The Fermilab Muon g-2 experiment: laser calibration system

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on behalf Muon g-2 Collaboration

The Fermilab Muon g-2 experiment: laser calibration system

- physics
- challanges
- calibration system
- schedule

Physics

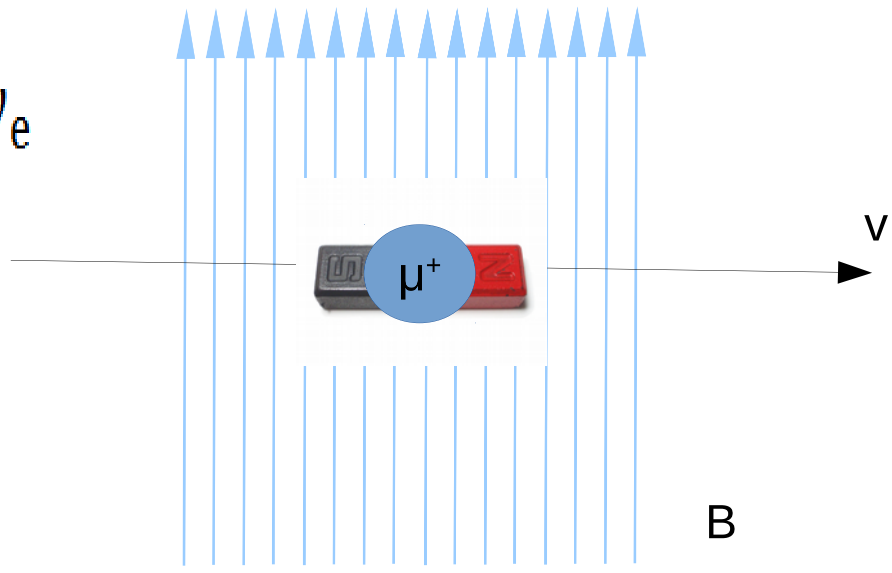
- Magnetic dipole
- Charged particle

Magnetic field

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

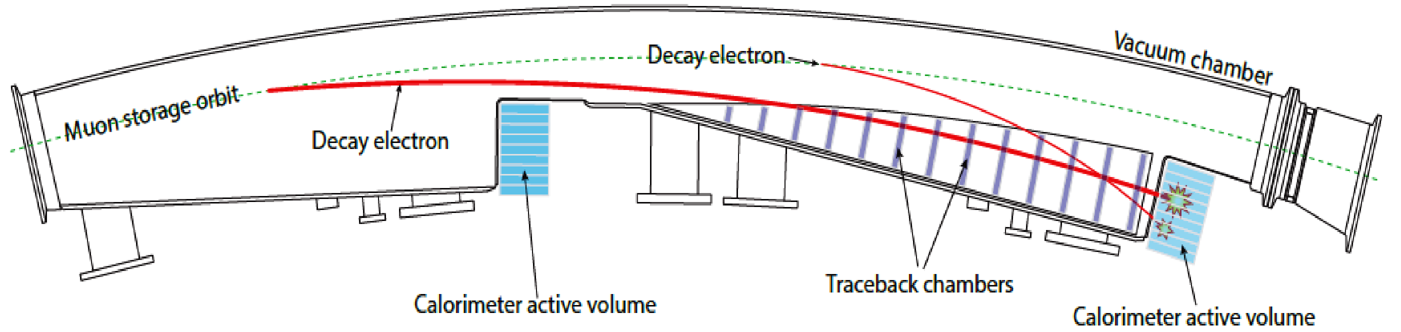
$$\omega_c = \frac{e\,B}{m\,\gamma}$$

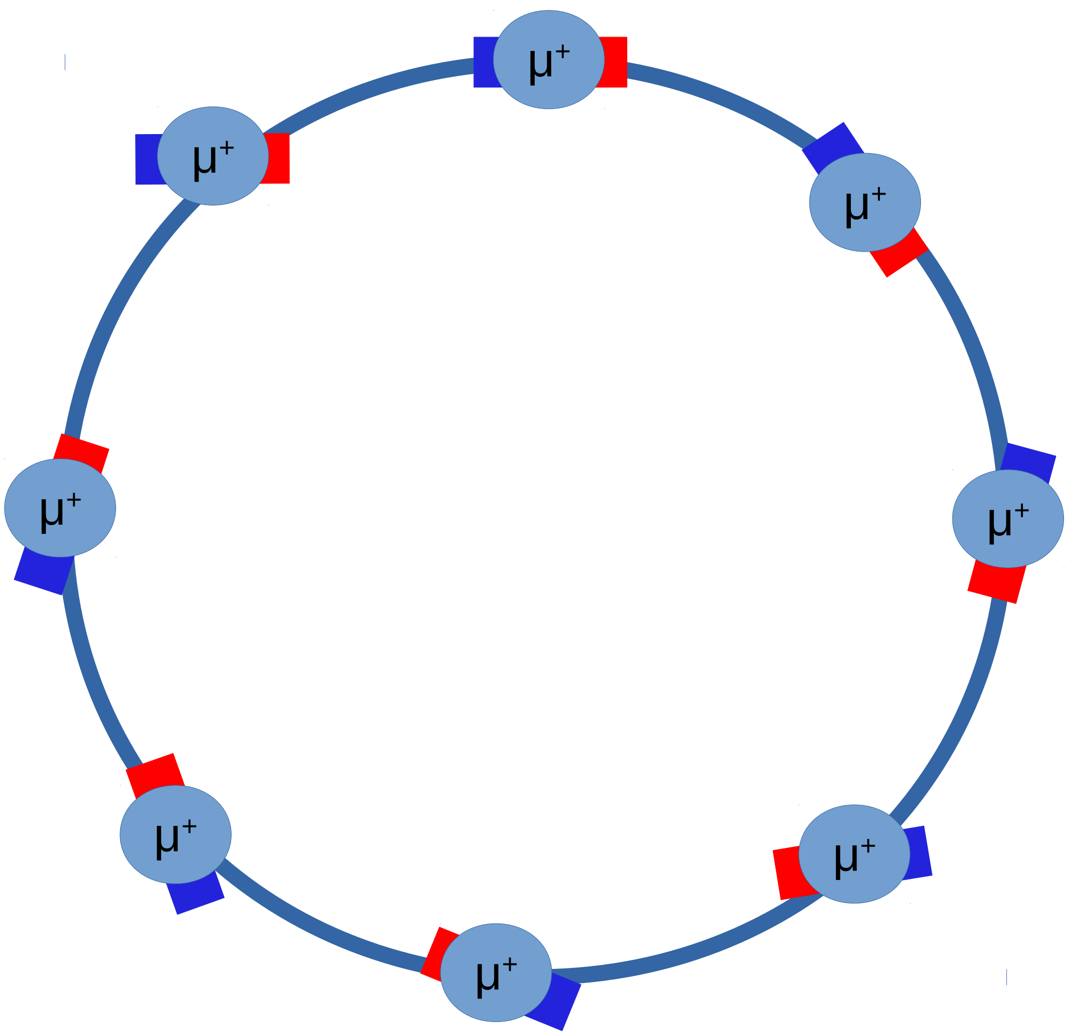
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



$$\omega_s = \frac{geB}{2\,m} + (1-\gamma)\frac{eB}{m\,\gamma}$$

Physics





$$\omega_a = \omega_s - \omega_c$$

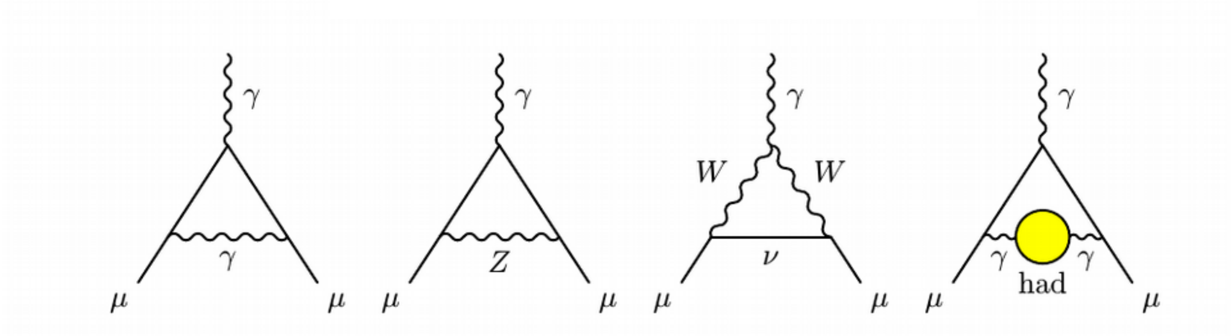
$$\omega_a = \frac{g-2}{2}\frac{eB}{m}$$

