Data Acquisition for the New Muon $g$-2 Experiment at Fermilab

Wesley Gohn

University of Kentucky

April 13, 2015
Outline

1. Introduction
   - Physics of Muon g-2
   - Project Status
   - Detectors and Backend Electronics

2. Data Acquisition System
   - System Requirements
   - GPU Processing
   - Prototyping

3. Conclusion
In the standard model, the muon is a spin 1/2 pointlike particle.

It has a magnetic dipole moment of $\vec{\mu} = g \frac{q}{2m} \vec{s}$, with $g = 2$ for a pointlike particle (Dirac).

Additional effects from QED, electroweak theory, and hadronic factors move the standard model prediction of $g$ away from 2. It has become customary to measure this discrepancy, $g-2$.

If a discrepancy with the standard model value is found, beyond standard model contributions to $g-2$ could come from SUSY, dark photons, or other new physics (NP).
Measurements of $g$-2

- BNL E821 measured $g$-2 to have a 3.3σ discrepancy from the standard model (2006).
- Fermilab E989 will measure 20 times the number of muons, reducing the uncertainty on this measurement by a factor of 4.
- Without theory improvements, discrepancy could reach $> 5σ$.

\[ a_\mu \equiv \frac{g-2}{2} \]

\[ \vec{\omega}_a = -\frac{Q_e}{m} [a_\mu \vec{B} - (a_\mu - \left( \frac{mc}{p} \right)^2) \vec{\beta} \times \vec{E} ] \]
The ring was moved from BNL to FNAL in 2013.

It has been installed in our new MC1 building and is currently being cooled.

Plan for data taking to begin in early 2017.
Measurement will utilize 24 calorimeters (each composed of 54 PbF$_2$ crystals read out by SiPMs), 3 straw trackers, and several auxiliary detectors.

Each calorimeter will be readout by a custom WFD in a $\mu$TCA crate with an AMC13 control module.

Images courtesy of David Sweigart
Requirements

- Accomodate a 12 Hz average rate of muon spills that consists of sequences of four successive 700 µs spills with 11 ms spill-separations.
- Handle the readout, processing, monitoring and storage of the data obtained from the twenty-four electromagnetic calorimeters, each comprising $9 \times 6$ arrays of PbF$_2$ crystals read out by SiPMs.
- The signals derived from individual crystals are read out by 1296 channels of custom 800 MHz, 12-bit, waveform digitizers.
- Provide both the readout of the raw ADC samples and the derivation of T-method, Q-method, and other calibration, diagnostic and systematic datasets.
- For a 12 Hz spill rate the time-averaged rate of raw ADC samples is 18 GB/s in total.
Layered array of commodity, networked processors
- FE layer for readout of digitizer (calo), MHTDCs (straws)
- BE layer for assembly of event fragments, storage
- Slow control layer for setting, monitoring of HVs, etc.
- Online analysis layer using ROME for monitoring the integrity of raw data, physics data.
MIDAS

- MIDAS is a data acquisition software developed at PSI and also used extensively at TRIUMF.
- Includes web interface for easy control.
- Frontend acquisition code written in C/C++.
- ROOT analyzer for online data monitoring.
- Data will be written to tape as MIDAS datafiles.
Multithreading with mutex locks

TCP Thread
Read and unpack data from TCP socket and copy to ring buffer.

GPU Thread
Memcpy to GPU and Process data

MFE Thread
Pack and send data to MIDAS banks and DQM
GPU Processing

- Data will be processed in an array of 24 GPUs (One GPU per calorimeter)
- Utilizing NVIDIA TESLA K40 GPUS
  - Peak double precision floating point performance: 1.43 Tflops
  - Peak single precision floating point performance: 4.29 Tflops
  - Memory bandwidth 288 GB/sec
  - Memory size (GDDR5): 12 GB
  - CUDA cores: 2880
- Data processing code is written using CUDA.

Results of bandwidth tests:

<table>
<thead>
<tr>
<th>Frontend Machine</th>
<th>GPU</th>
<th>Host to device, Pageable</th>
<th>Host to device, Pinned</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE01</td>
<td>K20</td>
<td>3326.6 MB/s</td>
<td>5028.3 MB/s</td>
</tr>
<tr>
<td>RAVE01</td>
<td>K20</td>
<td>5628.6 MB/s</td>
<td>6003.6 MB/s</td>
</tr>
<tr>
<td>RAVE01</td>
<td>K40</td>
<td>6647.8 MB/s</td>
<td>10044.3 MB/s</td>
</tr>
</tbody>
</table>
CUDA routines process data with two complimentary methods.

- **T-method**
  - Positron events in the calorimeter are individually identified, sorted and fit to obtain time and energy.
  - All events above an energy threshold are included.
  - $\tilde{\omega}_a$ is determined from a fit to a pileup-subtracted histogram.
  - This was the method used in BNL E821.

- **Q-method**
  - Individual positron events are not identified.
  - Detector current is integrated as a proxy for event energy.
  - No pileup correction is necessary!
Test Stands

- Test stands operating in parallel at Fermilab and U. of Kentucky
- Currently includes backend, frontend, gateway, and $\mu$TCA crate with WFD and AMC13
- Plan to expand to a 25% DAQ system within the next month.
AMC13 Simulator

- Generates realistic waveforms and packs the data in the AMC13 data format.
- Allows us to exercise the DAQ without dependence on hardware.
- Plan to develop this into a tool that will recreate the full spectrum of DAQ input, which will be used for testing the complete data acquisition system.
Event building test

12Hz Event builder data performance

- 100 MB/sec total rate
- >80MB/s
- 50 MB/sec total rate

Data volume per calorimeter per spill (MB)
Time is dominated by memcpy to GPU.

- MFE_thread sent data
- MFE_thread got data
- gpu_thread process data
- gpu_thread copy data
- tcp_thread got data
- tcp_thread got header

1.25 GB/s physical limit
0.75 GB/s required rate
1.0-1.25 GB/s measured rate

tcp_thread Δt = 20-25 ms
gpu_thread Δt = 12-15 ms
mfe_thread Δt = 2-10 ms (poll)

meets the FE specs for 60.4 MB 12Hz readout and GPU processing
Dual GPU rate test

- Test completed at full rate over 10 GbE in UKY test stand using older generation GPUs.
- TCP/IP tuned to achieve maximum rate.
- Repeating test at MC-1 test stand with two Tesla GPUs.
- Test will determine if single machine can sustain total rate of two calorimeters.
First WFD readout

- First readout of WFD by DAQ occurred during SLAC test-beam last year.
- Since then, Cornell has continued development of the WFD hardware and firmware, and the first WFD has just been delivered to the DAQ group for testing.
- We hope to have \( \approx 5 \) WFDs for testing later this Spring, and a full crate of 12 in the Fall.
The new muon $g$-2 experiment will run at Fermilab beginning in 2017 with the goal of reaching $20 \times$ the BNL statistics.

A new state-of-the-art data acquisition system utilizing parallel data processing in a hybrid system of multi-core CPUs and GPUs is required to achieve the necessary data rates.

The DAQ will acquire data from 1296 channels of custom $\mu$TCA waveform digitizers, as well as straw trackers and auxiliary detectors at a rate of 18 GB/s.

Prototyping of the DAQ is underway, and construction will be complete by mid-2016.