CMS DT Chambers Read-Out Electronics

C. F. Bedoya, J.M. Cela, G. Dellacasa, J. Marín, V. Monaco,
J.C. Oller, P. De Remigis, A. Staiano, C. Willmott

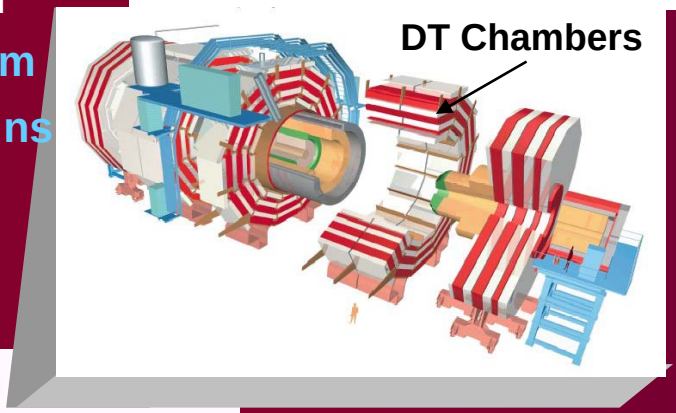
INFN. Torino, Italy. • CIEMAT. Madrid, SPAIN.

LHC & CMS.

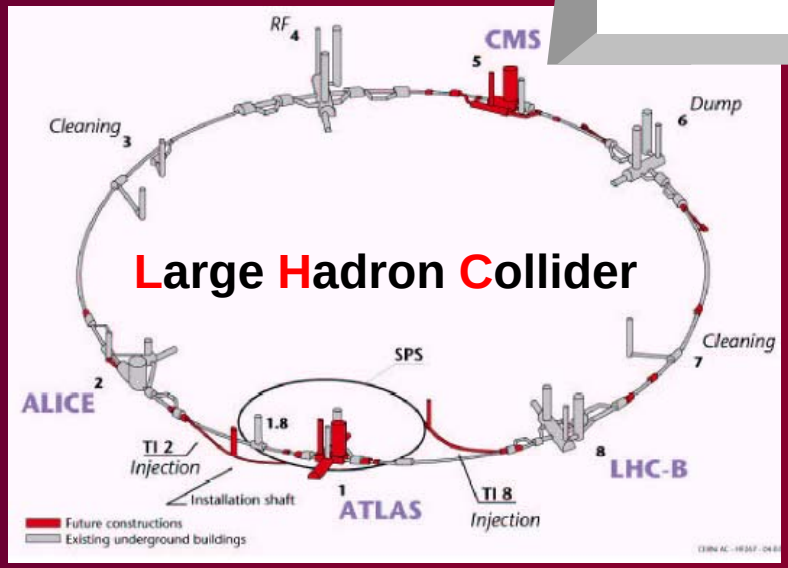
LHC: proton-proton collider

- **Energies up to 7 TeV per beam**
- **Bunch crossing period of 25 ns**
- **Luminosity 10^{34} cm^{-2} s^{-1}**

Compact Muon Solenoid

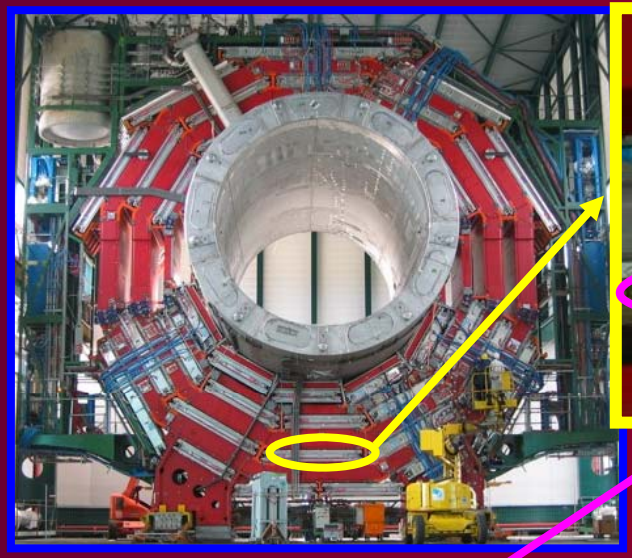


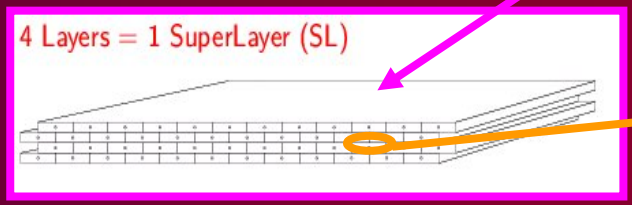
CMS is a general purpose particle detector, designed to run at the highest luminosity of LHC and optimized for muon detection and track reconstruction.

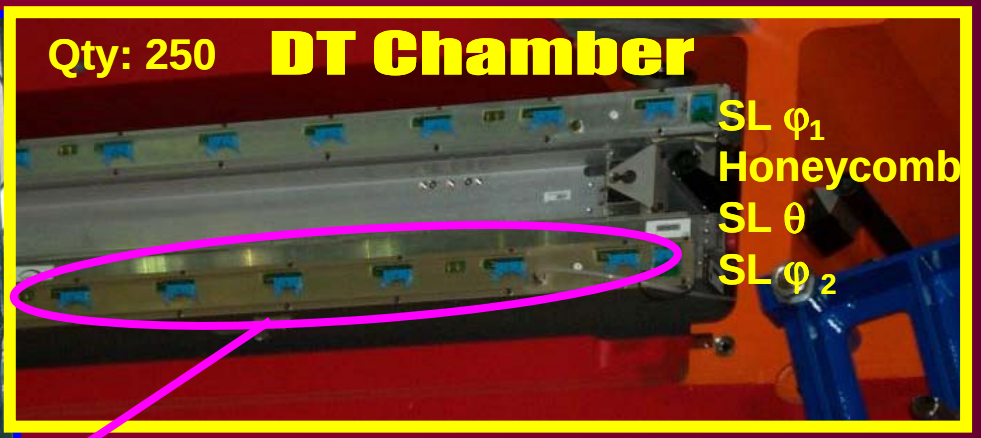


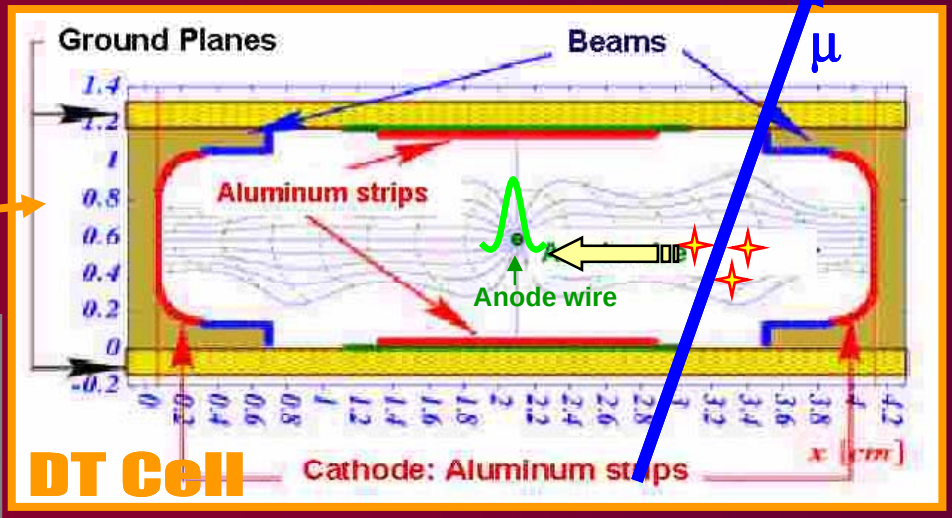
- 15 m length, 21.5 m diameter, 12500 Tons
- Large solenoid for generate up to 4 T.
- Inside the solenoid:
  Tracker, ECAL, HCAL
- Outside the solenoid:
  Muon system:
  - Cathode Strip Chambers (CSC),
  - Resistive Plate Chambers (RPC´s),
  - Drift Tube Chambers (DT´s).

