Data Acquisition with GPUs for Muon g-2 at Fermilab

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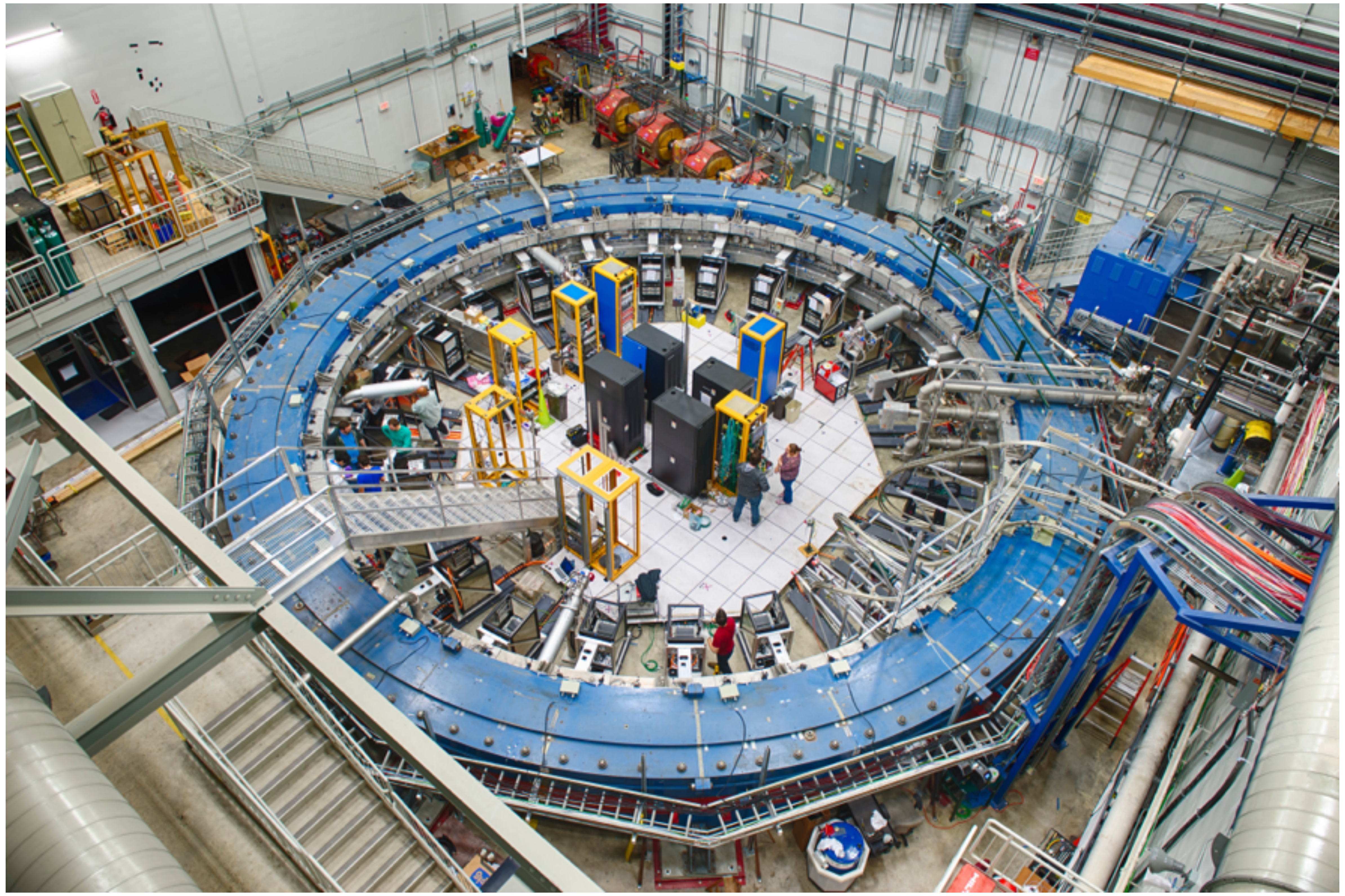
g-2

Muon g-2 Experiment Overview

- Goal is to measure the anomalous magnetic moment of the muon to 140 ppb, which is a factor of 4 better than has been previously measured.
- Muon fills are injected into the ring at a rate of 12 Hz.
- The precession frequency of the muons is measured by detecting decay positrons in 24 segmented calorimeters inside the ring.
- We finished a five-week commissioning run on July 7.

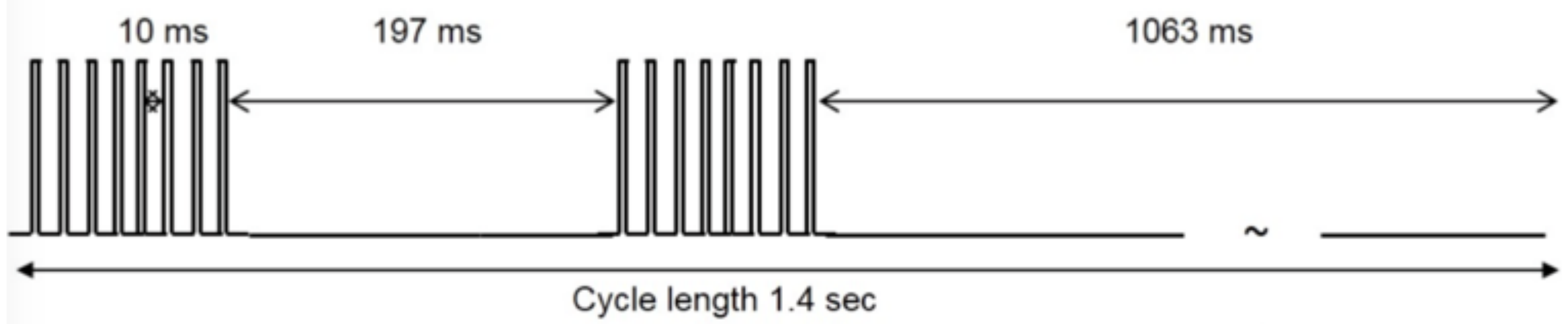


g-2 Detector Systems

- 24 Calorimeters
  - 1 uTCA crate for each calorimeter
  - 54 channels * 24 calos = 1296 channels of digitized data.
  - Data provided by 12 Cornell waveform digitizers.
- 4 Fiber Harps
  - 7 channels * 4 harps = 28 channels
  - Data provided by Cornell waveform digitizers
- Quads and Kickers
  - Write 4 quad channels and 15 kicker channels
  - Data provided by Cornell waveform digitizers
- 3 Trackers
  - Data from Multihit TDCs sent from FC7s in a uTCA crate
- IBMS and quads
  - Running on CAEN digitizers
- Slow control SCS3000 devices

Rate requirements

- Accommodate 12 Hz average rate of muon fills that consist of sequences of eight successive 700 μs fills with 10 ms fill-separations.

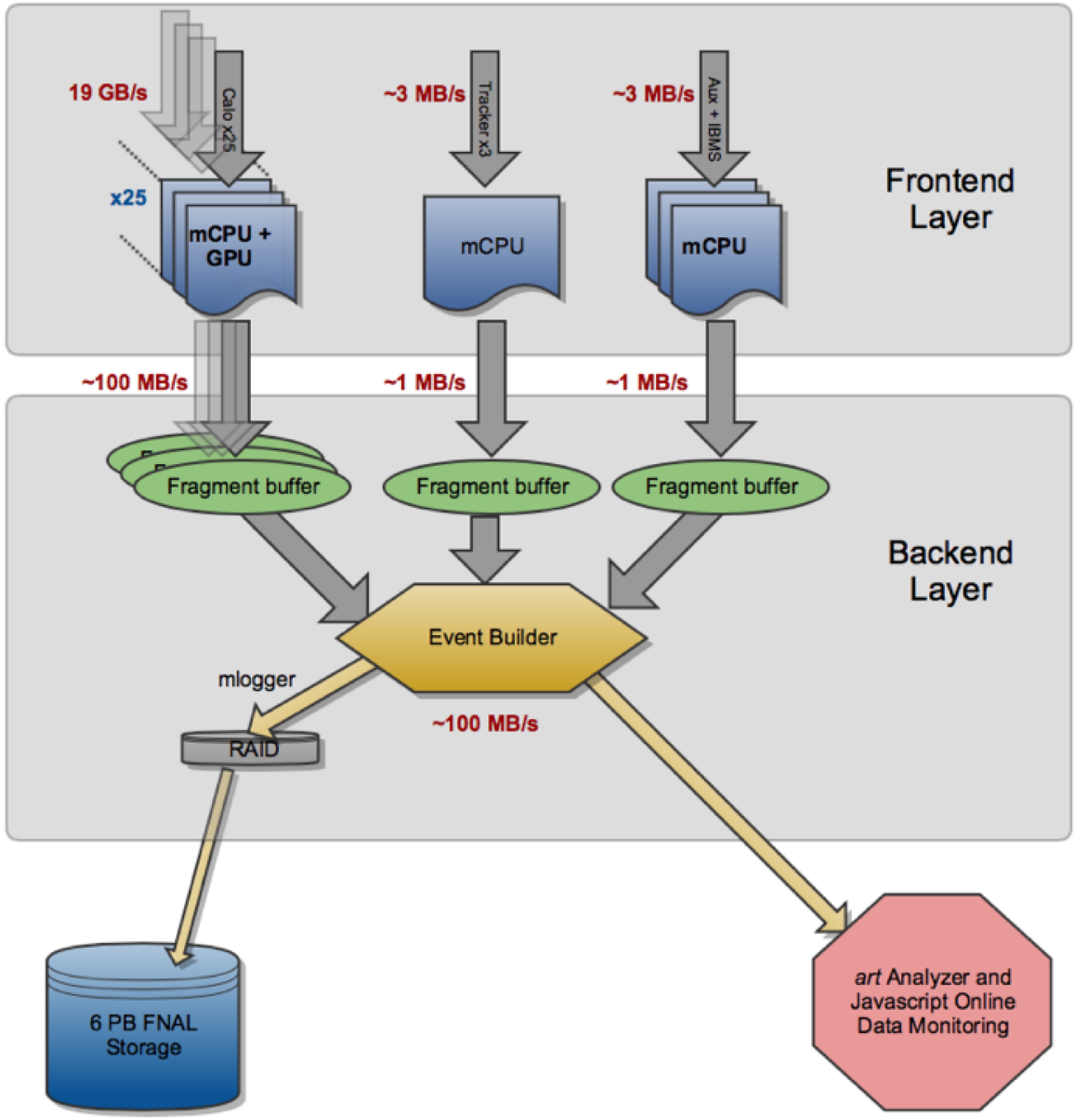


- Time-averaged rate of raw ADC samples is 20 GB/s, which must be reduced by a factor of 100.
- Data is processed in GPUs to accomplish this task.
- Total data on tape after 2 years of running will be 10 PB.

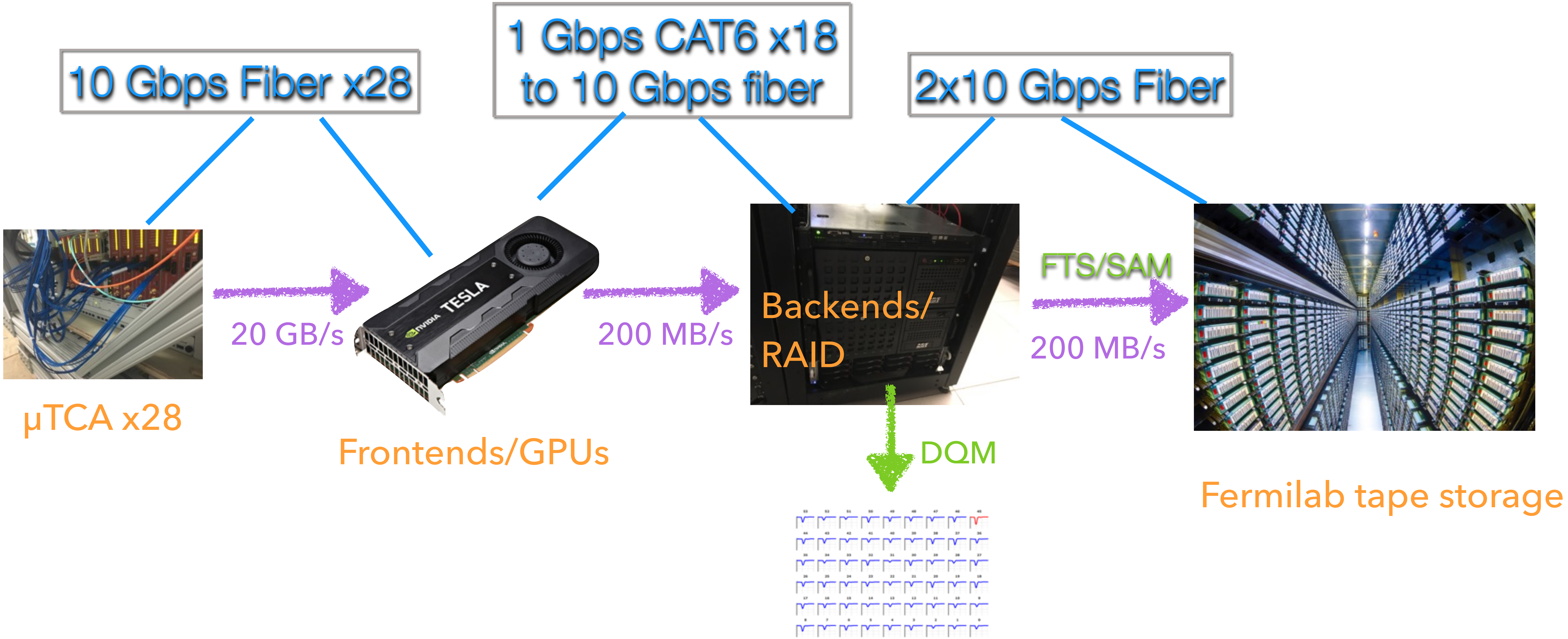
Source	MB Per Fill	MB Per Second
Raw data	1,600	19,400
T-Method	9.4	112.5
Q-Method	4.0	48.5
Prescaled Raw	1.6	19.4
Tracker	0.75	9
Laser Monitor	0.08	1
Auxiliary	0.33	4
Event Builder:	**16.2**	**194.4**

DAQ Design

- Layered array of commodity, networked processors
- Frontend layer for readout of detectors.
- Backend layer for assembly of event fragments.
- Slow control layer.
- Online analysis layer using *art*+JS.
- Field DAQ operates independently, but with a similar design.



Data Flow

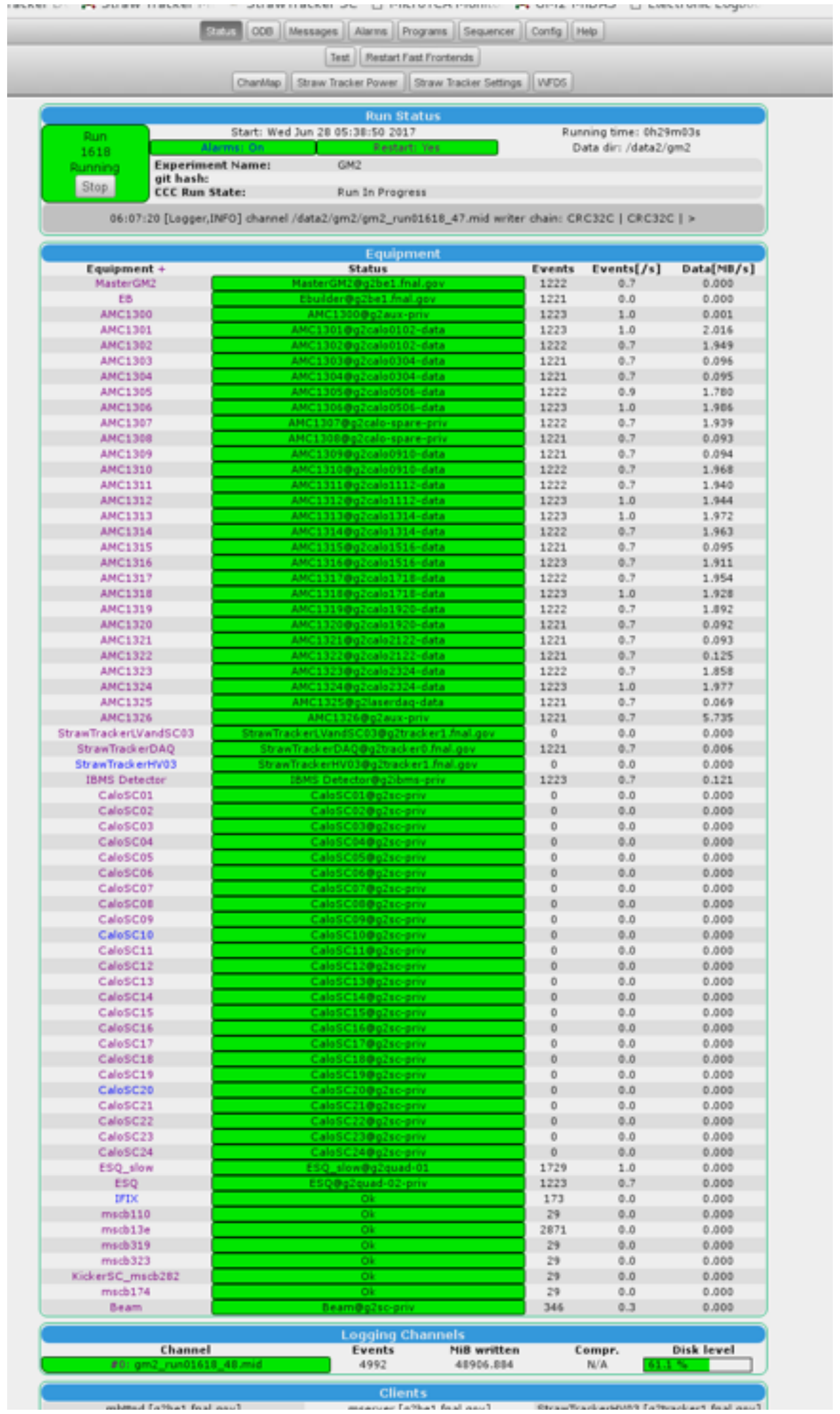

10 Gbps Fiber x28
1 Gbps CAT6 x18
to 10 Gbps fiber
2x10 Gbps Fiber
20 GB/s
200 MB/s
FTS/SAM
200 MB/s
Backends/
RAID
μTCA x28
Frontends/GPUs
DQM
Fermilab tape storage

DAQ Hardware

- The DAQ hardware includes:
  - 17 frontend machines
  - 5 backend machines
  - 2 dedicated near line analysis machines
  - 3 computers for HV control
  - 3 servers
  - 24 beagle bones running slow controls
- Each frontend contains two Nvidia Tesla K40 GPUs
  - 2880 CUDA cores at 740 MHz
  - 288 GB/s memory bandwidth
  - 12 GB on board memory
  - ECC memory protection
- 70 TB RAID for temporary data storage.

