pEDM Review Report
(Dec. 30, 2009)

Executive Summary

A first technical review was held on Dec. 7-8, 2009 for the conceptual design and R&D plan of a proposed experiment to measure the intrinsic electric dipole moment (EDM) of the proton with a sensitivity approaching ~10^{-29} e·cm. The experiment would utilize counter-rotating longitudinally polarized proton beams simultaneously stored in a dedicated ring with purely electrostatic bending. The electric field strength and ring bending radius would be chosen to select a "magic" energy which would cancel horizontal beam spin precession with respect to the momentum vector associated with the proton's anomalous magnetic moment. The signature of a non-zero EDM would be a slow buildup in the vertical polarization component of the stored beams, monitored with internal polarimeters sensitive to polarization asymmetries of order 10^{-6}. This novel technique is the only one proposed to date that promises to provide charged-particle EDM measurements of comparable or better sensitivity than planned neutron EDM measurements. Results for both neutron and proton can significantly constrain the isospin-dependence, hence the physical origin, of any revealed CP-violating interactions. If the storage ring technique were demonstrated to be feasible at interesting sensitivity levels, analogous experiments could be performed for other charged particles, such as muons, deuterons and ^{3}He ions.

In addition to the conceptual design and scientific motivation for the proton EDM experiment, the Review Committee reviewed the status and plans for several areas of technical development that push the state of the art, most notably: precision and stability of stored beam position monitoring; spin coherence times of stored polarized beams; spin tracking software and simulations; electric field strength; and precision proton beam polarimetry.

The Committee judges the proton EDM experiment to be intriguing, important and very challenging, and the overall design to be informed by many clever ideas, especially the use of the magic momentum and simultaneously counter-rotating beams. A proton EDM measurement to the goal sensitivity of 10^{-29} e·cm would represent a profound contribution to the search for non-Standard Model CP violation in nature. Furthermore, the unique systematics of a storage ring EDM search allow it to provide crucial independent confirmation of an EDM signal from another, more conventional, EDM experiment. While the Committee expresses a number of significant concerns about technical performance requirements needed for the experiment and about some of the proposed solutions, it has not identified anything considered to be a technical showstopper at this point. The Committee is thus enthusiastic about seeing this project move forward, and encourages the collaboration to continue to identify key systematic issues and crucial R&D. The Committee commends especially the excellent progress made to date in demonstrating polarimeter stability and precision in measurements made at COSY.

The Committee makes a number of specific recommendations herein for how the Collaboration should proceed to an R&D stage and toward a DOE critical decision regarding mission need for this experiment. It also suggests a number of technical issues that it feels need greater conceptual attention and/or crisper presentation. Overall, it finds that the project is at a suitable stage to launch serious discussions with funding agencies and with potential collaborating institutions, in order to strengthen the efforts moving forward.

1. Introduction

On December 7-8, 2009 the concepts and plans for a project and experiment to search for a permanent electric dipole moment (EDM) of the proton were reviewed at Brookhaven National Laboratory. The review panel was convened and chaired by the BNL Associate Laboratory Director for Nuclear and Particle Physics, with membership given in Appendix A of this report. The charge for the review is given in Appendix B and the agenda of presentations is given in Appendix C.

The planning for this experiment has evolved over a period of years, and through several distinct stages. It began when a subset of the collaboration that performed AGS experiment 821, to measure the anomalous magnetic moment (g-2) of the muon to unprecedented precision, considered the possibility of greatly improving existing limits on the muon's EDM in a dedicated storage ring experiment. Intrinsic EDM's of fundamental particles are of great interest because their existence would violate both parity and time-reversal invariance, and they thus provide a potentially fruitful way to look for CP violation beyond the Standard Model, as is needed to account for the observed baryon asymmetry of the universe. Active plans are under development to advance the experimental state of the art by two to three orders of magnitude in sensitivity to neutron and electron EDM's. However, it is not easy to come up with an experimental technique to permit EDM measurements of comparable sensitivity to charged particles not bound in atoms. The storage ring technique, in principle, provides a path toward such measurements.

The present collaboration coalesced at first around the idea of measuring (or placing limits on) the EDM of the deuteron in a dedicated storage ring, at a sensitivity ($\sim 10^{-29}$ e·cm) an order of magnitude better than the goals of the new generation of neutron EDM experiments being planned. This idea was presented to the RHIC/AGS Program Advisory Committee at several stages, first as a Letter of Intent, and finally as an experiment proposal in May 2008. The PAC found the science goals compelling, but was dissatisfied with the absence of a clear, staged realization plan for accomplishing the necessary R&D and for performing measurements at successive stages of sensitivity, perhaps initially at existing storage rings. They urged the BNL ALD to assemble a dedicated review panel to assess technical feasibility of such a staged approach, when it was developed.

