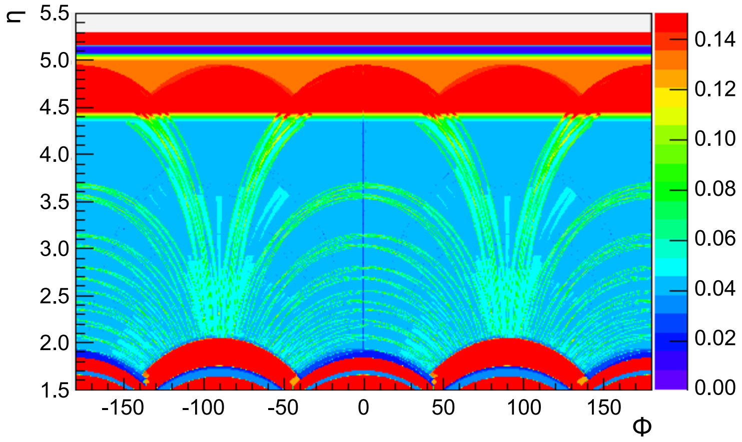

Figure 5.33: Radiation length of the TT as a function of the pseudorapidity η and the azimuthal angle ϕ.

Material budget

A careful analysis was performed of all materials that are located inside the acceptance of the experiment. Based on this analysis, a detailed description of all active detector elements and a simplified description of the passive components has been implemented [71, 72] in the XML based LHCb detector geometry description.

For the TT, where most of the dead material from detector supports, cooling etc. is located outside the acceptance, the material distribution is rather uniform. In total, it amounts to about 0.04 X_0, where more than 0.02 X_0 are due to the active material of the silicon sensors. An increase up to almost 0.13 X_0 is observed in the very forward region, due to the material of the insulation piece around the beampipe. The result of a material scan as a function of the azimuthal angle ϕ and the pseudorapidity η is shown in figure 5.33. The scan was performed by generating straight tracks originating from the nominal interaction point, extrapolating them through the TT station, and adding up the radiation lengths of all volumes in the geometry description that they crossed.

The material distribution for the IT is much less uniform, due to the readout hybrids, mechanical supports, cooling pipes and cables that are located inside the LHCb acceptance. In the active region of the detector, close to the beampipe, the material budget adds up to about 0.035 X_0 per station, out of which more than 0.015 X_0 are due to the active material of the silicon sensors. The material budget peaks at almost 0.30 X_0 in the very narrow region of the cooling rods. The result of a material scan for one IT station is shown in figure 5.34.

5.3 Outer Tracker

The LHCb Outer Tracker (OT) is a drift-time detector [73], for the tracking of charged particles and the measurement of their momentum over a large acceptance area. Excellent momentum resolution is necessary for a precise determination of the invariant mass of the reconstructed b-hadrons: a mass resolution of 10 MeV/c^2 for the decay $B_s^0 \rightarrow D_s^- \pi^+$ translates into a required momentum resolution of $\delta p/p \approx 0.4\%$. The reconstruction of high multiplicity B decays demands a high tracking

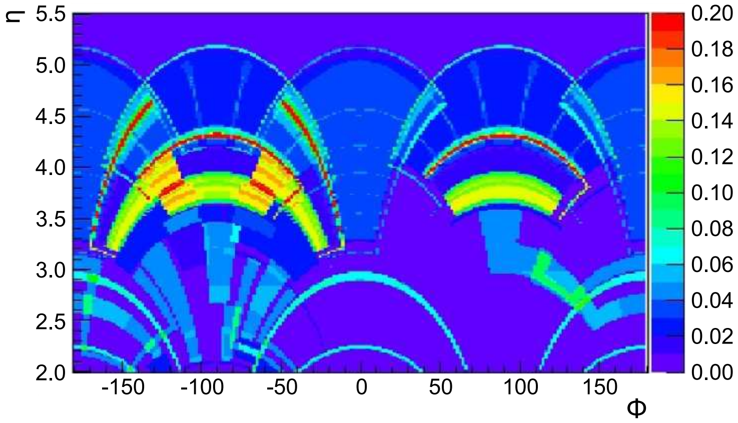

Figure 5.34: Radiation length of one IT station as a function of the pseudorapidity η and the azimuthal angle ϕ.

efficiency and at the same time a low fraction of wrongly reconstructed tracks: a track efficiency of 95% would result, for the decay $B_s^0 \to D_s^- \pi^+$, in an overall reconstruction efficiency of 80%.