Drift Tube Chambers.









Performance requirements:

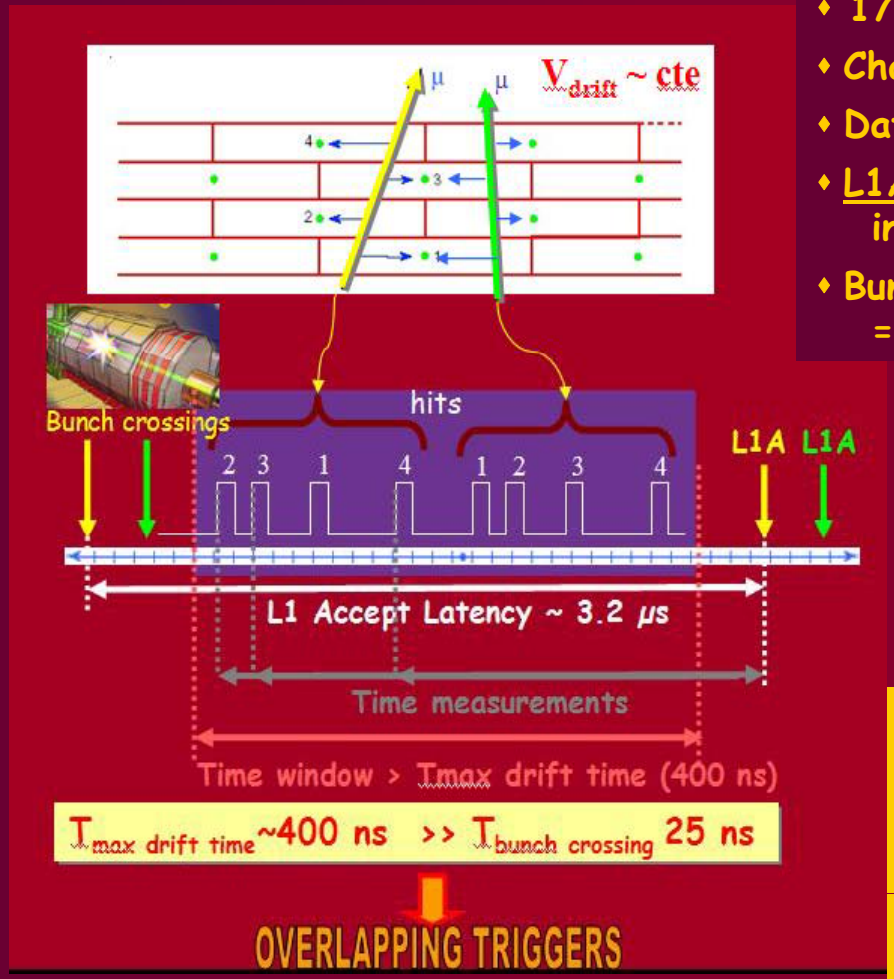
- muon identification
- transverse momentum measurement:
  8-15% $\delta p_t/p_t$ at 10 GeV
  20-40% $\delta p_t/p_t$ at 1 Tev
- Charge assignment:
  correct to 99% confidence
- trigger with unambiguous bunch crossing identification on single and multimuon events.

GAS: Ar/CO2 (85/15)
High Voltage: wires 3.6 kV
strips 1.8 kV
cathodes -1.2 kV

T_{max} < 400 ns
Drift velocity ~ 55 μm/ns
Resolution < 200 μm => 1 ns
Efficiency ~ 99%

DT Read-Out Electronics.

GOAL: Time digitalization related to Level 1 Accept of the DT chamber signals, and data merging for reading-out the whole detector at 100kHz L1A rate.



Requirements

- 172,200 channels.
- Charged particle rate ~ 1 kHz/channel.
- Data processing at 100 kHz L1A rate.
- L1A latency ~ 3.2 μs => Need to store information from several events.
- Bunch crossing time (25 ns) > max drift time => overlapping triggers.

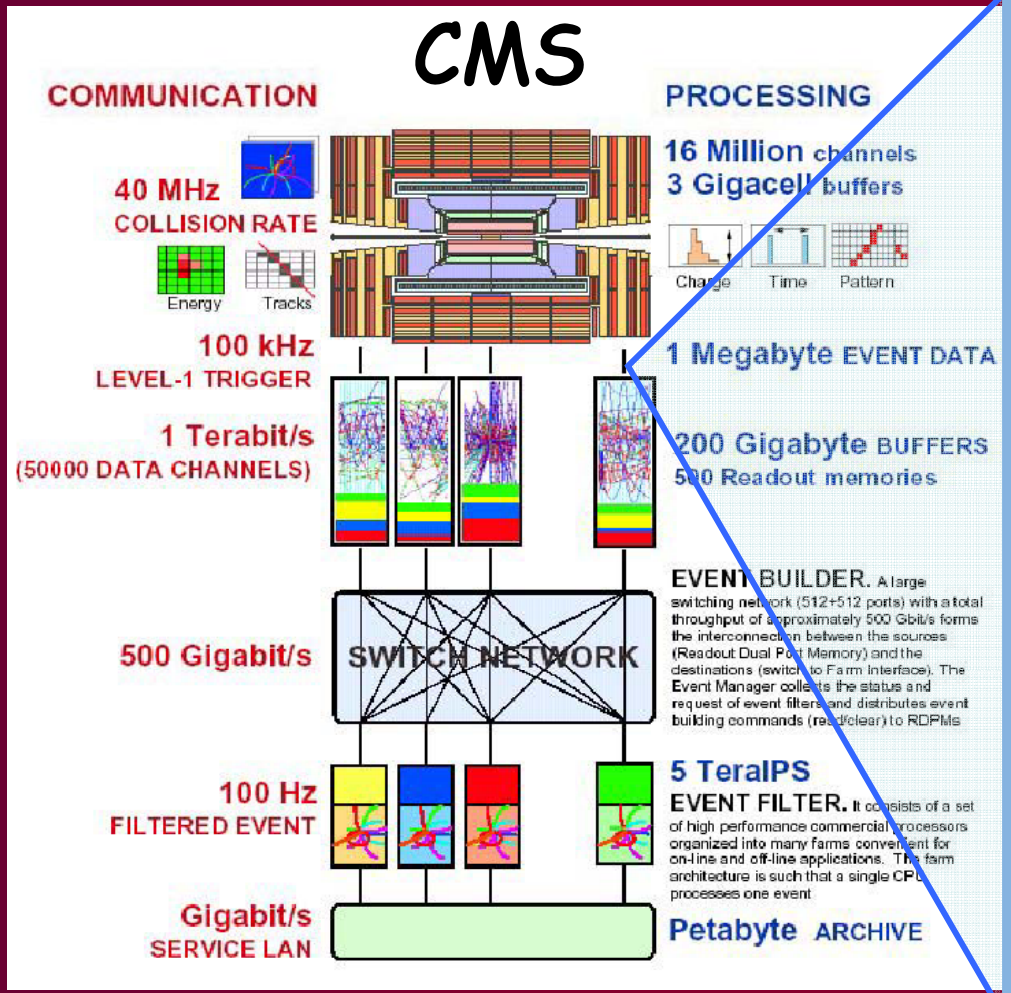
- Multiplexation, data merging and data reduction to read-out at max 320 MBps/wheel.
- TTS (Trigger Throttling System) for backpressure notification or synchronization or HW problems.

