Muon g-2 Experiment at Fermilab.

g-2: Real Collaboration / Virtual Ring

Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

National Labs

- Argonne
- Brookhaven
- Fermilab

Italy

- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:

- Shanghai

The Netherlands:

- Groningen

Germany:

- Dresden

Russia:

- Dubna
- Novosibirsk

England

University College London

Liverpool

Oxford

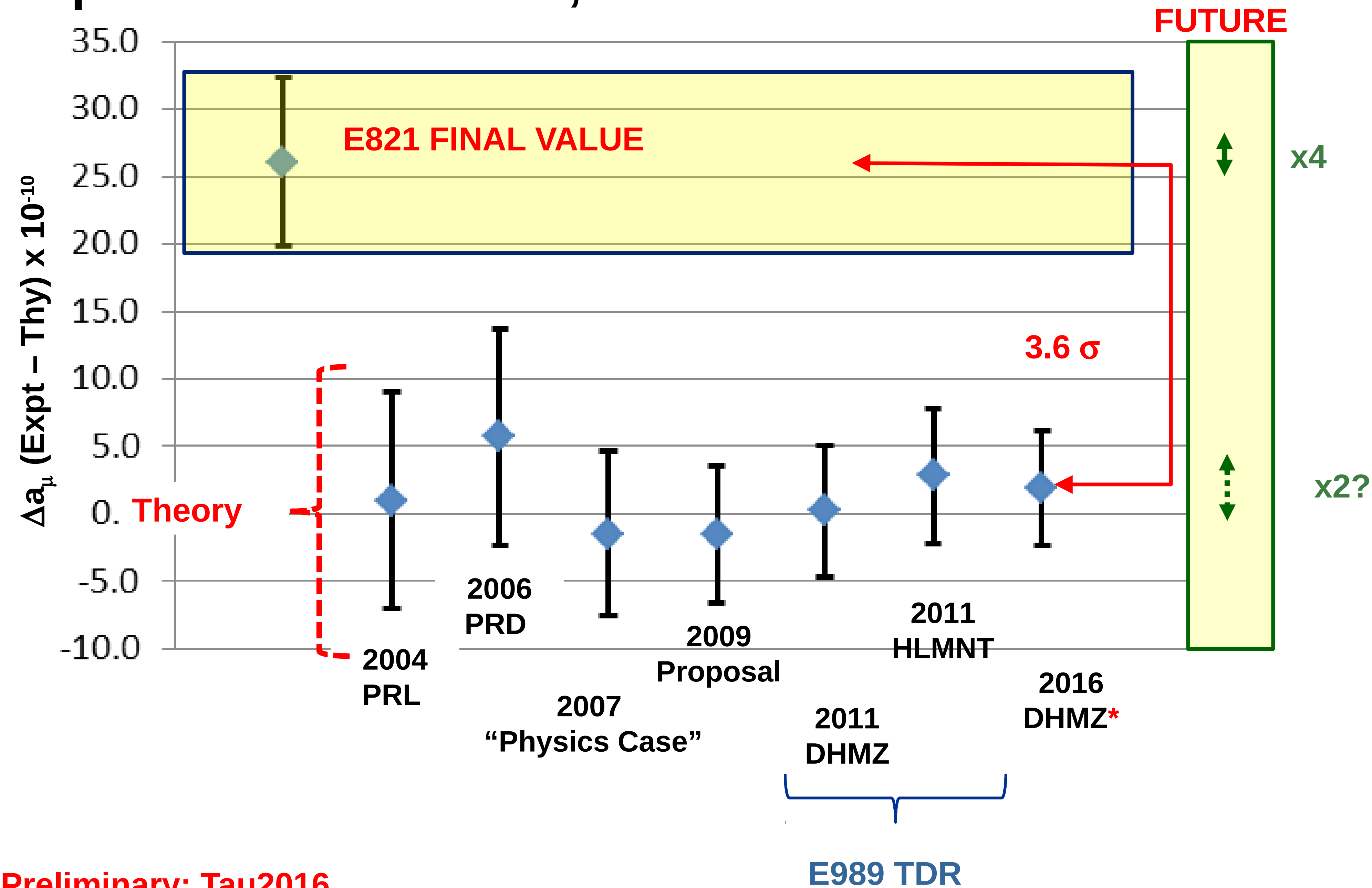
Korea

KAIST

~33 institution, ~150 members

D.W. Hertzog, Co-Spokesperson
B.L. Roberts, Co-Spokesperson
C. Polly, Project Manager

The goal of E989 is a x4 improvement over BNL That's 140 ppb. 100 ppb statistics; 70 ppb systematics for precession and field, each



*Preliminary; Tau2016

Layout of FNAL experiment

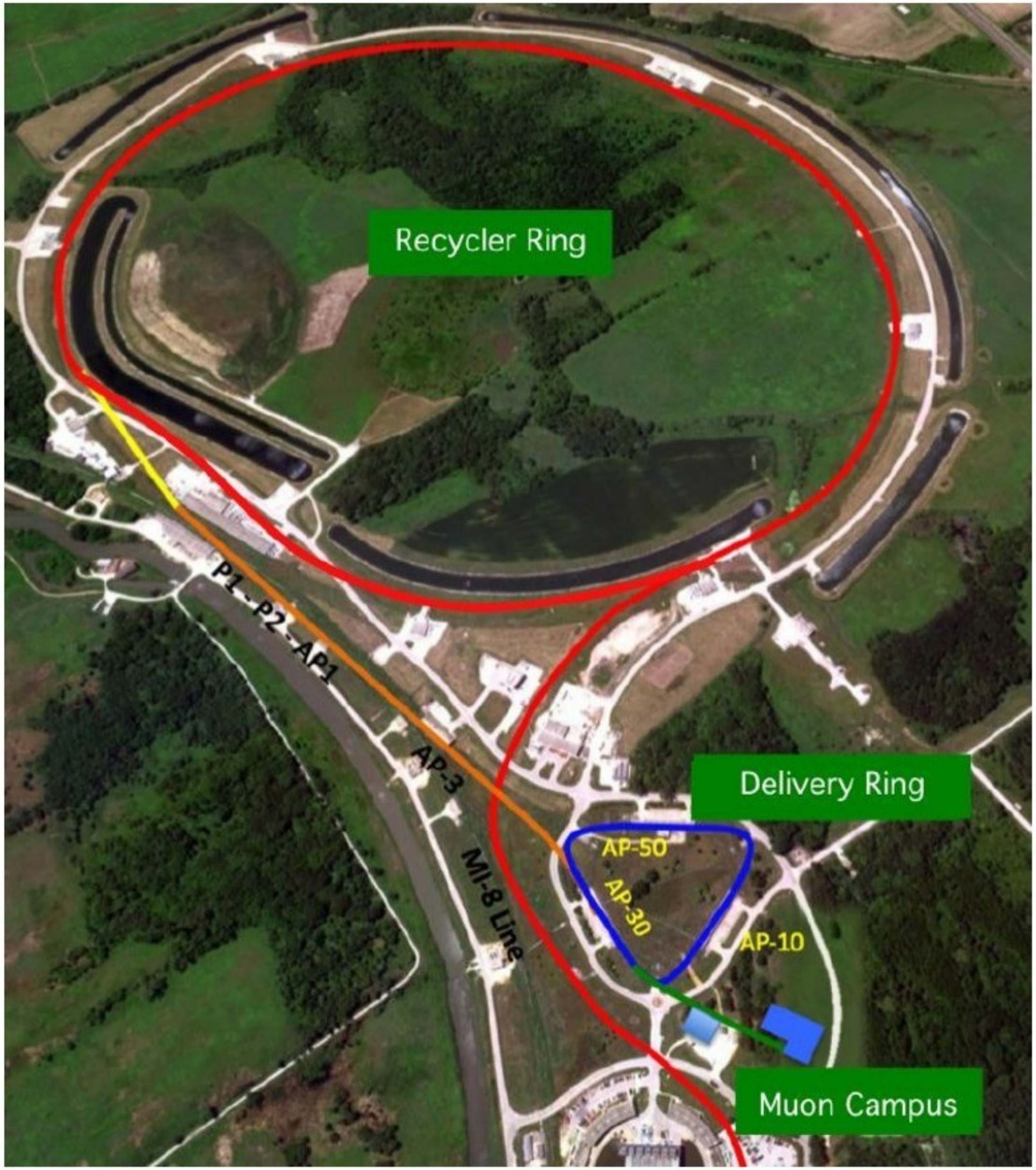
- 8 GeV/c protons from the Booster are rebunched in Recycler Ring
- Transfer line and Delivery Ring (part of old $\bar{p}$ source) make ~2 km decay line. No hadron background!

20 times more statistics!

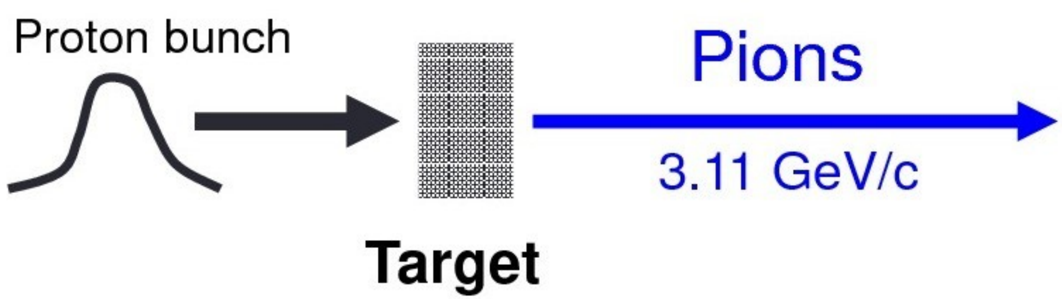
The effective beam power is smaller at FNAL by x4.

