Phase III of the Dedicated Muon EDM Experiment Using Muons from Stage II of the Neutrino Factory

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Abstract

During the second stage of a future neutrino factory unprecedented numbers of bunched muons will become available. In the second stage the cooled medium-energy muon beam could be used for high sensitivity searches for an electric dipole moment (EDM) of the muon with a sensitivity better than $10^{-24}\,\mathrm{e}\cdot\mathrm{cm}$ in both statistics and systematics. This will make the sensitivity of the EDM experiment to non-standard physics competitive and in some models more sensitive than the other EDM experiments, like that of the electron, neutron and nucleon. The experimental design exploits the strong motional electric field sensed by relativistic particles in a magnetic storage ring. [1, 2]

1 Introduction

The discovery of a muon electric dipole moment would indicate a new source of CP violation and point to physics beyond the standard model. A three-phase program [1, 2] of EDM studies is under consideration at BNL. The first two phases would use the existing g-2 ring and expects to use a muon beam flux of about 10^8 /s. The goal of phase 3 is a sensitivity of $10^{-24}\,\mathrm{e}\cdot\mathrm{cm}$. In this paper we are giving the theoretical motivation for such an experiment and the experimental technique which is capable of taking advantage of the large amount of muons that will be available after stage II of the neutrino factory project.

A fundamental particle is described by only a few parameters, such as its mass, its intrinsic angular momentum, its electric charge (electric monopole moment), its magnetic dipole moment, and a set of conserved quantum numbers, like lepton flavor [3]. A permanent EDM is not known for any of them. It would violate both parity (P) and time reversal (T) invariance. If CPT is assumed to be a valid unbroken symmetry, a permanent EDM would hence be a signature of CP violation [4].

The standard model of particle physics predicts a CP violating EDM in fundamental particles at the multi loop level of amplitude more than five orders of magnitude below the sensitivity of present experiments [5]. Therefore searches for a permanent particle EDM render excellent opportunities to test models beyond standard theory where in some cases they predict effects as large as the presently known experimental bounds. Despite the non-observation of a positive EDM signal such research has nevertheless been most successful in steering the development of theoretical particle physics over many decades and also was the incentive for the ever increasing precision in the experiments themselves. The absence of any observed finite EDM for the neutron, for example, has disfavored more speculative models than any other experimental approach so far. [6]

The Muon g-2 Experiment, E821, now being conducted at BNL, has been designed to probe physics beyond the standard model. [7, 8, 9, 10, 11] This includes super-symmetry (SUSY) with large $\tan\beta$ where the muon EDM also has sensitivity. The experiments complement each other, because the magnetic anomaly and the EDM are related to each other as real and imaginary parts of the same physical quantity. [12, 13] The recent new limit on the muon magnetic anomaly [14] corresponds (assuming the CP-violating phase to be of order 1 as it naturally occurs in SUSY) to a dipole moment of order $3.5 \times 10^{-22}\, e \cdot cm$, [15] which is well within the reach of this experiment, and demonstrates how the explored parameter space can be expanded. There are recent $L-R$ SUSY models[13] using the see-saw mechanism to provide for the observed finite neutrino mass, where the EDM contribution could be as much as $5 \times 10^{-23}\, e \cdot cm$ and still be consistent with the electron EDM limit. [16] In those models the EDM values of the leptons do not follow a simple mass ratio scaling giving a large advantage to the muon [17]. The experimental limits for the first generation particles, i.e. electron, neutron, and nucleon are below the theoretically predicted values from SUSY for CP violating phases of order 1. In order to accommodate this discrepancy the following three possibilities have been suggested [18]:

1. The SUSY mass scale is above 1 TeV but this is not very popular, especially if the muon g-2 result becomes much more statistically significant.

2. The CP violating phases are small, below 10^{-2} but this constitutes fine tuning.

3. There is a natural cancellation of the CP violating phase at the scale of 10^{-2} which takes care of both the electron and neutron experimental EDM limits.

It is the last option that Nath chose to take and explain the recent g-2 result [19]. In this case there is no reason for the cancellation mechanism to apply to the second generation particle, the muon [20, 21, 22]

It should be mentioned that the muon is the only second generation particle for which a precision EDM experiment is feasible [22, 21]. Since CP violation is associated with the second and third generation of quarks only, the muon may have a unique window for new physics in the lepton sector. Therefore, even if there were an EDM observed in another system, a measurement on the muon would be extremely important to understand the nature of the effect [23].

