Multichannel SiPM arrays for the LHCb scintillating fibre tracker

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Introduction
A major upgrade of the LHCb detector is foreseen during the LHC LS2 in 2019/2020.

Two main changes:
- 40 MHz trigger-less read-out
- Luminosity $\mu$J$^{-1}$ cm$^{-2}$ ns$^{-1}$ (5x the current)

Several detector systems need to be replaced. In particular, the current downstream tracking system will be exchanged with a large scintillating fibre (SciFi) tracker, resulting in a reduced and homogeneously distributed material budget.

Challenges for the SiPMs in SciFi
- Neutron irradiation of SiPMs leads to a dramatic increase in dark count rate
- Increase in noise cluster rate due to signal-like noise clusters
- Irradiation of fibres leads to reduction of light output seen by the SiPMs
- Low light (single photon) yield after irradiation (10-12 p.e.)

This requires:
- Low dark count rate & low correlated noise
- High PDE

Achieved by:
- Fast read-out (short integration time)
- Cooling to $-40^\circ$C
- Efficient noise rejection by clustering

Expected cluster rate at 40 MHz read-out: less than 3 MHz per SiPM array

Pulse shape and quenching resistor ($R_Q$)

The H2017 features a quenching resistor of 520 kΩ, which allows a large operating range. The recovery time is 85 ns with typically 10% channel-to-channel variations due to dependence on $R_Q$.

We can distinguish three time components:
- $t_{R_1} \approx 1$ ns
- $t_{R_2} \approx 70$ ns
- $t_{R_3} \approx 85$ ns

Breakdown voltage ($V_{BD}$)

To achieve uniform detection efficiency in the SciFi tracker, all SiPM channels are operated at the same over-voltage $V_{BD}$. $V_{BD}$ measurement prior to installation
- Measurement based on low light spectrum
- Grouping SiPMs with similar $V_{BD}$ together (same bias channel)
- Bias voltage adjustment per channel at FE

Photon detection efficiency (PDE)

A high PDE matching the emission spectrum of the Kuraray SCSF-78 scintillating fibres is an important requirement for the SciFi SiPMs.

PDE measurement:
- Xe light source with monochromator
- Photodiode for light calibration
- Correction for correlated noise and dark counts

Produced status

- All SiPMs have been delivered (5000 in total)
- SiPMs are mounted on flex cables
- QA procedure:
  - Optical inspection for all detectors
  - $V_{BD}$ measurement (all)
  - 2 per 500 detectors: full characterisation

The LHCb SciFi Tracker

The tracking system is going to replace the current inner (silicon strip) and outer (straw tubes) trackers and will cover a total area of 340 m$^2$. It consists of staggered layers of scintillating fibres, which are readout by Silicon Photomultipliers.

- 3 stations (T1, T2, T3) with 4 layers ($0^\circ$, $5^\circ$, $10^\circ$)
- Each station is 6 x 5 m$^2$ large
- 8 fibre mats of 2.5 m length per module (128 modules)
- 11,000 km of fibre (250 µm diameter)

Requirements:
- Hit detection efficiency $\approx 99$
- Spatial resolution better than 100 µm in the horizontal plane
- X000 ≤ 1% per detection layer
- 35 kGy close to the beam pipe for the fibres
- $6 \times 10^{10}$ n$_{eq}$/cm$^2$ for the photodetectors

SiPMs for LHCb SciFi

- Customised 12-channel linear arrays (Hamamatsu MPPC S13352 – H2017)
- Channel size 0.25 x 1.62 mm$^2$
- 104 pixels (57.5 x 62.5 µm$^2$) per channel
- Optimised for:
  - High PDE (large pixels)
  - Low after-pulse and cross-talk
  - Thin entrance window (105 µm epoxy layer)

Correlated noise

The detector shows three types of correlated noise: direct cross-talk, delayed cross-talk and after-pulse. Correlated noise probabilities were determined by statistical analysis of waveforms based on a threshold based peak finding and selection algorithm.

After R&D the total correlated noise probability could be reduced to 7% for the H2017 at the operating point $V_B = 3.5$ V. Direct and delayed cross-talk are the dominant sources of noise clusters. Delayed cross-talk can produce ghost clusters in the consecutive bunch crossing.

Observed radiation effects

At the end of the lifetime a fluence of $6 \times 10^{11}$ n$_{eq}$/cm$^2$ is expected.

We observe:
- Massive increase in dark count rate (DCR)
- Less than 5% PDE change
- Less than 10% change in gain
- No change in cross-talk
- Single photon detection still possible at $6 \times 10^{11}$ n$_{eq}$/cm$^2$

References