5.3.1 Detector layout

The OT is designed as an array of individual, gas-tight straw-tube modules. Each module contains two staggered layers (monolayers) of drift-tubes with inner diameters of 4.9 mm. As a counting gas, a mixture of Argon (70%) and CO_2 (30%) is chosen in order to guarantee a fast drift time (below 50 ns), and a sufficient drift-coordinate resolution (200 μm). The gas purification, mixing and distribution system foresees the possibility of circulating a counting gas mixture of up to three components in a closed loop [74].

The detector modules are arranged in three stations (see figure 5.35). Each station consists of four layers, arranged in an *x*-*u*-*v*-*x* geometry: the modules in the *x*-layers are oriented vertically, whereas those in the *u* and *v* layers are tilted by $\pm\, 5^o$ with respect to the vertical, respectively. The total active area of a station is $5971 \times 4850\,\mathrm{mm}^2$. The outer boundary corresponds to an acceptance of 300 mrad in the magnet bending plane (horizontal) and 250 mrad in the non-bending plane (vertical). The inner cross-shaped boundary of the OT acceptance was determined by the requirement that occupancies should not exceed 10% at a luminosity of $2 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (this area is covered by the IT, see section 5.2.2).

The OT assembly is shown in figure 5.35. The detector modules are supported by aluminium structures. Each station is split into two halves, retractable on both sides of the beam line. Each half consists of two independently movable units of two half layers (C-frames). The modules are positionned on the C-frames by means of precision dowel pins. The C-frames also provide routing for all detector services (gas, low and high voltage, water cooling, data fibres, slow and fast control). The OT C-frames are sustained by a stainless steel structure (OT bridge), equipped with rails allowing the independent movement of all twelve C-frames.

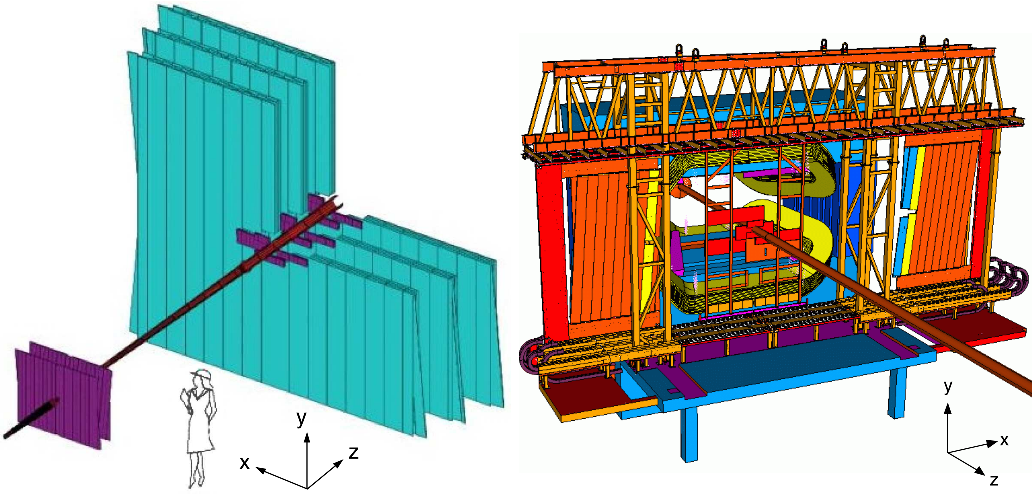

Figure 5.35: Arrangement of OT straw-tube modules in layers and stations (left) and overview of the OT bridge carrying the C-frames (right). The C-frames on both sides of the beam pipe are retracted.

5.3.2 Detector technology

Design

The design of the straw-tube module is based on the following requirements:

- Rigidity: the mechanical stability must guarantee the straw-tube position within a precision of 100 (500) μm in the x (z) direction; the anode wire has to be centered with respect to the straw tube within 50 μm over the entire straw length. The module box must be gas-tight and must withstand an overpressure of 10 mbar. The leak rate at this pressure has to be below 8×10^{-4} l/s.
- Material budget: to limit multiple scattering and the material in front of the calorimeters, the material introduced in the OT active area must not exceed few percent of a radiation length X_0 per station.
- Electrical shielding: the drift tubes must be properly shielded to avoid crosstalk and noise. Each straw must have a firm connection to the module ground. The module envelope itself must form a Faraday cage connected to the ground of the straw tubes and of the front-end electronics.
- Radiation hardness: the detector should withstand 10 years of operation at the nominal luminosity without a significant degradation of its performance. During that time the anode wires will accumulate a charge of up to 1 C/cm in the most irradiated area. As a consequence, all detector materials have to be radiation resistant and must have low outgassing.

