AGS Letter of Intent-Search for a Permanent Muon Electric Dipole Moment

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1 Abstract

We propose to modify the existing muon g-2 storage ring at the Brookhaven National Laboratory (BNL) to carry out a dedicated search for a permanent electric dipole moment (EDM) of the muon. In a stage-wise approach we aim for a sensitivity at a level of 10^{-24} ecm. The experiment is exploiting the strong motional electric field sensed by relativistic particles in a magnetic storage ring [1, 2]. As a key feature a novel technique has been invented in which the g-2 precession is compensated with radial electric compensation field.

Contents

2 Introduction

This Letter of Intent is mainly based on the old one on the Muon EDM. [1] The main differences with the old one are:

1. The introduction of an inclinometer, i.e. a system of measuring in situ the misalignment of the average radial electric field direction (which is used to cancel the spin motion of the muon) and the direction of the average dipole magnetic field. The requirement of this experiment for a sensitivity to the Muon Electric Dipole Moment at the $1 \times 10^{-24}\,\mathrm{e \cdot cm}$ level is that $\frac{\vec{E}\cdot\vec{B}}{|\vec{E}|\,|\vec{B}|} \leq 10$ nrad or to know it to that level. This is done by injecting polarized Deuterons in the ring and the method is described in the systematic errors section.

2. The introduction of a monitoring system of the above alignment of the electric and magnetic field directions by a set of laser interferometers in between the Deuteron runs. This is also described in the systematic errors section.

3. The proposed improvement on the Muon EDM is more than five orders of magnitude over its present limit. We have now taken a new stepwise approach with well defined goals:

    - First we run with polarized Deuterons without modifying the pole pieces of the g-2 ring. At this point we measure the misalignment (with Deuterons) and time stability (with laser interferometers) of the $\vec{E}$ field and the orthogonal plane to $\vec{B}$ fields to 10 nrad.
    - Next we run with muons and set a first limit of order of $10^{-22}\,\mathrm{e \cdot cm}$.
    - Finally we modify the g-2 pole pieces to store more muons and reach a couple $10^{-24}\mathrm{e \cdot cm}$.

Further improvements over the $10^{-24}\,\mathrm{e \cdot cm}$ will depend on both statistics, i.e. the availability of intense muon sources (like those assumed for the muon storage rings), and systematics, i.e. the stability of the $\vec{E}$ and $\vec{B}$ fields with time.

3 Motivation

The standard model of particle physics is a very successful theoretical framework, which describes all confirmed observations to date. Even surprising recent observations in neutrino physics could be possibly accommodated with small modifications. However, the model leaves important questions concerning the physical nature of observed processes unexplained, although it provides an accurate description of them. Among the not yet understood phenomena are the reasons for parity violation, the particle masses and the violation of the CP symmetry, the combined charge conjugation (C) and parity (P) transformation. In some cosmological scenarios, the latter may be related to the matter anti-matter asymmetry found in the universe. In order to obtain a deeper insight, speculative models have been suggested which often are connected to observable deviations from standard theory predictions, particularly violations of assumed symmetries or yet unknown properties of particles. The spectrum of these theories includes super symmetry [3], left-right symmetry [5], multi Higgs scenarios [6, 7] and many other important approaches. This strongly motivates sensitive searches for forbidden decays, e.g. the lepton number violating muon electron conversion [8] , the decay $\mu \to e\gamma$ [9] and precise measurements of particle characteristics such as the muon magnetic anomaly [10].

Fundamental particles are described by a few parameters only such as their mass, their intrinsic angular momentum, their electric charge (electric monopole moment), their magnetic dipole moment, and a set of conserved quantum numbers, like lepton flavor [11]. 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 [12, 3].

The standard model of particle physics predicts a CP violating EDM at the multi loop level. Their size is more than five orders of magnitude below the sensitivity of present experiments [4] (see Table 1). Therefore searches for a permanent particle EDM render excellent opportunities to test models beyond standard theory where in some cases the effect could be as large as the present known experimental bounds. Despite the non-observation of a positive EDM signal yet such research has 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 [13].

Searches for EDMs have been performed with highest sensitivity for electrons (e) and neutrons (n). Further there are experimental limits for muons (μ), taus(τ) and protons (p) (Table 1) . The experimental techniques include beams of neutral atoms, molecular beams, stored neutrons and stored charged particles. In heavy atoms and particularly in polar molecules there are substantial enhancement factors due to the utilization of the rather strong internal electric fields within these systems [14].

	Present Limit on $\|d\|$ [10^{-27} e cm]		Standard Model Prediction [10^{-27}e cm]	New Physics Limits [10^{-27} e cm]	
e	1.8 (1.2) (1.0)		$\lesssim 10^{-11}$	$\lesssim 1$	
μ	$< 1.05 \cdot 10^{9}$	(95% C.L.)	$\lesssim 10^{-8}$	$\lesssim 200$	$\times(\frac{m_\tau}{m_e})^x$
τ	$< 3.1 \cdot 10^{11}$	(95% C.L.)	$\lesssim 10^{-7}$	$\lesssim 1700$	$\times(\frac{m_\mu}{m_e})^x$
p	$-3.7\,(6.3) \cdot 10^{4}$		$\sim 10^{-4}$	$\lesssim 60$	
n	$< 63 \cdot 10^{0}$	(90% C.L.)	$\sim 10^{-4}$	$\lesssim 60$	

Table 1: Limits on Electric Dipole Moments d for electrons (e) [17], muons (μ) [18], tauons (τ) [19], protons (p) [20] and neutrons (n) [21]. For various speculative models the scaling with the lepton mass is stronger than linear (x>0).

The upper bound extracted from electron and neutron experiments already disfavor supersymmetric models with CP violating phases of order unity and suggest variants with phases of order α/π [15, 16]. Other significant restrictions of the parameter space would also be an option, however at a loss of generality. A muon EDM experiment at 10^{-24}e cm will be competitive here. Moreover, it will provide valuable complementary information, because the muon belongs to the second generation of particles where in the quark sector CP violation sets in. In two Higgs doublet models [6] with large ratios for the vacuum expectation values of the involved Higgs fields ($\tan\beta$ (≤ 15)) and for left right symmetry a muon EDM could be as large as a few 10^{-24}e cm [5] and some special models allow values up to 10^{-21}e cm.

The most sensitive experiments employ spin precession in an external electric field E. Therefore an observable effect is proportional to the applied field E and the respective interaction time (see Table 2). Most of these experiments were dedicated searches. The potential signal should have arisen in an electric field produced by a voltage difference between field electrodes. The muon result was obtained in parallel to measurements of the magnetic anomaly. This experiment takes advantage of the significantly higher motional electric field experienced by relativistic particles moving in a ≈ 1.5 T magnetic field [18].

In principle there exist alternate experimental approaches. Although, e.g., for the muon suggestions were discussed to limit any muon EDM through the lifetime of the 2s state in muonic helium, up to now no such methods could be shown to produce successful and competitive results in an experiment.

	$\lvert d\rvert$ [10^{-27} e cm]	Method	E-Field [$\frac{\mathrm{kV}}{\mathrm{cm}}$]	Interaction Time [s]
e	$1.8\,(1.2)\,(1.0)$	^{205}Tl-beam	107	$\sim$0.01
μ	$< 1.05 \cdot 10^{9}$ (95% C.L.)	μ g-2 storage ring experiment	$130{\cdot}10^{3}$	$\sim 64{\cdot}10^{-6}$
τ	$< 3.1 \cdot 10^{11}$ (95% C.L.)	τ–decay asymmetry	“atomic” field	$\sim 290{\cdot}10^{-15}$
p	$-3.7\,(6.3) \cdot 10^{4}$	TlF-beam	29.5	$\sim$0.01
n	<63 (90% C.L.)	stored neutrons, Ramsey technique	4.5	130

Table 2: Some edm Experiments. Of importance for the sensitivity is the product of electric field and the interaction time. The motional eleectric field in the magnetic storage ring of the muon experiment is 3 orders of magnitude higher than the technically produced fields between electrodes.

Sensitive searches are presently carried out on neutral objects, i.e. neutrons, atoms and molecules. This choice was strongly influenced by the Ramsey-Purcell-Schiff theorem [22] which states that for point-like charged objects in electromagnetic equilibrium the net electric field averages to zero. The widely known loopholes so far were weak and strong nuclear forces, weak electron-nucleon forces and relativistic forces. It is recognized now in the community that this theorem is also not applicable to particles in a storage ring, particularly the method proposed here, where motional fields are employed, because it is not allowed here to factorize particle velocity and electric field, which constituted the basis of the theorem [23, 22]. Therefore these electric fields, which are very strong for relativistic particles, can be beneficially exploited. Such fields can be three orders of magnitude higher than technically achievable fields between electrodes, where 4 MV/m are regarded a reasonable limit.

