Letter of Intent: Development of a Resonance Method to Search for a Deuteron Electric Dipole Moment using a Charged Particle Storage Ring

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August, 2006

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Abstract

We request support to develop a proposal for a new, sensitive method of searching for an electric dipole moment (EDM) of charged particles in a magnetic storage ring. The ring design is based on forced synchrotron oscillations that accumulate an EDM signal with each oscillation. Slow extraction of the beam onto a target provides a scattered flux whose asymmetry as a function of the time during the beam store can be related to the growth of the component associated with the EDM. In the proposed arrangement, RF is used to produce a 1% modulation of the speed of the stored particles, causing the component of spin normal to the orbit plane to increase with time at a rate proportional to the EDM. The result is a left-right spatial asymmetry proportional to the EDM. By our creating multiple beam bunches with different properties and subjecting them simultaneously to different perturbing fields, the EDM signal can be reversed or set to zero, and systematic error signals arising from spurious field components can be measured and removed. Systematic errors must be studied further using spin tracking simulation and other tools in order to develop a final design for the EDM storage ring.

Contents

1 Introduction

If a particle carries an intrinsic electric dipole moment (EDM), that vector must be along the particle spin [1], $\vec{d} = (e/2m)\eta\,\vec{s}$. Such a pairing of the direction of an EDM with the spin produces an object violating P (parity) and T (time-reversal) symmetries [1, 2, 3]. Under the assumption of CPT conservation (the simultaneous operation of charge conjugation, parity, and time-reversal symmetries), time-reversal violation also implies CP-violation. Cases of time-reversal violation are rare, and the place afforded to this effect within the Standard Model predicts an EDM that is so small that it is at least two orders of magnitude beyond the reach of any search so far proposed. But if we are to understand the matter-antimatter asymmetry that remains in our universe following the Big Bang, then additional sources of CP-violation must exist [4].

Such sources are proposed in a number of new model schemes, including supersymmetric constructs that pair each fundamental particle with an as yet undiscovered supersymmetric partner. The predictions of these models are within the reach of the next generation of EDM searches. Using certain charged particles such as the deuteron in an EDM search extends the sensitivity to quark-color EDMs by more than an order of magnitude when compared to the same nominal neutron EDM [5, 6, 7]. The deuteron also carries a sensitivity to an EDM associated with the CP-odd interaction between nucleons, but unlike heavier nuclei it does so in a system whose structure is well understood.

Using a storage ring to search for an EDM opens up the domain of such searches to include charged (rather than just neutral) particles [8, 9, 10]. In the past, sensitive searches for an EDM have been made on neutral particles such as the neutron or neutral atoms. These searches have been limited by the strength of the electric field that can be imposed in the laboratory without breaking down. In the storage ring experiment proposed here, the electric field appears only in the rest frame of the particle traveling around the ring, and represents the central force that holds the charged particle in its orbit. These fields can be much larger than any laboratory field, providing the storage ring method with an advantage in sensitivity.

For the deuteron, high intensity beams of high polarization can be stored with long coherence times and large polarimeter spin sensitivities (for momenta near 1.5 GeV/c) that make possible especially sensitive EDM searches using this nucleus. Utilizing these advantages allows us to consider a statistical sensitivity for the deuteron that is $\sim 10^{-29}$ e·cm, which may be compared to the present limit on the neutron of $|d_n| < 3.0 \times 10^{-26}$ e·cm (90% CL) [11]. A detailed consideration of the design of such a ring has revealed no problems at our proposed level of sensitivity. We are at the stage where further progress depends on detailed simulations followed by a design of the ring components. We are eager to move ahead.

Table 1 shows the main features of the proposed resonance EDM search method for a storage ring.

2 Theoretical Motivation

Modern interest in particle and bound state electric dipole moments began with the pioneering work of Norman Ramsey and his collaborators. Their more than 50 year

Table 1: **Features of the resonance EDM search method**

Velocity modulation	at the $g-2$ frequency
$g-2$ precession	in the ring plane
EDM precession	perpendicular to the ring plane
Polarization monitor	continuous, scattering from thick C target
Signal size	$\sim 1\mu$rad/1000s in dS_y/dt at $d = 10^{-29}$ e·cm
leading to an asymmetry sens.	3×10^{-7} per 1000 s beam store
Similar asymmetry experiments	Parity violation, with $< 10^{-7}$ asymmetry [12, 13]
Systematic problem	**Remedy**
(1) Oscillating B_r	alternating vertical tune bunches
(2) Polarimeter alignment	alternate bunches with reversed EDM signal
(3) High $g-2$ precession harmonics	momentum compaction factor $\alpha_p = (\Delta L/L)/(\Delta_p/p) = 1$

quest to find a non-zero neutron EDM anticipated parity (P) and time-reversal (T or CP) violation, necessary ingredients for the existence of an EDM, and paved the way for the current very restrictive bound

$$|d_n| < 3.0 \times 10^{-26}\,\mathrm{e}\cdot\mathrm{cm} \quad (90\%\,\mathrm{CL}). \tag{1}$$

Over the years, improvements in the bound on d_n have been used to rule out or constrain various models of CP-violation, a testament to the power of null results.

