Chapter 9

Integration and installation

9.1 Introduction

The ATLAS detector has been installed underground in a huge cavern, situated in Switzerland at point 1 on the LHC ring, directly opposite the main entrance to the CERN site. The installation task has involved a large team from across the whole collaboration (see annex 11.3).

The soil conditions at point 1 were favourable for the large amount of excavation work required. Once the experiment was approved, preparations for the infrastructure began: civil engineering, electrical power distribution, cooling water, ventilation, etc. In parallel to the work on the infrastructure, many studies on the assembly, integration, layout, support structures, services (pipes and cables), safety issues and access requirements/means for the experiment were carried out.

The construction of the component parts for ATLAS was distributed over many institutions around the world. The components then had to be brought to CERN in a timely manner, a considerable challenge in itself in terms of their size, complexity and fragile nature. In most cases, final assembly and testing were done at CERN on the surface, prior to installation underground.

The main cavern is 92.5 metres underground and the detector is almost as large as the cavern in which it is housed. Supervising the construction of such a complex project meant that rather formal and uniform management and engineering tools had to be used to monitor and document the progress of the project and ensure that items arrived on time and satisfied the requirements. Ensuring that all the pieces of the puzzle fitted together turned out to be a particularly difficult challenge, since the physics goals and the geometry of the detector require minimal clearances between neighbouring parts. One of the most stringent requirements of the ATLAS detector is to ensure hermetic coverage over most of the solid angle: installation of the detector had therefore to be performed to great accuracy, in order to guarantee optimal coverage.

After a brief description of the processes and tools used to fulfil the infrastructure, integration and installation tasks (section 9.2), this chapter briefly describes the mechanical integration (section 9.3), the overall infrastructure and services at point 1 (section 9.4), the support and access structures (section 9.5), the detector installation process (section 9.6), the detector opening and access scenarios (section 9.7), the beam-pipe (section 9.8), safety issues (section 9.9), and the interfaces to the LHC machine (section 9.10).

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Table 9.1: List and function of the various software tools used by ATLAS technical coordination during the installation of the detector.

Tool	**Function**
Engineering data management system (EDMS)	Structured storage and retrieval of engineering data
CERN drawing directory (CDD)	Processing of technical drawings
Project progress tracking (PPT)	Regular Web-based notification and reporting system
Equipment management database (EMD) and manufacturing and test folder (MTF) database	Traceability of all equipment installed in the cavern
Rack wizard and ATLASeditor3D	Configuration of electronics rack connectivity (from detector to counting room)
ATLASsurvey3D	Monitoring of ATLAS sub-system displacements (also uses survey data)
Cable database	Assist cable installation team (labels, routing, connector specifications, etc)
The Glance Project	Interacts with all equipment data residing in distinct and geographically spread repositories

9.2 Organisational issues

The ATLAS project involves many people who are spread around the world. It has also generated a huge, complex and multi-disciplinary volume of data which needs to be organised and shared in an easy and transparent way. The management of the integration and installation work was the responsibility of the technical coordination team. In order to help manage the design, production and installation phases of the ATLAS project, various organisational processes and computing tools were developed [242]. The design phase of the project required the production of drawings, schedules and specifications for procurement. A number of review processes were included during this phase of the project. The goal of these reviews was to evaluate the feasibility and technical validity of the proposed designs. In addition to these reviews, and before launching the production of major items, internal design reviews and production-readiness reviews were organised. Then, during the production phase of the sub-systems, production-advancement reviews were implemented to check progress and compare it with the production milestones in the schedule. In case of specific and major technical issues, experts were called in from within and outside the collaboration to solve such problems in a timely fashion.

The ATLAS technical management board meets on a monthly basis and provides a forum for regular reporting of the status and problems in all areas relevant to the work at point 1 to the collaboration scientists and engineers. During these meetings, the installation schedule is discussed and proposed future strategies are agreed upon. During the installation of ATLAS, the progress and status of the work were monitored on a weekly basis in dedicated meetings with each main detector system. The Web-based tools shown in table 9.1 were used to assist in the communication and organisation process.

9.3 Mechanical integration

The mechanical integration process had to address both static issues related to installation and survey of major detector components and dynamic issues related to detector placement, movements of parts during installation, and to access and maintenance (see section 9.7). This section deals with the mechanical integration aspects related to installation.

The mechanical integration process defined the overall experimental layout, where each nested sub-system has its well-defined shape and position and has no overlaps with any other sub-system. This integration process started from an initial input for the positioning of the sub-systems and for the space needed for access and services. It then defined mechanical envelopes and the overall three-dimensional layout of the ATLAS detector, using most of the tools listed in table 9.1.

9.3.1 Envelopes (individual, global, dynamic)

Envelopes define the space allocated to each part of each sub-system. Three types of envelopes have been created, individual, global and dynamic, and they are defined as follows:

- The individual envelope is the space allocated for the manufactured object, including some space added to the nominal design drawing envelope, in order to take into account fabrication and assembly tolerances.
- The global envelope includes, in addition to the individual envelope, some space dedicated to the inaccuracy of the positioning inside the detector and the deformations applied during installation and operation.
- The dynamic envelope includes, in addition to the global envelope, space for deviations and deformations during displacements (e.g. during access) of the object inside the detector.

After the manufacture and installation of each sub-system, the envelopes were checked and compared to the measurements performed by the survey team. Envelopes have been created as 3D objects with the help of various CAD systems. All this work on modelling and conflict-checking has been most important in order to facilitate the installation process and avoid cost and schedule problems between conflicting objects during installation.

9.3.2 Survey and placement strategy

ATLAS is being assembled in a cavern which is not much larger than the detector itself. Thus any available space had to be optimised once an installation was complete. As soon as the cavern was delivered to ATLAS by the civil engineers, and before any infrastructure was installed, an exhaustive scan was carried out in order to check the as-built work. The task of surveying for the ATLAS detector has been a very challenging one due to the size, nature, complexity and global scale of the work.

9.3.2.1 Survey reference grid in the cavern

The nominal beam-line was defined and used during the installation and positioning of the detectors in the cavern. It is defined by the best-fit alignment line of the low-β quadrupole magnets, located at a distance of 30 m from either side of the interaction point. This reference line can deviate from the real beam-line by as much as 2-3 mm. It is determined by the reference sockets in the tunnel, from which the machine elements are installed. The final control is carried out on the machine elements themselves (inner focusing quadrupole triplets included) relative to each other. Spatial uncertainties from 0.5 mm to 1.2 mm at the one sigma level was estimated for any fiducial mark with respect to the nominal beam-line depending on the location of the given target.

The datum (interaction point, radial orientation of the colliding beams and reference plane) is given by the initial geometry in the tunnel and the final positioning of the low-β quadrupole magnets. The survey grid reference in the cavern is linked to the machine geometry by standard geometrical measurements and permanent monitoring systems. These include hydrostatic and wire positioning capacitive sensors, implemented in the survey galleries and joining the low-β quadrupoles via the cavern and radial tubes [243]. The reference grid will thus be monitored throughout the lifetime of the detector.

9.3.2.2 Stability measurements of the floor and the bed-plates

Civil-engineering calculations indicated possible vertical floor movements of up to 6 mm settlement due to the loading of the detector and a 1 mm per year lift due to excavation heave. ATLAS has a very limited adjustment capability once the detector elements have been placed in-situ. A placement strategy was therefore developed to position all elements within the best achievable mechanical tolerance, relatively to the interaction point and the nominal beam-line [243].

To monitor these predicted movements, periodical measurements have been carried out on about 20 reference marks embedded in the cavern floor. The measurements are referenced to the machine levelling and to deep reference points in the tunnel.

In addition to these measurements, a permanent hydrostatic system has been implemented in the ATLAS support feet bed-plates. It consists of six capacitive sensing stations monitoring the water plane in two 25 m long tubes, 55 mm in diameter, parallel to the beam and linked by a transversal tube. Two additional stations have been installed in the extreme trenches, recognised as stable zones, and linked to the bed-plate system. Altogether, this is equivalent to a reference water plane of 75 m length, inspected by eight sensors attached to the structure (bed-plate and stable floor) within an accuracy of better than 20 microns.

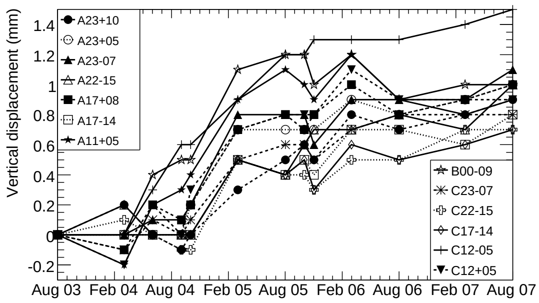

Figure 9.1: Vertical displacements of the ATLAS cavern floor, measured as a function of time in various reference points since August 2003. The beam interaction point is at the origin ($x = 0$, $z = 0$). The labels used for the reference points are the following: C23-7 represents a point on side C at a distance of 23 m longitudinally from the interaction point and of 7 m radially opposite to the centre of the LHC ring. In contrast, A23+10 represents a point on side A at the same longitudinal distance from the interaction point, but at a distance of 10 m radially towards the centre of the LHC ring. The points labelled B are located right in the middle of the cavern, nominally at $z = 0$.

The results from the measurements on the floor, as displayed in figure 9.1, show that, after an initial stable period, during which presumably the heave of the floor was balanced by the loading, a global heave of the floor of up to 1.2 mm happened in the central part of the cavern between March 2004 and March 2006. By August 2006, approximately 85% of the total load had been installed and, over the past 12 months, the cavern floor seems to have settled more or less and the upward heave is no longer visible.

The hydrostatic system in the bed-plates gives immediate movements of the supporting structure with an accuracy of a few microns and has been used to monitor local movements when inserting the calorimeters. It will now be operated continuously to monitor movements in real time during data-taking.

9.3.2.3 Placement of ATLAS sub-systems

The ATLAS detector had to be assembled in the main cavern mostly because of the nature of the barrel toroid magnet structure, which is 26 m long and 20 m in diameter. As discussed above, once assembled and cabled, the detector and its main components cannot in practice be adjusted any more relative to the nominal beam-line. Careful consideration had therefore to be given to the optimal placement of sub-systems during the assembly process. Many sub-systems were prepared on the surface, while others were prepared in the main cavern, prior to their installation in their final position. The aim was to place all the detectors such that they will all be at their appropriate positions relative to the nominal beam-line, once the installation is completed. In the process of defining the initial placements, the following input had to be taken into account:

- floor movement in the ATLAS main cavern (see above);
- deflections of the barrel toroid structures as they were loaded with the muon chambers and the services passing throughout ATLAS;
- deviations of as-built dimensions with respect to the nominal ones for neighbouring sub-systems;
- deviations from nominal of the relative placements of different components, which were installed as one assembly. For example, the solenoid and the LAr barrel electromagnetic calorimeter were assembled on the surface inside their common vacuum vessel with a non-negligible relative error with respect to their theoretical placement. When placing the whole assembly in the cavern, the priority was therefore given to the solenoid regarding the relative importance of nominal placement for ATLAS operation;
- uncertainties on the position of the interaction point from the uncertainties on the closed-orbit calculations and on the placement of the machine components.

Once an assembly of different sub-systems was completed, the relative position of its components was fixed. As the most prominent example, the barrel calorimeter assembly consists of: the barrel tile calorimeter, itself assembled from 64 individual tile modules, the barrel LAr cryostat, which includes the solenoid, the barrel LAr electromagnetic calorimeter and the support rails for the inner detector, located on the inner bore of the cryostat.

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Table 9.2: Placement accuracy and current average position along the vertical y direction of different components of the ATLAS barrel system. The average positions in y are given as an illustration of the priorities set in the placement strategy between conflicting requirements from different components of the barrel system.

