LHCb Note 2007-009

Design and Production of Detector Modules for the LHCb Silicon Tracker[*]

M. Agari, C. Bauer, J. Blouw[†], W. Hofmann, S. Löchner, F. Maciuc,
M. Schmelling, N. Smale, B. Schwingenheuer, H. Voss
Max Planck Institut für Kernphysik, 69117 Heidelberg, Germany

V. Pugatch
National Academy of Science, Institute for Nuclear Research, 03680 Kiev, Ukraine

A. Bay, M.-O. Bettler, P. Fauland, R. Frei, J. van Hunen, M. Knecht,
L. Nicolas, A. Perrin, O. Schneider, M.T. Tran, K. Vervink
LPHE, EPFL Lausanne 1015 Lausanne, Switzerland

B. Adeva, D. Esperante, J. L. Fungueirino Pazos, C. Lois,
A. Pazos Alvarez, E. Perez Trigo, M. Plo Casasus, P. Vazquez
Universidad de Santiago de Compostela, 15706 Santiago de Compostela, Spain

R.P. Bernhard, R. Bernet, J. Gassner, F. Lehner, M. Needham[‡],
T. Sakhelashvili, S. Steiner, O. Steinkamp, U. Straumann, J. van Tilburg,
A. Vollhardt, D. Volyanskyy, A. Wenger
Physik-Institut der Universität Zürich, 8057 Zürich, Switzerland

February 27, 2007

Abstract

The LHCb Silicon Tracker consists of four planar tracking stations and will cover a sensitive surface of about 12 m^2 with silicon micro-strip detectors. Detector modules of two different designs will be employed in different parts of the detecor. The production of these detector modules is coming close to its completion. A brief overview over the module designs, production and quality assurance programmes is given and a few lessons are drawn from the production experience.

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), both of which use silicon microstrip detectors with long readout strips and with strip pitches of about 200 μm. The TT is a 150 cm wide and 130 cm high planar tracking station that is located upstream of the LHCb dipole magnet and covers the full acceptance of the experiment. The IT covers a

---

[*] Presented at the 11th Vienna Conference on Instrumentation, Vienna, Austria, February 19-24, 2007; Proceedings submitted for publication in Nucl. Instr. and Meth. **A**

[†] now at *Physics Institute, University of Heidelberg, 69120 Heidelberg, Germany*

[‡] now at *CERN, 1211 Geneve, Switzerland*

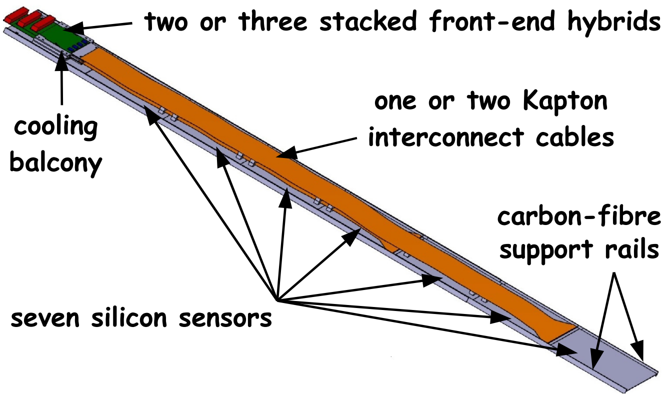

Figure 1: “4-2-1” type detector module for the Trigger Tracker.

roughly 120 cm wide and 40 cm high cross-shaped region in the centre of three large planar tracking stations downstream of the magnet. Each of the four Silicon Tracker stations consists of four detection layers. In total, an active surface of about 12 m^2 is covered with about 272k readout channels.

TT and IT use the same front-end readout chip (the Beetle [4]) and readout link [5], but different designs of detector modules. Including 15% spares, 148 TT modules and 386 IT modules have to be built. The module productions have been run by two small teams of physicists and technicians in two production sites, one for TT and one for IT. At both sites, a lot of effort went into quality assurance at all steps of the production. In particular, systematic “burn-in” programmes were set up through which each module has to pass at least once during the production. At the time of writing, the production and testing of TT modules has just been completed and about 300 of the IT modules have been assembled and fully tested.

In the following, a brief overview of the module designs, the main production steps and the quality assurance programmes will be given and the achieved module quality will be illustrated for a number of key parameters.

