LHCb Scintillating Fibre Tracker
Technical Design Report

The LHCb collaboration†

Abstract

This will be the TDR for the LHCb Scintillating Fibre Tracker.
LHCb collaboration

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Part I

The LHCb Scintillating Fibre Tracker
1 Introduction

The different options for the upgrade of the downstream tracking system were described in LHCb Letter of Intent \[1\] and the LHCb Framework TDR \[2\]. This TDR describes the subsequent development of the project. The major changes are:

- Electronics review on 11th of December 2013.
- Choice of cooling technology. Cooling review
- Decision to go for full fibre tracker solution?

The following sub-sections describe the current downstream tracking system, the upgrade environment, and finally an overview of the options for the upgraded downstream tracker. The results from R&D on the scintillating fibres and Silicon photomultipliers (SiPMs) are given in Sec. 3. The scintillating fibre module design and the read-out electronics will be described in Secs. 4 and 5 respectively. The infrastructure and services required for will be discussed in Sec. 6. The expected performance of the detector estimated from simulation studies is presented in Sec. 7. Finally, the organisation of the project is described in Sec. 8.

1.1 Current Downstream Tracking System

The current LHCb tracking system downstream of the dipole magnet consists of three tracking stations constructed from Silicon micro-strips in the innermost region, the Inner Tracker (IT), and straw tubes in the outer region, the Outer Tracker (OT). Each station in the IT and OT contains four detection layers, denoted \((x1, u, v, x2)\), with strips or straws orientated at \((0^\circ, +5^\circ, -5^\circ, 0^\circ)\) with respect to the vertical axis. This leads to a total of twelve tracking layers in the current tracking system.

Each station in the IT consists of four boxes arranged in a “Swiss-cross”-like shape covering a 120 cm by 40 cm region around the beam-pipe. The boxes contain four detection layers with seven modules in each layer. The modules have either one or two silicon sensors connected to a front-end read-out hybrid. The modules in the the boxes either side of the beam-pipe have two 410 \(\mu\)m thick \(p^+\)-on-\(n\) sensors bonded together while those in the boxes above and below the beam pipe are made using a single 320 \(\mu\)m thick sensor. Each sensor has 384 read-out strips with a strip pitch of 198 \(\mu\)m. The sensors are 7.6 cm wide and 11 cm long. There are 336 read-out sectors with a total of 129,024 readout channels. The total active area is around 4 m\(^2\) and.

\(LHCb\) follows a right-handed co-ordinate system with positive \(z\) defined as the direction of the beam away from the interaction point at \(z = 0\) where positive \(y\) points “upward”, and positive and negative \(x\) point towards the access cavern and the LHC cryogenics respectively. Positive and negative \(x\) are thus labelled A-side and C-side.
The Outer Tracker is a gaseous straw-tube detector which covers an area of approximately 5 m by 6 m. Each detection layer has double layer of straw tubes and there are a total of 53,760 straw tubes. The straw tubes are 2.4 m long and 4.9 mm in diameter, and they are filled with the gas mixture Ar/CO$_2$/O$_2$ (70%/28.5%/1.5%). A high voltage is applied to the 25 $\mu$m diameter gold-plated tungsten anode wires which corresponds to a gain of about $5 \times 10^4$. The cathode consists of an inner foil of electrically conducting carbon doped Kapton-XC and an outer foil of Kapton-XC laminated with a layer of aluminium. The straws are glued to panels and sealed with sidewalls. The result is a stand-alone detector module contained in a gas-tight box.

The performance of the IT is described in Ref. [3]. The spatial resolution was measured to be 50 $\mu$m with a hit efficiency greater than 99%. The performance of the OT is described in Refs. [4,5]. The spatial resolution is about 200 $\mu$m and the hit efficiency is greater than 99%.

1.2 Upgrade Conditions

The LHC will collide protons at a centre-of-mass energy $\sqrt{s} = 14$ TeV. The instantaneous luminosity at LHCb will be in the range $1 - 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$. This will be achieved using 25 ns bunch spacing and having up to 6.7 interactions per crossing. The integrated luminosity collected over the lifetime of the upgraded detector will be 50 fb$^{-1}$. The detector will be read-out at 40 MHz.

1.3 Overview of Upgrade Downstream Tracking System

The geometry of the current tracking system was chosen such that the maximum occupancy in the hottest regions of the OT was limited to 10% for an instantaneous luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ [6]. Improvements were made to the track reconstruction so that LHCb could collect data at instantaneous luminosities up to $5 \times 10^{32}$ cm$^{-2}$s$^{-1}$. In this case, the occupancy in the OT increased up to a maximum of 25% with no loss in track finding efficiency. However, it was shown in Ref. [1] that the occupancy in these regions in OT would be too large at the upgrade luminosity, $\mathcal{L} = 1 - 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$, and the OT would need to be replaced. The read-out electronics must also be replaced to enable the LHCb detector to read out data at 40 MHz.

The upgraded tracker will completely replace the IT and OT with scintillating fibre detectors. There will still be twelve detection layers each covering an area of 5 m by 6.1 m. As before, the twelve detection layers will be split across three stations, and provide measurements of $(x, u, v, z)$ co-ordinates. In total, there will be 144 modules with twelve mono-layer modules in each detection plane. Each mono-layer module consists of a mat of scintillating fibres sandwiched between a layer of honeycomb with an outer layer of carbon fibre as shown in Fig. [1]. The fibre mats will be constructed using 250 $\mu$m diameter fibres arranged in five (or six) layers and read out with SiPMs. There will be 32 SiPMs per module with 16 each located at the top and bottom of the detector. The SiPMs and other electronics will be contained in in so-called read-out boxes at the top or bottom of
the detector stations outside the acceptance. Mirrors will be attached to the opposite end of the fibres. A sketch of one detection layer is shown in Fig. 2. The completed fibre tracker will require 7400 km (or 8880 km) of fibres and the total number of channels will be 589,824. The total active area will be around 360 m².

Figure 1: PLACEHOLDER: Sketch of the monolayer. Update plot.

1.4 Material Scans

The total material seen by particles which pass through the current T1 station (z from 767.3 cm to 803.8 cm) is shown in Fig. 3. The average material traversed is 4.0% of a radiation length ($X_0$). The material seen by particles passing through the upgraded T1 station is shown in Fig. 4. The total material traversed is estimated to be 2.6%$X_0$. 
Figure 2: PLACEHOLDER: This is the layout of a single layer with only scintillating fibres. Get
closer plot.
Figure 3: Distribution of material in T1 (current).
Figure 4: Material distribution in T1 for the upgraded detector.
2 Requirements

The detector performance required for the tracking is a high hit efficiency, spatial resolution of 60-100 µm in the bending plane, low material budget in the acceptance, and read-out electronics operating with 40 MHz sampling. The detector must also be able to operate for the full lifetime of the upgraded LHCb detector.

The main requirements of the detector performance are discussed in detail in Sec. 2.1 and the radiation environment in the tracker volume is shown in Sec. 2.3.

2.1 Detector Performance

The main requirements on the upgraded tracking detector are given below:

- The hit detection efficiency should be greater than 99% with a noise cluster below 2 MHz per 128 channels to enable efficient track reconstruction. These numbers were determined from simulation, see Sec. 7.
- The spatial resolution must be in the range 60-100 µm. A resolution less than this is not needed as the extrapolation of tracks from the VELO becomes dominated by the effect of multiple scattering in the detectors upstream of the magnet.
- The material in the acceptance region should be minimised.
- The read-out electronics should be able to run at a frequency of 40 MHz, and the recovery time of the read-out channels should be short to minimise inefficiency due to dead-time.
- The detector should be able to operate with the required performance for an integrated luminosity up to 50 fb$^{-1}$.
- The detector should re-use the existing infrastructure as far as possible.

2.2 Geometry Constraints

Something here about the layout?

3 stations, re-use OT frames?

2.3 Radiation Environment

The radiation level expected at the tracker station T1 has been estimated from a FLUKA simulation of the LHCb detector. The simulation was performed under the expected upgrade conditions at $\sqrt{s} = 14$ TeV using the latest geometry description. The simulations are described in more detail in Ref. [9]. The estimated 1-MeV neutron-equivalent fluence is shown in Fig. 5 and the dose is shown in Fig. 6.
Figure 5: The expected 1-MeV neutron equivalent fluence per cm$^2$ at $z = 783$ cm after an integrated luminosity of 50 fb$^{-1}$. The red lines indicate the position of the SiPMs.

The radiation dose after an integrated luminosity of 50 fb$^{-1}$ was estimated to be $6 \times 10^{11}$ n$_{eq}$/cm$^2$ at the position of the SiPMs ($y = \pm 250$ cm). The peak dose absorbed in the fibres is expected to be of the order 26 kGy.
Figure 6: The expected dose in the $x - y$ plane at $z = 783$ cm after an integrated luminosity of 50 fb$^{-1}$. The position of the SiPMs is indicated by the red lines.
3 Research and Development

Summary of results from all R&D.

3.1 Scintillating Fibre R & D

Summary of results from fibre R&D.

Blake’s edits + copy paste from Viability doc, updated on 18/12 by Christian Scintillating plastic fibres are considered as the active detector elements for the SciFi upgrade project. For the time being, all experimental work has been concentrated on the multi-clad blue emitting fibre of type SCSF-78MJ from Kuraray, which is currently considered as the baseline fibre due to previous experience and knowledge using scintillating fibres in other experiments. Co-operation with the supplier Saint–Gobain (formerly Bicron) is at an early stage. Saint–Gobain offers the fibre type BCF-12 which has, at least on paper, similar specs than the SCSF-78MJ. The delivery of BCF-12 fibre samples (several km) is imminent. The known properties of the scintillating fibre and its impact on the SciFi Tracker are presented in the following subsections.

