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SciFi – A large scintillating fibre tracker for LHCb

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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. Concept, design and operational parameters are driven by the challenging LHC environment including significant ionising and neutron radiation levels. Over a total active surface of 360 m^2 the SciFi Tracker will use scintillating fibres ($\varnothing = 0.25$ mm) read out by state-of-the-art multi-channel Silicon Photomultipliers (SiPMs) arrays. A custom ASIC will be used to digitise the signals from the SiPMs. The project is now at the transition from R&D to series production. We will present the evolution of the design and the latest lab and test beam results.

1. Introduction

The LHCb detector is a single-arm forward spectrometer [1] located at the Large Hadron Collider (LHC). The experiment is dedicated to heavy flavour physics and searches for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons. The current LHCb detector is optimized for an instant luminosity of $2{\cdot}10^{33}\ \mathrm{cm^{-2}\,s^{-1}}$. An upgrade of the LHCb detector [2] is necessary to collect a significantly larger dataset after 2020 to extend the physics reach of the experiment by allowing a higher luminosity of up to $2{\cdot}10^{33}\ \mathrm{cm^{-2}s^{-1}}$. The upgrade relies on two major changes, firstly a 40 MHz read-out matching the full interaction rate and secondly an improved detector granularity to cope with the higher occupancy due to the increased luminosity. The LHCb collaboration has chosen a high granular Scintillating Fibre (SciFi) tracker [3] to replace the current outer and inner tracker, which covers the full acceptance after the magnet leading to a total area of 360 m^2. The main requirements on the SciFi tracker are: A hit detection efficiency of larger than 98% is needed with a noise cluster rate of less than 10% of the signal cluster rate. The spatial resolution for single hits must be better than 100 μm. A trigger-less read-out at 40 MHz and with a minimum dead time is necessary. The SciFi tracker has to cope with a high occupancy of up to 4.5 clusters for a detector array of 128 channels (32 mm) in the hottest region. A single detection layer must have a low material budget of ≈1% of a radiation length (X_0). The SciFi tracker should be able to operate with the required performance over the lifetime of the detector up to an expected integrated luminosity of 50 $\mathrm{fb^{-1}}$. The radiation environment leads to an iodizing dose of 35 kGy for the scintillating fibres in the centre of the detector at the beam pipe and of 80 Gy at the location of the silicon photomultipliers (SiPMs), 2.5 m away from the beam pipe. The SiPMs have to withstand a neutron fluence of $\approx 1{\cdot}10^{12}\frac{n}{cm^2}$.

2. The scintillating fibre tracker

The LHCb SciFi tracker is following the technology developed for the PERDaix detector [5], the Beam Gas Vertex detector (BGV) [6] and a Muontomograph [9]. These experiments used staggered layers of 250 μm thick scintillating fibres forming a fibre mat and SiPM arrays for the readout with channels extending the full height of the fibre mat [9]. The pitch of the SiPM arrays were similar to the fibre pitch so that the light was spread over few SiPM channels (Fig. 1). The measured spatial resolution was around 50 μm [7–9]. The fibre mats for these experiments had a length of 30–100 cm, a width of 3–64 mm and 4–5 layers. The challenge for the LHCb SciFi tracker is to build fibre mats with a length of 2.5 m, a width of 130 mm and to operate with the required performance in the LHCb radiation environment.

The new SciFi tracker will consist of three tracking stations (T1, T2, T3) each with four detection planes aligned with different stereo angles (0°, ±5°) with respect to the vertical. Each detection plane will have 12 SciFi modules, placed in parallel next to each other constituting a 30 m^2 detection surface. In total 144 SciFi modules will be needed for the complete detector with a total active area of 360 m^2.