In the process of developing a staged approach with clear R&D milestones, the collaboration has convinced itself that there are multiple potential advantages to aiming first for a storage ring measurement of the proton EDM. A proton result or limit would be somewhat more easily interpretable than one at comparable sensitivity for the deuteron, with questions of nuclear structure removed from any comparison with a neutron EDM result. Furthermore, the positive anomalous magnetic moment of the proton allows design of a somewhat simpler storage ring, with bending provided by purely electrostatic fields, where operation at a well-defined "magic" momentum (0.7 GeV/c) automatically cancels any horizontal precession of the stored proton's spin with respect to its momentum vector, as would otherwise be caused by the anomalous magnetic moment in the motional $(\vec{v}\times\vec{E})$ magnetic field seen in the proton's rest frame. The experimental signature of a non-zero EDM for a proton beam prepared with initial longitudinal polarization would then be a slow vertical precession of the beam polarization vector arising from the electric torque on the EDM in the strong radial confining electric fields.

This defines the basic concept of the experiment presented to the review panel. The conceptual design also includes a number of features aimed at reducing systematic error concerns to the desired ($\sim 10^{-29}$ e·cm) sensitivity level. Chief among these is the proposed use of simultaneously stored (and, at various points, colliding) beams following essentially identical orbits, and hence exposed to the same external fields, in opposite directions around the storage ring. Each beam would furthermore have distinct rf buckets prepared, in equal numbers, with positive and with negative helicity protons. Ring designs with either electrostatic or magnetic focusing elements were considered, and shown to have different advantages and systematic error concerns.

Detailed evaluation of how to achieve the desired sensitivity level makes it clear that the experiment places demands at or beyond the current state-of-the-art in at least the following technologies: (1) achievement of stable electric field strengths in excess of 15 MV/m across 2 cm gaps and large transverse areas; (2) design of a ring capable of storing beams with spin coherence time (hence, useful measurement time intervals) of 1000 seconds or more; (3) monitoring of relative positions of the counter-rotating beams with a precision ~ 1 pm, averaged over the full running length of the experiment; (4) beam polarimeters offering stability approaching 1 ppm over time periods of 1000 seconds; (5) spin tracking simulations capable of unveiling instrumental effects that would mock up the EDM signal at the $\sim 10^{-29}$ e·cm level.

The first-day presentations by the collaboration provided the review panel with detailed discussions of the scientific motivation and overall conceptual design of the experiment, and with the current status and R&D needs in planning for each of the above state-of-the-art technical development areas. On the morning of the second day of the review, the collaboration provided at least initial answers to detailed questions posed by the review panel at the end of the first day, after there had already been extensive discussion of many details of ring and experiment design.

The following section of this report provides the committee's overall comments and recommendations concerning the project and its initial R&D component. Subsequent sections then provide more detailed responses to various aspects of the project.

2. Overview of Committee Assessment

Comments:

- The Committee wants to thank the Collaboration members for their clear presentations and answers to questions, which helped us to appreciate often subtle aspects of the experiment and equipment design.
- The Committee judges the proton EDM experiment to be intriguing, important and very challenging, and the overall design to be informed by many clever ideas, especially the use of the magic momentum and simultaneously counter-rotating beams. A proton EDM measurement to the goal sensitivity of 10^{-29} e·cm would represent a profound contribution to the search for non-Standard Model CP violation in nature. The storage ring technique also opens up the possibility of important EDM measurements for other charged particles.
- The Committee recognizes that a great deal of thought and development has already gone into preparations for the experiment, and commends especially the excellent progress made via in-beam tests of polarimetry at COSY.
- The Committee has a number of significant concerns about technical performance requirements needed for the experiment and about some proposed solutions, as detailed in following sections, but has not identified anything we consider to be a showstopper at this point.
- The Committee would like to have seen a crisper identification of R&D priorities going forward with assessment of areas of greatest risk. The Committee judges the most urgent R&D needs to be those associated with (1) design of relative beam position monitoring with the required precision, stability and redundancy to ensure that the very demanding performance requirement can be met; and (2) development, benchmarking by experiment, and utilization of state-of-the-art beam dynamics and spin tracking simulations, informed by analytical calculations, to assess spin coherence time and simulate systematic errors that can mock up the proposed EDM signal.
- The R&D plans for further development of the necessary polarimetry and tests of the ability to achieve the desired radial electric field in the storage ring are well thought through for the current stage of development, and should proceed in a timely manner. But the Committee judges these items to be of lower technical risk than the most urgent ones identified above.
- The Collaboration has considered many sources of systematic error at a fairly deep level, but it is critical for the presentation of these to include an overall table laying out each error source for both electric and magnetic focusing options, the associated beam and detector performance requirements, cancellation strategies from the counter-rotating and opposite helicity beam bunches, and auxiliary