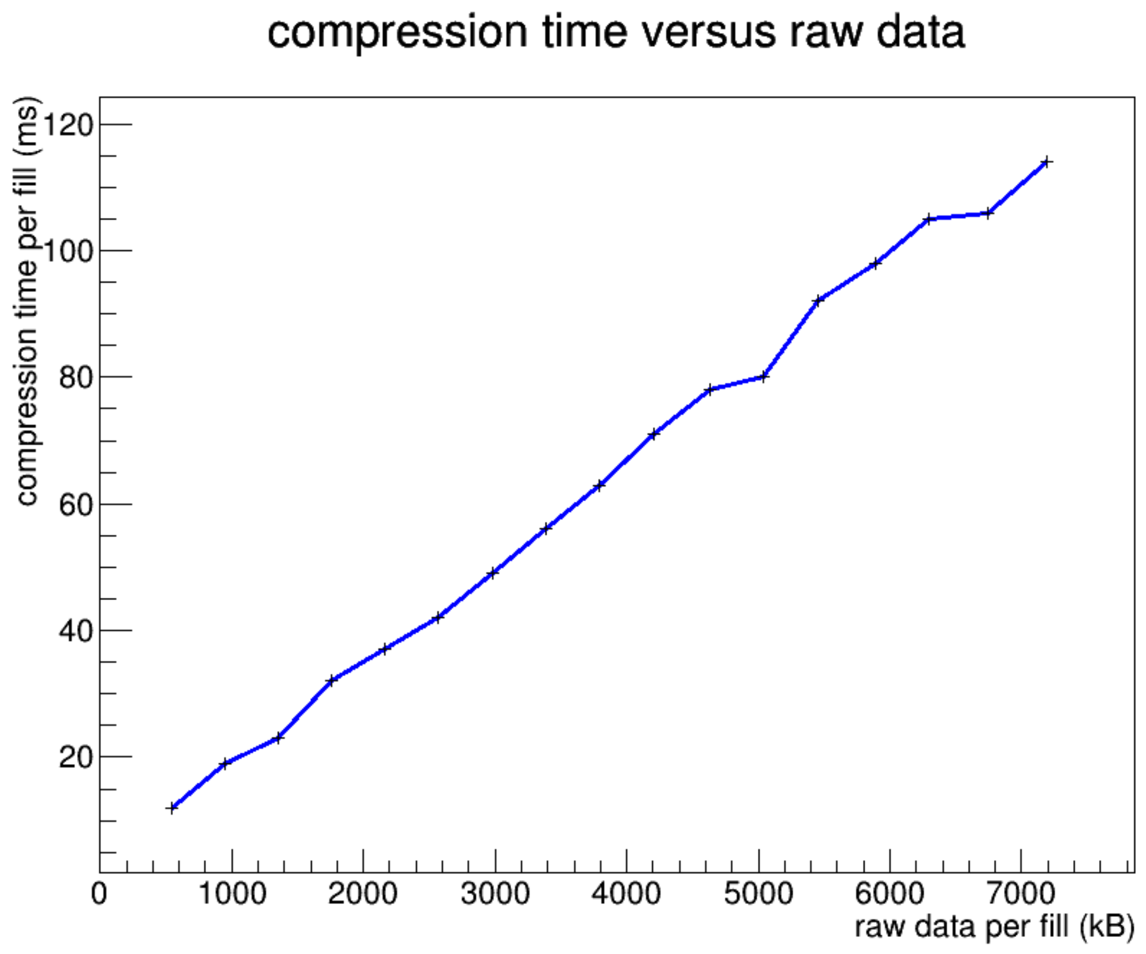
MIDAS Software

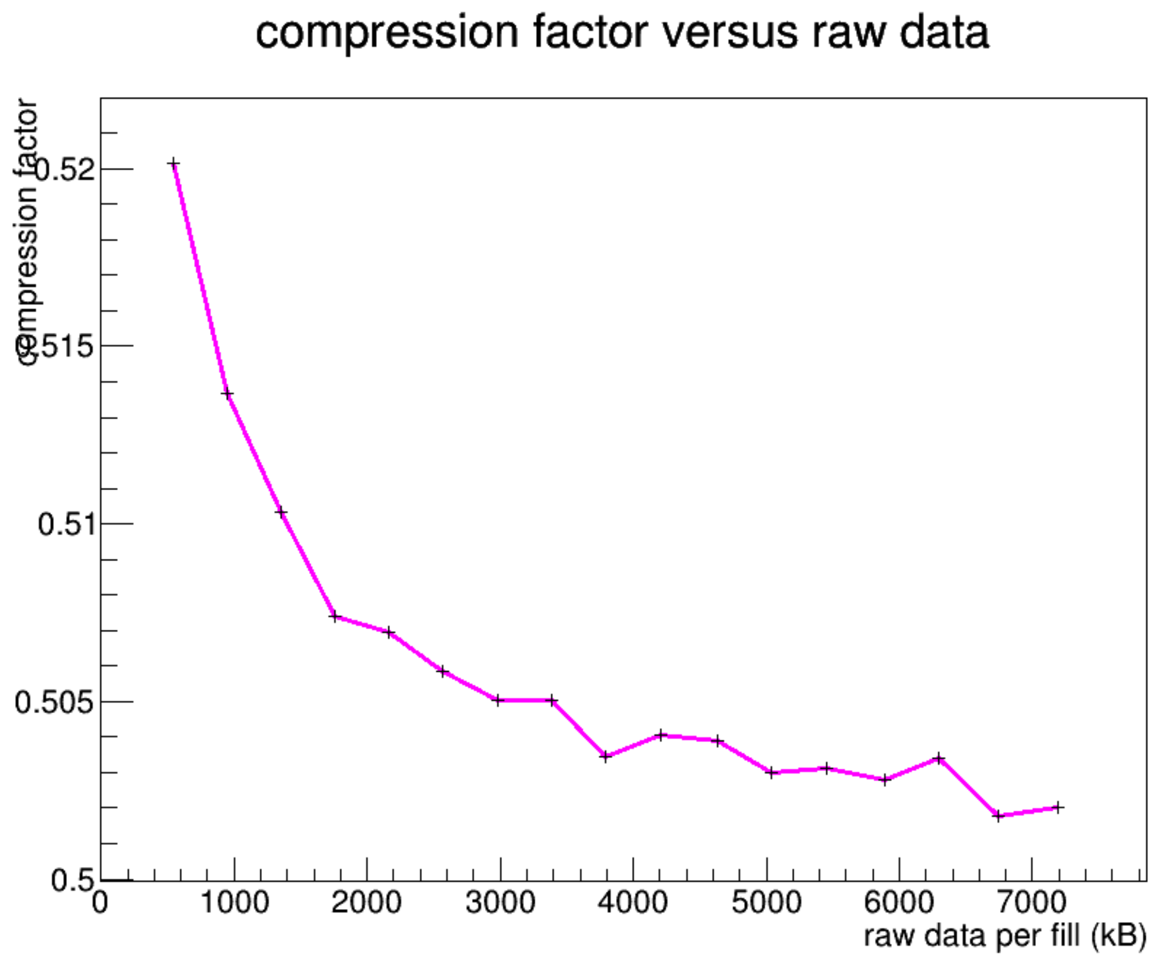
- MIDAS is a DAQ software package developed at PSI and TRIUMF and used by T2K, SCDMS, MEG, and many other experiments.
- Provides a web-interface for control of the experiment, data logging, and event building.
- We write frontend code in C++ and CUDA that processes the data and sends it to the event builder.
- 32 fast frontends reduce data volume for each event by a factor of 100 and store data in Midas banks.
- 35 slow control frontends process slow data.
- Includes alarm system and sequencer.
- Software configuration is dumped to a JSON file and saved to a PostgreSQL database at the end of each run.

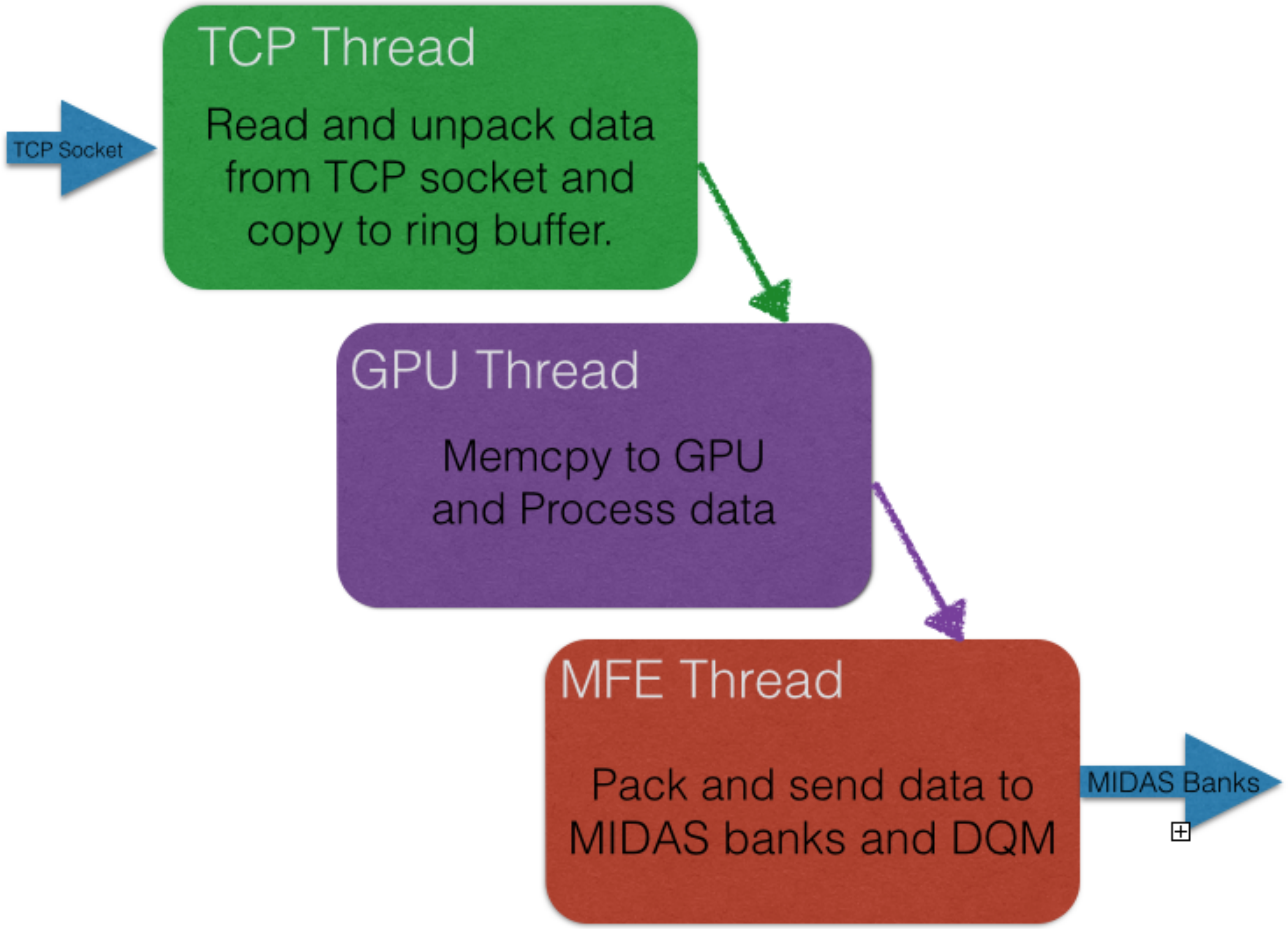


Calorimeter-GPU Frontend

- Each frontend process reads data from one uTCA crate over 10 Gb ethernet with TCPIP.
- Frontend is multithreaded with mutex locks.
- Data is processed in Nvidia Tesla K40 GPUs using CUDA code that is integrated into the frontend.
- Midas banks are losslessly compressed using zlib.
- Full configuration of the uTCA crate is performed via the MIDAS ODB.





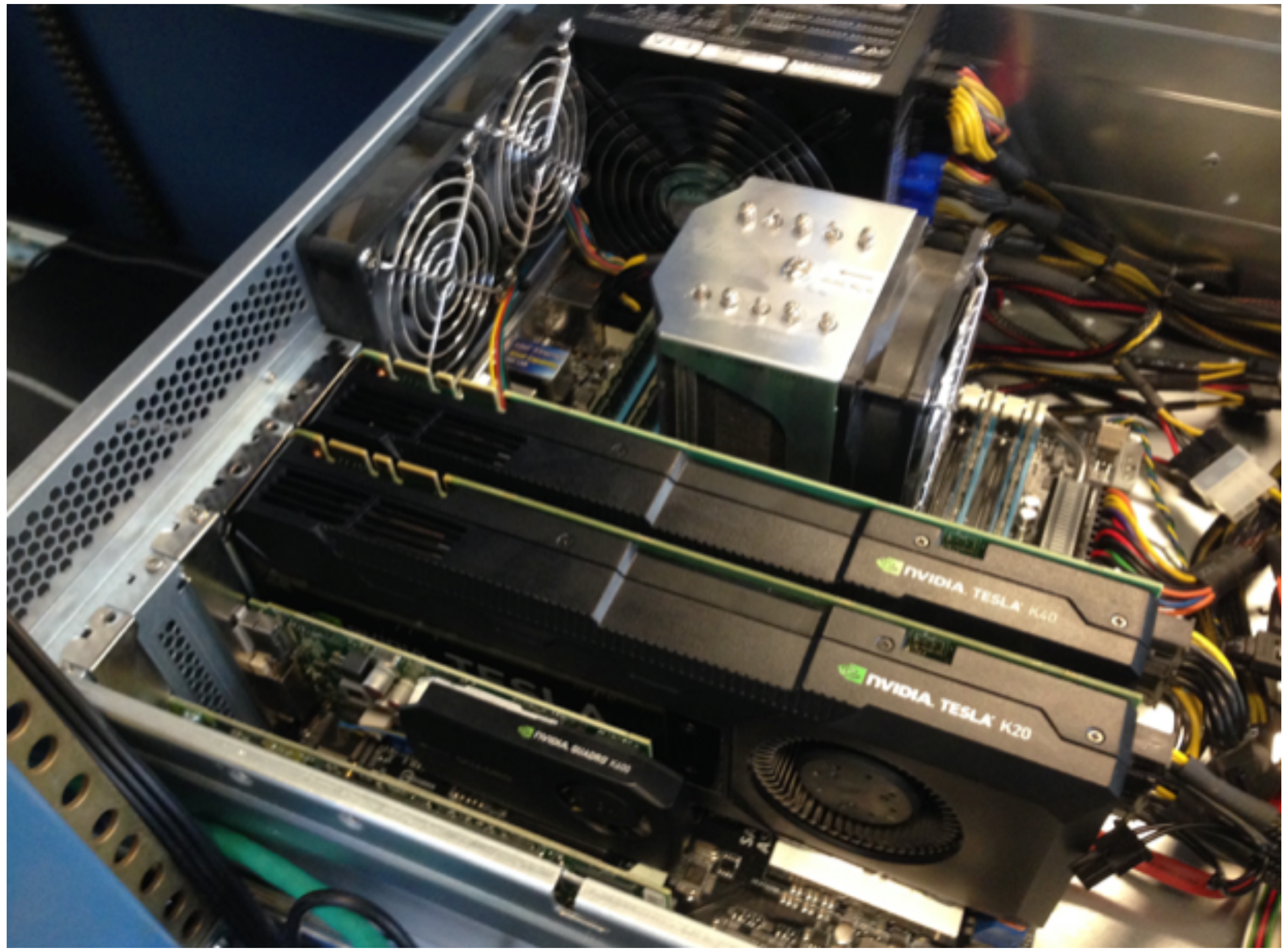


Why GPUs?

- The GPUs dramatically improve performance by parallelizing processing.
- Technology was developed for commercial applications, so it is well supported.
- Easier to code in C++ than to learn specialized language.
- Without GPUs, we could not keep up with our data rates.

GPU Processing

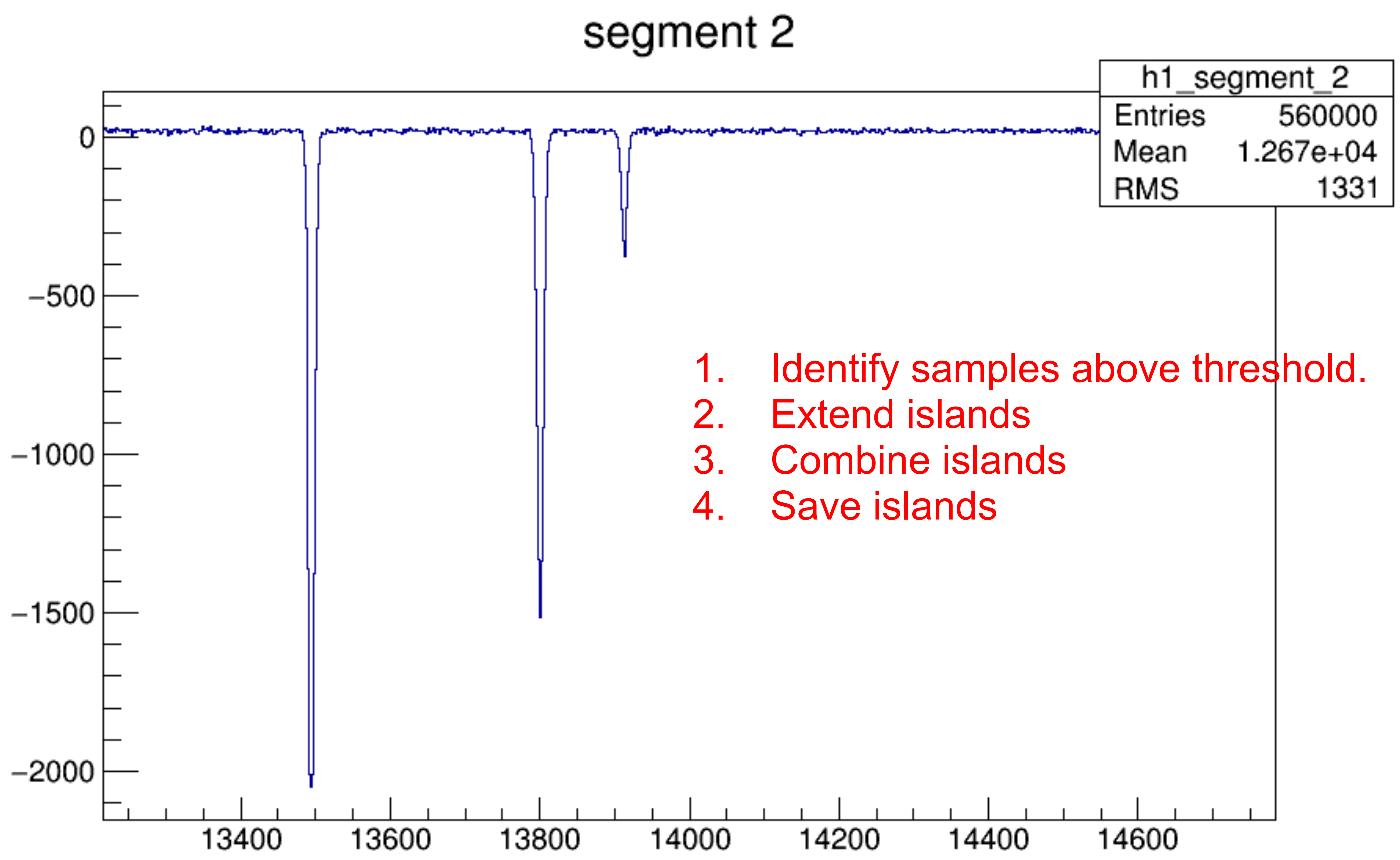
- The frontend includes CUDA routines for data processing.
- Each GPU processes data from one calorimeter.
- Raw fill is copied to GPU memory, where it is reduced using T-method (island chopping), Q-method (histogramming), pedestal calculation, and template fitting.
- The output of each process is written in one MIDAS bank.



