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The operational experience, challenges and performance of the ATLAS Semiconductor Tracker during LHC Run-2 and SCT operation prospect for Run-3

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The Large Hadron Collider recently completed its Run-2 operation period (2015–2018), which delivered an integrated luminosity of 156 fb^{-1} at the centre-of-mass proton-proton collision energy of 13 TeV. This marked 10 years of successful operation of the ATLAS Semiconductor Tracker, which operated during Run 2 with instantaneous luminosity and pileup conditions that were far in excess of what the SCT was originally designed to meet. The first significant effects of radiation damage in the SCT were also observed during Run 2. The SCT operations, performance and radiation damage studies were published as a paper [1]. This document summarises the operational experience, challenges and performance of the SCT during Run 2, and Run-3 operation prospects with a focus on the impact and mitigation of radiation damage effects.

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1. Introduction

The ATLAS detector [2] records the proton-proton (pp) collisions of the Large Hadron Collider (LHC) [3], which operated at a centre-of-mass energy of 7 to 8 TeV between 2010 to 2012 (Run 1), 13 TeV between 2015 to 2018 (Run 2) and is operating at 13.6 TeV since the beginning of July 2022 (Run 3). The ATLAS detector has a symmetric cylindrical layout around the LHC beam pipe. An intricate multi-layer system of sub-detectors was designed to record, reconstruct and identify the particles produced in the pp collisions with high-precision and at high rates. The so-called inner detector (ID) system is closest to the beam pipe and reconstructs the trajectories, “tracks”, of charged particles. A solenoid surrounding the ID provides a magnetic field to measure charged particles’ momenta. The ID consists of three sub-detectors (from inwards to outwards): the Pixel detector, the Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT). The SCT extends across radii of 299 mm to 560 mm around the beam pipe and provides crucial information to tracking and the reconstruction of interaction vertices. It has been operational since its commissioning in 2008 and participated in the data taking of Run 1 and Run 2. It will continue operating during Run 3, which is expected to conclude at the end of 2025. During Run 2 the conditions under which the SCT operated were significantly harsher than in Run 1 and far exceeding the conditions assumed during the initial design of the SCT [4]. This had implications on the operation of the SCT and caused considerable radiation damage, which are discussed in the following sections. Section 2 provides a brief summary of the SCT layout and its operation during Run 2. The data acquisition chain and adjustments to it for Run 2 are described in Section 3. Radiation damage measurements are detailed in Section 4. Section 5 gives an outlook to Run 3. Section 6 provides a conclusion.

2. SCT layout and operation

The SCT consists of 4088 modules that are arranged in four cylindrical central barrel layers and nine endcap disks in each side in the forward regions[1]. Each module comprises 1536 strips contained in two or four p^+-on-n silicon sensor pairs assembled back-to-back with a stereo angle of 40 mrad. Dedicated chips attached to hybrids connected through wire bonds to the strips amplify, shape and discriminate the pulses from the charges that are invoked by charged particles passing through the sensors. The modules are supplied with a low voltage, $O(5\,\text{V})$, for the readout chips and high voltage (HV), $O(150\,\text{V})$, to the sensors. In total, the SCT has around 6.3 million read-out channels and provides a spatial resolution of approximately 20 μm [5]. The SCT is cooled down to about 0 °C, with the exception of the outer-most barrel layer, which is operated at 6 °C warmer to avoid mechanical stress on the neighbouring TRT. During operations the SCT is continuously monitored, e.g. temperature, voltage, to ensure stable operation. Regular calibrations are performed to adjust thresholds and identify strips with high levels of electronic noise. If faulty modules, chips or strips are found and cannot be corrected, they are disabled to optimise hit efficiency (as disabled elements are not considered as holes during track reconstruction). At the start of Run 2, 38 modules were disabled, which increased to 46 modules up to June 2022 [6]. The most common issue in modules disabled after the start of Run 2 was the stability of the HV. The fraction of disabled

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[1] “Central” refers to the detection volume surrounding the pp collision point ($|\eta| \lesssim 1.5$) and “forward” to detection volumes surrounding the beam pipe further away from the collision point.

strips also increased over time however at the start of Run 3 there are still more than 98% of strips active [6]. There is no significant impact on the reconstruction of tracks expected from these disabled components. SCT can impact ATLAS data taking in two ways: it can assert a busy signal that inhibits triggers, e.g. when bandwidth limits are exceeded, or the quality of the SCT data can be compromised, e.g. due to operational issues such as loss of HV to multiple modules. The former is quantified by data taking efficiency, i.e. the fraction of time during collisions for which SCT is available to record data, and the latter by data quality, i.e. the lumi-weighted fraction of recorded data for which SCT data qualify as good for physics. The occurrence of the aforementioned SCT issues during data taking were extremely rare in Run-2, with the SCT data taking efficiency and SCT data quality in excess of 99.9% and 99.85%, respectively.

