Detector R&D for g-2

David Hertzog*
University of Washington

- Context: The new Muon g-2 Experiment
  - What you need to know
- Lead Fluoride Crystals
- Silicon Photo-Multipliers
- SLAC Test Beam

*Team: UW group: P. Alonzi, A. Fienberg, P. Kammel, J. Kaspar, M. Smith, T. VanWechel, K. Wall, B. Kiburg (now FNAL); P. Winter (now ANL); and K. Yai (Osaka);
CONTEXT

Some things you need to know to follow this talk better
The statistically limited g-2 measurement is $3.6\sigma$ from the Standard Model. Now what?

“Do the measurement better …”

need More Muons
need Reduced Systematics
Implications for detectors

$$\omega_a = \frac{q}{m} a_\mu B$$

Momentum
Spin

Old Calorimeter

Counts per 15 ns

E989 completed CD-1; 38 Institutions, > 150 members; Start end of 2016
How is data obtained?

1. Bunch of $\mu^+$ (up to 10,000) injected into the storage ring
   - Muon lifetime: $\gamma \tau = 64 \, \mu s$
   - Decay $e^+$ range: $0 – 3.1 \, \text{GeV}$
   - Strike one of the 24 calorimeters

2. Observe events for $\sim 700 \, \mu s$
   - Record continuous waveforms
     - 12-bit resolution @ 500 MHz
     - 1296 channels $\rightarrow$ 680 MB per fill
   - Transfer, sort, pulse-find, pre-analyze during time between fills
   - Repeat sequence at 12 Hz
     - 8.1 GB/s transferred to GPU farm*
   - Run continuously for more than a year
   - Vary conditions for systematics

*not counting calibration, straw chambers, etc.
24 “finite” detector stations define acceptance

“Michel” spectrum, all decays

R(E) oscillates with g-2 and falls by decay

Various energy cuts

Geant simulation from E821

Strikes Calo

Actual Measure

Muon Central Orbit

High energy, strike calos

Low energy, mostly miss
What you “want” is different from what you get

- **Desire:** Electrons with $E > 1.8 \text{ GeV}$ (12%)
- **You get:** Everything that hits detectors
  - Modulated by $g-2$: 4.3 $\mu$s period; Amp is $A(E)$
  - Modulated by Fast Rotation of incoming beam bunch

High rate exacerbates pileup & gain stability issues

149 ns cyclotron frequency exaggerates actual rate on detectors

Pileup scales at $(R_{\text{wiggle}+FR})^2 \Delta t$, where $\Delta t$ is the resolving time. For $\Delta t = 6 \text{ ns}$, we can expect an unresolved pileup fraction after 30 $\mu$s when physics fit starts of ~0.9%

>2 MHz per calo minimal

Note: Rates are estimated, but could be much higher as FNAL is working on injection efficiency improvements.
What drives the detector choice?

- **Compact** based on fixed space
- **Non-magnetic** to avoid field perturbations
- **Resolution** not too critical for $\delta \omega_a$
  - Useful for pileup, gain monitoring, shower partitioning and low thresholds
- **Gain stability** depends on electronics and calibration system
- **Pileup** depends on signal speed and shower separation
  - Subdivide calorimeter

![Diagram of calorimeter with Moliere-R](image)

For 1.6 GeV cut, resolution hardly matters for best $\delta \omega/\omega$
Pileup for g-2 is special

- 2 low-energy electrons can look like 1 (good) high-energy electron
- Avg. spin direction of Blue ahead of Red
- Probability of these has $e^{-2t/\tau}$ dependence
  - early to late change systematic

- Waveform digitization: essential
- Fast pulses: essential
- Controllable tails: essential

We can separate down to about 5 ns
Choice of Calorimeter
We considered these three materials:
All are dense and non-magnetic and relatively “fast”