Fermilab

T-Method

- Identify and save regions of the waveform containing positron hits.
- A typical waveform will have ~180 islands.



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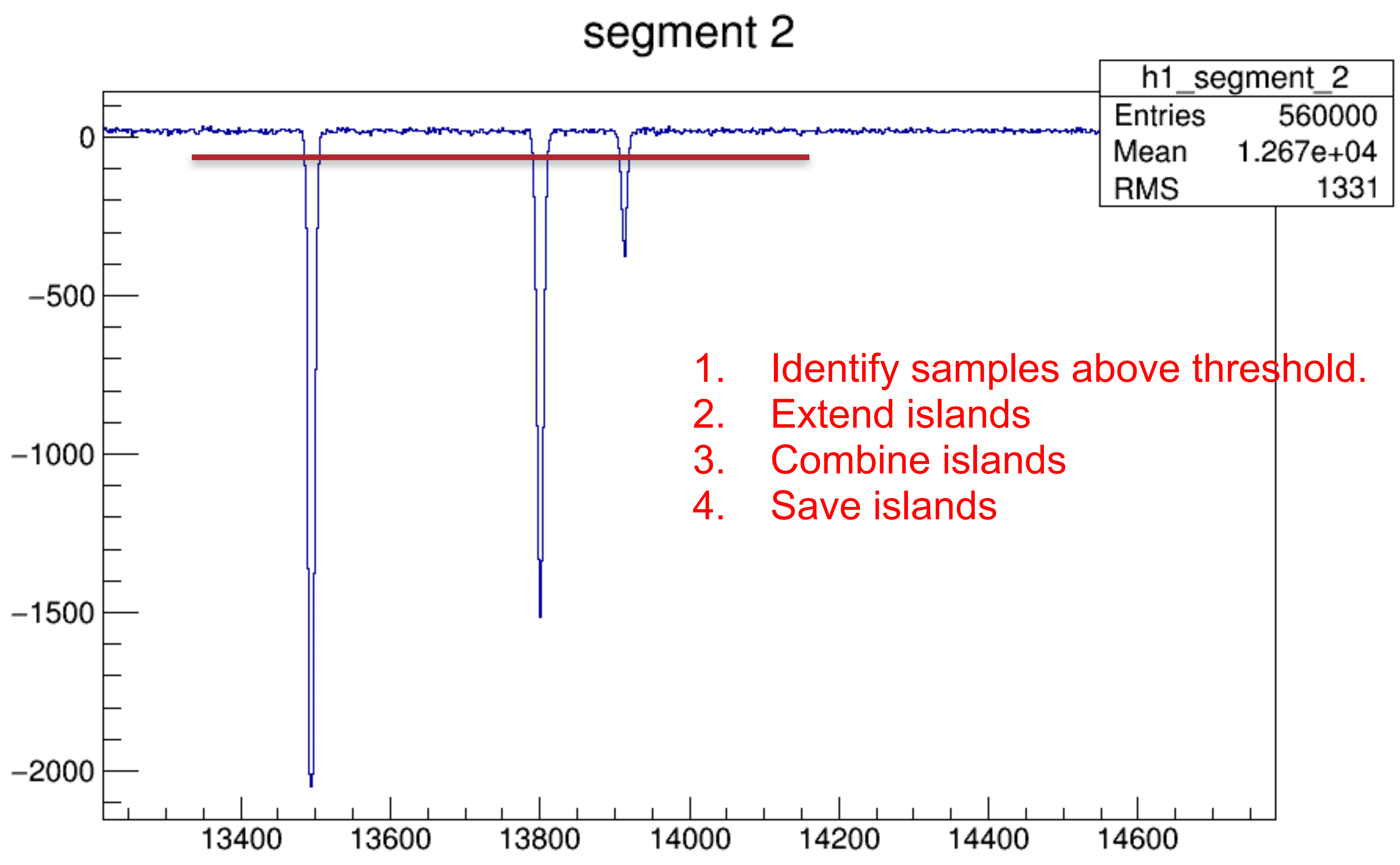

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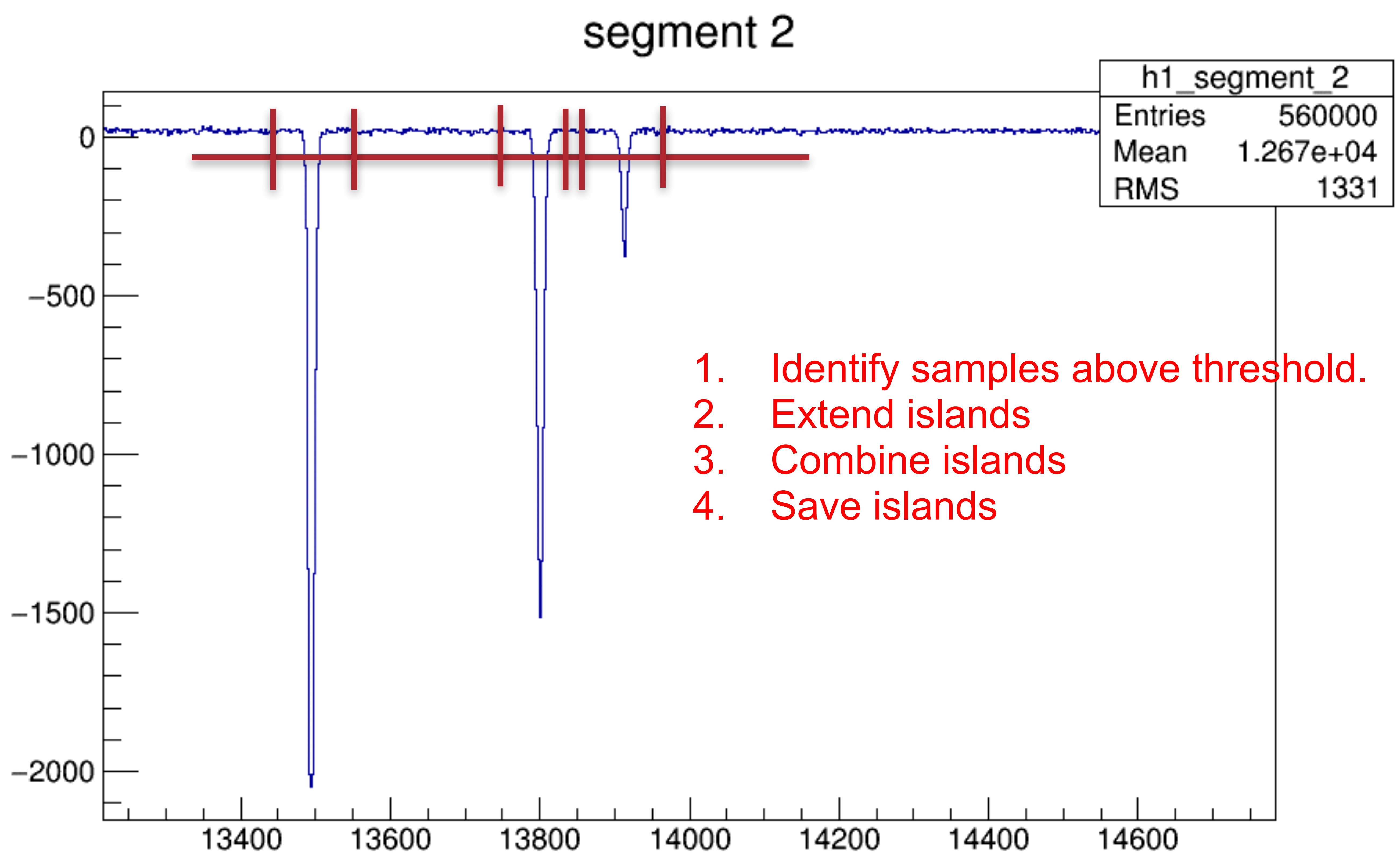

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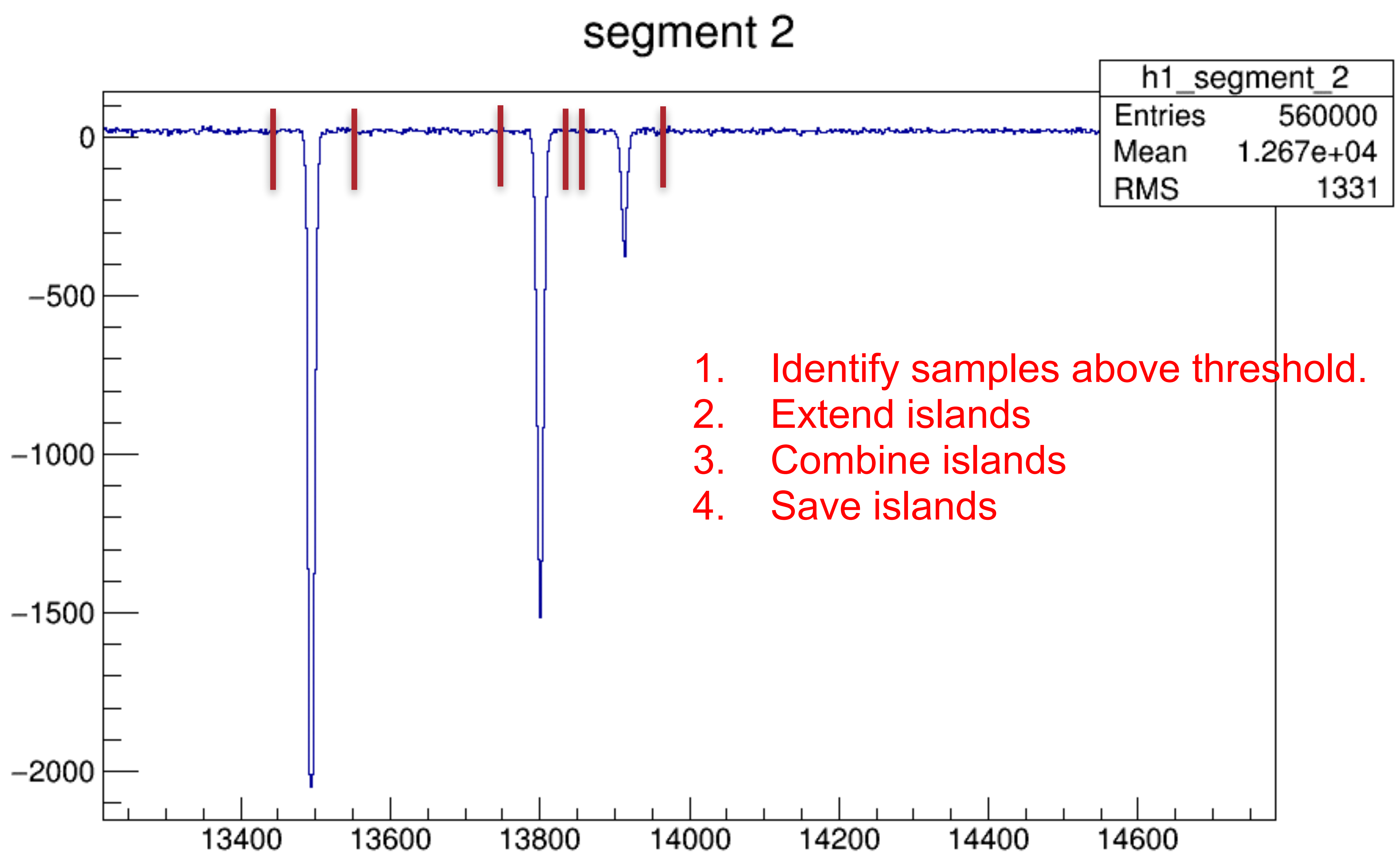

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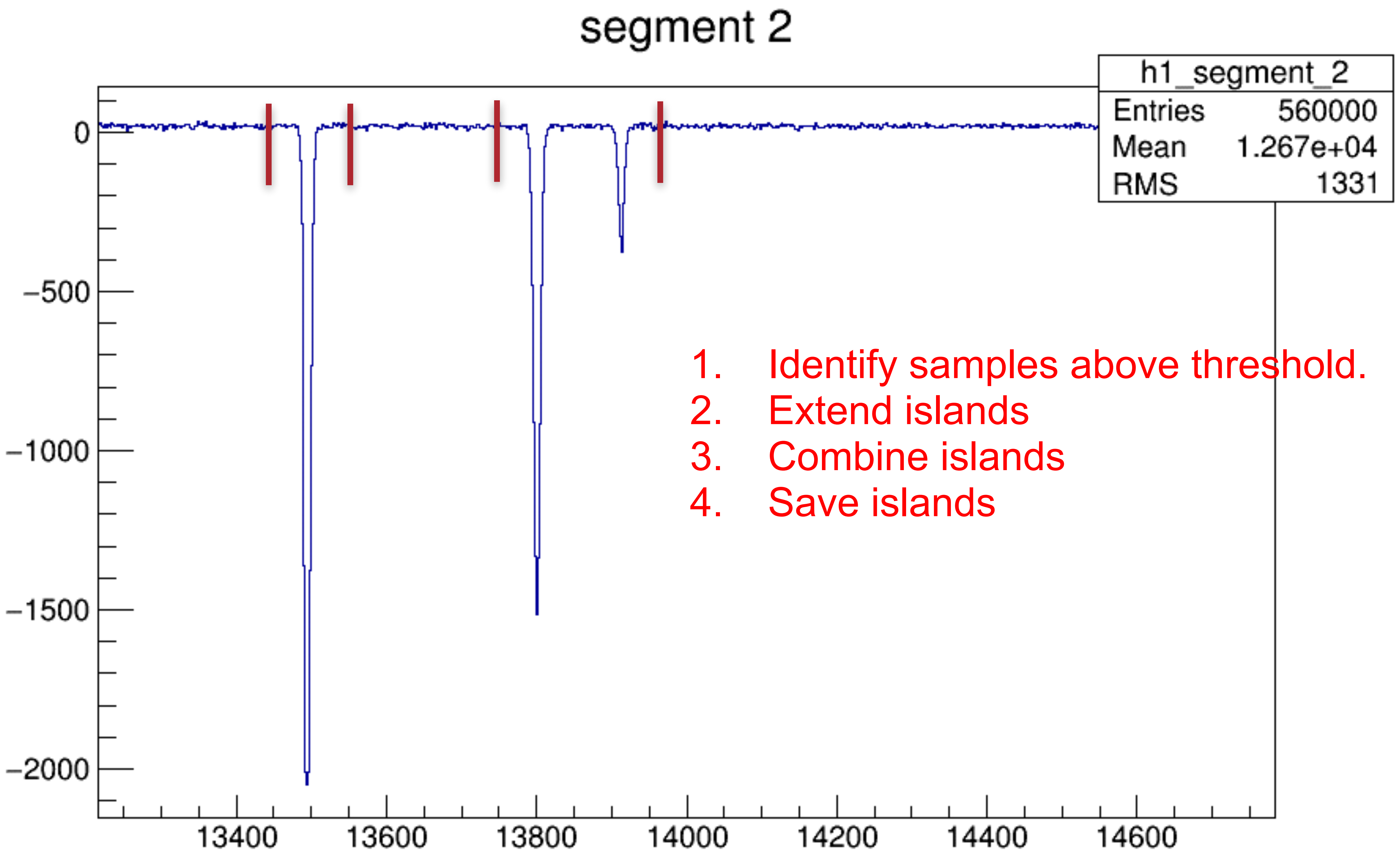

