Development of the SHiP Timing Detector Based on Scintillating Bars Readout by SiPMs

12th Trento Workshop on Advanced Silicon Radiation Detectors
Feb. 20-22 2017, Trento, Italy

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22.02.2017
Motivation

- The Standard Model provides an explanation for many subatomic processes
- Although very successful, it fails to explain many observed phenomena
  - Dark Matter
  - Neutrino oscillation and masses
  - Matter/antimatter asymmetry in the universe
- May have a whole Hidden Sector of weakly interacting particles BSM
- Energy Frontier
  - Heavy particles $\rightarrow$ High energy events
- Intensity Frontier
  - Light particles $\rightarrow$ Rare events
The SHiP experiment

- The SHiP (Search for Hidden Particles) experiment is a proposed fixed target facility at the CERN SPS.
- SPS proton beam:
  \[ 4 \times 10^{13} \text{ protons per spill @ 400 GeV} \rightarrow 2 \times 10^{20} \text{ collisions in 5 years} \]
- Will probe long lived exotic particles with masses below $O(10)$ GeV.
- Programme will include searches of very weakly interacting low-energy SUSY states as well as direct searches for Dark Matter, Sterile Neutrinos and Dark Photons.
- Neutrino detector consists emulsion target with tracking in a magnetic field followed by a muon spectrometer $N_{\nu_\tau} \sim 10^4$.
- Hidden particle detector will consist of a long evacuated decay volume with a magnetic spectrometer, calorimeters, and a muon detector located on the far end.
A dedicated timing detector can be used to reduce random crossing in the detector.

Combinatorial di-muon background can be reduced to an acceptable level by requiring a timing resolution of 100 ps or less.

Two options have been proposed for the timing detector:

1. Plastic scintillators read-out by PMTs or SiPMs
2. Multigap resistive plate chambers

This study focuses on the plastic scintillator option read-out by SiPMs.
PMT option: Set-up

- 10 GeV/c muon beam produced from the CERN PS (T9 beamline)
- 3 m long bar (EJ-200) readout by PMTs
- 2 reference counters used for trigger → 40 ps resolution
- Two DAQ systems are studied
  1. WAVECATCHER: 8 channel, hardware trigger ∼ few kHz
  2. SAMPIC: 16 channel, self triggering ∼ 150 kHz
- Time resolution of entire system is taken as Gaussian width of the following
  $$\Delta t = \frac{t_1 + t_2 + t_3 + t_4}{4} - t_{5,6}$$
135 ps resolution halfway between bar (1.5 m)

About 130 p.e./PMT when interaction is at middle of the bar

Path length dispersion in the bar dominates time resolution at large distances
→ Main limiting factor for long bars
→ Faster electronics won’t help
SiPM characterization

- SiPMs from two manufacturers:
  - Hamamatsu Photonics
  - SensL

- SiPM characterized by:
  - Current-Voltage behavior
  - Dark count rate
  - Cross-talk probability
  - Single photon time resolution

![Graphs showing current-voltage, dark count rate, and cross-talk probability for different SiPMs.](image)
SiPM single photon time resolution

- Back-to-back $\gamma$s from pair-annihilation in $^{22}\text{Na}$ is used as a source
- Single photon time resolution is taken as the Gaussian width in the time difference spectrum from coincidence signals
- Very good resolution $\sim 100$ ps is observed in $3 \times 3$ mm HPK SiPM

2.7 V - 1.5 photon level
SiPM+bar: Set-up

- Signal generated by $^{90}\text{Sr}$ source
- Scintillating plastic bar: EJ-200, $120 \times 11 \times 2.5$ cm
- Read out on both ends by SiPMs / SiPM Arrays
- Signal sent to amplifier and readout out by 4 GHz oscilloscope
SiPM+bar: Time resolution

- $^{90}$Sr pointed at bar center (60 cm)
- $3 \times 3$ mm$^2$ SiPM on either end of bar
- Initial measurements indicate time resolution of 800 ps
- Assuming $\sigma \propto \frac{1}{\sqrt{N}}$
  - $\sim 100$ ps for 25% sensor coverage
  - $\sim 50$ ps for full sensor coverage

![Graph showing time resolution measurements](image)

[Table 4.7: Asummary with the SPTR up to 3.72 V OV for the HPK-S13360-3050CS sensors.]

The results so far show that even with suboptimal settings a SiPM-SPTR of 70 ps can be reached with the HPK-S13360-3050CS sensors.

