Assembly of the Inner Tracker Detector Boxes

Prepared by: Bettler Marc-Olivier[a], Conti Géraldine[a],
Voss Helge[b], Gauvin (Gueissaz) Neal[a], Frei Raymond[a],
Esperante Pereira Daniel[c], van Hunen Jeroen[a], Fauland Peter[a]
[a]EPFL,Switzerland
[b]Heidelberg, MPI, Germany
[c]Universidade de Santiago de Compostela, Spain

Abstract

This document exposes the final assembly of the Inner Tracker detector boxes. The components and their preparation are described. The assembly steps are detailed to prepare for a potential intervention on a detector box.
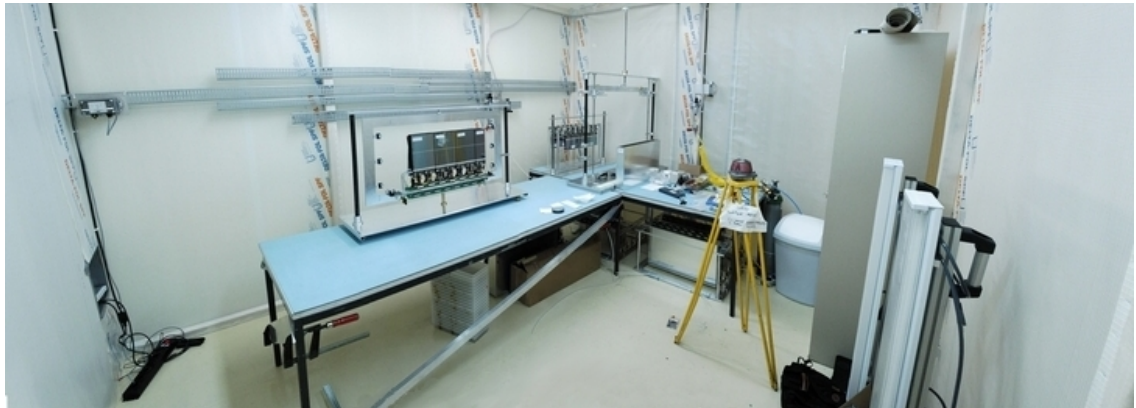
Figure 1 View of the clean room where the Inner Tracker detector boxes were assembled.

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1   Introduction

The Inner Tracker detector is part of the tracking system of the LHCb experiment [1]. This document describes the procedure used for the assembly and mounting of the Inner Tracker detector boxes.

B physics studies foreseen at LHCb require excellent momentum resolution, typically $\delta p/p \approx 0.4\,\%$. The momentum resolution is dominated by multiple scattering, consequently minimization of the material budget is crucial. The design of the Inner Tracker posed a further challenge, since the front-end electronics, the mechanical support and part of the cooling are located inside the experiment acceptance. The required momentum resolution translates into a spatial resolution of $\approx 70\,\mu$m for the Inner Tracker.

Minimisation of the Outer Tracker and Inner Tracker occupancies led to the layout and dimensions of the Inner Tracker and to its granularity. It covers a roughly $120\,$cm wide and $40\,$cm high cross-shaped region in the center of three large planar tracking stations downstream of the magnet, using Silicon microstrip technology with a strip pitch of $198\,\mu$m.

The silicon sensor technology is sensitive to temperature. The leakage currents increases with temperature, and above some temperature threshold a thermal runaway process occur, leading to the destruction of the sensor. This situation worsens with radiation damage since it also increases leakage currents. Consequently, due to the front-end electronics power dissipation, active cooling of the Inner Tracker is required, to keep the sensor below 5° C. This cooling is brought by liquid C_6F_{14} at -25° C. As a consequence, the humidity in the detector enclosure has to be controlled; this is done by a constant flow of N_2 and good airtightness of the box envelope.

The Inner Tracker consists of three stations broken down into four independent detector boxes (Figure 2). The boxes above and below the beam pipe are called respectively Top and Bottom central boxes, whereas the boxes on each side of the beam pipe are called Access and Cryo side boxes. Each detector box contains 28 detector modules. The active region of a module consists of either one or two $110\,$mm $\times\ 80\,$mm silicon microstrip detectors. Side boxes contain two-sensors modules, whereas central boxes contain one-sensor modules. The assembly of the 12 boxes is described in this document.

This document is organized as follows: in Section 2, the various components used to build a detector box are briefly presented and in Section 3, the actual assembly process is detailed. The aim is to be able to build a box following those instructions, profiting from the experience gained in the first attempts.

2   Description and preparation of the detector components

In this section, we describe the components entering in the assembly of an Inner Tracker box. We indicate how each was prepared for use in the assembly procedure detailed in Section 3.

2.1   The cover

The cover fulfills several roles. It provides a mechanical interface between the Inner Tracker support frame (Figure 2, left) and the detector modules inside the box (Figure 2, right), as well as an electronics and power interface between the cables and the front-end hybrid (see Section 2.4 and Figure 12). Being part of the whole box envelope, the cover provides a thermal insulation, as well as electric and light shielding.

The cover is made of foam[a] sandwiched between carbon fiber sheets (Figure 3). This sandwich is covered on both sides with $81\,\mu$m thick aluminum foil[b]. Four printed circuit boards (interface PCBs) are glued into slits in the cover, one for each layer of detector modules. They act as:

- the interface of the electrical connections from the outside to the inside of the box.

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[a] Airex R82
[b] 3M 1170 Tape

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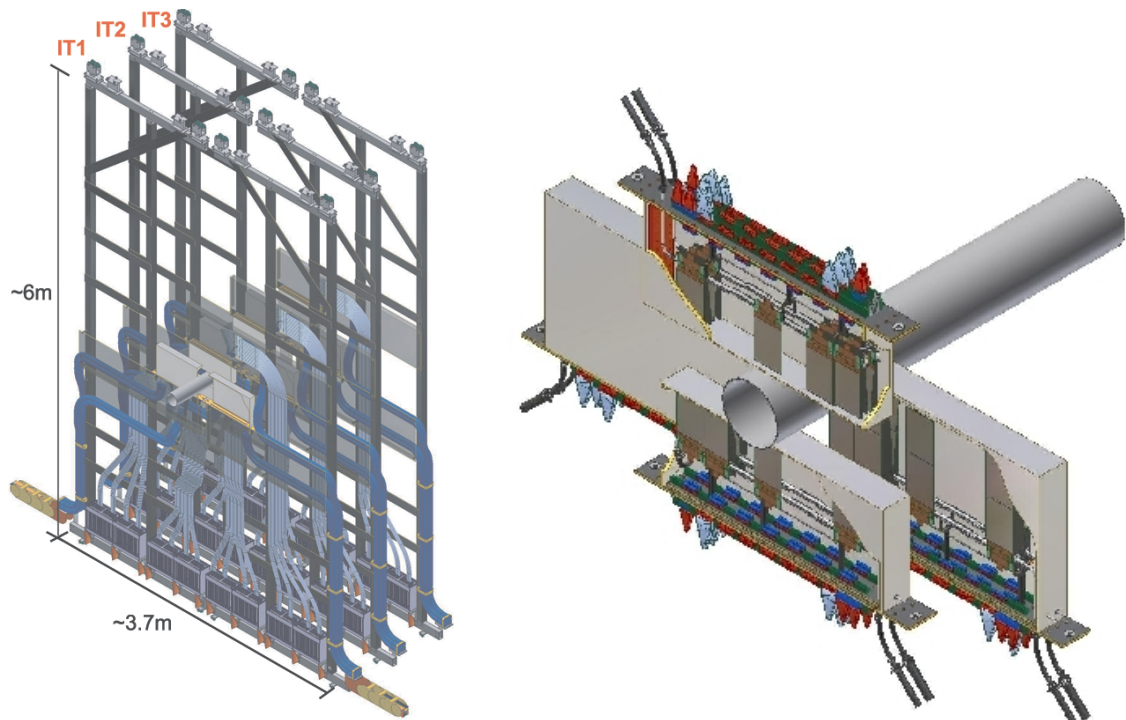**Ref:** *LHCb-2008-074*
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Figure 2 The Inner Tracker detector consists of three stations IT1, IT2 and IT3 (left), each broken down into four independent detector boxes located around the beam pipe (right). The boxes above and below the beam pipe are called Top and Bottom central boxes and contain one-sensor modules, whereas the boxes on the side of the beam pipe, called Access and Cryo side boxes, contain two-sensors modules.

- they contain lines for the high- and low-voltage supply, I2C and data lines of the readout hybrids, four temperature probes of the box container and one humidity sensor located on one of the PCBs.

- They contain lines for the grounding of the container inner shield and for the grounding of the detector modules.

A line of epoxy resin mixed with microballoons to increase the viscosity was used on both sides of the PCB to ensure air tightness. This glue mixture was applied using a syringe with a flexible plastic needle made out of a plastic tube with $0.8\,\mathrm{mm}$ inner diameter.

The cover provides mechanical fixation for the sensor support structure, which is attached to it via three M3×20 screws. The cover is fixed to the box container using twelve nylon M2.5×20 screws. In the LHCb cavern, the detector box is fixed to its final position using three M4 nylon screws on both sides of the cover. The cover either rests on (Top boxes) or hangs under (Bottom, Access and Cryo boxes) two carbon fiber brackets of the Inner Tracker support frames. On both sides of the cover, a stesalite insert has been designed to house a survey target for theodolite measurements [2].