3.1.1 Properties

We intend to use plastic scintillating fibre with a circular cross section having a total diameter of 0.250 mm, including two cladding layers of nominally 3% total thickness each. A schematic of the fibre is shown in Fig. 7. The core of the fibre is doped polystyrene with two outer claddings of decreasing indexes of refraction. The inner cladding is made of polymethylmethacrylate (PMMA) and the outer cladding made of fluoronated-PMMA. The trapping efficiency for isotropically emitted (scintillation) light in a single hemisphere is maximally 5.34% (helical path or non-meridional light rays will reduce this) and the numerical aperture of the fibre is 0.72. The nominal emission spectrum (for emission very near to the detection point) for the SCSF-78MJ fibre extends from about 400 to 600 nm and peaks at 450 nm, as seen in Fig. 10a with a bulk optical absorption length of >3.5 m. Typically, there is a short and long component to the attenuation length, due to geometrical effects in the fibre, as well as a strong wavelength dependence on the attenuation length due to reabsorption of the shorter blue wavelengths by the scintillation dyes and some discrete higher wavelengths by the polystyrene, as seen in Fig. 10b. The effect on the emission spectrum and the optical absorption length by radiation will be further addressed in Sec. 3.1.2.

The decay time constant of the scintillation light is nominally 2.8 ns. The mean propagation time of light along the length of the fibre is 6 ns/m, slightly longer than that calculated from only total-internal-reflection considerations. The light rays will follow paths that are at an angle to the central axis and will reflect from the cladding at multiple points, resulting in a longer path length for the light ray. Measurements of the propagation time agree with GEANT4 simulations, as seen in Fig. 8.

The light yield is around 8000 photons/MeV (from the manufacturer’s specifications) though has been observed to be lower than this by a factor of two. Typically, one observes
Figure 7: The wavelength spectra observed in Kuraray SCSF-78MJ scintillating fibres at three positions. A 370 nm LED was used to stimulate the fibre and was readout with an intensity calibrated Hamamatsu C10083CA-2050 photospectrometer.

Figure 8: Mirco’s timing image

between 15-20 photoelectrons per mm of scintillating fibre near the source as seen by a SiPM. This light yield and timing is more than sufficient for the needs of the scintillating fibre tracker. Measurements of the light yield with a SiPM photodetector will be shown in Subsection. ref.

18/12, Christian: I believe we have actually non-S-type, but I’m checking this with Kuraray!

The investigated fibre is of the S-type (the polystyrene chains in the fibre core are aligned along the fibre axis) which gives the fibre a higher strength against cracking.
However, the attenuation length is typically 10% shorter for S-type compared to the Non-S-type, according to the manufacturer. The minimum bending radius, recommended by Kuraray, for this fibre type, is about 12.5 mm.

**Fibre Diameter:** 18/12, added by Christian

The extrusion of dual-cladded scintillating plastic fibres from a preform is a delicate process requiring the control of a multitude of parameters. The temperature of the furnace and the rotation speed of the mandrel which receives the fibre have a direct impact on the fibre diameter. The producers online-monitor the diameter during production and achieve average diameters within about 1% from the nominal value. However, according to information from Kuraray, also inhomogeneities of the base material can lead to fibre diameter variations on small length scales (order of cm) which can’t be controlled by regulating temperature and speed. These bumps become a concern if their size exceeds about 300 µm.

Our current understanding of the technical specification of the fibre is summarized in ... refer to Internal note

18/12, added by Robert, edited by Blake Due to the extrusion production method of the fibre, the outer diameter fluctuates (see Fig 9) at well defined spots on the order of 1 cm in length, with a frequency of 0.25 – 1 per km. The measured nominal fluctuations are tolerable for production, although they lead to deviations of the perfect position of below x µ m (cite). The problem deviations in the diameter are thicker, and appear as bumps, with a diameter of 300-500 µm on a length of X-Y cm. These large fibre diameters cause mispositioning of fibres during the fibre mat production and should not (cannot) be used. The manufacturer is working on reducing the frequency of the bumps. The remaining bumps are detected by the fibre quality control and can be excluded from the production of the fibre mats.

![Dummy image](image)

Figure 9: Fibre diameter of x km of fibre. It is visible that blablub

The fibres will be bonded into ribbons consisting of five staggered fibre layers with a pitch of 280 µm, and a total length of about 2.5 m. The fibres will be covered with a thin,
clear epoxy layer (Epotek 301-2) during ribbon production, and yet again during final ribbon molding. A small percentage of titanium-dioxide will be added to the epoxy to reduce channel cross-talk. The difference between fibre diameter and positioning pitch mitigates the effect of fibre diameter variations or other imperfections (e.g. duct grains). Readout of the fibres will be by SiPM arrays on one fibre end only. The other end will be equipped with a reflecting mirror to increase light yield at the readout end (refer to specific section and mirroring note).

![Wavelength spectra observed at three positions.](image1)

(a) Wavelength spectra observed at three positions.

![Attenuation lengths.](image2)

(b) Attenuation lengths.

Figure 10: The attenuation of discrete wavelengths seen in Kuraray SCSF-78MJ scintillating fibre. The attenuation length is found from a single exponential fit of the measured intensities along positions from 50 cm to 270 cm. A 370 nm LED was used to stimulate the fibre and was readout with an intensity calibrated Hamamatsu C10083CA-2050 photospectrometer.

3.1.2 Radiation Tolerance of the Fibre

The scintillating fibres are exposed in the inner most region of the detector, at about 8 cm from the beam pipe axis, to an accumulated radiation dose of approximately 35 kGy. The expected dose drops rapidly, both in the horizontal and vertical direction, and becomes expectedly marginal (<1 kGy) at distances of about 50 cm [9]. Radiation damage to plastic fibres has been systematically investigated in the early 1990s [10], and the optical changes to the base material were identified as main cause for the degradation of their light output. Radiation damage leads to a reduction of the optical absorption length and the viability of a fibre at a given radiation load depends crucially on its length. However, also the basic scintillation and wavelength shifting mechanisms (fluors) as well as other additives can suffer damage and contribute to the performance degradation. From the beginning, the impact of radiation dose rate, radiation type and environmental effects (presence of oxygen) as well as recovery effects were controversially discussed in the literature. Analysis of the publications of a number of irradiation experiments which have been performed for our baseline fibre or similar polystyrene based blue emitting fibres revealed results which...
partly disagree and the conclusions which are vague or even in full contradiction [11]. It was therefore considered mandatory to perform a series of radiation experiments with the SciFi baseline fibre in a configuration which comes close to the one in the final detector. A few different fibre irradiation experiments have been conducted under differing conditions but all on the same fibre type.

**Dortmund measurements:** Several bundles of fibres with protons of 24 MeV energy to doses of up to 100 kGy. A significant degradation of the optical transparency was observed for the highest dose, however the small length of the irradiated zone and the absence of control measurements on non-irradiated samples prevented the extraction of quantitative results.

In-situ irradiations in the LHCb cavern on 3 sets of 1.1 m long fibres. The samples were installed in 2012 during TS1 on the shielding wall close to the VELO. The expected doses were in the sub-kGy range. Measurements of the relative light yield as a function of the position of a Sr-90 source were performed during TS2 and TS3. The measurements and the analysis suffer from a number of limitations inherent to the in-situ set-up and the availability of only two data points (TS2, TS3). The relatively low dose levels make it difficult to derive a conclusive result but are shown with the combined analyses below.

**CERN-PS measurements:** A radiation test was performed at the CERN PS with 24 GeV/c protons on a test sample which contains 8 SCSF-78 fibres of 2.94 m length. Details of this test and the performed characterization measurements can be found in Ref. [12]. A second identical sample was kept un-irradiated as reference. The samples consist of aplexiglass plate with a groove in which 8 fibres, arranged in 4 layers of 2 fibres each, are placed together with a thin layer of epoxy glue of type EPOTEK 301-2FL (see Fig. 11). To accommodate the total fibre length of $L = 2942$ mm on the plates, the fibres are arranged as 4 legs (of approx. 75 cm length) with 3 turn points (TP). The bending radius at the turn points is 25 mm and hence a factor 2 larger than the recommended minimum radius. The glue was unloaded, i.e. no TiO$_2$ powder or other substances were admixed to it. The two ends of the fibre set reach the edge of the plate and, after polymerization of the glue, they were machined to optical quality by means of a diamond tool on a milling machine. One end serves as port to connect a photodetector or spectrometer. The other end of the fibre allows to investigate the effect of a reflecting mirror on the fibre characteristics.