Of course, we now know that P and T violation occurs in the $\mathrm{SU(3)_c \times SU(2)_L \times U(1)_Y}$ Standard Model via weak interactions and 3-generation quark mixing. So it is rather certain that all non-zero spin particles and bound states possess EDMs, unless prevented by an exact symmetry. For example, a Majorana neutrino is self-conjugate under C and therefore cannot have an electric or magnetic dipole moment.

However, CP-violation due to quark mixing is small and only contributes to hadronic EDMs at the 3-loop level (leptonic EDMs at the 4-loop level). Hence the Standard Model predictions for EDMs are currently unobservably small and will remain so for many years. To illustrate the situation, we give in Table 2 current bounds on the neutron, thallium and mercury EDMs (the three best constrained). We note that the bound for d_{Tl} is primarily used to provide a stringent upper limit on the electron EDM, d_e, via $d_{Tl} = \; -585\, d_e$

$$|d_e| < 1.5 \times 10^{-27}\,\mathrm{e}\cdot\mathrm{cm} \quad (90\%\,\mathrm{CL}). \tag{2}$$

CP-violation in the leptonic sector of the Standard Model occurs via neutrino masses and mixing. However, the loop-induced EDMs will be extremely small because of the tiny neutrino masses. Very rough estimates suggest $d_e^{leptonic} \leq 10^{-60}\,\mathrm{e}\cdot\mathrm{cm}$.

The unobservability of the SM EDM predictions provides us with an opportunity to search for new sources of CP-violation by continuing to improve EDM sensitivities via new experiments. The existence of those new sources is very well motivated for several reasons: 1) As pointed out by Sakharov [4], CP-violation is one of the necessary ingredients required to explain the matter-antimatter asymmetry of our universe. However, the Standard Model fails to explain this asymmetry by many orders of magnitude, thus

Table 2: **Current EDM limits in** [e · cm]**, Standard Model (SM) predictions and long-term goals for the neutron, ^{205}Tl and ^{199}Hg. Screening severely limits the sensitivity of ^{199}Hg, see text.**

Particle/Atom	EDM limit (90% CL)	SM prediction	Long-Term Exp Goal
Neutron	3×10^{-26}	10^{-31}	5×10^{-28}
^{205}Tl	9×10^{-25}	10^{-35}	N/A
^{199}Hg	2×10^{-28}	10^{-33}	2×10^{-29}

pointing to a need for new stronger sources of CP-violation. 2) New physics extensions to the Standard Model such as supersymmetry (SUSY) naturally introduce additional CP-violating phases that can contribute to ordinary particle EDMs at the 1-loop level. In fact, the existing bound on d_n already provides a severe constraint on supersymmetric models, requiring them to have very small phases or relatively high mass scales in those loops. An observation of any non-zero EDM in the forthcoming generation of experiments, which are expected to improve by several orders of magnitude, would find a natural explanation in supersymmetry and nicely complement direct collider searches for SUSY particles. The high payoff and strong motivation have made EDM experiments an exciting research frontier strongly endorsed by the atomic, nuclear and high energy physics communities.

In this letter of intent (LOI), we discuss a completely new approach to EDM studies employing a charged particle storage ring. An intense electric field appears in the particle rest frame due to an applied laboratory B-field, which, acting on a putative EDM, affects the observed spin precession. This novel technique promises significant sensitivity improvements for the deuteron, proton, ^{3}He and perhaps other charged ion systems, and is very complementary to the neutron and neutral atom experiments of the type listed in Table 2. So far, the deuteron (a stable spin 1, pn bound state) appears to be the best charged particle candidate capable of reaching 10^{-29} e · cm. That phenomenal capability promises to provide a powerful probe of new physics and new CP-violation, with potential discovery rivaling or exceeding other methods such as those of ultra-cold neutrons or atoms. To demonstrate that potential, we compare d_n and d_D for some well-motivated new sources of CP-violation.

2.1 The QCD CP-violating parameter $\bar{\theta}$

Consider the $\bar{\theta}$ CP-violating parameter of QCD. It can be introduced into the Standard Model via appendages at some high scale which contribute to $\bar{\theta}$ via the quark mass matrix at the loop level. In the case of nucleons, one has the well known relation

$$d_n \approx -d_p \approx 3 \times 10^{-16} \bar{\theta} \ \text{e} \cdot \text{cm}, \tag{3}$$

which implies the severe constraint

$$\bar{\theta} < 1 \times 10^{-10}. \tag{4}$$

In the case of the deuteron

$$d_D \approx d_n + d_p + d_D^{nuclear}. \tag{5}$$

The nucleon contributions tend to cancel, but the nuclear contribution (which can be reliably calculated because of the deuteron's simple nuclear wavefunction [6, 14]) coming from an induced CP-violating pn interaction gives

$$d_D(\bar{\theta}) \approx -10^{-16}\,\bar{\theta}\,\mathrm{e}\cdot\mathrm{cm}. \tag{6}$$

At the level of $d_D \approx 10^{-29}\mathrm{e}\cdot\mathrm{cm}$ sensitivity, one probes $\bar{\theta}$ at 10^{-13}, three orders of magnitude beyond the current bound and about an order of magnitude beyond projected future d_n experimental goals. Since $\bar{\theta}$ contributes to d_n and d_D differently, it is clear that d_n and d_D experiments are highly complementary. Indeed the prediction

$$d_D(\bar{\theta})/d_n(\bar{\theta}) \approx -1/3 \tag{7}$$

provides a beautiful check as to whether $\bar{\theta}$ is the source of the observed EDMs should both d_n and d_D be measured. In fact, it would be important to measure d_D, d_p and $d_{(^3\mathrm{He})}$ all in the same storage ring to see if they satisfy the expected relation (up to isoscalar contributions)

$$d_D(\bar{\theta}) : d_p(\bar{\theta}) : d_{(^3He)}(\bar{\theta}) \approx 1 : 3 : -3. \tag{8}$$

^{3}He should have properties very similar to the neutron, which provides most of the spin, and could be used in this method to probe the neutron EDM.

