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

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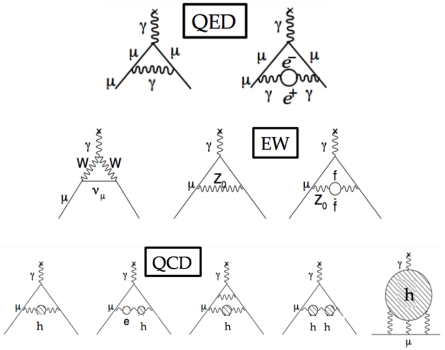
Outline

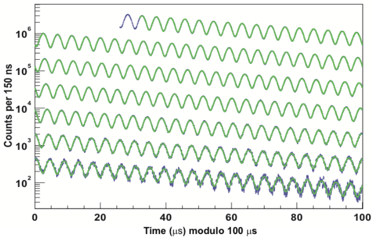
Physics of Muon g-2

- 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).



$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD} + a_\mu^{NP}$$

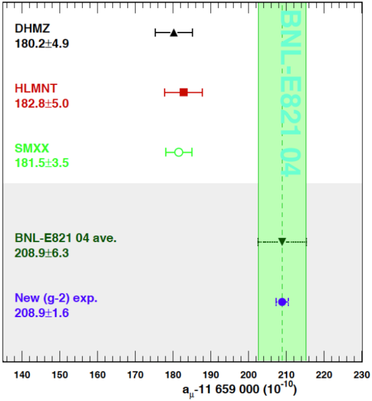
Measurements of g-2



$$a_\mu \equiv \frac{g-2}{2}$$

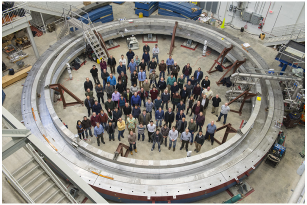
$$\vec{\omega}_a = -\frac{Qe}{m}[a_\mu \vec{B} - (a_\mu - (\frac{mc}{p})^2)\frac{\vec{\beta}\times\vec{E}}{c}]$$

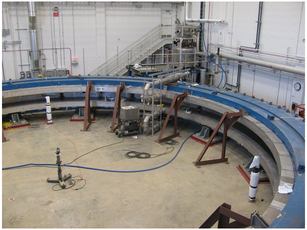
- BNL E821 measured g-2 to have a 3.3σ discrepancy from the standard model (2006).
- Fermilab E989 will measure 20 times the number of muons, reducing the uncertainty on this measurement by a factor of 4.
- Without theory improvements, discrepancy could reach $> 5\sigma$.



Project Status

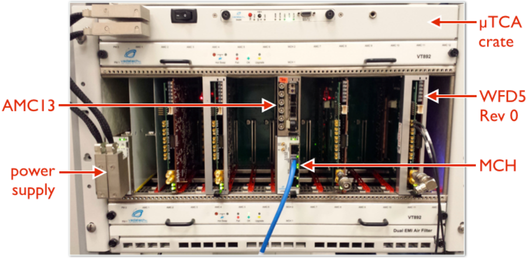
- The ring was moved from BNL to FNAL in 2013.
- It has been installed in our new MC1 building and is currently being cooled.
- Plan for data taking to begin in early 2017.

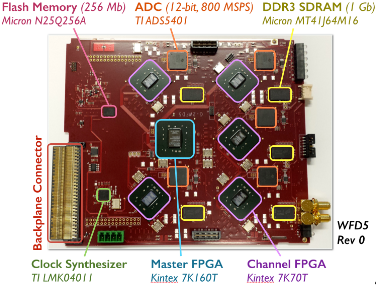




Detectors and Backend Electronics

- 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 μTCA crate with an AMC13 control module.



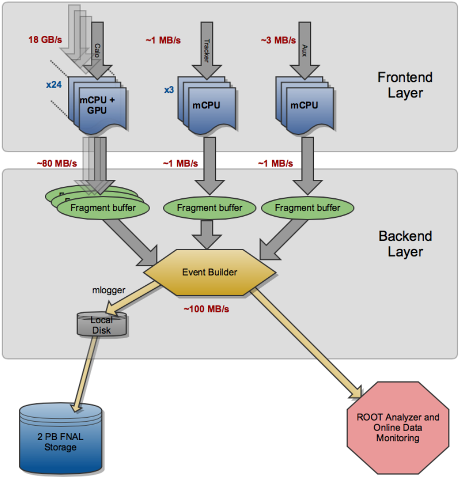


Images courtesy of David Sweigart

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 9×6 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.