measurements planned to assess sensitivity to the error in experiments performed either before or during a pEDM run.

- Based on the information available at this time, the Committee judges the sensitivity goal to be worthy of pursuit, but expects that the timeline to achieve sensitivity approaching that goal will be substantially longer than the Collaboration presently admits. A well thought-out program of measurements at existing rings (e.g., COSY and RHIC), testing particular critical aspects (e.g., spin coherence time and resonant BPM stability) of the eventual experiment, to the best sensitivity achievable with the existing rings, can certainly help to keep the timeline manageable.
- In order to assess resource needs realistically, and to establish productive cooperative agreements among institutions (e.g., BNL and COSY), it is important for the Collaboration, in parallel with addressing the critical R&D needs mentioned above, to formulate a more realistic measurement plan including necessary auxiliary measurements, and to produce a more detailed ring and injection scheme design and cost estimate.
- The Collaboration needs to be strengthened significantly to carry out the necessary R&D and experiment design tasks in a timely and effective way. Addition of expertise on critical technical issues such as BPM development and spin tracking, of project management expertise, and of greater integrated time and energy commitment from collaborators, is essential.
- Even with a compelling physics goal, a strengthened collaboration, and more crisply defined R&D, design and project plans, the likely cost of the new ring is sufficiently high that it will be a great challenge to obtain sufficient funding from DOE alone.
- The Committee estimates that it will take the Collaboration at least a year to develop the proposal and cost range to a level suitable for a DOE CD-0 review.

Recommendations:

- Prepare a risk-based R&D plan for presentation to DOE to attract pre-conceptual R&D funds. This should include an assessment (low, medium, high) of the technical, cost and schedule risk associated with each item for which R&D funding will be requested, together with risk mitigation strategies reflected in a detailed timeline with milestones for R&D programs. It should be made clear what the R&D funds will be used for, in detail.
- Prepare an overall systematic error table, laying out for each identified source of bias and uncertainty: the associated beam and detector performance requirements, cancellation strategies from the counter-rotating and opposite helicity beam bunches, and auxiliary measurements planned to assess sensitivity to the error in experiments performed either before or during a pEDM run.
- Prepare a reasonably detailed measurement plan, laying out the auxiliary measurements needed to cancel and assess sensitivity to systematic errors from various sources. Auxiliary measurements that would be needed during each long storage ring run for statistics should be clearly identified.

- Flesh out measurement plans for a COSY experiment to benchmark simulations of spin coherence time and for possible RHIC tests of BPM performance.
- Start immediately to attract additional collaborators who bring expertise on the most urgent R&D tasks, particularly, spin tracking simulations and BPM development.
- Proceed with the R&D plans laid out for further development of polarimetry and of tests of electric field strength achievable in the storage ring environment.
- In preparation for a CD-0 review, the Collaboration will have to produce: a convincing demonstration on paper (supplemented by critical R&D results) that a storage ring experiment can in fact achieve a sensitivity substantially better than presently planned neutron EDM measurements; a credible cost range estimate for an experiment that can achieve that sensitivity; a collaboration that can be judged adequate to meet all the technical and engineering challenges that will be faced in reaching that sensitivity; simulations demonstrating that the needed spin coherence time can be achieved with a realistic ring lattice.

3. Scientific Motivation and Overall Design

Scientific Motivation:

- Particle EDMs provide one of the most sensitive means to search for new physics in the CP-violating sector of particle interactions.

- Hadronic EDM searches at the level of $10^{-28} – 10^{-29}$ e-cm can probe potential new physics at very high mass scales (> 1000 TeV).

- Proton and neutron EDM searches can provide complementary information in understanding the origin of the new CP-violating physics. Depending on the origin of the effect (e.g., θ_{QCD} vs SUSY), hadronic EDMs could be predominantly isoscalar or isovector. Thus, a proton vs. neutron comparison is essential.