Moreover, it will provide valuable complementary information, because the muon belongs to the second generation of particles where in the quark sector CP violation occurs.

Unlike the magnetic dipole moment, the existence of a permanent electric dipole moment in a muon (or any other elementary particle) is a violation of time and parity symmetries, with the predicted value for the muon from the Standard Model, being well below the sensitivity of our proposed measurement. Therefore, a non-zero measurement of the muon EDM is unmistakable evidence of physics beyond the standard model.

In the presence of an electric field and if the muon EDM is non-zero the muon spin will precess about the direction of the E-field. In a storage ring such a field exists because the external B-field is partially converted to an electric field in the muon rest frame due to the Lorentz transformation. For example, the external dipole magnetic field used in the muon g-2 ring of ≈ 1.5 T is partially transformed to an electric field of ≈ 450 MV/m. The directions and energies of the decay electrons are correlated to the muon spin directions. In particular, when the plane of spin precession is tipped out of the plane of the storage magnet the decay electrons will have average upward and downward momentum components as the muon spin moves up or down. Using this principle the last muon g-2 experiment at CERN reported [24] a limit of $3.7 \pm 3.4 \times 10^{-19}\,\mathrm{e \cdot cm}$. The error is the combined result of the statistical and systematic errors:

- Statistical: $\pm 2.7 \times 10^{-19}\,\mathrm{e \cdot cm}$
- Systematic: $\pm 2 \times 10^{-19}\,\mathrm{e \cdot cm}$

2 Experimental Overview

The muon spin precession angular frequency (relative to the momentum vector) in the presence of both electric and magnetic fields is given by

$$\begin{aligned} \vec{\omega} &= -\frac{e}{m}\{a\vec{B} - \frac{a\gamma}{1+\gamma}(\vec{\beta}\cdot\vec{B})\vec{\beta} + (\frac{1}{\gamma^2-1} - a)\frac{\vec{\beta}\times\vec{E}}{c} + \\ & \frac{\eta}{2}[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}] - \frac{\eta\gamma}{2(\gamma+1)c}(\vec{\beta}\cdot\vec{E})\vec{\beta}\}, \end{aligned} \tag{1}$$

where $a = (g-2)/2$ and η is the EDM in units of $\frac{e\hbar}{4mc}$. This simplifies to

$$\vec{\omega} = -\frac{e}{m}\{a\vec{B} + (\frac{1}{\gamma^2-1} - a)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B})\}, \tag{2}$$

assuming the muon velocity is orthogonal to the external magnetic and electric fields ($\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$). η plays a role for the EDM corresponding to the g factor for the magnetic dipole moment. The muon EDM couples to the external magnetic field because in the muon rest frame it looks like an electric field due to the Lorentz transformation. The EDM value in MKS units is given by

$$d_\mu = \frac{\eta}{2}\frac{e\hbar}{2mc} \simeq \eta \times 4.7 \times 10^{-14}\,\mathrm{e}\cdot\mathrm{cm}. \tag{3}$$

From the above equation (2) is apparent why the present $g-2$ experiment uses muons at the "magic" γ, i.e. $\gamma = 29.3$ since at this value the coefficient

$$\frac{1}{\gamma^2-1} - a = 0, \tag{4}$$

and the muon spin precession becomes independent of the electric field present in the lab frame. For the dedicated EDM experiment we propose to use muons with much lower energy as well as a radial electric field which cancels the g-2 precession leaving the EDM precession to operate on its own and accumulate over many microseconds. It should be noted that the main component which causes the spin to precess vertically in the muon rest frame is the lab dipole magnetic field which is partially transformed into a radial electric field in the muon rest frame. The electric field in the lab required to cancel the g-2 precession is

$$E = \frac{aBc(\gamma^2-1)}{\beta(1-\alpha\gamma^2+\alpha)} \approx 2\,\mathrm{MV/m}, \tag{5}$$

for $\gamma = 5$, $B = 0.24\,\mathrm{T}$ and a magnet radius of 711 cm. Concentric cylindrical plates 10 cm apart with ± 100 KV voltage will satisfy this condition.

