ATLAS status and first run scenarios for B physics

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This article summarizes the status of the ATLAS detector and its commissioning as of autumn 2006, one year before the expected LHC start-up. The initial running scenarios and goals for B physics are presented for the foreseen pilot run with 900 GeV centre-of-mass energy in autumn 2007, as well as for the first physics run in 2008 at the nominal centre-of-mass energy of 14 TeV.

1. INTRODUCTION

ATLAS [1] is a general-purpose experiment at the Large Hadron Collider (LHC), with an emphasis on high-p_T physics beyond the Standard Model (SM). ATLAS has also capabilities for a rich B-physics programme, thanks to precise vertexing, tracking, high-resolution calorimetry, good muon identification, and a dedicated and flexible trigger scheme. Furthermore, ATLAS has a well-defined B-physics programme for all stages of the LHC-operation, from the commissioning run all the way up to the highest luminosity running at the LHC.

The ATLAS B-physics goals comprise both precision measurements and a search for new physics beyond the SM. The CP-violation parameter $\sin(2\beta)$ will be measured with a high precision (at the percent level), and the contributions from a possible new physics phase Θ_{NP} can be distinguished if they contribute at this level or more.

ATLAS will be able to measure a wealth of B-hadron parameters. In particular, measurements of B_s, B_c and b-baryon properties will be highly interesting since the B-factories cannot produce these particles, and the statistics at the Tevatron will be limited. ATLAS will be able to measure, for example, the mixing parameter Δm_s, the lifetime difference $\Delta\Gamma_s/\Gamma_s$, and the weak phase Θ_s of the B_s-meson system with good precision. Properties of the B_c-meson such as mass and lifetime will be measured with high statistics, giving insight to the strong potential binding the heavy quarks together, as well as to the interplay between strong and electroweak effects. b-baryon spectroscopy has just been started at the Tevatron [2], and ATLAS will continue these measurements, as well as other measurements such as the Λ_b polarization. Finally, the family of rare decays $B\rightarrow \mu^+\mu^-(X)$ will give a handle on exploring the new-physics parameter space.

2. ATLAS STATUS AND COMMISSIONING

The ATLAS detector is formed of three parts: the Inner Tracking Detector located in a magnetic field of 2 T and covering the pseudorapidity range $|\eta| < 2.5$ [3], the calorimeter, composed of electromagnetic, hadronic, and forward sections and covering $|\eta| < 5$, and the magnetic muon spectrometer with $|\eta| < 2.7$. The ATLAS detector layout is shown in Fig. 1.

In the following, an overview of the main characteristics of the individual detector components

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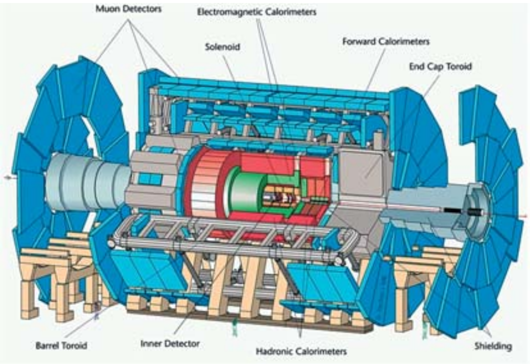

Figure 1. The ATLAS detector layout.

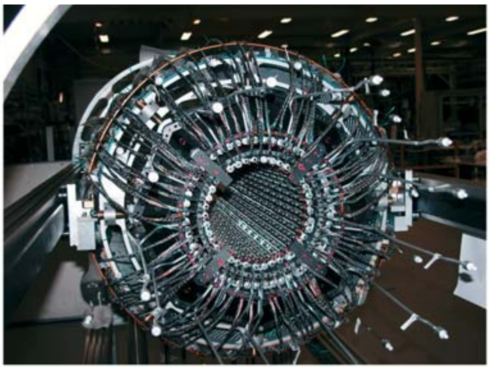

Figure 2. The Pixel Barrel layers 1 and 2.

is given and their state of assembly; installation and commissioning is described as achieved in November 2006. Finally, an outlook to the global commissioning procedures will be given.

