Chapter 11

Outlook

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The broad range of physics opportunities and the demanding experimental environment of high-luminosity 14 TeV proton-proton collisions have led to unprecedented performance requirements and hence technological challenges for the general-purpose detectors at the LHC. The overall ATLAS detector design is the result of a complex optimisation process between conflicting requirements. These requirements can be expressed tersely as a set of four basic criteria over a large acceptance in pseudorapidity and basically full azimuthal coverage for all of the major detector systems (see chapter 1 for details):

- very good electromagnetic calorimetry for electron and photon identification and measurements, complemented by full-coverage hadronic calorimetry for accurate jet and E_T^{miss} measurements;
- high-precision muon momentum measurements with the capability to guarantee accurate measurements at the highest luminosity using the muon spectrometer alone;
- efficient tracking at high luminosity for high-p_T lepton momentum measurements, electron and photon identification, τ-lepton and heavy-flavour identification, and full event reconstruction capability;
- efficient triggering with low p_T-thresholds on electrons, photons, muons and τ-leptons, thereby providing high data-taking efficiencies for most physics processes of interest at the LHC.

After approximately fifteen years of detector design, construction, integration and installation, the ATLAS detector is now completed and almost entirely installed in the cavern (see chapter 9). All detector teams, together with the ATLAS performance and physics working groups, have developed detailed commissioning strategies using cosmic rays, single-beams, and initial data with colliding beams. As more and more detector components become operational, detector calibrations and extensive stand-alone and combined studies with cosmic-ray events are being carried out. These commissioning periods also exercise the full data acquisition chain, including the online and offline data-quality assessment tools and the streaming of events into several physics streams based on the trigger decision. During the spring of 2008, calibration tests and cosmic-ray data-taking are ramping up, while the few remaining components of the detector are being installed and commissioned. The ATLAS detector will be ready for the first LHC collisions in summer 2008.

11.1 Detector installation and hardware status

The status of the ATLAS detector systems at the time of final submission of this paper in April 2008 is summarised below and in table 11.1.

As described in chapter 2, the superconducting magnet system comprises the central solenoid, the barrel toroid, two end-cap toroids, and their services. Both the central solenoid and the barrel toroid magnets have been successfully commissioned at full current, and their safety systems have been tested in situ. Their mechanical behaviour as well as the magnetic-field measurements have confirmed the design expectations (see section 2.2). The magnetic field in the inner-detector cavity has been carefully mapped and the residual fractional bending-power uncertainties are well within specifications, i.e. below 5×10^{-4}. In the muon spectrometer, a preliminary analysis of B-sensor readings in a quarter of the field volume yields systematic uncertainties a few times larger than the ultimate desired precision. The end-cap toroids have been tested successfully in stand-alone mode at 50% field. An extensive field-reconstruction campaign over the entire spectrometer volume will be carried out during the full ATLAS magnet-system test which is scheduled just before the start of LHC operation.

As described in chapter 4, the inner tracking detector combines three concentric detector systems, namely the pixel detector, the SCT and the TRT. Substantial parts of the integrated barrel and end-cap TRT and SCT systems as well as parts of the pixel detector have been successfully operated on the surface in cosmic-ray tests before these systems were installed in the cavern. The tests of the installed inner-detector components are ongoing in parallel with completing the connection of the inner-detector services (cables and pipes). The TRT and SCT systems are already operational in cosmic-ray runs. The completion of the pixel service connections and subsequent stand-alone and cosmic-ray testing will follow next.

As described in chapter 5, all three calorimeter cylinders, the barrel and the two end-caps, with the tile calorimeter surrounding the LAr cryostats, are installed in the cavern. The three cryostats are cold and filled with LAr. Now that all the calorimeter channels are part of the regular readout chain, the main activities are focused on the overall system commissioning.

As described in chapter 6, the muon spectrometer is instrumented with precision chambers for momentum measurements (MDT's and CSC's) and with fast chambers for triggering (RPC's and TGC's). The construction of the various types of chambers has been completed for the initial detector configuration. The installation of the barrel stations and of the small and big end-cap wheels has also been completed. In parallel with the completion of the installation of the end-wall chambers (MDT's) over the next months, the commissioning with cosmic rays is ongoing for both the barrel and end-cap regions, gradually increasing the number of sectors involved in these tests.

