An overview of the CMS experiment for CERN guides

Preliminary version 0.1, Dave Barney, CMS Outreach Coordinator, 27 November 2003

Purpose of this document

The following is a brief (!) summary of CMS: what it is for, how it is built, what is at the Cessy construction site. It is not meant to be a detailed explanation of everything (that would require a few thousand pages – see the CMS Technical Design Reports!). Hopefully this document will give you a little more *useful* information for when you talk to visitors about CMS. Any additional information you may have, that you find useful for visitors, is more than welcome! Please send me an email at David.Barney@cern.ch and I will try to incorporate it into this document, which will always be available at: http://cmsinfo.cern.ch/Welcome.html/guidesfaq.html

Disclaimer

As things change on an almost daily basis at the CMS construction site in Cessy, it is impossible to be completely up-to-date. More information can be found in the references in section 12.

1 Introduction

The acronym "CMS" stands for: Compact Muon Solenoid. It is always useful to remind visitors of this, emphasising "compact", BEFORE they enter the visitors' gallery! The reasons for this name are:

Compact

Relative to ATLAS, which is ~1.5x the diameter of CMS and 2x as long (but ATLAS is half the weight of CMS!).

Muon

There is a BIG emphasis on muon detectors in CMS. The reason for this is that muons are excellent signatures of interesting physics (they can be easily identified and, contrary to electrons and mesons etc., can essentially only come from the decay of a heavy (=possibly interesting) particle). The large amount of material between the interaction point and the muon chambers acts as an absorber for virtually all other particles: if a muon chamber sees a signal, it is almost certainly due to the passage of a muon. For these reasons the muon chambers contribute strongly to the CMS Trigger system – the system that tries to identify interesting proton-proton interactions from the multitude of non-interesting events!

Solenoid

The basis for most large collider experiments is the choice of the type of magnet (to allow momentum measurements – see section 4.2). CMS has chosen to use a solenoid – essentially a big cylindrical coil of wire that generates a magnetic field down its axis when an electrical current is passed along the wire. More details can be found later in this document, as much of what is presently in the SX5 hall concerns the magnet.

2 Physics Motivation

The Standard Model precisely describes the electroweak and strong interactions. No significant deviations from its predictions have so far been observed. But, there are a number of unexplained issues:

- The SM has ~20 free parameters (e.g. masses of particles) that have to be input by hand

- Why are there only three families of particles?
- Why is the electric charge on an electron an exact integer multiple of the quark electric charge?
- Why do some particles have mass whilst others do not? (Especially the fact that the W and Z particles are extremely massive whilst the photon has no mass at all).
- Does the Higgs particle exist? (The Higgs mechanism is not explained within the SM)

The main goals of the LHC are:
- Search for new particles in the mass range ~50 GeV → ~5 TeV
- Find the Higgs particle or exclude its existence in the region allowed by theory (<~1 TeV)
- Test the theory of Supersymmetry (SUSY) over the LHC energy range and search for SUSY particles
- Look for deviations from the Standard Model

The basic requirements for the LHC accelerator, in order to achieve these goals, are:
- It should be a proton-proton collider (see below)
- The energy of the protons should be as high as possible, within the constraint of having to place the LHC in the existing LEP tunnel; this will maximise the extent of the search for very heavy particles. The proton energy in the LHC is 7 TeV
- The interaction rate needs to be extremely high, as the chances of finding something interesting (e.g. a Higgs particle) are extremely small (due to very small production rates and the large backgrounds expected)

2.1 Why a proton-proton collider?

The main point is that we do not know the masses of the interesting particles that we are looking for (Higgs, SUSY particles….) – indeed we don't even know if they exist! So we need to be able to create collision energies over a wide range, as the collision energy governs the mass of any particles created (together with probability) through Einstein's famous equation $E=mc^2$.
Consider the collision of two protons. We know that in fact the proton is not a fundamental particle – it is essentially composed of 3 quarks. In addition, the proton can contain, at any moment in time, a number of gluons and other quarks. The simplified diagram below shows two protons colliding, with only the "normal" three quarks shown.

The energy of the protons is given by:

$$E_{proton1} = E_{d1} + E_{u1} + E_{u2} + E_{gluons1} + E_{quarks1}$$
$$E_{proton2} = E_{d2} + E_{u3} + E_{u4} + E_{gluons2} + E_{quarks2}$$

We know that the total energy of each proton is 7 TeV. We also know that the real interaction will be between quarks in each proton, or between gluons in each proton. Thus the actual collision energy $E_{collision} = E_{particle1} + E_{particle2}$ could be in the range $0 < E_{collision} < 14$ TeV. Thus with fixed energy protons we can create collisions over the complete range of energy.
If we compare this to the collision energy in an electron-positron collider (e.g. LEP), as shown in the diagram below:

$$E_{collision} = E_{electron} + E_{positron} = \text{constant}$$

This means that we can “tune” the beam energy to create particles of a known mass. To search for unknown particles using an electron-positron collider we would need to scan through the energies by changing the beam energy (indeed this is what was done by LEP in its final year to try to find the Higgs).

3 Detector Requirements

The fact that we don’t know what we will find in LHC collisions means that the detector needs to be ready for anything[1]! It should be noted that we will never really “see” Higgs and/or SUSY particles with a detector at the LHC as they are unstable and decay to lighter particles (except for the lightest supersymmetric particle, which is stable but invisible in our detector) – it is these lighter (stable) particles that we will see.

If we assume the Higgs particle exists we cannot accurately predict its mass. However, we do know, for any given mass, how it will decay. For a light Higgs (<150 GeV) the best chance of detecting its presence is through its decay to two photons – which means that we need to build an excellent electromagnetic calorimeter (ECAL). For heavier Higgs’ there are many decay modes into electrons and muons – again requiring an excellent ECAL but also excellent muon reconstruction. For SUSY events, one of the best signatures is actually “missing” energy in the detector! In SUSY’s simplest form a SUSY particle will decay into lighter SUSY particles, until it reaches a stable state known as “the lightest SUSY particle – LSP”. We have not yet seen this LSP so we know that it must be electrically neutral and also interact with matter in a different way to normal particles – hence if we have them in CMS (or ATLAS) then we will not see them. However, we know the total energy we started with in the collision, so we can sum-up all of the energy in the detector and see if everything balances. If we find an imbalance then this is a good signature for SUSY particles (and neutrinos of course). To do this sum effectively we need to surround the interaction point with detector elements as completely as possible – this means a “hermetic” detector. We also clearly need excellent calorimeters to measure the energy – both electromagnetic and hadronic calorimeters.

Finally, for all types of event we need to reconstruct momenta of charged particles and also find any vertices[2]. This requires an excellent “tracker”. The tracker is also used for particle identification purposes – linking tracks to calorimeter hits for example can enable you to tell the difference between electrons and photons.

The design objectives of CMS are thus:

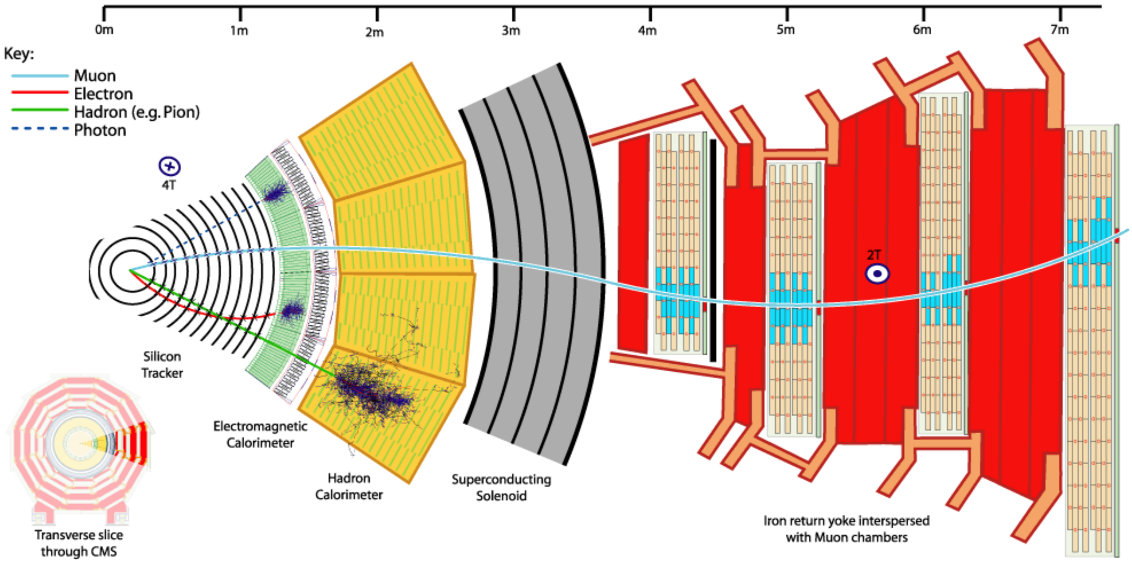
- A very good and redundant (=many layers, so that if one fails we can fall-back on the others) muon system
- The best possible electromagnetic calorimeter
- A high quality central tracking
- A hadron calorimeter with sufficient energy resolution and that is as hermetic as possible

How we achieve these goals is described in the next section.

[1] Of course, the ALICE and LHCb detectors are dedicated experiments looking to address specific issues – so they do know what they are looking for; in this document we only consider the two general purpose detectors – CMS and ATLAS.

[2] The primary vertex is where the protons collided; other vertices can be due to particle decays

4 The CMS Detector



Transverse slice of CMS, showing the different sub-detectors and how different particles interact

There are essentially 6 types of particle that can be observed in CMS, and their detection methods are given in the table below (it is also useful to look at the diagram above):

Particle	**Detection method**
Photon	No signal in tracker; signal in ECAL; no signal in HCAL or muon chambers
Electron/positron	Signal in tracker; signal in ECAL; no signal in HCAL or muon chambers
Charged hadron (e.g. p^+, π^-, K^+…)	Signal in tracker; essentially no signal in ECAL; signal in HCAL; no signal in muon chambers
Neutral hadron (e.g. n…)	No signal in tracker; no signal in ECAL; signal in HCAL; no signal in muon chambers
Muon	Signal in tracker; no signal in ECAL or HCAL; signal in muon chambers
Neutrinos, SUSY particles….	No signal in any sub-detector; presence inferred from missing energy

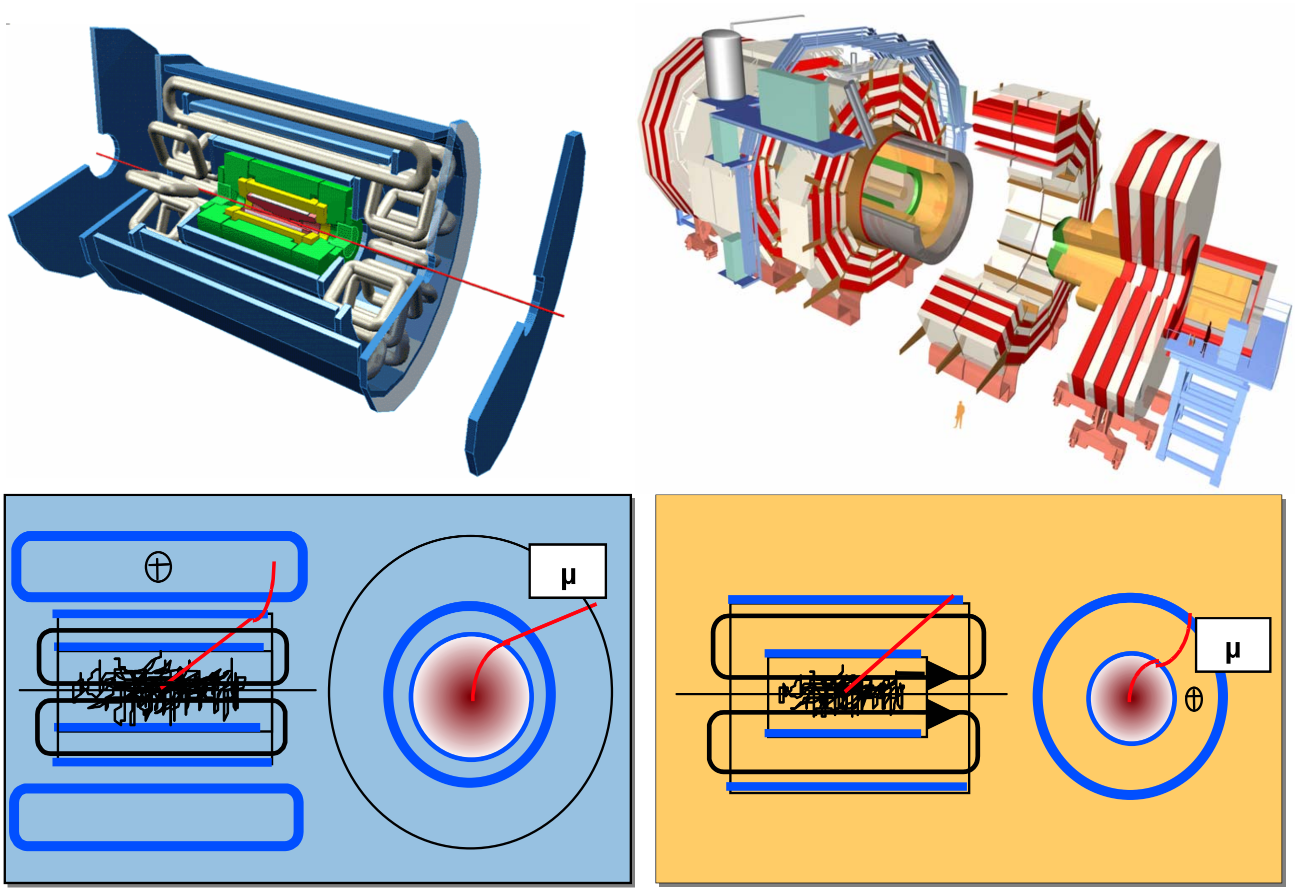
The basic physical parameters of CMS are given in the table below:

Length	21.6 m
Diameter	14 m
Mass	12500 tonnes
Nominal magnetic field	4 Tesla

The following descriptions of the sub-systems of CMS are not extensive, and do not detail the principles of the various detector types as there are many good references for these. One of the best resources is the series of lectures for CERN Summer Students. For example, in 2000 Jim Virdee (CMS Deputy Spokesman) gave the lectures on “Particle Detectors” – they can be found at http://webcast.cern.ch/Projects/WebLectureArchive/ssl/2000. Here we just try to pick-out some interesting points concerning the CMS sub-systems.