Due to the weak interaction decay of the muon to an electron, a muon neutrino and an electron anti-neutrino, the electron angular distribution in the muon rest frame is given by:

$$dP(y,\theta) = n(y)[1 + A(y)\,\cos\theta]dy\,d\Omega, \tag{6}$$

with $y = p_e/(P_e)_{\max}$, the distribution function $n(y) = 2y^2(3-2y)$ and the asymmetry $A(y) = (2y-1)/(3-2y)$. $d\Omega$ is the solid angle element, and θ the angle between the electron momentum and the muon spin. The number of detected electrons above an energy threshold in the lab frame thus probes the angular distribution of the decay electrons in the muon rest frame [25]. The oscillation frequency in the number of detected electrons is given by equation (2). The detector position and the energy threshold in the g-2 experiment is optimized by maximizing NA_L^2, where N is the number of the detected electrons and A_L is the amplitude of the average vector asymmetry given by

$$\vec{A_L} = \int A(y)\, \hat{e}\, dy\, d\Omega, \tag{7}$$

where $\hat{e}$ is the unit vector along the electron direction in the muon rest frame.

From equation (2) (at the muon "magic" momentum) it is apparent that the EDM influence on the spin precession is two-fold: 1) The spin precesses about an axis which is not exactly parallel to the magnetic field, but is at an angle $\delta = \tan^{-1}\frac{\eta\beta}{2a}$. The maximum excursion of the muon spin from the horizontal plane, due to an EDM, occurs when the spin is at 90° with respect to the momentum vector. When the spin and momentum vectors are aligned there is no excursion from the horizontal plane. 2) The spin precession frequency is increased by a factor of $\sqrt{(1+\delta^2)}$.

Both of the above methods were used in the last CERN muon g-2 experiment to set a limit on the EDM [24]. They searched for an up down asymmetry in the counting rate with a detector split on the vertical mid-plane. The presence of an EDM induces a difference between the counting rate of the two parts of the split detector at the anomalous spin precession frequency. The reported limit is $3.7 \pm 3.4 \times 10^{-19}\,\mathrm{e \cdot cm}$. We propose to use a radial electric field to cancel the $g-2$ precession. This together with other improvements will significantly reduce many systematic errors and improve the experimental sensitivity to a muon EDM. The muon spin direction will be "frozen" relative to the muon spin if the EDM is zero. In the presence of a non-zero EDM, the proposed radial E-field (i.e. the motional E-field in the muon rest frame due to the lab dipole B-field) will rotate the spin around an axis parallel to the E-field, thereby tipping the spin vertically. This results in an up-down asymmetry in the number of electrons which is growing linearly with time and this is the quantity which we will measure.

Other improvements over the present $g-2$ experiment include:

1. Use *magnetic* focusing instead of electrostatic focusing as is used in the present g-2 ring. A 10 by 10 cm area is available for muon storage which will increase the number of stored muons substantially.

2. Eliminate all vertical electric fields from the system during normal data taking. Any radial magnetic field in the presence of compensating vertical electric field introduces a systematic limitation [26, 27]. For example, in the g-2 ring, a net radial magnetic field of 10 ppm of the main field would produce a systematic error in the EDM of $1 \times 10^{-21}\,\mathrm{e} \cdot \mathrm{cm}$. A vertical electric field can be used, as discussed later in this note, to calibrate the system sensitivity with high accuracy.

3 Proposed Stages for the Dedicated Muon EDM experiment

The schedule for the muon EDM is given below:

- Stage I: First we run with polarized deuterons with weak magnetic focusing without modifying the pole pieces of the g-2 ring. At this point we measure the misalignment with deuterons (see below) and time stability (with laser interferometers) of the $\vec{E}$ field from a plane to 10 nrad. Next we run with muons and set a first limit of $10^{-22}\,\mathrm{e} \cdot \mathrm{cm}$, controlling the systematics 100 times better, in 400 hours.

- Stage II: We modify the g-2 pole pieces to store more muons and reach $10^{-23}\mathrm{e} \cdot \mathrm{cm}$ in 4000 hours.

- Stage III: We will use the muon beams available from stage II (after muon cooling) of the neutrino factory project to improve the limit down to $10^{-24}\,\mathrm{e} \cdot \mathrm{cm}$ by injecting 100 times more muons.

4 Systematic Errors

Potential systematic errors include the following:

1. Early to late electron counting (rate) effects. With almost 10^7 muons entering the ring and a good fraction of them decaying within $10\,\mu s$ the rates are very high. Our detector will be scintillating lead-glass calorimeters with photodiode readout. The readout electronics are specially made so that they maintain their linearity to 10^{-4} [28] and will be measured to 10%. With 800 such systems the error is further reduced another factor of 30. We are investigating the possibility of interchanging electronically the top/bottom detector readout randomly about 100 times, which brings us to 3×10^{-8} linearity error in the electronics. Other possibilities include the injection of unpolarized muons in between normal injection with polarized muons to look for gain changes. Also without the compensating E-field the average energy within a g-2 cycle vs time should be constant.