Electronics in the cavern (ROB & ROS)

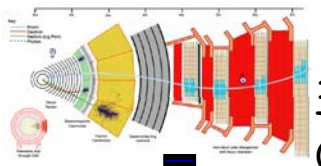
- Environmental radiation:
  - neutron fluence $10^{10} cm^{-2}$
  - charged particle flux 10 cm^{-2} s^{-1}
  - 10 years integrated dose 1Gy.
- Up to 0.08T magnetic fields.
- 10 years limited maintenance operation.

Read-Out System.

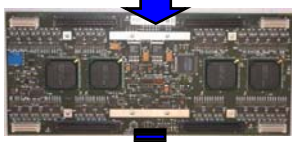
CMS



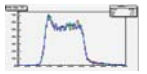
DT Muon Read-Out



172200 channels
Time digitalization
(channel resolution 0.7 ns)



128 ch/ROB
1500 ROB



30 m copper link
240 Mbps
~16 Mbps throughput

25 ch/ROS=> 1 sector
60 ROS
~ 260 bytes
muon event size/ROS

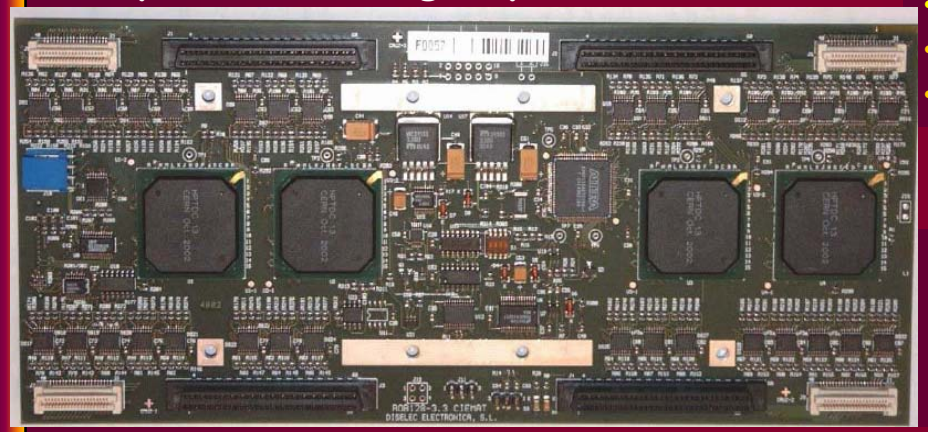
100 m optical link
800 Mbps
~80 Mbps throughput

12 ch/DDU => 1 wheel
5 DDU
~ 1.4 kB event size/DDU

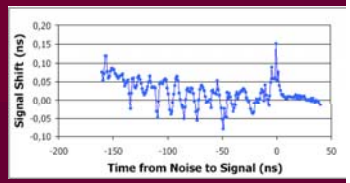
S-LINK64 output
320 MB/s
~ 200 MB/s throughput

ROB: Read-Out Board.

- Developed at CIEMAT, Madrid (SPAIN).
- Based on the High Performance Time to Digital Converter (HPTDC) developed by CERN/MIC group.

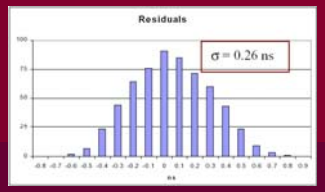


•128 LVDS input channels
•Measured Cross-talk between channels < 350 ps.
•Average Occupancy : 0.3 hits/(event · HPTDC)



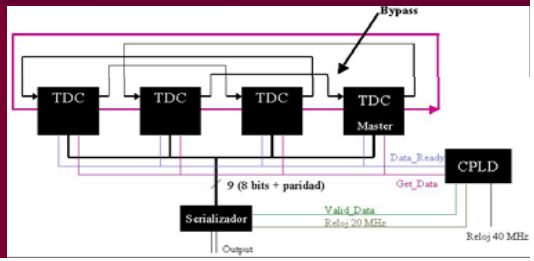
•I,V,T on board sensor.
•Overcurrent protection:
powering on cycles every 700 ms
(reduces to 10% power consumption).

240 Mbps serializer.
BER < 10^{-15}



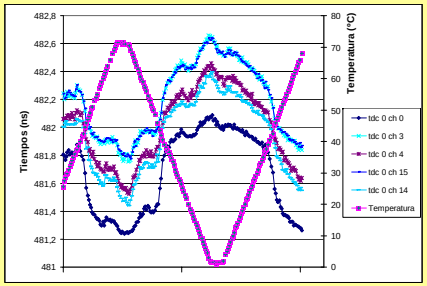
HPTDC
•Highly programmable which provides great flexibility.
•LHC clock 40,08 MHz
•Low resolution mode =0.78125 ns /bin.
•Measured RMS resolution 260 ps.
•Manages overlapping triggers, special reject mechanism.
•JTAG interface for configuration and monitoring.
•Bunch and event identification.
•Implemented in a radiation tolerant technology, up to levels of 30 Krad total dose

ALTERA CPLD
•Clock synchronous token ring passing scheme.
•Bypass on error mechanism implemented.
•The Altera CPLD manages the data_ready/get_data transmission protocol.
•Triple redundancy registers implemented for SEU protection.



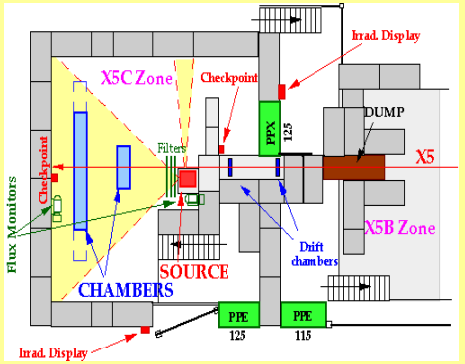
ROB.Validation tests.

- **Irradiation tests at the Cyclotron Research Centre (UCL):** $5 \cdot 10^{10}$ p.cm^{-2} of 60 MeV protons. SEU: $MTBF_{HPTDC}$ = 3.8 days in the whole detector
  $MTBF_{ALTERA}$ = 3.4 days in the whole detector



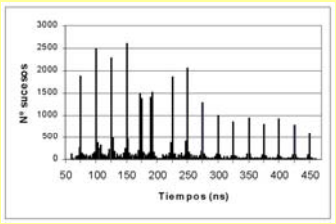
- **Temperature cycling:**
  - Regulators (< 5mV/30°C).
  - 2.5 V current variations 0.4 mA/°C.
  - Time shift: 900ps/70°C (14ps/°C). Max variation ~40 ps/°C. (30% due to LVDS-TTL receptors).

- **Lifetime test:**
  ROB fully operational at 105°C ambient temperature for 4 months (3100 hours).



- **Test beams with 25 ns structured beam at CERN.**
  - Oct. 01: test beam at GIF. Including a 25 ns structured beam
  - May. 03: One full DT chamber + Minicrate operated.
  - May. 04: Two DT chambers + Minicrates operated.

  ROB can stand high hit rates, including noisy channels (~MHz) and this only affects 1 group of 8 channels.



