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Design and production of detector modules for the LHCb Silicon Tracker

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Abstract

The LHCb Silicon Tracker will cover a sensitive surface of about $12\,m^2$ with silicon micro-strip detectors. The production of detector modules is currently coming close to its conclusion. In this paper, the design of the detector modules, the main module production steps, and the module quality assurance programme are described. Selected results from the quality assurance are shown and first lessons are drawn from the experience gained during module production.

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1. Introduction

The Silicon Tracker is part of the tracking system of the LHCb experiment [2], which is layed out as a typical forward magnetic spectrometer and covers an acceptance out to 250 mrad × 300 mrad around the LHC beam axis. The Silicon Tracker comprises two detectors, both of which use silicon microstrip detectors with long readout strips and with strip pitches of a little less than 200 μm. The first of these detectors, the Trigger Tracker (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 second of the two detectors is the Inner Tracker (IT). It covers a roughly 120 cm wide and 40 cm high cross-shaped region in the centre of three planar tracking stations downstream of the magnet.[2] Each of the four Silicon Tracker stations comprises four detection layers. In total, the Silicon Tracker covers an active surface of about $12\,m^2$ with about 272k readout channels.

The two detectors use the same front-end readout chip (the Beetle [4]) and the same readout link [5]. Due to different experimental constraints, however, different designs have been adopted for their detector modules. Including 15% spares, 148 TT modules and 386 IT modules have to be built. At the time of writing of this paper, all TT modules and 80% of the IT modules have been assembled, and more than 90% of these have undergone an extensive quality assurance programme.

The module production and testing is run by two small teams of physicists and technicians in two production sites, one for the TT and one for the IT. Given the available resources and the relatively small number of modules that need to be produced, the production proceeds largely manually. A significant amount of effort was, however, invested to set up automated "burn-in" test stands for module quality assurance measurements. In the remainder of this paper, I will briefly describe the design of the detector modules, followed by a short description of the module production and the quality assurance programmes. For a few key parameters, I will demonstrate the quality of the modules completed so far. Finally, I will try to draw some first lessons from our experience gained during the module production for the Silicon Tracker.

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[2]The outer part of these approximately 450 cm high and 600 cm wide tracking stations is covered by a straw-tube tracker [3].

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2. Module design

The design of the TT modules is illustrated in Fig. 1. A main feature of this design is that most of the "dead material" that is invariably associated with front-end readout hybrids, cooling, mechanical supports, and cables, is kept outside of the acceptance of the experiment. Each detector module consists of a row of seven silicon sensors[3] with a stack of either two or three front-end readout hybrids at one end. Depending on the location of the module in the detector, the seven sensors are organised into two or three readout sectors. For all modules, the first of these is formed by the four sensors closest to the hybrids. They are directly connected to the lower-most readout hybrid, which carries a short pitch adaptor and the front-end readout chips. For the majority of modules ("4-3" type), the remaining three sensors form a single readout sector. It is connected via a 38 cm long flexible Kapton interconnect cable to a second front-end hybrid, which is mounted on top of the first one. For modules that will be installed in the central region of the detector, the remaining three sensors are further split into a two-sensor and a one-sensor readout sector ("4-2-1" type). In this case, each of the two readout sectors has its own Kapton interconnect cable (of 38 cm and 57 cm in length, respectively) and is read out via a separate front-end hybrid. Mechanical stability of the modules is achieved by gluing two thin fibre–glass/carbon-fibre rails along the sides of the sensors and the lower-most readout hybrid. Bias voltage is connected to the sensor backplanes via a thin Kapton cable that runs along the back of the module. Two such detector modules, glued together end-to-end, form a 14-sensor long super-module which spans the full height of the LHCb acceptance. The hybrid stacks at each end of this super-module are located just outside of the 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 of the detector modules, as well as cooling of the front-end readout chips and the detector volume, is provided by so-called cooling plates that are located at the top and bottom of the detector box and onto which the modules are mounted via individual cooling balconies. As these cooling plates and balconies are located outside of the LHCb acceptance, no special care had to be taken with respect to their material budget.