4.1 The Magnet System

The overall design of a particle detector depends heavily on the type of magnet system chosen (to deflect electrically charged particles, therefore enabling measurements of charged-particle momenta). A very crucial difference between CMS (right) and ATLAS (left) is the type of magnet system employed – see the diagram below.



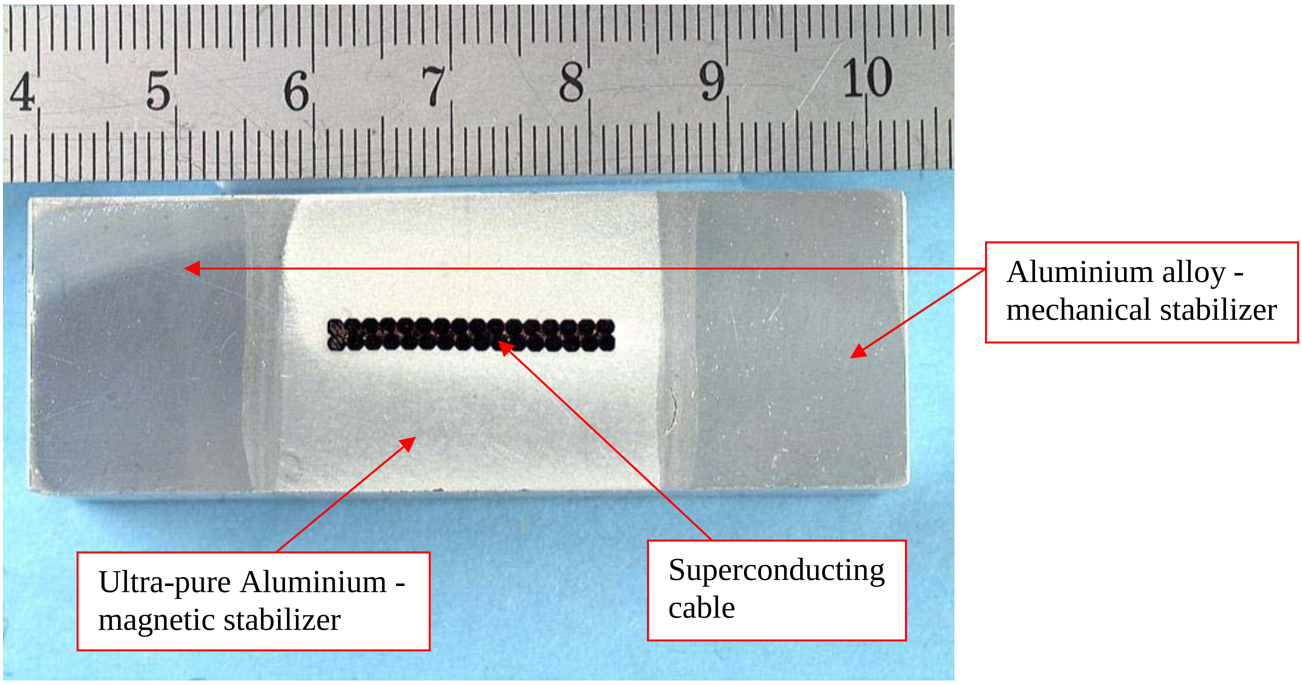
The magnet configurations for ATLAS (left) and CMS (right)

ATLAS has a huge air-cooled toroid system, as well as a central solenoid. Charged particles bend in 3 dimensions, giving the possibility to measure the momenta twice. CMS has a single large superconducting solenoid, such that charged particles bend in the transverse plane but not in the longitudinal plane, simplifying track reconstruction etc.

4.1.1 The Superconducting Solenoid

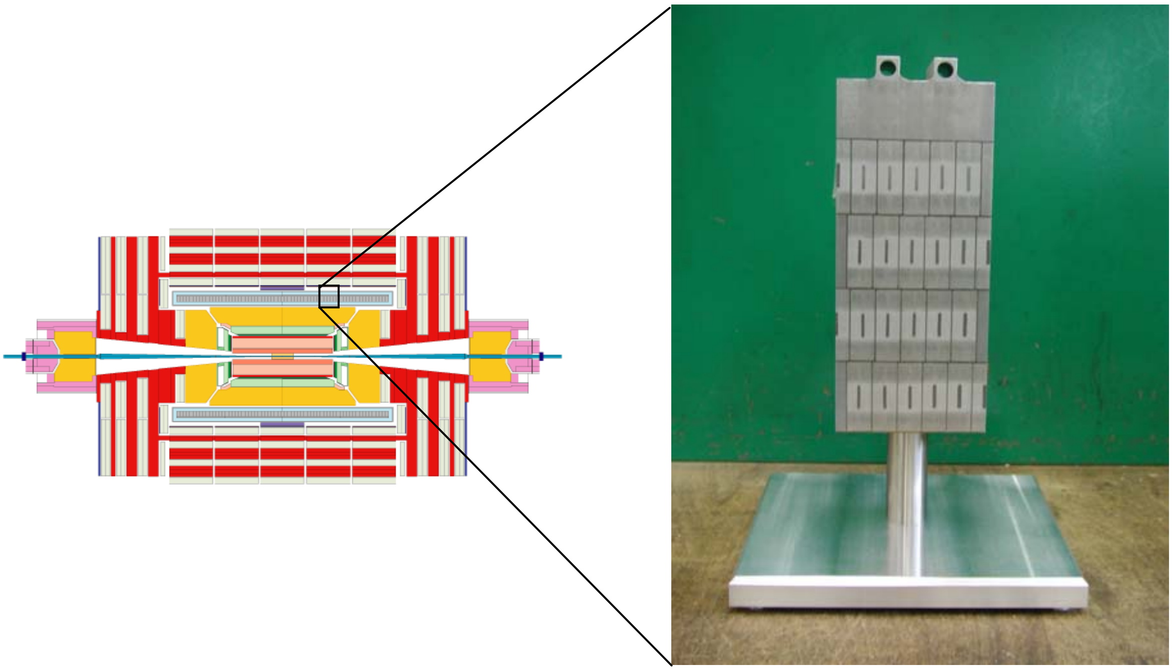
A solenoid is essentially a large cylindrical coil of wire. Passing an electric current down the wire will create an axial magnetic field. The CMS solenoid is designed to create an axial field of **4 Tesla** – about 100000 times the strength of the Earth's magnetic field. The solenoid length is **13m**, with an inner diameter of **5.9m**. **It will be the world's largest superconducting solenoid**. To achieve the high field a current of around **20kA** is necessary, which can only be achieved by using a superconducting coil (zero resistance). The photograph below shows a cross-section of the CMS superconductor.

The actual superconductor is a "Rutherford Cable" comprising **Niobium-Titanium** (NbTi) superconducting strands coated with copper. There are 16x2 strands per cable. Each strand can carry more than ~2000 Amps when cooled to 4.4 K using liquid helium. The energy stored in the solenoid at nominal field is 2.7 GigaJoules, enough to melt ~18 tonnes of solid gold!



Cross-section of the CMS conductor

The solenoid will consist of four layers of the conductor, as shown below (this piece is actually kept in the visitors' gallery at point 5).

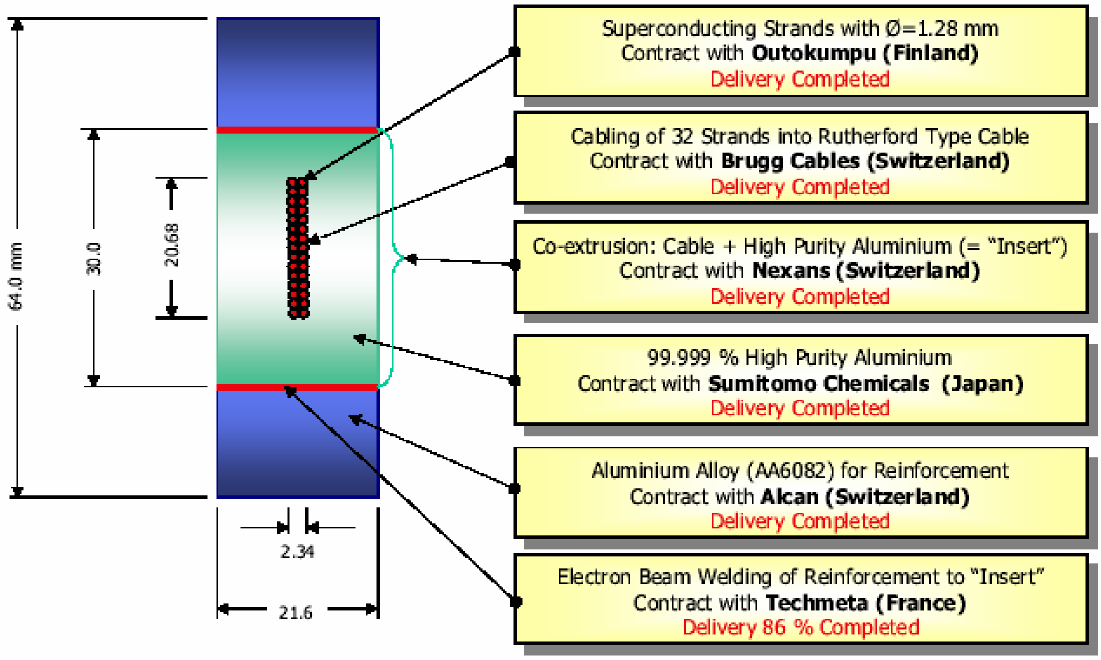


Mock-up of the four layers of conductor. The bending direction is out of the page

The construction of the conductor is a non-trivial affair, involving four countries, as shown below.

4.1.2 The Vacuum Vessel

As the superconducting solenoid needs to operate at liquid helium temperature (~4 K = -269°C), it needs to be maintained within a vacuum vessel to isolate it from the exterior. The vacuum vessel comprises two concentric cylinders made from stainless steel (Inox) connected via structural welds at the end flanges. The solenoid will be inserted between the two cylinders. The outer cylinder will be supported by the central barrel yoke ring (see below), which will in turn support the solenoid and then the inner vacuum cylinder. The inner cylinder will then support the barrel detectors – the hadronic and electromagnetic calorimeters and the tracker (see next sections).



Co-extrusion of CMS conductor finished on January 31, 2003

4.1.3 The Return Yoke

The superconducting solenoid requires a "return yoke", to control the field outside of the solenoid. The field strength in the return yoke is around 2 Tesla. The return yoke is constructed from steel, and also acts as the main support system (or "skeleton") of CMS as well as a muon filter. The amount of steel required is extremely large – more than 11000 tonnes. As there is no crane on earth that can lift this mass, and as we build most parts of CMS on the surface and subsequently lower them into the underground cavern, we have divided the return yoke into segments.

The barrel yoke comprises 5 "rings", whilst each of the two endcaps comprises 3 "disks". Each of the rings is constructed from several layers of steel – 4 layers for the central ring and 3 for the others. This layered structure allows the insertion of muon chambers. Muon chambers are also put between the 3 endcap disks. The barrel rings are supported by "feet" (also made from steel), whilst the endcap disks are supported by steel "carts".

The masses of parts of the return yoke are given in the tables below, whilst section 7 describes the components of the return yoke that can be seen in the CMS assembly hall at Cessy.

