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Status of the Compact Muon Solenoid Detector at the Large Hadron Collider

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Abstract

The Compact Muon Solenoid (CMS) detector is being constructed at the Large Hadron Collider (LHC) at CERN for the purpose of exploring new physics in proton-proton collisions at 14 TeV. The detector is to be designed, constructed and commissioned in time for the start of the LHC in April 2007. This article summarises the current status of the detector and foreseen program for completion.

1 Introduction

The Compact Muon Solenoid (CMS) detector is being constructed at the Large Hadron Collider (LHC) at CERN for the purpose of exploring new physics in the highest energy collisions ever achieved at an accelerator. The particle decay products from the 14 TeV proton-proton collision will be studied for evidence of Higgs boson production, supersymmetric particles, black holes and quark gluon plasmas (from heavy ion collisions) as well as numerous interesting Standard Model studies such as the physics of the top quark and m_W . The intense background radiation and very high rate of events resulting from bunch crossings every 25 nanoseconds and overlapping events impose many demanding constraints on the detector. To fulfil the physics and tolerance requirements, the detector employs a variety of technological solutions within its 12500 tons. The target completion date for the detector is set by the foreseen April 2007 turn-on date for the LHC. This article summarises the progress to date that the CMS collaboration (which consists of nearly 2000 scientists from over 35 nations) has made towards achieving this goal.

1.1 Infrastructure

The CMS detector will be located at access point 5 on the 27 km LHC ring near Cessy, France. At a depth of about 100 m below the surface hall (SX5) is the 26.5 m high and 53 m wide experimental cavern (UXC5) where the detector will ultimately be located on the beam line. So far, the floor and over half of the walls have been concreted. The caverns will be completed by the middle of 2004. The lowering of the major pieces of CMS into UXC5 will occur between the end of May and the end of September 2005.

1.2 Detector Overview

Starting from the innermost systems and going out, the CMS detector (Fig. 1) consists of pixel and strip trackers followed by a lead tungstate electromagnetic calorimeter, a brass hadron calorimeter, a solenoid and finally a resistive plate, drift tube and cathode strip muon system. These systems are now briefly described and their current status and foreseen completion schedule given.

Figure 1: The layout of the CMS detector.

1.3 Coil

The tracking and calorimeter barrel systems are in a uniform 4 Tesla field provided by the 5000 ton solenoid coil [Acquistapace et al.(1997)]. The coil is 13 m long with a free inner diameter of 5.9 m. The magnetic flux is returned by a 1.5 m thick saturated iron yoke which has a mass of 7000 tons. The iron in the yoke also forms part of the muon detector which is discussed in a later section.

1.3.1 Coil Status

As of the writing of this article, all 21 reinforced coil conductor lengths have been successfully produced by Techmeta in Annecy. The winding is 50% complete and the final module delivery is expected in June 2004. The first test of the magnet in the surface hall should occur during the first half of 2005.

Figure 2: The layout of the CMS tracker showing the arrangement of the silicon pixel and silicon strip detectors.

1.4 The Tracker

The need for precise position and momentum measurements in a harsh radiation environment leads to a unique multi-technological solution for the tracker involving silicon pixels and silicon strips. The pixel tracker [Rohe et al.(2003)][Cremaldi(2003)] occupies the innermost volume given by radius(R) ; 20 cm. This is followed by the silicon strip tracker (SST) [Angarano(2003)][Abba for 20 cm ; R ; 110 cm. The layout of the tracker is shown in Fig. 2.

1.4.1 Pixel Tracker

The unambiguous three-dimensional space points provided by the pixel tracker are essential for correct pattern recognition at small radii. The pixel system has layers at 4.3 cm, 7.2 cm and between 10 to 11 cm from the beam axis. The $100 \times 150 \mu\text{m}$ pixels yield spatial resolutions of about 15 microns in the azimuthal (ϕ) and longitudinal (z) directions. The improvement over the typical $35 \mu\text{m}$ expected for the pixel size is accomplished by purposely not compensating for the large Lorentz angle thus leading to significant charge sharing. The pixel barrel detector has an area of 0.8 m^2 and provide three high resolution hits out to a pseudorapidity of $|\eta| = 2.2$. In addition, there are two endcap disks at $|z| = 32.5 \text{ cm}$ and 46.5 cm covering an additional 0.28 m^2 . The total pixel count for the detector is around 50 million pixels. The detector is designed to endure fluences up to $6 \times 10^{14} \text{ neutrons/cm}^2$.

