

A Central Rapidity Straw Tracker and Measurements on Cryogenic Components for the Large Hadron Collider

Thesis for the degree of Doctor of Philosophy in Physics

by

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1. Preface

This thesis describes the work performed on the Large Hadron Collider project (LHC). It contains two parts, the first of which is the more recent and deals with the Transition Radiation Tracker (TRT), one of the sub-detectors in ATLAS. The second part deals with the accelerator and in particular thermal measurements on cryogenic components for the superconducting magnets in the LHC.

After an introduction to the LHC project in Chapter 2 and a general description of the ATLAS detector in Chapter 3, the work on the TRT is discussed in detail in Chapter 4. It consisted of the development of a Transition Radiation Tracker (TRT) for the inner detector in ATLAS. The work focused on the design of the barrel TRT, which resulted in the construction and operating of the first barrel-module prototype in August 1996. Numerous studies were carried out to find an optimal solution for the detector layout, e.g. tracking optimization, thermal and mechanical calculations. After the construction of the first 0.5 m prototype, a series of tests were carried out including measurements in the test beam. This work is part of the ATLAS inner detector design report, currently undergoing extensive referee review as a step towards the construction approval of the ATLAS experiment. It was carried out in close collaboration with the Technical Assistance group TA1 at CERN.

Chapter 5 deals with my work on the cryogenics, which is a vital part of the accelerator itself as it will keep the superconducting magnets cold. These superconducting magnets will operate at a maximum temperature of 1.9 K in a bath of superfluid helium. This requires careful design with regard to the thermal insulation properties of components in physical connection with both the cold mass and the outside world as the heat load on the LHC cryogenic system is very much dependent on the heat inleak through these components. In order to evaluate the full system, the thermal behaviour of individual components is necessary. For this reason, two measuring benches were built to test two different types of cryogenic components: support posts and quench relief valves for the magnets. Precise measuring techniques had to be developed, able to detect very small heat flows. The work on the first measuring bench was presented at the fourteenth International Cryogenic Engineering Conference (ICEC) in 1991 (Paper I). In Paper II, the thermal evaluation of different support posts was presented. A second measuring bench was built, dedicated to investigating the thermal behaviour of a quench relief valve. The results are presented in Paper III. I was the editor of Papers II and III.

This work has been carried out within a team of many other people. It is often difficult to distinguish one's own contribution from those of others. The different areas which are based on my work or where I think I have made significant contributions are:

In Chapter 4:

- Straw and module layout in the barrel TRT.
- Overall design of the barrel, including connectivity and alignment principles for the straws.
- Tracking studies for the barrel and the optimization of the straw layout.
- Detailed material-budget calculations following the design.
- Cross-talk measurement on the 0.5 m barrel prototype.
- Thermal calculations and the design and experimental verification of the cooling principle for the barrel modules.
- Analysis of the test-beam data and estimation of the TR performance for the barrel TRT.

In Chapter 5:

- Design and development of the heatmeters.
- Design, construction and operation of the data acquisition system.
- Calibration and validation of the measurement methods by cross-checking with other measuring principles such as classical boil-off methods.
- Thermal evaluation of various support-posts.
- Design of the measuring system for the second measuring bench for the quench relief valve.
- Analysis of the test data for the quench relief valve.

2. The LHC project

The Large Hadron Collider (LHC) will be the first high-energy project where the quark and gluon constituents of protons collide in the TeV range. Two proton-proton detectors, ATLAS and CMS, will be built to collect data from these collisions. It will penetrate even further into the structure of matter and will recreate the conditions in the early universe just 10^{-12} s after the Big Bang, when it is expected that the temperature was 10^{16} °K. Our present understanding of the forces in nature at short distances are summarized in the Standard Model. Both the weak and strong interactions are of short range, i.e. less than $\sim 10^{-13}$ cm. The third force, the electromagnetic interaction, has a much longer range and is responsible for the bound states in atoms and molecules. In this picture there are three types of particles: leptons*, quarks and gauge bosons. All three types of particles are assumed to be fundamental, i.e. they have no inner structure and are pointlike.

Fundamental questions like why there seems to be a predominance of matter over antimatter in our universe or the origin of mass are not yet fully understood. These and perhaps other new questions will be addressed at LHC. In particular, the Standard Model predicts that vacuum is filled with a Higgs field and that the Higgs boson is the interaction particle. According to our Standard Model, it should be visible at LHC. Before going into detail, there are some questions in experimental high-energy physics that deserves answers.

- Why high energies?
- Why collider?
- Why high luminosity?
- Why such big experiments?

To probe deep into the structure of matter one needs a good microscope. The wavelength of the probe will determine the smallest object we can see. The smaller the object, the shorter the wavelength has to be. When the particle energy increases the wavelength becomes smaller, which is why we always need higher energies to see even deeper inside matter. At LHC, the wavelength is of the order 10^{-17} cm. A normal optical microscope has a wavelength of the order 10^{-5} cm and can be used to see down to the bacteria level. This is the first reason why we need high energies.

From Einstein's famous formula $E = mc^2$, we know that energy and mass are interchangeable. When particles like the protons in LHC collide head-on at high energies, new particles may emerge. The higher the energy the heavier the particles that can be produced. The Higgs boson is an example of such a heavy particle which

* Words marked with an asterisk appear in the glossary on page 123.

has not been found experimentally yet. It is expected that the LHC will cover a big part of the possible mass range of the Higgs boson. This is the second reason why we need high energies: heavier particles mean higher energy.

When one particle is at rest (fixed target), a large fraction of the energy is used to conserve the momentum, which has to be the same before and after the collision. When particles with equal and opposite momenta collide head-on, the total momentum is zero and the interaction energy is the sum of the two incoming energies. The collider therefore offers higher available interaction energy for the same beam energy. Unfortunately the probability of elementary processes falls with increasing mass or momentum transfer. The rate of *interesting* events such as

$$\text{Higgs} \rightarrow 2Z \rightarrow 4\mu$$

at LHC is therefore very low. To obtain detectable rates, the rate of interaction or luminosity must be increased to the limit of what is possible for both the machine and the detectors.

LHC will collide protons with protons (not protons with antiprotons) to achieve the required higher luminosity. A double beam chamber is required as the field has to be opposite for the two beams. Antiprotons have been used in the Super Proton Synchrotron (SPS) at CERN before, but the probed mass scale was lower (of the order 100 GeV) and therefore the required luminosity. The problem with antiprotons is that they are difficult to produce in great quantities. It takes 300 000 protons to obtain one antiproton!

Given the existing LEP (Large Electron Positron collider) tunnel geometry, the only way to obtain the very high guiding field required in LHC is by using superconducting magnets and at superfluid-helium temperatures, i.e. 1.9 K.

2.1 The experiments

The particle physics detector consists of several sub-detectors, each designed for a specific task. The electromagnetic calorimeter measures the energy of photons and electrons and the hadronic calorimeter measures the energy of strongly interacting particles. To be able to measure precisely the energy of the particles, the detector has to contain the full shower in the calorimeter volume. The higher the energy the more material is necessary, therefore the detector becomes bigger with increasing energy.

In addition, the detector needs to measure the momentum of the charged particles and this is done by measuring the curvature in a magnetic field. The energy of the muons is also measured through their momentum as they traverse all detector layers including the calorimeter. The higher the momentum the bigger the bending radius of the particle and, therefore, the longer the required particle path to achieve the required precision. This results in a very large detector: the muon spectrometer, for example, dominates the overall dimensions of the ATLAS detector [1].

The physics in the LHC project will be explored by two proton-proton detectors: ATLAS and CMS. In addition there will be one experiment, ALICE, which will collect data from heavy-ion collisions. As a complement to the capabilities of the LHC's big detectors ATLAS and CMS to look for CP violation in B-meson decays, one dedicated experiment, called LHC-B, is being studied.

In LHC, the proton beams will collide every 25 ns. They will hit the different detector elements in the detector at very high rates. The time between the collision of two successive bunches is 25 ns, which means there will be events from three bunch crossings in the detector at the same time! This arises from the fact that 25 ns represents a distance of 7.5 m at the speed of light and the detector is ~ 40 m long. In each collision there will be in mean 23 inelastic proton-proton collisions. Clearly this puts very high accuracy requirements on the timing between the different detector parts. In addition the rates at which particles traverse many of the detector elements are very high and the detector occupancy is a limiting factor in LHC. When a detector element is hit by a charged particle it takes a certain time to develop a signal which can be recorded and read out before the next particle arrives. For the TRT barrel straws the average occupancy is 20% and it takes ~ 45 ns to register a hit and be ready for the next. The read out situation for the TRT is explained in more detail in Chapter 4.

2.2 The accelerator

The LHC machine will be situated in the 27-km-long LEP tunnel [2, 3]. Figure 2-1 shows a schematic layout of the LHC injection scheme. The two proton beams, each with an energy of 7 TeV, will circulate in opposite directions and guided by a 8.4 T field generated by superconducting magnets. Proton-proton colliders require two separate beam channels with opposite fields of equal strength. As mentioned above, the interesting interactions occur at a very low frequency. To produce detectable rates of interesting events there is a need for high luminosity: the nominal LHC luminosity is $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Luminosity is a measure of the interaction rate per unit area and is used to define the performance of the collider. The most important luminosity limitations come from the beam-beam effects. Beam-beam effect is a common name for perturbations that the beams impose on each other in a collider. There is the unavoidable head-on interaction of the colliding beams at the interaction points and there is also the long-range interaction which occurs in the common stretch of the beam on either side of the interaction regions. Here both beams run side by side in the same pipe. The bunch spacing will be 25 ns, resulting in a total of 2835 possible bunches. In order to prevent them from colliding in many places outside the interaction regions, the beams collide at a small angle.

CERN has always used existing accelerator installations as injectors for the new machine and LHC is no exception. Some modification has to be done to the RF systems in the injection chain to be able to match the 25 ns bunch spacing.

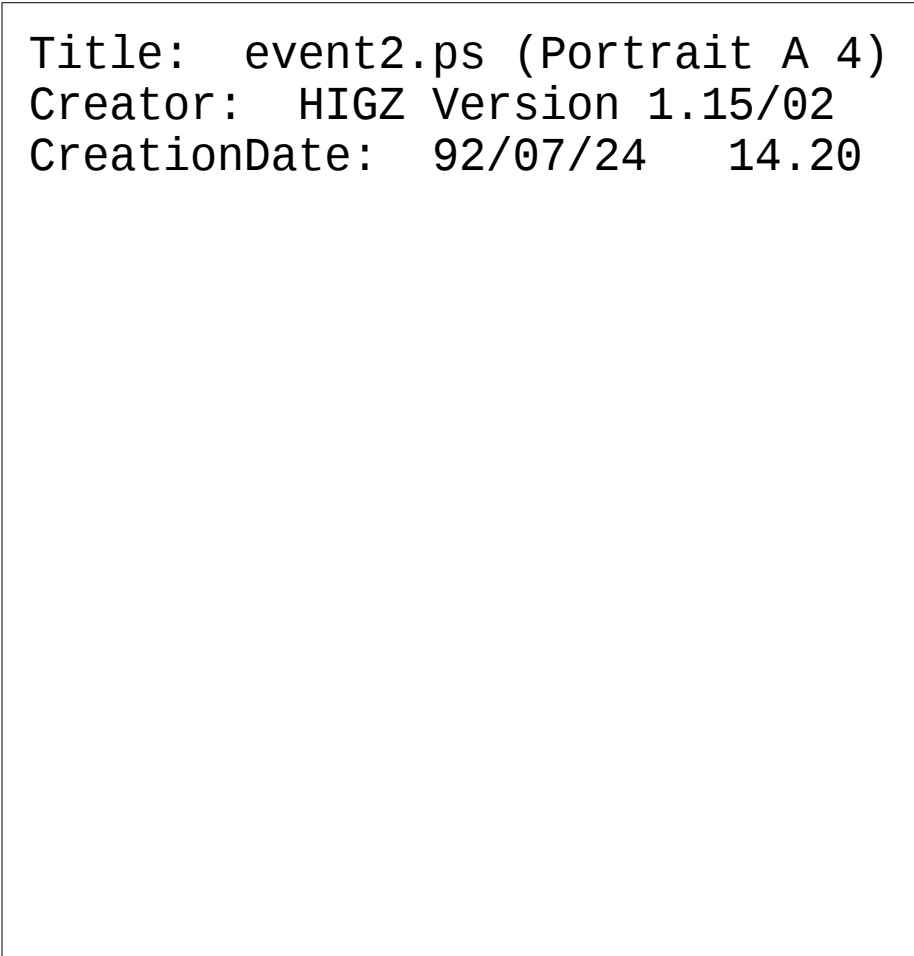
Figure 2-1: Schematic layout of the CERN accelerator complex showing the filling scheme of the LHC.

2.3 References

1. ATLAS Technical Proposal, LHCC/94-43 (1994).
2. The LHC Study Group, The Large Hadron Collider - Conceptual design, CERN/AC/95-05 (1995).
3. The Large Hadron Collider accelerator project, LHC CERN AC/93-03 (1993).

3. ATLAS

At present, all experimental observations in particle physics are consistent with the Standard Model, in which the strong interaction is mediated by gluons and the electroweak interaction by photons and Z and W bosons. But the Standard Model leaves many questions to be confirmed experimentally, for example the origin of mass. This is one of the major questions to be answered in future particle physics experiments. Therefore, one of the most crucial design criteria for the ATLAS detector is to cover the largest possible Higgs mass range. Figure 3-1 shows a simulated decay of $H \rightarrow 4\mu$.



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Figure 3-1: Simulation of a Higgs decay to four muons in the ATLAS detector.

For the Standard-Model Higgs, the detector has to be sensitive to the following processes (l = electron or muon, H = Higgs):

- $H \rightarrow b\bar{b}$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^* \rightarrow 4\ell^\pm$
- $H \rightarrow ZZ \rightarrow 4\ell^\pm, 2\ell^\pm 2\nu$
- $H \rightarrow WW, ZZ \rightarrow \ell^\pm \nu 2\text{jets}, 2\ell^\pm 2\text{jets}$

Figure 3-2 shows the discovery potential for the different decay channels indicated above.

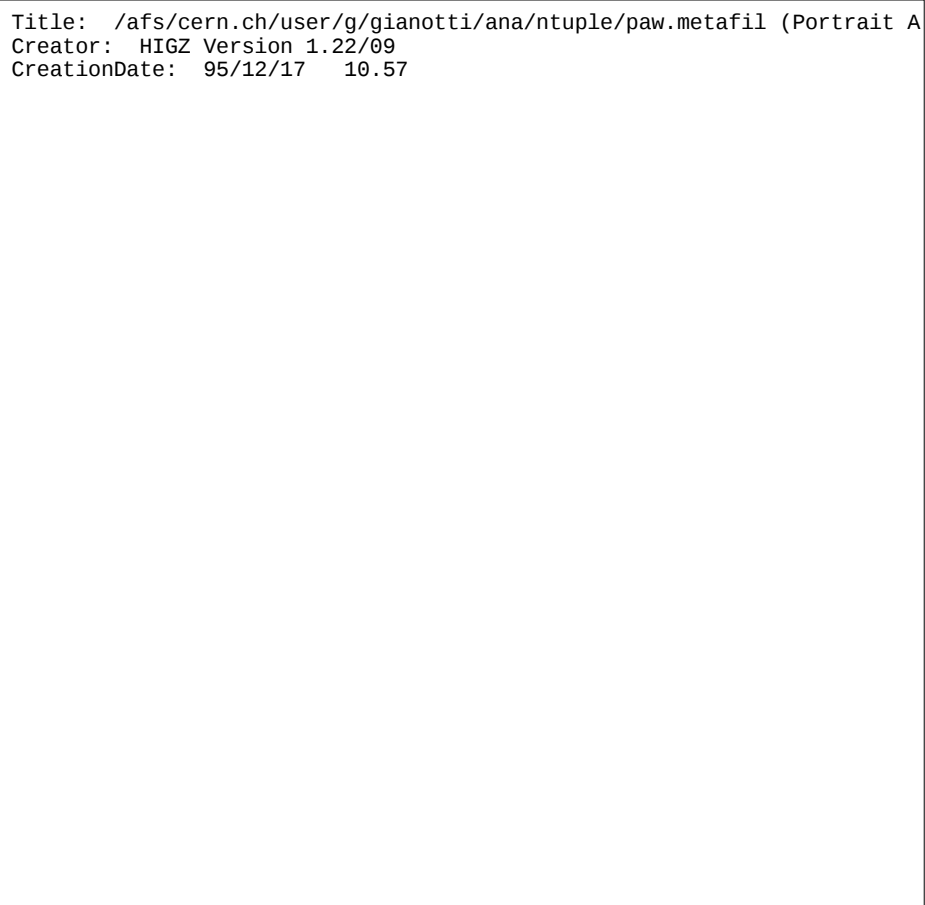


Figure 3-2: Expected significance in ATLAS of the Standard Model Higgs boson signal, as a function of the Higgs mass, for an integrated luminosity of 10^5 pb^{-1} and for several decay channels (from Ref. [1]).

LHC will also allow searches for new phenomena like supersymmetric particles. In addition important physics is expected in the heavy-quark systems. As mentioned above, one of the key questions today is why there seems to be an imbalance

between matter and antimatter in the universe. The observed small CP violation in the neutral kaon system gives a small asymmetry between matter and antimatter. The Standard Model describes this effect and predicts a stronger effect with the neutral B-mesons. This will be measured by ATLAS and the TRT is a main instrument for this measurement, both for the K_s^0 reconstruction and the pion rejection for the J/ψ reconstruction. This is explained in more detail in Chapter 4. The requirements for the ATLAS detector can be summarized as:

- very good electromagnetic calorimetry for electron and photon identification and measurements, complemented by hermetic jet and missing E_T -calorimetry.
- efficient tracking at high luminosity for momentum measurements, for b-quark tagging, and for enhanced electron and photon identification, as well as tau and heavy-flavour vertexing and reconstruction capability of some B-decay final states at lower luminosity.
- stand-alone, high-precision, muon-momentum measurements up to the highest luminosity, and very low p_T^* -trigger capability at lower luminosity.

The detectors at LHC will work in very extreme conditions. At high luminosity there can be up to 10^9 events per second. Most of these will produce uninteresting particles. But sometimes there will be an interesting event like the Higgs decay shown above.

The challenge here is to find these rare decays and eliminate this huge background as fast as possible with what is called a ‘trigger’. It is like looking for a ‘needle in a haystack’. ATLAS has a hierarchical trigger system and also some dedicated detectors for this task (see Section 3.1.5).

The layout of the detector is shown in Figure 3-3 [2]. Each detector focuses on a specific task, e.g. the tracker determines the trajectory of charged particles and the hadronic and the electromagnetic calorimeters measure the energy of the particles. ATLAS will be 20 m high, 44 m long and weigh ~ 6000 tons.

Today ATLAS incorporates about 1700 physicists and engineers from 140 institutes.

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Figure 3-3: The ATLAS detector. The detector is 42 m long with a radius of 11 m.

3.1.1 The magnet system

For a general purpose detector like ATLAS it is essential to measure the momenta of the charged particles. The ATLAS magnet system consists of a central solenoid and a large outer toroid. Charged particles with $p_T > 0.5$ GeV are measured in the solenoid field and muons with $p_T > 3$ GeV are measured in the toroidal field. Only the muons are measured in the toroidal field as they are the only particles to penetrate the hadron calorimeter (except neutrinos). Toroids have the advantage that they produce a field close to perpendicular to the particle trajectory at all h^* for both end-cap and barrel, and in addition, the open structure of the toroidal magnet minimizes multiple scattering. High accuracy is very important in the search for Higgs-boson decay to four leptons for $m_h < 2 m_z$ (see the dip in Figure 3-2) and this is achieved with this toroidal field in combination with instrumentation outside the

calorimeter system. The size of the field volume, the moderately large bending power, the open structure and the demanding spatial resolution in the planes of the muon chambers yield momentum resolution of 2% for a transverse momentum of 100 GeV.

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Figure 3-4: Longitudinal view of a quadrant of the inner detector and calorimeter.

The solenoid, which is placed inside the vacuum vessel of the electromagnetic calorimeter to minimize the degradation of the calorimeter performance, produces a 2 T field parallel to the beam axis. The momentum resolution varies from $\sim 22\%$ in the barrel region to $\sim 70\%$ at $|h| = 2.5$ for muons with $p_T = 500$ GeV. The reason for this poorer resolution is that the solenoid only reaches to about $h = 1.8$ and in addition, there is reduced radial track length (see Figure 3-4). The length of the solenoid is determined by the calorimeter performance, which is degraded by the material in front of it. One could imagine a big solenoid outside the calorimeter as in CMS. This would take care of the problem of the material in front of the calorimeter, but the showers would broaden instead because of the magnetic field. In addition, cost is an important parameter in the overall design of the experiment and a smaller inner solenoid is cheaper.

3.1.2 The inner detector

The purpose of the inner detector (ID) is to perform tracking over the rapidity range $|h| < 2.5$. Furthermore, it should carry out momentum and vertex measurements and electron identification. To achieve this, the ID combines high-resolution tracking at inner radii with continuous tracking at outer radii. At inner radii, for the high-precision points, semiconductor detectors (SCT) have been used and for the continuous tracking at the outer radius proportional tubes (TRT) have been used. The overall dimensions of the inner detector are $r = 110$ cm and 2×340 cm and it is divided into three parts: one barrel and two end-caps. The layout of the inner detector is shown in Figure 3-5. As mentioned above, a solenoid is situated inside the cryostat of the electromagnetic calorimeter to produce a field of 2 T. The fact that it is integrated with the calorimeter saves material which is important for the calorimeter performance. The inner radius of the inner detector is determined by how close to the interaction point a detector can operate with respect to the radiation. The outer radius is optimized with respect to calorimeter performance and cost, total size of the detector and required field integral for the magnetic tracking. The inner detector length is determined by the required rapidity coverage of the tracking. To ensure optimal calorimeter performance it is absolutely essential that the material in the inner detector is kept to a minimum. The aim is to place material such as supports and services at a large radius as far as possible. There are two reasons for this. The first is that if the photons convert to a positron and an electron at inner radii, the reconstruction becomes more difficult as the positron and the electron diverge in the magnetic field before they reach the electromagnetic calorimeter. The second reason is purely geometrical: the traversed material becomes less as the radii increases if the amount of material stays constant. The latest technology, using fibre composite materials, has been applied to make precise and stable structures to hold the different detector elements with a minimum amount of material. This put tight constraints on the engineering design of the detector.

The aim for the inner detector is to have six precision points at small radii and cross at least 36 straws in the TRT for $0 < |h| < 2.5$. There is a dip in the number of crossed straws in the crack region between the barrel and the end-cap TRT at $75 \text{ cm} < |z| < 83 \text{ cm}$. As will be seen in the next Section, 36 hits is not fully reached in the barrel TRT. In addition to the tracking capabilities, the TRT can contribute to the identification of electrons by the detection of transition radiation. The physics motivation and features of the TRT are explained in more detail in Chapter 4.

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Figure 3-5: The layout of the inner detector in ATLAS.

3.1.3 The calorimeter

The purpose of the calorimeter is to measure the energy of electrons, photons and jets, as well as measuring missing transverse energy. The calorimeter is divided into a hadronic calorimeter and an electromagnetic (e.m.) calorimeter. The e.m. calorimeter consists of an inner barrel cylinder and two end-caps with lead plates as absorbers in liquid argon. The calorimeter is of the sampling type which means the absorbers and liquid argon are put in layers. The absorbers develop the showers which then are sampled by the ionization measurements in the argon layers. The calorimeter is segmented in squares of size $\Delta h \times \Delta f = 0.025 \times 0.025$. The goal for the e.m. calorimeter is to reach an energy resolution of

$$\frac{s(E)}{E} = 0.01 \oplus \frac{0.1}{\sqrt{E}} \oplus \frac{0.40}{E} \quad (E \text{ in GeV})$$

where the first term is a constant, the second the sampling term and the last the noise in the electronics. The constant term which is most important at high energies comes from inaccuracies in the energy scale and the sampling term comes from statistical fluctuations. Shower leakage behind the e.m. calorimeter contributes to the constant term. A minimum depth of the of $26 C_0^*$ is required in the barrel calorimeter and $28 C_0$ in the end-cap to achieve the desired value on the constant term.

The purpose of the hadronic calorimeter is to measure and identify jets and to measure their energy and direction, although a significant jet energy is already deposited in the e.m. calorimeter (up to 50%). The hadron calorimeter consists of a

hadronic tile barrel calorimeter and liquid argon end-caps (see Figure 3-3). The active calorimeter depth at $h = 0$ is 11 absorption lengths l^* . A compromise has to be made between calorimeter performance and cost: a thicker calorimeter performs better but is more expensive as the size of the muon spectrometer outside the calorimeter has to be increased accordingly. A hadron calorimeter which is too thin results in problems for the trigger as there is a risk of punch-through of hadrons into the muon chambers. To reduce this effect a plug around the beam pipe of passive tungsten and iron has been added in the forward region.

3.1.4 The muon detectors

Among the important measurements to be made in the outermost detector layer (the muon spectrometer) is the four-muon signature of a Higgs decay. This requires good stand alone performance with high momentum resolution. The muon-detector system consists of muon-chamber planes before, inside and outside the toroidal field and the muon system has three super-layers, each of which is one track segment. The three track segments are joined to one track with a measured curvature. There are also special trigger chambers to fulfil the trigger demands. In addition to their primary function, the trigger chambers also give information about the ‘secondary co-ordinate’ in the non-bending plane. As mentioned above, the muon detector will play an important role not only in the searches for a decaying Higgs, but also in the search for rare decays like $B_d^0 \rightarrow \mu^+ \mu^-$ and searches for high-mass vector bosons such as $Z' \rightarrow \mu^+ \mu^-$.

3.1.5 The trigger system

The high rate of proton-proton interaction in the LHC experiments places great demands on the trigger and data acquisition system. The ability to produce physics will be very much determined by the capability of the trigger and data acquisition system to choose interesting events and acquire data at a very high speed. This selection is done in a multi-level trigger, which has to reduce the event rate by a factor $\sim 10^6$. Firstly, at the level-3 trigger a decision is made whether the data should be saved and written to mass storage for further analysis. The input interaction rate is of the order 40 MHz and after the level 3-trigger, the data rate should not exceed 100 Hz. The level-1 and -2 triggers will work on algorithms to identify high- p_T muons, electrons, photons, jets and missing transverse energy.

As an example, the electron identification capabilities of the TRT will be used at the level-2 trigger to select decays of the type

$$J / \psi \rightarrow e^+ e^-$$

with electron transverse momenta down to 1 GeV.

The electron identification features of the TRT will be discussed in detail in Chapter 4.

The level-3 trigger contains more sophisticated selection algorithms and will have to work correctly from the start. If not, valuable data will be lost for ever as it will never reach the data storage.

In the LHC experiments, timing, trigger acceptance signals and control signals must be distributed from a small number of sources to many thousands of front-end chips. The LHC timing is crucial for a successful experiment, as mentioned earlier, and must be delivered with sub-nanosecond jitter.

