An Expression of Interest for a Proton Electric Dipole Moment Experiment at Fermilab with 10^{-29} *e*•cm sensitivity

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The storage ring EDM collaboration is very interested in exploring the feasibility of launching an electric dipole moment experiment at FNAL using the old antiproton accumulator ring tunnel. The goal of this effort will be to achieve a sensitivity of 10^{-29} *e*•cm for the proton, and if stochastic cooling on the stored protons can be achieved within appropriate parameters, we may be able to improve the sensitivity by another order of magnitude. The same ring can be used to launch a deuteron EDM experiment with ~10^{-29} *e*•cm sensitivity after a major upgrade of the ring.

The collaboration has already submitted a proposal (November 2011) to the Office of Nuclear Physics of DOE for a proton EDM experiment at BNL with a sensitivity of 10^{-29} *e*•cm. This proposal requires the construction of a new ring at BNL with a circumference of about 300 m. As far as we know, DOE NP has not yet sent the proposal for a review. The situation is expected to remain the same until there is a clear path to funding it. The experiment cost estimate sent to DOE by the collider accelerator department (C-AD) of BNL was a little less than $100M in FY2017 dollars.

The collaboration has decided to explore the possibility of doing this experiment at FNAL, where an existing tunnel and beam-lines including some ring hardware can be used and thus potentially provide substantial savings to the experimental cost. The tunnel plus the beam-lines at BNL were estimated to account for about 40% of the total cost of the experiment. The total realized savings at FNAL may be less, however, since the circumference of the accumulator tunnel is about 500 m, almost a factor of two larger than the EDM ring assumed at BNL. In addition, there may be a need for some civil construction to extend and connect the existing beam-line tunnel from the booster to the accumulator ring as well as a polarized proton source and beam-line polarimeters.

Last but not least, for the collaboration to proceed to the stage of making a formal proposal to FNAL, we would need to either find the necessary resources or come to an

understanding with the funding agencies that are currently supporting the Storage Ring EDM Collaborators to agree to continue that support in the FNAL context.

Below (adapted from the abstract and introduction of the DOE proposal for BNL) is a description of the goals of the EDM effort, the basic lattice parameters, the main systematic errors, and a rough idea of the observables.

Proton EDM Experiment

The storage ring EDM collaboration proposes a new method to search for and measure the electric dipole moment of the proton by using polarized protons at the so-called "magic" momentum of 0.7 GeV/c in an all-electric storage ring housed in the accumulator ring tunnel, with a minimum bending radius of ~40 m and an E-field of ~10 MV/m between plates separated by 3 cm. The sensitivity level (of 10^{-29} e·cm) will be one or two orders of magnitude greater than that of hadronic EDM experiments being planned elsewhere. The strength of the storage ring EDM method comes from the fact that we can store a large number of highly polarized particles for a long time, achieve a large horizontal spin coherence time (SCT), and probe the transverse spin components as a function of time with a high sensitivity polarimeter.

At their magic momentum of 0.7 GeV/c, the proton spin and momentum vectors precess at the same rate in any transverse electric field. When the spin is kept along the momentum direction, the radial electric field acts on the EDM vector and precesses the proton spin vertically for the duration of the storage time, building up its vertical component. The storage time is limited to 10^3 s by the estimated SCT of the beam within the admittance of the ring. Stochastic cooling might be used to extend the SCT and experimental sensitivity by another order of magnitude. Having considered various methods of "freezing" the spin along the momentum direction by applying a combination of magnetic and electric fields, the collaboration believes that the proton EDM method at the magic momentum using only electric fields is the simplest to implement.

For contact interactions, the mass scale sensitivity is at the 3000 TeV range, and for SUSY-like new physics 300 TeV. If there is new physics at the LHC scale, the experiment will be able to probe CP-violating phases down to 0.1 μrad, making it the most sensitive probe for CP-violation beyond the standard model. Finding a non-zero EDM value will point to a new, strong CP-violating source, which is needed to solve the mystery of the baryon-antibaryon asymmetry of our universe.

