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Operational Experience with the D0 silicon tracker

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The D0 Silicon Micro-strip Tracker (SMT) has been successfully in operation at the Tevatron Collider at Fermilab since 2001. The detector is performing very well, providing good tracking and vertexing capabilities for the D0 experiment. In 2006 an additional inner layer (Layer-0) of silicon sensors was installed with an innermost radius of $R = 1.6$ cm. This article describes a few key ingredients for the successful long term operation of the D0 silicon detector.

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1. Introduction

The D0 Silicon Micro-strip Tracker (SMT) was installed in 2001 as part of the Run II Tevatron collider project. It is located inside a 2 Tesla solenoid magnet and provides precise track and vertex reconstruction capabilities over the pseudo-rapidity range of $|\eta| < 3$. In 2006 an additional layer of sensors (Layer-0) was installed between the beam pipe and the innermost existing sensors. Layer-0 is fully integrated in the data collection and offline reconstruction showing excellent performance. The SMT has been successfully operated and maintained for over 7 years, delivering high quality physics data. To this conference date the Tevatron collider has delivered more than 4.5 fb^{-1} of integrated luminosity to the D0 experiment.

2. Design and performance

The design of the D0 SMT is driven by the length (with an RMS of about 25 cm) of the luminous region at the Tevatron collider and is based on a set of barrels with disks interspersed between them. The barrels provide tracking for particles with high transverse momentum p_T and $|\eta| < 1.5$, while the disk detectors allow for the precise reconstruction of particles traveling with pseudo-rapidity up to $|\eta| = 3$. The SMT is part of the central tracking system of the D0 detector together with the Central Fiber Tracker. A quarter sectional view of the tracking system is shown in Figure 1. A drawing of the silicon detector is shown in Figure 2.

The barrels have a length of 12 cm in the beam direction and consist of 72 ladders arranged in 8 sublayers, with pairs of sublayers forming four layers (L1 to L4). The barrels cover a radial region from 2.7 cm to 9.4 cm. L1 and L3 consist of single sided (SS) sensors for the two barrels located most forward (backward) in beam direction, and a double sided double-metal (DSDM) technology with 90° stereo strips was used for the four central barrels. Double sided (DS) ladders with $\sim 2^\circ$ stereo are used for L2 and L4 in all barrels. The twelve F-disks are located in between and just in front of the barrels. They are composed of 12 double sided wedges with the strips on the two sides forming a 30° opening angle. The two H-disks cover the most forward tracking and are composed of 24 pairs of single sided detectors glued back to back such that the strips form a 15° stereo angle. Originally, four H-disks were installed, but two of them were removed to rassign the readout channels to a new layer of sensors installed in 2006. Readout assemblies, referred to as HDIs (High Density Interconnects), are made of Kapton flex circuits laminated to Beryllium substrates and carry the SVX-IIe readout chips [1] and related components and provide bias voltage to the sensors. Each readout assembly is glued onto a silicon sensor, forming a module. There are 432 such modules for the barrel sensors, 144 for the F-disks and 96 for the H-disks, with a total of 5616 SVX-IIe chips installed. A description of the D0 SMT can be found in [2].

From 2003 to 2006 the D0 collaboration designed and built a new layer of silicon strip sensors (Layer-0) which was successfully installed inside the existing SMT. Layer-0 consists of one layer of single sided sensors directly supported by a carbon fiber structure at 1.6 cm from the interaction point [3]. Radiation hard single sided sensor and SVX4 readout chips [4] are used and a novel approach to grounding was pursued [5]. The carbon fiber support surface is covered with a copper mesh which provide electrical contact to the carbon fibers allowing it to be used as ground. The sensors are placed in a six-fold geometry providing 98.5% acceptance in φ. For each longitudinal