An aluminum cooling pipe runs along both cooling rods (Section 2.3) and both ends are passed through the cover through two custom made round polyamid pieces with an internal O-ring providing an air tight fitting.

2.1.1   Features of the cover construction

Electrical shorts were found between HV lines of the PBCs and carbon fibers of the cover as well as between LV lines and the carbon fiber in the first mounted box. To prevent this from happening, the interface PCBs were covered with an additional layer of Kapton tape prior to insertion into the slits of the cover.
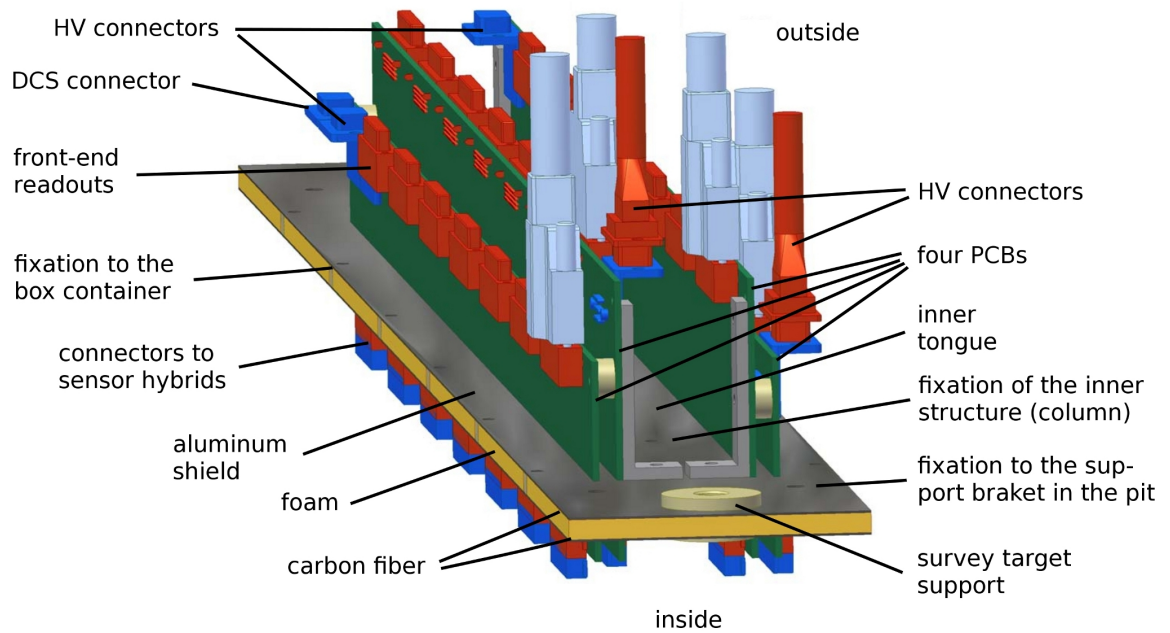
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Figure 3 Schematic view of a cover.

After the PCB were inserted into the cover, they were fixed with screws and glued to the cover along their edges. The PCBs act as a stiff skeleton for the part of the cover that is between the inner PCBs, called the tongue (Figure 3), which was quite flexible. It was important to control the position of this tongue before gluing, else the position of the modules was found to be unreliable. This was done using a dedicated jig, which controlled the position of the tongue while gluing it.

After several connectivity problems with the first cover, leading to dead readout ports being discovered during the full electronic test (see Section 3.11), all the 64 lines of each of the 28 connectors in a cover plate were tested as a standard procedure of cover testing. The test consisted in the checking the continuity of each line using a multimeter.

Thermoswitches[c], which were required inside the detector boxes by the DSS[d], were tested for operation in high magnetic field [3]. As their presence was not foreseen in the initial design, no line was available in the interface PCBs. A small hole was therefore drilled in the sandwich structure of the cover to allow for the thermoswitch circuit wires to cross it. One thermoswitch was glued to the bottom side of each cover with Araldite (Figure 4). The hole in the cover was then filled with Araldite from both sides.

A small PCB was designed as a mini patch-panel for the the DSS thermoswitch and the BEAMS circuit (see Section 2.2 for a description of the BEAMS system). It consists of a $4 \times 3\,\mathrm{cm}$ PCB glued on the 2 inner PCBs as shown on Figure 5.

2.1.2   Cover preparation

The cover was first mounted on its support, taking care that the latter was adapted to the kind of boxes, side or central boxes, as they do not have the same dimensions. Figures 6, 20,left and 21, right show the whole set-up with a mounted cover. A screw at each end keeps a small pressure on the cover to prevent it from moving. A piece of plastic was placed between the cover and the screw to prevent it from damaging the cover (Figure 15). The support allows the cover to be moved up and down, a vertical screw controlling this motion.

The cover was then carefully cleaned with compressed air and alcohol to remove the residual dust. As shown in Figure 6, the columns (a) were fixed to the cover, using M3×20 screws and hard-paper collars, in order not to damage the thin aluminum film that makes the cover a Faraday cage.

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[c]Thermik CO 60 model
[d]Detector Safety System [4].

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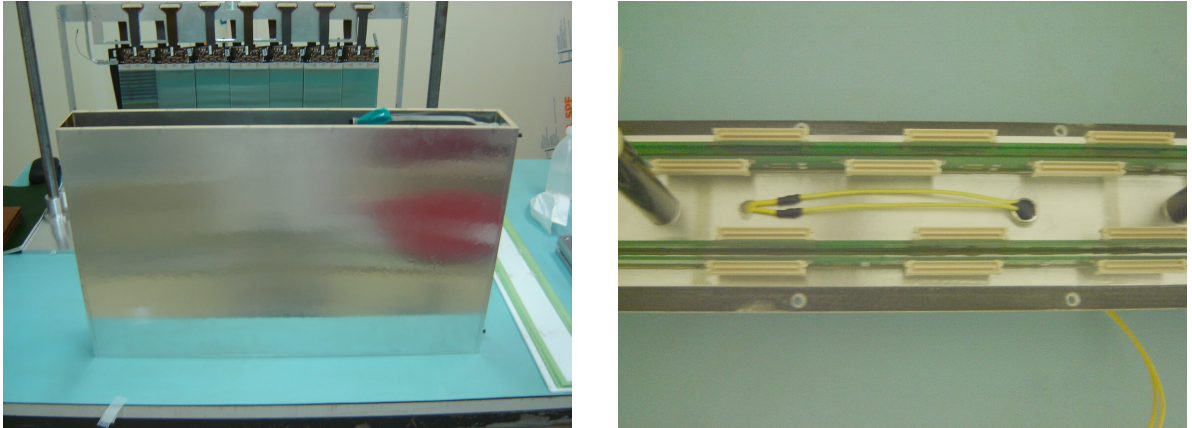Issue: *1*
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Figure 4 An empty box container (left). The wires visible scotched on the inner wall are the temperature probes readout and the inner shield ground wires. This bunch of wires will be connected to a PBC on the inside of the cover, when the modules are slid down in the box container (Section 3.13). The thermoswitch is glued under the cover to prevent it from touching the sensors (right), its wires traversing the cover structure through a hole ultimately filled with Araldite.
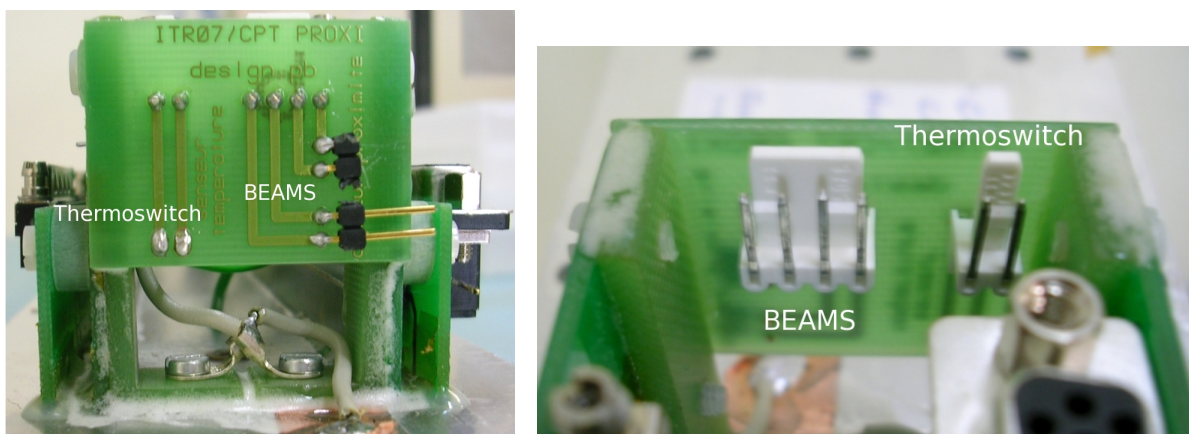
Figure 5 The same mini patch-panel for BEAMS and thermoswitch connections, viewed from either direction. In the left picture, the connectors to which the BEAMS device wires will be connected once the box is assembled can be seen. This particular cover belonging to a side box, thus equipped with only one BEAMS device, the upper connectors were cut away leaving only the needed connectors, as can be seen in the left picture. The right picture depicts the same mini patch-panel from the opposite point of view.

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Figure 6 A cover mounted on its support. (a) columns, (b) fork, (c) bar, (d) special piece to control the position of the fork while it is being screwed tight.

