pEDM Review Report
(March 14-15 2011)

Executive Summary

We congratulate the collaboration for excellent progress since the past review.

First of all we wish to thank the review committee for doing such a great job, for taking the time to understand the experimental method and appreciate its physics reach. We have addressed and discussed all the issues raised by the committee. We enjoyed the process and we hope it was a similar experience for you. Below we respond briefly to the particular point and refer to a longer response when appropriate. The longer responses are all located in the same web site as this document.

The electrostatic ring design is a novel and potentially the most effective approach to reach the proton electric dipole moment goal of 10^{-29} e-cm. The present lattice design is a recent invention and requires much more development before it would be considered mature for a CD1 review. An electrostatic ring is not a common object and recent evaluation of an existing electrostatic machine, ELISA, has revealed unexpected problems (e.g., long stores and low Q_y difficulties). 3D simulations and field maps will be required to understand the design of pEDM ring components.

The concern expressed is that the understanding of electric field rings may not be advanced enough to allow confidence in the acceptance estimations of the ring. The observed lifetimes at the (low energy and tens of nA of beam currents) storage rings is of order 10 s (limited by beam-gas interactions) and smaller for higher currents whereas we favor more than 500 s. This would be a minor statistics issue, not a systematic error, provided that a storage time of greater than a minute is achieved. The main differences between the existing rings and our proposed ring are (see attached EDM note by Bill Morse on the comparisons of the electric rings): 1) The bending radius of our ring lattice is generally one to two orders of magnitude greater (this is significant when induced non-linearities are important), and 2) The deflector potential to beam kinetic energy ratio is two orders of magnitude smaller for our ring than the ELISA and ESR rings and similar to the AGS Electron Analog. Both of those differences point to our favor.

For the IBS estimations we used the modified Twiss parameters and the dispersion function for an electric ring and not an equivalent magnetic ring. In addition we do take into account the change in velocity going from the bend regions into the straight sections (this is important when estimating the slip-function).

Finally, we plan to follow this committee's recommendation and organize a workshop on electric rings. One of its topics will be the acceptance of such rings and members of the ELISA and ESR teams will be invited to participate.

The committee was unable to comment on a cost estimate. The collaboration did not present an estimate that could be evaluated. The ring design is at a very preliminary stage where there are only the barest of engineering concepts available.

At the time of the review we hadn't finalized the cost estimate. We considered two candidate ring locations: 1) The North Area as an extension of a branch off AGS to RHIC beam-line, and 2) the East Area, at the (former) AGS slow extraction area. The final cost estimates by C-AD engineers, commercial companies and our collaborators are $25.6M for the ring, or $39.5M with contingency. The ring housing and the beam-line cost estimate depends on the ring location:

1) North Area: The cost of conventional plus the beam-line is $20M, and $29.2M with contingency. The total experiment cost for the North Area is then $45.6M and $68.7M, which includes an average of 50% contingency.

2) For the East Area the corresponding numbers are: $14.2M for conventional and beam-line. When contingency is included it comes to $23M. The total experiment cost then becomes $39.8M, or $62.5M when an average of 57% contingency is included.

See attached presentation on the cost estimate for more details.

The present collaboration is technically strong and enthusiastic to achieve CD0 status approval. The collaboration intends to present a proposal to DOE within the next several months. A priority list of proposed R&D items, with budget and time scale, was presented. The committee believes that this is a good starting point to develop the final proposal. In order to obtain funding for these R&D items, CD0 approval will be required.

We intend to submit the proposal by the end of this spring. The R&D schedule is now expanded to include further "string-tests" which include the BPM operation in the presence of the RF cavity and charged E-field plates. The purpose of these tests is to prove the adequate BPM operation under realistic proton EDM experimental conditions.

The committee is concerned that the collaboration believes too much in the "magic momentum" of the beam and its ability to cancel many effects at the necessary level of accuracy. The effects of misalignments, fringe fields, changing stray magnetic fields, mechanical vibrations, etc. are non-trivial to understand and compensate for, and we believe that the collaboration should study this more intensely. It is very important to distinguish between requirements to operate the accelerator (beam dynamics, lifetime, etc.) and to do the EDM measurement. The requirements should be separated and tolerances clearly spelled out.