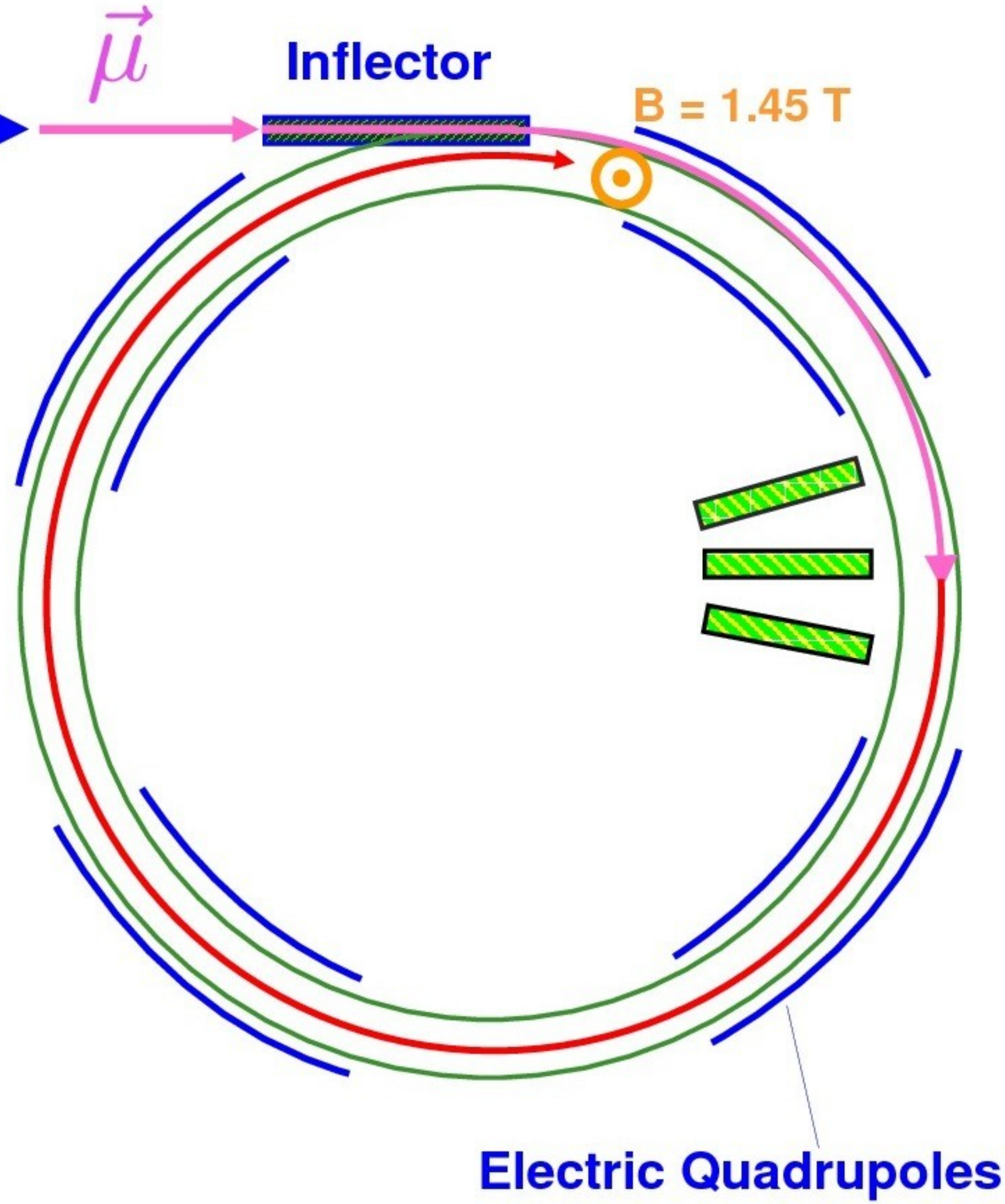
Need to recover factor ~80:

- more efficient collection and transmission
- longer decay line
- longer running time
- more efficient data analysis

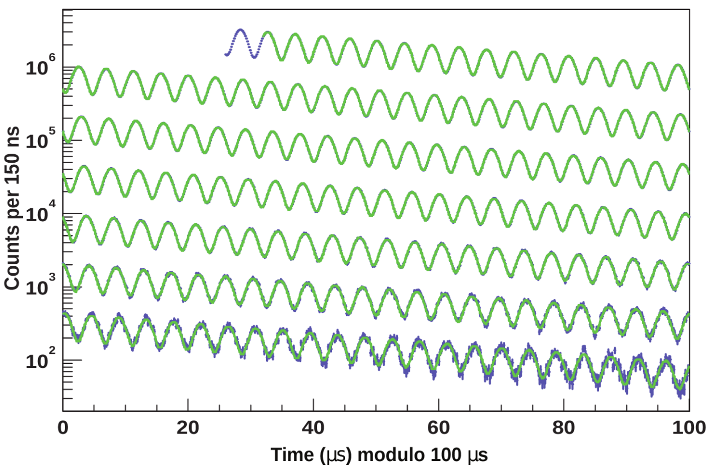


Muon g-2: Storing Muons

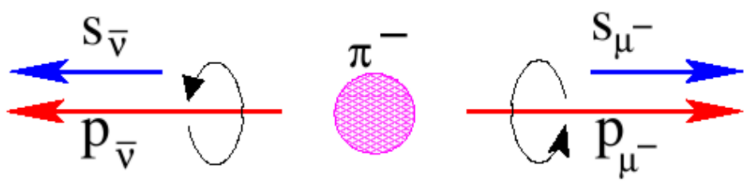




- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are off central orbit
- Kicker magnets move the orbit to the centre of the storage ring
- Muons focused vertically with electrostatic quadrupoles



1. Produce & inject polarized muons from pion beam



2. Kick the muon beam onto the ring closed orbit

3. muon γ=29.3 → vertical E-field focusing

$$\vec{\omega}_a = -\frac{Qe}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

~0

4. Muon spin precession relative to momentum in cyclotron is directly proportional to a_μ

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{\mu_e}\frac{g_e}{2}$$

$$\omega_p \propto |\overrightarrow{B}|$$

Two quantities to measure to extract a_μ

5. muon V-A decay → highest energy positron emitted with its momentum parallel to muon spin.

Look at the rate of the highest energy positron → ω_a modulation:

→ Count e^+ with $E_{e+} > E_{threshold}$

From ω_a/ω_p to a_μ (1)

How to extract a_μ from the frequencies we measure?

$$\left.\begin{aligned} \omega_a &= \frac{e}{m_\mu} a_\mu B \\ \hbar\omega_p &= 2\mu_p B \\ \mu_e &= g_e \frac{e\hbar}{4m_e} \end{aligned}\right\} \rightarrow a_\mu = \frac{\omega_a}{\omega_p} \cdot \frac{g_e}{2} \cdot \frac{\mu_p}{\mu_e} \cdot \frac{m_\mu}{m_e}$$

measured in experiment, 140 ppb (ω_a/ω_p)

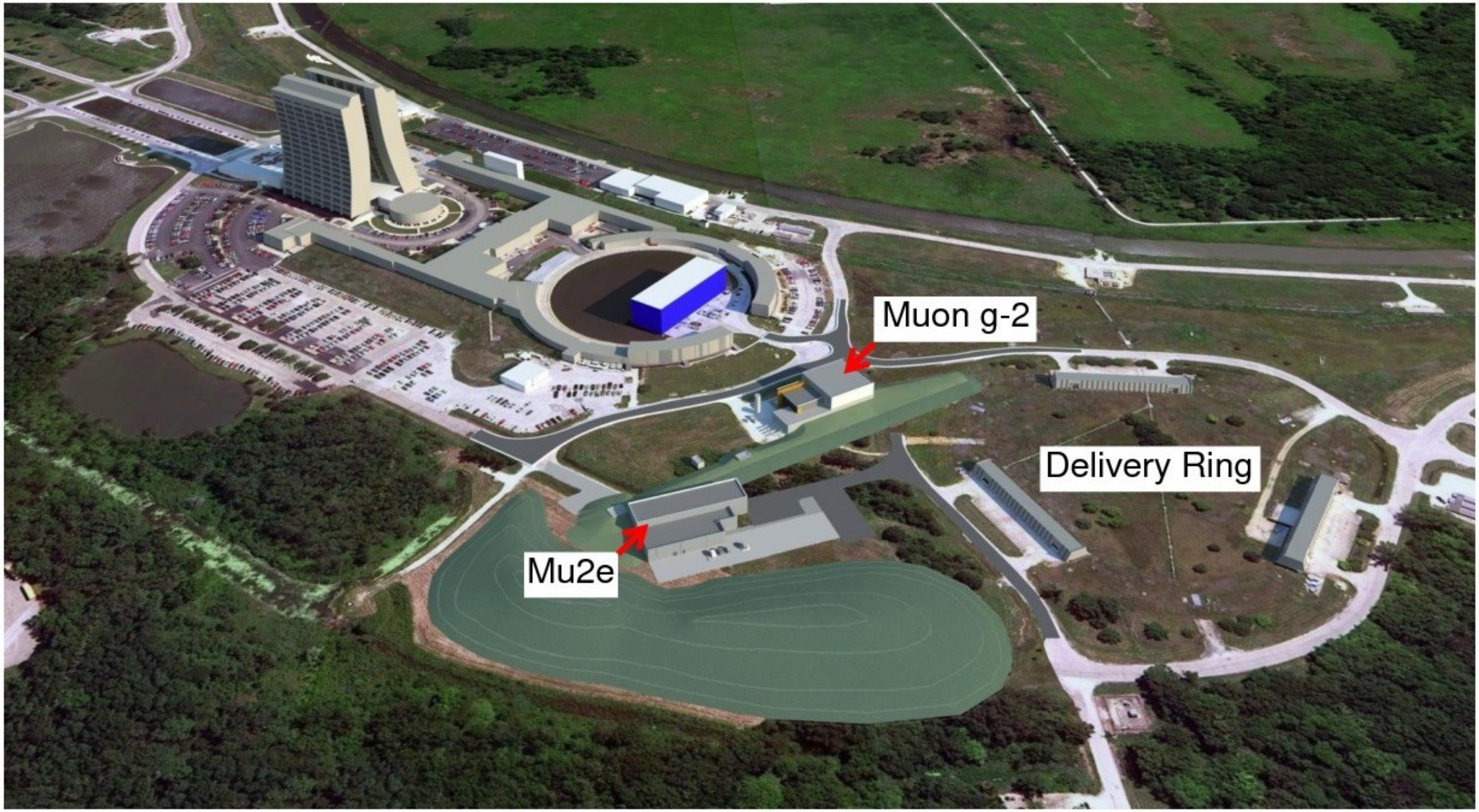
0.28 ppt ($g_e/2$) 8.1 ppb (μ_p/μ_e) 25 ppb (m_μ/m_e)

But there is a catch: m_μ/m_e is obtained from hyperfine structure of muonium using SM prediction:

$$\Delta\nu_{Mu}(SM) = \frac{16}{3} c R_\infty \alpha^2 \frac{m_e}{m_\mu}\left(1 + \frac{m_e}{m_\mu}\right)^{-3} + \text{HO terms} = \Delta\nu_{Mu}(exp.)$$

If there is beyond-the-SM contribution to a_μ, it will affect m_μ/m_e as well – should be taken into account.