The method is patterned after the celebrated muon g-2 experiment, on which about half the collaboration has previously worked. The collaboration has had two successful technical reviews by experts in the field: one in December 2009 and one in March 2011. Running with polarized deuteron beams at KVI (Groningen/The

Netherlands) and beams stored in COSY (Jülich/Germany), we have shown the polarimeter systematic errors to be well below our statistical sensitivity level [1].

The collaboration's understanding of and confidence in the proposed experimental method are the result of many years of development, during which we have studied polarimeter systematic errors, efficiency and analyzing power; developed tracking programs that can accurately simulate the spin and beam dynamics of stored particles in an all-electric ring; developed *E*-field measurements at BNL, using technology developed as part of the International Linear Collider (ILC) and energy recovery linacs (ERL) R&D efforts; developed a plan to build a beam position monitor system capable of probing the main systematic error source in the experiment (an average radial *B*-field around the ring); and using precision spin tracking and analytical estimations of the geometrical phase effects we are establishing the position and alignment specifications of the electric field plates.

The collaboration believes we will be in a position to design in detail a proton EDM experiment with 10^{-29} e·cm sensitivity, after two years of R&D and a total estimated cost of about $2M.

A note on CP-violation. In quantum mechanics, a non-degenerate system with spin is defined by the spin vector. If a particle has an electric dipole moment (EDM), the vector of the EDM is aligned with the spin vector of the particle. The EDM then violates both time (T) and parity (P) symmetries and conserves charge (C) symmetry. Assuming conservation of the combined CPT symmetry, T-violation also means CP-violation. The weak interaction CP-violation contributes a very small EDM, one that is orders of magnitude below current experimental limits. However, most models beyond the standard model (SM) predict EDM values near the current experimental limits. Hence, the study of EDMs is a search for CP-violation beyond the SM.

We plan to search for the EDM of the proton in a storage ring with a statistical sensitivity of 1.3×10^{-29} e·cm per year. This level of sensitivity will be at least an order of magnitude greater than that of the currently planned neutron EDM experiments at SNS (Oak Ridge, Tennessee), PSI (Villigen, Switzerland), and ILL (Grenoble, France). After a major upgrade, the ring could accommodate a deuteron EDM experiment with similar sensitivity.

Technical requirements. We plan to measure the proton EDM by observing the spin precession in an external electric field. This approach has limited previous experiments to neutral systems (neutrons, atoms) to avoid accelerating the trapped particles. However, the storage ring can use this electric field to confine the particles to a closed path, thus opening up the domain of EDM experiments to *charged*

particles, ions, and other species. The radial E-field force is balanced by the particle centrifugal force without affecting the EDM effect.

The stored beam must be spin polarized. Given that the best sensitivity may involve rotations as small as micro-radians, it is prudent to begin with the spins aligned parallel to the beam momentum; then the radial electric field acting on an EDM will precess these spins into the vertical direction (out of the ring plane), where the growing polarization component is stable and measurable. This imposes two requirements: the storage ring lattice must be capable of (1) defeating the tendency of the spins to precess in the ring plane so that they remain longitudinal, and (2) maintaining the spin coherence for times long enough to accumulate a measurable EDM precession. For the proton or any charged particle with a positive anomalous magnetic moment, the first requirement is met by operating the storage ring at the so-called "magic" momentum (p = 0.7 GeV/c for the proton), where the spin precession induced in the proton frame by a rest-frame magnetic field proportional to $\mathbf{v} \times \boldsymbol{E}$ is just enough to match the rotation of the velocity vector ($\mathbf{v}$). The second requirement makes it necessary to limit those properties of a stored beam, including momentum spread and emittance, that alter the $\mathbf{v} \times \boldsymbol{E}$ precession rate enough to cause the spin directions in the beam to disperse. These considerations point to a ring design with weak vertical focusing and a tune of order 0.1. Our current spin tracking simulations indicate that the SCT is long enough for 10^3s storage time without needing compensating electric (or magnetic) sextupoles. A development project is already underway at the COSY ring at the Forschungszentrum-Jülich to benchmark the analytical estimations as well as the results using simulation tracking software. Even though the COSY ring is magnetic, the tests will show the level of trust one can put into the analytical estimations as well as the results from the simulation software.