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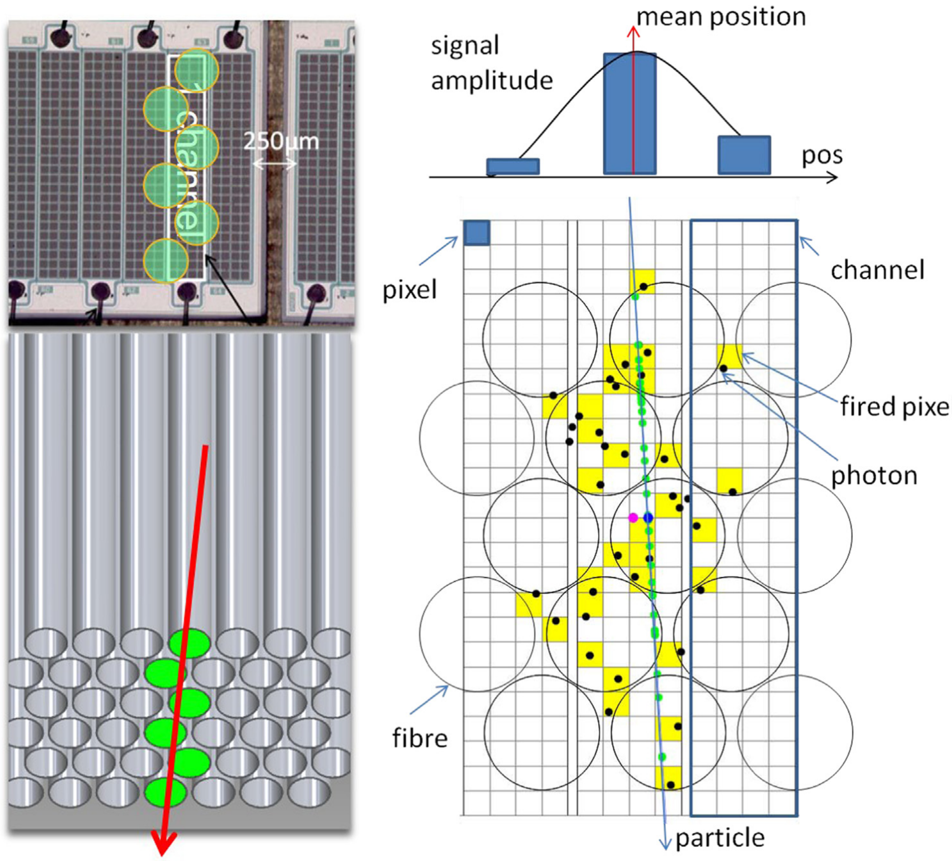

Fig. 1. A sketch of the basic principle of the SciFi tracker. A charge particle passing through the fibre produces scintillation light which travels to the end and is detected in a SiPM array. The black dots indicate photons arriving at the SiPM, the yellow squares indicate the pixels that fire. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A SciFi module has a length of 5 m and a width of 0.53 m and consists of eight scintillating fibre mats. Layers of Honeycomb and carbon fibre reinforced polymer (CRFP) are glued to both sides of the fibre mats to make the module rigid (Fig. 2).

The production of the fibre mats is done by winding the 0.25 mm diameter plastic scintillating fibres on threaded winding-wheels into ribbons with six staggered layers. The pitch between the fibres in each layer is 0.275 mm. The epoxy glue Epotek 301 loaded with 25% TiO_2 to minimize optical crosstalk between adjacent fibres is used to glue the fibres to a composite. After the unforming of the fibre ribbons from the wheel they are laminated with black Kapton XC foil to increase the robustness and to make the handling and shipment of them easier. On both ends polycarbonate endpieces are glued to the ribbons and then they are precisely cut into 2.5 m long, 13 cm wide fibre mats (Fig. 3). The ends of the fibre mats which are located in the centre of the modules are mirrored with a reflective foil to increase the light yield at the readout end of the fibre mat outside the acceptance and will be readout by multi-channel SiPM arrays with a channel width of 0.25 mm. More than 590 k SiPM channels will be required for the readout of the 144 SciFi modules and more than 11,000 km of scintillating fibres will be needed to cover the total active area of 360 m^2.