2.2 Supersymmetry

Supersymmetry (SUSY) and the new particles associated with it (sparticles) are generally considered to be a very possible extension of the Standard Model. Generic predictions of such a scenario include a plethora of new particles which may be discovered at the LHC and new CP-violating phases that can generate EDMs for quarks, leptons and their associated bound states. In fact, existing EDM bounds already severely constrain the parameter spaces of SUSY models. The next generation of EDM experiments has an extremely good chance of yielding positive results if SUSY turns out to be correct.

Below, we use SUSY as a way of comparing d_D with other EDM studies, primarily d_n, which is expected to be pushed to about $5 \times 10^{-28}\,\mathrm{e}\cdot\mathrm{cm}$ in the coming generation of experiments.

Following the work of Lebedev *et al.* [15] and the review article by Pospelov and Ritz [5], we note that SUSY loops give rise to ordinary quark EDMs, d_q, as well as quark-color EDMs, d_q^c. One finds

$$d_n \approx 1.4(d_d - 0.25 d_u) + 0.83e(d_d^c + d_u^c) + 0.27e(d_d^c - d_u^c), \tag{9}$$

where the color EDM contribution has been divided into isoscalar and isovector parts. Currently, the experimental bound on d_n suggests for color EDMs

$$|e(d_d^c + d_u^c)| \leq 4 \times 10^{-26}\,\mathrm{e}\cdot\mathrm{cm} \tag{10}$$

$$|e(d_d^c - d_u^c)| \leq 1 \times 10^{-25}\,\mathrm{e}\cdot\mathrm{cm}. \tag{11}$$

Almost an order of magnitude better bound on the isovector component comes from $^{199}\mathrm{H_g}$

$$|e(d_d^c - d_u^c)| \leq 2 \times 10^{-26}\,\mathrm{e} \cdot \mathrm{cm}. \tag{12}$$

Those constraints are already quite stringent. In the case of d_n, they are expected to be pushed by two orders of magnitude in the long term.

Now consider the SUSY prediction for the deuteron,

$$d_D \approx (d_d + d_u) + 6e(d_d^c - d_u^c) - 0.2e(d_d^c + d_u^c) \tag{13}$$

Comparing d_D with d_n in eqs. (9, 13) illustrates a significant advantage of d_D. It is about 20 times more sensitive to the isovector component $e(d_d^c - d_u^c)$ than d_n because of the large two body, $I = 1$, pion exchange contribution. At a d_D sensitivity of $10^{-27}\,\mathrm{e} \cdot \mathrm{cm}$ (the old proposal goal), the bound on $e(d_d^c - d_u^c)$ in (11) is extended by 2 orders of magnitude and is more than an order of magnitude better than the ultimate goal of d_n experiments. It is much better than $^{199}\mathrm{Hg}$ capabilities and, of course, much cleaner theoretically. When d_D is pushed to $10^{-29}\,\mathrm{e} \cdot \mathrm{cm}$ (our present goal), those constraints are extended by another two orders of magnitude, a remarkable capability. In the case of quark EDMs and the isoscalar combination $e(d_d^c + d_u^c)$, a sensitivity of d_D to $10^{-29}\,\mathrm{e} \cdot \mathrm{cm}$ is still more than an order of magnitude better than the best d_n expectations. It is clear that d_D is not only complementary to other EDM searches, but for some potential sources of EDMs, it is superior.

To put the above d_D sensitivities into perspective, we consider the results of Lebedev *et al.* [15] for some specific SUSY models. At $d_D \approx 10^{-27}\,\mathrm{e} \cdot \mathrm{cm}$, SUSY squark masses well beyond 10 TeV are probed, i.e. beyond LHC capabilities. At $10^{-29}\,\mathrm{e} \cdot \mathrm{cm}$, one explores scales extending beyond 100 TeV, a very impressive sensitivity. Indeed, very roughly speaking, one expects SUSY loop effects to generate EDMs of about

$$d \approx \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2 \times 10^{-22}\,\mathrm{e} \cdot \mathrm{cm} \tag{14}$$

for CP-violating phases of order 1, where M_{SUSY} is the heaviest loop particle. At $d_D \approx 10^{-29}\,\mathrm{e} \cdot \mathrm{cm}$, one is probing up to $M_{\mathrm{SUSY}} \approx 3000$ TeV. Of course, one hopes that the LHC may actually observe squarks in the TeV or lower range. If that is the case, d_D will provide precise EDM measurements that will unveil their CP-violating nature and perhaps help to explain the matter-antimatter asymmetry of our universe.