For the ring to be of a practical size, large electric fields are needed, up to 10 MV/m. Current technologies in use at laboratories such as Fermilab, and improved at Jefferson Lab and Cornell, have achieved larger electric fields with a combination of careful surface preparation, including electro-polishing and high pressure water rinsing. External magnetic fields that would perturb the spin precession must be measured to an accuracy of 1 nG at 1 Hz in the radial direction averaged around the ring. This requires a multilayer shield (both active and passive) as well as a way to monitor the success of the field suppression. Consideration of this problem has led to the idea that a crucial way to control systematic errors would be doing the experiment with two beams traveling around the storage ring along the same path but in opposite directions. These two beams, which are dispersed enough to minimize any significant effects from inter-beam scattering, in fact represent the time reverse of each other. An EDM, being T-violating, responds oppositely to a large class of systematic errors that are T-conserving. The radial magnetic field is the main source of systematic errors, since it produces a vertical spin rotation signal just like an EDM. In addition, the radial magnetic field causes the two counter-rotating beams to separate vertically inside the ring, a fact that can be observed

using suitable beam position monitoring equipment down to a level small enough to meet the sensitivity goal of this experiment (see Section 9 of the proposal [2]).

Lastly, the experiment must provide a technique for measuring the several micro-radians change in the average spin direction between the beginning and the end of the beam store. At the magic momentum of the stored protons, we happen to be almost on top of the peak in spin sensitivity for protons elastically scattered from carbon nuclei. The storage ring plan includes a mechanism for slowly extracting particles from the beam to a point where they enter a carbon target block several centimeters thick. This thickness is enough to raise to nearly 1% the efficiency of spin-dependent scattering into a detector array that surrounds the beam, with counting changes due to a flip of the spin direction that exceed 60%. Experiments at COSY have already demonstrated [1] that systematic errors from counting rate and geometric changes can be managed to well below one part per million, by using counting rates available from beam bunches with opposite spin orientations and a suitable calibration.

The Fermi National Laboratory already has in place most of the accelerator assets required to accommodate the proton EDM experiment; the only new investment needed is a polarized proton source. The protons in the Booster ring need to be accelerated to 233 MeV kinetic energy, with their spins kept in the vertical direction. The experiment needs simultaneous clockwise and anti-clockwise storage in the EDM ring. The beam needs to be extracted from the Booster into the accumulator ring at FNAL, as is shown in Figure 1 below.