The layout of the straw-tube modules is shown in figure 5.36. The modules are composed of two staggered layers (monolayers) of 64 drift tubes each. In the longest modules (type F) the monolayers are split longitudinally in the middle into two sections composed of individual straw

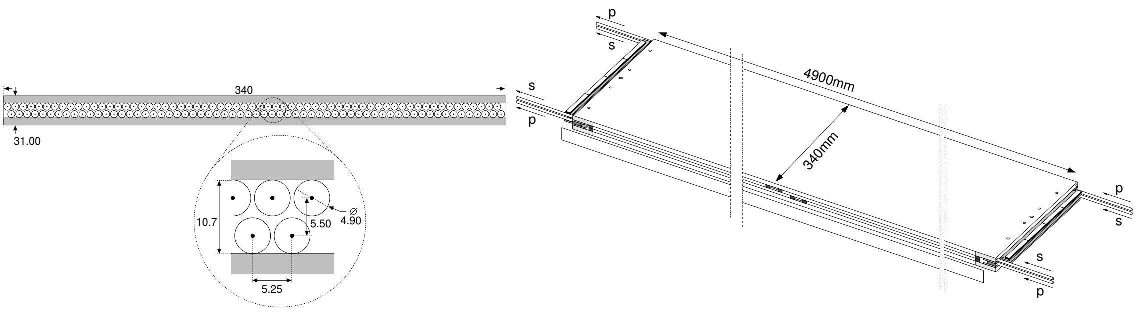

Figure 5.36: Cross section of a straw-tubes module (left) and overview of a straw-tubes module design (right).

tubes. Both sections are read out from the outer end. The splitting in two sections is done at a different position for the two monolayers to avoid insensitive regions in the middle of the module. F-modules have an active length of 4850 mm and contain a total of 256 straws. In addition to the F-type modules there exist short modules (type S) which are located above and below the beam pipe. These modules have about half the length of F-type modules, contain 128 single drift tubes, and are read out only from the outer module end. A layer half is built from 7 long and 4 short modules. The complete OT detector consists of 168 long and 96 short modules and comprises about 55000 single straw-tube channels.

Construction

The straw tubes are produced by winding together two strips of thin foils,[29] as shown in figure 5.37: the inner (cathode) foil is made of 40 μm carbon doped polyimide (Kapton-XC[30]); the outer foil (Kapton-aluminium) is a laminate[31] made of 25 μm polyimide, to enhance the straws gas tightness, and 12.5 μm aluminium, crucial to ensure fast signal transmission and good shielding.

To build a monolayer the straw-tubes were glued to panels with a cored sandwich structure consisting of a 10 mm Rohacell core and two 120 μm carbon fibre skins. High precision aluminium templates (figure 5.37) were used during the glueing to position the straw-tubes to better than 50 μm over the entire module length. After the straw-tubes were glued to the panel the wiring was started. A gold-plated tungsten wire[32] with a diameter of 25.4 μm is used for the anodes. The wire was sucked through the straw-tube. At each end the wire is guided using injection-molded Noryl endpieces. To centre the wire also along the straw-tube Noryl wire locators had been placed every 80 cm inside the straws. The wires were strung with a tension of 0.7 N and were soldered to 5 mm long pads of a printed circuit board.

Special holding-devices, shown in figure 5.38, were used to keep the support panels flat to within 100 μm during the glueing of the straws and wiring. They were also used to assemble two monolayer panels into a detector module (figure 5.38). The sides of the modules were closed by 400 μm thick carbon fibre sidewalls. Spacers at the two module ends ensure the proper separation

[29]Lamina Dieletrics Ltd., UK.
[30]DuPont^{TM}.
[31]GTS Flexible Materials Ltd., USA.
[32]California Fine Wire, USA.