Quantum mechanics requires that there is only one vector possible in any fundamental particle, e.g. its angular momentum $\vec{J}$ [24]. Hence all vectorial quantities must be proportional to this single vector. The magnetic moment $\vec{\mu}$ of a particle is defined as

$$\vec{\mu} = g \cdot \mu_X \cdot \vec{J} \quad , \tag{1}$$

with the magnetic g-factor and the magneton corresponding to the species X of mass m_X

$$\mu_X = \frac{q\hbar}{2m_X} \quad . \tag{2}$$

Permanent EDMs can be defined in a similar fashion

$$\vec{d} = \eta \cdot c^{-1} \cdot \mu_X \cdot \vec{J} \quad , \tag{3}$$

where η in analogy to the magnetic g-factor carries the "interesting physics". For various theoretical models η can be proportional to m_X^2, m_X^3, m_X^4.... The remaining factors of equation 3 multiply to $9.7 \cdot 10^{-12}$ e cm for electrons, $4.7 \cdot 10^{-14}$ e cm for muons, $5.3 \cdot 10^{-15}$ e cm for nucleons. For a comparison of absolute d values the spin and mass of the particles need to be taken into account.

In an external electric field $\vec{E}$ a particle with an EDM $\vec{d}$ experiences a spin precession at a frequency of

$$\vec{\omega_e} = \frac{\vec{d}\vec{E}}{\hbar} \cdot \frac{\vec{E} \times \vec{J}}{|\vec{E} \times \vec{J}|} \quad . \tag{4}$$

In a transverse electric field the precession at frequency is then

$$\omega_e = \eta \cdot c^{-1} \mu_X \cdot E \cdot \frac{J_z}{\hbar} \quad , \tag{5}$$

which for a typical EDM of $d = 10^{-24}$e cm, an electric field strength of $E = 100$KV/cm and $J = 1/2$ is $\omega_e = 15.2$ mHz.

In the general field of EDM searches progress in sensitivity can be expected from several approaches. In particular,

- a beam experiment at Berkeley on atomic Tl [17] is expected to announce a new limit for a electron EDM very soon.

- an experiment on trapped ultra-cold neutrons at ILL has very recently reported a new upper limit on the neutron EDM [21]. Technical improvements are expected to gain half an order of magnitude. Neutron flux is expected to be a severe limitation. Approaches using He-3 as a magnetometer are under way.

- a new technique is expected to yield significant progress for ultra-cold neutrons which are introduced into supra-fluid He at temperatures below 1K. Here He-3 is chosen as a co-magnetometer. This experiment is presently performing technology studies at Los Alamos [24] .

- a Hg atom experiment at Seattle [25] is expected to yield an order of magnitude improvement which includes a higher sensitivity to nuclear EDMs. This will require a NEDM experiment at GSI to reach 10^{-25}e cm sensitivity in order to be competitive.

- experiments on YbF in Sussex and on PbO at Yale could promise significant improvement [26]. In this case an enhancement factor arises from the internal fields in the polar molecules.

- for the muon one order of magnitude improvement is expected from a search in parallel to the measurement of the muon magnetic anomaly at the Brookhaven National Laboratory (BNL) in Upton, USA [27].

- there are more ideas, which include atoms and molecules in solid He [28] or laser trapped molecules [29].

It has been recognized that the method proposed here is also applicable to searches for permanent EDMs of nuclei [30], provided the system under observation has a suitable magnetic anomaly. Searches for a nuclear EDM would be complementary and competitive, with neutron EDM searches. For heavy nuclei one could expect a quite regular enhancement over a nucleon effect by some factor of 60 due to CP-odd nuclear forces. The feasibility of a nuclear EDM experiment is presently explored at GSI in Darmstadt, Germany. At a level of 10^{-24}e cm a nuclear EDM will be competitive with present results extracted from the searches for a neutron EDM. In this experiment, the deuteron will be used to serve a investigation tool for the experimental setup.

With the expected sensitivity at a level of 10^{-24}e cm the proposed novel muon experiment is comparable with present limits on the electron EDM, if the size of the effect is assumed to be inversely proportional to the particle mass. Apparently, the experiment is of special interest for theories where the EDM scales stronger than linear with the inverse particle mass [3].

It should be mentioned that the muon is the only second generation particle for which a precision EDM experiment is feasible. 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 [31].

The muon g-2 experiment has been designed to probe physics beyond the standard model. This includes super-symmetry with large $\tan\beta$ [32, 33, 34, 35, 36] where the muon

EDM also has sensitivity. Both experiments complement each other, because magnetic anomaly and EDM are related to each other as real and imaginary part of the same physical quantity [37]. The present new limit on the muon magnetic anomaly [38] would correspond in more general super symmetry scenarios to a dipole moment of order $5 \cdot 10^{-22}$ [39], which is well within the reach of this experiment here, and demonstrates, how the explored parameter space can be expanded.

4 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

$$\begin{aligned} \vec{\omega} &= -\frac{e}{m}\{a\vec{B} - \frac{a\gamma}{1+\gamma}(\vec{\beta}\cdot\vec{B})\vec{\beta} + (\frac{1}{\gamma^2-1} - a)\frac{\vec{\beta}\times\vec{E}}{c} + \\ &\quad \frac{\eta}{2}[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}] - \frac{\eta\gamma}{2(\gamma+1)c}(\vec{\beta}\cdot\vec{E})\vec{\beta}\}, \end{aligned} \tag{6}$$

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

$$\vec{\omega} = -\frac{e}{m}\{a\vec{B} + (\frac{1}{\gamma^2-1} - a)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}(\vec{\beta}\times\vec{B})\}, \tag{7}$$

using the fact that $|E| << |B|$ and assuming the muon velocity is orthogonal to the external magnetic field ($\vec{\beta}\cdot\vec{B} = 0$). 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

$$d_\mu = \frac{\eta}{2}\frac{e\hbar}{2mc} \simeq \eta \times 4.7 \times 10^{-14}\,\mathrm{e\,cm}. \tag{8}$$

From the above equation (7) 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

$$\frac{1}{\gamma^2-1} - a = 0, \tag{9}$$

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 so that the radial electric field cancels the $g-2$ precession leaving the EDM precession to operate on its own and accumulate over many microseconds. The required electric field is

$$E = \frac{aBc(\gamma^2 - 1)}{\beta} = 2\,\mathrm{MV/m}, \tag{10}$$

for $\gamma = 5$, $B = 0.24\,\mathrm{T}$ and a magnet radius of 711 cm. Two parallel plates 10 cm apart with ±100 KV voltage can create such a field.

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:

$$dP(y,\theta) = n(y)[1 + A(y)\,\cos\theta]dy\,d\Omega, \tag{11}$$

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. [40] The oscillation frequency in the number of detected electrons is given by equation (7) when the detectors are placed on the inside of the muon storage region. [27] 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

$$\vec{A_L} = \int A(y)\,\hat{e}\,dy\,d\Omega, \tag{12}$$

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

From equation (7) (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 at the last CERN muon g-2 experiment to set a limit on the EDM. [18] 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 $3.7 \pm 3.4 \times 10^{-19}\,\mathrm{e} \cdot \mathrm{cm}$. This is the combined result of the statistical and systematic errors:

- Statistical: $3.7 \pm 2.7 \times 10^{-19}\,\mathrm{e} \cdot \mathrm{cm}$
- Systematic: $\pm 2 \times 10^{-19}\,\mathrm{e} \cdot \mathrm{cm}$

Both errors are at the same level. There are at least two sources of systematic errors when the spin is let to precess: 1) The spin precession plane is not exactly orthogonal to the detector plane which results to an up-down modulation of the average decay positron position with the g-2 frequency. 2) As the muon spin precesses the decay positrons travel through different magnetic and electric fields before they reach the detector and as a result again to an up-down modulation of the average decay positron position with the g-2 frequency..

Instead, here we are proposing 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" so that an EDM will induce an asymmetry in the electron counting from early times (shortly after muon injection into the ring) to late times.

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

1. Use *magnetic* focusing and 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. [43, 44] 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 1×10^{-21} e cm. A vertical electric field can be used to calibrate the system sensitivity with high accuracy.

4.1 Target and Beam Line (numbers not done yet!)

In order to obtain sufficient muon storage at a momentum of 0.5 GeV/c, it will be necessary to increase the acceptance of both the beam transport and the storage ring. A strong focusing upgrade of the g-2 ring would require replacement of the present pole face of the magnet with 36 alternating gradient poles to give a $\beta^x_{max} = 4.5$ m, $\beta^y_{max} = 4.3$ m and a momentum acceptance of $\pm3\%$.