Assembly	Component	Placement accuracy (mm)	Average position in y (mm)
Barrel toroid		10 (all coils)	Magnetic axis at -8
Barrel calorimetry	Solenoid	2	Magnetic axis at -2.3
Barrel calorimetry	EM calorimeter (side A)	3	-3.1
Barrel calorimetry	EM calorimeter (side C)	3	-2.3
Barrel calorimetry	Cryostat	2	-0.1
Barrel calorimetry	Tile calorimeter	3	Axis at -0.5
ID pixel		0.2	-1.2
ID barrel	SCT	0.5	-1.3
ID barrel	TRT	0.5	-1.6
ID end-cap (side A)	SCT	0.5	-1.9
ID end-cap (side A)	TRT	0.5	-1.6
ID end-cap (side C)	SCT	0.5	-2.4
ID end-cap (side C)	TRT	0.5	-1.6

The strategy for the placement of a given assembly was the following:

1. determine the best position for the assembly, taking into account the input described above;
2. after the initial placement was completed, survey the assembly as installed and perform adjustments wherever possible to come as close as possible to the optimal position;
3. once a major component has been placed, update the envelope drawings to take advantage of the as-installed envelopes of the various components. In most cases, the components respected the assigned envelopes, and it was possible to recuperate some space, which was used either to increase the stay-clear area between assemblies or to optimise further the position of subsequent assemblies. In rarer cases, such as the barrel and end-cap inner detector assemblies, the distance between the assemblies had to be increased by 5 mm with respect to nominal. These deviations are accounted for in the final detector description of the as-installed detector.

Table 9.2 shows the placement accuracies achieved along the vertical axis for the main components of the ATLAS barrel system relative to the nominal beam-line. Table 9.2 also shows the measured offsets in the vertical direction, illustrating the priority given to the placement of the solenoid as close as possible to the nominal beam-line and to the subsequent placement of the inner-detector components as close as possible to the nominal solenoid axis.

The placement accuracy along the beam-line is also in the few millimetre range, but there are exceptions in some cases due to conflicts in envelopes between neighbouring sub-systems. The components of a given assembly are grouped together under the same heading to indicate clearly that their relative position with respect to each other was determined prior to final installation. These relative positions are in many cases more precise than the overall placement accuracy of the

Table 9.3: Placement accuracy and current average position along the vertical y direction of different components of the ATLAS end-cap systems.

Assembly	**Component**	**Placement accuracy (mm)**	**Average position in y (mm)**
End-cap toroid (side A)		3	Align magnetic axis with barrel toroid
End-cap toroid (side C)		3	Align magnetic axis with barrel toroid
End-cap calorimeter (side A)	FCal	1	Align FCal symmetrically around beam-pipe
End-cap calorimeter (side A)	EMEC	3	-0.8
End-cap calorimeter (side A)	HEC1	3	-0.6
End-cap calorimeter (side A)	HEC2	3	0.5
End-cap calorimeter (side A)	Tile	3	-1.9
End-cap calorimeter (side C)	FCal	1	Align FCal symmetrically around beam-pipe
End-cap calorimeter (side C)	EMEC	3	-0.9
End-cap calorimeter (side C)	HEC1	3	-0.1
End-cap calorimeter (side C)	HEC2	3	-0.3
End-cap calorimeter (side C)	Tile	3	-0.4
Small wheels	MDT/CSC/TGC	4	Align on nominal beam-line
Big wheels	MDT/TGC	4	Align on nominal beam-line
End-wall chambers	MDT	4	Align on nominal beam-line

assembly, as for example in the case of the SCT and TRT, or even as in the case of the pixels with respect to the ID barrel, for which special care was taken to adjust the fixation points between the two sub-systems on the surface after assembly of the complete ID barrel in order to ensure that the geometrical axis of the pixel sub-system will be within 0.2 mm of the nominal beam-line. It is also important to note that the placement of the ID components with respect to the inner warm vessel of the barrel cryostat has been surveyed with an accuracy of approximately 0.3 mm, which is very similar to that achieved for the survey of the mapping machine used for the mapping of the solenoidal field (see section 2.2.4).

In a similar way, albeit less complete because of installation work still ongoing in the end-cap regions of the detector, table 9.3 summarises the positioning status of the end-cap calorimeters, the small wheels, the big wheels, the end-cap toroid magnets and the end-wall chambers. All the end-cap detectors can in principle be adjusted relative to the nominal beam-line, when the ATLAS detector is in the open position. In order to monitor possible small changes of detector positions after opening and closing the apparatus, an active optical system has been installed, which will provide a precise monitoring (20 μm in the transverse plane and 100 μm along the beam) of the relative position of these components with respect to the barrel system.

The placement strategy explained above has been quite successful and all major ATLAS components are located well within the initial target of being aligned to within a few millimetres from the nominal beam-line at the start of data-taking.

More detailed information on the location of individual assemblies is kept in the various databases and will be updated as movements are monitored over time. As an example, figures 9.2 and 9.3 show the current deviations of the geometrical axes of the main components of the ATLAS

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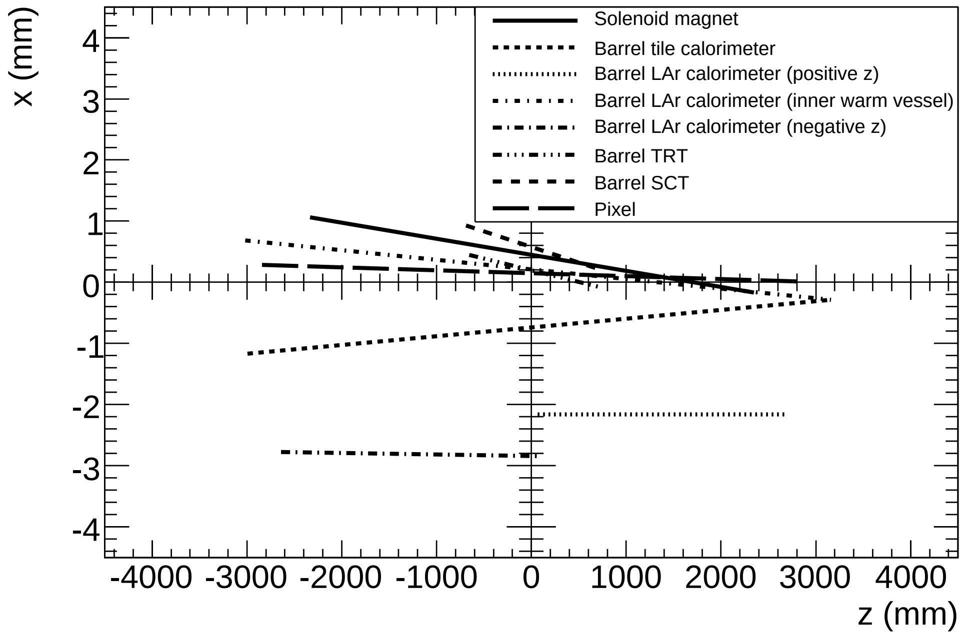

Figure 9.2: Deviations of geometrical axes of main components of the ATLAS barrel from nominal. Shown are the deviations in mm in the $x-z$ plane.

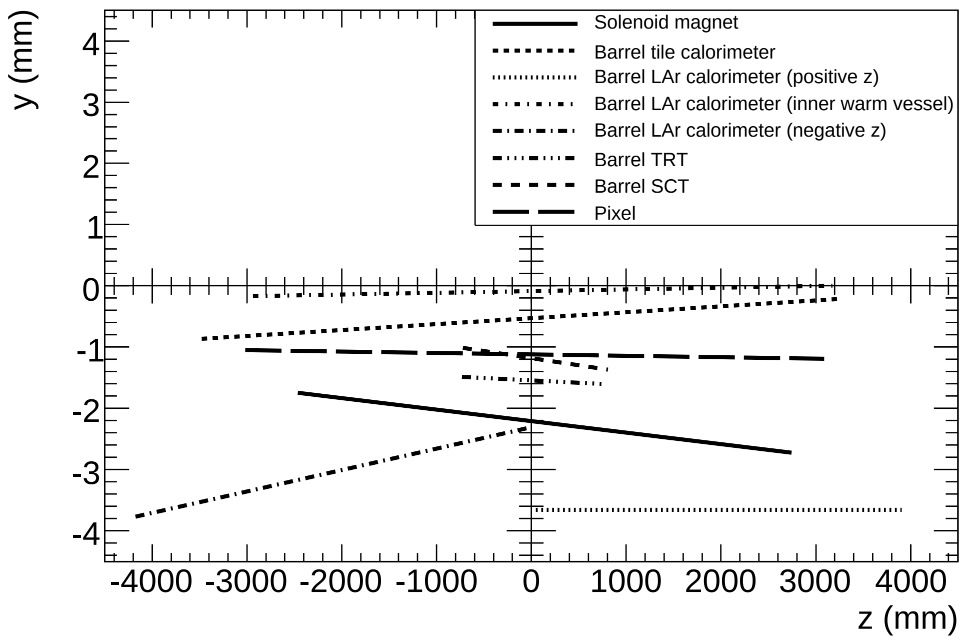

Figure 9.3: Deviations of geometrical axes of main components of the ATLAS barrel from nominal. Shown are the deviations in mm in the $y-z$ plane.

barrel from the nominal beam-line, respectively in the $x-z$ and $y-z$ planes. Since the full loading of the detector in the barrel region, a larger than expected compression of the support feet has been observed. This has led to a 1.5 mm downward shift of the whole barrel, as can be seen more precisely from the average y-positions of the axes of the inner-detector sub-systems in figure 9.3. All these initial positions are recorded in the overall database and they will be monitored with time as soon as new survey numbers become available or as the access and maintenance scenarios will require.

It will also be necessary to monitor the global movements of the detector to understand possible future deviations in position between the detector and the actual beam. In the case of such deviations at the level of 1 mm, the beams can be adjusted and steered, using the field in the triplet magnets and/or adjusting the position of the last magnet. In the event of larger movements, it will be necessary to adjust the magnets over the last 300 m on either side of the interaction point. It has been expected that such an exercise can be done once every three to four years.

9.4 Infrastructure and detector services

This section describes the infrastructure for the surface and underground areas and the services, fixed and mobile, which are connected to the ATLAS detector [244].

9.4.1 Civil engineering

The civil engineering work for the ATLAS experimental area started in November 1997 whilst the previous accelerator (LEP) was still in operation and the situation remained so until the end of 1999. The work included the excavation and concreting of two new shafts, two new large caverns along with the linking galleries, and the construction of six new buildings on the surface, as shown in figure 9.4.

The underground work included the excavation and concreting of the following:

- The PX14 and PX16 shafts, respectively 18 m and 12.6m in diameter, both 60 m deep.
- The PX15 shaft was an existing shaft that required concreting only.
- The main cavern UX15 (50 m long, 30 m wide and 35 m high), which houses the ATLAS detector. Due to the continued operation of LEP in 1999, the vault had to be concreted before the support walls were put in place, leading to a non-standard anchoring technique of the 7000 t roof of the UX15 cavern. UX15 was delivered to CERN for the installation of the infrastructure in June 2003.
- The counting room and service cavern USA15, which houses the electronics racks and services that need to be close to the detector and is accessible during machine runs.
- The seven linking galleries for personnel access and the distribution of services between the UX15 and USA15 caverns.

The surface buildings include the following:

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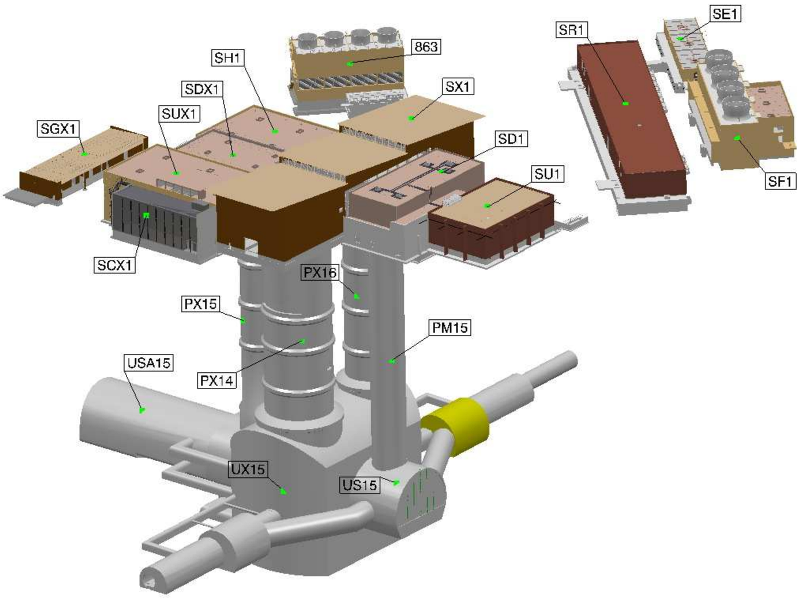

Figure 9.4: Layout of surface buildings and of access shafts to the ATLAS cavern at point 1. The main areas of underground activity are the main cavern (UX15) and the main counting room and service cavern (USA15). The main control room is in building SCX1 on the surface.

