A method to reduce the coherent betatron oscillations in a muon g-2 storage ring experiment using RF fields

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The muon g − 2 storage-ring experiments store a beam of polarized muons in a weak focusing storage ring. As the ensemble of muons goes around the ring, their spins precess, and when they decay through the weak interaction: \( \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \), the decay positrons are detected by electromagnetic calorimeters. In addition to the expected exponential decay in the positron time spectrum, the weak decay asymmetry causes a modulation in the number of positrons at the difference frequency between the spin and cyclotron frequencies, \( \omega_a \). This frequency is directly proportional to the magnetic anomaly \( a = (g - 2)/2 \), where \( g \) is the gyromagnetic ratio of the muon, which is slightly greater than 2. The detector acceptance depends on the radial position of the muon decay, so the coherent betatron oscillations (CBO) of the muon bunch following injection into the storage ring amplitude modulates the measured muon signal with the frequency \( \omega_{CBO} \). A new method using radio frequency (RF) electric fields has the potential to significantly decrease the beam CBO, and additionally to scrape the beam to reduce muon losses from the storage ring during the measurement period.

I. INTRODUCTION

Efforts to measure the muon magnetic anomaly \( a_\mu \equiv (g_\mu - 2)/2 \) with storage rings has been ongoing since the 1960s. Several key methods like the magic momentum were introduced in experiments at CERN [1–3]. The use of electrostatic quadrupoles was first introduced in the third CERN experiment, which obtained a precision of 7.3 ppm [3]. With the significant increase in the number of muons and direct muon injection into the storage ring, the Brookhaven National Laboratory (BNL) experiment E821 achieved 0.54 ppm precision [4]. At present there appears to be a greater than 3.5 standard deviation difference between the experimental measurement of \( a_\mu \) and the Standard model value [5, 6]. Currently, the Fermilab g − 2 collaboration is conducting a new experiment (E989) with an upgraded muon beamline, storage ring and detector systems [7]. The E989 goal is to measure \( a_\mu \) with four times the precision reached by BNL E821.

The positive muon beam in E989 is produced in two steps: First, a proton beam hits a target to produce copious pions that decay into muons and neutrinos. After the pions decay, a small muon momentum bite is selected, yielding a longitudinally polarized (> 95%) muon beam at the magic momentum \( p_m = 3.09 \text{ GeV}/c \) that is then injected into the 14 m diameter storage ring. The beam is stored radially by a \( B_0 = 1.45 \text{ T} \) vertical dipole magnetic field and vertically by four sets of electrostatic quadrupoles.

When the stored muons decay, the highest energy positrons in the muon rest frame are correlated with the muon spin. As the muon spin precesses relative to the momentum vector, the number of high-energy decay positrons observed in the lab frame oscillates with the frequency \( \omega_a \). This feature is exploited by selecting the highest energy positrons in the calorimeters and measuring the muon spin precession rate in the horizontal plane.

Assuming that \( \vec{\beta} \perp \vec{B} \) and \( \vec{\beta} \) is uniform, the difference between this spin frequency and the cyclotron frequency is:

\[
\vec{\omega}_{a_\mu} = \vec{\omega}_S - \vec{\omega}_C = -g_\mu q \vec{B} / 2m_\mu - (1 - \gamma) q \vec{B} / \gamma m_\mu + q \vec{B} / \gamma m_\mu
\]

\[
= - \left( \frac{g_\mu - 2}{2} \right) \frac{q}{m_\mu} \vec{B} = -a_\mu \frac{q}{m_\mu} \vec{B},
\]

where the muon charge \( q = \pm|e| \). This difference frequency provides a direct measurement of the magnetic anomaly. With the presence of the electric quadrupole field, and assuming that \( \vec{\beta} \perp \vec{B} \) and \( \vec{\beta} \perp \vec{E} \), the spin

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The betatron frequencies in the horizontal and vertical directions are \( \omega_x = \omega_c \sqrt{1-n} \) and \( \omega_y = \omega_c \sqrt{n} \) respectively.

The horizontal betatron oscillation frequency is slightly less than the cyclotron frequency. Therefore, a localized detector sees the beam oscillate inward and outward at \( f_{\text{CBO}} \approx 0.5 \text{ MHz} \), namely the CBO frequency [4], defined as

\[
2\pi f_{\text{CBO}} = \omega_{\text{CBO}} = \omega_c - \omega_x = \omega_c (1 - \sqrt{1-n}).
\]

A cartoon of this motion is shown in Figure 2.

