Status of CMS

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Abstract.

The status of the construction of the Compact Muon Solenoid (CMS), a multi-purpose detector due to operate at the Large Hadron Collider, is briefly discussed. Details are given on the recent steps forward in the construction of the Silicon Strip Tracker, the Electromagnetic Calorimeter and the superconducting magnet. The rôle of CMS as a tool for b physics is briefly outlined.

Presented at the 10th International Conference on B-Physics at Hadron Machines-Beauty 2005, Assisi (Perugia), Italy June 20-24, 2005
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Abstract. The status of the construction of the Compact Muon Solenoid (CMS), a multi-purpose detector due to operate at the Large Hadron Collider, is briefly discussed. Details are given on the recent steps forward in the construction of the Silicon Strip Tracker, the Electromagnetic Calorimeter and the superconducting magnet. The role of CMS as a tool for b physics is briefly outlined.

1. The Large Hadron Collider and CMS

The second half of 2007 will see the birth of the Large Hadron Collider (LHC) at CERN. The LHC is presently being constructed in the already-existing 27 km LEP tunnel. It will provide head-on collisions of two proton beams of 7 TeV each, with a design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. The LHC proton bunches are spaced 25 ns, yielding a collision rate of 40 MHz. Only a very low luminosity pilot run is foreseen to take place in 2007, followed by at least two years of increasing luminosity, before reaching the designed target of 100 fb$^{-1}$ per year.

The LHC will house four main experiments: two multi-purpose detectors (ATLAS and CMS), one experiment specifically dedicated to b physics (LHCb) and one experiment optimized for heavy-ion collisions (ALICE). A fifth experiment (TOTEM), devoted to the study of diffractive physics, will be located on both sides of CMS. The aim of multi-purpose detectors, such as ATLAS and CMS, is the search for the Higgs boson and for physics beyond the Standard Model; nevertheless b physics will be a very interesting by product.

The large cross sections, at proton-proton centre-of-mass energy of 14 TeV, and the high LHC luminosity provide huge rates and a challenging environment for LHC multi-purpose experiments. As an example relevant for this conference, \(b\bar{b}\) pairs are produced with a rate of \(10^6\) Hz at design luminosity, implying that only a small fraction of \(b\bar{b}\) events, following very tight trigger criteria, can be kept on tape. As a matter of fact \(b\bar{b}\) production is an important background for many searches and only a limited amount of the trigger budget can be dedicated to b physics. Particularly interesting, in this respect, is the initial, low luminosity, phase.

In the severe LHC environment, tight constraints are set on multi-purpose detectors. Fast response is very relevant, with important implications on the readout electronics. Because of the high occupancy (at design luminosity, 20 soft reactions between proton constituents are superimposed on average to the process under study), high granularity is required, with a corresponding large number of electronic channels. The high flux of particles from proton-proton collisions results in a high-radiation environment, placing constraints on detector radiation-hardness.

The CMS detector (Fig.1) complies with these requirements while maintaining the necessary performance to exploit the physics potential of LHC. The apparatus is composed by several subsystems arranged in a cylindrical onion-like structure. The main features characterizing its design are

- a powerful tracker with layers of pixel sensors, followed by layers of silicon-strip sensors;
- a compact, granular and high-energy-resolution electromagnetic calorimeter, followed by a hadron calorimeter;
- a superconducting solenoid with high magnetic field (4 T) surrounding both calorimeters;
- a complex, hermetic and redundant muon system.
Figure 1. Schematic layout of the CMS experiment.

The detector has an overall length of 24 m and a diameter of 14.6 m, with a total weight of approximately 14500 tons. It consists of a barrel and two endcaps, covering a pseudorapidity range of $|\eta| \leq 1.5$ and $1.1 \leq |\eta| \leq 3.0$, respectively. Very forward calorimeters extend the pseudorapidity coverage down to about $|\eta| \approx 5$. An even higher forward coverage is obtained with other dedicated calorimeters and with TOTEM.

