger for every hit produced on chamber wires. One of its main advantages is the size and management of the buffers, that minimise the “bottleneck” of merging data from 32 channels per chip into one common data path. In figure 2 a scheme of the buffers and registers in this TDC is shown.

This is a highly programmable TDC based on the Delay Locked Loop (DLL) principle, providing a time measurement of 25/32 ns = 0.78 ns bin resolution when it is clocked at 40 MHz and operated in the low resolution mode. Internal frequencies can be selected from a Phase Locked Loop (PLL) at the clock input, that allows higher resolution measurements if required and also reduces the input jitter in the clock signal.

The digitalized signals from each of the 32 channels are first stored in the input "hit registers" and then are driven to the 256 words deep group memories common to every 8 channels (Level 1 buffers). The output of these group memories is merged into a common 256 deep memory after the trigger matching is performed. Until this operation can be done, the arriving triggers are stored in a 16 deep FIFO. Besides its complexity, matching is done in a rather fast way, selecting from memory hits within a programmable time window, chosen to accommodate the maximum drift time of the muon chambers. This maximum drift time is less than 400 ns. Accordingly, hits coming from the chamber channels are related to a common trigger allowing correlation of particle tracks to the event where they were generated.

Another of the multiple programmable parameters on the TDC is the trigger latency, which depends on the trigger generation system. In CMS the expected Level-1 Acceptance latency is 3.2 μs, and meanwhile, hits have to remain stored in the buffers, which explains the importance of its dimensions.

One of the main features of this TDC is the ability to handle overlapping triggers, as an individual hit may fall inside several time windows, which is necessary due to the high bunch crossing frequency in the detector, that exceeds widely the cell drift time.

In the following figure 3, it is represented the different basic programmable parameters in the TDC related to the trigger matching. A match window, with a width depending on the drift tube cell dimension, establishes the time interval within which hits will be related to a particular trigger. A wider search window performs a deeper exploring in the memories as hits are not always stored in strict temporal order. Finally, emptying older hits is performed through a rejection mechanism with a programmable rejection time.

Other remarkable features of this TDC are the JTAG programming interface, a flexible signal interface and readout modes, a clock PLL at the clock input, etc. It also has internal counters for the event identification count and for the bunch crossing identification count. This information can be attached to the output data with each event, as well as programmable headers, error flags and debugging information.

2.2. *Read Out Board (ROB)*

Each ROB (Fig. 5) has 4 HPTDC's (128 channels) in a token ring, where one of them is programmed as the master to control the token of the read-out data in a data_ready/get_data handshake protocol managed by an FPGA. The token ring scheme is designed following a failsafe mechanism (Fig. 4), trying to avoid that failure in one of the TDC's stops whole ROB operation. A hardware and software bypassing system has been implemented.

When the read out is performed, the HPTDC having the token drive its data in a byte-wise mode (8 bits in parallel out of the 32 bits per word) into a LVDS link serializer operating at 20MHz. This 480 Mbps copper link sends data directly to the Read Out Server boards (ROS) at the towers in the periphery of the detector.

The JTAG interface for TDC programming and monitoring is included in a parallel bus shared by every ROB in a DT chamber. This bus also carries among others: trigger signal, event reset, bunch reset and other test pulse control signalling.

In the CMS detector these ROB's will be located in mini-crates attached to the chambers placed inside the iron yoke. Each complete chamber will need between 5 to 7 ROB to be fully read out, for the 250 chambers in the detector, the total amount of necessary ROB's is about 1500.

To validate the operation of HPTDC and ROB design under real chamber conditions two test beams have been performed, one of them with a 25 ns bunched muon beam, reproducing as much as possible LHC final operation conditions.

Those tests have taken place at the GIF facility [5], that is located downstream of the final dump of the X5 beam, which is one of the secondary beams of the SPS (Super Proton Synchrotron accelerator) injection for the LHC. At the end of this beam line it is situated the irradiation facility where a weak muon flux can be used to test large detectors together with gamma source to create background conditions similar to those existing in the experiments during the operation of the LHC machine.

2.3. Test Beam Set-up

An MB2 type chamber was placed at GIF and operated under normal gas and voltage conditions [Fig. 6] with one Resistive Plate Chamber (RPC) attached to it. One ROB was connected to 96 chamber channels from all three superlayers in the beam region, where the collimated beam goes through (~10 cm^2).

The trigger signals were provided by a set of scintillators placed in front of the chamber and their corresponding electronics, delayed to simulate trigger latency as will be found under normal CMS/LHC operation. Triggers were synchronised to RO system clock and non-synchronised trigger signals were fed into two ROB channels for relative time measurement and to have a redundant information of the trigger arrival time.