- SX1, a steel frame building located on top of the main shafts and housing the travelling cranes, maximum 280 t capacity. Used as short term storage of detector components, prior to their lowering into the main cavern. It also acts as a shelter from the external environment and allows better control of the conditions in the cavern. This building was the first to be structurally achieved allowing the infrastructure works to take place in dry conditions.
- SDX1, located on top of the personnel access shaft and used for the personnel and material access control to the underground areas. It also contains the uninterruptible power supplies for the detector services, an electrical sub-station, and the DAQ room.
- SUX1, the ventilation building, containing the water chillers and air-conditioning units for the underground areas and the new surface buildings.
- SCX1, the main ATLAS control building, used during the detector assembly phase as an engineering design office.
- SH1, a concrete building, containing the noisy cryogenic compressors and other cryogenic equipment.
- SF1, the new cooling towers for the final dissipation of heat recovered from all the underground areas and surface buildings via the water cooling circuits.

Figure 9.5: Air ducts installed for ventilation in the shaft and main cavern.

9.4.2 Electrical power distribution

The total electrical power required on the ATLAS site at point 1 is about 13 MW, which has resulted in the installation of a new 66 kV sub-station, the reorganisation of the existing 18 kV sub-station, and a new 3.3 kV sub-station. Some 21 new transformers with a total power of 42 MW have been installed both on the surface and underground to bring the 3 kV or 400 V/230 V power to all ATLAS systems.

There are different power networks to deal with the appropriate levels of continuous and safe operation:

- Assured power: the normal power is backed up by two diesel generators of 1 MW each, located on the surface;
- Secured power: the technical solution is as for assured power, but it is not interrupted when emergency stop buttons are activated;
- Un-interruptible power: these very critical systems are fed by battery back-ups with a total power of approximately 700 kW.

9.4.3 Air-conditioning and cooling systems

The global environmental requirements in the bulk of the ATLAS cavern are driven by general considerations and by more specific ones from the muon spectrometer chambers. The temperature should remain stable at 25$\pm$3°C and the humidity should be between 25% and 60%. The cooling and ventilation installation was one of the first infrastructure items to be installed, once the surface buildings had been handed over to CERN, in order to rapidly provide ventilation to the underground

Table 9.4: Overview of main characteristics of the major cooling systems operating in the ATLAS cavern.

System	Medium	Capacity (kW)	Channel count	Operating temperature (°C)
Tile calorimeter	Water	55	24 cooling loops supplying 256 tile fingers	17 to 22
LAr calorimeter	Water	250	24 cooling loops supplying 60 electronic boxes	17 to 22
Diffusion pumps	Water	50	12 cooling loops supplying 26 diffusion pumps	14 to 19
Muon spectrometer and general-purpose stations	Water	300	26 cooling loops supplying CSC's plus racks for small and big wheels	17 to 22
ID evaporative (pixel and SCT)	C_3F_8	60	4 distribution areas supplying 204 cooling channels	-30 to 10
ID mono-phase (TRT)	C_6F_{14}	70	4 distribution areas supplying 176 cooling channels	14 to 22
ID mono-phase (cables)	C_6F_{14}	80	32 distribution manifolds placed all over the detector	14 to 22

areas. This installation included new cooling towers in SF1, the liquid chillers in SUX1, 16 air-handling units in SUX1, SDX1, SX1, and USA15 and kilometres of water pipes and air-ducts. The system is able to cope with emergency cases in fast-extraction mode (see section 9.9).

One of the most challenging tasks was the installation of air supply and extraction ducts in the PX14 shaft, as shown in figure 9.5, and on the vault of the UX15 cavern, this system having the task of extracting the 200 kW of heat released into the air of the cavern by the ATLAS detector. The air-conditioning system has been up and running since summer of 2004. Provision has been made for thermal screens to be incorporated inside the detector to prevent a too large temperature gradient across the inner layer of muon chambers.

Table 9.4 summarises the characteristics of the main cooling systems used for extracting the heat from the detector itself (silicon-sensor leakage currents and ionisation in the TRT gas, as summarised in table 4.10), from the on-detector and off-detector electronics, and from dissipation in the power cables. Most cooling systems are leakless by design and the inner detector has chosen fluorinert systems to minimise risks to the detector in case of leaks. In the case of the pixel and SCT sub-systems, a novel and complex evaporative system has been designed and brought into operation to minimise the amount of material devoted to cooling pipes, fluids and connectors on the detector itself. The detector-specific cooling systems are installed in the USA15 side cavern and have been brought into operation in 2005 and 2006.

9.4.4 Gas distribution

The ATLAS detector requires a variety of gases for its normal operation. Table 9.5 summarises the characteristics of the main gas systems used for normal operation.

The surface gas building SGX1 was designed for the storage, distribution, and mixing of inert and flammable gases in accordance with the CERN regulations. The building was completed

Table 9.5: Overview of main characteristics of the gas systems operating in the ATLAS cavern.

System	Gas mixture	Pressure (bar)	Volume (m^3)	Channel count	Impurity limits
TRT active gas (normal operation)	$Xe/CO_2/O_2$ 70/27/3	1.005	2.5 (detector) 2.0 (gas system)	48 for barrel 14 per end-cap	$<$ 100 ppm CF_4
TRT active gas (cleaning mode)	$Ar/CO_2/CF_4$ 70/26/4				$<$ 100 ppm H_2O
TRT ventilation (flushed to atm.)	CO_2 (barrel)	1 ± 0.001	2.9	48	$<$ 100 ppm H_2O
TRT cooling (closed loop)	CO_2 (end-cap)	1 ± 0.001	6.0	4	$<$ 1% N_2 $<$ 100 ppm H_2O
SCT ventilation (flushed to atm.)	N_2	1.004		4	$<$ 350 ppm H_2O
Pixel ventilation (flushed to atm.)	N_2	1.004		1	$<$ 350 ppm H_2O
ID ventilation (flushed to atm.)	CO_2	1.0005		13	$<$ 1% N_2 in ID
MDT active gas	$Ar/CO_2/H_2O$ 93/7/($\leq$ 1000 ppm)	3 (abs.)	710	112 for barrel 81 per end-cap	$<$ 100 ppm O_2
CSC active gas	Ar/CO_2 80/20	1 ± 0.001	0.5	32	$<$ 100 ppm O_2
RPC active gas	$C_2H_2F_4$/Iso-C_4H_{10}/SF_6 94.7/5/0.3	1 ± 0.001	14	128	$<$ 1% O_2 $<$ 100 ppm H_2O
TGC active gas	CO_2/n-pentane 55/45	1 ± 0.001	16	128 for active 56 for CO_2 purge	$<$ 5 ppm at entrance of n-pentane liquefier

in 1997. Large quantities of liquid gases are stored, both inside and outside this building, in particular N_2, CO_2, Ar, Xe, He, $C_2H_2F_4$, CH_4, C_4H_{10}, and n-C_5H_{12}. The building is also fitted with an anti-deflagration roof, mechanical ventilation, permanent gas extraction and gas detection, and an alarm system. The mixing room contains the mixing systems for the different sub-detectors. The TRT, MDT's, CSC's and RPC's use non-flammable gases. Only the muon TGC's will use flammable gas (CO_2/n-pentane).

The underground installation consists of a large network of stainless-steel pipes, which convey the gases to the gas room located in the USA15 cavern and then to the gas racks in the main cavern. From the gas racks, many kilometres of pipes have been installed. They connect to all the different types of muon chambers (see section 6.9.1) and to the inner detector (see section 4.2.2).

9.4.5 Cryogenic systems

The ATLAS detector includes two independent systems requiring cryogenic technologies: the superconducting magnets and the liquid argon calorimeters. The cryogenic systems for the magnets and the LAr detectors have each been divided into three parts:

1. External cryogenics, which comprise all the equipment needed to provide the required cooling capacity at given temperature levels, including refrigeration plants and infrastructure. This equipment is located on the surface in the SH1 building and underground in the USA15 cavern. Also, six large helium gas storage tanks (3 m diameter, 21 m long) have been installed on the surface behind the SX1 building.

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2. Proximity cryogenics, which comprise all the equipment linking the internal cryogenics to the external cryogenics. This equipment is located in the main cavern, on the steel structure (HS) that surrounds the detector (see section 9.5).

3. Internal cryogenics, which comprise all the devices located inside the system concerned (magnets or liquid argon calorimeter).

The cryogenics systems for the magnets are described in some detail in section 2.1.4.2. This section is devoted to a brief description of the cryogenics systems for the LAr calorimeters.

The primary cooling source for the LAr calorimeter installation is a 20 kW nitrogen refrigerator, which operates at 80 K. Under normal circumstances, the LAr cryostats are filled only once and the liquid argon is never replaced. The argon is kept in the liquid phase by cooling it with liquid nitrogen (which has a slightly lower boiling point than argon) circulating in cooling pipes surrounding the calorimeters. These cooling pipes are also used during the cooling down of the cryostats. The flux and pressure of the liquid nitrogen are regulated such that its boiling point temperature corresponds to the cooling power required to keep the liquid argon at its operating temperature.

The compressor station is placed in the SH1 surface building and the cold box in the USA15 side cavern. The high- and low-pressure gas lines connecting these two items pass through the PX-15 shaft. The cold box delivers its cooling power to a 15,000 litre phase-separator dewar placed in the main cavern. Two 50,000 litre liquid nitrogen storage tanks placed on the surface will supply liquid nitrogen to the phase-separator dewar via a 283-metre long transfer line, in case of problems with the nitrogen refrigerator system. A cryogenic centrifugal pump circulates the liquid nitrogen from the phase-separator dewar through the thirteen heat exchangers placed in the liquid argon cryostats. Each cryostat has been equipped with a valve box, which regulates the mass flow and pressure of the liquid passing through each of the individual heat exchangers. These valve boxes are placed on the HS surrounding structure.

The gaseous nitrogen coming from the heat exchangers is returned to the phase-separator dewar and from there returned to the nitrogen refrigerator system or, in case it is not operational, vented to the surface through a 120-metre long gas line. The three cryostats, placed at the heart of the detector, are linked by large-diameter argon lines to their individual expansion vessel placed on the HS structure. The liquid/gaseous argon boundary of each of the cryostats is located in these expansion vessels.

The need to move the calorimeter end-cap cryostats over a 12 m distance required the implementation of a movement system for the argon and nitrogen lines connecting these cryostats with their expansion vessels and the nitrogen regulation valve boxes. These movement systems are located on the HS structure and are described in section 9.7. Figure 9.6 shows the underground layout of the proximity and external cryogenics for the LAr calorimeters (shown as if installed alone for convenience). One can clearly see the fixed cryogenic lines supplying the barrel calorimeter at the top and also the cryogenics lines in the flexible chains, which supply the two end-cap calorimeters and which follow them whenever they have to move for access and maintenance of the detector.

