Characterization of SiPM radiation hardness for application in hadron calorimeters at FAIR, CERN and NICA

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Hadron calorimeters

- Projectile Spectator Detector (PSD) at NA61 (CERN)
- Forward Hadron CALorimeter (FHCAL) at BM@N (NICA)
- Projectile Spectator Detector (PSD) at CBM (FAIR)
Hadron calorimeter module

**Design:** compensating lead-scintillator calorimeters which measure the energy distribution of forward going projectile nucleons and nuclei fragments (spectators) produced close to the beam rapidity

**Features:**
- transverse granularity by 44+ modules,
- longitudinal segmentation of 10 sections per module
- light from each consecutive 6 layers collected via WLS-fibers and read-out by SiPM
- ability to operate at high collision rates up to 1MHz

**Module properties:**
- 60 lead+scintillator plates in one module
- 1 section = 6 scintillator plates
- size = 20 x 20 x 120 cm$^3$
- depth ~ 5.6 hadron interaction lengths $\lambda_{int}$
- optimized for beam energy range of 2 – 35 GeV

**Requirements for Silicon Photomultipliers (SiPMs):**
- wide dynamic range ~ 1000 to measure signals from few MeV up to several GeV
- good recovery time ~ tens ns to operate at reaction rates up to 1 MHz
- radiation hardness to neutrons ~ $2 \times 10^{11} \text{ n}_{eq}/\text{cm}^2$ for CBM and BM@N (lower for other experiments)
Radiation conditions

**Simulation of neutron fluence at the SiPM plane**

Up to $2 \times 10^{11}$ neutrons/cm$^2$ for SiPMs located 10 cm close to the beam center. *Beam hole in the center significantly reduces the radiation damage*

- SiPMs were irradiated by neutrons at cyclotron of NPI Řež with fluence in a wide range from $6 \times 10^{10}$ up to $9 \times 10^{12}$ n$_{eq}$/cm$^2$.
- All SiPMs were systematically studied in our lab before and after irradiation.

*V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete*
SiPM dynamic range and recovery time

<table>
<thead>
<tr>
<th></th>
<th>Zecotek MAPD-3A</th>
<th>Zecotek MAPD-3N</th>
<th>Hamamatsu S12572-010P</th>
<th>Sensl uF-C30020</th>
<th>Sensl uF-B30020</th>
<th>Ketek PM-3350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating voltage</td>
<td>~ 65 V</td>
<td>~ 90 V</td>
<td>~ 70 V</td>
<td>~ 25 V</td>
<td>~ 25 V</td>
<td>~ 25 V</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>135000</td>
<td>135000</td>
<td>90000</td>
<td>11000</td>
<td>11000</td>
<td>3600</td>
</tr>
<tr>
<td>Real pixel size</td>
<td>8 µm</td>
<td>8 µm</td>
<td>10 µm</td>
<td>29 µm</td>
<td>29 µm</td>
<td>50 µm</td>
</tr>
<tr>
<td>Gain</td>
<td>~ 6×10^4</td>
<td>~ 1×10^5</td>
<td>~ 1×10^5</td>
<td>~ 1×10^6</td>
<td>~ 1×10^6</td>
<td>~ 6×10^6</td>
</tr>
<tr>
<td>PDE</td>
<td>~ 20%</td>
<td>~ 30%</td>
<td>~ 10%</td>
<td>~ 25%</td>
<td>~ 25%</td>
<td>~ 40%</td>
</tr>
<tr>
<td>Pixel recovery time</td>
<td>~ 2 us</td>
<td>~ 10 us</td>
<td>~ 10 ns</td>
<td>~ 100 ns</td>
<td>~ 100 ns</td>
<td>~ 2 us</td>
</tr>
</tbody>
</table>

Dynamic range of different SiPMs

Normalized response vs proton beam rate measured at NA61 PSD calorimeter

Hamamatsu SiPM was chosen for the further investigation because it has best recovery time and:
- Zecotek SiPMs have too slow pixel recovery time and can not operate at rates > 10 kHz
- Sensl and Ketek SiPMs have significantly lower radiation hardness and dynamic range
Dark current after irradiation

Hamamatsu S12572-010P IVR vs fluence

- Non-irradiated
- 6.2E+010 n_{eq}/cm²
- 2.0E+011 n_{eq}/cm²
- 6.2E+011 n_{eq}/cm²
- 9.1E+011 n_{eq}/cm²
- 1.5E+012 n_{eq}/cm²
- 4.7E+012 n_{eq}/cm²
- 9.0E+012 n_{eq}/cm²