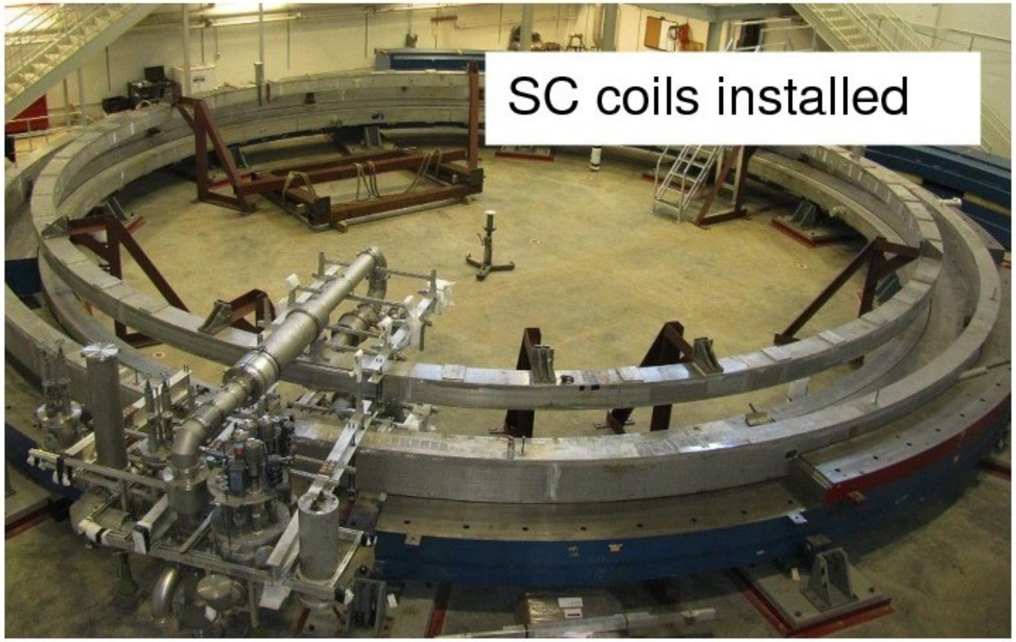
Muon Campus (g-2 + Mu2e): the plan

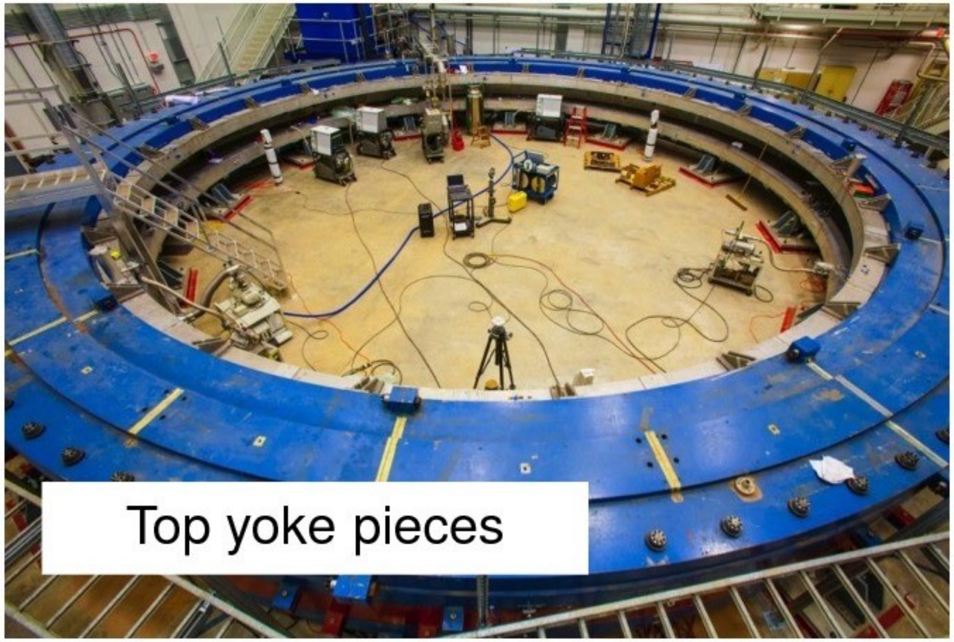


Muon Campus: today

- g-2 building (MC-1) is fully operational
- Mu2e building is under construction

Reassembly of the ring (2014-2015)





Magnet reached the full power in September 2015

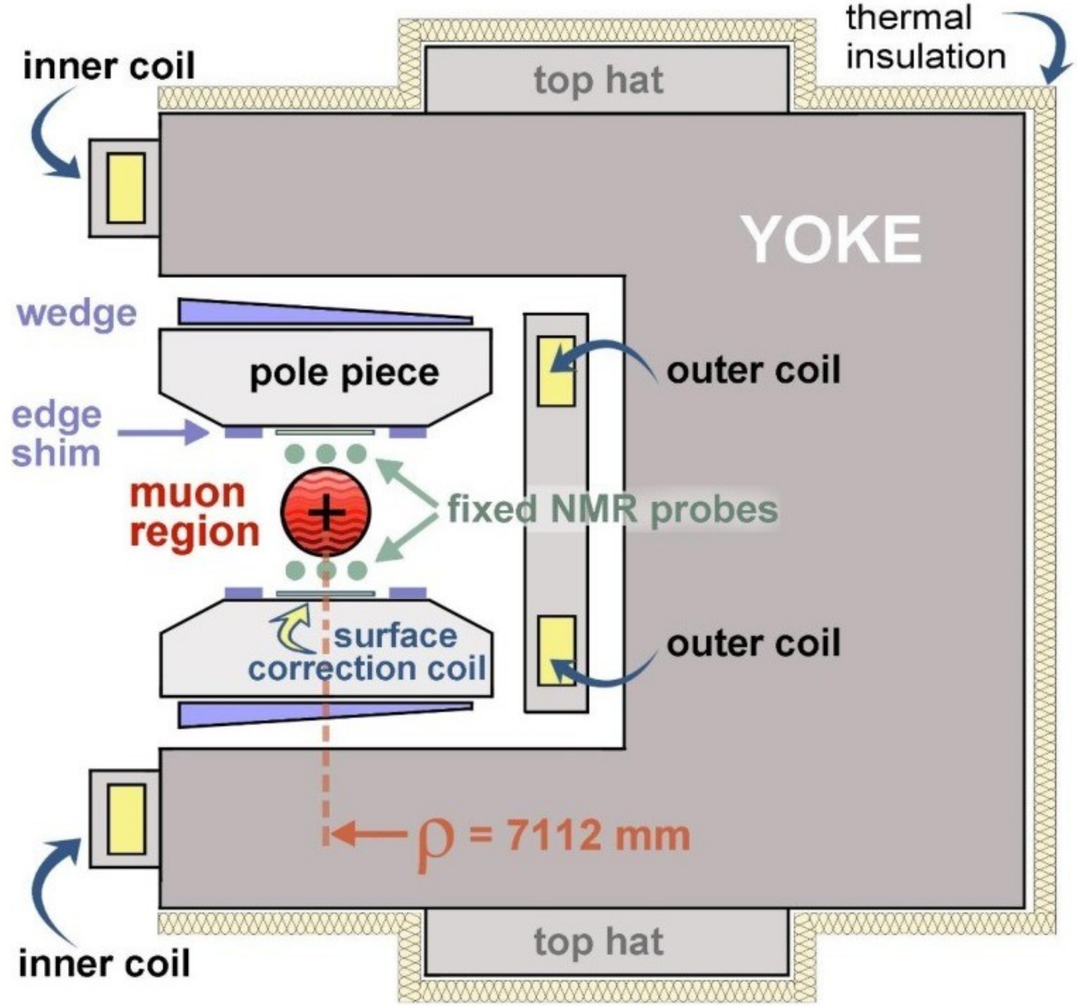
To the shimming…

Reaching ultra-uniform field

C-shaped design with 1.45 T dipole field between poles

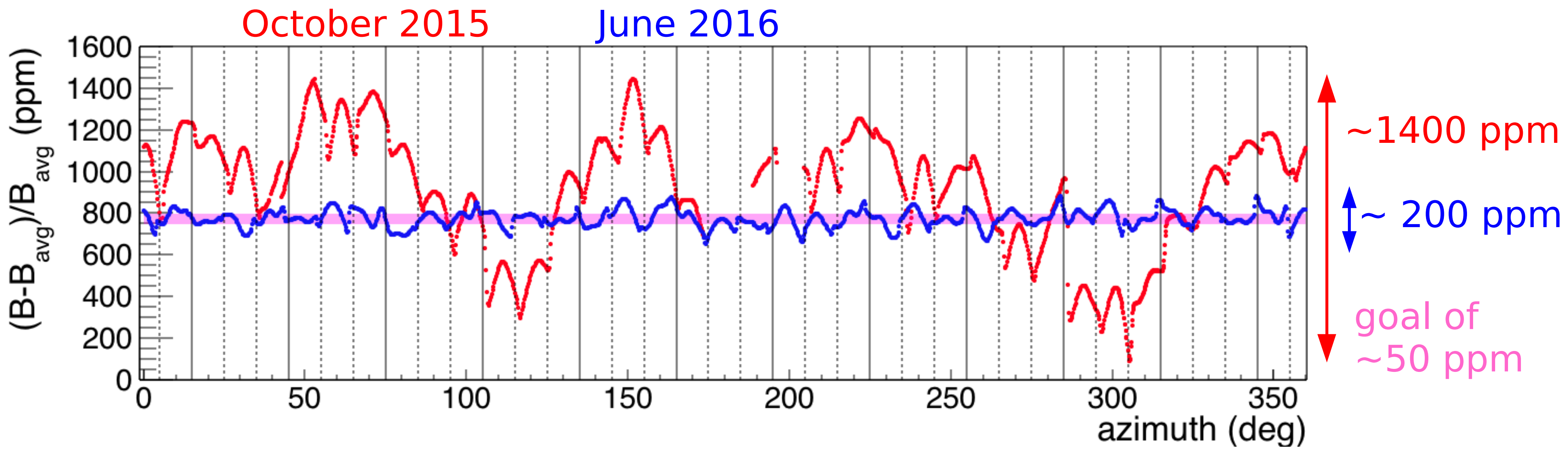
Many “knobs” to shim the field:

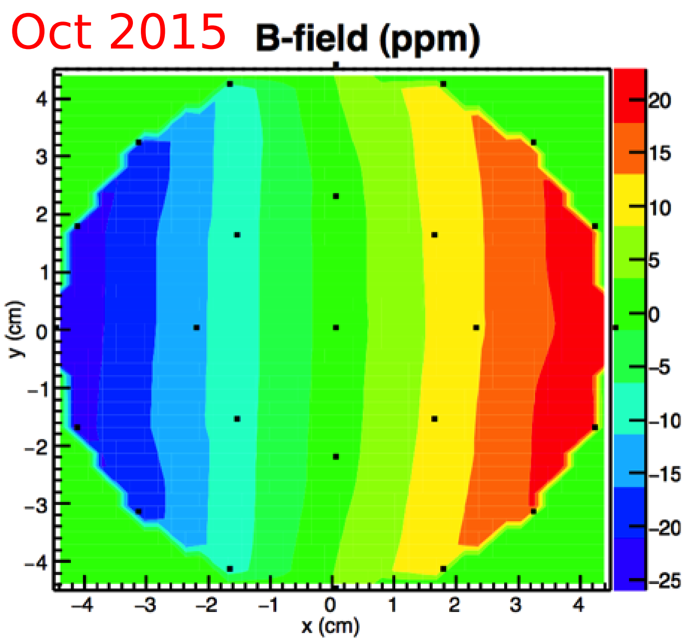
- 72 pole pieces
- 864 wedge shims
- 48 iron top hats
- 144 edge shims
- 8000 surface iron foils
- 100 active surface coils



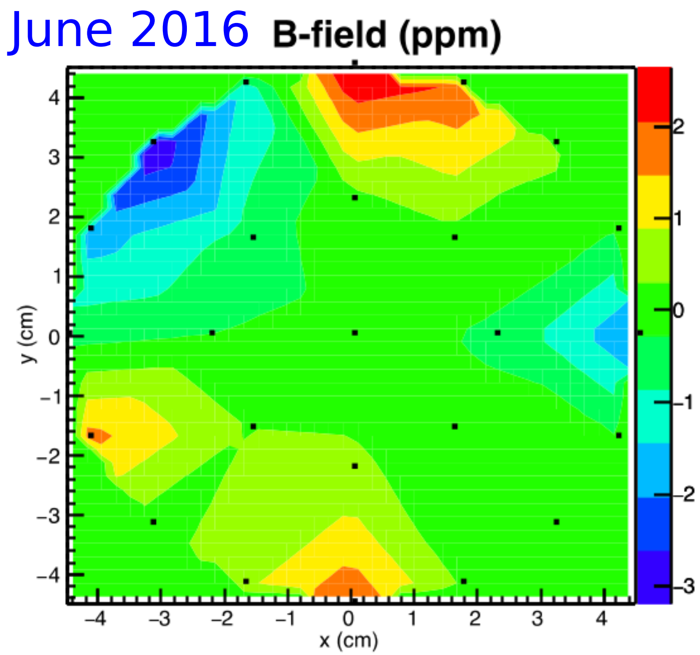
g-2 Magnet in Cross Section

Shimming status June 2016



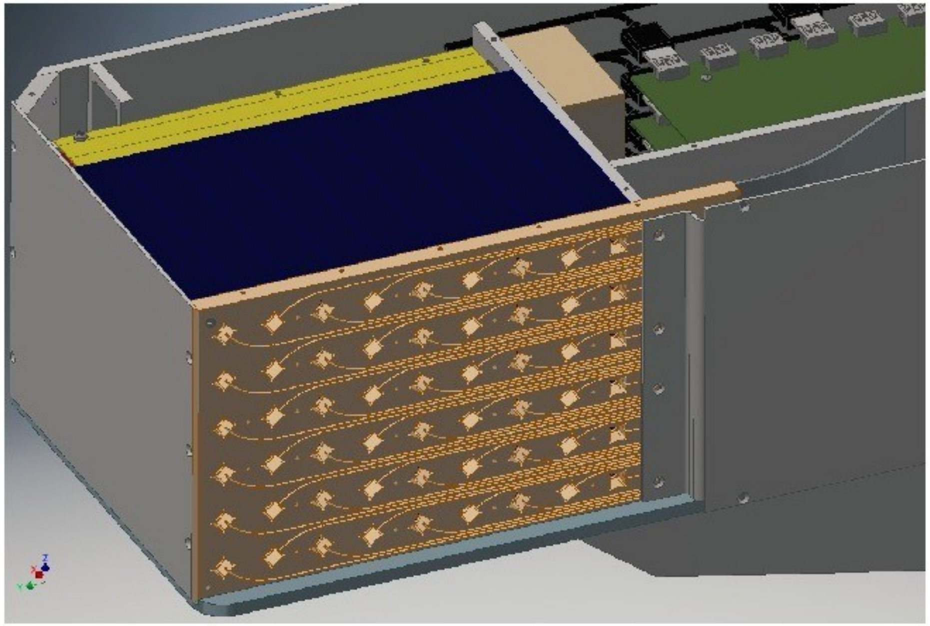


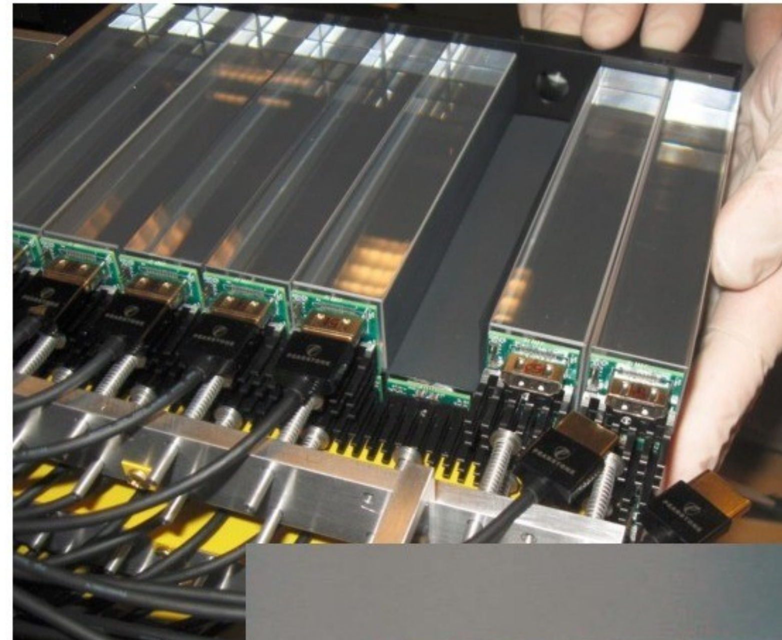
+/- 25 ppm

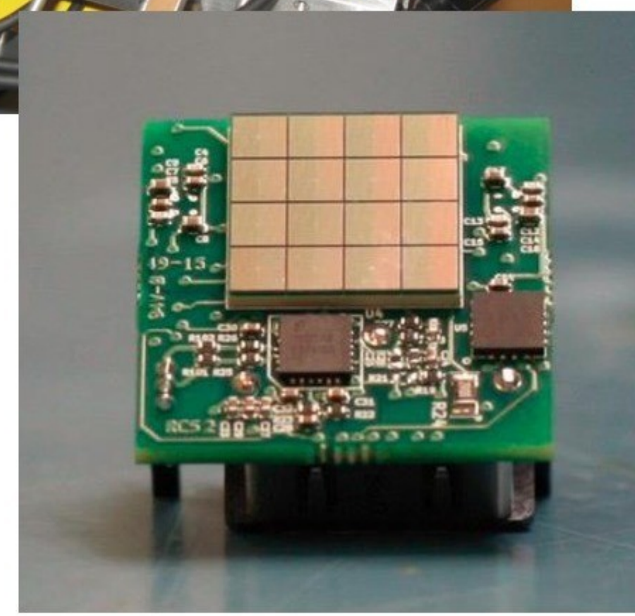


+/- 3 ppm (goal < 1 ppm)

FNAL calorimeters



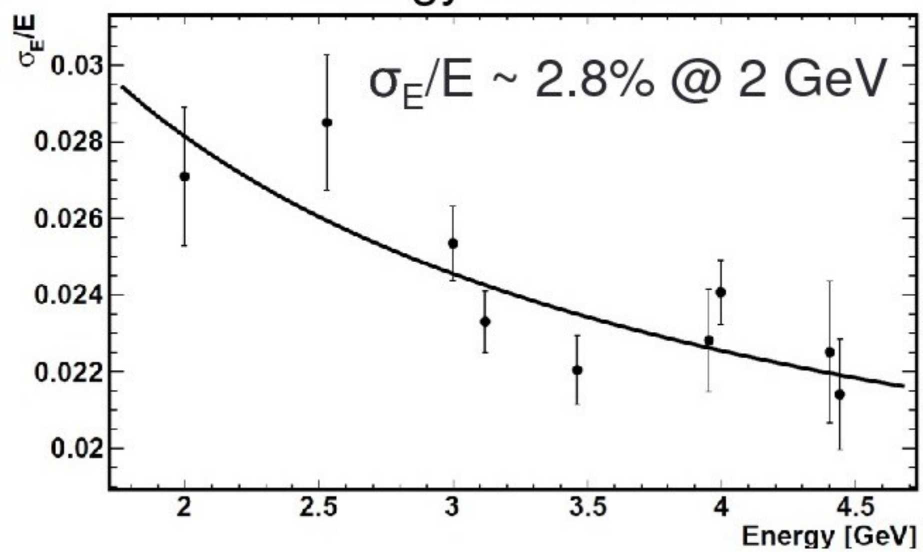




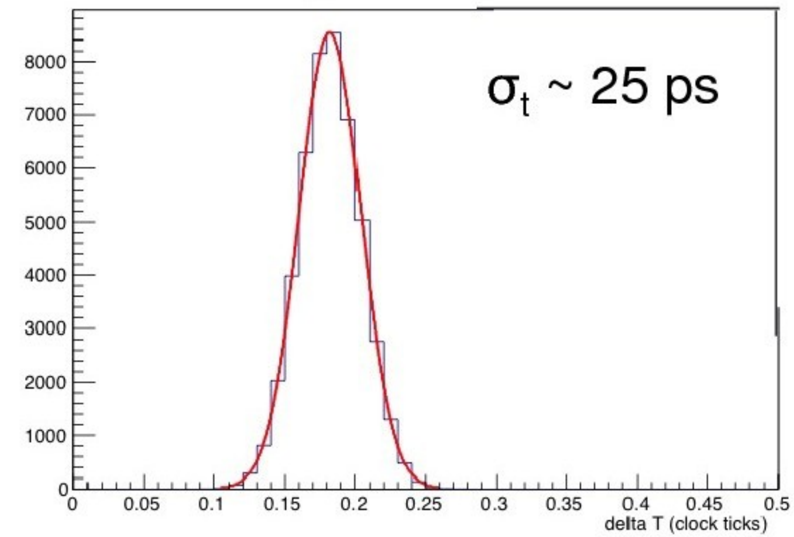
- 24 calorimeters: each is array of 6 x 9 PbF_2 crystals - 2.5 x 2.5 cm^2 x 14 cm (15X_0)
- Readout by SiPMs to 800 MHz WFDs (1296 channels)
- Advanced laser calibration system

