The CMS Muon system

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Abstract

The Compact Muon Solenoid Muon system, designed to trigger and identify muons, is based on three different technologies; drift tube (DT) in the barrel region, cathode strip chamber (CSC) in the endcap and resistive plate chambers (RPC) in both the barrel and endcap. The three subsystems, the local muon trigger and the global muon trigger will be described here giving some results obtained during the quality control tests. The chambers installation is now underway; the strategy adopted for the commissioning of the muon system will be described in this paper.

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Introduction

The Compact Muon Solenoid [1] is one of the four experiments of the Large Hadron Collider [2] at CERN. CMS is a complex apparatus consisting of several subdetectors in order to identify particles and measure their energies and momentum.

A principle feature of CMS is its strong magnetic field of 4 Tesla, which is produced by a superconducting coil. The coil volume houses the tracker and the electromagnetic and hadrons calorimeters. An iron return yoke surrounds the coil and houses the muon chambers as is shown in figure 1.

Since the very high collision rate and the low cross section of the “new physics” events a very important part of the experiment is the trigger and data acquisition system [3][4].

The experiment is currently being assembled and tested in a surface hall SX5 and it will be lowered into the cavern during the 2006.

1. The Muon Spectrometer

At LHC, electrons and muons will play a fundamental role in the studies of any physics sector; from the Higgs search, where the $H \rightarrow \ell\ell\ell\ell$ are the so called “golden channels”, to the “new physics” and from the electroweak precision measurements to the b and t physics. For these reasons the CMS muon system [5] has been designed and built to have excellent trigger, identification and reconstruction performances.

The LHC physics signatures and their separation from the large expected background, the muon trigger rates and the trigger limits dictated by the DAQ and trigger systems, impose several requirements to be fulfilled by the muon system:

- **Muon trigger**: excellent trigger performances on single and multi-muons events and an unambiguous identification of the bunch crossing is obtained by combining fast dedicated trigger detectors, Resistive Plate Chambers, with detectors having precise spatial resolution, Drift Tube and Cathode Strip Chambers.
- **Redundancy**, in both trigger and reconstruction, is obtained using three technologies, combined in order to have two independent muon systems in the whole angular region.
- CMS has been designed with a magnetic field of 4 Tesla and the possibility to measure muons twice, in the tracker and in the muon spectrometer in order to perform very good results in the **muon momentum and charge** measurements in the whole $\eta$ region and from few GeV up to a TeV.
- **Muon identification**: to achieve a very high efficiency (> 95%) up to $\eta = 2.4$ are required at least 16 interaction lengths of material and a very sophisticated set of algorithms able to use the three sub-detectors data.
- **Robustness**: The detectors must be capable to work with a strong magnetic field and high radiation and interaction background [5].
The muon spectrometer consists of 250 DTs, 540 CSCs and 912 RPCs chambers to be built and installed for the 2006. It covers an angular region delimited by $0 < |\eta| < 2.4$ and is divided in two major regions: barrel and endcap (figure 2).

The **barrel region** ($0 < |\eta| < 1.2$) is composed by 5 wheels, each divided in 12 sectors with 4 iron gaps. The muon stations consist of one DT chamber and two RPC chambers joint together and are placed in the gaps of the iron return yoke plates. In this region the magnetic field is low and almost uniform and the expected muon rate is about 1 Hz/cm$^2$ compared with a neutron induced background of 1-10 Hz/cm$^2$.

The **endcap region** ($0.9 < |\eta| < 2.4$) has a strong and not uniform magnetic field (up to 3.5 T) with a $\gamma$ and neutron induced background rate of about 1 KHz/cm$^2$. The two endcaps made of 3 iron disks and 4 layers divided in 2 or 3 stations (ME1/1, ME1/2, ME1/3, ME2/1, ME2/2, ME3/1, ME3/2, ME4/1 and ME4/2) of CSC and RPC chambers.

![Figure 2. The CMS muon spectrometer ($\eta$ view) is based on three different technologies; Drift Tube (DT), Cathode Strip Chamber (CSC) and Resistive Plate Chamber (RPC).](image2)

2. **The CMS Muon Trigger system**

For the nominal LHC design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$, an average of 17 inelastic events occur every 25 ns. This input rate of $10^9$ interactions per second must be reduced by a factor of at least $10^7$ to 100 Hz, the maximum rate that can be achieved by the DAQ.

The CMS trigger system [3] is based on two levels, at first level (L1) all data are stored for 3.2 $\mu$s, after which no more than 100 KHz (50 KHz for the first year) of the stored events are forwarded to the second level, called High Level Trigger. The L1 is an hardware trigger based on custom electronics while the HLT is a software trigger based on commercial processors.