At "magic" momentum

$$\omega_a = a_\mu \frac{eB}{m}$$

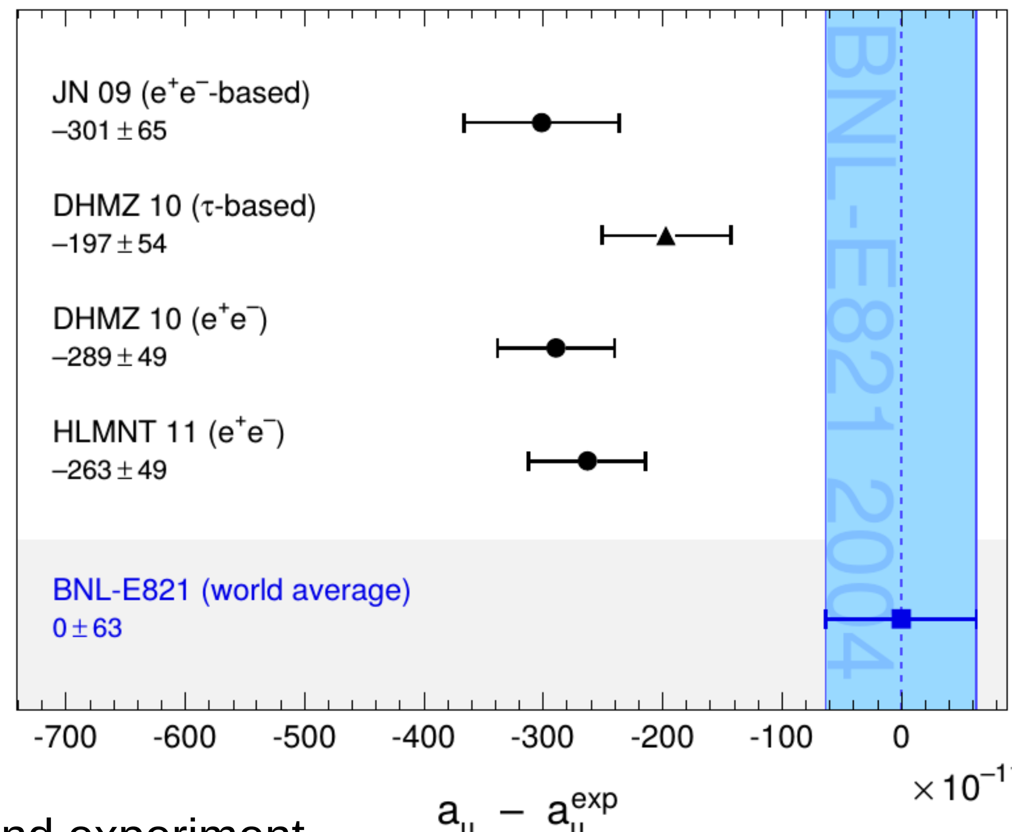
Physics

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}}$$



$$a_\mu^{\mathrm{exp}} = 11\,659\,209.1(5.4)(3.3) \times 10^{-10}$$

Contribution	Result in 10^{-11}
QED	116 584 718
HVP (LO)	6 923
HVP (NLO)	-98
HLBL	105
EWK	154
	116 591 802



3.5 sigma discrepancy between SM and experiment

Challenges
- Logistic (summer 2013)

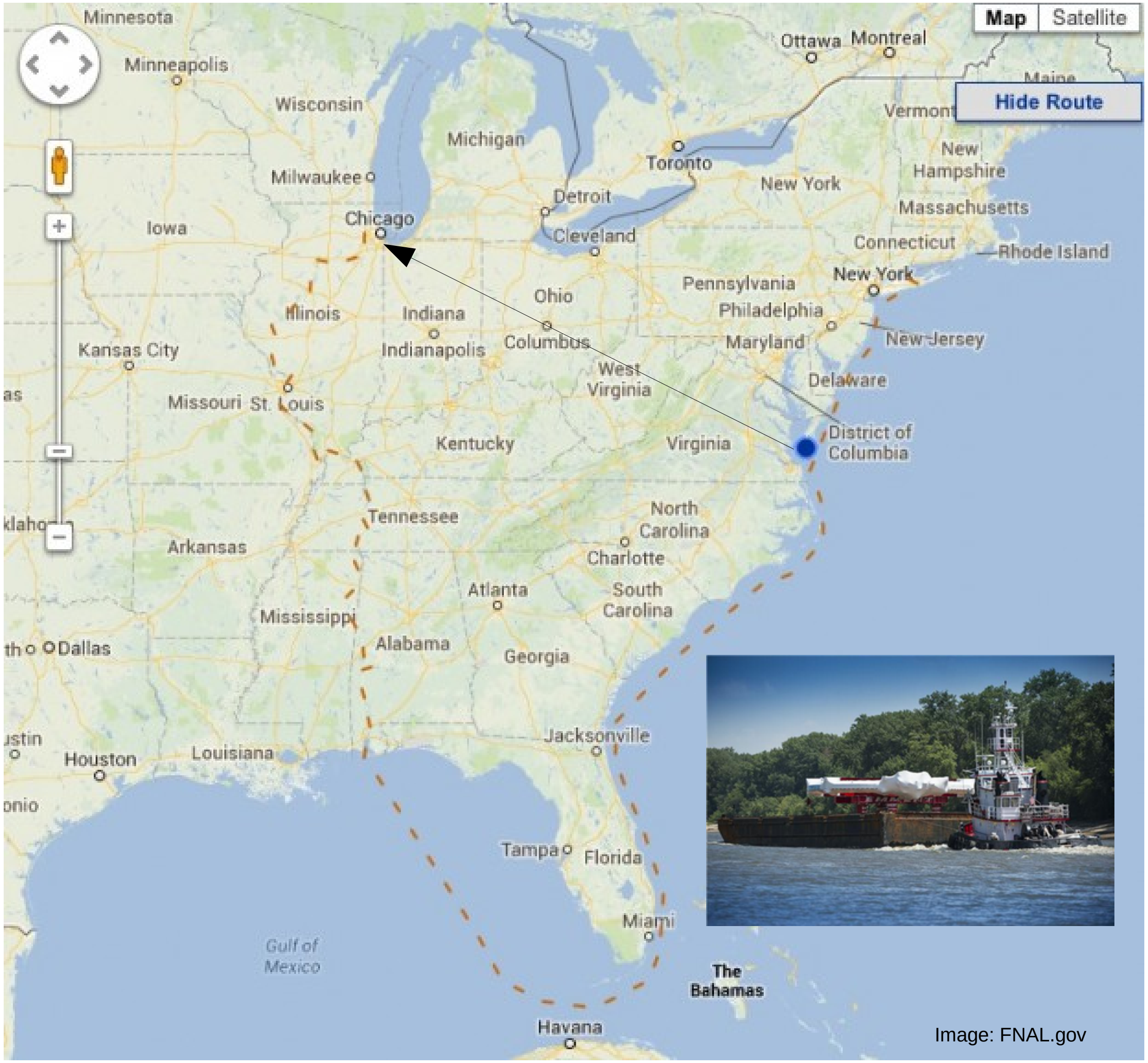
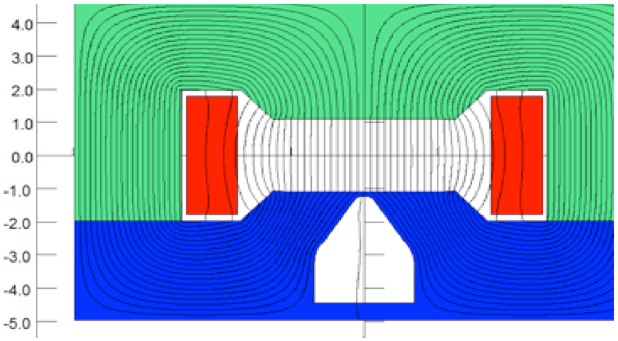