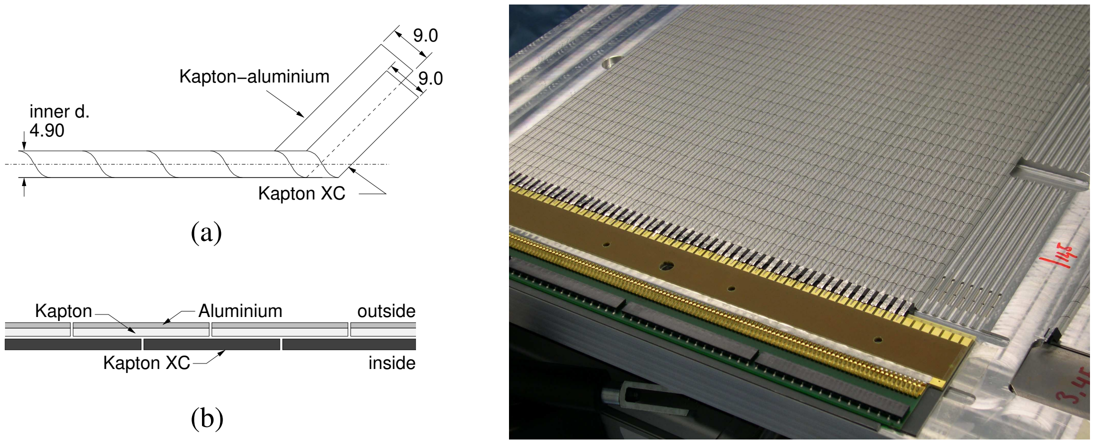

Figure 5.37: Left: (a) scheme of the straw winding using two foils; (b) Kapton-XC as inner foil and a Kapton-aluminium laminate as outer foil. Right: straws on the high precision aluminium template.

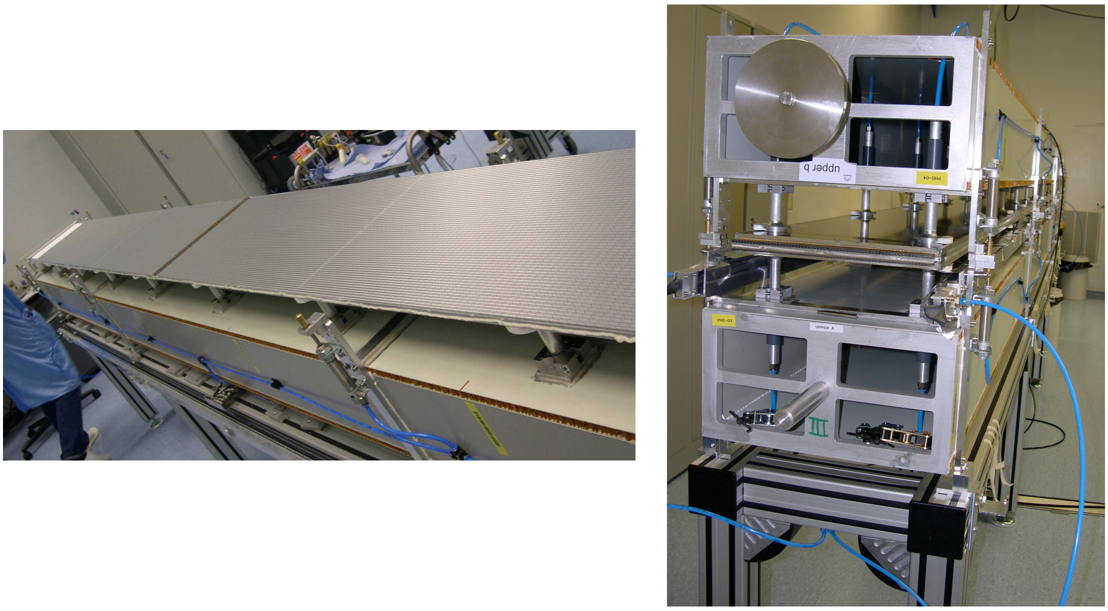

Figure 5.38: Left: straw-tube monolayer on a holding-device ready for gluing. Right: two straw-tube monolayers in a holding device while being glued to form a detector module.

of the two monolayers and provide an interface to the module gas pipes. All glueing steps were performed using Araldite AY103 in combination with the HY991 hardener. The glue viscosity was enhanced by adding silica gel.

The side walls and also the inner sides of the support panels are covered by the Kapton-aluminium laminate, which ensures the gas tightness of the module and provides a closed Faraday cage.

The construction of the detector modules was completed by three production sites in about two years. All detector parts were centrally checked and then distributed to the production sites. The production procedure and the quality monitoring steps and tools were the same in all produc-

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tion sites. Quality assurance included the check of the wire tension, pitch, and leakage current (in air) prior to the module sealing. Finished modules were tested for gas tightness. Using CO_2 as counting gas the modules were operated with a slowly increasing anode voltage to ensure that the leakage current per wire dropped below 1 nA for a voltage of 1700 V. Finally, the uniformity of the signal response of all drift cells was checked with a radioactive source.