An experimental set-up was developed to implement ROB control and data acquisition. The ROB was connected through a set of purpose-dedicated boards and a VME interface to a PC for HPTDC programming and monitoring and data storage. Control of the read out system, data decodification and spills management was done by software. A diagram of the set-up can be seen in figure 7, where the boards in dark blue are VME boards that implement, among other functions, data storage, operation control, clock and trigger signal supply and management of system interruptions for beginning and end of spill.

Tests were made under two different beam conditions. In the first place at P2B (Oct. 4 to Oct. 23, 2001) where there was a non structured beam with an intensity of about 6000 triggers/spill, that is, 1200 triggers/s, with spill duration of 5.1s in periods of 16.8 s. In the second place during P2C period (Oct. 25 to Nov. 4, 2001) where the beam had a 25 ns structure, with about 26000 triggers/spill, i.e. 5000 triggers/s.

Some of the basic TDC configuration parameters are the following: 40 MHz clock, PLL to reduce jitter, leading measurements, 0.78125 ns bin resolution, 8 bits parallel read-out at 20 MHz synchronous bus, with only global headers and trailers so bandwidth is not significantly reduced, 1.1μs latency, 900 ns, 1μs or 1.1μs of searching window (depending on the run), 700 ns, 800 ns or 900 ns of matching window (depending on the run) and 1.3μs reject window.

3. P2B TEST BEAM RESULTS

During the first test beam period 7 runs of 5 10^5 events/run were registered. The correct operation of the system was confirmed, with no TDC errors, no FIFO overflows and only a few overlapping triggers. Considering that the matching window was set to 800 ns and we had about 1 trigger/ms, the probability of having overlapping triggers was only 8 10^{-4}.

As we were measuring also the non-delayed trigger signals as hits, overlapping triggers appear as multiple trigger signals in the same event, so they can easily be recognised. In this kind of events, hits belonging to one muon track appear in two consecutive events, as time window is longer than drift time. But when time measurements are studied, the hits belonging to the muon that generated a certain trigger can be clearly identified, as hits from a different muon will not produce a valid track. In this way, overlapping triggers can be disentangled.

Another aspect of the TDC concerning bunch identification was checked. At LHC there will be 3564 bunch crossings per machine cycle 25 ns apart. HPTDC keeps the count of the bunch number that corresponds to a specific event. A bunch count reset signal resets the bunch counter, but it shall be activated only at the end of a cycle. We confirmed the correct operation of this mechanism.

Data were taken also with gamma irradiation over the whole chamber, to simulate background under normal LHC operating conditions. The effective noise increase was observed but had no effect on TDC behaviour (Fig. 8).

4. P2C TEST BEAM RESULTS

The second test period was more determinant because of the beam characteristics and chamber conditions. There were 9 runs taken, a total amount of 5 10^6 events, with basically the same set-up and configuration as in the first testbeam, but the results were somewhat different.

In the first place, HPTDCs occasionally sent error messages indicating buffer overflows. The reason for that was that there were two noisy channels, number 16 and 19 of TDC 1, belonging to the same buffer group. That is exactly what shows the debug occupancy information of one of the runs (Fig. 9). Those channels were not working properly, giving noise rate in the range of a few MHz, so they could be disabled in normal operation, as they do not provide any useful information. The important point is that HPTDC flags in case there is too much noise and this noise will only affect one 8-channel group, without any lose of hits in the other groups.

We can also see from the debug information the maximum and minimum occupancy of the trigger FIFO and of the read out FIFO. The trigger FIFO is far from overflowing, so matching is done much faster than the trigger rate. The read-out FIFO has a fairly high occupancy in the TDC with noisy channels, but we can see that it can stand this amount of noise at the given transmission bandwidth.

This figure also shows that there were up to 5 trigger signals per event (group 2 of TDC 2 and 3), this does not appear in trigger FIFO because some of the triggers were already being processed. This amount of triggers is not surprising due to the relatively high trigger rate during the test. However the number of events with multiple triggers is about one hundred times of what we had in the first test beam period, while the intensity is only 5 times. This difference is due to the structure of the beam, as muons came grouped, spaced multiples of 25 ns, and not uniformly distributed. In table 1 we can see the ratio of events with multiple triggers for one of the runs.

2 trigger signals/event	38610	12.6 %
3 trigger signals/event	3256	1.1 %
4 trigger signals/event	154	0.05 %
5 trigger signals/event	6	0.002 %

Table 1: Number of multiple triggers/event from 3 10^5 events.

