Status of the Muon g-2 experiment at Fermilab

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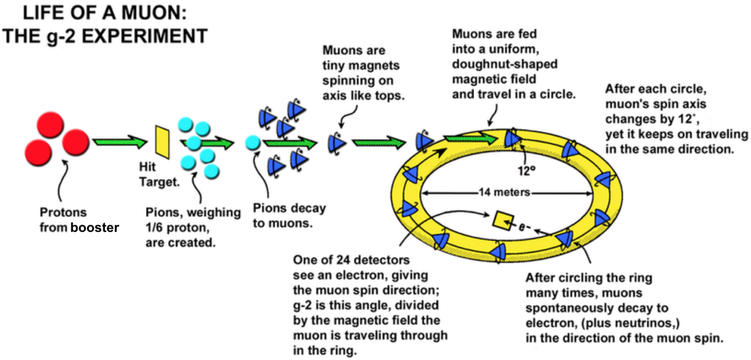
Muon g-2 experiment



Spin motion

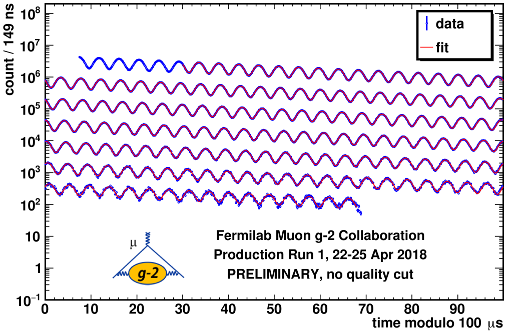
- Spin precession rate relative to the momentum

$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \left(\frac{mc}{p}\right)^2 \rightarrow 0\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

- Electric contribution cancels at magic momentum: $p_m = m/\sqrt{a_\mu} = 3.1\text{GeV}/c$
- $\longrightarrow \vec{\omega}_a = a_\mu \frac{e}{m}\vec{B}$ (on horizontal plane)
- B-field must be uniform to ppm level for precise measurement of ω_a
- Therefore magnetic quadrupole is avoided
- For $B_y = 1.45$ T, $\omega_a = 1.45$ kHz
- $\vec{\omega}_a$ makes a whole cycle in ≈ 30 revolutions around the ring

Measurement of a_μ

$$\frac{dN}{dt} = N_0 \exp^{-t/\gamma\tau_\mu} (1 + A \sin(\omega_a t + \phi))$$



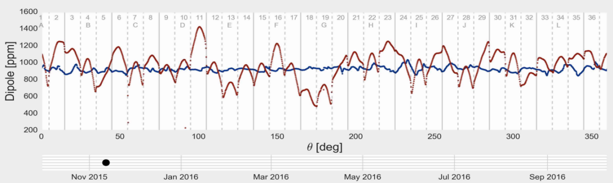
- BNL experiment showed $\approx 3.5\sigma$ deviation from the SM: $a_\mu^{BNL} = 116592089(54)_{stat}(33)_{sys}(63)_{tot} \times 10^{-11}(\pm 0.54 \text{ ppm})$
- Difference may originate from HVP, or new physics.
- Fermilab aims to measure a_μ with 4 times better sensitivity
- More details on Liang Li's talk on July 7, 11AM

Original improvement plan at Fermilab

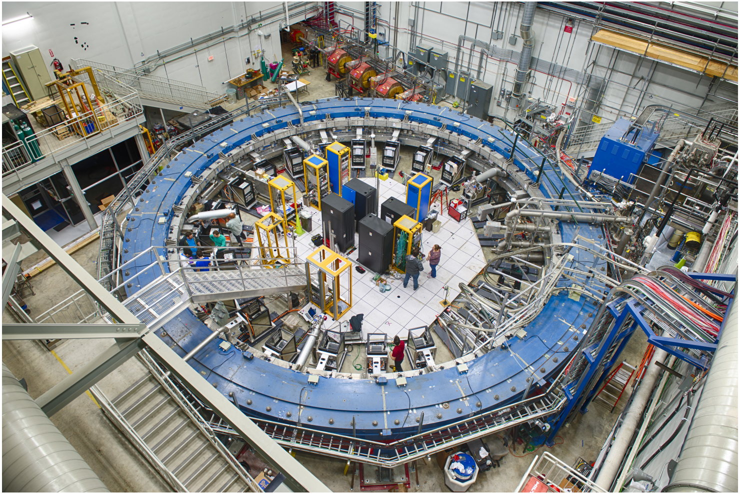
From TDR

Category	BNL [ppb]	Fermilab 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

