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LHCb Upgrade: Scintillating Fibre Tracker

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ABSTRACT

The LHCb detector will be upgraded during the Long Shutdown 2 (LS2) of the LHC in order to cope with higher instantaneous luminosities and to read out the data at 40 MHz using a trigger-less read-out system. All front-end electronics will be replaced and several sub-detectors must be redesigned to cope with higher occupancy. The current tracking detectors downstream of the LHCb dipole magnet will be replaced by the Scintillating Fibre (SciFi) Tracker. The SciFi Tracker will use scintillating fibres read out by Silicon Photomultipliers (SiPMs). State-of-the-art multi-channel SiPM arrays are being developed to read out the fibres and a custom ASIC will be used to digitise the signals from the SiPMs. The evolution of the design since the Technical Design Report in 2014 and the latest R & D results are presented.

1. Introduction

The LHCb detector [1] is a single-arm forward spectrometer designed to study the properties of *b*- and *c*-hadrons in proton–proton collisions at the LHC. The detector collected an integrated luminosity of around 3 fb^{-1} during LHC Run 1. The majority of the data was taken during 2011 and 2012 where the centre-of-mass energies were 7 TeV and 8 TeV, respectively. The LHC provided collisions with instantaneous luminosities up to $4 \times 10^{32}\ \text{cm}^{-2}\ \text{s}^{-1}$ and a bunch spacing of 50 ns. The resulting average number of visible interactions per bunch crossing, μ_{vis}, was approximately 1.7. A hardware trigger was used to reduce the data output rate from 40 MHz to 1.1 MHz [2].

The LHCb detector will be upgraded during the Long Shutdown 2 (LS2) of the LHC in order to collect data at instantaneous luminosities up to $2 \times 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$ with $\mu_{vis} = 5.2$ [3,4]. The centre-of-mass energy will be increased to 14 Tev and the bunch spacing reduced to 25 ns. A trigger-less read-out system will be used to read out the data at 40 MHz and the data will be processed using a full software trigger [5].

2. Tracking system

The current detector has a high precision tracking system with a silicon micro-strip detector around the proton–proton interaction region; a large area silicon micro-strip detector which covers the full acceptance before the dipole magnet; and three tracking stations downstream of the magnet (T1, T2 and T3) with silicon micro-strips in the region closest to the beam-pipe (Inner Tracker, IT) and straw tubes outside (Outer Tracker, OT). The performance of the tracking detectors during Run 1 is described in Refs. [6–8].

In the LHCb upgrade, the tracking system downstream of the magnet must have a single hit efficiency greater than 98% and the hit resolution should be 100 μm or less (in the bending plane of the magnet). The material within the acceptance should be minimised such that $X/X0 \leq 1\%$ in each layer and the detector must be read out at 40 MHz. Finally, the detector performance must be maintained up to an integrated luminosity of around 50 fb^{-1}.

The occupancy in the central part of the Outer Tracker will be too high in the upgrade conditions so these modules have to be replaced. The read-out electronics in both IT and OT must be replaced in order to read out the detector at 40 MHz. The IT and OT will be replaced by a completely new detector, the Scintillating Fibre (SciFi) Tracker [9], based on scintillating fibres read out by Silicon Photomultipliers (SiPMs). It has the advantage that it is based on a single fast and light technology, and that the read-out electronics and services will be located outside of the acceptance. The use of a single technology also simplifies the track reconstruction and eases the mechanical integration and installation of the SciFi Tracker during LS2.

3. Scintillating Fibre Tracker

There are a number of challenges involved in the construction of the SciFi Tracker: the radiation hardness of the fibres and the SiPMs; the mechanical precision required while building large

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active detector components; and the cooling required to mitigate the effects of radiation damage to the SiPMs.

3.1. Layout and module design

The SciFi Tracker will cover the full acceptance ($6\ m \times 5\ m$) downstream of the magnet. There will be three stations each with four detection planes arranged in an x–u–v–x geometry. Each detection plane will have 12 modules. The fibres have a diameter of 0.25 mm and are wound into ribbons (mats) with six staggered layers of densely packed fibres as shown in Fig. 1. The modules will be constructed from 2.4 m long fibre mats and read out by multi-channel SiPMs. The distance between the fibres in each layer is 275 μm. The total active area that must be covered is around 360 m^2 and a total of 10,000 km of fibres will be needed to construct the full detector!

An expanded view of a SciFi Tracker module is shown in Fig. 2. Eight fibre mats are required for each module and the module is split in the middle where a mirror is attached to the end of each fibre mat. The fibres are read out using SiPMs that are enclosed in so-called "read-out boxes" (ROBs) located outside the acceptance at the top and bottom of every module. The ROB is a light and gas tight box that ensures a precise optical coupling of the SiPMs to the fibres. It provides cooling for the SiPMs and houses the read-out electronics. The SiPMs are connected to the read-out electronics via flex PCBs. The ROB also provides the mechanical coupling to the support structure.