The 84 m^3 of liquid argon present in the cryostats can, in the event of problems, be emptied by gravity into two 50 m^3 argon storage tanks placed at the lowest point of the main cavern. A

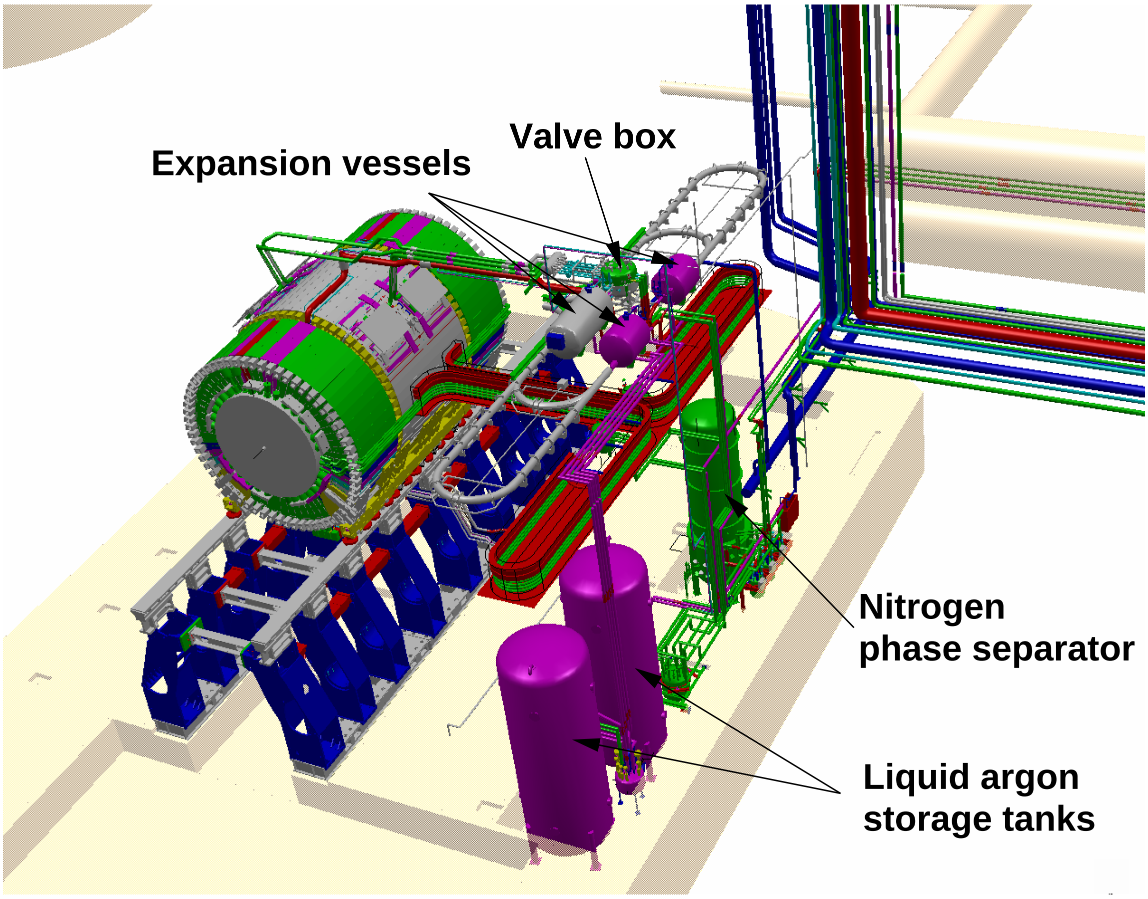

Figure 9.6: Layout of the underground external and proximity cryogenics lines for the LAr calorimeters.

DN500 safety valve line collects any gas coming from the pressure safety valves placed on the cryostats, or storage tank volumes venting it to the surface.

9.4.6 Racks and cables

Prior to the start of the civil engineering work, the detailed cabling and rack needs were not known. The consolidated data from the various sub-systems was provided only much later and the correct provisions for the distribution of cables from the detector to the electronics racks in the counting room and service caverns were therefore made just before the start of the installation work. These included:

- locations for 100 racks in the main cavern, supported from the HS steel structure which surrounds the detector;
- the arrangement of the service cavern and counting room (USA15) with provision for 250 racks on two floors, equipped with a 2.5 MW water-cooling system;

- two main cable distribution galleries, which connect the main cavern to the counting room with provision for 44 cable trays, each $600 \times 100\,\mathrm{mm}^2$ in cross-section;
- the distribution of these 44 cable trays on the HS supporting structure around the perimeter of the detector and to the HO supporting structure on the end-walls of the cavern (see section 9.5).
- locations for 70 racks in another service cavern (US15) together with about 20 holes, each 300 mm in diameter, through the 2 m-thick connecting wall for the passage of cables, with the associated cable-tray distribution system in the existing false floor and with a dedicated cooling system of 500 kW capacity;
- locations for 100 racks in a self-contained data-acquisition room in the SDX1 surface building with a 500 kW total water-cooling capacity and a dedicated 100 kW air-conditioning system.

The various electronics units for the detector are thus installed in racks, implanted in USA15, UX15 and US15 in the underground areas, and in the data-acquisition room on the surface. The total number of racks (electronics, gas and water) for ATLAS amounts to approximately 500. The Rack Wizard tool mentioned in section 9.2 is essential to monitor the evolution of the racks with time. The power requirements, specific contents and the connections are constantly updated as they evolve: this is required not only for the maintenance of the detector and the understanding of its evolution on the long term, but also to meet (Installation Nucléaire de Base) regulations (see section 9.9).

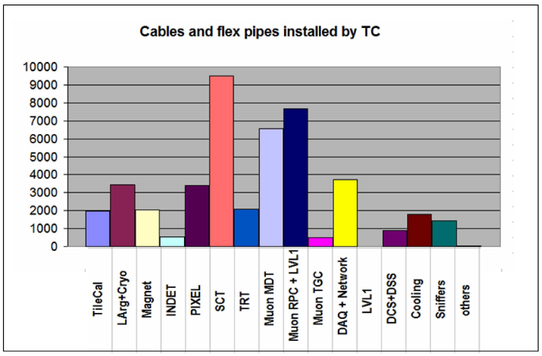

Figure 9.7: Quantities of cable and flexible-pipe bundles installed by the cabling team.

It was necessary to design new types of racks with respect to what existed in the previous projects, due to the increased power consumption, which therefore required more cooling capacity. The rack cooling is provided by turbine units located at the top of the racks, which push the air down in ducts at the sides of the racks. A deflector at the bottom directs the air upwards through the equipment to be cooled, which is interspersed with heat exchangers. The turbine units comprise an ELMB-based monitoring system (temperatures, humidity, air flow, etc.), which is supervised by the common infrastructure control of the DCS (see section 8.5). It was also found useful to increase the width of some racks. All these requirements have led in the end to the production of four types of racks, from 46 to 57 units in height, from 900 to 1000 mm in depth, and 600 mm in width.

Most of the installed cable trays are made of stainless steel to minimise the perturbations to the magnetic field (see section 2.2.2). A total of about 50,000 cable bundles, 3000 flexible pipes and 3500 metallic pipes (see figure 9.7) were installed over a period of two years (May 2005 to May 2007). Many additional proximity cables were installed by the individual sub-systems. Space had to be found to route the large quantity of cables and pipes of the inner detector and barrel

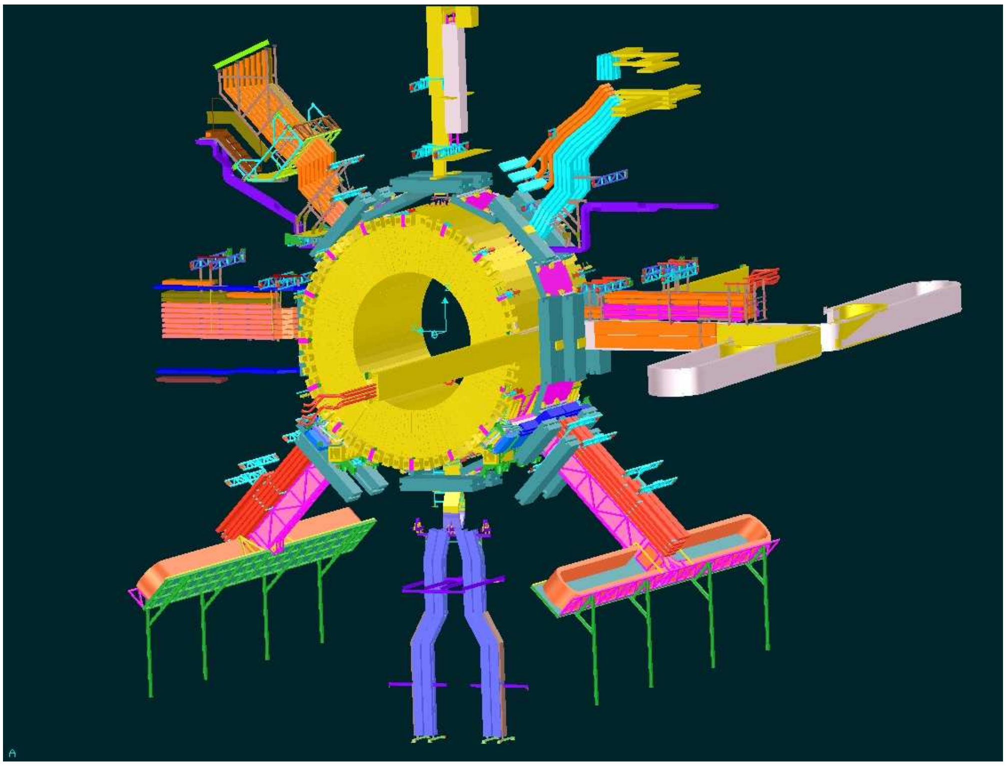

Figure 9.8: Detailed three-dimensional layout and routing of cables and services for the ATLAS barrel system. The three flexible chains for the end-cap calorimeters can be seen in the horizontal plane (right) on the side where the end-cap calorimeter trigger cables can reach the main service cavern (USA15) along the shortest possible path, and at 45° below the horizontal plane. One also sees the cryogenic lines for liquid argon at the top and bottom of the drawing. The inner barrel muon chambers in the central region are shown. One clearly sees the holes in the acceptance caused by the considerable volume of services exiting the detector at $z \sim 0$.

calorimeter systems through the muon spectrometer; this was accomplished by routing most of them radially outwards at $z = 0$ and at fixed azimuthal locations, as illustrated in figure 9.8. All the relevant cable and pipe data are stored in the cable database and constantly updated for the same reasons as those described for the racks above.

9.4.7 Drag-chains and mobile services

Many of the ATLAS sub-systems must move away from the run position to allow access into the detector. As well, the end-cap calorimeters need to remain in a cold bath of liquid argon for the duration of the experiment. The end-cap toroids are cooled with liquid helium and these are also to remain cold during the movement to avoid the lengthy cool-down and warm-up periods (20 to 40 days).

In order to satisfy the above requirements it was decided to use so-called drag-chains, which allow for the services to be supported in a flexible structure. They are used as follows:

- For each end-cap calorimeter there are three chains, as shown in figures 9.8 and 9.9, non-standard commercial products, each around 30 m-long with parts in stainless steel, specifically developed for this application. They also have a force-assist system that enables the chain to be pulled back into its stored position when the calorimeter is being closed. Particularly challenging was the construction of two of the three chains, which are at 45° downwards with respect to the beam axis.
- For each muon inner layer (small wheel) there are four chains, each about 3 m in length inside the ATLAS detector.
- For each end-cap toroid there are two chains. These are in aluminium and have been custom made. They run unsupported over a 9 m length at 24 m from the floor when the toroids are moved to their fully open position off the beam axis.

9.4.8 Grounding and electromagnetic compatibility

The ATLAS detector consists of many complex components, installed and operating in contiguous volumes, resulting in a large amount of installed equipment with multiple interconnections and shared services. For these reasons, the performance of the detector components could be heavily affected by electromagnetic interference or induced electronic noise, if these issues are not properly taken care of already at the design stage and systematically followed up on during installation. This is particularly important for detector systems with a large dynamic range and with analogue front-ends and/or readout.

Figure 9.9: The end-cap calorimeter on side A in its fully open position with all three drag-chains and the flexible LAr fill-line connected.

An ATLAS policy was developed and adopted already in the design phase [127, 245] to minimise possible electromagnetic interference effects. Apart from safety considerations, one of the main concerns has been the prevention of ground-loop currents which could couple to the signals of the detector systems. The proposed implementation of the ATLAS policy on grounding and electromagnetic compatibility has been put in place during the construction and installation phases [128]. The main guidelines can be summarised in three rules: all detector systems are electrically isolated, there are no connections to ground other than through the safety network, and there are no connections between different detector systems.

Even though these rules have been implemented and validated early on in the design phase, it has been a challenge to preserve the electrical isolation of certain large systems during installation. For these reasons, several alarm systems [128] have been installed and operated to ensure that the various detector components remain electrically isolated and grounded to single points. This effort was especially relevant for large structures with many connections like the LAr cryostats, which act as a support for other detector elements and are themselves supported by other parts of ATLAS (see section 5.6.1.1).