In the case of the IT, it was impossible to keep the readout hybrids outside of the acceptance. A lot of attention, therefore, had to be payed to minimising the "dead material" from mechanical supports and cooling. The resulting module design is illustrated in Fig. 2. Depending on their location in the detector, modules consist of either one or two silicon sensors[4] that are directly connected to a readout hybrid carrying a short pitch adaptor and the front-end readout chips. Sensor bias voltage is provided to bond pads on the strip-side of the sensors, which are in contact with the sensor backplane via n^+-wells. Sensor(s), pitch adaptor and hybrid are glued onto a common backplane that consists of a thin layer of polyetherimide foam, sandwiched in between two sheets of thermally highly conductive carbon fibre. Electrical insulation between the silicon sensors and the electrically conductive carbon-fibre sheets is ensured by a thin Kapton foil. A small aluminium insert ("cooling balcony") that is embedded into the backplane at the location of the readout hybrid provides a direct heat path between the front-end chips and a thin aluminium cooling rod onto which the modules will be mounted. The carbon fibre sheets are also in thermal contact with the cooling rod through this aluminium insert. Due to their high thermal conductivity, they form large cold surfaces that contribute to cooling the detector volume to the desired ambient temperature of 5 °C.

3. Module production

The production of TT modules is run by a team of three physicists and technicians at Universität Zürich. It proceeds in two or three stages, depending on the module type. After each of these production stages, the module undergoes a two to three day long burn-in test, which will be described in Section 4. The first production step consists in placing the seven sensors and the lower-most hybrid on an assembly template. They are positioned by pushing them against an alignment rail embedded in the template. Vacuum is switched on to fix the sensors and the hybrid in place. Their positions are verified under a precision coordinate measurement machine and corrected if necessary. The first carbon-fibre rail is then glued against the free edge of the sensors and the hybrid. After overnight curing of the glue, the alignment rail is removed from the template and the second carbon-fibre rail is glued against the second edge of the module. The glue is left to cure overnight, before the vacuum is released, the module is removed from the template, and the final sensor positions are measured. The module is then flipped over and the bias voltage cable is glued along its back. The electrical connection of this cable to hybrid and sensors was initially made using silver paint or silver glue. As this turned out to be unreliable (see Section 5), all modules later went through a repair cycle in which these connections were in addition bonded. Once the bias voltage cable is attached,

[3]The 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 to the OB2 sensors used in the Outer Barrel of the CMS Silicon Tracker [6] and were produced by HPK, Hamamatsu, Japan.

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

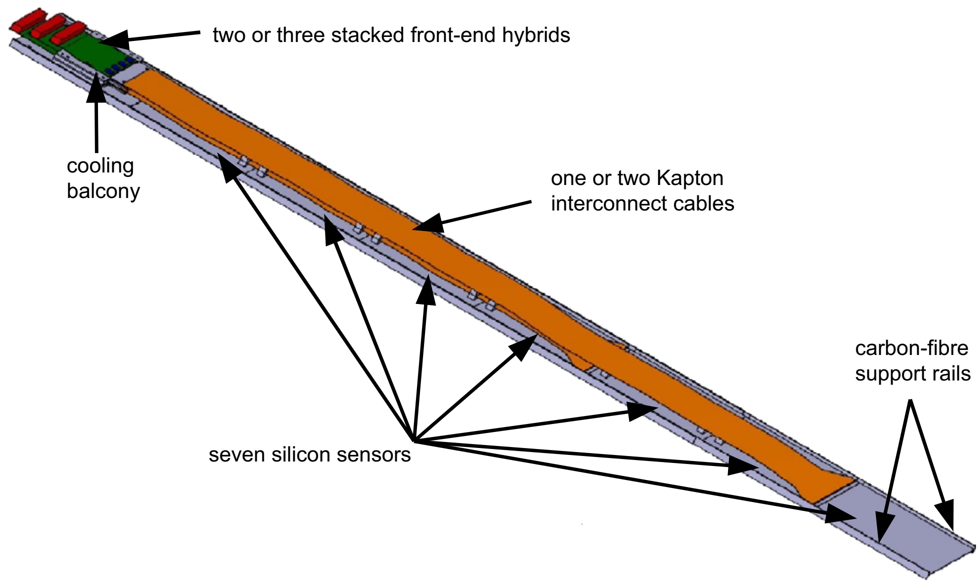

Fig. 1. “4-2-1” type detector module for the TT.