Indeed the “magic momentum” condition is not a panacea and it only works exactly for E-fields. The magnetic fields are still a major, although well understood and thought to be a manageable problem. The longitudinal E-fields, in which particles are accelerated/decelerated, are less of an issue since they average out very well, see note by Bill Morse. The analysis of the magnetic field effects is in the attached file by YkS. This effect was a major issue in the deuteron proposal and in the proton option with magnetic focusing. This was the main reason for the Dec 2009 review committee strongly recommending the adoption of electric focusing. In the all-electric ring we plan to have enough B-field sensitivity to eliminate the DC as well as the non-commutativity issues. The non-commutativity issues rise due to the fact that spin rotations don’t commute in three dimensions. However, they are of second order and our magnetometers have more than enough sensitivity to eliminate them.

The work carried out to date at KVI and COSY using the EDDA detector is commendable. Significant progress has been attained in understanding the underlying parameters that contribute to the systematic errors. We believe the goal of reaching a handle on the systematic errors to the level of 10^{-6} is within reach.
We agree.

1.1 Physics

Findings

The committee considers the high sensitivity proton EDM experiment as a highly challenging experiment with a compelling physics case. As a comparable system to the neutron, the proton is very valuable for the understanding of the underlying physics of EDMs.

The program's aim to improve the current experimental limit on the neutron EDM of $3\cdot10^{-26}$ e-cm to a limit of the EDM of the proton of 10^{-29} e-cm is extremely interesting and exceeds the projected sensitivities of experiments based on neutrons by at least one order of magnitude.

Although Standard Model predictions clearly are out of reach for all competing experiments (also for the new proton EDM experiment), the physics beyond the Standard Model can potentially be well tested. EDM experiments already now probe a scale that is not yet accessible by accelerators, and while ‘naïve’ super-symmetric (SUSY) models have been excluded by EDM measurements, predictions of most other SUSY models mostly lie within the sensitivity range of the proposed experiment.

The approach is novel and unique. The BNL based scientific group has made significant advances in the conceptual design and a general layout of the required storage ring, as well as in several details (like precise magnetic field measurements). An accelerator appears to be a very difficult environment to perform an EDM measurement with a sensitivity of a phase resolution of ~ppm over 1000 sec. integration time. The approach is very different when compared to other approaches with similar accuracy where the environment is better controlled. It will be a major challenge to the experimentalists to trace all spurious false effects that might occur in the new storage ring. However, due to the extremely different measurement scheme compared to other experiments in the field, it will show very different systematic effects.

The expected EDM signal for 10^{-29}e•cm is a few ppm. The polarimeter systematic errors are expected to be << 1ppm level. The remaining systematic error sources originating from beam and spin dynamics are also expected to be below our sensitivity level. Part of the R&D plan is to operate the BPM magnetometers in RHIC as well as part of a “string test” with RF and E-field plates under operating conditions.

The committee strongly endorses the program and finds excellent potential for the group to contribute on a significant and competitive level to the worldwide efforts.

1.2 Electrostatic Storage Ring

Findings

The proton beam will be injected into the storage ring after acceleration in the Booster and transfer through the AGS. The intensities of the clockwise and counter-clockwise rotating beams will be adjusted after injection to be very nearly equal.
The counter-rotating beams need to be equalized to 0.1% after injection time and, by using the beam-current monitors and/or one turn transformers (Bergoz stated sensitivity better than 0.01% per ms integration time), we will keep them the same to better than 0.1% level for the duration of the storage. In the absence of B-fields the beam losses should be very symmetric and therefore the intensity equality should hold for the duration of the storage.

Then the injected up-down transversely polarized beam would be de-bunched, re-bunched, and finally rotated to longitudinal polarization via a time-varying solenoidal field. The result would be ~50 bunches with + helicity and ~50 bunches with – helicity in each beam (clockwise and counter-clockwise).
Correct, except that our simulations show that a much smaller number of bunches may be adequate in keeping the spin forward to ±20° of the forward direction.

The storage ring lattice is of a very recent design and has been under development for about 3-4 months.
This particular design is indeed very recent and the changes are a reflection of improvements in the experimental sensitivity. However, even the current model is just a working lattice intended to facilitate the study of certain effects. The changes do not reflect fundamental changes to the method. We expect to freeze the lattice at some point after CD0.

It is planned to develop an E-field prototype structure. The results of these tests will determine the size of the ring and the distance between the plates.
We agree.

Comments

The proton storage ring is very challenging from both the accelerator (beam dynamics, lifetime, optics, technology, etc.) and the EDM experimental side. It is very important to distinguish between the accelerator and experiment requirements
Richard Talman gives the storage ring parameters in the attached document.