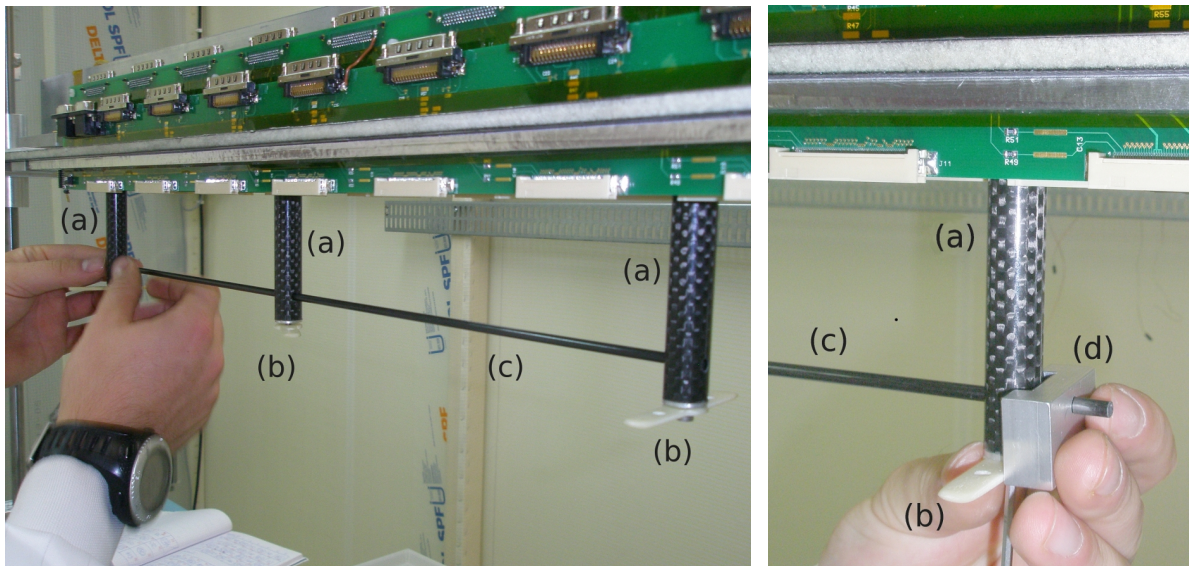A stesalite transverse piece (b), called a fork, was screwed to each column using a M3×8 screw. The fork connects the columns to the two colonnettes (Figure 7), the whole having the form of a fork. The dimension of this piece is larger than the distance between the two cooling rods. The extremities of the forks are $0.5\,\mathrm{mm}$ away from the container wall. This was done to prevent any damage to the detector modules in case of shock to the box, the extremities of the forks stopping the movement before the sensors could touch the container wall. Furthermore, to prevent grounding loops, it is made of stesalite.

Each extremity of a fork has a beveled edge to be placed downwards to avoid potential damage to the inner walls of the box when the cover is moved downwards into the box. There are holes at the bottom of each column to allow a thin carbon fiber bar (c) to be inserted through the three columns (a). This bar was used only to align the three forks while they were screwed in place. For this a special piece (d) was used to get the forks perpendicular to the carbon fiber bar. The thin bar (c) was then removed.

2.2   The box container

The box container is made of a sandwich of glass fiber and PIR-foam covered with aluminum shielding on the inside and outside. The foam part of the walls is $8\,\mathrm{mm}$ thick, except for the walls close to the beam-pipe, which are $3\,\mathrm{mm}$ thick to allow the sensitive parts of the detector to lie closer to the beam-pipe.

The box enclosure will be continuously flushed with N_2 to prevent condensation inside the box. The humidity has to be such that the dew point remains above the temperature of the coldest element in the box (which is at the coolant temperature). The incoming N_2 flow is spread within the box volume using a perforated channel made out of glass fiber.

Before using the box container in the assembly, several tasks are performed :

- depth measurement,

  The depth of the container was measured with a depth gauge. The depth was measured from the lip of the container to its inside bottom, at six places along the container length. The measurement locations were defined by the position of the screw holes on the container lip. Conservatively, the minimal depth was considered when assessing whether the detector modules will fit the container, as for central boxes, they are really close ($\sim 0.5\,\mathrm{mm}$) to the bottom of the box container. For side boxes, this distance is not as small, but the container depth was measured anyway.

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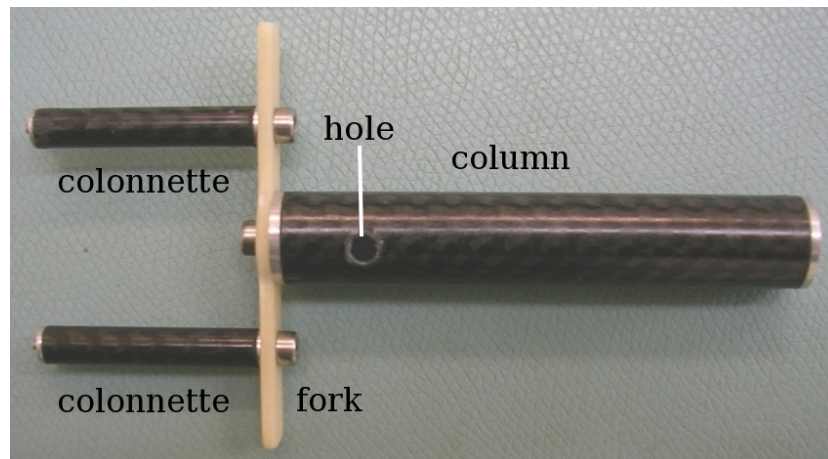**Issue:** *1*
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Figure 7 Detail of the assembly of a column, a fork, and two colonnettes. The hole in the column tube through which the carbon fiber bar is inserted when the fork is aligned can be seen. On this picture the alignment was not done, thus the hole is not centered with respect to the fork.

- temperature probes,

  Four PT1000 temperature probes are placed inside the box container in addition to the probe installed on each readout-hybrid. These measure the temperature of the box environment. Three of them are located at the bottom of the box and one on the side wall facing the beam-pipe (side boxes) or the opposite of the N_2 inlet (central boxes).

- inner shield grounding,

  The inner and outer shielding of the container are connected to the ground by a wire glued onto the aluminum shielding. To glue the wire on the shielding using conductive glue, the insulation of the wire was removed on approximately $2\,cm$. After two days of drying, a protective layer of Araldite was applied on top. The grounding of the inner shielding is soldered to the ground of the temperature probes, which is connected to the ground of the cover during the assembly process. The grounding of the outer shield (Figure 8, right) connects to the ground line on one of the PCBs via a small connector.

- verticality control,

  As the containers are standing on the base plate during the sensor modules insertion procedure, their verticality is important. Therefore, it was carefully checked and, if needed, corrections were brought by applying $100\,\mu m$-thick layers of Kapton tape on the appropriate side of the container bottom.

- RMS support,

  The Radiation Monitoring System (RMS) detector [5] is supported by the IT container boxes for three (Top, Access, Cryo) out of the four detectors of station T2. Therefore, stesalite pieces to fix the RMS detector were glued onto the wall of appropriate containers. To maximize the adherence of the glue, the aluminum shielding was locally removed, the glass fiber surface was scratched and three small holes were cut into the glass fiber surface. A dedicated jig was used to constrain the relative position of the RMS support pieces with one another during the glue drying process.

- BEAMS (Beam-pipe approach monitoring system) finger support,

  The BEAMS is a system that raises an alarm in case a detector box is too close to the beam-pipe in order to avoid possible damage. The nominal distance of the detector boxes to the beam-pipe is $7\,mm$, and anything closer to $5\,mm$ is supposed to trigger the alarm.

  It consists of two gold plated metallic fingers which are in contact with each other in their nominal position (Figure 8, left). The touching fingers are part of an electric circuit which is closed in
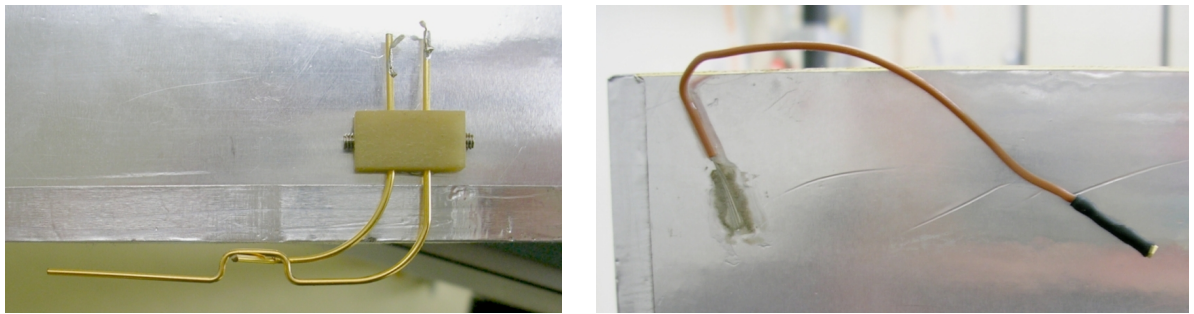
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Figure 8 A BEAMS device (left) and the ground wire of the box external shield (right). This particular BEAMS device is located on the long edge of a central box, in such a position that it will lie just above or below the beam pipe, once the IT station closed. This picture allows to understand how the BEAMS electric circuit opens if something pushes the lower finger up.

nominal position. If the outermost finger touch the beam-pipe, the fingers would separate from each other and consequently open the circuit.