- In principle, the opportunity for a proton EDM measurement (in addition to the previously discussed deuteron measurement) enhances the possibility of convincing the Nuclear Physics community and funding agencies to support a storage ring EDM project.

- Particle EDM searches maintain high discovery potential independent of the results from the LHC. In fact, the motivation for EDM searches is significantly increased should new physics be discovered at the TeV mass scale.

Overall Experiment Design:

- The storage ring approach for the proton EDM is a new and exciting opportunity. It is a unique environment that suggests it possesses much different systematic effects when compared to conventional EDM searches. This also suggests that potential new challenges will need to be addressed. The collaboration has already begun to attack these challenges with analytical and simulation tools.

- In the proposed concept a counter-propagating beam of protons is simultaneously stored in the ring with the beams at a "magic" energy, which is intended to preserve the helicity of the beams. In addition, both helicity states are present in separated bunches within the ring. This combination is a powerful control on potential systematic errors that could produce a false EDM signal.

- The proposed experiment will clearly push the state-of-the-art along several avenues. This aspect is certainly not unique to the proposed experiment, as many of the other new EDM searches share this feature. In particular, the requirements on the magnitude of the electric field, the sensitivity and accuracy of beam position monitors and the spin relaxation rate in a storage ring are all exciting challenges.

Sensitivity Goals:

- The ultimate sensitivity goal for the experiment is ~ 3×10^{-29} e-cm. This exceeds the reach of most other ongoing hadronic EDM searches. For example, this enhanced sensitivity increases the physics reach of the pEDM experiment beyond that of ongoing neutron EDM experiments by a factor of three in mass sensitivity to new heavy particles.

- The different sensitivities to the underlying physics of CP-violation in the various hadronic EDM searches (specifically proton, neutron and diamagnetic atoms) allows this experiment to remain well-motivated even after the next round of EDM searches begin to report results.

Worldwide Competition:

- This experimental concept is unique when compared to existing EDM searches. It relies on the extensive experience developed in building high precision particle storage rings. In particular, the collaboration's previous experience with the g-2 experiment at BNL allows them to put this extensive expertise into the design of a pEDM storage ring.

- The unique systematics of a storage ring EDM search allow it to provide crucial independent confirmation of an EDM signal from another, more conventional, EDM experiment.

Additional Comments:

Clearly, the scientific motivation for this experiment is significant and the projected sensitivity is very exciting. The review committee is enthusiastic about seeing this project move forward and encourages the collaboration to continue to identify key systematic issues and crucial R&D.

This experiment proposes a very ambitious plan to measure the proton EDM. As this latest design appears to have been discussed for ~ 6 months, more work on assessing systematic errors is certainly needed. The collaboration appears to agree with this assessment. The review committee has certainly not had the time to consider or identify the full spectrum of possible systematic uncertainties. But based on the written proposal, other documents presented to the committee and the presentations, a number of key items need to be carefully studied:

1. The experiment requires knowledge of the relative positions of the two counter-rotating beams at the level of 10^{-12} m if magnetic focusing is used and 10^{-13} m if purely electrostatic focusing is implemented. This is clearly a beyond state-of-the-art requirement. The collaboration believes they can achieve this by statistical averaging of a large number of measurements using the best beam position monitors in existence. Of course, this requires that systematic effects do not spoil this statistical averaging. Presently the collaboration is working to enhance their expertise on BPMs by consulting with the experts and hopefully adding additional collaborators. This should be encouraged. Also it is likely that, in the future, an R&D study would be required to demonstrate that this level of sensitivity is feasible.
2. In order to minimize the cost for the project it is essential that the highest available electric fields be used to confine the particles in the ring. The collaboration is working on developing prototype field plates that can demonstrate their required field strength. This is certainly the correct approach. The requirement of low sparking rate will likely be challenging to achieve.
3. The proton spin coherence time is required to be very long (on the order of 1000 s). While this has certainly been achieved in atomic physics experiments and is the goal of neutron EDM measurements, it has not been demonstrated in a storage ring. R&D studies are underway and these should be continued.

4. Field Quality in the Storage Ring

Findings:

- The proposed proton EDM experiment relies on electrostatic bending fields in storing two counter-rotating polarized beams.

- The storage ring is proposed to consist of two arcs, each with 32 modules, and two straight sections, instrumented with polarimeters, injection kickers, beam position monitors, and other instrumentation. Auxiliary (electric or magnetic) fields will be used for focusing and to achieve actual storage of the beams. An RF cavity and sextupole fields will be used to maintain spin coherence over the beam fill.