A 10 cm diameter by 25 cm lithium lens pulsed at 800 KA with a gradient of 3.2T/cm located 20 cm, center to center behind the production target would capture 0.9 GeV/c secondary pions beyond the maximum production angle of 8-10 degrees indicated in the Sanford-Wang [41] parameterization.

The beam transport upgrade is designed to transport pions of higher momentum than the desired muons. We use 0.9 GeV/c pions in order to take advantage of the steep increase in pion production with increasing pion momentum. Backward emitted (in the c.m. frame) 0.5 GeV/c muons would then be transported to and injected into the g-2 ring.

The design upgrade requires the installation of 20 additional 4Q24 quadrupole magnets in the pion decay region. In addition 3 new quadrupole magnets in the matching section can be employed in order to capture more pions into the beam channel.

Simulations using the Sanford-Wang parameterization of particle production indicate 8.6×10^5 stored muons per bunch of 10^{12} protons on target is a realizable goal (assuming the inflector has 100% injection efficiency) at the present AGS intensity, and 13.4 GeV/c proton beam.

Assuming a proton intensity of 100 TP (100×10^{12}) every 1.5 s it would take 7200 hours to accumulate 1.5×10^{15} stored muons needed for $2.5 \times 10^{-24}\,\mathrm{e} \cdot \mathrm{cm}$ limit. We are investigating the possibility to use a smaller diameter lithium lens by a factor of 3 to further increase the number of captured pions and reduce the required total running time.

For the weak focusing case and a 10 cm by 10 cm square aperture the muon storage ring is estimated to accumulate a smaller number of muons by a factor of 100. A limit of $1 \times 10^{-22}\,\mathrm{e} \cdot \mathrm{cm}$ is then possible in less than 500 hours.

4.2 Inflector

The injection of beam into the storage ring is usually done with a septum magnet (inflector), which locally cancels the field of the main magnet, so that the beam enters the storage region nearly tangential to the equilibrium orbit.

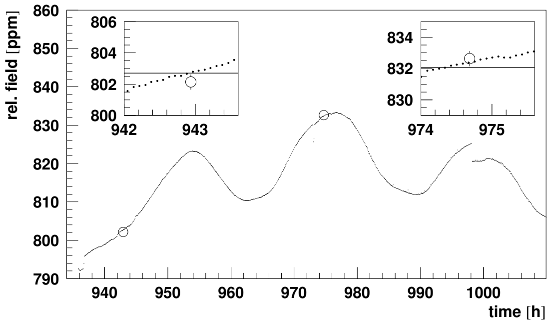
A direct current non-ferrous super-conducting inflector has been designed and constructed for E821 (muon g-2) experiment [27]. Double cosine function related current density is applied on an arc with a radius of 5 cm. Truncation is carried out along one of the constant vector potential lines, by placing conductors corresponding to certain current density. [42] The dipole field is uniform in the beam channel and there is very low fringe field in the vicinity of the device. E821 required 2850 A current in 88 turns to provide a 1.5 T channel field. For the muon EDM experiment, only one sixth of the current is required. Using the existing E821 SC inflector is one of the options, but the aperture would be limited.

In the EDM experiment the leakage field requirement is much more relaxed and simpler designs are acceptable. We are planning to use a water cooled normal conductor with the geometry shown in Fig. 3 The figure shows the cross section of the inflector (the two parallel plates with the enclosed flux) and the $g-2$ magnet with the pole pieces as shaped currently. Fig. 4 shows the magnetic flux when both the main magnet and the inflector are powered. Fig. 5 shows the vertical component of the magnetic field in gauss over the storage region (from 706.7 to 715.7 cm) with both the inflector on and off. The influence of the inflector at the muon storage area can be further reduced by shimming it to the required accuracy.

4.3 Storage Ring-Weak Magnetic Focusing

The g-2 ring magnet has been built to provide excellent field stability and homogeneity for precision measurements. For the EDM experiment the field homogeneity is of relatively little concern, but the stability of the magnetic field, specifically it's direction, is extremely critical. The limit for the average radial field in the g-2 experiment is 50 parts per million (ppm) relative to the vertical field strength. Measurements of the minor field components were done with Hall probes to an accuracy of about 10 ppm. During data taking runs the maximum number of muons is stored if the beam is vertically centered with respect to the electrostatic quadrupoles. Current coils on the pole faces are used to compensate the static radial field average. From these measurements we know that the average radial field $< B_r >$ is constant to within our measurement accuracy of 10 ppm over several months.

For the EDM experiment we aim to improve our knowledge of $< B_r >$ by three orders of magnitude. From the NMR measurements of the absolute field we know that the variations in the magnetic field are dominated by changes in the vertical gap between the upper and lower pole pieces due to thermal expansion/contraction of the magnet steel including the super-bolts that hold the yoke pieces together. A uniform temperature rise leads to an increase of the air gap and thus a reduction of the magnetic field in the storage region but does not change the direction of the field. However, the thermal time constant of the yoke is several hours, and changes in the ambient temperature do not only change the average vertical gap but also cause a transient relative tilt of the top pole with respect to the bottom. This affects the direction of the magnetic field, introducing a small radial field component, as well as the normal quadrupole moment, i.e. the gradient of the vertical field along the radial direction. In a weak focusing magnet we can use NMR probes to keep track of the radial field change by precisely measuring the normal quadrupole moment. These measurements should be compared to direct measurements of the gap variation using optical interferometry. During the first g-2 run in 1997 data was taken in a constant current mode and the ambient temperature changes are clearly visible in the average field, see Fig. 1. Fig. 2 shows the change of the normal quadrupole moment in the same time period. This change is highly correlated to the temperature difference



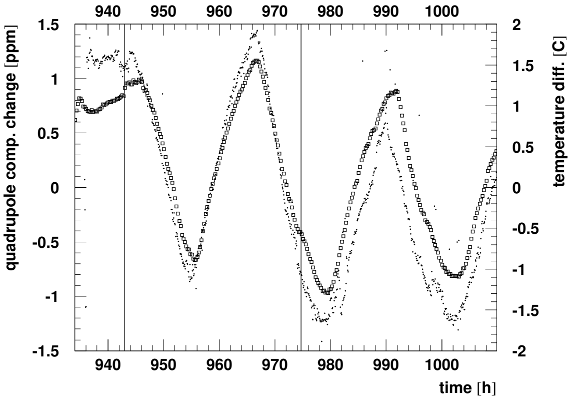


Figure 1: The average magnetic field over a period of about three days during the 1997 run. The inserts indicate measurements with the beam tube trolley.

Figure 2: Temperature difference between the magnet yoke surface and the experimental hall temperature (squares) and the change of the normal quadrupole component (dots) during the same time interval.

between the magnet yoke surface temperature and the ambient temperature, also shown in Fig. 2. Since 1997 the magnet yoke has been insulated and the temperature effects are reduced by about a factor of 5 but the radial field component could still change by a few hundred nanoradians over a day. Even with further improvements in the temperature stability, this change will have to be monitored and compensated, e.g. with the existing pole surface current coils.

Most of the pulsed NMR equipment for g-2 could be used in the EDM experiment. Only the passive probes and the pulse amplifiers have a narrow bandwidth and would have to be redone.

In order to measure the average field component in the E-field direction with a deuteron beam, either the E-field or the B-field will have to be changed. In both cases the dependence of the field direction on the field strength is a concern. For the B-field there is a strong dependence due to the attractive magnetic force. At the g-2 field of 1.45 Tesla the average gap is reduced by 0.3 mm relative to the zero field value and the top pole rotates by about 0.3 mrad with respect to the bottom pole during the ramp. This translates into a tilt change of about 2.6 μrad or a change in the radial field component in the mid-plane by 1.3ppm while going from 0.2 T (deuteron) to 0.24 T (muon). Again this change can be monitored accurately with NMR probes and also with optical interferometers. Using both methods would give additional information on field perturbations due to permeability changes which are expected to be small at these low field values.

4.4 Storage Ring-Strong Magnetic Focusing

Since the search for an EDM does not require an accurately known magnetic field, the use of strong magnetic focusing is very advantageous. We plan to use the 36 pole pieces on top and 36 on bottom shaped in such a way that they provide $\frac{\partial B}{\partial R} = 1.45$ T/m of 36 alternating gradient focusing regions. The main dipole field (for the 0.5 GeV/c muon momentum case) is 0.24 T and therefore the regional field focusing index is $n = 43$. The phase advancement is 44.5° per region. Assuming the same muon storage region of 9 cm in diameter, as in the current g-2 experiment, the estimated beta functions are $\beta^x_{max} = 4.5$ m, $\beta^y_{max} = 4.3$ m. The compactification factor is 5.9 giving an overall factor of 50 improvement in the number of stored muons over a comparable system with an electrostatic weak focusing. We are also considering a redesign of the beam storage vacuum chamber to optimize it for the EDM experiment.