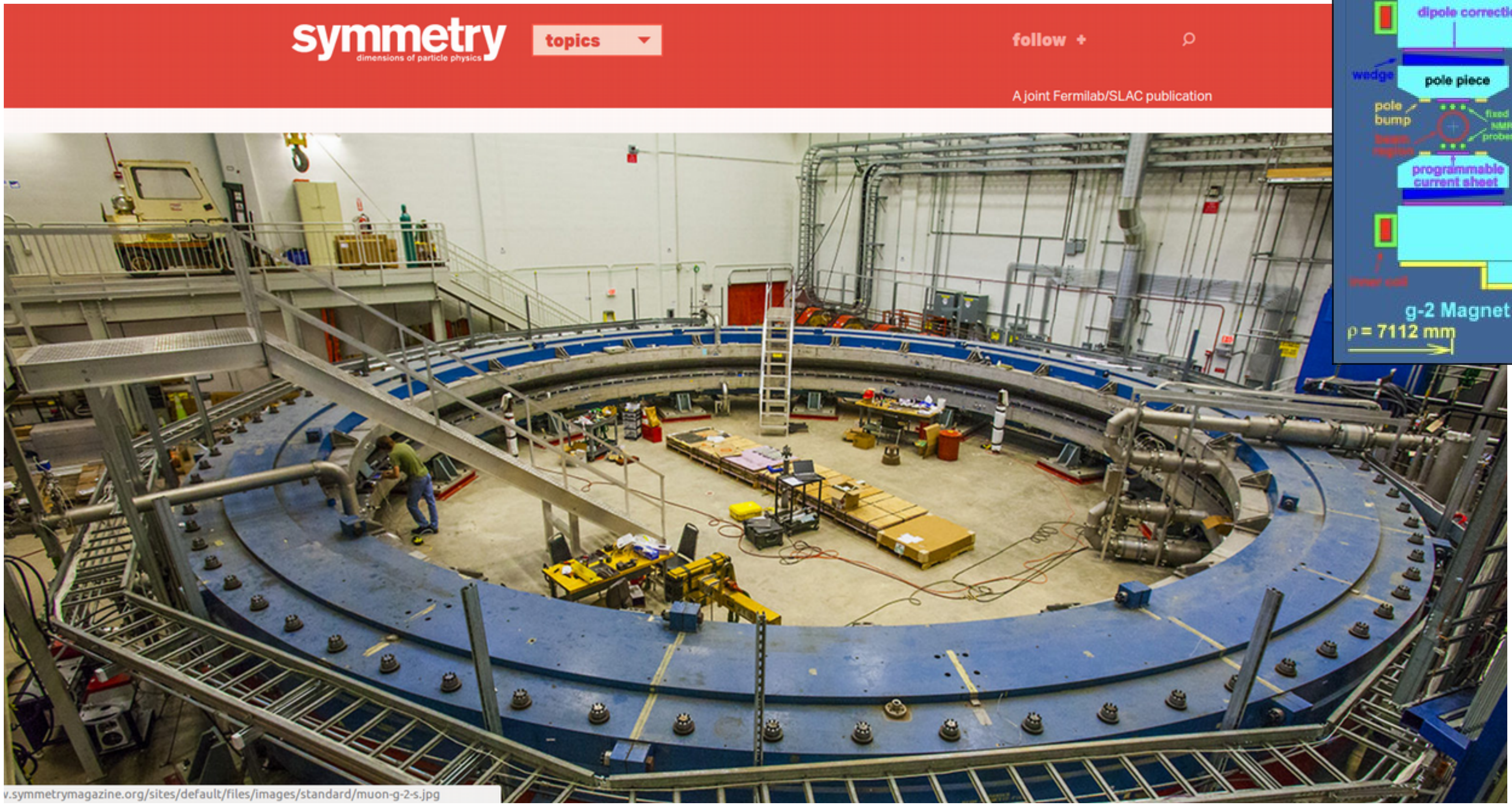
Image: FNAL.gov

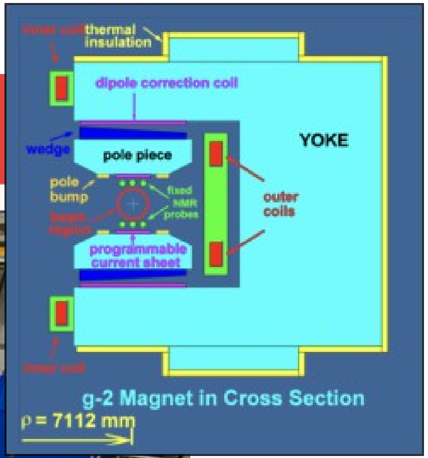
23 of the Biggest Machines Ever Moved On Wheels
No. 5 Muon storage ring
gizmodo.com

Challenges
- Engineering

Environmental
2’9” heavily-reinforced floor installed on 12’ deep excavation of undisturbed soil
Temperature control to +/- 1C
Construction tolerances
26 ton pieces of yoke steel (30 of them) placed to 125 micron tolerance
Pole pieces aligned to 25 micron

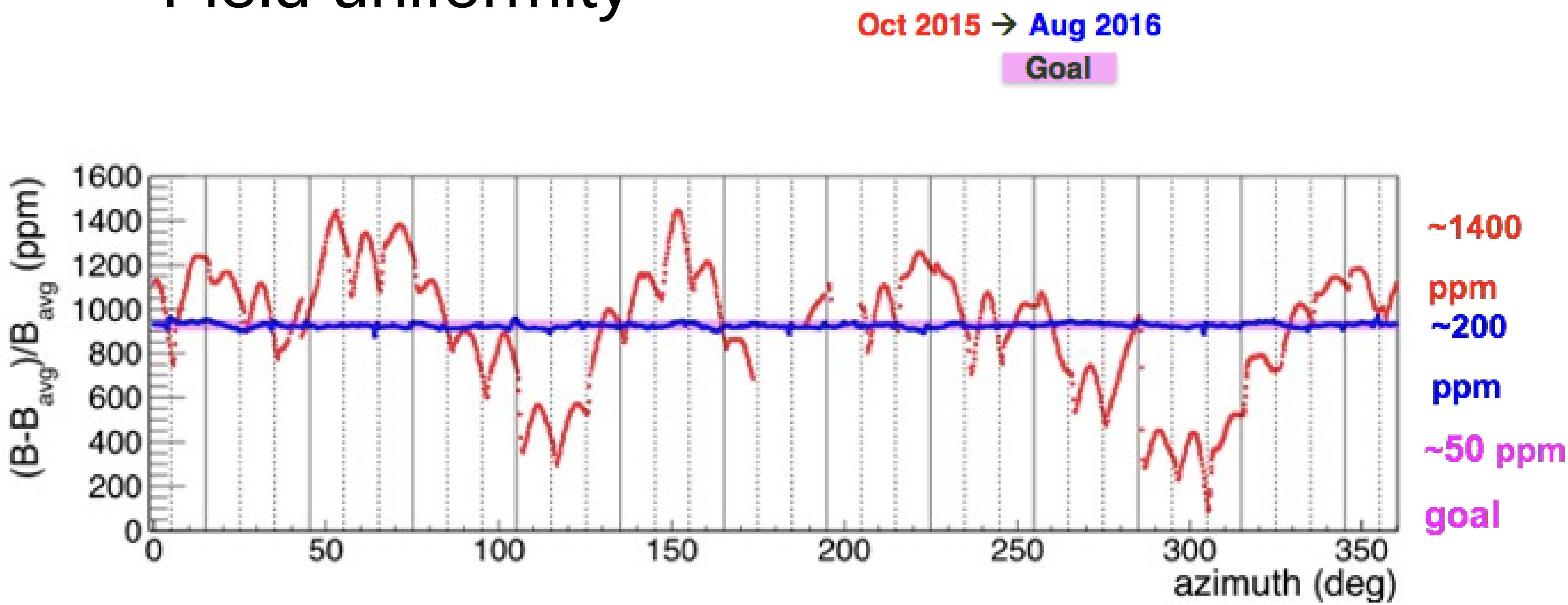

TD:FNAL FEM 2D simulation of the G-2 experiment Lambertson Magnet





Muon g-2 magnet successfully cooled down and powered up (April 2015)

Challenges
- Field uniformity



Magnet achieved full power September 21, 2015
Field started out with a peak variation of 1400 ppm
June 2016 peak to peak variation was reduced to 200 ppm
The goal of shimming is 50 ppm with a muon weighted systematic uncertainty of 70 ppb
BNL achieved 100 ppm with an averaged field uniformity of +- 1ppm. They estimated their systematic uncertainty of 140 ppb. We would like to improve of a factor 2!

Challenges
- Engineering

Chris Polly :
Major success! Inflector is operational 17.01.2017
Vacuum chamber celebration this Friday 25.01.2017

Hi all,
We quietly hit a major milestone yesterday as the final vacuum chamber was installed in the magnet gap. We consider this a pivotal point in the project because we can now begin the final construction phase where every detector, field, and injection device that interfaces with the chambers can now proceed with installation.
This represents the culmination of dozens of FTE*years of work if you think about all of the pieces that had to come together from the design to the final product, including…
- inflector connections
- quadruple refurbishment and alignment
- new kicker plates
- new Q1 mylar plates
- machining to accomodate trackers
- reconstructing the E821 tracker chamber to house the new calibration platform
- extensive cage and trolley rail alignment to meet demanding specifications
- bar code markings and reader
- automated, newly designed collimators
- fixed NMR probes

…and finally, the installation of the chambers themselves.