- A proton spin coherence time at the level of 1000 s needs to be achieved to be able to make the measurement at the proposed sensitivity.

- The proposed sensitivity of the measurement relies crucially on both beams sampling equal fields on average over the measurement period.

- The proposed measurement sensitivity is well beyond what can be achieved with field uniformity alone and, to achieve cancellation of systematic differences in sampled field, the experiment will use counter-rotating beams that have to be stored at equal positions. The level of accuracy to which this needs to be achieved is 0.1-1 pm on average over the measurement period, depending if electrostatic or magnetic focusing is used.

- The beam positions will be measured throughout the ring with an array of (state-of-the-art) beam position monitors that will measure the (difference of) beam positions upstream and downstream of each beam element. The 0.1-1 pm position requirement relies on statistical averaging of the measurements with the beam position monitors, and on control or cancellation of systematic effects in these measurements (to be demonstrated). Mapping of the beam response to changes in each of the beam elements is part of the measurement plan.

- The electrostatic bending field will be achieved with parallel electrodes that will be separated by 2 cm and held at voltages of +/- 170kV, in each of the 2x32 modules.

- The modules are conceptually similar, but not identical, to the separator modules at the Tevatron, which use electrodes that are 5 cm apart and are operated at comparable voltages. The pEDM modules are thus expected to benefit significantly from Tevatron experience with electrode leads, feedthroughs, etc. The pEDM electrodes will, unlike the Tevatron separators, be (water-) treated to remove impurities that lead to discharges. They will also be curved.

- R&D is required to understand if the higher field strength can be achieved with a sufficiently low number of discharges to run the experiment. The minimum goal is to achieve a field strength of 15 MV/m. The higher the achieved field strength, the smaller are the experiment size, sensitivity, and cost.

- The proposed R&D aims to extend earlier research of the discharge mechanisms to the proposed configuration (in particular, gap distances) and to (water-) treated electrodes, and on a timescale of May 2012 to construct and commission a first full scale module with curved electrodes.

Comments:

- The field strength and hence electrode R&D is critical to the experiment. The committee considers the presented R&D plan reasonable.

- Preliminary analytic/empirical estimates have been made for many of the systematic uncertainties that arise from static effects, such as misalignments, impurities, stray fields, the effects of gravity, etc. The committee has identified no show-stoppers in these estimates.

- The committee finds that the estimates of time-varying effects (e.g., from RF fields) on the measurement are considerably less advanced, although no show-stoppers were identified during the days of the review.

- The systematic error estimates lack confirmation to date by spin-tracking simulations of the full experiment.

Recommendation:

- The committee recommends that the collaboration pursue full spin-tracking simulations of the entire experiment in a systematic way and with high priority. Full simulations should make it possible also to assess effects that could not be evaluated at the review. A specific example of the latter is the possibly uneven sampling (across the beam phase space) of the beam polarization with the polarimeter(s). The argument that spin precession effects in horizontal magnetic field components sampled in quadrupoles must average to zero if the beam is to be maintained stably in the stored orbit could potentially be compromised if the polarimeter preferentially samples beam particles most likely to leave the ring acceptance. In addition, full simulations should allow evaluation (and optimization) of the proposed configuration of beam position monitors.

5. Storage Ring Design Requirements

Beam Parameters and Collective Effects

From the AGS Booster 2×10^{11} polarized protons per bunch are available with an emittance of about 6 mm-mrad and rms dp/p = 5×10^{-4}. Scraping this beam to the required horizontal emittance (2 mm-mrad) and dp/p (2×10^{-4}) will reduce the intensity by a factor of about 8, giving a bunch intensity of 2.5×10^{10}. A flat beam is probably not stable under collisions and therefore the beam should also be scraped in the vertical plane, reducing the intensity further. The final bunch intensity will then just barely reach the required intensity of 1×10^{10}.

- *A higher initial bunch intensity may be required, especially since there will be longitudinal emittance growth during the rebunching from 1 to 50 bunches.*

Intrabeam scattering (IBS) simulations show that for these beam parameters the intensity loss from IBS is negligible compared to the loss from the polarization measurement during the 1000-second store.

- *Since the statistical significance of the EDM measurement is largest when the vertical polarization has built up, one could consider doing an initial polarization measurement and then delaying the second polarization measurement to the end of the spin coherence time.*

The Laslett tune shift and beam-beam parameter have a similar magnitude of about 0.01. This is tolerable for a 1000 second store time. However, this is only the case if the beam positions and sizes are matched at the collision points.