Other new models of CP-violation from Left-Right symmetric gauge theories, additional Higgs scalars, etc. can also be studied using EDM experiments. In such cases, d_D at $10^{-27}\,\mathrm{e} \cdot \mathrm{cm}$ is competitive with or better than other EDM measurements, while at $10^{-29}\,\mathrm{e} \cdot \mathrm{cm}$ it is our best hope for finding new sources of CP-violation. Couple that sensitivity with the relative theoretical simplicity of the deuteron wavefunction for calculating d_D and the possibility of extending the storage ring approach to p, $^3\mathrm{He}$, heavier ions, etc., and it becomes clear that the deuteron EDM holds great discovery potential and the storage ring method should therefore be vigorously pursued.

3 Ring and Polarimeter for EDM Search

3.1 New ring concept

Since the EDM $\vec{d}$ is directed along the spin $\vec{S}$, as is the particle magnetic moment $\vec{\mu}$ (which is much bigger than $\vec{d}$), the EDM precesses together with $\vec{S}$ in the storage ring magnetic field. In our experiment, by design, the $\vec{S}$ precesses mostly in the ring plane. In addition to this precession, the spin gets the torque $\vec{d}\times\vec{E}$, rotating it in the vertical plane. The rest frame electric field $\vec{E}$ is proportional to $\vec{v}\times\vec{B}$ and points radially inward toward the center of the ring. For commonplace storage rings, this field can exceed the size of a static electric field made in the laboratory by more than an order of magnitude, thus giving the storage ring method a distinct advantage. However, this advantage cannot be used in any commonplace storage ring, since the phase between $\vec{d}$ and $\vec{E}$ in the torque $\vec{d}\times\vec{E}\propto\vec{S}\times\vec{E}$ quickly oscillates in such a ring, so the average (in time) deviation of the spin in the vertical plane due to a non-zero EDM is practically zero.

To avoid such an averaging, an earlier version of the EDM search in a storage ring introduced a lab frame radial electric field into each ring dipole magnet so that the $\vec{\mu}$-precession relative to the orbit in the original magnetic field—the so-called $g-2$ precession—is canceled by its precession in the opposite direction due to the lab frame radial electric field. This effectively stops the $g-2$ precession. As a result, the torque $\vec{d}\times\vec{E}$ is not averaged to zero in time [8, 9], allowing the slow vertical EDM precession to act for the length of time that the beam is stored and become large enough to detect. A proposal for such a ring was considered by the BNL Program Advisory Committee at its fall, 2004 meeting [16]. The concern of the committee was the expense of the ring (large because the limits on laboratory electric fields forced a severe requirement on the size of the ring dipole magnetic field, increasing the ring size) combined with the limit on expected sensitivity of 10^{-27} e·cm that came from a systematic error arising from limitations in our ability to maintain the coplanarity of the electric field around the ring.

At the end of 2004, work began on a new concept [10] permitting both a much smaller ring size and much, much bigger sensitivity. In this concept the particles are allowed to precess in the ring magnetic field but the velocity of the beam is modulated in phase, that is, in resonance with the magnetic moment precession in such a way that the EDM precession no longer cancels. The basic idea of this resonance is rather simple and similar to that of the Rabi resonance. In the rest frame, we have a big vertical magnetic field B_V around which the spin $\vec{S}$ precesses due to the magnetic moment $\vec{\mu}$. Instead of Rabi's horizontal magnetic field B_H oscillating in resonance with the spin ($\vec{S}$) precession, we introduce a horizontal electric field oscillating in resonance with the spin $\vec{S}$. The resonance interaction of this electric field with the electric dipole $\vec{d}$ leads to a spin-flip. Statistically, this spin-flip will be observed as the slow change of the vertical spin component S_y in time.

The rest frame electric field is the radial field $\vec{E}=\gamma\,\vec{v}\times\vec{B}$; its oscillations are initiated by the forced and hence coherent synchrotron oscillations of particle velocities $\vec{v}$. The frequency and phase of these oscillations follow the frequency and phase of the $g-2$ precessions. As a result, the torque $\vec{d}\times\vec{E}\propto\vec{S}\times\vec{E}$ now has the necessary constant-in-time component. A lab frame radial E-field is no longer needed.

The forced coherent synchrotron oscillations of particle velocities, with $\Delta v/v\sim 1\%$, are generated by a combination of the two RF cavities in Fig. 1. This part of our design has been intensively simulated and is very well understood.

The ring associated with this new concept, shown in Fig. 1, is much smaller (5 m by 10 m), and has many fewer magnetic elements, than that in the non-resonance design [16]. The straight section on the right contains the RF cavities that will maintain a bunched beam in the ring and at the same time force a velocity oscillation in phase with the spin precession. In this part of the ring the radial deviations of the beam due to the velocity synchrotron oscillations vanish, so that all particles follow the same course even as the velocity changes, minimizing coupling between the spin and off-axis fields in the focusing quadrupoles Q and RF cavities. In the straight section on the left side, some oscillation of the orbit size in phase with the velocity is required; the ring has been designed so that the orbit length increases in proportion to the beam momentum, i.e. it has a momentum compaction factor $\alpha_p = (\Delta L/L)\,/\,(\Delta p/p) = 1$, eliminating higher harmonics in the $g-2$ precession.

The RF magnetic quadrupole RFQ in Fig. 1 is a part of the two vertical tunes technique, which has been designed to cancel parasitic resonances caused by oscillating skew B_R fields.