3.2 References

1. ATLAS TDR 1, Calorimeter Performance, CERN/LHCC/96-40 (1996).
2. ATLAS Technical Proposal, LHCC/94-43 (1994).

4. A central rapidity straw tracker

4.1 The transition radiation tracker (TRT)

The outer part of the inner detector in ATLAS will have a combined tracker and transition radiation detector, which will cover the whole inner detector rapidity range [1, 2]. The TRT is divided into three parts: two end-caps and one barrel part.

Figure 4-2 shows a cross-section of the TRT. The end-cap consists of 36 wheels with a total of $\sim 320\,000$ proportional tubes (straws) each with diameter of 4 mm. The basic properties of a straw are discussed in Section 4.4. The barrel has $\sim 54\,000$ straws which are grouped into three layers of modules. Each layer has 32 modules giving a total of 96. In the end-cap the straws are placed radially and they have a length of ~ 40 cm (see Figure 4-1) [3]. There are three different types of wheels with different straw densities and straw lengths to obtain as uniform a number of hits as possible as a function of h .

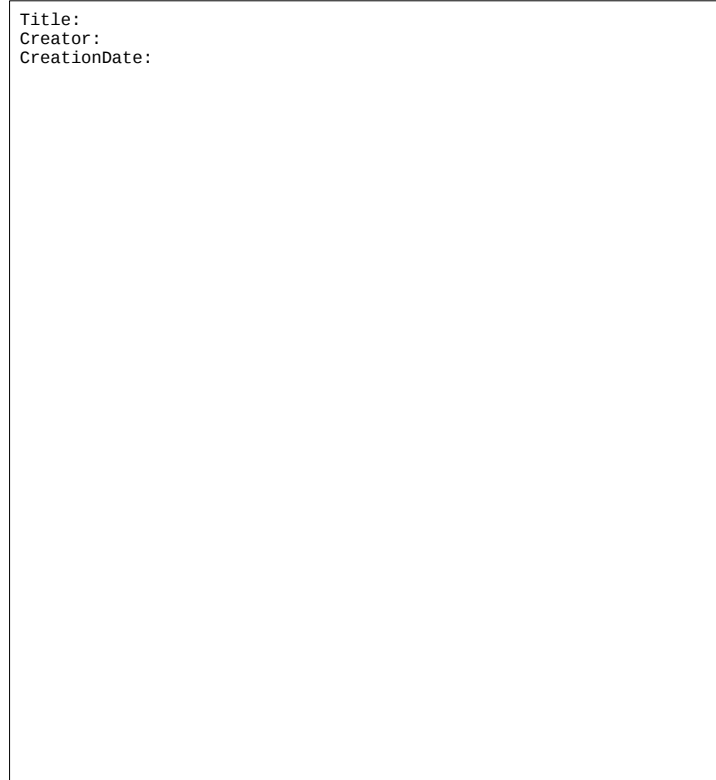


Figure 4-1: One of the 36 end-cap wheels in the TRT containing $\sim 12\,000$ straws divided into 16 straw planes. Stacks of foils (radiator) are placed in between the straw planes. The dimensions are $48\text{ cm} < r < 103\text{ cm}$ and $z = 13\text{ cm}$.

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Figure 4-2: The layout of the transition radiation tracker in the ATLAS inner detector (ID).

In the barrel the straws are parallel to the beam and are 150 cm long. Because of the high occupancy, the anode wires are electrically disconnected at $z = 0$. The barrel is therefore read out at both ends while the end-cap straws are read out only at the outer radius. Radiators are placed in between the straws to produce transition radiation X-rays. These X-rays are then absorbed in the straws and in this way the TRT can be used to identify electrons. The production is discussed in more detail in Section 4.2. In the end-cap the radiator is made from stacks of polypropylene foils, placed in between the straw layers. Each stack contains 20 foils and each foil is 15-20 μm thick. The distance between foils is 250 μm . In the barrel polyethylene/polypropylene fibres are used with a fibre diameter of 15 μm (see Section 4.6.4). In contrast to the barrel, which is water cooled, the cooling of the end-cap is performed with an increased flow of the CO_2 which is also used for the ventilation of the radiator. Ventilation of the radiator is necessary to evacuate any Xe that has escaped the detector gas volume either by diffusion or by leakage. The reason for straw cooling is discussed in detail in Section 4.6.9. On the tracking part, the barrel gives information about the R and $R-f$ co-ordinates, while the end-cap measures z and $R-f$ directly. There is also some indirect information from the entrance and exit of a track in the end-cap. The barrel part of the TRT is treated thoroughly in Section 4.6.

The TRT provides continuous tracking inside its envelope over the full rapidity range inside the inner detector. The crucial feature of the TRT for this task is the drift-time measurement (see Section 4.4). It will determine to what precision a the position of a track can be determined with respect to the wire. This implies strict requirements on the positioning of the wires and the geometrical stability over time. The drift-time accuracy at low luminosity is $\sim 150 \mu\text{m}$ and degrades to $\sim 180 \mu\text{m}$ at high luminosity ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$) due to the high rate in the straws. Note that this is for the worst case, i.e. straws at the inner radius of the barrel TRT, and the rate falls off as $\sim r^{-2.5}$ [4]. The tracking makes use of a low-level threshold on the energy read out in the read-out chip to detect ionization particles. There is also a high-level threshold used to detect the transition radiation photons.

4.2 Transition radiation (TR)

TR is produced when ultra relativistic particles ($\gamma > 1000$) pass suddenly from one medium into another. The reason for the emission of these TR photons is that the electromagnetic properties are different in the two media and the accompanying field around the particle is different in the two media. It is this ‘reorganization’ of the field when the particle goes from one media to another which gives the emission of TR photons. The radiation is emitted in the forward region within an angle of the order $1/\gamma$. In order to emit the TR, i.e. reorganize itself, the particle has to travel a certain distance in the new medium called the ‘formation zone’. The length of this formation zone is approximately proportional to $1/w_p$ where w_p is the plasma

frequency. The formation zone for vacuum is of the order 1 mm and for polyethylene it is 100 times smaller, i.e. $\sim 10 \mu\text{m}$. If the thickness of the new medium gets thinner, the TR tends to zero. From this point of view the TR is a macroscopic effect. In practice the thickness of a radiator foil is 10-20 μm (15 μm in our case), i.e. of the order of the formation zone, which is not surprising. A rigorous elaboration of the production of the transition radiation can be found in Ref. [5, 6, 7, 8]. The TR is related to Cherenkov radiation but is not the same, as Cherenkov radiation is emitted whenever a particle moves faster than the speed of light in that medium. The TR property can be used to identify particles when Cherenkov does not work due to a too high γ . Figure 4-3 shows how the energy deposition in a straw varies as a function of the Lorentz factor γ . It is this γ -dependency which is exploited in TR detectors to distinguish particles of different masses at a given momentum. It can also be used to measure the energy of particles with a known mass at very high energy when other techniques becomes inoperative, i.e. above $\gamma \approx 1000$. The problem is that the probability for emitting a TR photon is small. The technique to overcome this in TR detectors is to have series of boundaries. As mentioned, above this is achieved with a stack of foils in the end-cap. To gain maximum positive interference in TR production, it is important to have a minimal distance between the foils: this distance is 250 μm between the end-cap foils. The end-cap geometry is suitable for such a mounting, where the stack of foils can be placed vertically between the straw planes.

Figure 4-3: The predicted γ -dependence (solid line) of the probability of an energy deposition of more than 5 keV per straw, compared with data (from Ref. [9]).

The barrel geometry and straw layout do not permit an efficient mounting of a foil radiator. For this reason the barrel has been equipped with a fibre radiator. Because of the non-optimized spacing of the boundaries in a fibre radiator the performance is lower than for equally spaced foils. In addition, as the TRT is also a tracker where it is important to have many hits on a track, and the detector length is limited, the radiator cannot be arranged for optimal TR production.

Examples of other radiator materials than polyethylene and polypropylene are: lithium and beryllium. These are all materials with low Z , i.e. as transparent to X-rays as possible. Lithium and beryllium have some disadvantages that make them difficult to use compared to polypropylene and polyethylene. Lithium is inflammable and beryllium is expensive and difficult to handle due to its toxic character. More on the radiators used in the barrel TRT can be found in Section 4.6.4. The price to pay for the electron identification capabilities increased material due to the radiator and Xe gas, and a more complicated read-out scheme due to the TR threshold. In addition, the radiator material contributes significantly to the material in the TRT. The use of Xe gas puts special requirements on the engineering as the detector must not have any leaks due to the high price of the Xe gas ($\sim 27\,000$ SEK/m³ NPT) and it takes about 3 m³ to fill the active gas volume in the TRT.

4.3 Physics motivation for a transition-radiation detector

The TRT in the ATLAS inner detector should be able to identify electrons. Furthermore, the TRT should provide ‘continuous’ tracking and match these tracks with the precision detectors at the smaller radii. The word ‘continuous’ is to some extent misleading as it refers to many measuring points uniformly distributed along the particle trajectory. The requirements on precision and granularity for the TRT are lower compared to the precision layers inside the TRT, which makes the TRT a cost-effective choice in the region $0.5\text{ m} < r < 1.0\text{ m}$. The precision in one single straw is in the worst case (high occupancy) $\sim 180\text{ }\mu\text{m}$ (inner barrel layers). The TRT will play an important role in the B-physics program which is planned at the initial low-luminosity period of the LHC programme [10, 11]. In LHC there will be a possibility to observe CP violation, which has so far only been studied in the neutral kaon system, through

$$\overline{B}_d^0 \rightarrow J/\Psi + K_s^0$$

with

$$J/\Psi \rightarrow e^+e^-, \mu^+\mu^-, \text{hadrons}$$

The branching ratios for these decays are 7%, 7% and 86% respectively. With the decay channel to an electron and positron, the statistics are doubled compared to only using the muons. The TRT will play a major role, in identifying the two electrons. Figure 4-4 shows the invariant mass distribution for $J/\Psi \rightarrow e^+e^-$ with and without the TR function. A rejection factor of about 20 can be achieved. As one will look for

two electrons with a total energy of ~ 3.1 GeV, the rejection against the hadron background will be the square of the electron efficiency for a single electron. In addition B-tagging can be used to identify

$$H \rightarrow b\bar{b}$$

and the Higgs channel

$$H \rightarrow 4e$$

will benefit from the TRT in the identification of the four electrons.

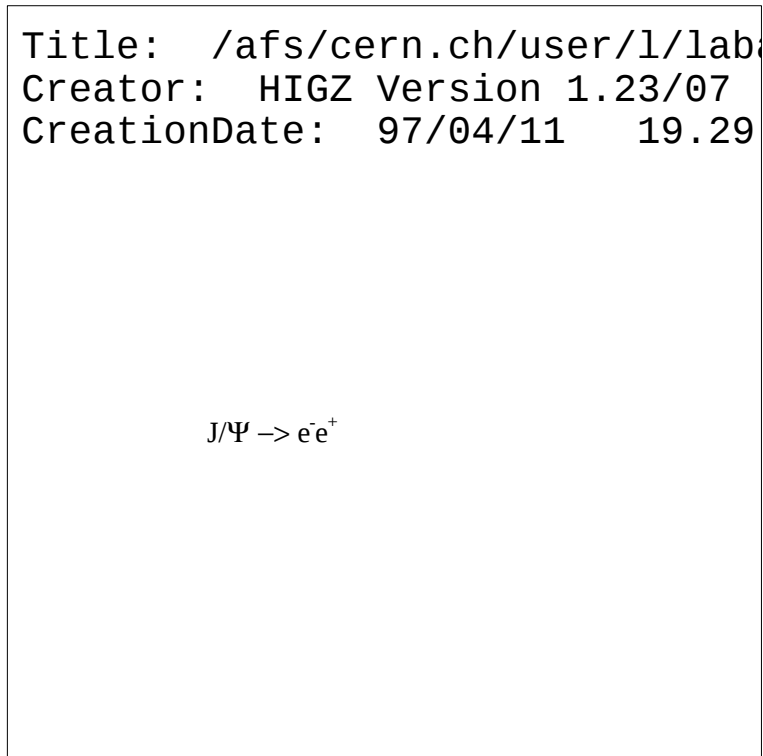


Figure 4-4: Invariant mass distribution for $J/\Psi \rightarrow e^+e^-$ before and after the transition radiation cuts.

4.4 Principal operation of the straws

The basic elements of the TRT are the thin proportional tubes (straws). The straws are made from polyimide film which has a conductive layer (2000 Å aluminium + 4 µm carbon-loaded polyimide) on one side and an insulating polyurethane layer (3 µm) on the other [12]. Two tapes (4-8 cm wide) are wound together in spirals at ~ 200 °C to form a straw which has a total wall thickness of ~ 60 µm. The straws are reinforced by four carbon-fibre strands, which are glued along the straws. Each

carbon-fibre strand contain 500-1000 filaments each with a diameter of 7 μm . The original argument for the reinforcement was the creep as the straws were put under tension in the end-cap wheels. Later it was found out that the signal properties of the straws, i.e. the signal attenuation length, were improved by the carbon-fibre reinforcement. Inside each straw there is a gold plated tungsten wire with a diameter of 30 μm and each straw acts as proportional chamber [13]. When a charged particle traverses the straw it ionizes the gas and the electrons start to drift towards the wire while the positive ions drift towards the cathode. Close to the wire, typically at a few wire radii, the electrical field gets strong enough that the primary electrons create new electrons and an ‘avalanche’ is created. This give rise to a current pulse which is read out at the end of the straw. Figure 4-5 shows the working principle of the straw. The fast-electron component contains only 3-5% of the total charge and a large part of the dominant very-slow-ion component has to be eliminated. To be able to determine which side of the anode wire the track passes, several layers of straws have to be read out. There are two thresholds: a low-energy threshold of 100-200 eV to detect ionizing particles and a high-energy threshold for the TR photons. The drift time for the electrons to the wire is measured and it gives, as mentioned earlier, a spatial accuracy of $\sim 150 \mu\text{m}$ at low luminosity. The total drift time is about 38 ns and therefore the electronic resolution has to be of the order 2-3 ns. The intrinsic resolution is limited by the statistics of the primary collisions, electronics noise, gas gain and the electronics shaping time. The multiplication or gas gain should be $2.5\text{--}4 \times 10^4$, which corresponds to a high voltage (HV) of 1520-1570 V for a 30 μm wire. A lower limit of the gas gain is determined by the signal-to-noise ratio. The upper limit is determined by space-charge effects, and in particular the streamer rate, which deteriorate the TR performance not only due to non-linearities in the energy response but also introduces dead time in the electronics. In addition these non-linearities depend on the deposited energy.

4.4.1 Gas composition

There are different requirements, very often conflicting, on the gas mixture to be used in the difficult conditions in LHC. There are three main requirements on such a gas mixture

- It must be a good absorber of the TR photons produced in the radiator. This means a gas with a high Z has to be present and Xe has this property.
- It must be fast to avoid pile-up in time. A fast gas like CH_4 has to be present in as high a concentration as possible.
- It must provide stable operating conditions for the HV applied to the chamber, and for this purpose a so-called quench gas is used. In our case CO_2 .

After extensive studies a gas mixture of 70% Xe, 20% CF₄ and 10% CO₂ was chosen. To avoid absorption of TR photons in the radiator volume due to leaking and diffusing Xe, the radiators are ventilated with a neutral gas like CO₂ both in the end-cap and in the barrel. The Xe content is necessary for absorbing the TR photons, but it is not as fast as, for example, Ar mixtures and this leads to a long ion tail.

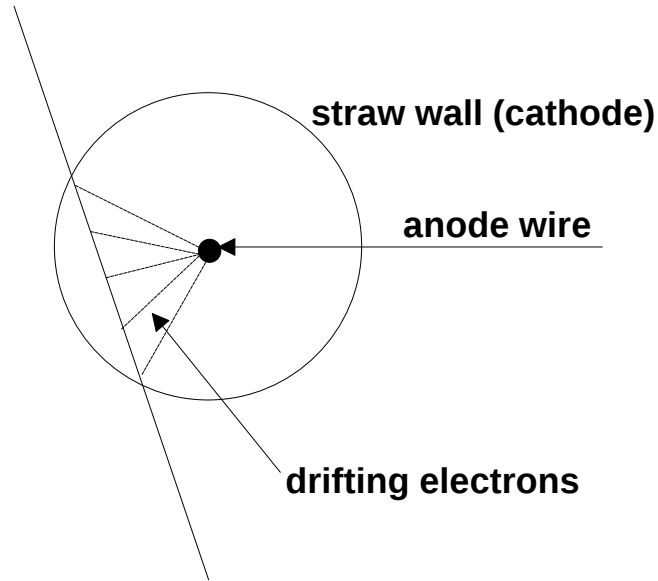


Figure 4-5: When a charged particle traverses the straw it ionizes the gas and the electrons drift towards the anode wire. If the drift velocity of the electrons is known the distance from the track to the wire can be determined.

4.5 Electrical connections

Figure 4-6 shows a principal layout of the electrical connection for the straws. The straws are divided into groups of 16 and each HV group is connected to the HV supply through a resistor-fuse. Experiments have shown that the optimal value for R_i is 300 Ω . The value of the decoupling capacitor is of the order 2000 pF. The decoupling capacitors are shared between 8 straws which means two capacitors per HV group. The discharge current of this chain goes through the input resistor of the preamplifier. In the end-cap the straws are read out only at the outer radius. Because of the high occupancy at full luminosity, the barrel straws have an anode wire which is electrically disconnected at $z = 0$ and the straws are read out at both ends.

Figure 4-7 shows the glass joint which divides the two sides electrically. The glass joint is 6 mm long and 250 μm in diameter and is melted on the wire [14].

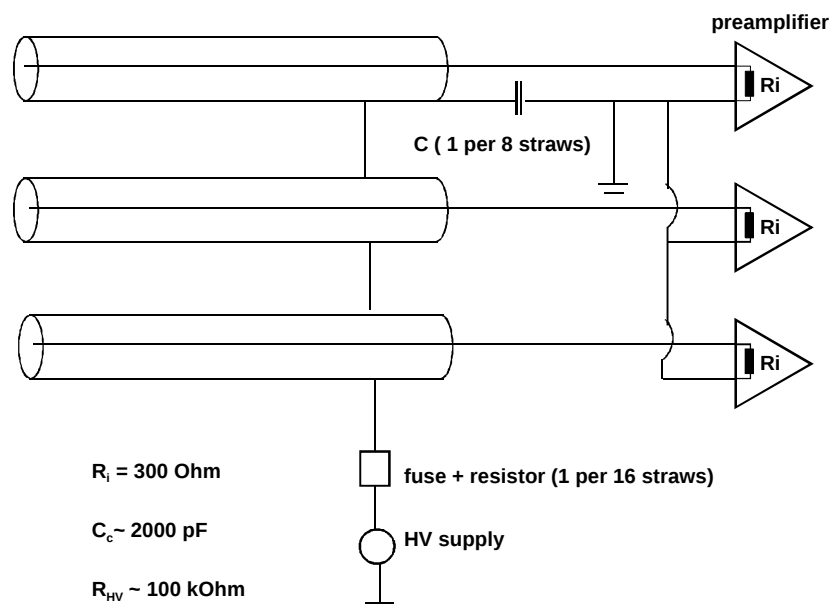


Figure 4-6: Principal view of the electrical connection of the straws to HV and preamplifier. The modularity is 16 and 8 straws for the HV and de-coupling capacitor respectively. In the barrel the straws are read out at both ends.

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a)

b)

Figure 4-7: The mid-joint at (a) $z = 0$ for $r > 63 \text{ cm}$ and at (b) $z = \pm 39 \text{ cm}$ for $r < 63 \text{ cm}$. The wire centring piece, called the twister, is shown around the glass joints and at the wire ends.

The wire is supported and centred at both ends and in the middle of the straw for straws at $r > 63$ cm. For straws at $r < 63$ cm, the anode wires are inactive for $-39 \text{ cm} < z < 39 \text{ cm}$ due to the high occupancy at inner radii. The gas amplification is eliminated with a thicker wire and two wire joints are used in this case.

It is important to have a noise level as low as possible for a good straw efficiency and it should be significantly less than the lower threshold of 100-200 eV.

4.5.1 The ASDBLR

The read-out electronics will be mounted near the straws; for the barrel this means at the module ends ($z \sim 76$ cm) and for the end-cap at the outer radius ($r \sim 105$ cm). In the present design there is an ASDBLR (Amplifier-Shaper-Discriminator with BaseLine Restoration) first in the read-out chain [15]. Figure 4-8 shows a block diagram of this circuit and the main architectural features. The preamplifier converts the charge at the input to a voltage. After the amplification in the preamplifier the very long tail due to Xe ions is removed with the shaper, leaving a pulse with a full width less than 50 ns. Figure 4-9 shows schematically the effect of ion-tail cancellation. The need for this ion tail cancellation becomes clear when the time between tracks can be ~ 60 ns and more than 30% of the peak signal remains after 100 ns. At this high luminosity there is a risk of pile-up and the baseline will drift.

Figure 4-8: Block diagram for the ASDBLR (from Ref. [15]).

Figure 4-9: Ion-tail cancellation leaving a pulse with full width below 50 ns (from Ref. [15]).

Figure 4-10: Output from the baseline restorer using 2 fC (solid) and 25 fC (dashed) signal, normalized to the same magnitude (from Ref. [15]).

If the baseline drifts threshold problems are experienced which are defined for a certain level of the signal. To avoid this and ensure an efficient tracking, there is a baseline restorer after the ion-tail cancellation. Figure 4-10 shows the shape of the signal at the shaper output, normalized to the same magnitude. Larger signals have a smaller fraction of overshoot.

4.5.2 The DTMROC

The DTMROC (Drift-Time Measurement Read-Out Chip) is designed to measure the time it takes for the electrons to drift from the particle trajectory to the wire, i.e. the distance from the wire [16]. It consists of two parts. One part measures the drift time and it measures the time between the rising edge of the beam crossing and the rising edge of low-threshold input signals. A special time measuring unit was designed for this purpose [17]. This unit delays the beam-crossing signal until the low threshold arrives and indicates how long the beam-crossing signal has been delayed. The resolution is 3 bits, which gives a resolution of 3.125 ns as the beam-crossing period is 25 ns. The delay of the delay elements is controlled by the phase detector and the loop filter (see Figure 4-11) which keeps exactly one period of the beam crossing over the whole line of delay elements. The location of the beam crossing in the delay is encoded into a digital word by an encoder.

Figure 4-11: Block diagram of the time measuring unit. The delay line together with the phase detector and loop filter makes up the Phased Locked Loop (PLL).

The result is captured in a register which is read out when triggered by the arrival of a low-level threshold.

The second part in the DTMROC deals with communication with the rest of the system and supplies reference signals, etc. Figure 4-12 shows the layout for the front-end electronics. From the DTMROC the data is sent via twisted-pair cable to the back-end electronics.

Figure 4-12: Schematic view of the read-out system. There are 8 straws per ASDBLR giving 16 straws per DTMROC.

4.6 The design of the barrel TRT

4.6.1 A modular approach

The work on the design of the barrel TRT has concentrated on a modular approach with three module layers [18]. A modular design has many advantages such as testing, parallel assembly, prototyping, etc. Many aspects, often contradictory, have to be taken into account when choosing the module size, e.g. physics performance, cost, mechanical stability, cooling, alignment, etc. It is a big optimization problem with many parameters and constraints and where it is important to find out the sensitivity of the different parameters. Many of the aspects will be discussed below and it should be pointed out here that a series of considerations led to the present design concept for the barrel TRT. In terms of the physics performance, there are three major parts that have to be taken into consideration:

- The tracking. Any modular structure will create ‘cracks’ in the detector volume where there are no straws. A successful modular design should therefore minimize the effect of these cracks. A special study was made to investigate the effects on the tracking performance of different modular designs.
- The TR performance. Any introduction of material in the active volume of the barrel TRT will absorb TR photons and degrade the TR performance.
- The amount of material. The total amount of material in the inner detector has to be kept as small as possible so as not to degrade the calorimeter performance.

If the modules are too big, the advantages of a modular structure are lost. On the other hand, small modules introduce more material through the carbon-fibre shells that surround each module and degrade the performance according to the points made above. In addition there are indirect effects on the physics performance. For example, the heat dissipation in the modules will change the density, i.e. the gas amplification, due to changes in the temperature. This has to be taken into account when considering the module size. Real prototype experience will indicate the optimal size. The present module geometry is based on three module layers with 32 modules in each layer [19]. It was found to be a good compromise between the different aspects mentioned above. As will be seen in the next section the modular structure is intimately connected to the design of the support structure and the mechanical and thermal behaviour of the modules. This is another ingredient in the concept for the barrel design. The support structure with its symmetrical triangular shape is shown in Figure 4-13. The reason for this symmetrical triangular geometry is that it gives very small deflections because the spokes experience only tension or compression and no bending moments. In addition, as will be seen in Section 4.6.9, an important feature of the present module size is that it allows water cooling of the module shells and that the maximum temperature difference inside the modules stays approximately the same for the three module types. The inner radius is at 56 cm and the outer at 107 cm.

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Figure 4-13: The barrel TRT showing the carbon-fibre support structure and modules. There are 3×32 modules in the present design with 329, 520 and 793 straws for the inner, middle and outer modules respectively [20] .

In addition, at the inner radius, the nine innermost straw layers contain wires with a shorter active length, see Figure 4-14. These short wires are essential in minimizing the dip in the number of the TRT hits in the crack region between barrel and end-cap. As h increases above 0.7, the tracks start to leave the barrel at outer radii but, this is compensated by the short wires at the inner radii. The length of the active wires is 36 cm for $56 < r < 63$ cm and 75 cm for straws at $r > 63$ cm. The shorter active wires have two electrical disconnections at $z = \pm 39$ cm. There are 329, 520 and 793 straws in the inner, middle and outer modules respectively. Some important layout parameters are summarized in Table 4-1.

The modules have a uniform shape, but the cross-section increases with the radius; they are formed by taking the two isosceles triangles ABC and BCD as shown in Figure 4-15. From the sine theorem we have

$$\frac{\sin(b)}{R} = \frac{\sin(q)}{R + dR} \quad (4-1)$$

where

$$R' = \frac{R}{\cos(a)}$$

and in addition

$$a = q - b .$$

By imposing three layers of modules, the tilt of the modules is determined by the number of modules as

$$a = p / N .$$

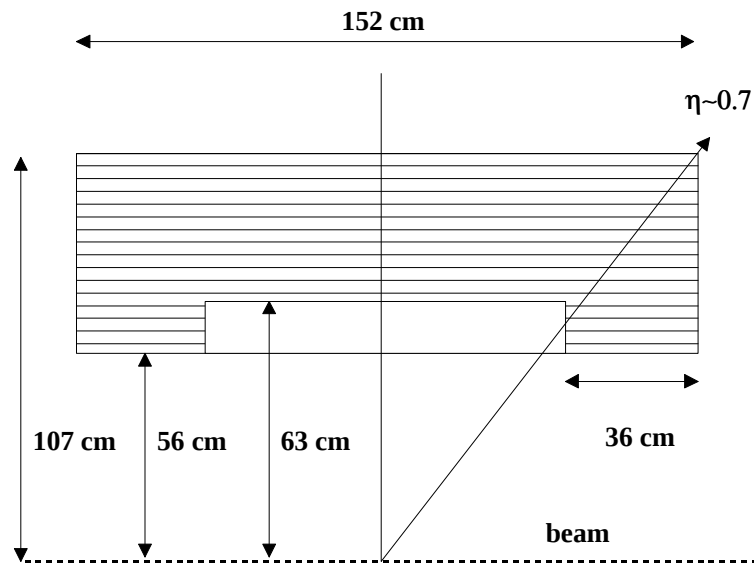


Figure 4-14: Schematic side view of the barrel TRT. For $r < \sim 63$ cm, the straws are equipped with short active wires of 36 cm.