- *Beam positions and sizes are naturally matched for electric focusing elements, which makes this the preferred focusing system in this regard.*

Beam Position Monitors

The resolution requirement for the BPM system for measuring the CW and CCW beam separation is ± 10 nm for a one second measurement. This performance is within the capabilities of existing systems.

- *For 64 BPMs and 10^7 seconds of cumulative measurement time, the statistical error then becomes ± 1 pm, as required with magnetic focusing. Should the systematic errors and drifts in BPM performance be at the same level? This would be very difficult to achieve.*

A resonant BPM located at the interaction point of the CW and CCW beams can be made very sensitive to the separation of the two beams, but also to the product of the absolute beam offset and the difference of the resonant frequency component of the two beams.

- *This second term has to be determined independently and continuously to the same accuracy as the first term.*

The collaboration proposed to use a separate monopole cavity to determine the difference of the resonant frequency components and to determine the absolute beam offset with only a single beam in the ring. Such a measurement would not be continuous.

- *The collaboration needs to develop a viable scheme to measure the CW and CCW beam separation with the required accuracy and stability. Ideally this should include a second method to independently verify the performance of the main system.*

- *The committee supports the plan to test the performance of a BPM module at an interaction point in RHIC with CW and CCW proton beams.*

Field Requirements and Associated R&D

The parameters for the large electrostatic bends are 340kV and a 2 cm gap, giving an electric field of 17 MV/m. These parameters are similar to the pbar-p separators at the Tevatron, except that the separator gap is 2.5 times larger and therefore the electric field utilized at the Tevatron is only 7.6 MV/m. Tests at Cornell with electrodes that were cleaned in the same way as SRF cavities have produced 28 MV/m with a gap of 0.5 cm. The pEDM parameters are in between these two values.

- *The committee supports the R&D plan that includes an initial test with 15 cm diameter discs to show that 17 MV/m and a 2 cm gap can be reached and a full length prototype of an electrostatic deflector. It should be considered to build a prototype that has properly curved electrodes.*

The goal for the spark rate was given as 1 spark per month and module. With 64 modules this amounts to 2 sparks per day.

- *A spark rate of two per day is too high to maintain appropriate stability and efficiency in the measurement periods for the experiment. A more appropriate goal would be one spark per week.*

6. Spin Dynamics

Comments:

- Two critical advances in the design of the accelerator for the experiment – use of an electrostatic storage ring and a system of two counter-rotating beams controlled by an RF field – provide reason for optimism concerning the technical feasibility of the experiment. In particular, they suggest a large reduction in the requirements for field accuracy, in comparison with a ring with magnetic dipoles.

- A precision analysis of the concept is in progress, but is still far from complete. Based on presented details, it is not possible yet to make an informed judgment about the feasibility of the concept. It will be necessary to show a complete list of deviation factors and precision constraints, and (conceptually) to validate the related compensation measures and their required accuracy, at the next review.

- The presented concept merits support with budget and manpower investments adequate to accomplish all the required (and extensive) conceptual studies and simulations of the proposed facility, related beam and spin dynamics, and high precision tools.

- A pure electric ring (with electric quadrupoles and sextupoles) seems preferable since it is free of issues of compensation for the effects of these components on spin (unlikely to be the case with magnetic components). The external magnetic perturbations would then be only from the Earth's field and the radial component of the RF magnetic field associated with cavity misalignments. Nevertheless, a comprehensive and careful analysis of magnetic quadrupole and sextupole compensations should also be performed.

- The designers have considered sextupole compensation for the second-order (quadratic) term in energy deviation when tuning to the magic value, while the beam revolution is controlled by a bunching RF field. They should also consider, however, constant energy spreads associated with energy-transverse emittance correlations (quadratic in particle angles) caused by the RF field. These effects were not mentioned in the presentations or provided documentation.

- The Collaboration should also consider space charge impacts on the orbital and spin motion, which can occur via two different mechanisms: spin precession due to magnetic moment interaction with the magnetic fields of (both) beams; quadratic energy spread across the beam's area, due to the intrabeam Coulomb interaction. The first effect might be insignificant due to averaging over particle betatron oscillations. The second one seems to impact the magic energy condition; it is direct (kinetic energy correlated with Courant-Snyder invariants) and easy to estimate. Its compensation (if needed) may be problematic because of non-linear behavior of the transverse Coulomb field. But this effect also might be found insignificant.