There are six BEAMS devices per station, distributed as follows: two of them on each central detector box, and one on each side box. On the central boxes, one BEAMS device is located in front of the edge of the container which passes close to the beam-pipe during the closure procedure of each half-station, like a bumper. This device is only useful during the closure of the half station, preventing a collision of the top or bottom boxes with the beam-pipe. The other BEAMS device is located on the wall that is close to the beam-pipe, so that it faces the beam-pipe when the station is completely closed (the device in Figure 8 is of that type). On the side boxes, there is just one BEAMS sensor such that the sensitive finger is at the level of the beam-pipe $5\,\mathrm{mm}$ away from it.

The BEAMS system is fixed on the box containers. The stesalite pieces that support the fingers (Figure 8, left) were glued to the container wall using a similar procedure as the RMS support. Their location was given by a dedicated jig.

2.3   The cooling rod

The cooling rods provide mechanical support, cooling, and grounding to the sensor modules. They consist of an aluminum part with a complex crenelated design which is glued to a pure aluminum tube (external diameter $6\,\mathrm{mm}$, wall thickness $0.3\,\mathrm{mm}$) in which flows the coolant liquid (Figures 9 and 10). Pure aluminum is highly ductile. Aluminum was chosen as it has a relatively low radiation length ($X_0 = 24.3\,\mathrm{gcm^{-2}}$) and can easily be bent into the desired shape without inducing cracks in the thin walls of the tube. Due to their extreme fragility, the cooling rods have to be manipulated with great care.

To measure the path of a particle in 3 dimensions the Inner Tracker is made of four sensitive layers in a typical stereo layout. The two external layers, called X1 and X2, are made of sensors with microstrips aligned vertically, whereas the two internal layers, called U and V, have strips which form a $\pm 5°$ angle with the vertical axis. A cooling rod supports two layers of 7 modules. There are therefore two different types of cooling rod: the type A supporting V-X2 layers and the type B supporting X1-U layers.

Looking at a cooling rod, a crenelated structure can be seen (Figure 9). This induces a slight staggering between a module and its neighbors and consequently ensures an overlap of the sensitive area. Thus, there is no dead space between two sensors, preventing the existence of gap in the sensitive surface. The gap between two crenels is measured to check the type, A or B, of the cooling rod, as the length of the interval between two crenels is about $0.5\,\mathrm{mm}$ larger for the U or V layers than for the X1 or X2 layers, as explicited in Figure 9. Thus, orientating the cooling rod so that the long tube (the part that exit the cover) is on the left-hand side in front of us, a B type (X1-U) cooling rod will have the longer interval on the side close to us.
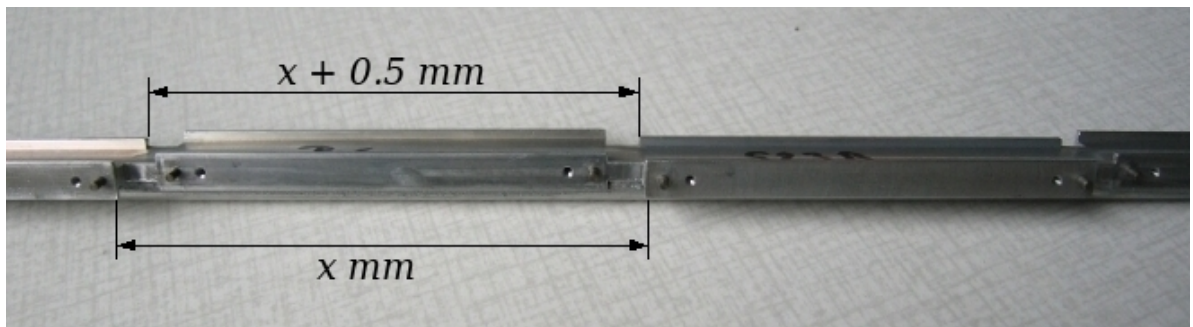
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Figure 9 The length of the interval between two crenels is about $0.5\,\mathrm{mm}$ longer on the U and V layers than on the X1 and X2 layers.
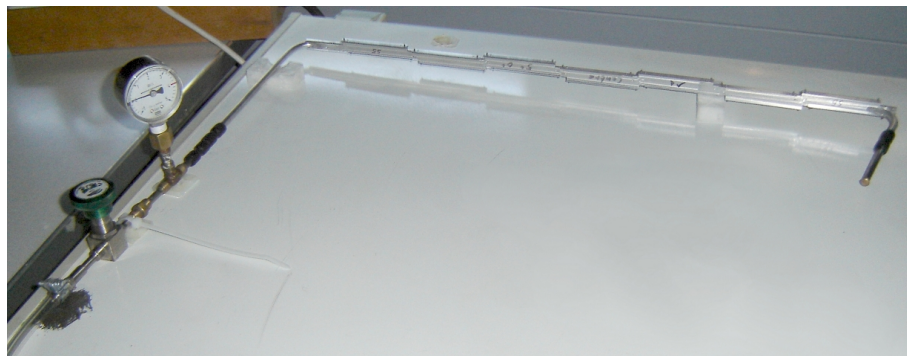

Figure 10 A cooling rod under pressure test.

Within the support structure of the sensor modules, there is an aluminum piece called the "balcony". This piece provides stiffness and acts as a thermal bridge. The precision holes that govern the positioning of the module are machined in the balcony. The back of the front-end chips were glued on the balcony with conductive glue and the balcony is in direct contact with the cooling rod. The precise positioning of the sensor modules is achieved by the use of pins fixed to the cooling rod, which are inserted in the holes of the balcony. While mounting the first modules, it was noticed that the distribution of the angle of the module with respect to the vertical direction was very broad. Consequently, most of the modules were neither vertical, nor parallel with each other. The cause was traced back to the alignment pins of the cooling rod. Although they were machine-inserted into the cooling rod, their orientation was found to be inaccurate. Therefore, each pin ha to be straightened using a small lever.

The cooling rods were individually tested for leaks. The procedure consisted in blocking one end of the cooling tube and connecting the other end to a manometer. The cooling rod was filled with Argon up to about 4.8 bars and the circuit is closed (Figure 10). After two days, the pressure was checked again. If any significant variation of pressure (more than a few tenths of bars) was noted the test was redone. A cooling rod would be rejected if the second test failed, too; this did not happen.

Finally, a ground wire was screwed on each cooling rod (Figure 11, right). The three colonnettes ($35\,\mathrm{mm}$ carbon fiber) were also screwed and secured with LOCTITE 932 to the cooling rod (Figure 11, left).

2.4   The detector modules

The design and production of the detector modules is documented elsewhere [6]. Figure 12 shows the composition of a sensor module. The IT modules consist of one or two silicon sensors bounded via a pitch adapter to a front-end hybrid. The support structure is made of a layer of AIREX foam sandwiched between two sheets of high thermal conductivity carbon fiber; a Kapton sheet is glued on top of this structure for electrical insulation. The balcony, a small aluminum insert, is embedded into

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Figure 11 View of a cooling rod mounted on its support (left) with the help of the three colonnettes of $35\,\text{mm}$ screwed on it (right). The thread for the grounding is also visible (right).
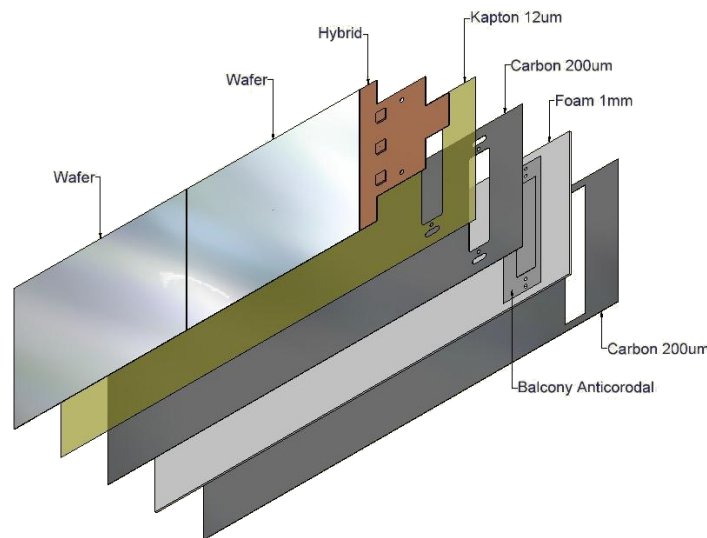

Figure 12 Detector module composition.

the module support at the location of the readout hybrid. It provides a direct heat path between the front-end chips and the aluminum cooling rod onto which the modules will be mounted.

Inside an IT detector box, the sensor modules are partitioned in groups of four modules. The modules within a group are supplied with sensor bias voltage from a single HV channel. The main criterion used for the positioning of individual modules in a box was therefore based on the depletion voltage. Groups of four modules with close depletion voltage were formed.

An other criterion was the overall quality of the sensor in terms of shorted, open or pinholed channels. The sensor specifications, which we adopted also for the modules, demanded $\leq 1\,\%$ of faulty channels. Most of the modules installed are $100\,\%$ working, but 111 strips faulty out of 129 k. The modules with faults (while still meeting the specifications) were placed where the particle density is expected to be the least.

The modules were cleaned with air to remove residual dust on the sensors. The bonds around the beetles, between the pitch adapter and between two sensors are checked visually with a magnifying glass to ensure that there was no dust nor carbon fiber element between them.