2. Proton or pion contamination of the muon beam. During the 1997 run of the g-2 experiment about 10^8 pions per spill were injected, the pion flash was the biggest problem. After striking a nucleus hadrons produce secondary neutrons which in turn produce gammas paralyzing the photo-multipliers mostly at the first half of the ring for tens of μs. When we tried the muon injection by lowering the accepted particle momentum by about 1.5% the light flash went down by a factor of 50.

   In the muon EDM experiment the secondary beam is 900 MeV/c whereas the muons have half that. One can expect a proton/pion leakage of less than 10^{-4} per muon. It is therefore the lost muons (assuming 50% storage efficiency) which will dominate the flash. Their efficiency (μ^+ case) of producing neutrons is down by approximately a factor of $\alpha \approx 1/137$ relative to those produced by pions/protons. We plan to study this effect with the kicker off and observe its time dependence and up/down asymmetry. This effect is still under study.

3. Muon losses as a function of time. If there are muon losses at an appreciable level and they get lost in a non-uniform way, they could provide a false signal. We are studying

the potential level of this effect and ways to minimize it (e.g. scraping, under-filling the vertical and horizontal acceptance of the ring, etc.).

4. Stored positrons. Positrons from the beamline with the same momentum as muons will be stored in the ring and will synchrotron radiate their energy at a rate of 0.8 KeV per revolution. For 0.5% momentum acceptance of the ring, it will take approximately 1 ms before all positrons reach the inner aperture, whereas almost all the muons decay within $50\,\mu$s. We are studying the potential problems and possible uses of the stored positrons.

5. Due to the cylindrical nature of the electrostatic plates which provide the radial electric field, the E-field decreases as $1/R$ making the cancellation of the g-2 imperfect as a function of the muon momentum. Also, taking into account that the spin precession cancellation depends on both the magnetic field and the value of gamma (see equation (5)), one can estimate that at the edge of the aperture, the muon spins will flip horizontally in $100\,\mu$s. Only a very small fraction of the muons will do that. We are investigating the requirement on the acceptance and detector efficiency uniformity so that this effect is also negligible. At any rate this error will be known by letting the muon spin precess and observing the precession plane as a function of the E-field.

6. The problem with radial B-fields when using electrostatic focusing is eliminated completely because we use only magnetic focusing. However the misalignment and time stability of the E-field is going to be monitored by the inclinometer and the laser interferometers described next.

7. Horizontal and vertical coupling of the betatron oscillations. Yuri Orlov has studied this effect and published the specifications for the field quality [29]. He concludes that if the horizontal and vertical betatron oscillation angles are, e.g., $\theta_R \approx \theta_V \approx$ 5 mrad, then the fraction of the vertical betatron oscillations $\Delta\theta_V/\theta_V$ having the same frequency as the radial betatron oscillations should be less than 10^{-4} for a muon EDM of $10^{-24}\,\mathrm{e}\cdot\mathrm{cm}$ which is possible to design for.

8. The "vertical" component of the E-field, i.e. the average component of the E-field along the B-field should be known to $\pm 10^{-8}$ of E for the $1 \times 10^{-24}\,\mathrm{e} \cdot \mathrm{cm}$ limit. This is addressed below.

We feel confident that we can analyze all sources of systematic errors and greatly reduce them due to the flexibility provided by a dedicated muon EDM experiment.

4.1 Electrode alignment

The vertical component of the electrostatic field in the muon storage region, averaged over the ring circumference, must be well suppressed. An average component of the out of plane E-field component (OPEC) of 10^{-8} will induce an effect mimicking an EDM of $10^{-24}\,\mathrm{e} \cdot \mathrm{cm}$. This implies that the OPEC must be known to that level and the electrodes, and the resistive top and bottom plates used to produce a uniform electrostatic field monitored to the same level. The laser interferometer we are considering has 5 nm relative position resolution and 33 KHz response speed. Integrating over 3 ms will result in 5 nrad angular resolution [30]. Another method we are looking into is a very sensitive capacitance micrometer [31].

We are investigating the possibility of constructing the electrode plates of scintillating lead glass to be used as an almost full acceptance detector for the decay positrons.