7. Polarimetry

Findings:

- Beam polarimetry is achieved by extraction of part of the beam onto fixed carbon targets and measurement of azimuthal asymmetries in the resultant (elastic plus inelastic) scattering. The extraction will be achieved with "wigglers" and the carbon targets are (expected to be) the limiting apertures in the ring.
- Carbon targets placed symmetrically fore and aft of the polarimeter tracking detectors will permit simultaneous polarization measurements for the counter-rotating beams.
- Previously measured differential cross sections and polarization asymmetries for p-C elastic and inelastic scattering in the vicinity of the "magic" energy for the pEDM ring permit design of a polarimeter that combines high (~1%) efficiency and analyzing power (~0.6).
- The goal set for the polarimeter is to have a sensitivity of 10^{-6} to vertical polarization. The polarimeter is to track continuously the magnitude of the polarization over the coherent time of the stored proton beam.
- The polarimeter scheme was tested with deuterons in the COSY ring at Julich where a stored beam of 250 MeV polarized deuterons was available. A carbon target of 1.5 cm in thickness was moved near the beam position while an upstream set of electric field plates were used to dither a fraction of the beam into the carbon. The existing EDDA detectors were used to detect the left-right asymmetry of the scattered deuterons.
- The results of the COSY test suggest that a sensitivity ~10^{-6} should be acheivable, with good control of systematics and corrections. A more complete demonstration of the required polarimeter sensitivity requires constructing a dedicated polarimeter with high-rate and high-resolution tracking capability.
- The Collaboration proposes further R&D at COSY aimed at improving the polarimeter. A thicker carbon target will be used, thereby increasing the efficiency to 1%. An improved set of detectors will be constructed that are based on resistive plate or micro-megas technology. This will permit the polarimeter to operate at high rates from 5 to 20^{o} in scattering angle where the figure of merit is optimum. A three year program is envisioned where in year one, the polarimeter is designed and partially constructed; year two, the polarimeter is installed at COSY; and in the final year, the polarimeter is commissioned and calibrated.

Comments:

- The collaboration should be commended for their excellent work on developing the internal target carbon polarimeter at COSY.
- Although the work was performed for a deuteron beam, it appears feasible that the design goal can be achieved for a proton beam.
- Geometry and rate dependent corrections were isolated, measured and parameterized in a clever scheme that made use of a minimum of parameters.

- The plans to develop a full-scale prototype polarimeter and test it at COSY are well thought out and reasonable, and take into account the lessons learned from the COSY runs to date.
- A clear demonstration of the polarimetry appears to be feasible and possible on a reasonable time scale given the requested funding. Furthermore the polarimeter employed at COSY can be used to investigate systematic effects for the pEDM experiment.
- Since any pEDM signal will increase gradually during the beam storage time, it may be possible to optimize the operation of the wigglers during the storage time to gain measurement precision. For example, would there be any advantage to dither and measure the polarization at the beginning of a spill, then stop dithering, wait until near the end of the spill, then dither and measure the polarization again? This method might preserve more protons for the measurement near the end of the spill where sensitivity to an EDM effect should be largest.
- The polarimeters will observe a small fraction, at the level of a percent, of the extracted beam. It may be advisable to find a way to monitor this percentage, as well as unintended beam losses.
- It is conceivable that the extraction does not sample the stored beams uniformly and identically. The possible effect(s) on the measurement should be evaluated and translated into requirements.
- Although symmetry for the two beams would seem to favor two polarimeters, placed in opposite straight sections of the ring, it is then not obvious that the carbon targets for both polarimeters would present limiting apertures for the ring. Detailed spin-tracking simulations, allowing for slight misalignments of the different carbon targets, may help in evaluating the advantages and disadvantages of a two-polarimeter scheme.

Recommendations:

- The collaboration is strongly encouraged to move ahead with the plans to develop the new polarimeter and test it in COSY.
- The collaboration should make a decision as soon as possible on the detector technology choice and scheme, since this could be a long-lead component.
- The collaboration should develop a way to measure the polarization profile of the beam and confirm that the extraction scheme gives a good representation of the polarization of the entire beam.
- The collaboration should ensure that the destructive scheme for measuring the vertical polarization is optimal.

Appendix A: Reviewers

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Appendix B: Review Charge

A collaboration of particle, nuclear and accelerator physicists led by groups from BNL, Indiana University, and the University of Groningen, has proposed a program of novel measurements of charged-particle electric dipole moments (EDMs), to be carried out with storage rings injected from Brookhaven's AGS. The basic idea is to store longitudinally polarized proton or deuteron beams in dedicated rings with fields tuned to cancel the horizontal spin precession normally associated with the anomalous magnetic moment. In the presence of strong static or motional radial electric fields, a non-zero EDM would then be detected via a buildup in time of a small vertical polarization of the stored beam. The aim is to achieve sensitivity as good as, or better than, the next generation of neutron EDM measurements, i.e., to EDMs as small as 10^{-28}—10^{-29} e·cm.