9.5 Support and access structures

9.5.1 Feet and rail system

The feet and rail system is shown in figure 9.10 shortly after installation in the pit and before the lowering of the first barrel toroid coil. This system is the main support, the back-bone, of the ATLAS detector. It is made of nine pairs of feet, bound by girders that altogether support the two bottom coils of the barrel toroid magnet. On top of these feet are two rails, and their supports, on which the central part of ATLAS can slide. The total load that the feet and rail system has to cope with is about 6000 t (of which approximately 1000 t correspond to the barrel toroid, which is only supported by the feet). The feet and rail system is mounted on bed-plates, which give the detector its 1.24% incline with respect to the cavern floor, an angle which matches the inclination of the LHC accelerator tunnel.

Since the two bottom toroid coils are placed inside the feet, there was a strong requirement for the material to be non-magnetic. In addition, the total deformation was to be kept to a minimum, and stresses well below the elastic limit. Low-carbon austenitic stainless steel was chosen for its good mechanical properties and very low magnetic permeability. One of the main technical issues has been to produce non-magnetic welds for such a huge number of welded joints (up to 15 t of filler metal in total).

In order to obtain a precise and reproducible geometrical path of the loads during the movement of the sub-detectors on their air-pad movement systems (see section 9.7.2), and also to preserve the integrity of the beam vacuum system (see section 9.8), the flatness requirement on the rails was one millimetre over their total length (more than 25 m), and 0.2 mm over any length of one metre. The maximum deflection of the system remains below 1 mm during the movement of the loads.

The requirement to preserve maximum acceptance for the muon spectrometer resulted in special chambers in the region of the feet and additional chambers alongside the rails (see section 6.3.2). Numerous improvements in the feet design were introduced to cope with constraints from the muon alignment system, with various designs of the muon support rails, as well as with the barrel toroid magnet instrumentation and contact surfaces.

9.5.2 Trucks

The so-called HF trucks are normal steel structures, which are placed directly below the two shafts of the main cavern. They allow for the main components of the detector to be lowered underground

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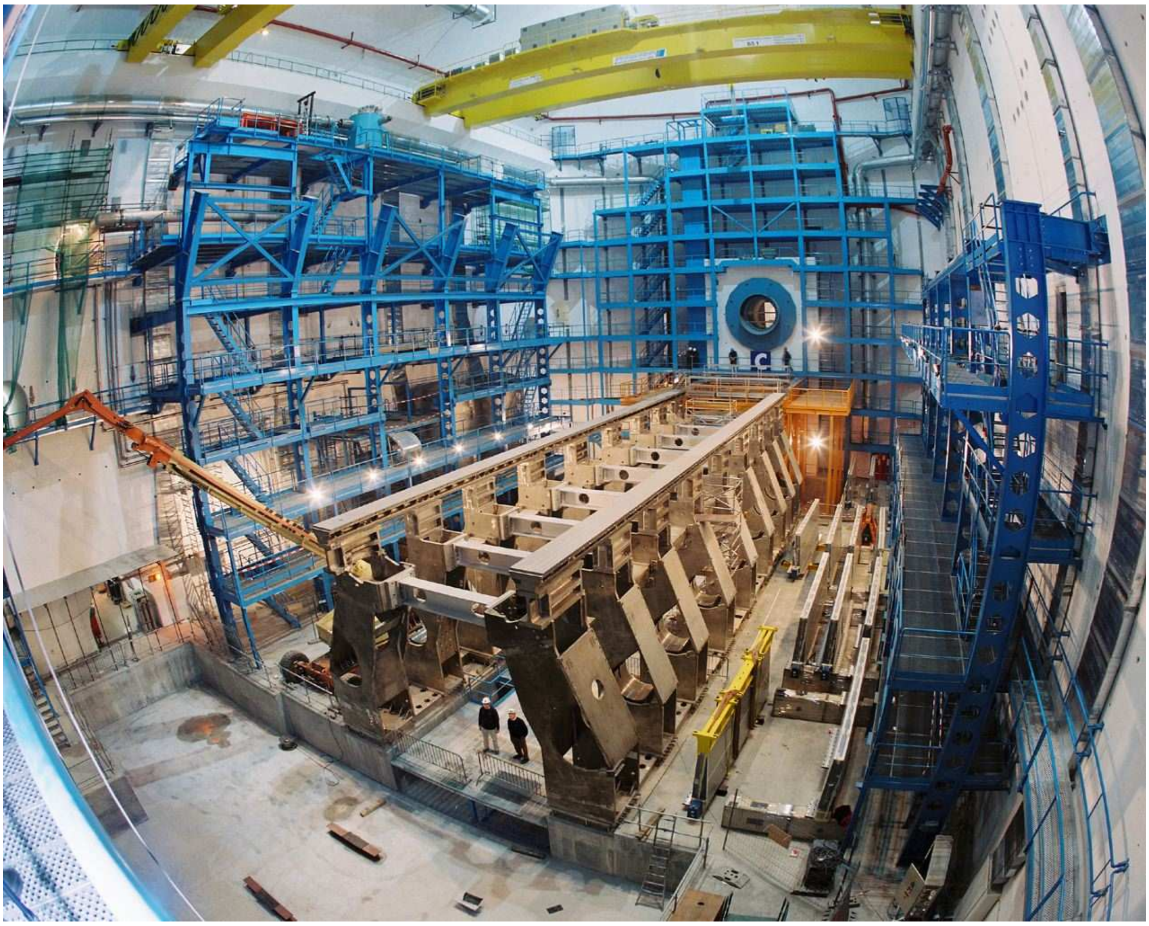

Figure 9.10: The ATLAS feet and rail system after installation and prior to the installation of the first barrel toroid coil. Also shown are the blue steel surrounding structures (HS and HO), and, in the background, one of the orange HF trucks.

using the surface cranes and remain there temporarily before moving into their final position, either by using the cavern travelling cranes (as for the barrel toroid magnet coils) or by using the air-pad movement systems (as for the calorimeters).

These structures also have the role of supporting the end-cap toroid magnets, as well as the end-cap calorimeters, in the opening sequences of the ATLAS detector (see section 9.7). During installation, they also support the forward shielding, whereas they will only support part of it when it is inserted in its final location. They are therefore able to cope with the 1000 t of maximum static load from the barrel calorimeter and they have to allow for the translation of the end-cap toroid magnets and of the forward shielding away from the beam (total weight of 400 t). For such movements, air-pads will be attached to the base of these structures to allow them to slide on the cavern floor.

Figure 9.11: The blue support structures (HS on the sides and HO at the ends of the main cavern) at the beginning of ATLAS installation. The arches which now connect the two sides of HS at the top of the main cavern were left out at the time for the installation of the barrel toroid. A barrel toroid coil is in the process of being lowered onto its temporary supports (see section 9.6).

9.5.3 Surrounding structures (HS and HO)

The blue HS structures, which surround the ATLAS detector, as shown in figure 9.11, have dual roles of providing personnel access to the periphery of the detector and to support all the equipment that has to be located close to the detector: proximity cryogenics, electronics racks, gas-distribution racks, electrical switchboards, and services distribution lines (gas, water, coolants, power). These structures were the most tricky to assemble, since they are very close to the detector in certain places and had to be assembled in two stages: the large pillars and gangways up to a height of 20 m were installed at the same time as the HO structures, but the tops of the HS arches were installed only after the completion of the installation of the barrel toroid magnet and with very little margin left. The two structures, which span distances of more than 20 m in three dimensions had to match each other to within 2 cm. The last arch was finally and successfully installed at the end of 2005.

The main role of the HO structures, which are to be found at the two ends of the cavern, are to support the end-wall muon chamber stations. They also serve as a useful means of assembling the sectors of the muon big wheels, before they are hung from the rail system. These structures also serve as viewing platforms for the thousands of visitors to the ATLAS cavern . Approximately 1000 t of normal steel have been used to build these 13-storey-high structures.

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9.5.4 Muon barrel access structures

The aluminium access platforms inside the barrel muon spectrometer have several functions:

- permanent access inside the barrel toroid, so that the muon chambers and their service connections can be accessed in a very short intervention (for example, to disconnect the gas supply to a specific chamber);
- permanent access to the patch-panels of the inner detector (PP2), so that they can also be accessed during a very short intervention;
- an emergency exit (through sector 1) in case of access to the barrel calorimeter;
- access for the installation of the barrel muon chambers;
- access to the vacuum pumps of the barrel toroid.

9.5.5 Big wheels

The muon spectrometer (see section 6.1) includes four big moving wheels at each end, each wheel measuring 23 metres in diameter (see figure 9.12). Of the eight wheels in total, six are composed of thin-gap chambers (TGC's) for the muon trigger system and the other two consist of monitored drift-tube chambers (MDT's) to measure precisely the position of the muons. The so-called big wheels comprise aluminium structures which support the muon end-cap chambers. These big wheels resemble bicycle wheels and are made of sectors, which had been pre-assembled on the surface prior to their transport to the cavern, where they were assembled on the end-wall HO structures. Once one of the wheels is completed on the HO structure, it is lifted onto the traction system, which allows it to move longitudinally towards the barrel toroid magnet and reach its final position in the closed configuration of the detector. It is important to note that the big wheels in their final position need to be inclined with a slope of 1.24% with respect to the vertical to account for the angle between the horizontal cavern floor and the inclination of the machine tunnel.

9.6 Detector installation

The installation of the detector can be sub-divided into six main phases, which are briefly described below. The barrel toroid magnet, once installed, occupies the central region of the cavern leaving the two sides, A and C, for the lowering and assembly of the remaining large detectors and magnets.

9.6.1 Phase 1: infrastructure in the main cavern, feet and rails

The main cavern was handed over to ATLAS in May 2003. The first operation was to install the general infrastructure (metallic structures around the cavern walls, temporary electricity and lighting, ventilation ducts, and the overhead travelling cranes).

With the steel structures installed, the first elements of the ATLAS detector to be brought down were the bed-plates, which were bolted to the concrete cavern floor. After the bed-plates, the stainless steel support feet, 18 in total, were lowered one by one and installed. The main rails

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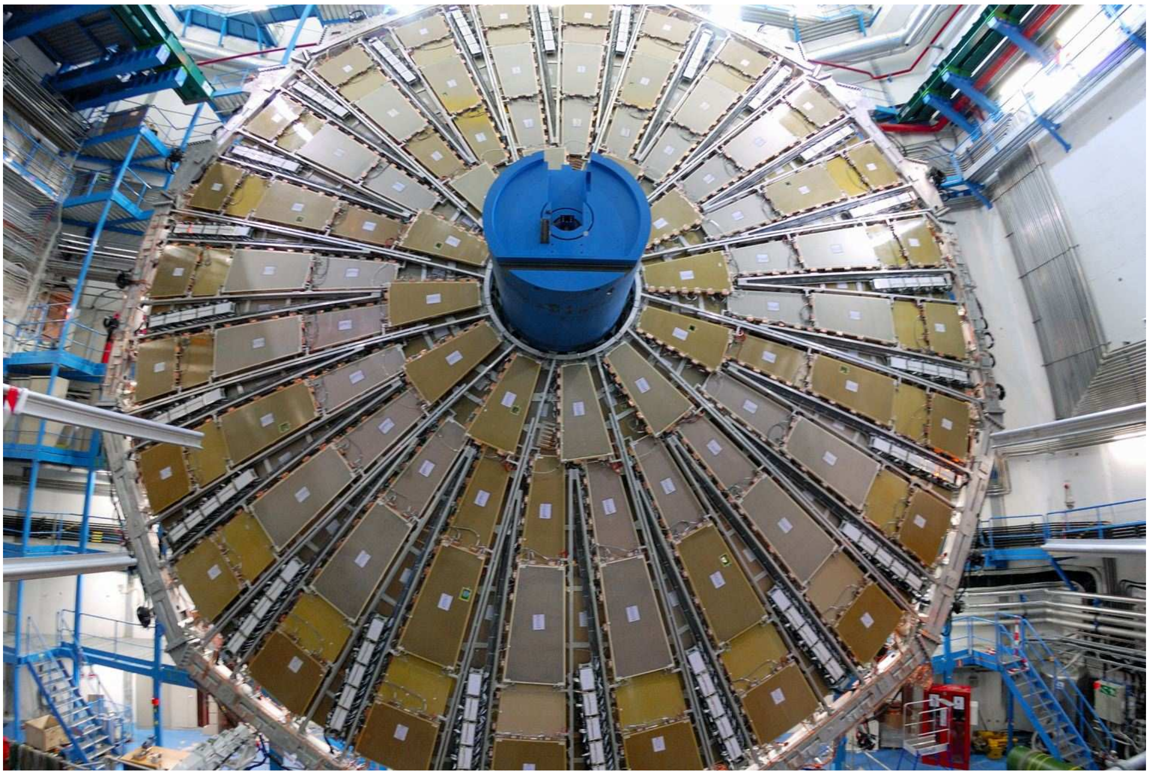

Figure 9.12: One of the assembled TGC big wheels in the ATLAS cavern. The chambers are fixed to an aluminium structure, which was pre-assembled into sectors on the surface and then assembled as a complete wheel in the cavern itself.

were installed and surveyed once positioned on the feet. The feet provide the mechanical support for most of the ATLAS sub-systems, namely the barrel toroid magnet, the calorimeters, the barrel muon chambers, the end-cap toroid magnets, the services and the access structures, amounting to about 6000 t.