The Inner Detector comprises three subdetectors: Pixel, Semiconductor Tracker (SCT) and Transition Radiation Tracker (TRT). Each one is split into a barrel and two end-caps. The innermost part is the Pixel subdetector, consisting of 80 million rectangular silicon pixels of size 50 μm × 400 μm, leading to a resolution of 14 μm in $r\phi$ and 115 μm in the z-direction. They are organized in three barrel layers at radii of 5.0, 8.5, and 14.5 cm, respectively, and in three disks on either side. These nine individual Pixel sections are all fully assembled and ready for integration, see Fig. 2.

The Semiconductor Tracker (SCT) comprises four barrel layers of 153 cm length which are located between a radius of 30 cm and 52 cm. The detector elements are 6 cm long silicon strips with 80 μm pitch. The end-caps consist of nine disks of radius 56 cm, positioned up to $z = 2.8$ m.

The Transition Radiation Tracker (TRT) is the outermost element of the Inner Detector. A total of 36 layers of straw tubes (4 mm in diameter and 150 cm in length) together with layers of radiator form the barrel. An individual straw tube has a resolution of 170 μm and it is equipped with electronics with two thresholds in order to distinguish tracking hits from radiation hits for electron-pion separation.

The Inner Detector is in quite an advanced state. The TRT Barrel part has been integrated with the SCT Barrel and acceptance-tested with cosmic rays. This assembly has already been installed at its final location. Fig. 3 shows the insertion of the SCT and TRT Barrel into the Barrel Calorimeter. All services have been connected and final commissioning has started. Also for both end-caps, the TRT and SCT have been combined and are ready for installation. The Pixel detector is presently being tested with cosmics on the surface and will then be installed as one unit.

A superconducting solenoid coil provides a field of 2 T for the whole Inner Detector volume. This magnet is installed and fully commissioned. Its field map has been measured with a precision of better than 10^{-3}T.

The Liquid Argon calorimeter is housed in a barrel and in two end-cap cryostats. The barrel contains the electromagnetic section, which is composed of 2 mm thick, accordion-shaped lead absorbers and electrodes with highly segmented read-out. In the end-cap region the same concept is used for the electromagnetic calorimeter, followed by a hadronic section with copper electrodes. The third element of the end-cap is the Forward Detector (outer radius of 45 cm), which

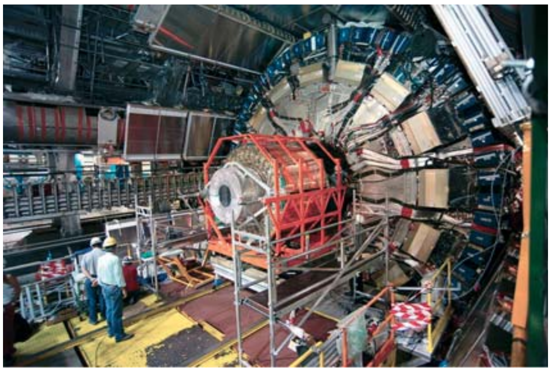

Figure 3. The insertion of the SCT and the TRT Barrel in the Barrel Calorimeter.

consists of a section with copper absorber and two sections with tungsten as absorber. All three cryostats have been operated and acceptance-tested with cosmics on the surface and are installed in the cavern. The barrel part is presently being commissioned with all of its services and with the final read-out.

The hadronic calorimeter is organized as a 564 cm long central barrel and two 290 cm long extended barrels. It uses iron plates as absorbers and scintillators as active material. The read-out via fibres is segmented in elements in $\eta - \phi$ of 0.1×0.1 rad and in three compartments in depth. Also the hadron calorimeter is installed at its final location and being commissioned.

The muon system consists of trigger chambers, precision chambers for measuring the tracks and the Toroid magnet system, again organized in a barrel part and two end-caps. The mechanical structure of the barrel is formed by the eight superconducting coils (25 m long, 5 m deep), interconnected by ribs as shown in Figure 4. The Barrel Toroid (BT) magnet has been fully commissioned at its operating current of 20500 A. Most of the barrel muon chambers have been installed in the BT volume. The End-Cap Toroids are in the final stage of assembly on the surface and will be installed in 2007. The End-Cap muon chambers are all produced and are presently being assembled in sectors, ready for installation in the ATLAS cavern. The first "wheel" of trigger chambers is already finished, as shown in Fig. 5.

