# THE COMPACT MUON SOLENOID (CMS) EXPERIMENT: THE LHC FOR HIGH ENERGY AND LUMINOSITY

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*Abstract*

CMS is one of the two high luminosity and high energy experiments at the LHC. It will be largely assembled and tested on the surface before being lowered into a specially-constructed cavern at Point 5 of the LHC. A brief description of the experimental area and of the detector construction and assembly status will be given and some specific interface issues with the LHC machine will be elaborated.

## INTRODUCTION

The CMS Collaboration is constructing a general-purpose proton-proton detector, which is designed to exploit the full discovery potential of the LHC machine. The experiment will be operational at the start-up of the LHC and will be able to investigate the physics accessible during the initial lower luminosity running as well as handling the highest luminosity that will be available later from the machine.

The primary aim of the experiment is to discover the Higgs boson and to search for other new particles predicted in theories beyond the Standard Model such as supersymmetry, or SUSY for short. In the framework of the Standard Model, particles acquire mass through their interaction with the Higgs field. This implies the existence of a new particle – the Higgs boson $H^0$. In extensions to the Standard Model such as the Minimal Supersymmetric Standard Model (MSSM) there are 5 Higgs bosons – $h^0$, $H^0$, $A^0$ and $H^\pm$. CMS has been optimised to discover the Higgs bosons in the complete expected mass range. SUSY also predicts that for every known particle there is a `sparticle' partner equal in charge but differing in spin. Production of `sparticles' will reveal itself through spectacular kinematical spectra even at low operating luminosities.

Moreover, the CMS experiment will be able to study the products from colliding beams of heavy nuclei such as lead. Collisions between these nuclei will produce `little bangs' at an equivalent temperature around 100,000 times that at the centre of the Sun, and a density up to 20 times that of normal matter. Under these extreme conditions, which mimic those in the period less than 1 second after the Big Bang, the constituent protons, neutrons and gluons `melt' to form a `Quark-Gluon Plasma' (QGP). CMS is well-suited to study some aspects of the formation of the QGP.

## THE POINT 5 EXPERIMENTAL AREA

The CMS detector will be hosted at the LHC Point 5 experimental area located at Cessy in France. The surface area is dominated by the SX5 main assembly hall. Other buildings to be used for gas, primary cryogenics, cooling, ventilation and the CMS control room will also be provided. The underground areas include the experimental cavern UXC55, the auxiliary service cavern USC55, the access pits PX56, PM54 and PM56 and the LHC machine by-pass tunnel.

Civil engineering works at Point 5 have been advancing well. Most of the surface buildings have already been handed over to CMS and excavation of the two underground caverns has been completed. Concreting of the floors is well-advanced in both caverns.

However, although the cavern crowns have been strengthened, water leaks have now appeared in both the PX56 and PM54 access shafts. Repair work must be carried out, and the extra time required to do this is under evaluation. Delays must be mitigated, particularly for the USC55 cavern since outfitting this cavern is on the critical path for operation in April 2007. Outfitting the USC55 service cavern is critical due to the short time available to install and commission the Trigger and DAQ system.

An agreed management structure for the Point 5 experimental area has been put in place, whereby the newly-formed EST-IC group provides the general management of Point 5 and CMS, together with the EST-LEA group manage, well-defined zones within this experimental area.

Sharing of the experimental area between CMS and the LHC Machine has also been agreed. Space for power supplies and control racks for LHC machine components such as the DFBX and vacuum equipment has been reserved in the USC55 cavern and the detailed lay-out of this zone is being worked-out. The PM54 shaft is a shared access for CMS and the LHC Machine and the PM56 shaft is to be made available to CMS as an emergency exit for personnel. The by-pass tunnel is reserved for the passage of LHC machine components. The Point 5 underground experimental area is shown in Figure 1.

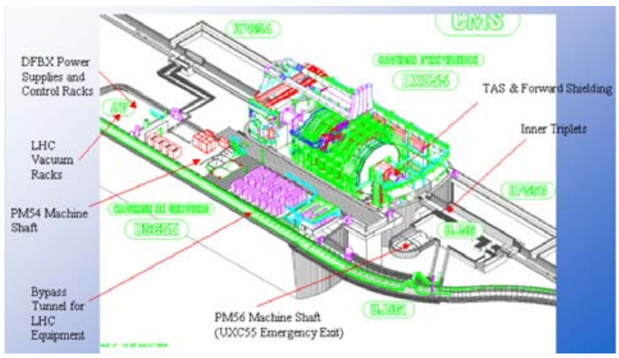


Figure 1: The Point 5 Underground Experimental Area.