Challenges
- Measurement

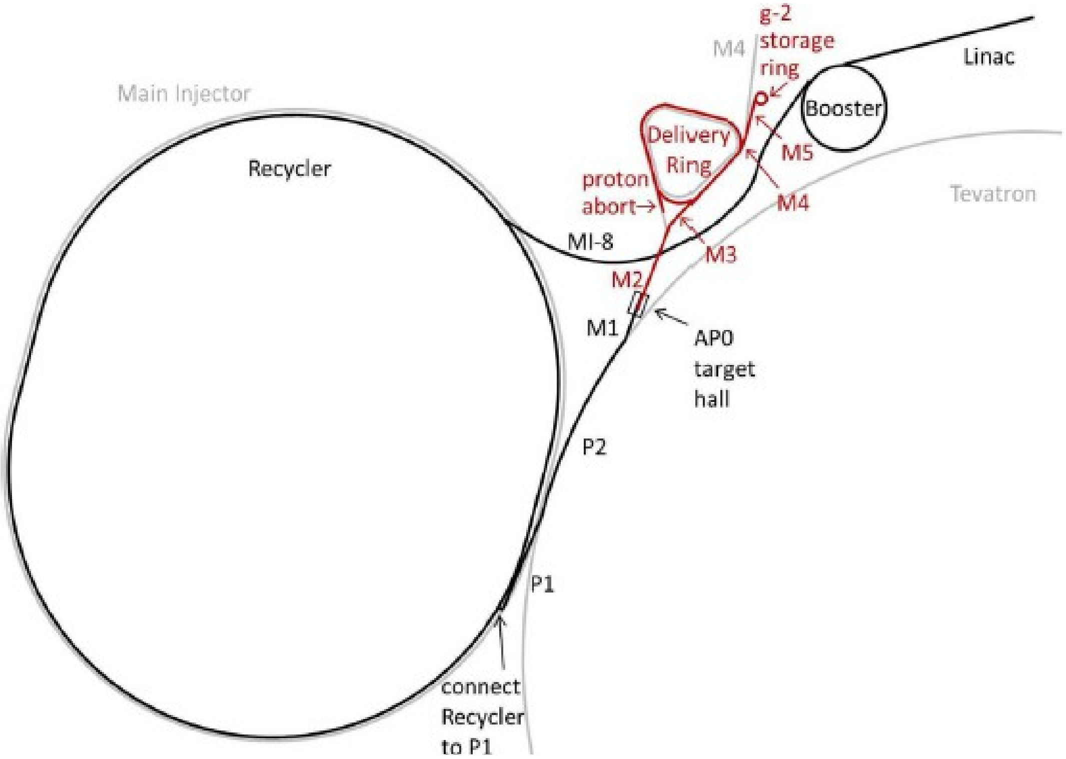
Measure anomalous precession frequency

$$\omega_a = a_\mu \frac{eB}{m}$$

Need magnetic field value
- proton precession frequency

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\lambda - \frac{\omega_a}{\omega_p}}$$

λ muon-to-proton magnetic moment ratio



Challenges
- Measurement

Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35
Trolley probe calibrations	90	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	30
Trolley measurements of B_0	50	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	30
Fixed probe interpolation	70	Better temperature stability of the magnet; more frequent trolley runs	30
Muon distribution	30	Additional probes at larger radii; improved field uniformity; improved muon tracking	10
Time-dependent external magnetic fields	–	Direct measurement of external fields; simulations of impact; active feedback	5
Others †	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	30
Total systematic error on ω_p	170		70

ω_p

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration low-energy threshold	20
Pileup	80	Low-energy samples recorded calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency) Better match of beamline to ring	< 30
E and pitch	50	Improved tracker Precise storage ring simulations	30
Total	180	Quadrature sum	70

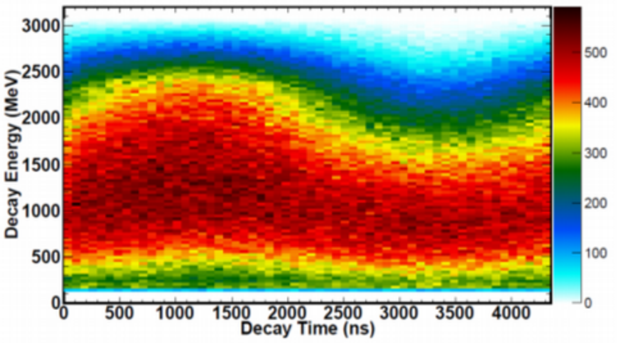
ω_a

Calibration system

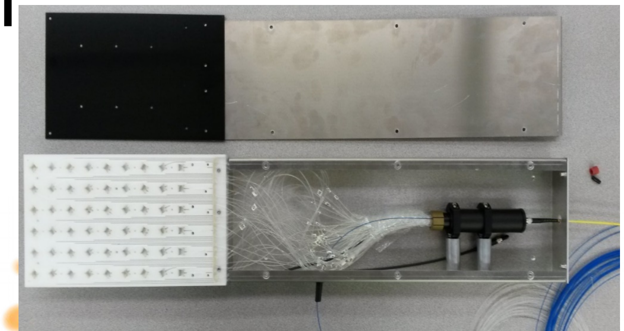
Calorimeters (54 crystals) --> 24 stations --> ~ 1300 channels
--> design light distibution system that sends a calibration pulse to every channel
--> each pulse ~the same intensity
--> each pulse in time equal to others --> stability
--> absolute light intensity (Am source --> SOURCE MONITOR)
--> control of the distribution chain (LOCAL MONITOR)

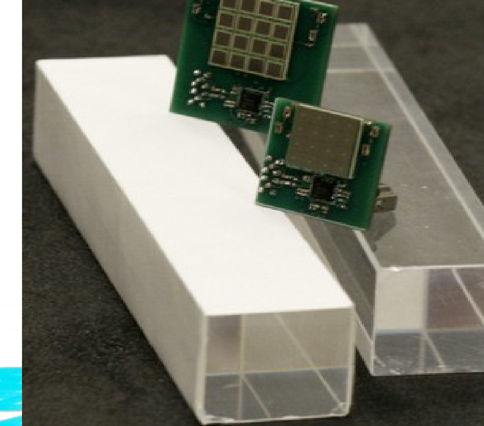
Photoelectron response calibration:
The photon detection efficiency of the SiPM must be calibrated.
We send laser pulses at high rate, with different intensity (filter wheel).

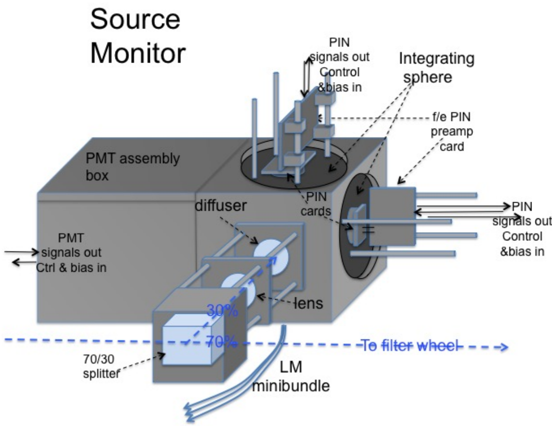
Gain calibration (short and long term):
SiPM gain is not stable, it depends on m rate, bias voltage and temperature.
We send a reference laser pulse (known energy) to each photosensor in/out of fill, during the data taking (procedure to be defined).