For the external layers (X1 and X2), there was a risk that the sensors, or the bonds, would touch the inner container wall. To prevent this, a foam buffer (Rohacell) of about $55\,\text{mm} \times 27\,\text{mm}$ was centrally glued with double-faced adhesive tape (3M type 467MP) on top of the forward sensors, at about $15\,\text{mm}$ from the bottom of the modules (Figure 13, left).

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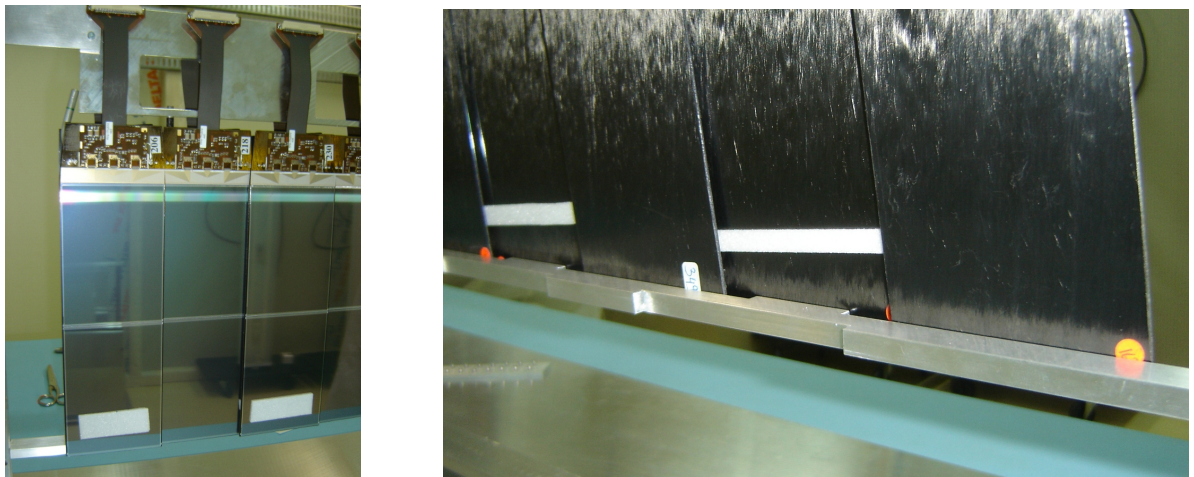**Issue:** *1*
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Figure 13 View of the foam protections glued on forward sensors of the external layers to prevent them from touching the inner walls of the IT detector boxes (left) and at the rear of all the forward modules to protect the backward sensors to be touched by those (right).
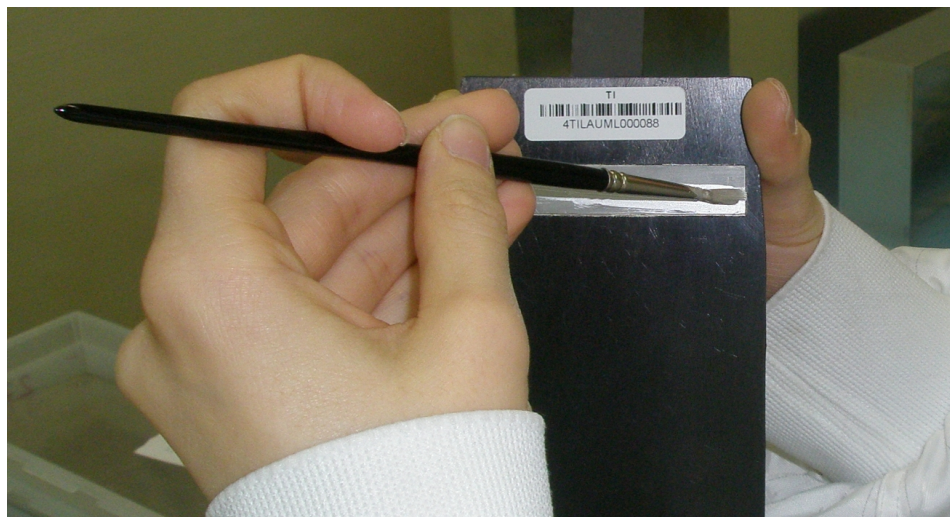

Figure 14 View of the sticker glued at the rear of the detector modules allowing their identification. The operator is applying thermal grease on the module balcony in preparation of the mounting of the module, as explained in Section 3.4.

To have complete spatial coverage, the modules within a layer are staggered in the z direction by four millimeters. Thus, to prevent the back of one module from touching the sensor behind, foam buffers of about $80\,\text{mm} \times 10\,\text{mm}$ were glued at the rear of the forward modules at about $20\,\text{mm}$ from the bottom of the modules (Figure 13, right). Each module is identified with a module number given at the production. In addition, a bar-code sticker was glued on the back of all modules (Figure 14) to identify them within a central database [7, 8, 9].

2.5   The assembly set-ups

Two set-ups were used in the assembly process. The first set-up is called the cooling rod station (Figure 11, left). Its function is to hold a cooling rod during the mounting of the modules. The second set-up, called sliding set-up, allows to hold the cover while the cooling rods are mounted on the cover and to control the sliding of the modules into the box container (Figure 21, right).

The cooling rod station consists of an aluminum frame on which a cooling rod can be fixed with three screws the same way it would be with an actual cover. The whole frame can be rotated along a
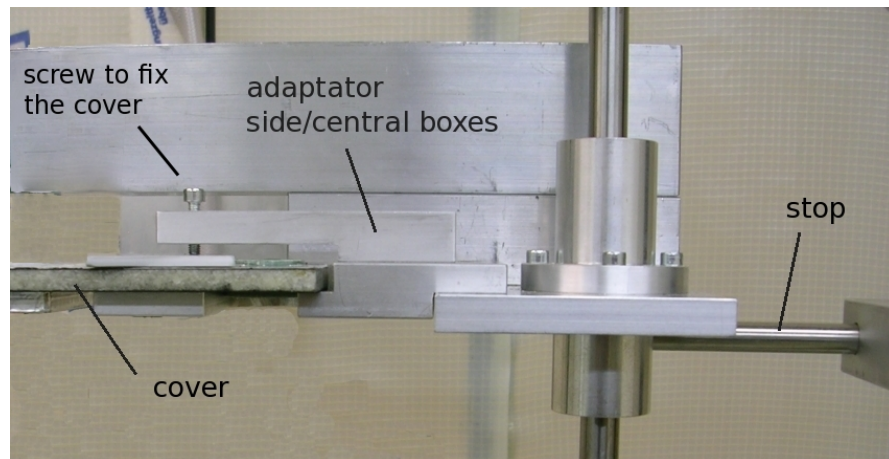
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Figure 15 The cover is just laid on the set-up, while a screw keeps a small pressure on the cover. A piece of plastic is inserted between the cover and the screw to prevent it from damaging the cover. On the right, a stop is visible.

vertical axis, so that the operator can access both sides of the cooling rod without moving the set-up base plate. An aluminum bar with specially designed crenelated shapes on both sides can be inserted in the frame. The bar acts as a stop, preventing the back of outer modules from touching the sensors or the bonds of the inner modules during the mounting of the modules (Figure 13, right). Two different bars are used, one for the X1-U cooling rods, and one for the V-X2 cooling rods.

The sliding set-up consists of two vertical round bars held at the bottom by a heavy stable base-plate and at the top by a bar. Two trolleys, one on each vertical bar on which they can slide, are linked together by an horizontal bar, whose vertical position can be controlled by a long vertical screw. The sliding trolleys have to be adapted to either central or side boxes, since the overall length of the cover is different according to the type of the box, as shown in Figure 15. Thus, the correct adapter piece has to be screwed in place. The horizontal bar linking the trolleys is bulky and limits the working space. Thus, the set-up was oriented so that the main operator of the assembly works with this bar away from him.

There is another set-up that is used for the survey measurements [2]. This set-up was particularly designed to cope with the little space available in the clean tent. It allows to survey both external sensitive layers alternatively without losing information about their relative distance.

Before each use, the surfaces the set-ups were cleaned with an alcohol soaked tissue. The cleaning of the upper bar of the sliding set-up was important, because dust could fall from there directly on the modules. Particularly, attention was paid to the brass piece holding the vertical screw. At this location, tiny metal chips from the screw were produced when the screw was used. A careful cleaning was needed there to prevent any of those metal chips to fall on sensor bonds or into open connectors.

3   Assembly procedure of an Inner Tracker detector box

The assembly procedure can be broken down into the following sequence:

- Preparation of the various components and definition of the assembly plan considering the different sensor modules characteristics;

- Mounting of the cover on the sliding set-up;

- Adjustment of the detector box container position;

- Mounting of two layers of modules on each side of the first cooling rod;

- Mounting of the cooling rod on the support below the cover;

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- Mounting of two layers of modules on each side of the second cooling rod, and mounting of this cooling rod on the support;

- HV test of the modules;

- Closing of the cooling circuit by connecting the two cooling rods;

- Cooling circuit leak test;

- Survey of the visible layers X1 and X2;

- Full electrical tests;

- Test of the height of the modules;

- Final insertion of the detector into container.

Those assembly steps are detailed below.

3.1 Components preparation

Before to start the actual assembly the various components have to be prepared. This was described in details in Section 2.