- Gain changes is solved by callibrating photodiodes almost realtime w/ lasers to 10^{-4} level [done]
- Pileup is solved with segmented crystals and higher resolution digitizers [done]
- 20 times more statistics [partially done]
- Smooth B-field (to 0.5 ppm level) [done]
- Plan for lost muons and CBO is upgraded [in progress]



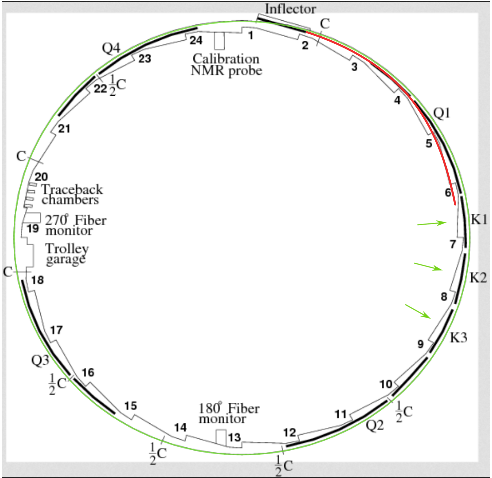
g-2 ring



- Ring transported from BNL
- More details on the ring and the magnetic field by Peter Winter's poster

g-2 ring (Injection and kick)

- The beam is injected through the inflector, a field-free region
- Its orbit is slightly off (red)
- The kickers correct the orbit by 10mrad

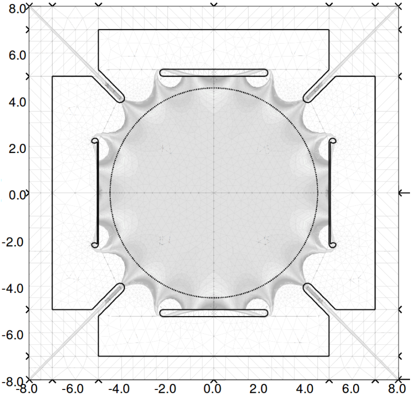


Beam

- Coasting beam of 10^4 muons with 150 ns revolution time
- Each storage takes 700 μs.
- Average muon lifetime: 65 μs
- Muon momentum: 3.1 GeV within $\pm 0.25\%$
- 95% muon polarization

g-2 ring (Storage)

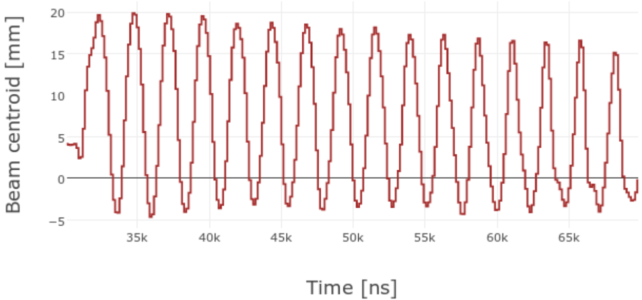
- The integrated vertical dipole B-field kept at ppm level by
  - Shimming
  - Fixed probe NMR
  - Measurement with trolley runs
  - Active cancellation
- Electric quadrupoles for vertical
- Tune can be adjusted by quadrupoles
  $n = \kappa \frac{R_0}{\beta B_0}$ (high n will help for CBO)
  $Q_y = \sqrt{n}; \quad Q_x = \sqrt{1-n}$
- Flat electrodes add higher multipoles



Coherent betatron oscillation (CBO)

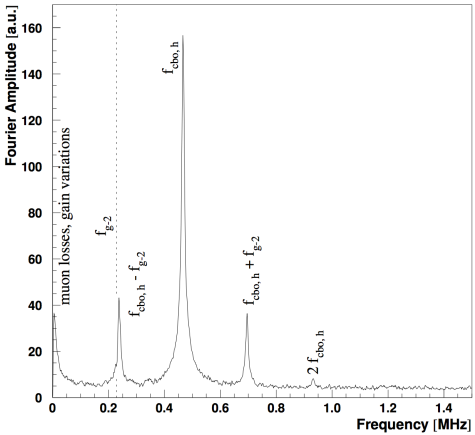
- CBO is basically the oscillation of beam centroid with time
- It is an issue because the detector acceptance changes with the radial location of the muon decay
- That means, the oscillations affect the electron count, g-2 phase and asymmetry
- Horizontal CBO: $f_{CBO} = f_c(1 - \sqrt{1-n}) \approx 500$ kHz
- The CBO amplitude is larger than the BNL experiment
- Enhanced by inflector misalignment and mismatched kicker power