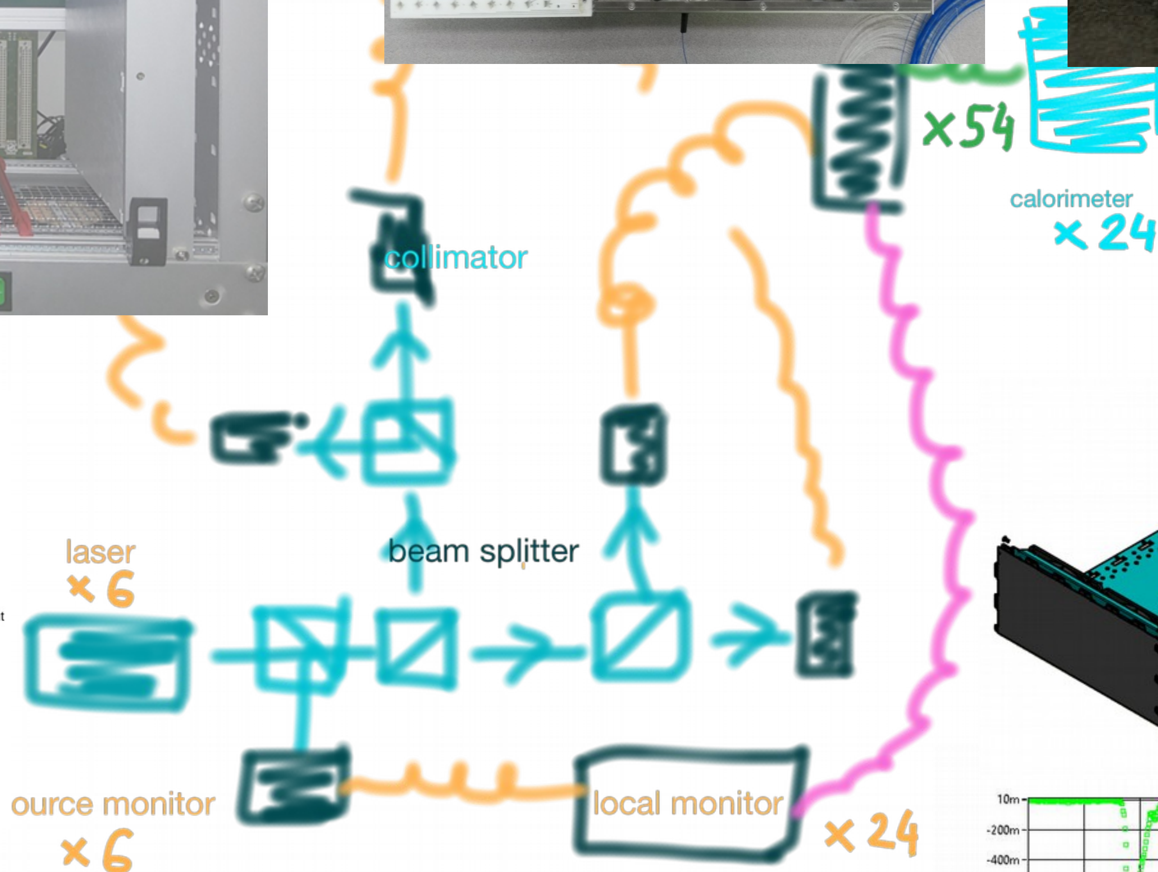


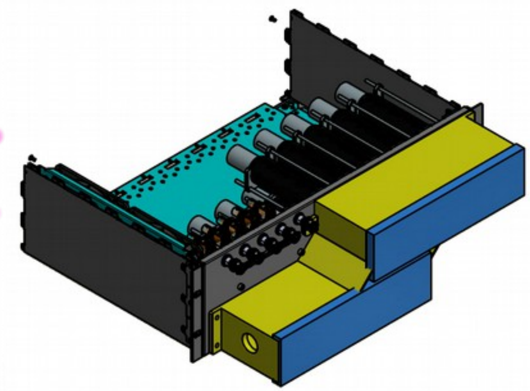
Calibration system

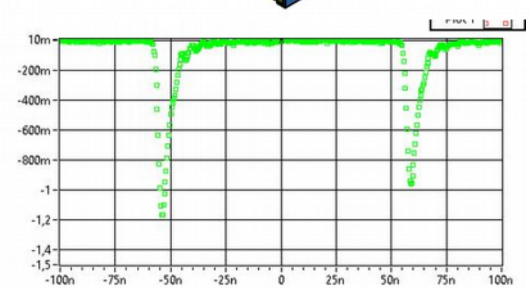








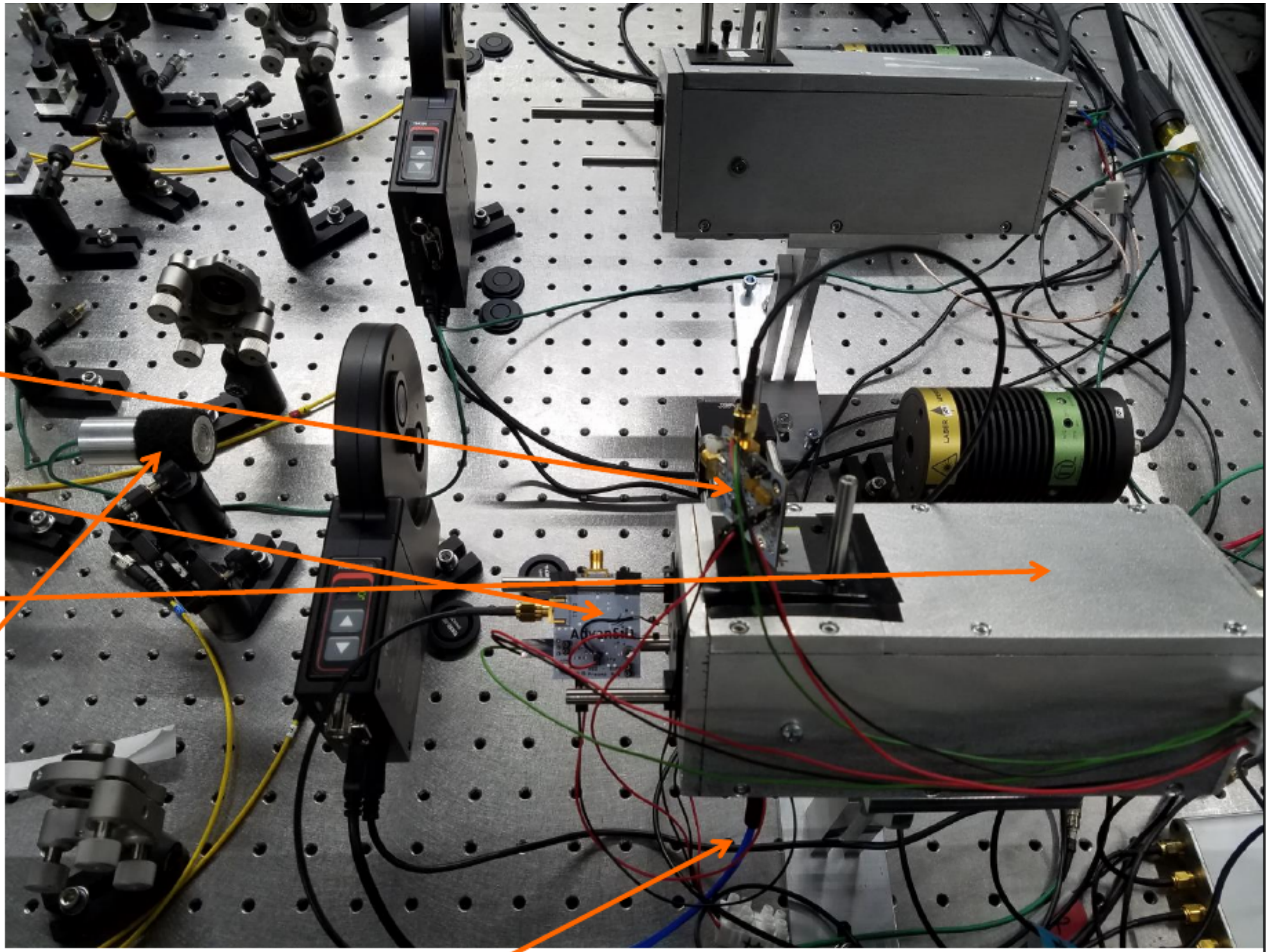




A. Anastasi et al, Electron beam test of key elements of the laser-based calibration system for the muon g-2 experiment, NIM A