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Figure 4-15: The geometrical principle of a triangular module geometry.

This geometry gives zigzag-shaped cracks between modules at an angle which reduces the degradation of the tracking performance. It also gives a natural shift between two neighbouring straw layers. It should be pointed out that, in principle, q could be different for the three module layers leading to different sized modules, but still keeping the advantageous geometry from a mechanical point of view. However, as will be seen in Section 4.6.8, the present three module sizes give almost equal temperature differences inside the modules.

	Inner Module	Middle Module	Outer module
Number of modules	32	32	32
Straws/module	329	520	793
Number of layers ¹	9 + 10	24	30
Inner radius ² (mm)	560.00	697.14	863.68
Outer radius ³ (mm)	697.14	863.68	1070.00

Table 4-1: Layout parameters for the barrel TRT modules.

4.6.2 Straw layout

The straw distribution is determined to a great extent by the module shape, but the distance between straws is kept at 6.8 mm as far as possible in both r and j . A program was developed to facilitate the calculation of the straw positions and enable fast optimization of the straw layout. The straw positions were calculated, written to a text file and directly generated on an AUTOCAD drawing. The straw co-ordinates were then fed into a tracking program for tracking performance studies discussed in Section 4.6.10. The principle for positioning the straws is shown in Figure 4-16 and Figure 4-17. After the module boundaries have been defined, the next step is to define the required clearance to the module boundary. From mechanical considerations, the shortest (orthogonal) distance from the module boundaries to the nearest straws is 5.2 mm on all sides of the module. It is important to keep this distance small as it determines the crack where no straw hits are possible. Some minimal distance is needed to be able to fit the straw connectivity at the module ends and for HV reasons. The shell is conducting and at ground potential while the straws are at HV. The influence on the tracking performance is discussed in Section 4.6.10. The lines A, B, C and D in Figure 4-16 are at 5.2 mm from the module boundaries and now define the outer boundary for straw centres.

¹ The first nine layers are equipped with short wires, i.e. 36 cm.

² The inner radius is measured to the module corners except for the inner module where it is the tangent to the module base (Figure 4-18).

³ The outer radius is measured to the corner of the modules.

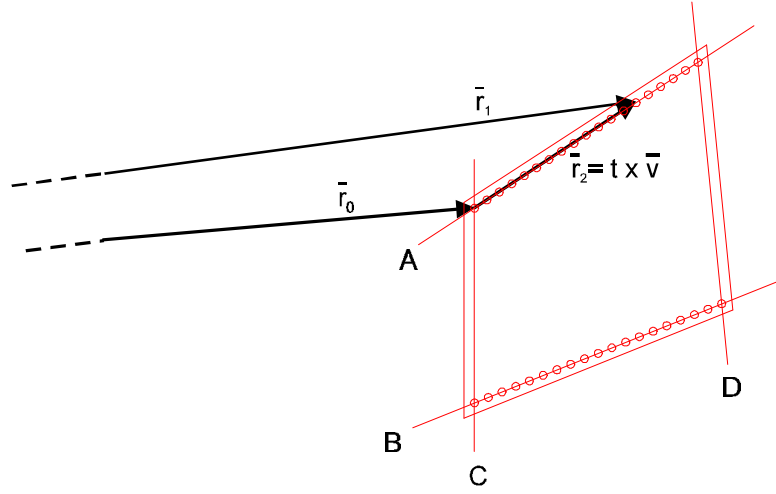


Figure 4-16: The method for calculating the different straw layers in a module.

After defining the number of straw layers (distance between straws close to 6.8 mm) the lines A and B are divided into equal segments by introducing the vectors $\bar{\mathbf{r}}_0, \bar{\mathbf{r}}_1, \bar{\mathbf{r}}_2$. From Figure 4-16

$$\bar{\mathbf{r}}_1 = \bar{\mathbf{r}}_0 + \bar{\mathbf{r}}_2 = \bar{\mathbf{r}}_0 + \mathbf{t} \times \bar{\mathbf{V}} \quad (4-2)$$

where

$$\bar{\mathbf{V}} = \begin{pmatrix} 1 \\ k \end{pmatrix}$$

is a vector along A with the slope k and the segment length $\mathbf{t}$. The segments now delimit the straw layers and also define the end straws in each straw layer as shown in Figure 4-17. The same procedure is used for the straws in each layer defined above. As one moves out in radius straws have to be added to the layers to keep a uniform straw density and, for example, for the inner module this means one extra straw for each five layers. The number of straws per layer for all three modules is listed in Appendix A.

The cooling of the modules is foreseen with two cooling pipes per module running down two of the module corners, see Figure 4-18. To provide room for the cooling pipes, the straws in these corners are removed leaving the other straws in the module untouched.

4.6.3 Support structure

The support structure consists of two end flanges, one inner and one outer cylinder. The total load on the structure will be ~ 450 kg, where 300 kg comes from the barrel modules and the rest from SCT and services. The mechanical requirement on the maximum displacement is < 40 μm . To achieve this with a minimum amount of material, carbon-fibre composite material had to be used. A Swedish company specializing in composite materials was contracted to perform Finite Element Model (FEM) calculations in order to optimize the geometry and the material [21]. The conclusion from the study is that only unidirectional fibres or unidirectional fibres in combination with an isotropic component are possible with the maximum allowed displacement of 40 μm . A 'standard' fibre, T300, is used in the calculation which results in a moderate Young's modulus of 125 GPa in the fibre direction, assuming 60% fibre content. Apart from its higher price, high-modulus fibre is very difficult to handle because of the brittleness of the fibres. The structure is made from carbon-fibre rings connected with a triangular cross-bracing structure. The rings (beams in tangential directions) have a cross-section of $1 \times 1 \text{ cm}^2$, and the spokes are 5 mm in the R - f direction and 10 mm in the z -direction. Figure 4-19 shows the calculated deflection of the support structure. The critical part in the design of the support structure is the junction of the beams: several methods are under study. The two end flanges are joined together with two carbon-fibre cylinders to prevent torsion in the f -direction. At the outer and inner radii, the cylinder has thicknesses of 3 and 2 mm respectively.

The structure coincides with modules as shown in Figure 4-13. This design permits maximum access to the module end-plates for electronics mounting. Furthermore it helps to minimize the crack in between end-cap and barrel as the space between the spokes is used by the electronics.

4.6.3.1 Module shells

Each module is surrounded by a carbon-fibre shell which prevents the straws from bending under the weight of the radiators. Both analytical and FEM calculations have been performed to optimize the design in terms of maximum stiffness for a minimum amount of material [22]. This study was performed by the same engineering consultant as for the structure. The results from these calculations show that a carbon-fibre composite skin of 400 μm is enough to satisfy a maximum deflection of 40 μm . Figure 4-20 shows the calculated displacement with a 300 μm

skin and 200 μm polyimide partitions. An isotropic lamina with a Young's modulus of 100 GPa was assumed in the calculation.

Figure 4-19: The displacement of the support structure. An amplification factor is applied to visualize the deflection. The maximum displacement is 22 μm .

Figure 4-20: The calculated displacements for 200 μm polyimide partitions and a 300 μm carbon-fibre shell.

4.6.4 Radiators

The radiator for the barrel cannot be made with foils as for the end-cap for geometrical reasons. Even if it were possible to find a mechanical solution where the foils could be put between straw layers it would not be efficient enough. For this reason a fibre radiator was chosen for the barrel as it will fill up the whole available volume between the straws. At an earlier stage different foam radiators turned out to

be quite promising, but later fibre radiators were found to give more TR. Therefore, present efforts are concentrating on finding the best fibre radiator. A so-called ‘oriented’ fibre is the solution. An oriented-fibre radiator has more fibres oriented perpendicular to the beam and more boundaries are traversed by the particles, producing more TR. The fibre is made from polyethylene and polypropylene. An important difference between these two materials is that polyethylene is more radiation resistant. The fibres have a diameter of 15 μm and the density, when installed, is 0.07 g/cm^3 . The fibre sheets have a thickness of 0.6 mm. Figure 4-21 shows the principle difference between the oriented and the non-oriented fibre. Both oriented and non-oriented fibres have been studied in terms of electron identification performance as part of the evaluation of the first barrel prototype. The results from this study are discussed in further detail in Section 4.6.12.

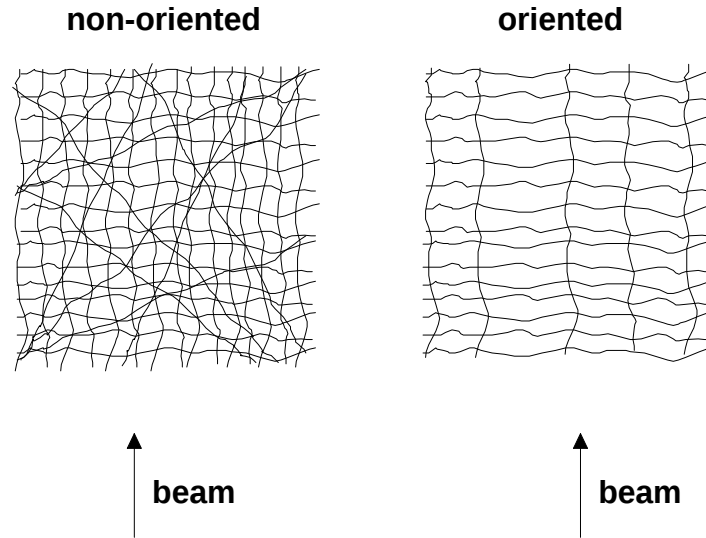


Figure 4-21: The difference between the oriented and non-oriented fibre. The fibre sheets are ~ 0.6 mm thick.

4.6.5 Ventilation of the radiator

As mentioned earlier, Xe inside the straws is there to absorb the TR photons. It is important to keep the Xe concentration in the radiator below a value where its contribution to absorption of the TR photons is negligible. In the present design the ventilation is achieved radially in the barrel through holes in the carbon-fibre shells. The flow rate required for the ventilation depends on the leak rate and on the diffusion of Xe into the radiator volume. An estimate of the maximum tolerable Xe concentration and the expected leak rate will give the required ventilation assuming uniform flow and Xe concentration in the radiator. Outside the straws the TR photons are mainly absorbed in the radiator itself and the Xe concentration should

not increase this absorption significantly. 1% Xe concentration is estimated to be acceptable.

Measurements have been carried out to determine the pressure drop over one 1.5 m module for radial ventilation of the barrel. The measurement was carried out on the 0.5 m prototype described in below. The holes in the shell, made for the alignment of the polyimide partition, were used as inlet and outlet holes for the gas. The equivalent total cross-section for the gas flow through the shell wall was calculated to be 6.4 cm^2 per metre of module and nitrogen was blown from the inner to the outer radius. The flow resistance was measured to be 30 l/h/Pa at a flow rate of 600 l/h, which is equivalent to 90 l/h/Pa for a 1.5 m module. It can be concluded from this measurement that the flow resistance in the module does not cause problems for the ventilation of the module even with relatively small openings in the module shells.

4.6.6 Design, assembly and testing of a 0.5 m barrel prototype

A 0.5 m barrel module prototype was built to evaluate the modular concept and assembly procedure. The prototype is an inner module with 329 straws and it contains the full complexity of the mechanical structure and connectivity. A section of the space frame was built to study the fixation of the module. The feasibility of the tooling, e.g. the alignment jig, was also tested. HV behaviour and leak rates in the active gas volume were studied using this prototype (see Section 4.6.9. and Section 4.6.12). After the assembly, the prototype was used for verification of the thermal calculations and for beam test analysis of the TR performance (see Section 4.6.9 and Section 4.6.12).

4.6.6.1 Design and assembly

Figure 4-22 shows schematically how the module is designed. The mechanical parts are the shells, the partitions, the end-plates, the tension plates and the straws. The shell is there to prevent the module, i.e. the straws, from deflecting more than $\sim 40 \text{ }\mu\text{m}$. The polyimide partitions ensure a correct positioning of the straws in R - f at equidistant points and are absolutely essential as the weight of the radiator sheets are taken by the straws (see Figure 4-23). In addition they prevent the straws from buckling under the wire tension. It should be pointed out that there is a wire tension to be taken by the module structure of about 70 g per straw which is 23 kg on the tension plate for the inner module. Cylinders around the decoupling capacitors together with the fibreglass end-plate and tension plate make a strong sandwich structure. This prevents deformation of the tension plate and loss of wire tension. This design also permits an easy change of capacitor with a minimum amount of dismounting, whilst keeping the capacitors close to the straws. Figure 4-24 shows some various parts used in the assembly the module and Figure 4-25 shows a detailed view of the end-plates which play a central role in the design.



Figure 4-22: Principal view of a barrel module. Polyimide partitions divide the radiator into sections and align the straws at equidistant points [20].

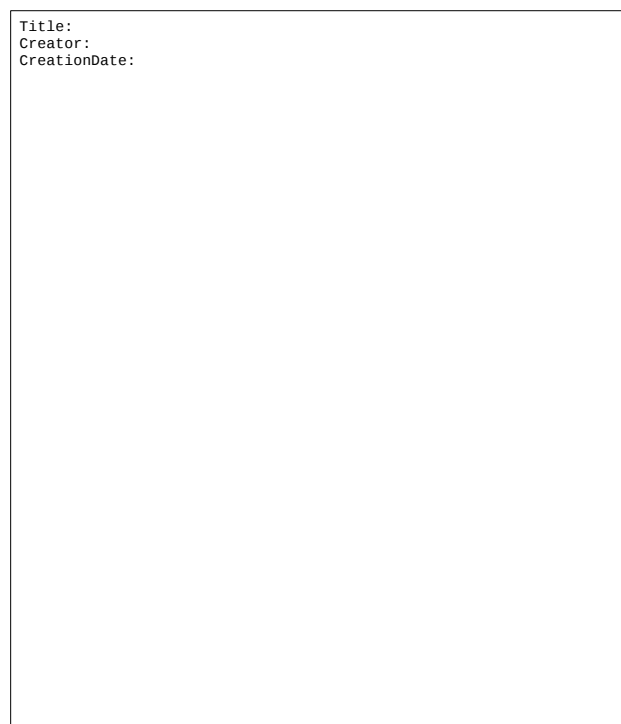


Figure 4-23: A polyimide partition with its eight alignment ears [20].

It is important to have a compact design in order to minimize the gap between the barrel and the end-cap. The drawback is that the module regions become very complicated and crowded. A lot of time was spent on the design optimization procedure and to fit all the different components within the envelope.

Figure 4-24: Various parts in the barrel module. From upper left: v-piece (side view) for wire centring, v-piece (top view), insulation socket for the capacitor pin, wire fixation socket and pin, capacitor, straw fixation socket, cylinder around capacitor, twister for wire centring (two).

The HV is brought to the straws by a polyimide sheet and brought to the outside at the two sides of the tension plates. Figure 4-26 shows the HV polyimide sheet. It has a conducting flower with six petals which connect to the inside of the straw when inserting the wire guides. Two different designs of the wire guides were tested and half of the straws are equipped with twisters, and the other half with v-pieces to evaluate their performance (Figure 4-24) [3]. In the case of the twister an additional 60- μm -thick polyimide cylinder is inserted around the twister to avoid a short circuit between twister and anode wire. The signal plane is on the back side of the tension plate and a complete ground plane is placed on the top side to shield the signal plane from the electronics side. Figure 4-35 shows the tension plate with the signal plane and the layout of the daughter cards. In addition, there is the gas inlet/outlet for the detector gas and water cooling of the module. A so-called 'roof board' will connect to the 16-channel daughter cards and bring in the cooling for the electronics. The design of this board is under study.

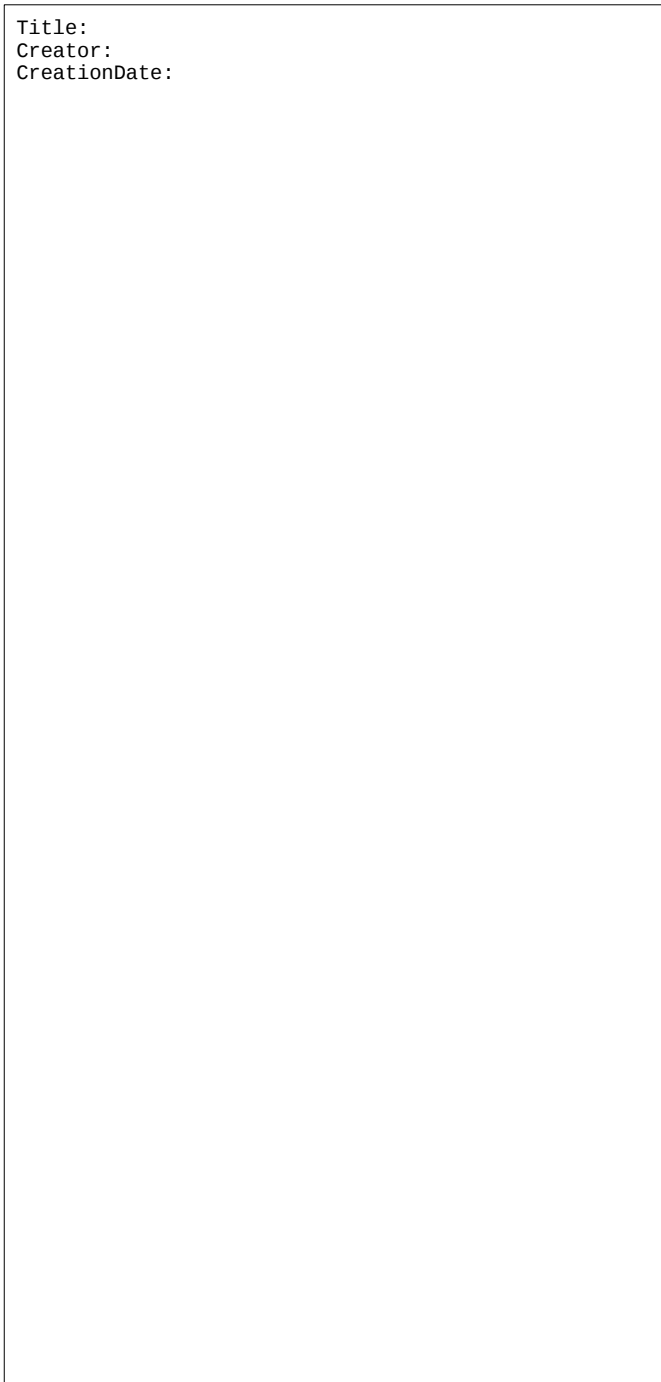


Figure 4-25: Detailed view of the barrel end-plates (mm) [20].

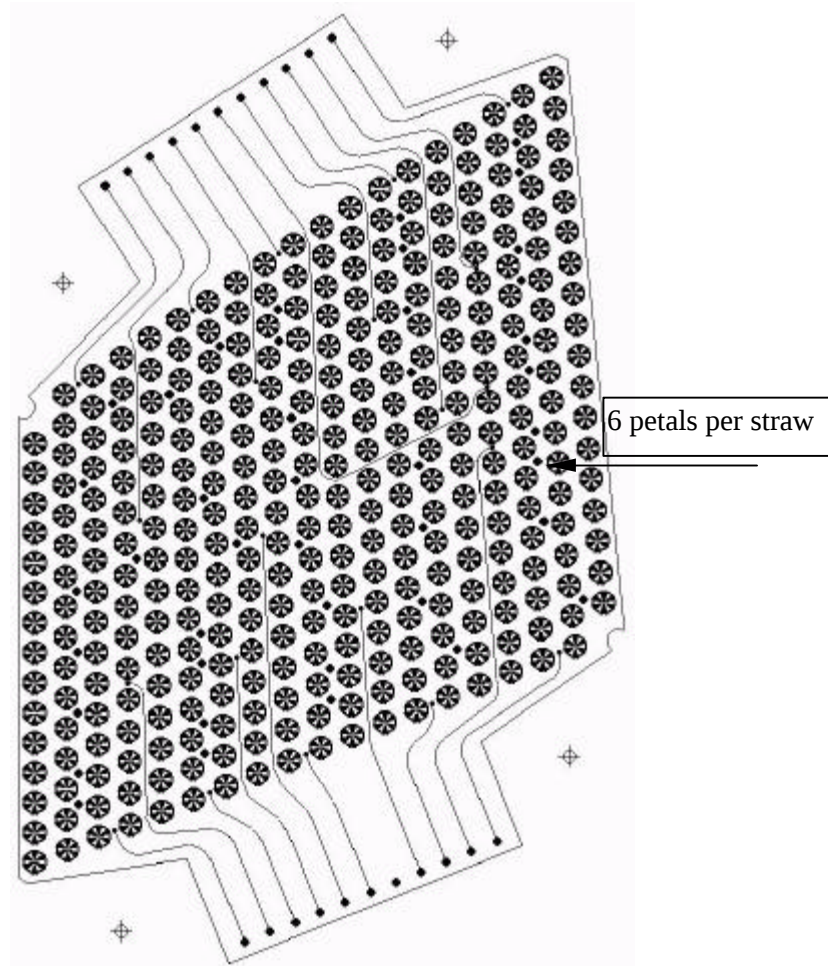


Figure 4-26: The HV polyimide sheet. The module is divided into 21 HV groups [20]. The electrical contact with the straws is made by the six petals which are pushed into the straw when the wire centring piece is inserted.

The assembly of the module began with the alignment tooling and a schematic view is shown in Figure 4-27. After the shell was put in place, a stack of fibre radiator sheets was inserted together with the polyimide partitions. Figure 4-28 shows the situation where the radiators, polyimide partitions, and the carbon-fibre end-plates have been inserted and are ready to be aligned and glued. It was realized that the partitions also helped in controlling the fibre density. The partitions were aligned with the carbon-fibre end-plates (where the straws are fixed) in the tooling. The partitions were then glued to the carbon-fibre shell. Figure 4-29 shows the next step, where the straws are inserted with the help of a reinforcing steel bar. After insertion,

the straws were glued to the white insulation socket. The radiator volume (the volume around the straws) was put at overpressure and filled with argon to detect leaks. The leaking straw joints were reglued. The next step in the assembly chain was the HV sheets and the insertion of the wire guides. The petals were preformed with a conical metallic head to facilitate the insertion of the wire guides. Then followed the last part of the assembly before stringing, i.e. the tension plate was mounted. The cylinders around the capacitors were preglued to the tension plate and then glued to the HV sheet on the inside of the cylinders. A complete leak test of the detector gas volume could be performed only after the wires had been put in. In the next section the results from these measurements are presented.

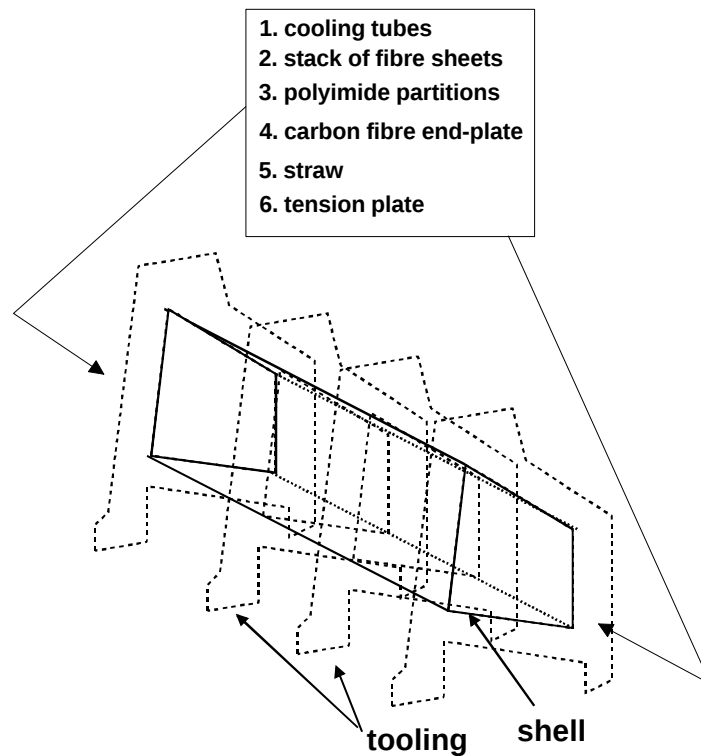


Figure 4-27: Some major assembly steps of the 0.5 m prototype.

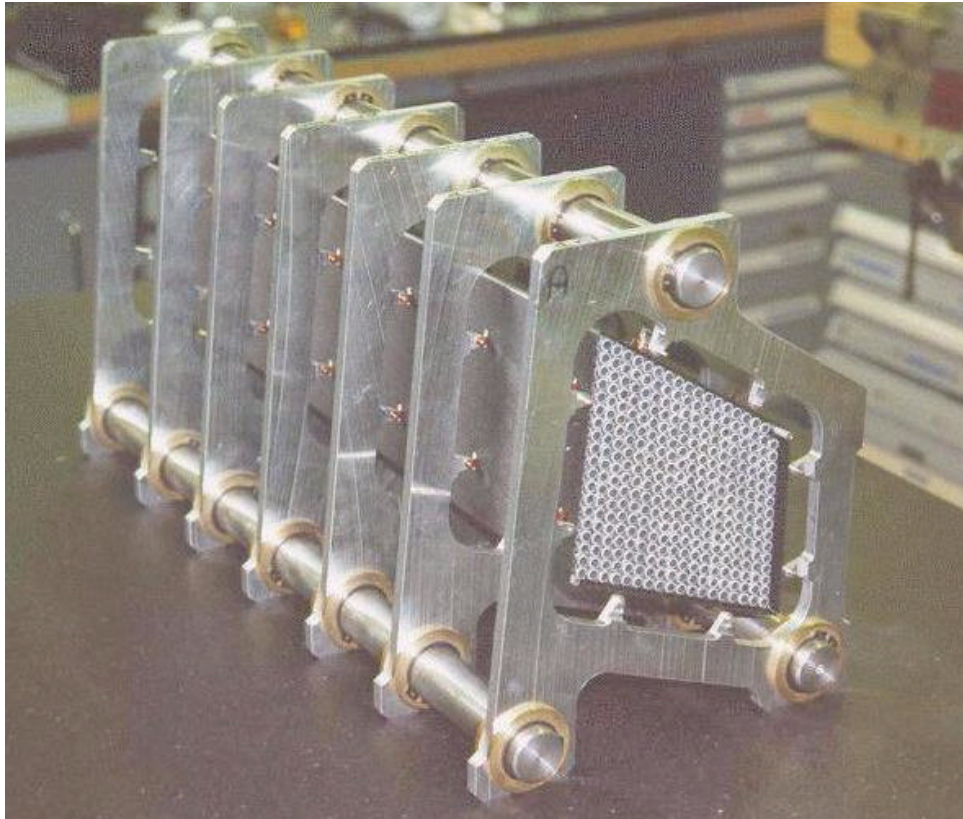


Figure 4-28: The 0.5 m barrel prototype mounted in the alignment tool. The polyimide partitions are aligned and glued to the shell and the straws are inserted ready to be glued.