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 experiment. The resulting module design is illustrated in Fig. 1. Each TT module consists of a row of seven silicon sensors[1] with a stack of either two or three front-end readout hybrids attached at one end. The seven sensors are organised into 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 (most of the modules are of this type), 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”). The sensors of the M sector and, where applicable, the K sector are connected to the upper front-

---

[1] TT sensors are 500 μm thick, 9.64 cm wide and 9.44 cm long and carry 512 readout strips with a strip pitch of 183 μm. They are identical in design to the OB2 sensors used in the Outer Barrel of the CMS Silicon Tracker [6] and were produced by HPK, Hamamatsu, Japan.

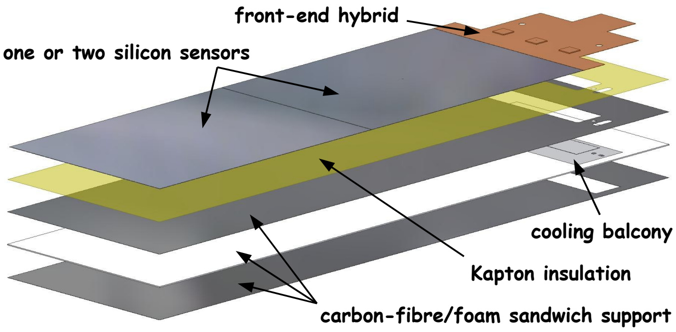

Figure 2: Two-sensor detector module for the Inner Tracker.

end 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 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, in which an ambient temperature of 5°C is maintained in order to suppress leakage currents and reverse annealing after irradiation. Mechanical support frames, cooling pipes, and readout cables are all located outside of the LHCb acceptance.

In the case of IT, 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. IT modules consist of one or two silicon sensors[2] 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 path 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.

3 Module Production

The production of TT modules proceeds in two or three stages, depending on the module type. After each production stage, the modules undergo a two to three day long burn-in test (see Section 4). The first production step consists in placing the seven sensors and the lower-most hybrid on an assembly template, attaching 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. After this production stage, the L sector is fully operational and the module undergoes the first burn-in test. In the

---

[2] IT sensors are 7.6 cm wide and 11 cm long, with thicknesses of 320 μm for one-sensor ladders and 410 μm for two-sensor ladders. They carry 384 readout strips with a strip pitch of 198 μm and were designed and produced for the Inner Tracker by HPK, Hamamatsu, Japan.

second production stage, the readout hybrid and Kapton interconnect cable for the M sector are mounted onto the module and this readout sector is bonded. The module then undergoes a second burn-in test, after which it is completed if it is of the “4-3” type. Modules of the “4-2-1” type 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. The production and testing of TT modules was finished in January this year. Using 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 147 modules produced, three were damaged beyond repair due to handling errors in the production and three more successfully went through a repair loop to replace 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. A first readout test is performed to assure the functionality of the readout hybrid. Depending on the module type, one or two silicon sensors are positioned on a second template, transfered to the assembly template using a vacuum transfer jig, and glued onto the support using a silicone-based glue. Bias voltage and ground connections are bonded and a first HV test is performed. When the module has passed this test, the readout strips are bonded and the completed module undergoes a comprehensive quality assurance programme, including the measurement of sensor positions and a 48 h burn-in test. At the time of writing, about 300 IT modules have been produced. Using five sets of assembly templates, a production rate of twelve modules per week has been achieved.

4 Quality Assurance

Quality assurance played an important role and took up a significant fraction of the resources at all stages of the module production. Silicon sensors were qualified by the manufacturer and underwent comprehensive acceptance tests upon reception. These tests included optical inspections, measurements of the full depletion voltage, geometrical measurements of the dicing edges (which are used to accurately position the sensors during the module assembly) and searches for bad strips. The quality of the sensors was found to be excellent and very good agreement between our results and the data provided by the manufacturer was found [7].

Readout hybrids went through first quality assurance tests, including several temperature cycles between -20°C and +60°C, at the vendor[3], where we had installed a dedicated test stand for this purpose. Upon reception, each hybrid underwent a further 96 h burn-in programme, which included measurements of its power consumption and various readout tests [8].