3.2. Radiation environment

The expected radiation environment was studied using a FLUKA [10,11] simulation of the upgraded detector [12]. The expected ionising dose is extremely non-uniform as shown in Fig. 3. The maximum dose absorbed by the fibres is 35 kGy in T1 and 25 kGy in T3 for the region around the beam-pipe. The ionising does falls rapidly such that it is expected to be 40 Gy and 80 Gy at the position of the SiPMs ($y = \pm 250$ cm) in T1 and T3, respectively.

The SiPMs are affected by non-ionising energy loss. The 1-MeV neutron equivalent, n_{eq} fluence was estimated to be $9.5 \times 10^{11}\ n_{eq}/cm^2$ and $13 \times 10^{11}\ n_{eq}/cm^2$ in the region of the SiPMs for T1 and T3, respectively. The simulations showed that the neutron fluence in the region of the SiPMs can be reduced by at least a factor of two by installing shielding (Polyethylene with 5% Boron) between T3 and the calorimeters.

3.3. Scintillating fibres

One of the major challenges is to obtain 250 μm diameter scintillating fibres with sufficiently high light yield and large attenuation length that meet the stringent requirements on the uniformity of the fibre diameter. The baseline fibre is the SCSF-78MJ from Kuraray[1] which has a polystyrene core with two wavelength shifting dyes. The core material is surrounded by two claddings with decreasing refractive indices.

The nominal emission spectrum extends from wavelengths around 400–600 nm as shown in Fig. 4 and the attenuation length is greater than 3.5 m for a wavelength of 450 nm. Typically, around 300 photons are produced when a minimum ionising particle crosses a single fibre but only a few photons will reach the photo-detector at the end of the fibre.

The second major challenge is the impact of ionising radiation on the light yield of the fibres. It is not trivial to irradiate the fibres in a way that represents accurately the non-uniform irradiation expected in the experiment (*cf.* Section 3.2). A bundle of eight 3 m

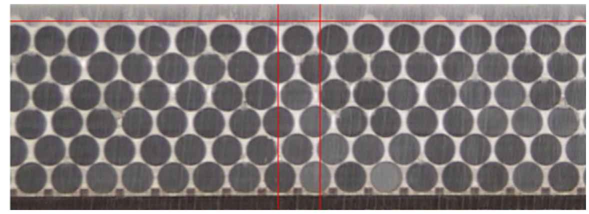

Fig. 1. Cross-section of a prototype fibre mat with six layers of fibres.

long fibres was irradiated with 24 GeV protons in the CERN PS facility. The fibres were embedded in glue and different sections were irradiated to different levels.

The relative light yield of the fibres before and after irradiation is shown in Figs. 5 and 6, respectively. The attenuation length before irradiation was measured to be 439 cm while the attenuation length measured after irradiation depends on the level of irradiation. The ionising dose that the fibres were exposed to is also indicated in Fig. 6 and the attenuation length was measured to be 52 cm in the region that was irradiated to an equivalent dose of 22 KGy. Irradiation tests have also been made using X-rays, gammas and electrons with similar results. Further tests will be performed to study the effects of irradiation at low doses (< 1 kGy)).

The diameter of the fibre and the attenuation length are checked for every 12.5 km spool. The diameter of the fibre is measured every 0.1 mm using a laser micrometer. The sections with diameter above 300 μm are removed during the winding of the fibre layers on a threaded wheel as "bumps" in the fibre will disturb the matrix structure of the fibres in the mat. The fibres are covered with a thin epoxy layer during the ribbon production and again during the casting of the fibre mat. Titanium-dioxide is added to the epoxy to reduce optical cross-talk between the fibres.

3.4. Silicon Photomultipliers

Silicon Photomultipliers with 128 channels per array and a channel width of 250 μm will be used. The devices are linear arrays where each channel has a height of 1.6 mm and contains around 100 pixels. Each pixel has an area of $62 \times 57\ \mu m^2$. Various different devices have been developed by Hamamatsu[2] and KETEK[3] for the SciFi Tracker. The pixel size has been optimised and new devices have been made with trenches between the pixels to reduced optical cross-talk.

The devices have a large gain with values typically in the range of 10^6–10^7 electrons per photo-electron (p.e.). The gain depends on the over-voltage, ΔV, which is difference between the applied bias voltage and the breakdown voltage.

The photon detection efficiency (PDE) of the SiPMs is defined as $PDE = QE \times GF \times \epsilon_{AT}$ where QE is the quantum efficiency of the device, GF is a geometrical factor related to the active size of the pixels in each channel and ϵ_{AT} is the probability to trigger an avalanche. The relative PDE is shown in Fig. 7 as a function of wavelength for different over-voltages. The maximum PDE for the latest Hamamatsu devices is measured to be 39% for a wavelength of 490 nm and $\Delta V = 3.5$ V.

The SiPMs are affected by dark noise and pixel-to-pixel cross-talk. A typical dark noise spectrum is shown in Fig. 8 for a non-irradiated detector. The photo-electron peaks corresponding to the pedestal (0 p.e.), dark noise arising from avalanches triggered by

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[3] KETEK GmbH, Hofer Str. 3, 81737 München, Germany.