$$\frac{dN}{dt} = N_0 \exp^{-t/\gamma\tau_\mu} (1 + A \sin(\omega_a t + \phi))$$



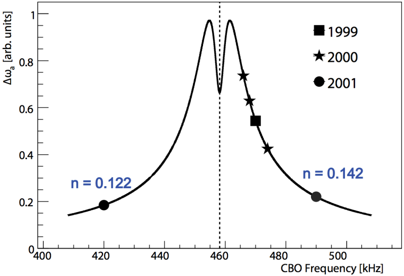
CBO oscillations and ω_a

- CBO becomes problem if one of its sidebands sits near $f_a = \omega_a/2\pi$
- Indeed, $f_{CBO} \approx 2f_a$ at BNL



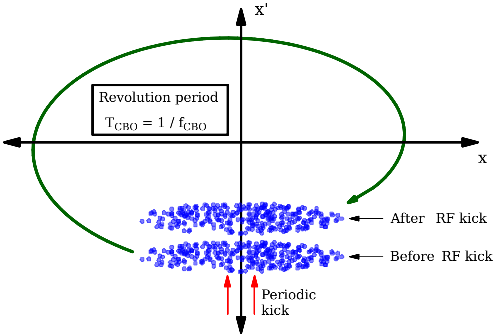
Elimination the CBO effect

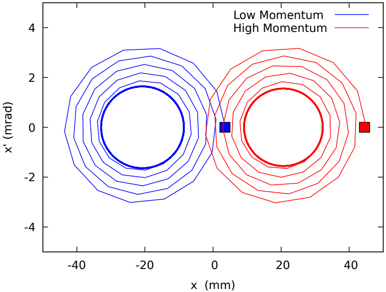
- $f_a = 460$ kHz at g-2 ring (constant)
- But f_{CBO} can be changed because it is related to focusing in the ring: $f_{CBO} = f_c(1 - \sqrt{1-n})$
- The effect can be suppressed significantly by moving the focusing index n away from $2f_a$
- More powerful kicker will fix part of the problem
- There is a more efficient method. The contribution comes from IBS/CAPP in Korea



RF reduction

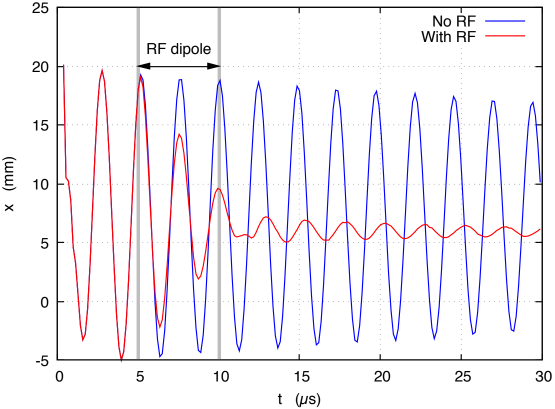
- The beam can be shaped in phase space by periodic kicks
- If high and low-momentum populations are in-phase, dipole field can decrease their oscillation amplitude simultaneously
- Quadrupole field can do the same if they are out-of-phase
- The method can compensate over/under kicking





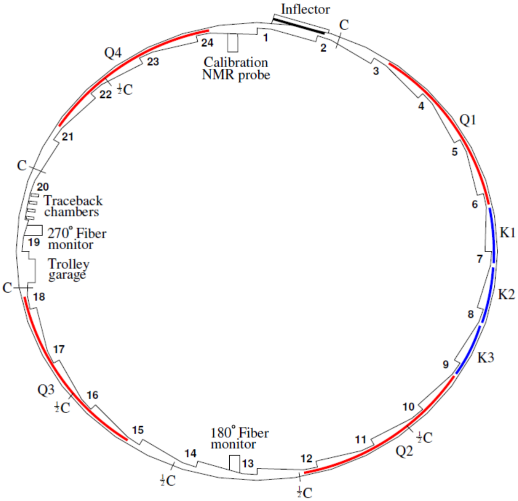
Simulation of RF reduction

- 1000 particles injected with a realistic distribution
- We applied 5kV amplitude on a 3.6m section of the ring for 5 μs after injection
- Scanned the phase of the RF field
- At the optimum phase, the CBO amplitude decreased to 1mm



