LHCb Upgrade: Development of a large Scintillating Fibre Tracker

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Abstract—The LHCb detector at the Large Hadron Collider (LHC) will undergo a major upgrade during the next long shutdown 2019/2020 in order to collect data at an instantaneous luminosity of up to $2\times10^{35} \text{ cm}^{-2}\text{s}^{-1}$. The higher detector occupancy and higher radiation level require the replacement of the current downstream tracking stations by a Scintillating Fibre (SciFi) Tracker. The SciFi Tracker comprises plastic scintillating fibres, read out by state-of-the-art multi-channel Silicon Photomultiplier (SiPM) arrays. Current status of studies of the radiation hardness of scintillating fibres and the SiPM arrays, the customized PACIFIC ASIC, the front-end electronics and the testbeam performance of the prototype module are described.

I. INTRODUCTION

The LHCb detector [1] is a single-arm forward spectrometer designed to study B and D meson decays at the Large Hadron Collider. In order to increase significantly the physics search capabilities, especially for very rare decays, LHCb will increase its instantaneous luminosity up to $2\times10^{35} \text{ cm}^{-2}\text{s}^{-1}$ [2], a factor of five higher than the current value.

The current downstream tracking stations consist of two separate sub-detectors: Outer Tracker (OT) and Inner Tracker (IT). The Outer Tracker comprises 5mm straw drift tubes, covering about 99% of the detector acceptance with a resolution of 200 µm [3], while the Inner Tracker is made of silicon micro-strip detectors, covering the 0.35 m² area near the beam pipe providing a resolution of 50 µm [4].

The increased luminosity will lead to a much higher detector occupancy, which is too high for the most inner part of the OT to handle. Therefore, a more granular Scintillating Fibre (SciFi) Tracker [5] is being developed to replace the current OT and IT as the downstream tracking stations, which covers the full acceptance leading to a total area of 360 m².

The SciFi Tracker must fulfill the following requirements:

- The detector must have a low material budget (less than 1% $X_0$ per detector layer).
- The detection efficiency should be as high as possible.
- The single hit spatial resolution in the bending plane of the magnet (horizontal) has to be better than 100um.
- As with all the other LHCb sub-detectors, the readout electronics should allow a triggerless readout at 40 MHz.
- The detector should be able to operate with the required performance over the lifetime of the detector up to an expected integrated luminosity of 50 fb⁻¹.

A full scintillating fibre module consists of eight of these fibre mats, four parallel on one side, four on the other side. The size of a full module is about 5 m long and 53cm wide. In order to make the module rigid, honeycomb and carbon fibre reinforced polymer (CFRP) layers are added on both the top and the bottom side of fibre mats. An exploded view of the SciFi module is shown in Fig. 2. One end of the fibre mats will be equipped with reflective foil as a mirror to increase the light yield, while the other end will be read out by multi-channel Silicon Photomultiplier (SiPM) arrays. Due to the small dimension of the fibre, one traversing particle will deposit energy in multiple channels. This will allow the application of a clustering algorithm to interpolate the track position.

II. SCINTILLATING FIBRE TRACKER

The active volume of the SciFi Tracker consists of 250 µm diameter plastic scintillating fibres, which are wound on winding-wheels to multi-layer fiber mats shown in Fig. 1. The mats are precisely cut to a length of 242 cm and a width of 130.6 mm.

A full scintillating fibre module is shown in Fig. 2. Each fibre mat will be equipped with reflective foil to increase the light yield, while the other end will be read out by multi-channel Silicon Photomultiplier (SiPM) arrays. Due to the small dimension of the fibre, one traversing particle will deposit energy in multiple channels. This will allow the application of a clustering algorithm to interpolate the track position.

Twelve SciFi modules placed in parallel next to each other constitute a 30 m² detector layer. The SciFi Tracker will consist of three tracking stations (T1, T2, T3), each contains four detector layers aligned with different stereo angles (0°,
The optical attenuation length of the scintillating fibres will decrease due to the ionizing radiation damage. Irradiation experiments have been carried out at various doses and particle types to study this effect and the results are shown in Fig. 4.

Integration of the radiation induced attenuation length (Fig. 4) along the length of the fibre according to the radiation profile (Fig. 3) results in a 40% reduction of the light yield for the most irradiated inner part of the SciFi tracker after the expected operation time corresponding to an integrated luminosity of 50 fb⁻¹.

IV. RADIATION HARDNESS OF THE SiPM

SiPMs become increasingly popular in both high energy physics and medical physics, due to many advantages such as high gain, low operational voltage, small granularity and insensitivity to magnetic field. A detailed introduction of SiPM characteristics can be found in [8].

The SiPM used for the SciFi Tracker is a custom 128-channel array with a channel pitch of 250 µm and a channel height of 1.6 mm to fully cover the stack height of the fibre mats. Each single channel contains ~100 pixels, with a pixel size of 57 um × 62 um. As Fig. 5 shows, one SiPM array is built out of two 64-channel silicon dies and assembled into one package, which is further mounted on 10 cm long polyimide flex-PCB to connect to the front-end electronics.