Minicrate Description

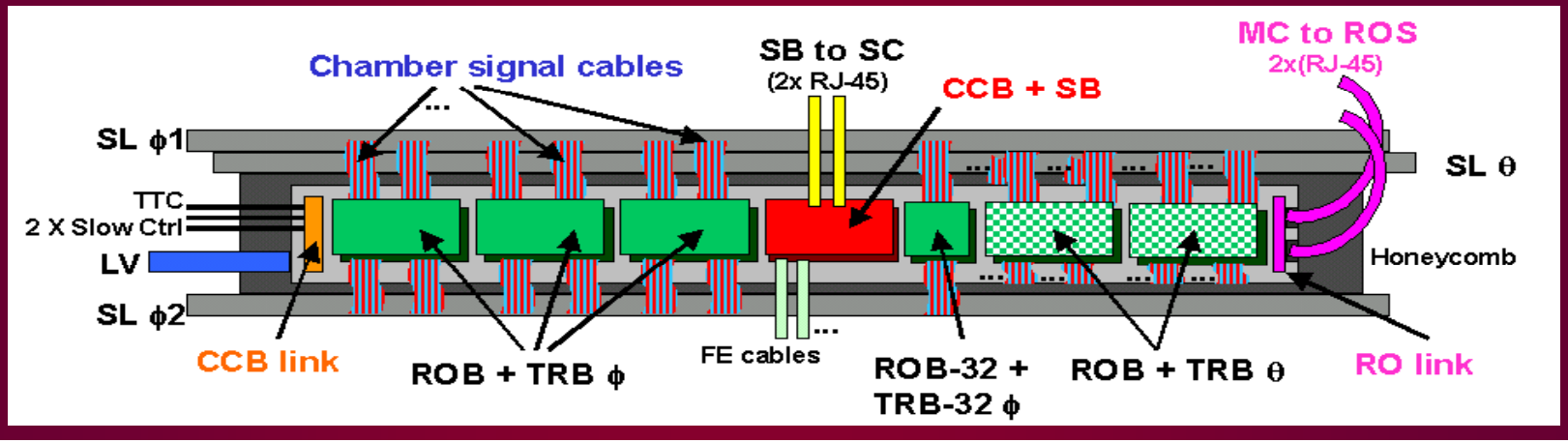
First Level of Read-Out and Trigger electronics is located inside the CMS wheels, in the so-called Minicrate, attached to the DT chamber.

It is an aluminium structure that contains:

- Read-Out electronics (RO-MC): ROB´s + ROLINK
- DT Muon Trigger system: Trigger boards (TRB´s) and Server Board (SB)
- MC & Chamber control: CCB (Chamber Control Board) + CCB-link

RO electronics is integrated sharing with the trigger system:

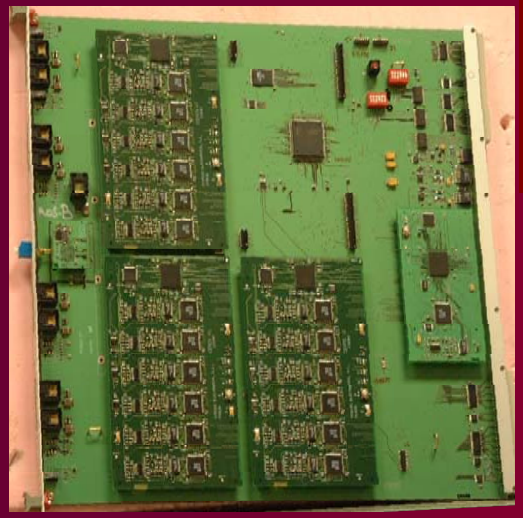
- LVDS to TTL translated wire chamber signals
- TTC (Timing & Trigger Control) signals: 40.08MHz clock, L1Accept trigger, Event and Bunch counters reset, test pulse sequence commands.
- power supplies
- cooling: water cooling system due to the magnetic field.
- and mechanics: up to 40 different pieces designed to ease conductive refrigeration.



ROS: Read-Out Server Board.

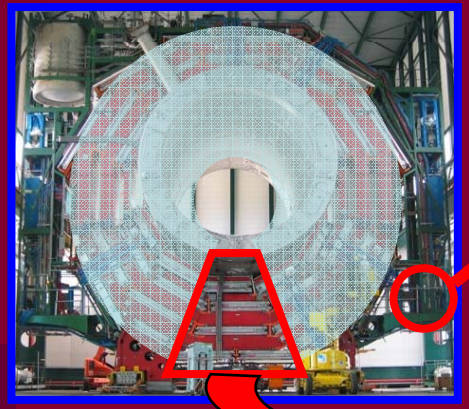
9U VME board developed at CIEMAT.
Reads-Out 25 ROB input channels => 1 sector

Main tasks

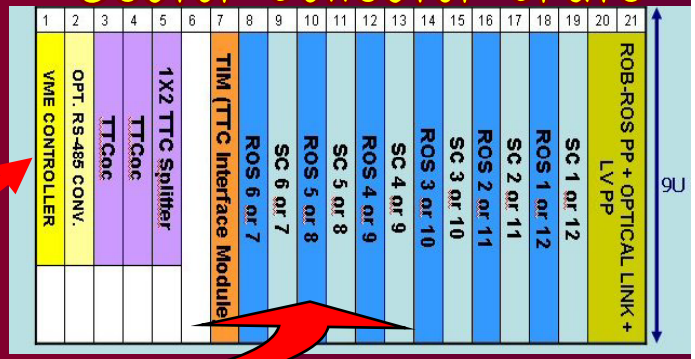


- **Storing** of the digital input data.
- **Data merging** in events **at 100 kHz L1A rate.**
- **Reduction of data overhead.**
- **Serialization and transmission** to the DDU through an optical link.
- **Data quality monitoring** and **event synchronization**.

ROS boards are located in the (SC) Sector Collector crates **integrated with the Trigger Sector Collector** (TSC) boards.



Sector Collector Crate



- There are **2 SC crates per wheel**.
- SC crates are in the **towers inside the CMS cavern**: Operation under **magnetic field**, **radiation** and **limited maintenance**.

A TIM (TTC Interface Module) board has been developed at CIEMAT to **receive the TTC optical signals and distribute them through a custom backplane** to the whole SC crate.

ROS Description.

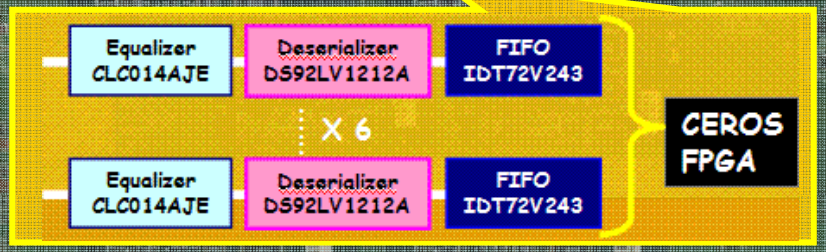
GOL (Gigabit Optical Link)
ASIC developed by CERN/MIC group for data serialization.
8B/10B Ethernet at **800 Mbps**.
HFE4190-541 **VCSEL optical transmitter at 850 nm** through 100 m.
Programmable laser driver current.

GOLROS

CEROS 0 CEROS 1
CEROS 2 CEROS 3

ROSVME & ROSMEM

ROSCTRL



VME interface.
- Board **configuration**.
- Status **monitorization**.
- Remote **FPGA re-programming**
- **Internal memory** for debugging purposes.

- **I, V, T sensor** on board.
- **Overcurrent protection** system.
- Average consumption ~ 3.6A.