3. SCT data acquisition chain and challenges

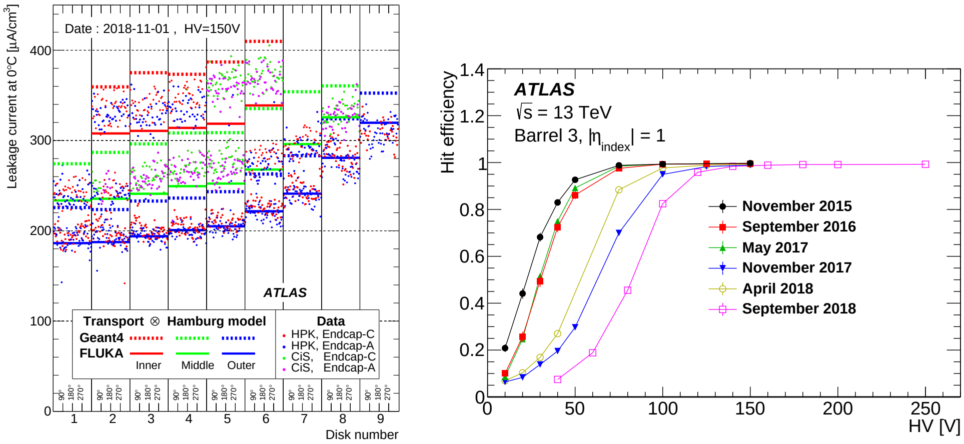
The SCT Data Acquisition System (DAQ) is integrated into the central ATLAS DAQ and trigger system and facilitates communication between those and the SCT modules. All communication and transmission of signals between the SCT DAQ, central DAQ and the modules is done using optical links. Clock and control commands are transmitted through so-called TX links. The data recorded by the SCT is transported from the modules via so-called RX links. Both communication paths, TX and RX, have built-in redundancy mechanisms. If individual links fails, communication is re-routed using the remaining links. In June 2022 less than 2% of links operate in the redundancy mode [6]. The SCT data is formatted and then transmitted to the central DAQ system via so-called S-links. If the rate of data transmission exceeds the bandwidth limits of the S-links, back-pressure will invoke a “busy” signal, which will halt the trigger signals and suspend data taking until the back-pressure is resolved. Due to the interruption to the data taking and thus loss of data for physics analyses, significant effort was put into improving and upgrading the SCT DAQ chain for Run-2 data taking. These upgrades include an increase in the number of S-links, remapping of links to distribute data more evenly, decreasing the data size through re-optimised compression and masking the most noisiest chips depending on pile-up conditions. This was necessary since in Run 2 the LHC operated regularly at levels of 50 to 60 pile-up collisions, which is far beyond the SCT’s design limit of ~23 pile-up collisions and led to an immensely increased number of particles being produced in the collisions. Without the aforementioned upgrades it was expected that almost all links would exceed their bandwidth limits for conditions with 40 to 50 pile-up collisions, whereas now SCT can operate at conditions with up to 70 pile-up collisions without significant bandwidth issues [6, 7]. This was crucial during Run-2 operations and will be crucial for Run 3 too, where similar pile-up scenarios are expected.

4. Radiation damage

The SCT is irradiated with a large amount of various particles with a large range of energies during data taking. This causes damage to the sensors in the form of additional states within the semiconductor band gap. Although the radiation dose received up to 2022 is well below what the SCT was designed for [4], changes in the SCT performance due to radiation damage were always expected throughout the lifetime of the SCT and operational margins were built-in to be able to mitigate the impact of radiation damage effects. The radiation dose received during Run 2 was three orders of magnitude higher compared to Run 1. The inner most barrel layer and the endcap disk modules closest to the beam pipe and collision point experienced the highest radiation doses whereas the outer most barrel layer experienced the lowest ones [1]. In the following two radiation damage effects that were observed in the SCT are discussed: leakage current in Section 4.1 and the effect of type inversion in connection with the full depletion voltage in Section 4.2.

4.1 Leakage current

Leakage current (I_{leak}) is created in silicon sensors due to thermally created electron-hole pairs. Therefore it is a temperature dependent effect with higher I_{leak} expected in sensors that are operated at higher temperatures. As radiation damage accumulates due to the creation of additional energy levels in the sensors, I_{leak} increases too. To be able to use I_{leak} as a measure for the SCT's radiation damage at the end of Run 2 the temperature dependence was factored out (more details given in [1]). The largest values of I_{leak} are measured for the regions of the SCT that are expected to have received the largest radiation doses during Run-2 operation. The results of I_{leak} measurement for the SCT endcap modules in November 2018 is shown in Figure 1a. It shows the I_{leak} patterns follow the radiation dose patters with the highest values measured for modules closest to the beam pipe ("Inner") and closest to the pp collision points (small disk numbers). Since I_{leak} creates heat in the silicon sensors, which in turn will create more electron-hole pairs the danger of a self-enhancing loop, "thermal runaway", arises, which will severely damage the sensors. Projections for Run 3 have been made using the expected integrated luminosity and connected expected radiation damage. It is expected that the SCT can be safely operated within margins below the thermal runaway limit. The largest danger is present in the outer-most barrel layer, which operates at higher temperatures and might reach 50% of the theoretical thermal runaway limit by the end of Run 3. This could be reduced to 45% by lowering the cooling temperature by 3 °C [6].