When the narrow time bunch muon beam enters the storage ring, each calorimeter sees the beam moving in and out with this CBO frequency. Because the detector acceptance depends on the radial position of the muon decay, this inward and outward motion of the bunched beam amplitude modulates the positron decay time spectrum. The principal issue is that its lower side band may overlap with \( f_a \) if \( f_{\text{CBO}} \) is close to \( 2f_a \) thereby pulling the \( g-2 \) phase. The effect can be significantly reduced, perhaps eliminated if the CBO can be suppressed by an order of magnitude (See Figure 3).

The coherent betatron oscillations were a well known effect in the BNL data, which was discussed in the E821 papers [4, 9, 10]. In E821 a conservative systematic error of \( \pm 0.07 \text{ ppm} \) (70 ppb) was assigned, based on changes to \( n_a \) when varying the CBO fit parameters over wide ranges [4]. Because the total E989 error budget for the muon frequency \( \omega_a \) is 70 ppb (0.07 ppm), we need to improve the knowledge of the CBO effect on \( \omega_a \) from 70 ppb to 30 ppb.

The CBO frequency depends on the \( n \)-value of the ring, \( \text{viz.} \) the quadrupole voltage. As the CBO frequency approaches \( 2f_a \), the systematic pull on \( \omega_a \) becomes significant as discussed in section 5.1 of Ref. [10]. Fig. 4 shows the relative systematic error from the CBO as a function of \( f_{\text{CBO}} \) caused by the lower sideband overlapping with \( f_a \).

In the next section we introduce the idea of using RF manipulation of the beam phase space to reduce the
FIG. 3: FFT spectrum of the residuals from fitting a Monte-Carlo simulation data to the five-parameter function. $N_0$, $A$ and $\phi$ are modulated at $f_{CBO}$ in the simulation. With $f_{CBO} \approx 2f_a$, the peak at $f_{CBO} - f_a$ may partially overlap with the $f_a$ signal.

CBO, and to scrape the beam to reduce muon losses from the storage ring during the data collection period. In the following sections we will show samples of different parts of the phase space and discuss how the CBO can be damped by this RF manipulation. We will use the conventions shown in Figure 5. The black ellipse shows the storage ring phase space acceptance. The blue and red ellipses represent the low- and high-momenta populations. We will use this color convention throughout this paper, both for phase space ellipses and for individual particles of low- and high-momentum in phase space.

FIG. 4: The maximum possible relative pull ($\delta \omega_a/\omega_a$) versus the CBO modulation frequency if not addressed by the fitting function. The systematic error $\delta \omega_a/\omega_a$ has a strong dependence on how close $f_{CBO}$ is to $2f_a$. The estimations were made by simulating the experiment with varying field index values $n$.

II. THE RF REDUCTION METHOD

This method relies on damping the coherent betatron oscillation by applying an oscillating transverse electric field with the CBO frequency. It can be applied in two different modes: dipole and quadrupole.

A. Analytical calculation of the CBO reduction by RF fields

The reduction of the coherent betatron oscillations by RF fields was first proposed in 2003 as a potential upgrade to the BNL E821 storage ring experiment [11]. We present that discussion here, since this reference is not published.

To damp the CBO, a harmonically varying horizontal dipole electric field $E_x(t)$, is applied to the beam out of phase with the CBO. The RF field is applied to the two vertical quadrupole plates, which begin at the longitudinal position $s_0$ and extend to $s = s_0 + \ell$.

$$E_x(t) = E_{x0} f(t) \cos[\omega_{CBO} t + \theta_0],$$

where, $\theta_0$ is the initial CBO phase and $f(t)$ is defined as

$$f(t) = \begin{cases} 1 & s_0 < t < s_0 + \ell \\ 0 & \text{otherwise} \end{cases},$$

