THE ATLAS EXPERIMENT

Introduction

In particle physics experiments, the discovery of increasingly more massive particles has brought deep understanding of the basic constituents of matter and of the fundamental forces among them. In order to explore Nature in its deepest elementary secrets, the Large Hadron Collider (LHC) was built at CERN, Geneva. The LHC provides the highest energy collisions in a laboratory, at very high rates to allow one to study very rare reactions. Two independent sophisticated huge instruments, called ATLAS and CMS detectors, are operated to explore in a most broad way the physics of these collisions. In addition to these two general-purpose detectors, smaller specialized experiments (LHCb, ALICE and some others) are collecting collision data as well.

Project History

The initial ideas for LHC detectors and their physics potential were studied in 1984 at a workshop in Lausanne bringing together experimental and theoretical physicists and accelerator experts. These studies evolved in the late 1980s and early 1990s to informal detector collaborations of many dozens of Institutes developing technologies to be used in a future LHC experiment. The ATLAS Collaboration was born in summer 1992 from the merging of two such working groups which both developed detector concepts based on a toroidal muon magnet configuration. ATLAS submitted in October 1992 a Letter of Intent (LoI, a 100-page document) to the new CERN LHC Experiments Committee (LHCC) proposing a general-purpose experiment for the LHC. The LHCC is an international peer reviewing committee examining closely all scientific, technical and financial aspects of the LHC experiments.

The LoI contained a number of conceptual and technical design options that needed to be narrowed down over the course of the following years, including the critical choice of the superconducting toroid magnet system. The detector concept was basically settled by the time of the submission of the Technical Proposal (TP) to the LHCC in December 1994, which also reduced cost wherever this was possible. Nearly 20 detailed Technical Design Reports were reviewed by the LHCC for the various detector components over the years 1995 to 2005. After the TP the design underwent several changes in regards to the detailed implementation of the selected technologies, based on prototype studies in particle beam tests as well as important further cost optimizations.

The project was formally approved in January 1996, and the budget for the full construction was established with an expenditure ceiling set at 475 MCHF (in 1995 currency rate) in 1998. Only a small fraction of the funding, shared among all partners of the project, was centrally available. Detector components were built all over the world in the collaboration Institutes and local industries, under their responsibility, and then delivered to CERN as ‘in-kind’ contributions to the ATLAS detector.

ATLAS is an international, worldwide Collaboration, which grew from about 850 scientists from 88 institutions at the time of the LoI to today’s size of 3000 scientists from 178 institutions located in 38 countries from all inhabited continents. A good third of these participants are PhD students.

Description of the ATLAS Detector and its Main Components

Overall Layout

A broad spectrum of detailed studies addressing the great physics potential offered by the LHC led to the final adopted overall detector design. The primary goal of the experiment is to operate at the highest proton-proton collision rates (a luminosity of 10^{34} cm^{-2} s^{-1}, for example, means almost 10^{9} collisions per second) with a detector that provides as many signatures (signals indicating that something interesting happened) as possible. Sensitivity to a variety of signatures is important in the harsh environment of the LHC; this is required to achieve robust and redundant physics measurements with the ability of internal cross-check, while being sensitive to as many physics scenarios as possible.

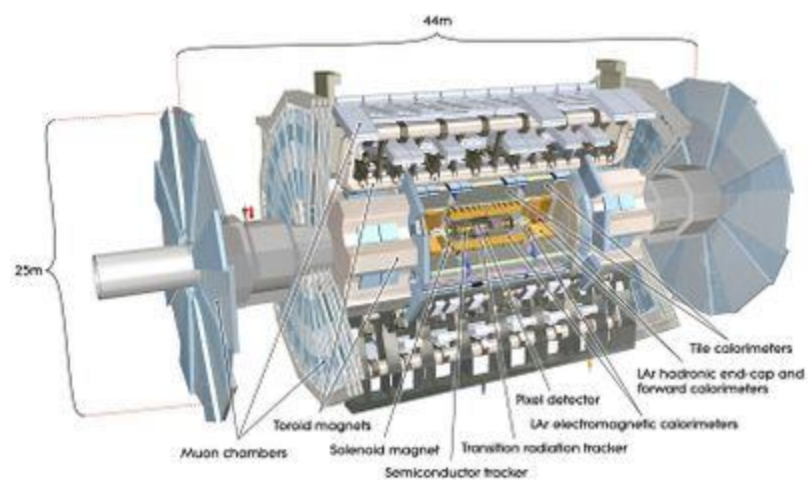

Figure 1: Longitudinal cut-away view of the ATLAS detector, showing the different layers around the LHC beam axis. The collisions occur in the centre of detector. The main detector components are indicated.