Calorimeter performance

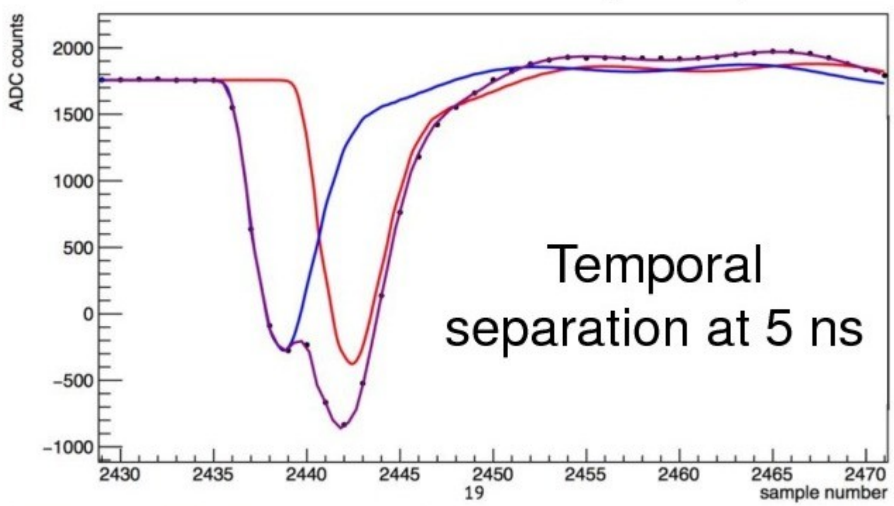
Energy Resolution



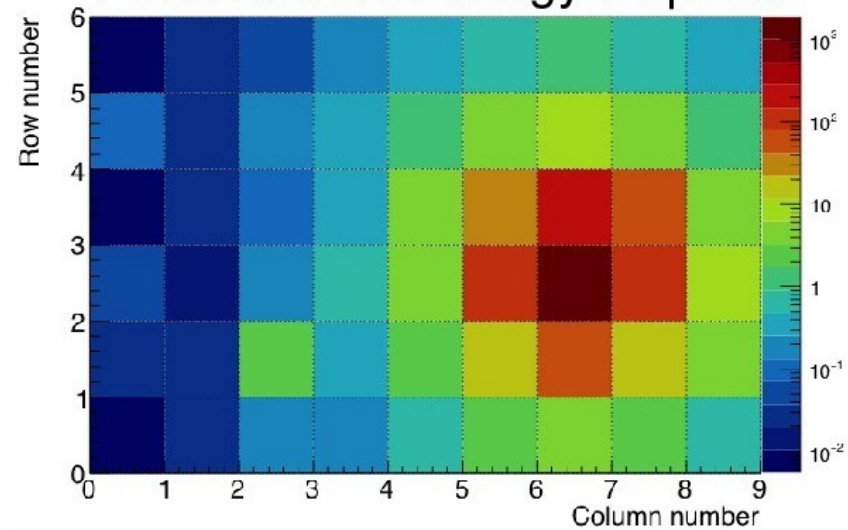
Timing Resolution



Electron pile-up

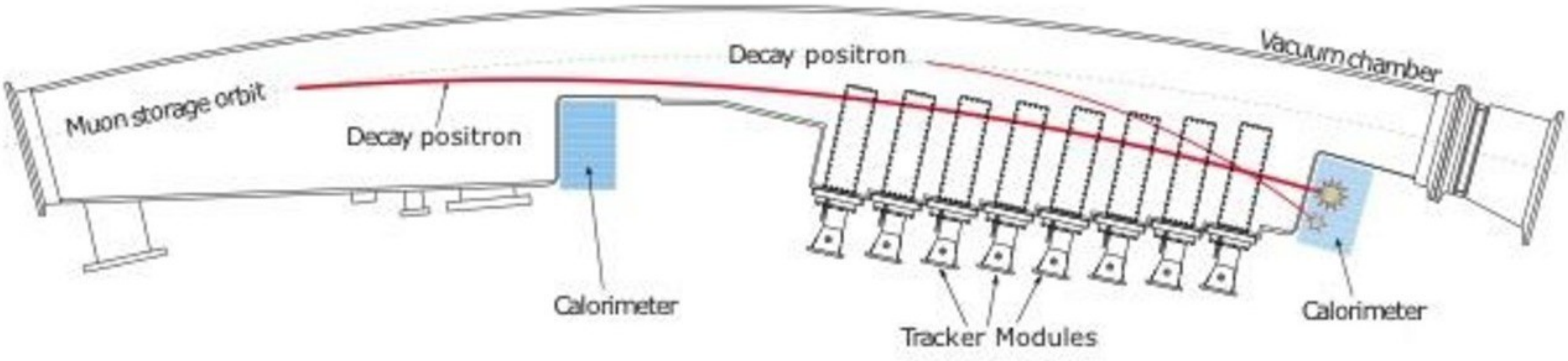


Position from Energy Deposit



NIM A 783 (2015), pp 12–21

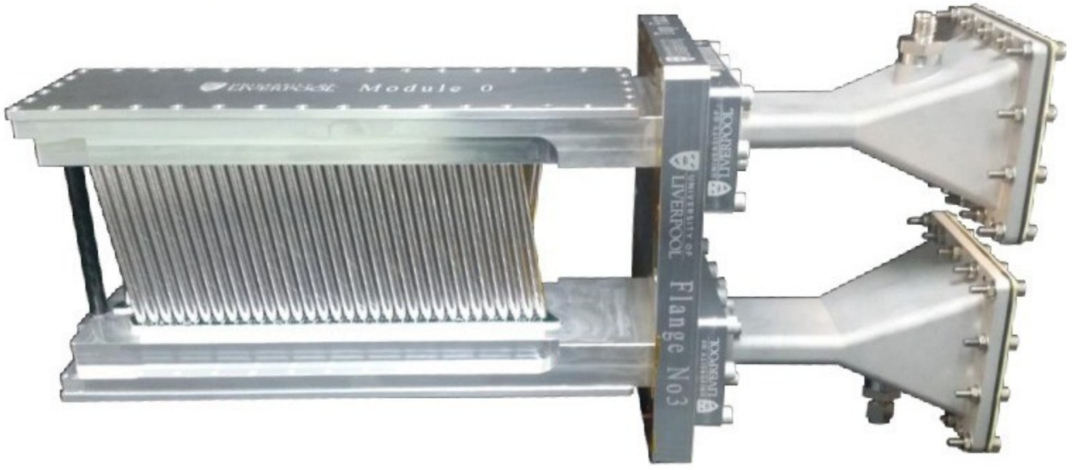
Tracker system (traceback)



Low-mass trackers are installed in 3 locations around the ring to measure muon decay position with ~1 mm precision

BNL: one station, outside of vacuum, limited performance
FNAL: 3 stations, inside the vacuum

Each tracker:
- 8 modules
- 4 layers per module, 128 straws per module



Straw tracker design:

- At 3 points around the ring, 8 modules per station, 128 straw per module.
- Low mass ~$0.1X_o$ per station, non-magnetic, OK in vacuum.
- 5mm diameter, 12cm long straws. Mylar coated with Al+Au.
- 25μm gold-plated tungsten wires.
- High-gain Ar:Ethane gas.
- ±7.5º UV layers to give vertical resolution.

The main characteristics of the tracker detector are:

- Large azimuthal acceptance with low material (15μm Mylar).
- Measures stored muon profile and its time evolution.
- Addresses pile-up systematics, measure positron momentum.
- Detects lost muons escaping storage region.
- Measures vertical pitch of decay positrons → EDM measurement.
- Determines area of magnetic field map seen by the muons.
- Limits the size or radial and longitudinal magnetic fields.
- Makes an independent measurement of positron momentum.

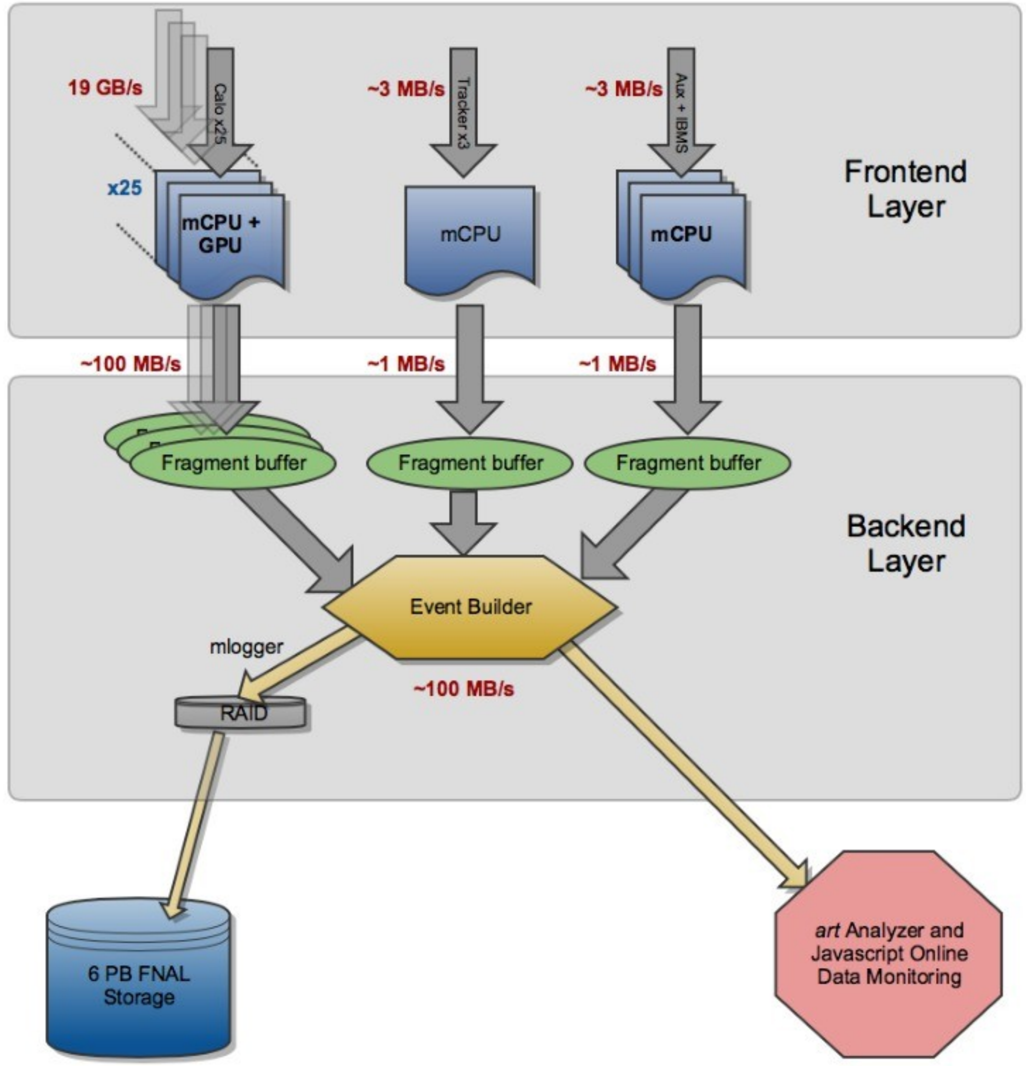
DAQ Requirements

- Accommodate 12 Hz average rate of muon fills that consist of sequences of four successive 700 μs fills with 11 ms fill-separations
- Handle the readout, processing, monitoring and storage of the data obtained from 24 electromagnetic calorimeters recorded by 1296 channels of custom 800 MSPS, 12-bit waveform digitizers.
- Provide both the readout of the prescaled raw ADC samples and the derivation of T-method, Q-method, and other calibration, diagnostic, and systematic datasets.
- For a 12 Hz fill rate the time-averaged rate of raw ADC samples is 19 GB/s.