Setting the muon injection time to be $t = 0$, we obtain Hill’s equation 6 with a harmonic driving term:

$$\ddot{x} + \omega_0^2 (1 - x) = \omega_0^2 R_0 \left( \frac{e E_{x0}}{\beta B_0} \right) f(t) \cos[\omega_{CBO} t + \theta_0],$$

where $\beta = v_\mu/c$, and

$$f(t) = \begin{cases} 1 & Tq < t < Tq + l/v, \quad q = 0, 1, 2, \ldots N \\ 0 & \text{otherwise} \end{cases}.$$
The definition of $f(t)$ means that the muon passes through the damping electric field $E_d(t)$ periodically with the revolution period $T = 2\pi/\omega_c$. $N + 1$ times, after which the RF perturbation is turned off. The exact solution of Equation 10 with $f(t)$ given by Equation 11 is

$$x(t) = a(t)e^{i\omega_d t} + a^*(t)e^{-i\omega_d t}, \quad (12)$$

$$a = a_0 - i\frac{e E_d B_0}{2\sqrt{1 - n}} \int dt f(t)e^{-i\omega_d t} \cos[\omega_{CBO} t + \theta_0], \quad (13)$$

where $a_0$ corresponds to $t = 0$. From Equation 13, one gets the solution at time $t = (N + 1)T + 1/\nu$, the time that the CBO damping finishes. At this time

$$a = a_0 - e^{-i\omega_d t} \frac{N + 1}{4\sqrt{1 - n}} \left( \frac{E_d(t)}{\beta B_0} \right) \times \left[ 1 + \frac{e^{i\theta_0}}{N + 1} - \frac{1}{1 - e^{-2i\omega_{CBO} T N + 1}} \right]. \quad (14)$$

Ideally, $a \to 0$, or very close to zero after $N + 1$ turns. After discussing the simulations of the RF method, we compare this the analytic formula with a simulation result.

**B. Introduction to the CBO reduction simulation strategy**

To minimize muon losses during the measurement period, and thereby minimize the systematic error from muon losses on the measurement of $\omega_c$, the beam halo is scraped against circular collimators with a 9 cm diameter. The scraping can be done in one of two ways: Asymmetrically powering the quadrupoles at injection; Using a radial RF dipole.

In BNL E821, and in E989 Run 1, the asymmetrical powering was used. Immediately before muon beam injection, the top and bottom plates on quadrupoles 1-4 were powered asymmetrically as were the vertical side plates on quadrupoles 2 and 4. This asymmetric powering shifted the beam both vertically and horizontally onto the collimators. Approximately 5 to 15 $\mu$s later the plate voltages were returned to a symmetric configuration near the aperture and significantly reduced muon losses from the storage ring during the data collection period. In Run 1 of E989, a $\sim 7$ $\mu$s scraping time was used [13]. A major issue with the E821 scraping method is that the beam can move through a resonance while going from the scraping high-voltage configuration to the final symmetric high voltage, causing unwanted muon losses.

The dipole mode with the resonant frequency can move the centroid of the beam along the vertical axis of the transverse phase space. It moves the high- ($\delta p/p_m > 0$) and low- ($\delta p/p_m < 0$) momentum populations together when they have the same CBO phase. Figure 6 shows the effect of the dipole RF field with $f_{CBO}$ in the phase space. By a correct choice of the RF phase, the beam can be shifted on the vertical axis to reduce the CBO amplitude (Figure 6a). The dipole RF field can also be used in "scraping mode" before the measurement period by switching to the opposite RF phase (Figure 6b).

FIG. 6: Cartoon explaining two different modes of the RF reduction method. The black elliptic arcs are the transverse phase space acceptances, red and blue spots are the high- and low-momentum populations respectively, and the green arrows represent the force exerted by the RF electric field.

In contrast to the RF dipole mode, the RF quadrupole mode moves the high- and low-momentum populations in opposite directions. The beam width decreases as they reach the design orbit (See Figure 7).

FIG. 7: Quadrupole RF mode. This is applicable only to the horizontal phase space. The red and blue spots are high- and low-momentum muon populations respectively, and the green arrows indicate the electric force on the beam.

**III. SIMULATIONS OF THE RF REDUCTION METHOD**

The simulations of the RF reduction were done with a precision tracking simulation tool written in C++ [14]. All of the essential parts of the ring were implemented in the program, such as the electrostatic quadrupoles [12], the fast kicker magnets [15], the vacuum chamber, and...
the collimators. In these simulations, a 3 kV RF voltage was applied to one 3.2 m azimuthal quadrupole section. The electric quadrupole plates have a cross section of $10 \times 10$ cm$^2$ [12]. In the proposed employment in the $g-2$ storage ring, RF with a voltage amplitude of $\sim 0.5$ kV will be applied to all eight quadrupole sections, covering 43% of the ring circumference. Particles are stored for up to 200 $\mu$s in the simulations.