There is a need to have a kicker in order to be able to inject muons into the ring. One third in length of the current kicker with two thirds the peak current would suffice. The eddy currents of this kicker would be sufficiently low not to become a source of systematic errors.

4.5 Storage Ring Lattice

There needs to be gaps in the dipole electric field electrodes for the inflector, kicker, pickup electrodes, and deuteron spin analyzer. Therefore, we have chosen four-fold symmetry for the lattice. At this time, 1m gaps seem to be adequate. Fourier analysis $F(s/R) = \sum A_N \cos(N_s/R)$ gives:

The effect on the equilibrium orbit is given by:

Table 3: Fourier Coefficients of the Ring Lattice

N	%	N	%	N	%
0	91.1	28	-4.2	56	1.7
4	-8.8	32	-3.1	60	1.4
8	-8.5	36	-2.1	64	1.9
12	-7.9	40	-1.1	68	1.9
16	-7.2	44	-0.2	72	1.7
20	-6.3	48	0.6	76	1.4
24	-5.3	52	1.2	80	1.0

$$dx_e = RE_N \frac{\cos(N_s/R)}{(Bv - E)(-N^2 + 1 - n)} \tag{13}$$

for the deuteron, and change the sign of E for the muon. We have not yet chosen the weak focusing field index n:

$$n = \frac{R}{(B_0 - E_0/v)} \frac{\partial(By - Ex/v)}{\partial R} \tag{14}$$

For n=0.137 (the current muon g-2 weak focusing field index) the effect is about ±1cm for the deuteron and ±1.7mm for the muon. The aperture will be defined by the electric dipole electrodes of ±5cm vertically and horizontally. This dx_e is acceptable, and could be further minimized by adjusting the electrode High Voltage as a function of azimuth.

For E821 the muons passed through the outer quadrupole #1 electrodes and insulators at x = 5cm between the exit of the inflector magnet and the kicker. The Coulomb multiple scattering in quadrupole #1 reduced the muon storage efficiency by about 20%. For the EDM experiment, the outer electric dipole electrode between the inflector and the kicker will be at larger radius than the inflector aperture, eliminating this loss of storage efficiency. With the new inflector magnet design where the beam passes through in vacuum, the E821 loss of muon storage efficiency of a factor of two will also be eliminated.

4.6 Detectors

We require a detector system which is sensitive to the number of muon decay electrons going upward compared to the number going downward, in an energy range of 100 to 500 MeV. The up-down asymmetry, $\frac{N_{up}-N_{dn}}{N_{up}+N_{dn}}$, is directly proportional to η and the EDM. The detector should be relatively insensitive to background from muons, neutrons, pions, protons, etc.

The detectors will also have to be capable of handling the extremely high instantaneous rates immediately following muon injection, and the efficiency for measuring the up-down asymmetry must remain stable when the rate diminishes as the muons decay.

We anticipate that 10^7 muons will be stored per AGS bunch, significantly more than what the Muon g-2 experiment currently receives. There will be 12 bunches, separated by about $33ms$, as in the g-2 experiment. The muons have momenta of 500 MeV/c, $\gamma = 4.83$, and mean lifetime=$10.6\mu s$. The average time spacing between muon decays is then $10.6 \times 10^{-6}s/10^7 \approx 10^{-12}s$. If we assume that we have approximately 1000-fold segmentation in the detector system, then each counter would have an average event spacing of $1ns$ immediately after injection. At ten lifetimes, the average spacing between events increases to $22.0\mu s$. Thus, the detector must be capable of measuring the number of electrons over a large dynamic range of rates and for a large initial rate.

Individual electron counting is impractical at early times because the time spacing between events is too small. Consequently, we plan to integrate the total charge from the detectors. This implies that the gains of the detectors must be exceptionally stable. The geometric arrangement of the counters will be up-down symmetric so as to minimize up-down asymmetries arising from backgrounds.

The proposed system consists of 2 cm thick lead-glass slabs placed above and below and on the sides of the storage region, with photodiode readout. The radiation length is about 1.5 cm. The electrons, on average, enter the lead-glass at steep angles. Simulations show that the rms energy resolution for 400 MeV electrons is about 14% due to shower fluctuations and losses. Photon statistics will increase this; for regular lead-glass, the resolution will increase to about 25%, less if scintillating lead-glass is used. About 60% of the electrons above 100 MeV fall into the main shower peak, with the rest falling in a low-energy tail. On average, the showering electrons will leave much more energy than, say, muons which are lost from storage or gamma rays from neutron capture, thereby minimizing background sensitivity.

The lead-glass slabs would cover the top and bottom areas of the pole tips, and will go around the 43 m circumference of the ring minus 4 m for the required gaps. Most of the decay electrons will be intercepted by such a geometry, as indicated by the radial distribution of electrons striking the detectors in Fig. 6. It will be segmented in 10 cm sections, each section being read out by a photodiode. This provides an overall segmentation of about 800.

The photodiodes will have time constants of about 1 μs. At the high anticipated rates, individual counting of decay electrons will not be attempted. Instead, we will integrate the total charge accumulated in approximately 1 μs intervals, as a function of time after injection. The charge will be calibrated to the number of decay electrons, and the up-down ratio as a function of time after injection will be deduced.

The measurements will be taken for about ten muon lifetimes after injection, or for about 106 microseconds, however, most of the data will be collected in the first 55 μs. The gains of the photodiodes must be extremely good over 55 μs: to about 1 part in 10^5. We are working with the electronics group at BNL to develop such an ultra-stable system. Their first estimations are that one can stabilize the gains to 1 part in 10^4 and then calibrate the gain to 10%, thus providing the needed 1 part in 10^5 stability.

Given the demanding stability requirements, we are investigating schemes where the effect of any drifting in the photodiodes would cancel. One possibility is to alternate the measurement between muon spins parallel and anti-parallel to the muon momentum; a non-zero EDM would lead to a positive value for $\frac{N_{up}-N_{dn}}{N_{up}+N_{dn}}$ in one case and a negative sign in the other. (This is not a perfect systematic check, however, since one spin direction would have a lower average energy than the other, as seen in Fig. 7).

One possible way to collect data for both parallel and anti-parallel spin orientations would be to alternate between injecting forward and backward muons, which have opposite spins. Unfortunately, even if a way could be developed to quickly switch between the two, the forward muons would probably have an intolerable pion and proton contamination.

Another possibility would be to allow the muons to precess naturally in the B-field of the storage ring until their spins are reversed, then switch on the radial E-field to halt the precession. In the proposed B-field at 500 MeV it would take 13.5 μs for the spin to precess 180 degrees, but this could be sped up if the radial E-field which is used to halt the spin is initially reversed. The challenge is to be to able switch the radial E-field in a sufficiently short time(few microseconds), and also to deal with the change in the muon storage radius as the radial field is changed.

Fig. 8) shows the number of decay electrons vs energy which strike the detector, the up-down asymmetry=$\frac{N_{up}-N_{dn}}{N_{up}+N_{dn}}$, and the relative statistical power of the electron data, which is proportional to the inverse of the relative error on the up-down asymmetry.

5 Sensitivity Level

The EDM sensitivity is given by (in MKS units)

$$\eta = \frac{2\theta_t}{\beta B t}\frac{m}{e}, \tag{15}$$

with θ_t the minimum transverse spin precession angle which can be detected, m, e the muon mass and charge respectively, and B, the average magnetic field seen by the muon. The uncertainty in η is

$$\sigma_\eta = \frac{1}{\gamma\tau_0 A_1 A\sqrt{2N_{Tot}}}, \tag{16}$$

with $A_1 = \beta eB/2m = 10^8$/s for $B = 0.24$T, N_{Tot} the total number of observed decays, τ_0 the muon lifetime at rest, γ the Lorentz boost factor, and A the asymmetry. If one observes 1.5×10^{15} decay electrons which have an average transverse asymmetry of 0.3 then the uncertainty in η is 5.5×10^{-11}, and on the EDM $2.5 \times 10^{-24}\,\mathrm{e\,cm}$. In two muon lifetimes (i.e. $2 \times 11\mu$s) this corresponds to a vertical precession angle of 120 nrad.

The sensitivity of the experiment increases as the B field and the lifetime increase. However, the necessary electric field which is canceling the muon $g-2$ spin precession also grows fast as can be seen by equation (10).