4.2 Inclinometer

As discussed above, the difference between the cyclotron and spin precession frequencies is:

$$\vec{\omega} = -\frac{e}{m}[a\vec{B} + (\frac{1}{\gamma^2 - 1} - a)\frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2}(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B})] \tag{8}$$

For this experiment, an electric dipole field is generated such that:

$$a\vec{B} + (\frac{1}{\gamma^2 - 1} - a)\frac{\vec{\beta} \times \vec{E}}{c} \approx 0 \tag{9}$$

$$E \approx aBcp\frac{(1+p^2/m^2)^{1/2}}{m} = BcpF \tag{10}$$

This equation is a useful approximation for the following discussion. It would be useful to find a particle which can be stored in much greater (polarized) numbers than the muon, and which has a similar factor:

$$F = a\frac{(1+p^2/m^2)^{1/2}}{m} \tag{11}$$

We give below F for the muon, proton and deuteron for E = 2MV/m and R=7.11m.

Table 1:

Particle	a	$(1+p^2/m^2)^{1/2}$	m [MeV/c^2]	F
μ	0.001166	≈ 5	105	0.054
p	1.793	≈ 1	938	1.912
d	-0.143	≈ 1	1876	-0.076

The deuteron has F close to the muon in magnitude. We show below p and B for E=2MV/m and R=7.11m for the muon and deuteron.

Table 2:

Particle	p [MeV/c]	β	γ	B[T]
μ	511.	0.979	4.94	0.233
d	396.	0.207	1.022	0.218

For the μ^+, B is directed up and E points toward the center of the ring (beam goes clockwise as seen from above the ring). In units of GeV/c, T, V, and m:

$$p = 0.3[B + E/v]R \tag{12}$$

For the deuteron, B is directed up and E points away from the center of the ring.

$$p = 0.3[B - E/v]R \tag{13}$$

The amazing coincidence is although the muon and deuteron a and γ differ tremendously, B is the same to 0.015 T for $|E| = 2$ MV/m and R = 7.11 m.

As discussed above, the flatness of the E field should be known to 0.01 μrad for a systematic error on the edm of the muon at the 10^{-24} e$\cdot$cm level, since this causes the same spin precession as an edm:

$$dS/dt = \mu\theta E/(c\beta\gamma^2) \tag{14}$$

For the deuteron, $\mu = 0.857e\hbar/(2m_p)$. For the muon, $\mu = 1.001e\hbar/(2m_\mu)$. For $\theta = 10^{-8}$, E=2 MV/m, ω_s = 14 mrad/s for the deuteron, and 2.3 mrad/s for the muon. Since the effect is six times greater for the deuteron, the deuteron integration time is much longer, much larger numbers can be stored, and the analyzing power is high, the deuteron is a great system to measure θ. Since the phase space is smaller, the deuteron measurements would have to be sampled where the muons live. How often we would need deuteron runs depends on the stability of θ

The spin precession due to the edm is:

$$d\vec{S}/dt = \vec{d} \times (\vec{E} + \vec{v} \times \vec{B}) \tag{15}$$

The ratio of the sensitivity of the deuteron to θ compared to the edm is 10^2 times larger than for the muon. From the present sensitive limits on the edm of the neutron and Hg, the edm of the deuteron is not a systematic error when using it as an inclinometer for the measurement of the muon edm at the 10^{-24} e $\cdot$ cm level. Since the deuteron is a composite object, it has an electric quadrupole moment of 2.86 e mbarn. However, $\vec{Q} \cdot \vec{\nabla} \times \vec{E}$ is much smaller than $\vec{d} \cdot \vec{E}$ for our geometry.

We are planning to use a pickup electrode which will measure the average deuteron vertical position to better than $\pm 1\mu$m. The average vertical position depends only on the radial component of the magnetic field and the vertical component of the electric field:

$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B}) = 0 \tag{16}$$

If the beam is injected "crooked", it will simply have larger betatron oscillations about the equilibrium orbit. The average beam height is given by:

$$dy = R\theta E/(n_{\mathrm{v}}\beta B) \tag{17}$$

For calculational purposes, taking the E821 value $n_{\mathrm{v}} = 0.137$ gives $dy = 0.07\mu$ m for $\theta = 0.01\mu$ rad. However, we can drive a resonance with quadrupole rf:

$$\frac{\partial B_{\mathrm{r}}}{\partial y} \cos(\nu\omega_0 t) \tag{18}$$

With $\nu \approx \sqrt{n_{\mathrm{v}}}$, the Q value will be about 10^2 for $\frac{\partial B_{\mathrm{r}}}{\partial y} \approx 1$ Gauss/cm, and $dy \approx 7\mu\mathrm{m} \times \cos(\nu\omega_0 t)$, which should be easily observable with the pickup electrodes. This would be done with various E and B field combinations.