The CMS experiment is located at LHC point 5, close to the French village of Cessy. It is currently being assembled in a surface hall, close to the shaft leading to its final location, a cavern about 100 m underground. The civil engineering is essentially completed and the underground cavern has been delivered to the CMS Collaboration in February 2005.

In the following sections the status of the construction of the main CMS components is reviewed. The main features of the trigger and data-acquisition system, particularly for what concerns b physics, are discussed afterwards.

2. The CMS Tracker

The CMS Tracker is designed to measure with high precision the coordinates of charged particles along their path in the detector. It occupies a cylindrical volume of 2.4 m diameter and 5.4 m length and it consists of two subsystems: a silicon pixel detector in the innermost region surrounded by a silicon strip tracker (SST). The tracker covers the pseudorapidity range of $|\eta| \leq 2.5$.

The pixel detector is made of three barrel layers located approximately at 4 cm, 7 cm and 11 cm radius. The pixel polar-angle coverage is extended by two disk-shaped forward pixel detectors consisting of a pair of layers each. In total there are 66 million pixels, with cell size of 100 $\mu$m X 150 $\mu$m, yielding a resolution of 15 $\mu$m using analog readout. The pixel readout comprises 16000 chips, made with 0.25 $\mu$m CMOS technology. The chips are bump-bonded to
the silicon sensors. About 10% barrel-pixel sensors have been delivered (April 2005), last delivery is expected by May 2006. The first delivery of forward-pixel sensors is expected for September 2005. The pixel detector will operate in a hostile high-radiation environment because of its closeness to the interaction point. The replacement of the pixel layers after a few years of operation is foreseen. For safety reasons the CMS pixel detector will not be installed during the LHC pilot run (2007), its commissioning is foreseen for the first LHC physics run (2008).

The silicon strip detector consists of more than 200 m² of silicon sensors, built as p+ type strips implanted on a n-type bulk. The aluminum readout strips are coupled to analog readout chips by means of capacitive coupling. The readout chips (APV25) are built in radiation-hard 0.25 µm CMOS technology and they are hosted, together with control chips, on a multilayer ceramic substrate (Front End hybrid). Each APV25 has 128 channels consisting of charge sensitive amplifiers, shapers and a 192 bunch-crossing-deep analogue-pipeline memory. The silicon strips are bonded to the FE hybrid through a glass-aluminum pitch adaptor, forming a SST module. The silicon strip tracker has a total of 9'648'128 electronics channels.

The SST modules are arranged in four inner barrel layers assembled in shells (TIB), two inner endcaps each composed of three small disks (TID), six outer barrel layers (TOB) and two large endcaps mounted in seven rings on nine disks per each side (TEC). The inner modules (TIB, TID and the four innermost TEC rings) consist of single silicon sensors of 320 µm thickness, while the outer modules are 500 µm thick and host two daisy-chained silicon sensors. The first two layers in TIB and TOB, the first two rings in TID and TEC and the fifth TEC ring are instrumented with double-sided stereo modules. These modules consist of two single-sided sensors mounted back-to-back, with one of the sensors tilted by 100 mrad with respect to the other. The SST modules are supported by a carbon-fibre mechanical structure.

To protect the silicon detectors from the harsh radiation environment, avoiding the effect of reverse annealing, the complete tracking volume will stay at a temperature of -10°C. Insulation will be provided by a thermal screen surrounding the tracker and a cooling system will extract the heat dissipated by the front-end electronics (60 kW).

The SST is on advanced stage of construction. All mechanical structures are ready and about 90% of the 24'328 silicon sensors have been delivered (June 2005). A quarter of the required modules have been assembled, the others will be completed by the end of 2005. Integration activities on complete shells have started (Fig. 2). The tracker support tube and thermal screen is ready and has been successfully cooled (June 2005).

3. The CMS Calorimeters

The CMS calorimeter system is made of a crystal-based electromagnetic calorimeter (ECAL), followed by a sampling hadron calorimeter (HCAL). Both calorimeters are inside the superconducting coil.