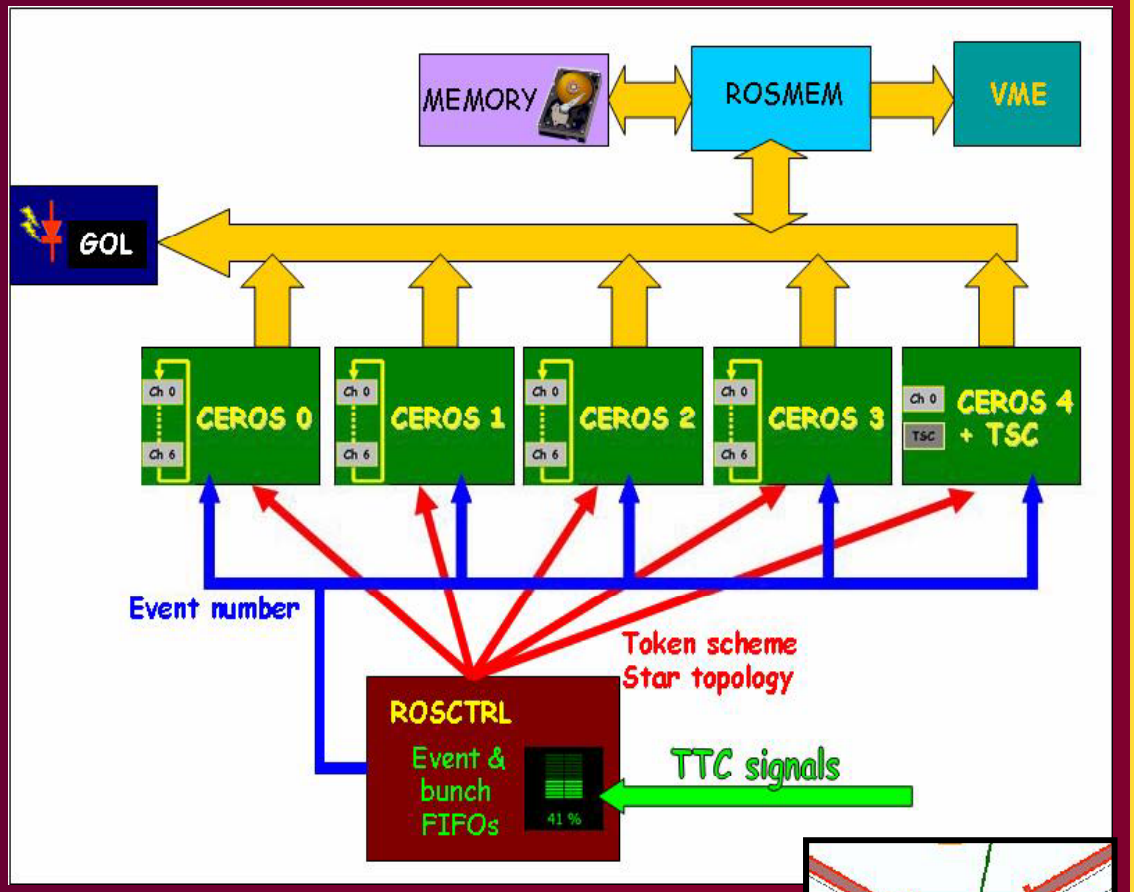
TSC channel.
Trigger information from the neighbour board is read and **transmitted within the read-out data flow**.

- **Digital data is deserialized and stored in 4 kB input FIFOs**.
- 25 input channels **grouped in blocks,** managed by each CEROS FPGA.
- To speed up the read-out, each block of 6 channels is processed in parallel.
- **Data consistency and transmission errors** checked by the FPGA in each group (links timeouts, parity errors, event id misalignment, missing trailers, FIFOs full and almost full, etc).
- **Data overhead reduction** to achieve ~ 8 kBytes per event in the whole detector:
  Only ROB events with **valid information** or **error status** are sent to higher levels of the read-out chain.

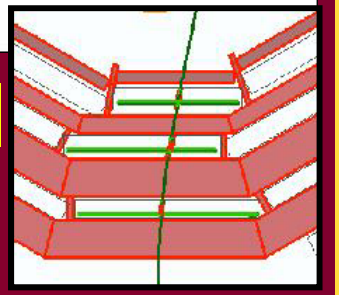
TTC input signals
(40.08 MHz clock, L1A, BC0…)
Event, bunch ID and orbit information are retransmitted in each event.
Monitorization of **event synchronization** is performed.

ROS Architecture.

Different Operation Modes



Empty event	16 bytes	68 Bxs	588 kHz
Average muon event	256 bytes	300 Bxs	134 kHz



Estimated throughput is ~80 Mbps.
(DDU through an optical link at 800 Mbps (640 Mbps effective)

Normal mode:

- Event and bunch information is received from the TTC system and stored in 255 words FIFOs
- Events are processed in parallel in each group of 6 channels.
- Data is sent to a common bus following a token ring scheme for serialization and optical transmission.

Spy mode:

- A programmable number of events/words are stored in a 512 kBytes memory and read-out through VME.
- Snapshots of the data flow. Does not interfere with normal operation.

Straight FIFO read-out:

- Input FIFOs can be read directly from VME.

GOL debugging mode:

- Data is written in the memory from VME and transmitted to the GOL.
- Selectable bandwidth.

ROS Validation Tests.

- ROS board has been extensively tested in the **laboratory at CIEMAT**, and also integrated with other parts of the subsystem in different set-ups:
  - **INFN Torino**: integration tests of ROS + DDU. Production tests of GOLROS.
  - **INFN Bologna**: test jig to validate TSC data read-out.
  - **INFN Legnaro**: **Integration tests with 2 DT Chambers, TSC, DDU and XDAQ SW**.

- **Irradiation tests** at the Cyclotron Research Centre (UCL):
  $5 \cdot 10^{10}$ p.cm^{-2} of 60 MeV protons.
  SEU:
  - $MTBF_{FIFO}$ = 2.3 days in the whole detector
  - $MTBF_{EQUALIZ}$ = 17.2 days in the whole detector
  - $MTBF_{DESERIALIZER}$ = 10.6 days in the whole detector

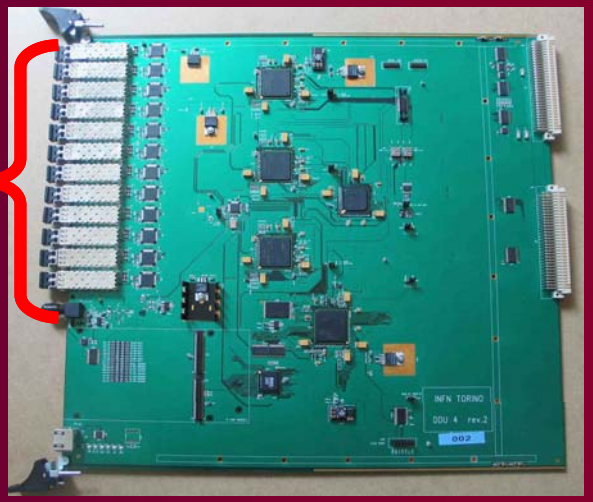
- ROS prototypes (ROS-8) have been successfully operated during different **test beams at CERN**:
  - May 2003: One full DT chamber + 1 ROS-8.
  - May 2004 : Two full DT chambers + 2 ROS-8.

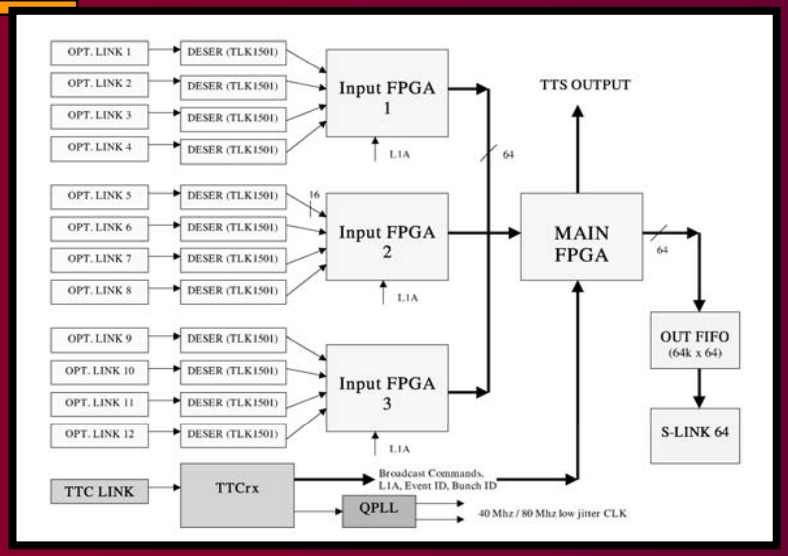
- Tests under **4 T magnetic field**:
  Final ROS was successfully operated in the Magnet Test and Cosmic Challenge for around 170 hours.
  No effect under magnetic field was shown.