As a curiosity we can take a look at figure 10 where the time separation between two trigger signals recorded in the same event has been plotted. It shows clearly the 25 ns structure, as most of triggers have arrived with a separation of a multiple of 25 ns.

5. CONCLUSIONS

We conclude that the present ROB design with four HPTDC's works satisfactorily in conditions similar to the ones in the LHC. It has stood perfectly the hit and trigger rate, being far from overflowing in normal operating conditions. The slow control during operation has also being tested and, for example, disabling of noisy channels can be done properly.

Adding this results to other tests performed to the ROB, such as irradiation tests, temperature cycling and other detailed studies, we can conclude that the ROB design is ready for production, with the guarantee that it will meet every requirement needed to operate in the CMS detector.

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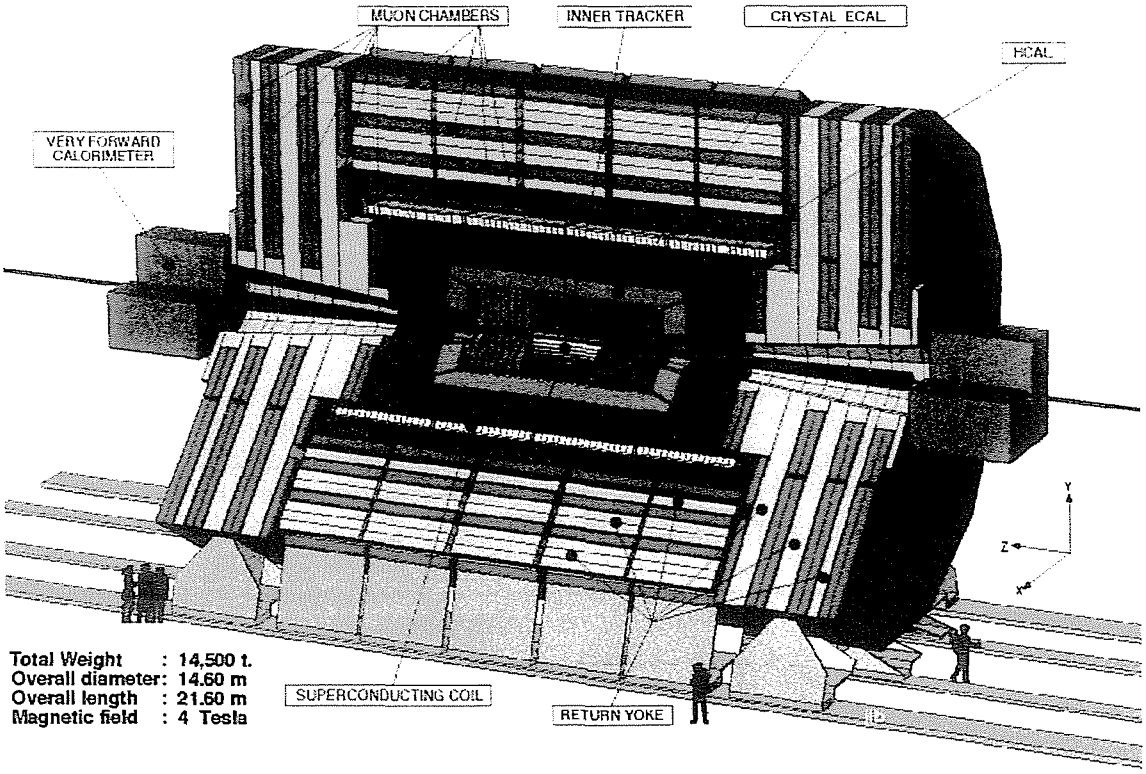

Figure 1: View of the CMS detector.