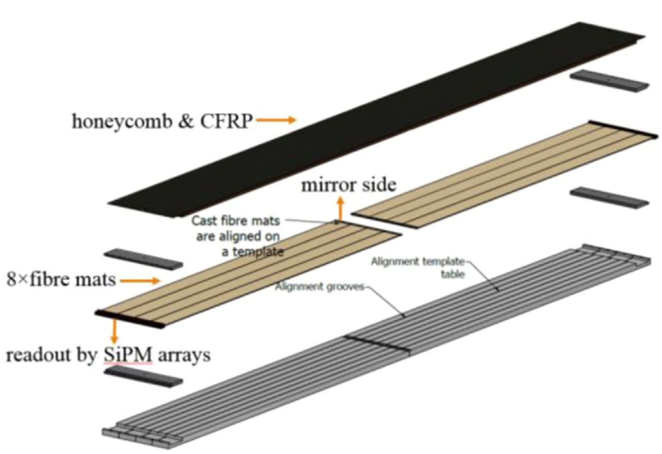

Fig. 2. Exploded view of the SciFi module.

3. Scintillating fibres

The baseline scintillating fibre for the detector is the Kuraray SCSF-78MJ. The fibres consist of a polystyrene core with added dye and wavelength shifter. The refractive index of the core is 1.59. The core is surrounded by two claddings with refractive indices of 1.49 and 1.42, respectively, which are approximately 10 μm thin. The fibres have a diameter of (0.250 ± 0.007) mm. Defects in the cladding and core material can create local increases of the fibre diameter (bumps). Bumps with a diameter of more than 350 μm can lead to local defects of the winding pattern during the winding of the fibre mats and therefore need to be removed using a splicing technique. The peak emission wavelength of the scintillation light is 450 nm and the attenuation length is ≥350 m. A minimum ionizing particle passing through a single fibre generates around 300 photons, but only a few of them will be detected by the SiPMs due to the low trapping efficiency of ~5% and the long propagation in the fibre. Since six layers of fibres are stacked together to form a 1.35 mm thick mat, the expected light yield of a fibre mat is

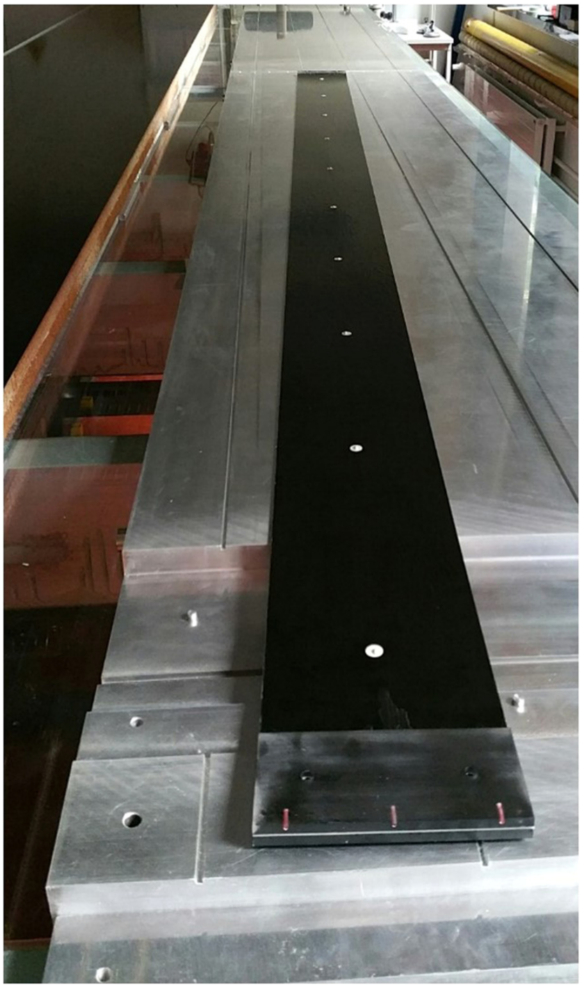

Fig. 3. A six-layer scintillating fibre mat laminated with a black Kapton XC foil and with endpieces glued to it. The SiPM arrays and the mirrors are mounted to the endpieces.

around 15–20 photo-electrons depending on the position where the particle passed through the mat. The scintillation decay time of 2.8 ns is fast. The propagation time for a signal to travel 2.5 m is approximately 15 ns.

