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The LHCb silicon tracker

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ABSTRACT

The Silicon Tracker is a large-surface silicon micro-strip detector that covers the full acceptance of the experiment in a single tracking station upstream of the spectrometer magnet and the inner-most part of three tracking stations downstream of the magnet. Special emphasis has been put on module quality assurance at all stages of the production. Various tests are performed after each production step and each module goes through several burn-in cycles. The design of the LHCb silicon detectors is described and the main lessons learnt from the R&D phase are summarised. Focus will be on the experience from module production and the quality assurance program.

1. Introduction

The Silicon Tracker is part of the tracking system of the LHCb experiment [2]. It comprises two detectors, the Trigger Tracker (TT) and the Inner Tracker (IT). Silicon microstrip detectors with 9.44 cm (TT) to 11 cm (IT) long readout strips and with strip pitches of about 200 μm are used for both. The TT is a $150 \times 30\,\text{cm}^2$ four layer planar tracking station which is located upstream of the LHCb dipole magnet and covers the full acceptance of the experiment. The IT covers a roughly $120 \times 40\,\text{cm}^2$ high cross-shaped region in the centre of three large planar tracking stations downstream of the magnet with four detection layers each. In total, an active surface of about $12\,\text{m}^2$ is covered with about 272 k readout channels. A common front-end readout chip (the Beetle [3]) and readout link [4] are used to readout TT and IT while the designs of the detector modules are different. Including 15% spares, 148 TT modules and 386 IT modules are needed. The module productions was split into two production sites, one for TT and one for IT. A lot of effort and resources have been devoted to the quality assurance program at all steps of the module production. In particular, systematic "burn-in" programmes were set up through which each module has to pass at least once during the production. A brief overview of the designs of the modules, the main production steps and the quality assurance programs for both sub-detectors will be given in the following. For key parameters the achieved module quality will be illustrated.

2. Module design

An important design goal for TT was to keep the dead material associated with front-end readout hybrids, mechanical supports, cooling, etc. outside of the acceptance of the detector. The resulting TT module design is illustrated in Fig. 1.

Each TT module consists of seven silicon sensors[2] with a stack of either two or three front-end readout hybrids attached at one end. The seven sensors are organised in either two or three readout sectors. For all modules, the four sensors closest to the readout hybrids form the first readout sector ("L sector") and are directly connected to the lower-most readout hybrid. For "4-3" type modules (majority of the modules), the remaining three sensors form a single readout sector ("M sector"), for "4-2-1" type modules (these are used in the central region of the detector) they are further split into an intermediate two-sensor sector ("M sector") and a third sector consisting of the single sensor farthest from the hybrids ("K sector"). This splitting around the beam-pipe helps to reduce the occupancy in the inner part of the TT. The sensors of the M sector and, where applicable, the K sector are connected to the upper frontend hybrid(s) via Kapton interconnect cables of 38 cm, respectively, 57 cm, in length. To give the modules mechanical stability, two thin fibre-glass/carbon-fibre rails are glued along the sides of the sensors and the lower-most readout hybrid. Bias voltage is connected to the backplanes of the sensors via a thin Kapton cable that runs along

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[2] The sensors used in the TT are 9.64 cm wide 9.44 cm long, with a thickness of 500 μm and 512 readout strips with a strip pitch of 183 μm. The sensors are identical to the OB2 sensors used in the Outer Barrel of the CMS Tracker and were produced by HPK, Hamamatsu, Japan.

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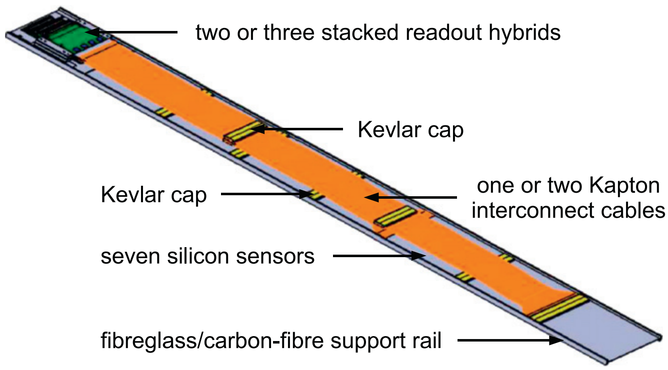

Fig. 1. Detector module design for the Trigger Tracker.

