Silicon Photomultipliers for the LHCb Upgrade Scintillating Fibre Tracker

Presented by
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(On behalf of the LHCb SciFi Tracker group)
The LHCb SciFi Tracker

Related talks at TIPP 2014:
- Cooling for the LHCb Upgrade Scintillating Fibre Tracker, by Petr Gorbounov, June 2nd
- Scintillating Fibre and Radiation Damage Studies for the LHCb Upgrade, by Mirco Deckenhoff, June 4th
- The LHCb Upgrade Scintillating Fibre Tracker, by Blake D. Leverington, June 6th

Technical Design Report:

Requirements on detector performances:
- Hit detection efficiency greater than 98%, with noise less than 10% of signal
- Spatial resolution better than 100 μm
- Operation at 25 ns interaction rate, 40 MHz readout
- High occupancy, up to 2.5 clusters for a detector array of 128 channels (32mm) in the hottest region
- Low material with $X/X_0 \leq 1\%$ per detection layer
- Radiation environment, fibres up to 35 kGy, SiPMs $6 \times 10^{11} n_{eqv}/cm^2$ fluence (with neutron shield) + 100 Gy ionising dose
SciFi working principle

**Threshold based clustering algorithm** is used to calculate the hit position.
Typical signal produced by a traversing particle is larger than one channel.

**Scintillating fibres:** 250µm diameter, 2.5m long, 6 layers near the beam-pipe and 5 everywhere else.

Multichannel array of SiPM 128 channels (Hamamatsu or KETEK devices under development).

**Channel:** size 0.25×1.5mm$^2$, 96 pixels (57.5×62.5µm$^2$)

Channel and fibres are not aligned (250µm channel and 275µm fibre pitch).
Noise cluster rate

The noise cluster rate \( f_C \) is defined as the frequency of noise clusters for a 128Ch SiPM array which depends on:

- **DCR:** the thermal noise increase with over-voltage (\( \Delta V \)), depends on the temperature (\( T \)), the total surface of the detector (\( S \)) and the neutron fluence (\( N_{\text{fluence}} \)).

- **Clustering algorithm:** the algorithm combines single channels into clusters, depends on the thresholds.

- **X-talk:** The pixel to pixel optical x-talk probability increases linearly with \( \Delta V \) and increases significantly the \( f_C \).

- **After-pulsing:** Small effect for LHCb SciFi application (because of very fast shaping).

- **Shaping:** Fast integration and shaping \( O(20 \text{ ns}) \) allows to cope with high DCR.
Important characteristics of the SiPMs for the LHCb SciFi Tracker

- **High PDE!** The 2.5m long fibres and the radiation damage of the fibres in the center of the detector, reduce the light output.

- **Low x-talk!** The noise cluster rate increases exponentially with x-talk. With the high DCR after irradiation, the noise cluster rate exceeds the acceptable level.

- **Support the radiation environment!** DCR increases with neutron fluence.

- **Small temperature dependence!** The operation temperature of the detector is set to -40°C. Temperature non-uniformity is expected for different regions of the detector.

- **Small dead regions!** Dead regions at the edges between adjacent SiPM arrays reduce the overall hit detection efficiency.

- **Thin entrance window!** The entrance window defuses the light and therefore the thick window increases the cluster size and makes the spatial resolution worse.

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Hamamatsu (2010)
(Hamamatsu Photonics K.K., Japan)

KETEK (highest possible fill factor)
(KETEK GmbH, Germany)
General characteristics

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Pixel size [μm²]</th>
<th>Tc [mV/K]</th>
<th>VBD [V]</th>
<th>Over-voltage [V]*</th>
<th>Gain [e/PE]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ham. S10262-11-050C</td>
<td>50×50</td>
<td>56</td>
<td>69</td>
<td>1.3</td>
<td>0.75*10⁶</td>
</tr>
<tr>
<td>Ham., with trench (2013)</td>
<td>50×50</td>
<td>43</td>
<td>55</td>
<td>3.5</td>
<td>2.0*10⁶</td>
</tr>
<tr>
<td>KETEK, W1C2, with trench</td>
<td>60×62.5</td>
<td>15</td>
<td>23.5</td>
<td>3.5</td>
<td>8.5*10⁶</td>
</tr>
<tr>
<td>KETEK, W1C3, with trench</td>
<td>82.5×62.5</td>
<td>15</td>
<td>23.5</td>
<td>3.5</td>
<td>12.0*10⁶</td>
</tr>
<tr>
<td>KETEK, W7C3, double trench</td>
<td>82.5×62.5</td>
<td>22</td>
<td>32.4</td>
<td>3.5</td>
<td>9.5*10⁶</td>
</tr>
</tbody>
</table>