	Central Barrel	*Outer Barrel*
Barrel ring	1250 tonnes	1174 tonnes
Vacuum vessel	264 tonnes	-
Superconducting coil	234 tonnes	-
Support feet	72 tonnes	66 tonnes
Cabling on vacuum vessel	150 tonnes	-
Support for racks and cables	10 tonnes	10 tonnes
Total	**1980 tonnes**	**1250 tonnes**

Mass distribution in central and outer barrel rings of the return yoke

Endcap disk 1 (YE1)	~730 (disk) + 90 (cart) tonnes
Endcap disk 2 (YE2)	~730 (disk) + 90 (cart) tonnes
Endcap disk 3 (YE3)	~300 (disk) + 90 (cart) tonnes

Mass distributions in the 3 disks of an endcap return yoke

4.2 The Tracker

CMS has chosen to construct its central tracking detector, called the "Tracker", from many concentric layers of silicon sensors. The purpose of the Tracker is twofold:

- Together with the magnetic field, allows a measurement of the momenta of electrically charged particles
- Allow the reconstruction of vertices, both the primary proton-proton interaction points and secondary vertices due to particle decays

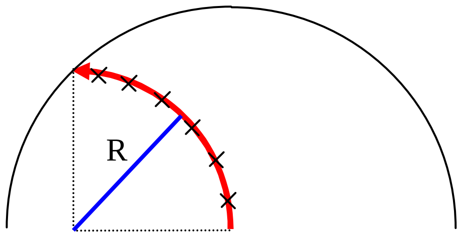
This requires a detector with a high channel density, for high spatial precision and so that close-by tracks can be distinguished. The detector must also be made from many low-mass layers ("low material budget") so that particles are not deflected from their paths.

4.2.2 Momentum Measurement

The basic idea is that a charged particle bends is a magnetic field, and when it traverses the silicon sensors it creates an electrical signal that can be detected. Dividing the sensors into strips or pixels allows an estimation of the incidence position of the charged particles. Combining the information from many layers enables a "track" to be reconstructed. Once the track path is reconstructed, measuring the radius of curvature of the track gives an estimation of the particle momentum, according to

$$p = R \times 0.3B$$

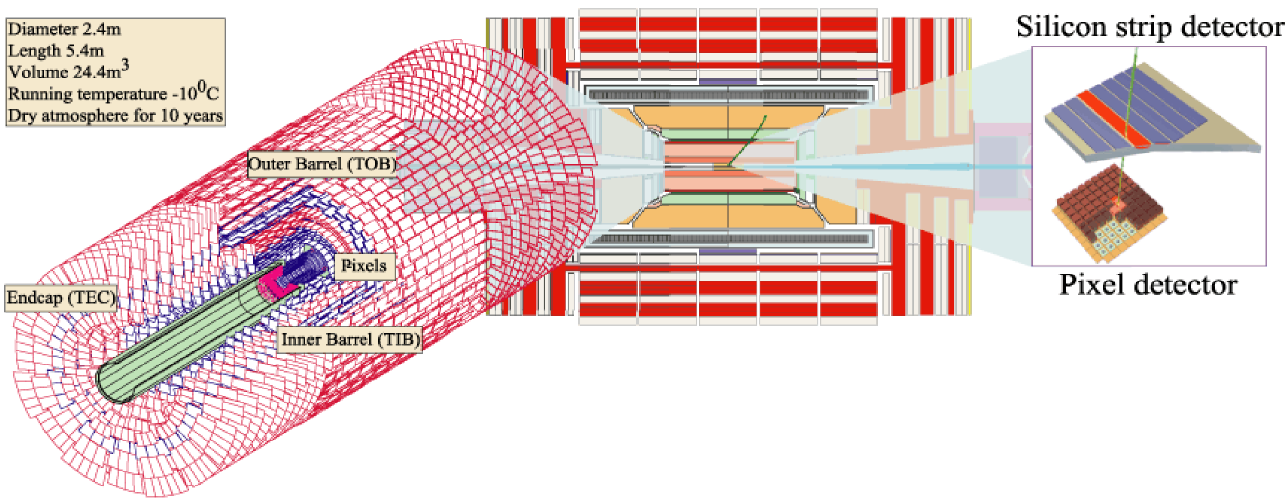
where "p" is the particle momentum in GeV/c, R is the radius of curvature in metres and B is the magnetic field strength in Tesla.



Schematic showing how the particle momentum is measured

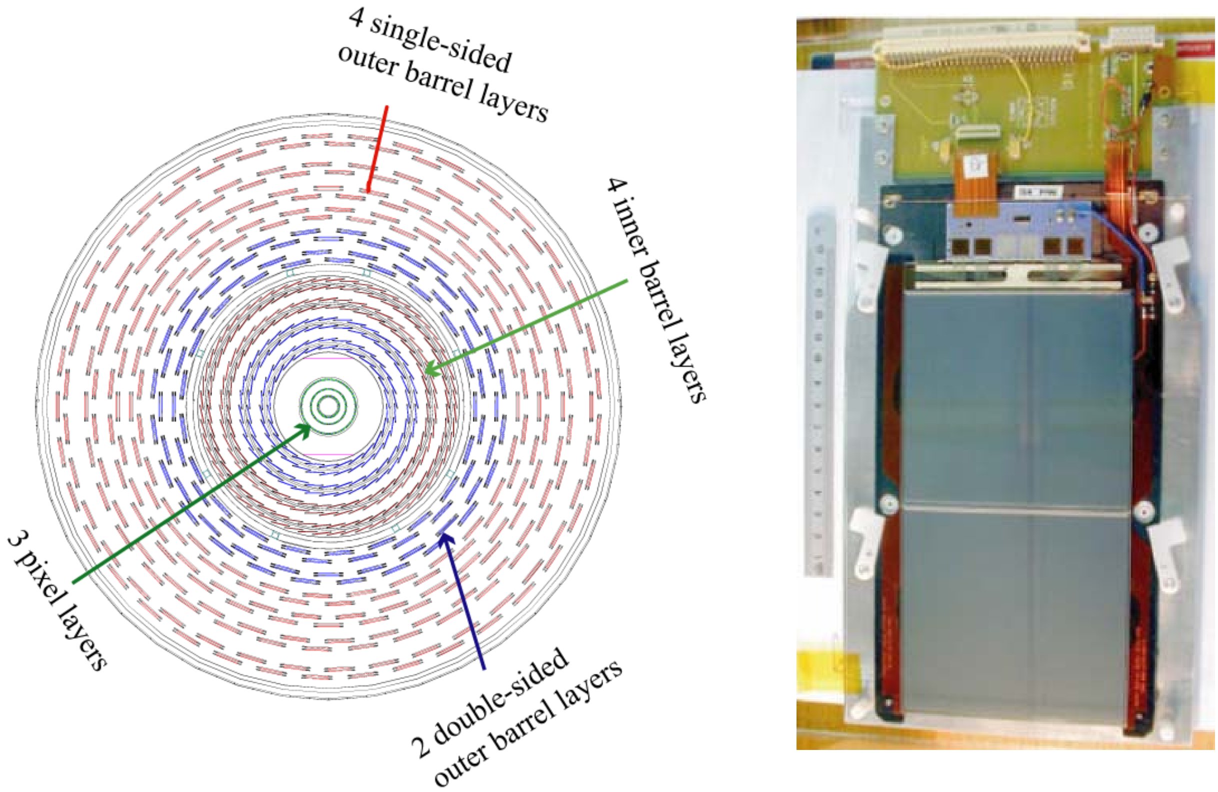
4.2.3 Characteristics of the CMS Tracker

The CMS Tracker comprises silicon pixel layers and silicon microstrip layers in a cylindrical volume ~5.4m long and ~2.4m diameter. The large volume of the tracker is required in order to allow significant bending (and therefore accurate momentum measurement) of very high energy charged particles. The pixel detector is close to the interaction region, in order to measure vertices accurately and also to "seed" tracks, whilst the silicon microstrips cover a very large volume for particle momentum measurement. The overall layout is shown below.



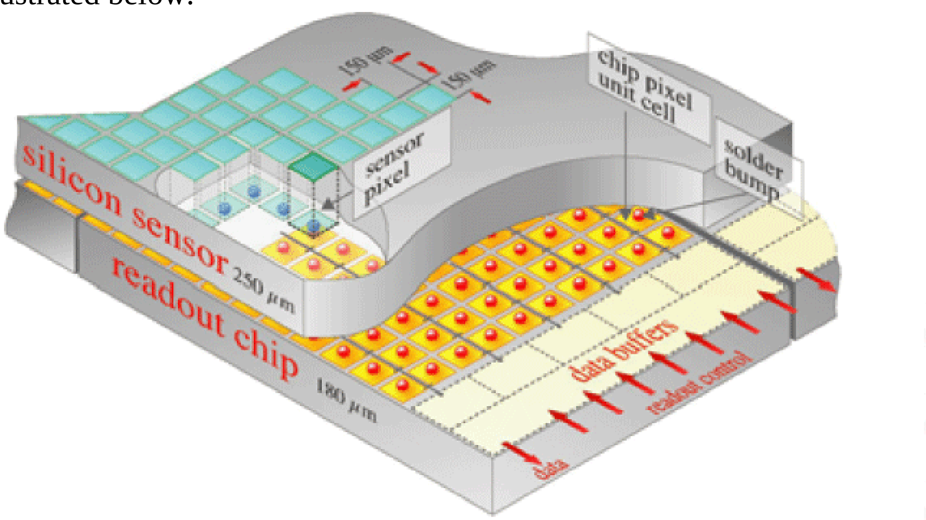
The layout of the CMS Tracker

The tracker has many concentric layers in the barrel, between radii of about 7cm and 95cm, and many parallel disks in the endcap. Each layer must be very thin, so that traversing particles are not diverted from there natural trajectories (if this happened, the measurement of the momentum would be compromised). For this reason the silicon sensors are only a few hundred microns thick. The support structure is made from lightweight carbon fibre. The figure below shows the layers in the barrel, as well as a photograph of a barrel sub-module.



The concentric layers of the barrel tracker and a barrel module comprising two silicon sensors and their associated readout electronics

The inner part of the tracker, the pixel detector, is a relatively new type of particle detector, made possible by the advent of "bump bonding" – a technique that allows the bonding of an electronics readout module directly on top of the silicon pixel detector (c.f. wire bonds for the silicon microstrips). A "pixel chip" is thus a combination of silicon sensor and readout electronics. The structure is illustrated below.



The structure of the pixel detector – silicon sensor bump-bonded to readout electronics

The individual pixels measure 150μm x 100μm. **There are 65.9 million pixels in the final proposed configuration (3 barrel layers and 3 endcap disks).**

The silicon microstrip tracker comprises a total area of **214m^2** – the largest device of its type ever made. The sensor size is around **11cm x 16cm**, with a typical microstrip pitch of **140 microns**. **There are 11.4 million microstrips.**

4.3 The Electromagnetic Calorimeter – ECAL

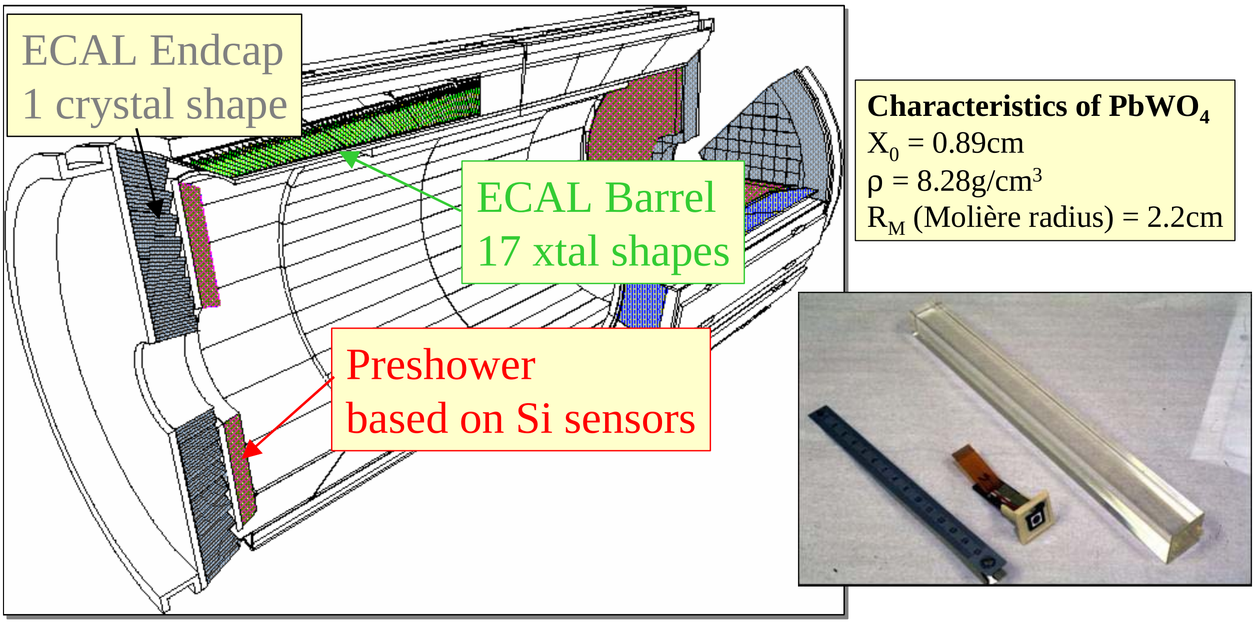
The principle aim of the CMS electromagnetic calorimeter (ECAL) is to measure the energy of incident electrons/positrons and photons. In addition, it performs measurements of the incidence position of electrons/positrons and photons, and also tries to distinguish incident single photons from pairs of closely spaced photons (from decays of neutral pions – we call this "π^0 rejection"). The ECAL surrounds the Tracker.