Material budget

The forward geometry of the LHCb detector allows all detector services and supports of the OT to be located outside the detector acceptance. The OT material inside the LHCb acceptance (12 layers of modules) is estimated from the weights of the single components and the total amount of glue used (140 g per panel, 400 g to glue straw-tubes and to close the module) [75]. The total material of one station (four layers of modules, i.e. 8 monolayer panels) is on average equivalent to 3.2% of X_0. The total OT material sums up to 9.6% of X_0.

Ageing tests

In the region closest to the beam axis, the OT detector modules are foreseen to operate under particle rates per straw length of up 100 kHz/cm. Extensive ageing studies of test modules and of scaled-down prototypes showed that the detector technology is resistant to radiation doses corresponding to accumulated charges of up to 1.3 C/cm. No hints of a change of the gas amplificaton were seen in these studies which were performed with an average acceleration factor of a approximately 25.

However, irradiating mass production modules with low intensity β or γ sources with acceleration factors of O(1) produced a significant drop of the gas amplification. Most strikingly, this gain loss was not observed in the region of highest irradiation intensity (anode currents around 20 nA/cm) but at modest intensities and anode currents of 2–5 nA/cm [76]. The damage was only observed upstream (with respect to the gas flow) of the irradiating source. An analysis of the affected anode wires revealed a thin (less than 1 μm thick) insulating deposit. Although the exact mechanism is not yet understood, the glue (Araldite AY103) used to build the modules is identified as cause of the depositions. A number of preventive and remedial actions have been studied: long-term flushing of the detector modules with gas (CO_2) as well as warming-up the modules to 40^oC while being flushed, significantly reduce this effect. Large anode currents deliberately provoked by increasing the high voltage above the nominal operating voltage can be used to clean the anode wires, should the insulating deposits reduce the gain beyond an acceptable level.

5.3.3 Electronics

The front-end (FE) electronics measures the drift times of the ionization clusters produced by charged particles traversing the straw-tubes with respect to the beam crossing (BX) signal [77]. The drift times are digitized for every bunch crossing (25 ns) and stored in a digital pipeline to await the Level-0 decision. On a positive L0 decision, the digitized data of up to 3 bunch crossings (to cover a time range of up to 75 ns) is transmitted via optical links to the Level-1 buffer (TELL1)

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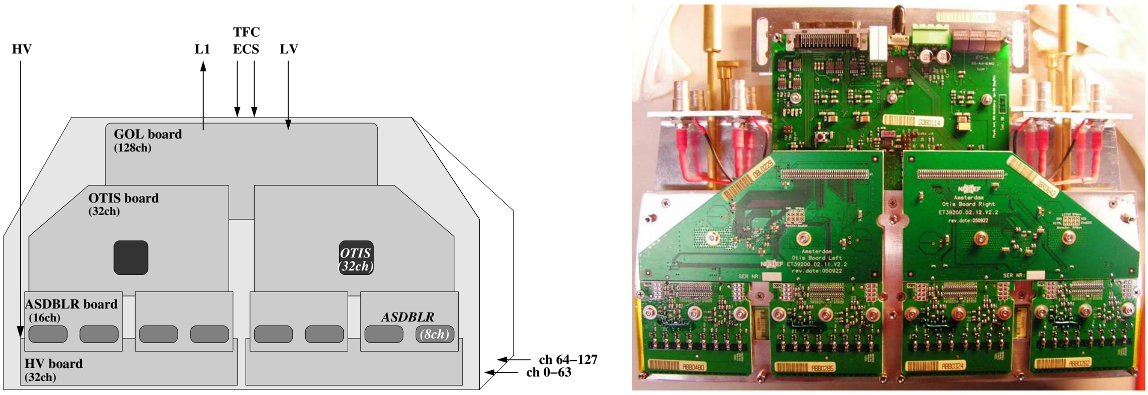

Figure 5.39: Design (left) and photograph (right) of the FE electronics mounted in a FE box. In the photograph the HV boards are not visible, because hidden by the ASDBLR boards.

boards. The radiation dose expected for the front-end electronics is only 10 kRad, well below the maximum tolerable dose of 2 Mrad.

As shown in figure 5.39, the FE electronics has a modular design, consisting of several interconnected boards housed inside a metallic box (FE box). These boxes are mounted at each end of the detector modules. A FE box is the smallest independent readout unit of the OT: the digitized data of the 128 channels of one module are sent via an optical link and received by the TELL1 board; high- and low-voltage, as well as fast- and slow-control signals are connected to each FE box individually. In total, 432 FE boxes are used to read out the OT detector.

The main components of the OT readout electronics are the High Voltage (HV) board, the ASDBLR board, the OTIS board, and the GOL auxiliary (GOL/AUX) board.