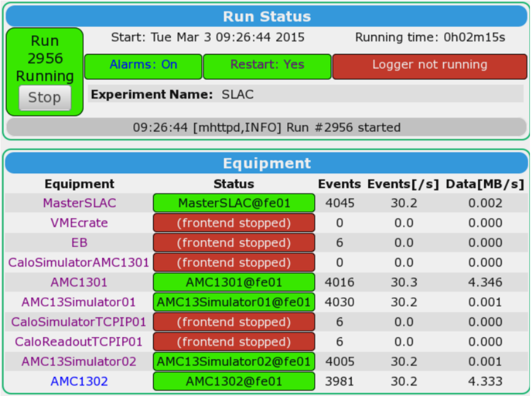
DAQ Schematic



- 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.



Run Status

Run 2956 Running

Stop

Start: Tue Mar 3 09:26:44 2015

Running time: 0h02m15s

Alarms: On

Restart: Yes

Logger not running

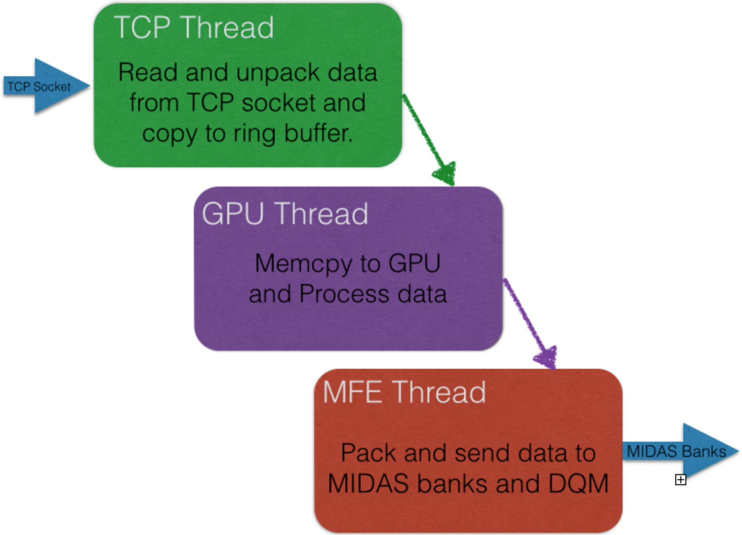
Experiment Name: SLAC

09:26:44 [mhttpd,INFO] Run #2956 started

Equipment

Equipment	Status	Events	Events[/s]	Data[MB/s]
MasterSLAC	MasterSLAC@fe01	4045	30.2	0.002
VMEcrate	(frontend stopped)	0	0.0	0.000
EB	(frontend stopped)	6	0.0	0.000
CaloSimulatorAMC1301	(frontend stopped)	0	0.0	0.000
AMC1301	AMC1301@fe01	4016	30.3	4.346
AMC13Simulator01	AMC13Simulator01@fe01	4030	30.2	0.001
CaloSimulatorTCPIP01	(frontend stopped)	6	0.0	0.000
CaloReadoutTCPIP01	(frontend stopped)	6	0.0	0.000
AMC13Simulator02	AMC13Simulator02@fe01	4005	30.2	0.001
AMC1302	AMC1302@fe01	3981	30.2	4.333

Multithreading with mutex locks



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.

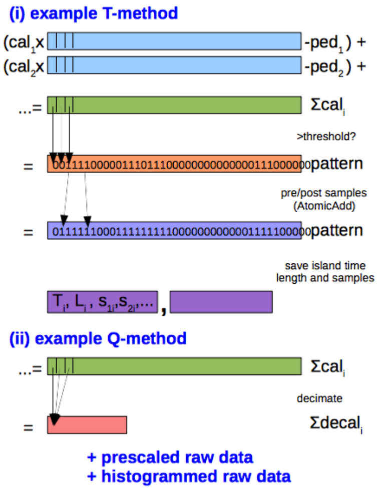
Results of bandwidth tests:

Frontend Machine	GPU	Host to device, Pageable	Host to device, Pinned
FE01	K20	3326.6 MB/s	5028.3 MB/s
RAVE01	K20	5628.6 MB/s	6003.6 MB/s
RAVE01	K40	6647.8 MB/s	10044.3 MB/s

T and Q Methods

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.
  - $\vec{\omega}_a$ 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!

