Silicon photomultiplier multichannel arrays for the LHCb scintillating fibre tracker

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Abstract—A scintillating fibre tracker read out by silicon photomultipliers (SiPMs) will be used in the upgrade particle tracking system of the LHCb detector at CERN. The multichannel SiPM array from Hamamatsu HPK (S13552-HRQ) is optimised for high photo-detection efficiency (PDE) and low correlated noise. The selected SiPM shows a peak PDE of up to 52\% at 475 nm, low pixel-to-pixel cross-talk (3\%) and almost zero after-pulse. Measurements on detectors irradiated with neutrons up to $12 \times 10^{11} \text{n}_{eq}/\text{cm}^2$ demonstrate that the detector characteristics remain unchanged after irradiation apart from a large increase of the dark count rate (DCR).

I. INTRODUCTION

LHCb is one of the large experiments placed at the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN). It is dedicated to the study of CP violation and rare decays of b- and c-hadrons. In the LHCb detector upgrade, SiPMs will be used for the read-out of the scintillating fibre tracker (SciFi tracker).

SiPMs are photo-detector arrays composed of avalanche photo-diodes operated in Geiger-Müller mode. They present high gain, excellent single photon detection capability, low correlated noise and high peak PDE. The most important drawback compared to vacuum tube based devices is the relatively low radiation tolerance. We present the SiPM array selected for the SciFi tracker.

II. LHCb UPGRADE

During the LHC long shut-down 2, the LHCb detector will be upgraded in order to prepare the detector to a higher trigger rate and luminosity. The front-end electronics read-out is currently limited by a Level-0 trigger to 1 MHz. All front-end electronics will be replaced and prepared for a read-out at 40 MHz. A software trigger will be applied using the full detector information. Several other sub-detectors will also be replaced in order to cope with the increased occupancy.

III. SciFi tracker

The tracking system downstream the magnet is currently silicon micro-strip detectors in the centre and straw tubes in the outer regions. For the upgrade it will be replaced by a single detector technology that can cope with the high density of tracks in the inner region and cover the full area of 320 m\textsuperscript{2}. The SciFi tracker can read out the inner region with high granularity without active or cooling services in the detector acceptance. The detection material is scintillating fibres which do not only generate the light pulse but also transport it to the photo-detectors at their end.

The SciFi tracker consists of 12 detection planes with 250 $\mu$m diameter fibres arranged in 2.5 m long mats with six layers of fibres (Fig. 1). The mats are read out outside the acceptance region by customised SiPM array optimised for high PDE. During the five years of operation, the hit detection efficiency will be in competition with the radiation damages to the fibres and the SiPMs. At the photo-detector’s location, the damage is dominated by neutrons (expected neutron fluence of $5 \times 10^{11} \text{n}_{eq}/\text{cm}^2$).

IV. THE SiPM ARRAY FOR THE SciFi TRACKER

The multichannel SiPM array has a total active area of $32.54 \times 1.625 \text{mm}^2$ and is made of two silicon dies with 64 channels each. The channels are 250 $\mu$m wide and contain 104 pixels of size $57.5 \times 62.5 \mu$m\textsuperscript{2}. A 220 $\mu$m non-sensitive gap is present between the two dies (Fig. 1). The optical window and the bond wires are protected with a 105 $\mu$m thick epoxy layer.

We have developed set-ups for the measurement of the breakdown voltage ($V_{\text{BD}}$), gain, DCR, correlated noise, pulse shape, quenching resistor ($R_Q$), PDE, as well as the temperature and irradiation dependence of these characteristics. In the following, we give an overview of the most important results on the SciFi tracker SiPM.

a) Breakdown voltage: $V_{\text{BD}}$ measurement is based on photon spectrum recorded at several bias voltages with uniform light source and temperature control. The precision achieved with this method ($< 100 \text{mV}$) allows to measure
the variation among channels of the same array which is present due to the silicon processing (Fig. 2). In the SciFi tracker, these differences will be compensated by tuning the pre-amplifier potential.

b) Correlated noise: The correlated noise of SiPM with different technologies was quantified. The implementation of opaque trenches between the pixels and the adjustment of $R_Q$ (505 kΩ) led to large improvement with respect to previous versions of the detector (Fig. 3). The precise composition of correlated noise (Fig. 4) is measured with a statistical analysis on SiPM pulse waveforms.

c) Photo-detection efficiency: A dense channel packaging and optimised pixel size result in a large fill factor. The PDE is up to 52% at the peak sensitivity (475 nm). The setup for PDE measurement comprises a Xe light source with a monochromator and a calibrated photodiode. Two independent measurements of the absolute PDE are obtained using, first, the pulse frequency and, second, the SiPM current. Figures 5 and 6 show the PDE, corrected for the contribution of correlated noise, as a function of the wavelength of the light and of the over-voltage, respectively.

d) Radiation effects: The main effect of radiation on SiPMs is a large increase in DCR. Random and correlated overlap of several noise pulses can create signal-like noise clusters. To reduce this so-called noise cluster rate, the operation temperature is reduced to $-40^\circ$C (Fig. 7). It can be further suppressed using a threshold-based clustering algorithm that combines together the signal of neighbouring channels. The algorithm used for the SciFi tracker is optimised to maintain a high hit detection efficiency. For a 40 MHz read-out, the rate of noise hits in a 128-channel array is expected to be below 1 MHz.

Using a fast front-end electronics (SPIROC, shaping time of 70 ns (6)), measurements performed with a short SciFi module equipped with a cooling system demonstrate that the other SiPM characteristics such as single photon detection capability (Fig. 8), $V_{BD}$, gain and PDE are unchanged after irradiation up to a neutron fluence of $12 \times 10^{11}$ n$_{eq}$/cm$^2$. The direct measurement of PDE for irradiated detectors is not possible with the experimental setup described above.
because the pulse frequency and the current are dominated by DCR. Instead, scintillation light is produced in the fibres using electrons from a $^{89}$Sr source. The sum of photons inside the clusters (cluster sum) is Landau distributed because it follows the distribution of energy deposit in a thin layer of matter. Apart from a peak at low cluster sum due to noise clusters, the distribution is unchanged with irradiated SiPMs (Fig. 9). This demonstrates that PDE remains unchanged after irradiation up to a neutron fluence of $12 \times 10^{11}$ n$_{eq}$/cm$^2$.

VI. Conclusion

The customised 128-channel SiPM array S13552-HRQ, manufactured by Hamamatsu, will be used to read out the scintillating fibres of the LHCb SciFi Tracker. The high PDE and extremely low correlated noise allow to operate the detector at the expected high neutron fluence and maintain single photon detection capability.

REFERENCES