The search for the Higgs boson strongly guided the desired capabilities needed for a general-purpose LHC detector. It has to select collisions containing signatures of particles that could occur in Higgs boson decays, and measure kinematical and geometrical (flight direction) properties of these particles as accurately as possible. This information allows one then to reconstruct what happened in the collision, for example the production of a massive new particle decaying into known measurable final state particles, which are either stable or decaying further in a known way into stable particles. Examples of such signatures are photons, electrons, muons, W and Z bosons, or quarks and gluons which manifest themselves as narrow sprays of particles, known as 'hadronic jets', resulting from their fragmentation into mesons and baryons. Finally, neutrinos can be produced, which, as neutral weakly interacting leptons, leave the detector without direct trace. Momentum balance appears to be violated, leading to the signature of missing transverse momentum (loosely referred to as missing transverse energy, ETmiss), where 'transverse' means perpendicular to the beam axis.

The basic design criteria of the detector included the following points:

- Excellent electromagnetic calorimetry for electron and photon identification and measurements, complemented by full-coverage hadronic calorimetry for accurate jet and ETmiss measurements;
- High-precision muon momentum measurements, with the capability of accurate measurements at the highest collision rates using the external muon spectrometer alone;
- Efficient charged particle tracking at high luminosity for high transverse momentum (p_T) lepton-momentum measurements, electron and photon identification, τ-lepton and heavy-flavour identification, and full event reconstruction capability at lower luminosity;
- Large acceptance in pseudorapidity (η) with almost full azimuthal angle (φ) coverage everywhere. The azimuthal angle is measured around the beam axis z, whereas pseudorapidity relates to the polar angle (θ) where θ is the angle from the z direction, $\eta=-\ln(\tan\theta 2)$.
- Triggering and measurements of particles at low-p_T thresholds, providing high efficiencies for most physics processes of interest at the LHC.

The overall detector layout is shown in Figure 1. The beams collide in the centre of the detector, which is the origin of the coordinate system. A cross-section through the barrel part, perpendicular to the beam axis, illustrating schematically the functions of the different detector layers, is given in Figure 2.

Detector component	Position	Channels (total)	[Expand] η - coverage

The main active detector components of the ATLAS detector, from the beam line towards the outside. The total readout channels for each component is given, as well as its pseudorapidity coverage.

The magnet configuration is based on an inner thin superconducting solenoid surrounding the inner detector cavity, and large superconducting air-core toroids consisting of independent coils arranged with an eight-fold symmetry outside the calorimeters. Details for the various detection layers including a breakdown of the total electronics channel count of almost 100 million signals are given in Table 1. It is remarkable that during operation almost all of them, typically 99% per detection layer, are fully operational.