4.2 Timing Measurement with Scintillator bar

As for the SPTR a sequence of measurement for CF values between 9 and 90% were carried out for OVs between 2.7 and 4.2 V. The threshold on both signal channels was set between the first and second pixel amplitude for the respective voltage. A sample of 15,000 time differences was recorded for each voltage and fitted with three Gaussian as presented in figure 4.24.

![Figure 4.24: Fit with three Gaussian for a measurement with the scintillator bar at 3 V and for the CF at 24%](image)

4.2. Timing Measurement with Scintillator bar

![Figure 4.26: Time resolution measurement for HPK-S13360-3050CS with the scintillator bar at a CF of 24% for different OV. The contributions of $el$ and $TW$ are so small that they are negligible.](image)

<table>
<thead>
<tr>
<th>OV [V]</th>
<th>SiPM [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.72</td>
<td>0.898 ± 0.023</td>
</tr>
<tr>
<td>2.82</td>
<td>0.887 ± 0.020</td>
</tr>
<tr>
<td>2.92</td>
<td>0.872 ± 0.023</td>
</tr>
<tr>
<td>3.02</td>
<td>0.847 ± 0.013</td>
</tr>
<tr>
<td>3.12</td>
<td>0.835 ± 0.021</td>
</tr>
<tr>
<td>3.22</td>
<td>0.859 ± 0.016</td>
</tr>
<tr>
<td>3.32</td>
<td>0.832 ± 0.012</td>
</tr>
<tr>
<td>3.42</td>
<td>0.878 ± 0.020</td>
</tr>
<tr>
<td>3.52</td>
<td>0.822 ± 0.013</td>
</tr>
<tr>
<td>4.02</td>
<td>0.870 ± 0.025</td>
</tr>
<tr>
<td>4.52</td>
<td>0.895 ± 0.012</td>
</tr>
</tbody>
</table>

[Table 4.8: The results for SiPM+plastic in the timing measurements with the scintillator bar and the HPK-S13360-3050CS sensors between 2.72 and 4.52 V OV.]

[C. Betancourt et al., *JINST* 12 2 (2017)]
MUSIC: Multiple Use SiPM Integrated Circuit

Operational Modes
- Single channel: analog or discriminated
- Up to 8 ch summation
- Trigger output

Performance
- Low noise
- High speed: > 500 MHz without filtering
- Tuneable PZ cancellation
- SPTR 100 ps
- Dynamic range: from < 1/5 to >2000 p.e.

Applications
- Cherenkov Telescopes
- High Energy Physics and nuclear detectors
- Lab test benches for SiPM characterization: flexibility
Sensor layout and connection

- Array of 8 SiPMs (6 × 6 or 3 × 3 mm$^2$)
- Investigate different manufacturers (HPK, SensL, AdvanSiD?)
- Connection in series or parallel
- Increasing number of channels leads to better resolution
Summary & Outlook

- SHiP is a proposed fixed target experiment at the CERN SPS
  - Tau neutrino physics
  - Sterile neutrinos
  - Dark Photon
  - Dark Scalars/Dark Higgses
  - Axion Like particles


- Exploring scintillator based option for SHiP timing detector

- Readout by SiPMs
  - \( \sim 800 \text{ ps in bar center for } 3 \times 3 \text{ mm}^2 \text{ sensors} \)
  - \( \rightarrow 100 \text{ ps for 25\% coverage, 50 ps for full coverage} \)

- DAQ based on MUSIC board being investigated

- Optimization ongoing (series vs. parallel, small vs. large sensors)

- Finalize design by end of 2017
BACKUP
Scan of CFD threshold indicated an optimal value of 24%.

Electronic noise at this value is $\sigma_{el} = 22$ ps for the optimal OV = 3 V.
Waveforms, rise time and decay time

3.2 Set-up for Measurements

3.2.1 SiPM Characterisation

A important part of this thesis was to assist in building up a test laboratory. Most of the equipment was not yet available and all the preliminary tests had to be conducted inside a 40x60x35 cm$^3$ box at room temperature (figure 3.9). The interior of the box was protected from light by a black rubberized fabric covering the box. The temperature was monitored by a Sensirion STS31 sensor but not controlled. The signal and power cables were fed trough a hole on the side of the box.