9.6.2 Phase 2: barrel calorimetry and barrel toroid

Side A: barrel toroid. The first barrel toroid coil was delivered to point 1 in October 2004. The coil with its weight of 100 t and total length of 25 m, was lifted by the surface crane, tilted with hydraulic winches, lowered, in an inclined orientation, through the 18 m diameter shaft down into the cavern. It was then turned back to the horizontal orientation, before being lowered onto the temporary supports (see figure 9.11). From there, it was picked up by the two 65 t underground travelling cranes and put into its final position inside the ATLAS feet. Once the coils were in position, the aluminium struts and girders were installed so that the next coil could be attached to them. This process was repeated until the assembly was completed. In parallel with the barrel-toroid assembly, the first 100 muon barrel chambers were installed in between the struts/girders and the ATLAS feet.

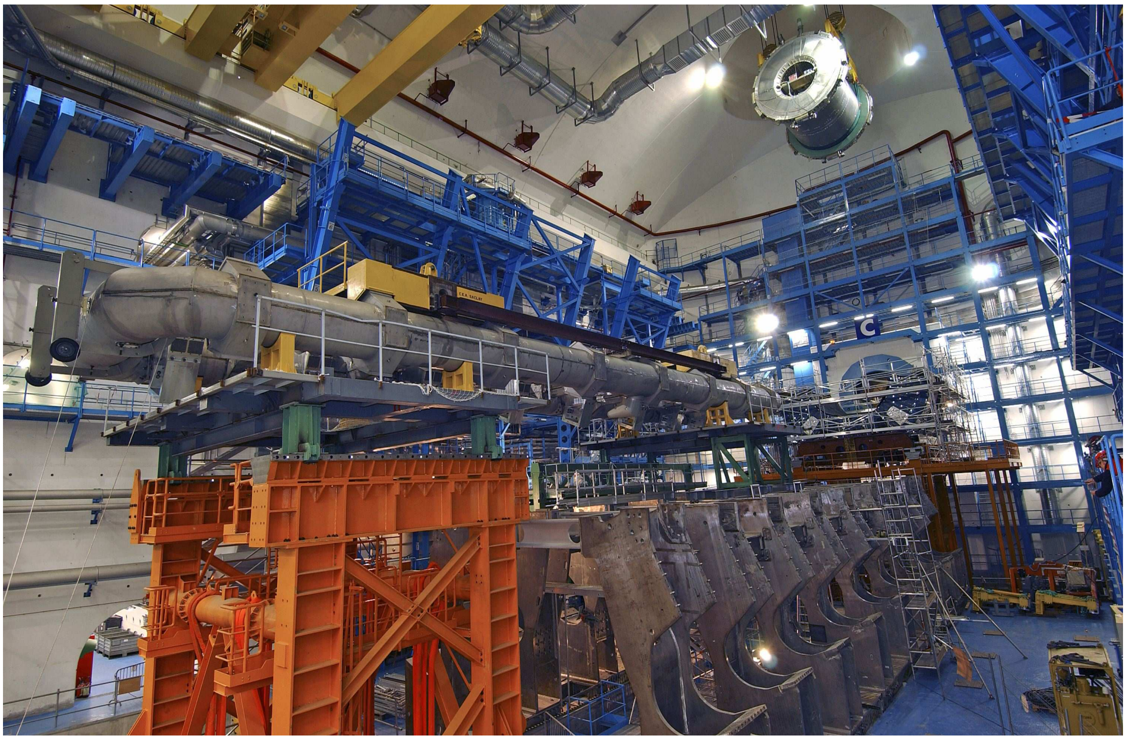

Figure 9.13: Lowering of the barrel LAr calorimeter down to the cavern in October 2004. The first barrel toroid coil can also be seen on a temporary support platform before it is installed in the cradles of the feet.

Side C: barrel calorimeter. The lower part of the tile calorimeter was lowered in March 2004. Individual tile calorimeter modules were then assembled together, one by one, until 32 of the 64 modules were completed. The LAr barrel calorimeter cryostat was then lowered into this half-cradle in October 2004, as shown in figure 9.13. The tile module assembly was then continued until the mechanical assembly of the full barrel calorimeter was completed.

Barrel: completion of barrel toroid and calorimeter installation. The last aluminium girder was put in place in September 2005, completing the mechanical assembly of the barrel toroid structure. Then the hydraulic jacks, which were supporting the complete structure during the assembly, were released. At this moment the load was transferred from the external temporary supporting structure (used during the magnet assembly) to the support feet at the bottom. The temporary support structure was then cut and removed to give space for the barrel calorimeter, which was moved inside the barrel toroid in October 2005.

9.6.3 Phase 3: end-cap calorimeters and muon barrel chambers

Side C: end-cap calorimeter. With the barrel calorimeter installed inside the bore of the magnet, the space on side C was now vacant for the assembly of the first end-cap calorimeter. This assembly was very similar to that of the barrel and was finished in January 2006. It was then moved inside the barrel toroid in February 2006, once the installation of the services (pipes, cables, etc.) was completed.

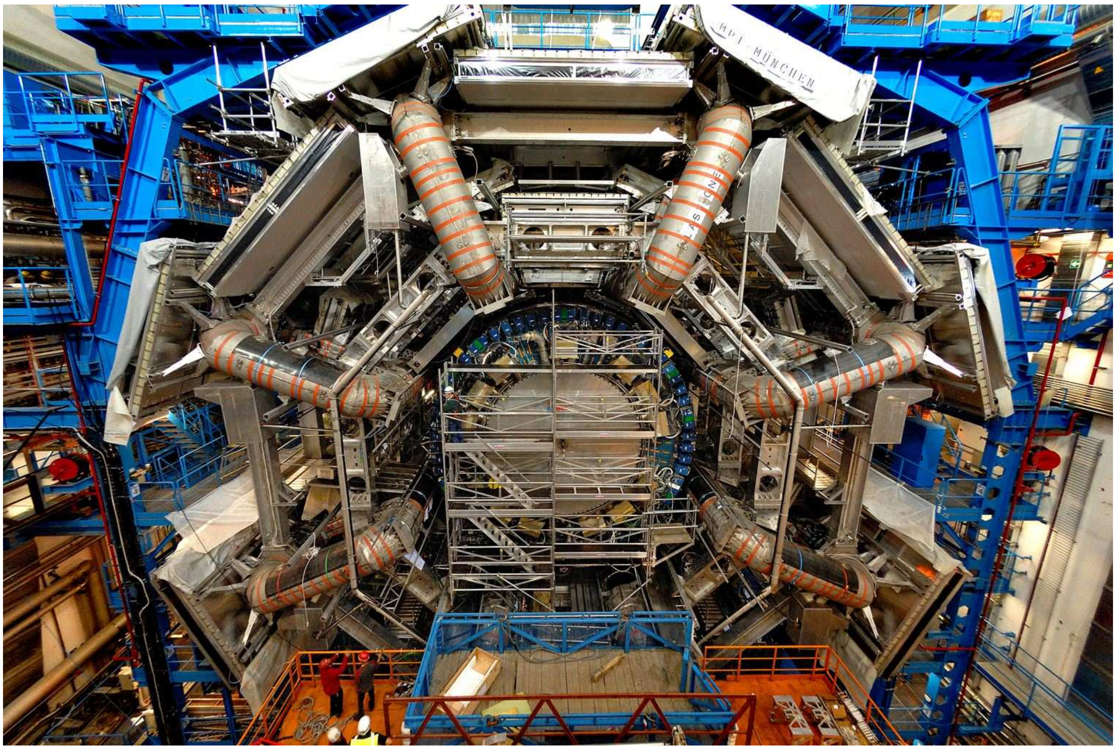

Figure 9.14: View of installed barrel muon spectrometer stations and end-cap calorimeter on side A.

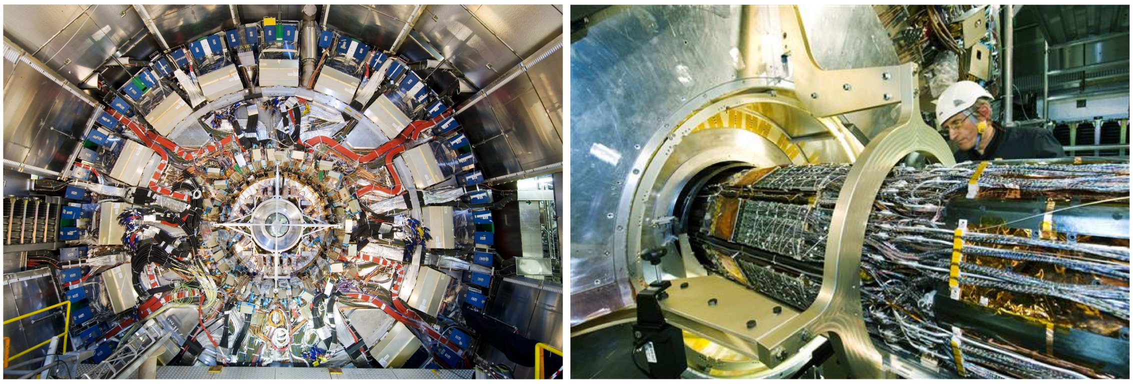

Figure 9.15: View of barrel calorimeter and inner-detector end-flange after installation of the first inner-detector end-cap in early June 2007 (left). This was followed shortly thereafter by the installation of the second inner-detector end-cap and of the pixel detector with the central VI section of the vacuum pipe (right).

Side A: barrel muon chambers and end-cap calorimeter. On side A, the first of the 656 barrel muon chambers was installed in February 2006. When the assembly of the second end-cap calorimeter started in March 2006, it had to be carried out in parallel with the muon-chamber installation. The second end-cap calorimeter was mechanically completed in May 2006. It stayed outside the barrel toroid for a further two months for the installation of the services while the end-cap calorimeter on side C was moved to its nominal position and the magnetic field of the solenoid was switched on and measured in June 2006 (see section 2.2.4).

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9.6.4 Phase 4: muon big wheels, inner detector and completion of muon barrel

Side C: big wheels. In April 2006, work started on the first end-cap muon middle station (often referred to as a big wheel) with the mounting of the tooling on the end-wall structure (HO). The first sector was installed in July 2006. Work progressed with an average rate of two sectors per week and this first wheel was mechanically completed in September 2006. After installing the services, the wheel was released from the end-wall structures and moved against the barrel magnet in November 2006.

In March 2007, the second of four big wheels was completed and the first wheel was then opened for the lowering of the inner detector end-cap C. Also all the remaining barrel muon chambers were installed before closing the end of the barrel on side C with the completed big wheels.

Figure 9.16: Lowering of the first end-cap toroid magnet onto the truck on side A in June 2007. One of the TGC big wheels can be seen on the right of the picture.

Side A: big wheels. After finishing the solenoid field mapping, the barrel section of the inner detector was lowered and installed inside the bore of the barrel cryostat in August 2006. While the work on the connections of the inner detector services continued, the end-cap calorimeter was moved partially inside to allow space for the completion of the muon barrel chambers. By the end of December 2006, 600 chambers or 90% of the total, had been installed (see figure 9.14).