5.1 Calibration of Sensitivity

A simple way to calibrate the experimental sensitivity to the muon EDM is to apply a vertical electric field in the muon storage region. The beam will be displaced vertically until the magnetic focusing will compensate with an equal and opposite force. The average radial magnetic field seen by the muons will be such that it compensates the vertical electric field. This non-zero radial magnetic field will induce a non-zero spin precession in the vertical plane mimicking an EDM effect.

The vertical spin precession angle with a vertical electric field E_v, and a vertical B magnetic field present is given by

$$\theta_t = \frac{e}{2m}[g\frac{E_v}{c\beta\gamma^2} + \eta\beta B]t, \tag{17}$$

which for $E_v = 5$ KV/m results in 30 mrad vertical spin precession which is easily measurable. This average electric field can be achieved by placing pulsed 25 KV on a pair of electrodes, 10 cm apart, covering 2% of the ring. The average vertical muon population will shift by about 10 μm (in the strong focusing case).

It should be noted that in the absence of an electric field the average radial magnetic field seen by the muons is exactly zero since we are using *magnetic* focusing.

6 Systematic Errors

Potential systematic errors include the following:

1. Early to late electron counting due to rate effects. With almost 10^7 muons entering the ring and a good fraction of them decaying within 10 μs the rates are very high. Our detector will be scintillating fiber calorimeters with photodiode readout. The readout electronics are specially made so that they maintain their linearity to 10^{-4} [45] and will be measured to 10%. With 400 such systems the error is further reduced another factor of 20. We are investigating the possibility of interchanging electronically the top/bottom detector readout randomly about 100 times which brings us to 5×10^{-8} linearity error.

2. Proton or pion contamination of the muon beam. During the 1997 run of the g-2 experiment where there were injected about 10^8 pions per spill, the pion flash was the biggest problem. After striking a nucleus they 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. If we assume that the lower momentum particles are less likely to produce a neutron by a factor of 2 and taking into account that most of the injected particles (i.e. 90%) are expected to be stored and not get lost, the total particle population in the ring producing a neutron will be 5×10^9 for a total of 10^{15} stored muons. Assuming that they cause a 0.5% asymmetry on top versus the bottom detectors (in the worse case) the effect will be below the sensitivity of the experiment.

3. Due to the cylindrical nature of the electrostatic plates which provide the radial electric field, the E-field decreases as $1/R$ making the cancelation of the g-2 non-perfect as a function of the muon momentum. Also, taking into account that the spin precession cancelation depends on both the magnetic field and the value of gamma (see equation (10)), one can estimate that at the edge of the aperture, the muons will flip the spin 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 observe the precession plane as a function of the E-field.

4. The problem with radial magnetic fields present, when electrostatic focusing is used, is eliminated completely because we only use magnetic focusing. However the mis-alignment and time stability of the E and B-fields is going to be monitor by the inclinometer and the laser interferometers described next.

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.

6.1 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 10 nrad will induce an effect mimicking an EDM of $10^{-24}\,\mathrm{e\,cm}$. This implies that the electrodes, and the resistive top and bottom plates used to produce a uniform electrostatic field, must be aligned with respect to the horizontal plane with high precision.

Fig. 9 shows a method that may be used to achieve this alignment and most importantly the monitoring of the relative distance to better than 10 nrad. The electrodes and top and bottom plates are clamped at intervals with pairs of U-shaped machinable ceramic yokes. The top and bottom plates are made of glass doped to produce a small but uniform conductivity bonded to insulating webbing for support. The outer surfaces of the conductive glass are covered with an anti-reflection coating so that the parallelism of the inner surfaces of the top and bottom plates may be tested, after clamping, by optical interferometry. Shimming may be necessary to insure that these inner surfaces are parallel. We are investigating the possibility to construct the plates by scintillating lead glass to be used as an almost full acceptance detector for the decay positrons. The cross section of the plates (10 cm by 10 cm) is shown on the right. The top and bottom plates consist of conductive glass plates. On the top of the figure the laser interferometer is shown which has 5 nm relative position resolution and 33 KHz response speed. Integrating over 3 ms will result to 0.5 nrad angular resolution. [46]

6.2 Inclinometer

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

$$\vec{\omega} = -\frac{e}{m}[a\vec{B} + (\frac{1}{\gamma^2 - 1} - a)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B})] \tag{18}$$

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

$$a\vec{B} + (\frac{1}{\gamma^2 - 1} - a)\frac{\vec{\beta} \times \vec{E}}{c} \approx 0 \tag{19}$$

This requires that over the ensemble of particles that $\vec{B} \cdot \vec{E} \approx 0$ and

$$E \approx aBcp(1 + \frac{p^2}{m^2})^{1/2}/m \tag{20}$$

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:

$$F = a(1 + \frac{p^2}{m^2})^{1/2}/m \tag{21}$$

In table 3 we give the factor F for the muon, proton and deuteron for E = 2MV/m and R=7.11m.

Table 4: The factor F for different particles

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. In table 4 we show the momentum p, the velocity β, the γ factor and the required B-field for E=2MV/m, R=7.11m for the muon and deuteron.

Table 5: Muon and deuteron parameters

	μ	d
p (MeV/c)	511.	396.
β	0.979	0.207
γ	4.94	1.022
B (T)	0.233	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:

$$p \approx 0.3[B + E/v]R \tag{22}$$

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

$$p \approx 0.3[B - E/v]R \tag{23}$$

The amazing coincidence is although the muon and deuteron a and γ differ by orders of magnitude, the B-field is the same to 0.015T for $\mid E \mid$= 2MV/m and R = 7.11m.

As discussed above, the angle θ between $\vec{B}$ and$\vec{E}$ over the ensemble of particles should be known to 10 nrad for a systematic error on the edm of the muon at the $10^{-24}\,\mathrm{e\cdot cm}$ level, since this causes the same spin precession as an edm:

$$dS/dt = \mu\theta E/(c\beta\gamma^2) \tag{24}$$

For the deuteron, $\mu = 0.857e\hbar/(2m_p)$, and for the muon, $\mu = 1.001e\hbar/(2m_\mu)$. For $\theta E = 10^{-8} \times 2\mathrm{MV/m}$, $\omega_s = 14\,\mathrm{mrad/s}$ 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, and much larger numbers can be stored, the deuteron is a great system to sense the average direction of the E-field compared to B-field. 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.

For the BNL muon storage ring with weak focusing, n=0.137, the mean radial magnetic field affects the mean height of the beam: 20 μrad moves the average beam height by 1mm. From year to year, this changes by typically $20 \pm 10\,\mu$rad. This is measured by applying a radial magnetic field with the current shims, and recording the number of stored muons. The optimum storage efficiency is when the average beam height is in the center of the vertical aperture. The $\pm 10\,\mu$rad uncertainty is due to changes in the beamline which affect the storage efficiency while the current shim "sweep" is being done. For the new experiment, we are planning to use a pickup electrode which will measure the average deuteron vertical position to better than 1 μm. The average vertical position depends only on the radial component of the magnetic field and the vertical component of the electric field:

$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B}) = 0 \tag{25}$$

If the beam is injected "crooked", it will simply have larger betatron oscillations about the equilibrium orbit. By varying E from -2MV/m to +2MV/m, we plan to map out the vertical component of the electric field by measuring the mean vertical height of the deuterons with the pick-up electrodes.

The spin precession due to the edm is:

$$d\vec{S}/dt = \vec{d} \times (\vec{E} + \vec{v} \times \vec{B}) \tag{26}$$

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 to using it as an inclinometer for the measurement of the muon edm at the $10^{-24}\,\mathrm{e}\cdot\mathrm{cm}$ level.

6.3 Deuteron Polarimeter

The number of highly polarized Deuterons potentially available from AGS is 5×10^9 with 5 Hz repetition rate.

6.4 Pickup Electrodes

7 Cost and Schedule

The cost of a dedicated EDM experiment is only incremental over the current g-2 experiment since the bulk of the equipment is going to be used as is. A rough estimate of the extra cost is about 5.4 million dollars with most of the money needed is for the new target with the lithium lens ($1000 K), beam transport line ($415 K) and installation ($390 K), detectors ($400 K), vacuum chambers ($400 K), new inflector ($100 K), ring modification (\$400 K), and electrostatic plates with feedback system (\$1000 K). A 30% overall contingency is \$1.05 M bringing the total to \$5.4 M for the experiment completion.

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 2001. In the meantime we would be building a prototype of the electrostatic plates, monitoring system with the laser interferometer and the Deuteron polarimeter.