A. Single Particle Simulation

Single particle simulations were conducted as a proof-of-principle. They used three particles of different momenta: magic ($\delta p/p_m = 0$), high- ($\delta p/p_m = +0.25\%$) and low- ($\delta p/p_m = -0.25\%$) momentum muons. In the absence of an RF field, each particle follows an elliptical trajectory in phase space, whose origin and radius are determined by its momentum and initial position.

Figure 8 shows the phase space trajectory of each particle in the presence of the dipole RF field applied with the optimum phase. The method works best if the particles are in phase. If they are out-of-phase, then a dipole RF increases the amplitude of one, and shrinks the amplitude of the other. On the other hand, the RF quadrupole mode shrinks the high- and low-momentum particle orbits if they are out of phase (Figure 9). Note that the particle with magic momentum is not affected by the RF quadrupole field as it oscillates around the design orbit.

Figure 10 shows the excellent agreement between this analytical calculation presented in Section II A and the result from a simulation. The parameters used in the calculation are: $n = 0.12$, $l = 3.2$ m, $E_x0 = 100$ kV/m, $B_0 = 1.45$ T, $f_c = 6.71$ MHz, $f_{CBO} = 400$ kHz and $\theta_0 = 134^\circ$. Note that the RF field should be turned off at the minimum, after which the CBO starts growing because of resonance. In this example, it takes roughly $N = 23$ oscillations to minimize the CBO amplitude.

B. Multiparticle Simulation

The multiparticle simulations were done with roughly 30,000 muons entering the storage ring. 95% of the particles hit the vacuum chamber or collimators and are lost after several turns around the ring.

The RF phase was initially optimized for the maximum CBO reduction without applying any scraping. After determining the optimum phase, the dipole RF field was applied from 2 to 7 $\mu$s for the scraping and from 10 to 20 $\mu$s for CBO reduction. Note that these two steps should have opposite phases.

Figure 11 compares the CBO without RF, and with the applied RF field at the optimum phase. The CBO amplitude decreases by itself within 100-200 $\mu$s, even in the absence of an RF field. The damping time depends on the momentum spread of the beam and the multi-pole components of the electric focusing field. Because of the electric 20-pole component, the CBO frequency of the different momentum muons vary, eventually leading to a decoherence (See Figure 12). However, the application of the RF field before 20 $\mu$s improves the CBO damping by almost an order of magnitude. The beating after 20 $\mu$s originates from the frequency spread of the beam shown in Figure 12.

The mechanism of the CBO reduction by a dipole RF is shown in Figure 13. The middle plot shows how high- and low-momentum particle phases are shifted to be opposite of each other. The significant reduction in the CBO amplitude is due to this effect. Applying the RF quadrupole field after the dipole mode does not have any effect on the beam centroid as shown in Figure 14. However the
FIG. 9: The horizontal phase space and position as a function of time when an RF quadrupole is applied for three momenta: black: $\delta p/p = 0$; red: $p/p_m = +0.25\%$; blue: $p/p_m = -0.25\%$. The magic momentum muons are not affected.

RMS modulations of the beam is significantly reduced by the application of the RF quadrupole as shown in Figure 15.

The total effect of the dipole and the quadrupole RF modes in the simulation are summarized in Figure 16, which shows three time slices of the phase space. The center of mass (CM) for the high-momentum population is represented by a purple square, and the phase space trajectory of the CM of the high-momentum particles is represented by a purple ellipse. The CM of the low-momentum particles is represented by a cyan box, and the phase space trajectory for this CM is shown by a cyan ellipse. The top snapshot is before the application of the RF fields. The dipole RF mode is then applied to the beam for 20 $\mu$s, resulting in opposite phases for the high- and low-momentum populations. Thus the centers of the two trajectories have become symmetric around the design orbit.

This opposite phase for low- and high-momentum particles provides the ideal condition for the RF quadrupole
FIG. 13: The CBO of the high (red), low (blue) and combined (green) momentum. Bottom: No applied RF. Middle: The damping of both high and low momenta populations by the RF dipole. Top: The combined CBO before and after the application of the RF dipole. The dashed orange line is without the application of RF.

FIG. 14: The beam centroid versus time with dipole RF (green) and with both dipole and quadrupole RF (blue). The difference in centroid is negligible.

FIG. 15: Beam RMS versus time with (blue) and without (green) the quadrupole RF field.

