CMS Strip Detector: Operational Experience and Run1 to Run2 Transition

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The CMS silicon strip tracker is the largest silicon detector ever built. It has an active area of 200 m^2 of silicon segmented into almost 10 million readout channels. We describe some operational aspects of the system during its first years of operation during the LHC run 1. During the long shutdown 1 of the LHC an extensive work program was carried out on the strip tracker services in order to facilitate operation of the system at sub-zero temperatures in the LHC run 2 and beyond. We will describe these efforts and give a motivation of the choice of run 2 operating temperature. Finally a brief outlook on the operation of the system in the upcoming run 2 will be given.

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1. Introduction

The CMS Silicon Strip Tracker (SST) [1] is located at the heart of the CMS experiment immersed in the 3.8 T magnetic field of the CMS solenoid magnet. Together with the CMS pixel detector described elsewhere [2] it provides high precision measurements of charged particle trajectories up to $|\eta| < 2.5$[1].
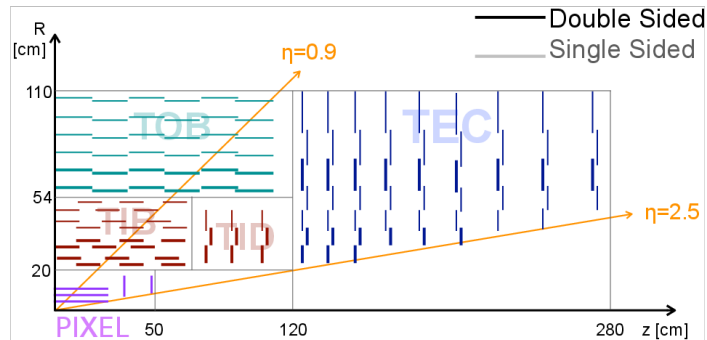

Figure 1: An *rz* view of one quarter of the CMS silicon tracker. Layers with so-called *stereo modules* (see text for details) are drawn as thick lines.

An *rz* view of one quarter of the CMS tracker is shown in Fig. 1. The active area of almost 200 m^2 is distributed among 15148 individual silicon modules. The system has 10 barrel layers, 4 in the *tracker inner barrel* (TIB) and 6 in the *tracker outer barrel* (TOB). In the forward region the system is complemented by 3 + 9 endcap disks in the *tracker inner disks* (TID) and *tracker end caps*, respectively. In the TID and TEC wedge-shaped modules are arranged in rings of equal radius. In the outer parts of the silicon tracker – TOB and TEC rings 5 to 7 – two silicon sensors are daisy-chained to form the silicon module. The readout pitch ranges from 85 μm in the inner layers of the inner barrel to 205 μm in the outer rings of the end caps for a total of 9.6 million readout channels. The strip tracker uses *p-in-n* silicon with 320(500) μm sensor thickness in the inner(outer) parts of the detector. In four layers (three rings) of the barrel (endcap) region, the strip tracker uses so-called *stereo modules*. These are modules in which two silicon sensors are mounted back-to-back with a 100 mrad stereo angle to effectively provide a 3D hit resolution. The strip tracker uses an analog readout of every detector channel via 72000 readout ASICs (APV25 [3]) and 360000 optical links to retain information about the absolute signal height. Common mode subtraction, zero-suppression, and cluster finding are performed in the off-detector front-end drivers (FED) located in the underground service cavern (USC) outside the radiation zone. The timing and trigger

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[1]CMS uses a right-handed coordinate system with *x* pointing towards the center of the LHC ring, *y* pointing upwards and *z* pointing in the direction of the counter-clockwise beam. The radial distance *r* is defined as $\sqrt{x^2+y^2}$. The polar angle is denoted ϑ, the azimuthal angle as ϕ. The pseudorapidity is defined as $\eta = -\ln\tan(\vartheta/2)$.

distribution to the individual silicon modules is performed using token ring networks of communication and control units (CCU). The SST has a total of 1944 low voltage (LV) power groups and 3888 high voltage (HV) channels to provide LV of 1.25 V and 2.5 V as well as HV up to 600 V to the individual silicon modules [4]. The HV operating point during run 1 was 300 V to ensure over-depletion of all silicon sensors. A monophase C_6F_{14} cooling system with two cooling stations is used to cool the tracker to its operating temperature.

2. Run 1 Operational Experience

Detector Status
The number of active channels in the strip tracker has been reasonably stable during its first years of operation from the end of 2009 to spring 2013. A total of 97.5 % of the channels of the strip tracker were active at the end of LHC run 1. Failures can mostly be attributed to failures of groups of modules for example due to failing control token ring networks, or problems in the LV or HV distribution.