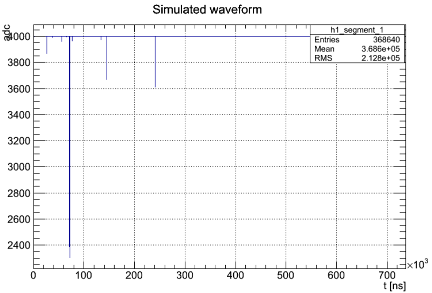


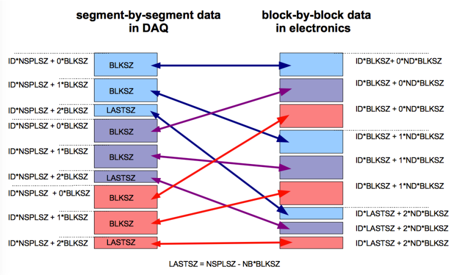
Test Stands

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

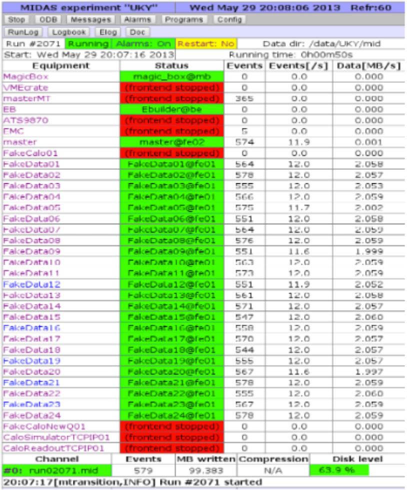
AMC13 Simulator

- Generates realistic waveforms and packs the data in the AMC13 data format.
- Allows us to exersize 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

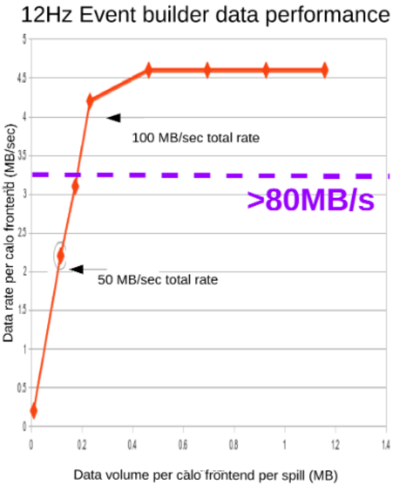


MIDAS experiment "UKY"		Wed May 29 20:08:06 2013	Refr:60	
Stop, ODB, Messages, Alarms, Programs, Config				
RunLog, Logbook, Elog, Doc				
Run #2071	Running, Alarms: On, Restart: No	Data dir: /data/UKY/mid		
Start: Wed May 29 20:07:16 2013		Running time: 0h00m50s		
Equipment	**Status**	**Events**	**Events[/s]**	**Data[MB/s]**
MagicBox	magic_box@mb	0	0.0	0.000
VMEcrate	(frontend stopped)	0	0.0	0.000
masterMT	(frontend stopped)	365	0.0	0.000
EB	Ebuilder@be	0	0.0	0.000
ATS9870	(frontend stopped)	0	0.0	0.000
EMC	(frontend stopped)	5	0.0	0.000
master	master@fe02	574	11.9	0.001
FakeCalo01	(frontend stopped)	0	0.0	0.000
FakeData01	FakeData01@fe01	564	12.0	2.058
FakeData02	FakeData02@fe01	578	12.0	2.057
FakeData03	FakeData03@fe01	555	12.0	2.053
FakeData04	FakeData04@fe01	566	12.0	2.059
FakeData05	FakeData05@fe01	575	11.7	2.002
FakeData06	FakeData06@fe01	551	12.0	2.058
FakeData07	FakeData07@fe01	564	12.0	2.059
FakeData08	FakeData08@fe01	576	12.0	2.059
FakeData09	FakeData09@fe01	551	11.6	1.999
FakeData10	FakeData10@fe01	563	12.0	2.059
FakeData11	FakeData11@fe01	573	12.0	2.059
FakeData12	FakeData12@fe01	551	11.9	2.052
FakeData13	FakeData13@fe01	561	12.0	2.058
FakeData14	FakeData14@fe01	571	12.0	2.057
FakeData15	FakeData15@fe01	547	12.0	2.060
FakeData16	FakeData16@fe01	558	12.0	2.059
FakeData17	FakeData17@fe01	570	12.0	2.057
FakeData18	FakeData18@fe01	544	12.0	2.057
FakeData19	FakeData19@fe01	555	12.0	2.057
FakeData20	FakeData20@fe01	567	11.6	1.997
FakeData21	FakeData21@fe01	578	12.0	2.059
FakeData22	FakeData22@fe01	555	12.0	2.060
FakeData23	FakeData23@fe01	567	12.0	2.059
FakeData24	FakeData24@fe01	578	12.0	2.059
FakeCaloNewQ01	(frontend stopped)	0	0.0	0.000
CaloSimulatorTCPIP01	(frontend stopped)	0	0.0	0.000
CaloReadoutTCPIP01	(frontend stopped)	0	0.0	0.000