4.3.1 The Crystal ECAL

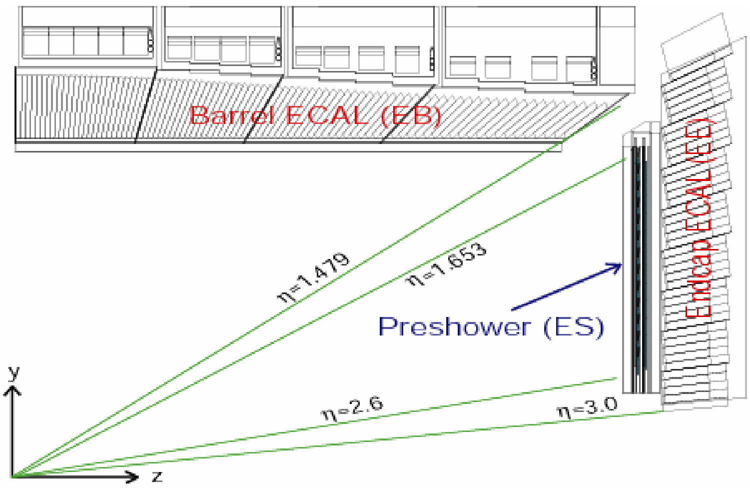
One of the principle design objectives of CMS is the construction of a very high performance electromagnetic calorimeter (ECAL). A scintillating crystal calorimeter offers excellent performance for energy resolution since almost all of the energy of electrons and photons is deposited in the crystal volume.
CMS has chosen to construct the main part of the ECAL from truncated pyramid crystals of lead tungstate ($PbWO_4$). These crystals are 98% metal but are completely transparent. They have a very high density – 8.3g/cm^3 and a high effective Z, leading to a small radiation length (X_0) of 0.89cm. The crystals are thus relatively short – 23cm in the barrel and 22cm in the endcaps, resulting in a very compact calorimeter system. CMS requires 61200 crystals in the barrel part, and 14648 crystals in the endcaps – a total of 75848 individual detector elements. The barrel crystals have front faces of about 22x22mm^2, whilst the endcap crystals have rear faces of 30x30mm^2.
Incident electrons and photons deposit energy in the crystals (through bremsstrahlung and pair-production) that results in scintillation light being emitted in the crystals. The amount of light created is a linear function of the particle energy. Light-sensitive detectors placed at the rear of the crystals (avalanche photodiodes – APDs – in the barrel; vacuum phototriodes – VPTs – in the endcaps) detect this light and give electrical signals that are again proportional to the amount of light, thus enabling an estimation of the incident particle energy.
The CMS crystal ECAL is known as "homogeneous": the crystals perform the functions of electromagnetic shower generation and light producer. A homogeneous calorimeter has the potential to achieve excellent energy resolution. One can compare this with the ATLAS liquid argon calorimeter - LiAr. The LiAr comprises alternate layers of lead and liquid argon. The lead layers create the electromagnetic showers, whilst the liquid argon layers produce light when charged particles from the shower traverse them – this is known as a "sampling" calorimeter.

4.3.2 The Endcap Preshower

In addition to the crystals, there is an additional detector in the endcaps of CMS. This is the "Preshower". Its primary function is π^0 rejection, by measuring the transverse profile of electromagnetic showers after ~3 X_0. To do this, we need to have a fine grain detector, as the average distance between photons from π^0 decays in the endcaps is just a few mm. CMS has chosen to construct the Preshower as a sampling calorimeter, with two thin layers of lead (to generate showers) each followed by a layer of silicon strip sensors for measurement of the charged particles created in the showers.
The silicon sensors used in the Preshower are 300μm thick, measure 6.3cm x 6.3cm and are divided into 32 strips. There are 4288 sensors, so a total of about 137000 detector channels.



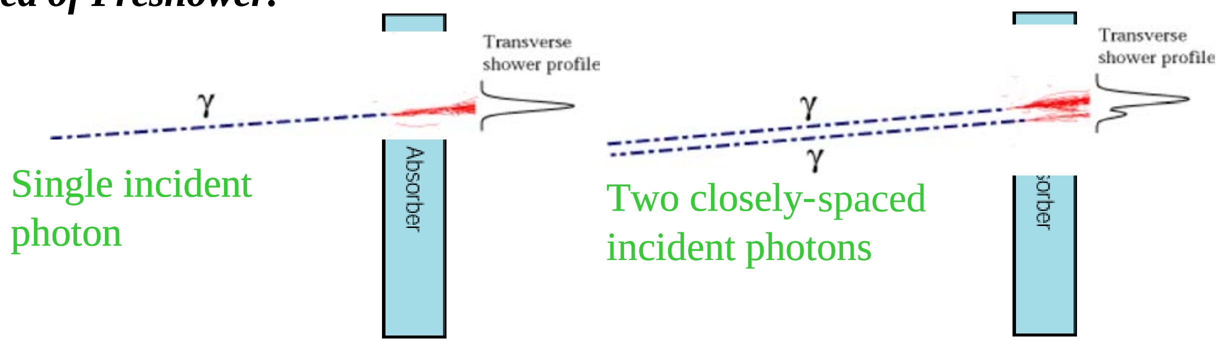
Schematic layout of the CMS Electromagnetic Calorimeter System
The inset shows a single crystal together with an APD for light detection in the barrel



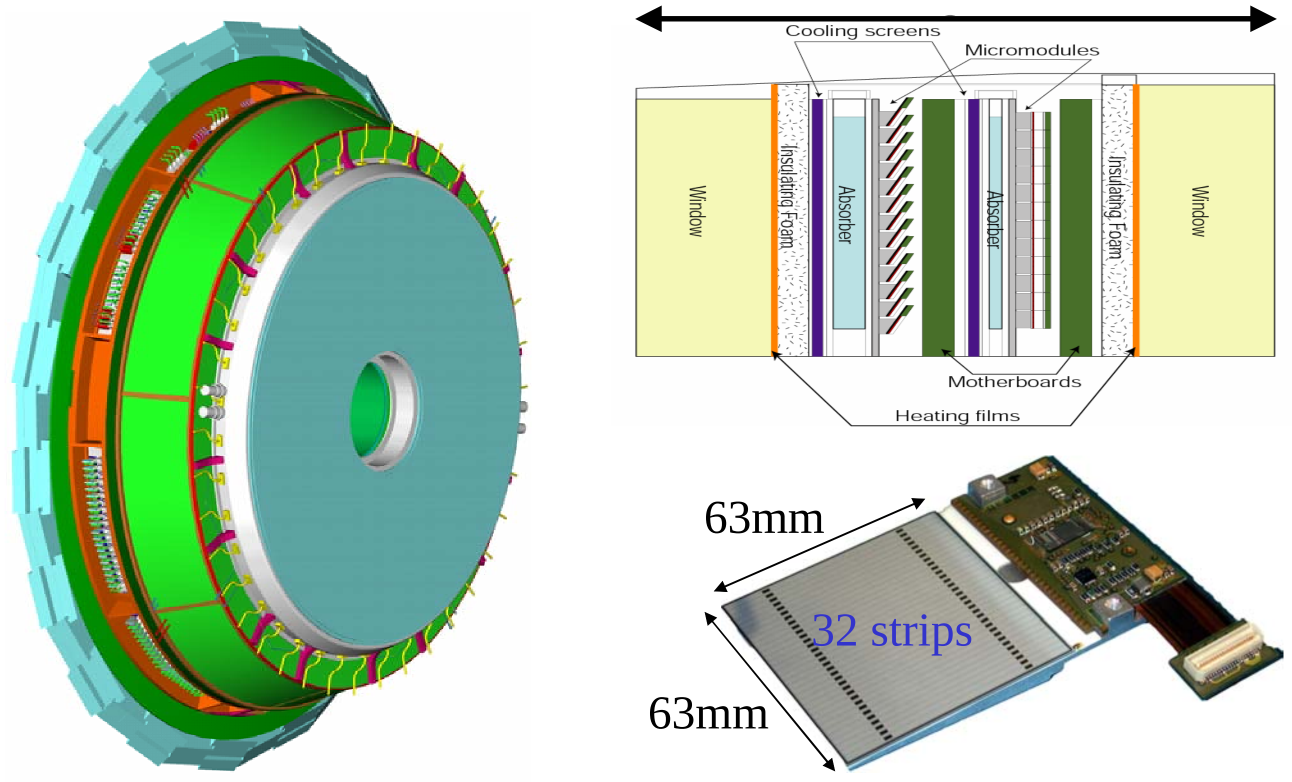
Parameter	Barrel	Endcaps
Coverage	|η|<1.48	1.48<|η|<3.0
Δϕ x Δη	0.0175 x 0.0175	0.0175 x 0.0175 to 0.05 x 0.05
Depth in X_0	25.8	24.7
# of crystals	61200	14648
Volume	8.14m^3	2.7m^3
Xtal mass (t)	67.4	22.0

Some of the characteristics of the CMS crystal ECAL

Idea of Preshower:



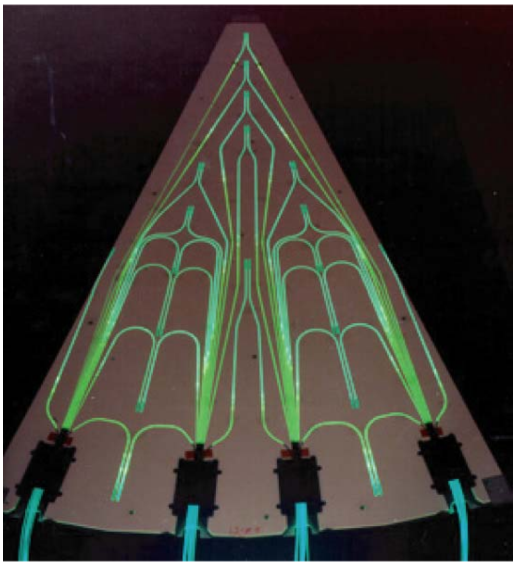
The basic principle of the endcap Preshower



The endcap ECAL with Preshower (left), transverse structure of the Preshower (top-right) and a Preshower micromodule showing the silicon sensor and the front-end electronics (bottom-right)

4.4 The Hadronic Calorimeter – HCAL

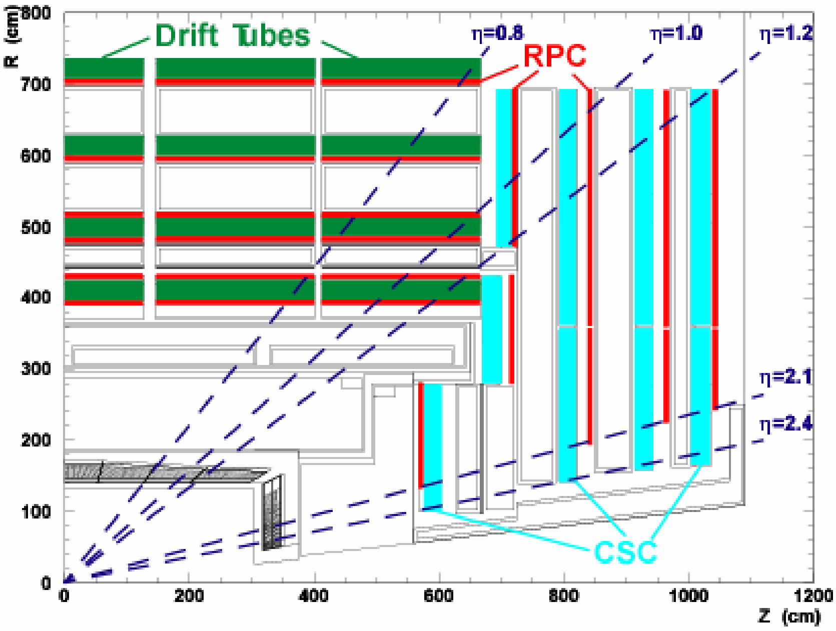
The Hadronic Calorimeter (HCAL) surrounds the ECAL.
The HCAL plays an essential role in the identification and measurement of quarks, gluons and neutrinos by measuring the energy and direction of jets and of missing transverse energy flow in events. Missing energy forms a crucial signature of new particles, such as supersymmetric partners of quarks and leptons. For good missing energy resolution, a hermetic calorimetry coverage to $|\eta|=5$ is required. The HCAL will also aid in the identification of electrons, photons and muons in conjunction with the other sub-detectors.
HCAL is divided into 3 sections: barrel HCAL (HB); endcap HCAL (HE) and forward HCAL (HF). HB and HE are sampling calorimeters with 50mm thick brass plates interleaved with 4mm thick plastic scintillator. Brass has been selected due to its high density and relatively low cost. HB is constructed from two half-barrels, each 4.3m in length. The thickness of HB is around 11 absorption lengths.
The scintillators emit blue-violet light; the amount of light is proportional to the energy of the incident hadron (neutron, proton, pion, kaon…). This light is then taken to the outside via wavelength-shifting optical fibres, which fluoresce in the green, through normal clear optical fibre waveguides to devices called Hybrid PhotoDiodes (HPDs) that measure the amount of light.
There are two HF calorimeters, one located at the extremes of each end of CMS. The high radiation field at high η has resulted in HF being designed as a large steel absorber (to generate the showers) embedded with quartz fibres. The energy of jets is measured from the Cerenkov light produced as charged particles traverse the fibres.
The construction of HB and HE absorbers/scintillators is complete, and these are in the assembly hall at Cessy (see section 7). Construction of all HF wedges is also complete but have not yet been transported to the Cessy site.
There are approximately 10000 detector channels in the HB, HE and HF combined.