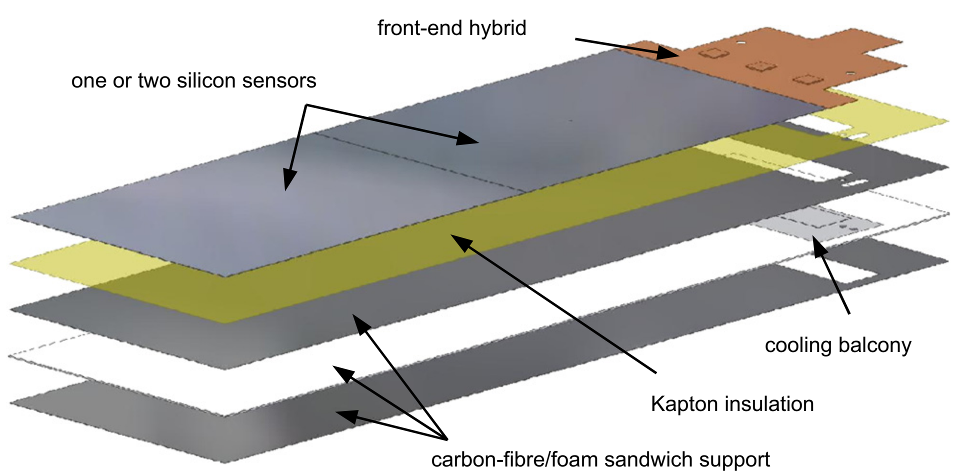

Fig. 2. Two-sensor detector module for the IT.

the module is flipped back over again and the sensor–sensor and sensor–pitch adaptor bonds for the first readout sector are bonded. The first readout sector is now operational and the module undergoes a first burn-in test. When the module has passed this test, protection caps made of Kevlar are glued over all sensor–sensor bonds to protect them from the Kapton interconnect cable that will run across them in the finished module. The second production stage consists in mounting the pre-assembled Kapton interconnect cable and readout hybrid for the second readout sector onto the module, followed by bonding the sensor–sensor and sensor–cable bonds for the second readout sector. A ground wire is soldered from the upper to the lower hybrid and the module is ready for the second burn-in test. If the module is of the “4-3” type, it is completed after this test. If it is of the “4-2-1” type, it now enters the third production stage, in which the Kapton cable and hybrid for the third readout sector are attached and bonded, followed by a third and final burn-in test. Using two assembly templates, an average production rate of five modules per week has been achieved and maintained over the duration of the production.

The production of IT modules takes place at EPF Lausanne and CERN and is run by a team of four physicists and technicians from EPFL and Universidade de Santiago de Compostela. It proceeds as follows: the prefabricated carbon-fibre sandwich support is positioned on an assembly template, using alignment holes in the support (the same that will later be used to position the module in the detector) and the readout hybrid is glued onto the backplane. Silver glue is applied locally to provide a good ground connection between the front-end readout chips on the hybrid and the aluminium insert imbedded in the support. The sensors are precisely positioned onto a second template by pushing them against alignment pins in this template. Vacuum is applied to fix the sensors in place. Thin strips of a silicone-based glue are then applied to the carbon-fibre support using a glue dispenser and a vacuum jig is used to transfer the sensors from their alignment template onto a well-defined position on the carbon-fibre support. When the glue has cured, the module is removed from the template and shipped to CERN, where it is bonded. The completed module then undergoes a comprehensive quality assurance programme, including the measurement of sensor positions, 48 h temperature cycling and readout tests. Using five sets of assembly templates, a production speed of twelve modules per week has been achieved.

4. Quality assurance

Quality assurance played an important role at all stages of the module production.