# THE CMS DETECTOR

Central to the design of CMS is the superconducting solenoid magnet. The solenoid will be 6 m. in diameter and 13 m. long. It will generate a field of 4 T, meaning that the stored energy will be 2.5 GJ.

A particle emerging from the collision point and travelling outwards will first encounter the Tracking system – consisting of the Pixel and Silicon Strip Tracker detectors. They will measure precisely the positions of passing particles allowing the particle track to be reconstructed. Charged particles will follow spiralling paths in the CMS magnetic field and the curvature of their paths will reveal their momenta. The energies of the particles will be measured in the calorimeters forming the next layers of the detector. The electromagnetic calorimeter (ECAL) is designed to measure the energies of electrons and photons. Hadrons deposit most of their energy in the next layer, the hadron calorimeter (HCAL). The only particles to penetrate beyond the HCAL are the muons and neutrinos. Muons will be tracked in dedicated muon chamber detectors – the drift tube (DT) and cathode-strip detector (CSC) - and their momenta will be measured from the bending of their paths in the CMS magnetic field. Dedicated muon chambers – resistive plate chambers (RPCs) – will provide the time and position of a muon hit with the accuracy required for trigger purposes. Since neutrinos are neutral and hardly interact with matter, their presence will be inferred by the `missing momentum' when adding up the momenta of the detected particles. Figure 2 shows the CMS detector.

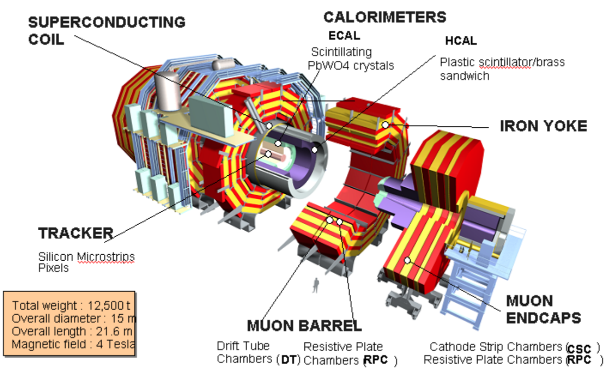


Figure 2: The CMS Detector.

CMS has been engineered from the beginning to ease installation, access and maintenance. Dividing the barrel yoke of the magnet in 5 ring-sections and the end-cap yoke in 3 disks allows all sub-detectors to be maintainable by opening CMS in large sections to provide a nominal maximum opening of 10 m. Movement of the sections is possible without de-cabling attached sub-detectors and without breaking the chain of services. Each major yoke section is supported on horizontal grease pads for movements of up to 300 mm. and can be moved on air pads up to 10 m. The added benefit of the grease pads is that CMS can be easily realigned around the beampipe to within ± 50 mm in all directions.

While waiting for the underground caverns to be completed, CMS is being assembled and tested in the SX5 surface hall. This provides the advantage of minimising the underground assembly operations while at the same time allowing CMS to rehearse the risky operations on the surface and to cope with the unplanned spread of the sub-detector delivery.

Once the underground hall will be available and following the surface magnet tests in mid-2005, all heavy elements of the detector will be slid over the SX5 building floor using high-pressure air pads to the top of the mobile radiation shielding plug above the PX56 shaft. This plug, which will be constructed starting at the end of 2003, will consist of a 2 m.-thick concrete structure and has been designed to support the 2000 t. weight of the central section of the magnet. A rented gantry crane will be installed over the SX5 building to lift and transfer the heavy pieces of the CMS detector to the underground area.

The requirements for transport, handling, access and temporary storage space, particularly for the installation phase, needs careful attention and together with the needs of the other experiments and the LHC machine is being followed in the LHC Experiment Installation Reviews.