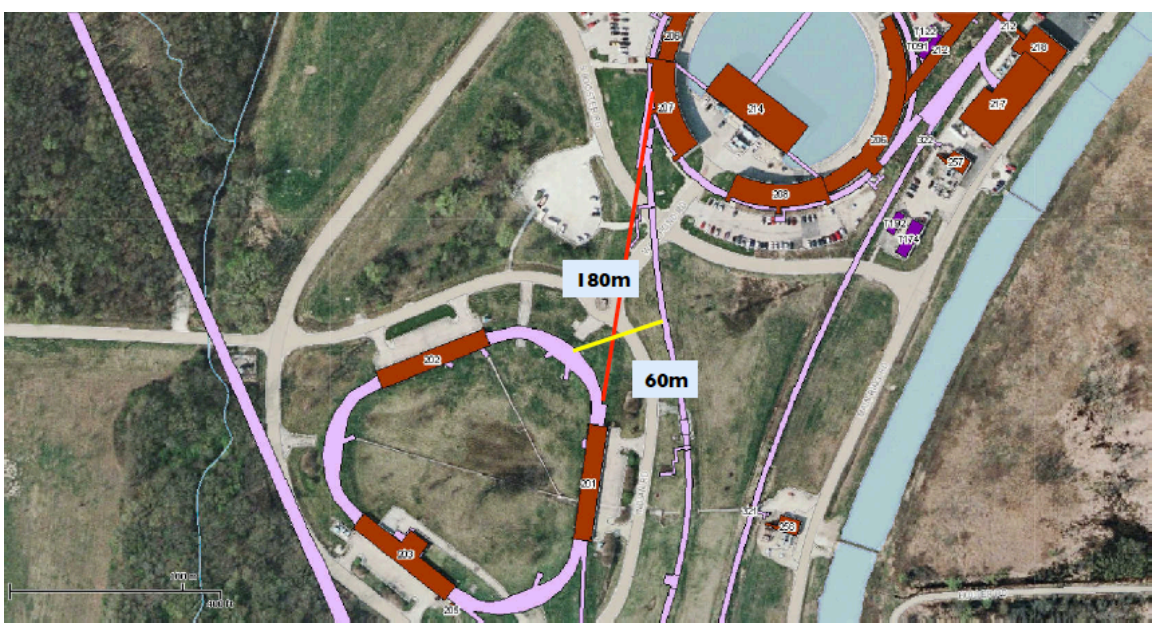

Figure 1. M. Popovic suggested two alternative ways to transfer the polarized protons from the Booster to the accumulator ring. One method includes using a new beam-line of ~180m (the straight line shown here in red). The second one includes building a new beam-line inside the existing tunnel and building an additional new tunnel and beam-line of about 60m to connect to the EDM ring (approximate location shown in yellow).

Proposed experimental method. Below is a simplified description of the experimental method, including how to distinguish between a genuine EDM signal and one potentially originating from the main sources of systematic error.

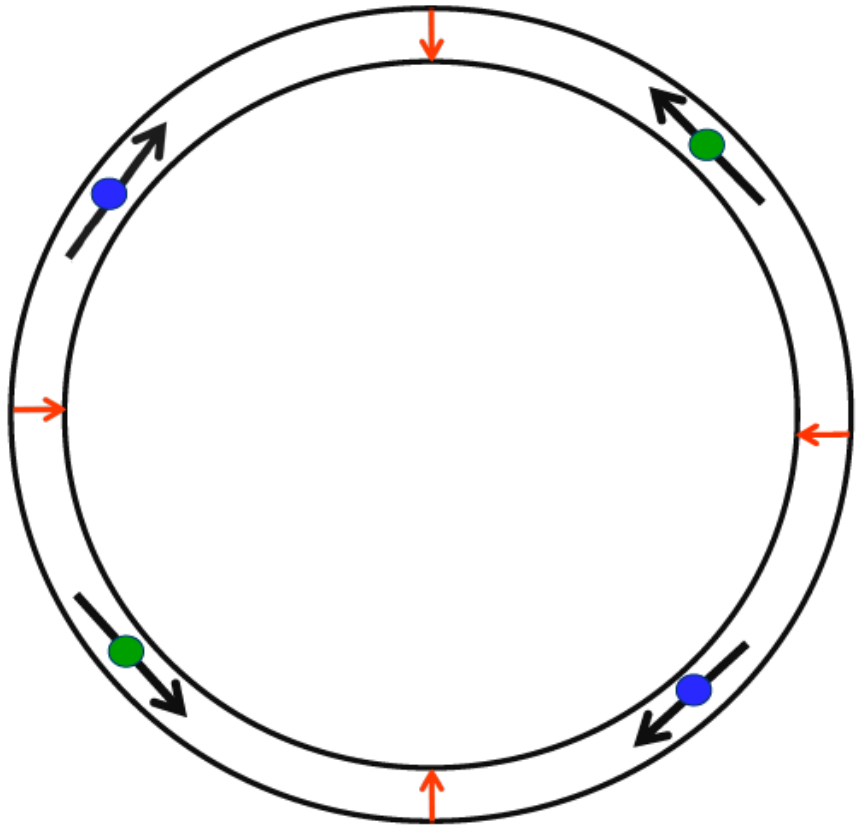

Figure 2. The proposed electric storage ring (top view). The ring is shown here as continuous (without straight sections) for illustrative purposes only. The radial electric field vectors between the plates (the two large concentric circles) are shown in red. Two proton bunches are shown in blue and two in green. The blue bunches are rotating clockwise (CW) while the green bunches are rotating counter-clockwise (CCW), with their momentum vectors shown in black. At injection, all the protons in all the bunches have the same spin direction along the vertical axis.