3.2 Corrections of systematic errors up to the level $\delta d \sim 10^{-29}\,\mathrm{e}\cdot\mathrm{cm}$.

We expect that most systematic errors will come from some undesired coupling between horizontal and vertical betatron oscillations—(x-y) coupling. Since we modulate coherent oscillations of particle velocities with the $g-2$ frequency, our particles coherently oscillate with that frequency radially. This does not cause systematic errors by itself. However, in the presence of the (x-y) coupling, it will generate coherent vertical beam oscillations with the $g-2$ frequency, thereby producing a very well-known parasitic spin resonance, and hence a false EDM signal.

We will be able to distinguish this false signal from the EDM signal, and hence cancel it, by using the two vertical tunes technique: Half of our beam bunches will be "control" bunches generating a much bigger false EDM signal than the usual "physical" bunches, although all particles in the ring meet the same lattice imperfections and, of course, have the same EDM. Playing with this difference in magnitude of false signals coming from different bunches, we can separate the parasitic part of the spin resonance from its EDM part.

The difference in magnitude results from the difference between the vertical betatron tunes of the different beam bunches. The reason is that the magnitude of coherent vertical oscillations generated by the same lattice imperfections strongly depends on these tunes. Furthermore, the bigger the vertical deviations, the bigger the radial magnetic field B_R gathered by the particles when they pass lenses Q, etc. The accumulated B_R-field is *additional* to all original field perturbations existing independently of the vertical beam oscillations. As a result, the original magnitude of the field perturbations can be highly amplified. And the bigger the resulting perturbations, the bigger the false signal. This conclusion has been confirmed by simulation.

To produce two types of bunches having two different tunes, we will use the RFQ cavity shown in Fig. 1. The shape and fields of this RFQ cavity have been intensively simulated.

We plan to use different types of bunches as control bunches. For example, using bunches with different phases between oscillations of the velocity and precessions of the

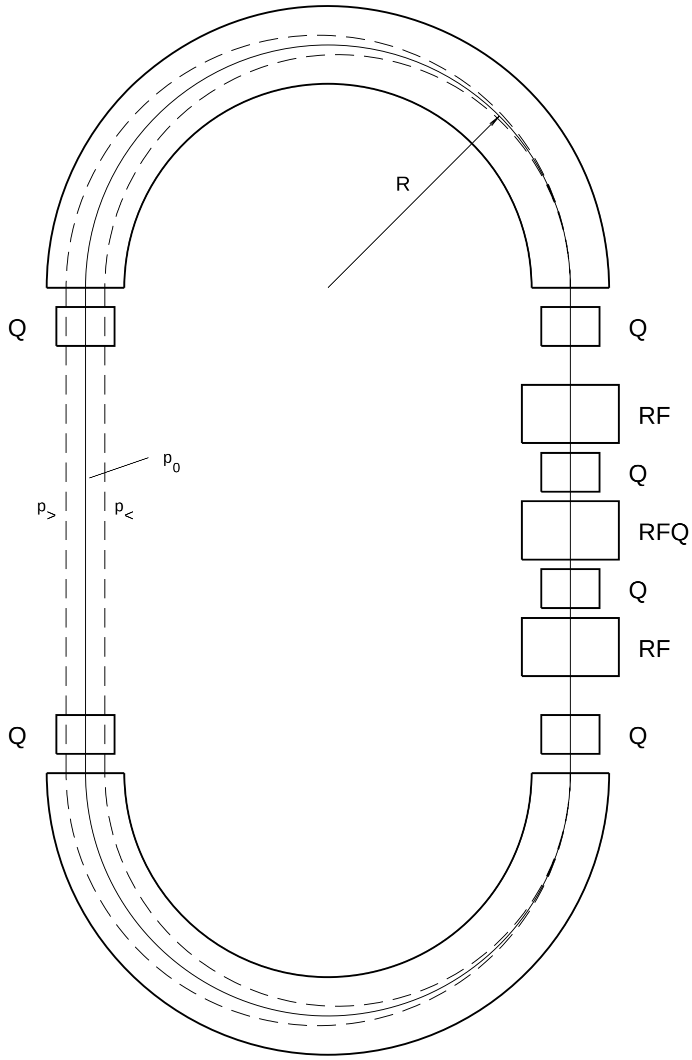

Figure 1: Schematic design of the EDM ring with $B = 2$ T, $R = 2.5$ m, 5-m straight sections, a cyclotron period of 137 ns, a $g - 2$ period of 0.66 μs (the same as the forced synchrotron oscillation period), and some 40 bunches around the ring with alternating bunches on opposite phases of the synchrotron oscillation. Q denotes the magnetic quadrupoles, RF refers to the radio-frequency cavities, and RFQ marks the RF quadrupole. See text for further details.

spin will permit us to distinguish, analyze, and cancel most imperfections not covered by the two vertical tunes technique.

Some systematic errors are canceled or essentially reduced by the special design of the ring as an EDM measuring apparatus. For example, the so-called momentum compaction factor $\alpha_p = (\Delta L/L)\,/\,(\Delta p/p)$ equals 1 in our ring. This eliminates the high $g-2$ modes in the Fourier spectrum of the $g-2$ precession, and hence eliminates all spin resonances connected with such modes. Further, the zero dispersion in the right-hand straight section of Fig. 1, already noted above, eliminates or reduces the influence of imperfections of many ring elements located in that section.