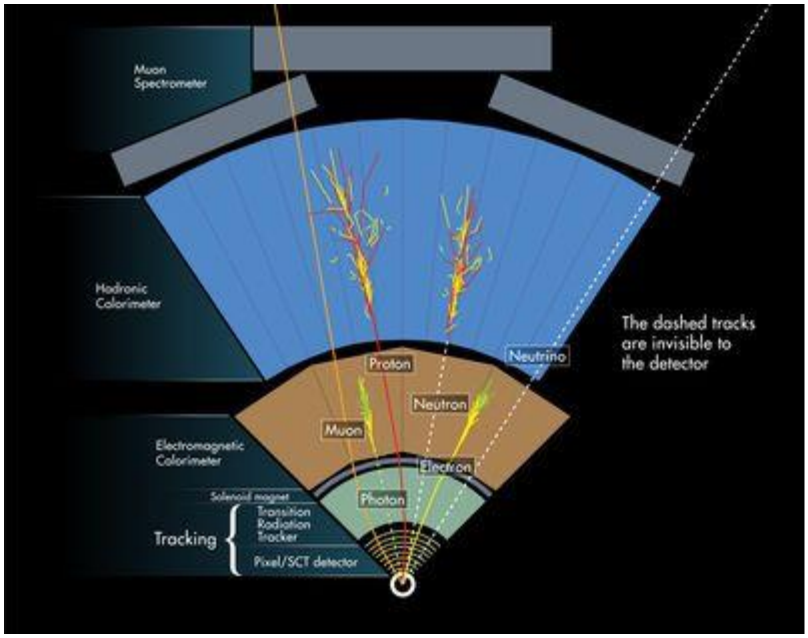

Figure 2: Schematic representation of the detector components in a plane perpendicular to the LHC beam line (transverse plane) in the barrel region. Only a small sector of the azimuthally symmetric detector is shown, starting outwards from the LHC beam vacuum pipe. Typical signatures for various particles as measured in the different detector layers are illustrated, where solid lines represent directly measurable trajectories of charged particles, and dashed lines the straight-line trajectories of neutral particles leaving no direct signals in tracking detectors.

The inner tracking detector around the collision point is contained within a cylinder of length 7 m and a radius of 1.15 m, in an axial magnetic field of 2 Teslas (T). Pattern recognition, momentum and vertex measurements, as well as additional electron identification, are achieved with a combination of a few discrete high-resolution semiconductor pixel and strip detector layers in the inner part of the tracking volume, and 'continuous' straw-tube tracking detectors giving 30-40 points along the tracks with transition radiation capability in its outer part.

Highly granular liquid-argon (LAr) electromagnetic (EM) sampling calorimetry, with excellent performance in terms of energy and position resolution, covers the pseudorapidity range $|\eta| < 3.2$. In the end-caps, the LAr technology is also used for the hadronic calorimeters, which share the cryostats with the EM end-caps. The same cryostats also house the special LAr forward calorimeters which extend the pseudorapidity coverage to $|\eta| = 4.9$ (which corresponds to only 0.85 degrees from the beam axis). The bulk of the hadronic calorimetry is provided by a novel scintillator-tile calorimeter, which is separated into a large barrel and two smaller extended barrel cylinders, one on each side of the barrel. The overall calorimeter system provides the very good jet and ETmiss performance of the detector. The LAr calorimetry is contained in a cylinder with an outer radius of 2.25 m and extends longitudinally to ±6.65 m along the beam axis. The outer radius of the scintillator-tile calorimeter is 4.25 m and its half-length is 6.10 m. The total weight of the calorimeter system, including the solenoid flux-return iron yoke which is integrated into the tile calorimeter support structure, is about 4,000 tons.

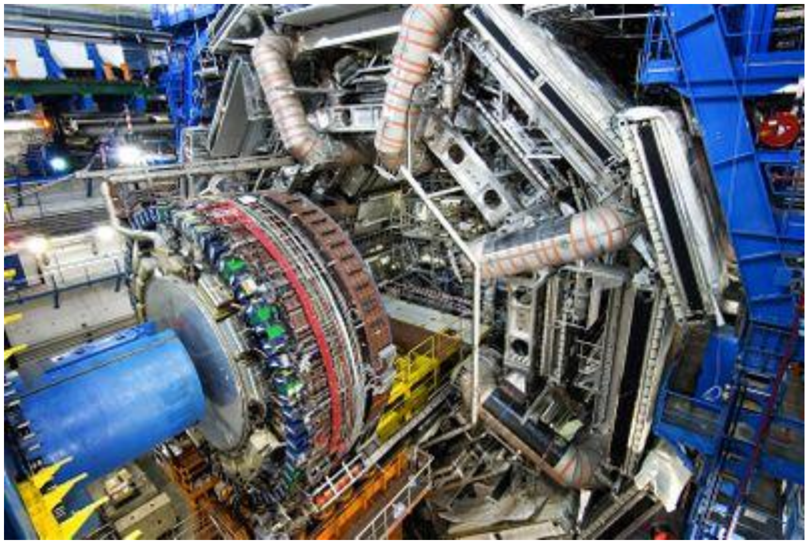

Figure 3: Photograph of one end of the ATLAS detector barrel with the calorimeter end-cap still retracted before its insertion into the barrel toroid magnet structure (February 2007 during the installation phase).