For the expected operation time corresponding to 50 fb^{-1} of integrated luminosity FLUKA predicts that the scintillating fibres will absorb a dose of up to 35 kGy of ionizing radiation in the regions closest to the beam pipe [4]. The absorbed dose will drop down to 80 Gy at the end of the fibres where the SiPMs are located and which is 2.5 m away from the beam pipe. The scintillating fibres will lose transmission under irradiation leading to a reduction of the attenuation length. The result of the different irradiation campaigns up to different doses are shown in Fig. 4 and lead to the expectation that the fibre tracker will be able to transmit enough scintillation light to the SiPMs to maintain a high hit efficiency despite a loss of nearly 40% of the signal in the worst region after an integrated luminosity of 50 fb^{-1}. An effect of the scintillation mechanism was not observed.

4. Silicon photomultipliers (SiPMs)

The light generated in several fibres by a particle passing through the mat is transported directly or by mirroring to the SiPMs. The channel dimension is adapted to the fibre spacing and

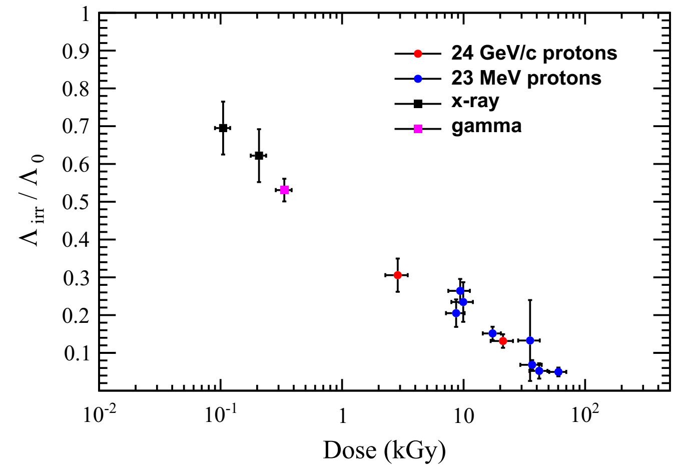

Fig. 4. Attenuation length measured with a PIN diode at different ionizing radiation doses.

diameter and the number of layers in a mat. The SiPM arrays from two manufacturers, HAMAMATSU and KETEK, are currently considered for the read-out of the scintillating fibre mats. One SiPM array is built out of two 64-channel silicon dies with a gap of 250 μM in between and assembled into one package (Fig. 5). The channel pitch is 250 μM and the height is 1.62 mm fully covering the stack height of the fibre mats. The channel height allows for at least 100 μM alignment tolerances between fibres and detector channels. A fibre mat is readout by 4 SiPM arrays. Each array is bonded to a Kapton flex-PCB to connect it to the front-end electronics.

The photon detection efficiency (PDE) of the SiPMs is a key parameter for the measured light yield and the single hit efficiency of the detector. The PDE depends on the overvoltage and the wavelength (Fig. 6). At the operational overvoltage of 3.5 V the maximum PDE of the HAMAMATSU and KETEK 2014 version is 45%, for the HAMAMATSU 2015 version the PDE is 50%.