1. Identify samples above threshold.
2. Extend islands
3. Combine islands
4. Save islands

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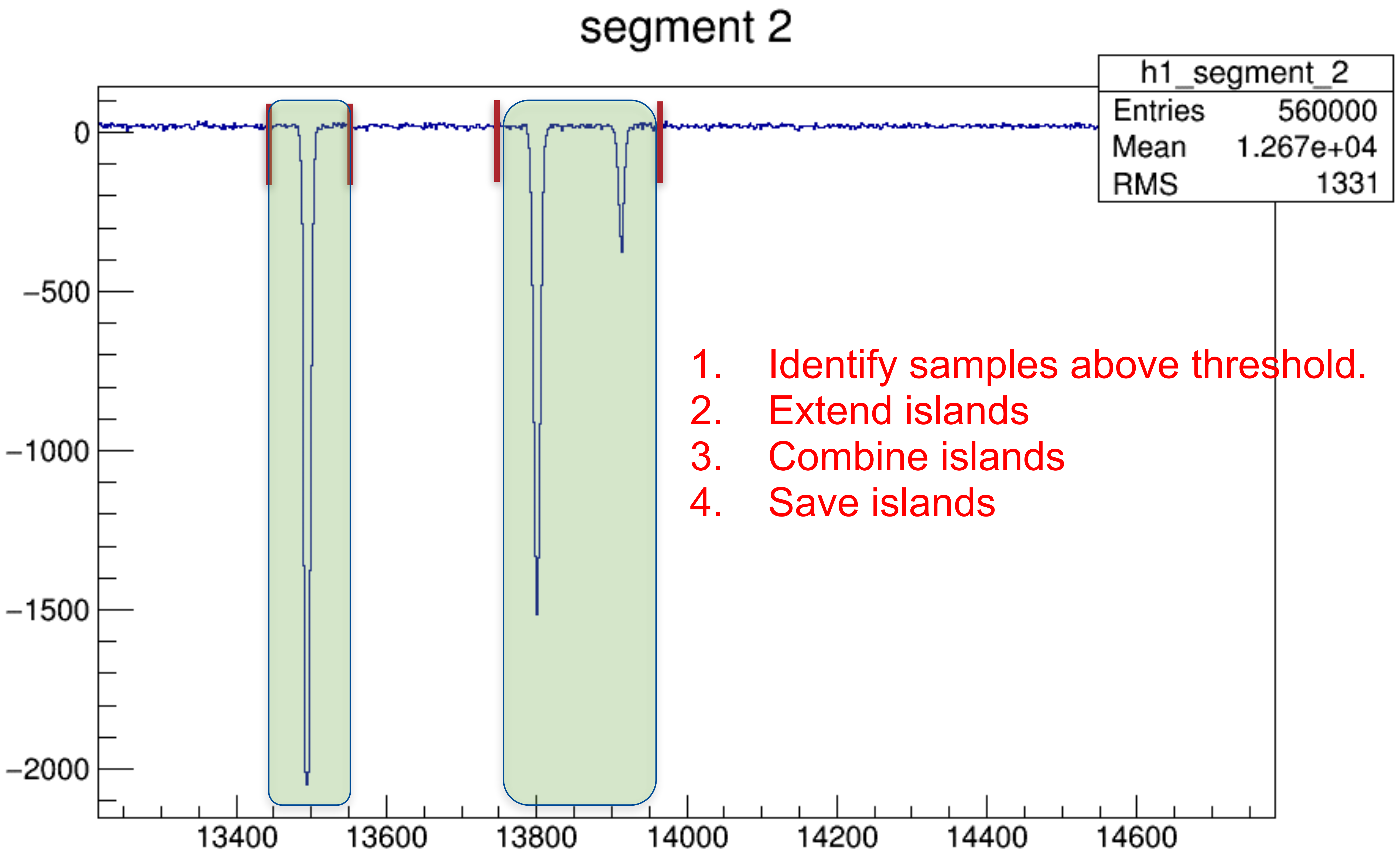
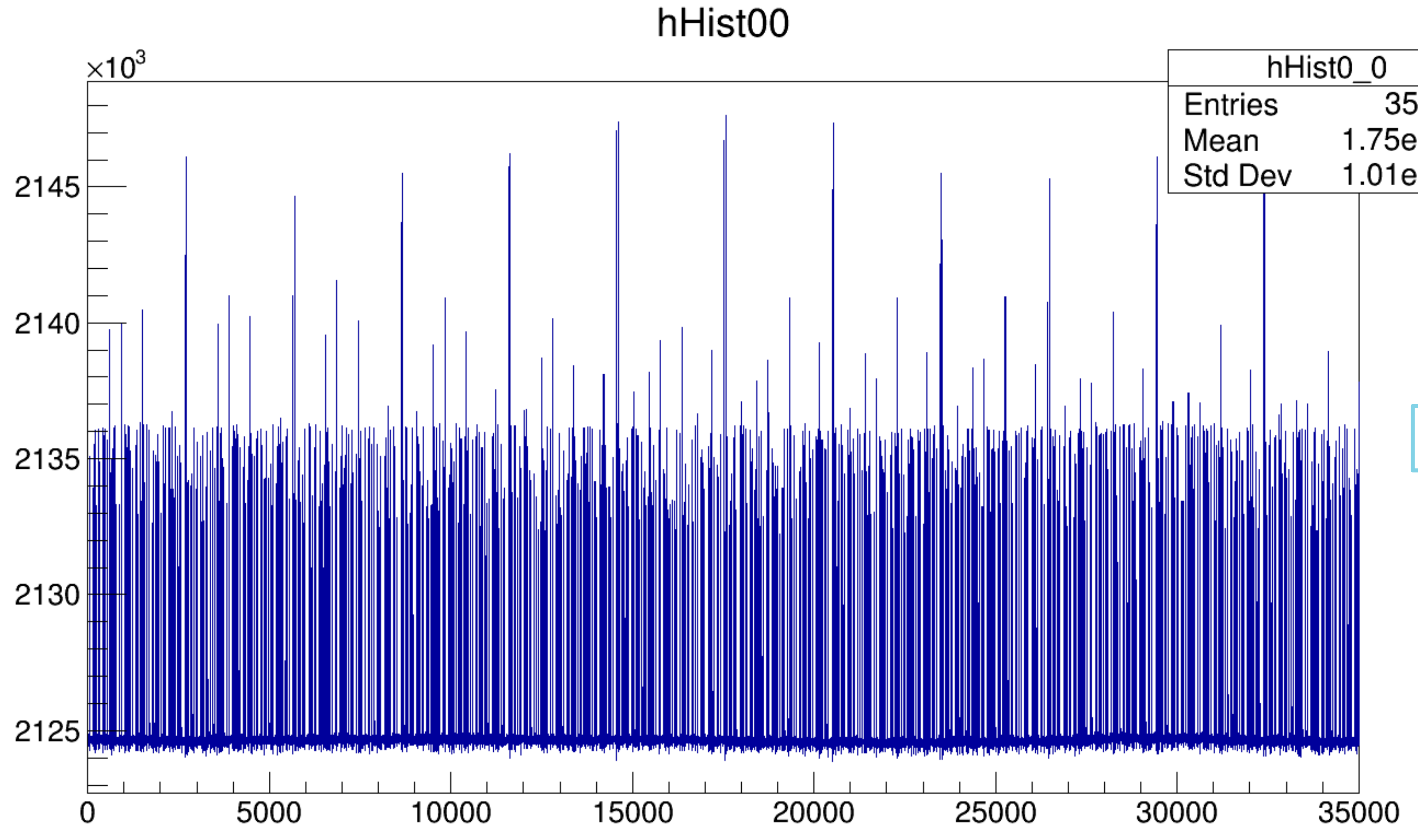
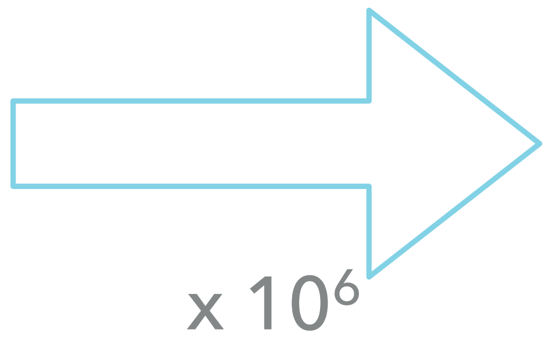
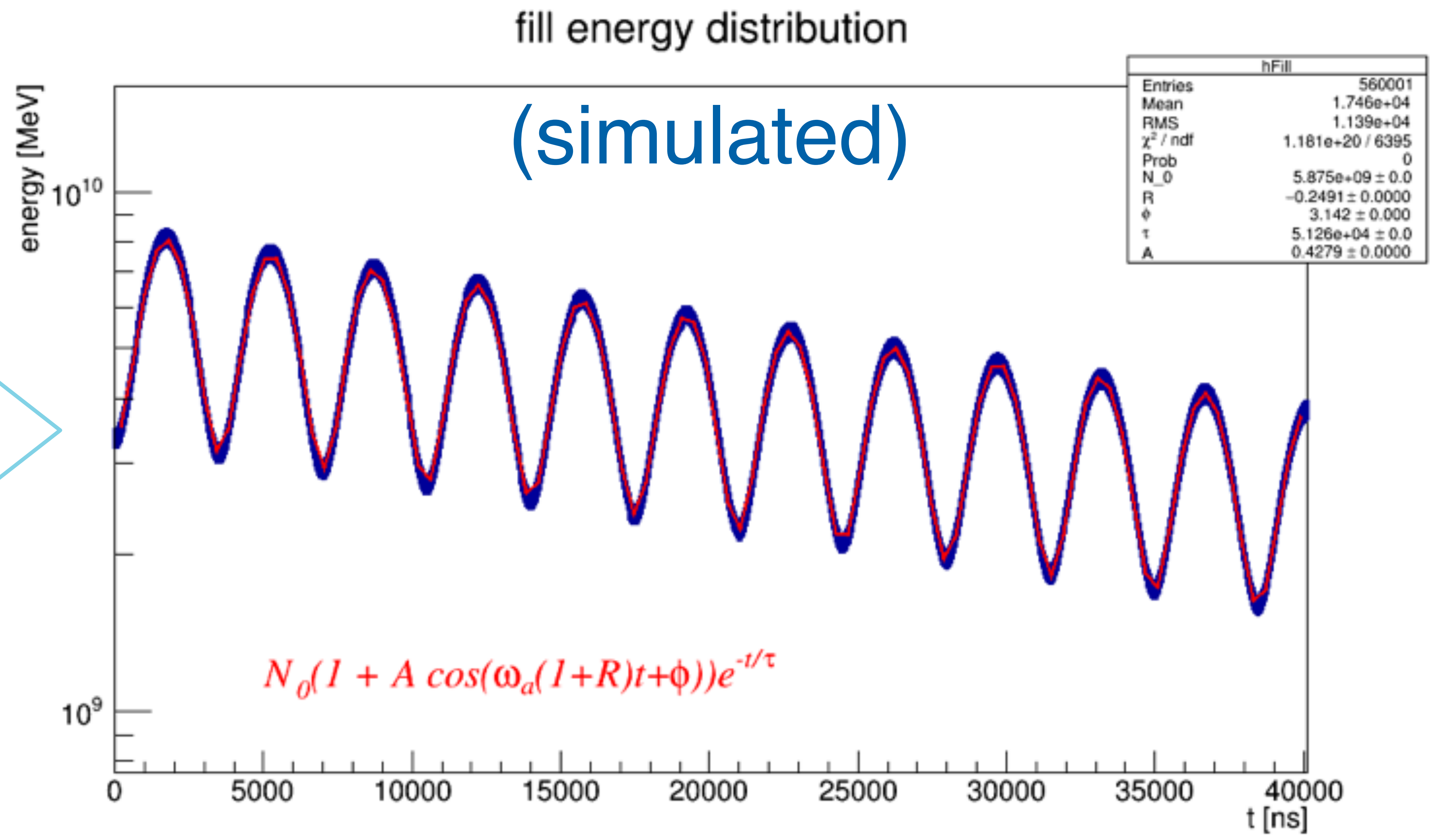


Q-method

- Full waveforms are decimated in time and summed over many fills to create a histogram that is saved in the data file.
  - i.e. If we decimate in time by 10 and flush every 100 fills, we reduce the data rate by a factor of 1000, so from 20 GB/s to 20 MB/s.
- Use smaller bins at lower times and wider bins at later times to insure that we can extract the pedestal.

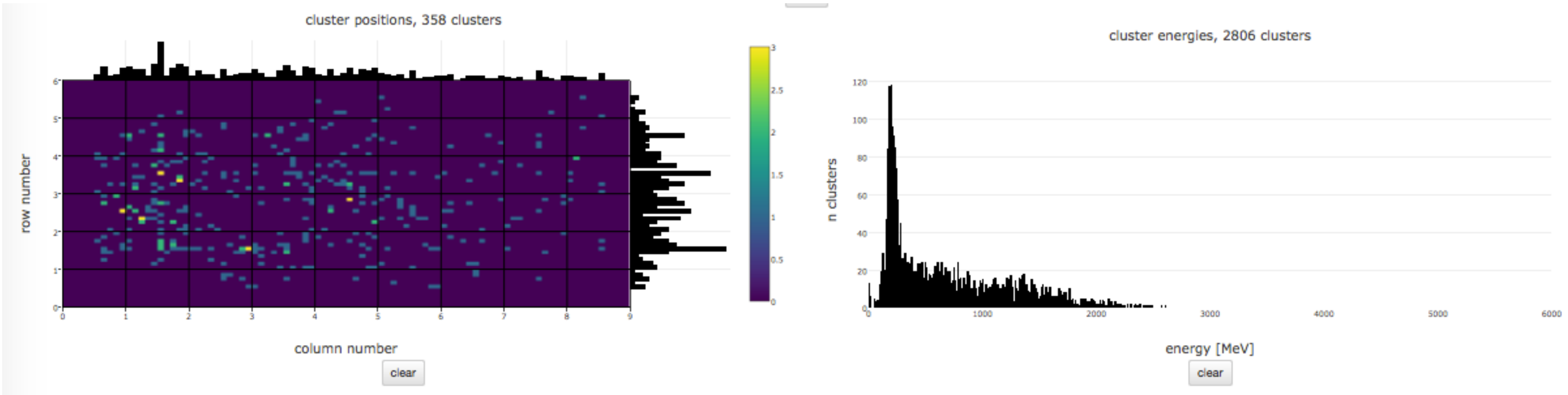






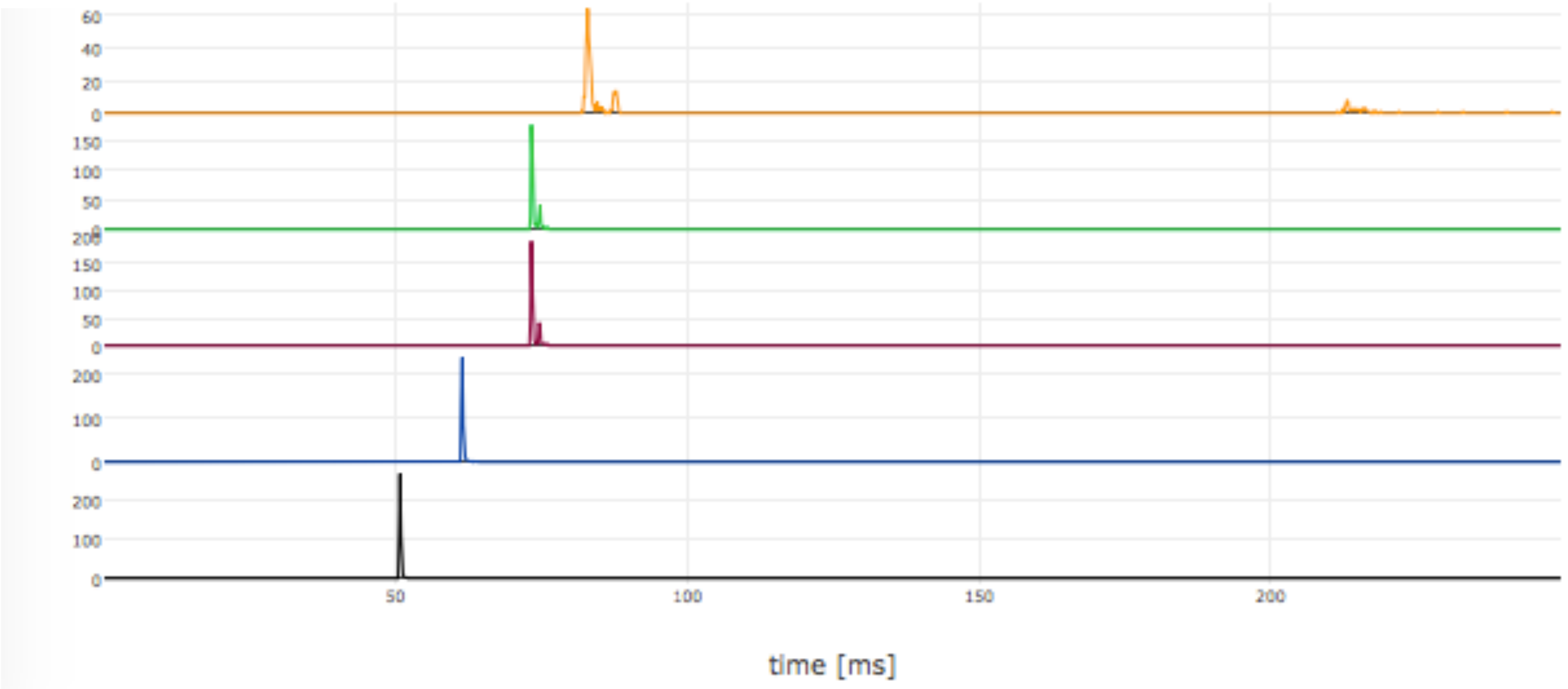
GPU Template Fits

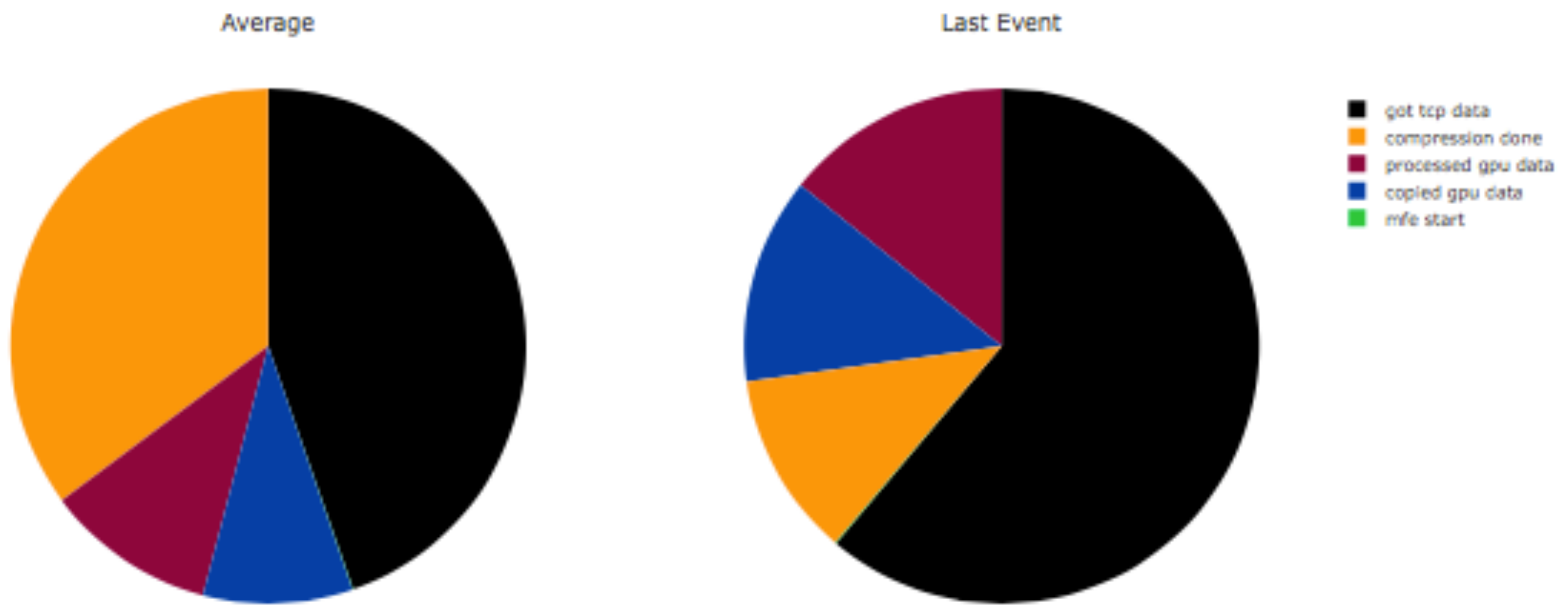
- Fit templates are loaded into the GPU memory and used to fit each peak above a certain threshold.
- A bank containing the fit results will be saved for each fill in addition to the chopped islands.
- Reduces the processing necessary in the online DQM.



Processing time

- Must process each event in 83 ms to keep up with average beam rate of 12 Hz.
- Most time is spent reading data from TCP socket and copying it to the GPU.
- Processing time in the GPU is very small.