SiPM arrays from two manufacturers, HAMAMATSU and KETEK, are currently investigated.
Mainly due to a higher fill factor, the upcoming versions of SiPM arrays from both KETEK and HAMAMATSU developed for SciFi Tracker are expected to increase the PDE up to a peak value of about 45%, which will increase the signal of the SciFi Tracker.

Dark count, optical cross talk (X-talk) and after pulsing are the main contribution to the detector noise. For the current SiPM arrays at room temperature and 3.5 V overvoltage, the dark count rate (DCR) is around tens of kHz per channel and the X-talk is about 11%. Future versions of SiPM arrays for SciFi are expected to have a reduced X-talk of about 5%.

The SiPM arrays are around 2.5m away from the beam pipe, where the ionizing radiation dose is rather mild, 80 Gy expected at the worst case scenario. The dominating radiation effect for the SiPMs comes from the large neutron flux, which is expected up to $6 \times 10^{11}$ n$_{eq}$/cm$^2$ after an integrated luminosity of 50 fb$^{-1}$. This will increase the DCR of the SiPMs to a level which severely compromises the detector performance.

DCR can be reduced by annealing or by operating the detector at lower temperatures. Therefore a sealed thermally insulated “cold box” has been designed, as shown in Fig. 7, to be installed at the end of the SciFi module to operate the SiPM arrays at -40 °C while isolating the cold volume from the electronics. In this condition, the DCR of the SiPMs can be reduced to tens of MHz per channel. By applying a threshold based clustering algorithm, the noise rate can be reduced further down to an acceptable level.

V. FRONT-END ELECTRONICS

A low Power ASIC for the scIntillating Flbre traCker (PACIFIC) has been designed, in order to most efficiently readout more than half a million SiPM channels at 40MHz with minimum dead time.

The PACIFIC has 64 channels with current mode preamplifiers, ~50 $\Omega$ input impedance and ~250 MHz bandwidth. Each channel has a 4-bit DAC adjustable input anode voltage, which allows to set the operational voltage of individual SiPM channel with a resolution of 50 mV. The power consumption per channel is less than 10 mW.

There are several features embedded into the PACIFIC, which are optimized for the SciFi Tracker:

1. The ASIC contains a configurable fast shaper to cope with the slightly different pulse shapes of the HAMAMATSU and the KETEK SiPM arrays: 90% of the charge can be integrated within 10ns to minimize signal pile up.

2. The shaper output is integrated by two interleaved gated-integrators to reduce the dead time to almost zero.

3. The analog signal is digitized by three threshold-tunable comparators, in order to effectively shrink the data bandwidth and subtract noise clusters while keeping sufficient information for tracking.

The first complete 64-channel prototype of PACIFIC using TSMC 130 nm technology was submitted in July 2015 and is currently under testing. Fig. 8 shows the die of this prototype.
The SciFi front-end electronics use a modular design for efficient testing and maintenance. It contains three parts: the PACIFIC board, the clusterization board and the master board, as shown in Fig. 9.

The PACIFIC board hosts four PACIFIC ASICs, which reads out 256 SiPM channels and digitizes the data.

The clusterization board uses two FPGAs to cluster and zero-compress the data, efficiently encode the hit information and transfer the data to the master board.

The master board uses the GBT chip sets [10] to transfer data via optical links to the back-end DAQ system [11]. It will also generate and distribute Timing and Fast Control (TFC), Experimental Slow Control (ECS) and the system clock to the clusterization board and the PACIFIC board.

The first prototypes of the clusterization and master board are shown in Fig. 10.

The performance of the SciFi module was tested at the CERN SPS with a 180 GeV/c mixed proton and pion beam in May 2015. At the mirror side where most particle interactions are expected in the final detector, the light yield is verified to be 16 photon electrons per MIP when the SiPMs are operated at 3.5 V overvoltage, as shown in Fig. 11. The spatial resolution at this position is about 80 µm depending on the clustering algorithm used, shown in Fig. 12. The hit detection efficiency is ~99%. All the characteristics are consistent with the technical design requirements and expectations.

![Collected charge distribution of the SciFi module at the mirror side, 2015 testbeam result in the CERN SPS, Fig. taken from [6]](image-url)
A large Scintillating Fibre Tracker has been designed for the LHCb upgrade with a total area of 360m² and 80µm resolution. The detector comprises multi-layer plastic scintillating fibres read out by custom state-of-the-art 128-channel SiPM arrays. Radiation damage for both the scintillating fibres and SiPMs has been systematically studied. A 64-channel low power, fast shaping PACIFIC ASIC and a modular designed front-end electronics are being developed, in order to readout the full detector triggerless at 40 MHz.

The mat and module designs have successfully passed their technical and engineering design reviews, with reviews for the other components in 2016. The mass production of the detector modules is planned to start in 2016 and the final installation is expected to take place in 2019.

REFERENCES