The ATLAS Semiconductor Tracker: operations and performance

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Abstract—The Semi-Conductor Tracker (SCT) is a silicon strip detector and one of the key precision tracking devices in the Inner Detector of the ATLAS experiment at CERN LHC. The SCT is constructed of 4088 silicon detector modules for a total of 6.3 million strips. The current results from the successful operation of the ATLAS SCT Detector at the LHC and its status after three years of operation are presented. We report on the operation of the detector, including an overview of the issues we encountered and the observation of significant increase in leakage currents (as expected) from bulk damage due to radiation. The LHC has delivered 47 fb^{-1} in 2010, 5.6 fb^{-1} in 2011 and to date in 2012 18.1 fb^{-1} of proton-proton collision data, and two times one-month periods of heavy ion collisions. The SCT has been fully operational throughout all data taking periods. It delivered high quality tracking data for 99.9% (2010), 99.6% (2011) and 99.3% (2012) of the delivered luminosity. The SCT running experience will be used to extract valuable lessons for future silicon strip detector projects.

Index Terms—Semiconductor Tracker, ATLAS, Operations, SCT.

I. INTRODUCTION

ATLAS is the larger of the two general purpose detectors built around an interaction point at the Large Hadron Collider, at CERN, the European Laboratory for Particle Physics. The LHC has delivered 5.6 fb^{-1} proton proton collisions at 7 TeV (centre of mass energy) in 2011 and 18.1 fb^{-1} at 8 TeV in 2012, at the time of this conference. The SemiConductor Tracker (SCT), together with the Pixel detector (which is closer to the interaction point) and the Transition Radiation Tracker (TRT), measures the parameters of charged tracks, in a 2 T magnetic field. The ATLAS inner detector is shown in Fig. 1. It has played a central role in the discovery of the Higgs-like particle. In this paper we report on the data taking operations of this part of the ATLAS apparatus. The Semi Conductor tracker is described in detail elsewhere [1] [2]. It consists of 4088 modules, each made of single-sided AC-coupled micro-strip detectors made with p-implants on n-type silicon [3]. The bias voltage is the same for all sensors in a module and is applied to the backplane, thus minimising the voltage drop across the coupling capacitor. Two sensors are glued back to back, with 40 milliradians between the strip directions, so to have a true space point measurement from each module. The barrel part consists of 4 layers of identical modules, all using sensors made by Hamamatsu with $\langle 111 \rangle$ and $\langle 100 \rangle$ crystals. The measurement of track parameters for tracks at an angle $9.4^\circ < \theta < 25^\circ$ with respect to the beam direction is done with wedge-shaped modules

arranged in 9 disks per side of the interaction point. The disk sensors were made by Hamamatsu and by CiS, using different design details. The SCT modules are operated at a temperature between 1.3° and 10°C , using evaporative cooling with C_3F_8 . The electronic signal is amplified, shaped and discriminated with 128-channel custom chips "ABCD3TA" [5], which also contain a digital shift register to store the hits while waiting for the trigger latency. The chips were made with a BiCMOS $0.8 \mu\text{m}$ DMILL radiation resistant process. A total of 49056 ASIC chips are read out with optical fibres, using opto-package devices [4]. The optical signal is converted again into electrical byte streams in 90 "Back of Crate" (BOC) VME cards and read out with 90 ROD cards. These cards are always accessible during operations, although they are located 80 m underground. Some of the HV and LV power supplies, however, only have limited access because are located in an accelerator area.

II. DATA TAKING

Redundancy in the tracking design is very important, so that malfunctioning of a small part of the tracking can be tolerated without loss in performance. It is anyhow essential that a very large part of the SCT is operational every time there are collisions, to avoid holes in coverage. At present 27 modules (0.66%), 46 single chips (0.09%) and 11100 single strips (0.17%) are excluded from data taking. 13 of these modules are excluded because of a leak in the evaporative cooling circuit of a quadrant in one of the outermost disks, others are excluded for HV, LV or readout problems. The number of excluded modules and chips has been largely stable in the last year of operations, with 3 modules having intermittent problems. The number of single strips excluded has increased slightly. Having this baseline as the fraction of established well-functioning detector, a defect was flagged in the data, during off-line data quality assessment, if more than 40 additional modules, representing 0.1% of the total, were delivering data with unrecoverable problems, or no data at all. With this definition of "good data", the SCT has delivered 99.6% of good data in 2011 operations and 99.3% in 2012 (till 26th October). This record of efficiency was due to a robust design, but also to 24/7 operations conducted by a dedicated team. The SCT shifter was in charge for 8 hours of the SCT operations during 2011, while during 2012 the shifter role covered Pixel, SCT and TRT operations. A SCT expert was permanently on-call during a period of about one week, to

respond to problems which the shifter could not handle, while the run coordinator, in charge for one year, was involved in case of major problems, when coordination with the other sub-detectors or with LHC was needed. The following section will focus on the main reason for SCT-related data loss.