![Figure 3. The Muon trigger schema from the chamber trigger to the Global Muon Trigger.](image3)
The L1 muon trigger [6] uses all three muon detectors DT, CSC and RPC, each with its own trigger logic as shown in figure 3. DT and CSC first process the local information of every chamber generating local triggers then muons from different chambers are collected by the Track Finder which combines them to form a muon track with an assigned transverse momentum value. Up to four best (highest $p_T$ and quality) muon candidates from each system are selected and sent to the Global Muon Trigger. In the case of RPC hits from all the stations are collected (PACT) [7] and if they are aligned along a possible muon track, a $p_T$ value is assigned and the information is sent to the Muon Sorter. It selects the four highest $p_T$ muon from the barrel and four from the endcaps and sends them to the Global Muon Trigger (GMT). Finally transverse momentum thresholds are applied by the GMT for all the trigger conditions.

3. Drift Tube chamber

The barrel muon system consists of 4 concentric shells of drift tube chambers (MB1, MB2, MB3 and MB4). Each chamber, except MB4, is made of 3 independent units, called superlayer (SL), and a thick honeycomb plate glued together (fig.4). Each superlayer is composed by 4 layers of drift tubes, with all wires parallel. The wires of odd layers inside a SL are staggered by half-cell width with respect to the even layers. The two external SLs measure the muon trajectory in the CMS bending plane ($r, \phi$) while the third SL measure the $z$ coordinate. The drift tube is $43 \times 13 \text{ mm}^2$ and is composed by three electrodes: a wire, two I-beams (cathodes) and two strips.

Figure 4. The drift tube chamber is made by 3 superlayers and a thick honeycomb plate glued together.

The time needed by the primary electrons to reach the anode is measured and the spatial position of the track is calculated from the time measurement and the known time-to-distance relationship. To resolve the left-right ambiguity of a single cell it is necessary to use the staggered layers and reconstruct the track position in at least three of the four layers. A spatial resolution of $100 \mu \text{m}$ in the ($r, \phi$) coordinate and of $150 \mu \text{m}$ in the ($r,z$) coordinate has been measured in the test beam [8].

3.1. DT local trigger system

The DT front-end electronics, called Bunch and Track Identifier (BTI), forms track segment from coincidences of at least three aligned hits in four layer of one DT superlayer, using the mean-timer method, obtaining a resolution of 1.4 mm and 60 mrad. The positions and directions of the segments are sent to the Track Correlator (TRACO), which attempts to combine segments from the two SL of the same chamber and produce $\phi$ coordinate with a resolution of 10 mrad. The Trigger Server collects the two best $\phi$ segments and the $\theta$ segments and selects, at every bunch crossing, two segments with highest quality and $p_T$. The Track Finder identify the best tracks per sector (30 sectors in $\phi$ and 12 in $\eta$) assigning the $\phi$, $\eta$, $p_T$ and quality.

4. Resistive Plate Chamber

RPC has been chosen in both the barrel and endcap as dedicated trigger detectors. Because of their fast response and good time resolution ($\sigma < 1.5 \text{ ns}$) they guarantee a precise bunch crossing assignment of the muon tracks.

The barrel muon stations are equipped with two RPC layers for the innermost stations (RB1 and RB2) and one layer for the outer stations (RB3 and RB4) for a total number of 6 layers per sectors. The endcap are instrumented with one RPC layer per station for a total of 4 layers.
Figure 5. The schema of a barrel RPC made by two double-gaps with a strip plane in the middle.

An RPC gap is made by two parallel bakelite plates (1-2 $10^{10}$ Ω cm) placed at a distance of 2 mm and filled with a gas mixture of 96% C$_2$H$_2$F$_4$, 3.5% i-C$_4$H$_{10}$ and 0.5% of SF$_6$. High voltage is applied to the outer graphite coated surface of the bakelite plates in order to have an electric field inside the gas gap able to generate a charge avalanche along the track of an ionizing particle. The avalanche induces a signal on the aluminum strips placed outside the gap and isolated from the graphite.

An RPC chamber (fig.5) consists of two double-gaps (forward and backward), made by 2 gaps with a read-out strips plane in the middle. Every chamber is equipped with 10, 12 or 18 front-end electronic boards [9] each connected to 16 readout strips.

4.1. Production, test and results

RPC barrel chambers are assembled at the HiTec and General Tecnica factories and in the Bari and Sofia laboratories, and then are characterized with cosmic rays at the station sites of Bari, Pavia and Sofia. The endcap chambers are assembled and tested at CERN.

Tests done during the production phase are: gas and cooling tightness, dark current versus high voltage and strip noise rate at the working point (9.5 KV). The chamber is accepted if the dark current distribution at 9.5 KV has a mean value lower than 5 μA and a standard deviation below 1 μA and if the noise rate is less than 5 Hz/cm$^2$. During the cosmic tests the chambers are characterized by the efficiency, dark current and noise rate curves as function of HV working point.

Figure 6. The endcap chamber efficiency distribution at 9.5 KV for a subset of chambers.