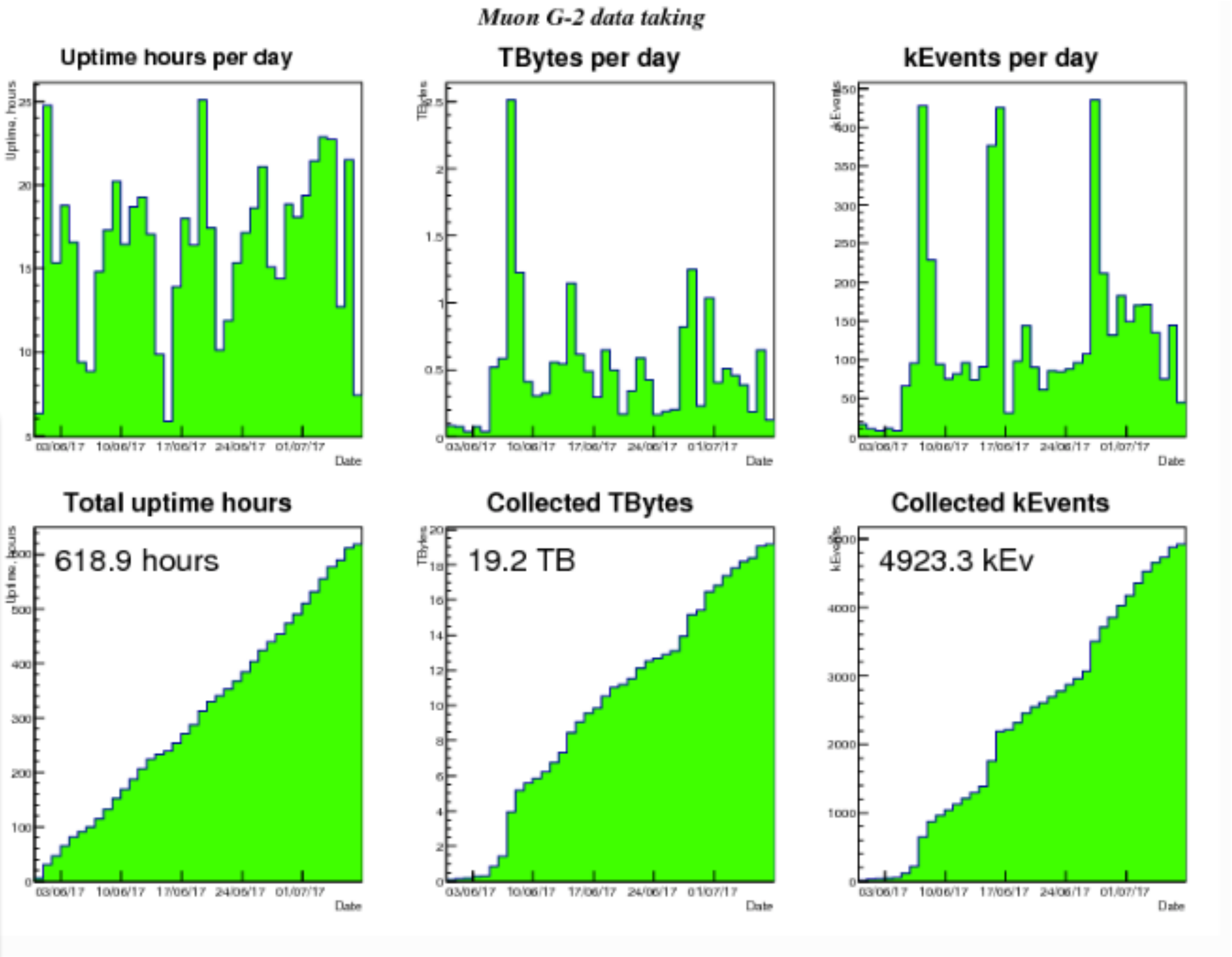


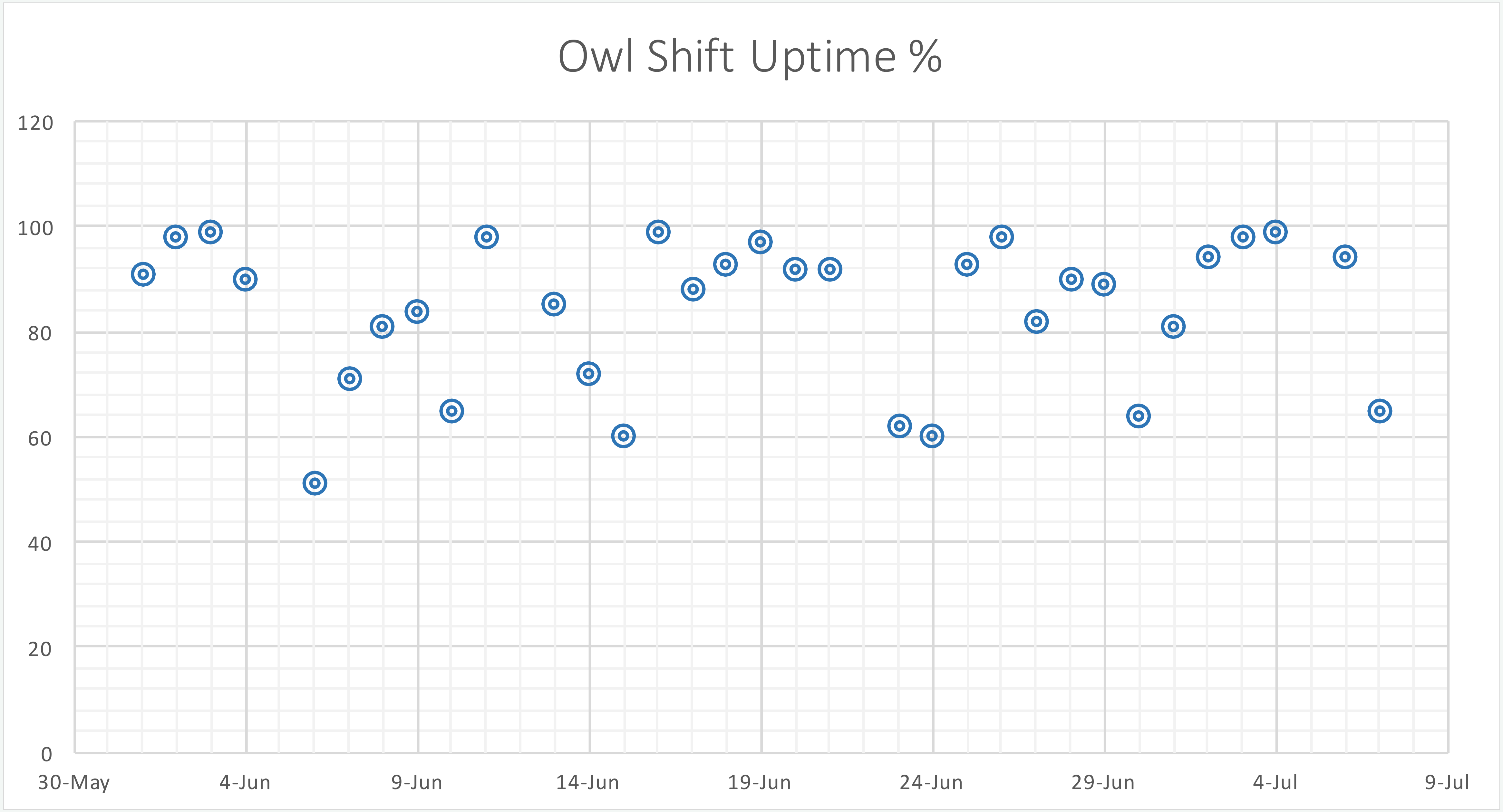
Data Quality Monitor

- Online DQM streams data from MIDAS mserver.
- Uses existing art modules to process the data.
- Data is extracted from the art job using ZeroMQ and published to a web GUI using node.js and plotly.

DAQ Performance During First Run

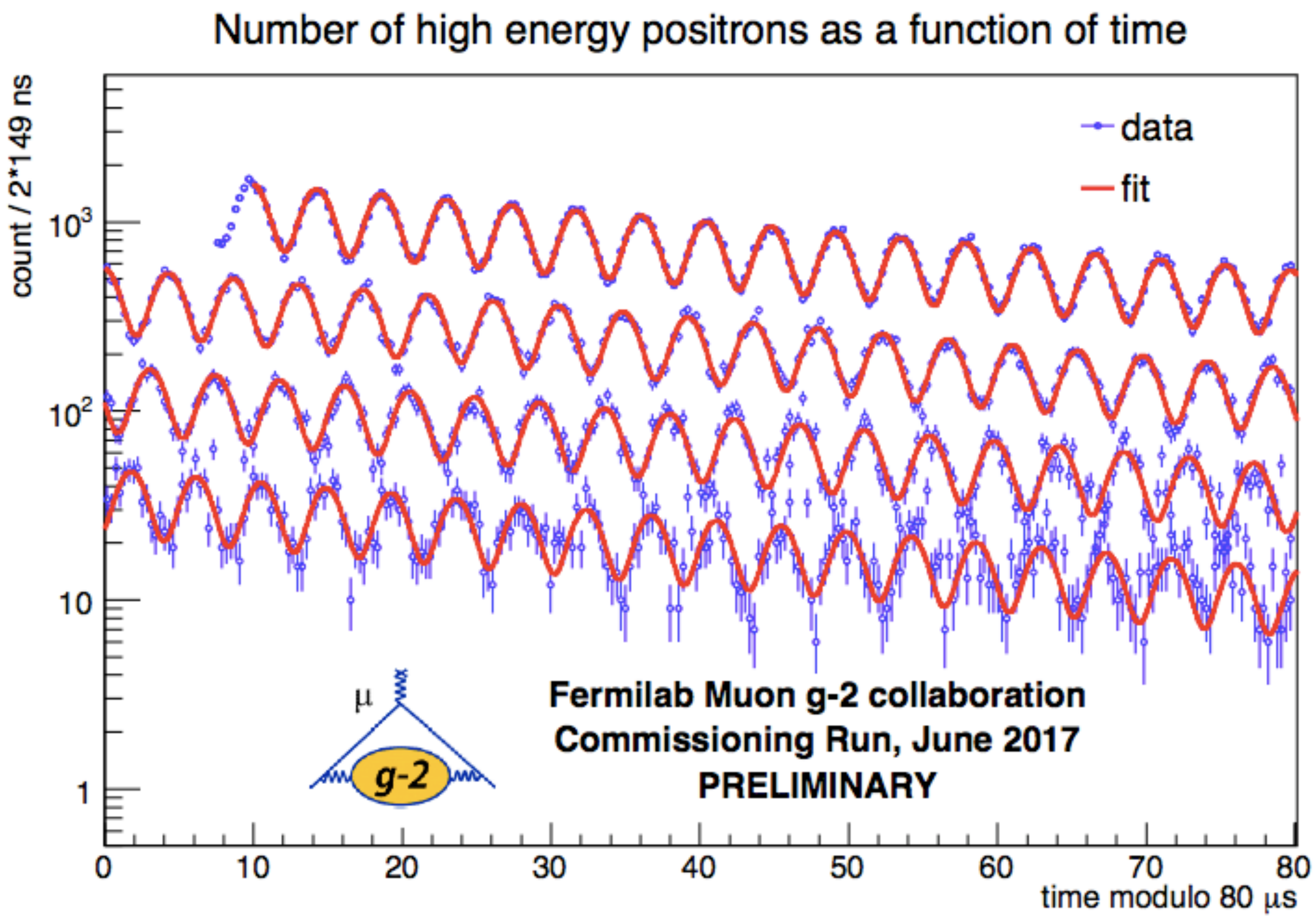
- The MIDAS DAQ performed well during our first run.
- Day shifts were mostly dedicated to beam line commissioning, so production data was taken at night.





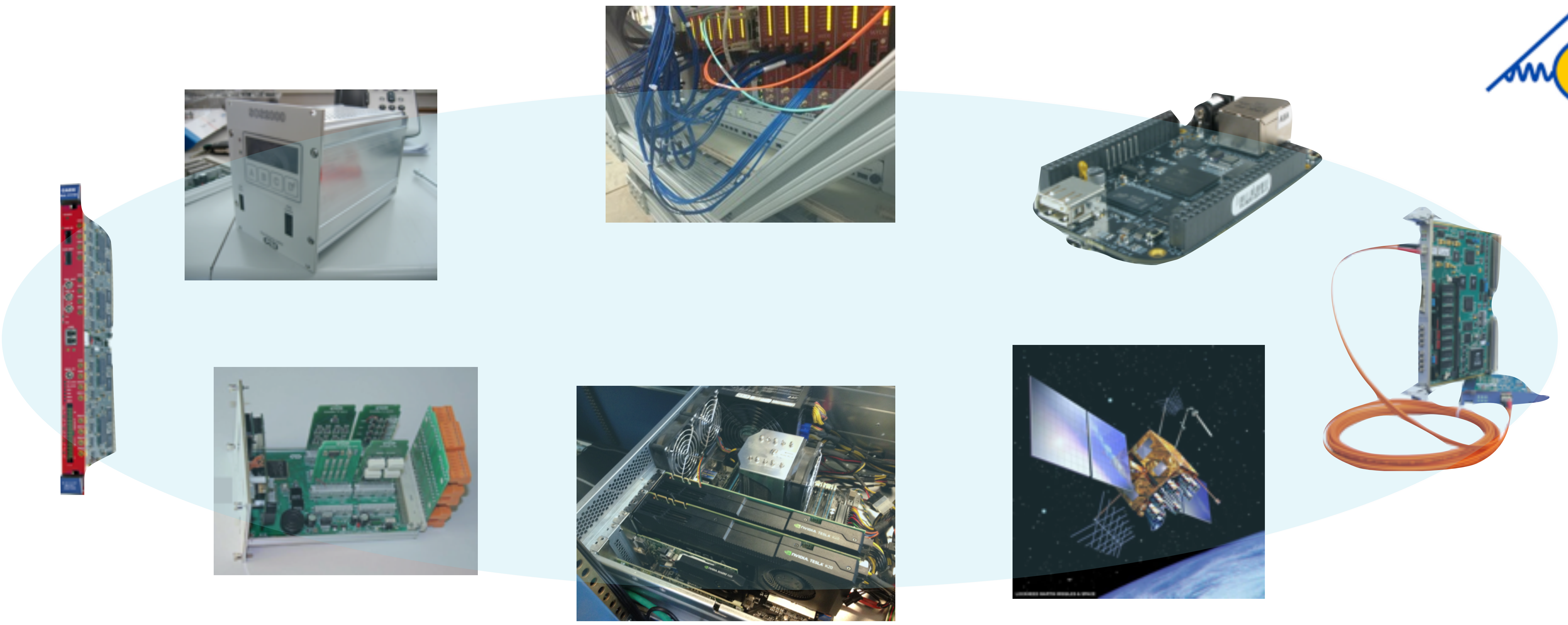
Summary

- The DAQ for Muon g-2 at Fermilab has been fully installed and performed well during commissioning.
- The DAQ hardware includes 17 frontend machines, 5 backend machines, 2 dedicated line analysis machines, 3 computers for slow control, 3 servers, and 24 beagle bones runni 67 MIDAS frontends.
- Takes an input data rate of 20 GB/s, and redu that to < 200 MB/s in the event builder via GP processing and lossless compression.
- Commissioning run in June 2017 yielded first “wiggle plot” created from ~700k positrons.



Backup

Overview



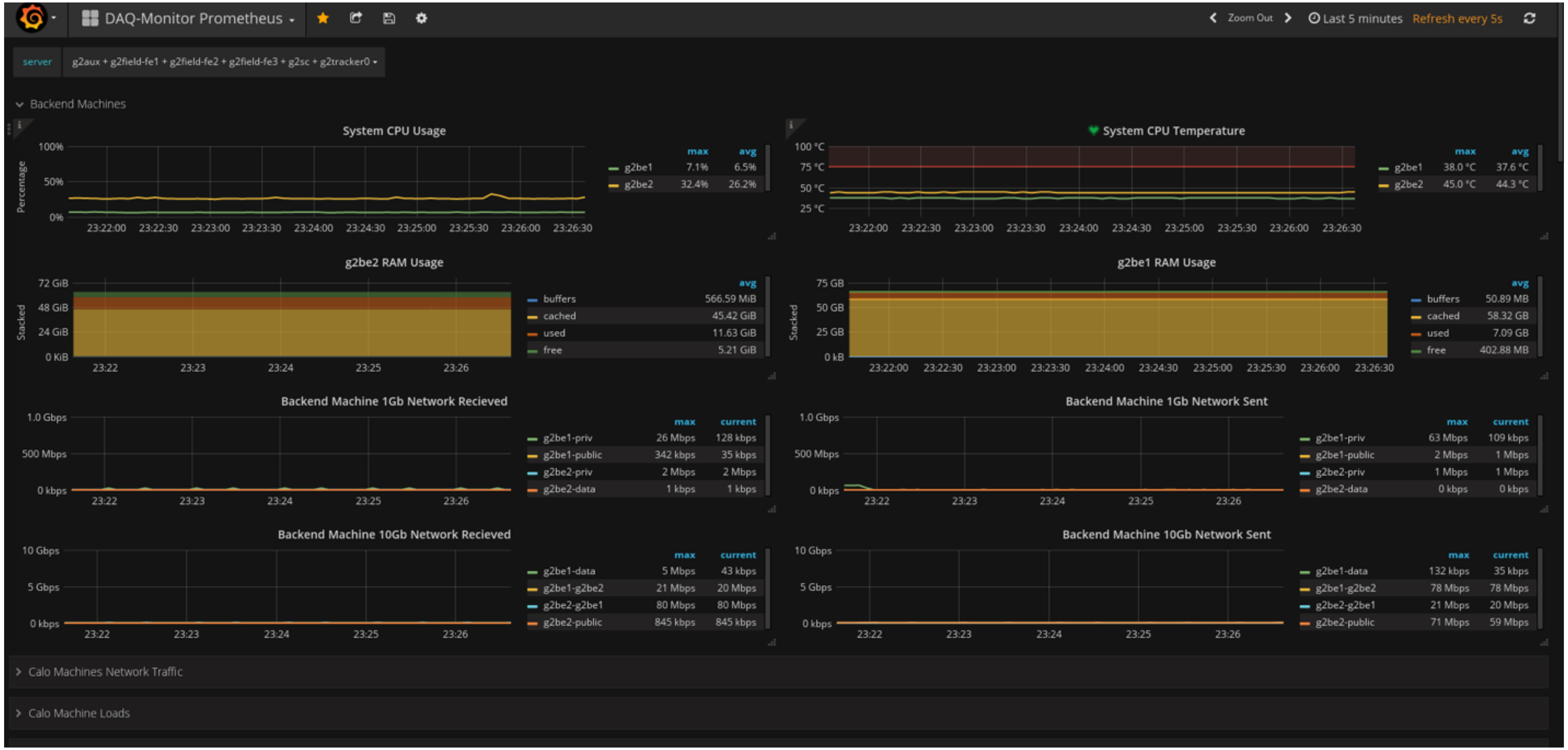
- The DAQ must assemble data from an “Internet of things” to form a complete picture of each muon fill.
- Expect an average data rate of 12 Hz for muon fills, plus some laser and pedestal fills.
- This provides data at a rate of 20 GB/s, which must be reduced via processing of data in GPUs.