![Waveform of a HPK-S13360-3050CS sensor recorded with LeCroy Waveunner 8404M.](image)

![Waveform of a HPK-S10362-33-050C sensor recorded with a DRS4 evaluation board.](image)

3.4 Characterisation of SiPMs

The characterisation of the SiPMs was performed in this plastic box. The box was covered by a fabric to keep the interior light tight.

![Fit to find the RT for sensL-MicroFC SMA 60035-1 at 2.5 V above BdV. The RT is the mean of the red Gaussian.](image)

![RT versus OV for four sensors. The RT shows at most a weak dependence on the voltage.](image)

4.1. Characterization of SiPMs

is not yet analysed but it can be assumed that both sensors have approximately the same value. The results for the analysed sensors are listed in table 4.6 where the RMS (standard deviation) of the values for HPK-S13360-3050CS-10980 is also added.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>OV [V]</th>
<th>CTP [%]</th>
<th>RMS [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPK-S10362-33-050C</td>
<td>2.8</td>
<td>42.62 ± 2.58</td>
<td></td>
</tr>
<tr>
<td>HPK-S13360-3050CS-10977</td>
<td>2.9</td>
<td>4.79 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>HPK-S13360-3050CS-10980</td>
<td>3.25</td>
<td>4.05 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>sensL-MicroFC SMA 60035-1</td>
<td>3.35</td>
<td>13.37 ± 0.18</td>
<td></td>
</tr>
<tr>
<td>sensL-MicroFC SMA 60035-2</td>
<td>2.85</td>
<td>7.20 ± 0.17</td>
<td></td>
</tr>
</tbody>
</table>

4.1.4 Recovery Time, Resistance and Pixel Capacitance

The recovery time is as described in section 2.3 essential for the dynamic range of the SiPM. It depends on the quenching resistor and the capacitance of the SiPM, these results are therefore presented together.

![The average of 10,000 triggered signals from a HPK-S13360-3050CS sensor fitted to an exponential decay function to determine the recovery time.](image)

![The quenching resistance $R_q$ is determined by fitting the IV Curve measured with Forward Bias with a linear function. Figure 4.13 shows the fit result for the HPK-S13360-3050CS sensor, the curve is linear above 0.5 V. The quenching](image)
DCR and cross talk

**4.1. Characterization of SiPMs**

The DCR is determined by looking at the time difference between the peaks of a given event. The one pixel events could not be clearly separated from the noise and the threshold voltage had to be set relatively high to be able to conduct a measurement at all.

**Figure 4.7:** The DCR of different SiPMs versus OV. The results for two sensL sensors are not fully reliable. The effect of the temperature difference on the DCR can be observed for both sensor types.

**Table 4.1:**

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>iv-Threshold</th>
<th>CTP (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sensL-MicroFC SMA 60035</td>
<td>3.0 V</td>
<td>0.5 µs</td>
</tr>
<tr>
<td>HPK-S13360-3050CS-10977</td>
<td>4.0 V</td>
<td>1.5 µs</td>
</tr>
<tr>
<td>HPK-S13360-3050CS-10980</td>
<td>3.5 V</td>
<td>0.75 µs</td>
</tr>
<tr>
<td>HPK-S13360-3050CS-10984</td>
<td>2.5 V</td>
<td>2.5 µs</td>
</tr>
</tbody>
</table>

The results for the sensL device below 3-4 V have to be regarded with reservation, because the one pixel events could not be clearly separated from the noise and the threshold voltage had to be set relatively high to be able to conduct a measurement at all.

**Chapter 4. Results**

Comparison of methods: A comparison of the two methods shows that the results are close and inside the error of the measurements and show that the dependence of the CTP from the trigger level is small.

**Figure 4.10:** Fit to calculate Cross Talk Probability for sensL-MicroFC SMA 60035 for data recorded with the oscilloscope.

**Figure 4.5:** Fit for thermal component of the DCR in a 100 µs event due to the lower resolution of the waveform. The longer event time allows a precision measurement of the minimum number of fired pixels and is therefore constant until the threshold reaches the next pixel number. The DCR above the 2-pixel-amplitude is negligible.

**Figure 4.8:** The DCR versus the trigger level at constant 3 V.

**Figure 4.6:** Comparison of Cross Talk Probability for different SiPMs versus Over Voltage. The HPK-S13360-3050CS's show a uniform behavior as the CTP is the resulting DCR composed of a thermal component and a after pulse component. To get the characteristic value of the device has to be divided by the area of the SiPM.