As described in the previous section, each detector module passed through a comprehensive burn-in test at least once during its assembly. The burn-in setups and programmes for IT and TT differ in details, but the main features are similar. 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 IV curves up to 500 V bias voltage. Extensive readout tests are performed, including pedestal and noise measurements and the measurement of signal pulse-shapes using an internal test pulse implemented in the Beetle readout chip. The TT setup also includes an array of infra-red laser diodes that permit to generate charges at pre-defined locations 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 have been accumulated in the

---

[3] The readout hybrids were assembled by RHe Microsystems, Radeberg, Germany

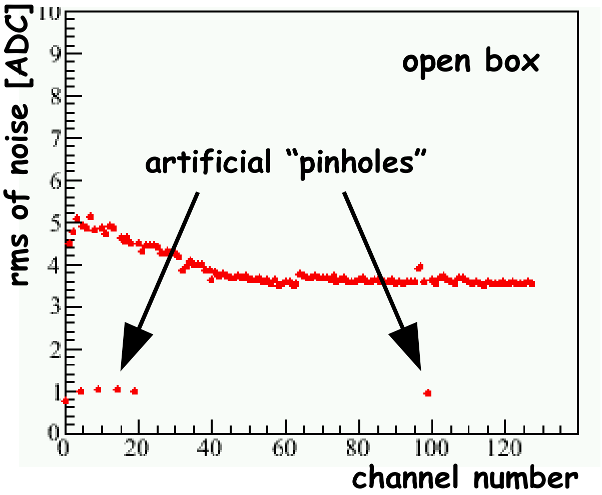

Figure 3: Root mean square of the noise distribution for each of the 128 channels on a Beetle chip, measured with an open detector box. Channels with artificially introduced "pin-holes" show up clearly due to their much reduced noise, as explained in the text.

TT burn-in tests alone.

"Bad" readout strips (interrupts, shorts and pinholes) are identified by analysing strip noise and pulse-shapes. Interrupts can be identified as channels with too little noise or too high test-pulse amplitude (due to their reduced load capacitance) and shorted strips as pairs of adjacent channels with too large noise or too small test-pulse amplitude (due to the increased load capacitance). In the case of IT, a second test is performed to identify shorts: Internal test pulses with the same amplitude but alternating polarity are applied to consecutive Beetle 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. To identify pinholes, pedestal runs are taken with open detector box, shining light onto the silicon sensors. In the presence of a pinhole, leakage currents that are created in the silicon bulk flow through the front-end pre-amplifier. Shining light onto the sensors, these currents are so large that they saturate the amplifier even if no bias voltage is applied to the silicon sensors. The rms of the noise distribution for the effected channels essentially drops to zero (for an example, see Fig. 3).

The overall quality of the modules produced so far is very good. The fraction of bad channels is around or below 0.1% for both TT modules and the IT modules tested so far. 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 IV curves taken at 5°C for TT modules. A few modules show higher-than-normal leakage currents, break down below 500 V or otherwise abnormal IV curves. The number of these modules is smaller than the number of spares we had planned for.

Another important quality assurance measurement is that of the positioning accuracy of the silicon sensors. 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. It is therefore important that the relative misalignment of sensors within a module is small compared to the expected spatial resolution of about 50 μm. As an example for the achieved precision, the distribution of relative sensor offsets on TT modules is shown in Fig. 5.

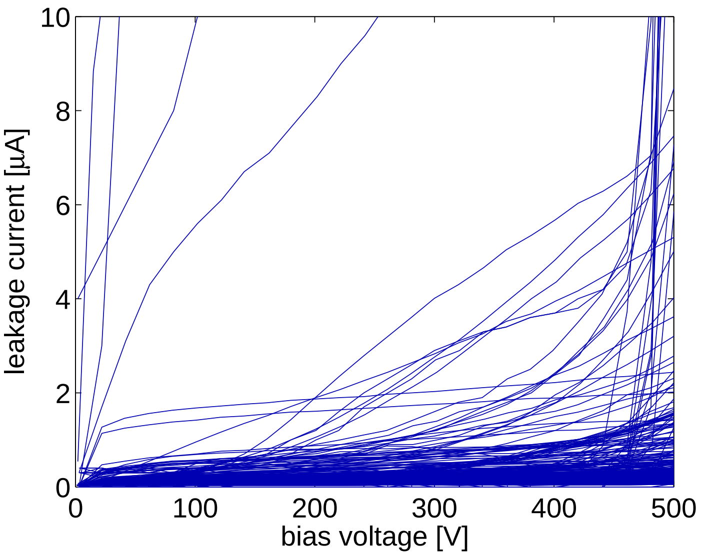

Figure 4: Overlay of all 900 IV curves measured on TT modules at 5°C. The “abnormal” IV curves are due to a small number of problematic modules that went through repeated burn-in cycles and therefore enter this plot several times.