Fluence

Breakdown voltage $V_{bd}$ determination

Linear dependence on fluence

V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete
Dark current after irradiation

- Increases linearly with neutron fluence
- Can exceed 1 mA
- Decreases with number of pixels

**Non-irradiated**

**Irradiated by 9.1x10^{11} \text{n}_{\text{eq}}/\text{cm}^2**

**Irradiated by 9x10^{12} \text{n}_{\text{eq}}/\text{cm}^2**
Response to LED after irradiation

Signal charge $\overline{Q}$ [V*s]:
- Signal does not decrease at $6.2 \times 10^{10}$ $n_{eq}/cm^2$

Noise $\sigma_{noise}$:
- Noise does not increase after $\sim 10^{12}$ $n_{eq}/cm^2$

SNR and resolution:
- SNR and resolution improve with overvoltage

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Response to LED after irradiation

Noise does not increase after $\sim 10^{12}$ n$_{eq}$/cm$^2$

Signal does not decrease at $6.2 \times 10^{10}$ n$_{eq}$/cm$^2$

SNR and resolution improve with overvoltage

V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete
Response to LED after irradiation

- Response to LED and SNR decrease by 1-3 orders of magnitude with fluence
- Noise increases up to an order of magnitude and then saturates or even decreases (gain drop?)
- Signal parameters degrade slower for SiPMs with high number of pixels

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Gain and voltage of Geiger discharge turn-off $V_{off}$ can be calculated.

\[ V_{off} = Voltage \text{ at Gain}=1. \]

$V_{off}$ is typically below the breakdown voltage $V_{bd}$ by 0 – 2 V (more pixels – lower $V_{off}$)

Gain and voltage of Geiger discharge turn-off $V_{off}$ can be calculated.
Single photon peaks are not distinguishable after irradiation with $6.2 \times 10^{10} \text{ n}_{eq}/\text{cm}^2$.
Low photon signals are not visible anymore after irradiation with $9.1 \times 10^{11} \text{ n}_{eq}/\text{cm}^2$.

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Capacitance after irradiation

Strange behavior below 1kHz, but no sizeable change of capacitance after irradiation.

Stable frequency = 10kHz was chosen for further investigation.

Intermediate frequency:
\[ C_{\text{par}} \approx C_d \times N_{\text{pix}} \]

High frequency:
\[ C_{\text{par}} \approx C_q \times N_{\text{pix}} \]

Formulas and schemas are from:
* R. Klanner, Characterisation of SiPMs
  https://doi.org/10.1016/j.nima.2018.11.083

V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete
Capacitance after irradiation

![Graphs of capacitance vs reverse voltage for different SiPMs](image1.png)

Gain = \( (V_{\text{rev}} - V_{\text{off}}) \times (C_d + C_q) / q_e \)

\( V_{\text{off}} \approx V_{bd}, \) \( C_d \gg C_q, \) \( C_d = C_{\text{par}} / N_{\text{pix}} \)

\[ \Rightarrow \text{Gain} \approx V_{\text{ov}} \times C_{\text{par}} / (N_{\text{pix}} \times q_e) \]

\[ \Rightarrow C_d = \text{const} \Rightarrow \text{Gain} = \text{const} \]

No sizeable change of capacitance after irradiation, therefore no change in gain

Decrease of SiPM response to LED is solely due to decrease of PDE?

V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete

Formulas are from
* R. Klanner, Characterisation of SiPMs
  [https://doi.org/10.1016/j.nima.2018.11.083](https://doi.org/10.1016/j.nima.2018.11.083)
Experiments at PSD in CERN

SiPMs soldered to PSD readout boards

PSD readout board assembled

CBM PSD supermodule at T9 CERN beamline

Readout board mounted to PSD
Performance of SiPMs in CERN

- Energy resolution dropped slightly for SiPMs irradiated by $2 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$
- Energy resolution dropped in $\sim 1.5 – 2$ times for SiPMs irradiated by $\sim 10^{12} \text{ n}_{\text{eq}}/\text{cm}^2$ but SiPMs were proven to operate even after such a high neutron irradiation

*Reconstruction was performed with the noise cut, which was applied individually for each section*
Conclusions and Outlook

- Investigation of SiPM radiation hardness for calorimeters of CBM (FAIR), NA61 (CERN) and BM@N (NICA) is presented.
- Radiation hardness scales with the pixel number (pixel pitch) like the dynamic range.
- Hamamatsu MPPC S12572-010P was chosen from 6 different studied SiPMs for superior radiation hardness, dynamic range and operation rate.
- Radiation sustainability is sufficient for 1 year of calorimeter operation at maximum reaction rate of 1MHz and for whole experiment lifetime with exchange of SiPMs.