The calorimeter is surrounded by the muon spectrometer. The air-core toroid system, with a long barrel and two inserted end-cap magnets, generates a large magnetic field volume with strong bending power within a light and open structure. Multiple-scattering effects are thereby minimised, and excellent muon momentum resolution is achieved with three stations of high-precision tracking chambers. The muon instrumentation also includes as a key component trigger chambers with very fast time response. The muon spectrometer defines the overall dimensions of the ATLAS detector. The outer chambers of the barrel are at a radius of about 11 m. The half-length of the barrel toroid coils is 12.5 m, and the third layer of the forward muon chambers, mounted on the cavern wall, is located about 23 m from the interaction point.

The overall weight of the ATLAS detector is about 7,000 tons. It is installed in a large underground cavern around the LHC beam line which is about 85 m below the surface at this place. A photograph of one end of the cylindrical barrel detector, taken in February 2007, is shown in Figure 3, after about 4 years of installation work and 1.5 years before its completion.

Magnet System

The ATLAS superconducting magnet system is an arrangement of a central solenoid (CS) providing the inner tracking with magnetic field, surrounded by a system of three large air-core toroids generating the magnetic field for the muon spectrometer. This magnet system configuration is unique in the history of large particle physics experiments. The overall dimensions of the magnet system are 26 m in length and 20 m in diameter.

The two end-cap toroids (ECT) are inserted in the barrel toroid (BT) at each end and line up with the CS. They have a length of 5 m, an outer diameter of 10.7 m and an inner bore of 1.65 m. The CS extends over a length of 5.3 m and has a bore of 2.4 m. The unusual configuration and large size made the magnet system a considerable technical challenge requiring careful engineering. The CS provides a central field of 2 T with a peak magnetic field of 2.6 T at the superconductor itself. The peak magnetic fields on the superconductors in the BT and ECT are 3.9 and 4.1 T respectively.

The performance in terms of bending power is characterised by the field integral $\int Bdl$, where B is the azimuthal field component and the integral is taken on a straight line trajectory between the inner and outer radius of the toroids. The BT provides 2 to 6 Tm and the ECT contributes with 4 to 8 Tm in the 0.0-1.3 and 1.6-2.7 pseudorapidity ranges respectively. The position of the CS in front of the EM calorimeter demanded a careful minimisation of the material in order to degrade as little as possible the calorimeter performance. Therefore the CS and the LAr calorimeter share one common vacuum vessel, thereby eliminating two vacuum walls.
Each one of the three toroids consists of eight coils assembled radially and symmetrically around the beam axis. The ECT coil system is rotated by 22.5° with respect to the BT coil system in order to provide radial overlap (see Figure 1). The coils are of a flat 'racetrack' type with two so-called double-pancake windings made of 20.5 kA aluminium-stabilised NbTi superconductors. Each ECT consists of eight coils cold-linked and assembled as a single cold mass, housed in one large cryostat. Due to the magnetic forces, the ECT magnets are pulled into the BT and the corresponding axial forces are transferred to the BT cryostats via axial transfer points linking both magnet systems.

A central refrigeration plant located in the side cavern supplies the cooling power. Electrically all toroid coils are connected in series; they have a 21 kA power supply and are equipped with control systems for fast and slow energy dumps. The CS is energised by an 8 kA power supply. An adequate and proven quench protection system has been designed to safely dissipate the stored energy (1.6 GJ total energy) without overheating the coil windings.

