9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada JACoW Publishing
ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF010

REDUCTION OF COHERENT BETATRON OSCILLATIONS USING RF ELECTRIC FIELDS IN THE FERMILAB MUON G-2 EXPERIMENT

On Kim[1,2], SeungPyo Chang[1,2], Jihoon Choi[1], Selcuk Haciomeroglu[1], Young-Im Kim[1],
Yuri F. Orlov[3], and Yannis K. Semertzidis[1,2]
on behalf of the muon g-2 Collaboration
[1]IBS, Center for Axion and Precision Physics, Daejeon, 34051, South Korea
[2]KAIST, Department of Physics, Daejeon, 34141, South Korea
[3]Cornell University, Department of Physics, Ithaca, New York 14853-2501, USA

Abstract

Coherent betatron oscillations (CBO) was one of the most significant systematic error sources in the muon g-2 experiment at BNL. The upgraded version of the experiment at Fermilab aims to eliminate this effect to achieve four times better sensitivity. We propose a novel method to reduce the CBO by applying RF dipole or quadrupole electric field to the existing quadrupole plates that provide vertical focusing in the storage ring. The simulation results show that 90% reduction of CBO is in principle possible. We made preliminary tests by applying dipole RF field to one of the quadrupoles of the g-2 ring. The vertical CBO was reduced by almost 50% while only being applied at one section. The change in the horizontal CBO was not visible in accordance with expectations. We are currently improving the hardware to implement it in all of the quadrupoles.

INTRODUCTION

The anomalous magnetic moment $a = (g-2)/2$ of the muon has been previously measured at CERN [1–4] and BNL [5]. The BNL experiment showed greater than 3σ discrepancy with the SM. Currently, it is being repeated at Fermilab with four times better sensitivity goal [6] .

The proton beam in the experiment hits a target to produce copious pions, decaying to muons and muon neutrinos. Then, a small muon momentum bite is selected, yielding a longitudinally polarized (95%) muon beam at 3.1 GeV to be injected into the storage ring of 14m diameter. The storage ring consists of 1.45T vertical dipole magnetic field and four sets of electrostatic quadrupoles for vertical focusing. The stored muons decay to electrons where the highest energy products are emitted in the direction of muon polarization. This way, the detectors located around the ring provide an indirect measurement of the polarization direction of the muon as a function of time.

$a \equiv (g-2)/2$ is basically estimated from the rotation frequency of the muon polarization on the horizontal plane. The spin rotates around the vertical magnetic field B faster than the cyclotron frequency by $\omega_a = 2\pi f_a = a\frac{eB}{mc}$. Here, e and m are the electric charge and the mass of the muon respectively. ω_a makes a whole rotation in about 30 revolutions of the beam.

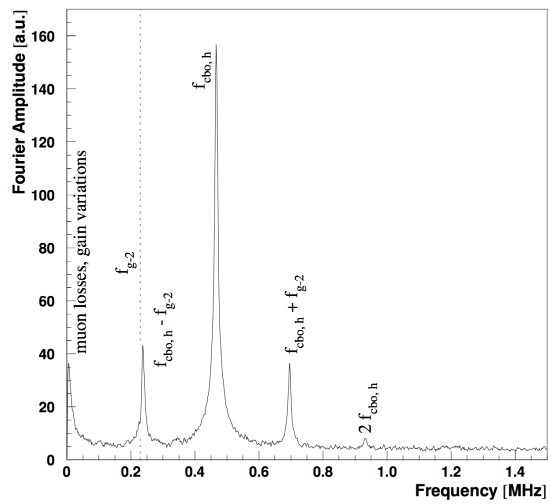

Figure 1: In the BNL experiment of 2000, $f_{CBO} - f_a$ and f_a almost overlapped. $f_a \equiv f_{g-2}$ is barely visible because of the sideband of the f_{CBO}. The plot is from Ref [5].

The Fermilab Muon g-2 Collaboration aims to improve several systematic errors, namely pileup, gain changes, pitch effect and finally lost muons and coherent betatron oscillation (CBO) [5]. This study aims to address the last one.