- Future plans:
  - Investigate new SiPMs to increase radiation hardness further

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Light yield measured with S12572-010 (~45 photoelectrons/section/muon) can be increased by a factor of 1.5

Lower dark current => Better radiation hardness.

Will be irradiated and tested at NPI in the Fall 2019
Backup
Response to LED: variability

Variation is below 20%  Neutron irradiation was quite uniform

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Dark current: variability

Many different samples, $V_{bd}$ was not always well defined

Neutron irradiation was quite uniform
Energy deposition in module

- Energy resolution dropped slightly for SiPMs irradiated by $2 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$
- Energy resolution dropped in $\sim 1.5 - 2$ times for SiPMs irradiated by $\sim 10^{12} \text{n}_{\text{eq}}/\text{cm}^2$ but SiPMs were proven to operate even after such a high neutron irradiation

Reconstruction was performed with the noise cut, which was applied individually for each section
CBM PSD readout electronics

**Preamplifier**
- Attached to photodiode
- Optimized for high capacitance inputs
- Gain ~ 60 V / V
- Good Signal / Noise

**PaDiWa-AMPS (GSI)**
- Method: Time-Over-Threshold (ToT)
- 8 MMCX input channels
- Time precision: < 50 ps
- Rel. charge resolution: < 0.5 %
- Dynamic range: 250 – 500
- Compact data: max. 50 MB/s

**TRBv3 Trigger and Readout Board**
- 4 FPGAs, 264 TDC channels
- Single edge & ToT measurement
- Time precision < 20 ps
- 50 MHz hit rate per channel
- Fast data transfer via gigabit Ethernet
- Internal trigger and slow control

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**Diagram Description**

- **SiPM**
- **Linear Amplifier** variable Impedance any peaking time
- **Integrator**
- **Constant discharge**
- **Switch & Delay 1**
- **Discriminator**
- **TDC**
  - time, width
  - width ~ charge

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CBM PSD: Alternative readouts

ADC64s/ADC125s electronics (AFI, JINR, Dubna)
- Method: direct waveform digitization
- 64 channels, 12 bit ADCs
- Speed: 62.5/125 MS/s
- Dynamic range: ~150
- Up to 100 kHz real event rate
- Huge amount of data
- DSP is required on top

Time-Over-Threshold (ToT) board
- Method: Time-Over-Threshold (ToT)
- 8 MMCX input channels
- NINO chip based design
- Dynamic range: ~ 250
- Compact data: max. 50 MB/s
- Coupled to TRB3

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# Difference between conducted tests

<table>
<thead>
<tr>
<th></th>
<th>Summer 2016 and 2017</th>
<th>September 2017</th>
<th>November 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beamline</strong></td>
<td>NA61</td>
<td>T10</td>
<td>T9</td>
</tr>
<tr>
<td><strong>Beam momentum range</strong></td>
<td>20 – 80 GeV/c</td>
<td>2 – 6 GeV/c</td>
<td>2 – 10 GeV/c</td>
</tr>
<tr>
<td><strong>Proton selection</strong></td>
<td>Not available</td>
<td>by TOF scintillators</td>
<td>By Cherenkov detector</td>
</tr>
<tr>
<td><strong>Proton selection approx.</strong></td>
<td>Not available</td>
<td>2 – 6 GeV/c</td>
<td>3.5 – 10 GeV/c</td>
</tr>
<tr>
<td><strong>mom. range</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SiPMs utilized</strong></td>
<td>Irradiated by 4E10, 4E11, 1E12 and 3E12 n/cm²</td>
<td>Irradiated by 1E12 and 3E12 n/cm²</td>
<td></td>
</tr>
<tr>
<td><strong>SiPMs calibration of overvoltages</strong></td>
<td>Calibrated by LED relative to the muon calibration of non-irradiated SiPMs</td>
<td>Previous calibration from NA61 was utilized</td>
<td>Relative to the breakdown voltage measured in lab (seems to be more accurate)</td>
</tr>
<tr>
<td><strong>Temperature stabilization</strong></td>
<td>All SiPMs kept at 20 °C</td>
<td>Not available</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature in the test hall</strong></td>
<td>Not available</td>
<td>~ 26 °C</td>
<td>~ 18 °C</td>
</tr>
</tbody>
</table>

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How the signals from 6 GeV/c protons look like

• Very high noise is clearly visible.