Tracking Detectors

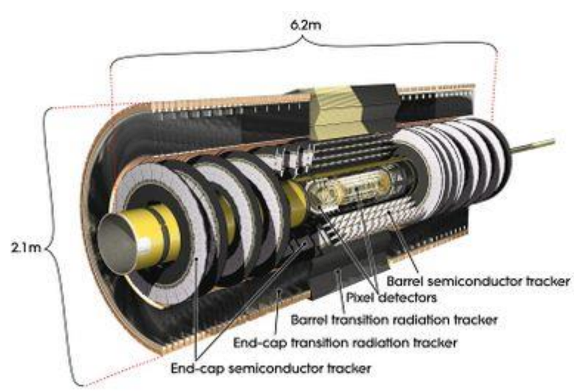

Figure 4: Cut-away view of the ATLAS tracking detectors. In this longitudinal view the different tracking layers around the LHC beam pipe are shown. The interaction point is in the centre of tracking detector.

The layout of the tracking detector is shown in Figure 4. Given the very large track density at the LHC, the momentum and vertex resolution requirements call for high-precision measurements to be made with fine-granularity detectors. Semiconductor tracking detectors, using silicon microstrip (SCT) and pixel technologies offer these features. The highest granularity is achieved around the vertex region using semi-conductor pixel detectors. The total number of precision layers was limited because of the material they introduce, and because of their high cost. Typically, three pixel layers and eight strip layers (four space points) are crossed by each charged particle. A large number of tracking points (typically 36 per track) is obtained by the straw-tube tracker which provides continuous track-following with much less material per point and a lower cost.

The combination of the two techniques gives very robust pattern recognition and high precision in both φ and z coordinates. In addition, the electron identification capabilities of the whole experiment are enhanced by the detection of transition-radiation photons in the xenon-based gas mixture of the straw tubes. Mechanically, the tracking consists of three units: a barrel part extending over ± 80 cm, and two identical end-caps covering the rest of the cylindrical detector of 6.2 m length and 2.1 m diameter. In the barrel region, the high-precision detector layers are arranged on concentric cylinders around the beam axis, while the end-cap detectors are mounted on disks perpendicular to the beam axis. The secondary vertex measurement performance is enhanced by the innermost layer of pixels, at a radius of about 4 cm, as close as is practical to the beam pipe.

Calorimeters

The ATLAS calorimeters, Figure 5, consist of an electromagnetic (EM) calorimeter covering the region $|\eta|< 3.2$, a hadronic barrel calorimeter covering $|\eta|< 1.7$, hadronic end-cap calorimeters covering $1.5 <|\eta|< 3.2$, and forward calorimeters covering $3.1 <|\eta|< 4.9$.

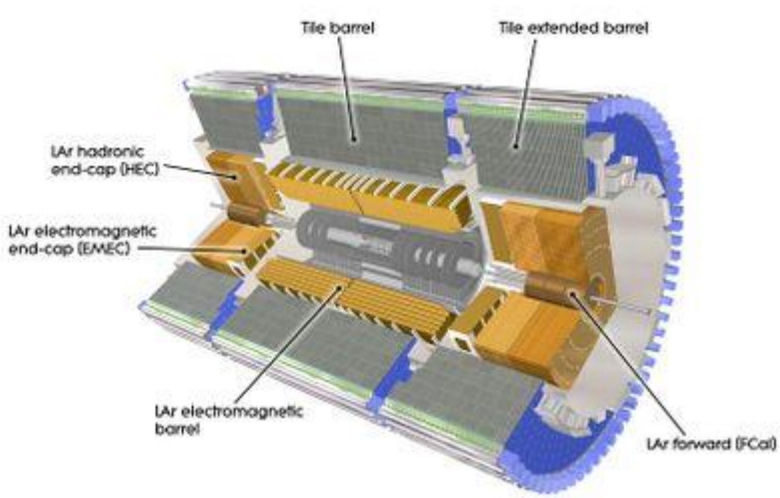

Figure 5: Cut-away view of the ATLAS calorimetry. The three distinct cylinders, barrel and end-caps, are visible. The smaller radial regions use the LAr technology requiring cryostats, whereas the outer cylinders use scintillator tiles embedded in an iron absorber structure. The end-caps can be moved longitudinally along the LHC beam line for creating access space to maintain the barrel region.