Cooling System Performance
The cooling system with two C_6F_{14} cooling plants (SS1 and SS2) has been running stably during run 1. During the first few years of operation one of the two cooling plants (SS2) exhibited larger than expected leak rates. Leak searches finally traced large leaks to 5 out of the 180 cooling loops which have subsequently been closed. The modules located on these cooling loops are being operated with passive cooling. After this, the leak rate of the cooling system was stable at around 1 kg of C_6F_{14} per day. The second plant (SS1) operated leakless during all of run 1.

Radiation monitoring
The SST acquired a radiation dose corresponding to an integrated luminosity of around 30 fb^{-1} during run 1. Radiation related quantities were monitored continuously and compared to simulation. For the *leakage current*, measurements are performed using both in-situ measurements from a dedicated ASIC on the front-end hybrid (DCU) of each module and current measurements from the power supply units. In the latter, the current measurement is integrated over several modules (3-12) due to the limited granularity of the power system. Both methods provide consistent results. In figure 2, the measured leakage current is compared to a prediction for a radiation dose corresponding to 25 fb^{-1} of integrated luminosity. There is good agreement between the simulation and the data.

Automatic High Voltage Raising
As one example for an improvement to the operational procedures introduced during run 1, we present the automatic procedure that was put in place during late summer 2012 to automatically raise the high voltages of the strip tracker upon the declaration of *stable beams* by the LHC. Prior to the introduction of this automatic procedure, the HV was raised manually by the detector control system shifter after checking a number of quantities related to the quality of the beam conditions. The automatic system relies on a semaphore which continuously checks the beam conditions as well as the status of the CMS beam radiation monitoring system itself. Upon the declaration of stable beams the HV of the system is switched on with no delay, provided that the conditions
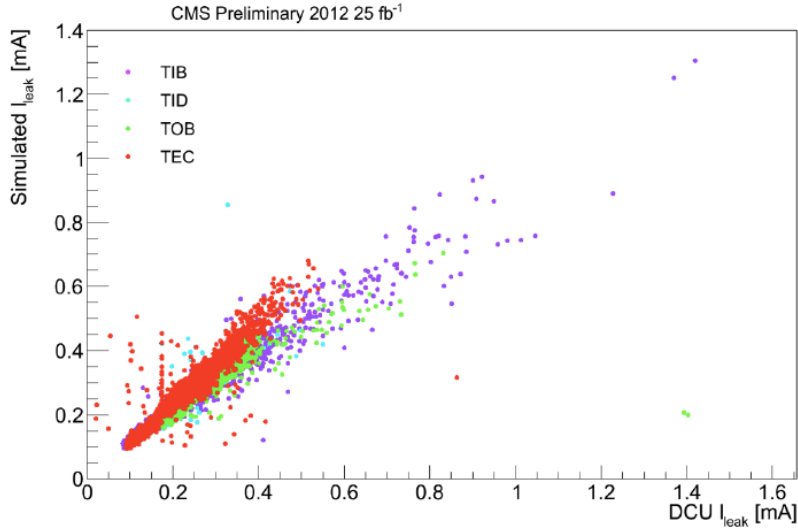
Figure 2: Plot of leakage current compared with simulation. Results are corrected for different module geometries, radius, and sensor temperature.

checked by the semaphore were good in the last 30 seconds prior to the declaration of stable beams. The effect of this automatic method is illustrated in figure 3 where the time between the declaration of stable beams and the full raising of the HV of the tracker is shown. The moment of switching to the automatic system is indicated by a vertical line. One can clearly see a marked drop in the average *time to HV on* with the automatic method. The remaining spread in the distribution stems from the complexity of the system with large number of commands propagating through a large infrastructure network tree. This improvement gains data taking efficiency for the strip tracker especially in the periods of highest instantaneous luminosity right after the declaration of stable beams.