The average efficiency measured for the RPC chambers is about 97% that become the 99% using the tracking capabilities of the cosmic tower (fig 6.) [10][11]. The accepted chambers are sent at ISR where the chamber stability is studied for a month, after that RPCs are ready to be joint at the DTs

5. Cathode Strip Chamber

The endcaps are instrumented with CSC chambers [12] providing precise time and position measurements. Each chamber is trapezoidal in shape and consists of six gas gaps, each equipped with a plane of radial cathode strips (3.15-16 mm) and a plane of anode wires (spacing 2.5-3.16 mm, diameter 30-50 μm) running almost perpendicular to the strips (fig.7).
The gas ionization and subsequent electron avalanche produces a charge on the anode wire and an image charge on a group of cathode strip. Thus each chamber measures up to six space coordinates \((r, \phi, z)\). The wire signal gives fast information with a spatial resolution of about 1 mm while a precise spatial measurement \((\sigma_{r,\phi} 100-240 \mu m)\) is achieved using the center of gravity of the charge distribution induced on the cathode strips [13].

All CSCs, except those in the station ME1/3 are overlapped in \(\phi\) to avoid gaps in the muon acceptance.

### 5.1. CSC local trigger system

The CSC local trigger uses both the cathode and anode data to found the local charged tracks (LCT). The two trigger views, based on different electronics boards and different algorithms, are able to find up to two local tracks per chamber during any bunch crossing. The two projections are then combined in a 3-D LCT by a timing coincidence. The data of each endcap sector (60°) are collected by the Track Finder that identify the best 3 muons assigning to them \(\phi, \eta, p_T\) and a quality bit.

### 6. Muon system installation and commissioning

The installation and commissioning of the muon system is going on since the 2004 when the first CSC chambers have been installed. At present every muon sub-systems is working on the installation and commissioning of the system following its own test procedures.

**CSC:** every installed chamber is commissioned with a gas leak test, an HV and electronics test made with a portable DAQ in which comics (fig. 8) are taken in a self-triggering mode. After that a long term electronic test is done keeping the low voltage on for a long period. Up to now about the 96% of the CSC chambers have been installed and 50% of those have been commissioned.

**DT-RPC:** after having been coupled with the RPC at the ISR, the chambers are sent at SX5 where are installed in the iron. At that point every chamber is commissioned testing the gas and the cooling connections, the high voltage and the electronics integrity, looking at dead channels and measuring the noise rate. More tests
are under development in both the DT and RPC groups. 20 sectors of the wheels +1 and +2 have been already installed, corresponding to about the 30% of the whole system.

About 50% of the endcap RPC chambers (reduced system) have been produced and they will be installed from October 2005. The commissioning will follow the same barrel procedures [14].

7. Expected muon system performances

A full detector simulation has given the following results for the transverse momentum resolution of muon tracks (fig.9):

- Muon system stand-alone
  - 8-15% $\Delta p_T/p_T$ at 10 GeV
  - 16-53% $\Delta p_T/p_T$ at 1000 GeV
- Muon system with tracker matching
  - 0.8-1.5% $\Delta p_T/p_T$ at 10 GeV
  - 5-13% $\Delta p_T/p_T$ at 1000 GeV

For low $p_T$ the resolution measured in the muon system is limited by multiple scattering in the iron yoke. For high $p_T$ the resolution is limited by the muon chambers resolution, even when the tracker is taken into account.

![Figure 9](image1.png)

Figure 9. The transverse momentum resolution of the muon tracks (with and without tracker matching) (left) and the muon reconstruction efficiency versus $\eta$ (right).

The efficiency of the reconstructed muon tracks is almost flat in $\eta$ up to $|\eta| \sim 2.1$ as is shown in figure 9, for $W \rightarrow \mu \nu$ events.

The Global Muon Trigger combines 3 independent triggers having a very high efficiency over the full $\eta$ angular coverage. The efficiency of the L1 muon trigger to identify a single muon as a function of the generated $\eta$ is shown in figure 9.

![Figure 10](image2.png)

Figure 10. Efficiency of the level-1 muon trigger to identify single muon tracks as function of $\eta$. 

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The DT, CSC and RPC trigger systems show different efficiencies in $\eta$ and $\phi$, and different behavior in $p_T$ due to cracks, construction properties and different trigger algorithms. The GMT can make use of these differences resulting not only in a higher efficiency overall but also a smoothing effect on the less efficient regions as is shown in figure 10.

![Figure 10. Muon trigger rate in barrel and endcap region as function of $p_T$.](image)

In figure 11 is shown the single muon trigger rates of the regional triggers and of the GMT as a function of the $p_T$ threshold applied (at a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$). A single muon rate of 8 KHz is obtained with a $p_T$ threshold of 25 GeV (efficiency 90%). The dimuon trigger rate is 2.8 KHz with a $p_T$ threshold of 8.5 GeV.

8. Conclusion

The construction of the three muon detectors is close to the end (summer 2006) and about 96% of the CSC and 30% of the DT-RPC chambers have been already installed at SX5. The commissioning of the system is going on showing very good results. In the first part of the 2006 a very important test, called cosmic challenge, will be done using a fraction of the whole CMS detectors (2 or 3 sectors for the muon system) in order to verify the estimated global performances of the muon system described in this paper.

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