Sample 1 was irradiated with protons of 24 GeV/c in the T7 area of the CERN PH Irradiation facility. Protons from the primary PS beam form a horizontal beam of about 1 \( \times \) 1 cm$^2$ in size. The sample was aligned with the beam axis and tilted by 10 mrad w.r.t. the horizontal plane. In this configuration the beam spot is expected to cover the full length of the sample (76 cm). The sample was mounted on a motorized XYZ station which allows changing the positioning of the sample during the irradiation. The irradiation was programmed to take place in two steps: in a first period lasting 4.5 hours, leg 4 (far end)
was irradiated to a total fluence of $7.1 \cdot 10^{13} \text{ p/cm}^2$ (equivalent to 22 kGy) followed by a second step lasting 8 minutes, in which leg 3 was exposed to protons up to a total fluence of $9.5 \cdot 10^{12} \text{ p/cm}^2$ (equivalent to 3 kGy). The relative uncertainty is 10% for both values. Legs 1 and 2 were expected to receive only background radiation from neutrons. This resulted in a neutron fluence of about $5 \cdot 10^{12} \text{ n/cm}^2 \pm 20\%$ which represents a negligible ionization dose. The actually received radiation doses and fluencies were extracted from the forward currents of a set of four PIN diodes and the activation of aluminium foils which were attached to the sample right above the fibre locations. From the discolouring of the plexiglass plate, visible in the region of leg 4, it appears that the irradiation was uniform over only about 70% of the plate’s length. In accordance with the rules in place at CERN, the sample could be extracted from the irradiation zone after a cool down time of 7 days.

The fibre samples were excited by UV light from a LED (wavelength = 385 nm, beam spot size = 3 mm) which was mounted directly above the test plate. The LED excites the second fluor of the fibre, i.e. the fibre will respond with its normal emission spectrum. The light output is measured by means of a calibrated (±2%) UV-enhanced photodiode of type Newport 818-UV of 10 mm active diameter. Its photocurrent is measured as a function of the distance of the excitation point from the end where the photodetector is placed. Despite manual positioning of the LED, the method proved to be reproducible on the level of <5%. The data for plate 1 before and after irradiation are shown in Figs. 12a and 12b. The bulk absorption length is typically extracted from a single exponential fit to the data, $I(d) = I_0 \exp(-d/\lambda_{abs})$, for positions greater then 50 cm. A double exponential fit is needed to account for the short attenuation component less than 50 cm owing to
geometrical path effects in the fibre. More complex parametrizations are needed when
including the mirror at the far end. A wavelength dependence on attenuation length is
also observed, as seen in Fig. 10a such that the bulk attenuation length also depends on
the quantum efficiency of the photodetector over the wavelength spectrum. The light
yield and the absorption lengths measured in this way correspond to the averages over the
fibres' emission spectra weighted with the quantum efficiency of the photodiode. The latter
varies in a rather linear way from 50% at 400 nm to 80% at 600 nm. The photon detection
efficiency (PDE) of the KETEK SiPM detector which was used for the measurements
with the Sr-90 source, described below, and which is intended to be used in the SciFi
detector, shows a very different spectral form. It peaks at about 425 nm, drops by 15% at
400 nm and by 50% at 550 nm. The knowledge of the fibre’s emission spectra before and
after irradiation, for different excitation distances, allows taking into account the different
spectral responses of the photodetectors.

(a) Before irradiation. Open symbols: As measured with the PIN diode. Full symbols:
Scaled to the spectral response of a KETEK SiPM detector.

(b) After irradiation: Relative light yields resulting from UV excitation and exposure
Scaled to the spectral response of a KETEK to electrons from the Sr-90 source.
SiPM detector.

Figure 12: Relative light yield with UV excitation as function of the excitation distance for
Plate 1 before and after irradiation.

The measurements after irradiation are described by a combination of exponentials,
where the individual segments of the fit were defined such that they coincide at the turn
point positions of the plate. The fits resulted in the absorption lengths summarized in
Table 1. The long and short components of the absorption length are shown. The short
absorption length describes the rapid light absorption of helical light rays and/or possible
‘cladding’ light along with wavelength reabsorption (in the far blue).

The Sr-90 data shows a very similar dependence on the excitation distance as the
UV-LED data (after scaling the latter to the spectral response of the SiPM). It therefore
appears that both, the scintillation and wavelength shifting mechanism of the fibre are, if
at all, only marginally affected by the applied radiation levels.
Table 1: Optical absorption length before and after irradiation. All values are in cm. The data for legs 1 and 2 include the long/short absorption length, 3 and 4 only contain the long component. The errors are statistical only.

<table>
<thead>
<tr>
<th>leg</th>
<th>sample 1 non-irrad.</th>
<th>sample 1 irrad.</th>
<th>sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 and 2 (0 kGy)</td>
<td>439$^{+25}<em>{-25} / 20^{+8}</em>{-5}$</td>
<td>422$^{+97}<em>{-66} / 20^{+5}</em>{-5}$</td>
<td>346$^{+13}<em>{-12} / 10^{+3}</em>{-5}$</td>
</tr>
<tr>
<td>3 (3 kGy)</td>
<td>439$^{-25}$</td>
<td>126$^{+13}_{-10}$</td>
<td>346$^{+13}_{-12}$</td>
</tr>
<tr>
<td>4 (22 kGy)</td>
<td>439$^{-25}$</td>
<td>52$^{+6}_{-5}$</td>
<td>346$^{+13}_{-12}$</td>
</tr>
</tbody>
</table>

**Heidelberg KIT measurements**: Similar to the CERN PS measurements, small bundles of four or six 0.25 mm diameter Kuraray\(^2\) SCSF-78MJ scintillating fibres were embedded in EPOTEK\(^3\) 301-2 epoxy arranged on boards with 1 mm × 0.5 mm shallow grooves. Boards were prepared with control samples as well.

The fibres were arranged in two configurations in shallow channels on a PVC board, as seen in Fig.13. The geometries of the boards were defined by the irradiation facilities and the X-Y stage used at KIT which had a 20 cm × 40 cm window. Precision holes for the base of the UV-led light holder allowed for simple and reproducible measurements for each position of the board.

![Figure 13: PVC boards with channels for (a) the 200 cm and (b) the 40 cm long fibre bundles. The shaded and numbered regions indicate the regions irradiated.](image)

The irradiation was conducted at the Karlsruhe Institute of Technology (KIT) using 25 MeV protons from the Compact Cyclotron at KIT Campus North. The samples were placed in a box on an XY stage and moved in front of the beam. The proton beam energy

\(^2\)Kuraray Co., Ltd., Ote Center Building, 1-1-3, Otemachi, Chiyoda-ku, Tokyo 100-8115, Japan

\(^3\)EPOTEK, Epoxy Technology, Inc., 14 Fortune Drive, Billerica, MA 01821, USA
is 22.9 MeV after exiting the box window, perpendicular to the plane of the PVC board. The stage was moved 27 or 40 cm in X and then stepped vertically 1 mm in Y to scan the shaded areas seen in Fig. 13. As the beam current was fixed, the speed at which the stage moved (115 mm/s in X) and the number of repetitions determined the integrated proton fluence for each of the regions. The width of the proton beam is nominally 7 mm at FWHM. The geometries of the boards were defined by the irradiation facilities and the X-Y stage used at KIT which had a 20 cm × 40 cm window.

A minimum stable beam current of ∼ 0.2 µA meant that the lowest dose achievable was ∼7 kGy, assuming a stopping power of 22.94 MeV cm²g⁻¹ for 22.9 MeV protons for a pure polystyrene fibre cite[ref]. The shorter fibre board was used to investigate higher levels of damage, as the attenuation length would become very short. The highest dose of 56 kGy was chosen to be higher than the FLUKA simulations for the upgrade by a factor of two. A range of doses over multiples of the minimum dose were tested due to the scanning method and fixed beam current.

The integrated fluences were measured in two ways. Thin nickel foils were placed next to the fibres for all the regions to be irradiated and the total integrated fluence after irradiation was determined through Ni⁵⁷ activity measurements with a Germanium detector cite[ref]. The calculated doses based on the fluence are shown in Table 2. A second cross-check of the integrated fluence was done with calibrated silicon PIN diodes. The leakage current is a measure of the neutron-equivalent integrated fluence. These were placed on select channels, also shown in the dose tables.

The uncertainties in the nickel foil measurements were estimated to be 20% citeDierlamm, and 30% for the PIN diodes. These uncertainties are similar to those experienced in other studies citeBay, citeHara. No errors are shown for 0 kGy dose in Table 2 as the uncertainties are small but unknown. These channels would have been exposed to background radiation due to scattering, however, the PIN diodes are only able to measure minimum fluences of the order 10¹² p/cm². The lowest dose of ∼9 kGy had an integrated fluence of the same order of magnitude as this lower limit. The nickel foils on these 0 kGy fibres had activity levels similar to the background before irradiation.

The light yield of the scintillating fibre bundles for both the long and short boards was measured before and after irradiation and the transmission from each board position compared. By taking the ratio of the measured light output, local variations in the board due to reflections were removed, and assuming the data fits well to a single exponential containing only the long component of Eq.refeq:doubleexp after a few cm, one can fit the ratio of the data to the following equation to extract the attenuation length after irradiation:

The light yield of the scintillating fibre bundles for both the long and short boards was measured before and after irradiation and the transmission from each board position compared. By taking the ratio of the measured light output, seen in Fig 14, local variations in the board due to reflections were removed, and assuming the data fits well to a single exponential containing only the long component after a few cm, one can fit the ratio of the data to the following equation to extract the attenuation length after irradiation:
Figure 14: Ratio of current measurements after irradiation to before irradiation of the 200 cm long fibres. The attenuation length for each dose was found by fitting Equation 1 to each dose region. Each group of ≈15 data points represents a single dose region, with gaps in between corresponding to the curved sections of the fibre bundle, which were not irradiated. Statistical errors in the ratio data points are ±2.8% and ±0.5 mm for the position.

\[
\frac{I'(x)}{I(x)} = \frac{I'_0 C(x) e^{-x/\Lambda'}}{I_0 C'(x) e^{-x/\Lambda_0}} = K' e^{-x \left(\frac{1}{\Lambda'} - \frac{1}{\Lambda_0}\right)}
\]  

(1)

where \(I'(x)\) and \(I(x)\) are the intensities of light after and before irradiation respectively, measured with a distance \(x\) between light source and fibre end; \(I'_0\) and \(I_0\) are the intensities of captured scintillation light after and before irradiation respectively; \(C(x)\) is the local scaling factor for each position; \(\Lambda'\) and \(\Lambda_0\) are the bulk attenuation lengths after and before irradiation respectively; and \(K'\) is a scaling constant, which would equal one if the positioning, UV LED intensity, and polish at the end of the fibres had remained identical for each set of measurements. The data showing the ratio of after to before irradiation as measured by a calibrated photodiode are shown in Fig. 14.