Input sources

- Digitization is performed in custom uTCA based waveform digitizers.
- Each digitizer runs at 800 MSPS, so each time bin is 1.25 ns, and a 700 us fill is 560,000 clock ticks.
- Each uTCA crate contains 12 WFD5s or 60 channels of digitization.
  - Crate 0 reads data from the clock and control center (CCC)
  - Crates 1-24 each read data from one calorimeter (+ spare channels)
  - Crate 25 reads data from the laser system
  - Crate 26 reads data from the Auxiliary detectors (Harps, Quads, and Kickers)
  - Crate 27 reads data from the three tracker detectors.
- Data from each crate is sent to a DAQ computer via a dedicated 10 Gb fiber. The total data rate is 20 GB/s.
- The data is then processed in Nvidia K40 GPUs.

DAQ Health Monitor

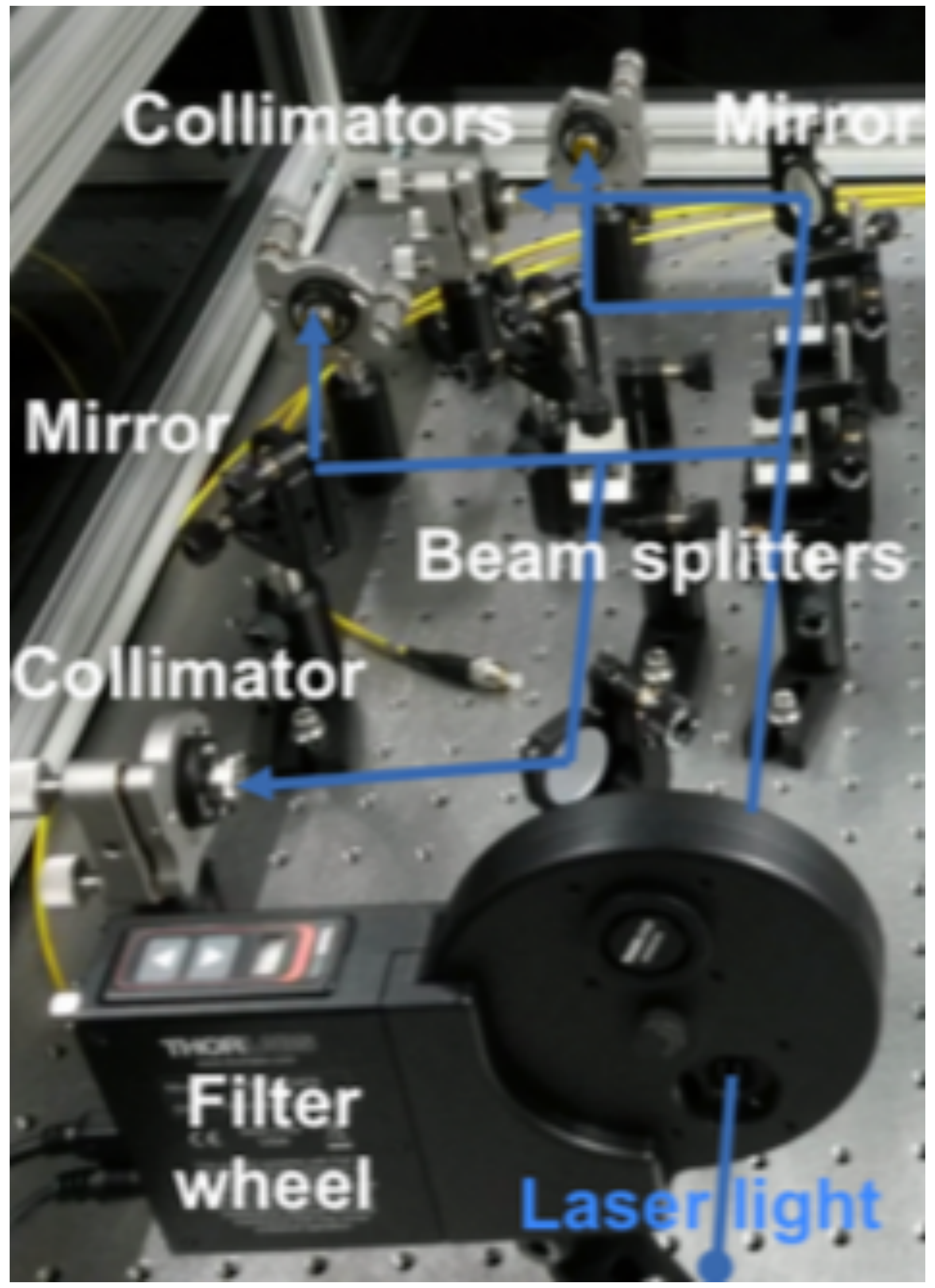
- Monitored health of DAQ systems using netdata for system monitoring, prometheus for short term data storage, and grafana to display data.

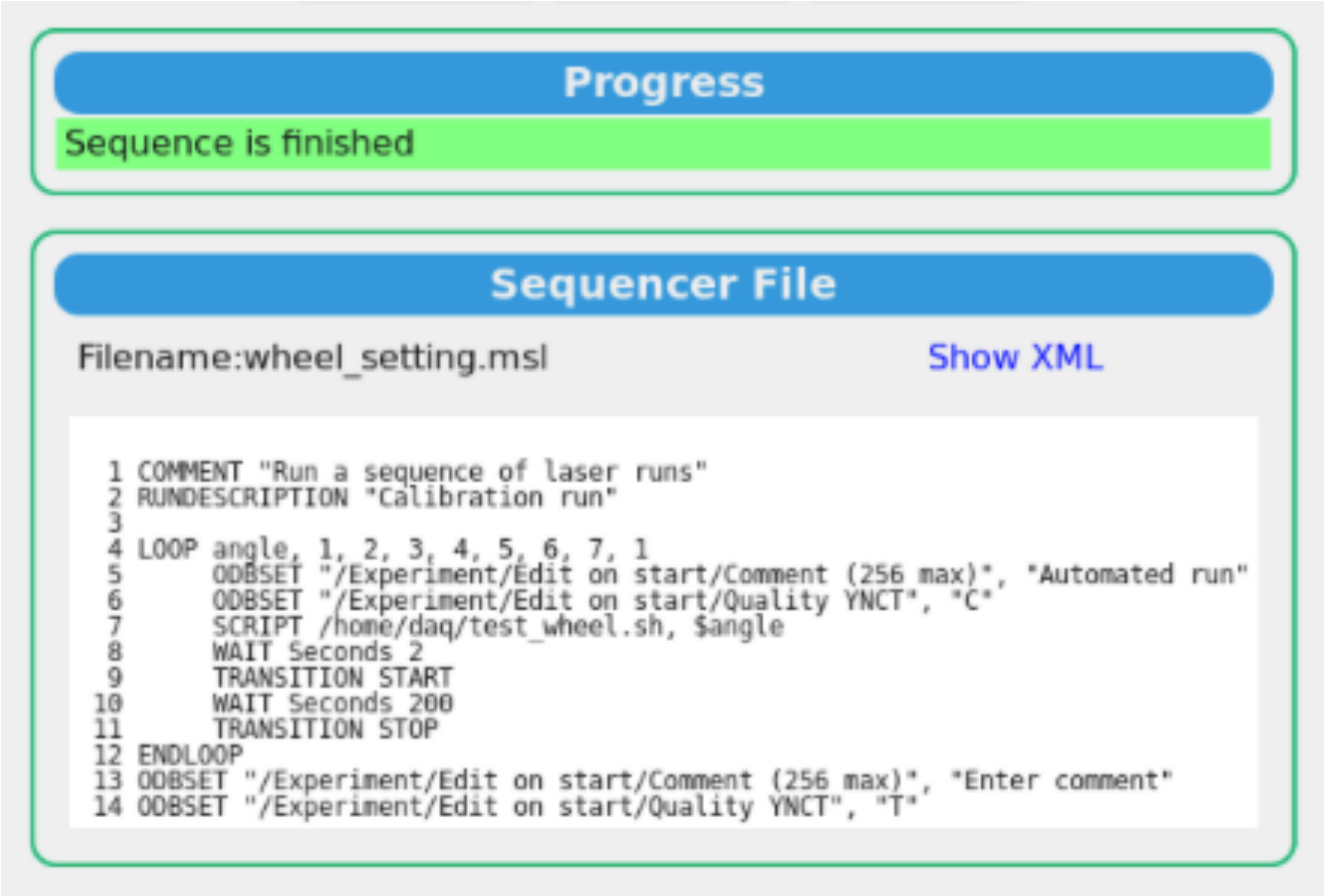


MIDAS Sequencer

- The sequencer was used extensively for calibration runs such as filter wheel scans and bias voltage scans.

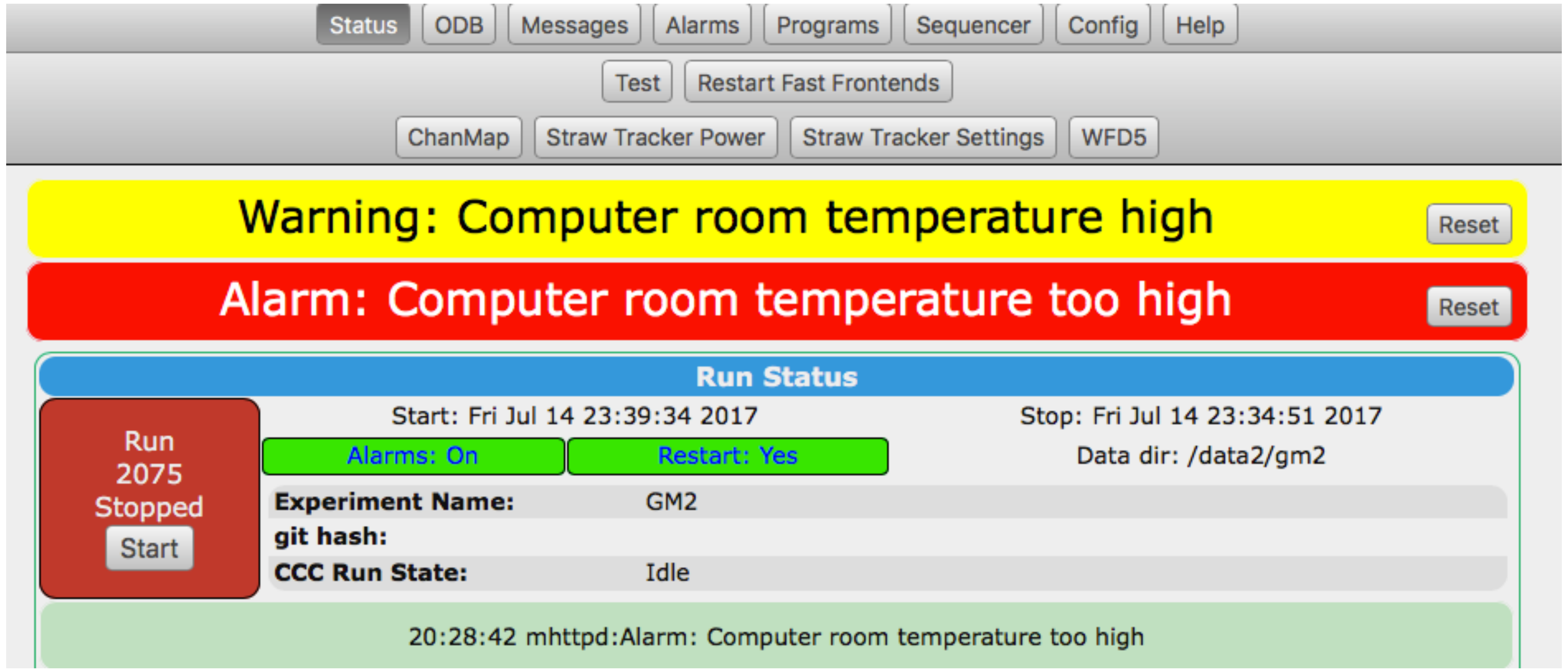
- A typical sequence would be:
  - Execute script to move wheel.
  - Update ODB values
  - Take data for 10 minutes
  - Repeat





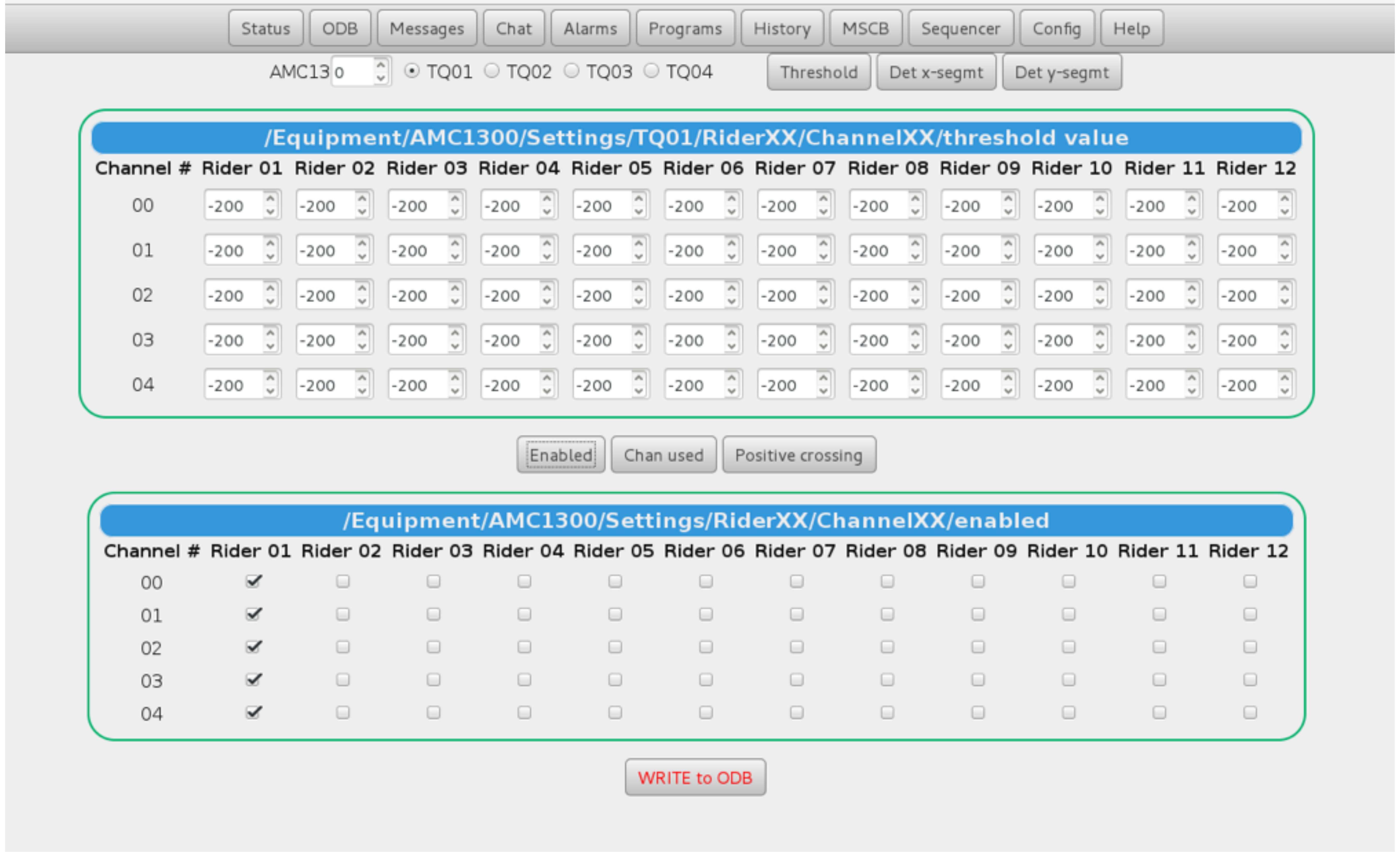
MIDAS Alarms

- The MIDAS alarm system was used as the primary alarm system.
- Alarms were set on temperatures and voltages from MSCB devices.
- Other slow frontends set alarms automatically when encountering an error.
- Periodic alarm reminded shifters to perform shift checks.
- Had problems at first with alarm audio, which was traced to a recent lack of mp3 support in scientific linux — this was later rectified with a recent update.



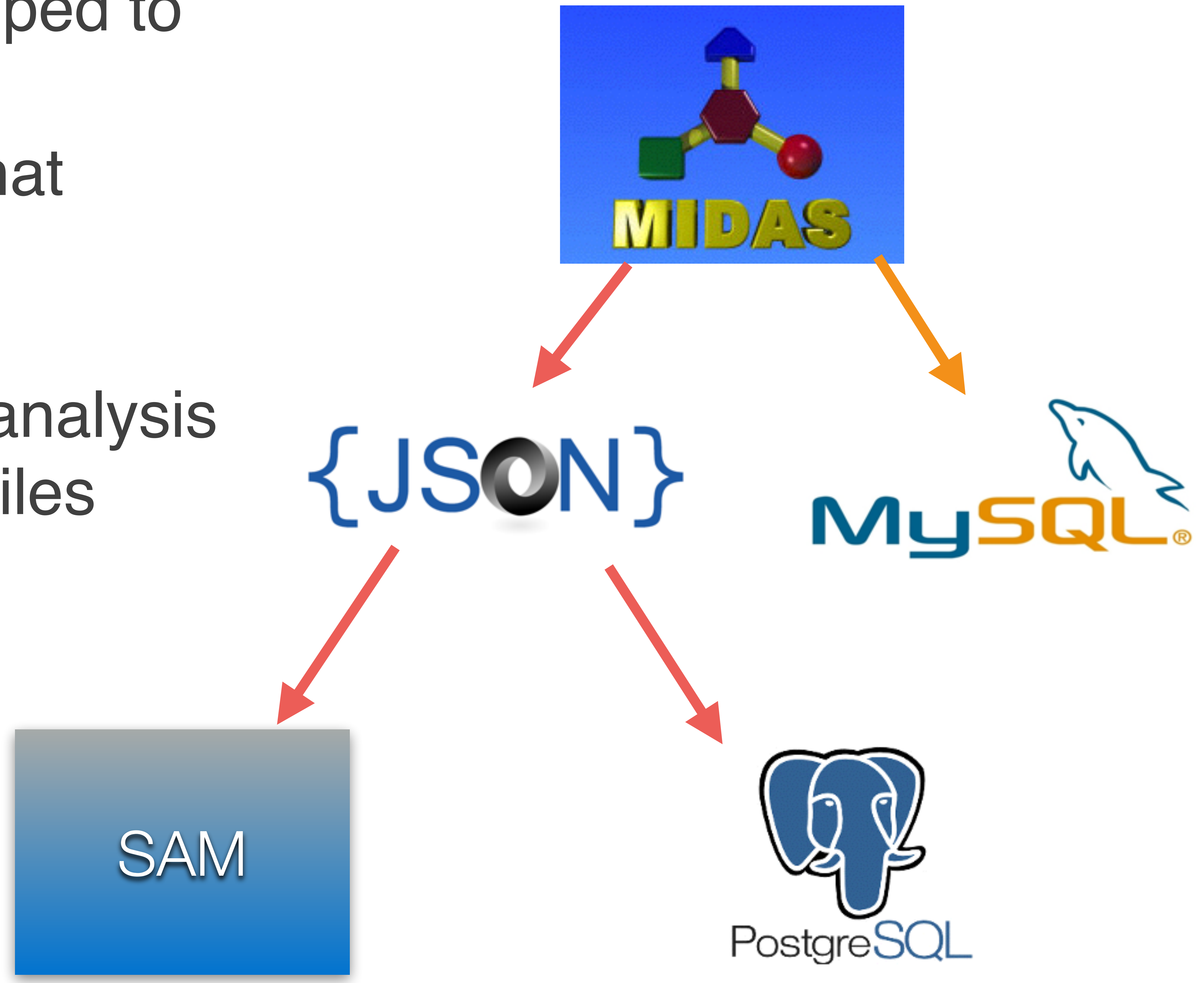
Custom Controls Page

- With this number of frontends, configuring settings via the standard ODB tree is very cumbersome.
- A set of custom Javascript pages were written to manipulate ODB values en masse.