At the start of the storage cycle, two bunches will be injected into the ring with their spins pointing in the vertical direction; one is injected CW and the other CCW. The bunches will be captured by either barrier buckets or low harmonic RF-system. Then, the power in the RF-system will be turned off. The two beams will then de-bunch due to momentum dispersion. Then, by turning on adiabatically a higher harmonic RF-system, e.g., $h \sim 10^1$-10^2 we will re-capture them, shown in Figure 2 above as only four bunches. An RF-solenoid running at the revolution frequency (~0.7 MHz) will be used to precess the proton spins from the vertical into the horizontal plane. Moving off the proton magic momentum, their spins will be allowed to precess for ~50 s. Using the (internal) polarimeter, we will then determine: a) the beam polarization, b) the average vertical spin direction, and c) the spin precession plane at early times. Finally, the spins will be

aligned with the momentum vectors (as shown in Figure 3, below) to prepare the beams for the EDM measurement.

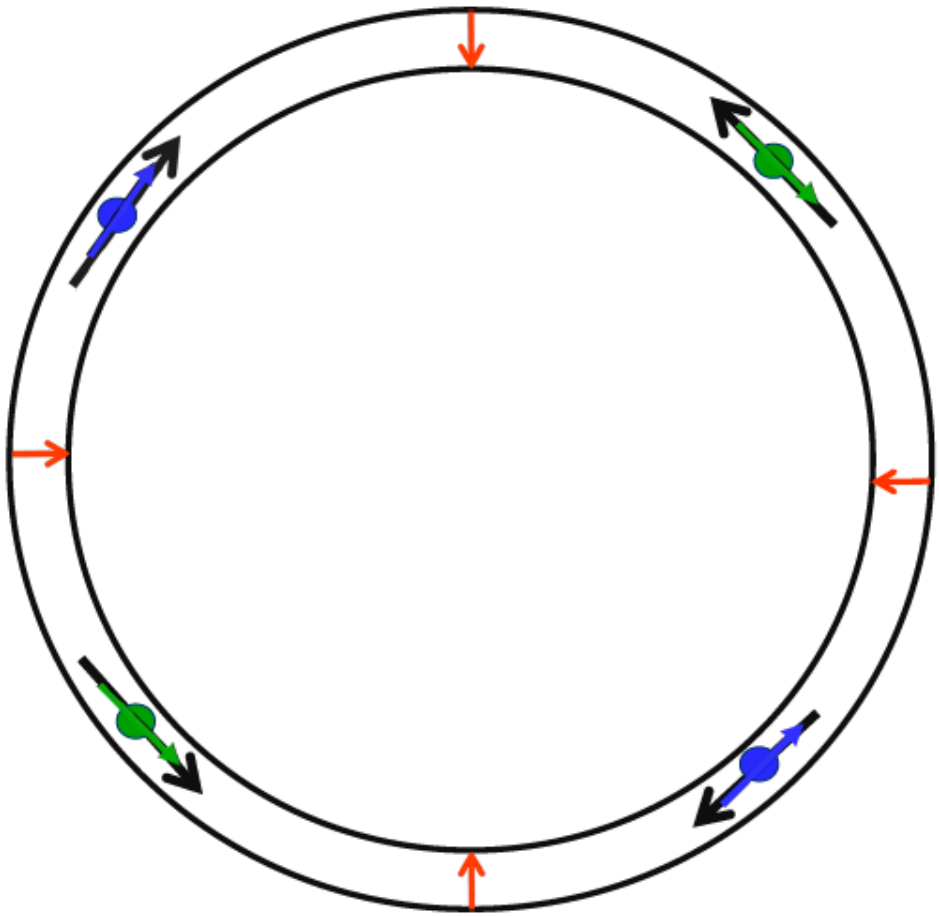

Figure 3. Direction (indicated by blue and green) of the average spin vectors in the corresponding bunches.