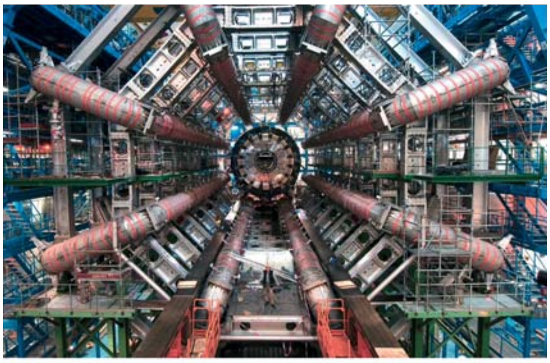

Figure 4. The coils of the Barrel Toroid Magnet with the Barrel Calorimeter.

In the cavern, the installation of the electronics is well advanced and the Data Acquisition (DAQ) and Detector Control systems (DCS) are available. As the first subdetectors, the calorimeter barrels are presently being integrated in this common read-out and control. Common data-taking with a cosmic-ray trigger will serve to set up coherent operation of all components and the data will allow a first study of the detector performance. The other detectors will be added during 2007 and cosmics runs with the full detector will be carried out well before LHC turn-on. In summary, the ATLAS schedule foresees all detector elements to be ready for physics data-taking for the first collisions in the LHC accelerator.

3. INITIAL RUNNING SCENARIOS

The current turn-on plans for the LHC are described below. The beam-pipe will be closed in August 2007, and the first collisions at $\sqrt{s} = 900$ GeV centre-of-mass (CM) energy will take place in November 2007. The full LHC commissioning up to 7 TeV per beam will be done

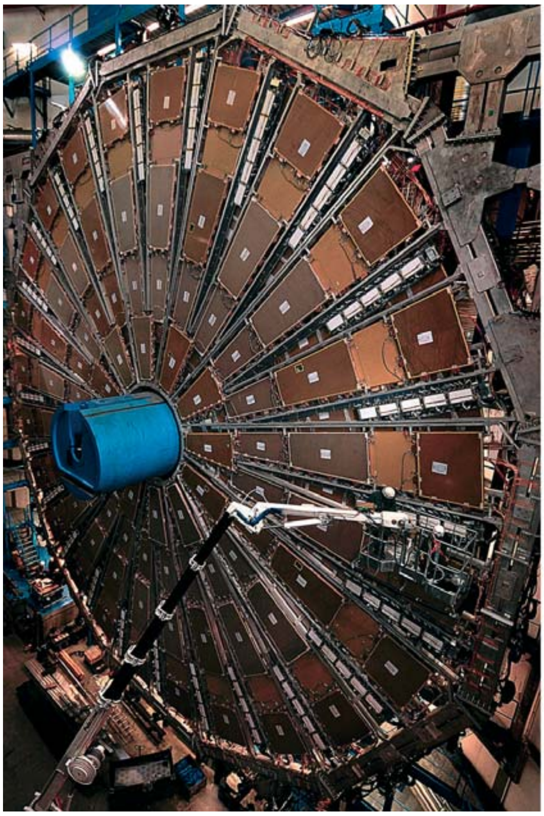

Figure 5. The End-Cap Muon Trigger chambers.

in the winter 2007/2008 shutdown, and the first physics run at 14 TeV has the goal to accumulate several fb^{-1} of data by the end of 2008.

3.1. 900 GeV running

The initial LHC operation at 900 GeV will be primarily a pilot run to debug the machine and the detectors. The LHC will operate in a static mode with the injected SPS beams, *i.e.* there will be no ramping nor squeezing of the beams. Furthermore, the LHC experiments have to be prepared for a flexible start-up scheme. Nevertheless, assuming a few weeks of stable running conditions at the injection energy, projections of the collected data sample can be made.