- **High rate tests:**
  Data simultating muons was injected in the ROBs and 1 sector was operated at a L1A rate of 100kHz (random, Poisson distribution).
  ROS can stand 1 moun per event => Around 3 times expected data rate!!

ROS production has already finalized and boards are being installed in the final detector.

DDU: Detector Dependent Unit.





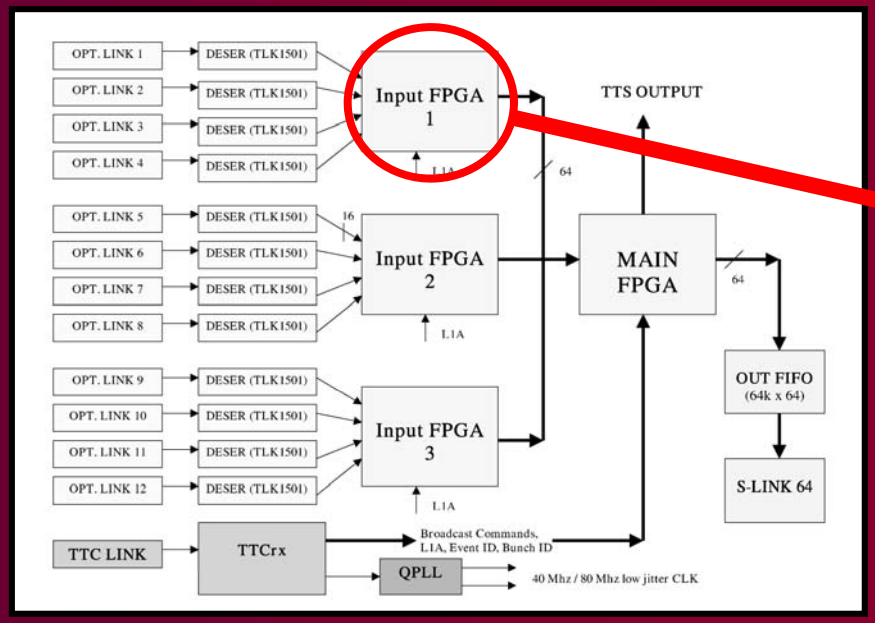
- VME64x 9U module that collects digital data from 12 ROS boards (1 CMS wheel).
- Total of 5 boards located in the service room in the CMS cavern (USC55).
- Main task:

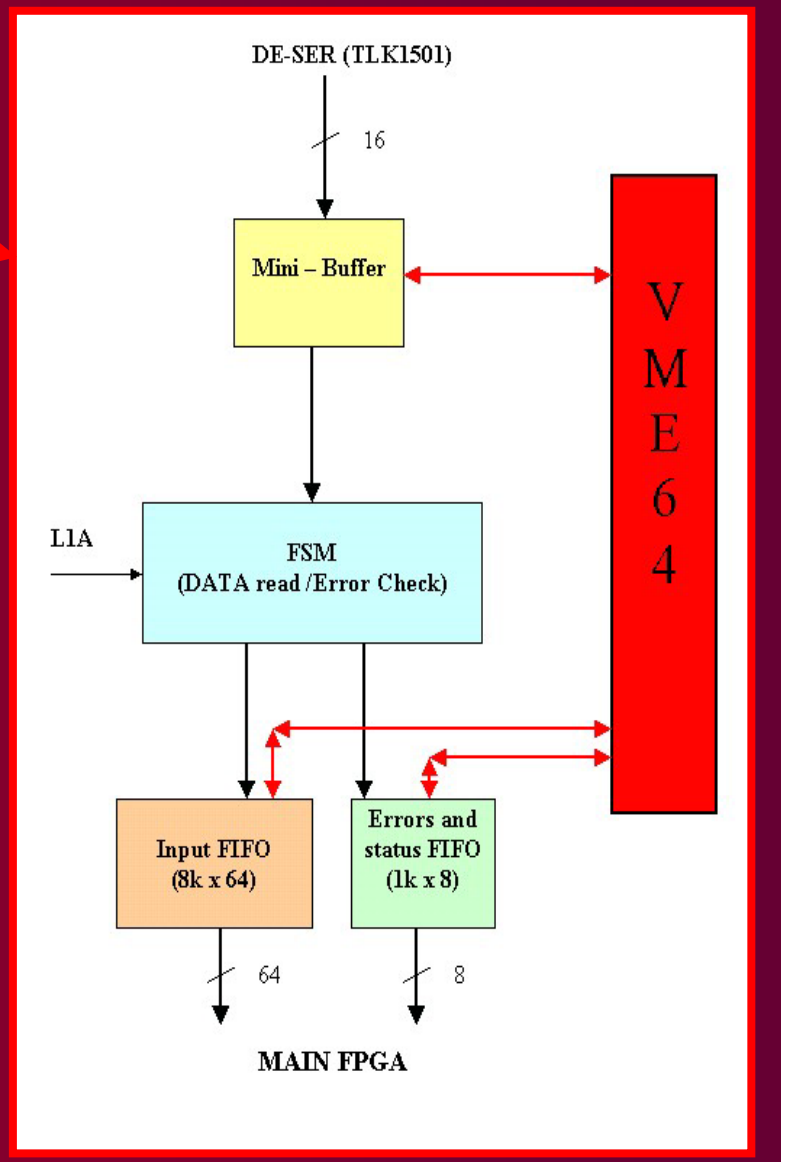
  send a consistent event fragment to the CMS DAQ every L1A trigger.

  - Merge data from 12 ROS
  - Check data synchronization
  - Scan for error codes
  - Keep synchronization with the rest of the DAQ chain through the TTC (Timing Trigger and Control) system.

- Output data readable through VME or S-LINK 64.
- Monitorization through VME plus status information embedded in the data flow.
- JTAG access for boundary scan operations and FPGA re-programming.

DDU: Detector Dependent Unit.