3.2 Mounting of the cover on the sliding set-up

We took the convention to orientate the cover on the sliding set-up so that the cooling pipe exit holes lie on left hand when one faces the set-up, as illustrated in Figure 20, left. The cover is maintained by a small pressure from a screw on each side. A piece of plastic was placed between the screw and the cover to protect the aluminum shield integrity, as can be seen in Figure 15.

With this convention, the type B (V-X2) cooling rod is behind the type A (X1-U) and thus has to be mounted first.

3.3 Adjustment of the detector box position

On the base plate of the sliding set-up, stops can be adjusted in order to maintain the box container at a precise location when the modules are slid down into the box container. The precise location of those stops had to be set before the assembly process of the detector box. The empty box container was placed on the base plate so that the cover, slided down, fited into it. When the box container was at the correct location, the stops were adjusted and screwed in place. The stop on the back of the box container and the stops on each side of the container were used. The stops on the front side of the box container would be in the way when manipulating the container, consequently they were removed and never used. For the side boxes, the position of the right-hand stop was set in order to have about $1\,\mathrm{cm}$ between the stop and the box wall. This precaution was needed because the distance between the edge of the module and the box inner wall is only $0.5\,\mathrm{mm}$ on this side. Thus, during the module insertion, one increased this distance for safety reasons. Once the stops were adjusted, the cover was moved up and the box was removed.

3.4 Mounting the first cooling rod (type B or V-X2)

The first cooling rod to be populated is a cooling rod of type B (supporting the V-X2 detection layers), because of the convention explained in Section 3.2.

The cooling rod was prepared as detailed in Section 2.3. A latest cleaning with alcohol was performed, specially for the surface that will be in contact with the modules. The cooling rod was fixed to the cooling rod station set-up (Figure 11, left).
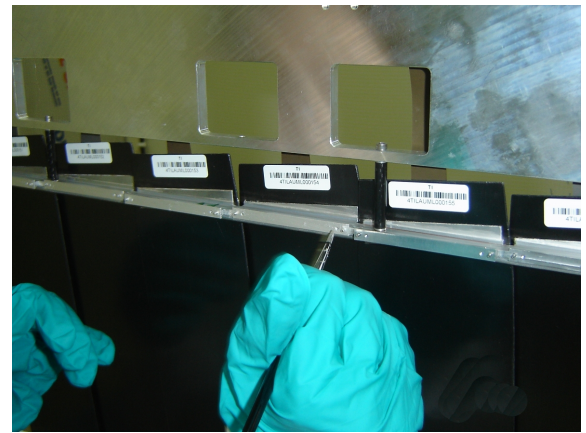
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Figure 16 The thermal and electric conductive grease (left) is spread on the cooling rod (right) where the modules are intended to be fixed.
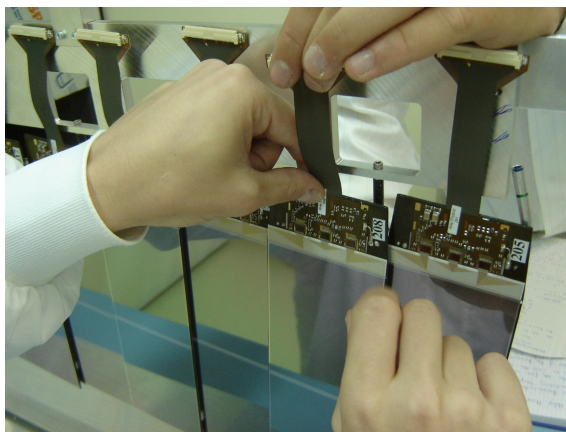

Figure 17 View of the fixing of the modules on the cooling rod, by starting with the backward modules and finishing with the forward modules.

To maximize the thermal transfer between the cooling rod and the back of the detector modules, a layer of thermally conductive grease was spread on the contact surfaces. The thermal grease used is Aremco Heat-Away 641-TEC, together with the Aremco Heat-Away 641-TEC-T thinner. This grease is electrically conductive, which is important in this use-case. The thinner allowed to control the viscosity of the grease, which had to be such that it could be spread effortless with a paintbrush. It was important not to use any force to spread it, due to the fragility of the modules. The grease was spread on the contact surfaces on each side of the cooling rod (Figure 16, right), as well as at the rear of each module on a line linking the two alignment holes (Figure 14).

The modules were placed starting with the ones located behind and then with the ones located afront (Figure 17). They were fixed with one M1.6×3 screw[e] at each side of the alignment pins (Figure 17, right). This had to be done with great care, in order not to damage the aluminum screw threads.

The bonds of each module were inspected with the help of a magnifying glass before and after the mounting procedure. Several damaged HV bonds were observed[f]. Usually, these could be pulled and replaced by new ones, as the HV bonds pads are quite large.

3.5   Fixation of the first cooling rod under the cover

The cooling rod, populated with modules, was handled carefully by a first person, who held it at both ends. This person had to control the pressure he applied on the aluminum tube, since he could crush

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[e]Since the screws are important in the grounding scheme they have to be electrically conductive rather than passivated.
[f]the HV bonds are the outermost bonds and as such are more likely to be damaged during module manipulations.

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it quite easily. The long pipe extremity was inserted into a hole in the cover. A second operator helped sliding the pipe through the cover without bending it, while the first operator moved up the cooling rod, taking care that it remained horizontal. While the first person held the cooling rod, the second person screwed it in place. This operation was delicate, since a falling screw could have severely damaged bonds or sensors.

3.6   Mounting of the second cooling rod

The procedure described in Sections 3.4 and 3.5 is repeated for the type A cooling rod. At the end of the step, the two cooling rods were fixed on their support.

Once the two cooling rods were screwed in place, the detector modules could be connected to the inside connectors on the cover. One had to check that the male connectors were fully inserted. The ground thread of each cooling rod was also connected to the cover, and the thread was secured to the vertical cooling pipe with a little band of Kapton tape. Bubble wrap was used to prevent the Kapton tails from touching one another, which is potentially a source of noise.

At this stage, we did not complete the cooling circuit. Closing/disconnecting the cooling circuit are delicate, accident-prone operations. Thus, to minimize the number of those operations, one performed an HV test, as described below, to detect and replace the possible faulty modules before to close the cooling circuit.

3.7   HV test of the modules

After the assembly of the cooling rods and their mounting on the cover plate (just before connecting the cooling rods together), a HV-test of the modules was performed. HV-problems were the most frequent disturbances during the module production and the HV-bond wires are the bonds closest to the edges of the modules and hence more prone to accidental damages. Therefore, we checked for HV-problems before the cooling rods were connected to each other, in case a module would have to be exchanged.For the HV-test, no cooling was necessary.

The test was done by inserting the assembly into a large aluminum test box, which provided light shielding for the modules. This box allowed for easy placement of the assembly without the insertion set-up needed for the real detector boxes where the box walls are much closer to the modules. Furthermore, this box has windows that can be opened to access to the readout hybrids which is helpful in tracing possible problems. The HV-connectors were then connected to the HV-modules as described in the full module test (Section 3.11). The modules were slowly ($\simeq 3\,\text{min}$) ramped to $500\,\text{V}$ and the test was passed if none of the modules showed signs of a breakdown.Typical leakage currents of the sensors were $200\,\text{nA}$ and $400\,\text{nA}$ for short and long modules, respectively. The leakage currents rarely exceeded $1.5\,\mu\text{A}$.

3.8   Closing of the cooling circuit by connecting the two cooling rods

Once the modules were HV tested and the faulty modules exchanged, the cooling circuit could be completed. The missing piece of the circuit is a steel tube bended in a U-shape. The use of steel was motivated by the observation that it was not possible to bend an aluminum tube to such a small radius without crushing it. For the same reason it was not possible to use plastic tube either.

It was difficult to insert the U-shaped tube into the Legris connectors, mainly because the ends of the cooling rods were usually not parallel to each other. A considerable strength was required but the cooling rods are fragile. To ease the process, the best way was to measure the distance between the connectors and to adjust the bend of the U-shaped tube accordingly. Using two screwdrivers, inserted into each end of the tube, and graping them as pliers, one could adjust the shape of the tube.

It was not straightforward to notice whether the U-shaped tube was inserted home in the Legris connectors or not. Thus, inserting a Legris connector in each end of the tube, one drew a line on the steel tube with a permanent marker.

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Even with the U-shaped tube adjusted, the closing of the cooling circuit was still the most delicate step of the box assembly. Two people had to slowly insert both ends of the tube simultaneously, and to push it until it reached the marker line on the tube, meaning it was home. During the operation, both cooling rod ends had to be held tightly to minimize the strain applied on them. Figure 18 shows the steel U-shaped piece in its final position.