III. OPERATIONAL ISSUES

The main reason of data loss was due to the occasional drop of one or more ROD from the ATLAS DAQ stream, followed by a recovery without stopping the run. In general these incidents lasted one or two "luminosity blocks" an unit corresponding to about one minute of data taking. The Single Event Upset of the ASIC chip from radiation is clearly noticeable when taking data at high luminosity as an increase of the error rate and of noisy modules; an auto-reconfiguration of modules producing DAQ errors was put in place, as well as forcing a reconfiguration of the entire SCT every 30 minutes of data taking. The detector coverage in 2011 has been modulated by one module or two due to a high failure rate of the Transmitter plug-in circuit (TX), with a Medium Time to Failure of 9000 to 10000 hours per device. The TXs drive the control data to the readout chips via optical fibres and use an array of 12 *GaAs VCSELs*. A single TX failure affects one module, which most of the time can be controlled using the neighbouring module as redundant path. All the 360 TX plugins are accessible when ATLAS is not taking data, so the failed TX could be continuously replaced. In February/March 2012 all the TX were replaced with plugins using *VCSELs* from a new vendor, and we have only had 8 single-VCSEL failures since then, a period of approximately 5000 hours.

IV. DETECTOR SAFETY AND TURN-ON PROCEDURE

The maximum energy stored in one LHC beam was about 100 MJ in 2011 and 150 MJ in 2012. A tiny fraction of this energy is sufficient to make permanent damage to the silicon, which is located at a minimum distance of 27 cm from the beams. Although a 3.5 TeV beam can not be possibly steered directly into the SCT, an intense flux of secondary particles from the interaction of part of the beam with collimators can still damage the detector, especially during injection and ramp. The SCT is operated at full nominal voltage (150 V) only if the beams are declared "stable" by the LHC operations team, or if there is no beam in the machine. In all other situations a stand-by voltage of 50 V, just below full depletion, is considered safe, but the detector can still deliver data, with higher noise and a lower hit efficiency. The intrinsic response time to turn the SCT on is about 50 seconds. Before turning on the SCT, in 2011 operations the shifter checked the beam related background from the Beam Conditions Monitor (BCM) [6], the SCT occupancy at stand-by voltage, the rates from the forward beam and luminosity sensors and the positions of the collimators around the interaction region. This resulted in about one to two minutes additional time delay. From June 2011 these checks have been automated, so that the average turn-on time is 69s in 2012 operations so far. Fig. 2 shows the SCT turn-on time as a function of time, during 2012. There were a small number of cases when conditions were not

met: sometimes a background spike occurs when the beams are steered into collision; in other cases an increase of noise in the BCM diamond faked high background for one beam. Runs with special optic settings require manual intervention or consultation with the LHC control room to turn on the SCT. The response time of the SCT is usually faster than the one of the other ATLAS sub-detectors and is small compared to the duration of a data-taking period, which is of the order of 10 hours.

V. ANOMALOUS INCREASE OF CURRENT AND NOISE: THE CiS MODULES

The LHC delivered instant luminosity has been increasing steadily in 2011, to reach a maximum of $3.65 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, while in 2012 after two ramps in April and May the peak luminosity has been almost constant at about $6.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ with a peak at 7.73. At the end of May we started to experience a series of un-recoverable ROD busy, which consistently occurred after a couple of hours of stable beam. The reason for this was found to be connected to some modules in the end-cap middle wheels, mostly wheel 3 and 5, which were producing data with high occupancy, mostly noise. The data were quickly filling the buffer, causing the corresponding ROD to issue a busy signal and to drop out of the data acquisition. These modules also featured a silicon bias current which increased during collisions at high luminosity, with a characteristic time of about 1-2 hours. However, the maximum value of the current was still orders of magnitudes below the value which would explain an increase in noise. Mostly the "middle" sensors made by CiS that are facing away from the interaction point are affected by this behaviour. The CiS sensors represent 32% of the wheels and have a different design with respect to the Hamamatsu: the metal strip is narrower than the *p*-implant underneath. This already gives some unintended behaviour when the CiS sensors are operated in a very dry environment [8]. We suspect that the surface charge accumulation on the oxide is responsible for the increase of current. The charge may originate in the nitrogen gas which surrounds the silicon and is ionised by an intense radiation. Not all CiS modules show this feature of the current, which is noticeable only when high luminosity collisions ($\geq 5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$) occur. The current is stable, within errors, when there are no collisions. A similar behaviour is often attributed to micro-discharges along the edge of the strips. In this case the current variations seem to be smoother than expected with micro-discharges and no obvious "hot spot" could be noticed in the noise hit distribution of the affected sensors. The effect appears to be extremely well reproducible and non permanent: after having kept the detector at a reduced bias with no collision, the current increase is much smaller. We therefore decided to keep the CiS sensors at 5 V instead of the standard 50 V stand-by voltage between fills of the accelerator. For a small set of CiS sensors we also had to reduce the bias, to avoid over-current trips, but they are still efficient to produce hits from tracks. While the investigation on the CiS sensors is on-going, it is unlikely that the behaviour could be reproduced in laboratory, or in an irradiation beam