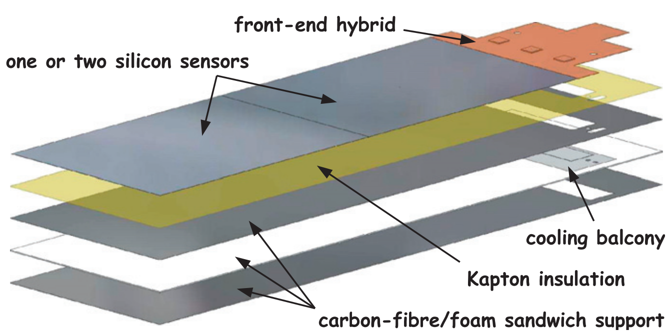

Fig. 2. Detector module design for the Inner Tracker.

the back of the module. Two detector modules, glued together end-to-end, form a 14-sensor long super-module that spans the full height of the LHCb acceptance. All (super-) modules are mounted inside one large detector box, where an ambient temperature of 5 °C is maintained using −10 °C fluid C_6F_{14} in the cooling system in order to slow down leakage currents and reverse annealing after irradiation. Mechanical supportframes, cooling pipes, and readout cables are all located outside of the LHCb acceptance.

In the IT detector design, front-end hybrids, mechanical supports, cooling, etc. could not be kept outside of the LHCb acceptance and a main goal in designing the detector was to minimise this dead material. The resulting module design is illustrated in Fig. 2. The IT modules consist of one or two silicon sensors[3] that are connected via a short pitch adapter to a single readout hybrid. Silicon sensor(s), pitch adaptor and hybrid are glued onto a flat backplane that consists of a thin layer of polyetherimide foam sandwiched in between two sheets of carbon fibre of high thermal conductivity. The silicon sensors are electrically insulated from the carbon-fibre sheets by a thin Kapton foil. A small aluminium insert (“cooling balcony”) is embedded into the backplane at the location of the readout hybrid. It provides a direct heat bridge between the front-end chips and a thin aluminium cooling rod onto which the modules will be mounted. It also provides thermal contact between this cooling rod and the carbon-fibre sheets of the module backplane such that the latter form large cold surfaces and contribute to cooling the detector volume to the desired ambient temperature of 5 °C by setting the cooling fluid to −10 °C.

3. Module production

The TT module production is performed in two or three stages, depending on the module type. Each production stage of the modules is followed by a two to three day long burn-in test (see Section 4). The production of a module begins by placing all seven sensors and the lowermost hybrid by hand on an assembly template, gluing the two carbon-fibre rails, measuring the sensor positions, connecting the bias voltage cable on the back of the sensors, and bonding the ground connections and readout strips for the L sector of the module. The L sector is fully operational afterwards and the module is fully (all tests as described in Section 4 are performed at every burn-in cycle) tested in the first burn-in cycle. During the second production stage, the readout hybrid and Kapton interconnect cable for the M sector are mounted and this readout sector is bonded. The module is tested in a second burn-in cycle and is then finished in the case of a “4-3” type module. The “4-2-1” modules enter the third production stage, in which the readout hybrid and Kapton cable for the K sector are attached and bonded, followed by a third and final burn-in test. With two assembly templates, an average production rate of five modules per week was achieved and maintained over the full duration of the production. Out of 150 modules produced, two were damaged beyond repair due to handling errors in the production. Three more modules were successfully repaired by replacing a damaged sensor or readout hybrid.

The production of IT modules proceeds as follows: The pre-fabricated support backplane is placed on an assembly template and the readout hybrid and pitch adapter are positioned and glued onto the support frame. A first readout test is performed to assure the electrical functionality of the readout hybrid. One or two silicon sensors, depending on the module type, are positioned on a second template, transferred to the assembly template using a vacuum transfer jig, and glued onto the support frame using a silicone-based glue. The bias voltage and ground connections are bonded and a first HV test is performed. If the module has passed this test, the readout strips are bonded and with the finished module a comprehensive quality assurance program is performed, including the measurement of sensor positions and a 48 h burn-in test. Using five sets of assembly templates, the achieved production rate was twelve modules per week.

4. Quality assurance

The quality assurance played an important role and took up a significant fraction of the resources at all stages of the module production for both TT and IT. The silicon sensors were qualified by the manufacturer but still comprehensive acceptance tests were performed upon reception. These tests included optical inspections, geometrical measurements of the dicing edges (which are used to accurately position the sensors during the module assembly), measurements of leakage currents, the measurement of the full depletion voltage and the identification of bad strips. The quality of the sensors was found to be excellent and a very good agreement between our results and the data provided by the manufacturer was found [5]. Readout hybrids went through first quality assurance tests, including several temperature cycles between −20 and +60 °C, at the vendor[4], where a dedicated test stand for this purpose had been set up. Each hybrid was tested after the delivery in a further 96 h burn-in program, which included measurements of its power

[3] The sensors used in the IT are 7.6 cm wide 11 cm long, with a thickness of 320 μm in case of one-sensor modules and 410 μm for two-sensor modules. Each of them has 384 readout strips with a strip pitch of 198 μm. The sensors were designed and produced by HPK, Hamamatsu, Japan.