Results:

In the Viability Document, the radiation damage to the scintillating fibre (the reduced attenuation length) was modelled in the same manner as in Hara et al, with a logarithmic function \(\Lambda(Dose)/\Lambda_0 = \alpha + \beta \log(Dose)\), and using only the three data points from the CERN-PS measurements, found values of \(\alpha = 0.381\) and \(\beta = -0.196\). Predictions of the light yield in the full SciFi detector were based on this model, folding in the expected radiation field of the LHCB Upgrade and predicted a reduction in the light yield of 40% from the most damaged region of the detector, which also happens to be the furthest from the photodetectors, near the beam pipe. Including the data from the Heidelberg-KIT measurements into the fit, results in values of \(\alpha = 0.435\) and \(\beta = -0.226\), which predicts less light loss than before for the same dose. However, this logarithmic description has two failings. The ratio of attenuation lengths goes to infinity near dose, and becomes negative.
Table 2: The doses requested, two dose measurements and the measured attenuation length for the 200 cm and 40 cm fibre bundles using Nickel foils and PIN diodes. The error weighted mean dose values were used as the received dose in the analysis.

<table>
<thead>
<tr>
<th>Sec.</th>
<th>Req. (kGy)</th>
<th>Ni Foil (kGy)</th>
<th>PIN Diode (kGy)</th>
<th>Mean (kGy)</th>
<th>$\Lambda/\Lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>$1 \pm 0.16$</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>$11.5 \pm 2$</td>
<td>$6.8 \pm 2.0$</td>
<td>$8.8 \pm 1.5$</td>
<td>$0.20 \pm 0.04$</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>$10 \pm 2$</td>
<td>-</td>
<td>$10 \pm 2$</td>
<td>$0.23 \pm 0.05$</td>
</tr>
<tr>
<td>4</td>
<td>28</td>
<td>$41 \pm 8$</td>
<td>$46 \pm 14$</td>
<td>$43 \pm 7$</td>
<td>$0.052 \pm 0.02$</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
<td>$36 \pm 7$</td>
<td>-</td>
<td>$36 \pm 7$</td>
<td>$0.13 \pm 0.11$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ch.</th>
<th>Req. (kGy)</th>
<th>Ni Foil (kGy)</th>
<th>PIN Diode (kGy)</th>
<th>Mean (kGy)</th>
<th>$\Lambda/\Lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>$9.5 \pm 1.9$</td>
<td>-</td>
<td>$9.5 \pm 1.9$</td>
<td>$0.26 \pm 0.03$</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>$19 \pm 4$</td>
<td>$16 \pm 5$</td>
<td>$18 \pm 3$</td>
<td>$0.15 \pm 0.02$</td>
</tr>
<tr>
<td>4</td>
<td>28</td>
<td>$37 \pm 7$</td>
<td>-</td>
<td>$37 \pm 7$</td>
<td>$0.067 \pm 0.012$</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>$59 \pm 11$</td>
<td>$64 \pm 19$</td>
<td>$60 \pm 10$</td>
<td>$0.048 \pm 0.012$</td>
</tr>
</tbody>
</table>

at large doses. Other models were proposed and describe the data as well or better. The combined data and model fits are seen in Fig. ref{SciFi:combinedfibredata}. Model 1 assumes a linear damage with dose effect. Model 2 assumes a power law where there is a saturation of the damage from irradiation. Model 3 is the logarithmic dependence similar to the study by Hara et al. cite[Hara]. Model 4 is another saturating model which has an exponential-like behaviour.

Using these other models an updated prediction of light loss in the scintillating fibre at the full 50 fb$^{-1}$ is seen in Fig. ref{SciFi:updatedlightloss}. The data is simulated with Model-4, the more pessimistic model where $\Lambda(D)/\Lambda_0 = \exp(-D/\alpha)$. The expected light loss is seen to be 27 ± 3% after 50 fb$^{-1}$ with 35 kGy of dose in the worst region. If the expected dose is greater by a factor of two, then the model predicts a loss of 43 ± 17%. A summary of the expected signal loss in the fibre after irradiation is presented in Tab. ref{Tab:signalloss}.

One can also estimate the wavelength spectrum after irradiation based on the above measurements, as we expect a shift in the peak of the wavelength spectrum due to increased absorption of the shorter wavelength. One can take advantage of this fact by increasing the quantum efficiency of the photodetector to match the irradiated fibre spectrum.
Table 3: The expected signal loss over multiple doses, the percentage of the signal lost due to irradiation, and the fraction of the total loss of signal relative to 35 kGy.

<table>
<thead>
<tr>
<th>Dose (kGy)</th>
<th>signal lost</th>
<th>fraction of total loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.031</td>
<td>0.12</td>
</tr>
<tr>
<td>8.75</td>
<td>0.11</td>
<td>0.41</td>
</tr>
<tr>
<td>17.5</td>
<td>0.16</td>
<td>0.61</td>
</tr>
<tr>
<td>26.25</td>
<td>0.22</td>
<td>0.81</td>
</tr>
<tr>
<td>35</td>
<td>0.27 ± 0.03</td>
<td>1</td>
</tr>
<tr>
<td>70</td>
<td>0.43 ± 0.17</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Figure 15: The combined data from three fibre irradiation studies and fits to 4 models.

3.2 SiPM R & D

Summary of results from SiPM R&D.
Figure 16: The relative photoelectron yield from a ROOT-based parametric Monte Carlo of the SciFi tracker. The model estimates the signal yield of a cluster from (1) an unirradiated, unmirrored fibre, (2) an unirradiated, mirrored fibre, (3) an unirradiated, mirrored fibre after cutting photons that arrive after 25 ns and (4) an irradiated, mirrored fibre after cutting photons that arrive after 25 ns. The signal loss is estimated to be $27 \pm 3\%$ after $50 \text{ fb}^{-1}$ with 35 kGy of dose in the worst region.

Figure 17: The spectra and quantum efficiency of the scintillating fibre and SiPM.
4 Module Design

What will the thing looks like? Describe the various components.

The design of all high energy trackers keeps several goals in mind: good hit detection efficiency, low occupancy, low material budget, and precision alignment. The choice of the fibre type and shape affect the first two, but to ensure the last two, the method in which the detector is constructed becomes important. To ensure that total mass of the detector or misalignment of the detector does not degrade the particle tracking performance, the detector must be built light, strong and precisely, especially near the region of the beam pipe which receives the majority of the particle tracks. The following design for producing a modular detector is proposed.

The full span of each detector plane covers 6 m by 5 m in the X-Y coordinate system, respectively. The plane is broken into modules that are 5 m in length, with a width of 0.52 m, resulting in approximately 10 full modules per plane. It is likely 2 half-width modules will be required on the outer edges. The module width and spacing is dictated by integer values of the width of the SiPM array package plus mechanical tolerances. At a single end of one 0.52 m module, 16 SiPM arrays can be placed. This number was chosen as a reasonable compromise between handling size, operability and maximizing detector coverage. Each SiPM array will be grouped into sub-arrays of four, having an outer active detector width of 130.19 mm. It was deemed feasible to produce fibre mats to match which cover this width. Each module would consist of eight 2.5 m long mats.

4.1 Fibre Mats

Winding: The single 0.250 mm fibres need to be arranged in multi-layer mats to produce a sufficient light yield. In this design, 6 layers are proposed for the final design. Current design efforts have focused on 5-layer mats, but a higher light yield has been called for. In the production of the fibre mat, the second layer is shifted by half the horizontal pitch with respect to the lower and upper one. A machine has been developed to produce these mats, controlling the speed, tension and winding of the fibre onto a wheel with $\approx 1$ m diameter (see Fig. refmissing). A spool of 12.5 km of fibre feeds a single, continuous fibre into the machine. The 1 m wheel provides precision alignment and guidance to the fibre with a milled screw thread on the surface. The thread has a channel depth nearly half the fibre diameter depth and a 270 micron horizontal pitch to guide the fibre of the first layer. Once one layer is complete, the fibre is cut and placed again at the beginning of the screw. The fibre of the first layer becomes the guide for the fibre that produces the second layer and so forth. A thin layer of stable, optically transparent epoxy is added on top of each fibre layer on the wheel to bond adjacent fibre and the subsequent layer together. The epoxy has a pot-life of 8 hours. After the epoxy has hardened enough, the fibre mat forms a cylindrical shell and is cut perpendicular to the fibres and taken off the wheel to be flattened. The principle of producing fibre ribbons this way has proven to work with shorter modules (80 cm) in the serial production for the (PEBS?) PERDaix detector [cite] ($\approx 80$ fibre mats)).
As alternative to the thread on the wheel, a second approach is being developed.