Source	MB Per Fill	MB Per Second
Raw data	1,600	19,400
T-Method	9.4	112.5
Q-Method	2.0	24.25
Prescaled Raw	1.6	19.4
Tracker	0.25	3
Laser Monitor	0.08	1
Auxiliary	0.33	4
Event Builder:	**13.7**	**164**

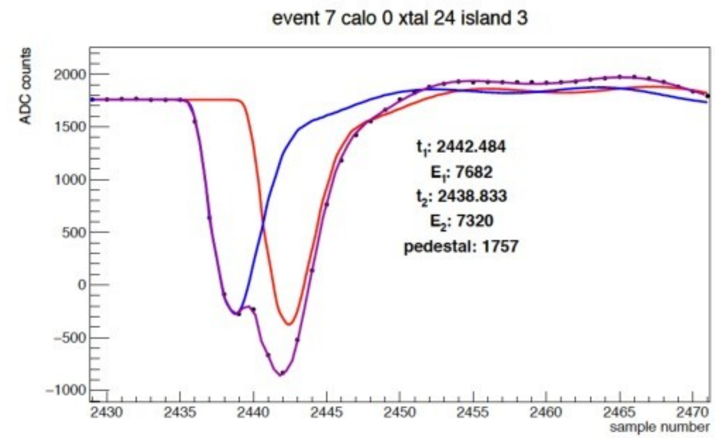
DAQ Design

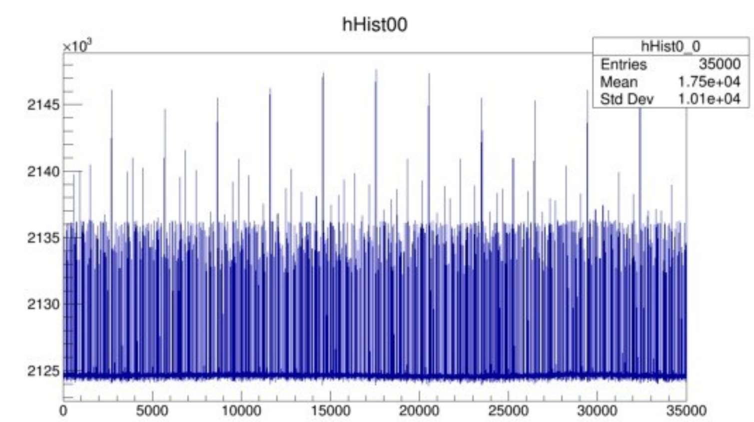
- Layered array of commodity, networked processors
- Frontend layer for readout of digitizers (calo) and MHTDCs (straws)
- Backend layer for assembly of event fragments, data storage.
- Slow control layer for setting, monitoring of High Voltage, temperature, etc.
- Online analysis layer using *art*+JS for monitoring integrity of raw and physics data.
- Field DAQ operates independently, but with a similar design.



T and Q Methods

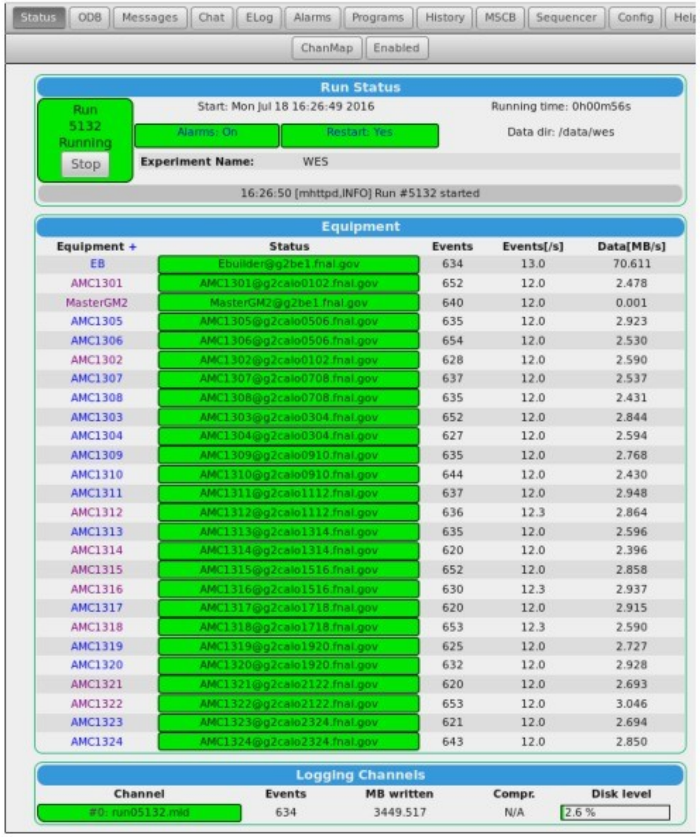
- T-method
  - Positron events in the calorimeter are identified, sorted, and fit to obtain time and energy.
  - All events above an energy threshold are included.
  - ω_a is determined from a fit to a pileup-subtracted histogram.
  - This was the method used in BNL E821.
- Q-method
  - Individual positron events are not identified.
  - Detector current is integrated as a proxy for event energy.
  - No pileup correction is necessary.





DAQ Software: MIDAS

- MIDAS is a data acquisition software package developed at PSI and Triumf.
- Includes web-interface for easy run control and experiment configuration via an online database.
- Frontend acquisition code written in C/C++ with CUDA for GPU programming and IPBus libraries for communicating with uTCA electronics.
- Javascript based analyzer for online data monitoring via a web gui.
- Data will be stored as MIDAS datafiles.

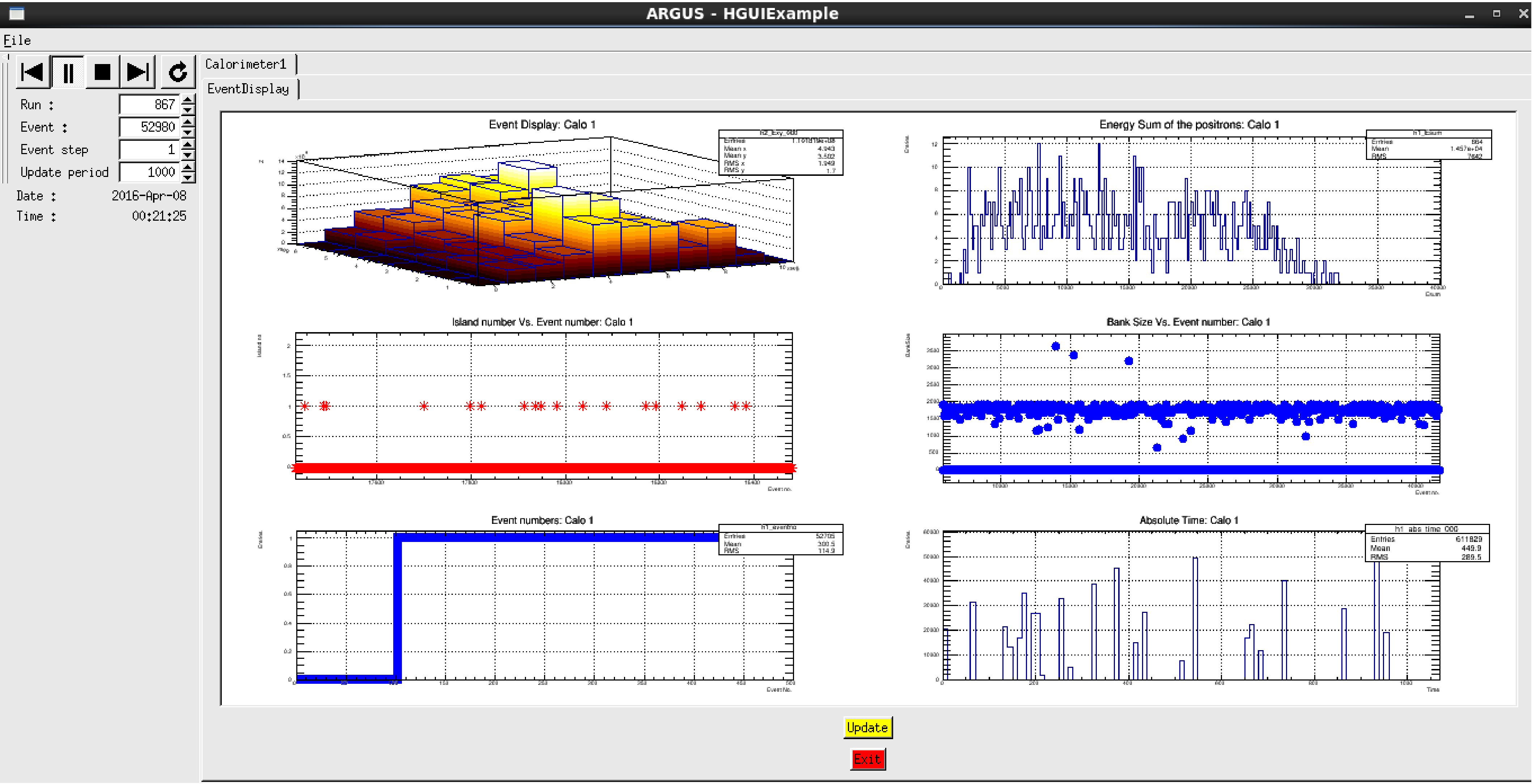


JINR contribution & plans

ROME online data quality monitoring software

The Muon g-2 DAQ is based on MIDAS (Maximum Integrated Data Acquisition System), a modern general-purpose software package for event-based data acquisition in small and medium scale physics experiments. Online data quality monitoring (DQM) software for the calorimeter prototype using the ROME (Root based Object oriented Midas Extension) framework has been developed and successfully used during test run at SLAC in April 2016. ROME is a framework generator for event based data analysis. In the ROME environment, the experimenter defines the analysis framework for his experiment in a very clear and compact way in a XML file. The Argus GUI extension of ROME was used to provide real time analysis and visualization of the data collected from a prototype calorimeter module.