Fluorescence of wavelength-shifting fibres in plastic scintillator (left) and loading quartz fibres into an HF wedge (right)

4.5 The Muon chambers

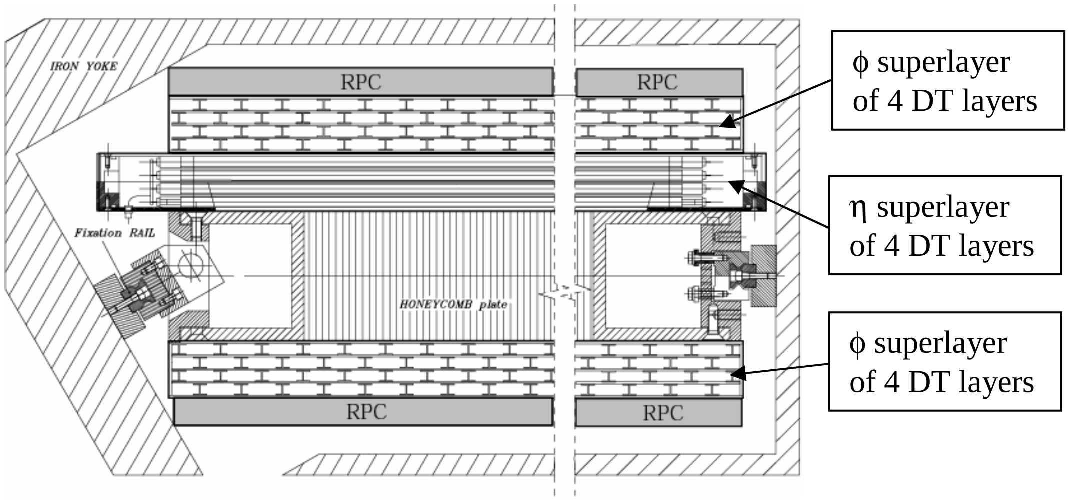
CMS has been specifically optimized for the detection and measurement of muons. This is achieved by using drift tubes (DT) located outside of the solenoid in the barrel region and cathode strip chambers (CSCs) in the forward region. The CMS muon system is also equipped with resistive plate chambers dedicated to triggering purposes. Positions of the three muon sub-systems are shown in the figure below.



Longitudinal cut of the CMS Muon system

4.5.1 Barrel

The barrel muon system comprises four muon stations at increasing radii, interleaved with the iron yoke to make full use of the magnetic return flux (~1.8 T). This allows for a standalone muon momentum measurement (i.e. not requiring the tracker), which is essential for the level 1 muon trigger system. This second momentum measurement is also useful for matching muons to tracks in the tracker in the analysis stage. Each muon station comprises one or two RPC modules and one DT module. Each DT module consists of three superlayers (SL), each of which is split into four staggered layers as shown below. Two SL measure the coordinates in the bending plane (ϕ) and one is for the longitudinal (η) direction.



Cross section of a barrel muon station

The barrel drift chambers provide a hit precision of 100µm.

4.5.2 Endcaps

Endcap muon stations are equipped with CSCs. These are multiwire proportional chambers with segmented cathode readout. High precision measurements of the muon position are obtained by extrapolation of charges induced on several adjacent cathode strips. In CMS the strip width varies between 3.2 and 16mm. The obtained hit precision varies between 80µm and 450µm for one layer. Endcap CSCs have already been produced and mounted on some of the endcap yoke disks – see section 7.

4.5.3 Parameters

The table below summarises some of the parameters of the CMS muon system.

Detector	Drift Tubes	Cathode Strip Chambers	Resistive Plate	
Function	Tracking p_T trigger BXID	Tracking p_T trigger BXID	BXID p_T trigger Resolve tracking ambiguities	
region	0.0 - 1.3	0.9 - 2.4	0.0 - 2.1	
Stations	4	4	Barrel 6	Endcap 4
Layers	Rϕ 8, Z 4	6	2	
Chambers	250	540	360	252
Channels	195000	Strips 273024 Wire groups 210816	80640	80642
Spatial resolution (σ)	per wire 250 µm Rϕ (6/8 pts) 100 µm Z (3/4 pts) 150 µm	R (6 pts) 75 µm (outer CSCs) 150 µm R(6pts) (15-50)/$\sqrt{72}$ µm	Cell size	
Time resolution	5 ns	6 ns	3 ns	
Within 20 ns window	> 98% (station) no parallel B field	> 92% (station)	98%	

Muon chamber properties and statistics

4.6 The Trigger and Data Acquisition System

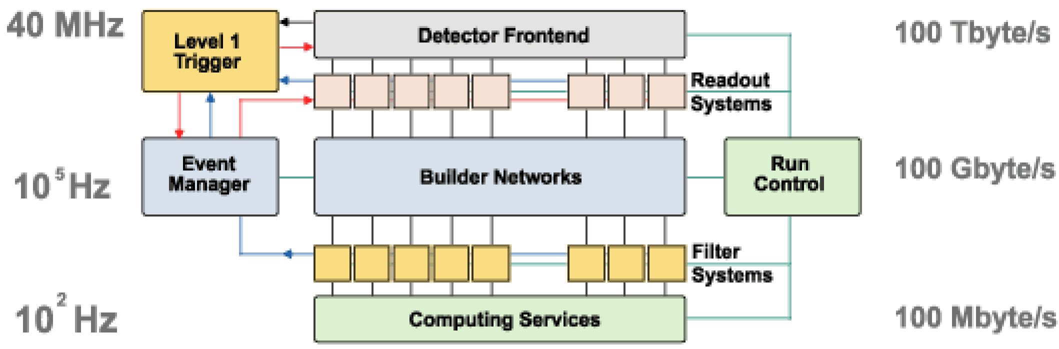
For the nominal LHC design luminosity of 10^{34} $cm^{-2}s^{-1}$, approximately 20 events occur at the beam crossing frequency of 40 MHz. Each beam crossing results in about 1Mbyte of zero-suppressed data. The input rate of $40x10^6$ bunch crossings every second must be reduced by a factor of at least

$4x10^4$ to around 100 Hz, the maximum rate that can be archived by the on-line computer farm. CMS has chosen to reduce this rate in two steps. At the first level all data are stored for 3.8µsec (equivalent to 192 bunch crossings), after which no more than 100kHz of the stored events are forwarded to the High Level Triggers. This must be done for all channels without deadtime. The Level-1 (L1) system is based on custom electronics – it is a “hardware” trigger. It uses coarse information from the calorimeters and muon RPCs to try to determine basic properties of the events – e.g. does the event contain high pT muons, or high energy electrons/photons/hadrons? While this decision is being made, the fine-grain information from the sub-detectors is held in pipeline memories on the front-end electronics.
The High Level Triggers (HLT) system relies upon ~1000 commercial processors – it is a “software” trigger. The data from the detector front-ends are passed through a high bandwidth switching network to the processor farm. The data flow through the switch is ~1 Terabit/second – about the same as the whole world’s telecom traffic! The HLT has access to all information from all sub-detectors and can therefore make combinations of information from different sub-detectors. E.g. trying to match an electromagnetic energy deposit in the ECAL with hits in the pixel detector can identify the presence of electrons.
The trigger is the start of the physics event selection process. A decision to retain an event for further consideration has to be made every 25ns. This decision is based on the events suitability for inclusion into one of the various data sets to be used for analysis. The data sets to be taken are determined by CMS physics priorities as a whole. These data sets include di-lepton and multi-lepton data sets for “top” and “higgs” searches, lepton plus jet data sets for “top” physics, and inclusive electron data sets for calorimeter calibrations.

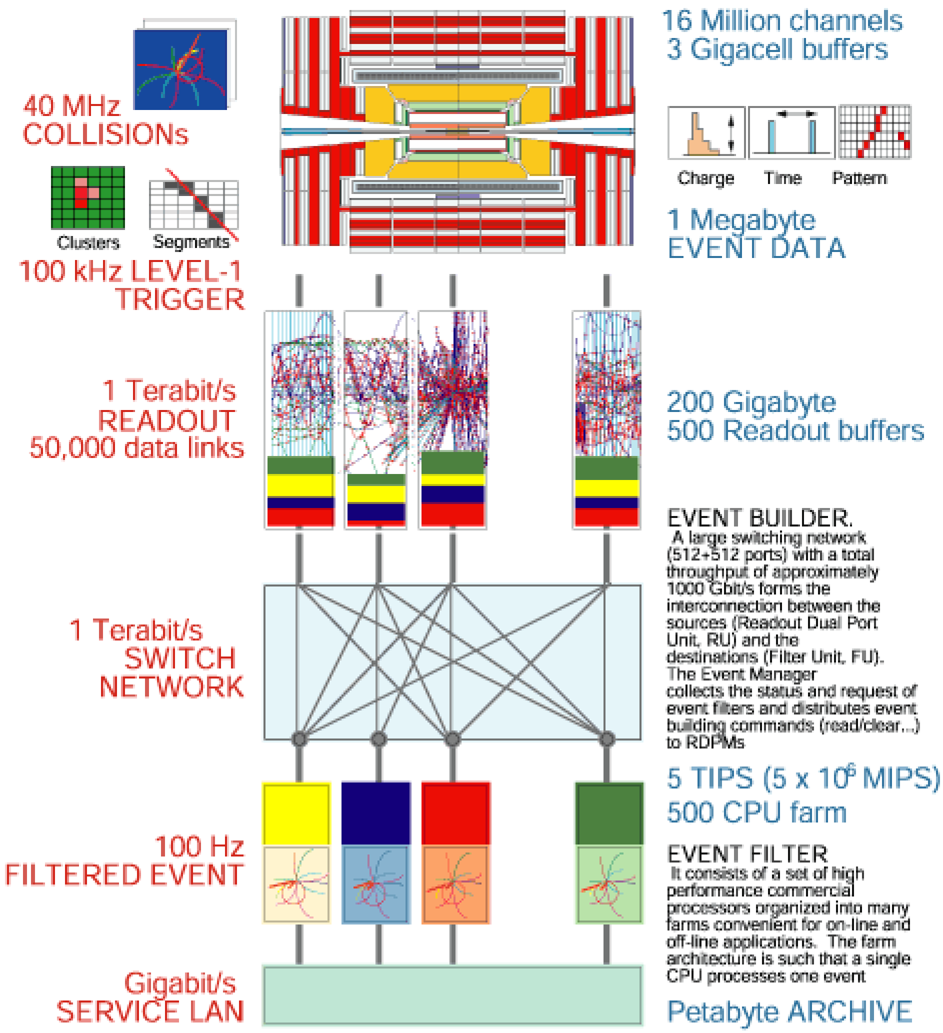
The HLT and the data acquisition system (DAQ) are considered together. The functionality of the CMS DAQ/HLT system is three-fold:

- Perform the readout of the front-end electronics after a Level-1 Trigger accept
- Execute physics selection algorithms on the events read out, in order to accept the ones with the most interesting physics content
- Forward these events, as well as a small sample of the rejected events, to the online services that monitor the performance of the CMS detector and also provide means of archiving the events in mass storage

Data Acquisition Main Parameters	
Collision rate	40 MHz
Level-1 Maximum trigger rate	100 kHz
Average event size	1 Mbyte
No. of electronics boards	10000
No. of readout crates	250
No. of In-Out units (200-5000 byte/event)	1000
Event builder (1000 port switch) bandwidth	1 Terabit/s
Event filter computing power	$5\ 10^6$ MIPS
Data production	Tbyte/day



Trigger and Data Acquisition baseline structure



4.7 Summary of detector channels

Detector	**Number of channels**
Pixels	66×10^6
Silicon microstrips	11.4×10^6
ECAL crystals	0.076×10^6
Preshower strips	0.137×10^6
HCAL	0.01×10^6
Muon chambers	0.576×10^6
TOTAL	$\mathbf{78.2 \times 10^6}$

5 Location

The CMS experiment site is located in the village of Cessy, in France. It is good to point-out to visitors that to get to Cessy from the CERN Meyrin site, they have had to travel approximately across the diameter of the LHC ring (~9km). It may surprise them to realise that they have travelled from one side to the other of what was (with LEP), and what will be (with the LHC), the largest scientific instrument in the world. Indeed this honour is still held by LEP (and is in the Guinness Book of World Records – see http://www.guinessworldrecords.com/index.asp?id=47105). The picture below forms part of one of the posters in the visitors' gallery at point 5, and is useful to show visitors "we are here" (and "the airport is there" etc.).

Location of the four LHC experiments around the circumference of the LHC ring

The actual location of CMS around the LHC ring is known as "point 5" (ATLAS is located at point 1; LHCb at point 7 and ALICE at point 2). Points 2, 4, 6 and 8 have existing large underground caverns (for the LEP experiments) but point 1 and 5 were simply access points to LEP – and thus two new caverns (and access shafts) had to be built to house CMS and ATLAS.