3. Work during Long Shutdown 1

The strip tracker groups carried out an extensive work program during the long shutdown 1 (LS1) of the LHC[2]. The prime objective of this work was to enable to run the strip tracker at temperatures significantly below 0°C to mitigate the effects from radiation damage, while during run 1 the cooling fluid set point was +4°C. For this, four main lines of activities were followed:

- refurbish cooling system,

- augment dry gas supply,

- improve humidity sealing,

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[2]The long shutdown 1 started in February 2013 after the end of the proton-ion data taking of the LHC and will end in the spring of 2015.
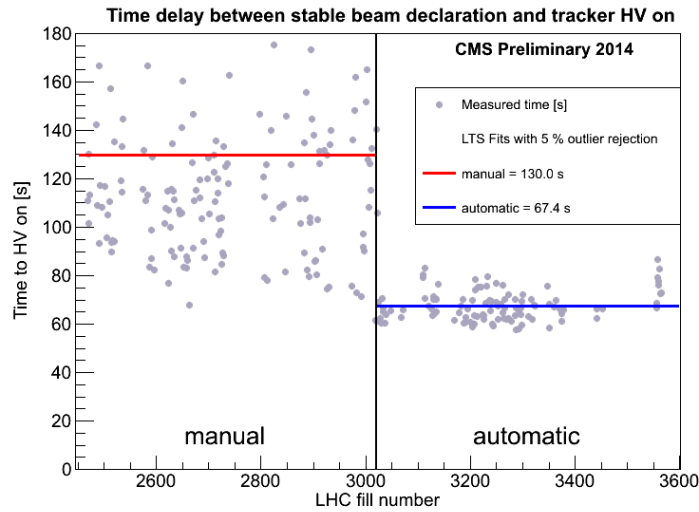
Figure 3: Time delay between the declaration of stable beams by the LHC and the switch-on of the HV for the strip tracker. The mean values with rejection of 5% outliers are 130 s for the manual and 67 s for the automatic procedure.

- improve environmental instrumentation.

3.1 Work on the Cooling System during LS1

In 2008 the tracker cooling system experienced a rupture of a heat exchanger. Following this incident, the layout of the tracker cooling was changed from a brine circuit as input to the strip tracker cooling plants to another C_6F_{14} circuit as primary. With this layout change the cooling power available was not sufficient to operate the system down to its design temperature. In LS1 the heat exchangers of the strip tracker cooling plants as well as the evaporator on the primary circuit have been changed. Also the monitoring and regulation of the plants have been improved at the same time. With these modifications the performance of the system meets all design specifications. In addition to the performance related modifications, also a refurbishment of the cooling plant cabinets with improved insulation and sealing was carried out.

3.2 The Tracker Humidity Improvement Project

During run 1 the environmental conditions in the tracker service channels and at the tracker bulkhead did not allow to operate the strip tracker cold safely. The volume of the tracker itself had good humidity conditions during all of run 1 while the dew points in service channels and bulkhead were compatible with them being relatively open to ambient air from the experimental cavern.

Figure 4 shows a cross-section of the inside of the CMS solenoid with the 'nose' carrying the foward calorimeters protruding into it.

Dry gas
In order to increase the drying capacity for the tracker volume and the adjacent service channels, a
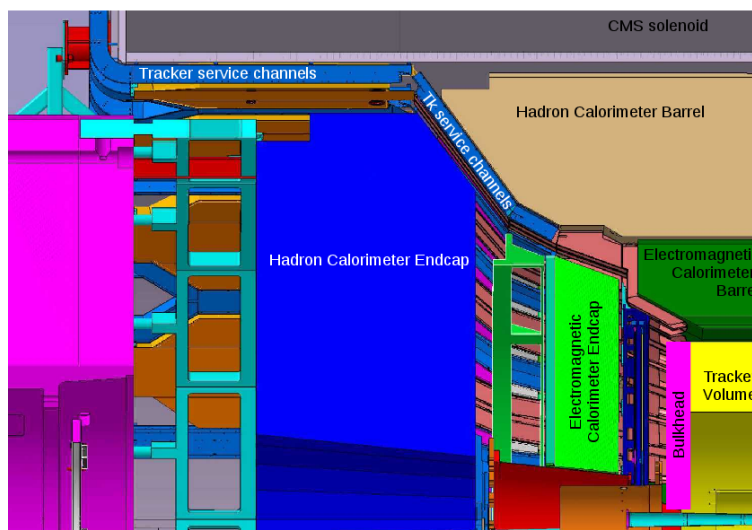
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Figure 4: The central region of the CMS detector in a *yz* cut-away view. Highlighted are the tracker service channels and the tracker bulkhead which are the path and end point, respectively, of all services like power, cooling, and dry gas.

new dry gas supply plant based on a membrane separation system has been installed and commissioned. The membrane separation system outputs de-oxygenated air with less than 5% of O_2, i.e. well below the flammability level. The new dry gas plant can provide almost ten times the amount of dry gas of the old system. In order to allow for a fine-grained distribution of this new dry gas supply, a total of 36 individually regulated multi-layer dry gas pipes were routed to the inside of the CMS solenoid. The distribution goes via three newly installed racks which have been installed in the USC. This allows adjustments to the dry gas flow even during beam operation. A total of 10 of the 36 pipes have been dedicated to inject dry gas into the cooling pipe bundles which bring cold liquid from the cooling plants to the detector. With this injection any ice formation inside the bundles, even in case of damaged insulation, can be prevented.

