Readiness of the ATLAS detector: performance with the first beam and cosmic data

F. Pastore*
CERN, Geneve (Switzerland)
on behalf of the ATLAS Collaboration

Abstract
During 2008 the ATLAS experiment went through an intense period of preparation to have the detector fully commissioned for the first beam period. In about 30 hours of beam time available to ATLAS in 2008 the systems went through a rapid setup sequence, from successfully recording the first bunch ever reaching ATLAS, to setting up the timing of the trigger system synchronous to the incoming single beams. So-called splash events were recorded, where the beam was stopped on a collimator 140 m upstream of ATLAS, showering the experiment with millions of particles per beam shot. These events were found to be extremely useful for timing setup. After the stop of the beam operation, the experiment went through an extensive cosmic ray data taking campaign, recording more than 500 million cosmic ray events. These events have been used to make significant progress on the calibration and alignment of the detector. This paper describes the commissioning programme and the results obtained from both the single beam data and the cosmic data recorded in 2008.

Key words: LHC experiment, commissioning, ATLAS

1. Introduction
ATLAS is a wide range discovery experiment built on the LHC accelerator ring at CERN and motivated by testing the Standard Model and its extensions to the highest energies. The commissioning of the ATLAS detector started in 2006 using cosmic rays that reach the hosting cavern, 100 m underground. Since then, the detector operated together the various sub-systems, even the ones that were only partially installed, testing the global infrastructure (DCS, DAQ, monitoring), the trigger systems, the data transfer and processing (including the computing model and the trigger selections). The whole system was installed and completed in summer 2008 and on September 10th ATLAS was ready for continuous operation with the LHC beams. After the LHC accident, ATLAS went through a long data taking campaign using cosmic rays which allowed optimization of the integration, the calibrations and the track-based alignment between different sub-detectors. Moreover, with the high statistics of cosmic-rays events registered in a period of about two months of data taking, each subsystem could verify its own performance and compare with the design. Here we summarize these results, while for more details one can refer to other proceedings at this conference. During the 2009 winter shutdown, most of the minor problems found on the different detectors were recovered, and the status of all of them is described in the next sections, together with the results from the cosmic data taking campaign and the first beam events seen in

*Corresponding author
Email addresses: francesca_pastore@cern.ch (F. Pastore)
the Level-2. The latter, after refining the L1 results with local
analysis inside the RoIs, effectively rejects events using more
granular information and adding tracking results from the inner
detectors. This requires only about 2% of the complete event
from the Readout System (ROS). Then the Event Filter (EF)
operates on fully assembled events, requiring an event building
rate of the order of 5 GB/s. A common High Level Trigger
(HLT) architecture includes L2 and EF, which have the same
key concepts, i.e. seeded reconstruction and early rejection,
and share the same infrastructure, implemented in Linux PC
farms (300 L2 nodes and 1800 EF nodes, with 2.5 GHz 8-core
processors).

The L1 trigger is designed to perform a rate reduction from
the 40 MHz LHC beam crossing rate down to 100 kHz, while
the L2 must reduce the event rate down to about 3.5 kHz. After
the EF rejection, the data are stored at up to 200 Hz rate. With
the expected event size of 1.6 MB, about 300 MB/s are written
to disk. The L1 trigger systems are completely operational,
being tested up to 50 kHz, while the HLT system has been tested
up to 60 kHz with 35% of the final system, since its deployment
will be completed when required by the LHC luminosity.

The data acquisition system has been working continuously
since 2008 with the complete ROS system, network infrastruc-
ture and local data storage farms (5 nodes with 50 TB storage
capacity) fully in place. Dedicated technical runs established
the performance and the scalability during system deployment,
testing the data acquisition system under very stressing condi-
tions: simulated data, whose size was half that of the expected
one, was used as input to the readout system. A request rate
on ROS of 30 kHz was reached (while the design one is of 20
kHz) with an event building rate of 4.2 kHz (3.5 kHz by de-
sign) and data storage was running at a steady rate of 550 MB/s.
Moreover, during summer 2008 a realistic test of the comput-
ing model has been performed, processing simulated high lu-
nositivity data from the online farms down to the Tier-2 analysis
centers.

A large amount of cosmic rays have been collected by
ATLAS with different detector and magnet configurations. After
the 2008 LHC startup, ATLAS recorded up to now more than
500 million events, corresponding to a raw data volume greater
than 1.2 PB. Most of the events have been collected with the
whole detector readout and trigger, with the exception of the
CSC chambers. In particular, Fig. 2 shows the accumulated
statistics during a combined global run in autumn 2008 pro-
duced by different trigger streams (over 200 millions events)
and reflects the high cross section of the Barrel muon system to
cosmic rays. A dedicated trigger stream, based on HLT tracking
algorithms, was used to enrich the inner tracking samples in
order to allow the test of the alignment, as described later in this
paper. A simulation of cosmic rays going through the ATLAS
detector has also been provided to allow for data/Monte Carlo
comparisons.