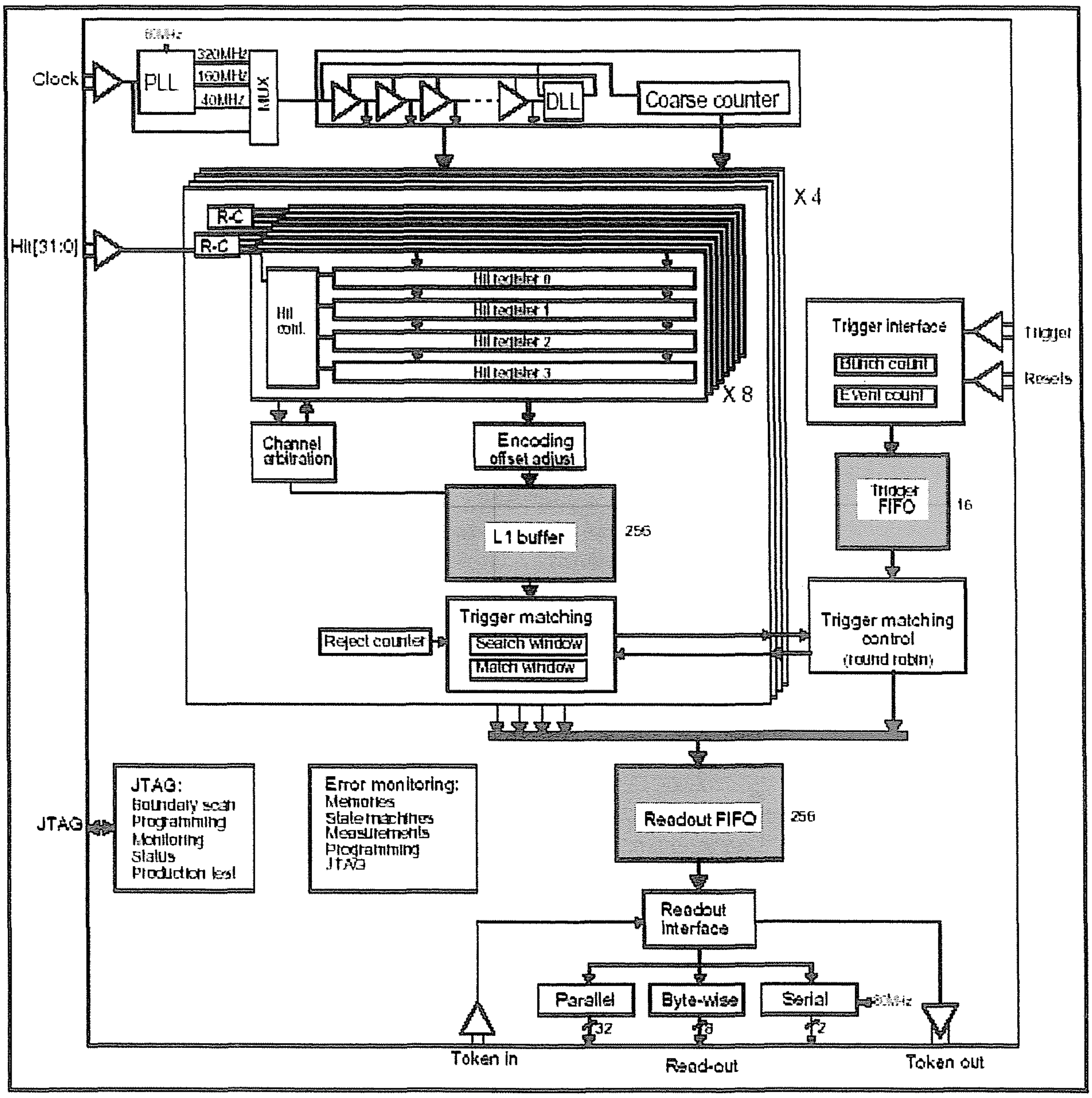

Figure 2: Architecture of the HPTDC.

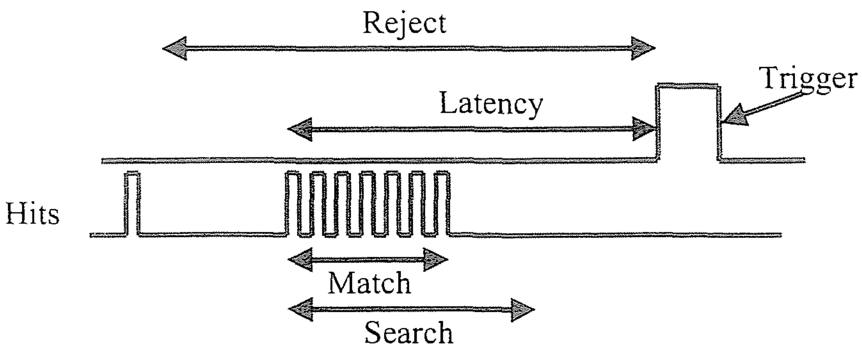

Figure 3: HPTDC time window.