As described in chapter 8, the components of the L1 trigger, of the DAQ/HLT system, and of the detector control systems are in an advanced stage of installation. The L1 trigger system (with its calorimeter, muon and central trigger processor sub-systems) is in its final production and installation phase for both the hardware and the software. The calorimeter trigger installation is

Table 11.1: Hardware status summary of the major ATLAS detector systems. Depending on the installation and commissioning status, the results are based on measurements on the surface prior to installation and/or measurements after installation in the main cavern, as described in the last column.

Component	**Operational readiness**	**Comments**
Magnets	Residual RMS values between mapping and model	Solenoid and barrel toroid tested at nominal field. End-cap toroids tested at 50% field.
- Solenoid - Barrel toroid - End-cap toroids	$\sim$ 0.4 mT for all three field components. 1–6 mT depending on position. Analysis in progress.	Nominal field: 2T Preliminary analysis in one sector. Goal is 2 mT.
Inner detector	Fraction of fully functional channels	Mechanical installation complete. In situ cabling almost complete.
- Pixel - SCT - TRT	99.7% 99.8% 98.4%	After final integration of system on surface. After integration with TRT system on surface. Measured in situ.
LAr calorimeters	Fraction of fully functional channels	Installed and operational. Electronics tuning ongoing.
- EM barrel/end-cap - HEC - FCAL	99.98% 99.91% 99.77%	Tested cool on surface. Tested cool on surface. Tested cool on surface.
Tile calorimeter	Fraction of fully functional channels	Installed and operational. Electronics/power supply tuning on-going.
- Barrel/extended barrel	99.2%	Measured in situ for part of detector.
Muon spectrometer	Fraction of fully functional channels	Installed except for some end-wall chambers.
- MDT - RPC - TGC - CSC	99.9% 99.5% 99.9% 99.9%	Tested on surface and partly in situ. Tested on surface and partly in situ. Tested on surface and partly in situ. Tested on surface.
Trigger and data acquisition	System used for cosmic-ray tests and performance verified in stand-alone and commissioning tests.	Readout system installed and operational. Trigger processing-power limited to 40 kHz L1 rate.

completed and the central trigger processor sub-system is in place and routinely used during detector commissioning runs. The readout system, the event builder, and the output to mass storage have been demonstrated in technical runs to deliver the required performance and data through-put rates. The HLT processing power, sufficient to handle a 40 kHz L1 acceptance rate, is planned to be installed for the run in 2008. The HLT algorithms have been successfully tested with physics events pre-loaded in the readout system, and also with cosmic-ray muons. Besides their own commissioning, these systems are used extensively and routinely for the commissioning of specific detector systems and of the overall ATLAS experiment.

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The ATLAS control room is fully operational and heavily used. It has become the centre of one of the most prominent activities in the collaboration over the past months, namely periods of global commissioning runs during which, in particular, cosmic-ray events are recorded with the components of the detector already installed and operational in the cavern.

11.2 Outlook on commissioning with data

Chapter 10 summarises the expected performance of the ATLAS experiment. Many of the results are supported by test-beam measurements, in particular for the single-particle response of the detector elements to electrons, photons, pions and muons at various benchmark energies. Other results on the expected performance rely solely on the simulation of the detector geometry, of the detector response, and of the underlying physics processes. These include jets, E_T^{miss}, hadronic τ-decays, b-tagging and trigger performance. Most of these results, particularly the expected trigger rates, are subject to large uncertainties because of the hitherto unexplored energy range for QCD processes at the LHC. At the LHC design luminosity, simulation uncertainties affecting the estimated detector performance also arise from pile-up of p-p interactions (mostly in the triggered bunch-crossing), and from background in the ATLAS cavern consisting predominantly of slow neutrons (see chapter 3).

In all detector systems, calibration runs of various types are used to map noisy and dead channels. The tile calorimeter also performs dedicated laser and caesium-source calibration runs. These initial calibration data, combined with test-beam measurements performed over the past years, are critical to achieve a sufficient quality of the first collision data. The cosmic-ray data will provide important additional information for aligning the detectors relative to each other. As an example, these data will define an absolute geometry for most of the octants of the barrel muon spectrometer, and will be used as a reference for the alignment based on optical sensors. These data will also be used to define an initial alignment of the major components of the inner detector relative to each other. As shown in chapter 10, cosmic-ray data are considered as an important ingredient in the overall alignment strategy of the inner detector.