(a) **(b)**

Figure 1: (a) Measured (dots) and expected (lines; from simulations) leakage current in the various SCT endcap disks in November 2018; several detector areas (inner, middle, outer) and manufacturers (HPK, CiS) are compared. (b) Hit efficiency as a function of applied high voltage for the inner-most barrel layer at different points in time in Run 2.

4.2 Type inversion and full depletion voltage

A known effect in p^+-on-n silicon sensors is type inversion due to radiation damage. This causes the sensors to behave like quasi-p-type sensors. This effect was observed in all regions of the SCT by the end of Run 2 [1]. Due to type inversion the depletion region grows from the opposite side of the sensor as before. This means if the sensor is operated at a voltage that does not fully deplete it ("full depletion voltage" V_{FD}) the charges have to pass through the inactive, undepleted region of the sensor for charge collection. This will result in a significant loss of charge and thus a decrease in hit efficiency. To ensure close to 100% hit efficiency the sensors have to be supplied with a high voltage that is larger than V_{FD}. Figure 1b shows the hit efficiency as a function of applied *HV* for the inner most barrel layers at various points in time between the start and end of Run 2. A significant increase in required *HV*, from around 70 V at the beginning of Run 2 to 140 V at the end of Run 2, is observed. Therefore, adjustments to the *HV* were made in September 2018 in Run 2 and further adjustments are expected to be necessary during Run 3. Dedicated measurements of the V_{FD} throughout Run 2 further confirm the type inversion in the SCT sensors [1].

5. Preparations for Run-3 operations and outlook

First pp collisions at the nominal Run-3 collision energy of 13.6 TeV were recorded on July 5. Before July 2022, the SCT used pp collisions provided at a collision energy of 900 GeV to perform timing corrections. Timing corrections, i.e. artificial delays to the trigger signal, are needed to ensure the trigger signal and transmitted data for a given collision coincide. The corrections compensate for several effects, e.g. time-of-flight of the particles, delay in electronics. A coarse correction of −5 ns due to upgraded trigger electronics and fine corrections with individual delays for each module (ranging between 1 ns and −2 ns) [6]) were applied. The SCT reported > 99% hit efficiency in all detector regions in June 2022 [6].

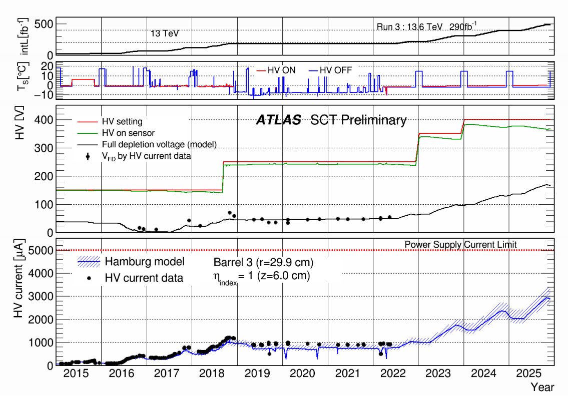


Figure 2: Measured (dots) and projected (lines) leakage current and full depletion voltage from 2015 until the end of Run 3 in 2025 for the inner-most barrel layer, as well as expected operational settings (high voltage and temperature) and evolution of integrated luminosity.

Based on the operational experience of Run 2 and expected conditions in Run 3 projections are made [6]. In particular the inner-most barrel layer, which receives a high amount of radiation damage, and the outer-most barrel layer, which has to operate at higher temperatures, were deemed critical. Without those SCT detection layers a significant reduction in the track reconstruction efficiency is expected, which cannot be recovered by loosening the track reconstruction requirements without increasing the amount of mis-reconstructed tracks, i.e. tracks not corresponding to any actual particle but just arising from deteriorated ambiguity resolution [6]. Figure 2 shows the evolution of several radiation damage measures and operational parameters for Run 2, in between Run 2 and Run 3 and a projection for Run 3 operations. The full depletion voltage and leakage current are expected to increase by a factor of 3 until the end of Run 3 compared to levels at the end of Run 2. Subsequently it is expected that the *HV* needs to be increased in several steps from 250 V to 400 V to prevent loss in performance. However, it is expected that the adjustments that can be made will be sufficient to ensure continued high SCT performance and operations will take place with a sufficient margin with respect to limitations from the SCT hardware.

6. Conclusions

The SCT is a crucial part of the ATLAS experiment for track measurements. It has been operated with a high efficiency and delivering high quality data ($> 99\%$) during the Run-2 data taking period (2015–2018). Several measures have been implemented to overcome bandwidth limitations in high pile-up conditions (>50 pile-up collisions). During Run 2 effects of radiation damage became visible and have been measured in the form of leakage current, type inversion and full depletion voltage. Regular adjustment of operational settings mitigate the effect of radiation damage on the performance of the SCT. In preparation for Run 3, which started in July 2022, timing corrections have been derived and in test runs a hit efficiency of $> 99\%$ was achieved. Projections for Run 3 suggest a significant increase in radiation damage effects, however the SCT hardware limits allow for further adjustments in the operational settings. This suggests that operations within sufficient safety margins will be possible and high performance will be achievable in Run 3.

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