Multi-Pixel Photon Counter characterization for T2K

F. Retière (TRIUMF) for the T2K photo-sensor group in collaboration with A. Vacheret (Imperial College)
Building block of T2K nd280 and INGRID detectors

- Building block: scintillator bar + wavelength shifting fiber + MPPC

Detectors:
- Fine Grain Detector
  - 1 end readout, 1 end mirror
- Electromagnetic Calorimeter
  - 2 end readout
- INGRID (on axis)
  - 1 end readout, 1 end mirror
- Pi0 Detector
  - 1 end readout, 1 end mirror
- Side Muon Detector
  - 2 end readout

~50,000 MPPC will be used in T2K
See M. Yokoyama’s talk on Wed and A. Vacheret’s poster for more details on T2K experiment and additional information on the MPPCs
MPPC fulfill requirements

- Sufficient number of photo-electrons even in worst case scenario
  - No fiber mirroring
  - End of the bar
  - 1x1 mm² MPPC
- Dark noise rate is acceptable
- Gain is large enough
  - >5 × 10⁵
- Everything under control?
  - T2K is the first experiment using MPPCs for a physics experiment

M. Bryant (UBC), P. Kitching (TRIUMF), S. Yen (TRIUMF)
Simple minded simulation does not work

- Missing elements
  - Cross-talk
  - After-pulsing

- Step 1: measure cross-talk and after-pulsing
- Step 2: assess effect of cross-talk and after-pulsing

Laser flashing the MPPC directly

Over-voltage = 1.7V

- Dark noise
- Photon-detection efficiency
- Electronics noise
- Gain fluctuations
Measuring after-pulsing
Step 1: pulse finding

- MPPC dark noise
  - Self trigger at ~0.2 PE
- Use fast amplifier
- Use 1GHz digitizer
  - CAEN V1729
- Fit waveform with superposition of single avalanche response function
  - Measure response function directly from data
Measuring after-pulsing
Step 2: pulse selection

Trigger pulses

All pulses (70V, 25C)

First pulse following the trigger
Select only triggers with 1 PE (70V, 25C)

- 8.75 ns time constant (1x1mm²)
- 12 ns for 1.3x1.3 mm²
Measuring after-pulsing
Step 3: fit timing distribution

- Distribution of first pulse arrival time can be expressed with a few parameters
  - Probability and time constant + Dark Noise rate
    - 1 exponential function does not fit well
    - 2 exponential function is best
  - Issue: distortion of the distribution in the 1st 10 ns
    - Pulse finder inaccurate when gain is low
    - Effect estimated by simulation

![Graph showing probability of the next avalanche (ns⁻¹) over time after trigger (ns)]
Temperature dependence
1x1 mm² device

[Graphs showing temperature dependence on dark noise rate, after-pulsing probability, and after-pulsing time constant for 25 C, 20 C, 10 C, 0 C, and -10 C.]
### Summary of the parameters measured for 5 MPPCs

<table>
<thead>
<tr>
<th>Parameters at 1V over-voltage for 1.3x1.3 mm² MPPC</th>
<th>Average</th>
<th>Variation between MPPCs (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark noise</td>
<td>500±5 kHz</td>
<td>70 kHz</td>
</tr>
<tr>
<td>After-pulsing probability (short)</td>
<td>6.3±0.2 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>Short after-pulsing time constant</td>
<td>18.5±0.9 ns</td>
<td>0.6 ns</td>
</tr>
<tr>
<td>After-pulsing probability (long)</td>
<td>5.9±0.2 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>Long after-pulsing time constant</td>
<td>84±5 ns</td>
<td>6 ns</td>
</tr>
<tr>
<td>Cross-talk</td>
<td>5.7±0.2 %</td>
<td>0.6 %</td>
</tr>
</tbody>
</table>
Cross-talk with optical microscopy