It is based on a thin (≈ 100µm) substrate foil, e.g. Kapton or PEEK, on which a
photo-imageable coverlay (Dupont) is laminated. Exposure through a mask, photographic
processing and thermal hardening lead to a foil with a fine line pattern (64µm high) which
acts as guides for the fibre winding. Stretched over a wheel, the foil replaces the thread.
After the winding process, the substrate remains attached to the fibre mat which has the
advantage that it can provide precise (≤10µm) alignment marks. Furthermore the winding
is always performed on a fresh substrate of constant quality, making thread cleaning and
the use of an anti-stick agent obsolete. Industrial producers for substrate sizes up to 3.5 m
have been identified.

Both methods to guide the fibres have been successfully tested. A crossection and
measurements of the interfibre spacing has seen that the mean inter-fibre displacement is
less than 8-16 micron, increasing from first to fifth layer.

Alignment:
In both approches, after the mat is taken of the wheel, it is still fragile. The fibre mat
has a tendency to split between adjacent fibres as the glue layer is quite thin and can
separate from the smooth surface of the fibre. Fibres near the edges are particularly prone
to becoming separated from the ribbon. For this reason, the ribbon is cast in bath of glue
to ensure a thin protection film around the mat, which also creates a precise flat surface.
Protected like this, the fibre mats are cut along the fibre axis to achieve the correct width
and rectangular cross section.

Alignment: While the interfibre To ensure the overall alignment of the fibre mats
within the detector, care must be taken. It has been seen that fibre mats of over 2.5 m
will deviate by more than 100 micron from a central axis in its plane under minimal load,
despite being mounted and fixed at either end. Aachen fibre mat measurements, curvature,
blah bla blah. Cite case for mechanical alignment. Optically aligning and affixing nearly

Figure 18: Cross-section of fibre mat with pattern recognition position marks.
1100 fibre mats is not feasible with precision.

A more robust and repeatable alignment procedure has been developed and is currently being implemented for further prototype fibre mats. Precision holes of approximately 1.5 mm in depth and 5 mm in diameter are drilled into the winding wheel, following the threaded screw pattern. Within the hole, a polycarbonate pin is placed and a small amount of glue is applied to the exposed surface. The method ensures that mechanical alignment pins are bonded to the underside of the fibre mat and are guaranteed to follow the axis of the fibre mat. The pins can then be placed in alignment holes in subsequent machining and detector assembly tooling. A similar hole and pin concept would also work for the coverlay winding substrate.

**Cutting:** The fibre mat must have two types of cuts done on them once they are cast and hardened. To produce a straight and precise detector element, the edges of the mats are cut parallel to the aligned central axis on a vacuum table. The precision of the edges is expected to be better than 100 micron, such that the fibre mats can be packed as close as possible in the module. The fibre mats must also be cut at the ends of their length to optical quality. A single diamond milling of the ends of the fibre mats provides a good quality finish.

**Test of a long 5-layer fibre mat** A 3 m long fibre mat and 3 cm wide fibre mat with 5 layers, produced at Dortmund, underwent meteorological tests and was also characterized with an electron beam from a Sr-90 source, available at CERN. The mat was left un-casted and equipped with two end-pieces made of black POM (Polyoxymethylene) which allowed machining the fibre ends with a single-point diamond tool to optical quality. The final length of the mat, incl. endpieces was 2.5 m.

Samples of 2 cm length were produced from the excess length of the fibre mat. These samples were fully immersed in epoxy glue and the fibre ends machined to optical quality. The samples were inspected with an optical 3D coordinate measurement machine (CMM) The pattern recognition of the CMM recognizes the boundaries of the fibres and calculates parameters like diameter, eccentricity and positions, which allows to deduce the fibre pitch. The average pitch, given by the thread, was found to be 270µm, consistently for all 5 layers and constant over the width of the mat. The RMS of the pitch increases from the first layer, which is in direct contact with the thread, $RMS_1 = 8.8\mu m$, to the fifth layer, $RMS_5 = 16\mu m$. These values are small compared to the expected position resolution of the final detector of 60µm and are therefore considered acceptable.

Figure 2 screen shots from CMM

The 2.5 m long fibre mat was mounted in a so-called e-gun set-up, available at CERN. It consists of a 370 MBq Sr-90 source with magnetic energy filter, which provides a collimated beam of electrons up to the end point energy of 2.2 MeV with a resolution of $\Delta E \approx 0.1$ MeV. A crossed arrangement of two scintillating fibres (1 mm, square cross section), read out by two SiPM detectors defines a 1 mm$^2$ beam spot. The fibre mat was mounted in between the exit slit of the e-gun and the trigger counters. The electron energy was chosen to be 1.7 MeV. The average energy loss $dE/dx$ of 1.7 MeV electrons in plastic scintillator

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*OGP SmartScope, available in the CERN Departmental Silicon Facility*
is $1.85 \text{ MeV/cm}^2$. The fibre mat was read at one end by a 128-channel SiPM array by Hamamatsu, identical to the model used in 2012 test beam experiments. The SiPM array was visually aligned to the fibre ends, however the required precision of better than 0.1 mm was found difficult to achieve. Full overlap of fibre ends and active SiPM area could therefore not be guaranteed. The SiPM was read out by a 128-channel VATA128 ASIC via a custom designed USB board. At the opposite end of the mat, a mirror could be attached. The mirror consisted of an aluminized glass plate with MgF2 protection layer. Alternatively, an aluminized mylar foil, was used. The fibre mat could be longitudinally displaced relative to the electron beam such that in addition to the photoelectric yield also the optical attenuation length of the fibres could be assessed. A transverse scan by means of a linear motion table allowed to assess the uniformity of the fibre mat. The results are summarized in Figs ... Application of a mirror (without optical glue or grease) was found to increase the photoelectric yield by 1.7 - 1.8, when the fibre was excited 10 cm from the mirror. This is in agreement with previous lab measurements\textsuperscript{5}. A yield increase by attaching the mirror by means of optical glue could not be found. Similarly, at the detector side, the SiPM window (epoxy) was in mechanical contact with the fibre ends. Adding a thin layer of optical grease had no noticeable impact on the photoelectric yield.

4.2 Mirroring

Christian’s mirroring note

4.3 Panels

The panel material is chosen to provide the maximum strength while have the lowest material budget. Number should be compared to the Inner and Outer Tracker material budgets. The OT has a material budget of $X/X_0=0.744\%$ per layer plus $0.191\%$ for sidewalls or $3.17\%$ per stationor $9.51\%$ for the entire detector citeLHCB-2004-114. For the IT citeLHCb note 2008-054, on average, a particle sees $62.72\%$ of a radiation length up to RICH2. The SciFi plans to replace all of the IT and the majority of the OT.

The prototype module materials are shown in Tab.\textsuperscript{4} The total radiation length per module is $0.92\%$ or $11.0\%$ for the entire detector. The majority of the material is a result of the six layers of fibres and the casting glue. The glue added to the fibre mat adds approximately $0.2 \text{ mm}$ to the total thickness.

The panels will be assembled on a vacuum table template such that all eight fibre mats can be aligned with respect to a single plane and reference axis. Polycarbonate blocks are added to the ends of the module to provide mounting support and contains the final alignment holes of the panel. The honeycomb and carbon fibre panels are bonded to the fibremats at room-temperature to ensure flatness.

\textsuperscript{5}NIST Standard Reference Database 124, ESTAR, in agreement with $\text{dE/}dx$ used by Geant4
Table 4: The material budget for a single module. The honeycomb assumes an interaction cross-section of 42 g/cm² cite [korex nikhef internal note] and density of 24 kg/m³.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness(µm)</th>
<th>Layers</th>
<th>$X_0$(cm)</th>
<th>$X/X_0$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nomex Honeycomb*</td>
<td>20000</td>
<td>2</td>
<td>1750</td>
<td>0.229</td>
</tr>
<tr>
<td>CF skin</td>
<td>200</td>
<td>2</td>
<td>23.3</td>
<td>0.172</td>
</tr>
<tr>
<td>Panel glue</td>
<td>85</td>
<td>2</td>
<td>36.1</td>
<td>0.047</td>
</tr>
<tr>
<td>Fibre mat</td>
<td>1700</td>
<td>1</td>
<td>42</td>
<td>0.405</td>
</tr>
<tr>
<td>Mylar Wrap</td>
<td>100</td>
<td>2</td>
<td>28.7</td>
<td>0.07</td>
</tr>
<tr>
<td>Total</td>
<td>4220</td>
<td></td>
<td></td>
<td>0.922</td>
</tr>
</tbody>
</table>

Figure 19: Picture of panel cross section and Read-out box

4.4 Read-out Box

The Read-out Box defines the enclosure of the ends of the module. This is where the SiPM arrays are attached to scintillating fibre ribbons, where the cold pipe presses to the back of the SiPM arrays and where the flex-PCB signal cables bring signals from the SiPMs to the front-end electronics. All this must be enclosed in a relatively small space, while ensuring the box remains well insulated, as well as light tight and the humidity must be below a few ppm to prevent condensation and frost buildup.

**Thermal considerations:** The majority of the heat load in the cooling system will be parasitic losses from heat leaking into the ROB from the outer sides of the module. As the only important part of the detector that needs to be at -40C is the SiPM silicon, a strong thermal gradient can exist within the module as the outpanels must be above the dew point of the LHCb cavern to prevent condensation on the outside of the ROB. The narrowing of the mounting pieces that are glued to the end of the fibre mat are designed to limit the thermal exposure of the SiPM from the outside environment and
maximize insulation. All remaining cavities within the ROB are to be packed with Rohacell
closed-cell foam to provide insulation.

A square-profile copper or aluminum cold pipe will be pressed to the back of the SiPM-
package stiffeners. The stiffeners are likely aluminum to provide increased thermal conduc-
tivity.