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CreationDate: L: Version 1.07 Nov 3 14:29:44 1996

Figure 4-29: Insertion of the straws using a steel bar.

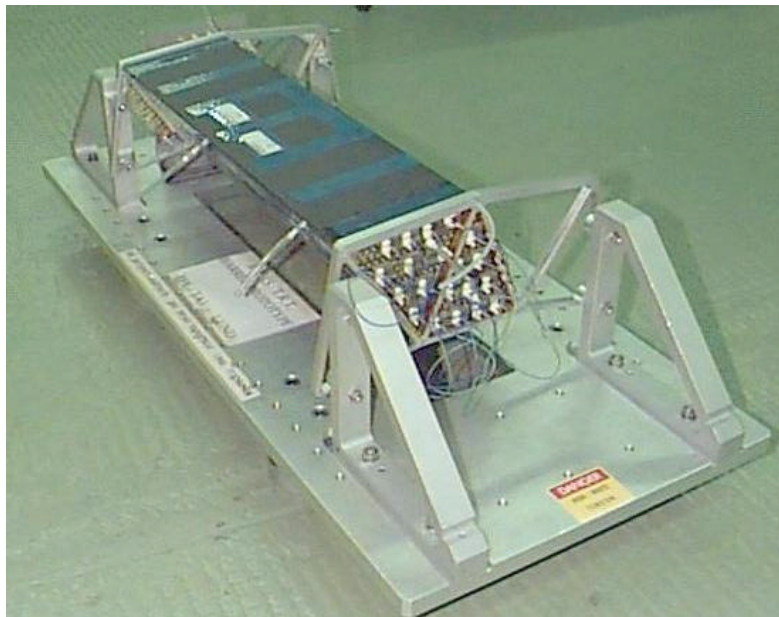


Figure 4-30: The 0.5 m barrel prototype mounted in a section of the space frame.

4.6.6.2 Tests during assembly

Various measurements were carried out on the prototype during assembly:

- Test of the HV system.
- Leak tests of the active gas volume.
- Survey measurements on the tooling.
- Wire tension test.

After the straws and the HV circuits had been installed, the HV was put on the HV groups one by one. The current was monitored as the voltage was raised slowly. It was realized at an early stage that it was necessary to work in inert conditions. Not only was the surface current too high but discharges were observed between the HV circuit and the carbon-fibre end-plate. In addition sparks were noticed inside the barrel volume. After drying out with dry nitrogen, the problems disappeared. The HV could be brought up to 2 kV and was stable for several hours with no discharges being observed. The working voltage is expected to be not higher than 1540 V, which corresponds to an amplification of $\sim 3 \times 10^4$.

All straws were leak tested before installation at the level of $\sim 1.6\%$ leak per minute at an overpressure of ~ 200 mbar [23]. Figure 4-31 shows a principal view of the straw leak-test set-up. The limiting factor in the precision of the measurement was the silicon rubber joints at the straw ends. The threshold for accepting a straw was a change of 1 mbar in 30 s. The straw volume is estimated to be 10% of the total pressurized volume.

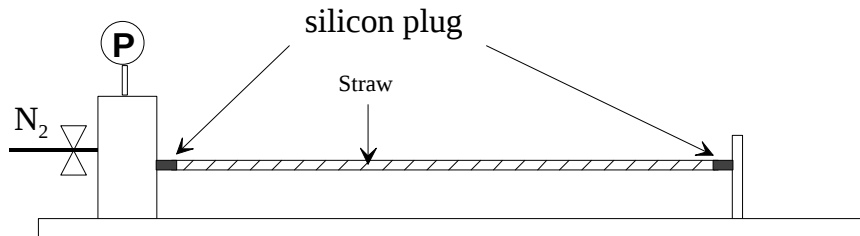


Figure 4-31: Schematic view of the test set-up for the straw leak test. The straw was pressurized with 200 mbar relative to the outside and changes in the pressure (P) were recorded.

The first leak test on the module was performed after installation of the straws to test the glue joint between the straws and the carbon-fibre end-plate. The radiator volume around the straws was given a small overpressure using CO₂ and a gas-leak detector was used to check for leaking glue joints between the straws and the end-plate. The leaking glue joints were repaired before the HV distribution circuit and the tension plates were installed. After the stringing of the wires and installation of

the capacitor cylinders between tension plate and end-plate, a global leak-rate measurement was performed. After repair of leaks, the leak rate was found to be 10 l/h at 4 mbar overpressure in the active gas volume. Remaining leaks were found in the shell itself between the tension plate and the end-plate (see Figure 4-25).

Before installation, the positions of the alignment pins for the partitions were measured on a flat table. The alignment pins for the polyimide partitions were positioned with an accuracy better than 50 μm in r - f and 0.1 mm in z . After the gluing of the partitions and the tension plates and before cutting the polyimide ears, the actual positions of the module fixation holes (the connection with the support structure) were measured. The fixation holes were found to be in position to within 0.1 mm in r - f relative to the theoretical values.

The wire tension was measured with a dedicated device [24]. It makes use of a permanent magnet and of an amplifier to excite and maintain the self-oscillation of the wires. Any displacement of the wire gives rise to a signal which is amplified in positive feedback loop. Thus an oscillation of the wire is maintained either at the fundamental resonant frequency or at a harmonic. It is similar to any electro-mechanical oscillator. A uniform constant dipole field of 4 kG over the whole straw length was used. This gives the fundamental resonance frequency, which was measured with a digital multimeter (DMM). Knowing the frequency (n), the length (l) of the wire and its mass per unit length (m), the wire tension is calculated as

$$m = \frac{4 \times m \times l^2 \times n^2}{g} \quad (4-3)$$

where g is the earth acceleration. The results from this wire tension test are shown in Figure 4-32. It shows first of all a shift in tension from the applied 50 g to ~ 27 g. Second, it shows a big standard deviation of ~ 8 g. One possible explanation for this effect is the wire fixation procedure in the tension plate. The wire was blocked with a conical pin in a socket, see Figure 4-25. No improvement was achieved after rewiring 27 wires with the lowest tension (< 15 g). It should be noted that tungsten wire has a high Young's modulus relative to, for example, copper-beryllium and therefore, the elongation of a 0.5-m-long wire is relatively small. The elongation for a 30 μm wire is ~ 0.9 mm for a 50 g load. However, the elongation is three times longer for a full-length prototype and therefore the problem will be three times smaller assuming that the loss in tension comes from pushing back the wire in the pinning procedure. The shift will decrease to ~ 8 g and the standard deviation to ~ 2.7 g. This shift can easily be compensated for by applying a bigger load. It should be noted that this method for measuring the wire tension cannot be used in the full-length prototypes because of the electrical disconnection at $z = 0$. Instead another method will be applied which makes use of a mechanical excitation of the module and measures the capacitance variance between wire and straw.

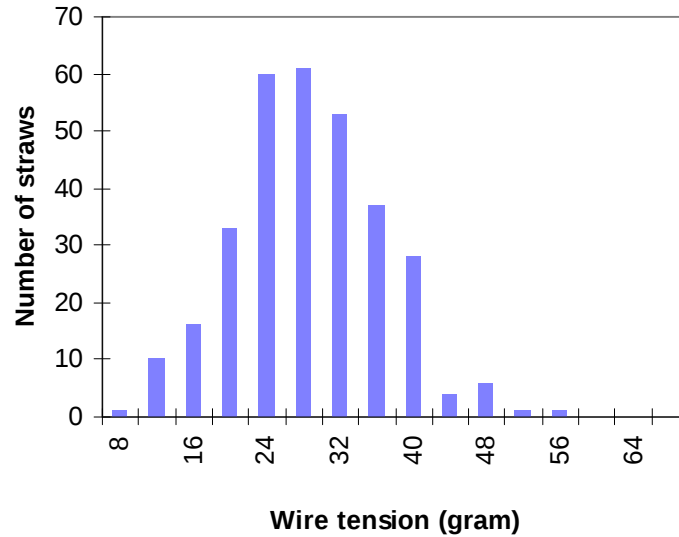


Figure 4-32: The measured wire-tension distribution (313 straws) with an applied weight of 50 g.

4.6.6.3 Experience learned from the assembly of the 0.5 m prototype

The experience gained from the first barrel prototype has verified the design and the assembly procedure. In particular, the feasibility of the very complicated module ends, the HV scheme and the alignment of the polyimide partitions has been demonstrated. Additional studies have been carried out, after assembly, on critical design issues, e.g. cross-talk, temperature distribution and TR performance. The assembly experience has resulted in the following modifications to the connectivity and assembly procedure [25]:

- During the alignment procedure the partitions were aligned with the straw fixation plate. The positioning of the tension plate, i.e. the fixation holes for the support frames, relied on the mechanical precision of the tension plate and the shell. Even though the result turned out to be satisfactory, an improvement would be to have the holes for the straws and the module fixation pins in one piece.
- Additional support (other than the polyimide ears) for the module when it is in the tooling.
- The leak-tightness of the shell at the module ends is not good enough. As can be seen from Figure 4-25, the shell is part of the gas volume and it was found that small capillaries in the shell made it possible for the

detector gas to leak into the radiator volume. A leak-tight seal on the inside of the shell will solve this problem.

- Capacitor sockets are difficult to glue to the HV polyimide sheet and are a potential source of gas leaks. New solutions for this are proposed and will be tested on the next prototypes.
- The end-plate should be fibreglass instead of carbon fibre for HV reasons.
- A different gluing procedure for the straws is necessary to improve leak-tightness and reduce the assembly time. Moulded pieces for the straws are under study.

Several of the above problems have already been corrected in the design of the next generation of barrel-module prototypes which are now under construction.

Two 1.5-m -long modules are planned to be assembled and tested in summer 1997.

4.6.7 Cross-talk

The straws in the barrel TRT have an anode wire which is electrically disconnected at $z = 0$ to reduce the occupancy, while the 158-m-long straws (cathode) are continuous. The cross-talk between the two straw ends should be low in order not to increase the occupancy. The 0.5 m prototype was equipped with electrically disconnected wires at $z = 0$ (one HV group with 16 straws). The 30 μm tungsten wires were electrically divided using a 0.8-cm-long glass tube with an outer diameter of 240 μm . The 0.5 m barrel prototype was used to measure the cross-talk from one side of the straw to the other [26]. The cross-talk in the end-plate traces was also measured.

4.6.7.1 Experimental set-up

Three different measurements were performed with two different set-ups:

1. Cross-talk on electrically divided wires at $z = 0$ using a Fe^{55} source⁴;
2. Cross-talk on electrically divided wires using a pulse-generator;
3. Cross-talk between straws using a pulse generator .

In the first set-up, a gas mixture of 70% Ar and 30% CO_2 was used and the HV was set to 1595 V. This corresponds to a gas gain of $\sim 2.6 \times 10^4$. The gas flow through the detector was in this case 15 l/h. A Fe^{55} source was placed half-way in on one side of the straw to study cross-talk induced on the opposite side (Figure 4-33a). The signal passed a preamplifier and a shaper before arriving at the oscilloscope.

⁴ Fe^{55} radiates γ -rays with an energy of 5.9 keV.

Figure 4-33b shows the connection scheme for the second set-up. A pulse generator was used to produce a square wave with amplitude 1 V and a period of $T = 350$ ns. The rise time was ~ 15 ns. The opposite side of the straw was measured with the oscilloscope.

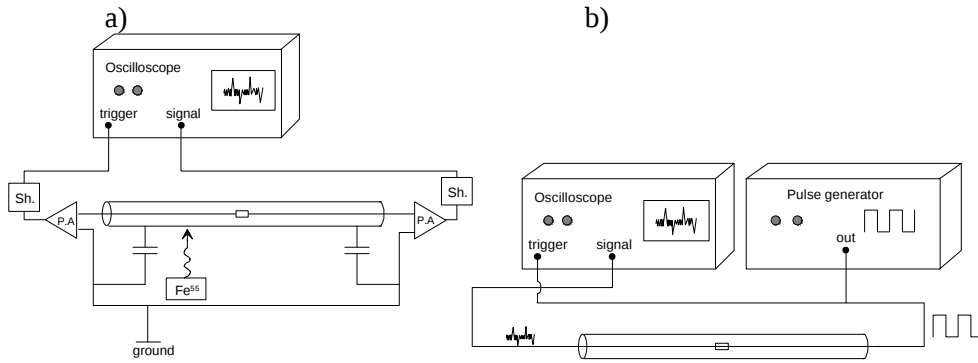


Figure 4-33: Set-up for cross-talk measurement on the broken wire with (a) a Fe^{55} source and (b) a pulse generator.

Figure 4-34 shows the third experiment. The signal was sent through different straws with continuous wires marked R1 to R10 in Figure 4-35. The cross-talk to neighbouring straws numbered 1.1 to 10.1 was measured with the oscilloscope. The same square wave as above was used and the rise time of the signal was 15 and 20 ns before and after the straw, respectively, as shown in Figure 4-36. As can be seen from Figure 4-35, some traces from wire fixation pin to connector are longer. An attempt was made to select first the channels with the longest parallel traces, i.e. the largest cross-talk.

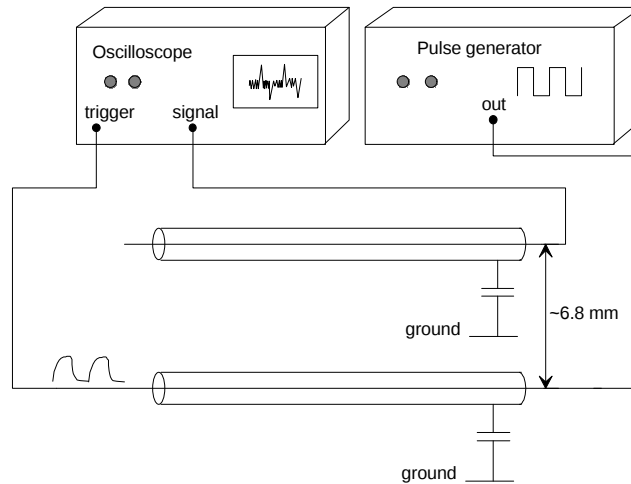


Figure 4-34: Set-up for cross-talk measurement between individual straws.

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Figure 4-35: View of the tension-plate layout where the signal straws are marked with R1 to R10 and the measured straws 1.1 to 10.1.

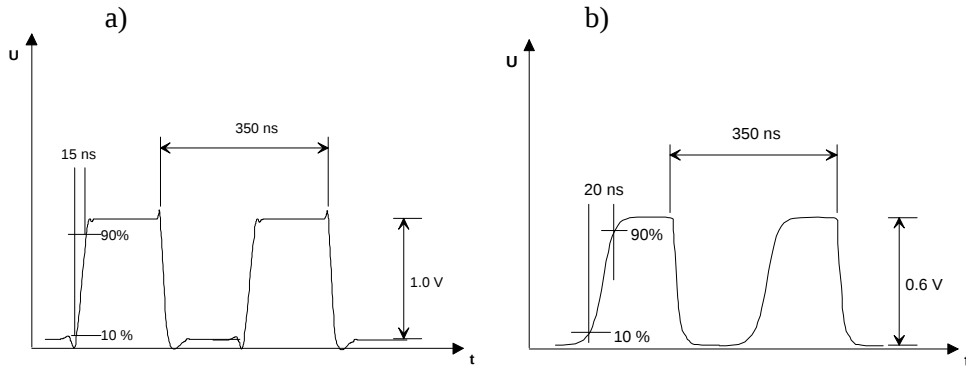


Figure 4-36: Signal shape (a) before and (b) after the straw.

4.6.7.2 Results

- Cross-talk over electrically divided wire.

Figure 4-37 shows the signal on the source side which was used to trigger the reading of the opposite side of the straw. A threshold of 65 mV was used which corresponds to $\sim 5\%$ of the signal on the opposite side of the straw. No cross-talk could be seen at this threshold. With the pulse generator, a few straws out of the 16 possible were measured and the cross-talk was found to be less than 0.5% in all cases.

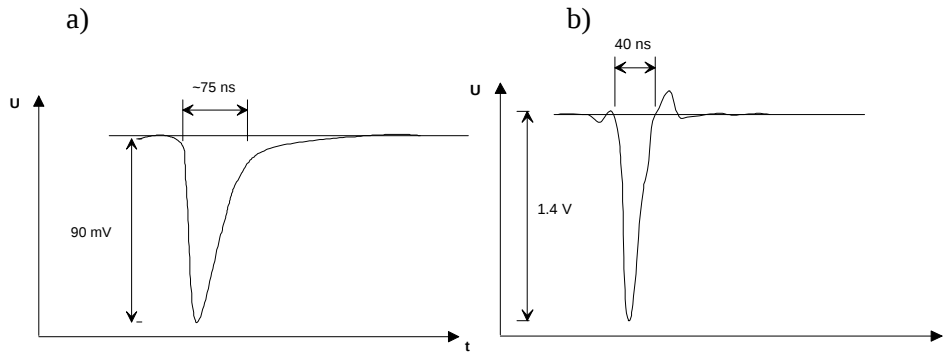


Figure 4-37: Signal from a Fe^{55} source (a) before and (b) after the shaper.

- Cross-talk between different straws

The cross-talk was defined as the ratio between the maximum induced amplitude (E_c) on a straw and a pulse with amplitude E_i on a neighbouring straw, as shown in Figure 4-38.

The cross-talk between straws was found to be dominated by the cross-talk in the tension plate. Straws far away from each other were found to have a cross-talk below $\sim 1\%$. If traces in the tension plate were long and close to each other the cross-talk could be as high as $\sim 8\%$. Neighbouring straws corresponding to well separated traces in the tension plate showed a

cross-talk of $\sim 1\text{-}2\%$, i.e. close to that measured for straws far away from each other. Detailed values for different measured straws are given in Table 4-2. Figure 4-39 shows the correlation between the cross-talk and the dimensionless parameter L/d , where L is the length of the traces and d is the distance between them. A mean value of L and d was estimated from the AUTOCAD drawing. The error in the cross-talk measurement is estimated to be $\sim 0.5\%$.

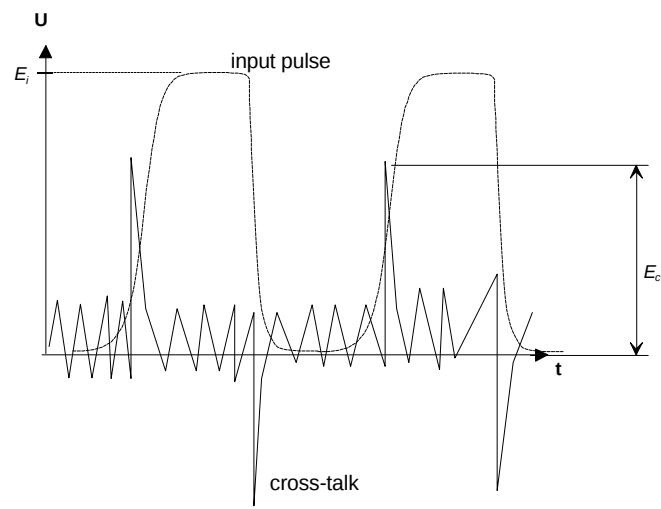


Figure 4-38: Typical cross-talk between two neighbouring straws where the traces on the tension plate are close to each other. Measured values are given in Table 4-2.

Signal straw	Measured straw	Cross-talk (%)	Signal straw	Measured straw	Cross-talk (%)
R1	1.1	4.1	R5	5.1	6.7
“	1.2	3.3	“	5.2	3.3
“	1.3	0.3	R6	6.1	6.7
“	1.4	1.6	R7	7.1	6.7
R2	2.1	8.3	“	7.2	2.5
“	2.2	1.6	R8	8.1	6.7
R3	3.1	4.1	R9	9.1	5.8
R4	4.1	2.5	R10	10.1	5.0
“	4.2	2.5			
“	4.3	4.1			

Table 4-2: Cross-talk between different straws (see Figure 4-35).

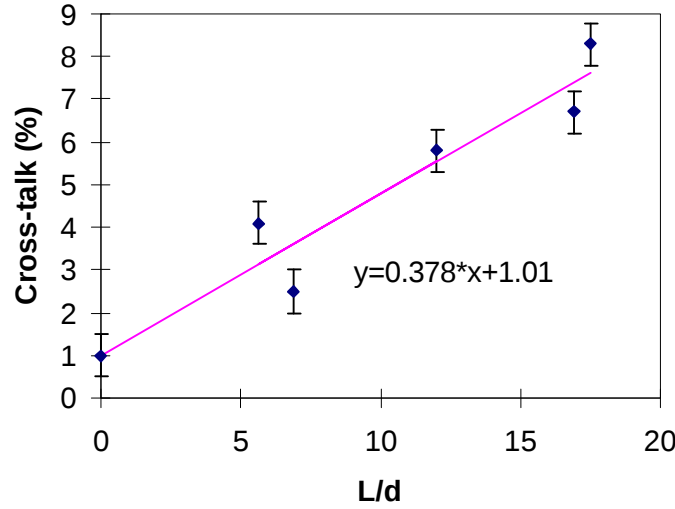


Figure 4-39: Cross-talk as a function of L/d , where L is the length of the traces and d is the distance between them (from Table 4-2).

4.6.7.3 Conclusion and discussion

- The results from the first measurement with the broken wires show that the cross-talk is below threshold when using the Fe^{55} source. The threshold in this case was $\sim 5\%$ after the shaper. With the pulse generator the cross-talk was found to be $< 0.5\%$.
- In the second experiment the cross-talk between neighbouring straws was found to be dominated by the cross-talk in the tension plate. A typical value is 1-2% for neighbouring straws, but it can be as high as $\sim 8\%$ (one straw) if nearby traces in the tension plate are long. It is important to note that channels with very long and close traces were picked out first. By adding measured straws above 5% plus the corresponding signal straws in Table 4-2, it can be estimated that the cross-talk is higher than 5% in $\sim 5\%$ of the channels.
- A typical figure of merit would be to relate the cross-talk to the average dE/dx pulse height of ~ 2 keV expected per straw. If the cross-talk were not to significantly increase the measured noise of ~ 70 eV, then it should not exceed about 2%.
- The tension plate has now been redesigned, based on the information in Figure 4-39.

4.6.8 Heat conductivity measurement on radiator materials

4.6.8.1 Experimental set-up

A schematic view of the experimental set-up is shown in Figure 4-40. A 50 mm inner diameter aluminium tube defines an isothermal surface around the radiator to be tested. In the centre of the radiator sample, a 5 mm hole is drilled to house a straw with a heating wire in the centre. The outer diameter of the straw is 4.4 mm. Two platinum resistors (Pt-100⁵) are mounted on the straw wall (T1) and on the outer aluminium cylinder (T2). A current is applied on the heating wire and the temperature difference between T2 and T1 is measured. Both the current I and the voltage U of the heater wire are measured with a digital voltmeter over the straw length of 0.5 m and the current is adjusted to obtain a temperature difference between the two sensors of a few degrees.

Three radiator samples were tested: two fibre radiators and one foam radiator. The fibre radiators are 50% polypropylene and 50% polyethylene, while the foam radiator is 100% polypropylene. The orientation is $\sim 80/20$ for the oriented fibre.

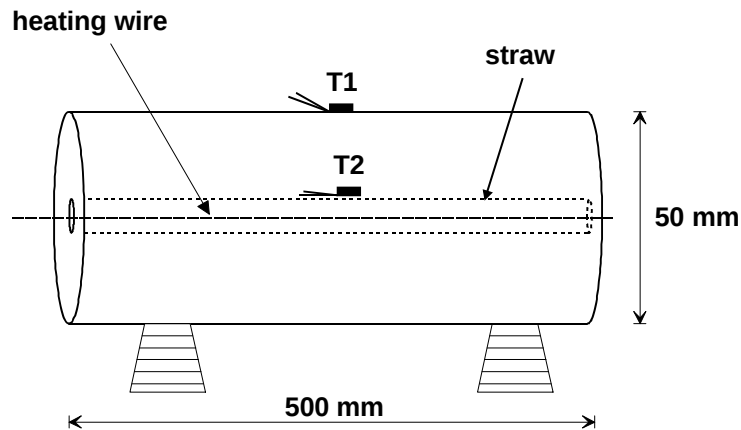


Figure 4-40: Schematic view of the thermal conductivity set-up.

4.6.8.2 Calculation method

Cylindrical co-ordinates and the temperature equation give

$$Q \times dr = 2 \times p \times r \times l \times dT \quad (4-4)$$

⁵ Pt-100 is a calibrated resistive thermal sensor.

where r is the radius, l is the thermal conductivity and dT the temperature difference. The heat Q is expressed in W/m and is calculated as

$$Q = \frac{U \times I}{l} . \quad (4-5)$$

From equation (4-4) follows

$$l = \frac{\int_a^b \frac{Q}{2 \times p} \times \frac{dr}{r}}{\Delta T} \quad (4-6)$$

and finally

$$l = \frac{Q}{2 \times p \times \Delta T} \times \ln\left(\frac{b}{a}\right) \quad (4-7)$$

4.6.8.3 Results

The results from the measurements are summarized in Table 4-3. The measurements were carried out in air at 20 °C. Despite its lower density, the oriented fibre radiator seems to have a greater thermal conductivity than the foam. This can be explained by the fact that the fibre is more transparent to convection.

Material	Density (kg/m ³)	Conductivity (W/m/K)
Foam	85	0.042 ± 0.006
Fibre non-oriented (installed in the 0.5 m prototype)	120	0.059 ± 0.008
Fibre oriented (installed in the 0.5 m prototype)	70	0.052 ± 0.007

Table 4-3: The measured thermal conductivities for some radiator materials and their estimated errors.

4.6.8.4 Estimation of the error

Assuming that the errors are uncorrelated and by differentiating equation (4-7), the error in l can be estimated as follows:

$$s_l^2 = \left(\frac{\partial l}{\partial \Delta T} \right)^2 \times s_{\Delta T}^2 + \left(\frac{\partial l}{\partial Q} \right)^2 \times s_Q^2 + \left(\frac{\partial l}{\partial b} \right)^2 \times s_b^2 + \left(\frac{\partial l}{\partial a} \right)^2 \times s_a^2 \quad (4-8)$$

where $s_b = 1\text{mm}$, $s_a = 0.5\text{ mm}$, $s_Q = 5 \times 10^{-3}\text{ W}$, $s_{\Delta T} = 50 \times 10^{-3}\text{ K}$.

With $DT = 5\text{ K}$, $Q = 0.5\text{ W/m}$, $b = 25\text{ mm}$ and $a = 2.4\text{ mm}$ the relative error in l becomes

$$\frac{s_l}{l} = \sqrt{0.01^2 + 0.01^2 + 0.017^2 + 0.089^2} \approx 0.1 .$$

It is concluded that the main error comes from the uncertainty in the positioning of the temperature sensor at the inner radius. The total error is estimated at 10%.