A proposal for the deuteron EDM measurement – requiring combined electric and magnetic fields to cancel the anomalous magnetic moment precession – was presented to the RHIC/AGS Program Advisory Committee in May 2008. The PAC found the science goal compelling, but judged that the collaboration needed to increase its strength considerably, to produce a realization plan for the experiment with clear R&D milestones, and to have the project undergo a technical review before approving the experiment or seeking funding for it. In considering a realization plan, the collaboration has also developed the concept for a proton EDM measurement of interesting sensitivity, which could in principle be carried out in a storage ring with bending produced only by static electric fields. They thus now have a staged approach to propose, with suitable R&D targets along the path to each stage.

I seek your help in evaluating the technical robustness of the collaboration's present plan. Specifically, I would like your advice on the following questions:

1) Are there technical showstoppers evident at this stage that would seriously imperil attainment of interesting sensitivity levels in the eventual experiments? If there is no single showstopper, are there nonetheless too many high-risk performance goals to maintain a significant probability of payoff?

2) Is the proposed R&D plan sensible and achievable on a timeline suited to mount a competitive experiment? Has the collaboration properly identified the highest risk assumptions and proposed an appropriate set of R&D milestones to manage the risk?

3) Are the collaboration's considerations of systematic errors and approaches to mitigate them unduly optimistic?

4) Are you aware of competitive plans or proposals for charged-particle (other than electron) EDM measurements? Is the need for proton and/or deuteron EDM measurements to complement neutron EDM experiments sufficiently strong to merit proceeding?

5) Do the cost estimates and timelines presented for the R&D stages and for the EDM measurements themselves seem reasonable? (A detailed cost review would be premature at this point.) Is the proposed sequence for the proton and deuteron EDM measurement optimal? Are both measurements worth doing?

6) How much time do you estimate the collaboration needs to develop the proposal to a stage suitable for a DOE Critical Decision 0 ("mission need") review?

It is understood that the collaboration needs to be considerably strengthened to proceed to DOE review of the project. But strengthening the collaboration requires first some stronger commitment from BNL to pursue funding, scheduling and integration with the ongoing RHIC program. Your advice will be essential in considering that commitment.

Appendix C: Review Agenda

Location for all sessions: Berkner Hall Room B, Brookhaven National Laboratory

Monday, Dec. 7, 2009

8:30 am	Executive Session	
8:50 am	Welcoming remarks	D. Lowenstein, BNL
8:55 am	Physics of the storage ring EDM experiment	W. Marciano, BNL (25 + 10 minutes)
9:30 am	Overview of the proton EDM proposal for BNL – including presentation of error goals and con siderations, R&D milestones needed and assess-ment of chief technical risks	Y. Semertzidis, BNL (45 minutes + 20 minutes discussion)
10:35 am	Coffee break	
10:50 am	Beam parameters and collective effects for the proton EDM ring at BNL	A. Fedotov, BNL (30 + 15 minutes)
11:35 am	E and B fields in the proton EDM ring	W. Morse, BNL (35 + 15 minutes)
12:25 pm	Lunch and Executive Session	
1:45 pm	Beam Position Monitors in the proton EDM ring: requirements and R&D plan	W. Morse (25 + 15 minutes)
2:25 pm	Study of spin coherence time (SCT) – Status, progress and plans	G. Onderwater, KVI (30 + 15 minutes)
3:10 pm	Coffee break	
3:30 pm	Development of simulation environment UAL for spin studies in EDM	F. Lin, BNL (30 + 15 minutes)
4:15 pm	Polarimeter R&D, status, progress and plans	E. Stephenson, IU (30 + 15 minutes)
5:00 pm	Concluding remarks: cost estimation, collab-oration needs and technical timeline	Y. Semertzidis, BNL (20 + 10 minutes)

5:30 pm Executive Session – homework questions for collaboration

7:00 pm Committee Dinner

Tuesday, Dec. 8, 2009

9:00 am	Homework answers from collaboration
10:00 am	Executive Session
12:00 noon	Working lunch for committee
1:00 pm	Report drafting
3:00 pm	Public closeout session
3:30 pm	Adjourn