The $b\bar{b}$ cross-section is $\mathcal{O}(10)$ μb at $\sqrt{s} = 900$ GeV, while the inelastic total cross-section is about 40 mb [4]. The fraction of $b\bar{b}$ events is thus roughly an order of magnitude lower than at the nominal energy of 14 TeV. If it is assumed that the pilot run luminosity is about 10^{29} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the interaction rate will be only about 4 kHz. Data will be collected with loose level-1 (LVL1) single muon triggers ($p_T > 5$ GeV) or minimum bias triggers, while the High Level Triggers (HLTs) are in pass-through mode for testing. For more details see Ref. [5].

Given 30 days of beam and assuming 30% machine and data-taking efficiency, $b\bar{b}$-events will be a source of about 4700 single-muon events ($p_T(\mu) > 5$ GeV), about 150 di-muon events ($p_T(\mu_1) > 5$ GeV, $p_T(\mu_2) > 3$ GeV), about 90 $J/\psi \to \mu^+\mu^-$ events and about 130 $\Upsilon \to \mu^+\mu^-$ events ($p_T(\mu_1) > 5$ GeV, $p_T(\mu_2) > 3$ GeV). (It is interesting to note that the triggered cross-sections, taking into account dimuon decays with p_T cuts, favour Upsilon decays over J/ψ, an effect which is more prominent at lower CM energy.) These samples are much larger than, for example, the samples of leptonic decays of W and Z, and the resonance decays can be used for first tests of mass reconstruction and mass scale calibration. The expected number of events are shown in Fig. 6. Although the hadron decays to muons dominate over the heavy quark decays due to the smaller $b\bar{b}$ fraction at 900 GeV and the softer p_T spectrum [6], it should be possible to reject most of this background by looking for the characteristic “kinks” in the muon tracks.

3.2. First physics run

The first physics run with the CM design energy of 14 TeV is foreseen to start in 2008, with luminosity in the range 10^{32}-10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Apart from collecting data samples for high-p_T physics, B physics and minimum-bias physics, data are also needed as a tool for understanding and mapping the trigger performance and various aspects of the detector, such as calibration, alignment, material thickness, magnetic field *etc.* These requirements are reflected in the trigger strategy, see Ref. [5].

The expected statistics during the first physics run is already sufficient for a rich B-physics pro-

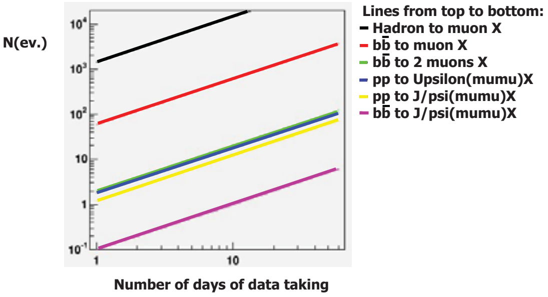

Figure 6. Number of events in ATLAS as a function of the number of days of data-taking at $\sqrt{s} = 900\,\text{GeV}$ and $\mathcal{L} = 10^{29}\ \text{cm}^{-2}\text{s}^{-1}$. Lines from top to bottom: hadron decays to μX (black); $b\bar{b} \rightarrow \mu X$ (red); $b\bar{b} \rightarrow \mu\mu X$ (green); $pp \rightarrow \Upsilon(\mu\mu)X$ (blue); $pp \rightarrow J/\psi(\mu\mu)X$ (yellow); $b\bar{b} \rightarrow J/\psi(\mu\mu)X$ (purple).

gramme:

- cross-section measurements at the highest LHC energy – QCD tests and optimization of B-trigger strategies;
- so-called "control" channels such as $B^{+} \rightarrow J/\psi K^{+}$ and $B^{0} \rightarrow J/\psi K^{*0}$ will be used for checking that variables such as masses and lifetimes are measured correctly, and for measuring data-tagging properties, production asymmetries and other features affecting the B-physics measurements;
- quark "onium" production: *i.e.* J/ψ and Υ; and
- searches for rare decays.