In January 2007, the preparations for the muon big-wheel assembly started. The first sector was installed in March 2007, because the end-cap calorimeter needed to be moved to the open position to allow the lowering of the first inner detector end-cap.

Barrel. The installation of the barrel muon chambers continued in parallel with the assembly of the first muon big wheels. The installation of the services for the inner detector, calorimeters and muon chambers also continued. In May and June 2007, the two inner detector end-caps and the pixel detector together with the central VI section of the beam-pipe (see section 9.8) were lowered into the pit and installed, as shown in figure 9.15.

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9.6.5 Phase 5: end-cap toroid magnets and muon small wheels

The two end-cap toroids were lowered onto the trucks in June-July 2007, as illustrated in figure 9.16. The muon end-cap small wheels were assembled to the shielding disks on the surface and installed in February 2008 (see also chapter 11).

9.6.6 Phase 6: beam-pipe and forward shielding

The last elements to be installed will be the beam-pipe and the forward shielding, and this will require that all the sub-systems are progressively moved into their closed positions along the beam axis.

9.7 Access and detector opening

9.7.1 Access scenarios

Three access scenarios have been defined, depending on the duration of the shutdown period and the degree of dismantling of the detector. These can be characterised as follows:

1. Very short accesses are typically of the order of a few hours. Such accesses can be provided immediately after the machine shut-down. They can happen on a daily basis, but are not scheduled. As a consequence, no detector components are moved and the access shaft to the surface is not opened (there is therefore no crane access through the shaft). All magnetic fields stay on.

2. Short accesses have a duration from a few weeks to five months. The shorter ones will be based on the needs of the ATLAS sub-systems. In agreement with the other sub-systems, the other LHC experiments and the LHC machine, such accesses can be provided for a short period. Short access is also considered as the standard configuration during the annual LHC shut-down for a period of approximately five months.

   During such accesses, the cavern shaft is opened so that crane access to the surface is possible. The removable elements of the forward shielding (see section 3.2) are brought up to the surface, while the muon big wheels, the end-cap toroids, the small wheels and the end-cap calorimeters can be moved along the beam axis. The beam-pipe is left in place, but at atmospheric pressure, and flushed with very pure neon gas (see section 9.8). All magnetic fields are turned off. A maximum of ten persons are allowed inside at each end of the detector.

3. Long accesses are dedicated to the inner detector and small-wheel removal and installation. Such accesses are also for non-standard interventions, which require a break of the beam-pipe. Their duration is the same as that of the LHC annual shut-down (of the order of five months), but their frequency is expected to be much lower and will be related to requests of the experiment for a detector upgrade or for a major maintenance operation. In contrast to short accesses, the beam-pipe is dismantled and one of the end-cap toroids is moved sideways. A second truck is installed along the axis of the detector in order to move back the corresponding small wheel and lift it to the surface. The corresponding end-cap calorimeter

is moved back so that sufficient access is possible to the inner detector. All magnetic fields are turned off. The number of people allowed access is defined according to the evacuation plan of the cavern and the detailed operations which need to be performed.

Given the high levels of induced radioactivity expected in the regions of the detector closest to the beams, as discussed in section 3.5, strict access control and compliance with regulations as laid out in section 9.9 will be of paramount importance during access to any part of the main cavern.

9.7.2 Movement system

During access, a number of sub-systems move into their position on air-pads: the end-cap toroid magnets, the shielding disks (small wheels) and the end-cap calorimeters. The equipment for each detector movement system is basically the same: in the closed configuration, the detectors rest on hydraulic cylinders called blocking jacks. They are equipped with nuts so that the load can be transferred to solid feet, without the need for oil pressure. During movement, the load is transferred from the blocking jacks to the air-pads, which consist of two main components: a rubber air-skirt, which allows the lifting of the detector on a thin film of air, and a hydraulic jack, which allows for the height to be adjusted to a set limit during the movement. Thus, the detector can slide on its rails using the air-pad system with a low friction factor of 0.01. The number of air-pads underneath a sub-system will depend on its weight. They are grouped so that the load is supported by three iso-static points. The movement itself is provided by two hydraulic cylinders, parallel to the rails, and the detectors are moved step by step according to the stroke of the cylinders.

Because of the sensitivity of the detectors to vibrations, shocks, or tilt, the movement must be smooth and well controlled. Moreover, the clearance between detectors and the beam-pipe is only about 15 mm, a distance of similar size to that of the air-pad lift. Therefore a compensation of the pneumatic action has been implemented, so that the sub-system under air-lift is not raised by more than 5 mm. Four height sensors, located on each mobile sub-system, provide feedback to the controller, which drives the hydraulic valves of the air-pads.

The movement of the sub-systems is further complicated because of the services connected to them through the drag-chains, as described in section 9.4. Some of these chains are equipped with their own movement system, therefore it is necessary to monitor these movements with respect to those of the main movement system.

9.8 Beam-pipe

The beam vacuum system represents the main interface between the experiment and the LHC machine. It must therefore fulfil a dual set of requirements:

- the ATLAS requirements, particularly excellent transparency to particles, limited beam-gas backgrounds and conformity with environmental constraints, in terms of radiation, electromagnetic noise and thermal behaviour;
- the accelerator requirements, namely safe operation of the machine, adequate beam aperture and static and dynamic vacuum conditions compatible with the ultimate LHC performance.

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The ATLAS beam vacuum system consists of seven beam-pipes of 38 m total length, spanning the distance between the two TAS collimators located at each end of the cavern. They are bolted together with flanges to form an ultra-high vacuum system, which can be fully baked out in situ. The central chamber, called vacuum inner detector (VI), is centred around the interaction point. It has an inner diameter of 58 mm and is constructed of beryllium metal with a thickness of 0.8 mm (see figure 4.34). The remaining six chambers are installed symmetrically on both sides of the interaction point and named after the detector, which supports them: VA (vacuum argon end-cap), VT (vacuum toroid end-cap) and VJ (vacuum forward shielding). They are constructed of thin-walled stainless steel tubes with diameters increasing progressively from 60 mm to 80 mm and finally to 120 mm. Chambers inside different detectors are mechanically decoupled by vacuum bellows, which also serve to absorb thermal expansion during bake-out.

The VI chamber was integrated into the pixel detector on the surface, and installed as part of the pixel package (see section 4.8.1). It is aligned on the beam axis using a system of laser and CCD cameras, which measure the chamber deformation. The VA chambers are centred inside the warm bore of the LAr end-cap cryostats by sliding supports, which allow the detector to move longitudinally along the beam-pipe. Special minimised ultra-high-vacuum flanges, with only 35% of the volume of a standard flange, have been developed to pass through the bore. The VT chambers are held by retractable jack supports on rails in the forward shielding. These can be adjusted from the back-face of the end-cap toroid or fully retracted to allow the end-cap toroids to move longitudinally along the beam-pipe. The VJ chambers are cantilevered from the forward shielding located on the cavern wall, inside a conical support designed to fit inside the opened end-cap toroid. The flanges between the VJ chambers and the TAS collimators are remotely actuated from the outside of the forward shielding, because of the high activation expected in this region at design luminosity.

This supporting system is conceived to allow ATLAS to rapidly move to a short access without the need to open the beam vacuum to air and hence re-activate the Non-Evaporable Getter (NEG) system (see below). However, the chambers are not able to support the stresses induced by offsets expected during opening whilst under vacuum. The chambers will therefore be vented to neon gas at atmospheric pressure, purified to the ppb level by a specially developed gas-purifying system mounted on side A of the HO structure. Neon is not pumped by the NEG system, so the beam vacuum system can be rapidly made operational at the end of a short intervention by simply re-pumping the neon gas.

The main pump used to eliminate desorbed gasses in the system is a non-evaporable getter (NEG) film sputtered onto the whole of the inner surface of the beam-pipe. After activation by heating the beam-pipe to $\sim 200°$C, this NEG film gives a very high distributed pumping speed for chemically active gasses. Chemically-inert gasses not pumped by the NEG system are removed by two minimised sputter-ion pumps [246] at $\pm$ 3.8 m and by larger pumps at $\pm$ 19 m from the interaction point.

The whole length of the vacuum system is permanently equipped with a mass-minimised system of heaters, thermocouples and insulation which allow the NEG system to be re-activated annually. This bake-out system consists of polyimide-foil heaters wrapped with silica aerogel, polyimide tape and aluminium foil. Flexible bellows, pumps and transitions are equipped with semi-permanent flexible heating jackets.

Significant optimisation of the forward beam-pipe chambers is planned for the LHC machine upgrade, as discussed in section 3.5. Stainless steel will be replaced by aluminium or other low-Z materials wherever possible to minimise both the background radiation in the muon chambers and access problems due to beam-pipe activation.

9.9 Safety in ATLAS

The safety responsibilities for ATLAS include the safety of the personnel as well as the protection of the environment, equipment and infrastructure during the installation and the various phases of operation of the detector (data-taking, access and maintenance).

The main risks are located in the underground experimental area, especially in the main cavern and the adjacent technical-service caverns. A risk assessment of these areas has been performed prior to the beginning of the installation. This was continuously revised and updated during installation and commissioning. The main risks are human operational errors, fire, cryogenic-fluid leaks, and radiation during beam operation. There are also dangers linked to the presence of magnetic fields, electrical hazards, laser beams, flammable gases and CO_2 gas. Other risks are related to the mechanical integrity of the detector components, in the case of major incidents or even of seismic events.

Potential risks, pertaining to the installation process of the various components, as well as to all operations of opening and closing of the detector during the shut-down periods, have received special attention. These risks are associated with the difficulties related to working at heights, to multiple parallel activities carried out by various working teams, which have to share the same working space, and to the manipulation tools for heavy objects. In order to minimise such risks, actions are taken at various levels:

- a safety organisation has been established in the experimental area and is enforced with an effective in situ presence;
- all activities are managed via the concept of work packages. Each activity is prepared, described and analysed before work can commence. All safety issues are discussed, and tasks optimised as appropriate to minimise risks;
- access to the underground areas is restricted to specialised and trained personnel;
- safety aspects are considered from the early design phase of the equipment and infrastructure, through all the installation and commissioning phases. For example, the barrel toroid coils have been equipped with surface-mounted heaters to warm the eight magnet cryostats and thus prevent condensation and ice formation in the event of a vacuum loss of the magnet system;
- safety systems have been designed and implemented to detect at a very early stage any possible sources of danger and to activate alarms and trigger the required safety actions;
- all alarm informations concerning underground safety and access are collected and managed in the ATLAS control room by the Shift Leader In Matters Of Safety (SLIMOS). This person acts in real time, a necessary condition to guarantee the highest level of safety for all personnel and equipment.

- specialised safety courses are required for all personnel working underground;
- dedicated courses for people doing specialised work such as electrical power, etc.

9.9.1 Organisation of safety

The ATLAS safety organisation is led by the GLIMOS (Group Leader In Matters Of Safety). The GLIMOS supervises the various activities, the specialised safety officers and the territorial safety officers, who are responsible for the safe operation of the underground areas and surface buildings. The specialised safety personnel includes officers for radiation protection, cryogenics, lasers, flammable gases, and electrical hazards. The territorial safety officers are responsible for the safety of the buildings and underground areas around the ATLAS site. Their duty, in particular for the underground area, is to ensure daily safety controls and visual inspections and to take appropriate actions where required. For the main cavern, given the size and the complexity of the work during installation or access, the territorial safety officer leads a team of technicians.

There is also an external safety coordinator, who leads a small independent team to verify the safety-condition levels inside the experimental area. This team has been active during the construction phase and will be kept operational during the access and maintenance periods. This group is reinforced by a team of engineers, who are in charge of supervising the installation, the commissioning and the maintenance of the various safety systems (see section 9.9.3).

From the beginning of the LHC operation, an additional safety organisation will be put in place around the SLIMOS in the ATLAS control room. The SLIMOS will be continuously on duty, as described in section 9.9.5.

The work packages for the underground activities are agreed upon and are integrated into the general planning to minimise overlap of work and resolve potential conflicts. These work packages cover all activities, from infrastructure or detector installation, to commissioning or maintenance work, and to the movements of heavy objects. A work package is declared active only when all crucial technical and safety issues have been reviewed and agreed upon.

