A Scintillating Fibre Tracker for the LHCb Upgrade

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A scintillating fibre tracker with multichannel silicon photomultiplier readout is an option for the LHCb upgrade. The radiation hardness of the scintillating fibres and silicon photomultipliers has been studied. Production methods and machines to build 5 m long modules with an accuracy of 50 μm have been designed and built. All developments are well on track for the technical design report in March 2014.

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1. The LHCb Upgrade

The LHCb detector is a single-arm spectrometer located at the Large Hadron Collider (LHC). The LHCb experiment is dedicated to heavy flavour physics and looks for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons.[1]
The current detector is optimised for an instant luminosity of $2 \cdot 10^{32}\mathrm{cm}^{-2}s^{-1}$. To collect a significantly larger dataset after 2019, the instant luminosity shall be increased with the LHCb upgrade up to $2 \cdot 10^{33}\mathrm{cm}^{-2}s^{-1}$.[2]
To reach this goal, an upgrade of the LHCb detector is necessary. The trigger will be changed to a full software trigger which desires to read out all the subdetectors with 40 MHz. To achieve this, nearly all the front end electronics will be replaced. In addition, several subdetectors will be exchanged to deal with the higher occupancy and to achive better performances. The next section will focus on the upgrade of the tracking stations downstream of the magnet.

2. Scintillating Fibre Tracker at LHCb

One of the subdetectors that will be upgraded are the trackings stations downstream the magnet (T stations). They consist of three identical[a] stations which are currently split in two detectors each. The inner part around the beampipe with high track densites is covered by the Inner Tracker (IT). The Outer Tracker (OT) covers the remaining part of the acceptance with a size of $5 \times 6\,\mathrm{m}^2$. At the upgrade luminosity the occupancy in the OT will be too high to maintain a good tracking performance.
At this stage there are two alternatives discussed as solution for the upgraded T stations:

- an enlarged Inner Tracker combined with partly shortend Outer Tracker modules
- a Fibre Tracker, based on scintillating fibres with silicon photomultiplier readout

The Fibre Tracker (FT) would be realised as Central Tracker combined with OT modules for the outer region or as a complete FT with one technology covering the whole acceptance of LHCb.
Two of the main challenges for a scintillating fibre tracker at LHCb are:

- the radiation hardness of the scintillating fibres and silicon photomultipliers
- to build 5 m long modules which provide the necessary precission to achieve a resolution of below $100\,\mu$m

The Fibre Tracker is based on 2.5 m long scintillating fibres with a diameter of $250\,\mu$m, stacked in five staggered layers 1.2 mm high with a $280\,\mu$m horizontal pitch. The scintillation light is detected by multichannel silicon photomultipliers (SiPM) with a channel width of $250\,\mu$m. Their height matches the height of the five layers. When a particle crosses the fibres, an optical signal is generated in more than one corresponding SiPM channel. The hit position is calculated from the charge baricentre (see Fig. 1). The fibres are mirrored at the middle of the 5m high acceptance and read out by the SiPMs at the outer edges. The readout electronics are to be based on a custom designed ASIC which includes pre-amplier, shaper, ADC, clusterization and zero suppression.

[a]The inner radius of the stations varies due to the increasing radius of the beampipe.

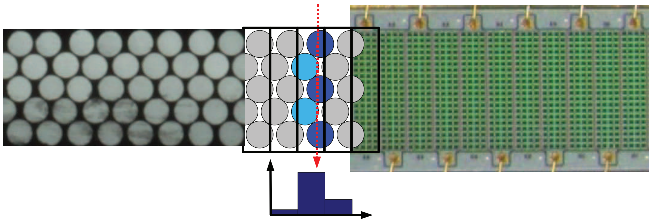

Fig. 1. Crosssections of fibre mat and multichannel SiPM. Determing the hit position by a weighted sum is indicated in the middle.