In conclusion, we believe we can measure the electric field flatness at the level of $\theta = 0.01\mu$rad using two methods with the deuteron beam.

5 Phase III

The goal of phase 3 is a sensitivity of 10^{-24} e·cm. This requires the number of muon decays times polarization squared of $\mathrm{NP}^2 = 10^{16}$. This is not possible in a reasonable amount of running time without neutrino factory technology. Therefore, phase 3 would require a new ring at the site of the neutrino factory front-end. The design of the phase 3 ring will be guided by the extensive experience we will have obtained during phases I and II at the g-2 ring.

The first question is the optimal muon storage momentum. The sensitivity factor vs. muon momentum is shown in Fig. 1. The following assumptions went into this plot:

1. Average radial E field of 2 MV/m.

2. The measurement begins 4 μs after injection.

The sensitivity factor SF is given by:

$$SF = \gamma(\vec{\beta} \times \vec{B})\sqrt{e^{-\frac{4\mu s}{\gamma\tau}}} \tag{19}$$

Also shown in Fig. 1 is the average magnetic field B so that the g-2 spin motion is canceled by the 2 MV/m average E field. The sensitivity is nil at the magic gamma of 3.1 GeV/c as well as above it. 500 MeV/c momentum requires $B = 0.24$ T, and $R = 7$ m. The $g - 2$ ring ($R = 7.1$ m) is a reasonable place to begin, since the sensitivity factor is within a factor of two of the maximum. Lower muon momentum results in better sensitivity, until $P < m_\mu$, whereupon β falls rapidly. However, the energy of the decay positrons is less, which is undesirable from the detector point of view, as the backgrounds, neutrons, etc., become more important at low energy. The background due to the out of plane electric field component (OPEC), i.e. a net vertical E-field, is also rising fast as β falls, as is shown in Figure 1 where we have placed an upper limit on the magnetic field value of 3 T. The running configuration of the dedicated EDM ring shown in Figure 2 would substantially reduce the main background to the muon spin due to OPEC. The OPEC is only present when there is a net vertical E-field component which is compensated by a radial magnetic field. In the configuration of Figure 2a the muons run through the E-field regions in the directions shown in the Figure. Let's say there is an OPEC as depicted in Figure 2a. Then we could switch the direction the muons run through the E-field regions as shown in Figure 2b. In this case the E-field directions need to flip sign in order to again cancel the g-2 precession and consequently the vertical components also flip sign. It can be shown that the background changes sign whereas the signal due to a genuine muon EDM does not.

The phase 3 ring optimization will depend on the experience we gain in the first phases of the experiment. However, to control the E field systematic error, we will probably need a dedicated deuteron linac for the edm ring. The energy would be 40 MeV (10 MeV) for 0.5 GeV/c (0.2 GeV/c) momentum. The cost of such a linac would be minimal.

6 Neutrino Factory

The goal of a neutrino factory (NF) program is to accelerate muons to high energy and store them in a ring with long straight sections, in order to produce prodigious numbers of neutrinos from muon decays. These neutrinos would then be used primarily for high rate oscillation experiments at a distant detector. In addition, specialized detectors near the storage ring could be used for high rate studies of neutrino interactions. Detailed studies have been completed of the neutrino physics opportunities at the NF [32]. In addition, studies have been done of the neutrino physics opportunities from a "superbeam" taken directly from the proton driver at the facility [33].

During the construction of a NF a number of particle beam resources would become available, which could, in principle, be used for other non-neutrino physics purposes. One possible scheme for staging the construction of the NF project is given in Table 3.

Table 3: Neutrino Factory Project Phases

Phase 1	High power proton driver and target	$0 - 24$GeV/c
Phase 2	Front end through cooling	μ: 200 MeV/c
Phase 3	Complete linac	μ: 2.5 GeV/c
Phase 4	Complete RLA and storage ring	μ: 20 GeV/c

6.1 Phase 1 Proton driver

The first phase of the NF would involve the construction of a high power proton driver and a target station. A proton driver with a beam power of 1-4 MW and a target system that can handle this power level opens the door to the study of many physics topics. Table 4 lists some properties of the 1 MW configuration of the proton driver.

This proton beam has a total intensity of 2.5×10^{14} p/s. The beam has a complex time structure. There is an overall 400 ms cycle time. Inside this there are 6 very intense bursts of protons lasting for ≈ 10 ns and separated from each other by 20 ms.