We should emphasize that the expected very high observability of most of the field imperfections in our experiment comes from the combination of gross amplification of the original perturbations in the control bunches, and observation and correction of the amplified parasitic growth of the vertical spin component S_y . This spin growth is *many orders of magnitude* more sensitive to ring imperfections than such beam parameters as beam position displacement and angular deviations. However, we need much more intensive analysis of the false EDM signals, especially simulating the simultaneous operation of all physical elements of the system and the simultaneous action of all relevant effects.

3.3 Measuring the beam polarization as a function of time

There are several requirements on the system that measures the orientation of the beam polarization. We need first of all to see the rise in the vertical component that is associated with the EDM, which requires continual monitoring of the polarization while the beam is stored. At the same time, the rapid horizontal oscillation of the transverse polarization component in the ring plane reflects the magnetic moment precession. This oscillation must be compared with the phase of the velocity oscillations and locked to either 0° or 180° phase difference to ensure that the EDM has a chance to appear. Both of these measurements need to be correlated with the particular beam bunch in the ring, so the time resolution needs to be much less than the typical bunch separation, which may be as small as 3–4 ns. Such timing is possible with plastic scintillation detectors. Lastly, sensitivity depends on good statistical precision, which in turn depends on both high efficiency and high spin sensitivity in the detector system.

The best efficiency and spin sensitivity are found in elastic scattering of the deuteron beam from a thick carbon target. The spin sensitivity is a result of the action of the spin-orbit force between the deuteron and the carbon nucleus. High energy resolution is not needed to separate out the elastic scattering channel, as the deuterons and protons from low-lying excited states in carbon have roughly the same spin dependence as the elastic scattering and can beneficially be included in the total data sample. The detector system needs only to remove the bulk of the protons from deuteron breakup, a process that has almost no spin dependence.

One way that this polarimeter might work would be to use a thin gas jet (or residual gas in the ring) to Coulomb scatter a small fraction of the beam on each turn around the ring. The scattered deuterons would strike a thick (15 cm at 1.5 GeV/c) carbon target in the shape of an annulus around the circulating beam. The opening in this annulus would be the defining aperture for the ring; any beam lost would be lost onto the annulus. This scheme is really slow extraction through Coulomb scattering. Downstream of the target, there would be a segmented array of scintillation detectors that is also arranged as an annulus about the beam. At 1.5 GeV/c, the array would span scattering angles between 4° and 9°. With these choices for the target and acceptance, the efficiency of the detector system is 4.2% of all deuterons that strike the carbon target. The average analyzing power is $\langle iT_{11} \rangle = 0.36$, based on the data of Bonin [17]. In order to reduce the number of non-elastic particles hitting the scintillator, an absorber is usually used in front of the scintillator.

The detector is logically segmented into quadrants along the directions left, right, down, and up. The left-right asymmetry carries the EDM signal. The down-up asymmetry carries information on the fast $g-2$ precession.

With the ring shown in Fig. 1 operating at a field of 2 T and with a velocity modulation amplitude of ±1%, the rate of vertical polarization accumulation is $\sim$ 1 nrad/s for an EDM of 10^{-29} e·cm. If we start with a polarized beam ($p_V = 0.95$) of 10^{12} particles in the ring and there is a polarization coherence time in the ring of 1000 s, then it is possible to reduce the statistical error in the change in the vertical polarization due to an EDM to $\sim 10^{-29}$ e·cm within a few years of running time [10].

Systematic errors in polarimeters are usually suppressed by flipping or reversing the polarization and repeating the measurement. In our ring design this can be done on alternate fills of the ring if the polarization is flipped at the ion source. We can also arrange for half of the bunches in the ring to receive an opposite push from the RF system, and thus have velocity oscillations that are 180° out of phase from the original scheme [18]. In this case, the EDM would also accumulate during the store, but in the opposite direction. The EDM signal would then be half of the difference in the polarization of these two sets of bunches at the end of the store. With the RFQ system described earlier, we would also have bunches with different vertical tunes to study. The combination of these data with opposite spin effects can eliminate errors from differential detector inefficiencies and luminosity changes with spin state. To ensure that this works at the level needed, errors that would change the average scattering angle into the detector between positive and negative polarization states must be held to less than 0.01°, which is achievable with presently available techniques.

3.4 Progress on experimental concepts

The collaboration has made great progress in defining the main elements of the ring lattice, the main systematic errors and the remedies associated with them, and finally the techniques needed to observe a potential signal. Toward these goals, a lattice has been specified for the ring as shown in Fig. 1. Its RF system has the dual function of bunching the beam, without which the polarization would very quickly disappear. In addition, this system must also create forced oscillations in the beam velocity. To accomplish this with gradients up to 15 MV/turn, there must be superconducting cavities operating at different frequencies. The beam in the ring will be divided into some 40 bunches (with about 3 ns bunch separation). The vertical tunes of half of the bunches will be near the spin tune and be used to determine the contribution of oscillating radial magnetic fields to the measurement. This requires an RF quadrupole (RFQ), which can be built using a corresponding mode in a superconducting cavity. The remaining bunches will be divided into two groups with positive and negative EDM accumulation directions. The false EDM signals in all the control bunches will be checked and corrected, thus reducing the background in the bunches that carry the actual EDM signal.