4.6.9 Cooling of the modules

4.6.9.1 Requirements

In the ATLAS TRT, heat is generated in the proportional tubes (straws) as the positive ions, created by the ionizing particles, form a current driven by the HV on the straws. This heat has to be removed and the barrel modules are cooled by water running along two cooling tubes on opposite corners of each module [27, 28]. The cooling tubes are thermally grounded to the shell to minimize the temperature difference between the shell and the coolant. The shell forms a semi-isothermal surface around each module. Even though the heat production is low the modules will experience a temperature difference (DT) because of the insulating properties of the radiator material. The DT , if it exceeds a certain value, can create problems. One problem is changes of the dimensions and displacement of the wires. Temperature changes will also influence the gas amplification due to changes in the gas density. The change in the amplification degrades the electron identification performance as the thresholds for TR hits are related to one value of the gas amplification. It also changes the threshold for the drift-time measurement. It has been shown that the limiting factor for the temperature differences in the barrel is the electron identification and mechanical aspects [29]. A 25% change in gas gain is acceptable and corresponds to a change of 15 K for a 30 μm wire and 10 K for a 50 μm wire. A maximum temperature difference of 10 K is considered acceptable. Therefore,

from a physics performance point of view, a temperature difference of 10 K contains some margin of safety when using the 30 μm wire.

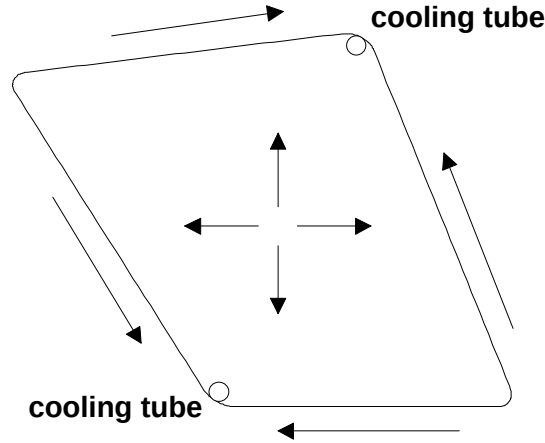


Figure 4-41: Schematic view of the heat transport and cooling of the barrel TRT modules.

4.6.9.2 Analytical calculations

In the calculation below, the shell is assumed to have infinite thermal conductivity and isothermal boundaries, but in reality a temperature gradient is present in the shell to drive the heat towards the cooling tubes. A schematic of the heat transport is shown in Figure 4-41. Results on thermal conductivity measurements of the shell material are reported in Ref. [30]. From these measurements of the thermal conductivity, the maximum DT in the shell walls can be estimated to be < 4 K.

Before the temperature difference in the modules is calculated, we consider the heat dissipation in the straws. The heat dissipation arises from the ions, created by the ionizing particles, drifting from the anode wire to the cathode. This current I can be written as

$$I = \text{Gain} \times \text{Rate} \times q \times N \quad (4-9)$$

where N is the mean number of primary ions. At full luminosity, the maximum expected values for a 1.6-m-long straw at a radius of 63 cm are [4]:

$$\begin{aligned}
Gain &= 4 \times 10^4 \\
N &= 65 \\
Rate &= 3 \times 10^7 \text{ s}^{-1} \\
q &= 1.602 \times 10^{-19} \text{ C}
\end{aligned}$$

Normalized to a 1-m-long straw and assuming a uniform rate distribution along the straw, the current density is $I = 7.8 \times 10^{-6} \text{ A/m}$, and for a potential $U = 1800 \text{ V}$, the power dissipation per 1-m-long straw is

$$P = I \times U = 14 \text{ mW / m} \quad (4-10)$$

Because of the rapidly decreasing particle fluxes in the barrel TRT as the radius increases, the rate varies with radius as $\sim r^{-2.5}$, and therefore a *mean* heat dissipation per 1-m-long straw (q_m) is calculated, which is used in both calculations and in the experiment below. The mean heat dissipation is calculated as

$$q_m = \frac{1}{R_o - R_i} \times \int_{R_i}^{R_o} Q(r) \times dr \quad (4-11)$$

where

$$Q(r) = \frac{q_s}{r^{2.51}} \quad (4-12)$$

and R_i and R_o are the inner and outer radii, respectively, of the inner module. The heat density is calculated to be 14 mW/m per straw, which is approximately the same as the heat dissipation at $r = 63 \text{ cm}$. For the two outer modules the corresponding values are 8.2 mW/m (middle) and 4.8 mW/m (outer). The estimate of the heat dissipation in the inner module is on the conservative side for the total heat as the wires have a passive part for $r < 63 \text{ cm}$ as discussed in Section 4.6.1. On the other hand all the wires are active over a considerable length (36 cm) at both ends of the modules.

The total heat production for the 329 straws in the 0.5 m prototype, with the values above, is then given by

$$P_{tot} = 329 \times 0.5 \text{ m} \times 14 \frac{\text{mW}}{\text{m}} = 2.3 \text{ W} \quad (4-13)$$

Furthermore, the module is approximately described as a rectangular block as shown in Figure 4-42, with the same volume per unit length and $a = b$ [5]. The equivalent sides for the three modules were calculated from the AUTOCAD file as 12.8 cm , 16.0 cm and 19.7 cm for the inner, middle and outer modules respectively. The total heat production in the module is translated into a *uniform* heat density q by dividing by the module volume. The temperature equation

$$\nabla^2 T(x, y, z) + \frac{q}{l} = 0 \quad (4-14)$$

is solved in the volume and with isothermal boundaries where l is the thermal conductivity of the bulk. The maximum temperature, i.e. in the centre, is calculated. The temperature difference between a point in the volume and the isothermal boundaries can be expressed as

$$\Delta T(x, y, z) = \frac{64}{\pi^3} \cdot \left(\frac{q}{\lambda} \right) \cdot \left[\sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\sin \left[(2l+1) \cdot \pi \cdot \frac{x}{a} \right] \cdot \sin \left[(2m+1) \cdot \pi \cdot \frac{y}{b} \right] \cdot \sin \left[(2n+1) \cdot \pi \cdot \frac{z}{c} \right]}{\left[\frac{(2l+1)^2}{a^2} + \frac{(2m+1)^2}{b^2} + \frac{(2n+1)^2}{c^2} \right] \cdot (2l+1) \cdot (2m+1) \cdot (2n+1)} \right] \quad (4-15)$$

by using Green's functions [31]. For a given geometry the maximum DT varies linearly with (q/l) . The value of the thermal conductivity is taken from the measurements on the two fibre radiators installed in the prototype, presented in the previous section. 10% of the fibre sheets were oriented and 90% non-oriented. The average of the two radiators is calculated as

$$l = (0.9 \times 0.059 + 0.1 \times 0.052) \frac{W}{m \times K} = \frac{0.058 \times W}{m \times K} \quad (4-16)$$

Note that this is an estimate of the bulk conductivity based on pure radiator material without straws, carbon reinforcements, wires, etc. Figure 4-43 shows the temperature difference as a function of the module length c , for the three module types. The inner module represents the worst case because of the strong radial dependence of the occupancy even though the outer module contains more than twice as many straws.

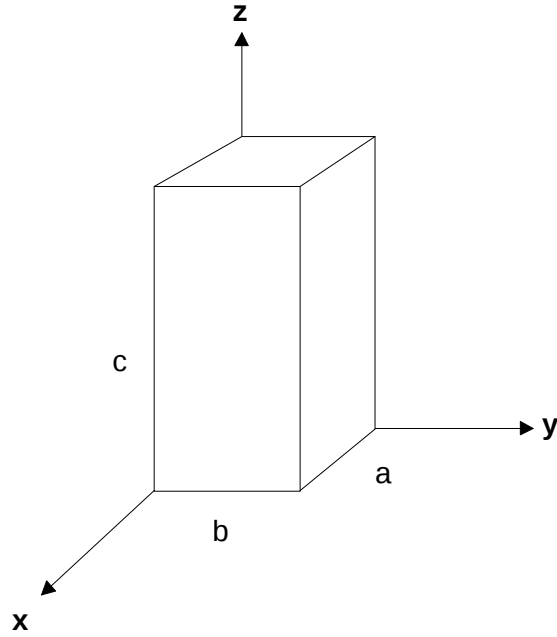


Figure 4-42: Geometrical model of the barrel module used in Equation 4-15.

By taking the maximum temperature difference in the centre one obtains

$$T\left(\frac{a}{2}, \frac{b}{2}, \frac{1.5\text{m}}{2}\right) - T\left(\frac{a}{2}, \frac{b}{2}, \frac{0.5\text{m}}{2}\right) < 0.1\text{K} \quad (4-17)$$

It is clear that a 0.5-m-long module is a good approximation of a 1.5-m-long module. The maximum calculated temperature differences are 5.9, 5.4 and 4.8 K for the inner, middle, and outer modules respectively.

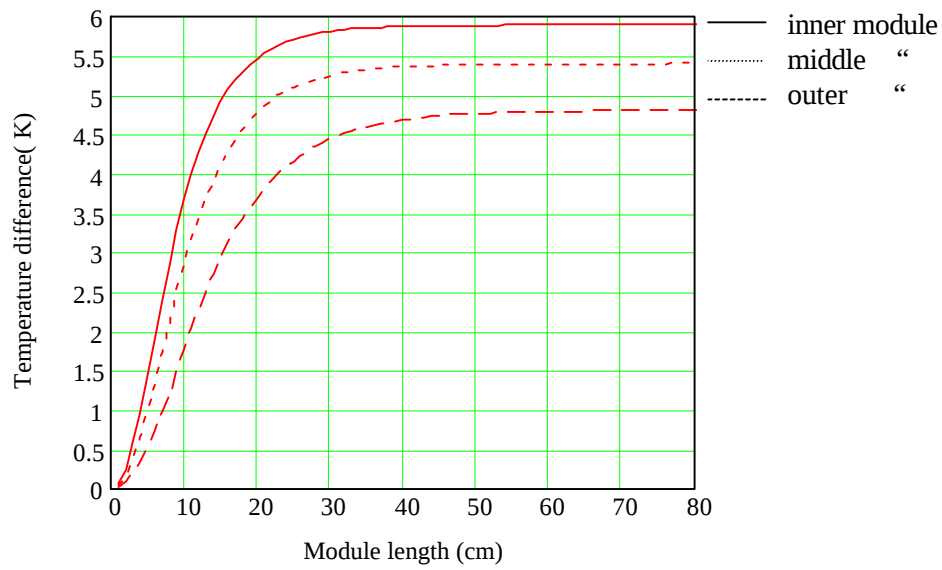


Figure 4-43: Calculated maximum temperature difference between the centre of the module and the shell, as a function of the module length for the inner, middle, and outer modules respectively, assuming isothermal boundaries.

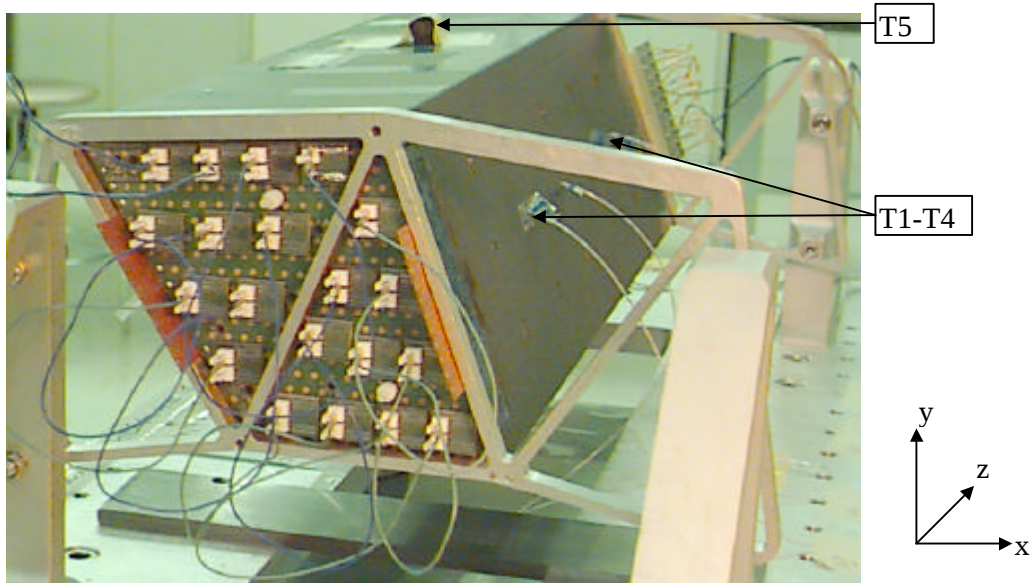


Figure 4-44: Experimental set-up showing the daughter cards on the tension plate and the positions of the thermal sensors T1 to T5. T6 is mounted on the aluminium support plate (not shown in picture).

4.6.9.3 Experimental set-up.

Pt-100s were used to measure the temperatures in six different positions: four inside the detector volume, one on the shell and one on the aluminium structure. The four sensors inside the module are placed in the centre of the module (in x, y). A side-view of the experimental set-up and the positions of the thermal sensors are shown in Figure 4-44. In the z -direction, T1 is placed at 32 cm, T2 at 24 cm, T3 at 16 cm and T4 at 8 cm from the module end-plate. A constant current of 100 mA was sent through the temperature sensors. The voltages were read by a DVM/scanner connected to a PC where the readings were converted to temperatures and written to a file. To simulate the heat dissipation in the ionization gas, as calculated in Equation (4-13), a current was sent through the wires. Groups of 16 channels were connected in parallel using small daughter-cards. The HV group which was equipped with the wire joints at $z = 0$ was not connected, but was compensated for by increasing the current through the other straws so that the total power was 2.3 W. It should be noted that the sensors integrate to some extent since they have a length of 10 mm. Taking into account both the error in the sensor positions and their dimensions, the uncertainty is less than ~ 0.1 K. The shell is considered to be isothermal and is cooled by convection by the surrounding air. In the final modules, the heat will be conducted by the semi-isothermal carbon-fibre shell to the two cooling tubes in the module corners.

4.6.9.4 Results from measurements

The measurements were recorded over a period of ~ 23 h, for which the full heating power of 2.3 W was switched on only after ~ 200 min. The measured absolute temperatures are shown in Figure 4-45. The room was air-conditioned and gave rise to temperature oscillations of ~ 2 K, but a *mean value* was calculated for $800 \text{ min} < t < 1300 \text{ min}$. The temperature differences for T1 to T4 are defined as

$$\Delta T_i = T_i - T_5 \quad \text{where } i = 1 - 4 \quad (4-18)$$

and are shown in Figure 4-46. In Figure 4-47, a comparison between calculations and the experimental points is shown. The calculations agree well with the measurements (with $l = 0.058 \text{ W/m/K}$ as measured in Section 4.6.8) for the four measuring points at different z . Note how the boundary effects from the end-plates become important at $z = 8 \text{ cm}$ (T4). For T1 to T3 on the other hand, the boundary effect is small. The maximum measured temperature difference is 5.8 K which corresponds to an effective bulk conductivity of $l = 0.059 \text{ W/m/K}$.

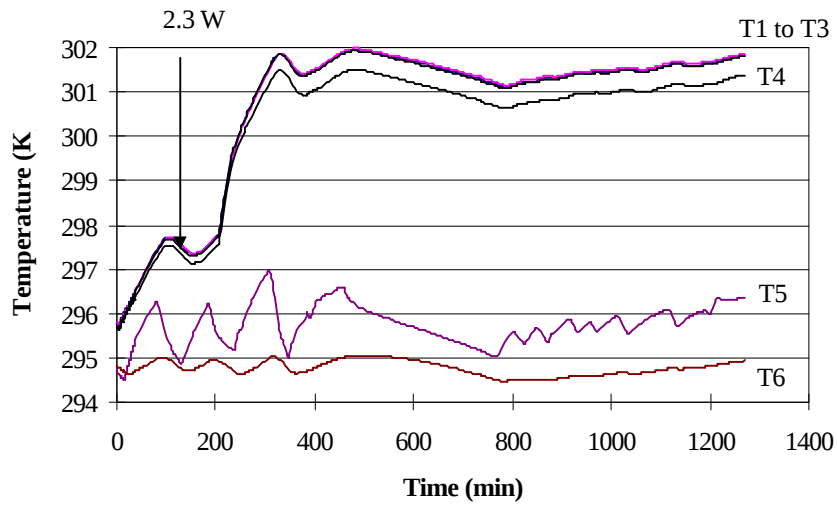


Figure 4-45: Temperatures measured by T1 to T6 over a period of 23 h. Note the fluctuations observed in the ambient air as measured by T5 (shell reference), which are smoothed out for T6 (aluminium structure).

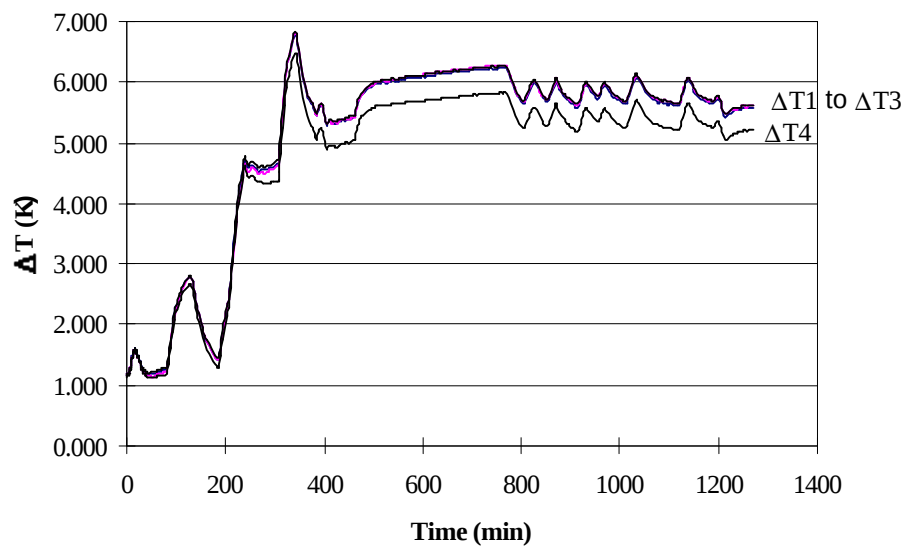


Figure 4-46: Measured temperature differences between the shell and the centre of the module.

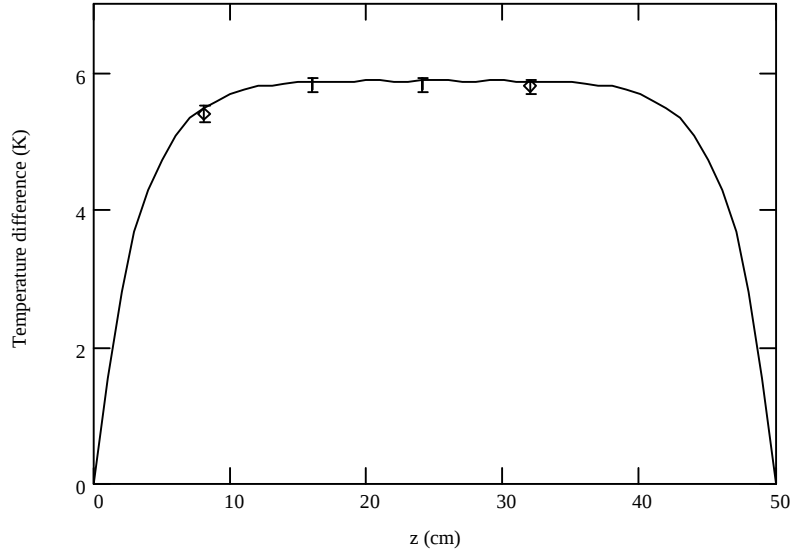


Figure 4-47: Calculated temperature difference in the centre of the module at different z (solid curve) and the experimental points (T1 to T4).

4.6.9.5 Temperature gradient at the cooling-tube interface

Different design options have been under consideration for the cooling of the shells. Figure 4-48 shows a cross-section of one of the module corners. An aluminium tube is glued on the inside of the shell in two opposite corners. A second tube is inserted in the first one. This second tube, which is longer than the module itself, permits the connection to be made away from the crowded module ends and avoiding joints close to the HV and the electronics. The DT along the tube is assumed to be negligible. With the notations of Figure 4-48, the temperature difference can be calculated as

$$\Delta T_n = \frac{q \times d_n}{2 \times p \times r_n \times l_n} \quad (4-19)$$

for the individual material components, where q is the heat flow per metre of tube, d_n the thickness, r_n the radius and the l_n the conductivity in layer n . The estimated fraction of the tube surface in contact with the shell is 25%. The total DT is the sum of the temperature differences and is calculated to be below 2 K even taking into account a double tube. The main contribution comes from the air gap between the two cooling tubes. It should be noted that this is conservative as in reality the tubes will inevitably be in contact with each other at certain points along the tube, which will help to decrease the DT . It should be pointed out that the DT between cooling

tube and coolant does not affect the temperature gradient in the shell itself, but only increases the absolute temperature.

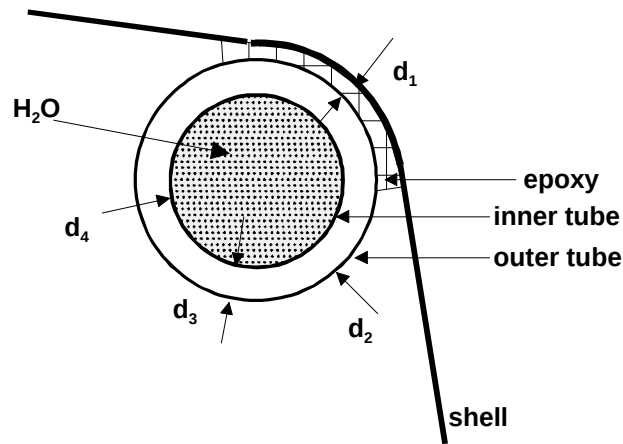


Figure 4-48: Schematic view of the cooling tube in the shell corner .

The temperature of the coolant therefore has to be adjusted so that the absolute module temperature is stable at the desired value.

4.6.9.6 Conclusions and remarks on the module cooling

The maximum acceptable temperature difference inside the barrel TRT has been determined to be 10 K. To achieve this, the barrel modules are cooled individually with water. Two cooling tubes are glued axially in two opposite corners, on the inside of each carbon-fibre shell.

We have demonstrated with both measurement and calculation that the DT is below 6 K in the barrel TRT modules assuming isothermal boundaries. The measurements are in good agreement with calculations. Taking into account the heat conductivity of the shells, the maximum total DT will be less than 10 K. In addition, the CO_2 ventilation of the radiator is expected to decrease the DT , but how much depends on the final flow rate.

The thermal conductivity between the shell and the coolant has been calculated, assuming reasonable design parameters. The DT over the joint was determined to be below 2 K.

One remark should be made concerning the electronics on the module ends. The calculation and measurements above assume that the electronics cooling is sufficiently efficient to avoid a flow of heat into the detector volume. To guarantee this the electronics cooling has to be able to keep the tension plate below the maximum temperature difference calculated above (6 K).

4.6.10 Tracking performance for a modular layout

An important consideration in the development of the barrel layout and the introduction of a modular geometry is the tracking performance. A dedicated program was developed to compare different straw layouts and module shapes [32, 33]. Of particular interest is the difference between an optimized uniform straw distribution and a straw distribution based on a modular layout. In all simulations 1000 tracks at $h = 0$ have been generated at random f , for each momentum and layout. The study is purely geometric, i.e. only the number of traversed straws are counted. A magnetic field of 2 T was used and the effective straw radius is assumed to be 1.9 mm. As a measure of the performance of the different layouts the following parameters are considered:

- mean number of crossed straws for each track (N_{STRAW});
- *rms* of N_{STRAW} ;
- maximum number of consequent *missed* layers for each track (N_{SPACE});
- *rms* of N_{SPACE} .

N_{STRAW} gives information about any dead zone and N_{SPACE} indicates the uniformity of hits along the tracks. Both negative and positive tracks are generated to indicate any charge asymmetry between the different straw layouts. In the layout below, a positive track is defined as a deflection to the left and a negative track to the right. In addition, the fraction of tracks with **31 and 30** hits or more is shown for the different layouts.

4.6.10.1 Geometry

The number of straws in the three modules is: 329, 520 and 793 for the inner, middle and outer modules respectively. Two straws are removed from each module to provide space for cooling pipes. The generated tracks are totally enclosed in the barrel ($|h| < 0.7$), only producing hits if $63 \text{ cm} < r < 107 \text{ cm}$ as the wires are inactive at $r < 63 \text{ cm}$. This reduces the number of active straws in the inner module from 329 to 182. The number of active layers is 10, 24 and 34 for the inner, middle and outer modules respectively. This is the same total number of layers as for the uniformly distributed straw layout without module boundaries referred to as Layout 1 below [34]. The mean distance between the straws in all layouts is close to 6.8 mm. Four different layouts were studied :

1. no modular layout and the layers are in groups of eight with the same number of straws (see Figure 4-49a);
2. two cooling pipes per module and $d = 5.2 \text{ mm}$ (see Figure 4-49b);
3. same as 2, but no cooling pipes;
4. same as 2, but no cooling pipes and $d = 0$;

5. same as 2, but $d = 6$ mm.

Layout 1:

This geometry has no modules and the straws are uniformly distributed. The total number of straws is 50 288, which corresponds to a mean distance between the straws of approximately 6.8 mm, see Figure 4-49a. The number of straws per layer is constant within a group of eight straws. There are 64 layers in total. This geometry is described in more detail in Ref. [34]. It can be considered as a 'reference layout' in the discussion of the tracking performance of the different modular layouts.

Layout 2:

The 3×32 module layout contains 182, 520 and 793 active straws for the inner, middle and outer modules respectively at $h = 0$. The 64 straw layers give a total of 47 840 active straws. The total number of straws is less than in Layout 1 because of the introduction of module shells for approximately equal straw density. The minimum distance between the straws and any boundary is $d = 5.2$ mm, see Figure 4-49.

Layout 3:

The same Layout 2 except there are no cooling pipes and there are 183, 522 and 795 active straws in the inner, middle and outer modules, respectively. The distance from the boundary to the nearest straw is $d = 5.2$ mm.

Layout 4:

The same number of straws as in Layout 3 and a slightly increased distance between the straws as $d = 0$.

Layout 5:

This layout contains two cooling pipes, i.e. the same number of straws as in Layout 2, but the distance between the module boundary and the nearest straw is increased to $d = 6$ mm.