Table 4: Proton driver parameters

< P >	24	GeV/c
σ_p	0.12	GeV/c
σ_x	1.5	mm
σ_t	3	ns
N_p/bunch	1.7×10^{13}	
N_{bunch}	6	
Time between bunches	20	ms
f_{rep}	2.5	Hz

6.2 Phase 2 muon beam parameters

Upon the completion of phase 2 of the NF project, there will be available a high-intensity cooled muon beam with the properties listed in Table 5.

Table 5: Muon beam parameters

< P >	203	MeV/c
σ_p	21	MeV/c
σ_x	15	mm
σ'_x	94	mr
bunch spacing	5	ns
σ_t	0.51	ns
N_μ/bunch	4.2×10^{10}	
N_{bunch}	6×67	
Time between bunches	20	ms
f_{rep}	2.5	Hz
Polarization	0.16	

This muon beam has a total intensity of $4 \times 10^{13} \mu$/s. The time structure is very complex. There is an overall 400 ms cycle time. Inside this there are 6 bursts of muons separated from each other by 20 ms. Each burst is further subdivided into 67 individual muon bunches separated from each other by 5 ns.

Although the muon intensity is very high, there are a number of attributes of this beam that makes it unsuitable for many muon experiments. The beam momentum of 200 MeV/c is relatively high for experiments that require muons stopped in a thin target. The rms momentum spread of 10% is also high, while the polarization of 16% is low. In addition, the beam has a bunched time structure, which is unsuitable for coincidence experiments. The experiment that might be improved using this beam is the search for the electric dipole moment (EDM) of the muon.

If there are strong reasons for using a momentum higher than 200 MeV/c, the beginning sections of the linac could be included in this phase of the NF project in order to accelerate the muons to the required momentum. The NF time structure seems fine for this experiment since the muons would be injected into the ring over the 340 ns bunch train length and then 20 ms would be available for the measurement before the next train of muons arrived. The NF produces a muon beam with a potential NP^2 factor per second

$$NP^2 = 4.2\,10^{13} \times (0.16)^2 = 10^{12} \tag{20}$$

This could, in principle, produce the required sensitivity level for the experiment in 10^4 seconds. In practice mismatches between the muon beam emittance and the likely ring acceptance will degrade the effective NP^2 factor. The momentum spread of the beam (10%) is large compared to typical ring designs (1%). If the length of the bunch train (100 m) is larger than the circumference of the ring, there may be additional injection losses. Unless the ring has a large aperture, there will be additional losses from the transverse size and divergence of the beam. Until a ring is designed it is not possible to make a firm estimate of these losses, but a factor of a few times 10^{-3} seems like a reasonable first guess. This would imply that the required sensitivity could be reached in less than a year of running.

7 Cost and Schedule

The total cost of the dedicated EDM experiment for Phases I and II is about 5.4 million dollars. The cost of Phase III is not estimated yet, nonetheless it is expected to be a very small fraction of the neutrino factory project cost.

The present muon g-2 experiment is accumulating data according to schedule. If this continues as planned, it is anticipated to take data until the year 2002. In the Fall of 2001 we will propose a dedicated muon EDM experiment using the current g-2 ring for stages I and II. If successful we will start building a prototype of the electrostatic plates, monitoring system with the laser interferometer, and sensitive gravitometer and the deuteron polarimeter.

The Numass proposal to use the g-2 ring to set a limit on the muon neutrino mass [34] has scientific approval, and is seeking funding approval. If approved it would run for one year for engineering/physics optimization and one year for data collection.

8 Conclusions

The stage 3 of the dedicated muon EDM experiment requires a large number of polarized muons which requires the use of NF technology. At the stage 2 of NF the muons that will become available will satisfy that condition with a running time of less than a year. For the systematic errors we believe we have several independent handles to distinguish between a genuine and a background signal. Those include running at different muon momenta since the signal to background depends on the muon momentum below 500 MeV/c, running with the ring configuration of fig 2, and following the deuteron spin precession as a function of storage time (inclinometer). This last one is done by injecting polarized deuterons in the ring and observing their vertical spin precession as a function of time. Finally, the introduction of a monitoring system of the alignment of the electrode plates as a function of time by a set of laser interferometers in between the deuteron runs.

The estimated sensitivity is at the level of $10^{-24}\,\mathrm{e}\cdot\mathrm{cm}$, an improvement of a factor of almost 10^5 to 10^6 over the last CERN muon g-2 experiment, with comparable improvement on the systematic errors.