* Possible operation point for SciFi application (note that the DCR increases with over-voltage)

- Detectors with trenches can be operated at higher over-voltage (3.5V) which leads to a better gain uniformity $\delta G/G \propto \delta(\Delta V)/\Delta V$ for same $V_{BD}$ variation.
- Higher gain uniformity within an array doesn’t require channel individual gain tuning.
- Lower bias voltage decreases break down voltage temperature coefficient ($T_C$) and increases gain.
- Low $T_C$ and high over-voltage reduces temperature dependence of the gain to 2-6% for 5K.
Cold box for SiPM characterization

1. SiPM array
2. VATA64 card
3. USB based ADC board
4. SiPM single
5. Fast amp
6. Peltier
7. Liquid coolant
8. Temp sensor
9. Dry gas injection
10. Humidity sensor
11. LED for light injection
12. Isolation
X-talk

- With low DCR (probability for two random pulses within shaping window small), the probability of x-talk is given by ratio $\frac{DCR_{th=1.5\;pe}}{DCR_{th=0.5\;pe}}$.

- Two methods (systems) were used to measure x-talk.
  - Use a fast (single channel) amplifier (FEMTO 2GHz bandwidth) and record threshold scan. This allows to measure x-talk without after-pulsing due to the fast shaping.
  - Record dark spectrum with custom multichannel data acquisition system based on a VATA64 chip (64 channels, >50ns shaping time, sample and hold mode with serial readout, 12-bit ADC). This cannot separate x-talk and after-pulsing due to the slow shaping.

- The difference between the two methods allows to estimate the effect from after-pulsing.

\[\text{Hamamatsu, 50um pixel with trench (2013), different over-voltages, threshold scan.}\]

\[\text{Hamamatsu, 50um pixel, standard (ref.), with trench (2013), without trench (2013), at typical over-voltage, recorded with VATA64.}\]
X-talk Hamamatsu and KETEK

Comparison of different Hamamatsu 50um pixel devices.

- Difference due to after-pulsing (1.3V over-voltage) (17% vs 10%)
- With trench, low after-pulsing, 7% x-talk at 3.5V over-voltage

Comparison of different KETEK devices with different pixel sizes.

- W1C3, with trench, large pixels (3.5V over-voltage) (10% vs 8%)
- W1C2, with trench, small pixels (3.5V over-voltage) (8% vs 7%)
- W7C3, double trench, large pixels (3.5V over-voltage) (3% vs 2%)

No trench, extremely high x-talk
The temperature dependence of the DCR is an important characteristic for the SciFi Tracker in LHCb. Cooling to -40°C is foreseen to reduce the DCR to an acceptable level.

We express the dependence in a temperature difference required to reduce the DCR by a factor 2 ($K_{1/2}$). The temperature dependence of the DCR is related to different SiPM technologies.

- Hamamatsu S10262-11-050C, after irradiation $K_{1/2}=10°C$
- Hamamatsu detector with trenches (2013), after irradiation $K_{1/2}=12.8°C$

The detector with trenches (2013) can work at a higher over-voltage (to increase the PDE) but this increases the DCR!

The detectors were annealed after irradiation (at 40°C, one week) to reduce the DCR. Annealing effect can reduce the DCR by a factor 2-2.5 for detectors operated at low temperature.
The temperature $K_{1/2}$ dependence of the DCR also changes between, before and after irradiation.

The DCR for the double trench KETEK device is a factor 2-3 higher than Hamamatsu with trench, at 3.5V over-voltage and -40°C. Note that the measurements need to be scaled to the same surface and the same neutron fluence.
**Photon Detection Efficiency**

We perform a relative Photon Detection Efficiency (PDE) measurement:

\[
PDE_{\text{rel, SiPM}}(\lambda) \propto \frac{I_{\text{SiPM}}(\lambda) - I_{\text{Dark}}}{(1 + P_{\text{x-talk}}) / G \cdot QE_{\text{PD}} / I_{\text{PD}}(\lambda)}
\]

Corrections for: Dark current \(I_{\text{dark}}\), x-talk (+after pulse) \(P_{\text{x-talk}}\), lamp emission \(I_{\text{PD}}(\lambda)\)

- Calibrated light source with photo diode
- Monochromator for wavelength selection
- Light coupled to optical fibre and optional illuminating PD or SiPM

The 128 CH SiPM array from Hamamatsu (based on the technology of the S10262-11-050C with adapted pixel size) is used as the reference and its peak PDE is set to 30% (after corrections). This value has been confirmed by different groups.
Non irradiated: Fibre emission spectrum (SCSF-78MJ). It extends from 400 to 600 nm and peaks at 450 nm.