Different streams gather data meant for calibrations and
alignment purposes or for physics studies. A sub-set of the
physics events are processed at the Tier-0 at CERN, in quasi real
time, running the complete reconstruction for monitoring pur-
pose. Dedicated calibration centers, which include some Tier-

Figure 2: Cosmic data recorded by ATLAS since Sept 13, 2008. 216 M events.
400,000 files in 21 inclusive streams.

2 Grid centers as well as the CAF (CERN Analysis Facility),
perform a first pass calibration and alignment within 24 hours
after the data taking. The obtained constants are then used for
the bulk processing of the data, after validation. Data are then
distributed to the Tier-1 and Tier-2 centers for data analysis.

Given the differences between LHC collision data and the
data recorded by ATLAS from cosmic rays and LHC single
beam operations, LHC collisions are of course needed to make
the final test of the operation chain. However, a very signif-
cant part has already been exercised with real data, showing stable
and robust operation of the Tier-0 processing, the data quality
monitor, the data analysis and the calibration procedures.

3. Commissioning with the beams

Bunches of $10^9$ protons with 450 GeV energy were injected
into the LHC ring in September 2008, over several days, circu-
lating without acceleration.

Although ATLAS was running stably, many components op-
erated with reduced gain, for safety reasons (SCT, Pixel, for-
ward calorimeters and forward muon chambers). In addition
in the ATLAS L1 trigger systems, there are several detectors
whose main task is beam control and monitor. Among these
there are scintillation counters designed to trigger on minimum-
bias events during early days running (MBTS) and are placed
on the endcaps cryostats. LUCID is a Cherenkov light detec-
tor primarily dedicated to online luminosity monitoring. Beam
pick-up detectors (BPTX), positioned in the beam pipe 175 m
upstream of the interaction point, provide a filled bunch trig-
ger and monitor the beam activity, identifying the bunches in
the beams, measuring their individual intensity and phase rel-
tive to the clock, and assigning them the correct LHC Bunch
Crossing (every 25 ns).

The bunches managed to circulate many times during the in-
jection: during the first turns, the good energy alignment of
the protons allowed the BPTX to detect the current, while af-
ter a few turns also the MBTS were illuminated, as well as the
calorimeters. Given the good quality of the beams, the Barrel
detectors showed very low activity, mostly detecting beam halo
particles (mainly muons and particles due to the interaction of

2
the protons with the beam pipe or residual gas) especially during the first turns when the RF capture was not active. The BPTX has been important for the first setup of the L1 trigger systems, given its excellent timing synchronized to the beam bunches. In fact during the few days of single beam running we were able to align all the L1 trigger systems to the bunch crossing time. In addition to this, a limited number of times the beams were dumped on closed collimators 140 m from the ATLAS interaction point, producing a splash of particles throughout the whole detector, with more than 100,000 hits in the muon chambers and huge energy deposits in the calorimeters (more than 1000 TeV in the hadronic calorimeter and several TeV in the electromagnetic one).

These events have been very useful to pinpoint dead channels and to validate the calibration procedures: energy calibration in the calorimeters (i.e. 4% for Tiles), timing performance for the calorimeters and the TRT (with a precision better than 2 ns and 1 ns respectively), high precision test for all the endcaps detectors.

4. Detector studies with cosmic rays

With over 200 millions cosmic ray events from an autumn 2008 run, the global performance of ATLAS as a whole detector has been tested as well as detailed studies of each subdetector. To demonstrate the good performance of the whole, interesting correlations between tracks seen in the muon spectrometer and in the inner detector confirm the expectations and the transverse momentum measured in the two systems shows the expected 3 GeV/c loss of energy within the intermediate region of the calorimeter, as visible in Fig. 3.

4.1. Muon Spectrometer

The large volume of the air-core toroidal magnetic field (with bending power in the range 1.5 to 7.5 Tm) hosts the Muon Spectrometer. It consists of precision tracking chambers, as Monitored Drift Tubes (MDT) and Cathode Strip chambers (CSC) in the innermost endcap region with high rate environment, as well as dedicated trigger detectors with excellent timing resolution, made out of Resistive Plate Chambers (RPC) in the Barrel and Thin Gap Chambers (TGC) in the endcap regions. This wide system comprises about one million readout channels and more than 12,000 m² of active detector area. Being the most external part of ATLAS, these detectors have been installed and commissioned later than the others. As a consequence, when LHC started, some parts were not optimally performing, but after the winter shutdown, the detector coverage and the calibration procedures has been completed.

The Muon Spectrometer is expected to provide a standalone transverse momentum ($p_T$) resolution of approximately 10% for 1 TeV tracks. The resolution is dominated by the position measurement resolution and requires the sagitta of the track to be measured with an error of 50 µm. This imposes a good spatial resolution of the drift tubes (reached by 3-4 multiple hits per track segment) as well as an accuracy of 30 µm on the position of the muon chambers. This is accomplished by a combination of track-based alignment algorithms and a system of about 12,000 optical sensors. Auto-calibration procedures produce the $r$-$t$ relation parameters and the track-based alignment constants using a dedicated stream of data with an enlarged muon sample, extracted from L2 trigger and sent to dedicated Tier-2 centers. Cosmic rays data with and without magnetic field have been used to demonstrate that the sagitta residuals are within the design specifications.