The schedule for the muon EDM is given below:

- 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) and time stability (with laser interferometers) of the $\vec{E}$ field and the orthogonal plane to $\vec{B}$ field to 10 nrad.
- Next we run with muons and set a first limit of order of $10^{-22}\,\mathrm{e}\cdot\mathrm{cm}$.
- Finally we modify the g-2 pole pieces to store more muons and reach a couple of $10^{-24}\mathrm{e}\cdot\mathrm{cm}$.

8 Summary

We have proposed to search for an EDM of the muon by performing a dedicated experiment in the existing g-2 ring. The main differences from the g-2 experiment are that we are going to place the detector calorimeters inside the vacuum chambers, use magnetic focusing (start with weak and continue with strong later on) with no vertical electric fields present, lower momentum muons, and a lithium lens target with modified beam transport and inflector system. The introduction of an inclinometer, i.e. a system of measuring in situ the misalignment of the average radial electric field direction (which is used to cancel the spin motion of the muon) and the orthogonal to the direction of the average dipole magnetic field. This is done by injecting polarized Deuterons in the ring and observe their vertical spin precession as a function of time. Finally, the introduction of a monitoring system of the above alignment of the electric and magnetic field directions by a set of laser interferometers in between the Deuteron runs. All of these are described in more detail in the corresponding sections.

The estimated sensitivity is at the level of a couple of $10^{-24}\,\mathrm{e\,cm}$, 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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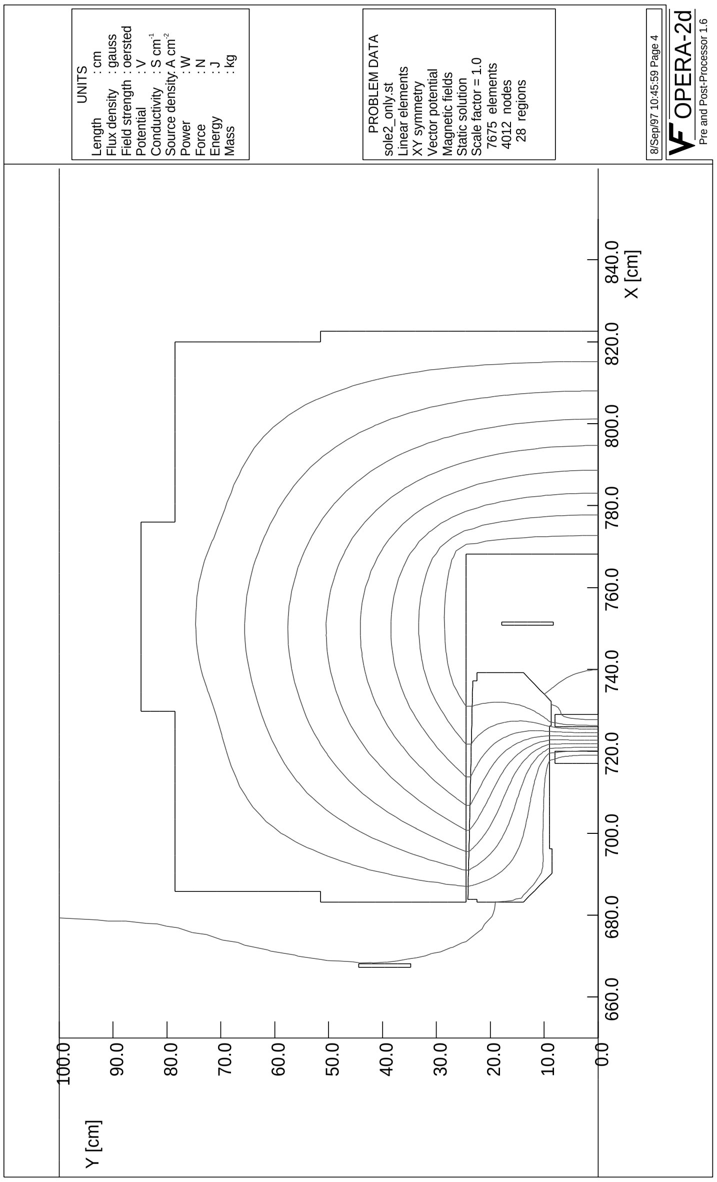

Figure 3: The proposed new inflector design for the EDM experiment located at 723 cm away from the center of the $g-2$ ring. The muon storage center is at 711.2 cm. The magnetic flux lines are shown with only the inflector energized.

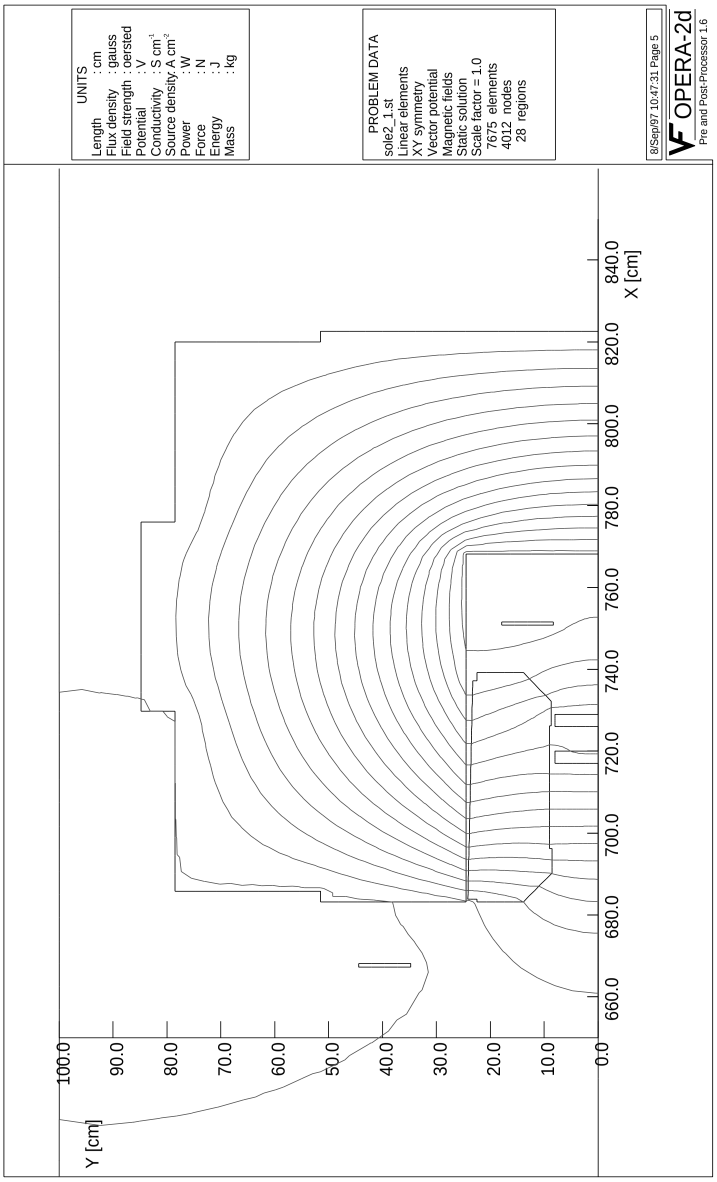

Figure 4: The magnetic flux when both the main magnet and the inflector are powered. The required current density for no magnetic field inside the inflector is $31.7\,\mathrm{KA-turn}$.