Silicon sensors were qualified by the manufacturer, and data on leakage currents, full depletion voltage and bad strips (pinholes) were provided to us. Upon reception at Universität Zürich, the sensors underwent a series of acceptance tests, including an optical inspection by eye and under a microscope and the measurement of the full depletion voltage. Geometrical measurements of the dicing edges (whose accuracy is used to accurately position the sensors during the module assembly) and the sensor flatness as well as searches for bad strips were performed on a randomly chosen sub-sample of sensors. The quality of the sensors was found to be excellent and very good general agreement between our results and the data provided by the manufacturer was found [7].

Readout hybrids also went through a first round of quality assurance tests at the vendor,[5] where we had installed a dedicated test stand for this purpose. The test programme included several temperature cycles between -20 and $+60\,^{\circ}$C. Upon reception at MPI Heidelberg, each hybrid underwent a 96 h burn-in programme, which included measurements of the power consumption of all chips and readout tests at the nominal trigger rate of 1 MHz, searches for dead channels and pipeline cells, the determination of gain, pedestal and noise for each channel, and pulse-shape scans using an internal test pulse on the Beetle chip [8].

The first measurement that is performed on a module is that of the positioning accuracy of the silicon sensors. As an example for the achieved precision, the distribution of relative sensor offsets on TT modules is shown in Fig. 3. The positioning accuracy is much better than the expected spatial resolution of about 50 μm. We therefore believe that it will later be possible to treat each module, resp. each readout sector, as a single unit during the software alignment of the detector.

[5]RHe Microsystems, Radeberg, Germany.

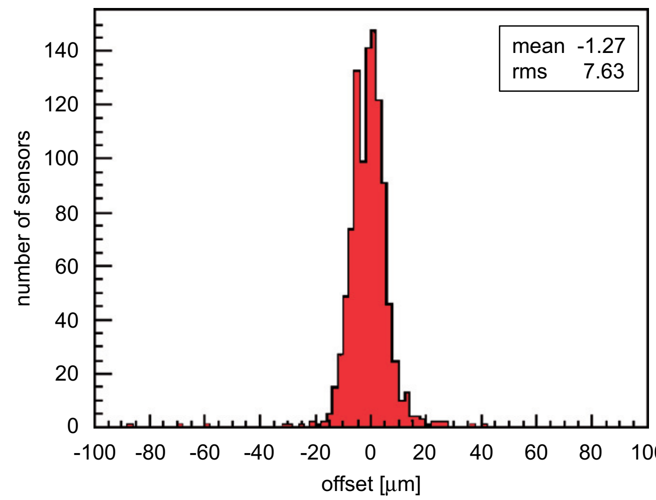

Fig. 3. Distribution of the relative offsets of silicon sensors on a TT module.

The most important module quality assurance measure is the comprehensive burn-in programme, through which each module passes at least once during its production, and which will be described here for the example of the TT. A considerable amount of effort was spent on setting up a burn-in test stand that can operate in a largely automatic fashion, the need for operator intervention being more or less limited to exchanging the modules under test in between two runs. This permits to perform extensive test programmes on all produced modules, running the test stands overnight and over weekends. Up to four modules can be tested in parallel in order to keep up with the module production rate. Furthermore, the burn-in stand uses to a very large extent final LHCb readout electronics and therefore serves as a long-term test of the final readout, as well as permitting us to gain valuable experience in its operation.

The typical burn-in programme takes 36 h and includes several temperature cycles between room temperature and $5\,^{\circ}$C, the latter being the operating temperature foreseen for the final detector. During these temperature cycles, the modules are continuously biased at 500 V and leakage currents are monitored as a function of time and temperature (see Fig. 4 for an example). Furthermore, I–V curves up to 500 V bias voltage are measured at warm and cold temperature. Pedestal runs are taken at both temperatures and the raw and common-mode subtracted strip noise is determined for each readout strip. Also, signal pulse shapes for all read-out strips are measured at both temperatures, using an internal test pulse implemented in the Beetle readout chip. Finally, the setup 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. ‘‘Bad’’ channels (interrupts, shorts and pinholes) are identified by analysing the strip noise. Interrupts can be identified as channels with too little noise (due to their reduced load capacitance) and