A screenshot of the Argus DQM window with a live event display and several ROOT histograms of the calorimeter prototype basic parameters (energy, timing, data size etc).



Создание прототипа straw-трекера

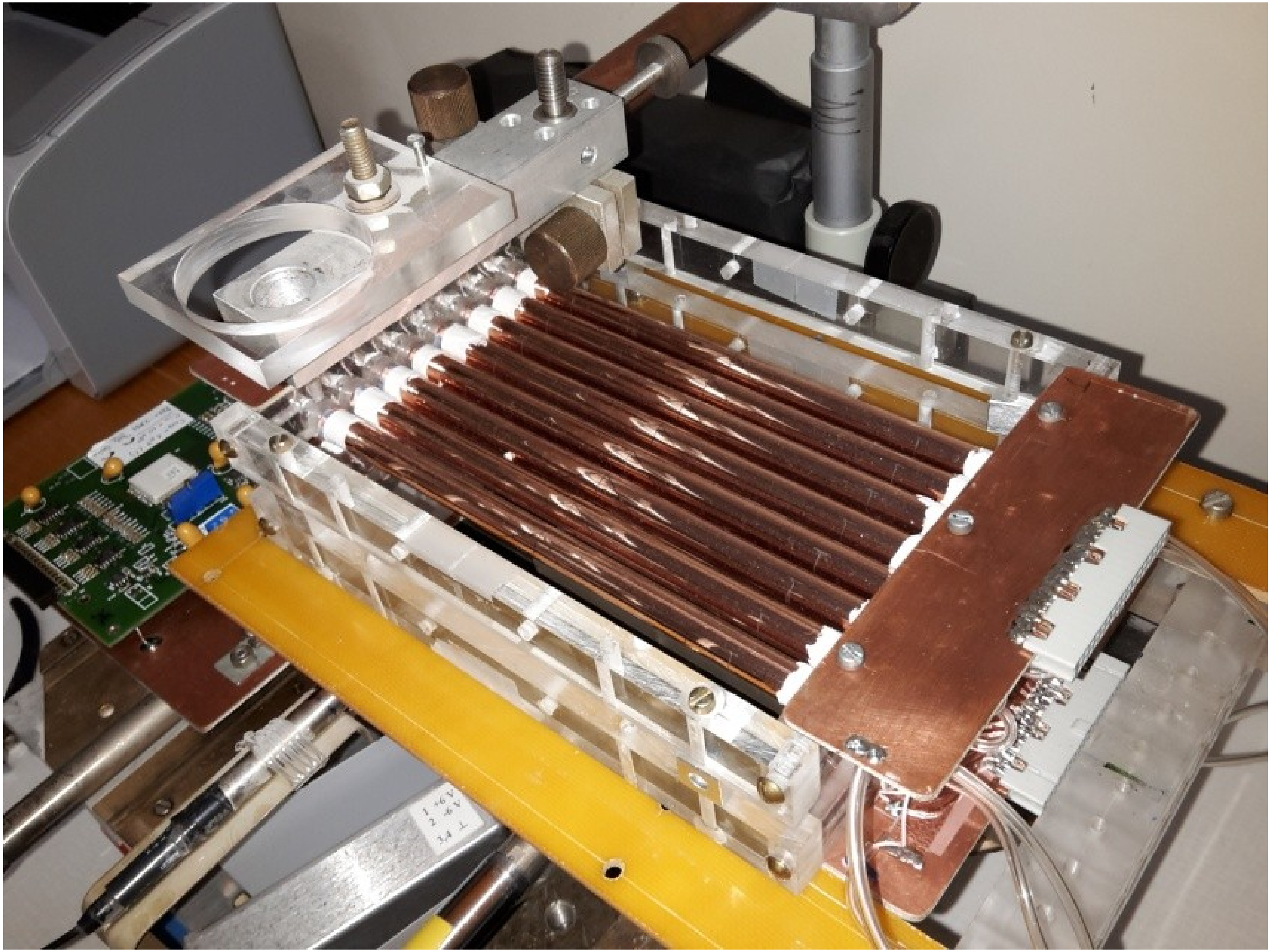
Предложено использовать для трекера разработанную нами методику детекторов “катодных” строу. Это позволяет при сохранении загрузочной способности трекера использовать трубки диаметром 10 мм.

Такие трубки обладают лучшими рабочими характеристиками, чем пятимиллиметровые трубки, и проще в изготовлении.

При этом полученная точность определения продольной координаты, менее 1 мм, сравнима с точностью радиальной. Радиальная координата измеряется стандартным методом по времени дрейфа.

Общее количество трубок в одной станции трекера и каналов электроники уменьшается в четыре и два раза соответственно.

The *tracking station prototype on a test stand at DLNP, JINR.*



MIDAS Alarm System Overview

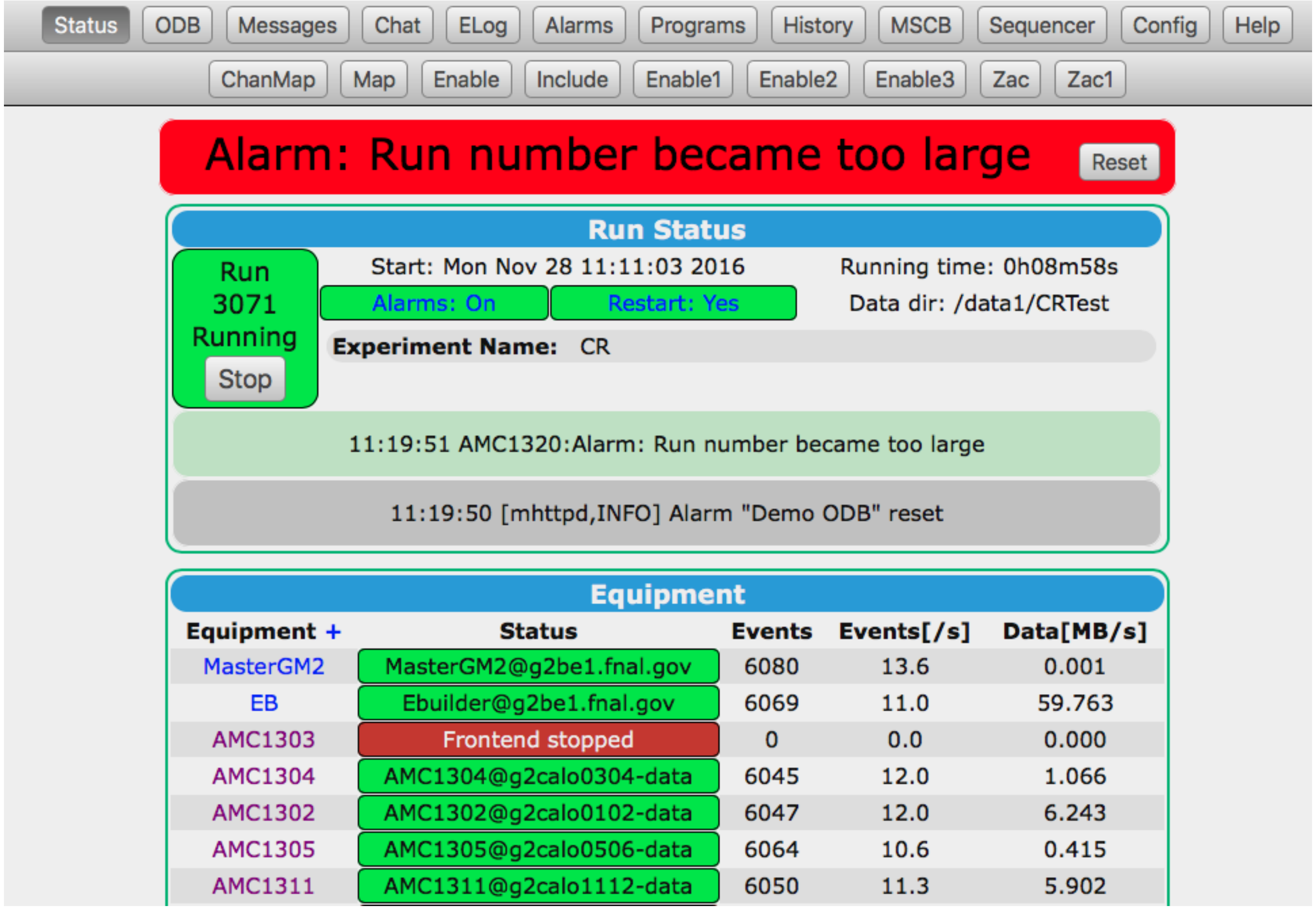
When the alarm system is activated and an alarm condition is detected, alarm messages are sent by the system which appear as an alarm banner on the mhttpd status page, and as a message on any windows running odbedit clients. The alarm system is flexible and can be extensively customized for each experiment using the mhttpd Alarms Page or odbedit.

The alarm system is built-in and part of the main experiment scheduler. This means no separate task is necessary to benefit from the alarm system. Its setup and activation is done through the /Alarms ODB tree.

Alarm system capabilities

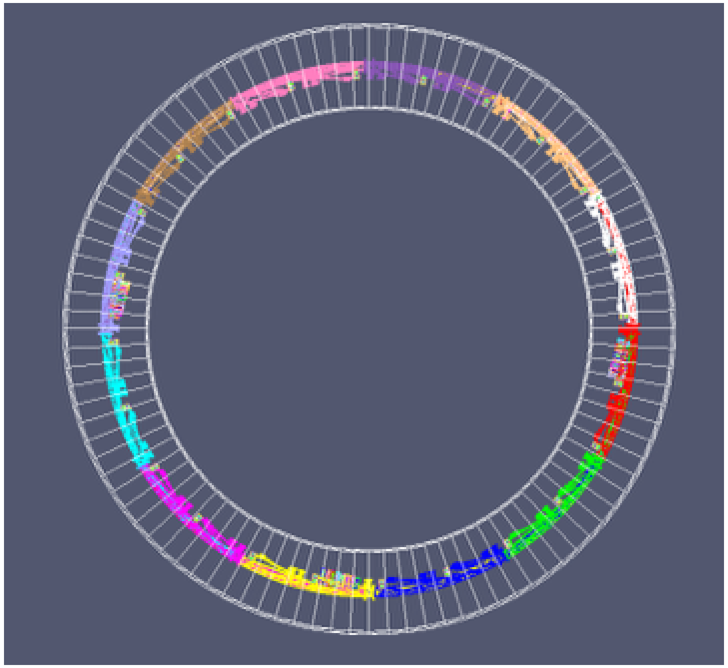
- Alarm setting on any ODB variable against a threshold parameter
- Alarm triggered by evaluated condition
- Selection of Alarm check frequency
- Selection of Alarm trigger frequency
- Customization alarm scheme: multiple choices of alarm type
- Selection of alarm message destination (to system message log or to elog)
- Email or SMS alerts can be sent
- Alarm triggered when a Program is not running

Alarm fired!