Calibration system
Optical table detail

Detectors

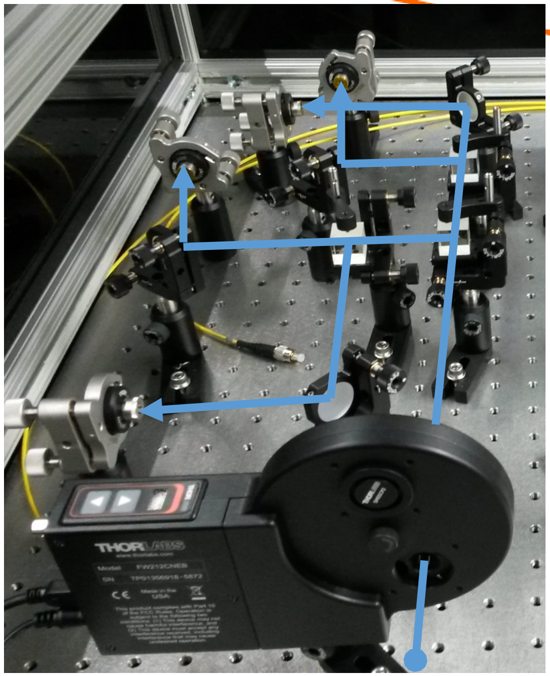


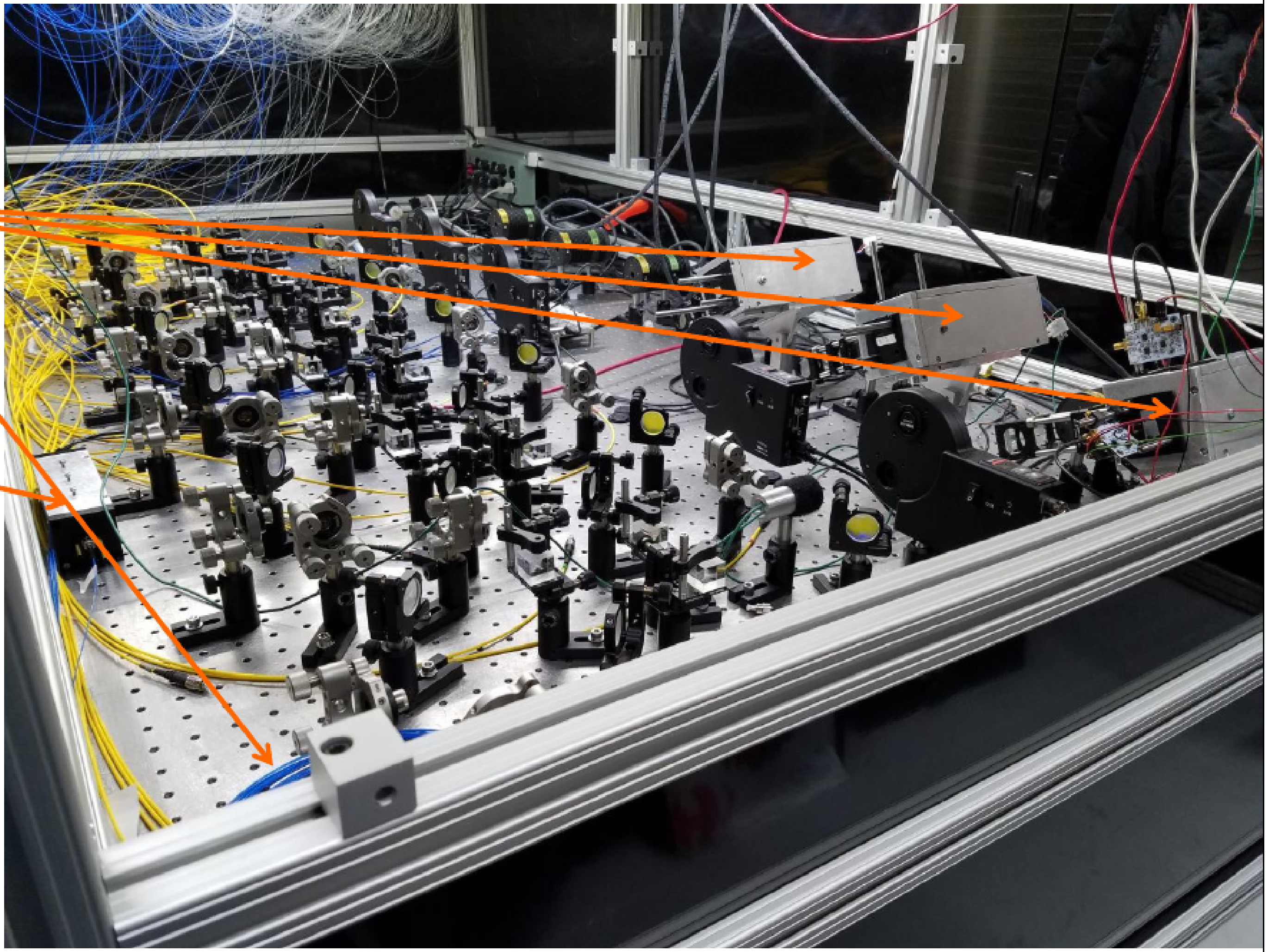
- SM PIN 1
- SM PIN 2
- SM PMT
- Additional PIN
- Minibundle to LM PM

Courtsey: D. Cauz

Calibration system
Inside laser hut

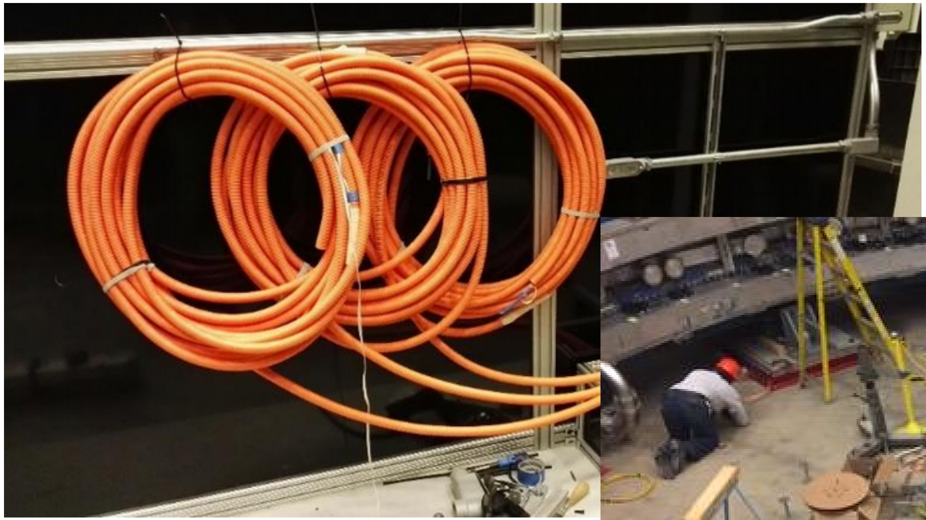
- 3 SMs
- Minibundle
- LM1 (for now)