Application of RF reduction

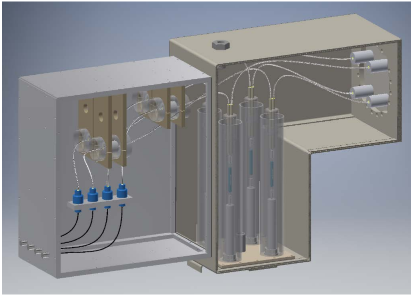
- The RF field can be applied on the quadrupoles
- Four quadrupoles of total 20m length
- Requires upgrade of the hardware

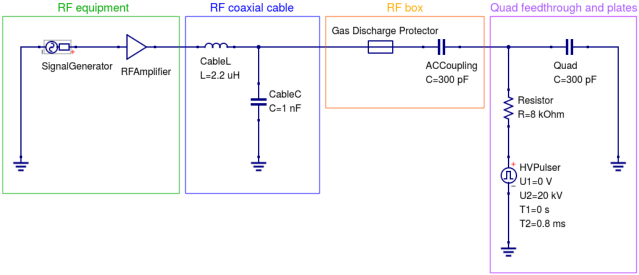


RF hardware (1)

Design from Jihoon Choi

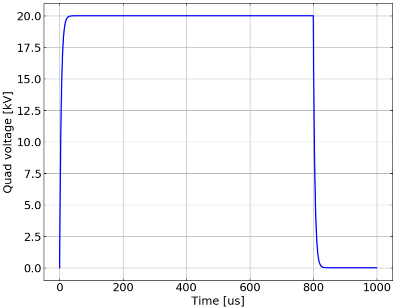
- The hardware is being developed in IBS, Korea
- The resistor design is being modified
- RF voltage will be superposed on the quadrupoles

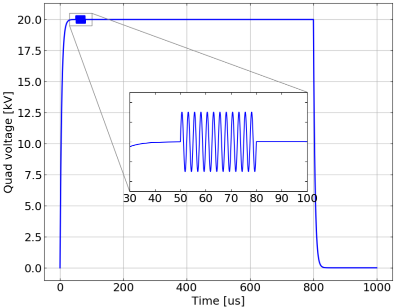




Superposition of the voltage on the quadrupole

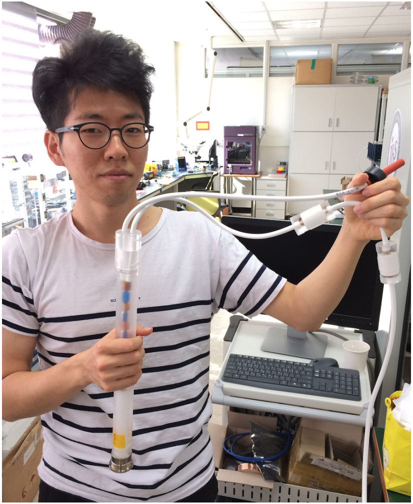
- The RF voltage is to be applied for $< 30\ \mu s$ at every injection





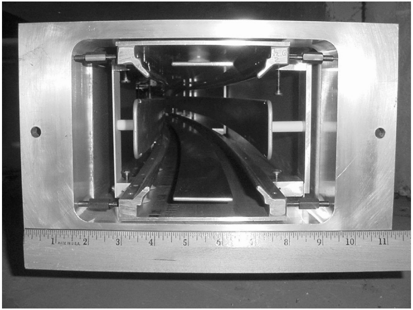
RF hardware (2)

- $\approx$ 20 kΩ resistors are potted with silicon to avoid sparks
- Orange plug is connected to the quadrupoles
- The other cable is connected to the RF voltage through AC coupling capacitors



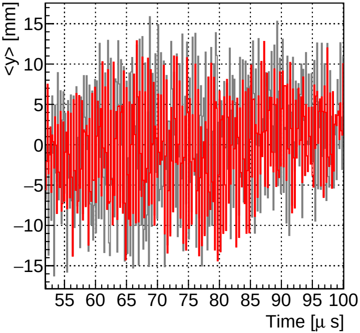
Preliminary tests

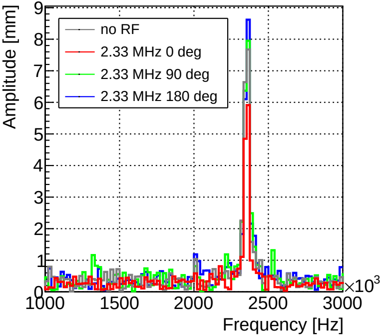
- We tested the RF reduction method on one of the quadrupoles of the g-2 ring
- The applied RF dipole with 400V in amplitude
- The quadrupole plate length was 3.2m (out of 20m)
- Fiber beam monitors was used for beam profile measurement



Preliminary tests (Vertical CBO reduction)