![Dummy image](image)

Figure 20: Thermal study of real endcap design.

**SiPM Alignment** Four SiPMs are aligned on a single carrier spine with respect to a
single dowel pin. The alignment spine is inserted and aligned with respect to the alignment
marks of the Fibre mat.

**Signal Routing and Electronics**
5 Electronics

5.1 Front-End Design

Each scintillating-fibre module is read out at both ends by readout units henceforth referred to as “Front-End (FE) Boxes”. A FE Box interfaces to the SiPMs on one side and to the experiment data-acquisition and control system on the other. All SiPM signals are digitized on board by the PACIFIC ASIC (see Sec. 5.2); they are then reduced via a clusterization algorithm, serialized and transmitted through optical links to the TELL40 buffer boards in the counting house (see Sec. 5.4). Each FE Box has also a complete interface for the distribution of bias voltages to the integrated circuits and to the SiPMs, of Timing and Fast Control (TFC) signals and of signals from and to the Experiment Control System (ECS) [?].

The architecture of the SciFi FE electronics follows the guidelines in Ref. [?]. At the functional level, it can be summarized by the block diagram in Fig. 21: all SiPM signals are amplified, shaped and digitized in the PACIFIC ASIC described in detail in Sec. ??; the ADC data are then routed to an FPGA that executes a fast clusterization algorithm to reduce the data volume; cluster data from various SiPM are then gathered by a “concentrator” FPGA, which formats them and transfers them to a fast serialization algorithm according to the specifications of the GBT project [?], running either on the same FPGA or on a dedicated GBTx ASIC. Serial data are then transmitted to the counting house via optical links [?]. A “Master GBT” connected to the SOL40 [?] via bi-directional optical links is in charge of distributing TFC signals to the FE and ECS signals to and from the FE through the SCA chip [?]. Dedicated DC-DC converters are also placed in the FE Box to provide low bias voltages to the PACIFIC, the FPGAs, the optical links etc.

In the following we will discuss the implementation of these concepts into a concrete design based on a combination of ASICs and printed circuit boards, taking also into account the mechanical constraints imposed by the scintillating-fibre modules and the surrounding infrastructure (cables, pipes, support frames etc.)

5.1.1 Geometrical Constraints

The FE Boxes will be connected by flex cables to SiPMs at each end of the scintillating fibre modules and attached to the detector frames for mechanical support. This defines a tight geometrical envelope for the FE design. The mechanical structure is still in the design phase, but an estimate of this geometrical envelope, shown in Tab. 5, can be obtained assuming that the present Outer Tracker C-Frames are re-used and that the scintillating-fibre modules have a width of about 530 mm (corresponding to 16 SiPMs of 128 channels with a pitch of 250 µm.

The final design will have to take into account that some services, most notably the SiPM cooling pipes and possibly some dry-air pipes, will have to be fed through this volume.
5.1.2 Input & Outputs

The single ended analog signals from the SiPMs to the FE electronics will be transmitted through flex cables, together with temperature sensor readings (temperature variations lead to gain variations, so small temperature sensors will be placed close to the SiPMs) and the SiPM bias voltage (adjustable via a DAC in the FE electronics).

In addition, a signal will be sent to control the intensity of a calibration LED placed close to the SiPM.

Each FE Box will have power inputs for the chips (LV) and the SiPM (HV) bias voltages.

Several optical links (the exact number depending on the occupancy handled by the FE Box) will transmit the cluster data to the TELL40 in the counting house, and bi-directional optical links will provide the interface between the GBT Masters in the FE electronics and the experiment TFC and ECS systems.
5.1.3 Design and Layout

A straightforward way to implement the FE Box design would be to distribute all readout elements in one plane over the full width of the scintillating-fibre module, one FE Box consisting of two units as the one shown in Fig. 22, each one in turn consisting of several identical boards hosting the PACIFICs and the clustering FPGAs interconnected with high-density high-pin-count connectors to one “Master Board” containing a Concentrator FPGA, the GBTx data serializers (unless these are embedded in the Concentrator FPGA), a Master GBT, the optical links and the DC-DC converters).

![Diagram of readout unit](image)

Figure 22: Readout unit of half module width, hosting the complete FE electronics for $8 \times 128$ SiPM channels. Each FE Box would consist of two of these units.

The main feature of this layout is the high density of input channels and resulting in PACIFIC and clustering FPGAs placed with a pitch of 32 mm (corresponding to 128 SiPM channels). Preliminary studies have demonstrated the feasibility of a PCB like that in Fig. ?? hosting the PACIFICs and the clustering FPGAs: a 16-layers PCB in combination with chip packages not exceeding $26 \times 26 \text{ mm}^2$ allows the routing of the 128 analog signals from one SiPM to a PACIFIC, the 128 differential output signals from the PACIFIC to the FPGA, and several control signals.

5.1.4 Occupancy simulations

A first estimation of the detector occupancy has been made with a preliminary modelling of the LHCb detector (LHCb unchanged but IT+OT replaced by FT). This was obtained with a pile up of $n_{\nu} = 6.5$ corresponding to the maximum luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$.
The results indicate that the maximum mean occupancy in the detector is 2.5 clusters/SiPM/event (100 MHz) near the beam pipe. Then it starts to decay quickly to around 0.1 clusters/SiPM/event on the edge of the detector (rate of about 4 MHz).

1000 MIP events are generated for each SiPM of a quadrant with a mean number of clusters given by XXXXXXXX in order to convert these simulations results into bandwidth requirement. The number of bits by event for a SiPM has been then computed as:

\[ N_{\text{bits}} = 16b \text{(header size)} + 16b \text{(coded cluster size)} \times N_{\text{clusters}} \]  

(2)

The simulation results are given in Fig. 23. The offset (0.64 Gio/s) is generated by the headers which have to be sent even with empty events.

![Figure 23: Bandwidth needs in one quadrant of on the hottest detector plane given in Gib/s, the two red lines represents the bandwidth of 1/2 GBT and 1 GBT. 1GBT/SiPM are used for the first 32 SiPM, then 1 GBT/2 SiPM for the next 32 SiPM, then 1 GBT/4 SiPM for the last 32 SiPM.](image)

The detector can be split in three zones. The first third uses 1 SiPM by GBT, the second third uses 2 SiPM by GBT and the last 4 SiPM by GBT. It leads to a drastic reduction of the needed links by quarter from 96 to 56. These simulations show that there is still room for optimization when the physics simulations accuracy will increase.

5.2 The PACIFIC ASIC

The front-end ASIC called PACIFIC for low-Power ASIC for the sCIntillating Fibre traCker is developed to fulfill a main function: process and digitize the analog signal from the SiPM in order to compute the hit position of the particle with a spatial resolution less than 100 µm. To do so four functions have been identified: amplification, shaping, integrating and digitize.
5.2.1 General overview

The PACIFIC chip will include all the elements to process the data from one SiPM. Hence, it will have either the same granularity (128ch/chip) or the half (64ch/chip).

It will have to be low power (1W/chip or 8mW/channel) and radiation tolerant. The chip will use the IBM 130nm technology. Several options are considered for the analogue and the digital processing.

The functional view of the ASIC is presented on figure 24. It is composed as below:

1. a input stage
2. a fast shaper
3. two interleaved gated integrators
4. a 2 bits 40 MHz ADC

It is a compromise between area occupancy, power consumption, and precision on the detector

![Figure 24: Fast shaper solution](image)

5.2.2 The Input Stage

The input stage is current mode preamplifier with the current flowing from the SiPM anode to the circuit. The goal is to achieve the following specifications in this block:

- High bandwidth ($\approx 250$MHz).
- Low power ($< 2$mW, maximum of 8mW/channel including all ASIC).
- Low input impedance ($20\Omega < Z_{\text{in}} < 40\Omega$).
- DC voltage controllable at input node ($\approx 0.5$V range).
- Good single cell resolution for calibration.

The input stage is based on a current conveyor developed for a PET application in Austriamicrosystem SiGe BiCMOS technology. This current conveyor, shown in figure 25, is based on a novel approach of double feedback and it is optimized for SiPM array with anode connection. The current conveyor is followed by a closed loop...
transimpedance amplifier that transforms the input current into a voltage and provides impedance isolation to drive the first stage of the shaper.

It provides a low input impedance in order to avoid affecting timing behaviour of the SiPM and increase input current. $HF_{FB}$ is the high frequency feedback path that keeps this input impedance constant (in a certain frequency range). The second labelled path, $LF_{FB}$ will provide the dc voltage ($V_{offset}$ in figure) of the input node using the virtual short circuit in the amplifier that will drive a follower in a lower frequency range. The design has been implemented taking into account that dominant pole should be set at the input node (SiPM parasitic capacitance is at the order of tenths of pF). In this way stability is not compromised when an important capacitance is added at the input.

To deal with different SiPM and different operating conditions the gain of the current conveyor is tunable by a factor 4, as summarized in table 3.

5.2.3 The shaper

Detector signal extends over several LHC clock periods. There are two main factors contributing the long signal tail: light generation and propagation in the fibre and SiPM recovery. The last factor completely depends on the SiPM. The role of this shaper is to perform tail cancellation prior to gated integration in order to minimize the spill over and the fluctuation of the integrated signal as function of the signal arrival time (i.e. to achieve...
an sufficient integration plateau).