1.4.2 Silicon Strip Tracker

The SST will occupy the radial range 20 to 110 cm and the longitudinal range $|z| < 280 \text{ cm}$, thus covering pseudorapidities out to $|\eta| < 2.5$. It consists of 10 concentric layers of silicon strip detectors (four in an Inner Barrel (TIB) and six in an Outer Barrel (TOB)). The strips are oriented along the beam axis for measurement of the azimuthal coordinates for the “single-sided” modules. The two innermost TIB and TOB layers are equipped with “double-sided” detector modules with one side having strips at a stereo angle of 100 mrad with respect to the longitudinal strips for providing measurement of the longitudinal coordinate as well. The TIB is complemented by three inner disks (TID) on either side. Nine End-Cap (TEC) disks are located between $|z|=120\text{--}280 \text{ cm}$. All endcap layers have strips oriented radially to allow measurement of the ϕ coordinate. In addition, “double-sided” layers at the inner and outer radii of the end-cap disks permit measurements of the radial coordinate. The full SST has roughly 10 million channels distributed over an active surface of approximately 200 m^2 .

1.4.3 Tracker Status

The pixel system is currently testing its first prototype modules. For the SST, all final contracts for module parts are active. Module production and validation has started. A prototype of the front-end driver has been designed. Much of the mechanical structures have been procured. The tracker inner barrel is foreseen to arrive and be tested at CERN by April 2005. The tracker outer barrel is expected to be completed by this time. The tracker endcap is expected to be tested at CERN in October 2005. These dates for the SST include a contingency of two months.

1.5 Electromagnetic Calorimeter

The electromagnetic calorimetry is located just outside the tracker. It includes a crystal calorimeter and a preshower detector.

The electromagnetic calorimeter (ECAL) is composed of 75000 lead tungstate (PbWO_4) crystals (60000 in the barrel, 15000 in the endcaps combined) which have a scintillation spectrum peaking at 440 nm [Gascon-Shotkin(2002)]. These transparent crystals have a density (8.28 g/cm^3) exceeding that of iron. The light from the scintillation produced by relativistic particles passing through the crystals is collected and converted to an analog signal by avalanche photodiodes (APD) in the barrel and vacuum phototriodes (VPT) in the endcaps. A primary reason for the selection of APDs for the readout is that they can provide gain in the presence of the high magnetic field. The radiation environment of up to 30 kGy and $3 \times 10^{14} \text{ N/cm}^2$ in the endcaps leads to the choice of VPTs for the endcaps. After digitization, the data is transferred to the counting room by fibre-optic links. One fibre is used for 25 channels (a trigger tower). This represents a change to the original design where one fibre per channel was envisioned. Each trigger tower consists of a motherboard for the distribution of the low voltage to the very front-end (VFE) cards, five VFE cards each containing the amplifiers and ADCs for five channels, front-end cards (for distributing the clock and control, collecting and shipping the data and calculating and shipping the trigger primitives), and a low voltage regulator board. The overall low voltage current that is used by the front-end electronics is estimated to be approximately 50000 Amps.

The barrel covers $|\eta| \leq 1.48$ and the endcaps cover $1.48 < |\eta| \leq 3.00$. The ECAL barrel uses trapezoidal crystals. The front face of these crystals is $22 \times 22 \text{ mm}^2$ corresponding to the Molire radius. In ϕ , the angular coverage of each crystal corresponds to 0.0175 radians ($=1^\circ$), and in η the coverage is 0.0175. They have a length of 23 cm equivalent to a thickness of 25.8 radiation lengths. The barrel contains 36 super-modules of 1700 crystals each. In the endcaps, the dimensions of the face ($24.7 \times 24.7 \text{ mm}^2$) remain the same as the pseudorapidity and azimuthal angle vary but the angular coverage increases to $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$ as $|\eta|$ increases. The crystals are 22 cm long. Each endcap contains 2 dees of 3662 crystals each. The crystals are supported by 0.4 mm thick alveolar structures made from carbon-fibre (in the endcaps) and glass fibre (in the barrel). Further details concerning the CMS electromagnetic calorimeter can be found in the design reports [eca(1997)][eca(2002)].

The preshower detector [Tournefier(2001)] is located in front of the ECAL endcaps in the pseudorapidity range $1.65 < \eta < 2.61$ and consists of two lead/silicon detector layers for π/γ separation. Its design was endorsed in March 2003. It will be installed in two steps to allow scheduling flexibility. The support structure will be installed before the beam pipe and the lead planes with electronics will be installed after.

1.5.1 Electromagnetic Calorimeter status

Figure 3: The first of two CMS ECAL supermodules beam tested during fall 2003.

For the summer 2003 test beam, two super-modules were tested. All aspects of the system were verified including the crystals plus APDs, new front-end boards, low voltage regulation and optical control and readout. The first super-module (SM0 - Fig. 3), tested in September, contained 100 channels of FPPAs (the original version of the floating point pre-amplifiers) but with the new architecture for the rest of the system. The second supermodule (SM1) used the complete new architecture including 50 channels of $0.25 \mu\text{m}$ Multi-Gain Pre-Amplifiers (MGPA's).