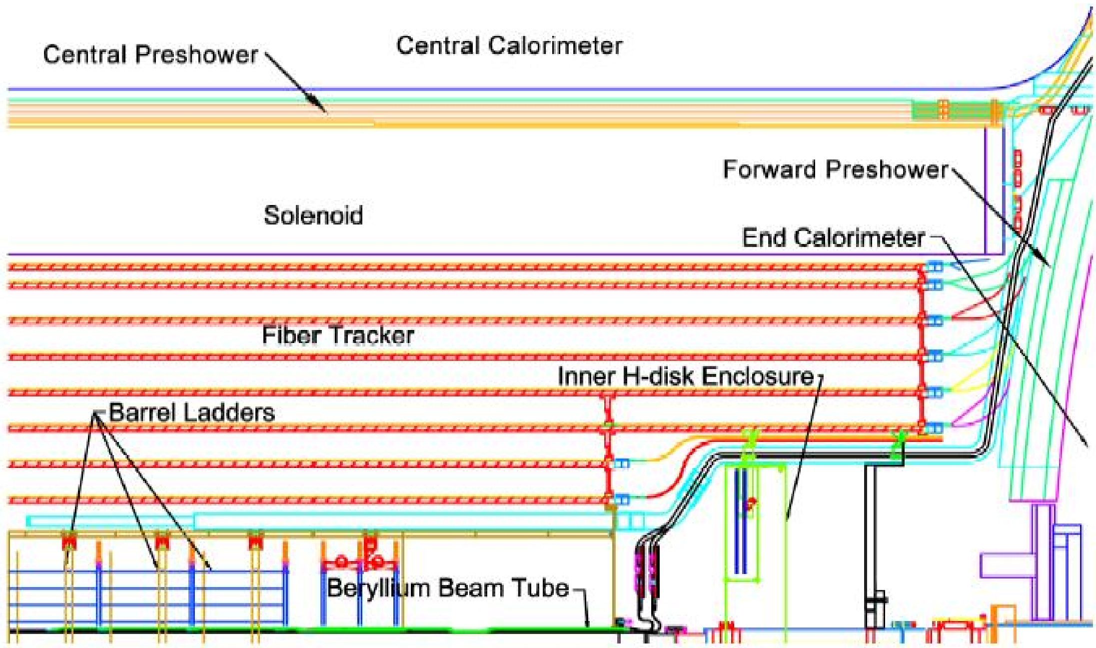

Figure 1: Quarter sectional view of the D0 tracking detectors as installed at the beginning of Run II. The lower left point is the center of the D0 detector corresponding also to the center of the luminous region. The barrels and disks of the silicon detector are shown as well as the Central Fiber Tracker layers and the 2 Tesla solenoid.

position in φ, eight sensors are placed in beam direction. All 48 sensor modules were functional and exhibited an excellent signal to noise ratio of $S/N \simeq 18$. A problem with the application of the bias voltage developed during operation and is under investigation.

The in-situ installation of Layer-0 constituted a major undertaking for the SMT group due to the difficulties in access and the tight space constraints. The complete Layer-0 assembly is a 2 meter long object that had to be cantilevered and inserted through the existing opening with less than 1 mm radial clearance. The installation necessitated passing the detector through the beam pipe inside the End Cap calorimeter.

Besides mitigating the tracking loss due to HDI failures and the radiation damage affecting the innermost layer L1, Layer-0 improves the impact parameter resolution due to its proximity to the interaction point. It also provides more robust tracking and pattern recognition capabilities for higher luminosity running.

The p_T dependence is in good agreement between the measurement on collider data and simulation for the originally installed SMT. Figure 3 shows the track impact parameter resolution at the interaction point as a function of the transverse momentum p_T of charged particles from simulation. Also shown in the Figure are simulations for a complete loss of the original innermost