The average spin vectors will be kept in the horizontal plane within ±30° of the forward or backward direction by using real-time information from the polarimeter and the beam position monitors (BPMs). The radial *E*-field, acting on a proton EDM, will precess the spins out of the horizontal plane for the duration of the storage time (~10^3 s). At the end of the storage time, we will again allow the spin precession in the horizontal plane for ~50 s. Using the polarimeter, we will again determine: a) the beam polarization, b) the vertical spin direction, and c) the spin precession plane at late times. It is possible to repeat the spin precession measurements at intermediate times, as needed, without significant loss of statistical sensitivity.

Below, Figures 4 and 5 show the early and late difference in the vertical spin direction plus the vertical beam separation between the counter-rotating beams. Figure 4 shows the effect of a genuine EDM signal, Figure 5 the effect of a non-zero radial magnetic field around the ring.

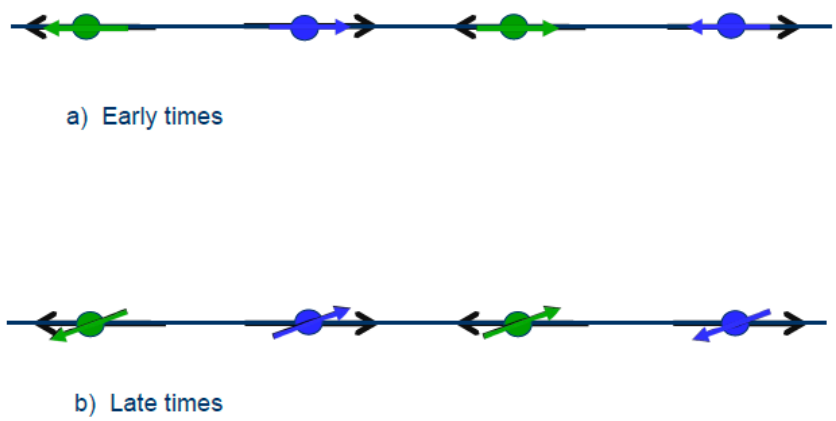

Figure 4. A side view of the spin direction of the various bunches at early (a) and late (b) times, assuming a proton EDM is present. The storage ring has been unfolded into an imaginary straight line. The blue bunches travel to the right while the green bunches travel to the left. The EDM signal is the difference of the average vertical spin component between early and late times. The difference between the spin precession rates of the blue bunches with opposite spin directions is needed to reduce the polarimeter systematic errors to well below our anticipated sensitivity level (see Section 10 of the proposal [2]). Comparisons with the corresponding difference in the green bunches eliminates systematic errors, e.g., due to vertical image charges (see Section 11 of the proposal [2], Table 11.1 of systematic errors).

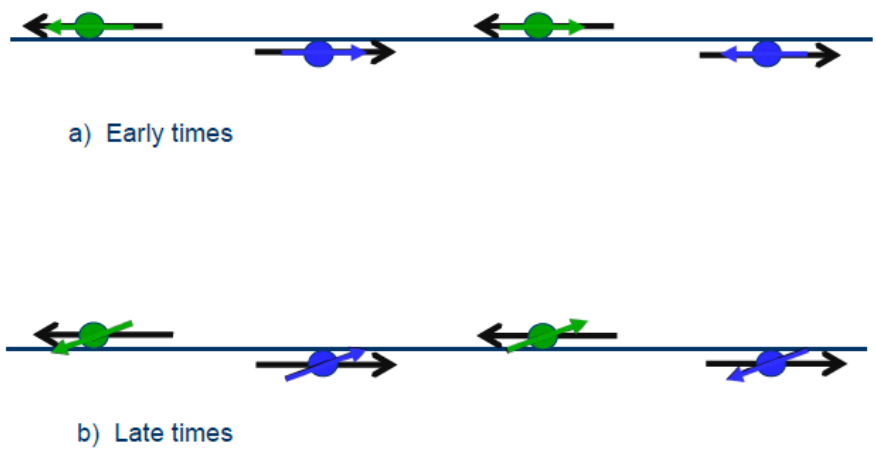

Figure 5. A side view of the spin direction and vertical positions of the various bunches at early (a) and late (b) times, assuming the presence of a constant radial B-field--the main systematic error source in the experiment. Obviously, the vertical spin precession signal is very similar to that from a proton EDM. The difference is that the counter-rotating bunches move vertically in opposite directions, depending on the strength of the vertical focusing. The vertical tune will be low (~0.1) to enhance the beam separation, and will be modulated with an amplitude of ~10% of itself, i.e., ~0.01 at a frequency of our choice in the range of 10 Hz – 10 KHz. The counter-rotating beams will oscillate vertically with the same frequency and amplitude of 1pm, for a 10^{-29} e·cm sensitivity level (See Section 9 of the proposal [2]).