The main contributions to the detector noise cluster rate are the dark count rate (DCR), the optical cross-talk and after pulsing. The dark noise in the SiPM is typically from thermal excitations of electrons into the conduction band of silicon, causing the pixel to fire, similar to as if a single photon is absorbed. The DCR increases with overvoltage, temperature, the total surface of the photodetector and with irradiation damages of the crystal lattice. The DCR is around 100 kHz/mm^2 at room temperature for the current SiPM arrays. Due to the strong temperature dependence, the DCR

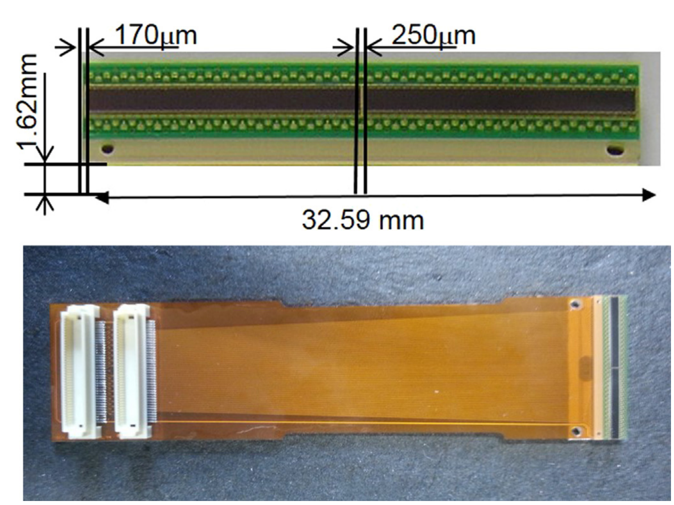

Fig. 5. 128-channel SiPM array (top) mounted on a kapton flex-PCB (bottom).

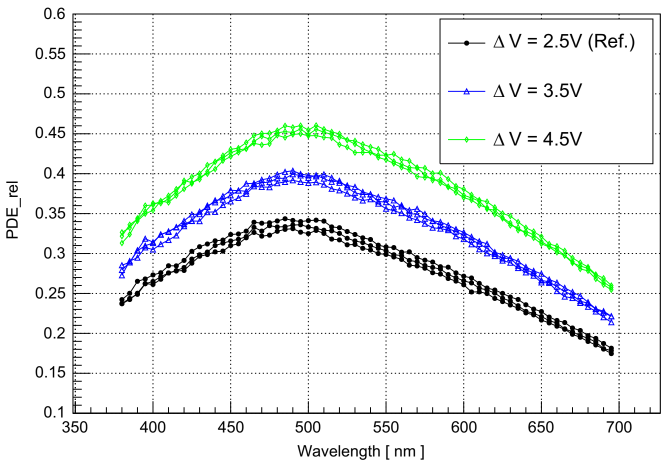

Fig. 6. PDE as a function of the wavelength and different overvoltages for the HAMAMATSU SiPM array (2014 Version).

can be decreased by a factor of 2 for every 10 K. The SiPM arrays with the new technology of trenches (optical barriers) have a reduced optical cross talk between pixels of around 5–10% for the HAMATSU devices and below 2% for the KETEK devices at an operating overvoltage of 3.5 V.

The radiation environment 2.5 m away from the beam pipe yields to an ionising dose of 80 Gy and a neutron fluence of 1×10^{12} neq/cm^2 for the SiPM arrays. Due to the neutron irradiation the DCR increases up to tens of MHZ per channel. It decreases again by annealing or by operating the SiPMs at lower temperatures. Therefore the SiPM operation temperature is chosen to be −40 °C. This will be achieved by a sealed thermal-insulated cold-box so that the DCR is at an acceptable level of around 100 kHz after irradiation.

5. Front-end electronics

The 40 MHz readout of 4096 128-channel SiPM arrays with minimum dead time in the LHCb upgrade will require zero-suppression of the data at the front-end electronics. A custom 64-channel low Power ASIC (PACIFIC) using TSMC 130 nm technology is being developed. The PACIFIC consists of a pre-amplifier and a fast shaper, dual gated integrators to ensure zero dead-time and three comparators for applying signal thresholds are used for the digitisation. Two SiPM arrays are read out by four PACIFICs which are hosted on the PACIFIC board. The digitized signals are sent to two FPGAs which are located on the clusterization board. The FPGAs combine individual channels into clusters and the data is zero-suppressed before being transferred via the master board to the computing farm.