The ATLAS B-physics programme is based on LVL1 muon triggers, using inclusive low-p_T single-muon triggers at low luminosity, and low-p_T dimuon triggers at higher luminosities. Specific final states are searched for in the HLT, either exclusively or semi-exclusively, by refining the muon selection, and then reconstructing tracks from B decays in the Inner Detector. Tracks are found in the Inner Detector by either performing a full track search, or searching in regions given by LVL1 "Regions of Interest" (RoIs), depending on the HLT processor capacity and the instantaneous luminosity [5].

Conservatively assuming 10^{6} s effective running time during 2008 with an instantaneous luminosity of $\mathcal{L} = 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, the integrated luminosity would be $100\,\text{pb}^{-1}$. The estimated statistics collected in ATLAS with this integrated luminosity, including both trigger and reconstruction efficiencies, is shown in Table 1.

3.3. B-production measurements

Measurements of B-hadron production, such as cross-section and correlation measurements as well as measurements of onium production, are important for:

- testing our models for heavy flavour production at the highest CM energy,
- measuring correctly the heavy flavour background for various new physics searches, and
- optimizing trigger strategies, both for B physics and for new physics searches.

All of the four LHC experiments ALICE, ATLAS, CMS and LHCb will measure the $b\bar{b}$ cross-section. The experiments cover different phase space regions in transverse momentum and in pseudorapidity, so the experiments are complementary, and the partial phase-space overlaps make it possible to cross-check the results. In ATLAS, the $b\bar{b}$ cross-section can already be measured with high statistics during the first year of running by using the inclusive semileptonic decays of b-quarks, $b\bar{b} \rightarrow \mu 6X$ and $b\bar{b} \rightarrow \mu 6\mu 3X$ (where both b-quarks decay semileptonically). Here the notation "$\mu 6$ (5,3)" refers to muons with $p_T > 6$ (5,3) GeV, respectively. $b\bar{b}$ correlations can be studied with good statistics by using the double-semileptonic decays $b\bar{b} \rightarrow \mu 6\mu 3X$. The available statistics with $B \rightarrow J/\psi(\mu 6\mu 3)X$ and $b \rightarrow \mu 5X$ in the same event will be significantly smaller, but the B decaying on the other side of the event will be very cleanly reconstructed. Furthermore, with increasing statistics, one can use exclusive

Table 1
The estimated statistics in ATLAS for 100 pb^{-1}.

Decay	Number of events	Measurement example
$bb \rightarrow \mu6X$	400×10^6	Cross-section
$c\bar{c} \rightarrow \mu6X$	200×10^6	Cross-section
$b\bar{b} \rightarrow \mu6\mu3X$	20×10^6	Cross-section, correlations
$b \rightarrow J/\psi(\mu6\mu3)X$ and $\bar{b} \rightarrow \mu5X$	25×10^3	Correlations
$pp \rightarrow J/\psi(\mu6\mu3)X$	1×10^6	Ratios of quark “onia”
$b\bar{b} \rightarrow J/\psi(\mu6\mu3)X$	4×10^5	Ratios of quark “onia”
$\Upsilon(\mu6\mu3)X$	1×10^5	Ratios of quark “onia”
$B^+ \rightarrow J/\psi K^+$	17×10^3	Control channel
$B^0 \rightarrow J/\psi K^{*0}$	8.7×10^3	Control channel
$B^0 \rightarrow J/\psi K^0_S$	1.3×10^3	Control channel
$B^0_s \rightarrow J/\psi\phi$	900	Control channel
$\Lambda_b \rightarrow J/\psi\Lambda$	260	Control channel

decays on the other side of the event, such as $B^+ \rightarrow J/\psi(\mu6\mu3)K^+$ and similar decay channels.

With an integrated luminosity of 100 pb^{-1}, ATLAS will be able to collect a sample of about 10^6 directly-produced J/ψ events, 4×10^5 J/ψ events produced in B-hadron decays, and 10^5 Υ-decays. These statistics will enable good measurements of production ratios and other properties of the events, such at p_T distributions, which are interesting for constraining the models for onium production, which is still a not-well understood issue.