The majority of the CMS detector sub-systems are well in the construction phase. All five barrel rings and the six end-cap disks of the magnet yoke have been assembled at SX5. Production of the conductor is progressing. All 21 lengths, each with a length of 2650 m., of the Rutherford cable and the insert have been produced and the four remaining lengths to be reinforced will be completed by July 2003. The winding operation has turned out to be faster than expected and the critical path now goes through the manufacture of the mandrels, which show a delay of 4 months with respect to the baseline CMS Master Schedule (Version 33). The estimated delay can be reduced by speeding up production of the coil and by limiting the underground test of the magnet to a functional testing of the cool-down, electrical and leak properties of the cold magnet. The proximity and external cryogenics should be available in time for the 4-month magnet tests on the surface starting in March 2005.

Construction of the Silicon Strip Tracker is underway. The first sensors from the series production have been received and all elements to start the module series production are in hand except for the front-end hybrid electronics, whose procurement has been delayed due to problems with the mechanical properties of the first prototypes. Good progress has been made on the Pixel electronics and sensors.

Production of supermodules for the ECAL is advancing. Although more than 15000 out of the 62000 of the Barrel ECAL crystals have been delivered, their continued delivery is now on the critical path due to earlier delays. In an effort to mitigate the delays, CMS is introducing a procedure to increase the production capacity by making four crystals per *boule* instead of the present two. The order for the end-cap ECAL crystals must be placed by the end of 2003 in order not to affect the schedule for completing the ECAL by April 2007. The ECAL electronics is undergoing a major revision primarily to contain costs. CMS expects to choose the final front-end electronics in the summer 2003 following a series of system tests.

The HCAL Barrel calorimeter has been assembled in the SX5 building and the onboard electronics will be installed by Q2 2004. Following actions to correct the perpendicularity of one of the HCAL End-cap calorimeters, the detector has now been remounted on its end-cap yoke disk in the SX5 building while the second HCAL End-cap calorimeter will be mounted in the summer of 2003.

Most of the CSC modules have been produced and their installation on to the end-cap disks is scheduled to commence in mid-June 2003. The DT chambers are being produced at the required rate and their installation is scheduled to commence in Q4 2003. Studies of Barrel RPC detectors are ongoing in beam and no sign of degradation has been observed while production of the gaps is continuing. An RPC End-cap gap factory has been set up and the first gaps are scheduled to be produced as of mid-2003.

CMS aims to complete the initial detector for first LHC operation in April 2007. The staged components, ME4 muon end-cap chamber, RE RPC end-cap system at $|\eta|>1.6$, and 50% of DAQ, will be installed for the high luminosity running. The proposed staging plan is aimed at minimising the adverse effect on the Higgs and SUSY sensitivity at luminosities of $\sim 10^{33}$ $cm^{-2}$ $s^{-1}$. The Pixel detector will be ready but will not be installed for the machine commissioning and pilot runs. Its installation, during a 3-month shutdown period in the summer of 2007, will be in time for the physics run starting in August 2007. The Silicon Strip Tracker schedule is considered to be tight but the aim is to keep any net delay within the shadow of the delay of the coil, and the ECAL schedule is challenging but it is realistic to have the complete ECAL installed by April 2007.

## THE CMS – LHC MACHINE INTERFACE

An Engineering Design Review for the CMS (and TOTEM) experimental beampipe in April 2002 approved the configuration of the region ±11 m. around the interaction point (IP). The call for tender for the Be central section was launched thereafter leading to the signing of the contract for the procurement of this section. The stainless steel material for the large cones has been ordered and awaits delivery to CERN. Installation of the experimental beampipe in CMS (and TOTEM) is scheduled for the period August to November 2006.

The lay-out of forward region beyond ±11 m. from the IP has been agreed to within the CMS and TOTEM collaborations. The region has been designed to host potentially the newly-proposed CASTOR calorimeter, whose primary aim is to study heavy-ion collisions but which will also take data in proton-proton mode, and a shortened version of the TOTEM T2 telescope based on silicon technology. The physics requirements for this set-up point to a smaller-diameter beampipe of 55 mm. ∅ between 13 m. $< | z | <$ 18 m. and a significantly enhanced forward radiation shielding due to the possible presence of CASTOR. Such a set-up would allow CASTOR to return regularly for heavy-ion runs throughout the early years of LHC operation and to run up to a luminosity of $\sim 2 \times 10^{33}$ $cm^{-2}$ $s^{-1}$ in proton-proton mode. Various aspects of the proposed lay-out of the experimental beampipe in this forward region, such as the vacuum stability, beam aperture, alignment and activation, are currently being evaluated. The present radiation shielding may still allow the baseline smaller-diameter beampipe to be used for the nominal LHC luminosity of $10^{34}$ $cm^{-2}$ $s^{-1}$ once CASTOR has completed its physics programme and been removed. Should this not be possible, then a beampipe with 400 mm. ∅ and a heavier forward radiation shielding may need to be installed.