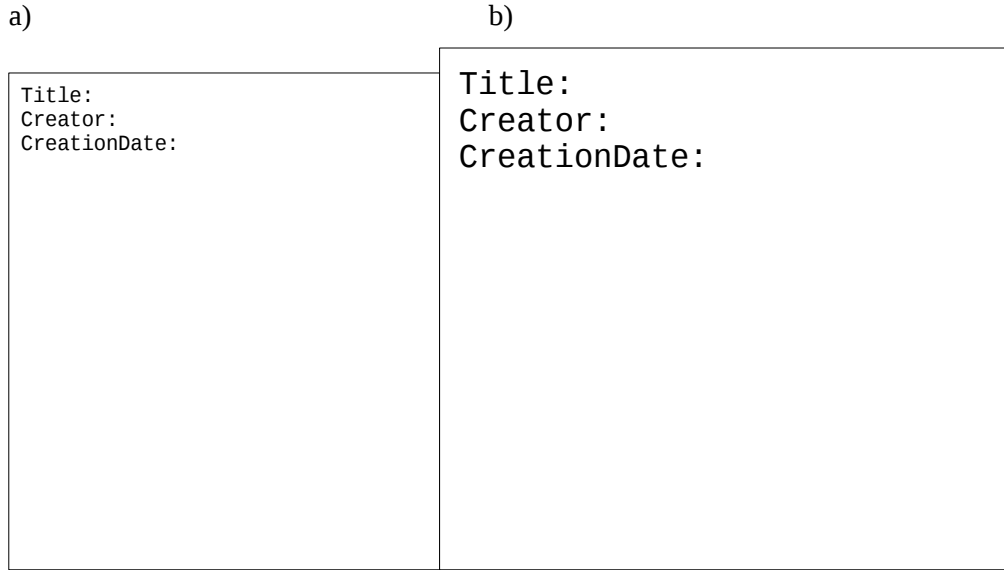


Figure 4-49: (a) Straw geometry as proposed in [34] with eight superlayers of eight layers; (b) a modular geometry with 3×32 modules, two cooling pipes per module and $d = 5.2$ mm (between each module boundary and the nearest straw).

4.6.10.2 Results

The results from the simulations are presented in Table 4-4 to 4-11.

	100 GeV	1 GeV positive	1 GeV negative	2 GeV positive	2 GeV negative	3 GeV positive	3 GeV negative
N_{STRAW}	35.8	37.1	37.0	36.0	35.9	35.7	35.7
rms	1.85	2.71	2.44	1.83	2.01	2.40	2.30
N_{SPACE}	2.76	4.51	4.19	3.44	3.28	3.40	3.63
rms	0.43	0.84	0.67	0.60	0.48	0.60	0.67
> 31 hits (%)	99.9	98.3	98.6	99.1	98.4	97.1	97.4

Table 4-4: Tracking performance for Layout 1.

	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
N_{STRAW}	35.8	34.14	34.36	34.34	34.09
rms	1.85	2.16	2.16	2.07	2.62
N_{SPACE}	2.76	4.05	3.92	3.25	4.49
rms	0.43	0.87	0.77	0.54	1.07
> 30 hits (%)	-	95.6	96.7	97.1	92.1
> 31 hits (%)	99.9	89.4	91.5	91.2	83.8

Table 4-5: Tracking performance for 100 GeV particles.

	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
N_{STRAW}	37.1	35.47	35.43	35.75	35.48
rms	2.71	3.36	3.42	3.33	3.34
N_{SPACE}	4.51	5.72	5.58	5.21	6.23
rms	0.84	1.57	1.59	1.34	1.99
> 30 hits (%)	-	92.8	93.5	94.2	92.4
> 31 hits (%)	98.3	88.0	87.4	90.3	89.1

Table 4-6: Tracking performance for **positive** 1 GeV particles.

	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
N_{STRAW}	37.0	35.44	35.53	35.51	35.38
rms	2.44	2.76	2.69	2.61	2.77
N_{SPACE}	4.19	5.13	5.02	4.68	5.42
rms	0.67	1.31	1.26	1.31	1.77
> 30 hits (%)	-	96.1	97.2	97.9	95.7
> 31 hits (%)	98.6	91.5	93.6	93.9	91.5

Table 4-7: Tracking performance for **negative** 1 GeV particles.

	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
N_{STRAW}	36.0	34.41	34.45	34.57	34.53
rms	1.83	2.44	2.47	2.53	2.66
N_{SPACE}	3.44	4.35	4.3	3.71	4.92
rms	0.60	0.84	0.86	0.70	1.1
> 30 hits (%)	-	95.2	95.2	93.1	94.2
> 31 hits (%)	99.1	90.5	89.6	88.6	87.8

Table 4-8: Tracking performance for **positive** 2 GeV particles.

	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
N_{STRAW}	35.9	34.35	34.54	34.62	34.49
rms	2.01	2.19	2.22	2.15	2.63
N_{SPACE}	3.28	4.38	4.24	3.58	4.73
rms	0.48	0.91	0.89	0.61	1.09
> 30 hits (%)	-	96.4	95.9	96.7	94.2
> 31 hits (%)	98.4	91.2	88.2	92.6	88.2

Table 4-9: Tracking performance for **negative** 2 GeV particles.

	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
N_{STRAW}	35.7	34.37	34.44	34.4	34.34
rms	2.40	2.53	2.47	2.41	2.78
N_{SPACE}	3.40	4.24	4.17	3.50	4.71
rms	0.60	0.78	0.75	0.61	1.01
> 30 hits (%)	-	94.3	94.6	94.8	94.1
> 31 hits (%)	97.1	88.7	88.3	89.7	88.3

Table 4-10: Tracking performance for **positive** 3 GeV particles.

	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5
N_{STRAW}	35.7	34.32	34.56	34.45	34.40
rms	2.30	2.33	2.35	2.33	2.69
N_{SPACE}	3.63	4.16	4.11	3.43	4.56
rms	0.67	0.87	0.86	0.59	1.08
> 30 hits (%)	-	95.5	96.1	95.6	93.0
> 31 hits (%)	97.4	88.5	89.9	90.9	85.5

Table 4-11: Tracking performance for **negative** 3 GeV particles.

4.6.10.3 Estimation of the errors

Suppose s is an estimate of s and $\bar{x}$ is the arithmetic mean, then

$$\frac{\bar{x} - m}{s \times \sqrt{n}} \text{ follows a } t\text{-distribution with } f \text{ degrees of freedom.}$$

The probability of getting

$$-t_{a/2}(f) < \frac{\bar{X} - m}{s / \sqrt{n}} < t_{a/2}(f) \text{ is } 1 - \alpha,$$

where $f = N - 1$. The confidence interval follows from

$$I_m = \left[\bar{x} - t_{a/2}(f) \times \frac{s}{\sqrt{n}}, \bar{x} + t_{a/2}(f) \times \frac{s}{\sqrt{n}} \right].$$

As an example we take values from column 3 in Table 4-5;

	No cooling pipes $d = 5.2 \text{ mm}$
N_{STRAW}	34.36
rms	2.16
N_{SPACE}	3.92
rms	0.77

With $a = 0.01$, $\bar{x} = 34.36$, $s = 2.16$ and $n = 1000$, we obtain for N_{STRAW}

$$I_m = \left[34.36 - 2.58 \times \frac{2.16}{\sqrt{1000}}, 34.36 + 2.58 \times \frac{2.16}{\sqrt{1000}} \right] = [34.18, 34.53]$$

and with $\bar{x} = 3.92$, $s = 0.77$ we obtain for N_{SPACE}

$$I_m = \left[3.92 - 2.58 \times \frac{0.77}{\sqrt{1000}}, 3.92 + 2.58 \times \frac{0.77}{\sqrt{1000}} \right] = [3.86, 3.98].$$

4.6.10.4 Conclusions

This study shows that the present layout ($d = 5.2$ mm and two cooling pipes per module) of the barrel TRT gives > 34 hits, as a mean, for stiff tracks with $h < 0.7$. This is just a scaling down with the total number of straws of what was found in the uniform straw distribution with no modules (Layout 1). There is a loss of about 1.5 hits for an approximately constant straw density. The *rms* values are also slightly increased. The minimum efficiency to obtain more than 31 hits is 89.4% for the designed modular layout, compared with 99.9% for a uniform straw distribution (Layout 1).

The results show also that the reduced number of straws produced by the introduction of cooling lines and carbon-fibre walls only introduces minor variations in the track qualities. It will not be difficult to maintain a high efficiency by requiring a slightly smaller number of hits on a track, without significantly increasing the fake track rate.

All modular layouts show some charge asymmetry including Layout 4. This is due to the asymmetry in the angular shift between successive module layers, imposed by the boundaries.

4.6.11 Material in the barrel TRT

The amount of material in the TRT in terms of radiation length should be kept as low as possible. A dedicated material budget program was formulated to facilitate the study of different designs and to study the contribution from individual components to the total material budget [35]. The program makes it possible to obtain a fast response and to change parameters such as the material and the dimensions of objects. The calculation is based on the present barrel TRT design as discussed above with 3×32 modules and 52 544 straws, and an extrapolation from the detailed design of the innermost module to the two outer modules was made. In addition, the pipes and cables in the crack region between the barrel and the end-cap are included as the only part of the services [36, 37].

4.6.11.1 Geometry

The detector is divided into several volumes (discs) in which the material is averaged. Each component is placed in one of these discs. Figure 4-50 shows schematically how the material is divided into discs. A list of all components included in the calculation is given in Table 4-12. Electronics cooling, fuses and fuse boxes are not yet included in the calculation. The material budget has been estimated for $0 < |h| < 1.2$ where h is defined as (see also glossary on page 123)

$$h = -\ln \left[\tan \left(\frac{q}{2} \right) \right] . \quad (4-20)$$

The material has been divided into three main discs as follows:

- a disc covering the electrical disconnection at $z = 0$;
- the active volume;
- the crack region with electronics, connections, services, etc.

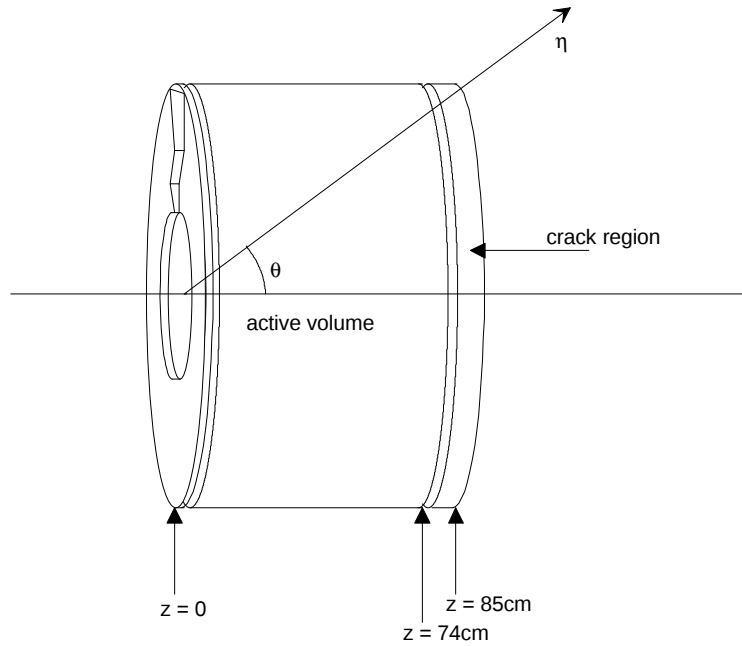


Figure 4-50: A schematic view of the division of the detector into discs.

Component	X_0 (cm)	Weight per piece (g)	Number of pieces	d^6 (cm)	Radius R_{out}/R_{in} (cm)
Ventilation gas	18300.1	2460.19	1	#	107/56
Shell (3 types)	25	1198.80	32	#	107/56
Radiator	48	98407.40	1	#	107/56
Wire (W, $d = 30$ mm)	0.35	0.01	52544	#	107/56
Straw Al	8.9	0.01	52544	#	107/56
polyimide	28	0.66	52544	#	107/56
C-fibre ⁷	25	0.30	52544	#	107/56
Xe+CO ₂ +CF ₄	1576	0.05	52544	#	107/56
Polyimide partitions	28.7	12.06	96	#	107/56
Cooling pipes (Al)	8.9	3.22	2	#	107/56
Water for cooling	36	18.60	96	#	107/56
Central partition (3 types)	28.7	12.06	32	0.2	107/56
Mid twister	30	0.03	52544	0.5	107/56
Twister	30	0.05	52544	0.8	107/56
Straw fixation	30	0.06	52544	0.8	107/56
Inner end-plate	19.4	144.33	32	0.2	107/56
Detector gas	1576	123.27	1	0.8	107/56
Capacitor + 2 female pins + 2 male pins	1.43	0.25	6568	0.6	107/56
Capacitor socket	30	0.04	6568	0.6	107/56
Tension plate	19.4	58.00	141	0.2	107/56
Wire fixation pin	1.43	0.06	52544	0.3	107/56
Wire fixation socket	1.43	0.02	52544	0.2	107/56
Sockets for electronics	1.43	0.01	72248	0.3	107/56
Support structure	25	149.00	32	1	107/56
Electronics card	19.4	2.10	3284	0.1	107/56
‘ASDBLR’	9.36	0.03	3284	0.1	107/56
Protective components	11.7	0.03	105088	0.1	107/56
‘DTM ROC’	9.36	0.02	1642	0.1	107/56
Pins on electronics card	1.43	0.44	3284	0.3	107/56
Cables	1.43	2000.00	1	1	107/56
Pipes	8.9	3000.00	1	1	107/56
Roof board	19.4	4439.73	1	0.2	107/56
Resistor (1 per 16 straws)	25	0.1	3284	0.2	107/56

Table 4-12: Detector components and some of the parameters included in the calculation. Heat exchangers for the electronics cooling, fuses and fuse boxes, are not yet included.

⁶ Thickness of the doughnut.

⁷ The fibre content is assumed to be 60%.

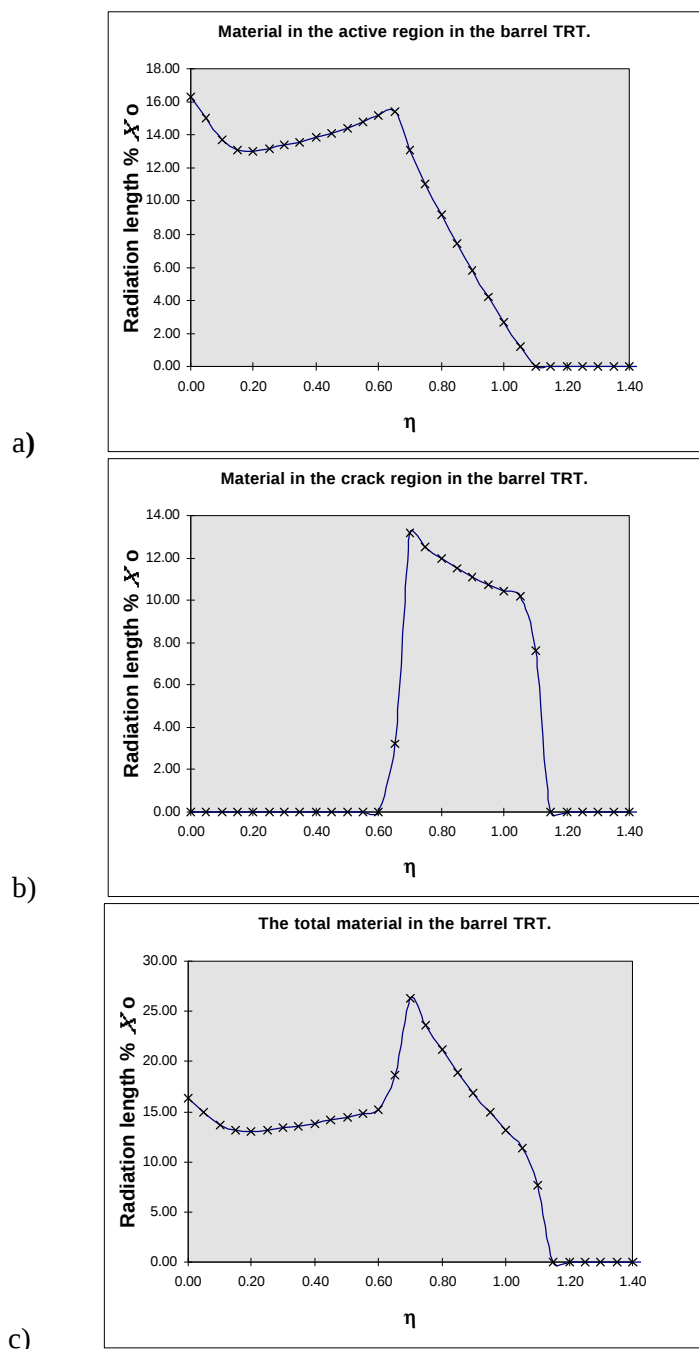


Figure 4-51: Material distribution in the barrel TRT as a function of radiation length versus h for different parts of the barrel: (a) active volume (up to $z = 74$ cm), (b) end-flange and services, (c) total material.

Additional discs can be added as the design develops or existing discs can be divided into smaller discs to increase the granularity.

A vertex spread with a $s = 5.6$ cm has been used in all calculations. This is of importance at $z = 0$ and $h = 0$ as the anode wire is electrically disconnected at this position and, accordingly, there is a high concentration of material in the rf -plane at $z = 0$.

4.6.11.2 Results from the material budget study

The material budget for the present design of the barrel TRT has been calculated in detail. Figure 4-51 shows the material distribution expressed in terms of percentage of X_0 vs. h . A somewhat higher value has been found compared with previous estimates at $z = 0$ and in the crack region. At $z = 0$, the electrical disconnection of the anode wire, including the glass disconnection and a wire centring piece, adds $\sim 4\%$ X_0 , if averaged over the nominal spread of vertices. There are several small contributions to the sum of material, especially in the crack region, and there is no particular component where savings can be made easily. For example, the four largest contributions (inner end-plate, wire fixation pin, tension plate and electronics card) are all between 0.72% and 0.95%. The total amount of material adds up to about 7% of X_0 axially, excluding services ($\sim 1\%$ of X_0) and there are still items to be precisely defined, e.g. fuses, fuse boxes, and heat exchangers for electronics cooling.

It should also be pointed out, that the TR function costs in material and at $h = 0$, the contribution from radiator and Xe is $\sim 6\%$ of X_0 . As already mentioned in Chapter 2, Section 2.1, the material in the inner detector degrades the performance of the electromagnetic calorimeter and the tracker because of photon conversions and bremsstrahlung.

4.6.12 TR performance

The ATLAS TRT is designed as a tracking device in the ATLAS inner detector with the capability of identifying electrons [38, 39, 40]. The optimization of the straw layout in the barrel TRT has been guided by tracking performance and mechanical considerations. The 0.5 m barrel prototype discussed above was used in the August '96 run to study different aspects of the design and assembly procedures [41]. In addition, it provided the possibility to study the TR performance for the barrel part under realistic geometrical conditions. The energy spectra of individual straws at different detector depths was measured and an extrapolation to the full detector length was made from these data.

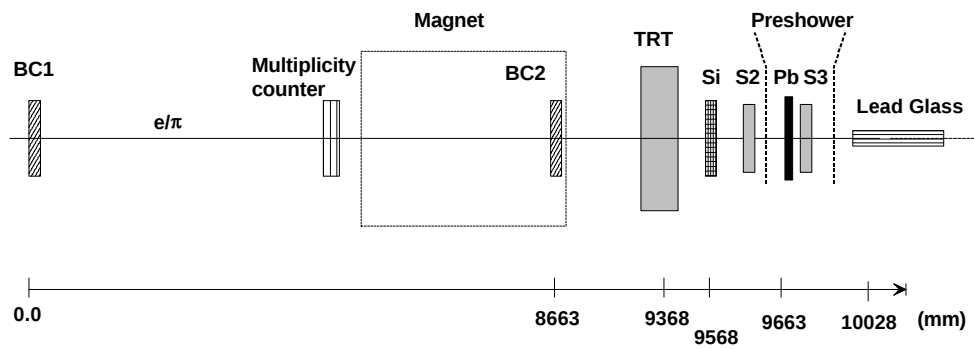


Figure 4-52: The set-up of the 0.5 m barrel prototype (TRT) for the August run in 1996. BC1 and BC2 indicate the beam chambers, Si the silicon counter, S2 and S3 the scintillators. The magnetic field was off during the whole run.



Figure 4-53: Cross-section of the prototype showing the three different straw groups: back, middle and front. One straw in the front group was used as a monitoring straw and did not acquire data.

The number of clusters was predicted based on the knowledge of the individual straw performance in combination with the expected number of hits per track. Two types of beams were at our disposal: pions at 50 GeV and electrons at 200 GeV. Because of the relativistic rise in the energy deposition to exceed the threshold, the probability for pions is higher at 50 than at 20 GeV. As can be seen in Figure 4-3 above, the curve flattens out for electrons above ~ 20 GeV but the 50 GeV pions are on a positive slope. This has to be remembered when making predictions for the electron identification performance.

4.6.12.1 Test beam set-up

Figure 4-52 shows the test set-up. A scintillator S2 was used to trigger a reading in a straw. No tracking was carried out as only three straws at the time were equipped with electronics. To obtain a clean pion or electron beam, a preshower and a lead-glass calorimeter were used. In addition a multiplicity counter ensured that only one particle at a time was registered in the straw. The beam was perpendicular to the straws, i.e. parallel to the fibre sheets. The angle between the straws and the beam was kept constant during all runs. The detector gas was a mixture of 70% Xe, 20% CF₄ and 10% CO₂. The gas flow was kept at 6 l/h and 0.5 l/h for the input flow and return flow respectively. To keep the radiators clean from Xe gas, the radiator volume was ventilated during the whole run with dry nitrogen at a flow rate of 150 l/h. This ventilation kept the Xe concentration at an acceptable level of a few per cent. Fe⁵⁵ sources were used for calibration of the straws and this was performed at the beginning of each data-taking period. In addition a ‘monitoring straw’, as shown in Figure 4-53, was used for operating-voltage stabilization. It used a feedback loop which measured the pulse height from a Fe⁵⁵ source. The operating voltage was set to 1560 V which corresponds to a gas gain of $\sim 3 \times 10^4$. Preamplifiers were mounted near the straws and connected to fast shapers. The straws were divided into three different groups and one group was read out at a time. In the front group only two straws were read out as one was used for operating-voltage monitoring. The prototype was equipped with two different fibre radiators with the same basic material, i.e. 50% polypropylene and 50% polyethylene. Table 4-13 shows the different runs carried out in the test beam.

Group	Oriented fibre	Non-oriented fibre
Back	e/ π	e/ π
Middle	e/ π	e/ π
Front	e	e

Table 4-13. The different combinations during the test-beam run.

The non-oriented fibre has a density of 0.120 g/cm^3 while the oriented has a density of 0.070 g/cm^3 . This difference in density has to be taken into account when evaluating the performance of the two radiators, as the radiator represents a significant fraction of the total material in the barrel TRT.

4.6.12.2 Beam purity

As mentioned above, the purification of the pion or electron beam is carried out with a preshower and a lead-glass calorimeter. Figure 4-54 below shows how the different cuts were applied to clean the beams. To determine the requirements on the beam purity, the statistical error on the probability to exceed a certain threshold is used as a reference. The error from beam impurities should be significantly less than this statistical error. As will be shown in Section 4.6.12.4 below, the probability to exceed 6 keV is $p_e = 0.235$ for electrons with a standard deviation $d_e = 0.006$. For pions the corresponding values are $p_\pi = 0.0635$ and $d_\pi = 0.003$. The electron beam is estimated to contain $\sim 60\%$ electrons without any cuts. After cuts have been applied in both the preshower and in the lead-glass calorimeter, the pion efficiency R_π is estimated to be less than 10^{-3} . The pion beam on the other hand is contaminated by $\sim 8\%$ electrons. After the cuts are applied, the efficiency to find electrons R_e is measured to be less than 10^{-3} . The increase in the probability to exceed the 6 keV for pions, due to electrons, is calculated as

$$e_p = p_e \times R_e = 2.35 \times 10^{-4} < d_p. \quad (4-21)$$

Thus, it can be concluded that the pion beam is sufficiently cleaned of electrons. In an analogous way, the decrease in the probability to exceed 6 keV for electrons, due to a contamination from pions, is calculated as

$$e_e = p_p \times R_p = 0.635 \times 10^{-4} \ll d_e. \quad (4-22)$$

It is concluded that the electron beam is sufficiently pure.



Figure 4-54. Histograms with the different cuts for pions and electrons.

4.6.12.3 Radiator performance

Figure 4-55 and Figure 4-56 show the energy spectra and the integrated energy spectra for the back straws with both electrons and pions. The next step is to plot the probability to exceed a certain threshold for pions against the probability to exceed the probability for electrons and this is performed in Figure 4-57, taking the values from Figure 4-55b and Figure 4-56b. As can be seen from this figure, the performance looks very similar for the two radiators, but the essential parameter is the electron identification properties which will be discussed in the next section.

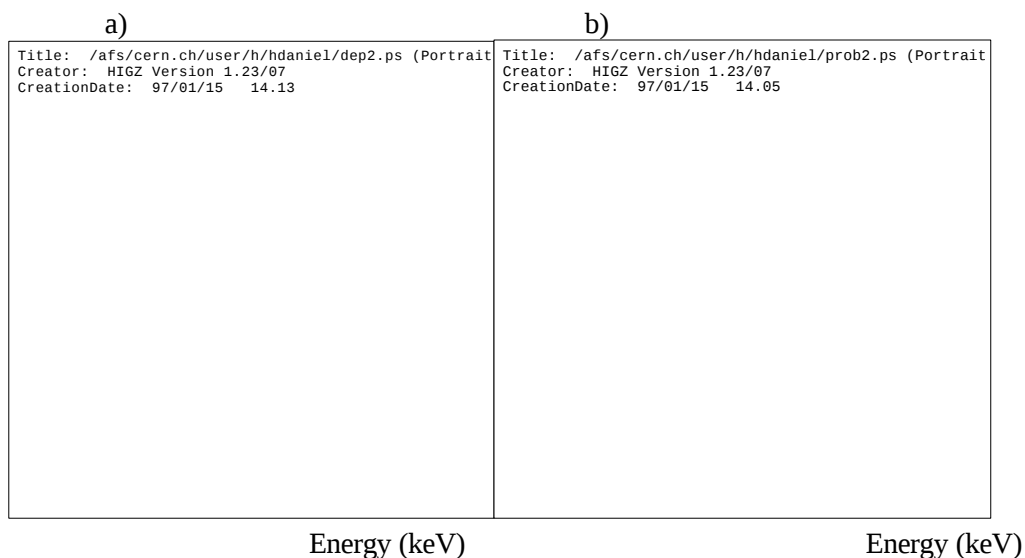


Figure 4-55: (a) Spectrum of energy deposition in straw and (b) the integrated energy spectrum for the back group with 200 GeV electrons.