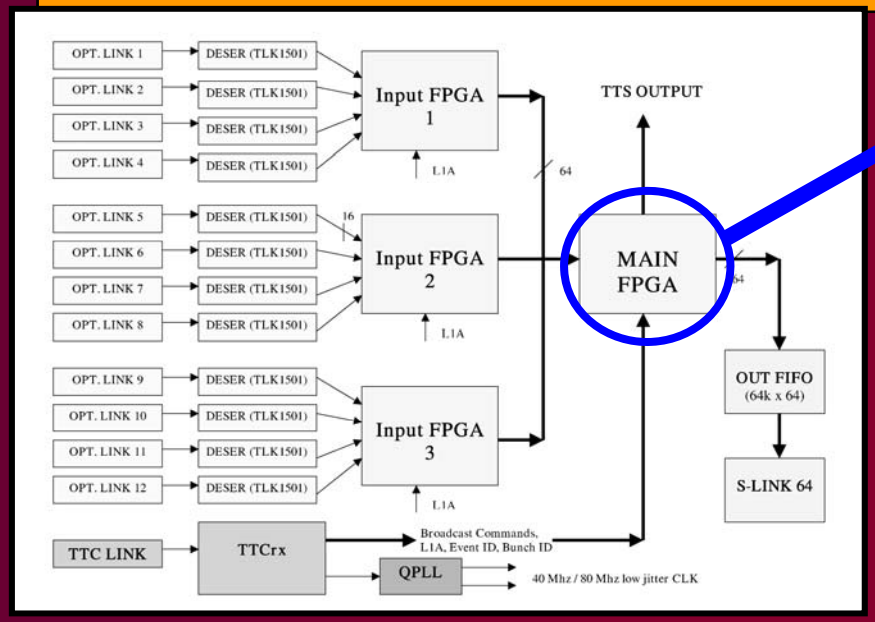


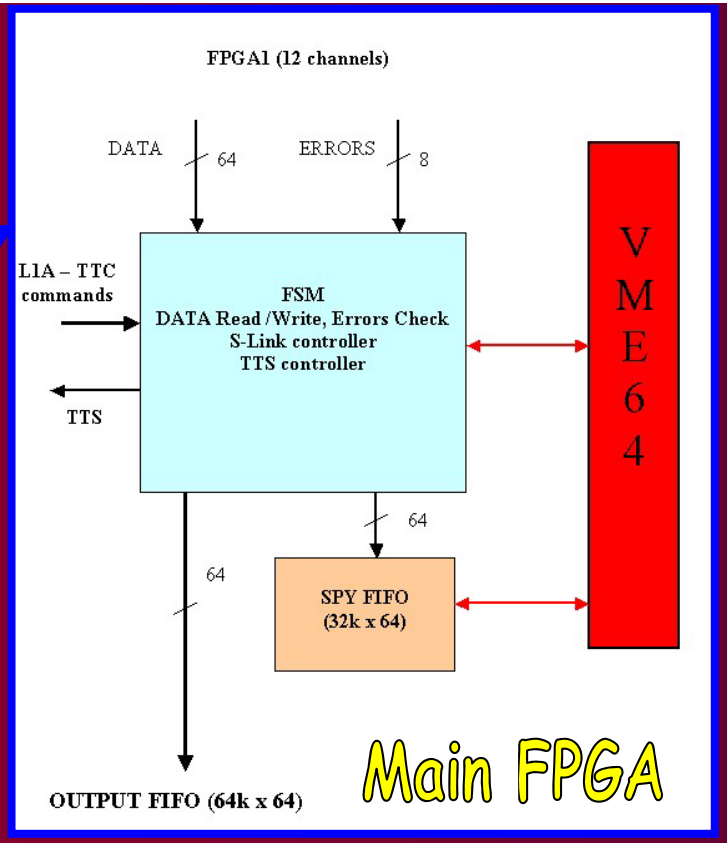


DDU Input part

- **12 inputs** (HFBR-5710 laser receiver + TLK1501 deserializer).
- **3 input FPGAs** (Xilinx XCV2P40) that process **4 channels in parallel**.
- Data packets are converted from **16 bits to 64 bits words** and stored in an internal 8K FIFO.
- **It performs data and transmission errors detection and consistency checks.**
- Status stored in another 1k FIFO.

DDU: Detector Dependent Unit.





The Main FPGA keeps synchronization with the whole CMS system.

TTC signals are received through an optical link, decoded in the TTCrx ASIC and sent to the Main FPGA.

In order to provide a fast feedback to the Central Trigger System, the Main FPGA is responsible of sending its status to the **TTS (Trigger Throttling System):**

- Slow down L1A rate,
- report **synchronization or hardware problems in the whole DT Read-Out electronics.**

Reads data stored in the input FIFOs through a 64-bit bus working at 40 MHz.

Builds event fragments to be sent to the DAQ.

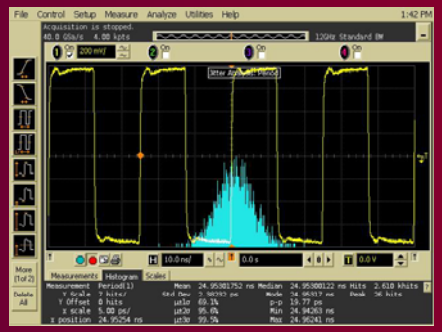
Output data is sent to an external FIFO (64k x 72-bit) readable:

- via S-LINK64 (320 MB/s)
- or through VME

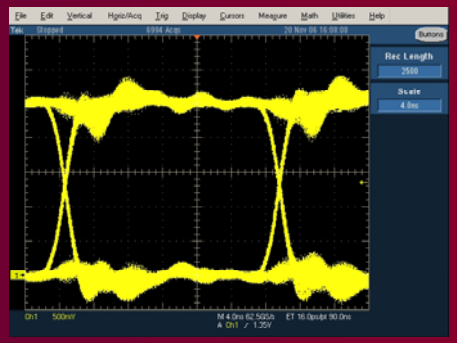
Internal Spy FIFO and random data generator for debugging purposes.

DDU: Detector Dependent Unit.

Full board functionality has been extensively checked at laboratory.



- The PCB has been optimized to guarantee quality of fast signals and low jitter clock distribution.
- Clock jitter is minimized in the board by using a QPLL ASIC plus low jitter differential buffers.
- The deserializer clock signal (40.08 MHz) has a jitter peak-to-peak value lower than 20 ps.



- A special configuration has been used in the FPGAs to validate data transmission through the 64 bit buses.
- A Pseudo Random Bit Generator (64-bit LFSR) is used to produce random data patterns.
- Several hours of tests show no errors in the transmission.

* The DDU board has been successfully tested with other components of the DT Read-Out and the CMS central DAQ, reaching a **total bandwidth of 200MBytes/s**
* Also, the DDU has been **fully validated during the Magnet Test and Cosmic Challenge (MTCC)** exercise performed at CERN during summer 2006.

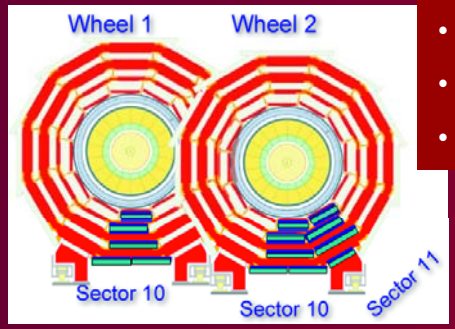
- The final version of the board is **under production.**
- First units are already been used for the **DT system commissioning**.

Magnet Test and Cosmic Challenge.

From **August to November 2006 most of the CMS subdetectors** were operated in the Magnet Test and Cosmic Challenge at CERN.

Main goals:

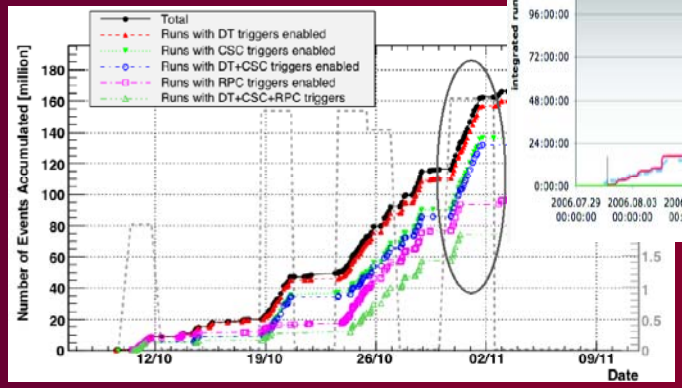
- Commission the magnet for the first time at its **nominal value of 4 T.**
- **Operate the whole sub-detector chain** in a 20°C slice.
- Test **local/global trigger and readout chains**, DQM, DCS, reconstruction.
- **Synchronization of different sub-detectors** to see common muons.