line, given the peculiar conditions of its onset. No sign of this behaviour is seen in the Hamamatsu modules.

VI. PERFORMANCE

In the 2012 data the charged track density is much larger than the corresponding data in 2011 and 2010. In particular, the proton-proton collisions, with more than 30 interactions per beam crossing, start to approach the track density of non-central heavy ion collisions. Depending on the instantaneous luminosity and on the Physics trigger, the space average of the SCT hit occupancy in p - p collisions peaks to about 2% per bunch crossing. The average hit efficiency for combined SCT tracks is 99.6%, but this number depends on the total number of tracks in the event and on the details of the pattern recognition algorithm, which do not assign hits to more than one track. The efficiency per barrel layer is shown in Fig. 3. The inner tracker alignment issues have been reported elsewhere in these proceedings [9].

VII. RADIATION DAMAGE

For the barrel region the SCT reverse current is in very good agreement with the calculations based on the luminosity profile and the temperature history. For the end-cap modules the agreement is less good but still within 25%. The 2012 data are being analysed. The SCT is still far from reaching the type inversion. At the present delivered luminosity the radiation damage can be displayed on-line from fill to fill. Even during the same data taking period the silicon detector current displays a clear increase, due to radiation damage. The beneficial annealing during technical stops are also clearly evident from on-line data.

VIII. CONCLUSIONS

The ATLAS Semi Conductor Tracker is taking excellent data, with $\geq 99.5\%$ hit efficiency, 99.3% of the data have an absolute SCT coverage larger than 98.2%. The main reasons for inefficiencies were presented, together with some highlights on operating difficulties, which we had to cope with in 2012. The radiation damage of the SCT is closely following the expected profile. The LHC will stop operations for maintenance and for energy upgrade to 14 TeV in February 2013, for about two years. During this time the SCT will upgrade the data acquisition system to cope with higher occupancy for a collision pile up of up to 80 events per crossing.

REFERENCES

- [1] The ATLAS Collaboration, JINST 3 S08003, (2008)
- [2] M. Moreno Llacer, ATL-INDET-PROC-2011-032 presented at IEEE-NSS, Valencia, (2011).
- [3] A. Ahmad, Z. Albrechtskirchinger, P. P. Allport, J. Alonso, L. Andricek, R. J. Apsimon, A. J. Barr and R. L. Bates *et al.*, Nucl. Instrum. Meth. A **578**, 98 (2007).
- [4] A. Abdesselam *et al.*, JINST 2 P09003 (2007).
- [5] F. Campabadal, C. Fleta, M. Key, M. Lozano, C. Martinez, G. Pellegrini, J. M. Rafi and M. Ullan *et al.*, Nucl. Instrum. Meth. A **552**, 292 (2005).
- [6] D. Dobos *et al.* [RD42, ATLAS Diamond Pixel Upgrade and ATLAS Beam Conditions Monitor Collaboration], Nucl. Instrum. Meth. A **628**, 246 (2011).

Fig. 1. The ATLAS inner detector. The SCT is located between the Silicon Pixel detector and the Transition Radiation Tracker.

Fig. 2. SCT turn-on time for 2012 running. For each period of stable beam we plot the difference between the time when stable beam is declared and the time when the SCT is reported to be ON by the detector control system. The outliers, with a response time larger than 100 s, are 8% of the total and correspond either to fills with special set-up, or to fills where one or more beam background conditions were not initially met.

Fig. 3. Hit efficiency, as a function of the sensor layer in the SCT barrel for combined inner detector tracks in one run (n. 206573) taken in 2012

- [7] A. Abdesselam *et al.*, JINST 3 P02007, (2008).
- [8] F. G. Hartjes, Nucl. Instrum. Meth. A **552**, 168 (2005).
- [9] P. Bruckman de Renstrom, "Advanced Alignment of the ATLAS Tracking System", IEEE-NSS-24-3, Anaheim, CA, (2012).