<table>
<thead>
<tr>
<th>Material</th>
<th>PbF2</th>
<th>PbWO4 (undoped)</th>
<th>W / SciFi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Cerenkov crystal</td>
<td>Cerenkov &amp; Scintillation crystal</td>
<td>Sampling / scintillating fibers</td>
</tr>
<tr>
<td>Radiation length</td>
<td>0.93 cm</td>
<td>0.89 cm</td>
<td>0.69 cm</td>
</tr>
<tr>
<td>Moliere radius</td>
<td>1.8 cm (Cerenkov)</td>
<td>2.0 cm</td>
<td>1.73 cm</td>
</tr>
<tr>
<td>Typical resolution @ 2 GeV</td>
<td>&lt; 3 %</td>
<td>2 %</td>
<td>10 %</td>
</tr>
</tbody>
</table>

![Image of PbF2 crystal and scintillating fibers]

PbF$_2$ (3 x 3 x 14 cm)
Our first PbF$_2$ prototype array was tested with various wrappings, couplings, and readout at FNAL.
Pulse Shapes vs. Wrappings

<table>
<thead>
<tr>
<th>Element</th>
<th>Ends</th>
<th>Jacket</th>
<th>Crystal</th>
<th>FWHM (ns)</th>
<th>FW20% (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR</td>
<td>Black</td>
<td>Black</td>
<td>PbF2</td>
<td>8.0</td>
<td>13.6</td>
</tr>
<tr>
<td>ML</td>
<td>Black</td>
<td>White</td>
<td>PbF2</td>
<td>12.4</td>
<td>22.4</td>
</tr>
<tr>
<td>MC</td>
<td>White</td>
<td>White</td>
<td>PbF2</td>
<td>8.8</td>
<td>20.4</td>
</tr>
<tr>
<td>MR</td>
<td>Al</td>
<td>Aluminum</td>
<td>PbF2</td>
<td>10.0</td>
<td>17.2</td>
</tr>
<tr>
<td>TR</td>
<td>White</td>
<td>White</td>
<td>PbWO4</td>
<td>15.2</td>
<td>29.2</td>
</tr>
</tbody>
</table>
Ocean Optics spectrometer used to measure transmission vs. wavelength
Moliere Radius / Energy Sharing
GEANT Simulation vs Measurement in Test Beam

Black points are scaled test beam data.

Center crystal
Crystal on side

Simulation Energy Deposition (GeV)

Binned beam impact points compared to continuous simulation
A 6 x 9 Array will be built for each of the 24 Calorimeter stations. Typical shower sizes and cluster separations, but TIMING (two-pulse resolution will be critical) Relatively Easy with a good algorithm

Some pileup events will not resolve by space
Silicon Photo-Multipliers

MPPCs
G-APDs
...

vs. PMTs
Comparing SiPMs to fast PMTs. Can the former replace the latter?

Hamamatsu R9800 PMT

Hamamatsu 16 channel SiPM

... and electronics for SiPM
Why we’d like to use SiPMs if we can

• Can work in 1.45 T field
  – Mount on board; **NO lightguides**
• Non-magnetic
• Lower cost

Crystal : SiPM size comparison. ~ 4:1 Is it enough ?
Our (working) Design Choice is this 12 x 12 mm² 16-channel SiPM from Hamamatsu

16 of these per unit

57600 individual photon detectors!

(Geiger mode avalanche photodiodes)
Because the larger SiPMs are still small compared to the crystal, light yield is a big issue.
Convert to photon yield and to SiPM expectation (will return to this again for SiPM)

- Low light level calibration with laser turned down

- Energy loss \[ \Delta E = 26.8 - 32.17 [\text{MeV}] \]

- Photons produced
  - Black Wrapping: \( \sim 24 \pm 4 \)
  - White Wrapping: \( \sim 55 \pm 6 \)

This will lead to an important test at SLAC
Many vendors …

- We are also evaluating SiPMs from all major vendors
SiPMs Require Custom Summing Board that affect the pulse shape