The successful test of the supermodules using beam demonstrated the functionality of the electronics and cooling and noise levels within acceptable limits. Some minor design changes are currently being implemented and a new set of full system tests will occur in summer 2004 including supermodules with all 1700 channels active.

About 32% of the crystals have been delivered. A production rate of 3800 crystals per quarter is expected in 2004. The alveolas should be completed by the end of 2003. The APD production and screening should reach completion by April 2004.

1.6 The Hadron Calorimeter

To identify and measure the energy of particles (primarily hadrons and muons) that are not stopped in or before the ECAL, a brass calorimeter is used. This hadron calorimeter (HCAL) [hca(1997)] consists of a barrel section covering $|\eta| < 1.3$ and $r=1.81$ to 2.95 m and endcaps which cover $1.3 < |\eta| < 3.0$. The barrel is 79 cm deep, which at $\eta=0$ corresponds to 5.15 absorption lengths in thickness. It has two half barrels of 18 calorimeter "wedges". Each is 4.3 meters long in z and weighs 25.7 metric tonnes. The brass plates are interleaved with plastic scintillator embedded with wavelength shifting optical fibres.

The endcap has 10 interaction lengths (19 active layers). The brass absorber sampling thickness is 8 cm and the front and back plates are made of stainless steel to increase strength. The absorber plates are bolted together to form a single monolithic structure, with gaps for scintillator insertion.

In the region $|\eta| < 3.0$ the first muon absorber layer is instrumented with scintillator tiles to form an Outer Hadron Calorimeter (HO).

To improve the hermeticity, the region $3.0 < |\eta| < 5.0$ is instrumented with a quartz fibre calorimeter.

1.6.1 Hadron Calorimeter status

The HB (Fig. 4) and HE structures are complete. The mechanics and optical links for all sectors has been completed. The installation and burn-in of the readout boxes for the HB will occur during 2004.

Figure 4: A photo of the completed CMS hadron barrel structure.

2 Muon Detector

The muon system consists of the iron flux return yoke of the magnet instrumented with detectors for triggering and position measurements. In the barrel, four layers of Resistive Plate Chambers (RPC) and Drift Tubes (DT) are used in the gaps between the iron layers. The RPCs provide good timing for the trigger and drift tubes provide accurate position measurements. The endcap has four layers of RPCs combined with four stations of Cathode Strip Chambers (CSCs) each containing six layers for the position measurements and main trigger. The full muon system covers $|\eta| < 2.4$, and provides three to four track segments along a muon track. The depth will be at least

Figure 5: The layout of one quarter the muon detector showing the position of the Drift Tubes, Resistive Plate Chambers (RPCs), and Cathode Strip Chambers (CSCs).

16 radiation lengths down to $|\eta|=2.4$ [Giacomelli(2002)]. The expected global momentum resolution is 1% to 4% depending on p_t . A schematic of the muon detector showing the locations of the DT, CSC and RPC chambers is shown in Fig. 5. Details concerning the muon system can be found in the design report[muo(1997)].

2.0.2 Muon Detector status

For the RPCs, as of September 2003, a total of 114 chambers have been assembled and 74 installed. As of December 2003, of the 186 drift tube chambers needed for the barrel, 128 have been built, and 99 have been tested. For the CSCs, as of September 2003, 439 of the 482 chambers have been assembled. Of these, 223 have been assembled with electronics and tested. There were 125 chambers at CERN and 105 of them ready for installation. At that time, 90 chambers had already been installed.

2.1 Level-1 Trigger

Given the short period between beam crossings and the high backgrounds, the task of the Level-1 Trigger [Dasu et al.(2000)] becomes very difficult. The trigger must reduce the event rate from 40 MHz to a maximum of 100 kHz while retaining a very high efficiency for potentially interesting physics events.

To date, prototypes of the level-1 trigger have been manufactured and final validation tests have been completed. Test are ongoing on the integration of the trigger with the detector and DAQ.

In 2004, further tests involving integration and using a structured LHC-like beam will be performed. All systems will enter the production phase.

3 Summary

The CMS detector design and construction is on target for completion before the commissioning of the LHC. However, the schedule is very tight for several systems. The yokes are finished as well as the assembly of the HCAL. The foreseen completion dates for the other subsystems are as follows. The muon barrel should be completed by summer 2004 followed by the tracker at the end of 2005 and finally the ECAL barrel in spring 2006 and the ECAL endcaps at the end of 2006. To insure completion by the required date and to respond to budgetary pressures, new techniques for detector preparation (such as the ECAL crystal cutting) and new technological solutions such as the $0.25 \mu\text{m}$ ASICs are being implemented. Successful prototype test runs indicate that production mode will be starting in the near term for those systems that have not already started. CMS will be ready for circulating beams by 1 April 2007.

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