Status
ODB
Messages
Chat
ELog
Alarms
Programs
History
MSCB
Sequencer
Config
Help
ChanMap
Map
Enable
Include
Enable1
Enable2
Enable3
Zac
Zac1
Alarm: Run number became too large
Reset
Run Status
Run
3071
Running
Stop
Start: Mon Nov 28 11:11:03 2016
Running time: 0h08m58s
Alarms: On
Restart: Yes
Data dir: /data1/CRTest
Experiment Name: CR
11:19:51 AMC1320:Alarm: Run number became too large
11:19:50 [mhttpd,INFO] Alarm "Demo ODB" reset
Equipment
Equipment +
Status
Events
Events[/s]
Data[MB/s]
MasterGM2
MasterGM2@g2be1.fnal.gov
6080
13.6
0.001
EB
Ebuilder@g2be1.fnal.gov
6069
11.0
59.763
AMC1303
Frontend stopped
0
0.0
0.000
AMC1304
AMC1304@g2calo0304-data
6045
12.0
1.066
AMC1302
AMC1302@g2calo0102-data
6047
12.0
6.243
AMC1305
AMC1305@g2calo0506-data
6064
10.6
0.415
AMC1311
AMC1311@g2calo1112-data
6050
11.3
5.902

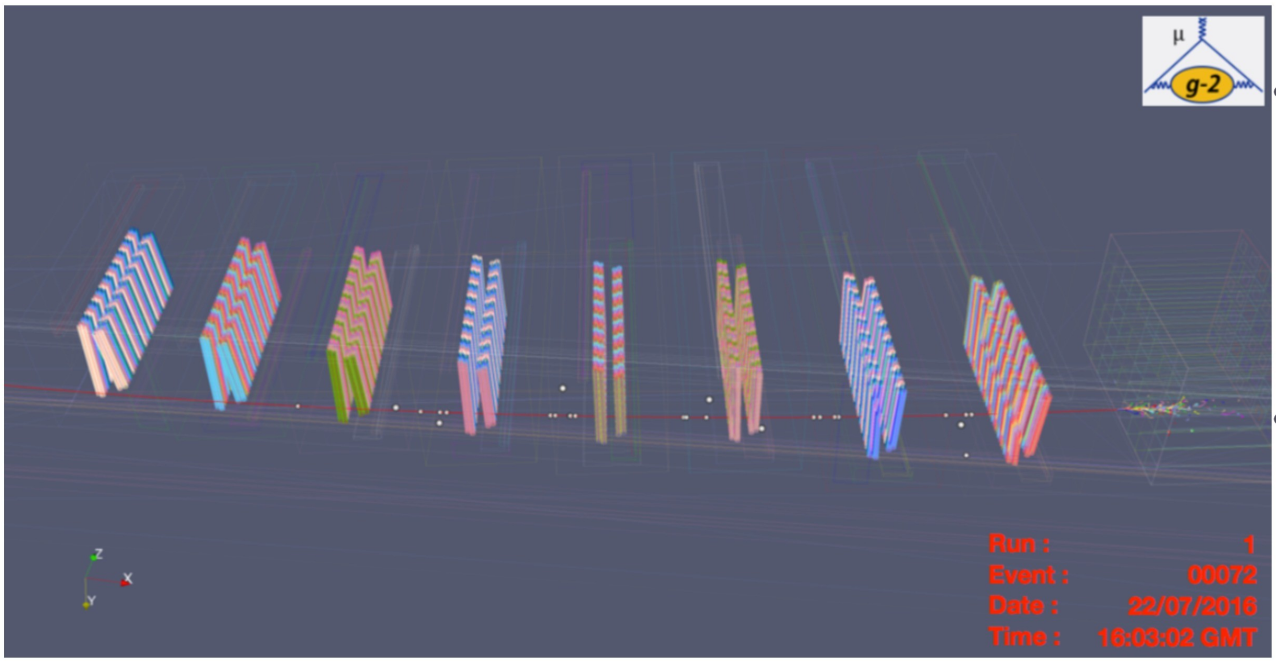
Development of PARAVIEW Event Display

A development of an online event display program based on PARAVIEW data analysis and visualization software is in progress. The real time data from the detector will be transferred to a special server where the MIDAS data are converted on-the-fly to the ART format. ART is an event-processing framework for particle physics experiments developed and commonly used at FNAL. An ART analyzer module will reconstruct calorimeter hits and straw tube tracks and send the event geometrical data to the PARAVIEW event display application for live visualization.
A modern ZeroMQ distributed messaging library is used for communication between the MIDAS data acquisition system, ART event-processing modules and the PARAVIEW event display.



A PARAVIEW generated general view of the Muon g-2 magnet and vacuum chamber that will be used in the event display program.

Paraview Event Display



- Event display will run as an *art*-online process that connects to mserver using midas2art, with module that outputs vtk object for Paraview visualization.
- Development is underway.
  - Dubna: N. Khomutov, V. Krylov
  - Liverpool: W. Turner

JINR plans for further participation in Muon g-2 experiment

- **PARAVIEW event display**

Development and debugging of the event display code. Support of a dedicated MacPro server for the event display. Integration of the event display with “near line” analysis software.

- **MIDAS Alarm system**

Integration of all required alarms from different experiment subsystems into the central MIDAS DAQ. Testing and debugging of the new alarm system during engineering runs before data taking. Support of the alarm system during beam runs.

- **MIDAS ODB support and interfacing**

Development of new custom JavaScript web pages for the MIDAS ODB control. Special applications/scripts for checking ODB integrity and correcting possible errors in the data structures will be also developed.

- **Participation in the test and data taking runs**

Participation in final integration and testing of the full DAQ system during the 2017 test runs and in the data taking run shifts starting from 2017-2018. Expert support of the general MIDAS software during physical runs 2018-2020.

Спасибо за внимание!

Measuring ω_a (T-method)

High energy electrons in LAB frame correlate to forward decay electrons in CM frame

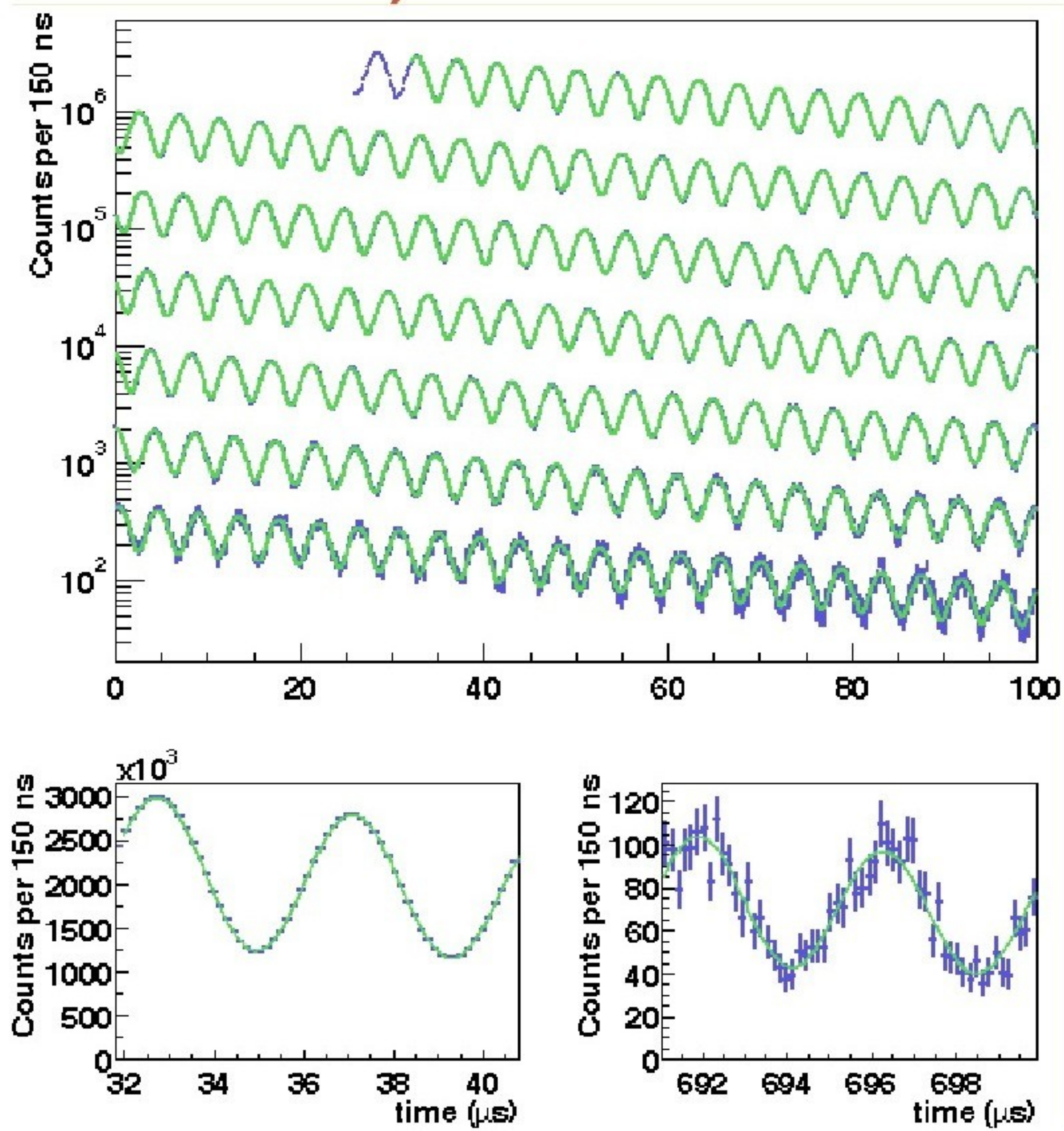
Number of forward decay electrons in CM frame correlates to spin direction

So: count electrons with $E > E_{thr}$

$$N(t) = N_0 e^{-t/\gamma\tau}[1 + A\cos(\omega t + \varphi)]$$

Simple 5-parameter fit! In real life, it is not that simple:

gain changes, pileup, coherent betatron oscillations (CBO), muon losses, …



Inside the ring