CBO is basically the oscillation of the beam centroid as a function of time [5] . It is an issue because the detector acceptance changes with the radial location of the muon decay. The CBO becomes harmful if one of its side bands sits on f_a. Indeed, $f_{CBO} \approx 500$ kHz was very close to $2f_a \approx 460$ kHz at BNL (See Figure 1), close to twice the g-2 frequency. Hence, the beat frequency $f_{CBO} - f_a$ sits on top of f_a, pulling the g-2 phase.

There are several methods to minimize the CBO problem:

- *Using multiple detectors around the ring* : It was shown in the BNL experiment to be an efficient method to eliminate the aliasing effect.

- *Move f_{CBO} away from $2f_a$* : This can be achieved by changing the quadrupole focusing index n, a measure of field gradient at the quadrupoles. Figure 2 shows how the CBO effect changes with n. The CBO effect decreases at the tails.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF010

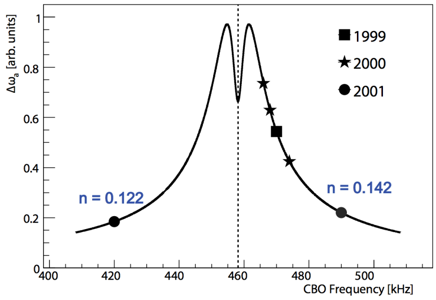

Figure 2: The BNL experiment was repeated with different f_{CBO} values corresponding to different field indices (n). The vertical axis shows the systematic error related to the CBO effect. The plot is from [5].

- *Suppress the CBO oscillations* : In this work we propose the RF reduction method based on application of an oscillating electric field at the CBO frequency to minimize the CBO effect.

BEAM DISTRIBUTION IN THE REALISTIC G-2 RING

We simulated a beam in the realistic g-2 ring. The beam in the simulations has a sample of 10^3 particles. It gets a horizontal kick by a pulsed dipole magnetic field at a specific location after injection to be settled on the design orbit. The storage in the experiment is made by 1.45 T vertical magnetic field for around 700µs. We monitor the beam for 100µs in the simulations. The vertical focusing is achieved by four sets of electrostatic quadrupoles, each 4.8 m length in total. The aperture is limited to 45mm radius by means of collimators.

After the beam is kicked and collimated, the particles populate two regions in the horizontal phase space according to their momentum. If the momentum of a particle is higher than the magic value $p_0 = m/\sqrt{a}$, then it occupies the right side ($x > 0$) of the phase space. Similarly, low momentum population occupies the left side ($x < 0$).

Figure 3 shows the beam distribution after $\approx$ 1.5 µs. The center of mass of each population orbits around some equilibrium orbit. The equilibrium point is determined by $x_{eq} = R\delta/(1-n)$ with the radius of the ring R, the field index n and the momentum spread $\delta \equiv dp/p_0$. The circular orbits show how the center of mass of high and low momentum beams move in the phase space. Since the high and low momenta populations are in-phase, the centroid of the whole beam makes the CBO oscillation of amplitude $\approx$ 12 mm.

APPLICATION OF AN OSCILLATING ELECTRIC FIELD

The simulations with two separate particles ($\delta > 0$ and $\delta < 0$) show that the CBO of this two-particle system can be reduced by the same dipole RF field (See Figure 4).

The method relies on application of a periodic field at f_{CBO} to damp the CBO oscillations. Figure 5 demonstrates how the beam can be moved in the phase space by a periodic

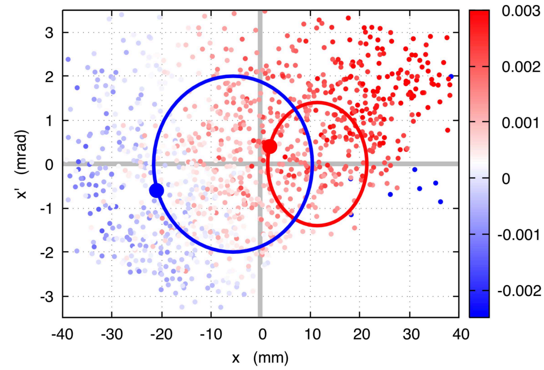

Figure 3: In the simulation, the beam achieves this distribution after 10 revolutions, which include kicking and collimation. The color of the dots show the momentum spread ($\delta \equiv \Delta p/p_0$). The filled circles on the ellipses represent the center of mass of each population. They orbit along the corresponding ellipses.

