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The CMS Muon Spectrometer

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Abstract

The **C**ompact **M**uon **S**olenoid (CMS) is one of the two multi-purpose detectors foreseen for the **L**arge **H**adron **C**ollider (LHC) being built at the European Organization for Nuclear Research (CERN). The CMS detector consists of several sub-detectors measuring energy, momentum, and charge of particles generated in collisions of proton beams with a centre of mass energy of up to 14 TeV. This paper gives a brief overview of the three different technologies used for the CMS muon spectrometer. The basic working principles, the current status (June 2005) of production and commissioning, and some results from tests are presented.

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1 Introduction

The CMS detector is designed to study proton-proton collisions as well as heavy ion collisions at the LHC. The cylindrical shape (see figure 1) is determined by the large superconducting coil generating a solenoidal magnetic

Figure 1: Artists view of the CMS detector.

field of 4 T strength and by the iron return yoke. The yoke is divided into five *wheels* and a group of three *endcap discs* at each end of the detector. The magnet yoke is instrumented with muon detectors while the tracking system (based on silicon pixel and silicon strip detectors), the electromagnetic calorimeter (ECAL, made of PbWO_4 crystals) and the hadronic calorimeter (HCAL, made of copper plates interleaved with scintillators) are placed inside the magnet coil. Detailed descriptions of the tracker, the calorimeters, and their current status can be found in [1–5].

2 The Muon Spectrometer

Muons occur in many final states of pp-interactions. Due to their high penetration power in matter they will give prominent signatures for "new" physics events. The detection of these signatures and their separation from the large background expected at the LHC imposes several requirements to be fulfilled by the muon system [6]:

- at least 16 interaction lengths of material are present up to $\eta = 2.4$ allowing a good **muon identification** by absorption of other charged particles before (ECAL, HCAL) and inside the muon system (iron yoke).
- **muon momentum** and **charge** are determined by measuring the sagitta of the muon tracks bent in the magnetic field. The muon momentum is measured twice, in the tracker **and** in the muon system, thus improving the momentum resolution and the track matching between tracker and muon system.
- **muon trigger**: an excellent trigger performance is obtained by combining fast dedicated trigger detectors, **Resistive Plate Chambers (RPCs)**, with detectors having a precise spatial resolution, **Drift Tube chambers (DTs)** and **Cathode Strip Chambers (CSCs)**. This provides an unambiguous identification of the bunch crossing associated to a muon track and triggering on single- and multi-muon events. All three sub-systems contribute to the dead-time-less trigger system of CMS.
- **redundancy** is obtained by using three different detector technologies. Two complementary technologies are combined to a *muon station* respectively.
- to achieve a large **acceptance** the muon system is instrumented up to $|\eta| = 2.4$. The muon stations are arranged in such a way that a muon traversing the detector is measured at four stations, each station featuring up to 14 sensitive layers.
- the **efficiency** of reconstructing muon tracks must be as high as possible (expected global efficiency 95–99% [10]).

- **robustness:** the muon detectors must be capable to cope with the strong magnetic fields in parts of the iron yoke and the high radiation and interaction background expected at the LHC.

Figure 2: Cross sectional view of one quadrant of CMS showing the detectors of the muon system.

For the muon system 250 DTs, 540 CSCs, and 912 RPCs have to be built and installed. It is divided into two major parts (see figures 1 and 2):

- **barrel region** ($0 < |\eta| < 1.2$): it consists of the five wheels instrumented with DTs and RPCs. The magnetic field is confined to the iron yoke plates. Within the muon stations the field is low and almost uniform. The expected muon rate is also relatively low: $R(\mu) \lesssim 1 \text{ Hz/cm}^2$. The neutron induced background is $1\text{--}10 \text{ Hz/cm}^2$.
- **endcaps** ($0.9 < |\eta| < 2.4$): to cope with the strong and non-uniform magnetic field (up to $\sim 3.5 \text{ T}$) the end-cap discs are instrumented with CSCs and RPCs. The muon rate is high at the order of $R(\mu) \lesssim 200 \text{ Hz/cm}^2$. The γ and neutron induced background rate reaches values of up to 1000 Hz/cm^2 for large $|\eta|$.

A spatial resolution of $\sim 100 \mu\text{m}$ is desired for reconstructed track segments, demanding a single hit resolution in the CSCs and DTs of $\sim 250 \mu\text{m}$ and a precise knowledge of the position of the muon stations w.r.t. the tracker and to each other. Therefore the muon system is equipped with an optical alignment system which monitors the position and the relative movement of the detectors during operation. The accuracy is comparable to the intrinsic resolution of the muon detectors (for details see [6]).

2.1 Resistive Plate Chambers (RPC)

RPCs are installed in both, the barrel and the endcaps, as dedicated trigger detectors. Because of their fast response and good time resolution ($\sigma_t < 1.3 \text{ ns}$ [7]) they guarantee a precise bunch crossing assignment of the muon tracks. The rather coarse spatial resolution is typically of the order of centimeters (e.g. $\sigma \sim 8 \text{ mm}$ for barrel RPCs). The barrel muon stations are equipped with two RPC layers for the two innermost stations and with one layer for each outer station (total 6 RPC layers). The endcaps are instrumented with one RPC layer per station (total 4 RPC layers).