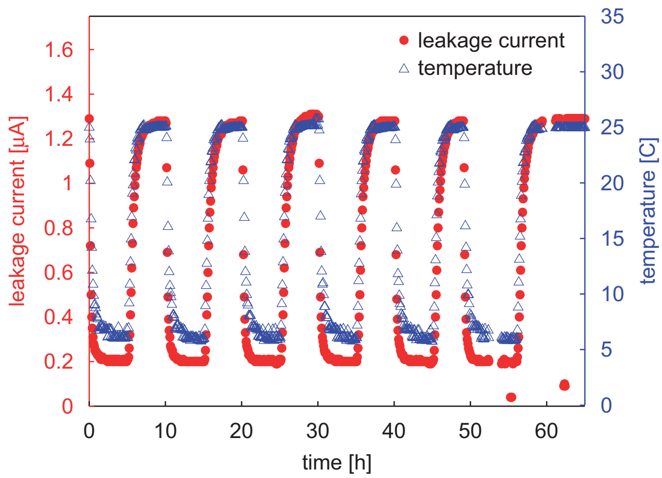

Fig. 4. Leakage current as a function of time as measured during a particularly long burn-in of a Trigger-Tracker module. The periodic variation of the leakage current is due to the temperature cycling between room temperature and 5 °C.

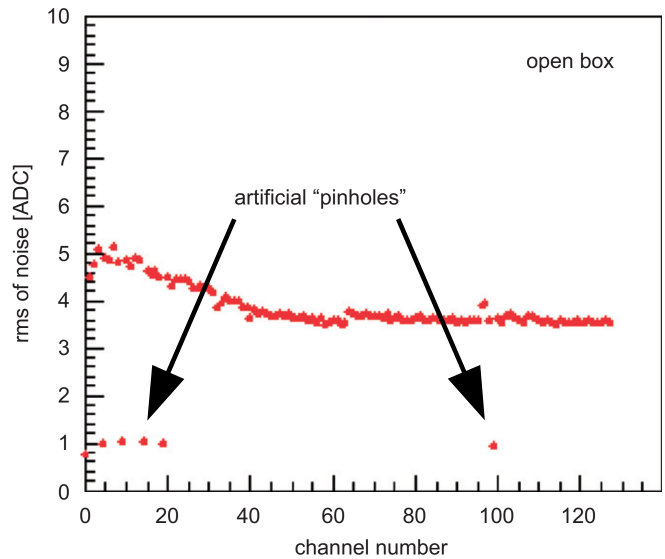

Fig. 5. Root mean square of the noise distribution for each of the 128 channels on a Beetle chip, measured with an open detector box. Channels with artificially introduced ''pin-holes'' show up clearly due to their much reduced noise, as explained in the text.

shorted strips as pairs of adjacent channels with too large noise (due to the increased load capacitance). To identify pinholes, pedestal runs are taken with open detector box. The light shining onto the silicon sensors generates leakage currents in the silicon bulk, which, in the presence of a pinhole, flow through the front-end pre-amplifier. Even without applying any bias voltage to the sensor, these leakage currents are so large that they saturate the amplifier and the noise for these channels essentially drops to zero (for an example, see Fig. 5).

The overall quality of modules produced so far was found to be very good, with a fraction of bad channels of below 0.1% and leakage currents at 500 V and 5 °C of typically below 0.5 µA per silicon sensor. On a small number of modules, a sensor, pitch adaptor or readout hybrid was damaged due to handling errors during the production and a few modules show higher-than-normal leakage currents or otherwise abnormal *I–V* curves. Since the number of these modules is still smaller than the number of spares we had planned for, they have been put aside for the time being and will be looked at in more detail once the main production is completed.

A general problem that was observed on TT modules concerned the long-term behaviour of the silver glue that was initially used to electrically connect the bias voltage cable to the 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 (see Fig. 6). Whereas all tested connections had initially very low resistivity, a significant fraction of them showed increased resistances of up to several hundred Ohms in the later measurements. This effect was observed both for a silver paint (Elecolit 340) that was used on the first produced modules and for a silver loaded two-component expoxy glue (Elecolit 325) that was used on later modules. 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 on aluminium is also used on IT modules to ensure the ground connection between the read-out chips and the cooling balcony, which provides the interface to the common ground in the detector box. In order to avoid future problems here, an additional ground connection soldering thin wires will be implemented on all modules.