The straight section on the right hand side of Fig. 1 has no dispersion, so that errors from misalignment of the RF cavities and focusing elements are minimized there. We are particularly sensitive to magnetic fields that appear when the beam is off-center in the RF cavities and out of proper phase with the driving field. In order to further desensitize the apparatus to anomalous EDM-like signals, the ring will be designed with a momentum compaction factor $\alpha_p = (\Delta L/L)/(\Delta p/p) = 1$, where L is the orbit length and p is the particle momentum. This will remove multiple harmonics in the precession of the polarization in the ring dipole fields, thus reducing the chance for systematic contributions to a false EDM signal. The bending magnets at the two ends of the ring, see Fig. 1, will have a field shaped so that $n = -R(\partial B/\partial R)/B = 1$, where R is the orbit radius, so that small rotations of the magnetic alignment will not perturb the field integral.

In the energy range from 76 to 133 MeV (spanning the energy range of an earlier design), measurements of the cross section for elastic, as well as inelastic and breakup channels for deuterons scattering from carbon were made at the KVI cyclotron in Groningen. These data have been used in a Monte Carlo simulation of the polarimeter acceptance that confirms the need to use an absorber ahead of the scintillator to remove breakup protons.

4 Development of an Experimental Design

We have already made significant progress in the experimental concept. The next step is to check the concept in order to verify that the plans are feasible (and to correct the concept as needed), and to specify the properties of the ring components so that engineering estimates of fabrication costs can be made. Central to this effort will be more sophisticated simulations of the ring in which all features and perturbations are included. Expertise on low-β superconducting cavities like those we need is locally (BNL) available [19]. In the EDM storage ring, such cavities provide the bunching fields, the velocity oscillations of the beam, and the change of the focusing quadrupole fields that differentiate between signal and control beam bunches.

Once a realistic lattice for the ring is available that includes finite component size, fringe fields, and RF cavities, it will be possible to proceed with the next phase of development. A major issue is the placement of sextupole magnets to lengthen the polarization coherence time in the ring. The goal for this is $\tau = 1000$ s [16, 20]. It will also be important to have as much rate as possible. This will lead us to consider the effects of large beam currents that can introduce various collective effects such as emittance growth from space charge, tune shifts in the polarization resonance, interaction with image charges in the ring hardware, and intra-beam scattering.

A plan needs to be devised for the production of the beam for the EDM ring. Siting at BNL will mean the development of a polarized deuteron beam. Most likely, accumulation and pre-acceleration will involve the Booster. After extraction, the polarization must be precessed from its usual vertical orientation into the horizontal plane before being injected into the storage ring. Next we require a system that must rapidly turn on to bunch the beam and begin the process of forced oscillations [18]. The components and injection scheme need to be specified in more detail.

Polarimeter development depends on obtaining better measurements of deuteron-carbon elastic scattering in the energy range from 200 to 525 MeV, so that more detailed simulations are possible. This also includes simulation of running conditions to optimize statistical precision in the extraction of any possible EDM signal.

The goal of these efforts is to have the major concepts of the EDM ring verified, along with the plan for the suppression of systematic effects. Then we will prepare a cost estimate and write a proposal for submission to the BNL Program Advisory Committee in 2007.

Support from Brookhaven National Laboratory during this next phase of our search for an EDM is crucial. The major concepts needed to reach our sensitivity goal are in place, but need to be verified and demonstrated with more complete simulations. Thus, in order to proceed to the proposal stage for this new and highly promising method, we are asking BNL for:

- allocation of resources from the laboratory for help from resident experts in the area of ring design and spin tracking to address the crucial ring issues. This means approximately one month full-time-equivalent from each appropriate BNL expert to work out in detail the solution to the requirement for the spin coherence time, the design of the injection and RF-capture scheme, and especially the spin tracking needed for detailed systematic studies.
- support for visitors and other advisors. The visitors should come for stays of a few weeks to deal with the issues that are their specialty.
- engineering support to develop a detailed design leading to a cost estimate.

5 Summary

This letter describes a new way to search for an EDM of charged, polarized particles in a storage ring using the enhanced electric field available in the particle rest frame. The EDM signal accumulates in the presence of fast rotations of the magnetic moment by having the beam undergo velocity oscillations in phase with the spin precession. The resulting EDM signal is the growth during the beam storage time in the vertical component of the polarization (perpendicular to the ring plane). This polarization will be observed continuously by slowly extracting the beam onto a polarimeter consisting of a thick carbon target and an annular array of scintillation detectors. There the EDM signal will create a left-right asymmetry whose initial rate of growth will be proportional to any possible EDM signal. False signals from oscillating radial magnetic fields in the ring will be mitigated using control bunches with vertical betatron oscillation frequencies *near*, but not exactly equal to, the $g-2$ frequency, whose signal will be scaled and subtracted from signal bunches to yield the EDM signal. Various features of the ring design and bunches with opposite EDM signals will be used to reduce the impact of other systematic effects. There is currently great interest in EDM experiments because of their potential to find new physics complementary to and even reaching beyond that which can be found at future accelerators (LHC and beyond). The new approach described here would be the most sensitive experiment for the measurement of several possible sources of EDMs in nucleons or nuclei for the foreseeable future, if systematic uncertainties can be controlled to the level of the expected statistical uncertainty of 10^{-29} e $\cdot$ cm. A significant amount of preliminary study shows no unmanageable sources of systematic errors. We are asking Brookhaven National Laboratory to support the continued development of this ring design through detailed simulations, so that it can be developed into a proposal in 2007.