Technical reviews. The collaboration has had two very successful technical reviews on the storage ring EDM method, one in December 2009 http://www.bnl.gov/edm/review/ and one in March 2011. The December 2009 review focused on the magic proton momentum, with CW and CCW rotating beams and momentum bending provided by electric field elements. At that time, the collaboration was working on two focusing options, one magnetic and the other electric. The review committee strongly recommended using an all-electric ring (including electric focusing), simplifying the experiment in several ways. Assuming a complete absence of magnetic fields, the CW and CCW beams will have exactly the same beta-functions everywhere in the ring and the beams will go through exactly the same positions. More precisely, their closed orbits will be the same.

In addition, effects like geometrical phases, which are very important for the neutron EDM experiments, are also important to guard against in this experiment. These can arise from a particular combination of horizontal and vertical spin precessions that occurs due to lattice construction errors. We plan to eliminate magnetic fields to well below the requirements imposed by the geometrical phase effect, by using the BPM information in both the horizontal and vertical directions. The electric field by itself cannot cause a first-order problem because the magic-momentum proton spins do not precess in any electric field. However, geometric phase effects could result from electric field plate misalignment and placement errors. We are currently studying the construction requirements to produce a geometrical phase effect below our sensitivity level. In addition, we are studying the possibility of using more than one azimuthal location around the ring as a polarimeter section, making visible the two lowest-order geometrical effects, which are most likely to dominate.

To increase the position splitting of the counter-rotating beams due to spurious magnetic fields, weak vertical and horizontal focusing will be used. The small vertical tune will have the additional benefit of substantially increasing the horizontal spin coherence time (SCT), thus further simplifying the experiment.

In the second review (March 2011), the all-electric ring method--including the sensitive BPM magnetometer system--was presented. The committee was enthusiastic about the method and encouraged the collaboration to proceed with the proposal.

With this Expression of Interest we request encouragement and support to proceed with a detailed proposal for a storage ring proton EDM experiment at FNAL with a sensitivity of $10^{-29}e\cdot$cm. Some R&D funding is needed to establish the viability of the beam position monitors with the required sensitivity in an accelerator environment. It is also needed to finalize the *E*-field strength that we can safely apply between large area stainless steel plates, which will determine the storage ring radius. Finally, it will allow us to continue the spin coherence time studies at COSY that are needed to benchmark our tracking simulations software, as well as develop a polarimeter prototype to be commissioned at COSY. The above R&D support is essential for a future smooth transition from CD0 into CD1-3. Its total cost is estimated to be $2M, with a duration of approximately 2 years of a technically-driven schedule, as outlined in Section 12 of the proposal [2]. Finally, in

Table 1 we show the beam parameters needed for the storage ring proton EDM experiment at FNAL.

Table 1. The proton beam parameters for the proton EDM experiment at FNAL.

Counter-rotating beams	0.7 GeV/c	>80% vertical polarization	$\sim 4 \times 10^{10}$ total protons/store
<200 m beam base length	Repetition period: 20 minutes	Beam energy: ~1J	Average beam power: ~1mW
Beam emittance: 95%, normalized	Horizontal: 2 mm-mrad	Vertical: 6mm-mrad	$(dp/p)_{rms} \sim 2 \times 10^{-4}$

References

1. N. Brantjes *et al.,* NIMA **664**, 49, (2012)
2. V. Anastassopoulos *et al.,* Proposal to the DOE NP submitted in November 2011, "A Proposal to Measure the Proton Electric Dipole Moment with 10^{-29} e·cm Sensitivity" by the Storage Ring EDM Collaboration.