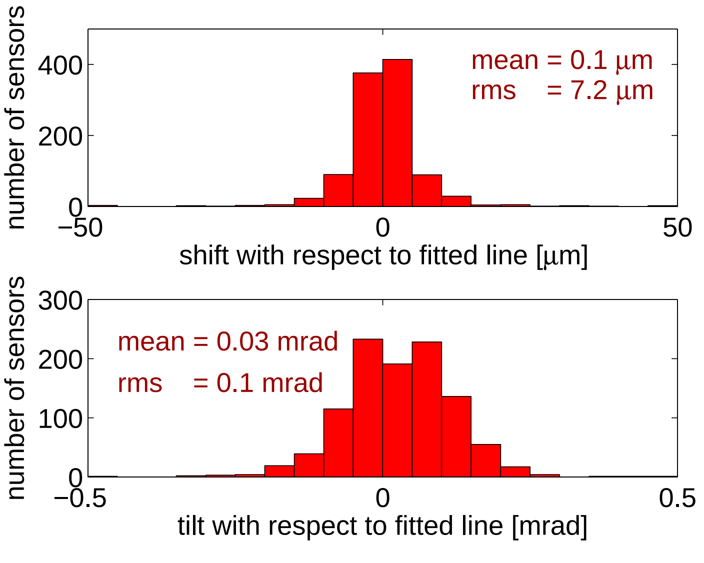

Figure 5: Distribution of the relative offsets and rotations of silicon sensors on TT modules.

One particular problem that was detected during the module production concerns the long-term behaviour of silver glue on aluminium surfaces. Silver glue was initially used on TT modules to connect bias voltage to the aluminium-coated backplanes of the sensors. The ohmic resistance of these connections was measured right after the assembly of the module and then again after a few weeks to months. Initially, all connections showed low resistivity, but in the later measurements a significant fraction of them showed significantly higher resistances of up to several hundred Ohms. Similar problems concerning the use of silver glue on aluminium surfaces had already been observed by the CMS Silicon Tracker community [9]. They are 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 fitted 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 that provides the interface to the common ground in the detector box. In order to avoid future problems here, additional thin ground wires will be implemented on all modules.

5 Summary and Outlook

The production and testing of detector modules for the LHCb Trigger Tracker has been completed, that for the Inner Tracker will be completed soon. Special emphasis was put on quality assurance and as expected the testing of modules dominated the overall production effort and determined the production rate. The quality of the produced modules is very satisfactory and the number of modules lost during the production is small. The initially foreseen module production rates were reached within the allocated resources.

Despite the overall positive experience, two lessons can and should be learnt from this production effort: (a) a few “final” modules should have been built much early on, using “final” production tools and assembly procedures, and (b) much more time should have been reserved for the transition from prototyping to series production. That this transition took much longer than we had anticipated was due to a wide range of reasons, including delivery problems at vendors (an example being 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 modules are foreseen to be installed in LHCb in March, and the integration of the detector should be finished by autumn 2007, when the experiment hall will close and the commissioning of LHC beams will start.

References

[1] O. Steinkamp et al., LHCb note 2007-009

[2] LHCb Reoptimized Detector Design and Performance - Technical Design Report, CERN/LHCC-2003-030

[3] LHCb Outer Tracker - Technical Design Report, CERN/LHCC-2001-024

[4] N. Bakel et al., LHCb note 2005-105

[5] A. Vollhardt et al., Proc. LECC 2005, CERN/LHCC-2005-038 (2005) 187-191

[6] J.-L. Agram et al., CMS note 2003-015

[7] C. Lois, Nucl. Instr. and Meth. A568 (2006) 277-283

[8] F. Lehner, Proc. LECC 2005, CERN/LHCC-2005-038 (2005) 67-70

[9] T. Affolder, private communication; M. Krammer, CMS CR 2006/095