3. Radiation hardness of the scintillating fibres and silicon photomultipliers

3.1. *Radiation environment*

The fibres and SiPMs have to withstand the high doses and fluxes of the LHCb environment. The expected dose for the scintillating fibres for ten years of datataking reaches up to 60 kGy near the beampipe but falls rapidly below 1 kGy at a distance of 50 cm. At the position of the SiPMs, outside the acceptance of LHCb, the dose stays below 100 Gy. The relevant number for the damage to the SiPMs is the 1 MeV neutron equivalent which reaches fluxes of $6 \cdot 10^{11}/\text{cm}^2$.

3.2. *Fibre R&D*

The scintillation mechanism of the fibres is known to be radiation hard, but the transmission is expected to drop quickly with dose. To quantify the damage, several irradiation campaigns have been performed covering total doses from 100 Gy to 100 kGy. The attenuation length was measured for different doses and wavelengths. It decreases with the logarithmic of the dose, this dependence is fitted with the empirical model introduced by Hara *et al.*[3] [b]. This data can be used to simulate the expected amount of photons to reach the SiPM as a function of the coordinate of the track and the runtime of the experiment. It shows that the fibres are mainly effected in the central region. The light loss due to irradiation damage sums up to 40% for the innermost part.

In order to achieve a sufficient light yield from tracks in the central region

[b]New physically motivated models to describe the data are currently being tested for a more precise description of the data, especially at low doses.

a mirror will be added at the inner edge of the fibres to regain the losses due to irradiation. Different mirroring technologies have been succesfully studied.

3.3. *SiPM R&D*

Silicon photomultipliers are arrays of Geiger mode avalanche photodiodes (G-APD). The number of G-APD (from now on referred to as pixels) which fire is proportional to the number of photons which hit the SiPM[c]. To distinguish signal from noise, you need signals of several photons and low noise rates.

The thermal noise of the SiPMs rises linearly with the integrated 1 MeV neutron equivalent fluence. Several irradiation campaigns of SiPMs of Hamamatsu and KETEK have been performed at accelerators, with radioactiv sources and *in situ* and have confirmed this. To keep the noise acceptably low, the SiPMs will be cooled down to $-40\,^{\circ}$C which will lower the noise rate by a factor of ≈ 64. An additional factor of two can be gained by adding shielding.

In addition improvements on the SiPMs itself have been made and are still to come: Lower pixel-to-pixel crosstalk to reduce the noise amplitude and higher and shifted photon detection efficiancy for greater signal amplitudes have already been achieved by the manufacturers.

4. Modules

The downstream tracker is built from three stations with four layers each ($0^\circ, +5^\circ, -5^\circ, 0^\circ$ stereo angle). Simulations have shown that missalignments between fibres of $75\,\mu$m perpendicular to the beam and $300\,\mu$m in direction of the beam can be tolerated without losses in tracking efficiency. Assuming a full Fibre Tracker ≈ 10000 km of fibres have to be positioned and mounted with this accuracy.

To produce five-layer fibre mats the fibres are precisely wound on wheel with ≈ 1 m diameter. Two alternatives for guiding the fibres on the wheel are currently tested:

- a milled thread on the wheel
- grooves on a Kapton sheet which is positioned on the wheel

[c]To calculate the exact number of photons you have to correct for photon detection efficiency, saturation effects, crosstalk between pixels etc..

The Kapton sheet has the advantage that it is glued to the fibre mat and can provide alignment marks. The fibre mat is taken off when the glue is cured enough and finally glued to a sandwich support made of honeycomb and carbon fibre. This sandwich provides a light and stiff support on a length of 5 m with a radiation length of $\approx 0.6\%$ ($+ \approx 0.3\%$ for the fibres) per layer.

The cooling of the SiPMs needs to achieve temperatures of at least $-40°$C and will be situated in insulated boxes at the outer edges of the modules. Different technologies are investigated (liquid cooling, air cooling, Peltier cooling and combinations) to achieve a reliable solution. Simulations were performed to estimate the heat load and optimise the materials and mock-ups are tested to proove the feasibility of the different technologies.

5. Conclusions

The radiation environment is an important issue for a scintillating fibre tracker with SiPM readout at LHCb, but the damage is understood and can be coped with.
The R&D for building full-size modules is on track for the technology choice in November 2013 and the Technical Design Report in March 2014.

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