Four 32-channel HV boards plug directly into the signal feedthrough of each straw-tube module. The signal feedthrough is provided by a passive printed circuit board (PCB) built into the module end and defining the reference ground for the straw-tubes and readout electronics. The HV board has a single HV connection and is thus the smallest independent HV supply unit. Anode signals are decoupled using 300 pF capacitors[33] on the PCB.

Each ASDBLR board hosts two ASDBLR chips [78]. These are custom integrated circuits, providing the complete analog signal processing chain (amplification, shaping, baseline restoration, and discrimination) for straw sensors. The ASDBLR is implemented in bipolar technology and produced with the radiation hard DMILL process It includes eight identical channels per chip, with a peaking time of 7–8 ns, selectable shaping circuits and a three-state LVDS output. The Equivalent Noise Charge (ENC) at the ASDBLR input is about 2200 e^- + 140 e^-/pF, corresponding to a global ENC of about 0.9 fC when connected to the detector.

The hit outputs of two ASDBLR boards (32 channels) are connected to an OTIS board, which hosts one OTIS chip for drift time digitization. The OTIS ASIC is a radiation hard 32-channel Time-to-Digital Converter (TDC), developed specifically for the OT and manufactured in a standard 0.25 μm CMOS process [79, 80]. The OTIS block diagram is shown in figure 5.40. The TDC core measures the arrival time of the ASDBLR signals with respect to the LHC clock propagating through a 25 ns long Delay Locked Loop (DLL), a regulated chain of 32 double-staged

[33]JOHANSON 302R29W331KV4E.

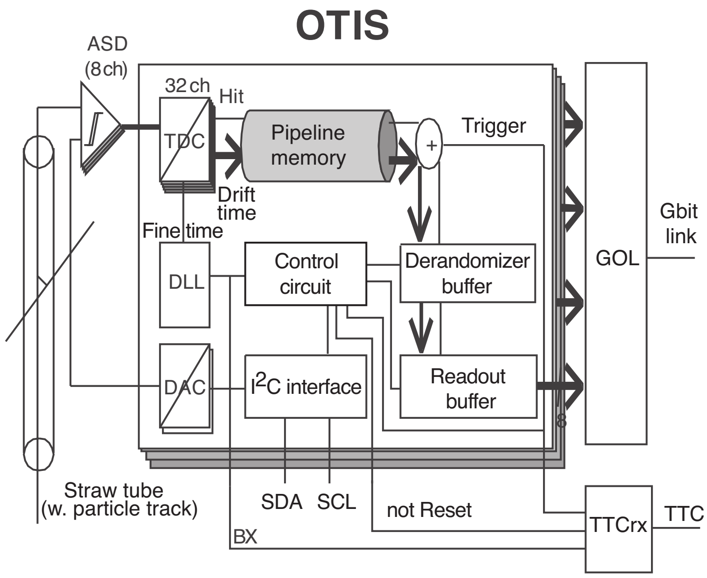

Figure 5.40: OTIS Block Diagram.

delay elements. The time digitization is done using the 64 delay-stages of the DLL (64 time bins) giving a theoretical bin size of 390 ps. The drift time data is stored in a pipeline memory with a depth of 164 events, allowing a L0 trigger latency of 160 clock cycles to compensate for trigger rate fluctuations. If a trigger occurs, the corresponding data words of up to 3 bunch crossings (the number of bunch crossings transferred is selectable) are transferred to a derandomizing buffer, able to store data from up to 16 consecutive triggers. Both, pipeline memory and derandomizing buffer are dual-ported SRAM memories. A control unit processes and reads out the data of each triggered event within 900 ns. The readout interface of the OTIS chip is 8-bit wide.

The data processing within the OTIS is clock driven. The chip operates synchronous to the 40 MHz LHC clock. A standard I^2C interface is used for setup and slow control.

The OTIS boards in a FE box are connected to one GOL/AUX board. This board [81] provides the outside connections to the FE box: the power connection, the interface to the fast-control (BX clock, triggers, resets) and the interface to the slow-control (I^2C). Three power regulators supply the different voltages (+2.5 V $\pm$3.0 V) needed by the OTIS and the ASDBLR chips. The GOL/AUX board hosts the GOL optical serializer chip [6] connected to an optical receiver mezzanine card on the TELL1 board.

As the data volume of the OT is large compared to other sub-detectors only the optical links of the nine FE boxes belonging to a layer quadrant are connected to a single TELL1 board. To read out the 432 FE boxes of the OT 48 TELL1 boards are used.