The implementation consists on a double pole-zero shaper. First time constant cancels the slowest time constant of SiPM response, the one associated to internal SiPM capacitances and quenching resistor. The second one cancels the fastest one, related to parasitic interconnect capacitance and input impedance of the preamplifier. The proposed implementation is shown in figure 26. It is a closed loop shaper based on the same OTA used for the transimpedance amplifier of the input stage. It is a OTA with > 300 MHz GBW and with high sourcing current capability (fast rising edge), with low power consumption (700 uV). The pole and zero frequency of both shaper is tunable, and they have been calculated to be able to operate with very different time constants of Ketek and Hamamatsu SiPMs.

![Fast shaper block diagram](image)

**Figure 26: Fast shaper block diagram**

**Hamamatsu SiPM pulse shaping** The result of post-layout simulation of the input staged followed by fast shaper connected to a Hamamatsu SiPM is shown in figure 27. Fast shaper (shape) and input stage (gain) are configured for Hamamatsu nominal parameters. The normalized input current ("Ii_norm"), input stage output ("VoInputStage_norm"), first pole zero cancellation output ("VmSh_norm") and final shaper output ("VoSh_norm") are compared. The integral of these signals is also shown. Integral rise time (5 % to 95 %) is about 10 ns. Parasitic packaging inductances are included in simulation and they are related to input signal ringing.

**Ketek SiPM pulse shaping** The result of post-layout simulation of the input staged followed by fast shaper connected to a Ketek SiPM is shown in figure 28. Fast shaper (shape) and input stage (gain) are configured for Ketek nominal parameters. The normalized input
current ("I_i_norm"), input stage output ("VoInputStage_norm"), first pole zero cancellation output ("V_{mSh_norm}") and final shaper output ("V_{oSh_norm}") are compared. The integral of these signals is also shown. Integral rise time (5% to 95%) is about 10 ns, even if original pulse shape is much slower. Indeed the FWHM of Ketek SiPM is even faster after shaping because the fast time constant of the pulse is faster than for the Hamamatsu one. SiPM parameters are evolving, this is also a reason to design a highly configurable shaper. Parasitic packaging inductances are included in simulation and they are related to input signal ringing.

Figure 27: Shaper response for a 9 cell pulse of a Hamamatsu SiPM

Figure 28: Shaper response for a 9 cell pulse of a Ketek SiPM
5.2.4 The interleaved gated integrator

To avoid any dead time during the acquisition, it has been decided to interleave two gated integrator as shown in Fig. 29.

![Interleaved gated integrators](image)

Figure 29: Interleaved gated integrators

The principle is as follow: when the first integrator is working, the second one is reset and inversely. In order to fit in the 40 MHz general frequency, each gated integrator is working at a frequency of 20 MHz. The ADC will convert the value at the output of the integrator each 25 ns just before the switches between one integrator to the other one. With this solution even if the signal arrives between two clock cycle the integration is still available at the output of the channel. Fig. 30 is showing a simulation of a particle arriving during the transition between two cycles. The signal in blue is the output of the shaper, the signal in green, the clock. It can be noticed that the output signal of the interleaved integrator (in pink) present successively the value of the integration of the output of the shaper in each cycle.

The integrator is composed of an amplifier, two switches, a resistor and a capacitor. This block allows to do the mathematical operation of integration. The equation (3) describe the relation between vin and vout:

$$v_{\text{out}}(t) = -\frac{1}{RC} \int_{0}^{t} v_{\text{in}}(t) \, dt - V_{\text{cm}}$$

As shown in (3) the maximum value of the output signal directly depends on the value of the resistor and the capacitor. The two switches allow to reset the system by setting the value of input and output voltages at the reference voltage (600 mV). The value of R and C will be definitively set when the final SiPM will be chosen.
5.2.5 The ADC used with the gated integrators

An ADC running at 40MS/s is required for the digitization of the analogue signal from the gated integrators. It needs to be 2 bits in order to obtain a resolution on the particle track that is better than 72 µm with the interpolation algorithm.

Three thresholds can be individually set up using 8 bits DAC.

5.2.6 Vbias fine control

In order to equalize the SiPM gain and/or PDE uniformity the input node (anode of the SiPM) voltage will be controlled per channel, so the over-voltage of each SiPM channel can be controlled. An internal DAC and a special feedback loop in the current amplifier permits to set this operating voltage.

5.3 Data processing

The LHCb FE Electronics architecture guidelines in Ref. [?] specify that data must be compressed before transmission off the FE. The large data volume from the PACIFIC chip needs to be significantly reduced before it can be transmitted to the Tell40 buffer boards in the counting house. The reason why ADC values encoding the amount of light seen by single SiPM channels are recorded is to be able to further reduce the resolution below the “binary” value of about 72 µm by means of a clustering algorithm [13]. Monte-Carlo studies have shown that after clustering data rates below three clusters per SiPM in the highest occupancy region can be achieved, and that “cluster noise” can be kept below 2 MHz per SiPM [14]. Therefore executing a data clustering algorithm in the FE electronics will provide the desired data reduction.
5.3.1 Cluster Finding

The scheme shown in Fig. 21, adopting an FPGA for clusterization, offers a flexible solution to the problem of data reduction. The hit finder and clusterization procedure will be analogous to that used for the clusterization of VELO and ST hits in the present Tell1 boards [?] and illustrated in Fig. 31: in a first step, the “seeding” SiPM channels are found using a programmable threshold; up to four neighbouring hits exceeding a second programmable threshold are then combined into clusters; the cluster position is calculated by computing the barycentre $b$ using a weighted average with a 2 bit inter-channel precision,

$$b = \sum_i i \times ADC(i)/\text{size(cluster)};$$

finally, the data recorded for each cluster are its position (a 7-bits SiPM channel number and a two-bits inter strip position corresponding to 1/4 of a strip pitch), the number of hits in the cluster and the total light (sum of the ADC values of the neighbouring strips).

The choice of the FPGA and the implementation of the clusterization algorithm in Fig. 31 have to reckon with two main difficulties: the usage in a radiation environment and the limited amount of FPGA resources available.

The radiation environment in which the FPGAs will have to operate has been discussed in Sec. ???. The SciFi FE Boxes will be in the same position occupied at present by the Outer Tracker FE Boxes. Detailed studies showing the feasibility of using Altera (Arria GX) and Actel (ProAsic3) FPGAs in such environment were carried out in the framework of the upgrade of the straw-tubes FE electronics [?]. The usage of Smartfusion2/Igloo2 Microsemi FPGAs [?] is being considered at present, as these flash-based FPGAs are expected to be more radiation hard [?] than the Actel ProAsic3 and offer also on-board fast transceivers where the GBT serialization protocol could be embedded. Dedicated irradiation tests are foreseen.
5.3.2 Data Concentrator

As shown in Fig. 21, the data from four clustering FPGAs will be collected by a “Data Concentrator” FPGA with a larger number of I/O and logic resources. This FPGA will format the data as required for serial transmission with the GBT [??], will handle timing and fast control commands [??].

The data section of the 120-bits GBT frame [?] will be split as shown in Fig. 32 [?], where are also shown different formats generated in response to various TFC commands [?].

The compressed-data section will be filled with a sequence of cluster data with the format in Fig. 32. Headers will be sent even if no clusters are found. To reduce the number of serializers and optical links, the wide-bus format of the GBT frame [?] will be used for the SciFi data.

---

Figure 32: Format of the LHCb data section of GBT frames (upper panel) and SciFi cluster data (lower panel).

As illustrated in Fig. 32, in response to an “NZS” command non-compressed data have to be sent, for monitoring and debugging purpose. The SciFi FE electronics will then transmit all ADC data, corresponding to 30.72 Gbits/s per SiPM (6-bits ADC data for 128 channels, see Sec. ??).

5.4 Back-end processing

The data packets, sent by the front-end (FE) boards through GBT optical links, are received and processed, on the back-end electronics side, by Tell40 boards [?]. The Tell40 is an ATCA format board housing 4 AMC40 mezzanine boards, each of them handling 24 input optical GBT links from front-end boards and up to 12 output optical links (e.g. 10 gigabit-ethernet links) towards the DAQ farm.

Most of the data packets processing is performed inside the AMC40 FPGA, which handles the following tasks:
1. The implementation of the GBT link reception module: deserialization, error correction, either in 80-bit or 112-bit frame mode.

2. The data packets incoming from the 24 GBT links are realigned according to their BCID. Events are then repacked, removing the redundant headers.

3. The events which are not rejected by the Low Level Trigger are then concatenated into Multi-Event Packs (MEP) and stored on an onboard memory. Eventually, the MEPs are sent to the DAQ processor farm through one of the output optical links (typically, 10 gigabit-ethernet link).

4. Monitoring of the dataflow

The development of the firmware for the AMC40 board is coordinated in the aim to provide a generic code available for all the detectors of the LHCb experiment. However, if specific processing is required, it is still possible to adapt the generic firmware to the need of the scintillating fibre tracker.

In Zero-suppressed mode, the SciFi front-end boards only send to their GBT links (see 5.3.1) the list of all the detected clusters for a given BCID (figure 32). In high-occupancy regions (5.1.4), the bandwidth of one GBT is necessary to readout the clusters of one SiPM; therefore 8 GBT will be necessary to collect data from one FE board reading 8 SiPM. Thus, each AMC40 will be able to handle data from 3 different FE boards (and each Tell40 ATCA board, data from 12 FE boards). On the other hand, in low-occupancy regions, only the bandwidth of at most 4 GBT is required to readout one FE board; each AMC40 (respectively each Tell40 board) will handle 6 FE boards, (respectively 24 FE boards). If 8 GBT were used to readout each front-end board of the full scintillating fibre tracker, 192 AMC40 boards, combined by 4 in 48 Tell40 boards, would be required. However, by combining, on the front-end side, in low-occupancy regions, the data from 2 SiPM into one single GBT, only 120 AMC40 boards (30 Tell40 boards) or even less will be needed. In any case, either in high or low occupancy regions, the AMC40 firmware will have to be able, for every data packet, to keep track of the original SiPM ID and SiPM channel.