<table>
<thead>
<tr>
<th>board</th>
<th>chann</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2x2</td>
<td>4 individually readout voltage amplifiers with trim pots for individual bias voltage change</td>
</tr>
<tr>
<td>B</td>
<td>2x2</td>
<td>no trim pots, voltage op amp with small load resistor.</td>
</tr>
<tr>
<td>C</td>
<td>2x2</td>
<td>all channels are summed first via a 2.5 Ohm load resistor and then amplified in two stages</td>
</tr>
<tr>
<td>D</td>
<td>4x4</td>
<td>First 16 ch board. 1 amp per 2 channels</td>
</tr>
<tr>
<td>E</td>
<td>4x4</td>
<td>Amp for each channel</td>
</tr>
<tr>
<td>F</td>
<td>4x4</td>
<td>Transimpedance amp (was ringing)</td>
</tr>
<tr>
<td>G</td>
<td>4x4</td>
<td>Individual shunt resistors and passive adding network with 2 gain stages; voltage amplifier</td>
</tr>
<tr>
<td>F</td>
<td>4x4</td>
<td>G board modified for current amplifier; This board has passed many requirements tests</td>
</tr>
</tbody>
</table>
Gain is highly sensitive to Over-voltage Bias or Temperature

\[ \frac{dG}{dmV} \bigg|_{72.5} = 0.12\% \]

Essentially the same effect.

The breakdown voltage of the diode is temperature dependent

Gain with and without fan

\[ y = 0.2561x \]

Factor of 4 change!
Evaluation tools: Test Setup at UW

- DRS 4, PSI
  - Bandwidth of 950 MHz
  - Sampling frequency from 0.7 to 5 GSPS

- DRS 5 GSPS, 4-ch Digitizer

- 407 nm PicoQuant Laser

- 1:12 E821 Optical Splitter

- USB-driven Neutral Density Filter wheel for remote intensity variation
SiPMs require custom-made amplifiers and summing circuits. Pulse shapes affected (significant ongoing effort to preserve intrinsic pulse shape
SiPM: 3x3 mm - 25µm
R_q = 24 Ω
τ = 10 ns

This is really good !!!

SiPM: 3x3 mm - 25µm
R_q = 24 Ω
τ = 10 ns

Electron PMT
29 mm

25 µm pitch

But, these are too small to be useful

R9800 PMT
τ = 3.6 ns

40 ns
SiPM: 3x3 mm - 50 μm

Electron PMT 29 mm

Better PDE, but slower response

R9800 PMT
τ = 3.6 ns

50 μm pitch
- Worse with 16 channels summed.
- Must minimize inductances and capacitances
- Must get lower average Quench Resistors on arrays

\[ \tau = 50 \text{ ns} \]

Surface mount

100 ns/div scale!
2-pulse resolution

An example lab / simulation study
Two – pulse separation studies using real pulse shape templates and Monte Carlo
A realistic example with $\Delta t = 6 \text{ ns}$

Actual SiPM waveforms at 500 MHz sampling
SiPM pulses are resolved for $\Delta t \sim 3.5 \text{ ns}$
In the lab

• 407nm, ~100 ps long laser pulse split into two channels: E1 & E2
• E2 delayed by optical fibers [0 – 60 ns]
• Each pulse digitized at 2.7 GS/s, independently and together
• SiPM coupled to PbF2 crystal to ensure uniform illumination
For two events close in time in the same SiPM, how is the gain of the second pulse affected? 

RED = hardware sum of pulse 1 and 2
BLUE = software sum of pulse 1 and 2

Reduction of second pulse for hardware sum
Map the response of the second pulse so it can be corrected if needed.

