Novel scintillation detectors for $\mu$SR-spectrometers

A. Stoykov       R. Scheuermann

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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>SiPM</td>
<td>Silicon PhotoMultiplier</td>
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<tr>
<td>AMPD (MAPD)</td>
<td>Avalanche Microchannel / Micropixel PhotoDiode</td>
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<tr>
<td>MRS APD</td>
<td>Metal-Resistive layer-Silicon Avalanche PhotoDiode</td>
</tr>
<tr>
<td>SSPM</td>
<td>Solid State PhotoMultiplier</td>
</tr>
<tr>
<td>MPPC</td>
<td>Multi-Pixel Photon Counter</td>
</tr>
<tr>
<td>G-APD</td>
<td>multi-pixel Geiger-mode Avalanche PhotoDiode</td>
</tr>
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</table>
**G-APD: principle of operation**

MRS APD  
[A. Akimov, Beaune05]

Signals from the breakdown of single cells:

**AMPD MW-3 (1x1 mm²)**  
(amplifier: gain ~ 80, bw ~ 600 MHz)

\[
Q_i = C_i \cdot (U - U_0)
\]

\[
M = \frac{Q_i}{e}
\]

\[
Q = \sum Q_i
\]

Crosstalk = 7.7 %
**G-APD: parameters**

- **Active area** (typ. 1 mm$^2$, max. 25 mm$^2$)
- **Number of cells → Dynamic range** (100 – 10000 mm$^{-2}$)
- **Photon Detection Efficiency:** $PDE (\lambda, U) = QE (\lambda) \cdot \varepsilon \cdot w (U)$
  
  $QE$ – quantum efficiency, $\varepsilon$ – geometric fill factor, $w$ – avalanche probability
- **Gain:** $M$ ($10^4$ – $10^7$)
- **Excess noise factor:** $F = 1 + \sigma^2 (M) / <M>^2$
- **Inter-pixel cross-talk:** $\alpha (M)$
- **Operating voltage:** $U$ (typ. 15 V – 150 V)
- **Dark current:** $I_0 (T, U)$ (typ. 10 nA – 100 µA, at RT)
- **Dark counts:** $N_0 (T, U)$ (typ. 0.1 – 10 MHz, at RT)
- **Cell recovery time** (typ. 0.1 – 10 µs)
- **Temperature coefficient of gain:** $(\Delta M / M) / T$ (typ. 0.2 – 5 %/C)
G-APD vs. PMT

**Advantages:**
- insensitive to magnetic fields;
- compact, robust;
- low operation voltage

compact, finely segmented detectors and detectors to be used in a high magnetic field environment

**Disadvantages:**
- small active area

cover larger area → G-APD arrays
A brilliant example of APD application

C. Woody et al., NIM A 571(2007) 14,

*Initial studies using the RatCAP conscious animal PET tomograph*

The RatCAP tomograph consisting of 12 LSO arrays with APDs and associated readout electronics

Awake rat wearing the RatCAP that is supported by the tether and mechanical counterbalance system
The 10 T High Field Project at the Swiss Muon Source at PSI

http://lmu.web.psi.ch/facilities/PSI-HiFi.html

main challenges: custom designed magnet (min. length) and fast & compact detector system

Larmor frequency: 1.35 GHz in 10 T

Muon + positron counter
\( \delta t < 300 \text{ ps (FWHM)} \)
\( \sigma < 125 \text{ ps} \)

Per counter
\( \sigma < 90 \text{ ps} \)
Development of fast timing detectors for the HF-spectrometer:
• research in the field of G-APD based detectors
• experience in the detector design for high fields

Detector development for ALC, understanding and optimization of its performance:
1. position sensitive detector to study the muon beam dynamics in high fields;
2. upgrade of the ALC detector system.
Muon Beam Profile Monitor (BPM)
for ALC instrument (28 MeV/c muon beam, up to 5 T field)

August 2004

10 x-, 10 y-channels, fibers Ø 1mm, spacing 10 mm

Preamplifier
bandwidth ~250 MHz
gain ~250

AMPD Dubna R8
active area:
0.75 x 0.75 mm

Scint. fibers
(POLIFI 0244-10)

Aluminum Frame
(100 x 100 mm)

Mother Board

no collimators,
beam window 70 mm diam.
The impact of the BPM:

- the profile of the muon beam in the center of the 5 Tesla solenoid of ALC was measured as a function of $H$;
- stimulated Monte-Carlo simulations (by T. Lancaster) on the muon beam dynamics in high fields;
- muon beam dynamics in high magnetic fields is understood.

3 years of operation:

- no change in the performance;
- being used for setup of ALC and DOLLY.