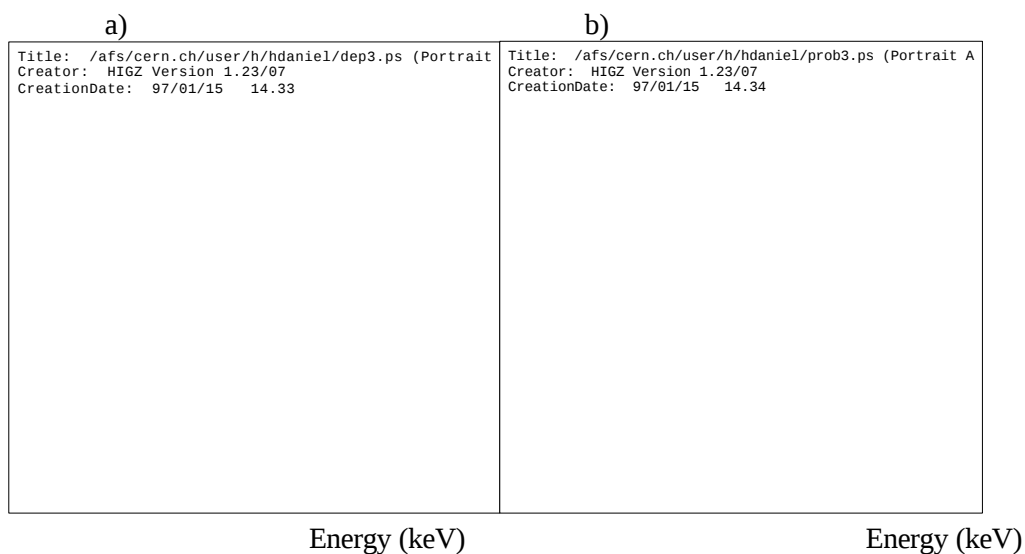


Figure 4-56: (a) Spectrum of energy deposition in straw and (b) the integrated energy spectrum for the back group with 50 GeV pions.

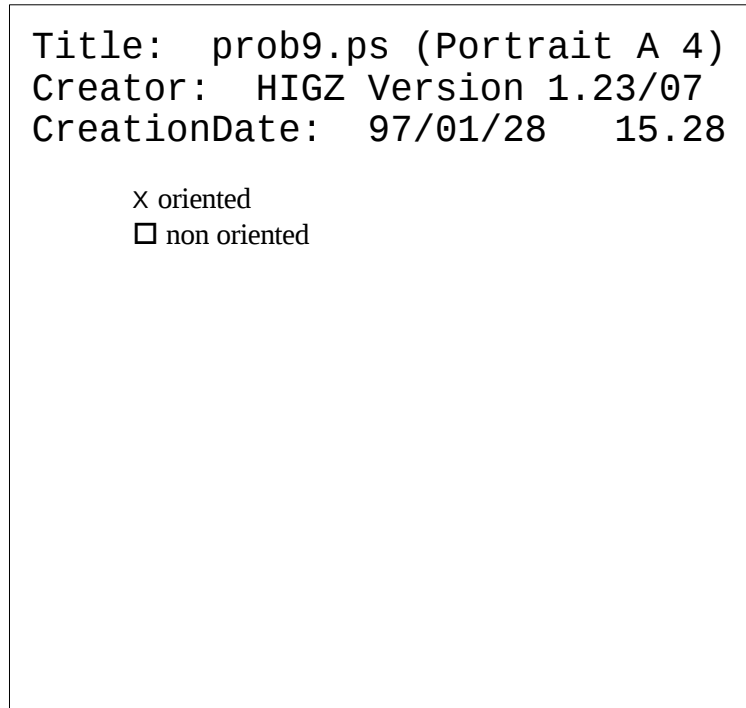


Figure 4-57: p_e as a function of p_π for different thresholds plotted for the two radiators.

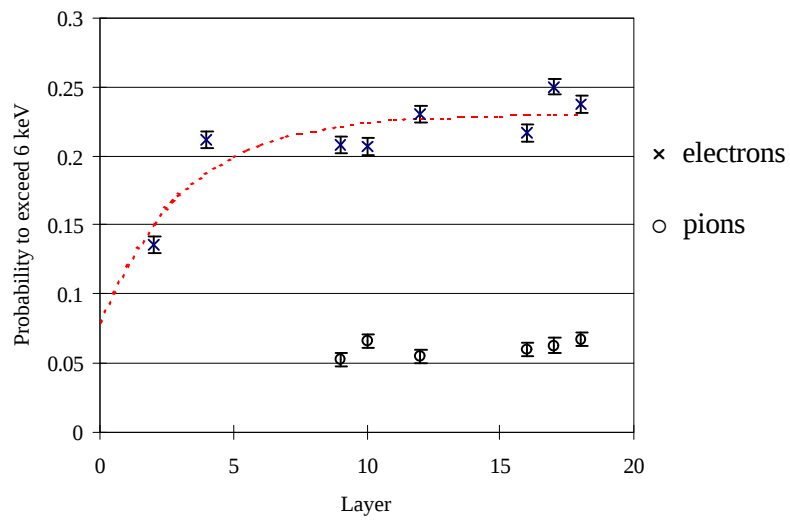


Figure 4-58: Probability to exceed the high threshold vs. straw layer for the oriented fibre radiator. A fit was made with the function $f(x) = a \times (1 - e^{-bx}) + c$.

Figure 4-58 shows the eight straws and their measured probabilities to exceed the 6 keV threshold for pions and electrons. The TR reaches saturation in the last straw group, but there is a difference between the three straws. One explanation for this difference may be the amount of radiator in front of the straws, which differs due to the geometrical arrangement of the straws. Furthermore, irregularities in the packing of the sheets and in the fibre sheets themselves might play a role. To determine the relation between the amount of radiator in front of each straw and the energy deposition in the straws it is necessary to run a Monte Carlo simulation. The predictions in the next section are based on the *mean* value of last three straws (layers 16-18) with the oriented radiator.

4.6.12.4 Extrapolation to the full barrel TRT

It is clear that drawing conclusions from only three measured straws can result in considerable uncertainty as the probability to exceed the threshold differs with different amounts of radiator in front of the straws. An estimate of the electron identification capabilities is given below using the mean value of the three back straws and assigning this probability to all the straws in the barrel. As will be seen in the next section, an attempt to take into account also the shell walls has been made by decreasing the probabilities for straws close behind any carbon-fibre wall in a systematic way.

First we calculate the *statistical* error in the pion and electron probabilities to exceed the high threshold: p is the estimated probability for having a hit above threshold and $q = 1 - p$ is the estimated probability of for a hit below threshold. The standard error, d , is estimated as

$$d = \sqrt{\frac{p \times q}{N}}. \quad (4-23)$$

With $N = 5087$, $p_e = 0.235$ and $p_\pi = 0.06$ we obtain $d_e = 0.06$ for the electrons and $d_p = 0.003$ for the pions.

4.6.12.5 Without carbon-fibre shells

A relevant way to look at the barrel performance is the hadron rejection. Here it is done by counting the number of clusters⁸, i.e. the number of hits above a certain threshold. A crude estimate is performed below, to investigate the electron identification performance for the full detector length in the barrel. For a track with $h = 0$ which is originating from $10 \text{ mm} < z < 400 \text{ mm}$, the mean number of hits per track is 34 with $s = 2.6$. The hit distribution with these values is shown in Figure 4-59. Assuming a normal distribution of the number of hits, an array with

⁸ There are other methods of electron identification, e.g. Ref. [7].

10 000 elements, each representing the number of hits per track, was created. A uniform probability to exceed a threshold of 6 keV was used and the mean value of the three back straws (Figure 4-53) was taken. The oriented fibre has a probability of $p_e = 0.235$ for the electrons (200 GeV) and $p_\pi = 0.0635$ for the pions (50 GeV) to exceed 6 keV. For each n in this array, the binomial distributions were calculated for pions and electrons. Note that this is an approximation as for stiff tracks at $h = 0$, and the mean number of hits in the barrel is 34.4, assuming an effective straw diameter of 1.9 mm. The sum of these distributions divided by the number of tracks was calculated and is plotted in Figure 4-60.

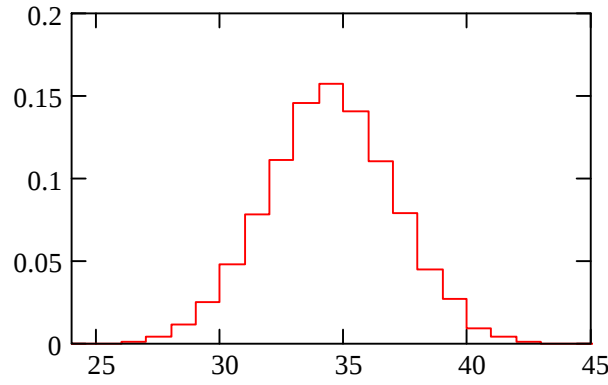


Figure 4-59: The hit distribution with $n = 34$ and $s = 2.6$ [42].

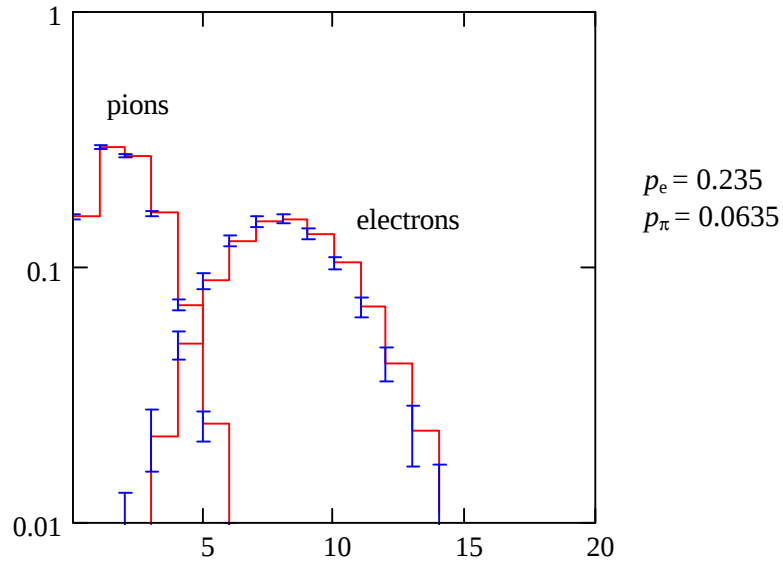


Figure 4-60: The distribution of high-energy threshold hits, with error bars, for pions and electrons at 6 keV. The mean number of hits on a track is 34 with $s = 2.6$.

The distributions for the non-oriented fibre have been calculated analogously. The corresponding electron identification performance for the two radiators is shown in Figure 4-61. It is clear from this graph that the performance of the two radiators is very similar. As the density of the non-oriented radiator is 70% higher than the density of the oriented fibre, it adds a significant amount of material. The non-oriented fibre contributes with $\sim 3.2\%$ of C_0 at $h = 0$, whereas the total material is $\sim 12\%$ of C_0 using the oriented fibre. Therefore, we can conclude that the oriented fibre performs better and it will be used exclusively in the calculations below.

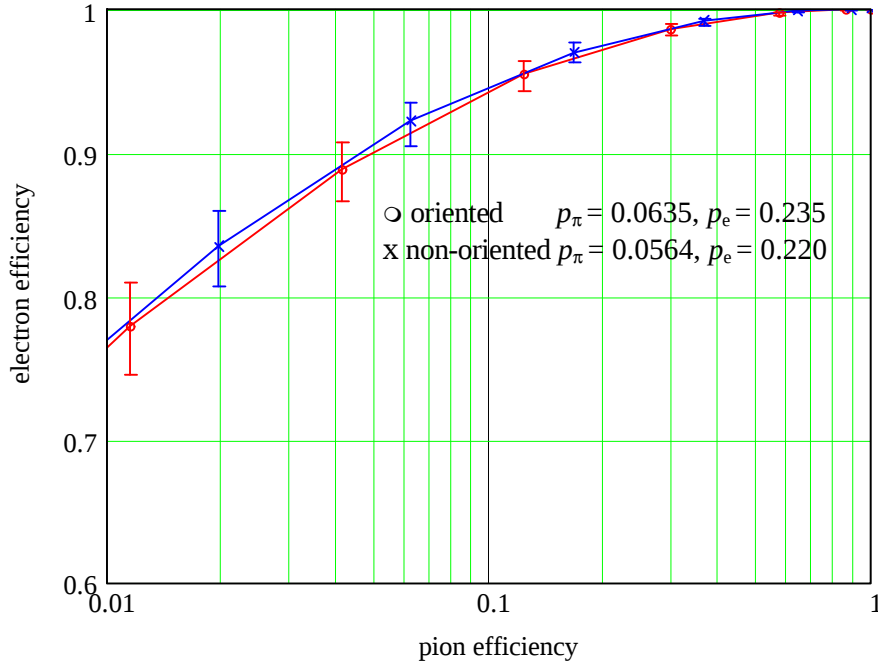


Figure 4-61: A comparison of pion efficiency vs. electron efficiency for the two radiators with a threshold of 6 keV. The error bars indicate the error propagation from the error in p_e and p_π . The mean p_e and p_π of the back three straws for the oriented fibre were used.

It should be noted that different energy thresholds can be applied in the integrated energy spectrum. Figure 4-60 shows the pion efficiency for different thresholds at 90% electron efficiency. The starting point is the pion efficiency vs. electron efficiency for the oriented fibre as shown in Figure 4-61. To see how the pion efficiency varies as a function of the applied threshold, the plot was produced at different thresholds from 4.5 to 8 keV. An interpolation was made to obtain the

pion efficiency at 90% electron efficiency. Figure 4-62 shows the pion efficiency as a function of threshold.

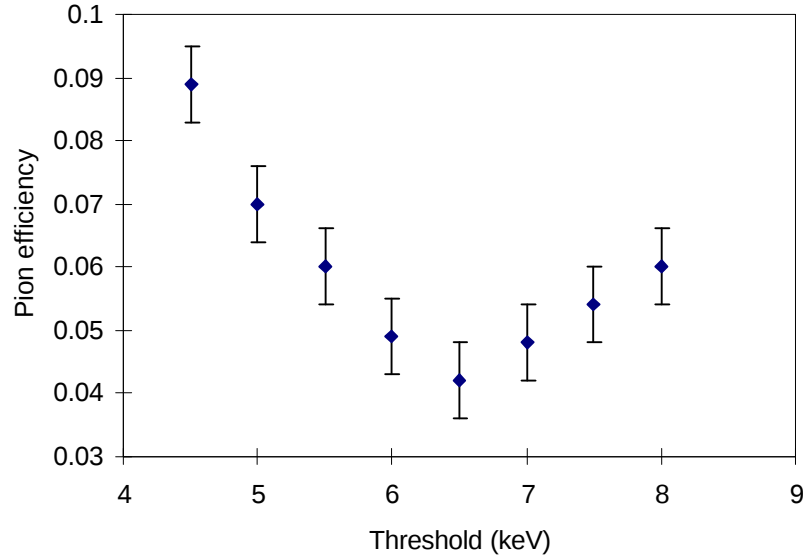


Figure 4-62: Electron efficiency vs. pion efficiency for various thresholds at an electron efficiency of 90%. A mean probability to exceed the threshold for the back three straws and oriented fibre was used.

A 6 keV threshold was considered as adequate, even if the efficiency is higher at 6.5 keV, and has also been used frequently by other authors [38, 40]. 6 keV is the threshold used in the diagrams and calculations below.

As mentioned earlier, the electron beam energy was 200 GeV and the pion energy 50 GeV. Figure 4-63 shows dE/dx as a function of g . The relativistic rise in the energy deposition for pions, results in a higher probability to exceed the threshold at 50 GeV than at 20 GeV. For the electrons the probability to exceed the threshold is assumed to be the same at 20 GeV and 200 GeV. If we would like to make a comparison between 20 GeV electrons and 20 GeV pions, we have to scale down the probability to exceed the threshold for the 50 GeV pions accordingly. An extrapolation was done from the 50 GeV pions used in the test beam to 20 GeV and 10 GeV pions, by taking the relative difference between the pion energies as calculated from Figure 4-63. Figure 4-64 shows the electron identification performance for beam data at 50 GeV together with two extrapolated values at 10 GeV and 20 GeV. The probability to exceed the high threshold for the pions was calculated to be 19% higher at 50 GeV than at 20 GeV. Accordingly, p_π is changed from 0.0635 to 0.0534 and this value is kept in the subsequent analysis.

Figure 4-63: Measured pion rejection as a function of the number of straws (N_s) crossed for different pion momenta (from Ref. [7]).

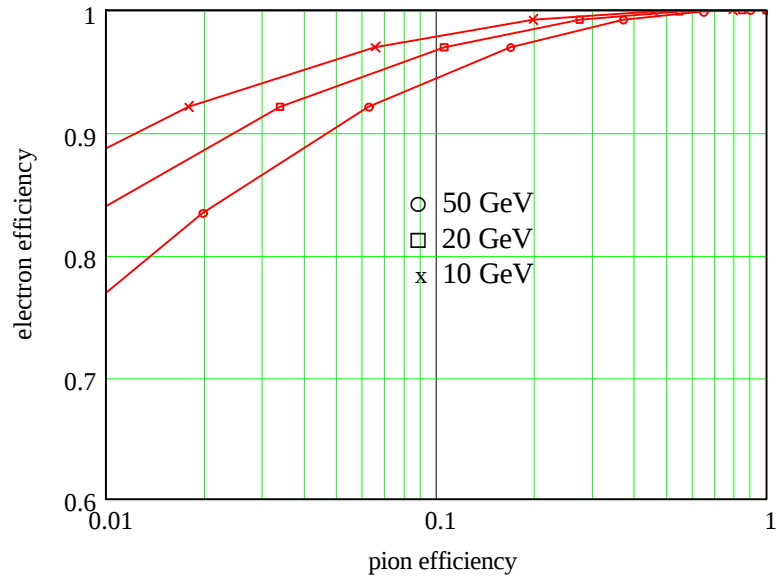


Figure 4-64: Calculated electron identification performance for 50 GeV, 20 GeV and 10 GeV pions where $p_\pi = 0.0635$ at 50 GeV ($p_e = 0.235$).

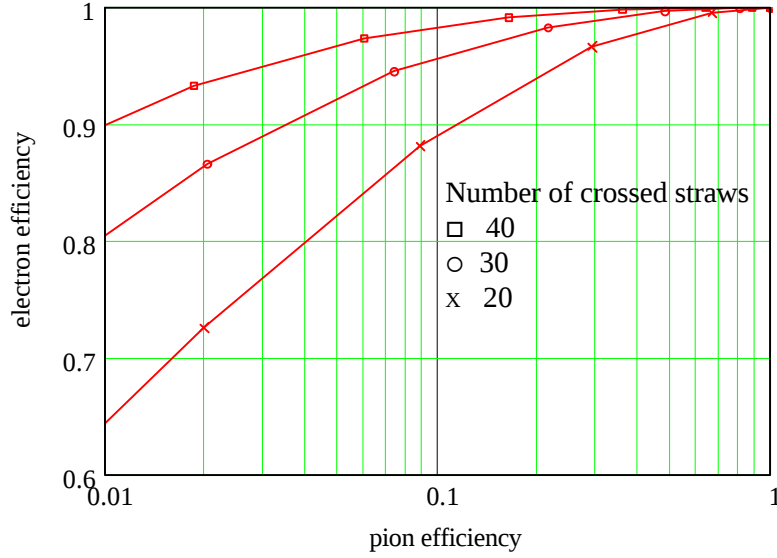


Figure 4-65: The electron identification performance for different numbers of crossed straws, where $p_e = 0.235$ and $p_\pi = 0.0534$ as found above for 20 GeV pions. Note that it assumes an extension of the detector in length and not replacing radiator with straws.

An important parameter which to a great extent determines the TR performance is the number of hits per track. It is important to distinguish between the case where the radiator is replaced by straws and the case where the detector length is increased to keep the straw density constant. Figure 4-65 shows the electron identification performance for three different straw numbers where the ratio between straws and radiator has been kept constant. Note, by doubling the detector length from 20 to 40 hits, the pion rejection is increased by a factor ten with $p_e = 0.235$ and $p_\pi = 0.0534$.

4.6.12.6 With carbon-fibre shells

The interesting region for the TR photons is above a few keV and below ~ 20 keV. To estimate correctly the degradation from the shell walls, it is necessary to know the TR spectrum accompanying the electrons. Furthermore, the attenuation length is energy dependent, i.e. low-energy photons have a higher probability to be absorbed. As an example, between 4 and 20 keV l increases almost two orders of magnitude. The attenuation length, l (g/cm²), in the carbon-fibre shells has been measured to be 0.080 g/cm² with an Fe⁵⁵ source [43]. We can calculate the damping in the module shells for a photon energy of 5.9 keV (Fe⁵⁵) as

$$I(x) = I_o \times e^{\left(-\frac{r \times x}{l}\right)} \quad (4-24)$$

where the density $r = 1800 \text{ kg/m}^3$. The damping in the shells can roughly be divided into two geometrical cases (see Figure 4-66):

- through two successive modules where the tracks are close to perpendicular to the shell wall and $x = 2 \times t$;
- through two successive side walls and

$$x = \frac{2 \times t}{\sin(q)} \approx 4 \times t$$

where q is the angle between shell wall and track and t is the shell thickness.

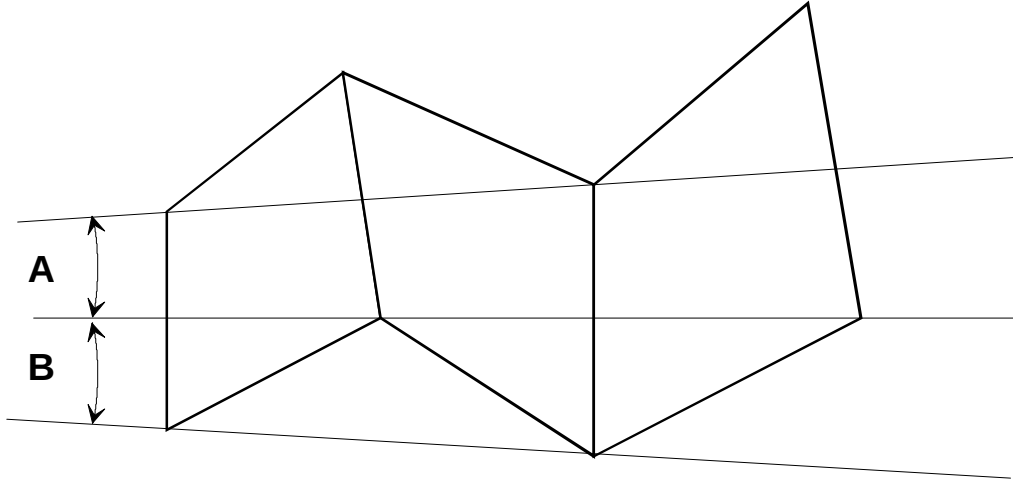


Figure 4-66: A schematic view of the two different angular regions of equal size in f . A is the region where tracks pass few boundaries while the B region contains tracks which pass through several boundaries.

The shell thickness is assumed to be $400 \mu\text{m}$ and $q = 25^\circ$. By inserting numbers into (4-25), we obtain $I/I_o = 17\%$ and $I/I_o = 3\%$ for cases (1) and (2) respectively. The conclusion is that the TR spectrum has to be rebuilt almost completely for photons in the lower part of the energy range, after traversing a shell boundary.

As indicated above, the absorption and production of the TR photons is a very complicated process. Here we have shown the absorption for only one energy (5.9 keV) without indicating what the TR spectrum looks like in detail or the absorption inside the straw. Nevertheless an estimate of the influence of the carbon-fibre shell on the TR performance has been made by assuming total absorption of

the TR at any traversed module boundary. This is a pessimistic estimation, especially for photons in the upper part of the energy range. On the other hand, a non-conservative estimate has been made with regard to the rebuilding of the TR as only the first few layers were degraded, as shown in Figure 4-67. A simplification was performed, dividing the straws into seven groups. Each group was assigned a p_e estimated from the results in Figure 4-58 with a saturation from the fifth layer. Figure 4-67 shows the resulting probabilities for straws in the middle module. The same exercise was carried out for the inner and outer modules. A simplified simulation was performed by generating 10 000 tracks at 20 GeV at random f . The rapidity was kept constant at $h = 0$. For each hit in a straw, a new random number was generated with the above described probability to exceed the threshold. The number of hits above this threshold was calculated. The effective straw radius was assumed to be 1.9 mm. By applying a cut on the number of clusters the pion efficiency was calculated as a function of the electron efficiency.

Title:
 Creator:
 CreationDate:

Figure 4-67: The middle module in the barrel TRT. The straws are divided into different groups with different probabilities to exceed the high threshold due to absorption in the carbon-fibre walls. A similar grouping is made for the inner and outer modules.

Figure 4-68 shows the difference in performance between damping of the TR from the carbon-fibre shells and no damping. As mentioned earlier, there is considerable uncertainty in p_π and p_e because of the small number of measured straws.

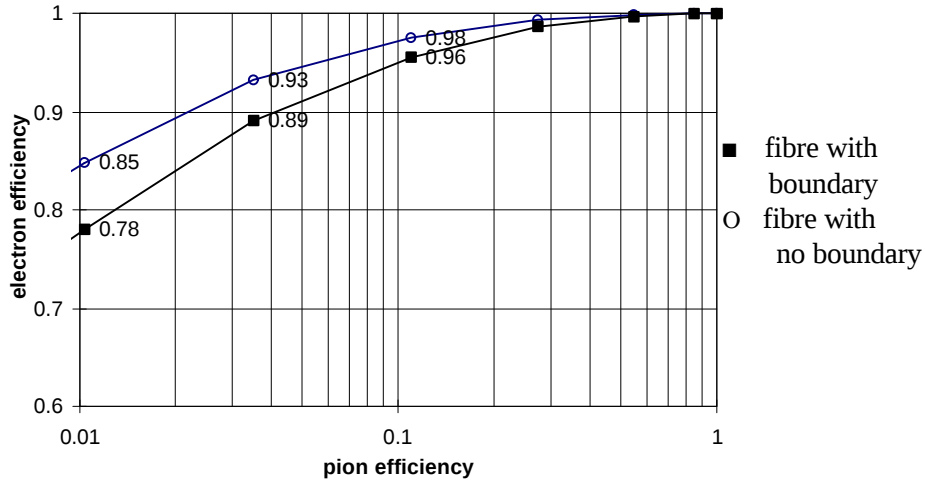


Figure 4-68: A comparison between uniform probability to exceed 6 keV with and without damping as shown in Figure 4-67. $p_\pi = 0.0534$ (20 GeV) and $p_e = 0.235$ (20 GeV) for the case of no damping due to boundaries. The TR degradation due to absorption at the boundaries is estimated according to Figure 4-67.