The EM calorimeter is a lead/liquid-argon detector with alternating sampling layers of 2.1 mm gaps filled by LAr with readout electrodes in the middle, and lead absorber plates (typically 2 mm thick), all shaped in a novel ‘accordion geometry’. This geometry provides fast response and full azimuthal coverage without dead regions. The EM calorimeter is preceded by a LAr presampler detector, installed immediately behind the cryostat cold wall, and used to correct for the energy lost in the material (tracker, cryostats, and solenoid coil in the barrel region) upstream of the calorimeter. The LAr technology requires cryogenic installations, as the operation temperature is typically 87 degrees Kelvin.

The hadronic barrel calorimeter is a cylinder divided into three sections: the central barrel and two identical extended barrels. It is based on a sampling technique with plastic scintillator plates (tiles) embedded in an iron absorber. The tiles are placed radially and staggered in depth. The structure is periodic along the beam axis. The tiles are 3 mm thick and the total thickness of the iron plates in one period is 14 mm. Two sides of the scintillating tiles are read out by wavelength shifting fibres into two separate photomultipliers.

At larger pseudorapidities, closer to the beams, where higher radiation resistance is needed, the intrinsically radiation-hard LAr technology is used for all the calorimeters: the hadronic end-cap calorimeter, a copper/LAr detector with parallel-plate geometry, and the forward calorimeter, a dense LAr calorimeter with rod-shaped electrodes in a tungsten matrix.

The barrel EM calorimeter is contained in a barrel cryostat, which surrounds the tracking detectors. The solenoid which supplies the 2 T magnetic tracker field is integrated into the vacuum of the barrel cryostat and is placed in front of the EM calorimeter. Two end-cap cryostats house the end-cap EM and hadronic calorimeters, as well as the integrated forward calorimeter. The barrel and extended barrel tile calorimeters support the LAr cryostats, and also act as the main solenoid flux return.

The approximately 200,000 signals from the LAr calorimeters leave the cryostats through cold-to-warm feedthroughs located between the barrel and the extended barrel tile calorimeters, and at the back of each end-cap. The electronics up to the digitisation stage is contained in radial boxes attached to each feedthrough and located in the vertical gaps between the barrel and extended barrel tile calorimeters.

Muon Spectrometer

The layout of the muon spectrometer is visible in Figure 1. It is instrumented with separate trigger and high-precision tracking chambers. Measurements are based on the magnetic deflection of muon tracks in the large superconducting air-core toroid magnets. The toroidal magnet configuration provides a field that is mostly orthogonal to the muon trajectories, while minimising the degradation of resolution due to multiple scattering.

The anticipated high level of particle fluxes has had a major impact on the choice and design of the spectrometer instrumentation, affecting required performance parameters such as rate capability, granularity, ageing properties and radiation hardness. Trigger and reconstruction algorithms have been optimised to cope with the difficult background conditions resulting from hadrons penetrating the calorimeters and from radiation backgrounds, mostly neutrons and photons in the 1 MeV range, produced from secondary interactions in the calorimeters, shielding material, beam pipe and LHC machine elements.

In the barrel region, tracks are measured in chambers arranged in three cylindrical layers (‘stations’) around the beam axis; in the transition and end-cap regions, the chambers are installed vertically, also in three stations. Over most of the η-range, a precision measurement of the track coordinates in the principal bending direction of the magnetic field is provided by Monitored Drift Tubes (MDTs). Close to the beam axis and near to the interaction point, Cathode Strip Chambers (CSCs) with higher granularity are used in the innermost plane, to withstand the demanding rate and background conditions. Optical alignment systems have been designed to meet the stringent requirements on the position accuracy and the survey of the precision chambers. The precision measurement of the muon tracks is made in the R–z projection, the direction parallel to the bending direction of the magnetic field; the axial coordinate (z) is measured in the barrel and the radial coordinate (R) in the transition and end-cap regions. The MDTs provide a single-wire resolution of ~80 microns when operated at high gas pressure (3 bars). The fast trigger system covers the range $|\eta| < 2.4$. Resistive Plate Chambers (RPCs) are used in the barrel and Thin Gap Chambers (TGCs) in the end-cap regions.

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