9.9.2 Access control

9.9.2.1 General aspects

Access to the underground areas is restricted to persons who participate in an ongoing declared activity (work package), are authorised and have completed specific safety-training courses. These cover, in addition to the standard general safety training, specific training associated with the hazards which may be encountered in ATLAS: evacuation of the underground areas, cryogenic risks, hazards associated with static magnetic fields, radiation protection, electrical hazards, and handling and removal of equipment inside the caverns.

The control of the access authorisation and the verification of the training and personal biometrical parameters are performed by the LHC access control and safety systems. Personnel and material access control devices are implemented at the top of the lifts and at the entry points of the ATLAS main cavern. In addition to these checks, the access system of the main cavern (UX15) will deliver to each person a safety token during controlled accesses.

9.9.2.2 INB regulations

By a convention signed in 2000, CERN and the French nuclear authorities have agreed to apply the INB (Installation Nucléaire de Base) rules and regulations to the LHC machine and experiments. These rules and regulations govern and impose stringent limitations on the operation, maintenance and future dismantling and disposal of the ATLAS detector. They are written down in two documents, the Règles Provisoires de Sûreté and the Règles Générales d'Exploitation. In particular, they define yearly integrated dose-rate limits and assign specific labels to different regions of the detector depending on the induced activation.

For what concerns the long term and in particular the final disposal of the ATLAS detector, the regions of ATLAS closest to the beams have already been classified as radioactive, whereas regions further away from the beams will remain classified as conventional. This is based on calculations using as input a scenario corresponding to ten years of operation and two years of cool-down.

Detailed rules of operation are therefore required, in particular for managing the flow and traceability of equipment and materials to and from the experiment. The procedures for radiological controls of material from the main cavern are being documented and the ATLAS control procedures will be put in place soon. All equipment leaving the cavern will be measured for radioactivity and tracked.

9.9.3 Safety systems

Following the various risk assessments related to the underground work environment and especially the ones concerning fire and cryogenic leaks, a number of dedicated safety systems have been implemented under the direct supervision of the ATLAS GLIMOS and of the CERN Safety Commission. These safety systems have been designed and implemented so as to detect at a very early stage any event which might endanger the safety of personnel, environment or ATLAS equipment. The readout of most of these systems uses the standard DCS tools described in section 8.5 (ELMB, CANbus and basic communication software).

9.9.3.1 Hazard-detection systems

The main and service caverns are equipped with standard detectors, which detect the presence of smoke inside the infrastructure and service areas of the caverns. The electronics racks have been equipped with smoke-detection points and some of them with an associated CO_2 gas extinguisher system.

Due to the large quantity of liquid argon (84 m^3) in the three LAr cryostats, which might fill a large part of the main cavern in only a few minutes with an asphyxiating gas in case of a catastrophic failure, three large trenches have been built in the floor of the cavern. In case of a major leak, the cryogenic liquids and the cold and heavy gases would be contained in these trenches. Access is restricted to these areas and there is an oxygen-deficiency detection system installed. In normal conditions, air is permanently extracted from the lowest point of these trenches. If a leak is detected, the gas extraction can be increased to a massive rate of 32,000 m^3/h.

The TGC's in the small and big wheels are filled with a flammable gas mixture (see section 6.8 and table 9.5). Their distribution racks have therefore been equipped with flammable-gas detection heads. The internal areas of the ATLAS detector are equipped with air-sampling tubes or sniffers, which may detect the presence of smoke, CO_2 or flammable gases, and hence a subsequent deficiency of oxygen. These tubes run on the inside of the various sub-systems and along the detector platforms. They serve as a protection of equipment and personnel working inside the ATLAS detector.

The barrel toroid warm structure, which supports the eight barrel toroid coils, is made of aluminium. In case of a major fire inside the ATLAS detector, the aluminium will begin to lose part of its structural properties at a rather low temperature of approximately 200°C. In order to minimise the risk of any mechanical-instability problem of the toroid warm structure, temperature sensors are fixed on these aluminium parts. These send the temperature information to the ATLAS SLIMOS desk in the control room.

The various safety systems, fixed detection systems and sniffers, generate alarms. Two different alarm-threshold values are defined for each type of detection. The first threshold generates a warning and triggers preventive actions on the ATLAS detectors via the Detector Safety System (DSS). The second threshold indicates that there is a serious danger to the personnel or the environment, which requires the immediate intervention of the fire brigade. In addition, this second threshold also triggers the evacuation from the ATLAS underground areas and immediate actions on the detector via DSS and on the infrastructure (for example, modification of the cavern-ventilation configuration as described above in the case of a cryogenic leak).

9.9.3.2 Foam extinguishing system

In addition to standard fire-fighting means, such as portable fire extinguishers and hose reels, a foam extinguishing system has been implemented in the vault of the cavern. This foam system may be used in the extreme case, to protect the detector and the CERN firemen in the event of a fire getting out of control. The system consists of 12 large blowers installed in the vault of the UX15 cavern which are fed by a mixture of water and detergent and can fill-up the cavern in less than 15 minutes, suffocating any fire. Since this foam has only a 1/1000 water content, personnel trapped in the foam would survive without problems until the foam settles (approximately one hour). Tests have also demonstrated that the foam does not penetrate into electronics racks.

9.9.3.3 Finding people inside ATLAS

The FPIAA system (Finding People Inside ATLAS Areas) detects the presence of persons in all areas of the ATLAS main cavern, including those inside the detector itself. This system does not require any special device to be worn by the personnel. It is based on the use of approximately 500 passive infra-red sensors, appropriately modified to be radiation-tolerant and to operate in a magnetic field. Each one of the 500 small volumes in the cavern and inside ATLAS is continuously monitored: if a person were to disappear without reappearing in the adjacent volume, an alarm would be generated.

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9.9.4 Detector safety system

The Detector Safety System, DSS [247], is the central tool to bring (parts of) the ATLAS detector in a safe state in cases when an abnormal operational situation arises or a safety hazard is detected. Its main task is to protect the detector equipment. DSS works ATLAS-wide, i.e. across sub-detector boundaries and including all common infrastructure components of the ATLAS detector. It has its own sensors to detect potentially dangerous situations (e.g. over-temperatures) and receives input from the hazard detection systems described in section 9.9.3. This information is collected by DSS stations distributed over the different counting rooms and is analysed centrally by a redundant system based on programmable logic controllers. In a matrix-like fashion, all input signals can be combined by logic operations to trigger the appropriate action, usually a shut-down procedure of the relevant equipment. This process is fully automatic: operator intervention is only needed to analyse and correct the fault and to bring the detector back into operation. Care has been taken when implementing the DSS system not to rely on external services, such as computer networks or normal electricity supplies. The principle of positive safety has been used throughout, i.e. in case of missing sensor information or possible internal system problems of DSS, all relevant safety actions are executed. A dedicated operator interface in the ATLAS control room provides the SLIMOS with the detailed status of the DSS at all times.

9.9.5 Safety during operation

As described above, the safety organisation and access control will be coordinated during operation around the SLIMOS desk in the ATLAS control room. Responsibility for access control will normally be transferred to the SLIMOS from the central LHC control room (CCC). The SLIMOS will be in charge of controlling in real time the safety conditions inside the cavern via the various safety systems described above. The SLIMOS will also be responsible for providing information to the fire-brigade on the status of the main cavern and the detector, including: beam status, configuration of the detector, detailed instructions for accessing the region of intervention, number of people in the underground areas, radiation levels and environmental conditions, relevant information concerning the status of the ATLAS detector and the infrastructure (cooling, cryogenics, magnets), and status of all possible safety alarms.

9.10 Interface to the LHC machine

For safe and optimal operation of both the LHC machine and the ATLAS detector, the two parties will continuously exchange information about their overall status as well as about the status of relevant individual sub-systems. This data exchange will be used to synchronise actions during the different states of operation, to provide online feedback on tuning operations, to rapidly react to errors, and to understand quickly and efficiently their causes.

ATLAS and the LHC machine exchange most data over the network through the DCS information server (see section 8.5). In addition, dedicated hardware links are used for critical signals that have to be transmitted on time and in a reliable fashion, such as the beam permission signals and timing signals.

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Table 9.6: Main operational parameters of the LHC machine for a few configurations: the nominal one (left), the initial one with a bunch spacing of 75 ns (centre), and the specialised one for the measurement of the total cross-section (right).

Machine operation configuration	**Nominal**	**75 ns**	**Roman pots**
Number of bunches	2808	936	43
Number of protons per bunch (10^{11})	1.15	0.9	0.1
Bunch spacing (ns)	25	75	2025
β function at the interaction point (m)	0.55	1–11	2625
Crossing angle (μrad)	285	250	0
Peak luminosity (cm^{-2}s^{-1})	10^{34}	10^{33}	10^{28}

The LHC communicates to ATLAS the total beam and individual bunch intensities, the average 2-dimensional beam size, the average bunch length, the luminosity at the four interaction points, the average beam loss, and the average horizontal and vertical beam positions. Table 9.6 lists basic beam properties for some of the interesting configurations envisaged for machine operation.

ATLAS reports to the LHC information that allows the machine to optimise and monitor the conditions of the beams, in particular the quality of collisions and machine-induced backgrounds. Experience from previous colliders shows that the machine-induced background in the detectors is very hard to predict. A number of different factors intervene in a complex manner:

- the local vacuum pressure as well as the vacuum at more distant places, such as the arcs, affects the halo entering the detector;
- inefficiencies of both the betatron and momentum-cleaning systems and the detailed settings of the collimators will also heavily influence the observed background levels;
- other factors, which have a direct impact on the beam halo, are of course the total beam current, the beam tune shift and the orbit positions.

It is therefore of prime importance to the experiment to define reliable background indicators and to communicate them to the LHC control room. These background indicators must be continuously available to the operating crew for monitoring, in particular before stable beam conditions have been reached during the setting-up phase of the machine. They must therefore be available in the experiment independently of the main data acquisition. The ATLAS beam conditions monitor (or BCM as described in section 3.4.1) meets these requirements and will be used in this context.

Among the parameters that ATLAS sends to the LHC are: the total luminosity, the luminosity per bunch, indicators for quality of collisions and amount of machine-induced backgrounds, counting rates for individual bunches, and the position and size of the luminous region.

The 40 MHz bunch clock of the LHC and a pulse per revolution is transmitted from the LHC radio-frequency system at point 4 to ATLAS over a total length of 14 km of optical fibre. Once received in the ATLAS counting room, these signals are fine-adjusted in phase and distributed via the L1 central trigger processor to all ATLAS sub-systems (see section 8.2.3).

ATLAS receives for each beam one signal from a beam position monitor, which is located 175 m upstream of ATLAS. These signals provide a precise timing reference in order to monitor the phase of the LHC clock with respect to the bunches. In addition, they serve as inputs to the L1 trigger, for which they provide a filled bunch trigger signal for each beam and a time reference with respect to the abort gap of the LHC bunch train.

When in operation, the LHC machine undergoes a sequence of operational modes such as filling, ramping, adjust, stable beams, and unstable beams. The current machine operational mode is received by ATLAS via software, which is appropriate in most cases for synchronising ATLAS operation with LHC operation. Before a state transition, a hand-shake protocol between the LHC and ATLAS is used: the LHC operators request from ATLAS confirmation before going into e.g. the state (adjust mode), where the low-β squeeze and other adjustments take place. A similar protocol is used before a scheduled beam dump by the LHC operator.

A fail-safe and reliable beam interlock system is installed around the LHC ring, with several systems giving permission for beams. The absence of a beam permission signal leads to an immediate beam dump: the safe extraction of the beam from the LHC in less than 300 μs. The ATLAS beam interlock system (BIS) consists of three parts, each of which gives beam permission: the detector BIS, the spectrometer magnet BIS and the Roman-pot position BIS. The detector BIS takes inputs from the BCM and possibly other detectors and gives beam permission only when background conditions allow safe operation of the detector.

Additional flags related to the machine modes are transmitted from the LHC to ATLAS through a fast, safe and reliable hardware link, as they are used in the context of the movement control of the Roman pots and for the Roman-pot position BIS (see section 7.2). The ATLAS BIS is complemented by additional interlocks, for instance to inhibit injection into the LHC and to apply more sophisticated logic. The system is flexible enough so that it can evolve with the experience obtained in the operation of the LHC and ATLAS.