Cooling

As the FE box is entirely closed, cooling of the electronic components inside the boxes is necessary. All electronic boards are therefore mounted on a cooling frame (see figure 5.39) which is screwed to water-cooled plates on the C-frames.

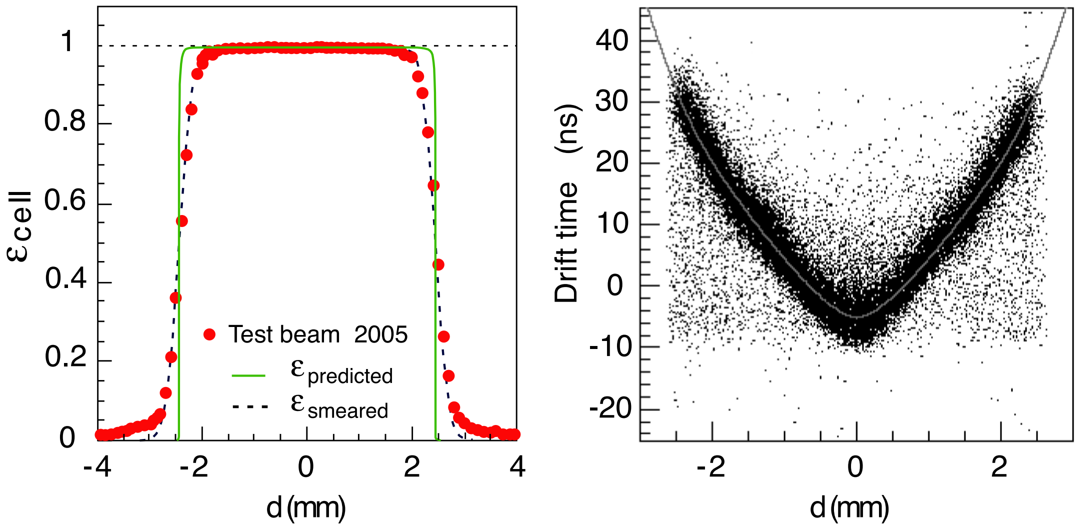

Figure 5.41: Left: hit efficiency as a function of the distance to the anode wire. Right: relation between the drift time and the calculated hit distance to the wire. Note the maximum drift time of approximately 45 ns.

High-voltage system

Each FE box has four independent HV connections, one for each 32-channels HV board. Two CAEN SY1527LC mainframes, each equipped with four 28-channels A1833BPLC supply boards, are used as HV supply. Using an 8-to-1 distribution scheme the 1680 HV connections of the detector are mapped on 210 CAEN HV channels. The distribution is realized using a patch panel wich offers the possibility to disconnect individual HV boards (32 channels) by means of an HV jumper. Both components, the HV supply as well as the patch panel are located in the counting house. Access to the HV system during data taking is therefore possible.

5.3.4 Test Beam results

To determine the performance of the detector modules in combination with the readout electronics, 4 short modules from the mass production equipped with FE boxes were tested at the 6 GeV electron beam of the DESY II facility in Hamburg [82]. Although the number of OT modules (4 modules, or 8 monolayers) was sufficient to allow full track reconstruction, a silicon strip telescope was used to provide redundant information for the determination of the coordinates at which the beam particle traverses the detector. The trigger signal (which was also used offline as a time reference) was generated by a coincidence of two scintillator counters installed downstream of the OT modules. The nominal counting gas mixture Ar/CO_2 was used.

The electron beam illuminated up to 7 straws per monolayer. In the offline analysis, the relation between the measured drift time and the distance to the wire (R-t relation, see figure 5.41) was established using the predicted distance of closest approach of the particle to the anode wire. The R-t relation was then used to convert measured drift times to coordinates. The hit finding efficiency, shown as a function of the distance to the wire in figure 5.41, is determined by verifying