6 Acknowledgements

We wish to thank S. Aronson, P. Bond, S. Dawson, H. Gordon, D. Lissauer, D. Lowenstein, P. Pile, T. Roser, and N. Samios for their advice and support during the LOI stage of the project. We are also indebted to Sidney Orlov for improving the style and readability of the manuscript.

7 Appendix I: EDM Efforts Reported at Lepton Moments Symposium

A White Paper summarizing all EDM efforts is being prepared and will be finished before we submit a proposal. Here, we give a brief summary of the experimental talks on EDMs from the recent Third International Symposium on Lepton Moments. All the presentations are now available on the Symposium web site http://g2pc1.bu.edu/lept06/.

Table 3: **Talks on EDMs of Molecules.**

Ed Hinds - Imperial College	Measurement of the electron EDM using cold YbF molecules
David DeMille - Yale	The PbO experiments at Yale
Eric Cornell - JILA/Colorado	Searching for an electron EDM in trapped molecular ions
Neil Shafer-Ray - Oklahoma	Possible measurement of the electron EDM with g=0 paramagnetic molecules

There was great excitement during the last decade when it was realized that one could obtain extremely high electric fields on an electron in a properly prepared molecular state. This was a very clever idea, and a lot of effort has gone into EDM searches using molecules. There were four talks on this subject at the Symposium (see Table 3). The first two talks in Table 3 are from more mature efforts; the last two talks are newer efforts. After a decade of heroic efforts, it is clear that the main problem for these types of experiments is obtaining a sufficiently high intensity beam with long coherence time and a sufficiently pure molecular state, as the molecular energy levels are vastly closer to one another than the atomic energy levels.

Table 4: **Talks on EDMs of Stable Atoms.**

Norval Fortson - Wash.	Search for an EDM of the 199Hg atom.
David Weiss - Penn State	Update on Measuring the electron EDM using Cs and Rb in optical lattices
Mike Romalis - Princeton	EDM experiments with Xenon

Table 4 shows the stable atom EDM talks. Although the effective electric field on the atom is orders of magnitude less than for the experiments given in Table 3, they make up for that deficit with statistical power. The first entry is a talk about a mature effort. They do not expect very large improvements over their already published values. The second entry represents a new effort. They are very excited about using this technique for a neutral atom quantum computer, studying 1-D Bose-Einstein gases, and the EDM of the electron. The third entry is an exciting idea to measure the EDM of liquid xenon. The spin of the xenon atom is just the spin of the nucleus (spin 1/2). Due to the Schiff theorem, the electric field at the location of the nucleus is tiny compared to the applied electric field, because the atomic electrons effectively shield the applied electric field. However, they make up for the tremendous loss of sensitivity from the very small electric field on the nucleus with the tremendous statistical power of a very large number of atoms in a liquid. They hope for a sensitivity of $10^{-30}\,\mathrm{e}\cdot\mathrm{cm}$ for the Xe atom, with an eventual sensitivity of $10^{-33}\,\mathrm{e}\cdot\mathrm{cm}$, which is in the same range of sensitivity as the neutron SNS experiment when the Schiff moment is properly taken into account.

Table 5: **EDMs of Radioactive Atoms Talks.**

Roy Holt - Argonne	Search for an EDM of ^{225}Ra
Klaus Jungmann - KVI	TRIμP: A new facility for fundamental symmetry research

Table 5 shows the radioactive atom EDM talks at the Symposium. The challenge they are now working on is to obtain sufficiently intense radioactive beams. Several heavy alkaline earth isotopes, such as ^{225}Ra, are known to have large octupole and quadrupole deformations which lead to an enhancement of the Schiff moment by a factor of up to 1000. In preparation for an experiment with radioactive atoms, the Argonne group has optically trapped ^{225}Ra atoms for the first time. The ^{225}Ra isotope is relatively long-lived ($\approx$ 14.9 days), and in principle can be produced without an accelerator. However, an exotic beam facility, such as the TRIμP facility reported on by Jungmann, would yield at least two orders of magnitude in useful atoms for the radium experiment, and would be required for EDM studies for other rare isotopes.

Table 6: **Neutron EDM talks.**

James Karamath - Sussex	The ILL Cryogenic neutron EDM experiment
Klaus Kirch - PSI	Search for an EDM of the neutron at PSI
Jen Chieh Peng - Illinois	The new search for a neutron EDM at SNS

Table 6 shows the neutron EDM talks. The largest breakthrough is the higher intensity one can reach by producing ultra-cold neutrons (UCNs) in liquid He. The revamped experiment at ILL is ready to start taking data using this effect. The SNS effort is the most ambitious in terms of sensitivity goals. Recently they have found that for presently unknown reasons, the break-down field in liquid Helium at 1.9 K is only $\approx$30 kV/cm, whereas it is 90 kV/cm at 5 K. A spark in the liquid Helium would deposit enough heat to cause a pressure wave which would probably destroy their extremely sensitive detectors.

Table 7: **Storage ring EDM talks.**

Gerco Onderwater - KVI	Search for EDMs in storage rings
Yuri Orlov - Cornell	Systematic errors

Table 7 gives the storage ring EDM talks, whose contents are incorporated into this LOI.

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