Perspectives:

- real two-dimensional mode of operation;
- detection of minimum ionizing particles.
A compact high time resolution detector (concept)

Connection of G-APDs into array:

- DC – parallel, AC – parallel
- DC – series, AC – series
- DC – parallel, AC – series

[ Y. Benhammou et al., CMS TN / 95-122 ]

10 x 10 mm² active area detector based on 1 x 1 mm² AMPDs: AMPDs are connected to a common load.
Array $4 \times MW-3 + 10 \times 10 \times 2$ mm$^3$ BC-422, MIP

Averaged waveform

Time resolution (telescope 2x)

Amplitude spectrum

1 detector: $\sigma \approx 108$ ps
Array $4 \times MW-3 + 10\times10\times2$ mm$^3$ scintillator, MIP

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>$\lambda_{\text{max}}$ nm</th>
<th>light yield photons/MeV</th>
<th>$A / A_{BC-404}$</th>
<th>rise time ns</th>
<th>fall time ns</th>
<th>time res. $\sigma$ ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCF-20</td>
<td>492</td>
<td>8000</td>
<td>0.79</td>
<td>2.10</td>
<td>11.2</td>
<td>209</td>
</tr>
<tr>
<td>BC-400</td>
<td>423</td>
<td>10000</td>
<td>0.76</td>
<td>1.50</td>
<td>8.3</td>
<td>160</td>
</tr>
<tr>
<td>BC-404</td>
<td>408</td>
<td>10400</td>
<td>1.00</td>
<td>1.42</td>
<td>7.0</td>
<td>127</td>
</tr>
<tr>
<td>BC-418</td>
<td>391</td>
<td>10200</td>
<td>0.70</td>
<td>1.24</td>
<td>6.5</td>
<td>124</td>
</tr>
<tr>
<td>BC-422</td>
<td>370</td>
<td>8400</td>
<td>0.70</td>
<td>1.00</td>
<td>6.6</td>
<td>108</td>
</tr>
</tbody>
</table>

The time resolution improves towards the fastest UV scintillators (even at some expense of the signal amplitude).
**Perspectives:** new larger area UV-sensitive G-APDs

1: **AMPD**  n-INT-1e  
   1.8 x 1.8 mm²  

2: **SSPM**  0609B4  
   2.1 x 2.1 mm²  

3: **MPPC**  PSI-33-050C  
   3 x 3 mm²

**Waveforms (MIP)**

- **AMPD**: $\sigma = 122 \pm 1$ ps  
  $U = 90.2$V, $I = 107$ µA

- **SSPM**: $\sigma = 124 \pm 1$ ps  
  $U = 32.30$V, $I = 40$ µA

- **MPPC**: $\sigma = 77 \pm 1$ ps  
  $U = 70.3$V, $I = 3.4$ µA

**Time resolution** (1x vs. ref.)  
ref. det.: $\sigma \approx 50$ ps

- **AMPD**: $\sigma = 122 \pm 1$ ps
- **SSPM**: $\sigma = 124 \pm 1$ ps
- **MPPC**: $\sigma = 77 \pm 1$ ps

**Perspectives**: new larger area UV-sensitive G-APDs

**1**  
**BC-418 10x10x2 mm**

**2**  
**BC-418 Ø8x5 mm**  
+ **PMT R5505-70**  
$\sigma \approx 50$ ps

**3**  
**90Sr**

* PDE (%) at 400 nm (producer’s data).
SSPM 0609B4 (custom designed package)
Photonique SA : www.photonique.ch

Waveforms (MIP) trigger -- PMT

Time resolution SSPM array + PMT

σ = 77 ± 1 ps

σ (corrected) ≈ 60 ps

R_{bus} = 1K
C_{in} = 5pF
R_{all} = 50Ω
Detector for the HF-spectrometer: current status

1. G-APDs comparable with PMTs in performance already exist.

2. The required time resolution (< 90 ps) is achieved for a G-APD based positron detector (on table).

Real conditions → problems to study and solve:

- light losses in the light guides (limited space and cryogenic environment);
- additional light losses for the muon counter (200 µm thick scintillator).

The light collection ($CE$) from a 200 µm thick (10x10 mm$^2$) plastic scintillator: [V.V.Zhuk et al., PSI TM-35-05-01 (2005) 1-7].

$CE$ strongly depends on the scintillator quality:
- maximum $CE$ achieved on test samples – 20%;
- maximum possible $CE$ (Monte-Carlo simulations) – 45%.
Detector for the 10 T μSR-spectrometer:

• area: \(\leq 1 \text{ cm}^2\)
• time resolution: \(\sigma < 90 \text{ ps}\)

Detectors for “standard” μSR-spectrometers:

• area: \(10 - 100 \text{ cm}^2\)
• time resolution: \(\sigma \leq 1 \text{ ns}\)
**A tile-fiber detector with AMPD readout**

BC-404 (80×40×5 mm$^3$), wrapped in Teflon tape

WLSF BCF-92 (Ø 1mm)

4x (1x1 mm$^2$) AMPD array

**Goal – MIP detection with:**

- 100% efficiency
- time resolution $\leq$ 1 ns
scintillator tile: 80×40×5 mm³ wrapped in diffuse reflector absorption length 1.4 m
light source: 5 mm long e⁻ track
fiber: 1×1 mm² multiclad, glued into the grooves

MC simulations by V. Zhuk
code: V.A. Baranov et al., NIM A 374 (1996) 335

Light Collection Efficiency (%)

Reflective index of wrapper = 0.9

non-uniformity: < 5%
MC results

Photon lifetime in the scintillator < 1 ns
MIP (e⁻) from $^{90}\text{Sr}$

- detection efficiency $\approx 100\%$
- time resolution $< 350\text{ ps}$

Uniformity:
- signal amplitude variation $< 5\%$
- detection time variation $< 100\text{ ps}$

Time resolution (ref. det.: $\sigma \approx 50\text{ ps}$)

- $\sigma = 314 \pm 4\text{ ps}$
ALC spectrometer in $\pi E3$
ALC spectrometer

J.W. Schneider
PhD Univ. Zurich 1989

Time-integral mode:
\[ A(H) = \frac{(B - F)}{(B + F)} \]

\( B, F \) – BW and FW integral counts;
\( A \) – asymmetry.