The electromagnetic calorimeter consists of 75'848 lead-tungstate (PbWO₄) crystals. The choice of lead-tungstate is motivated by the very small radiation length (0.89 cm) and by the fast response (95% of light emitted in 25 ns). These properties, combined with a small Moliere radius (2.19 cm) allow the construction of a compact, highly granular and fast calorimeter.

In the ECAL barrel the crystals are mechanically organized into modules (6 X 2 crystals) and supermodules (12 X 4 modules). The modules inside a supermodule are tilted by 3° such that the crystals do not point to the interaction vertex, reducing the effect of gaps. In the ECAL endcaps the crystals are organized in 6 X 6 supercrystals arrays. A preshower, with three-radiation-length thickness, is placed in front of each endcap. It is made of two parallel planes of silicon strip detectors interleaved by a lead radiator. The preshower is needed to separate the two photons from Z⁰ decays in the endcap rapidity region.

Lead-tungstate crystals show high radiation tolerance because the scintillation mechanism is intrinsically radiation hard. Nevertheless temporary
radiation damage occurs, because the creation of colour centres reduces the crystal transparency. The latter must be monitored by means of a laser system.

The relatively low light output of lead-tungstate crystals, the requirement of compactness and the presence of a strong magnetic field put tight constraints on the readout system. Silicon avalanche photodiodes (APD) have been selected for the light readout in the barrel, while vacuum phototriodes (VPT) are used for the endcaps. The different readout technique in the endcaps is motivated by the higher radiation environment. The APD working principle is similar to that of conventional silicon photodiodes, with an additional p-n junction reverse-biased providing high electric field and signal amplification (between 50 and 200). The VPTs operate similarly to conventional photomultipliers, with an electrode configuration suitable for high magnetic field.

At present (June 2005) 37'300 barrel crystals have been delivered and 18 (out of 36) bare barrel supermodules have been assembled. All 130000 APDs have been delivered and 70% of the 11000 VPTs are available.

In October 2004 the first fully dressed ECAL supermodule has been tested with high energy electrons. Its energy resolution is consistent with expectations, i.e.,

\[ \frac{\sigma(E)}{E} = \frac{3\%}{\sqrt{E}} + \frac{150\text{ MeV}}{E} + 0.40\% \]

where \(E\) is given in GeV.

The crystal delivery limits the speed of the ECAL construction. The entire ECAL barrel will be ready for the LHC pilot run (2007), while the ECAL endcaps will be installed in 2008, in time for the first LHC physics run.

The HCAL is composed by five parts: a barrel (HB) and two endcaps (HE) calorimeters placed inside the coil and two forward (HF) calorimeters installed outside the muon system to cover the high rapidity region. The barrel shower containment is enhanced by two layers of scintillator tiles located on either side of the first layer of return yoke, acting as absorber (HO). The HB and HE are made of brass plates interleaved with plastic scintillator embedded with wavelength-shifting optical fibers. The choice of brass is due to the relatively low Z, minimizing the muon multiple scattering, and to its non-ferromagnetic nature. The HF is made of steel wedges stuffed with quartz fibres, chosen because of their good radiation tolerance.

The HCAL barrel and endcaps are ready for installation and the HF is essentially completed.

3. The CMS magnet system.

The CMS superconducting coil is a solenoid of 6 m inner diameter and 12.5 m length. It provides a 4 T magnetic field allowing the measurement of the momentum of 1 TeV muons with 10% resolution. Its conductor consists of Niobium-Titanium wrapped with copper, cooled at liquid Helium temperature. The operating current is 20 kA, monitored with a precision of 10^-6. The coil will store 2.7 GJ in its magnetic field; several safety elements are provided for secure removal of the stored energy. Because of the large coil size, a modular design was required. Five modules were built and assembled vertically. The cold mass was ready in March 2005. The assembled coil is going to be swiveled to its horizontal position (August 2005) and inserted into the yoke. Figure 3 shows the coil in vertical position.