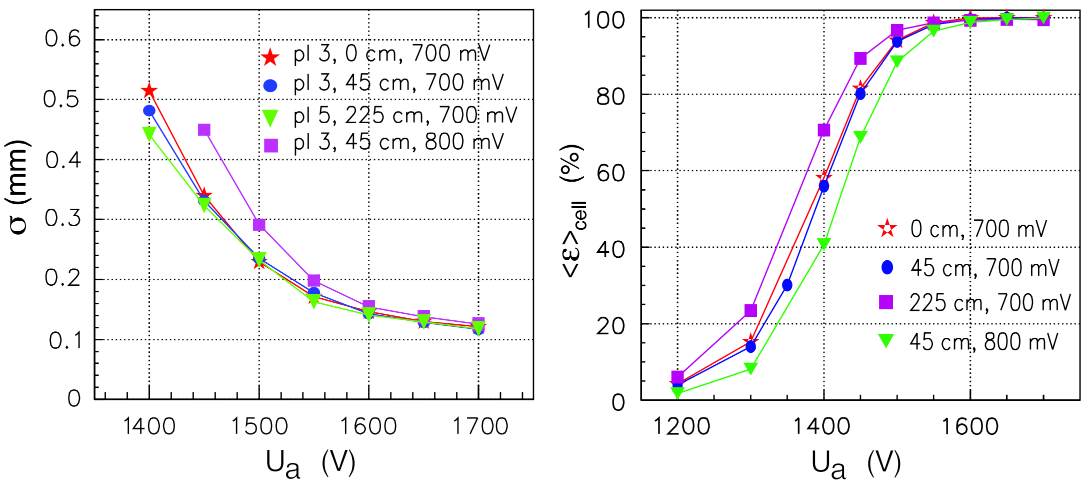

Figure 5.42: Performance of the straw-tube module: the position resolution (left) and the average efficiency (right) of a single cell are shown as a function of the HV value. The different curves correspond to different discriminator threshold voltages, and different distances between the electron beam spot and the front-end electronics.

whether the OT produced a hit at the predicted position. The position resolution is determined by comparing the measured hit coordinates to the predicted ones (residual) and by fitting a single gaussian to the distribution.

The performance of the OT straw-tube modules is determined for HV values ranging between 1200 and 1700 V, and for ASDBLR discriminator thresholds ranging from 1.5 fC to 5.5 fC. As shown in figure 5.42, efficiencies larger than 99% in the centre of the straw (dropping at the edge of the straw) and position resolutions of single cells below 200 μm can be attained for high voltage values above 1550 V. The noise level was found to be low: at a high voltage of 1550 V and a discriminator threshold voltage of 800 mV (corresponding to a signal threshold of 4 fC), the noise rate is below 1 kHz per channel. This corresponds to an average channel occupancy of $\left(7.5 \times 10^{-3}\right)$%. The probability to find a coherent hit in neighbouring channels (crosstalk) is found to be lower than 5% for high voltage values below 1600 V and discriminator threshold voltages above 800 mV (4 fC).

5.3.5 Alignment and monitoring

Errors in the mechanical alignment of the drift tubes can significantly degrade the track reconstruction. A single cell resolution of about 200 μm requires that the drift tubes be aligned within an accuracy of 100 μm (1 mm) in the x (z) coordinate. Therefore, care was taken during each step of the detector construction and installation to minimize alignment errors. The issue of the mechanical tolerances in the module production has been discussed in section 5.3.2. All detector C-frames which hold the modules were built with stringent requirements on the mechanical tolerances [83, 84]. During installation the positions of all modules were surveyed and the C-frames positions have been adjusted accordingly.

The reproducibility of the C-frames positioning after movement was checked to be better than the 200 μm precision of the optical survey.

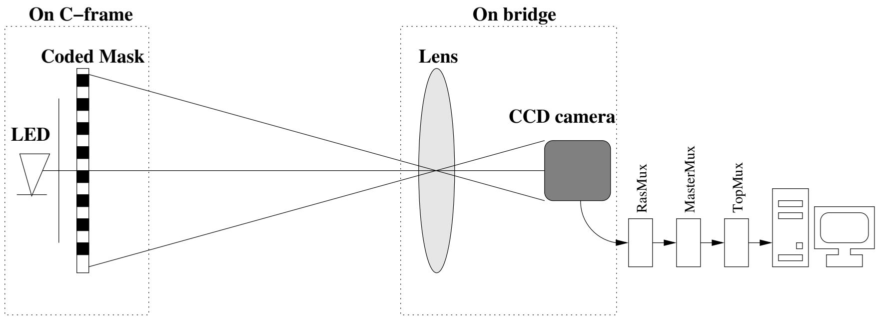

Figure 5.43: Schematic of the RASNIK alignment system.

The stability of the C-frames relative position during data taking is monitored by means of the RASNIK system [85], whose basic idea is to project the image of a detailed pattern through a lens onto a CCD camera (figure 5.43). Movements perpendicular to the optical axis are observed as change of the pattern position processed by the CCD camera, whereas movements along the axis are measured by the change in the image size. A total of 50 RASNIK lines are used for the OT monitoring. The intrinsic resolution of the system perpendicular (parallel) to the beam axis is better than 10 (150) μm respectively [86].