6. Light injection system

A light injection system (LIS) is used to calibrate the gain of the SiPM arrays. The LIS has to generate a low intensity 5 ns long light pulse. The system provides adjustable light intensity of about 1–5 photo-electrons per SiPM channel. The light will be injected into the transparent polycarbonate endpiece with the help of a light leaking fibre with 1 mm diameter to ensure a homogenous light distribution over all channels of the 4 SiPM arrays per fibre mat (Fig. 7). The light will be generated using a red vertical-cavity surface-emitting laser (VCSEL, wavelength 670 nm, operated at voltages <2.2 V) which is mounted on a mezzanine board in the endplug of the SciFi module. The GigaBit Laser Driver (GBLD) is a

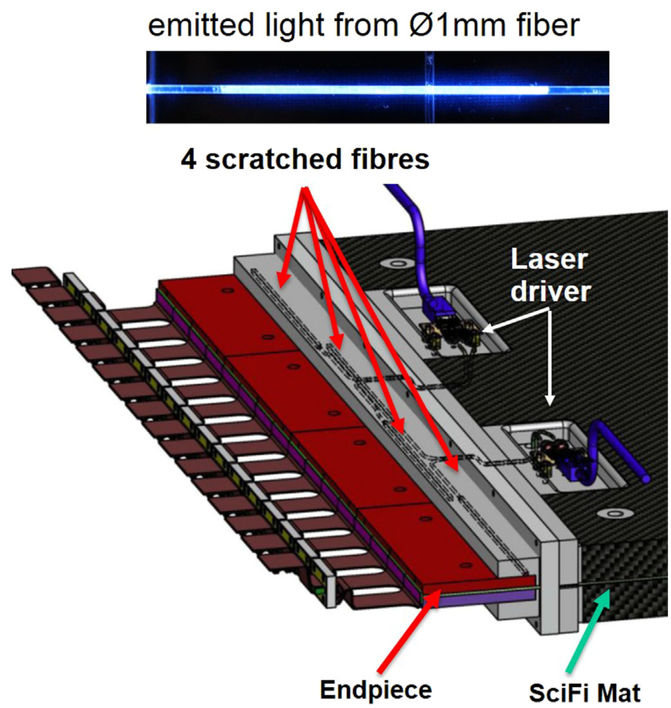

Fig. 7. Light injection system (LIS) to calibrate the gain of the SiPM arrays.

radiation hard chip made by CERN and is driving the VCSEL. The light injection system is powered from 2.5 V only.

7. Testbeam measurements

The performance of a 6-layer scintillating fibre module was tested in the CERN SPS with a 450 GeV proton beam in May 2015. The measured light yield of the 6-layer SciFi module at an overvoltage of 3.5 V is 16 photo-electrons per minimum ionizing particle at the mirror side where most particle interactions happen (Fig. 8). The spatial resolution at this position is 70–80 μM depending on the clusterization algorithm (Fig. 9). The measured hit efficiency is 99%. All the characteristics are consistent with the technical design requirements and expectations.

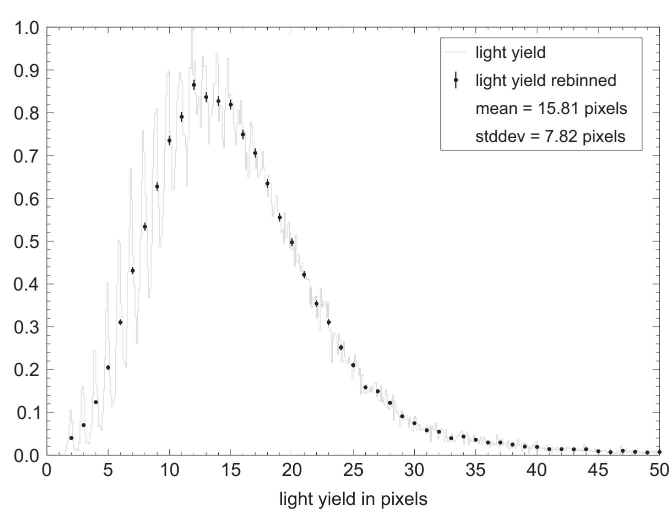

Fig. 8. Light yield in pixels distribution of the six layer SciFi module at the mirror side. Result of 2015 testbeam in the CERN SPS.