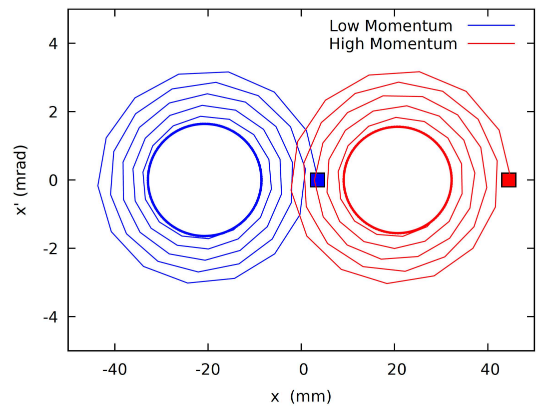

Figure 4: One-particle simulations show how a dipole RF field shrinks the CBO amplitude for high and low momentum particles if they are in-phase. The squares show the initial positions of the corresponding particles. One needs to use a quadrupole RF field if they are out-of-phase.

pulse of this kind. The method can be efficiently applied by sinusoidal dipole or quadrupole electric field at several locations in the ring.

In the simulations, we applied the dipole RF field of 5 kV amplitude on a 3.6 m section for 5µs and scanned the phase of the RF field for maximum CBO reduction. After finding the optimum phase, the CBO amplitude is observed to decrease to 1 mm (Figure 6).

PRELIMINARY TESTS IN THE G-2 RING

We tested the method in the Fermilab muon g-2 ring for vertical and horizontal motions separately. We used fiber beam monitor [5] measurements to get the beam profile as a function of time. The RF field was applied by adding the signal on top of a 3.2m long quadrupole section by capacitive coupling [7]. The amplitude of the applied RF field was 400V.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF010

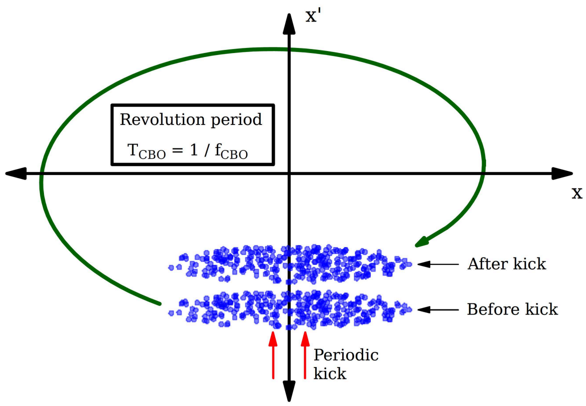

Figure 5: The unsettled beam oscillates with CBO frequency along a closed orbit as observed by one detector. The oscillation can be reduced by applying a periodic kick at f_{CBO}. This way, the beam gets closer to the center at every turn.

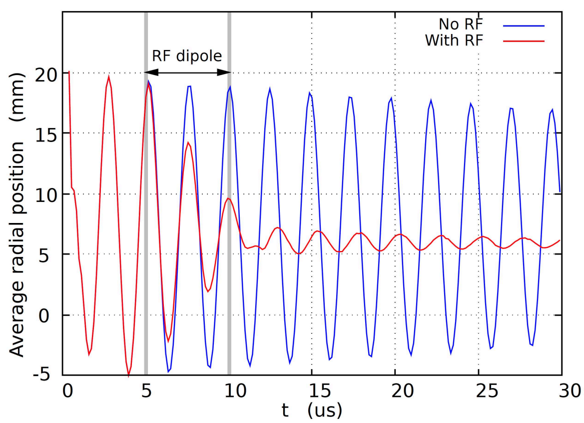

Figure 6: The dipole RF field is applied with several phases in the simulations from 5µs to 10µs. At the optimum phase, after 10µs, the CBO oscillation amplitude decreases to 10%.