Sealing

To improve the humidity situation in the service channels and in front of the final carbon disk which separates the tracker volume from the outside (the so-called bulkhead), a continuous sealing was created all the way from the tracker bulkhead to the edge of the solenoid. For this, also service channels belonging to the Barrel Electromagnetic and Hadronic calorimeters were completely sealed. Additional insulation was installed in a few places close to the bulkhead in order to reduce the demand for heating elements which are used to counteract low temperatures on the outside of the service channels where they are facing a much less humidity controlled environment.

Instrumentation

In order to closely monitor the effectiveness of both the sealing and the augmented injection of dry

gas, a large number of digital hygrometers have been installed. A three-fold approach with in-situ sensors as well as remote sensing is being employed which is described below.

Fiber Optic Sensor (FOS): the fiber optic sensors are utilized for both temperature and humidity monitoring [5] in-situ. The working principle relies on a Bragg-grating manufactured into the optical fiber which enables measurements via wavelength analysis. FOS are intrisically very radiation-hard and are expected to survive until the end-of-life of the strip tracker at about 500 fb^{-1} of integrated luminosity.

Arduino-based sensors: these sensors are digital thermometers and hygrometers which are being read out using Arduino© [6] microcontrollers. The sensors are not radiation tolerant and thus will not survive once operation with beam starts. In the meantime they are providing valuable cross-checks of the other sensor systems and due their lower price they could be installed in bigger numbers to have a more fine-grained understanding of the humidity situation in the various volumes.

Sniffer System: In order to have a second, completely decoupled system of measurements, a sniffer system with a total of 26 lines has been installed. This system extracts gas from different positions inside the tracker, outside the tracker and fully outside of the tracker seal and transfers these air samples to a gas analysis rack located in the USC. The analysis of the dew point is performed using 26 industrial Vaisala dew point sensors [7]. In addition a total of 5 chilled mirror devices [8] are installed which can be connected to individual sniffer lines to provide a very precise absolute calibration.

Detector Status for Run 2

The strip tracker was completely inaccessible during LS1 for repair actions on the inside of the detector volume. Thus any repair action was confined to repairs in the patch-panels at the edge of the solenoid magnet where cables from the inside of the tracker are joined with cables from the power supplies situated on balconies inside the underground experimental cavern (UXC). For few power groups, problems could be identified and cured and the connected silicon modules are being reintegrated into the data acquisition.

4. Run 2 Preparations

4.1 Choice of Run 2 Operating Temperature

During the so-called *Tracker Master Cold Test* in January and February 2014 the SST operated at various temperatures down to -20°C (set-point of cooling fluid temperature). Dew points were monitored during the whole operation and found to be very good — at least -30°C and in most cases much lower, i.e. with sufficient safety margin. Because of the various problems experienced during run 1 with the cooling system, an operating temperature of -15°C is deemed safer than the -20°C shown to be possible during the cold test, but studies were performed to ensure that this choice does not come at the price of unsustainable increase in depletion voltage at the end of life of the detector. Two scenarios are compared:

1. operation at -15°C up to long shutdown 2 (LS2) and -20°C afterwards, until long shutdown 3 (LS3)

2. operation at -20°C from after LS1 until LS3.

The expected integrated luminosity at the start of LS2 is about 150 fb^{-1}. Figure 5 shows the difference in full depletion voltage between the two scenarios. It can be seen that the maximum difference in full depletion voltage is only around 10-15 V which has to be compared to a typical full depletion voltage of 300-400 V at the end of life. The limit imposed by the CAEN power supply system is 600 V of bias voltage. From this it can be concluded that there is no penalty incurred from operating the detector at -15°C set-point during run 2.
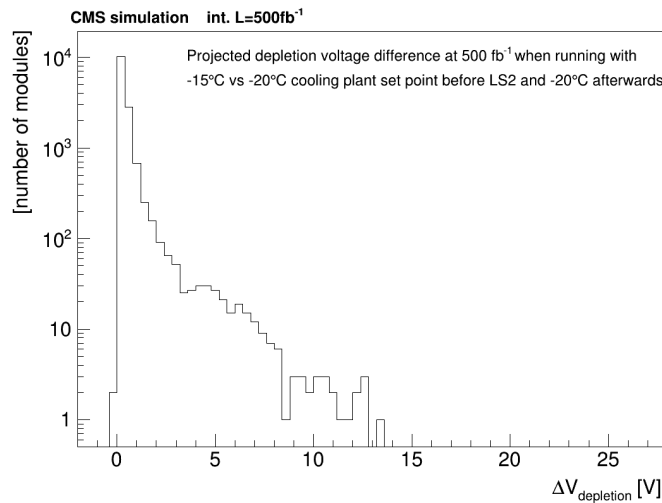