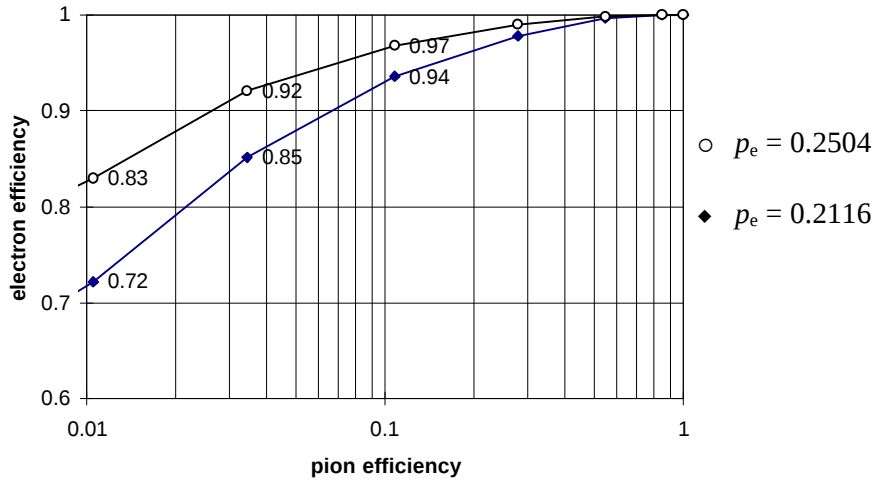


Figure 4-69: An estimate of the uncertainty in the performance prediction, made by taking highest ($p_e = 0.2504$) and lowest ($p_e = 0.2168$) values for the three back straws in Figure 4-53. $p_\pi = 0.0534$ assuming 20 GeV pions. The calculation is performed with absorption in the module shells according to Figure 4-67.

Figure 4-69 shows the performance when applying the highest and the lowest values for the back three straws as shown in Figure 4-58.

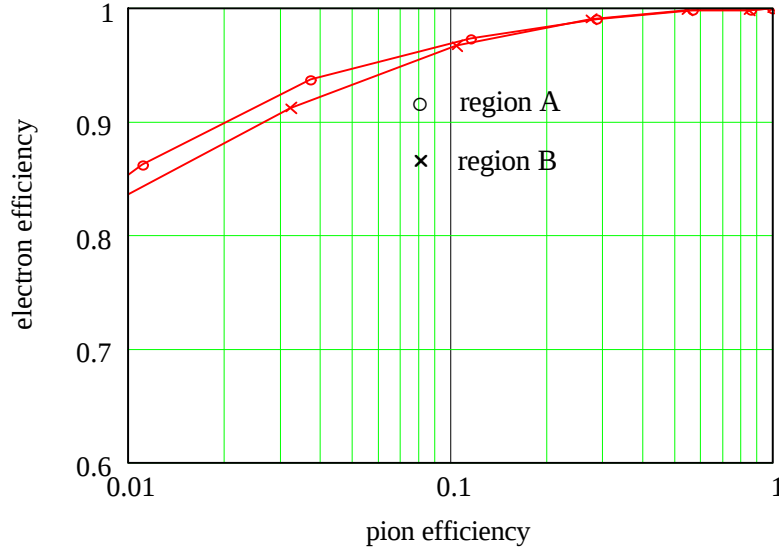


Figure 4-70: A comparison between tracks in regions A and B as shown in Figure 4-66, with uniform p_e and p_π . The difference in performance comes from the difference in the mean numbers of hits, which are found to be 35.3 and 33.3 for A and B respectively.

As we have seen from Figure 4-66, the number of boundaries a track traverses in the barrel depends on f . For simplicity we assume stiff tracks, i.e. a track is either totally in A or totally in B. Figure 4-70 and Figure 4-71 show the difference between region A and B. Figure 4-70 shows the difference if there were no boundaries to absorb the TR. The difference between A and B comes from the fact that the density of straws, i.e. number of hits per track, is less in B than in A. In region A, the *mean* number of hits is 35.3 while in B it is 33.3. This is due to the space taken by the module walls. Therefore, it can be concluded that the main difference between the two regions originates from the absorption of the TR photons in the carbon-fibre shells, assuming total absorption and rebuilding of the TR according to Figure 4-67.

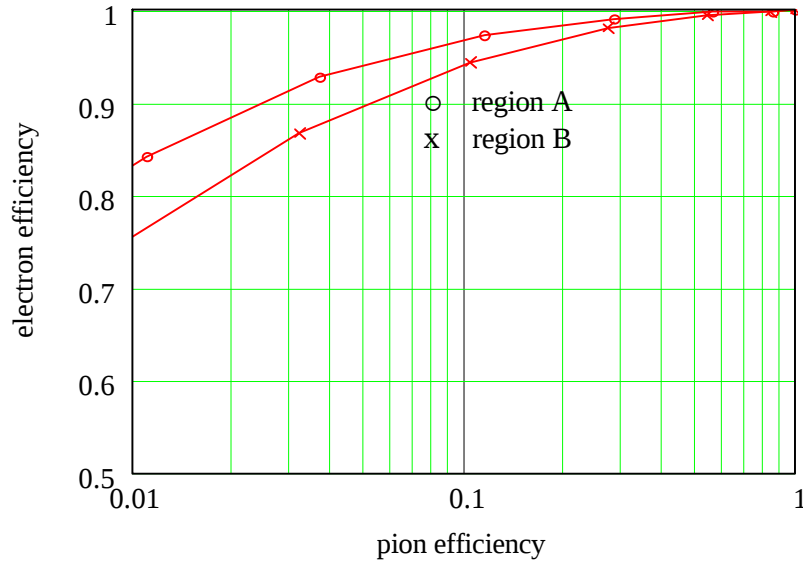


Figure 4-71: A comparison of tracks in regions A and B as shown in Figure 4-66, with the degradation as shown in Figure 4-67.

4.6.12.7 Conclusions and remarks

The results from measurements on the 0.5 m prototype in the August 1996 run, show small differences in TR performance between the non-oriented and the oriented fibre. The oriented fibre was chosen as the preferred radiator. The reason for this was its lower density and therefore its smaller contribution to the total material. At $h = 0$, the total material is $\sim 12\%$ of C_0 and 15% of C_0 for the oriented and non-oriented fibre respectively, not taking into account the wire centring piece at $z = 0$.

From the probabilities to exceed 6 keV for the individual measured straws, an extrapolation was performed to the full TRT. It has been shown that the carbon-fibre shells will have a significant influence on the electron identification performance using a simplified model for the TR degradation. The shells also introduce an in-homogeneity in electron identification performance in f . The results give an indication of the optimal performance even though there is great uncertainty in terms of absolute numbers. The most important assumptions are:

- a uniform probability (p_e) for electrons to exceed 6 keV was used (from test beam data);
- an extrapolation of the probability (p_π) for pions to exceed 6keV from 50 GeV pions in test beam to 20 GeV pions;
- total absorption of TR in module shells.

With this approach the rejection power in the barrel TRT at $h = 0$ was calculated to be between 15 and 40. The uncertainty is mainly due to low statistics and uncertainties about the degradation from the carbon-fibre shells. A full Monte Carlo simulation is necessary to simulate correctly the influence of the carbon-fibre wall on the electron identification performance. Alternatively, this can be measured, together with the rebuilding of the TR, but requires that many more straws are read out.

4.7 Conclusions

A modular concept of the ATLAS barrel TRT has been designed. It is based on a series of geometrical, mechanical, thermal and physics performance considerations. Based on this design, a 0.5 m barrel-module prototype has been built and tested. Major design principles and functionality of the design have been demonstrated, e.g. connectivity, assembly procedure and cooling of the modules. The advantages in terms of testing, repairing and prototyping cannot be stressed enough. The costs of prototype work and mistakes are also reduced with a modular design.

The advantages of a modular design must be compared to the possible loss in physical performance. Tracking studies show that degradation in tracking performance compared with a uniform straw distribution is acceptable even though a small decrease in the mean number of hits is inevitable for a constant straw spacing. The electron identification performance has been estimated for the barrel from experimental data. It can be concluded that the depth of the detector is short and this influences the electron identification performance. The introduction of a modular structure in the barrel will have some degrading effect on the TR performance. However it can be concluded that a rejection factor of 20 for two electrons, as shown in Figure 4-4, will be achieved by the barrel TRT.

In summary I consider that the design, calculations, construction and measurements presented in this chapter have demonstrated the viability of the detector.

4.8 References

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Appendix A - Number of straws in the modules

Module 1		Module 2		Module 3	
layer #	Number of straws in each layer *)	layer #	Number of straws in each layer	layer #	Number of straws in each layer
1	15	1	19	1	23
2	16	2	20	2	24
3	16	3	20	3	24
4	16	4	20	4	24
5	16	5	20	5	24
6	17	6	20	6	25
7	17	7	21	7	25
8	17	8	21	8	25
9	17	9	21	9	25
10	17	10	21	10	25
11	18	11	21	11	26
12	18	12	22	12	26
13	18	13	22	13	26
14	18	14	22	14	26
15	18	15	22	15	26
16	19	16	22	16	27
17	19	17	23	17	27
18	19	18	23	18	27
19	18	19	23	19	27
Total:	329	20	23	20	27
		21	23	21	28
		22	24	22	28
		23	24	23	28
		24	23	24	28
		Total:	520	25	28
				26	29
				27	29
				28	29
				29	29
				30	28
				Total:	793
				Total number of straws in barrel: 52544 where 4704 are equipped with short wires.	

Table 4-14: The number of straws per layer for the three modules.

5. Measurements on cryogenic components for the Large Hadron Collider (LHC)

This part of the thesis is based on the following papers:

- I. H. Danielsson, Ph. Lebrun, J-M. Rieubland, Precision Heat Inleak Measurements on Cryogenic Components, Cryogenics Vol. 32 (1992) ICEC Supplement 215-218.
- II M. Blin, H. Danielsson, B. Evans, M. Mathieu, Design Construction and performance of Superconducting Magnet Support Posts for the Large Hadron Collider, Advances in Cryogenic Engineering Vol. 39, 671-677, 1993.
- III. Cryogenic Performance of a Superfluid Helium Relief Valve for the LHC Superconducting Magnets, H. Danielsson, G. Ferlin, B. Jenninger, C. Luguët, S-E. Milner, J-M. Rieubland, Advances in Cryogenic Engineering, Vol. 41 A, 805-810, 1996.

5.1 Introduction

LHC is limited by its overall dimensions as it will be seated in the LEP tunnel, which has a circumference of 27 km [1, 2]. The two proton beams, each with an energy of 7 TeV, will circulate in opposite directions. Proton-proton colliders require two separate beam channels with opposite fields of equal strength. High-energy LHC beams require high magnetic field. This calls for superconducting coils at superfluid* -helium temperature of 1.9 K, and to reach the required field level, NbTi will be used. The only alternative superconductor niobium-tin (Nb₃Sn), which would allow conventional cryogenics at 4.5 K, had to be rejected because it is not available on a sufficiently large scale.

5.2 Superconducting technology for the accelerator magnets

Superconductivity is a property that some materials acquire when they are cooled to very low temperatures and their electrical resistance virtually disappears. The current in the superconducting coils is 11 500 A, which will give a magnetic field of about 8.4 T. Such a field is close to the maximum field possible without quenching the magnet. Quenching is when a superconductor with no electrical resistance becomes normally conducting.

The technology of using copper-clad niobium-titanium cables was invented at the Rutherford-Appelton Laboratory, UK. The coils in the LHC magnets consist of two layers of different cables. The inner (outer) cable layer consists of a number of strands each with a diameter of 1.065 mm (0.825 mm) and each strand has 8900 (6500) filaments each with a diameter of 7 μ m (6 μ m). These filaments can carry over 1000 A/mm².

The magnetic channels will be housed in the same yoke and cryostat and the cold mass (14.2 m) will be bent to a 2700-m radius of curvature with a horizontal sagitta of 9.7 mm in the centre to match the beam path. This does not correspond to a perfect circle of 27 km, the reason being that the bending dipoles only cover a part of the total circumference. Figure 5-1 shows a cross-section of a dipole magnet. This is a unique configuration that saves space and up to 25% in costs compared with two separate channels. The weight of the cold mass is roughly 23.8 tons and it is supported by three feet made of composite material (see Paper II). To absorb the thermal movements during cool-down and warm-up, only the central support post is fixed. The other two support posts are mounted on rollers. Two thermal shields are installed in the cryostat to minimize the heat inleak to the cold mass at 1.9 K. There is one inner and one outer radiation screen operating at 5-10 K and 50-70 K, respectively, intercepting the largest fraction of the incoming heat. Both screens use a multilayer of super-insulation*, which in the case of the outer screen covers a self-supporting aluminium screen. In the latest design of the magnet cryostat, the cryogenics is placed in a separate cryogenic distribution line running parallel to the

magnet cryostats. Because of changes in the lattice in the latest design, the length of the dipole magnets has been increased to 14.2 m and the packing factor improved, which leads to a reduction of the nominal field of 0.3 T for the same beam energy. There will be a total of 1232 dipoles and 386 quadrupoles.

Figure 5-1: A cross-section of a superconducting dipole in LHC.

The very high bending field calls for superfluid helium at 1.9 K as the coolant of the superconducting coils. Figure 5-2 shows a schematic view of how a decrease in temperature allows a higher magnetic field while still retaining the superconductivity for a selection of alloys.

The magnets are situated in a bath of pressurized superfluid helium and the heat is extracted through the heat-exchanger tube running in the direction of the magnets where saturated superfluid helium flows [3]. This solution gives a very small mass flow and the special properties of superfluid helium are fully exploited. Pressurized superfluid helium (1 bar) below 2 K will enhance the superconducting performance of the coils. In addition, below 2.17 K helium becomes superfluid and it changes its properties drastically compared to normal fluids, e.g. lower viscosity and infinite thermal conductivity [4].

Figure 5-2: The upper critical field for a selection of alloys as a function of temperature [5]. A higher critical field can be obtained at the expense of lower temperature and lower heat capacity in the coils.

5.3 Superfluid helium as magnet coolant

Superfluid helium as the magnet coolant is very attractive from a thermal point of view. In addition to low temperatures, high specific heat and low viscosity, superfluid helium has a maximum thermal conductivity at 1.9 K some 10 000 times that of copper. These properties can be exploited to provide a good stability of the superconductor and heat extraction from the magnet windings. As can be seen from Figure 5-3, working with saturated helium at 1.9 K implies low pressure and hence a risk of air inleak and contamination. For this reason, the technology with sub-cooled helium at 1 bar was invented at CEA in Grenoble and implemented in the Tore Supra tokamak [6]. In this very efficient heat-transfer system, kilowatts of refrigeration can be transported over more than one kilometre with a temperature drop of less than 0.1 K. However, the lower operating temperature considerably lowers the heat capacity of the windings, with a consequently increased risk of quenching the magnets. Between 4.2 K and 1.8 K the heat capacity is decreased by almost an order of magnitude which leads to a faster increase in temperature for a given energy deposition.

When helium becomes superfluid at 2.17 K it goes through a phase transition of the second order according to Erhrenfest's classification. This means that there is a discontinuity in the specific heat and this discontinuity is often called

the λ -point of ^4He (see Figure 5-4). The fact that the specific heat of helium below 2.17 K increases as the temperature rises is something which helps to protect the magnets against a quench as it is a natural buffer for any deposited heat.

It is interesting to note that the transition from normal conductor to superconductor is also a phase transition of the second order if there is no external field. If an external field is present, it is a transition of the first order and heat is produced when the sample becomes superconducting.

Figure 5-3: Phase diagram for ^4He (from Ref. [7]).

Figure 5-4: The specific heat of helium around the so-called λ -point (from Ref. [8]).

5.4 The LHC cooling scheme

The LHC magnets will operate in a bath of pressurized superfluid helium below 2 K and at a pressure of 1 bar (sub-cooled). The generated and deposited heat will be transported away by a heat-exchanger tube, penetrating the magnet string. In this tube, saturated superfluid helium at quasi-constant temperature will be circulated to carry away the heat. Figure 5-5 shows a schematic view of the cooling principle in LHC. This design decreases the flow of helium in magnets as the heat transport is effected by conduction in the superfluid to the heat-exchanger tube.

The cooling scheme is implemented in independent cooling loops and it corresponds to one ‘half-cell’ (about 51 m) of the magnet lattice (see Figure 5-6). Sub-cooled superfluid helium distributed through line A is expanded to saturation through valve TCV1 and fed to the far end of the half-cell through the heat-exchanger tube. The helium absorbs heat and the superfluid helium gradually evaporates as it flows back. The low saturation pressure is maintained by pumping through pipe B. Global measurements have been performed on a long prototype cryomagnet [9, 10] and on the prototype test string [11]. The results prove the function of the proposed scheme, and the ability to extract the LHC heat loads across very small temperature differences (a few tens of mK). The price to pay is of course the refrigeration power one has to invest to cool the helium to 1.8 K. It is also the reason it is important to keep the heat inleak low at this temperature level.

Cool-down and warm-up of each half-cell is achieved by forced circulation of high-pressure gaseous helium, supplied by line C, tapped through valve CFV and returned through valve FV and line D to the refrigerator.

Figure 5-5: A schematic view of the LHC cooling principle of the superconducting magnets.

Figure 5-6: Cryogenic flow scheme of an LHC half-cell.

5.5 Critical cryogenic components

The increased thermodynamic cost of refrigeration below 2 K is acceptable only if the heat inleak can be kept to a minimum. Heat will leak through critical components to the cold mass and increase the refrigeration power required. It is therefore necessary to evaluate separately these cryogenic components such as support posts and quench relief valves. The support posts are made from non-metallic composite material and are the solid connection between the cold mass (1.9 K) and the cryostat wall (293 K) (see Figure 5-1). The quench relief valve (SRV) is there to evacuate the helium in case of a magnet quench. The helium will be discharged into a recuperation line D (see Figure 5-6) to ensure that the pressure does not exceed the design pressure of 2 MPa in the cryostat helium vessel. Different prototype support posts and a quench relief valve, for the LHC, were thermally evaluated and the results from these measurements will provide inputs for the final design of these components. The results from the measurements were compared with analytical calculations.

There are two other sources of heat loads besides the heat inleaks: beam-induced heat and resistive heating. Beam-induced heating consists of synchrotron radiation, ohmic heating due to eddy currents induced in the conducting wall of the beam channels, and loss of particles from the circulating beam. Resistive heating arises from the ohmic dissipation in the magnet windings. Table 5-1 shows the heat inleaks per metre of magnet in an arc* for the different temperature levels. In the present design there are three support posts for a 15-m-long dipole magnet.

Source of heat load	Temperature levels		
	50-75 K [W/m]	4.5-20 K [W/m]	1.9 K [W/m]
Heat inleaks	6.38	0.125	0.269
Resistive heating	0.036		0.107
Beam-induced heating (nominal) ⁹		0.659	0.057
Beam-induced heating (ultimate)		1.35	0.045
Total nominal	6.42	0.784	0.433
Total ultimate	6.42	1.48	0.421

Table 5-1: Distributed heat loads in an arc of the LHC (from Ref. [2]).

⁹ ‘Nominal’ means operation at 7 TeV beam energy with 2×0.536 A beam current and ‘ultimate’ means operation at 7 TeV beam energy with 2×0.848 A beam current.

5.6 The heat-inleak measuring bench

To evaluate the heat loads from the different cryogenic components, dedicated heat-inleak measuring benches were developed. The measuring bench is constructed around a standard test cryostat which houses three nested vessels.

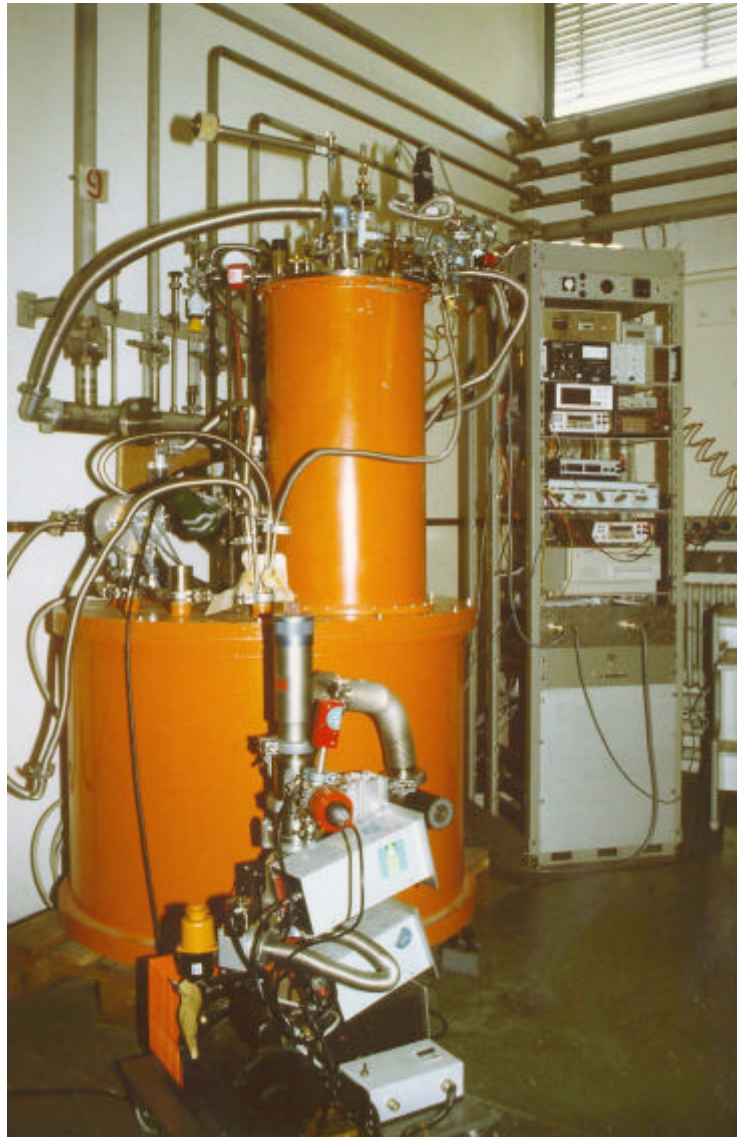


Figure 5-7: The heat-inleak measuring bench for the quench relief valve. The upper cylindrical part houses a standard cryostat and the bottom part the quench relief valve to be tested.

The principle is to simulate the three temperature levels in the magnet cryostat, as explained in Section 5.2, and to measure the heat inleak at the three temperature levels simultaneously. Both the quench relief valve and the support posts have a warm end, as they are connected to the magnet cryostat wall, which has a temperature of ~ 293 K. A thorough explanation of the design of the test cryostats is presented in Paper I (support post) and in Paper III (quench relief valve). Figure 5-7 shows the heat-inleak measuring bench used for the thermal evaluation of the quench relief valve.

The main instrument for measuring the heat loads is a calibrated thermal conductance, a so-called 'heatmeter'. The heat flow to be measured generates a small temperature difference which is measured by two thermal sensors. In addition each heatmeter is equipped with a heater which permits calibration *in situ*. Figure 5-8 shows a heatmeter which was developed to measure heat loads of different cryogenic components. Calorimetric measurements and standard boil-off methods were used to cross-measure the heat loads measured by the heatmeters.

Figure 5-8: A side view of the heatmeter. The thermal impedance is visible in the centre and on the top part is mounted an electrical heater for calibration.

5.7 Short comments on the papers

I. Precision heat inleak measurements on cryogenic components.

In this paper we describe the cryostat design and measurement principles used for thermal evaluation of cryogenic components at three different temperatures simultaneously, i.e. 50-70 K, 5 K and 1.8 K. These temperatures are approximate because they depend on the heat load from the tested component. The development of the 'heatmeters' allows very accurate measurements, especially at the 1.8 K level, even when a very small temperature difference (typically 0.1 K with a heat load of 100 mW at 1.8 K) is used over the heatmeter. We used two heatmeters in parallel at each temperature level and as built, they are slightly different from the ones described in this paper. The thermal resistance was increased at all temperature levels to give a bigger temperature difference, which is easier to measure, and the calibration heater was changed to a demountable printed circuit. The calorimetric measurement on the superfluid helium bath was later tried out in a more detailed way and found to be at least as accurate as the heatmeter and very easy to use.

II. Design construction and performance of superconducting-magnet support posts for the Large Hadron Collider.

Two prototype support posts from different firms were tested under similar conditions. A third carbon-epoxy prototype, made by CERN, was also tested thermally at 5 K and 1.8 K. At lower temperatures, the carbon epoxy has a lower thermal conductivity and at higher temperatures (≥ 40 K), a higher conductivity. So, the optimum solution from a thermal point of view would be a mixed support post with carbon epoxy in the colder part (≤ 40 K) and glass-fibre epoxy in the warmer part. Mechanical properties and the cost increase for manufacturing such a post must be taken into account and compared with the gain in refrigeration power.

III. Cryogenic performance of a superfluid-helium relief valve for the LHC superconducting magnets.

A quench relief valve was designed and built at CERN. Following mechanical tests, we report from the thermal evaluation of the valve under working conditions, i.e. with pressurized superfluid helium. A dedicated measuring bench was built for this purpose to simulate the LHC conditions. The heat load was measured as a function of the temperature in the helium recuperation line. Furthermore, the mass leak through the valve was measured at different pressures on the valve poppet.

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7. Glossary

Part A

<u>C_0</u>	Radiation length is defined as the thickness of a medium which reduces the mean energy of an electron beam by a factor e . This parameter is important for the inner detector as material in front of the calorimeter deteriorates the energy resolution.
<u>h</u>	The pseudorapidity h is often defined as $h = -\ln(\tan(q/2))$ where q is the angle to the beam axis. h is used instead of q to define the direction of particle trajectories inside a detector. The pseudorapidity is not the same as the rapidity, but approximately equal for high p_T.
<u>l</u>	Absorption length determines the scale for the longitudinal development of the shower. l is often used in the discussion of the hadron calorimeter.
<u>b</u>	v/c , where the c is the speed of light.
<u>g</u>	$\frac{1}{\sqrt{1-b^2}}$
<u>p_T</u>	The momenta transverse to the beam axis.
<u>hadron</u>	Strongly interacting particle composed from three quarks or a quark-antiquark pair.
<u>lepton</u>	Elementary particle which carries an electrical charge of 0 or $\pm e$, e.g. electrons and neutrinos. Leptons do not experience strong interactions.
<u>luminosity</u>	The interaction rate per unit cross-section.
<u>quark</u>	The fundamental particle with the fractional charge $\pm 2/3 e$ or $\pm 1/3 e$ which is the building blocks of hadrons.

<u>ASDBLR</u>	Amplifier-Shaper-Discriminator with BaseLine Restoration. It is a bipolar integrated circuit for the ATLAS TRT.
<u>DTMROC</u>	Drift-Time Measurement Read-Out Chip. It measures the drift time of the electrons the straw.
<u>SCT</u>	The semiconductor detector in ATLAS.
<u>TR</u>	Transition Radiation.
<u>TRT</u>	Transition Radiation Tracker.

Part B

<u>arc</u>	The part of the ring occupied by regular half-cells with three dipoles and one quadrupole. One half-cell is about 50 m.
<u>heatmeter</u>	Calibrated thermal impedance for measuring heat flows.
<u>quench</u>	A sudden transition from a superconducting state to a normal resistive state.
<u>quench relief valve</u>	A valve mounted on the magnet which opens on a quench trigger and discharges the helium into a recuperation line. This is necessary to protect the magnet from a too high helium pressure in case of a magnet quench.
<u>superfluid</u>	Helium below 2.17 K (saturated pressure). It shows peculiar thermophysical properties, e.g. mass flow without resistance, high specific heat and highly effective thermal conductivity.
<u>super-insulation</u>	A stack of thin aluminized foils, normally 10-20, which reduce the heat radiated from a warm to a cold surface.
<u>support post</u>	Support made of composite material for the cold mass in the LHC superconducting magnets.

Paper I

Paper II

Paper III