The combination of the results of the detector-specific calibration and commissioning runs with those from the analysis of future large-scale cosmic-ray data will define to a large extent the expected calibration and alignment accuracies for the major ATLAS detector components at the LHC start-up. These ATLAS start-up goals and the ultimate design goals of the experiment, in terms of tracking and calorimeter performance, are summarised in table 11.2.

At the start-up of the LHC, after timing-in the detector systems with the colliding LHC bunches and the trigger signals, minimum-bias triggers from scintillator counters will provide large event statistics for initial physics studies at luminosities of 10^{31} cm^{-2} s^{-1} or less. All the triggered events will be used to perform a thorough shake-down of the ATLAS detector systems, thereby refining and completing the dead, noisy and faulty channel maps. The large rates of rather high-p_T isolated tracks (leptons or pions) will be used to refine the inner-detector alignment. High- and low-threshold transition radiation hits from isolated electron and pion tracks will be compared to the expectations from simulation studies.

Minimum-bias events will help to monitor the azimuthal uniformity of the calorimeter response and, to a certain extent, the amount of material in the inner detector. In this initial phase,

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Table 11.2: Expected calibration and alignment accuracies at the LHC start-up and the ultimate design goals. Examples of physics channels or measurements driving the requirements are indicated in the last column.

	Start-up of LHC	**Ultimate goal**	**Physics goals**
Electromagnetic energy uniformity	1–2%	0.5%	$H \to \gamma\gamma$
Electron energy scale	∼2%	0.02%	W mass
Hadronic energy uniformity	2–3%	$< 1\%$	$E_T^{\rm miss}$
Jet energy scale	$< 10\%$	1%	Top-quark mass
Inner-detector alignment	50–100 μm	$<$ 10 μm	b-tagging
Muon-spectrometer alignment	$<$ 200 μm	30 μm	$Z' \to \mu\mu$
Muon momentum scale	∼1%	0.02%	W mass

it will also be crucial to validate the ATLAS calorimeter simulation by comparing shower shapes for isolated lepton and hadron tracks. The statistics corresponding to a few days of low-luminosity data-taking without toroid field should provide enough straight muon tracks to calibrate the muon optical alignment system to less than 100 μm. This will be improved to 30 μm at higher luminosity, which is required to take full benefit from the spatial resolution of 40 μm per muon chamber. These steps are all necessary to achieve the goal of measuring 1 TeV muon tracks with approximately 10% accuracy.

The commissioning of the overall trigger system will be a gradual process (see section 10.9.5). Simple inclusive L1 calorimeter and muon triggers will be included first, followed by more complex L1 triggers, involving for example $E_T^{\rm miss}$. At the same time, the HLT system will begin to operate, initially in pass-through mode in order to test the algorithms, and later using the full power of the HLT. The data collected with the complete low-luminosity trigger menu will contain copious quantities of low-energy leptons from heavy quark decays and also from direct J/ψ and Υ production. The data will contain approximately 5×10^5 $W \to \mu\nu$ and 5×10^4 $Z \to \mu\mu$ decays reconstructed per 100 pb^{-1} of integrated luminosity (the expected rates are somewhat lower for electrons). The low-luminosity trigger menu will also provide abundant samples of high-p_T jets, of prompt photons, mainly from γ-jet events, and of hadronic τ-decays.

All these events will be crucial for an initial validation of the ATLAS performance. More specifically, the inner-detector material can be mapped with photon conversions to an accuracy of 1% X_0 with the statistics available after several months of data-taking. Inclusive electrons can be used to test bremsstrahlung recovery in the inner detector. The inner-detector alignment is expected to converge to the required accuracy of approximately 10 μm soon after the full detector commissioning has started, allowing the constant term in the tracking resolution to be kept below 20% of the overall resolution. Residual inner-detector misalignments can be studied with the use of resonances of known mass and lifetime using their decays to lepton pairs, with E/p comparisons for well-measured electrons in the electromagnetic calorimeter, and with high-p_T muons in combined track fits with the muon spectrometer.

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A preliminary electromagnetic inter-calibration can be obtained at low luminosity using the azimuthal symmetry of inclusive isolated electrons from various sources. The next phase of the electromagnetic inter-calibration will use $Z \rightarrow ee$ events. If the inner-detector material is well understood at that point, data corresponding to an integrated luminosity of 100 pb^{-1} would be sufficient to significantly improve the expected initial uniformity of 1–2% to a statistical precision of approximately 0.7%. Further improvements will require the use of E/p distributions from inclusive electrons and/or $W \rightarrow e\nu$ decays.