The Muon Spectrometer has also trigger functionalities and is equipped with dedicated detectors with the aim of selecting muons with a given $p_T$, assigning the correct bunch crossing and providing the second coordinate measurement $\phi$, orthogonal to the bending $\eta$ plane. All these detectors are now fully operational, except for few endcap chambers under repair, showing chamber efficiency very close to the expected values (95% single wire efficiency for TGC and 97% chamber efficiency for RPC). Their good timing performance are accompanied by timing algorithms which allow for aligning the signals coming from different parts of the detector. As for all the other L1 trigger systems, this item is particularly crucial for the preparation to the collisions, even if the geometrical distribution of the cosmic rays (not starting from the interaction point) makes this job only preliminary to the final timing-in with collisions.
4.2. Calorimeters

The calorimeter system consists of two different technologies: the Liquid Argon calorimetry with an accordion geometry to identify with excellent performance both electromagnetic and hadronic showers up to pseudorapidity $|\eta| < 4.9$, and iron-scintillator-tile hadronic calorimeter in the Barrel region. This calorimeter system provides, in the overlap region with the inner detector, fine granularity with good resolution and linearity for precision measurements of electrons and photons, while coarser granularity in other regions is sufficient for jet reconstruction and missing transverse energy measurements.

Both technologies are fully operational and the very few problems already present in September 2008 have been solved during the winter shutdown. Long term stability checks currently show a very low number of noisy and dead channels and a stable behavior: electromagnetic pedestals are stable within 1 MeV over five months period, while Tiles electronic noise, calculated as the standard deviation of the digital samples at cell-level, varied within 1% over the same period. The calibration procedures are fully operational (with Cs source, laser and charge injection): an important validation of the energy inter-calibration of the Tiles down to 4% level have been provided with splash events during the beam activities. Cosmic ray data have allowed very detailed studies of the calorimeters with minimum ionizing particles: for example in the electromagnetic calorimeter the linearity of the response has been validated checking that the amount of the energy deposit strongly depends on the cell depths and is in good agreement with the expectation at level of 2%, even with different cluster algorithms, that could then be optimized (see Fig. 4). For events accepted by the L1 trigger, typically five samples per channel are readout in the LAr calorimeter, but with an extended readout window of 32 samples the complete pulse shape for cosmic muon is monitored and again compared with the predictions.

Since the calorimeters are trigger sources, their timing misalignment has been corrected, in order to exploit their excellent time resolution (order of ns): for example, after the calibration with electronic pulses, cosmic rays seen as minimum ionizing particles in the Tiles are detected in different parts of the detector with an error less than 2 ns on the expected time-of-flight.

4.3. Inner Detectors

The ATLAS inner tracking system, immersed in a 2T solenoidal field, includes three different technologies: a combination of high-resolution silicon pixel and microstrip detectors (Pixel and Semiconductor Tracker SCT respectively) closest to the beam pipe, to ensure pattern recognition, momentum and vertex measurement of charged particles, and straw-tubes transition detector tracker (TRT) in the outer part to improve the electron identification and the pattern recognition (with typically 36 hits per track). The silicon cooling system is now fully operational after some problems were solved during the winter shutdown. Hit efficiency is more than 98% and noise occupancy well below the design specifications.

The distributions of the residual position of hits with respect to the track characterize the tracking performance and clearly reflect both the spatial resolution and the aligned position of more than 6,000 inner-detector detector modules. The alignment accuracy obtained in the Barrel with cosmic tracks is close to the performance predicted by the Monte Carlo studies with perfect detector alignment. Using tracks from particles with transverse momentum larger than 2 GeV/c and passing near the interaction point, the iterative alignment procedures result in 30 $\mu$m residual width for SCT, 24 $\mu$m for Pixels and 187 $\mu$m for TRT. When extrapolating the track through the three detectors, the combined track parameters show the expected residual distribution.

All the physics properties of the silicon detectors have been validated with simulated data, as for example the charge distribution of clusters along the tracks and the dependency of the cluster size on the incident track angle respect to the surface of the module. This latter, and in particular the minimum of the distribution, can be used to estimate the Lorentz angle within each detector, i.e. the drift angle due to the magnetic field. The measurement confirms the expected values, within the systematic error due to secondary effects of temperature gradients.

5. Conclusions

ATLAS is a great challenge, due to its size, the complexity of its sub-detectors and its physics objectives. The robustness and stability of the complete experiment are now under optimizations, with the final system completely integrated, and continuously exercised with cosmic rays. Nevertheless the trigger systems are being prepared for different LHC scenarios and the first beams will give important inputs to better understand the detectors.

References