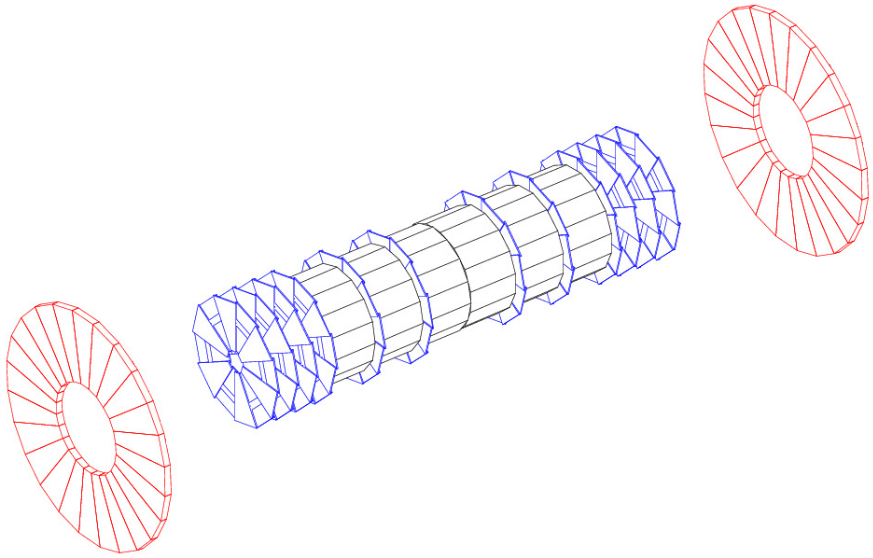

Figure 2: Isometric view of the D0 silicon tracker. The design is driven by the length of the luminous region at the Tevatron collider and includes a set of barrels interspersed with disks between them. There are 6 barrels with 12 central F-disks and a set of two forward H-disks.

layer L1 due to radiation damage, for the case with and without Layer-0. The addition of Layer-0 improves the impact parameter resolution and fully compensates a hypothetical complete loss of L1.

3. Operation and maintenance

A major task in the operation of a detector is the online monitoring of its performance and data quality. The D0 detector is continuously operated 24 hours per day and seven days per week. One dedicated scientist is present in the control room at all times to monitor the tracking detectors, supported by a team of on-call experts. In general, the operation is very stable and the response and recovery from problems is quick. The data from the delivered luminosity is written to tape with an efficiency of 90%, which includes non reducible inefficiencies due to detector configurations and readout dead-time. Of the recorded data, only about 2.5% has to be rejected because of bad quality for the silicon detector. Almost all the bad data is caused by missing readout channels due to power supply failures.

The long term high data taking efficiency is attained by a good balance and optimal prioritization between the collection of collider data and detector maintenance and improvements. The time for physics data collection is maximized while still performing enough maintenance to reduce the failures to a minimum. Continued and well planned detector studies also assure the influx and fostering of new experts. This greatly contributes to maintaining the necessary knowledge for operations and repairs over the long running period since 2001.