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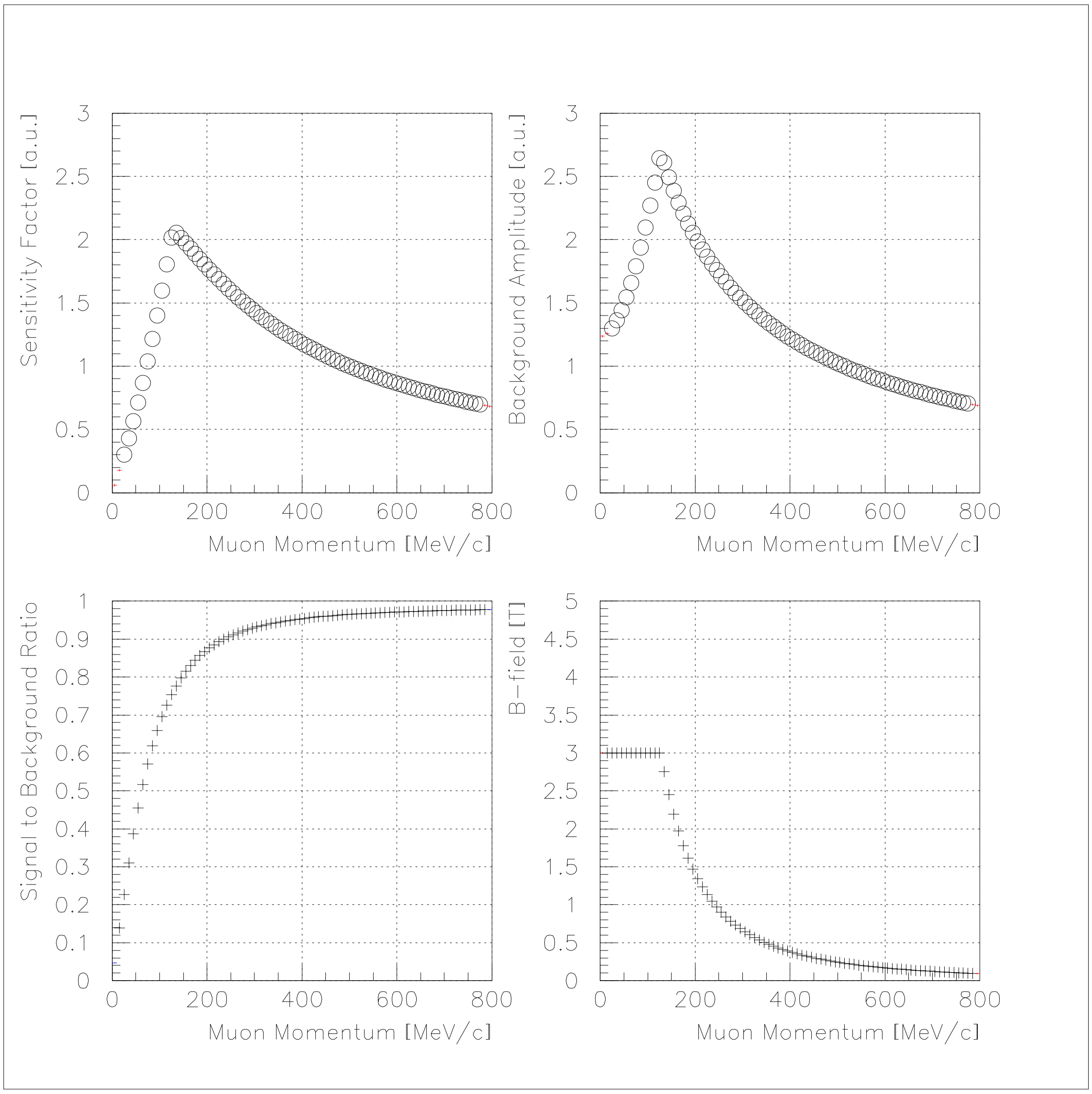

Figure 1: In a dedicated muon EDM ring where the E-field strength is fixed to 2 MV/m and the required magnetic field is limited to 3 T.

Top: The muon vertical spin rotation sensitivity factor due to an EDM (left) and due to background (right) is shown vs muon momentum.

Bottom left: The signal to background ratio (SNR) as a function of the muon momentum. One may use the SNR dependence to distinguish between a background due to the OPEC and a genuine signal.

Bottom right: The magnetic field strength vs muon momentum with an upper limit of 3 T. The ring radius is 7 m for a muon momentum of 500 MeV/c.