5. Summary and lessons learnt

With the detector module production for TT and IT approaching its completion, we can already dare to draw first lessons from our experience made, at least as far as aspects of planning and organisation are concerned.

The clear sharing of responsibilities between the institutes involved in the detector module production (front-end chips and readout hybrids at MPI Heidelberg; silicon sensors at Universität Zürich; TT modules again at Universität Zürich; IT modules at EPF Lausanne, in collaboration with Universidade de Santiago de Compostela) and the concentration of the responsibility for all aspects concerning the production of a given part (design, assembly/procurement and quality assurance) in a single site permitted to keep logistics simple, ensured direct paths of communication between the involved technicians, engineers and physicists, simplified decision making, and allowed a large amount of flexibility in planning as well as fast reaction to unexpected problems.

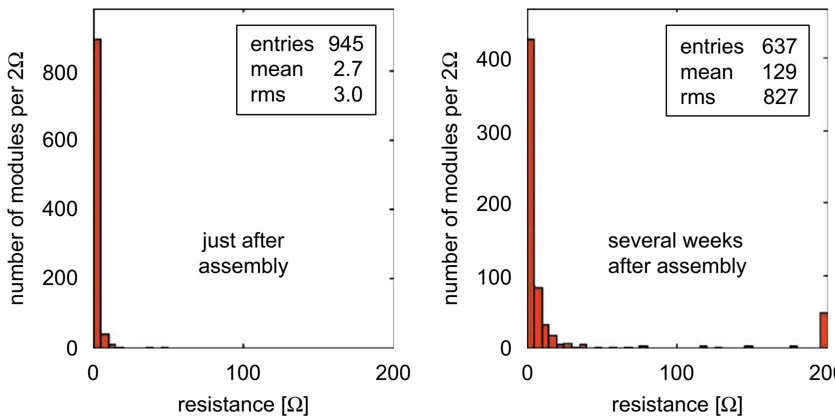

Fig. 6. Distribution of the resistance across silver glue connections between bias voltage cable and sensor backplane, measured right after the module assembly (left) and a few weeks to months later (right).

At both module production sites, the production was run by rather small teams of dedicated physicists and technicians. This again contributed to simplifying communication and decision making but also posed a certain risk, due to an almost complete lack of redundancy. For example, the Zürich group had only one fully qualified bonding technician throughout the full duration of the module production. We were lucky that no incidents happened that could have significantly slowed down or even stopped the module production for extended periods of time.

For both TT and IT, the initially foreseen module production rate was eventually reached and maintained more or less continuously. As anticipated, the overall production effort was dominated by the quality assurance measurements. However, the transition from prototyping to series production took much longer than we had anticipated, resulting in significant delays with respect to the original planning. Delays were due to a wide range of reasons, including delivery problems at vendors (a major hickup was, for example, caused by production yield problems at the vendor of Kapton interconnect cables for the TT modules), longer than expected learning curves (for example, for the training of bonding technicians) and various small weaknesses 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 certain ad hoc modifications of the module design and/or assembly procedures. If more time had been available (or these weaknesses had been discovered earlier) one would have liked to go through one more revision of the module design in order to implement these modifications in a proper way.

Two very basic lessons that we can therefore draw from our experience are (a) that a few ‘‘final’’ modules should be built as early as possible, using ‘‘final’’ production tools and assembly procedures, and (b) that the production schedule should include ample time for the transition from prototyping to production and for a slow ramp-up of the production rate. For anyone who has built a large detector before, these two conclusions may not come as surprising news, but they are so fundamental that I think they nevertheless deserve to be stated once again.

6. Outlook

The production and testing of detector modules for the LHCb Silicon Tracker will be completed soon. The modules will be assembled into detector stations and will be installed in the experiment early next year. This leaves us with about half a year for detector integration before the commissioning of LHC beams will start in autumn 2007.

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