The present space allocated to straight sections is very “tight”. Careful considerations need to be given to the detailed design of the polarimeters, the

presence of large electric fields, and the space for sufficient beam diagnostics, etc. A small amount of contingency space (for example for an unforeseen monitoring device) should be included.
We agree. We are therefore investigating two tentative lattices one of which has generous drift spaces.

The requirement on the allowable fractional difference in intensity of the clockwise and counter-clockwise beams needs to be clarified. Although a method to equalize the intensities at the beginning of a fill was mentioned, it was uncertain whether this would work to maintain the equality during the “fill”, or whether some other method was envisioned.
See comments above. The requirements on the equality of the counter-rotating beams are given in the attached EDM note by YkS. In the absence of magnetic fields the losses are expected to be symmetric to very high accuracy and therefore the equality should remain for the duration of the storage.

The use of an all-electric field storage ring with beams at the “magic momentum” has considerable advantages in minimizing systematic effects. However, there is a concern that the collaboration has placed too much faith in the properties of the “magic momentum” of the beam, specifically the predicted ability to cancel many systematic effects at the necessary level of accuracy. Of particular concern is the understanding and compensation of possible systematic errors from misalignments, fringe fields, changing stray magnetic fields, mechanical vibrations, off-momentum components of the beam, etc., etc. and the coupling of two (or more) of these effects.

The possible systematic errors are several, however the important ones originate from the (possible) presence of B-fields. The main one, a DC radial magnetic field around the ring is the hardest one and our magnetometers are designed to have the needed sensitivity. Our magnetometers constitute the highest risk in this experiment. Per storage time (10^3 s) the DC component of the radial magnetic field needs to be known to the 0.02 nG level.
The time dependence of those magnetic fields is also relevant: The most dangerous are the ones with frequency f_1 in the mHz range while they diminish linearly with frequency. Higher frequency (f_2) B-fields need to be reduced to below $(f_2/f_1) \times 20$ pG. For example, B-fields oscillating at 100Hz (e.g. due to vibration) would be a 0.1 million times less effective than a B-field with mHz frequency dependence with their average amplitude needed to be reduced below 2 μG per storage time.

Another effect involving B-fields is the so-called geometrical phase, a combination of spin rotations with respect to two orthogonal axes. The net result is a spin rotation with respect to the third axis, and equal in magnitude to the product of the two rotations (see attached note by YkS). The magnetometer system will have more than adequate resolution to be able to handle this systematic error. Higher order effects require the presence of much higher B-fields to be relevant and our BPMs should be able to handle those as well.

Since the number of BPM locations around the ring is limited there is a need to know the magnetic field to $(N / Q_y)^2 \times (f_2 / f_1) \times 20$ pG level per storage time, with N the Fourier component of the radial B-field around the ring and Q_y the vertical tune. As an example, for $N = 10$, and $Q_y = 0.1$ the fields need to be known and reduced below 20 mG for $f_2 = 100$ Hz, and 0.2 μG for $f_2 = 1$ mHz. There are two possible ways of eliminating the fields with N>0: 1) use a beam-tube trolley that can easily have nG B-field sensitivity, and 2) change the phase of the vertical tune modulation around the ring and thus obtain an excellent position resolution of the B-field disturbance.

A similar effect can be produced by the electric field in case the particles are slightly off magic momentum. We haven't referred to this case in the proposal since a back of the envelope estimation shows it is completely negligible but it is now addressed in the attached note by YkS.

Electrostatic storage rings are not commonly used and poorly understood. The software tools for machine optics design and beam dynamics simulations are not well developed yet. The team is in the process of adapting existing software packages and making good progress, but more effort is needed to carefully benchmark the new tools.

The simulations have to be able to describe the second order effects accurately. Currently one simulation program does this, however, it is rather slow. It can simulate many if not most of the systematic errors we could think of. Other, much faster simulation programs are also under development. Also, see response by Alfredo Luccio.

Managing high electric field / DC voltage at the levels proposed is not a low-risk, but rather a medium-to-high risk. While comparable and even higher levels have been achieved elsewhere, the scale of the proposed system is much larger than previous efforts. Maintaining a dust-free environment inside the accelerator during installation and operation is non-trivial. One should take advantage of the Tevatron experience in this area.
We agree, also see attached file by Bill Morse.