- Scaling does not fit simple photon induced cross-talk model well
  - 5-5 cross-talk too large compared to 1-5
- Could cross-talk be induced by charge diffusion?
  - Longer range than photons

Positions illuminated
Beam spot width = 5 μm
(Pixel pitch = 50 μm)

Possible range of x-talk inducing photons

A. Vacheret (Imperial College)
Cross-talk probability within a pixel

- Clear dependence on position
  - Point against the detector side generate less cross-talk
  - Measurement somewhat limited by statistical and systematic errors

A. Vacheret (Imperial College)
Adding after-pulsing and cross-talk to the simulations

Use the measured after-pulsing and cross-talk parameters

Over-voltage = 1.7V

- Dark noise
- Photon-detection efficiency
- Electronics noise
- Gain fluctuations

- Add cross-talk and after-pulsing

T. Lindner, Scott Oser (U. of British Columbia), FR
A peculiar feature to finish up

- Fire 405 nm laser with low light level
- Find individual pulse
- Plot the distribution of pulse arrival time
- Fit the mirrored fiber distribution by a sum of blackened fiber responses

![Graph showing reflectivity comparison]

**Reflectivity**

- Reflectivity\(_{\text{MPPC}} = 0.3 \pm 0.15 \) !!
- Reflectivity\(_{\text{Mirror}} = 0.8 \pm 0.15 \)
Summary

- Cross-talk and after-pulsing have been measured with good precision
  - Cross-talk model needs to be clarified
- MPPC response is overall well understood and simulated
- Surprising MPPC reflectivity

Next step
- Finalize cross-talk parameterization
- Investigate response to large amount of light
  - Complicated by dynamic range issue
  - See A. Vacheret’s poster
- Investigate response with T2K electronics
  - Slow digitizer
  - Integrator + discriminator
- Take neutrino data in 2009!
The end
After-pulsing fit formulas

\[ P_{AP}(t) = \sum_{i=1}^{\infty} \frac{\lambda^i}{i!} e^{-\lambda i} e^{-t i / \tau} \quad \text{and} \quad P_{DN}(t) = R \cdot e^{-R t} \]

Sum over i avalanches
\( \lambda \): average number of AP/avalanche
\( \tau \): AP time constant

\[ P(t) = \int_0^t [1 - P_{AP}(x)] dx \cdot P_{DN}(t) + \int_0^t [1 - P_{DN}(x)] dx \cdot P_{AP}(t) \]

Combining Dark Noise with 1 exponential AP

R: Dark noise rate
MPPC to MPPC variation at room temperature

Large for dark noise, limited for other parameters
Dark Noise is the only parameter strongly sensitive to temperature

At constant over-voltage

Very strong effect of temperature on Dark noise
Not so significant for after-pulsing
Null for cross-talk
Fiber characterization test setup

- Pulser
- Bias
- 1 nF
- 1 pF
- 100 kΩ
- Light tight box
- 1 GHz waveform digitizer
- 405 nm laser diode
Experimental set up

- **Light source**
  - $\lambda = 463 \text{ nm}$, pulse FWHM 1 ns

- **Microscope**
  - Narrow beam spot: $\sigma = 5 \mu m$

- **Micro-metric X-Y linear stages**
  - Beam positioning 0.5 $\mu m$ resolution

- **Fast low noise pre-amplifier**
- **Ghz waveform digitiser**
  - 1 $\mu s$ samples
  - 1 ns resolution
Beam spatial resolution

1-D scan over a few pixels to measure beam width: $\sigma \sim 5 \mu m$

~64%
Avalanche model

• Avalanche mechanism well studied and modelled in single pixel device (A. Spinelli and A. Lacaita IEEE TED 1997).
  - Avalanche starts from seed point where photon is absorbed and develops across the junction in well confined region. Then laterally expands by carrier diffusion.
  - 2 mechanisms: multiplication assisted and spreading assisted by secondary photons emitted by hot carriers.