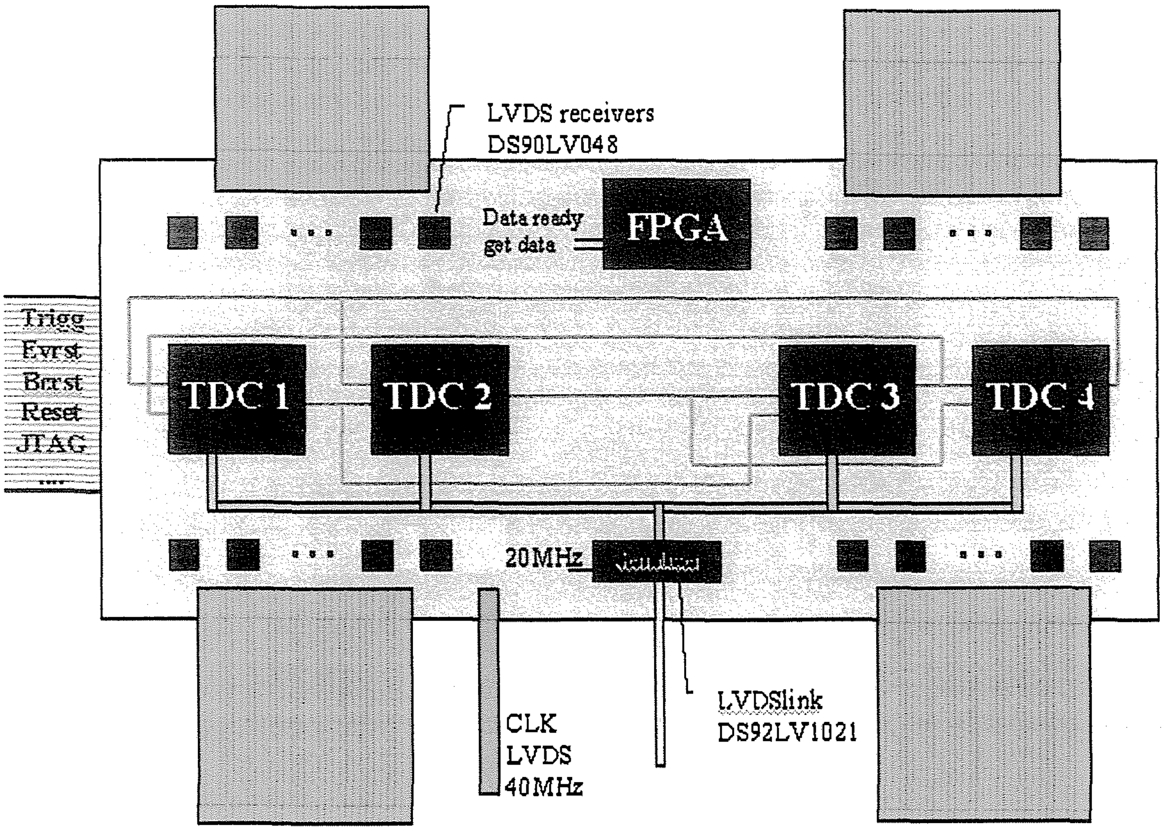

Figure 4: TDC's token ring scheme in a ROB.