Figure 5: Difference of full depletion voltage for individual silicon modules when running with cooling fluid set point of -15°C until LS2 and -20°C afterwards compared to running with -20°C set-point for the full period.

4.2 Detector Commissioning

With the new operating temperature of -15°C established, the commissioning of the detector has begun. Fresh calibration constants are being derived at this temperature for the various parts of the readout chain, the APV25 readout chip and several parameters of the optical link system for the data transfer. One example for the latter is discussed in the following. The optical link system makes use of edge-emitting laser diodes and has four gain stages to compensate for non-uniformities in the link system as well as future radiation effects. The gain of the optical link system typically increases with decreasing temperature. Hence in the absence of substantial radiation damage[3] the optical link gain can be expected to increase compared to the run 1 performance at

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[3]The currently acquired dose corresponds to only 5% of the design level.

+4°C. Since the target gain remains fixed at 0.8 ADC counts/mA of input signal, the commissioning procedure will choose – on average – lower gain settings to compensate for the increased link gain. This can be seen in figure 6 where the height in ADC counts of the so-called *tick mark*, a digital one that is emitted by the APV25 readout chip every 70 clock cycles in the absence of data, is shown comparing data from 2010 and 2014 at +4°C and -15°C, respectively. At -15°C more laser diodes are being operated in gain settings 0 and 1 compared to 2010, as expected. This situation leaves ample room for future adjustments of the link gain to compensate for radiation induced loss of link gain.
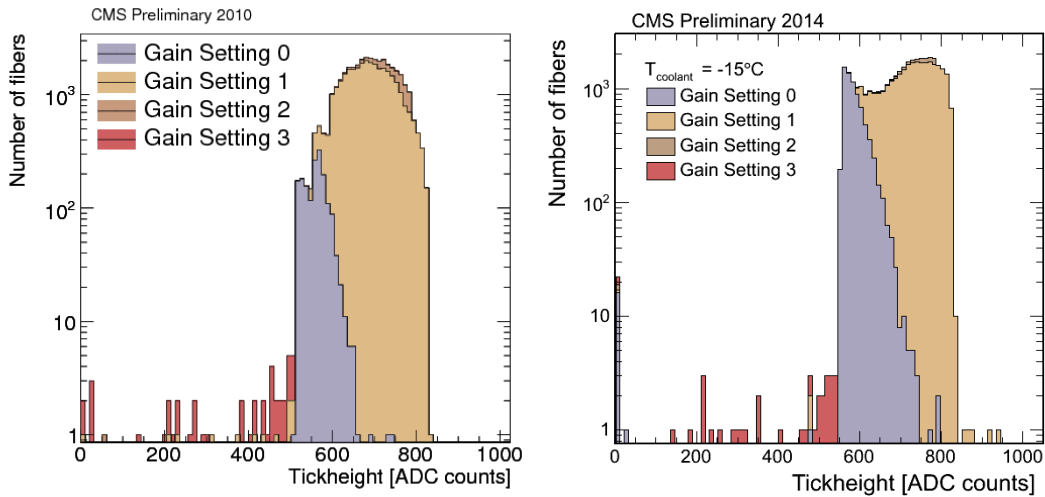

Figure 6: Distribution of laser driver gain settings for operation at +4°C (left) and -15°C (right). A shift to lower gain values can be seen due to the increase of link gain with decreasing temperature.

5. Summary and Outlook

The CMS silicon strip tracker operated very successfully during the LHC run 1 providing high quality tracking to CMS physics analyses. Many operational procedures were improved over the course of the running, such as the introduction of an automatic procedure to raise the high voltages upon the declaration of stable beams.

During the long shutdown 1 of the LHC an extensive work program was carried out which now enables cold operation of the tracker. Repair works were carried out, increasing the number of active channels compared to the end of run 1. Recalibration at low temperatures has started and is expected to finish soon, well in time for the start of beam operation in the spring of 2015.

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