Irradiated fibre: The emission spectrum changes with irradiation. The simulated spectrum, taking into account a graded irradiation, shows a green shift.
The emission spectrum from a long and irradiated fibre peaks at 480nm and is therefore green shifted compared to the peak PDE of SiPMs, especially for KETEK.

The Hamamatsu with trench (2013) has a peak PDE of 37% and has a rather flat PDE over the full emission spectrum of the fibre.

The KETEK detectors tested reach a peak PDE of up to 43% at 3.5V over-voltage.

The weighted integral over the emission spectrum of the fibre reaches identical values for Hamamatsu (pink line) and KETEK (red line) (each detector with trench and at 3.5V over-voltage)
### Summary

<table>
<thead>
<tr>
<th>Detector type</th>
<th>H. S10262-11-050C</th>
<th>H. with trench (2013)</th>
<th>K. W1C2, with trench</th>
<th>K. W1C3, with trench</th>
<th>K. W7C3, double trench</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface [mm²]</td>
<td>1</td>
<td>1</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
</tr>
<tr>
<td>Pixel size [µm²]</td>
<td>50×50</td>
<td>50×50</td>
<td>60×62.5</td>
<td>82.5×62.5</td>
<td>82.5×62.5</td>
</tr>
<tr>
<td>$T_C$ [mV/K]</td>
<td>56</td>
<td>43</td>
<td>15</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>Over-voltage [V]</td>
<td>1.3</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>X-talk + After-pulsing</td>
<td>17%</td>
<td>7%</td>
<td>8%</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>$V_{BD}$ [V]</td>
<td>69</td>
<td>55</td>
<td>23.5</td>
<td>23.5</td>
<td>32.4</td>
</tr>
<tr>
<td>Gain [e/PE]</td>
<td>0.75×10⁶</td>
<td>2.0×10⁶</td>
<td>8.5×10⁶</td>
<td>12.0×10⁶</td>
<td>9.5×10⁶</td>
</tr>
<tr>
<td>PDE @peak</td>
<td>30%</td>
<td>37%</td>
<td>42%</td>
<td>44%</td>
<td>40%</td>
</tr>
<tr>
<td>Weighted PDE integral</td>
<td>1.26</td>
<td>1.61</td>
<td>1.44</td>
<td>1.55</td>
<td>1.47</td>
</tr>
<tr>
<td>Irradiation [n_{eqv}/cm²]</td>
<td>~3</td>
<td>~3</td>
<td>~2</td>
<td>~2</td>
<td>~2</td>
</tr>
<tr>
<td>DCR (annealed), -40°C [MHz]</td>
<td>~7</td>
<td>~25</td>
<td>~25</td>
<td>~25</td>
<td>~12</td>
</tr>
</tbody>
</table>

- For LHCb SciFi Tracker we evaluated custom SiPM arrays from KETEK and Hamamatsu, which both have high PDE, low x-talk and sufficient radiation hardness.
- The KETEK technology shows a very high peak PDE where for the Hamamatsu the broad sensitivity gives an advantage for the green shifted emission spectrum of the fibre. They have equal weighted integral of PDE at the 3.5 V overvoltage.
- Detectors with (double) trenches have low x-talk and better gain uniformity due to lower $T_C$ and higher over-voltage.
- The high DCR for these detectors require cooling to -40°C in order to reach an acceptable noise cluster rate. $K_{1/2}$ dependence for different technologies might lead to lower DCR.
Major tracking upgrade of LHCb (for after LS2, ≥2020, 50fb⁻¹)

Aim for the same performance at high luminosity ($2 \cdot 10^{33}$ cm⁻²s⁻¹, 25 ns, $\nu = 7.6$) as under current conditions ($<4 \cdot 10^{32}$, 50 ns, $\mu = 1.7$).

- New VELO, Si pixel based
- New Upstream tracker (UT), Si-µstrip
- SciFi Tracker, scintillating fibres
Relative PDE measurement for SiPM with monochromator

1. Xe lamp
2. Step motor for changing \( \lambda \)
3. Light to fibre coupling
4. Light out of fibre
5. Calib. Photo Diode
6. SiPM under test
7. To picoamp meter

Adjustable distance
KETEK channel-to-channel uniformity

W7C3 ~6% variation

W1C3 ~12% variation

W7C2 ~3% variation

W1C2 ~8% variation
KETEK x-talk for different channels

![Graphs showing x-talk for different channels w1c2 and w7c3.](image-url)