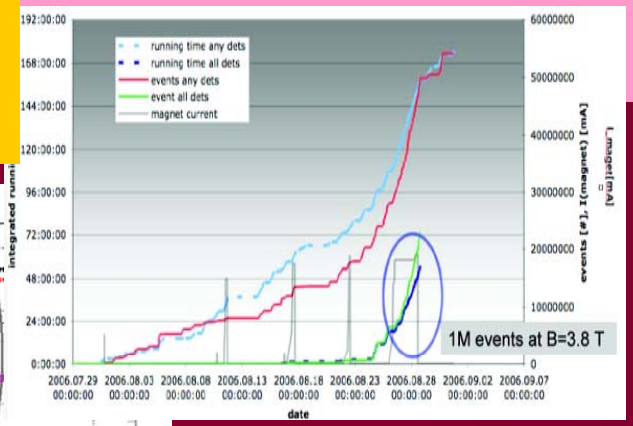


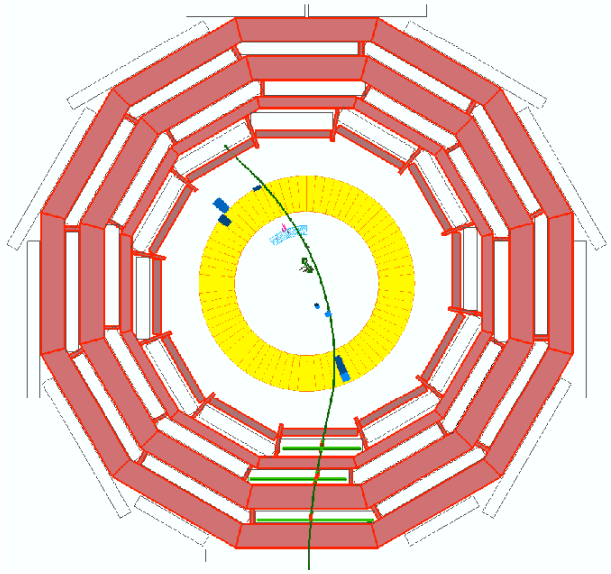
The **whole DT Read-Out chain was successfully operated in local and in global mode**:

- 14 DT chambers/Minicrates.
- 69 ROB boards.
- 3 ROS boards.
- 1 DDU board.

~~170 hours data taking~~
200 million events collected
(40 M events at B=4T)







Event display of a cosmic muon with a current of 18159 A (3.8 T) in the CMS solenoid. Reconstructed muon track from the DT muon segments and extrapolation into the detector.

Summary.

- After several years of design and production, the **complete DT Read-Out system is almost ready for operation** in the CMS detector.

- **Various prototypes** of the different parts have been developed and tested in laboratory as well as in diverse tests where chambers plus electronics have been **debugged and optimized**.

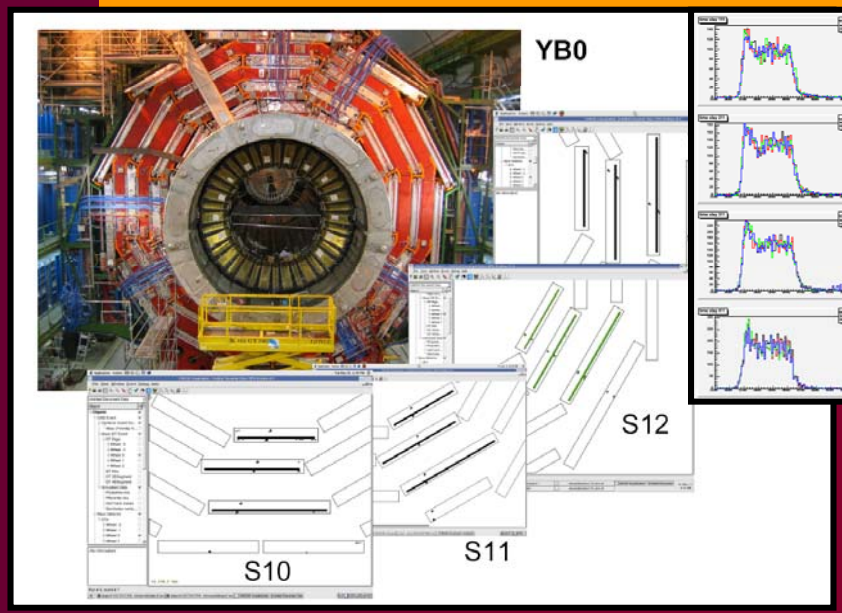
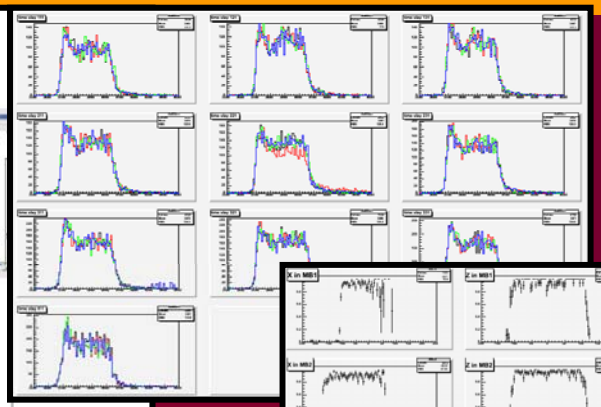
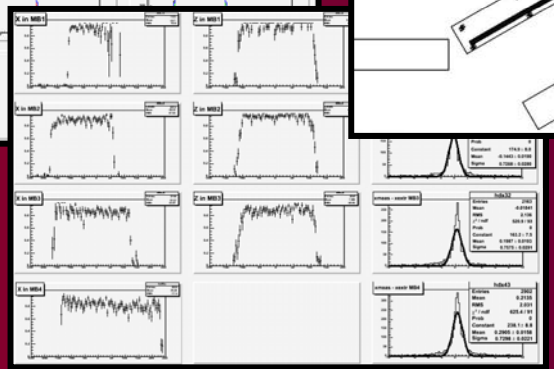
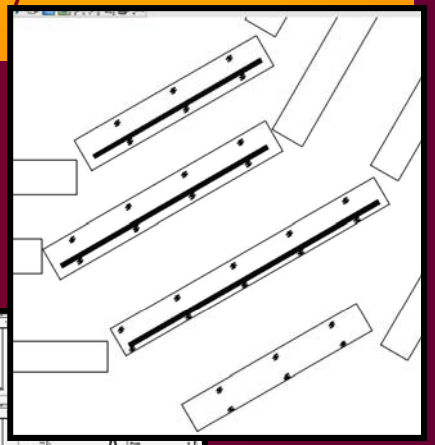
  Test beams with 25 ns structured beams, operation under the CMS magnet (MTCC), radiation tests, etc.

- **The functionality of the Read-Out electronics has been satisfactorily tested and the design has been thoroughly validated**.

- The different parts show **adequate behaviour under the environmental conditions** expected during the **10 years operation of CMS in LHC**.

- **Production of the read-out electronics** has taken place at CIEMAT (Madrid) and at INFN (Torino) and it has comprised:

  - **1500 ROBs boards**
  - **250 Minicrates**
  - **60 ROS boards**
  - **10 TIM boards**
  - **5 DDU boards**

Summary.

- **Installation and commissioning** of DT chambers and Minicrates in the CMS detector has been going on for the last 2 years.
- At present, ROS and DDU boards are being installed and the system is being commissioned **sector by sector**.
- **70% of the detector has been commissioned up to now with satisfactory results**.
- Tests include:
  - **cosmic runs** in surface and in the cavern and
  - **test pulse runs**, where the whole electronic chain is tested, by generating pulses at Front-End level that simulate vertical tracks.
  - **Noise runs,** to evaluate the amount of noise coming from the system.