6 CMS Construction Site

6.1 Safety First

Note that this is indeed a real “construction” site, and thus safety for you and any visitors is the first priority. Indeed the main reason for a visitors gallery is that it is potentially dangerous to walk through the assembly hall (and this practice is heavily discouraged unless prior permission has been obtained from the site foreman – Jean-Pierre Girod – 163703). When walking around the outside of the hall you must encourage visitors to stay in a tight pack. If you do enter the hall you must again remain as a tight pack, visitors must not touch anything, and EVERYONE MUST WEAR SAFETY HELMETS, even at weekends[3].

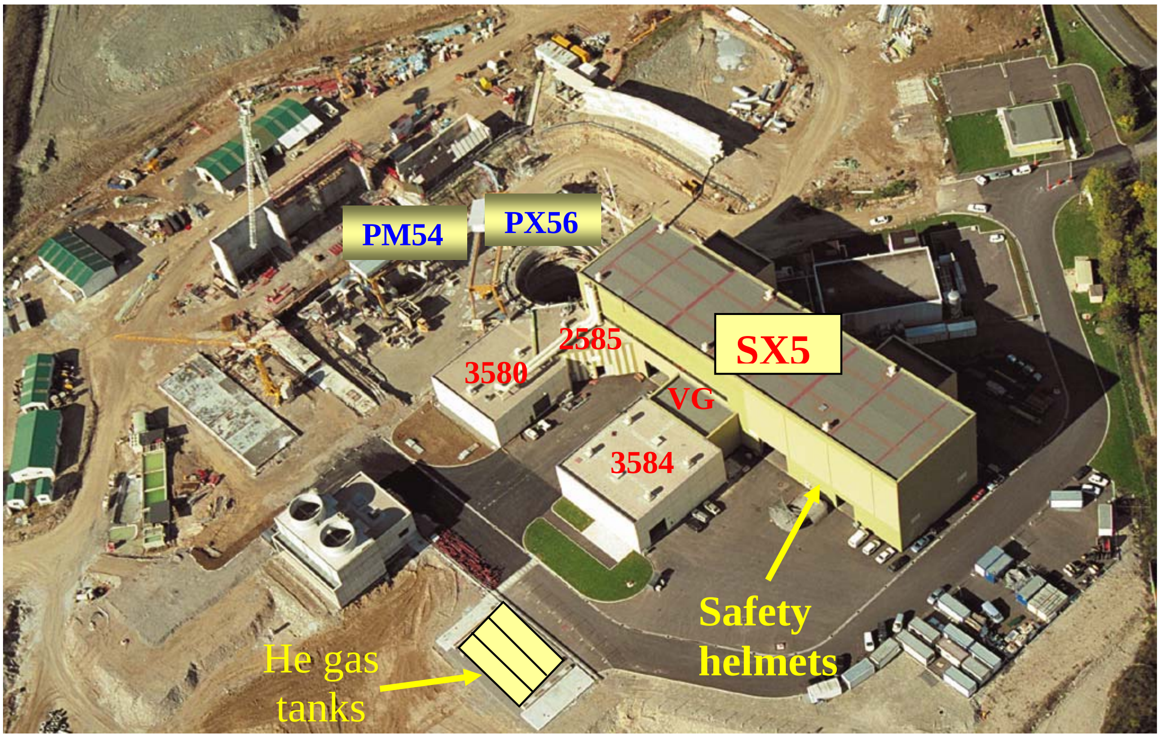
Ignoring this rule will result in an immediate suspension of all visits to CMS.

6.1.1 What to do in the event of an accident etc.

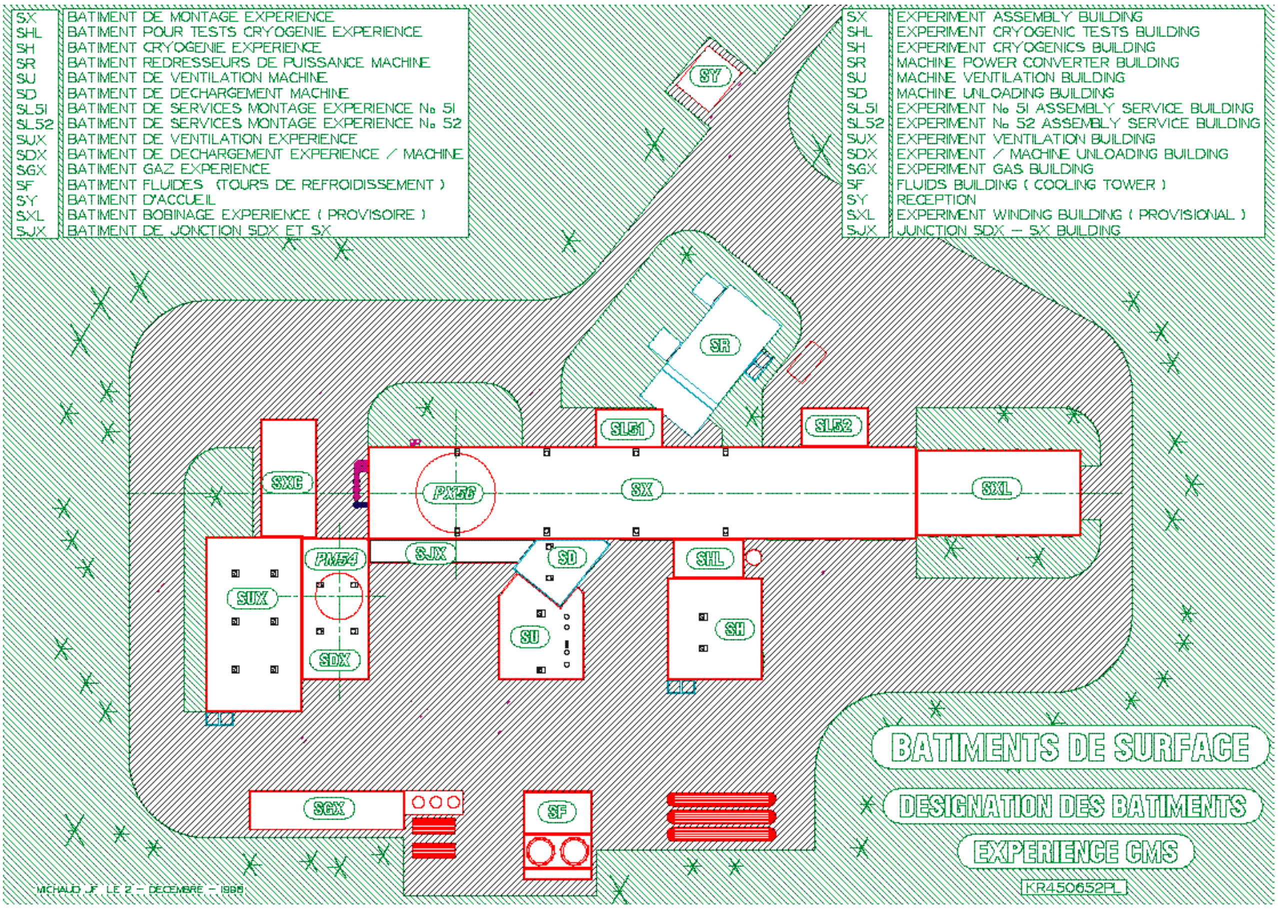
Be aware that the CERN pompier service is at least 15 minutes away! In the event of an accident of any type at the CMS construction site the first thing to do is to call the local safety officer (also Jean-Pierre Girod) on 163703, who should be present during the working week. Depending on the seriousness of the situation you should then call the CERN pompier on 74444.

[3] On most occasions it is impossible to enter the assembly hall at weekends; however, it is sometimes possible. In the past it has been rare to see people working in the assembly hall at weekends. However, due to the extremely tight schedule from now until 2007 it is expected that shift-work, including weekends, will soon commence.

6.2 The Surface Buildings



Photograph of the surface buildings at point 5 (Cessy) in 2000



Schematic of the surface buildings at point 5 (Cessy) with descriptions

The large hall is called "SX5" (bat 3585). It is the main assembly hall for the large components of CMS. The large (~20m diameter) hole at one end – called PX56 - is where the large pieces of CMS

will be lowered into the "experimental cavern" ~100m underground. There is a second (smaller, ~12m diameter) access shaft – PM54 - that will be used for lowering electronics into the underground "service cavern".
There are several buildings attached to SX5 on the near side, one of which (SHL) houses the visitors gallery ("VG") and the CMS cryogenic cooling plant for testing purposes (installed on the same balcony as the visitors gallery) amongst other things. The "SD" building houses an elevator for future access to the underground areas – visitors moving between the visitors' gallery and the access shaft viewing platform go through this building. ***Note: behind the elevator it is possible to walk along a grid and look down 100m!***

One thing that is not yet built on the surface (and indeed there is still discussion concerning the possibilities of putting it underground) is the CMS Control Room.

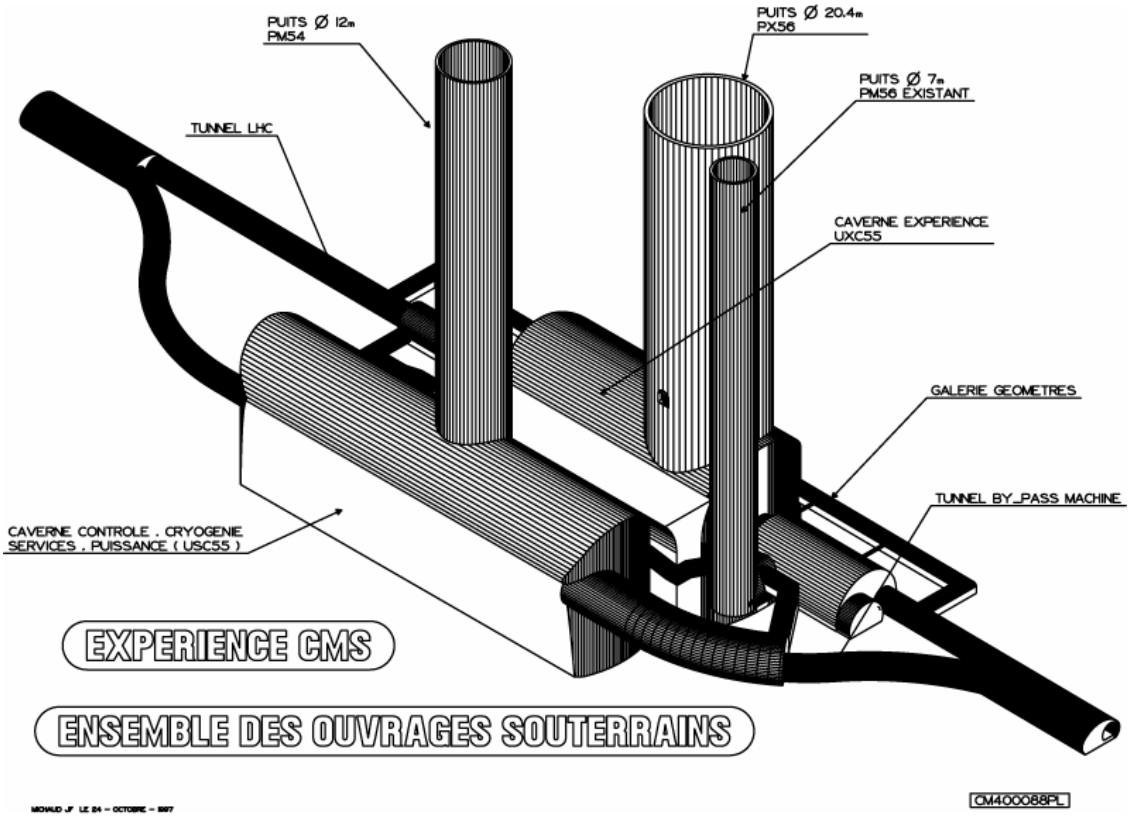
Opposite the main assembly hall is a group of 6 large yellow cylinders, as shown in the photograph below. These cylinders will contain gaseous helium. Two tanks will supply the helium that will be cryogenically cooled for the CMS superconducting solenoid **– a total of ~5000 litres of liquid He will be produced. The cooling of the CMS solenoid will take about 3 weeks.** The remaining 4 cylinders will supply the helium for a section of the LHC, the dipoles of which need to be cooled to ~1.9 K.

The cylinders that will contain the gaseous helium for the CMS/LHC cryogenic systems

6.2.1 SX5

- The SX5 hall is about 140m long, with a height and width of 23.5m.
- All the large components of CMS are being assembled in this hall. This allowed us to start construction of the detector at the same time as the civil engineering works (the digging of the two access shafts and the excavation of the experimental caverns, none of which existed in the LEP era)
- The hall will be extended longitudinally, to cover the PX56 access shaft
- After CMS has been installed underground, the idea is to reduce the size of SX5 to about 100m in length and 16m in height, thus having no major impact on the environment.