**Function:** \( G_2(E_1, E_2, \Delta t) \)
- \( G_2 \) is the gain and time of the second pulse
- \( E_i \) is the energy of the \( i \)th pulse
- \( \Delta t \) is the time separation

**Pulse fitter model: single pulse**
- Gaussian for laser pulse
- Exponential rise time for avalanche discharge
- Exponential decay time for SiPM recovery

**Pulse fitter model: pileup**
- Same laser pulse parameters
- Same rise and decay times
- Time delay
Energy and Time Resolution of Pulses

- Typical data set: 4000 fit results for energy and time of second pulse
- Time and energy resolution are very good even for low gain

\[ \sigma = 110 \text{ ps} \]

\[ \sigma = 7.4\% \]
Pulse recovery depends on pulse size:
(missing amplitude is proportional to the amplitude)

Consistent with a drop in the over-voltage
Drop in 2\textsuperscript{nd} pulse vs. time for 3 different 2\textsuperscript{nd} pulse energies vs time $\Delta t$

Consistent with a fixed 20 mV drop in all 3 cases

These studies are continuing
Preliminary Results from SLAC test beam

5 Hz, pure $e^-$ in range 2.5 – 4 GeV (for us)

Prepared by Jarek Kaspar
An array of 9 crystals

5 older 3x3 cm$^2$ and 4 newer 2.5x2.5 cm$^2$

5 PMTs and 4 SiPMs
Add SiPMs
Stabilized temperature

dried air nozzle to SiPMs
45 CFPH, 0 deg C
Temperature sensor

ADT7420
0.25 deg C accurate
0.0078 deg C resolution
3x3 mm, I2C (LabJack)
(batteries included)
5 inside, 1 ambient
Bias control

BK precision 9124
0—73 V
1 mV step
floating on 5 V
USB controlled
Laser Calibration

number of photons equivalent to 0.5 — 4.0 GeV
Using the mean and standard deviation of distribution

- Assume all variance comes from Gaussian photostatistics
- Relation: \[ \mu = \sigma^2 \implies \sigma_{\text{mean}} = \sqrt{\frac{\mu}{N}} \]
- Calibrate as a linear fit of \( \mu \text{ vs. } \frac{\mu^2}{\sigma^2} (= N_p e) \)
- Gives a lower limit since not all noise is photostatistics

Worked well for PMT

Has been trickier for SiPM (a good one)
Calibrating the Gain in terms of Fired Pixels vs pulse amplitude (or area)

\[
N_{pe} = \frac{M^2}{\sigma_{pe}^2} \quad \text{\(\Rightarrow\)} \quad aM = \frac{M^2}{\sigma_{obs}^2 - \sigma_{noise}^2} \quad \text{\(\Rightarrow\)} \quad a(\sigma_{obs}^2 - \sigma_{noise}^2) = M
\]

\[
N_{pe} = \frac{M^2}{\sigma_{pe}^2} \quad \Rightarrow \quad aM = \frac{M^2}{\sigma_{obs}^2 - \sigma_{noise}^2} \quad \Rightarrow \quad a(\sigma_{obs}^2 - \sigma_{noise}^2) = M
\]
Note: In principle, one can also use the pixel saturation of the SiPM

• As $N_{pe} \rightarrow N_{\text{pixels}}$, the probability of multiple photons hitting a single pixel is non-negligible

• The relation is given by:

$$N_{\text{pixels, fired}} = N_{\text{pixels}} (1 - \exp(-N_{pe}/N_{\text{pixels}}))$$
SLAC beam

Beam exiting vacuum chamber is small

Beam hitting detector (Al windows, 6 m air) grows

Width RMS 0.3 mm

Width RMS 0.3 mm

Width RMS ~12 mm

Width RMS ~15 mm
SLAC beam

single particle Poisson distribution
2.5, 3, 3.5, 4 GeV
Intrinsic Pulses

pole zero correction, laser shot, 2 GeV, ~2000 pe

Struck

DRS: ~2 nsec FWHM

No pole zero correction, 2 GeV, ~2000 pe

laser

beam: ~7 nsec wider
First light
Calibrate each block one by one

- First find Calibration constants for each detector at their center
- Cut on 1 electron and avoid events that smear into other blocks
Position Scan

Horizontal Scan Run 977

Crystal 5

mean 5

174.9

Crystal 4

mean 4

199.1

table position X (mm)
Position Scan

[Graph showing data points and curves for Crystal 2, Crystal 5, and Crystal 8, with annotations and measurements.]