3.4. Exclusive B decays

The ATLAS statistics for exclusive B decays such as $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow J/\psi K^{*0}$ will be of the order of 1000 – 10000 events for an integrated luminosity of 100 pb^{-1}. These statistics are already sufficient for sensitive tests of those Inner Detector features which have a strong impact on B-physics measurements. For example, the lifetime of the B^+ can be measured with a 1.5% statistical precision given a sample of 17000 $B^+ \rightarrow J/\psi K^+$ decays. Given the same integrated luminosity, the lifetime precisions of B^0, B^0_s and Λ_b can be measured with statistical precisions of 2.2%, 6% and 8%, respectively. Furthermore, these channels provide reference data for tagging, production asymmetries and other systematic uncertainties affecting, for example, CP-violation and mixing measurements as well as searches for new channels such as $B^0_s \rightarrow \mu^+\mu^-$.

Rare B decays have increasingly become the focus of the LHC B-physics programme. ATLAS has very good possibilities for an excellent physics programme from rare B decays thanks to the dimuon signals which make it possible to collect statistics even during the highest luminosity running. The statistics for the rare decays $B^+/B^0/B_s/\Lambda_b \rightarrow \mu^+\mu^-(X)$ at an integrated luminosity of 100 pb^{-1} will nevertheless be small, $\mathcal{O}(10)$ events, so measurements will have to wait for the coming years with more statistics. The LHC rare-decay plans are explained in detail in Ref. [7].

4. CONCLUSIONS

The ATLAS detector installation is proceeding well and on schedule. The barrel part of the ATLAS Inner Detector, apart from the Pixel detector, has been integrated and installed at its final location. The Pixel detector is fully assembled and it is presently being tested with cosmic rays on the surface. The Pixel detector will then be inserted into the Inner Detector as one unit. The End-Cap Inner Detector (TRT and SCT) has been assembled and it is ready for installation.

The superconducting solenoid coil around the Inner Detector, providing a field of 2 T, is installed and fully commissioned.

All three cryostats housing the Barrel Liquid

Argon electromagnetic calorimeter, the End-Cap Calorimeter comprising both an electromagnetic and a hadronic section, and the Forward Detector have been assembled, operated and acceptance-tested with cosmics on the surface, and they are now installed in the cavern. The barrel part is presently being commissioned with all of its services and with the final read-out. The barrel and extended Barrel Hadronic Calorimeters are installed at their final locations and being commissioned.

The Barrel Toroid magnet has been fully commissioned at its operating current. Most of the Barrel Muon chambers have been installed in the Barrel Toroid volume. The End-Cap Toroids are in the final stage of assembly on surface and will be installed in 2007. The End-Cap Muon chambers are all produced and are presently being assembled in sectors, ready for installation in the cavern.

In the cavern, the installation of the electronics is well advanced and the Data Acquisition and Detector Control systems are available. All detectors are foreseen to be integrated into the common DAQ and DCS systems and cosmic-ray running with the full detector, and this will be carried out before the LHC turn-on.

The LHC commissioning run in autumn 2007 at 900 GeV centre-of-mass energy and with a very low luminosity will serve for commissioning the detector, the trigger, the offline reconstruction and the analysis chains, in addition to the LHC machine commissioning itself. Given 30 days of running at $\mathcal{L} = 10^{29}$ cm^{-2}s^{-1}, about 4700 b-decays to single muons and about 370 dimuons from b- and c-decays can be collected, serving as the first tests of trigger and offline muon reconstruction. ATLAS also expects about 90 $J/\psi \rightarrow \mu^+\mu^-$ and 130 $\Upsilon \rightarrow \mu^+\mu^-$ events which are useful for testing and calibrating the mass reconstruction procedures.

The first physics run in 2008 at 14 TeV CM energy is foreseen to provide ATLAS with an integrated luminosity in the range 100-1000 pb^{-1}. Measurements of B-hadron masses and lifetimes will provide a sensitive test of understanding the detector alignment, material thickness, magnetic field, event reconstruction *etc.* The cross-section and correlation measurements at a new centre-of-mass energy will serve for QCD tests, optimization of B-trigger strategies, and measuring the background for new physics. Control B-channel measurements will help prepare for further B-physics precision measurements as well as for new physics searches.

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