**Figure 4.4:** Fit for the DCR in a 2 µs event for HPK-S13360-3050CS-10977. It is composed of a thermal component as it has the same value for 100 pairs of DCR above the 2-pixel-amplitude is negligible. The error for IV-curve-method is half of the measured steps.

**Figure 4.11:** Comparison of Cross Talk Probability for different SiPMs versus Over Voltage. The results for two sensL sensors are not fully reliable. The effect of the temperature difference on the DCR can be observed for both sensor types.
Timescale and costs

WP1 in LS3 Spending Profile

Design phase
Hidden Sector particles can be explored by coupling to Standard Model particles

- Vector Portal (e.g. Kinetically mixed dark photons, HNL)
- Scalar Portal (e.g. dark scalars, dark Higgses)
- Neutrino Portal (e.g. right handed neutrinos, sterile neutrinos)
Main decay modes and backgrounds

Main decay modes of hidden particles

<table>
<thead>
<tr>
<th>Models</th>
<th>Final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino portal, SUSY neutralino</td>
<td>$\ell^\pm \pi^\mp, \ell^\pm K^\mp, \ell^\pm \rho^\mp, \rho^\pm \rightarrow \pi^\pm \pi^0$</td>
</tr>
<tr>
<td>Vector, scalar, axion portals, SUSY sgoldstino</td>
<td>$\ell^+\ell^-, \pi^+\pi^-, K^+K^-$</td>
</tr>
<tr>
<td>Neutrino portal, SUSY neutralino, axino</td>
<td>$\ell^+\ell^-, \nu$</td>
</tr>
<tr>
<td>Axion portal, SUSY sgoldstino</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>SUSY sgoldstino</td>
<td>$\pi^0\pi^0$</td>
</tr>
</tbody>
</table>

Background sources with $V^0$ particles

<table>
<thead>
<tr>
<th>Background source</th>
<th>Decay modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ or $\mu$ + nucleon $\rightarrow X + K_L$</td>
<td>$K_L \rightarrow \pi e\nu, \pi \mu\nu, \pi^+\pi^-, \pi^+\pi^- \pi^0$</td>
</tr>
<tr>
<td>$\nu$ or $\mu$ + nucleon $\rightarrow X + K_S$</td>
<td>$K_L \rightarrow \pi^0\pi^0, \pi^+, \pi^-$</td>
</tr>
<tr>
<td>$\nu$ or $\mu$ + nucleon $\rightarrow X + K_\Lambda$</td>
<td>$\Lambda \rightarrow p\pi^-$</td>
</tr>
<tr>
<td>$n$ or $\mu$ + nucleon $\rightarrow X + K_L$, etc</td>
<td>as above</td>
</tr>
</tbody>
</table>
The Target

- SHiP target is very challenging due to high average beam power → 2.56 MW per 1 sec. spill
- Need heavy target to suppress $\pi$/Kaon decays → reduce the muon and neutrino induced backgrounds
- Longitudinally segmented hybrid target
  - Core of shower - four interaction lengths of titanium-zirconium doped molybdenum alloy
  - Followed by six interaction lengths of pure tungsten
  - Water cooling
- Neutral particle absorber protects upstream beamline from neutrons and other neutral radiation
- Target embedded in cast Iron bunker
The Muon Shield

- \( \sim 5 \times 10^9 \) muons / spill
- Muon shield needs to be as compact as possible along beamline
- Both active and passive shields being investigated
- Active shield needs \( B_y = 40 \) Tm to bend 350 GeV muons away from the 5 m aperture of vacuum vessel
  1. Need to separate \( \mu^+ \) from \( \mu^- \)
  2. Bend muons further outward
- Passive shield uses dense material to slow down muons \( \sim 40 \) m of tungsten
- Backscatter from wall of experimental hall still lead to an unacceptably large flux of muons

Figure 3.11: The \( x, z \) configuration of a possible active muon shield showing the trajectory of two 30 GeV muons with a range of initial angles. The blue and dark green show the regions of field and return field respectively. The muons are bent out sufficiently by the first part of the shield such that they encounter the return field. This return field directs the muons back towards the detector. The field (return-field) is shown in light blue (green). The large winged shape section with \( 19 < z < 48 \) m is needed to sweep out particles that still traverse the return field of the first section of the shield (see Figure 3.11). Multiple scattering effects muons traversing the shield and a full three-dimensional GEANT simulation is used to assess the performance. The simulation indicates that with the proposed configuration it is possible to reduce the number of muons to the required level. A three-dimensional view of the shield as simulated is shown in Figure 3.12. The different colours again indicate the different field directions in the iron.