\( H_0 \) – resonant loss of integral muon spin polarization

\( B_0 = B - \Delta B \quad F_0 = F + \Delta F \)

\( A_0 = A - \Delta A \)

Field dependence of \( B \) and \( F \) not related to the resonance conditions:

- variation of the PMT gain;
- muon beam spot movement and oscillations (studied by BPM);
- variation of the counters solid angle due to the altered positron trajectories →

Flexibility in the detector design → G-APD based detector technology

Æ to study (and possibly improve): a versatile detector system is needed !!!
Prototype of the new ALC detector

... design
... implementation

BW ring

FW ring, sample

“BW collimator”
Detector module
... design

Support plate
MSR 20.04.101

Front bar
MSR 20.04.103

Scintillator tile
MSR 20.04.106

Middle bar
MSR 20.04.105

Optical connector 11
MSR 20.04.107

Optical connector 12
MSR 20.04.108

G-APD

Amplifier

Rear bar
MSR 20.04.104

Lid
MSR 20.04.102
…implementation

EJ-204A (120 x 20 x 5 mm³)

BCF-92

SSPM_0701BG

Amplifier: gain ~ 20, bw ~ 100 MHz
Response to MIPs, rate capabilities
(measured with 28 MeV/c beam positrons)

Depend on: 1) recovery time a single G-APD cell;
2) number of cells in the G-APD (576);
3) signal amplitude (~100 phe).

$d5: N_e = 2.3 \times 10^3 \text{ s}^{-1}, \quad I = 4.0 \mu A$

$d5: N_e = 1.3 \times 10^5 \text{ s}^{-1}, \quad I = 6.2 \mu A$

$d5 (1 \text{ fiber } + 1 \text{ SSPM}) \quad d3 (2 \text{ fibers } + 2 \text{ SSPMs})$
Gain vs. magnetic field

G-APD + amplifier gain -- 1e- signals

$H = 0 \text{ T}$

$H = 4.8 \text{ T}$

$d5$: 1 x SSPM, 20.0V, 3.8µA

$<10\%$ change of the detector gain at $H = 4.8 \text{ T}$ is determined by the amplifier

[NIM A 567 (2006) 246]
Performance stability and reproducibility of the data

PEA/Water with “BW collimator”

5 scans, ~12 hours
Summary (new detector for ALC)

1. A prototype of the new ALC detector consisting of 6 detector modules with G-APD readout was built and tested under the real experimental conditions.

The G-APD based detector module shows performance satisfying the requirements to the ALC detector in terms of:

-- signal-to-noise ratio;
-- operation in high magnetic fields;
-- rate capabilities;
-- stability of the response vs. temperature variations;
-- long term stability and reliability.

2. The effect of the magnetic field on the ALC spectra (dependent on the geometry of the detector) is almost understood thanks to GEANT-4 simulations by T. Shiroka and K. Sedlak.
From the prototype to the new ALC detector:

1. GEANT-4 simulations to find an optimal detector geometry (two rings: diameter, length, gap between the rings) – July 2007;

2. Detector design – August 2007;

3. Production of the components and assembly of the detector modules – December 2007 – April 2008;


Summary (G-APD based detectors)

The novel G-APD based technology allows building a wide spectrum of scintillation detectors comparable in performance with the ones based on PMTs.

The main advantages of the G-APD vs. PMT based detectors are:

- compact size and higher flexibility in the detector design;
- operation in magnetic fields;
- low operation voltage.
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NMI3 – Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy, Joint Research Activity (JRA8): MUON-S

Ultrafast position-sensitive detectors on the basis of new avalanche micropixel photodiodes with single photon detection efficiency and with high amplitude resolution for visible and UV light

Project leader: Dr. D. Renker
AMPD :  Z. Sadygov (JINR)

SSPM :  D. McNally (Photonique SA)

MPPC (prototypes, Hamamatsu) :  D. Renker (PSI)

Consultations on G-APDs:  D. Renker,  
Yu. Musienko (CERN)

DAQ:  T. Prokscha,  K. Gritsay (JINR)

Electronics:  Ch. Buehler,  U. Greuter

Detector development & Measurements:  V. Zhuk (JINR)

Measurements:  A. Werner (PSI, summer student – March 2006)

Mechanical work:  M. Elender,  R. Venturi

Simulations of the new ALC detector:  T. Shiroka  
K. Sedlak
**Publications:**


**PSI Technical Reports:**