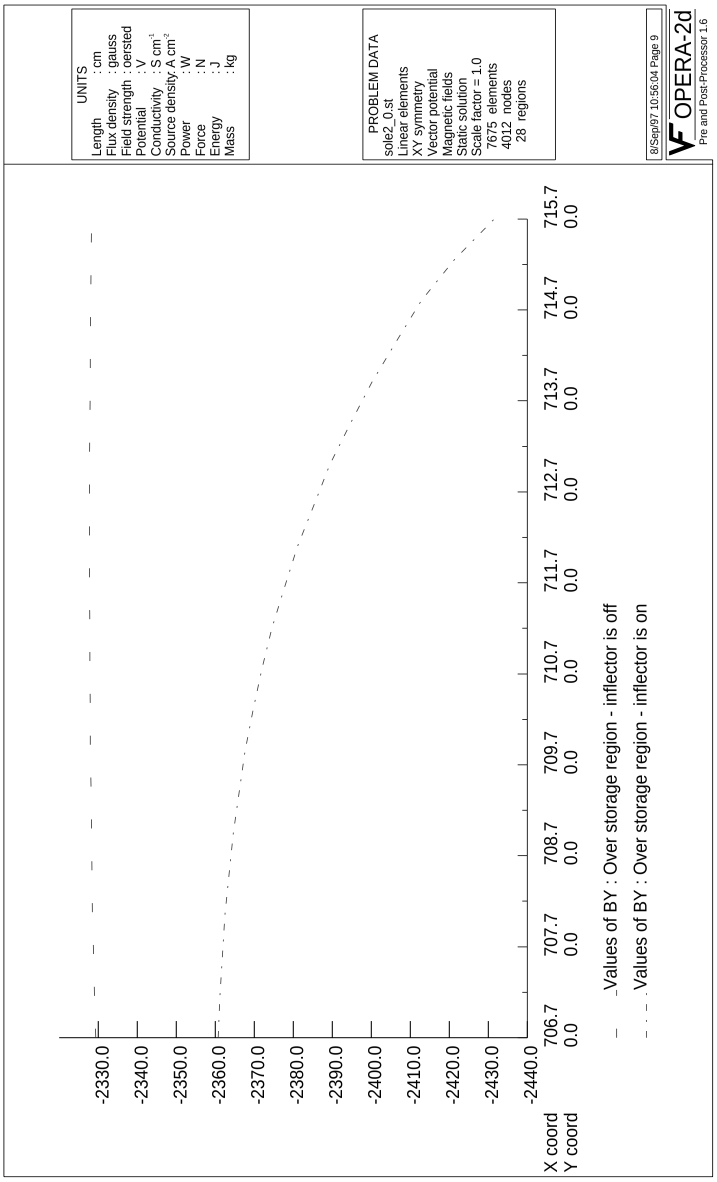

Figure 5: The vertical magnetic field in gauss at the location of the muon storage region with and without the inflector energized.

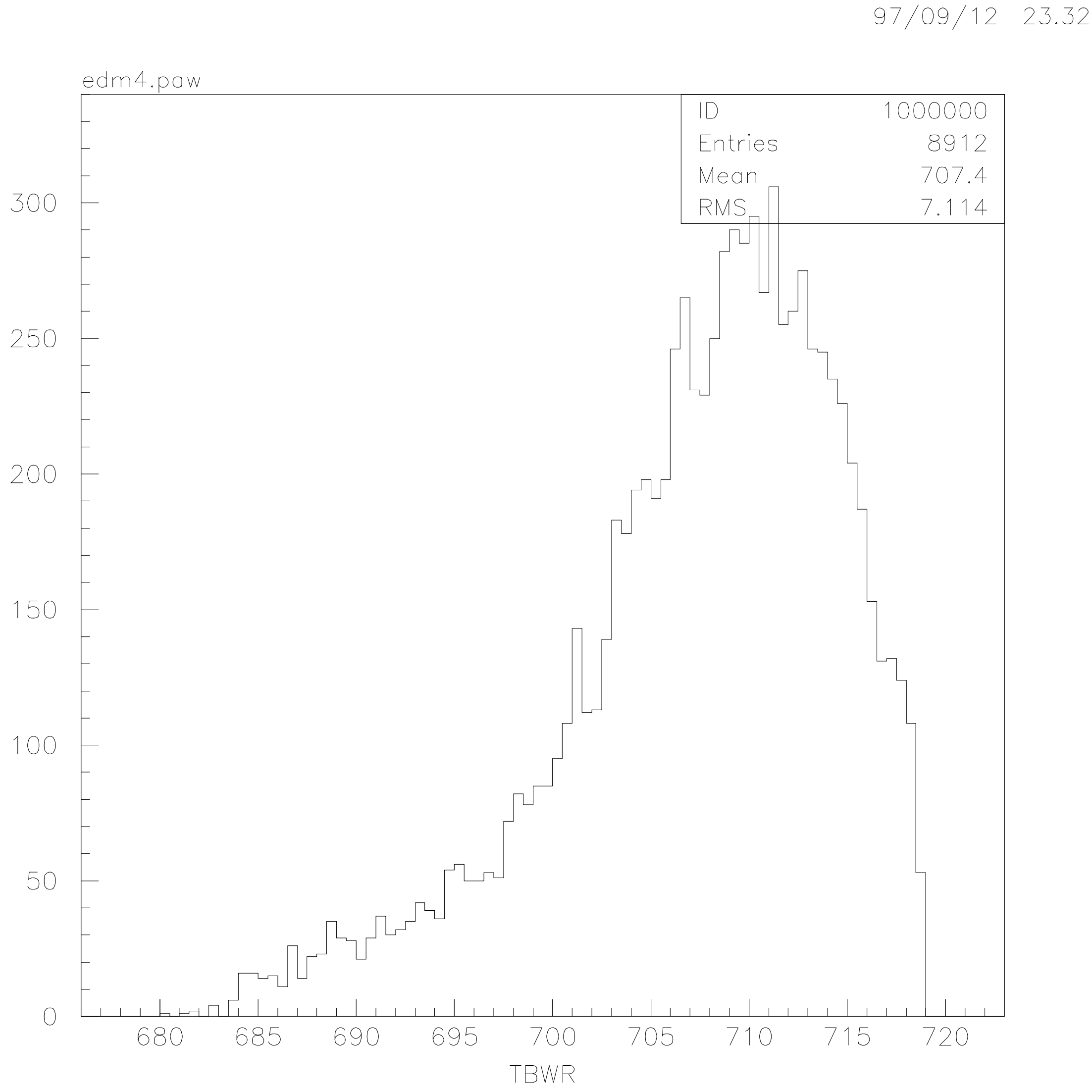

Figure 6: The distribution of the radial position of the decay electrons when they strike either a top or bottom detector. The radius is to be compared with the central storage radius of 7.11 m. The peak is at a slightly smaller radius than 7.11 m.

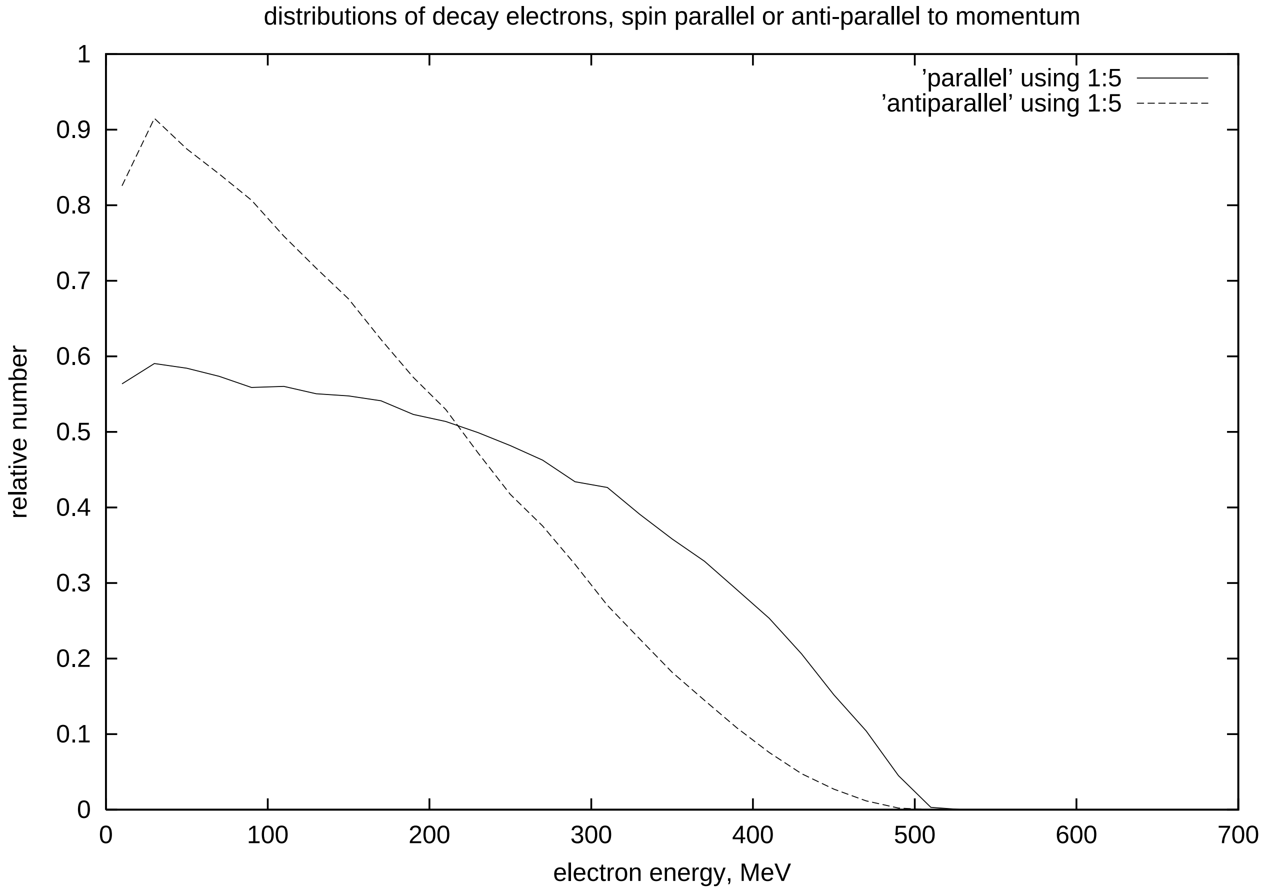

Figure 7: The decay electron energy distributions for forward and backward muon spins.