An RPC consists of two parallel high resistive bakelite plates ($1\text{--}2 \cdot 10^{10} \Omega \text{ cm}$) separated by a 2 mm gap filled with a gas mixture of 96% $\text{C}_2\text{H}_2\text{F}_4$, 3.5% $\text{i-C}_4\text{H}_{10}$, 0.5% SF_6 . High voltage ($\sim 10 \text{ kV}$) is applied to the outer graphite coated surface of the plates such that the electric field inside the gas volume is sufficient to generate a charge avalanche along the track of an ionizing particle. The moving charges induce a signal in the aluminium

Figure 3: Schematic drawing of an RPC.

strips placed outside this unit but isolated from the graphite. The signal on the strips is read out. When the avalanche is formed the graphite coating is discharged locally. Thus the electric field drops abruptly and the gas amplification stops. This prevents the charge avalanche from spreading over the whole gas volume. Because of the resistance of the graphite coating the electric field in the rest of the RPC is not affected by the local discharge such that the detector remains sensitive to further particle crossings while it recovers at the place of the discharge.

CMS uses *Double Gap RPC* modules (see figure 3) with two combined plate pairs in order to increase the efficiency. The RPCs are operated in avalanche mode to ensure proper operation at high background rates of up to $\sim 10 \text{ kHz/cm}^2$.

2.2 Cathode Strip Chambers (CSC)

The CMS endcaps are instrumented with CSCs providing precise time and position measurements despite the high background rates and inhomogenous magnetic field in this region.

Figure 4: Schematic layout and operating principle of a CSC.

The trapezoidal shaped chambers consist of six detection layers whereas each layer is a multi-wire proportional chamber. A layer is defined by two parallel cathode planes with a small gas filled gap inbetween (see figure 4). One cathode is segmented into radial strips (width: 3.15–16.0 mm) running perpendicular to the anode wires (spacing 2.5–3.16 mm, diameter 30–50 μm) inside the gas volume. The chambers are operated at high voltages of 3000–4100 V. The charge avalanche produced when a muon passes through the gas volume is collected by the closest anode wire while on the cathode strips image charges are induced. The wire signal gives a fast information with a rough spatial resolution $O(\text{mm})$. It is used for triggering. A precise spatial measurement ($\sigma_{r,\Phi\text{-plane}} \sim 100\text{--}240 \mu\text{m}$) is achieved by determining the center of gravity of the charge distribution induced on the cathode strips.

The sampling of the rather long strip-signals is time consuming thus leading to a coarse time resolution. The gas used in the CSCs is a mixture of 30% Ar, 50% CO₂, 10% CF₄. Due to their multi-layer structure the CSCs have the capability of triggering on particle tracks.

2.3 Drift Tube Chambers (DT)

The barrel region is instrumented with DT chambers. Each chamber except the outermost ones measures both, the (r, Φ) - and (r, z) -coordinates of a muon. A muon chamber is built up from three so-called superlayers with four layers of half-a-cell width staggered drift tubes. Eighth layers in a chamber measure the (r, Φ) -coordinate while only four layers measure the (r, z) -coordinate.

Figure 5: Drift tube cell with simulated drift lines and isochrones.

When a muon passes through a DT cell it produces ionization along its track in the gas (the gas is a mixture of 85% Ar and 15% CO₂). The primary generated electrons drift towards the anode wire in the centre of the cell (see figure 5). In the high electric field close to the wire gas amplification generates an electrical signal on the wire. The time needed by the primary electrons to reach the anode is measured. The spatial position of the track is calculated from the time measurement and the known time-to-distance relationship. To resolve the intrinsic left-right ambiguity of a single cell it is necessary to exploit the staggered layout of the layers and to reconstruct the track position in at least three of the four layers. From test beam measurements a single hit resolution of $\sigma \sim 190 \mu\text{m}$ has been established [9].

The DT trigger electronics assigns the correct bunch crossing to a muon track with $> 99\%$ efficiency. The spatial resolution of the DT trigger electronics reaches a precision $O(\text{mm})$.

3 Expected Performance

Full detector simulation yields for the transverse momentum resolution of muon tracks [10]:

- 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 muons the momentum resolution of the muon system (without the tracker) is limited by multiple scattering of the muons in the iron yoke. For high p_t muons the limitation is due to the resolution of the muon chambers, even when combined with the tracker information (see figure 6).

The reconstruction efficiency obtained from the simulation as function of η is almost flat up to $|\eta| \sim 2.1$ (see figure 7). Small efficiency drops, caused by the geometrical acceptance, are visible.

Figure 6: Momentum resolution of the muon system stand-alone and combined with tracker information.

Figure 7: Global muon reconstruction efficiency as function of $|\eta|$.

4 Status

The following numbers were quoted at the recent annual review held in June 2005 [11]:

- **RPCs:** 30% of the endcap detectors and 70% of the barrel chambers are built. While 20% of the barrel detectors are already installed the endcap installation will start soon.
- **CSCs:** All chambers including spares are built. 50% of the chambers needed for the start-up are installed on the endcap discs. Almost the same amount is fully commissioned.
- **DTs:** More than 70% of the barrel chambers have been produced. The production sites will finish the superlayer assembly soon. Approximately 20% of the chambers are installed in the barrel wheels. The commissioning is in progress.

5 Conclusions

The technologies of the three sub-detectors of the CMS muon system have been presented. It has been shown that the detectors meet the necessary requirements for operation at LHC conditions. The status of the production and installation of the detectors in June 2005 makes the collaboration confident that the muon system will be operational at the LHC startup in 2007.

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