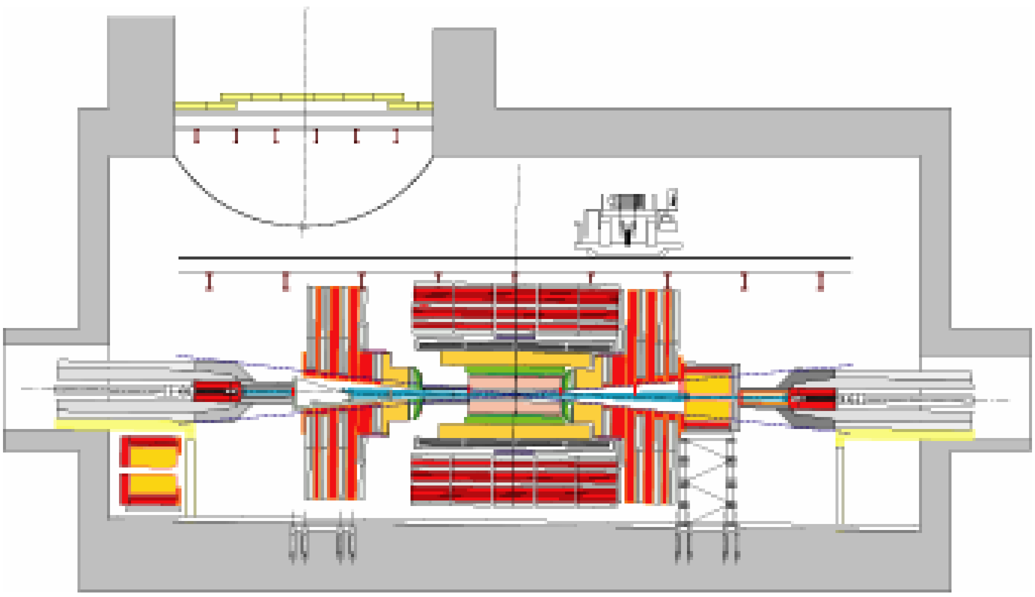
6.3 Underground Areas



The underground area at point 5, showing the access shafts, the two large caverns and the wall between them

There are two large underground caverns. UXC55 (Underground eXperimental Cavern 55) will contain the actual CMS detector, whilst USC55 (Underground Service Cavern 55) will contain readout electronics, gas supplies, cooling units etc. The two caverns are separated by a 7m-thick concrete wall. This wall serves two major purposes:

- It is a structural element for the ceilings of the two caverns
- It protects the electronics etc. in USC55 from radiation coming from CMS (mostly muons)



The CMS detector being assembled in UXC55

7 What is in SX5?

7.1 The return yoke, vacuum vessels and muon chambers

- CMS is built around a 13m long, 6m inner-diameter superconducting solenoid. When completed it will be the largest superconducting solenoid ever built. It will produce a magnetic field of 4T inside its volume, equivalent to about 100000 times that of the magnetic field of the Earth.
- The solenoid becomes superconducting at ~4 Kelvin. It must thus be contained within a "vacuum tank" (a bit like a Thermos flask).
- The solenoid requires a "return yoke" (essentially to control the field), made of steel that becomes magnetically saturated at 2T. Virtually all of the large pieces that you see in SX5 are components of the return yoke.

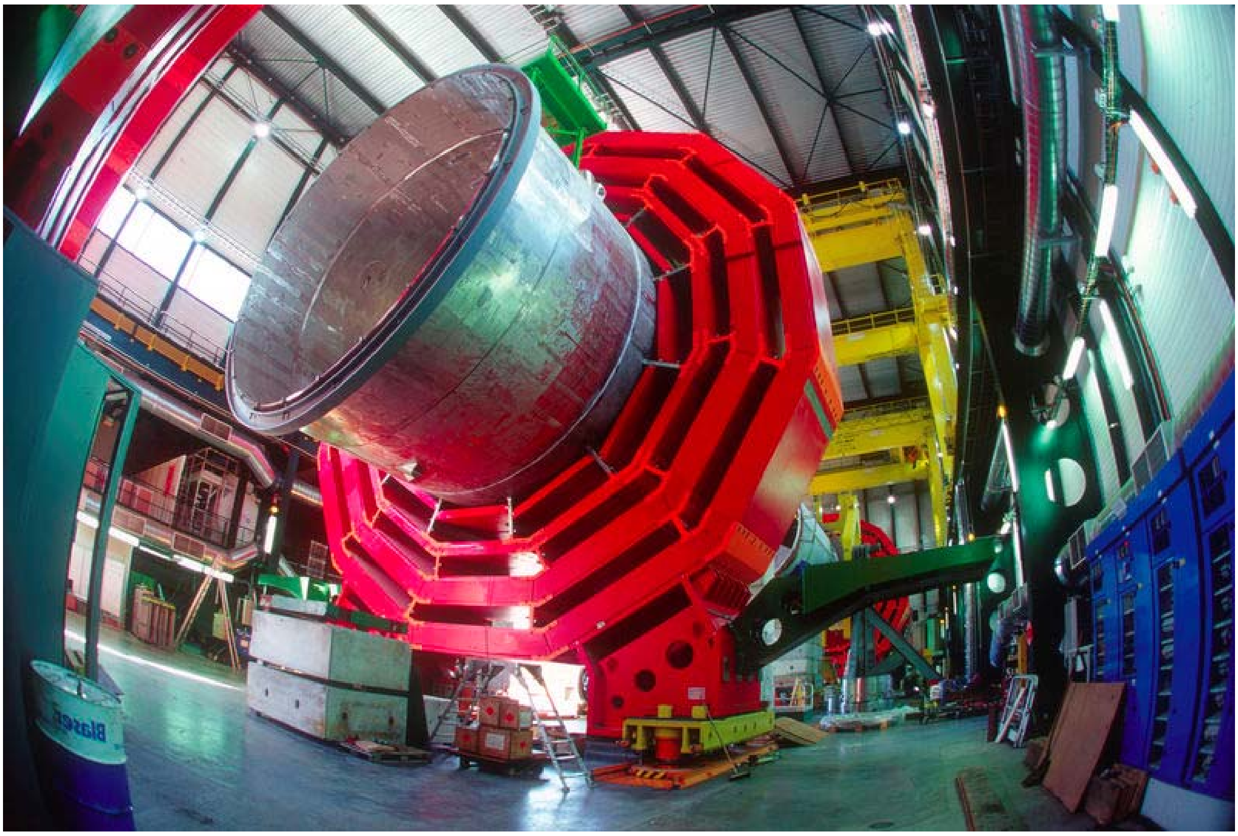
The barrel rings of the CMS return yoke

- The amount of steel required for the return yoke is more than is used in the Eiffel Tower!
- The large amount of steel also acts as a "filter" to absorb any stray particles - except muons - that punch through the calorimeters. This means that essentially the only particles that are incident on the muon chambers are…..muons!
- The steel also acts as the "skeleton" for CMS.
- The total weight of CMS will be around 12500 tonnes. No crane on earth can lift this amount, so the return yoke (most of the mass) is divided into sections.
- There are essentially three sections of the return yoke:
  - a central barrel - which is itself divided into 5 "rings" - all of which are complete and in the hall
    - each barrel ring weighs around 1250 tonnes – except for the central ring, which weighs nearly 2000 tonnes due to the fact that it will include the superconducting solenoid in its vacuum vessel
  - two "endcaps", each of which is divided into 3 disks" – all of which are built and in the SX5 hall

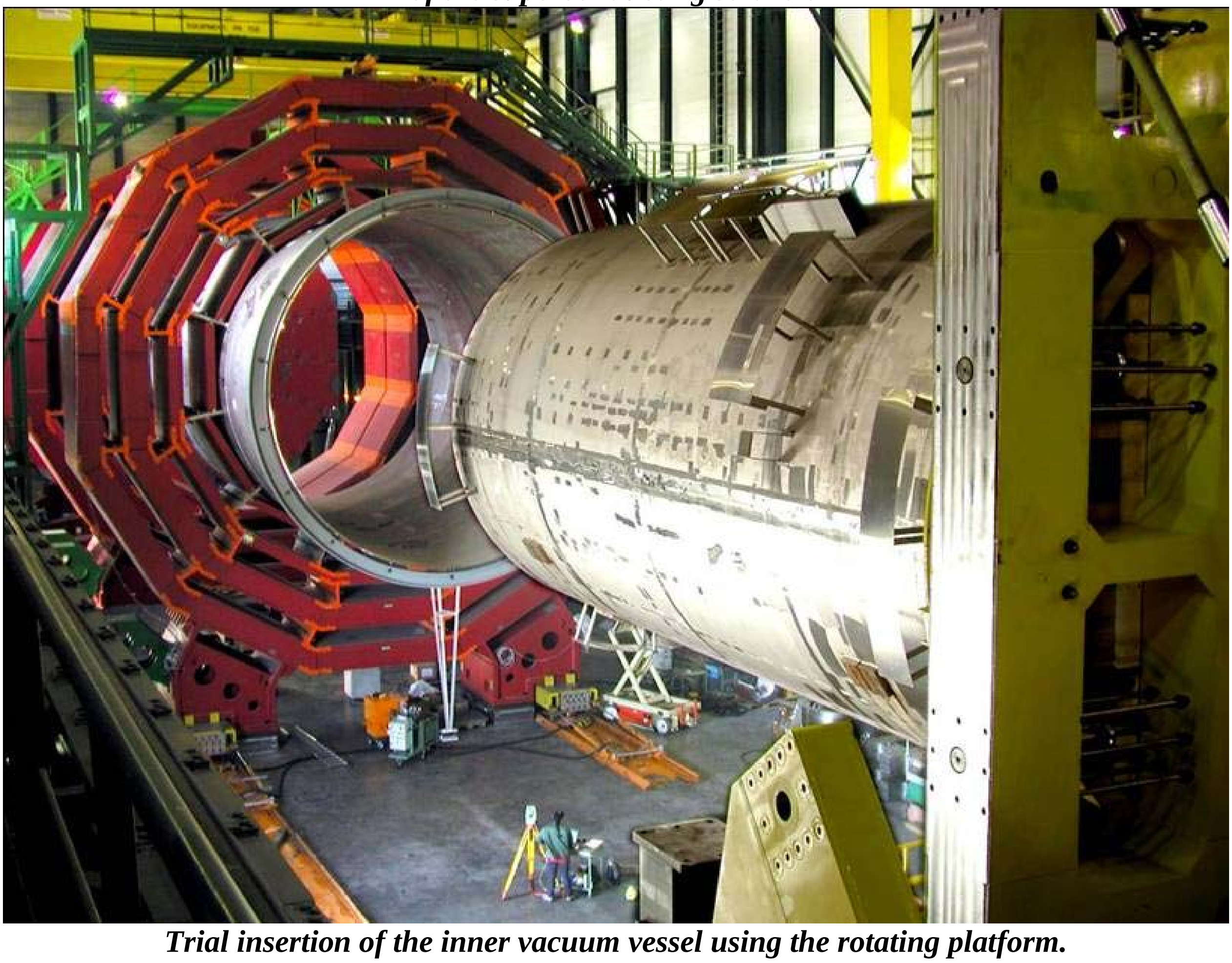
- The large pieces are moved around the surface hall, and also underground, by means of an "air pad" system (similar to that used for the Sapporo stadium in Japan). These air-pads are essentially hovercraft: compressed-air, at 24 atmospheres, is pumped into circular discs under the feet of the barrel/endcap yoke pieces, causing the structures to float about 1cm – at which point it is essentially frictionless. The air-pads are manufactured by Noell GmbH (Germany). Each pad can lift ~350 tonnes. There are 4 pads per "foot" for the barrel rings. The air-pad discs are bathed in oil, to make a good seal with the floor (so that no air leaks out). The pads (and the large pieces of CMS!) move along guide rails on the floor. A compressed-air powered piston system grips to the rails and the piece being moved, and pushes the piece along. The piece moves ~1m in 10 minutes.

The air-pad system under the feet of one of the barrel yoke rings, used to move the large pieces of CMS around the surface hall

- The central barrel ring supports the outer vacuum tank of the solenoid (see photo below), which in turn supports the solenoid itself. This supports the inner vacuum tank (currently in a vertical direction, see photo), which in turn supports all of the barrel sub-detectors (going from the outside in: Hadronic Calorimeter (HCAL), electromagnetic calorimeter (ECAL) and Silicon Tracker). These detectors will be inserted into the solenoid vacuum vessel underground.
- The barrel rings are constructed as concentric layers: 4 for the central ring and 3 for the other rings. Muon chambers will be placed in the gaps between the layers, and also on the outside of the rings.
- Muon chambers will also be placed between the disks of the endcap yoke.