Once the cooling circuit closed, the distance between the cooling rods was measured. If the measured distance was found smaller than the nominal one, one inserted a spacer cut at the right length in a carbon fiber rod. This spacer was secured in place with Kapton tape.
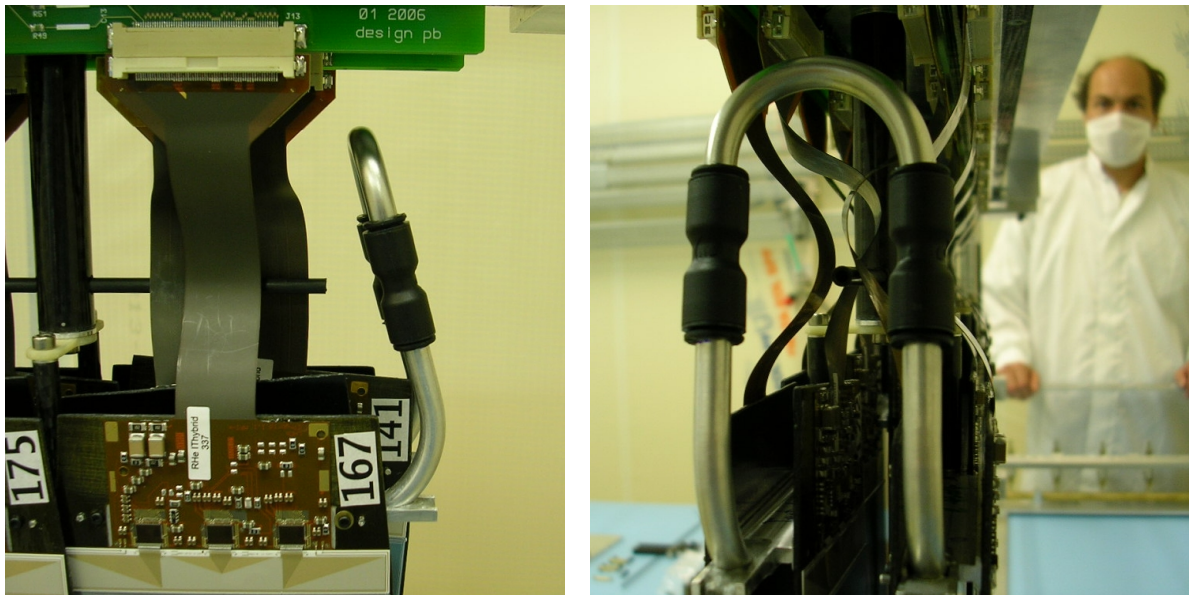

Figure 18 The cooling circuit is closed when one connects both cooling rods via the steel U-shaped tube.

3.9   Cooling circuit leak test

An electronic device was designed to read out a pressure probe[g] and to display the measured pressure. The test set-up consists of a bottle of argon (Ar), the pressure probe, a valve on one side, and a brass plug on the other side. The tests consists in putting the cooling circuit under pressure for some time and to record any pressure drop.

The Ar bottle, pressure probe and valve were connected to one end of the cooling circuit with a Legris connector and the air it contained was flushed away with some Ar. Then, the other end of the circuit was blocked with the brass plug via a Legris connector. This was secured with Kapton tape, preventing it from flying around in case the Legris connector was faulty. The circuit was pressurized up to about 5 bars, the valve was closed, isolating the cooling circuit, and the Ar bottle was disconnected.

To compute a leak rate, one took down the current pressure in the circuit, the temperature and pressure of the room, and the time. After about two days, the same physical quantities were measured again. These data allowed to compute the leak rate of C_6F_{14} in cubic centimeters per year. This computation and the conversion from Ar leak rate to C_6F_{14} leak rate was based on the method used for the ATLAS TRT and documented in [10].

If the leak rate was found to be higher than tolerated, which happened a few times, two actions were taken: the connectors of the pressure set-up were tightened, the set-up itself was retested and the four Legris connectors composing the cooling circuit were changed for new ones. Eventually, all the twelve detectors boxes were found to be OK. Once the cooling circuit was validated as leak free, it was possible to circulate coolant. It was then safe to power up the beetles and a full electric test is possible.

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[g]the pressure probe model is sensortechnics CTE9010AQ4, available at CERN store under SCEM 22.64.12.026.8

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3.10   Survey of the visible layers X1 and X2

The goal of the survey is to provide first estimates of the position of the sensors. No hardware correction can be performed to correct imperfect positioning, the alignment will be done by software using tracks. However, the more accurately the position of the modules is known the best is the result of the software alignment. Cross-shape fiducial marks engraved on each silicon sensor were surveyed by theodolite. Their coordinates were calculated with respect to targets located on the cover of the detector box, which are still visible once the box is close and installed in the LHCb cavern. The details of the survey procedure can be found in another LHCb note [2].

3.11   Full electrical tests

A full readout test of a cooling rod assembly with 28 ladders was carried out before the assembly was placed in the final detector box container. This was done in the large aluminum box used for the HV-test (Section 3.7) which provides an easy access to the hybrids. The readout system used for this test acted as a development bench of the PVSS control system for the ST[h] subdetectors. It used all the final parts of the detector readout [11]. It consisted of:

- Two IT Service Boxes, each containing a Control Board (CB) [12] and 16 (12)[i] Digitizer Boards (DB) [13]. These are the final Service Boxes as used in the experiment including the water cooling of the backplanes.

- Three A1511B High Voltage CAEN Power supplies modules [14], in a CAEN SY1527 crate [15], to provide the $500\,\mathrm{V}$ bias voltage to the sensors;

- One Wiener MARATON Low Voltage Power supply [16] to power the Service Boxes that distribute the power to the Control Boards, the Digitizer Boards and to the front-end chips on the detector modules;

- Four Tell1 boards [17] for the data collection and one ODIN board [18] for Clock and Timing and Fast Control (TFC) signals distribution;

- One optical splitter to dispatch the TFC signals from the ODIN to the Tell1 boards;

- An Ethernet switch to interconnect the Tell1 boards and the readout PC;

- A PC running a Gaudi job to read and analyze the data;

- N_2 supply to lower the humidity in the detector boxes and two water cooling circuits. The first circuit uses a reservoir of distilled water as cold source to absorb the heat released by the hybrids front-end electronics. This is connected to the box cooling circuit. The second, connected to a PC water cooling circuit, is used to cool the Service Boxes.

- A set of 28 data readout cables, the same cables as in the experiment with $3.3\,\mathrm{m}$ and $3.9\,\mathrm{m}$ length, connecting the readout hybrids to the Digitizers Boards.

The box was connected to the cooling circuit, the N_2 supply, the HV and the readout. The LV power to the Service Boxes, from which the readout hybrids on the modules receive their power was switched on and the power consumption was verified. Before switching on the power to the ladders, one had under normal circumstances $\simeq 0.3\,\mathrm{A}$ on channel 1 ($5.5\,\mathrm{V}$) and $\simeq 1.3\,\mathrm{A}$ on channel 2 ($7.5\,\mathrm{V}$). The low voltage power supply had to be switched on before the high voltage was applied to the sensors, as the grounding potential in the detector is given via the LV power supply. (This could not be done for the HV-test of Section 3.7, as in that case, the cooling circuit was not closed and hence the hybrids could not be cooled.)

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[h]The Silicon Tracker project regroups the Inner Tracker and the Turicensis Tracker subdetectors. In particular most of the read-out electronics is common.

[i]One detector box is read out by 2 service boxes, one containing 16 Digitizer Boards and a second one, only partially filled with 12 Digitizer Boards, giving a total of 28 Digitizer Boards, one for each ladder.

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Next the sensors were slowly ramped up to $500\,\mathrm{V}$ testing for leakage current and possible early break down. Afterwards the readout hybrids were powered and configured. The configuration was done via I2C which allowed to read the data back and check them against what had been programmed. The power consumption of the Service Boxes with powered hybrids was then also verified to be $\simeq 11\,\mathrm{A}$ ($9\,\mathrm{A}$) on channel 1 and $\simeq 8.5\,\mathrm{A}$ ($7\,\mathrm{A}$) on channel 2 for the service box with 16 (12) Digitizer Boards, respectively. Any significant deviation was an indication of a problem. We never had significant over currents, but smaller currents typically hinted to missing configuration of parts of the detector.

After configuration of the TELL1 readout boards and the ODIN readout supervisor, raw data was recorded for all ladders. Data was taken for both, with and without (pedestal) testpulse injection into the Beetle readout chip.

A typical problem observed was that channels belonging to individual Beetle readout ports[j] show very low noise and no testpulse signal. This was attributed to the hybrid-PCB connections in the box, as it usually disappeared after re-plugging. The most likely origin is bad soldering or cracks on the female connectors (on the PCBs, inside the box) as those connectors are delicate to solder, but the actual cracks were never really found. During the box test, all the observed "open ports" (typically 0 or 1 per box) vanished after re-plugging the cable. However, as this obviously doesn't repair any micro cracks, but only provides temporary connection. In the installed detector we observe 7 faulty ports, most likely due to this crack/soldering problem, among them some appear to be working "sometimes", just as expected.

During these tests, two ladders with high common mode noise were exchanged solving the problem of the noise, which had not been observed in the previous individual module test. In one case, it was due to a badly soldered ground wire on the hybrid, which was later fixed. One faulty interface PCB in the detector box cover was discovered as somehow causing a "delay" in the signal line as the channels of the readout of one ladder was shifted compared to all other ladders. Although it was not understood how this could be introduced, exchanging the cover solved the problem (while exchanging the ladder did not).

The four temperature probes (PT1000) inside the detector box (in addition to the probes on each hybrid) were read out and the temperature reading was checked. The same was done for the HMX2000 humidity sensors[k]. The operating temperature of the boxes was about $25°\,\mathrm{C}$, which was far outside the temperature range for which the humidity sensors were calibrated[l]. Therefore, the actual humidity output could not be reliably checked against other measurements, but we checked that the measurements reacted to increases in humidity and that the measured value was in a reasonable range (40–60 % R.H.).