Channel	Events	MB written	Compression	Disk level
#0: run02071.mid	579	99.383	N/A	63.9 %

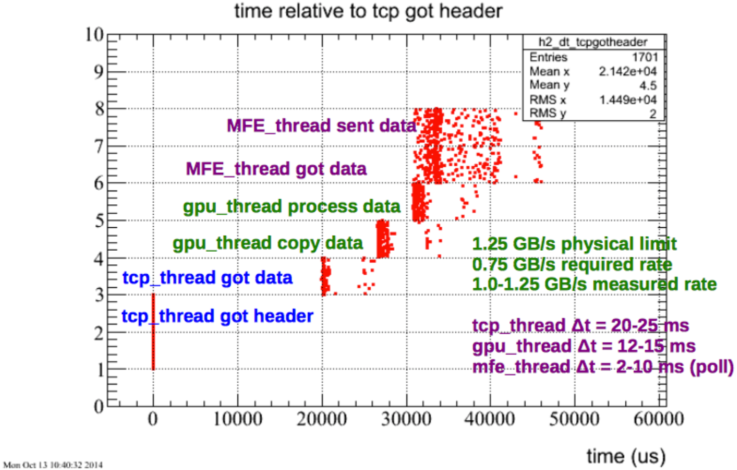
20:07:17[mtransition,INFO] Run #2071 started

------------------------ Event# 1 ------------------------
Evid:0001- Mask:0000- Serial:0- Time:0x512b8c40- Dsize:2881352/0x2bf748
#banks:48 - Bank list:-FD01SR01FD02SR02FD03SR03FD04SR04FD05SR05FD06SR06FD07SR07FD08SR08FD09SR09FD10SR10FD11S
R11FD12SR12FD13SR13FD14SR14FD15SR15FD16SR16FD17SR17FD18SR18FD19SR19FD20SR20FD21SR21FD22SR22FD23SR23FD24SR24-



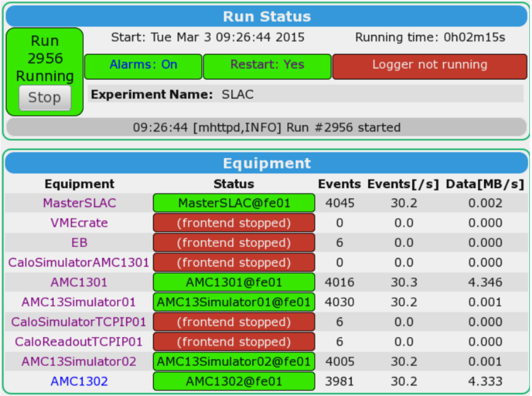
GPU Processing Time

Time is dominated by memcpy to GPU.



meets the FE specs for 60.4 MB 12Hz readout and GPU prcessing

Dual GPU rate test



Run Status

Run 2956 Running

Stop

Start: Tue Mar 3 09:26:44 2015

Running time: 0h02m15s

Alarms: On

Restart: Yes

Logger not running

Experiment Name: SLAC

09:26:44 [mhttpd,INFO] Run #2956 started

Equipment

Equipment	Status	Events	Events[/s]	Data[MB/s]
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EB	(frontend stopped)	6	0.0	0.000
CaloSimulatorAMC1301	(frontend stopped)	0	0.0	0.000
AMC1301	AMC1301@fe01	4016	30.3	4.346
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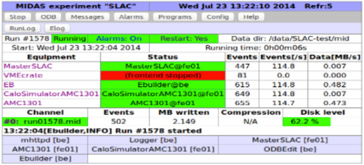
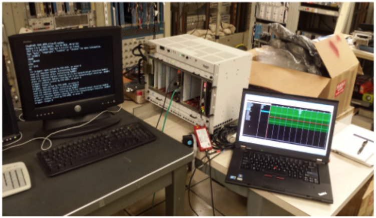
CaloReadoutTCPIP01	(frontend stopped)	6	0.0	0.000
AMC13Simulator02	AMC13Simulator02@fe01	4005	30.2	0.001
AMC1302	AMC1302@fe01	3981	30.2	4.333

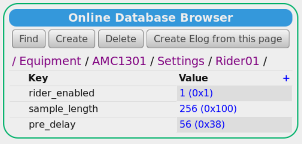
- Test completed at full rate over 10 GbE in UKY test stand using older generation GPUs.
- TCP/IP tuned to achieve maximum rate.
- Repeating test at MC-1 test stand with two Tesla GPUs.
- Test will determine if single machine can sustain total rate of two calorimeters.

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 ≈5 WFDs for testing later this Spring, and a full crate of 12 in the Fall.







Conclusion

- 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 μTCA 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.