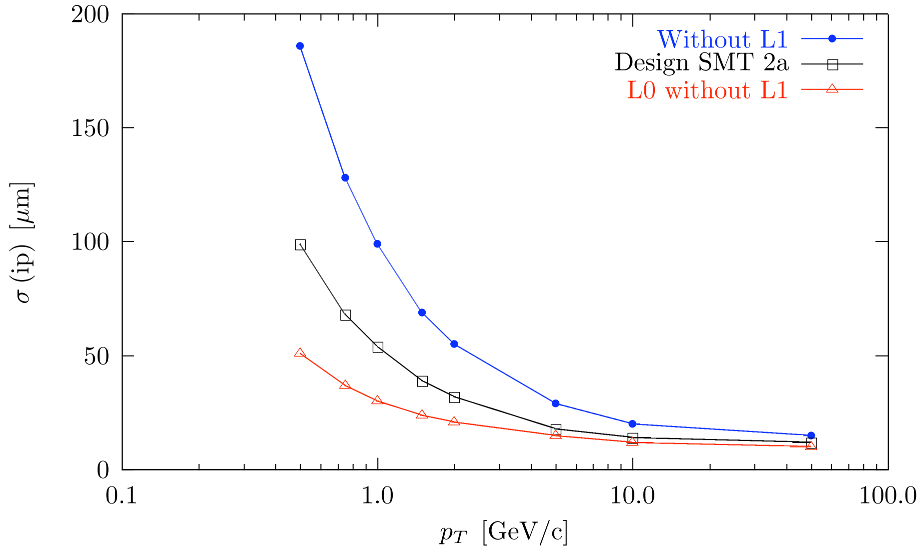

Figure 3: Impact parameter resolution (μm) as a function of the transverse momentum p_T (GeV/c) of charged particle tracks. This plot is obtained from Monte Carlo simulation. The line connecting the squares shows the performance of the silicon detector, as installed at the beginning of Run II. The other two lines correspond to simulations with total loss of the innermost layer L1 of the Run II detector: one with the addition of Layer-0 (triangles) and one without (circles).

Crucial to the operation is an extensive set of monitoring tools. It is a great advantage to have monitoring available at all levels of the data taking, from the hardware response to the reconstructed physics objects. More advanced displays showing summary status information of the system can be very useful, but the implementation of such automated monitoring requires substantial operating experience to be effective. Typically, only known problems can be addressed by such tools, and this is not sufficient for the complete monitoring.

Radiation from the beams is a concern for silicon detectors. We will discuss here the operational radiation protection of the silicon detectors. Studies on radiation damage to the silicon sensors from the colliding beams are shown in a separate contribution to these proceedings [6].

A set of radiation protection devices are installed to protect the D0 silicon detector. Radiation losses from the proton and anti-proton beams in the Tevatron accelerator are monitored by ionization chambers. Eight of these chambers are specifically dedicated to the protection of the SMT and included in the Tevatron beam abort system. The beam abort system has been triggered several times since 2001 and resulted in a clean and safe termination of the beams ensuring the safety of the D0 silicon detector. Very few incidents with elevated radiation did occur with estimated radiation doses of up to $O(\mathrm{kRad})$ deposited into the silicon detector. Further, during beam setup and accelerator studies some occurrences of high currents in detector modules and power supply problems originating from enhanced radiation were observed. Very good collaboration with the accelerator operators addressing such issues reduces the radiation to a minimum. In some instances new hardware measures were implemented or operational procedures improved.

About 90% of the integrated radiation dose in the silicon detector comes from the collisions during physics data taking. The rest is mainly related to beams setup with incidents adding up to a negligible fraction.

Besides the ionization chambers, additional monitoring for the radiation doses are implemented. Since the ionization chambers are located outside the tracker volume they only provide an extrapolated measurement of the radiation dose. A set of silicon finger diodes are installed on the disk detectors to provide a direct and alternative measurement.

The luminosity counters are used to assess the rate of beam halo and decide if safe conditions for physics data taking with full bias voltages are met.

There is no single number to quantify the overall health of the SMT, and the physics performance is the ultimate measure. However, a useful monitor is the fraction of powered sensor modules as shown in Figure 4. Several failures, from the sensor modules themselves to the readout chain make it necessary to disable some sensors from the readout during operation. Dedicated recovery efforts are made during shut-down periods to repair the problematic devices. These recovery efforts include routine fixes and replacement of failed electronics modules as well as repairs and improvement to the hardware based on additional new insights in the system. The latter is still possible after many years of operations at the D0 experiment. A key ingredient for this is the continued fostering of young physicists by letting them acquire the necessary knowledge and experience in leading operational positions.