FIG. 16: Snapshots of the horizontal phase space at different times. The momentum is represented through a color-code from $\delta p/p_m = -0.3\%$ (blue) to $\delta p/p_m = +0.3\%$ (red). The purple and cyan colored ellipses show the phase space trajectories of the high- and low-momentum population respectively.

IV. HARDWARE DEVELOPMENT

The muon beam is stored for around 750 $\mu$s with 12 Hz repetition frequency. The quadrupole plates are pulsed in such a way that the at-voltage time coincides with the measurement time. The pulsed voltage is transferred to
the quadrupoles through high voltage (HV) resistors with approximately 5 $\mu$s RC time constants. The E821-type scraping is also applied at this ramping period.

The quadrupole plates and cages are the same as used in E821 [12], with the exception of the first quadrupole (Q1) where the beam enters the storage ring through the quadrupole plate. Q1 has been redesigned and is significantly thinner than in E821. The E989 high voltage pulcing circuit is new and will be described in Ref. [16].

The RF voltage is superimposed on the HV pulses (Figure 17) to modulate the field at the quadrupole plates. Figure 18 shows a 3D drawing of the electrical elements connecting a quadrupole to the HV pulsers and RF electronics. There are four copies of each element in the box for each quadrupole plate. While the RF voltage is applied through the RF feedthrough on the left, the main field of the quadrupole is applied from the bottom of the resistors. Each RF source is protected by a gas discharge protector (GDP) (shown in blue in Figure 18), which is followed by a potted HV capacitor that couples the RF to the quadrupole plates. Figure 19 shows the circuit diagram of the entire system.

The RF reduction method has an efficient scraping mode as well, where it may be preferable since the field index does not change during scraping in this method. The RF electronics can be disconnected and the RF branch of the circuit can be shorted to the ground (shown with 0.1 Ohm resistor in Figure 20) for back compatibility with the original scraping scheme.

A. Preparation of the resistors and the capacitors

HV breakdowns are initiated by the emission of electrons from the cathode to anode at high voltages. The exchange of charged particles between the cathode and anode can be enhanced through several mechanisms [17–19]. One way of avoiding electron HV breakdowns is to eliminate the contact between the air and conductors. The HV resistors and capacitors were potted in respective containers with silicone elastomer (SE) for this purpose (Figure 21). The resistors and capacitors were potted one at a time. The potting procedure was as follows:

1. Preparation of the electrical connections and placing the components inside the containers.
2. Preparation of the SE mixture.
3. Keeping the SE mixture in vacuum at 0.6 bars for half an hour to remove the bubbles.
4. Pouring the SE into the container.
5. Keeping the setup in vacuum at 0.2 bars for half an hour.
6. Releasing the vacuum up to 0.6 bars and waiting at that state until the SE cures ($\approx$ 12 hours).

Preliminary tests with the hardware were done by installing the RF system into one of the 3.2 m quadrupole sections in E989. The motion of the beam centroid was observed with scintillating fiber beam monitors inside the storage ring [4], and the results were consistent with simulations [20].

The HV RC circuit in the preliminary tests had 140 pF capacitors, and the power transfer was less than the optimal. The upgraded RF system (Figure 21) uses capacitance values that are better matched to the quadrupole plates. This is expected to result in almost twice the transfer efficiency compared to the previous design. In addition, installation of the RF system on all of the

FIG. 17: The RF voltage is superposed with the original HV pulse (20 kV in this example). The beam is stored for around 750 $\mu$s, while the RF field is applied during a small fraction of it.

FIG. 18: Interface between the quadrupoles and the RF electronics. RF box, potted HV capacitors and the connection to the RF feedthrough did not exist in the original design. HV pulse ends up at the quadrupoles through the potted HV resistors, while the HV capacitor limits it to less than 2 kV at the RF feedthrough.
FIG. 19: Circuit diagram of the RF system and original quadrupole feedthrough design.

FIG. 20: The HV circuit is back-compatible. The RF electronics part of Figure 19 can be shorted to the ground to go back to the E821-type scraping.

quadrupoles will increase the azimuthal coverage by a factor of 6 along the ring. Consequently, we are expecting a greater than 10 times more effective CBO reduction after the complete installation.

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FIG. 21: The resistor and the AC coupling capacitor are potted separately. The capacitor and the cable to the RF electronics did not exist in the original design.

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