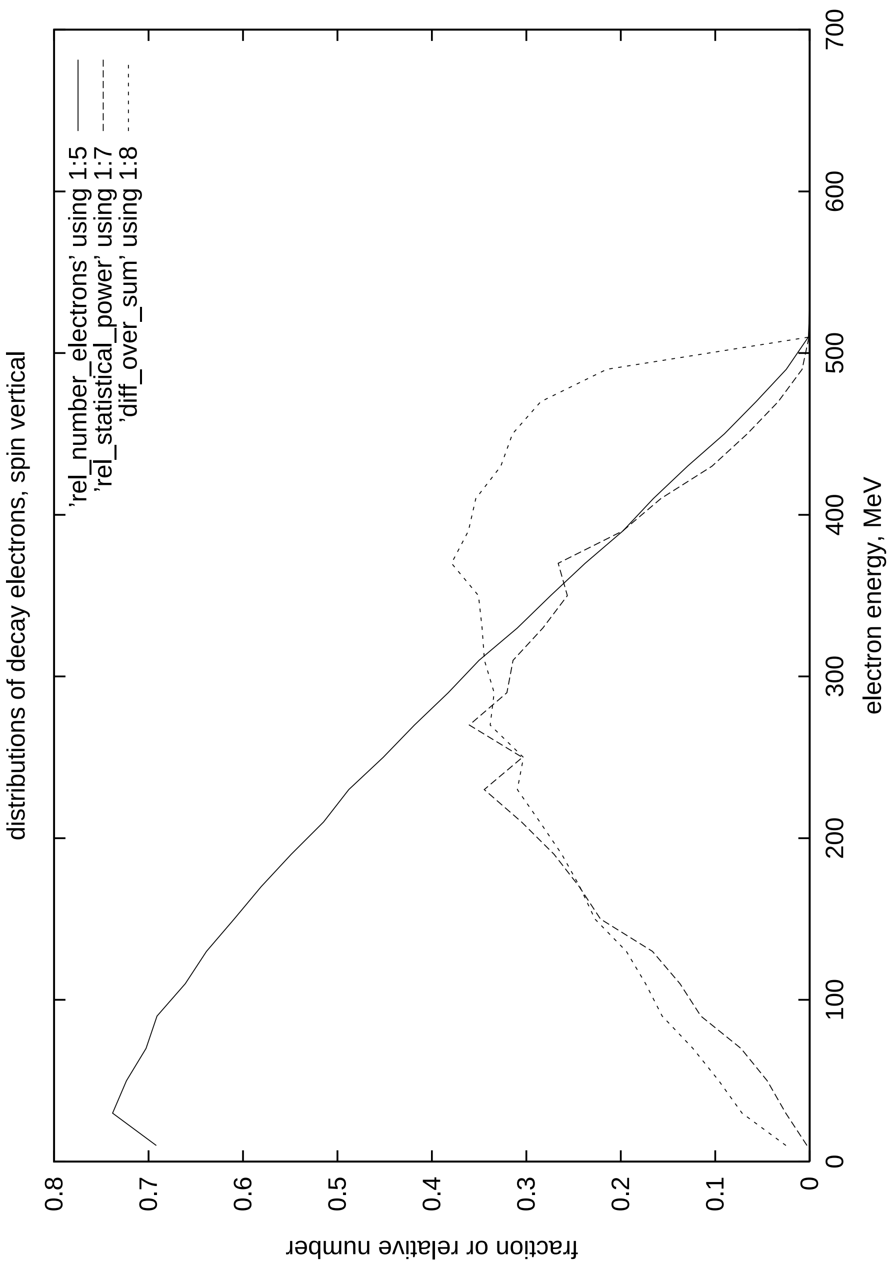

Figure 8: The number of decay electrons vs energy which strike the detector, the up-down asymmetry$=\frac{N_{up}-N_{dn}}{N_{up}+N_{dn}}$, and the relative statistical power of the electron data, which is proportional to the inverse of the relative error on the up-down asymmetry. The most statistically significant electrons are those with energies above 100 MeV, with a peak around 275 MeV. The energy distribution shown is for vertically oriented spin, which gives a distribution somewhere between the energy distribution for forward and backward muon spins.

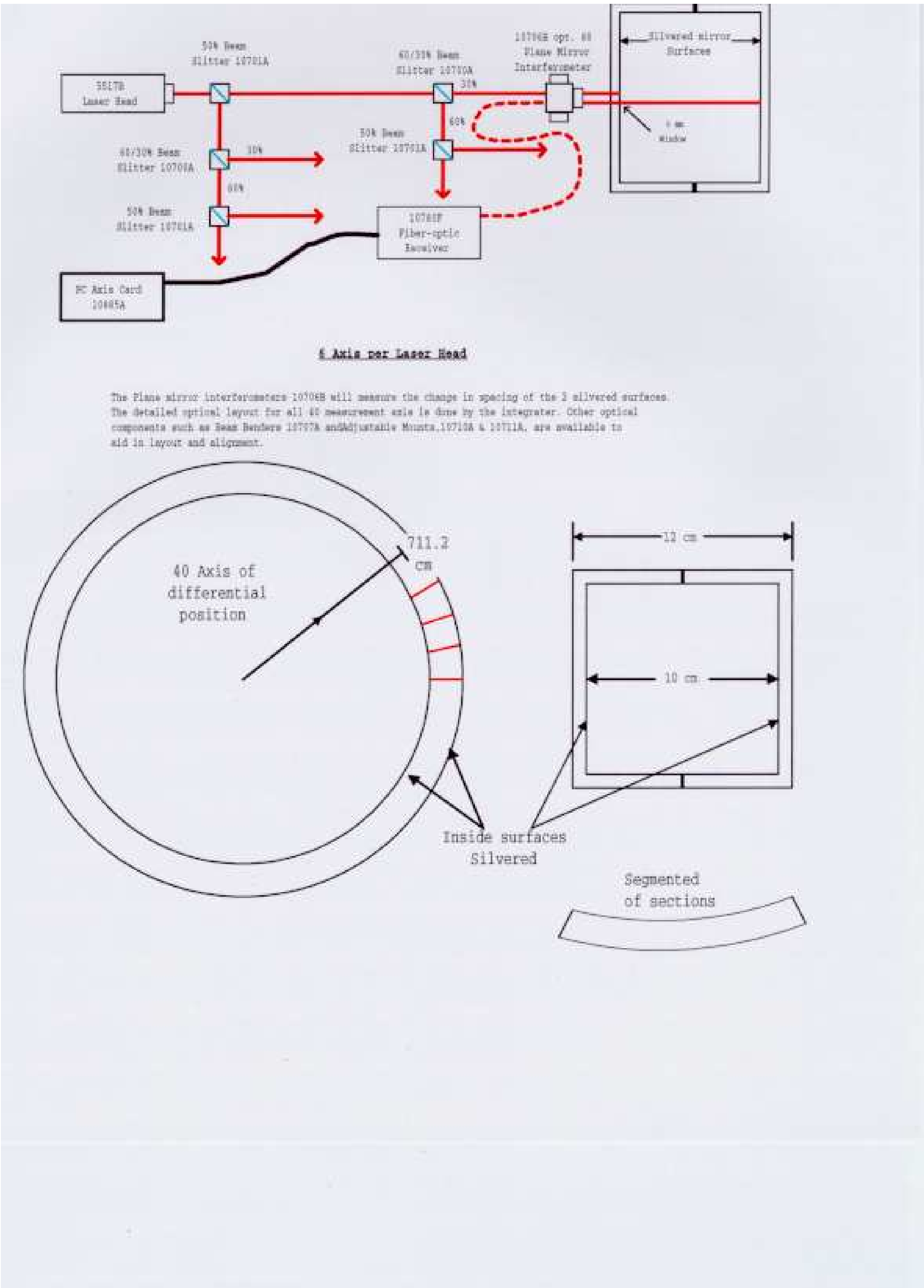

Figure 9: The cross section of the plates (10 cm by 10 cm) is shown on the right. The top and bottom plates consist of conductive glass plates. On the top of the figure the laser interferometer is shown which has 5 nm relative position resolution with 33 KHz response speed.