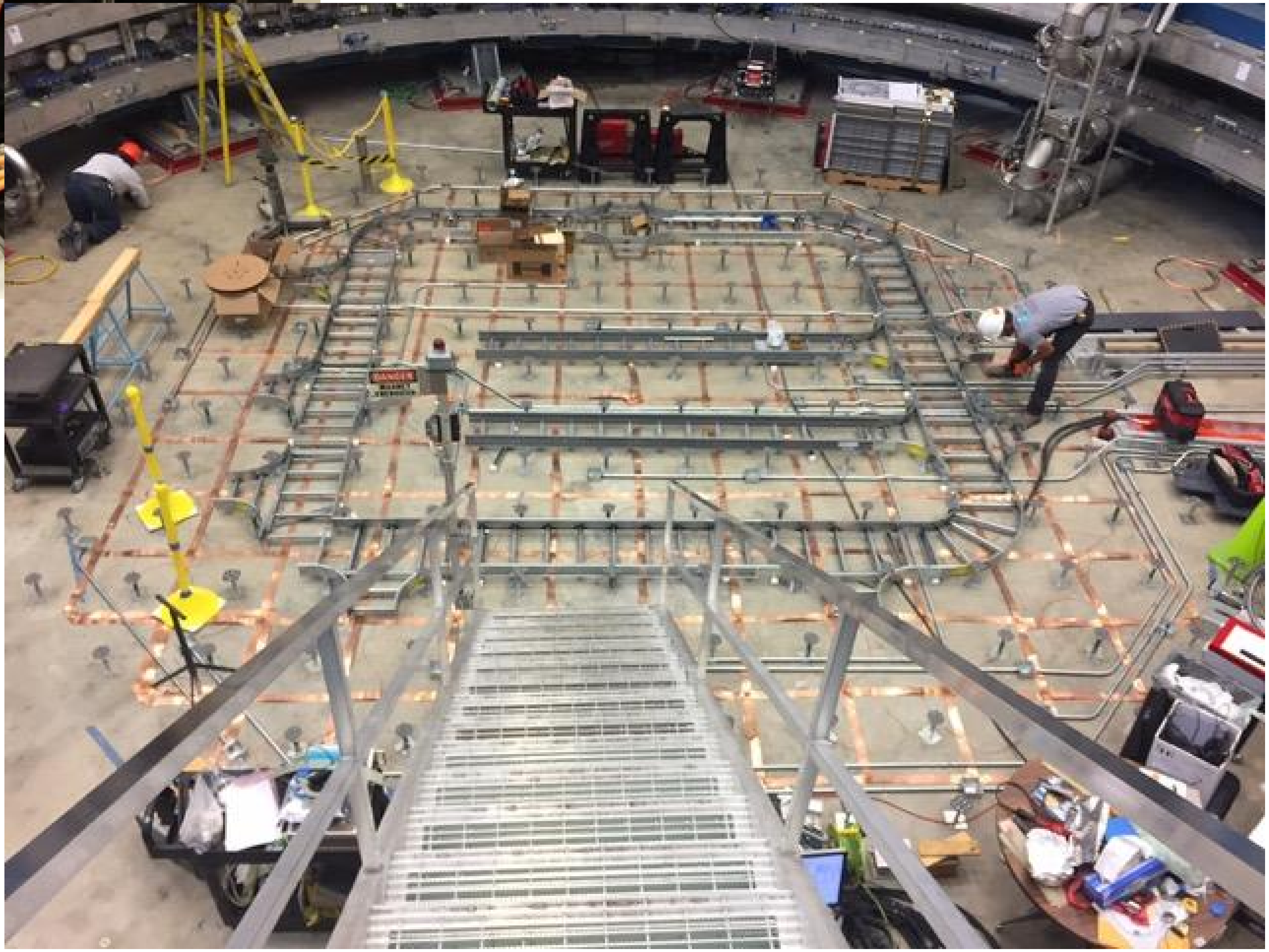




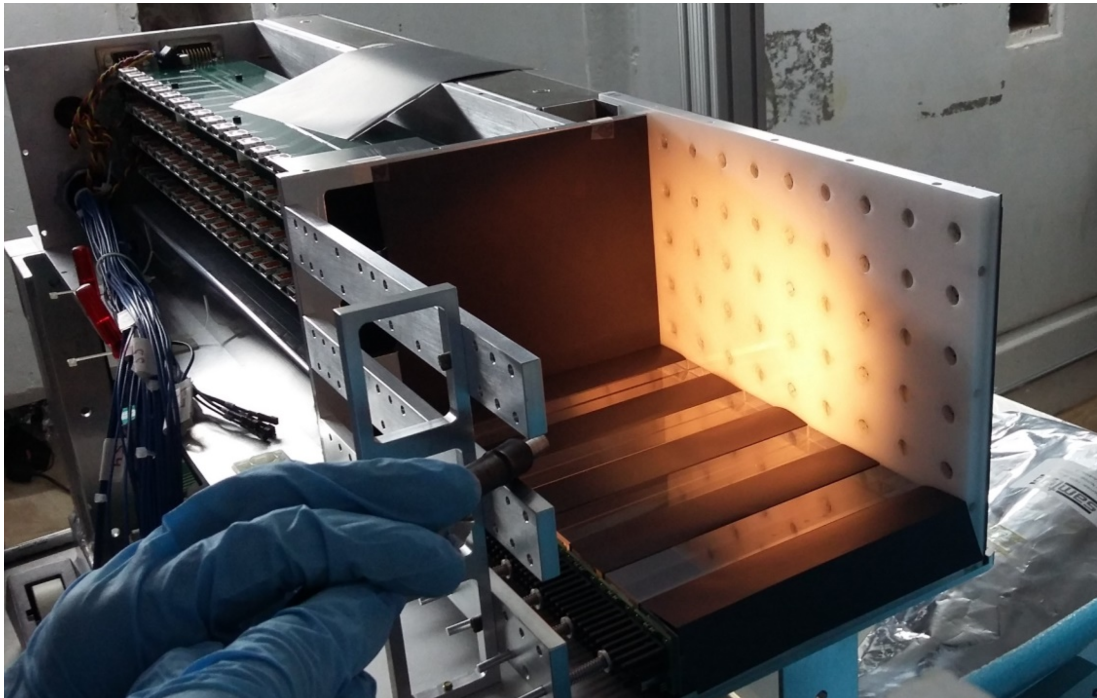
Courtsey: D. Cauz

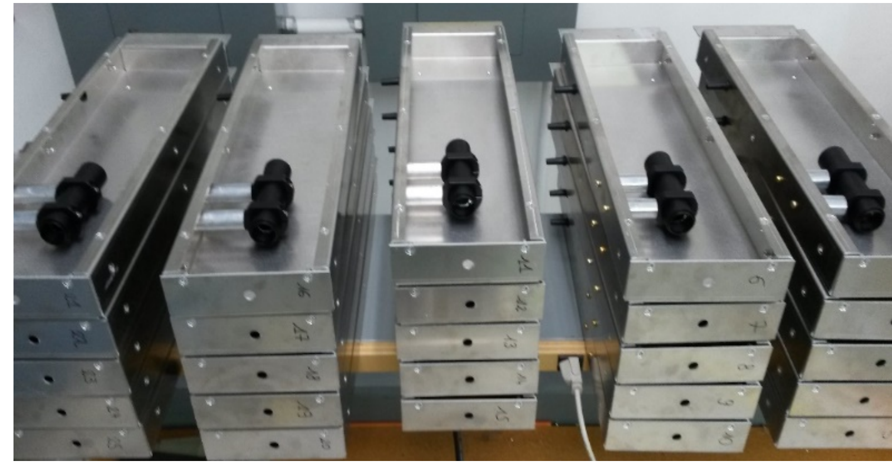
Calibration system
Inside ring

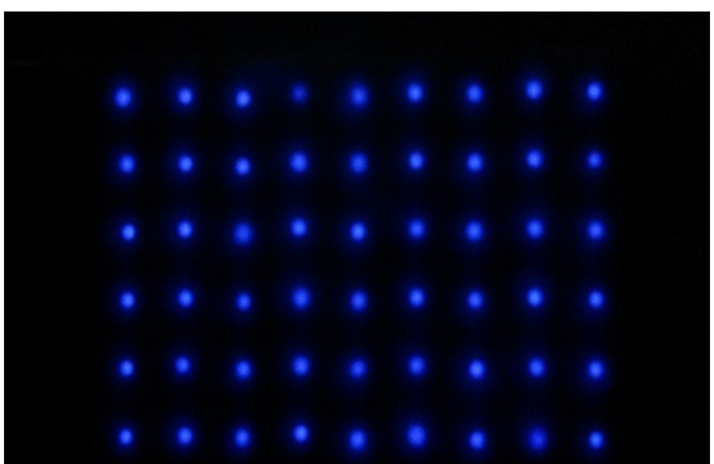


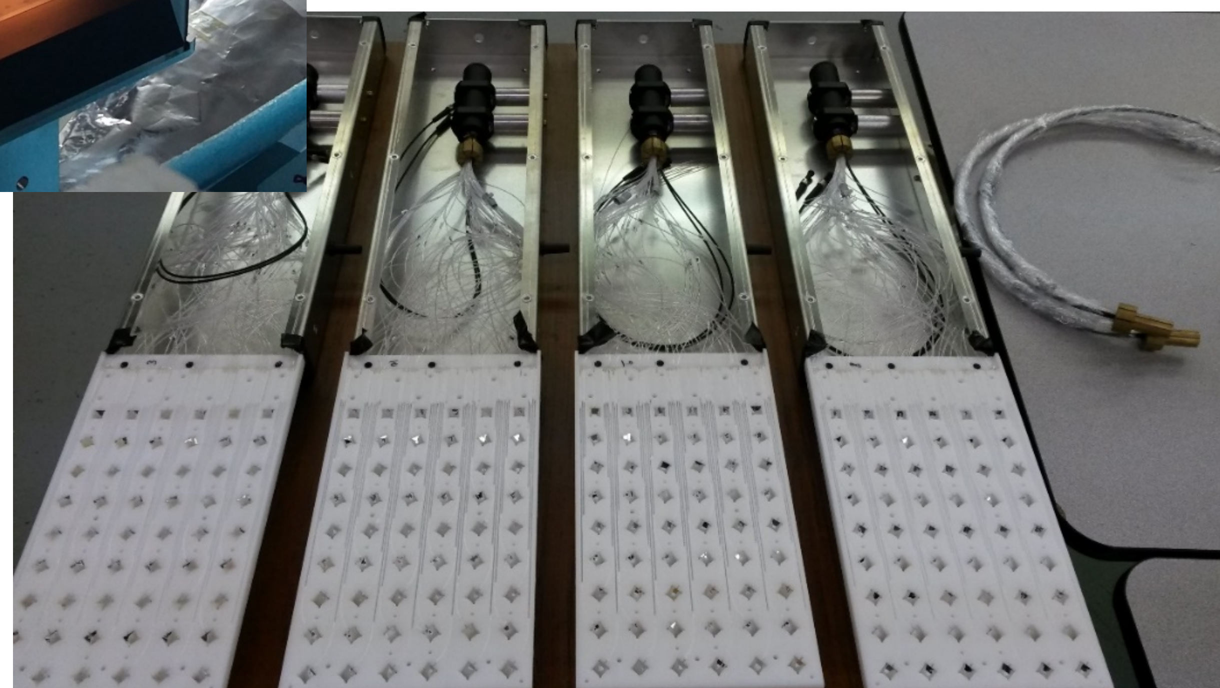


Calibration system
Diffuser boxes









Updated schedule

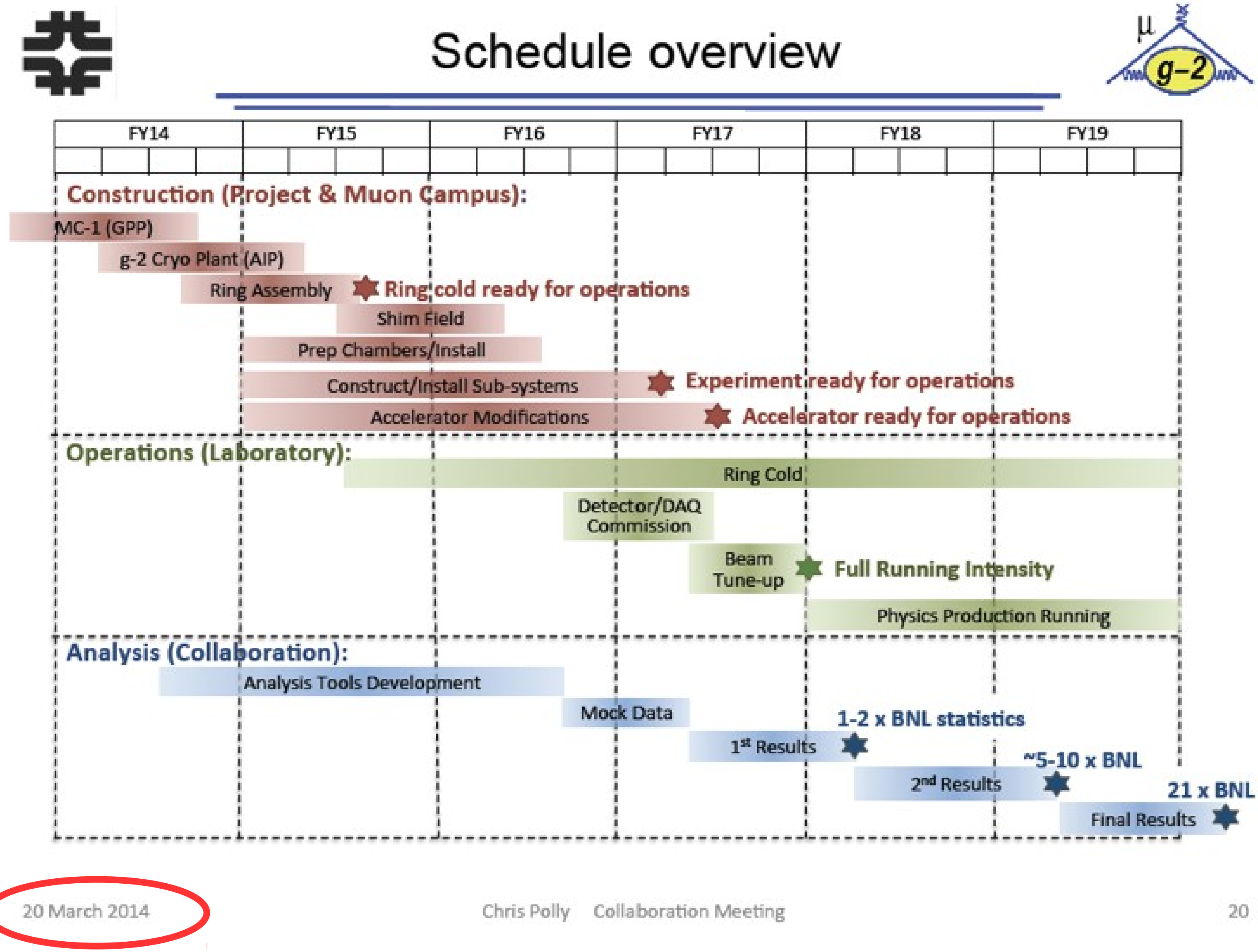
Targets:

- Complete 23 calorimeter by December
- Complete 25 calorimeters by January
- Turn on lasers by mid December
- Monitors by January/February
- Working system by February
- Full system by May

	Dec 16	Jan 17	Feb	March	April	May
23 Panels						
6 spare panels+prisms						
25 bundles						
3 spare bundles						
25 boxes + diffusers						
23 Assembled boxes						
25 Assembled boxes						
Optical comp laser hut						
Optical fibers						
Source monitor HW						
Local monitor HW						