[4] The readout hybrids were assembled by RHe Microsystems, Radeberger, Germany.

consumption and various readout tests [6]. As described in Section 3, during production each detector module passed through burn-in tests at least once. For the two productions sites, the burn-in setups and programmes were different, but a set of basic test were designed to be in common. Both include temperature cycling (at least 36 h cycling between room temperature and 5 °C for TT, 48 h cycling between +40 °C and −5 °C for IT) with detectors continuously biased at 500 V, as well as several measurements of *I–V* curves up to 500 V bias voltage. Extensive readout tests were performed, including pedestal and noise measurements and the measurement of signal pulse-shapes using the internal test pulse implemented in the Beetle readout chip. An array of infra-red laser diodes was used in the TT burn-in test stand to generate charge on each readout sector and to measure signal pulse-shapes as well as charge-collection efficiency curves using detector signals. More than 2 TByte of data were recorded in the TT burn-in tests alone. "Bad" channels (interrupts of the aluminum, shorts between two channels and pinholes) are identified by analysing the noise on the strips and the pulse-shapes of the internal test pulses and laser signals. Interrupts can be identified as channels with too little noise or too high test-pulse amplitude (due to a reduced load capacitance). Shorted strips, as pairs of adjacent channels, have with too large noise or too small test-pulse amplitude (due to a larger load capacitance).

For the IT modules, a second test is performed to identify shorts between two adjacent channels: Internal test pulses with the same amplitude but alternating polarity are applied to consecutive Beetle readout channels. If two channels are shorted, the two test pulses cancel out and the amplitude of the output signal for these two channels drops to zero. Pinholes are identified by reading out the modules with an open detector box and daylight shining on to the silicon sensors. If a pinhole is present the leakage currents that are created in the silicon bulk flow through the front-end pre-amplifier. With light shining onto the sensors, these currents are so large and the amplifier saturates even if no bias voltage is applied. The spread of the noise distribution for the affected channels essentially drops to zero. The overall quality of the modules produced is very good. The fraction of bad channels is around or below 0.1% for both the TT modules (see Fig. 3) and the IT modules.

Leakage currents at 500 V and room temperature are typically around 0.5 μA or less per silicon sensor. As an example, Fig. 4 shows an overlay of all 900 *I–V* curves taken at 5 °C for TT modules.

A few modules (six) show higher than normal leakage currents, break down below 500 V or otherwise abnormal *I–V* curves. The number of these modules is smaller than the number of spares. The measurement of the positioning accuracy of the silicon sensors is

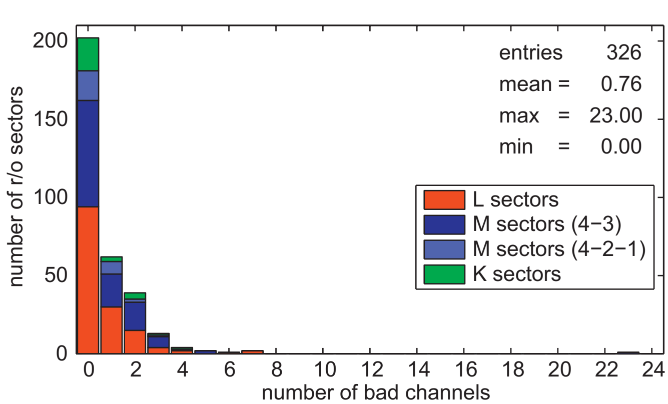

Fig. 3. Number of bad channels for TT modules split into readout sections.

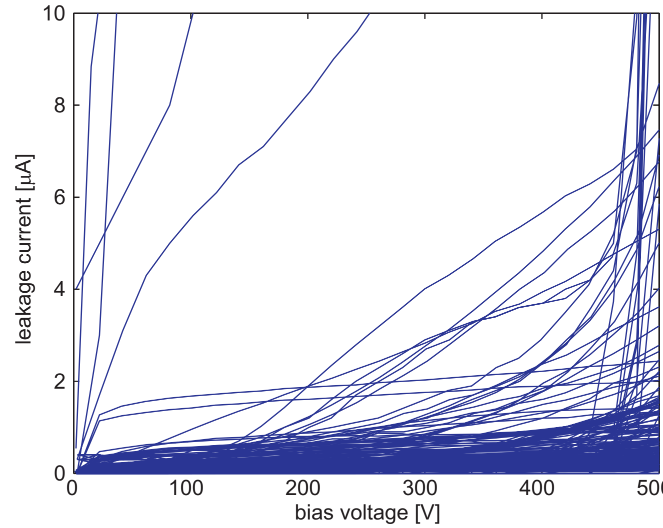

Fig. 4. Leakage currents of 900 *I–V* curves taken at 5 °C for TT modules.

important, because it is foreseen to treat each detector module—resp. each readout sector in the case of TT—as one single unit in the software alignment of the detector. The relative misalignment of sensors within a module therefore needs too be small compared to the expected spatial resolution of about 50 μm. As an example of the achieved precision, the distribution of relative sensor offsets and rotation on TT modules is shown in Fig. 5.