5.5 Voltage Distribution

Each FE Box needs various Low Voltage (LV) bias lines: 1.2 V for the GBT-SCA, 1.5 V for the GBTs and the Microsemi FPGAs, 2 V for the optical links, etc. The distribution of bias voltages to the FE electronics will follow the scheme adopted for the present tracking system [?]: each FE Box will be provided one positive and one negative LV line, and then a number of DC-DC voltage converters will be used to produce all necessary bias voltages.

As DC-DC converters, The SC01 converters developed at CERN [?] for usage in radiation and magnetic field will be used (<12 V $V_{in}$ → 0.6-5 V, 4 A, 1.8 MHz). Positive-voltage prototypes have already been tested and found meeting the requirements of noise and stability.

As power supplies we will adopt the Wiener MARATON (MAgnetic field and RAdiation TOleraNt) power supplies, low-noise and low-ripple modular systems already used in the
present LHCb tracking detectors. The MARATON power boxes are mounted in 19-inches power bins located in the LHCb cavern in the concrete bunker below the tracking system, thus avoiding the high cable losses that would result from the high current consumptions in the FE electronics combined with the long distance between the experiment cavern and the counting room. They have been tested with radiation levels up to 140 Gy with protons and 722 Gy with neutrons. The power boxes are then connected to rectifier modules (385 V DC) and controller boards located behind the wall separating the experimental area from the counting house (UX AB). Each power box has 12 channels (6 power modules with 2 channels each); the power distribution scheme will be analogous to that presently used in the straw-tubes tracker [?] schematically illustrated in Fig. 33: each LV channel (300 W, 8 V × 50 A) is routed with 35 mm² cables through a movable cable duct to the C-Frames, where it is distributed to various FE Boxes via a dedicated LV distribution box. If the number of power supply channels presently available will turn out to be too low, the distribution system can be scaled to accommodate for additional MARATONs.

Figure 33: LV distribution in the present straw-tubes tracker, from the power boxes in the concrete bunker to the FE Boxes, through cable trays and especially designed distribution boxes in the C-Frames.

5.6 Cooling
For the cooling of the FE electronics, the scheme presently used by the straw-tubes tracker, based on demineralized water at 19°C, will be adopted. Preliminary thermal simulation
studies of the FE layout presented in Sec. ?? have shown that temperature values can be limited to a maximum of 50 50°C at the location of the PACIFIC chips. A detailed estimate of the power budget that needs to be cooled is needed in order to determine whether the capacity of the present cooling plant to dissipate 23 kW [?] will be sufficient for the needs of the SciFi FE electronics. A worst-case scenario (assume low DC-DC conversion efficiency and largest number of components in the final design) estimate leading to a total value of about 30 kW indicates that a re-design of the demineralized-water cooling plant may become necessary.

5.7 Slow and Fast Control

Each FE Box has also a complete interface for the distribution of Timing and Fast Control (TFC) signals and of signals from and to the Experiment Control System (ECS). Its design follows the specifications in Ref. [?]. Its implementation is based on the usage of a radiation-hard bi-directional optical link to transmit and receive timing, trigger and experiment control information, developed in the framework of the GBT project [?].

5.7.1 TFC

Timing and fast control information will be received through the GBT Master. From the 24 TFC bits a number of commands will be decoded [?]: BXID reset and FE reset; BX veto and Header-only; Sync, TFC align, and Snapshot; Calibration and NZS mode. We have more than one option to distribute these commands to the FE electronics. The Concentrator FPGA could act as a decoder and fan-out and then distribute the commands to the Clustering FPGAs and the PACIFICs, as shown in Fig. Alternatively, one could directly connect to the Clustering FPGAs E-links from the Master GBT, or even from the GBTx chips in case these are used as data serializers.

5.7.2 ECS

A dedicated Slow Control Adapter (SCA) chip [?] will be used for the slow control and monitoring of the FE electronics. The GBT-SCA system implements a point-to-multi-point connection between one GBT, henceforth called Master GBT, and several front end ASICs through dedicated 80 Mbps bidirectional ports, and is capable of handling 16 I²C buses, 1 JTAG controller port, an ADC to monitor up to 8 external analog signals, etc. It will thus be sufficient for each of the FE boards in Fig. 22 to host one GBT-SCA chip. In addition, a GBT-SCA chip next to the Master GBT will ensure the control of the Concentrator FPGAs, the optical links, the DC-DC regulators and eventually the GBTx data transmitters.
6 Infrastructure

6.1 Mechanics
Module, station, service mechanics.

6.2 Cooling
How will the detector be cooled?

6.3 Calibration

6.4 DAQ?
7 Simulation and Physics Performance

How to fix everything in software!
Oh Oh Oh
Figures of the geometry section

Figure 34: Arrangement of the Monolayers with the Tracker volume.
Geometric acceptance in XZ plane

Figure 35: Opening angle of the FT in the XZ plane

Geometric acceptance in YZ plane

Figure 36: Opening angle of the FT in the YZ plane
Figure 37: The structure of one Monolayer is made up of 12 Fibre modules.

Figure 38: The geometry of the Fibre module and the definition of the stereo angles. The size of the dead material is increased to be visible.
Figure 39: Logical structure of the Fibre Tracker.

Figure 40: Correction factor applied to the hit energy as a function of the hit position one quarter of a fibre layer. Black lines represent the edges of the layer. The plot on the left shows the effect of the scintillating fibre attenuation length on signal reaching directly the SiPM whereas the plot on the right gives the correction factor applied on the signal reflected by the fibre mirrors. Both figures include the fibre irradiation damage after 50 fb$^{-1}$ of collected data.
Figure 41: On the left: distribution of the number of fired SiPM-channels per GEANT4 hit. On the right: number of hits per fired SiPM-channel.

Figure 42: On the left: Distribution of energy deposited by hits. On the right: 2D-plot of ADC counts as a function of the deposited energy. The light blue dots show the mean ADC per bin of energy. The red line is the associated linear fit. The obtained slope is consistent with input parameters.
Figure 43: The number of channels with some deposited energy versus the time of arrival at the SiPM ($t_{\text{SiPM}}$) for (left) without spillover, and (right) with spillover. No ADC conversion and no clustering is applied at this stage. The five different bunch crossings can be identified; the central peak is the signal spill.

Figure 44: The time response function of the electronics on a single pulse. The arrival time of the pulse at the SiPM is arbitrary.

Figure 45: (a) Channel ADC values (noise only) and (b) the cluster charge distribution (including signal hits) $T = -30^\circ\text{C}$.
Figure 46: After-pulse time distribution. The different bunch crossings are numbered and indicated in red. The distribution is not normalised.

Figure 47: (a) Channel ADC values (noise only) and (b) the cluster charge distribution (including MC hits) due to hit after-pulsing.

Figure 48: Format of data from GBT cards to TELL40 readout board.
8 Project Organisation

Everything you wanted to know about how (dis)organised the project is!

8.1 Tasks

The institutes participating in the scintillating fibre upgrade project are listed in Table 6.

Table 6: List of institutes participating in the scintillating fibre upgrade project.

<table>
<thead>
<tr>
<th>Country</th>
<th>Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
<td>Centro Brasilheiro de Pesquisas Físicas (CBPF)</td>
</tr>
<tr>
<td></td>
<td>Clermont-Ferrand</td>
</tr>
<tr>
<td>France</td>
<td>LAL</td>
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<td>LPNHE</td>
</tr>
<tr>
<td>Germany</td>
<td>RWTH Aachen</td>
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<tr>
<td></td>
<td>Technische Universität Dortmund (TUD)</td>
</tr>
<tr>
<td></td>
<td>Ruprecht-Karls-Universität Heidelberg (UH)</td>
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<tr>
<td>Netherlands</td>
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<td>IHEP</td>
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<td>CERN</td>
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<td></td>
<td>Ecole Polytechique Fédérale de Lausanne (EPFL)</td>
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<tr>
<td>UK</td>
<td>Imperial College London (IC)</td>
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</table>

The division of responsibilities between the different institutes is listed in Table 7.

8.2 Schedule

Date for removal, installation.
Activities.
Figure of the schedule.
GANTT chart?

8.2.1 R&D

Design it.
Table 7: Division of responsibilities. TO BE DEFINED!

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<thead>
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<th>Task(s)</th>
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<td><strong>Detector</strong></td>
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<tr>
<td>SiPM assembly / QA</td>
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</tr>
<tr>
<td>Fibre mat production</td>
<td></td>
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<tr>
<td>Panel constructions</td>
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<tr>
<td>Read-out box</td>
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<tr>
<td>Module assembly / Q.A.</td>
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<td>PACIFIC ASIC</td>
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<td>Tell40 boards</td>
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<tr>
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<td>Cooling</td>
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<td>etc..</td>
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<td>Software</td>
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8.2.2 Construction

Build it.

8.2.3 Installation and commissioning

Use it.

8.3 Costs

How much will it cost? Take a look at Table 8.
Table 8: Cost matrix. Not the final numbers!

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<td><strong>Total (including 30% spares)</strong></td>
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9 Conclusions

We should be given all of the money we are asking for.

References