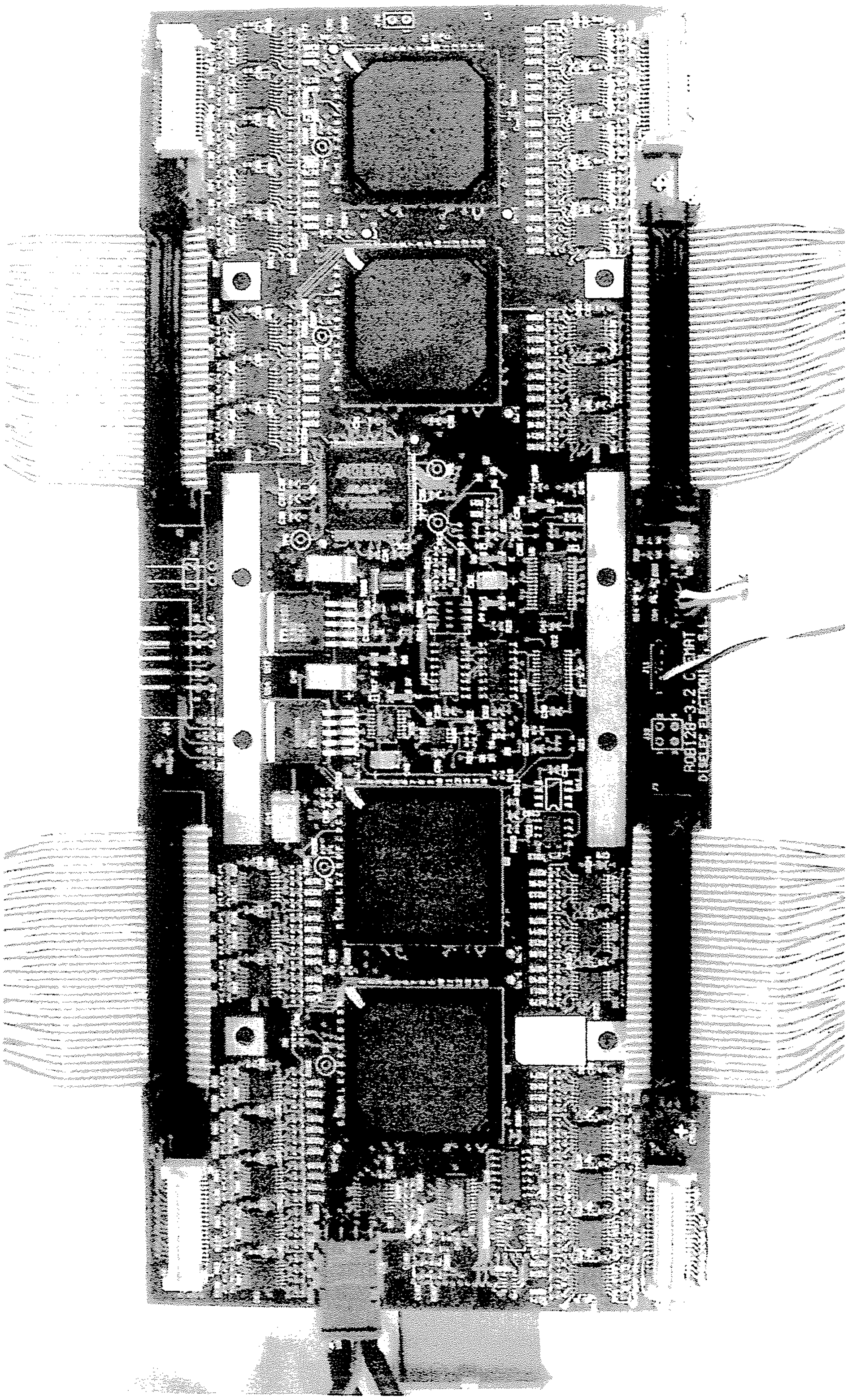

Figure 5: Read Out Board.

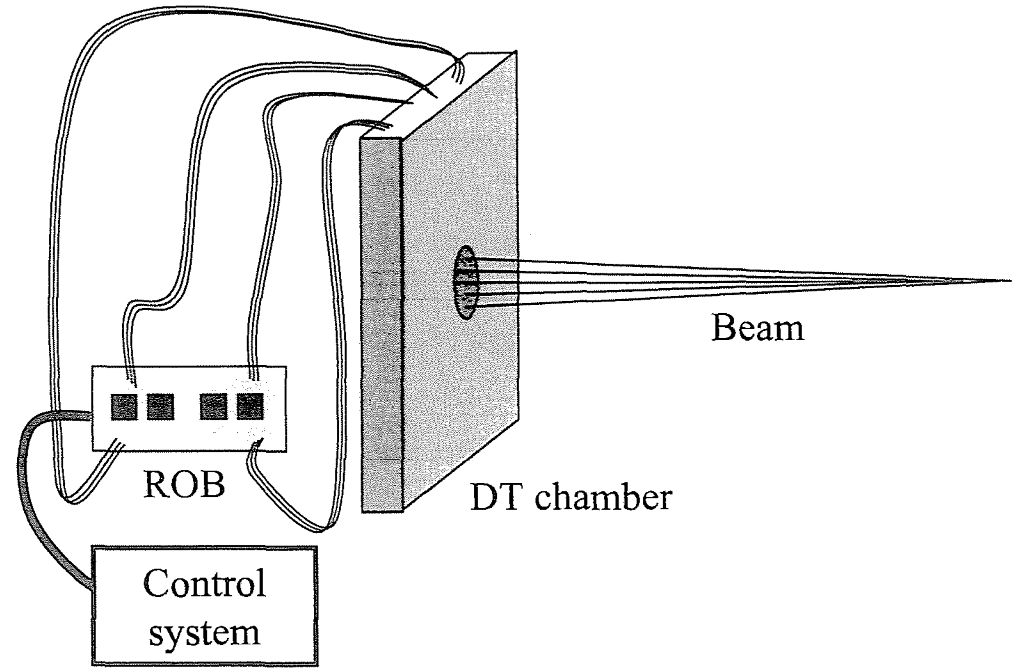

Figure 6: Set-up diagram of the test beam at CERN/GIF with MB2.