Table Y position (mm) vs. Entry$\times 3017.\times(60.) + 109.$ (mm)
Our laser calibrations are now working well and we find the “expected” light yield from our detectors (this has been a big worry)

Corresponds to a light yield above 1000 pe/GeV (as we had hoped)

\[
\text{Slope} = \frac{\text{pe}}{\text{pulse area}}
\]

\[
\begin{array}{|c|c|}
\hline
\chi^2 / \text{ndf} & 4.459e+04 / 4 \\
p_0 & -1060 \pm 62.08 \\
p_1 & 0.4243 \pm 0.005031 \\
\hline
\end{array}
\]
Energy Linearity

It is a calorimeter.
Energy sum for array

\( \sum \) for array

\[ 3.5 \text{ GeV} \quad (0.75 \times 3.5) \]

- \( \chi^2 / \text{ndf} = 38.65 / 32 \)
- Constant: \( 103.1 \pm 2.7 \)
- Mean: \( 1.284 \pm 0.001 \)
- Sigma: \( 0.04478 \pm 0.00122 \)
Grand sum, using combination of Monte Carlo study of shower containment and calibration constants

Centered on the array

On a crack between blocks

Centered on the array

Run 1087
Runs at 10 deg.

center of crystal

crack between crystals
Conclusions

PbF2 works as calorimeter

Good energy resolution

(Good timing resolution)

SiPMs work for readout
Summary

• High-intensity experiments have complex implications on detector design
  – Optimization is multi-faceted

• PbF2 Cherenkov crystals are fast and dense

• SiPMs are wave of future
  – Can live in high magnetic fields
  – Are quite cost effective compared to PMTs
  – But have lots of growing pains to resolve

• Situation evolving fast
Prompt Flash Studies
E821 Delayed Flash Shifted Baseline during Fill

Prompt Flash was avoided by blanking off PMT gains

Gating for 5 to 15 $\mu$s; Recovery in 1 $\mu$s

Baseline shift caused by thermal neutron capture in scintillating fibers

Question: Can we survive the Prompt Flash without blanking circuits?

Estimate: 90% of $\sim$50,000 m+ don’t store $\rightarrow$ If 10% hit some unlucky crystal, that will more than saturate all pixels of the SiPM. How fast can we recover?
Setup: Prompt Flash $\rightarrow$ LED
Decay Positron $\rightarrow$ Laser
Logic: Compare laser with and without preceding LED “FLASH”

Event Trigger ≈100Hz

Gate Delay Generator

Laser Trigger

LED Trigger

Adjust trigger width for size of flash in pixels

Delay controls timing between LED and Laser ≈ 1 μs at right

SiPM Response

SiPM-v2: Expected Photons From LED

$f(x) = 58,226.31x - 535,592.64$

Expected detected per from LED

Flash width (ns)

1 μs
First attempt: Miserable failure (ugh)

Unacceptable gain sag at 100 μs

Red and Blue are two different devices with same SiPM board
Modifications to SiPM Board Schematic and Bias Supply Input

CHANGE 1: Addition of Capacitor

CHANGE 2: R2 swapped 10kΩ → 10Ω
Current Results are Promising
(will be repeated for next generation boards)

- \(\approx 100\%\) recovery by 15 μs
Electronics

NIM trigger logic
  > trigger on beam or “on light”
  > scint. paddles online
  > beam finder offline (SiPM/scint)
  > remote switch/delay control

SiPMs
  > pole zero network (opt)

PMTs
  > T-bridge (impedance match, opt)

Digitizers
  > SiPMs, PMTs
  > scint. paddles, beam finders
Scintillator paddles

2 paddles in coincidence
trigger “on light”
data quality flag

moveable beam finder (remote)
Digitizers

Struck SIS 3350
  > Pipelined Flash ADC
  > 500 MSps, 12 bit, 4 ch

PSI DRS4
  > Capacitor Array (1024, 5GHz, 8ch)
  > then ADC (33 MSps, 16bit)
Light Yield

1.0 pe/MeV