Local monitor boards I						
uTCA						
HV+LV supply						
Source monitor boards						
Local monitor boards II						

slide : C. Ferrari

Schedule

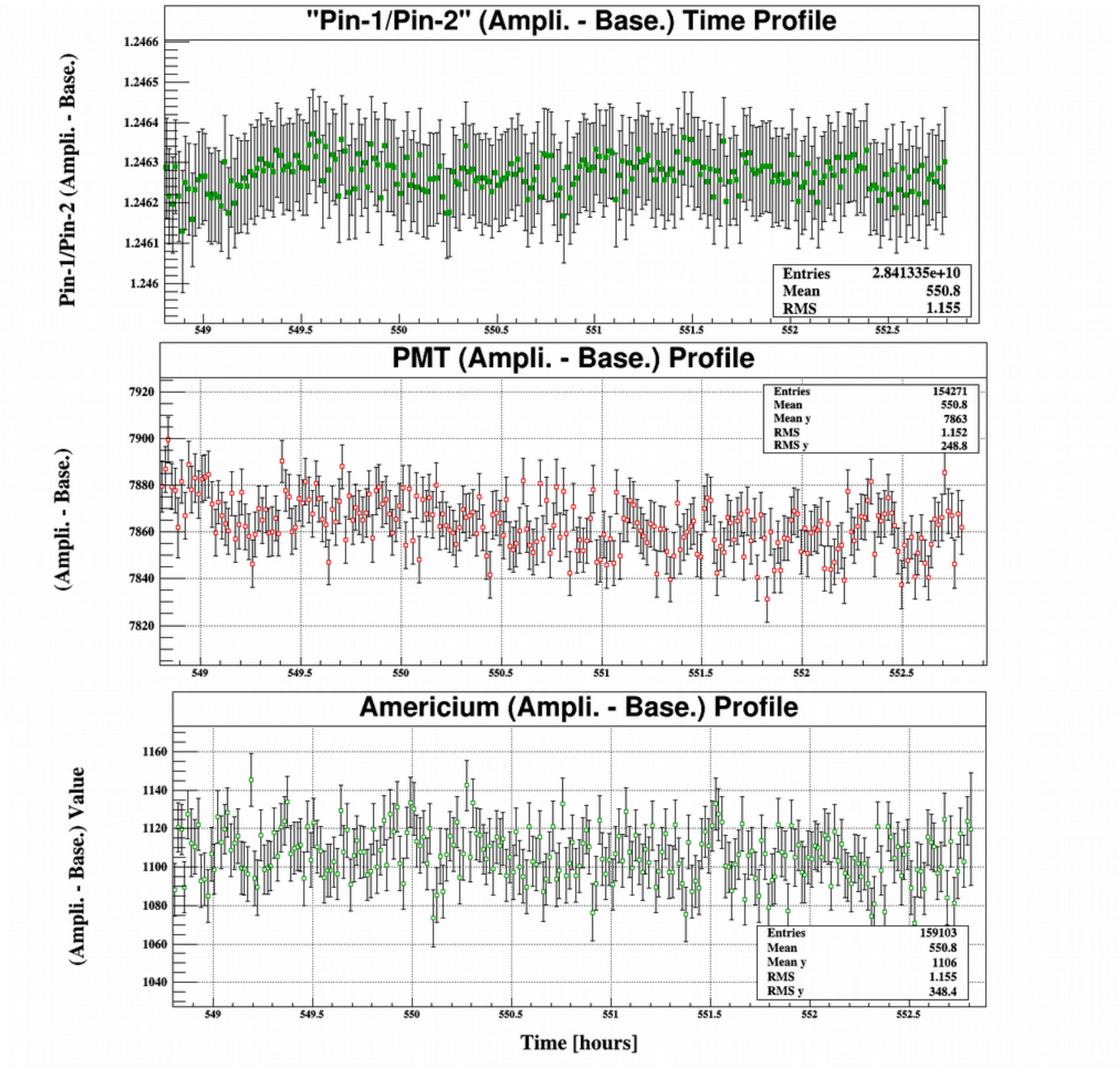


The experiment is on schedule.

Conclusion

- the experiment is following the schedule
- all systems are completed or close to completion
- the calibration system is performing well
  (test beam results)
  - will be ready in a few weeks (LM final assembly)
- looking forward for the first data

Backup


"Pin-1/Pin-2" (Ampli. - Base.) Time Profile
Pin-1/Pin-2 (Ampli. - Base.)
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Mean 550.8
RMS 1.155
PMT (Ampli. - Base.) Profile
(Ampli. - Base.)
Entries 154271
Mean 550.8
Mean y 7863
RMS 1.152
RMS y 248.8
Americium (Ampli. - Base.) Profile
(Ampli. - Base.) Value
Entries 159103
Mean 550.8
Mean y 1106
RMS 1.155
RMS y 348.4
Time [hours]