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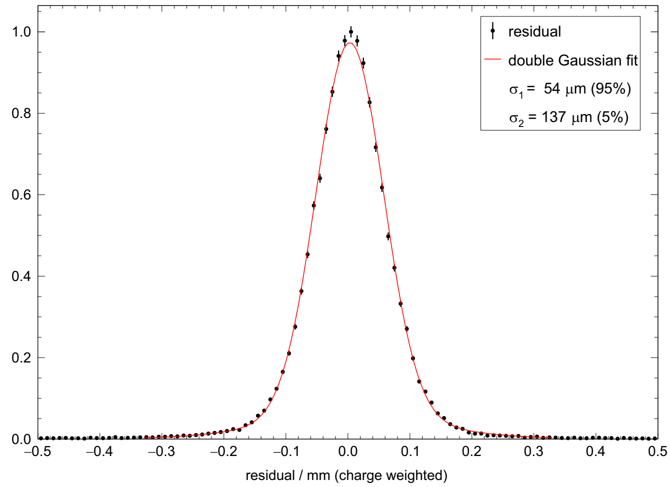

Fig. 9. Residual distribution of hits to the reconstructed track of the SciFi module at the mirror side. Result of 2015 testbeam in the CERN SPS.

8. Conclusion

A large area scintillating fibre tracker has been designed for the LHCb upgrade with a total area of 360 m^2 and a spatial resolution of better than 100 μM. The SciFi modules are made out of six layer plastic scintillating fibre mats and read out by customized 128-channel SiPM arrays. The scintillating fibres and the SiPMS are qualified for LHCb radiation environment. In order to readout the SciFi tracker trigger-less at 40 MHz with a minimum dead time a 64-channel low power, fast shaping PACIFIC ASIC and modular designed front-end electronics are being developed. The SciFi tracker is a close collaboration of 18 institutes in 9 countries. The fibre mat and module production will beginn in 2016, the installation will be done in 2019 and the LHCb-SciFi-tracker will be ready for data taking in the LHC Run 3 from 2021 on.

References

[1] LHCb collaboration, The LHCb Detector at the LHC, JINST 3 (2008) S08005.
[2] LHCb Collaboration, Letter of Intent for the LHCb Upgrade, CERN-LHCC-2011-001, March 2011.
[3] LHCb collaboration, LHCb Tracker Upgrade Technical Design Report. CERN-LHCC-2014-001.
[4] N. Lopez March, M. Karascon, Radiation Studies for the LHCb tracker upgrade, LHCb-PUB-2014-022, CERN-LHCb-PUB-2014-22, LHCb-INT-2013-003.
[5] Th. Kirn, et al., The PERDaix detector, Nucl. Instrum. Methods A 695 (2012) 91–95.
[6] M. Rihl et al., Imaging the LHC beams with silicon and scintillating fibre vertex detectors, these proceedings.
[7] B. Beischer, et al., A high-resolution scintillating fiber tracker with silicon photomultiplier array readout, Nucl. Instrum. Methods A 622 (2010) 542–544.
[8] B. Beischer, et al., The development of a high-resolution scintillating fiber tracker with silicon photomultiplier readout, Nucl. Instrum. Methods A 628 (2011) 403–406.
[9] Th. Kirn et al., Production of Scintillating Fibre Modules for High Resolution Tracking Devices, PoS (TIPP 2014), p. 108.

Please cite this article as: T. Kirn, Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j.nima.2016.06.057