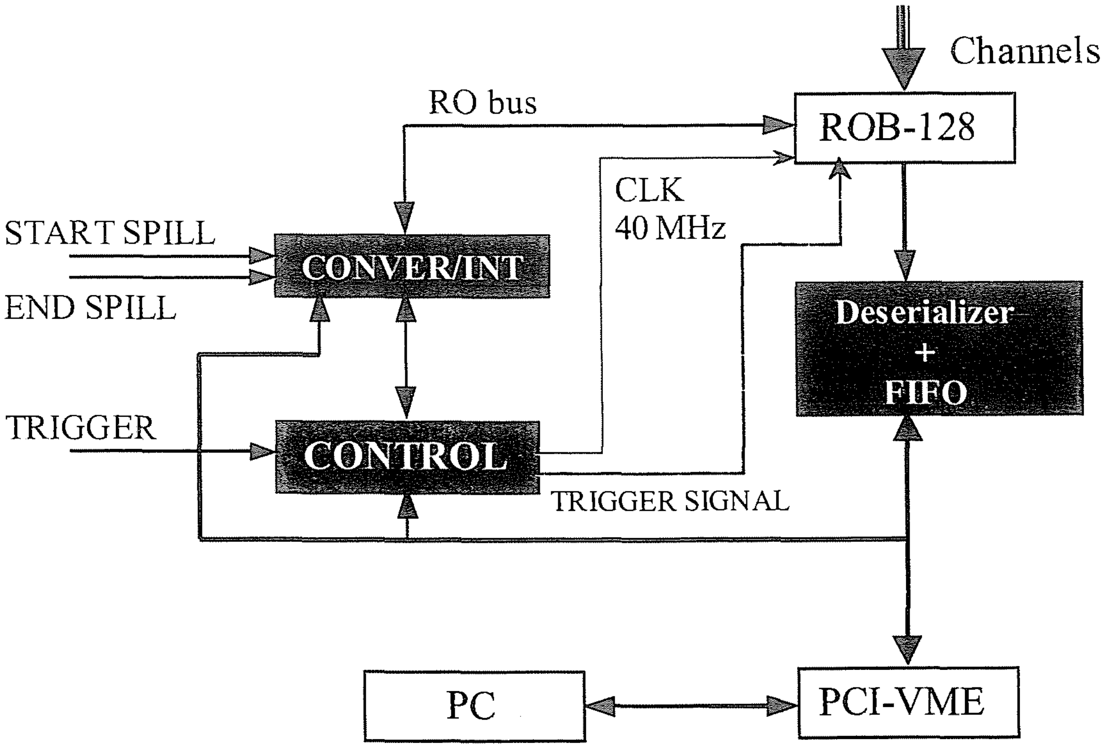

Figure 7: Scheme of the ROB control system for the test beam.