![Figure 3. The CMS superconducting solenoid in vertical position.](image)

4. The CMS muon system.

The muon system consists of three different types of muon chambers: drift tubes (DT) in the barrel, cathode strip chambers (CSC) in the endcaps and resistive plate chambers (RPC) in both barrel and endcaps. Four layers (stations) of DT/RPC and CSC/RPC chambers are installed into the iron return
yoke, for a total of 16 radiation lengths before the last muon station. A magnetic field of about 2 Tesla is present in the muon system. The DTs are made of layers of tubes with wires, each layer staggered by half tube. The CSCs are multiwire proportional chambers, with cathode planes segmented into strips and perpendicular anode wires. The RPCs consist of two parallel resin plates, with high resistivity, separated by a gas-filled gap. The muon track segments are reconstructed from the DT and CSC signals in order to precisely measure the muon transverse momentum and charge. The RPCs provide a fast response for the trigger. Useful information for the trigger is also available from the DTs and CSCs, with coarser measurements [1].

5. Trigger and Data Acquisition.

As already mentioned, the LHC delivers proton-proton collisions at 40 MHz, with approximately 20 interactions superimposed at every bunch-crossing at high luminosity. The amount of information produced by CMS corresponds to about 1 Mb of zero-suppressed data every 25 ns, requiring a trigger reduction of five orders of magnitudes. In CMS this reduction is achieved by a two-level trigger system. The level-1 (L1) trigger selection is accomplished with a custom-designed electronic system based on FPGA (Field Programmable Gate Arrays) and ASIC technology. It is designed to reduce the event rate to 100 kHz by means of a pipelined system with latency time of 3.2 µs. The L1 trigger is composed by a Calorimeter Trigger (collecting information from ECAL and HCAL) and a Muon Trigger (collecting information from the RPC, DT and CSC), combined in a Global Trigger. The level 1 trigger tables are focused on the detection of high energy electrons, muons and taus, on the presence of large jet transverse energy and of large missing energy. The L1-accepted events are transferred to a computer farm based on commercial processors and performing as High-Level Trigger (HLT). The HLT complete the filtering in a fully software way, by running fast versions of offline-reconstruction algorithms. A reduction rate of three orders of magnitudes by the HLT is foreseen, delivering events to the offline reconstruction at a rate of 100 Hz. The HLT latency time is 1 s, this long latency time is achieved thanks to a large number of processors (about 1000).

6. CMS and B-physics

Most of the CMS trigger bandwidth is allocated to cover the widest possible kind of discoveries. Only a small fraction of the bandwidth, typically 5 Hz, is foreseen for b physics and the trigger criteria are focused on the most interesting exclusive channels. Sophisticated reconstruction algorithms, using the tracker information and combining several detectors, can be employed at HLT level. The events need, however, to be L1-accepted and the most interesting L1 streams for b physics are based on the detection of inclusive single muons and di-muons. The momentum thresholds during the initial low-luminosity period should be low enough to make the first LHC phase interesting for b physics.

The HLT strategy is to select b±events where one of the b quarks semileptonically decay to a muon (giving the L1-accept) and the other b quark decays, after hadronization, to interesting channels such as B± → Dπ or B± → J/ψ ϕ [2]. The exclusive B± decays are reconstructed by the HLT algorithms in a region of interest around the muon responsible for the L1 trigger. A special case is the decay B± → μ+ μ−. The low threshold of the L1 di-muon trigger (3 GeV at low luminosity) allows the direct selection of these rare B± decays with good efficiency [3], making CMS particularly competitive in this channel.

As a final comment it should be reminded that b-jet tagging is an important tool to enhance the CMS potential for new physics, for top physics and for the Higgs boson discovery [4]. B-tagging algorithms based on impact parameter measurement and on secondary vertices reconstruction have been implemented in the CMS reconstruction software [5].

Acknowledgements. I wish to thank Patrick Janot, Guido Tonelli and Jim Virdee for their help in preparing this report.

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