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Energy scan

Non-irradiated

Irradiated 1E12 n/cm2
Neutron shielding simulation

- We reduced the neutron flux by 50-70% adding borated polyethylene between the PSD module lead/scintillator blocks and SiPMs.
- Low energetic neutrons are shielded the best, so we reduce the neutrons captured in SiPM by silicon and dopants, especially $^{10}$B dopant having huge n cross-section.

8 cm boron (3%) polyethylene in newly assembled module

<table>
<thead>
<tr>
<th>Relative flux [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0E-05</td>
</tr>
<tr>
<td>2.5E-05</td>
</tr>
<tr>
<td>2.0E-05</td>
</tr>
<tr>
<td>1.5E-05</td>
</tr>
<tr>
<td>1.0E-05</td>
</tr>
<tr>
<td>5.0E-06</td>
</tr>
<tr>
<td>1.0E-06</td>
</tr>
<tr>
<td>0.0E+00</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Energy [MeV]</th>
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<tbody>
<tr>
<td>1.0E-08</td>
</tr>
<tr>
<td>1.0E-06</td>
</tr>
<tr>
<td>1.0E-04</td>
</tr>
<tr>
<td>1.0E-02</td>
</tr>
<tr>
<td>1.0E+00</td>
</tr>
<tr>
<td>1.0E+02</td>
</tr>
<tr>
<td>1.0E+04</td>
</tr>
</tbody>
</table>

**Courtesy of O. Svoboda**
Test of Hamamatsu SiPMs response at NA61 PSD: Waveforms

Non-irradiated

Irradiated 3e11 n/cm²

Irradiated 3e12 n/cm²

RMS ~ 50 ADC

RMS ~ 500 ADC

RMS ~ 1500 ADC

With the noise increased at 10-30 times SiPM cannot detect MIPs (~10-15 photons)!

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Details on neutron irradiation experiments

SiPMs prepared for irradiation

SiPMs located at the holder

SiPMs located at cyclotron

Intensity for fluence = $1 \times 10^{12}$ n/cm$^2$

Intensity for fluence = $3 \times 10^{12}$ n/cm$^2$

Proton energy = 35 MeV

16 cm from target

$T_{\text{irr}} = 8$ min

$T_{\text{irr}} = 24$ min

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Displacement damage in Silicon for neutrons, protons, pions and electrons

A. Vasilescu & G. Lindstroem

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SiPM breakdown voltage after irradiation

<table>
<thead>
<tr>
<th>Sample N</th>
<th>V_{breakdown} V \pm 0.2V</th>
<th>V_{breakdown} V \pm 0.2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>64.4</td>
<td>66.7</td>
</tr>
<tr>
<td>21</td>
<td>64.8-&gt;65.2</td>
<td>67.6-&gt;67.1</td>
</tr>
<tr>
<td>22</td>
<td>65</td>
<td>67</td>
</tr>
<tr>
<td>23</td>
<td>64.9</td>
<td>67.1</td>
</tr>
<tr>
<td>24</td>
<td>64.9</td>
<td>67.4</td>
</tr>
<tr>
<td>25</td>
<td>64.7</td>
<td>66.7</td>
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<tr>
<td>26</td>
<td>64.7</td>
<td>66.7</td>
</tr>
<tr>
<td>27</td>
<td>64.4</td>
<td>66.1</td>
</tr>
<tr>
<td>28</td>
<td>64.4</td>
<td>66.0</td>
</tr>
<tr>
<td>29</td>
<td>64.2-&gt;64.3</td>
<td>65.9</td>
</tr>
</tbody>
</table>

Variation of V_{breakdown} measured for few SiPMs is less than 0.5V.

* SiPMs irradiated by “white” neutron spectrum

\( V_{break} = 65 \pm 0.2V \)

\( \Delta V_{break} (6.4e11 \text{ n/cm}^2) \sim 0.4V \)

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Details on laboratory test setup for SiPM measurements

Connection scheme

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Details on laboratory test setup for SiPM measurements

Connection scheme

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Interface of software developed for IV, CV, CF, SNRV measurements