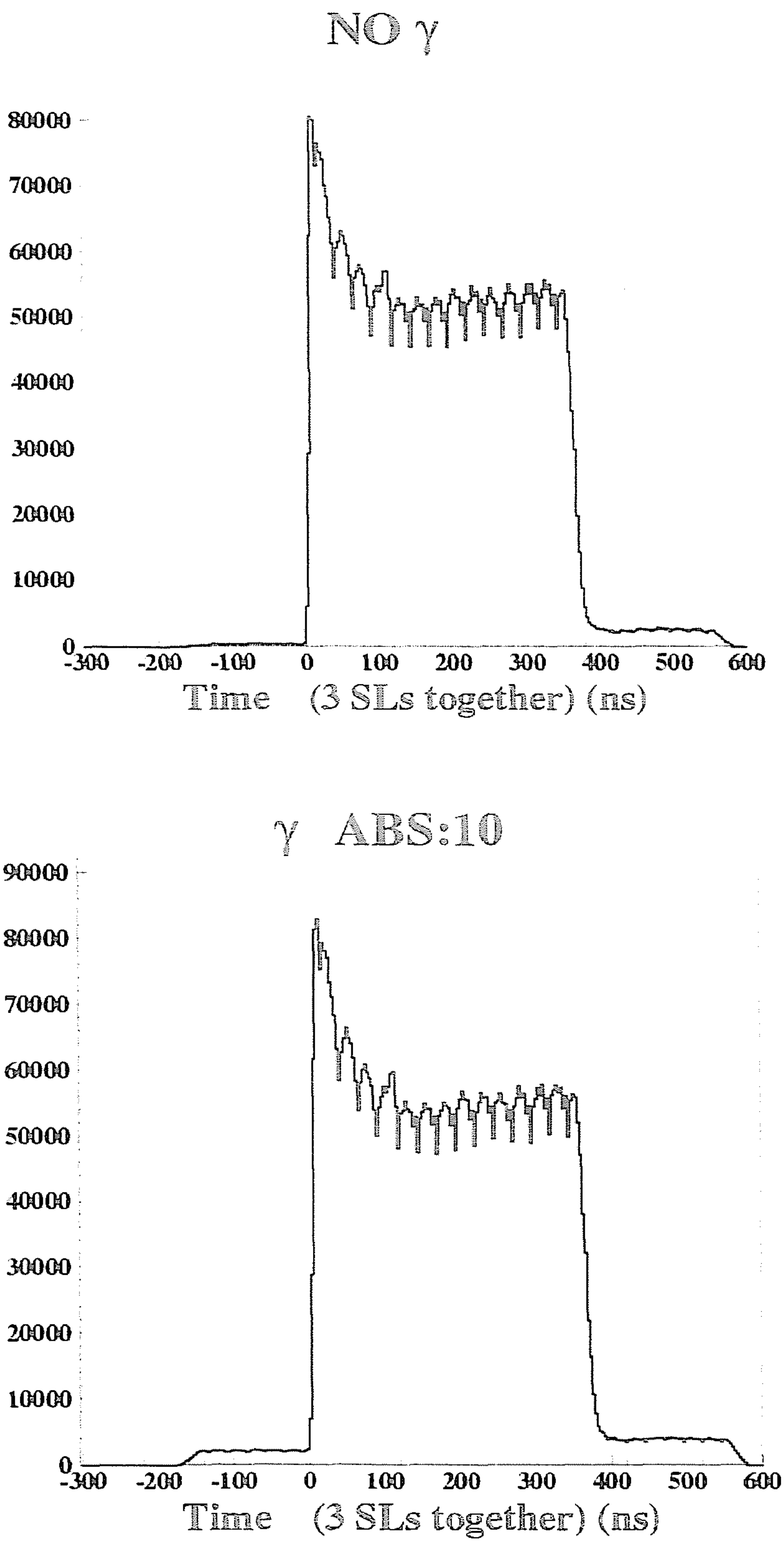

Figure 8: Drift time distribution of a cell without gamma irradiation (top) and with a filter of 10 for gamma irradiation (bottom).

L1 buffer (max)	TDC 0	TDC 1	TDC 2	TDC 3
group 0 (0-7)	6	16	14	11
group 1 (8-15)	17	17	21	12
group 2 (16-23)	16	254	5	5
group 3 (24-31)	13	15	0	0

∘L1 buffer minimum occupancy = 0; except TDC 1 group 2 = 8

Trigger FIFO	TDC 0	TDC 1	TDC 2	TDC 3
max occupancy	3	3	3	2

∘Trigger FIFO minimum occupancy = 0

Read out FIFO	TDC 0	TDC 1	TDC 2	TDC 3
max occupancy	56	120	79	59

∘Read out FIFO minimum occupancy = 3

Figure 9: Debug information of 4 HPTDC's.

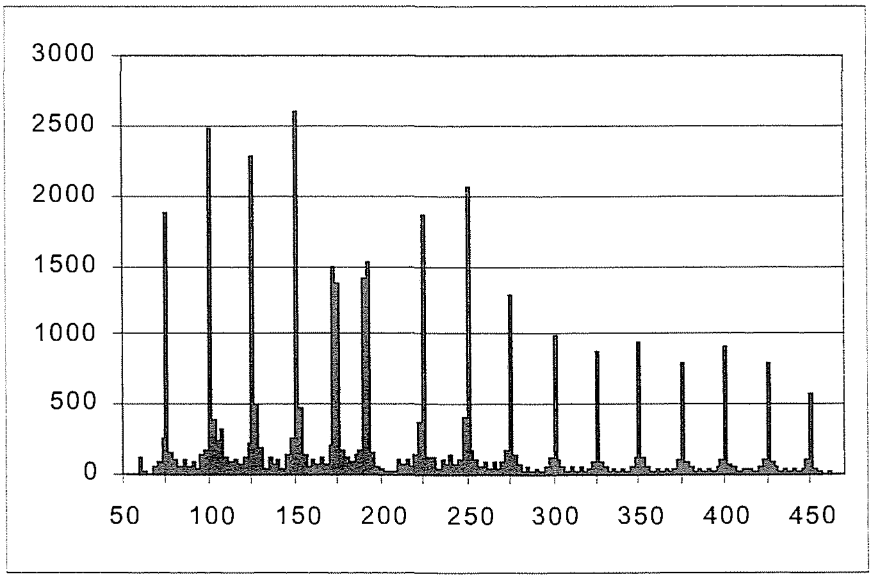

Figure 10: Time separation between two trigger signals of the same event.