The shield is divided into a number of different magnets, each of which is approximately 6 m in length. The implementation of two of these magnets, magnet 1, which is located at the start of the shield \( 0 < z < 6 \) m and magnet 4, which is located in the region \( 19 < z < 25 \) m, is discussed in the next section. After the first 19 m in \( z \), it is necessary to move walls of the experimental hall out to \( x = \pm 10 \) m in order to stop muons from being scattered back towards the detectors.

3.4.2.2 Engineering design

In order to demonstrate the feasibility of constructing an active muon shield system as proposed above, finite element simulations of two of the key magnets, 1 and 4, have been made in the software OPERA-3d (http://operafea.com/). These simulations demonstrate that such
The Neutrino Detector

- Downstream of muon shield is the neutrino detector
- $\nu_\tau$ and anti-$\nu_\tau$ interaction detected by decay of $\tau$ lepton
- Detector consists of two parts
  - Neutrino Emulsion target in magnetic field
  - Muon Magnetic Spectrometer (MMS)
- Neutrino target based on Emulsion Cloud Chamber (ECC)
  - ECC brick - Lead as passive material
  - Compact Emulsion Spectrometer (CES) - sandwich of light material plates and emulsion film
- Muon Spectrometer
  - Resistive Plate Chambers (RPC)
  - Drift Tube Tracker (DTT)
The Vacuum Vessel

- Neutrino and muon interactions suppressed by $10^{-6}$ bar vacuum vessel
  → Vessel containing a helium filled ballon also under consideration, physics impact still under investigation
- Elliptical structure used to reject large muon flux entering the vessel horizontally by the active muon shield while maximizing geometrical acceptance
- Vessel is double walled structure
  → space filled with liquid scintillator that acts as a high efficiency background event tagger
- Charged particles passing through the background tagger is read out with photo-sensors
- Background tagger also offers possibility to decide offline if particles in tracker and calorimeter are entering from outside
The Spectrometer Tracker and Magnet

- Spectrometer used to reconstruct tracks from hidden particle decay products while rejecting backgrounds.
- Consists of large dipole magnet and two tracking telescopes on each side.
- Straw tracker made up of thin polyethylene terephthalate tubes used for each station.
A dedicated timing detector can be used to reduce random crossing in the detector

Combinatorial di-muon background can be reduced to an acceptable level by requiring a timing resolution of 100 ps or less

→ Requires dedicated timing detector located after spectrometer and before calorimeters

Two options have been proposed for the timing detector

1. plastic scintillators read-out by PMTs or SiPMs
2. multigap resistive plate chambers
Calorimetry

1. Electromagnetic calorimeter (ECAL)
   - Located right after timing detector
   - Provides electron, photon and pion identification and energy measurements
   - Cells made of scintillator-lead structure read out by plastic WLS fibers

2. Hadronic calorimeter (HCAL)
   - Right after ECAL
   - Provide pion identification
   - Pion/muon discrimination for low momentum
   - Tag neutral particles ($K_L$, $n$) for background rejection
Need to identify muons with high efficiency in signal channels

\[ N \rightarrow \mu^+\pi^-, \mu^+\mu^- \nu_\mu \]
\[ V \rightarrow \mu^+\mu^- \]
\[ S \rightarrow \mu^+\mu^- \]

Separate signal from \( \nu \) and \( \mu \) induced backgrounds

Downstream of the calorimeter system

Four stations of active layers separated by three muon filters

Granularity dictated by muon filters and multiple scattering in calorimeters (5-10 cm in the transverse direction)

Active layers - extruded plastic scintillator strips with WLS fibers and opto-electronic readout
Very little difference between WAVECATCHER (135 ps in center) and SAMPIC (140 ps in center) using weighted average.

Degradation of time resolution is worse for SAMPIC at the far end → too small of an interval to fit baseline.
Angular scans

**Horizontal rotation**
- $42^\circ$, $45^\circ$, $48^\circ$, $52^\circ$, $60^\circ$, $70^\circ$, $80^\circ$, $90^\circ$
- Track length increases, effective bar length decreases
  $\rightarrow$ time resolution improves

**Vertical rotation**
- $60^\circ$, $70^\circ$, $90^\circ$
- Track length increases
  $\rightarrow$ time resolution improves