3.12   Test of the height of the modules

With this operation, we checked whether the sensor modules fit in the box container, such that they do not touch the bottom of the container. For this, we measured the distance between the lower edge of the modules and the lip of the cover and compared this value with the depth measurement of the container to be used, as explained in Section 2.2. For the central boxes, the nominal space between the bottom edge of the modules and the bottom of the box container is $0.5\,\mathrm{mm}$. The motivation for such a tiny distance is to have the sensitive area as close to the beam pipe as possible. For side boxes, the space underneath the tip of the modules is not critical in term of acceptance and hence the space is much larger ($\approx 5\,\mathrm{mm}$). The minimal distance is found between the lateral edge of some modules and the container side wall facing the beam pipe which is only $0.5\,\mathrm{mm}$, for the same acceptance reason.

It was not straightforward to measure the distance from the bottom of the lip of the cover to the bottom tip of the module support, l_{eff}, as defined in Figure 19. The solution consists in the permanent installation, on the sliding set-up, of two pairs of stops, one pair for the central boxes and one for the side boxes. Those stops can be engaged or disengaged. When a pair of stops is engaged, the sliding

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[j]A readout port is a block of 32 consecutive channels. There are 4 ports per Beetle, and three Beetles per detector module. A detector box represents thus $28 \times 3 \times 4 = 336$ readout ports.

[k]http://www.hygrometrix.net

[l]Each humidity sensor is provided with an individual calibration data sheet by the company. For the readout we use per sensor a linear interpolation + offset to the calibration data giving the the measured sensor output voltage as a function of the temperature and the humidity.
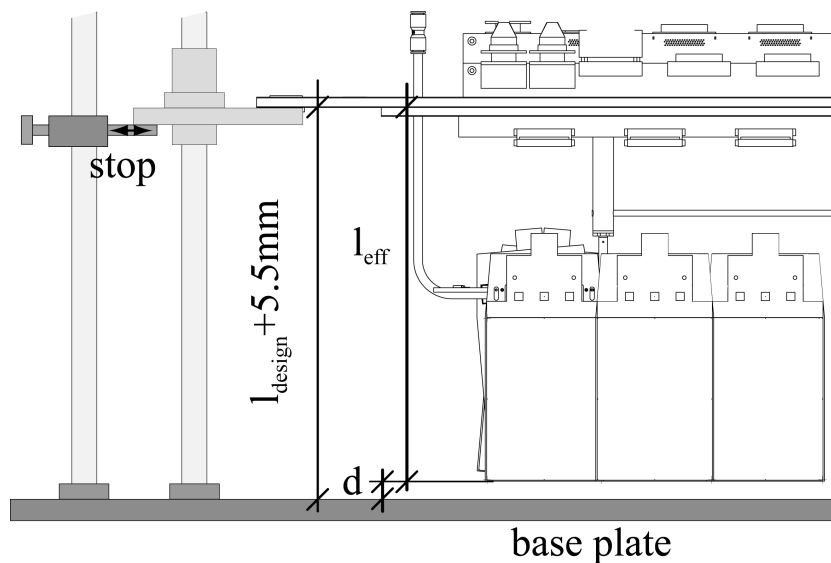
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Figure 19 Scheme of the different distance involved in the measurement of the distance between the cover and the tip of the sensor modules.

bar of the set-up can rest on it, as shown in Figure 15, and the cover-module ensemble is maintained. The stops are positioned so that, when the sliding bar rests on the stops, the distance between the tip of the module supports and the base plate is $5.5\,\mathrm{mm}$, nominally. This means that the bottom lip of the cover lies at $l_{\mathrm{design}} + 5.5\,\mathrm{mm}$ from the base plate. The positioning of the four stops was performed using an electrical height gauge[m] to control the distance to the base plate. Thus, by measuring this distance, we measured the deviation of the actual assembly from the nominal design. This distance, d, is measured using calibrated wedges and precision blades (Figure 20, right). The simple arithmetic of Equation 1 allows to get the effective distance l_{eff}.

$$l_{\mathrm{eff}} = l_{\mathrm{design}} + 5.5\,\mathrm{mm} - d \tag{1}$$

Conservatively, we considered the minimal depth measurement of the box container from which ones subtracted the maximal l_{eff} value to assess whether the modules fit into the box container.

If it was not the case, an appropriate number of glass fiber frames $0.2\,\mathrm{mm}$ thick were added between the cover and the top of the box container. To raise its upper lid is equivalent to increase the depth of the container. The eventual glass fiber frames were fixed using Kapton tape. A strip was centered on the frame and secured on the inside and outside wall of the container on each four sides of the container lid. The result of this operation was a flat lid, without any ripple, enhancing the air-tightness of the detector box. The Kapton covering the screw holes was removed with a lancet blade.

3.13   Final insertion of the detector into the container

The verticality of the box container and the height of the module have been checked before. The box container is placed under the cover according to the stops set on the base plate as mentioned in section 3.3. The detector box was then ready to be closed (Figure 21, right). The ensemble composed of the cover and the detector modules was slowly moved down into the container, actioning the vertical screw on top of the set-up. One person actioned the vertical screw while another person supervised the process. Critical moments were when the bottom of the modules, then the intersensor bonds (for side boxes), and then the sensor-hybrid bonds entered the container. The descent was not perfectly smooth and the modules could slightly shake. This was mainly due to the screw and was negligible at low descent speed. At each of these moments, the second person checked that the container was properly placed and that there was no danger of collision.

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[m]TESA Micro-Hite 600 Electric Height Gauge

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Figure 20   Resting on the dedicated stops, an assembly is ready for the test of the height of the sensor modules (left). On the right, one measures the distance, d, between the base plate and the bottom of the module supports, as shown on the drawing of Figure 19, using a calibrated wedge and precision blades.
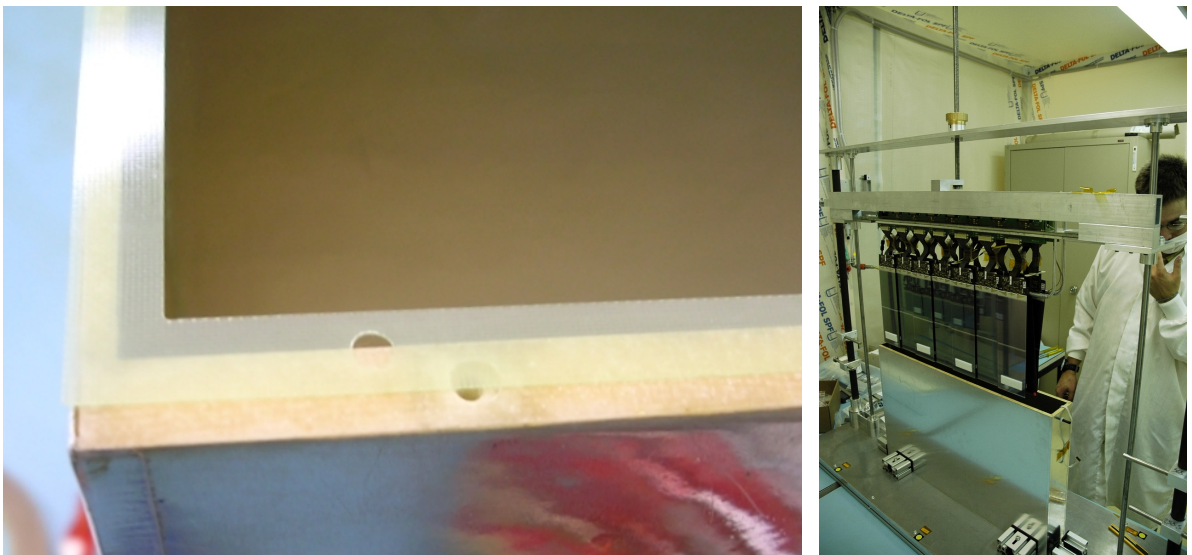

Figure 21   A glass frame used to adapt the depth of the container (left). The sliding set-up and a box being closed (right).

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For the side boxes, one of the lateral wall of the container was only at $0.5\,\mathrm{mm}$ from the edge of the modules. Thus, for the delicate insertion operation, one shifted the container laterally so that this distance was increased to a safe value of 1–$2\,\mathrm{cm}$.

A few centimeters before the completion of the insertion process, the temperature probes and the inner shield ground thread (Figure 4, left) had to be connected to one PCB. The bundle of wire was secured to one of the cooling pipe to prevent any constraint on the connector, which could lead to a disconnection.

A part of the cover has to enter in the container. So, just before the inside of the cover reached the lip of the container, one could readjust its position to allow a smooth entry of the cover in the container. With certain covers, this was not straightforward and one had to help by slightly opening further the container mouth. Particularly, for the side boxes, it was also time to shift the container back at its nominal position. This operation should be performed very carefully, because of the tiny distance from the wall to the modules.

Once the box was closed, and before the screws were inserted in their holes, a large band of Kapton tape was glued on the cover so that it covered the screw holes and so that a larger part was in the air, not glued to anything. Then, the screw holes were pierced in the Kapton and the cover was screwed to the container with 12 M2.5×20 plastic screws. When the screws were tightly screwed, the free part of the Kapton tape was glued to the container wall. In the process, the Kapton band also covers the foam section (Figure 3) of the cover. The motivation for the Kapton seal is to maximize the air tightness of the detector boxes. The air tightness is crucial to minimize the transfer of humidity to the inside of the box.

4   Conclusion

The assembly procedure for the 12 Inner Tracker detector boxes has been presented. This was done in the hall of the PH Department Silicon Facility in building 186, at CERN, in a "clean tent". The twelve boxes have been installed in LHCb pit. Their commissioning was described elsewhere [19].

5   Acknowledgments

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