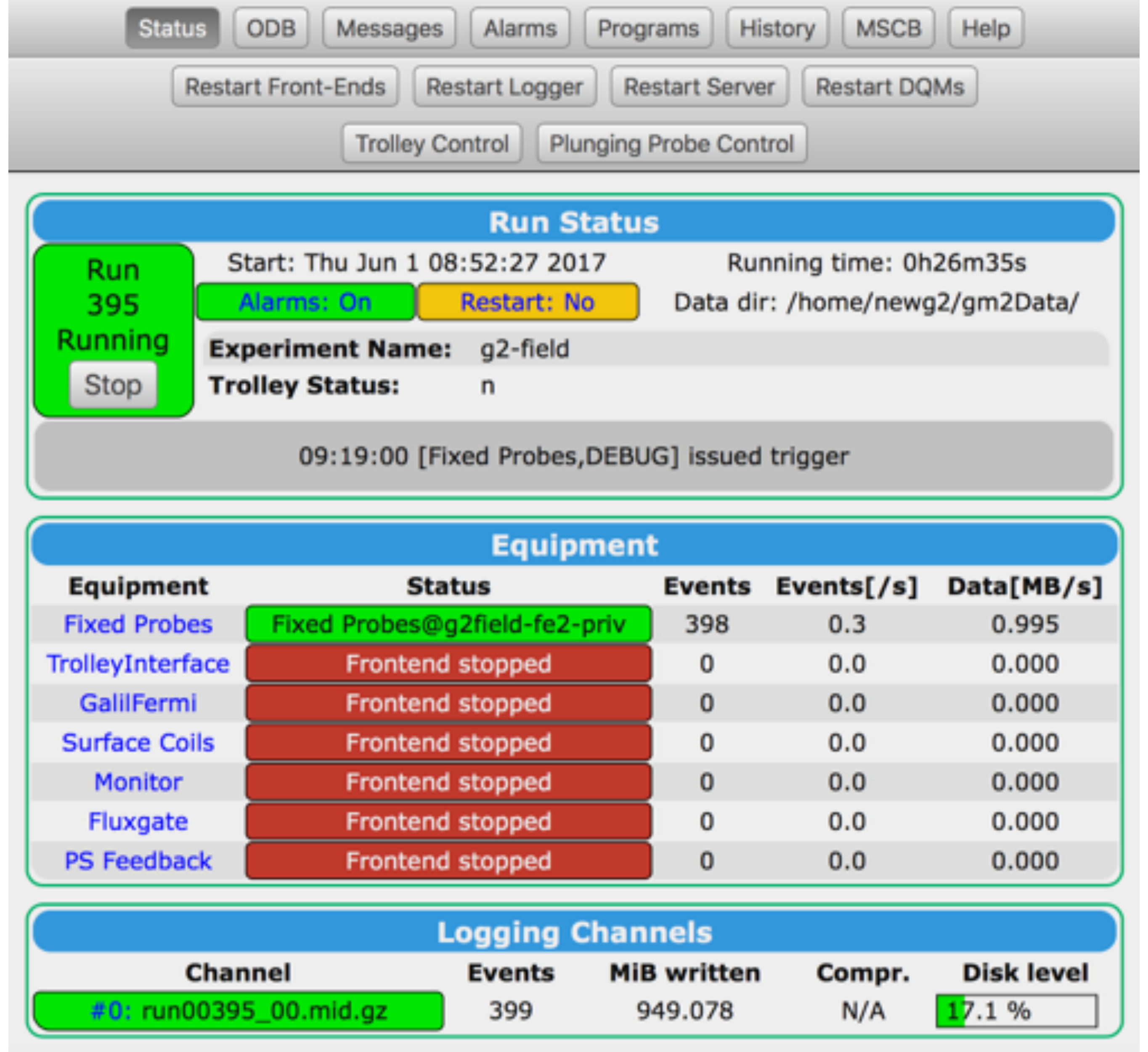
MIDAS ODB Archive

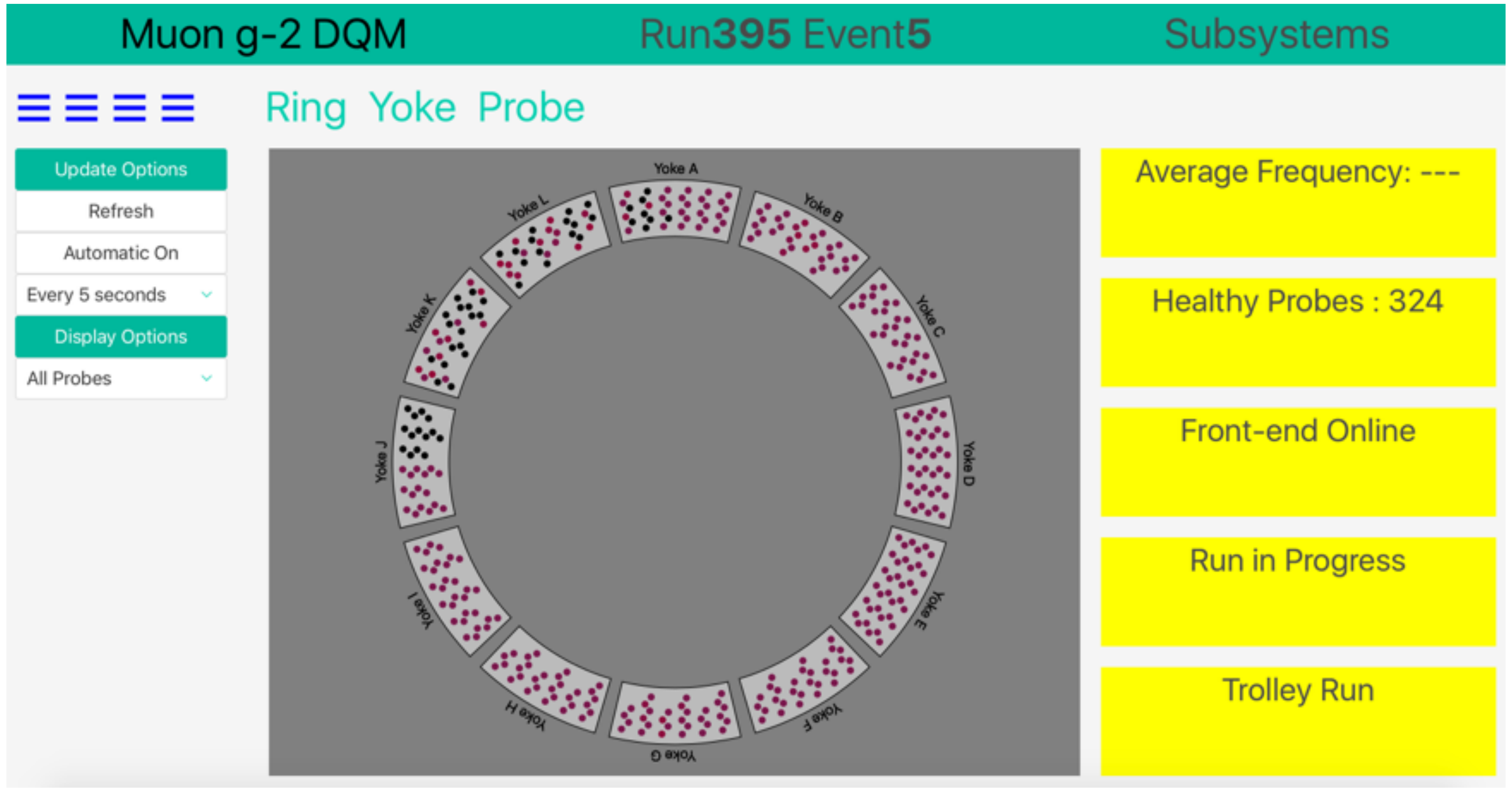
- At each end of run, the ODB is dumped to a JSON file.
- A python routine is then executed that imports the entire JSON file into a PostgreSQL database.
- Metadata that is used in the offline analysis is also extracted from these JSON files using python plugins.



Field DAQ

- Field DAQ runs in independent MIDAS experiment.
- Contains seven asynchronous frontends reading data from fixed magnetic field probes and from a trolley that periodically transverses the ring to perform precision measurements of magnetic field.
- Data is correlated with the fast DAQ offline using GPS timestamps.





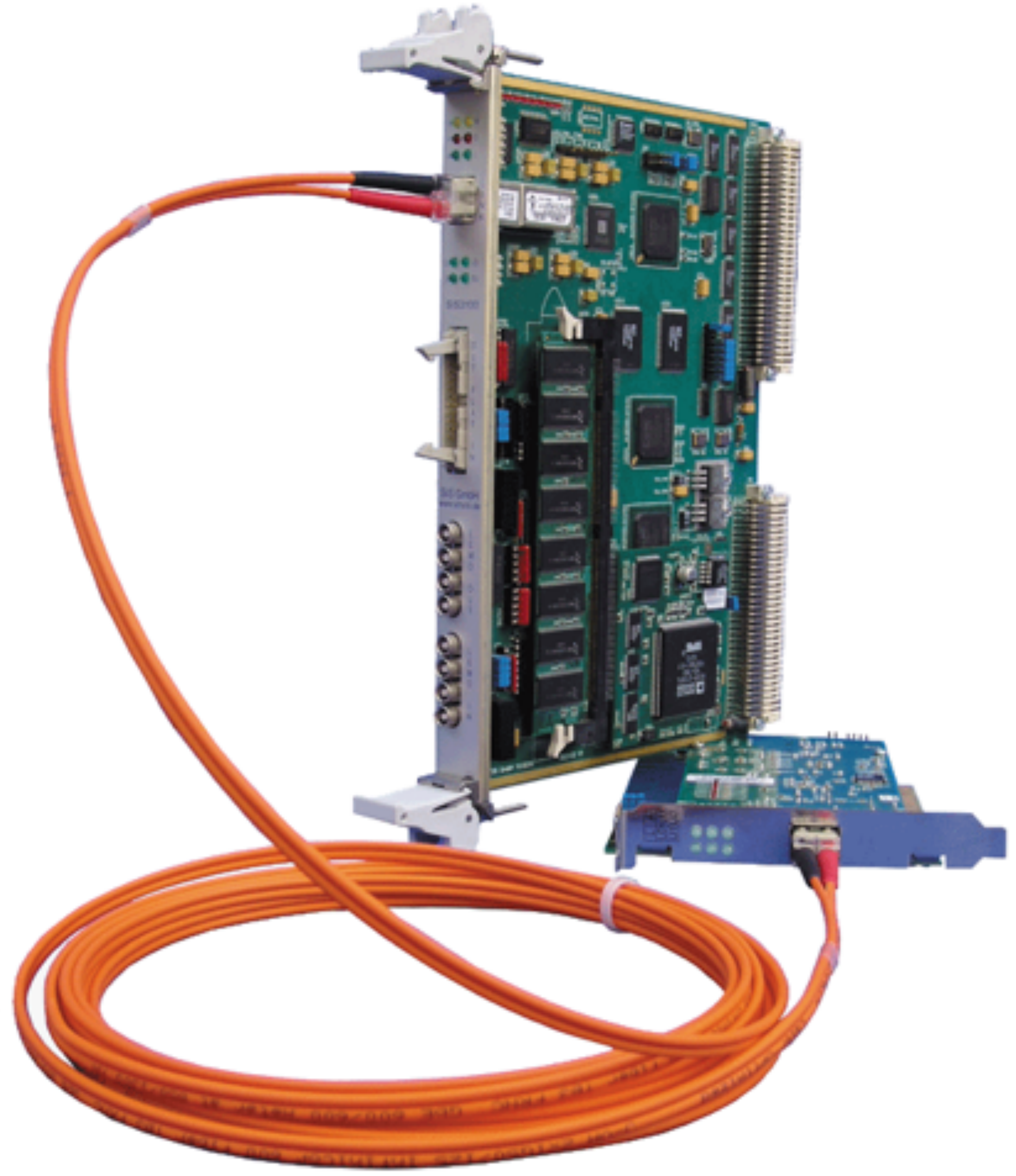
Slow Controls

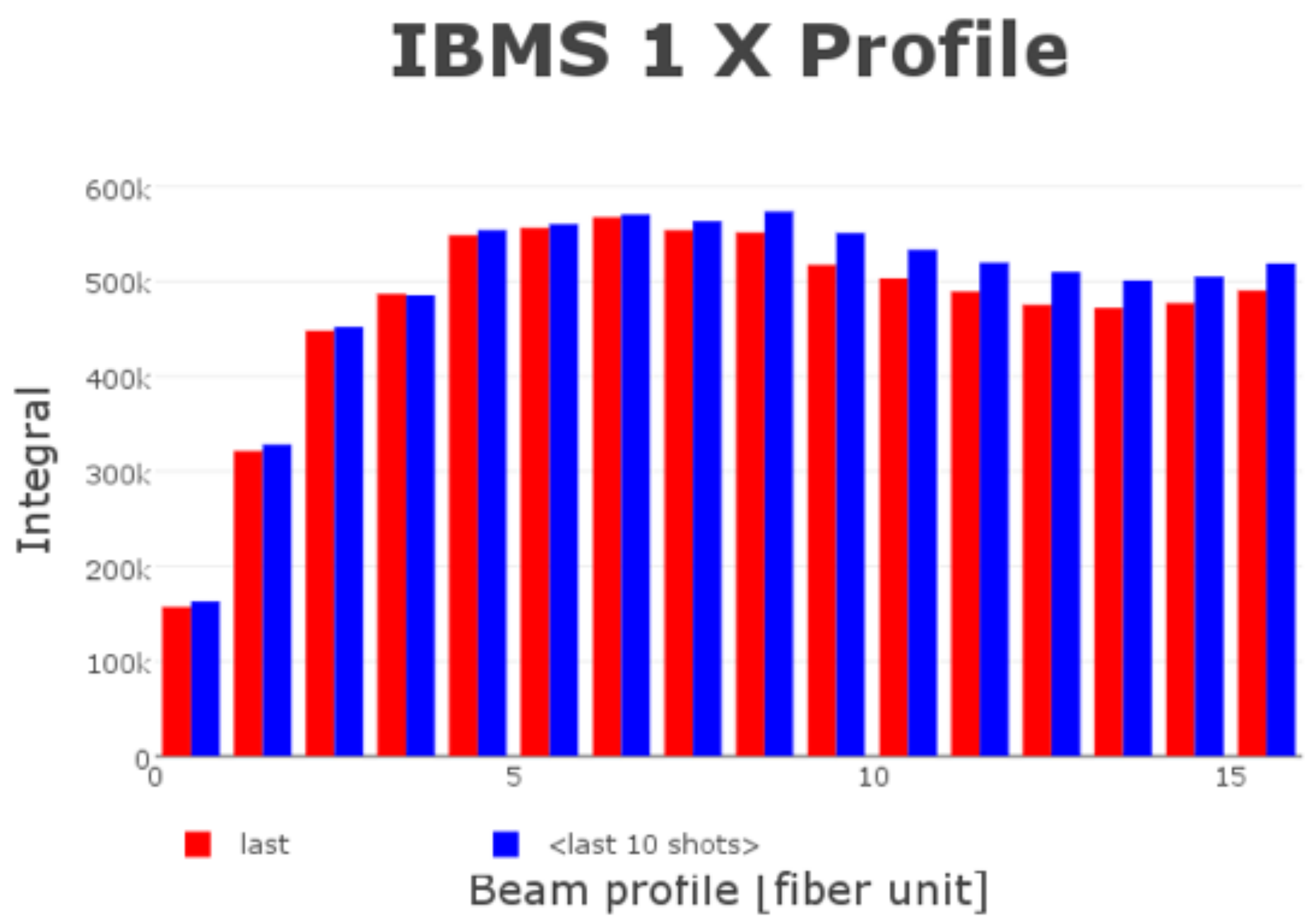
- DAQ includes six SCS3000 mscb devices.
- 24 beaglebones reading slow control data from calorimeters.
- HV and LV frontends for tracker system.
- Slow frontend reading magnet properties from IFIX via an OPC client.
- Beamline frontend periodically reading output of beam components from database.
- Slow control data is stored in a Postgres database and displayed using a custom Django web display.