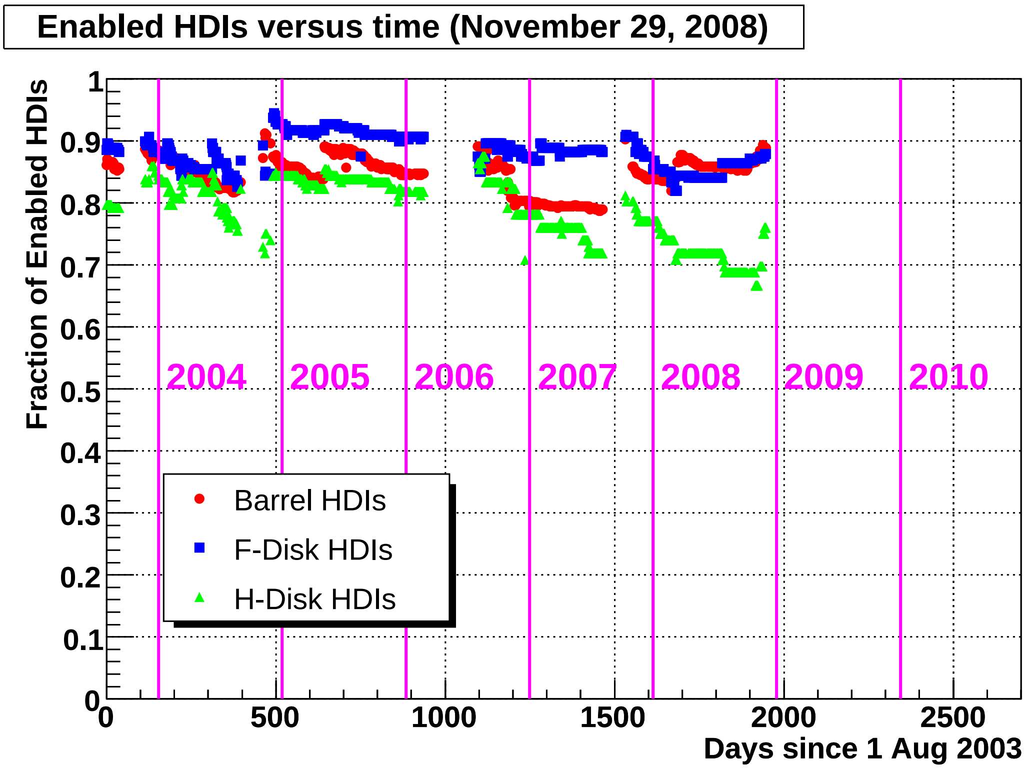

Figure 4: This figure shows the the fraction of enabled readout assemblies (HDIs) as a function of time. One can see the slow decrease of the fractions during continued operation due to hardware issues needing the removal of the HDIs from detector readout. During the shut-down periods (interruptions in the lines) the maintenance and repair efforts allow to recover the HDIs.

An example of such insight is the recent progress made on module failures due to runaway digital currents. This has been identified by dedicated investigation to likely be caused by dynamic memory latch-up in the CMOS electronics causing the digital power lines to the affected chips to be interrupted. Since as many as nine front-end chips are daisy chained on a readout module, the failure of the digital power to one chip implies the loss of all subsequent readout chips because of the interruption of the chain. The studies and insight have resulted in the design and implementation of a repair mechanism to restore the functionality of the daisy chain in 2008. A special hardware board was installed to supply power to the faulty chips via an alternative path when they are supposed to be active. The failed readout chips cannot be recovered but the readout of the subsequent chips on a module is fully restored. In this way the readout of 514 out of 914 readout chips in faulty modules could be restored.

4. Conclusions

The D0 SMT has been in operation for more than 7 years since it was installed in 2001. It provides excellent tracking and vertexing capabilities to the D0 experiment. In 2006 a new layer of silicon detectors (Layer-0) was installed in-situ inside the innermost layer of the existing detector which constituted a major undertaking for the silicon detector group. Layer-0 is fully integrated in the readout and reconstruction and shows excellent performance. The D0 collaboration has found the right balance between stable operations and detector maintenance to assure long-term operation. The data recording efficiency is very high at 90%, with only about 2.5% of the recorded data which has to be discarded because of bad quality from the silicon tracker. The continued influx and fostering of detector expertise has facilitated key insights necessary for the maintenance and important recoveries of readout modules even in the 8th year of operation.

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