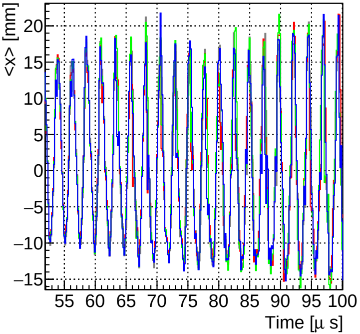
- Dipole RF (400V) was applied at the betatron frequency ($f_V = 2.33$ MHz)
- We tested several RF phases. 0° decreased the oscillation amplitude while 180° increased
- 2.3mm reduction was observed

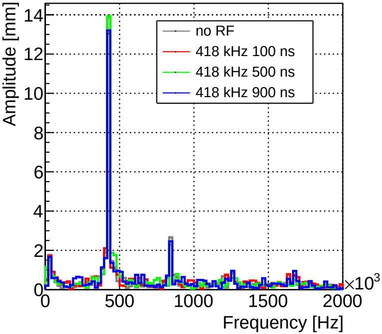




Preliminary tests (Horizontal CBO reduction)

- The effect was expected to be 1.3mm in horizontal motion because of the stronger focusing
- The fluctuations of the data from the fiber monitors were at the same level
- Hence, effect is consistent with zero





Muon loss

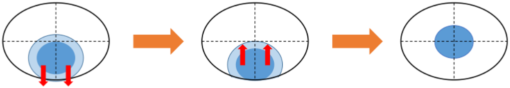
- The muon beam can be scraped at the beginning for a more controlled storage
- In the current scheme, this is achieved by introducing an asymmetry on the quadrupole voltage for a few μs, then taking it back
- RF method can be used at the “wrong” phase for scraping as well

RF modes

I. Dipole RF Centering

Give an additional kick to locate the beam to the center

II. Dipole RF Scraping



Scrape an undesired halo to reduce the muon loss

III. Quadrupole RF Squeezing

Reduce the beam width by lowering the individual CBO amplitude for HM and LM

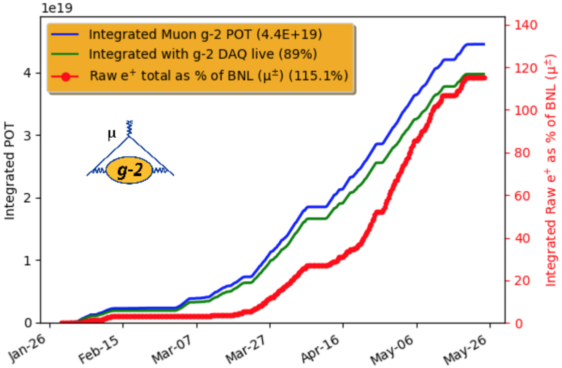
● High momentum ($dp/p > 0$) ● Low momentum ($dp/p < 0$)

Next step on RF reduction

- We are developing the hardware to be applied on all of the quadrupoles
- The RF circuit is also optimized for power transmission
- In total we expect a factor of 12 improvement
- This means ≈ 1.5 cm reduction of horizontal CBO
- More details at On Kim's poster

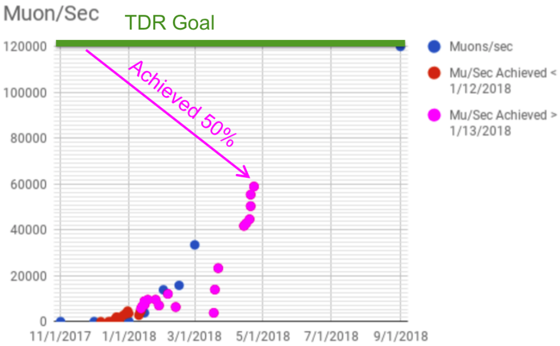
Overall status of the experiment

- Physics runs going on
- Exceeded the amount of data at BNL
- Shutdown in a few days



Shutdown plan

- Major fixes and upgrades in summer, including
  - improvement of momentum distribution
  - obtaining higher flux
  - reducing CBO
- Can reach the BNL sensitivity next year



Summary

- Fermilab g-2 experiment is an upgrade to the BNL experiment
- It aims to resolve the 3.5σ discrepancy with four times more sensitive measurement
- Several of the improvement goals are achieved. Remaining ones are being worked on
- CBO is one of the critical items remained
- Korean Collaboration introduced a novel method for solving the systematics regarding the muon losses and CBO reduction
- The system will be installed in the summer shutdown
- Expected to achieve the BNL sensitivity next year and go beyond