One particular problem detected during the module production concerns the long-term behaviour of silver glue on aluminium surfaces. Silver glue was initially used on TT modules for the bias voltage connection to the aluminium-coated backplanes of the sensors. During production the ohmic resistance of these connections was measured immediately after the module assembly and then again after a few weeks to months. Initially, all connections showed a low resistivity, but later measurements showed that a significant fraction of them had a resistances of up to several hundred Ohms. The problem is attributed to a slowly continuing oxidation of the aluminium surface underneath the glue. In order to avoid possible long-term problems, all bias voltage connections on the TT modules were subsequently modified with additional wire bonds. Silver glue is also used on IT modules to ensure the ground connection between the readout chips and the aluminium cooling balcony as a common ground in the detector box. In order to avoid problems, also here additional thin ground wires have been implemented on all modules, without introducing any further failure.

5. Summary and outlook

The production and testing of detector modules for the LHCb Trigger Tracker as well as the production of modules for the Inner Tracker have been completed, the testing of Inner Tracker modules will be completed soon. The testing of modules dominated the overall production effort and determined the production rate. This was expected since special emphasis was put on the quality assurance. The quality of the produced modules is very satisfactory with a small number of modules lost during the production. The initially foreseen module production rates were reached within the allocated resources. To mention is that the transition from prototyping to series production took much longer than anticipated. This was due to a wide range of reasons, including delivery problems at vendors (an example being

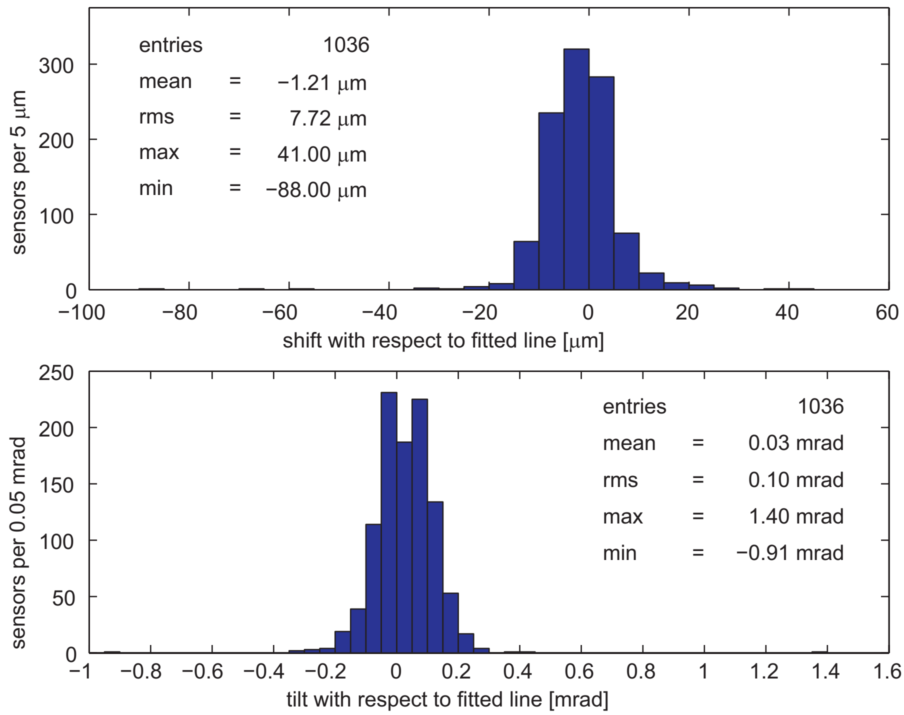

Fig. 5. Relative offsets and rotations distributions of the TT silicon sensors modules.

production yield problems at the vendor of Kapton interconnect cables for the TT modules), less steep than expected learning curves (for example, training of bonding technicians), and some weak points in the module design that became apparent only when the first final modules were produced (most of these concerned bias voltage and grounding) and required last-minute modifications of the module design and/or assembly procedures. The focus of attention now shifts to the assembly of detector modules into tracking stations and their installation and integration in LHCb. The first TT module is already installed in the LHCb detector.

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