Jet calibration will use E_T-balancing in di-jet, γ-jet and also Z-jet events. The latter two channels will be important to determine the global jet-energy scale with an expected precision of better than 5% after a few months of data taking. The expected number of ~ 500 fully reconstructed $t\bar{t}$ events for 100 pb^{-1}with one W decaying hadronically and the other one leptonically, will allow a calibration of the jet-energy scale using invariant mass fits to $W \rightarrow jj$ decays.

The most widely studied method to measure with data the performance of b-tagging algorithms at the LHC relies on the selection of $t\bar{t}$ events. However, recent developments show that the techniques extensively used by the Tevatron experiments, combining track-based and soft-muon b-tagging algorithms in di-jet events, could also be used at the LHC. Once large-statistics samples of $t\bar{t}$ events become available, b-jet samples with very high purity will be extracted and used to calibrate, for example, the b-tagging likelihoods directly, thereby reducing the reliance on Monte-Carlo simulation.

One of the most difficult detector observables to measure accurately is E_T^{miss}. Because it is sensitive to many new physics signatures, the tails of its distribution must be precisely calibrated with data before E_T^{miss} measurements can be used for discrimination and especially reconstruction purposes. A reliable measurement of E_T^{miss} requires the removal from the data sample of beam-halo muons, beam-gas collisions, cavern background and cosmic rays. Moreover, all calorimeter cells must be calibrated (for both electromagnetic and hadronic showers), and noise levels and deficient cells must be mapped and corrected for. Initial data-driven E_T^{miss} studies will use minimum-bias and di-jet events, analysing the missing E_T resolution as a function of the summed transverse energy. With larger statistics, the use of $W \rightarrow l\nu$ decays, of mass-constrained $t\bar{t}$ events and of $Z \rightarrow \tau\tau$ decays should lead to a calibration of the E_T^{miss}-scale to about 5%.

Initial physics measurements will primarily focus on Standard Model processes with high cross-sections. The most prominent among these will be the production of hadronic jets, of W and Z bosons, and also of $b\bar{b}$ and $t\bar{t}$ pairs. Analyses aiming at searches for new phenomena will first concentrate on the understanding of the detector performance and on these Standard Model processes. The ATLAS performance and physics working groups will exploit to the full the rich variety of known physics processes at the LHC to calibrate the analysis tools and thus to prepare for the exciting searches for new physics, which have been the driving motivation of large numbers of physicists during the many years of work which have brought the collaboration this far.

11.3 Future changes to the ATLAS detector system

As the luminosity of the LHC machine reaches its design value of 10^{34} cm^{-2} s^{-1}, the detector parts which have been staged due to budgetary constraints need to be completed. The main items falling into this category are a significant part of the HLT processing farm, some parts of the muon spec-

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trometer including in particular the monitored drift-tube chambers in the transition region between the barrel and end-cap toroids, and also some of the shielding elements in the forward region. During this phase, the performance of the ATLAS detector will be continuously evaluated and optimised, in particular as physics samples are used to further study and improve the calibration and alignment procedures. Pile-up effects will also need to be understood and dealt with as the luminosity increases.

After reaching design luminosity, the challenge will be to operate and optimise the ATLAS detector, its multi-faceted trigger system and the various physics analyses over several years of data-taking. The detector parts are generally designed for ten years of operation (conservatively estimated to correspond to an integrated luminosity of up to 700 fb^{-1}). The most critical element is the innermost layer of the pixel detector or vertexing layer, which is located at a radial distance of only 5 cm from the beam-pipe. This layer is designed to survive a 1 MeV neutron equivalent fluence of approximately 10^{15} cm^{-2}, which corresponds to less than half the integrated luminosity mentioned above. Changes in the pixel system may therefore be needed earlier than for other parts of the detector.

If the LHC luminosity were to be increased significantly beyond the current estimates, as suggested in some studies for the LHC machine upgrade on a time-scale not earlier than 2015, several detector components are likely to need substantial changes. In particular, the inner-detector system would need to be completely replaced, and certain calorimeter, muon and shielding elements in the forward directions would also require significant changes and improvements. Research and development work has started in earnest within the collaboration in several of the areas mentioned above. However, a decision about the necessity, scope and time-scale of such an upgrade can only be made after a few years of LHC and detector operation, considering both the physics results and the performance of the machine and the status of the experiments at that point.

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