Central barrel ring supporting the outer vacuum vessel
of the superconducting solenoid



Trial insertion of the inner vacuum vessel using the rotating platform.
The inner vacuum vessel is currently in the vertical direction (November 2003)

Three disks of one endcap return yoke

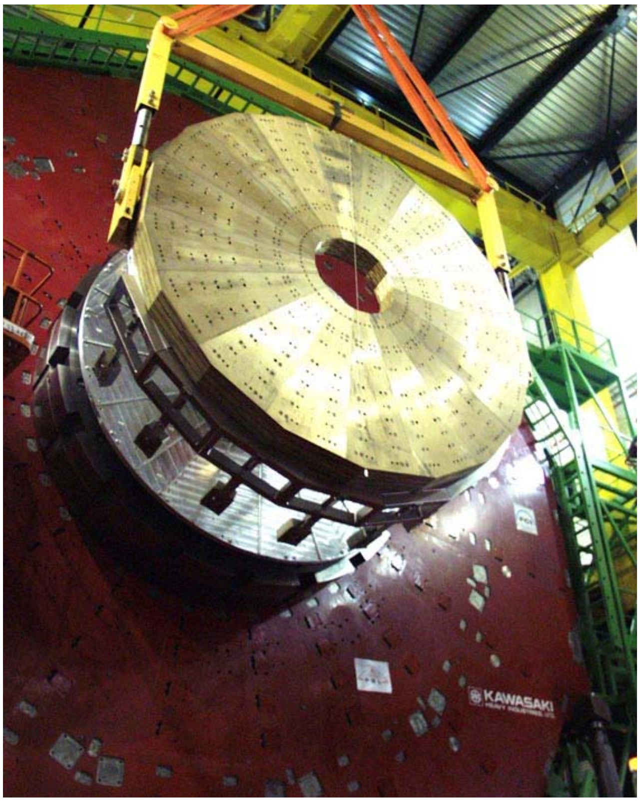
One endcap disk loaded with muon chambers

7.2 Hadron Calorimeter (HCAL)

- There are four parts to the HCAL that are currently in the surface hall:
  - two half-barrels (called HB) - sitting in alcoves on the opposite side to the visitors gallery – i.e. difficult to see.
  - two endcaps (called HE) - both of which are installed on the endcap disks on the far right and left of the hall

Installing the final wedge (18/18) of one HCAL half-barrel

A completed HCAL half-barrel



Installing the first part of an HCAL endcap

Finished HCAL endcap

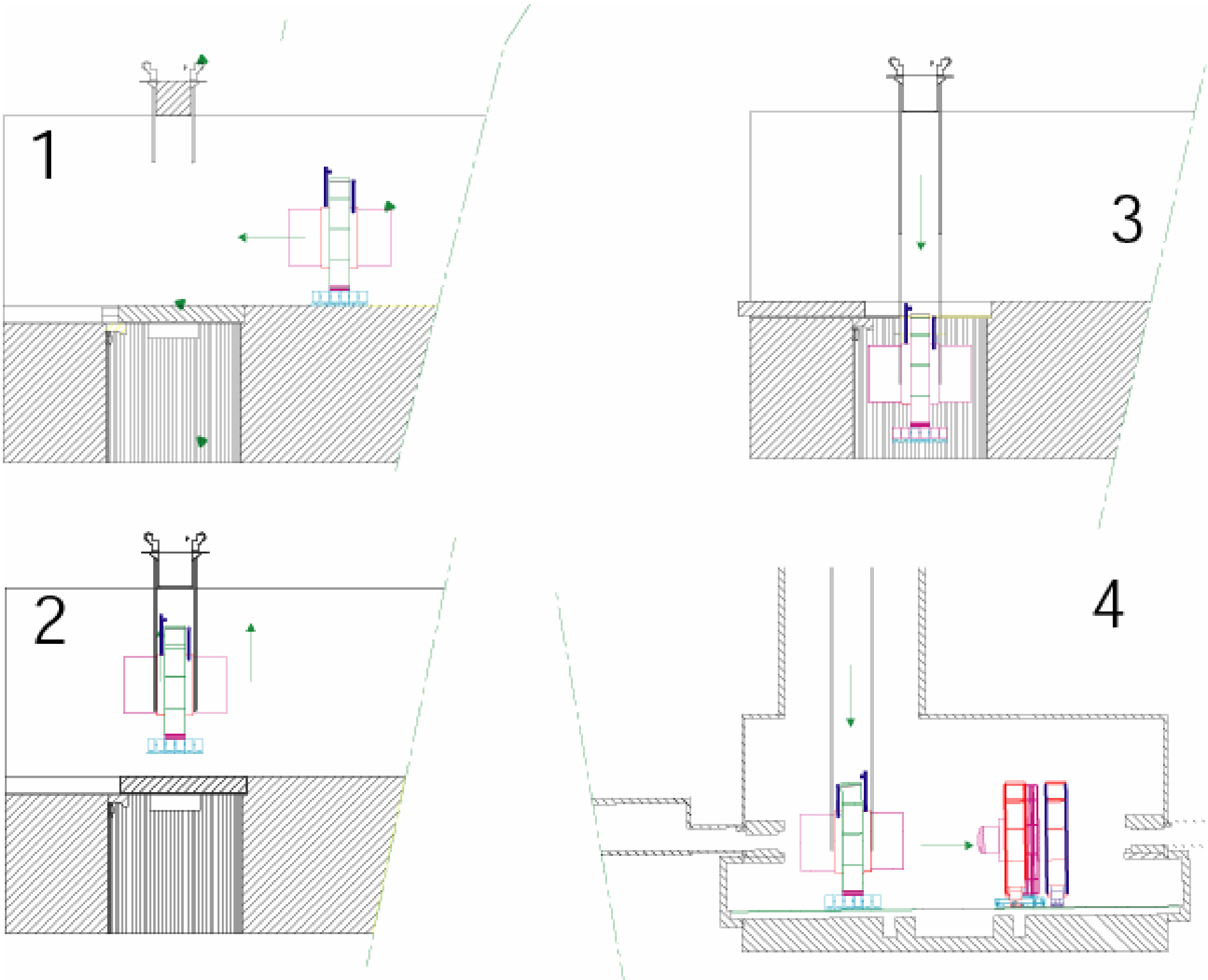
8 Where things come from etc.

- everything coloured red or orange is steel
- the red "feet" for the central barrel yoke ring came from Germany. They weigh about 30 tonnes each.
- the red "feet" for the other 4 barrel yoke rings came from Pakistan
- the red pieces forming the 5 barrel yoke rings came from Russia
- the orange pieces joining the red parts of the barrel yoke rings came from the Czech Republic
- the wedge-shaped red pieces forming the endcap disks came from Japan
- the "carts" for the endcap disks (the parts the disks sit on) came from China (designed in the US)
- the huge steel bolts holding the endcap disks upright came from the US
- the yellow rotating table that is currently holding the inner vacuum tank (for the solenoid) came from South Korea (Doosan Heavy Industries, Changwon, South Korea)
- the inner vacuum tank was fabricated in France (France-Comte Industrie (FCI), Lons-Le-Saunier, France) and transported by road over the Jura as a single piece
- the outer vacuum tank (being supported by the central barrel yoke ring) was delivered to CERN in pieces from FCI and welded at Cessy
- the machinery used to put the barrel yoke rings together (the Ferris wheel structure - now dismantled) came from Germany (Deggendorfer Werft & Eisenbau, Deggendorf, Germany)
- The HCAL barrel modules were constructed in Spain (Felguera Construcciones Mecanicas, Barros, Spain) and assembled into half-barrels at CERN
- The brass for the HCAL endcaps came from Russia – from melted casings of artillery shells! The manufacture of the brass plates for the endcaps was done in Belarus. Assembly of the HCAL endcaps was done at CERN.

9 The access shafts and lowering of CMS into the cavern

As mentioned previously, there are two large access shafts for lowering pieces of CMS and its electronics into the underground caverns. The diagrams below illustrate the procedure for lowering the large pieces down the PX56 shaft into the UXC5 cavern using a huge gantry (stationary) crane that will be borrowed from a shipyard.

1. Move large piece onto the steel cover above the access shaft, using the air-pad system
2. Lift the large piece using the stationary gantry crane
3. Slide the shaft cover to the side and lower the piece down the shaft
4. Move the piece into position in UXC5, again using air-pads



9.1 The PX56 Access Shaft

When the PX56 access shaft was being excavated, the builders reached the level of the water-table – effectively a huge underground lake. Clearly it was impossible simply to “dig through the water”, and it is not possible to do things like “drain the water” or “block the source of the water”. Small pipes were inserted around the circumference of the shaft, going down to a level below the water. Brine (salt-water) at -5^{o}C was circulated in these pipes for many months. The water inside the circumference (and a small distance outside) of the shaft was ~frozen. To ensure the ground water was really frozen, the brine was removed from the pipes and replaced with liquid nitrogen for ~1 month. The frozen water+earth+rock were then able to be excavated and the shaft walls constructed.

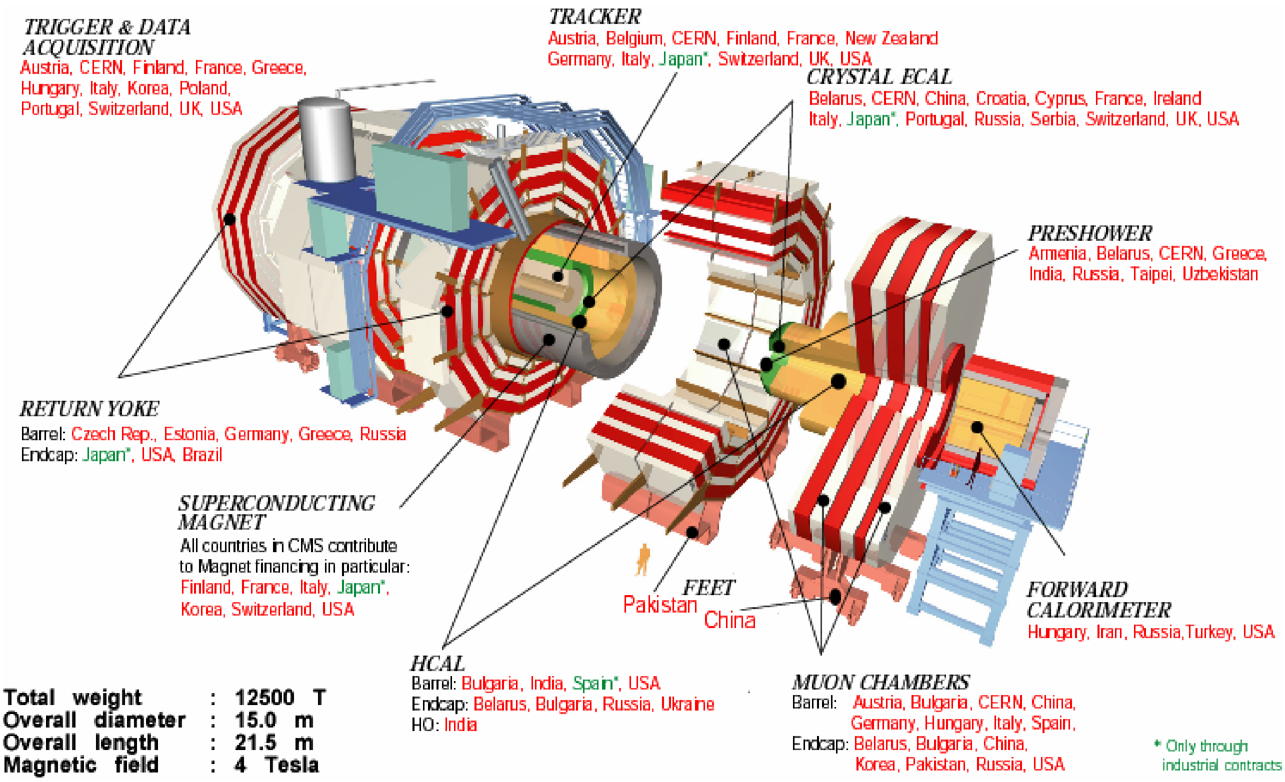
The photograph below shows the exterior of the PX56 shaft on November 25 2003.

The PX56 access shaft. The concrete surface is being constructed, in preparation for lowering pieces of CMS.

9.2 The UXC5 Cavern

10 CMS Collaboration

As of November 2003 there are 2008 scientists and engineers from 160 institutes in 36 countries involved with CMS.
The figure below summarizes the involvement in CMS by country. Details of each country can be found on the CMS Outreach web site.



11 CMS Milestones and Schedule

The following lists some of the important milestones for CMS, both in the past and in the future.

Task	**Foreseen Date (as of November 2003)**
Surface hall (SX5) finished construction	31 January 2000
Assembly of barrel yoke finished in SX5	31 August 2001
Assembly of endcap yokes finished in SX5	30 April 2002
Assembly of barrel HCAL finished in SX5	20 November 2002
Assembly of endcap HCAL finished in SX5	30 September 2003
Solenoid coil segments completed	30 June 2004
Underground experimental cavern completed	15 July 2004
Solenoid inserted into vacuum vessel	15 November 2004
Yoke closed and magnet test started in SX5	30 January 2005
End of magnet test in SX5	30 April 2005
Racks installed into underground service cavern	30 April 2005
Start lowering large pieces into UXC5	30 May 2005
End of lowering of major pieces into UXC5	30 September 2005
End of installation and cabling in UXC5	30 June 2006
CMS ready for circulating beam (including 20% computing capacity)	**1 April 2007**
Fully operational computing systems	1 April 2009

12 Information Resources

CMS Outreach site: http://cmsinfo.cern.ch

- Posters
- Photographs
- Collaboration information
- Etc. etc.

CMS document server: http://cmsdoc.cern.ch/cms.html

- Technical information (some of which is restricted)

CMS Technical Coordination: http://cmsdoc.cern.ch/~cmstc/schedule_and_milestones/

- Schedule and detailed milestones

13 Acknowledgements

The information contained within this document can be found in the official CMS documentation, such as the Technical Proposal, Technical Design Reports etc., and thus I thank the members of the CMS collaboration who contributed to these documents.
I also wish to thank Dr. Alick Macpherson for having the courage to read through the first version of this document and cover it with red ink!