On the vertical direction, the CBO reduction was clearly visible after applying the RF dipole field at the betatron frequency $f_y = 2.3$MHz. Figure 7 shows that the vertical CBO was reduced by 2.3mm with RF field at 0° phase. As expected, the CBO grown when the RF field is applied in the opposite phase and remains almost the same at 90°.

The effect on the horizontal direction was not visible as it was estimated to be 1.3mm, roughly the same value with the fluctuations on the fiber harp data.

We will improve the RF system to be applicable to all of the quadrupoles to increase the effect by a factor of 6. Also, the design used in the tests had 50% efficiency because of impedance mismatch. We will fix it to gain another factor of 2. Then, the effect on the horizontal direction is expected to increase by a factor of 12 compared to the previous tests.

CONCLUSION

Coherent betatron oscillations is one of the major sources of systematic errors in the muon g-2 experiment. We use RF

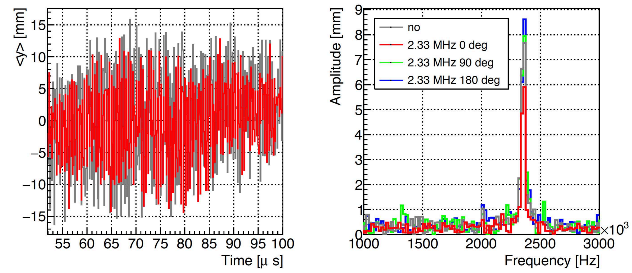

Figure 7: CBO reduction with RF dipole is clearly visible when applied at 2.3MHz. At 0° degree phase, the CBO amplitude decreases by 2.3mm at the end of 100 µs. The left plot is on the time domain and the right is on the frequency domain.

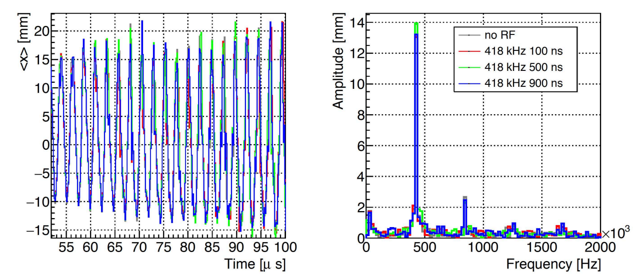

Figure 8: We did not observe any reduction of CBO on the horizontal direction. This seems to originate from the large fluctuations of the fiber harp data. Again, the left plot is on the time domain and the right is on the frequency domain.

dipole fields to reduce the amplitude of this oscillation by means of an RF electric field. According to the simulation re-sults, the effect can be reduced by 90% with an appropriately applied RF field of a specific phase and frequency.

We made preliminary tests in the Fermilab muon g-2 ring to test the method. The vertical CBO could be reduced by 2.3mm with the RF dipole field at 2.3MHz. The effect on the horizontal CBO was not visible as the fluctuations on the fiber harp data used to measure the CBO were as large as the expected reduction. We are developing the hardware to increase the effectiveness of the applied RF field by more than an order of magnitude.

ACKNOWLEDGEMENT

This work was supported by IBS-R017-D1-2018- a00 of the Republic of Korea, and also authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. We also would like to thank Hogan Nguyen, Jason Crnkovic, Vladimir Tishchenko, Brendan Kiburg, Jarek Kaspar, Lee Roberts and William Morse.

REFERENCES

[1] G. Charpak *et al.*, *Phys. Rev. Lett.* **6**, p. 128, 1961.
[2] G. Charpak *et al.*, *Phys. Lett.* **1**, p. 16, 1962.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF010

[3] J. Bailey *et al.*, *Nuovo Cimento A* **9**, p. 369, 1972.

[4] J. Bailey *et al.*, *Nucl. Phys. B* **150**, p. 1, 1979.

[5] G.W. Bennett *et al.*, *Phys. Rev. D* **73**, p. 072003, 2006.

[6] Muon g-2 Collaboration, “Muon g-2 technical design report” arXiv:1501.06858, 2015.

[7] Y.K. Semertzidis *et al.*, *NIM A* **503**, p. 458, 2003.