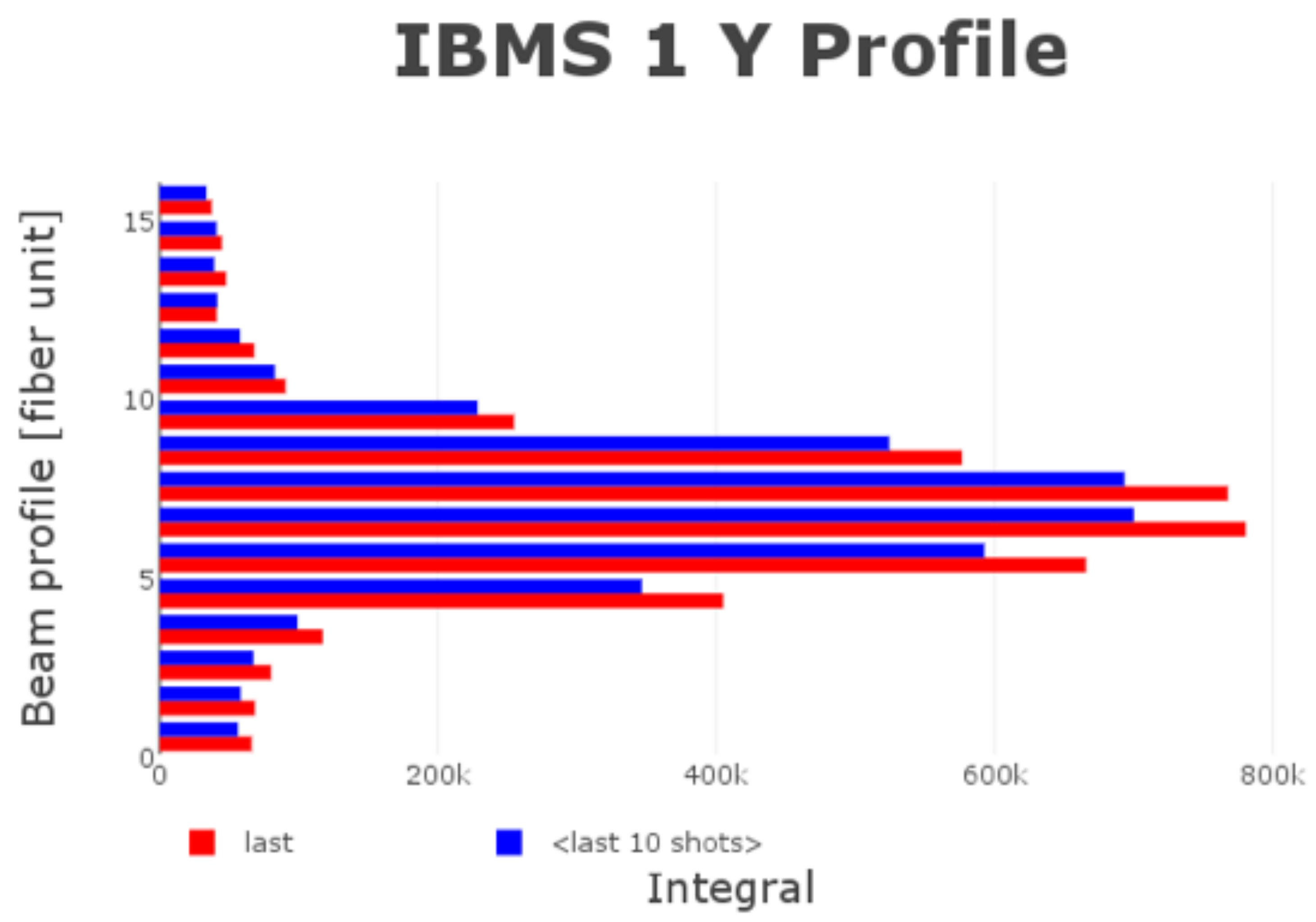
Fermilab

IBMS Frontend

- Data from the inflector beam monitoring system (IBMS) is read out via a CAEN digitizer.
- A custom MIDAS frontend was written to integrate this detector into the DAQ.

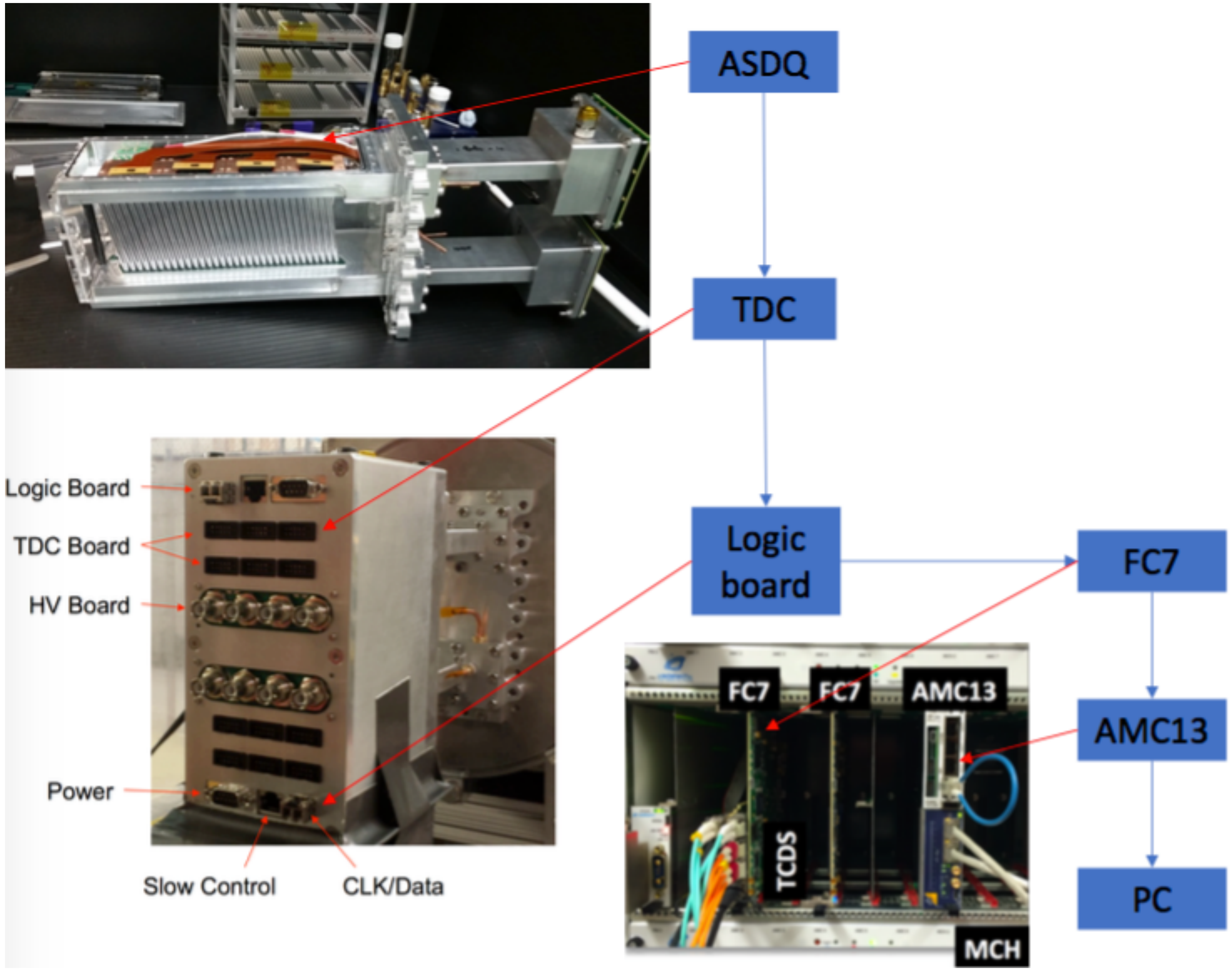






Tracker Frontend

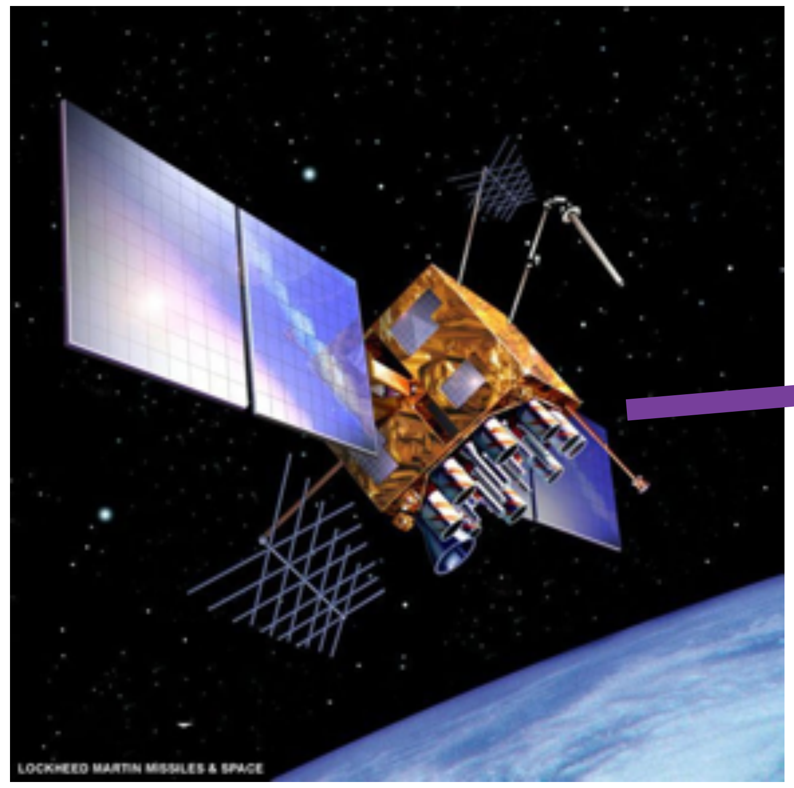
- Three tracker stations will be read via one uTCA crate.
- Reads data from AMC13.
- Instead of digitizers, data comes from multihit TDCs that are read via FC7 cards.



(Thanks R. Chislett for the diagram)

MasterGM2 frontend

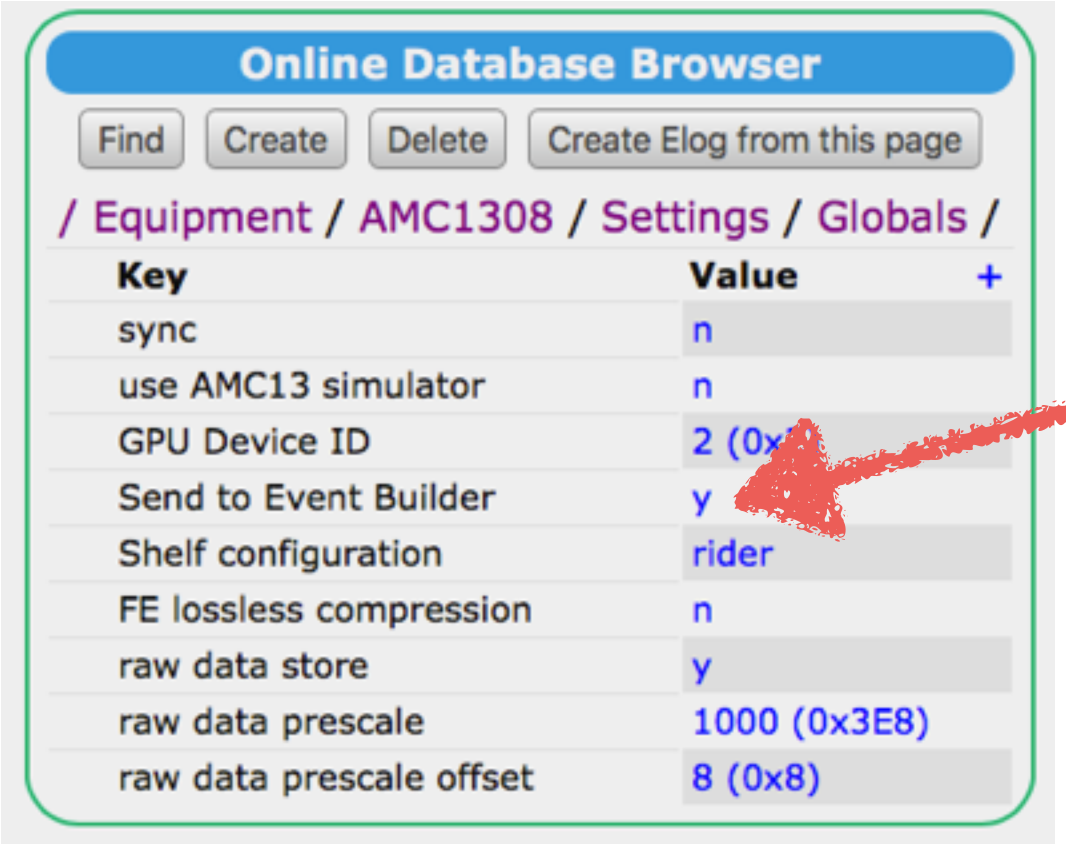
- Communicates with other frontends using RPC calls.
- Provides begin of run and end of run RPCs to all frontends.
- Provides end of fill trigger to synchronous frontends.
- Configures clock and control system.
- Reads trigger times from Meinberg GPS unit and writes them to a MIDAS bank.



```
Bank:GPS0 Length: 20(I*1)/5(I*4)/5(Type) Type:Unsigned Integer*4
   1-> 0x000018c2 0x580838bc 0x5dcabfb0 0x580838bc 0x5dd48308
```

Event builder

- Modified event builder to change how it is enabled — now done entirely in ODB Equipment of each frontend.



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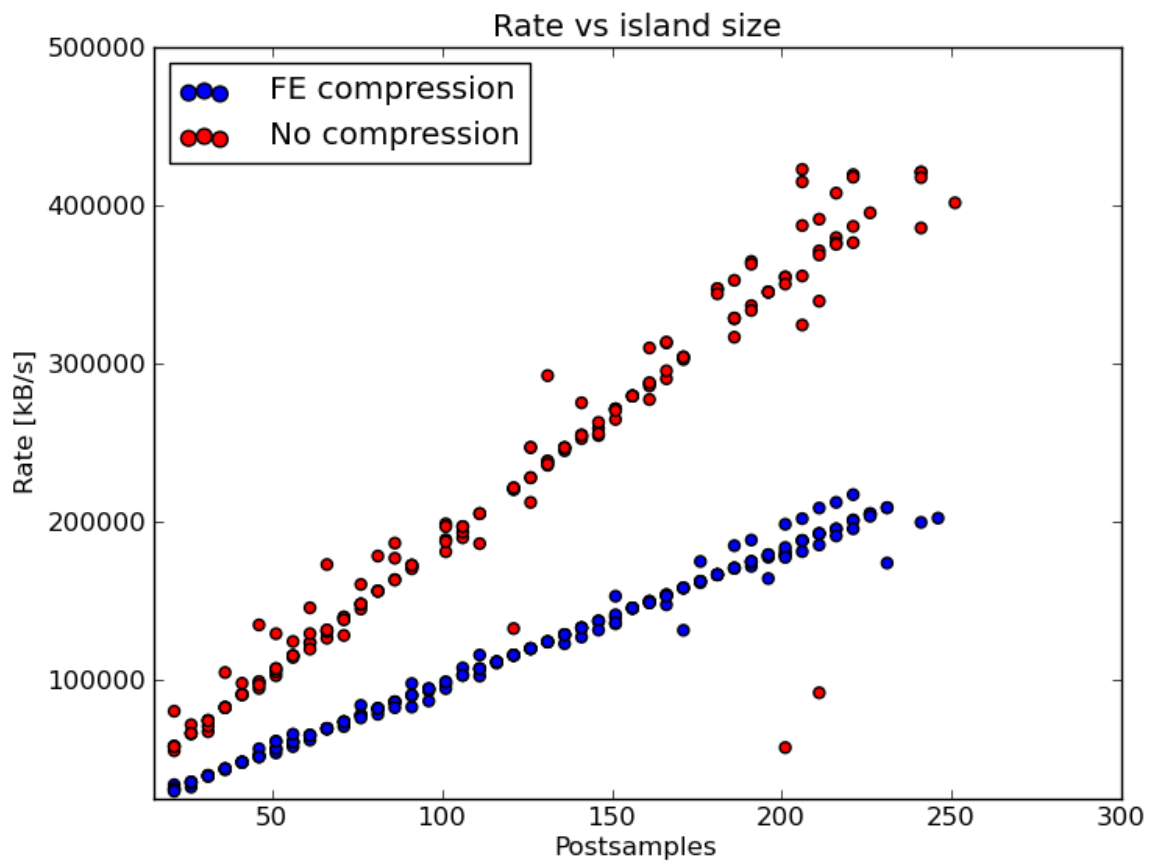

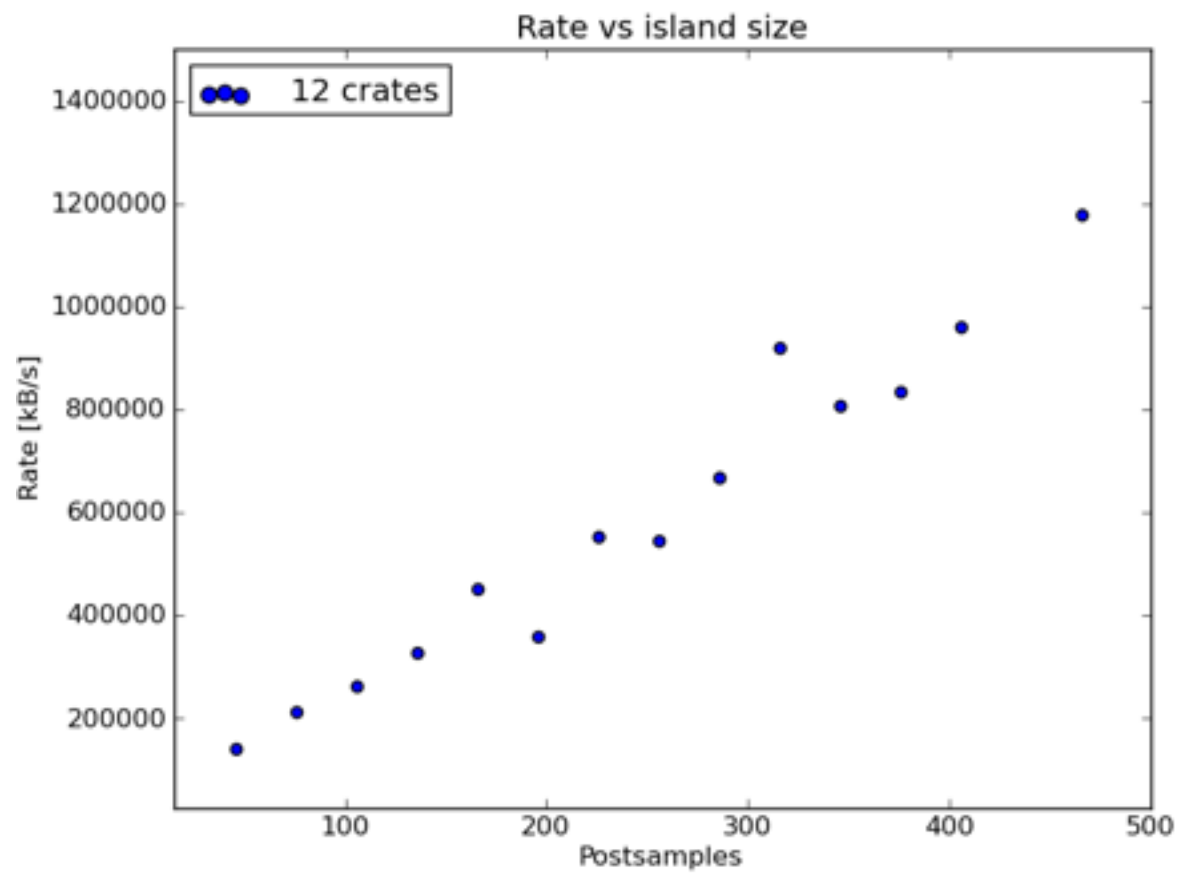

- Total EB rate maxed out at > 1.2 GB/s (limited by network bandwidth)
- The event builder combines up to 270 banks for each event.