The CMS maintenance procedure provides for a minimal interference between the opening of CMS and safeguarding the experimental beampipe. Normally, the beampipe remains in place under clean gas and is covered with a shell for mechanical protection. The beampipe must, however, be opened for the removal of the Tracker. Removal and installation of the Pixel detector requires a special study as it will most likely be an annual operation and it may be necessary to install local temporary shielding around activated components.

The contact doses and those at a typical 50 cm distance from the beampipe allow for about 100 h. of annual handling and access [1]. As the dose decreases by about a factor of 10 towards the end of an annual long shutdown period, the expected more time-consuming operation of re-installation is done in more favourable conditions.

Finally, CMS has requested that the average total pressure inside the vacuum system should be in the range $10^{-8}$ to $10^{-9}$ Torr in order to limit beam-gas interactions which give rise to backgrounds particularly in the Tracker.

The outgoing 14 TeV total energy from the collision region will be shared between components of the CMS detector and the LHC machine, with the latter receiving the bulk of the energy. The Forward Radiation Shielding is being built to a) provide effective shielding along the beamline, b) protect the experimental area against machine-induced background emerging from the LHC tunnel, c) reduce the rates in the CMS outer muon chambers by up to 3 orders of magnitude, d) protect the electronics in the cavern and e) form an integral part of the personnel shielding. The Forward Radiation Shielding, made up of the Cubical Steel Frames, the Fixed Iron Noses and the Rotating Shielding, consists of heavy components made primarily from steel and concrete and is being built at IHEP Protvino. The Cubical Steel Frames are complete while construction of the Fixed Iron Noses is well-underway and the Rotating Shielding is entering its production phase following a recent Engineering Design Review. As a result of the Forward Radiation

Shielding, the radiation level in the UXC55 cavern is about 1 Gy/yr and CMS will be rather insensitive to machine-induced backgrounds such as upstream beam losses [2]. Muons, which remain as the only particles that penetrate the shielding from the machine side, are estimated to arrive at CMS at a rate of < 10 $\mu$ $cm^{-2}$ $s^{-1}$ [2].

The inner triplet quadrupoles, being built at KEK and FNAL to provide the low-$\beta$ needed for the high average luminosities requested by CMS, will extend into the UXC55 experimental hall and will be positioned on a solid concrete platform in order to guarantee a stable foundation. The platform serves as a radiation-shielded alcove for the HF forward hadronic calorimeters and as a support for the Cubical Steel Frames of the Forward Radiation Shielding. They will be installed from the machine tunnel in Q2-Q3 of 2005 and will be surveyed subsequently with respect to the LHC geometry and cavern reference network.

Beam screens in the inner triplets are required to ensure vacuum stability. The baseline lay-out is similar to that for the arcs and consists of the `racetrack' design. The orientation of the beam crossing plane is fixed once such `racetrack' beam screens are installed and the current baseline crossing plane is vertical at Point 1 and horizontal at Point 5. However, the uncertainty and reduced safety margin of the energy deposition in the inner triplet coils may result in a difference of luminosity between ATLAS and CMS as there may be a need to increase $\beta^*$ and/or decrease the crossing angle at the more problematic IP. At luminosities much below nominal, the safety margin is sufficiently large to allow for proper operation. However, for LHC operation at the nominal luminosity and above, CMS requests continued evaluation of alternative schemes, such as the `marguerite'-type racetrack design, as an upgrade option if needed.

## CONCLUSION

CMS expects to be closed and ready for first LHC beam in April 2007 and, following a short shutdown in the summer of 2007, will be ready for the physics run starting in August 2007. Exciting physics is likely to be within reach soon after LHC start-up and a continued common effort between CMS and the LHC machine is needed to ensure the highest data quality for physics.


## ACKNOWLDEGEMENTS

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## REFERENCES


[1] M. Huhtinen, Radiation Safety Officers Committee, December 2002.

[2] M. Huhtinen, private communication.