It is proposed to use a toroidal deflector (vertical curvature to the plates) combined with separate defocusing quadrupoles as the way to account for low Q_y. In order to conclude on the final parameters of the deflector and of the lattice cell, more beam and spin dynamics studies are needed.

We agree.

It would be useful to verify how low Q_y can be, including the available margin in the distance to zero. Beam and spin dynamics studies demonstrating the low-Q_y regime should consider realistic emittance and energy spread conditions, account for amplitude and momentum detuning effects, fringe fields, coupling, effects of defects and of non-linearities, possible impact of space charge, range of validity of various compensation schemes as delta-length, delta-energy. Controlled slow extraction (e.g., resonant) might be studied, to possibly relax on low-Q_y constraint in that respect.

We agree with all listed points. Low Q_y is required to enhance the separation of the counter-rotating beams. Other extraction methods could also be used, so we will study them. The value of Q_y will only be finalized after studying the relevant effects some of which are listed above.

The collaboration should consider hosting a “Focusing of Charged Particles” workshop, “à la Septier”, sort of remake of the eponym 1967's workshop organized by Albert Septier in Orsay, but focused on electrostatic elements and application to the electrostatic storage ring. Such a workshop would provide the opportunity to summarize the present state-of-the-art and be an impetus for the experts to consider the pitfalls and possible solutions.
We agree and are looking forward to this workshop. Steve Vigdor found this recommendation very appealing.

Recommendations

The storage ring lattice design must be completed and reviewed before committing to the proposed approach.
We agree. The final ring lattice will be similar in design to the ones presented so far. The most important (although high risk) system is the BPM magnetometer, the design of which will be optimized as we build and test it.

The storage ring and experiment requirements should be separately defined and tolerances clearly spelled out.

Develop a description of the machine operation (injection, storage, beam gymnastics, etc.) and a table of parameters.

High pressure rinse treatment of the electrodes should be done in conjunction with assembly in a cleanroom.

We will follow the recommendations in the proposal to DOE.

1.3 Beam and spin numerical simulation

Findings

Two different approaches are foreseen, one based on fast tracking methods (e.g., kick-drift) so to allow long term tracking, in the 1000 sec. time scale, and a slower approach (stepwise ray-tracing) based on a realistic representation of the electric and magnetic fields. Code benchmarking is part of these developments and involves crosschecks as well as comparisons with known theoretical and experimental data. An example of the latter is the ongoing and the planned experiments at COSY, regarding corrections of second order geometrical and momentum dispersion effects on SCT, and possible tests of electrostatic devices on COSY chicane.

Comments

The first type of numerical method may not allow modeling of the electrostatic and magnetic fields in a realistic enough manner to allow appropriate precision and understanding of long term beam and spin dynamics. The second method, is assumed that, due to it's being slow, it would not allow direct access to SCT. On the other hand, tools for multi-turn tracking in E-fields (field models or field maps) are few in number, which reduces the possibilities of comparisons. Benchmarking may even be impossible when it comes to including realistic (large) 6D excursion conditions.

We plan to use the fine-grained programs in the SCT estimation by tracking particles with larger emittance parameters than we plan to store and by extrapolating to 10^3s. The fast programs should be able to take into account the realistic B and E-fields for the duration of the storage time of ~10^3 s.

In addition to extensive code development the design stage of the storage ring requires, and will rely on, extensive computer simulations. The collaboration should consider the improvement and expansion of beam and spin dynamics computing tools as part of the design studies.

Plan on including a full 3D computation of the toroidal condenser in the design and optimization stages. Use the computed 3D field maps in a multi-turn stepwise ray-tracing tool, so to evaluate the condenser specification performance, to study and optimize ring parameters, for long term beam and spin tracking, possible parasitic E and B fields, low-Q_y vertical extraction of beam and spin and to benchmark spin and beam dynamics software.

We will do this, mostly after we submit the proposal.

Plan on performing measurements of the effective electric-lengths of deflector and quadrupoles, 3D measurements at device ends, effects of possible shielding and shims, and compare with the 3D computer design – including validation of the use of computed field maps in further beam and spin dynamics simulations.

We will simulate the E-fields with 3-D computer design and will come up with the required specs. Our first order spec estimations show that those should be possible to achieve with present, commonly available, technology.

A "Computer tools" workshop, aimed at reviewing methods of lattice design, beam and spin dynamics calculations should be considered.

We are inclined to combine the two suggested workshops into one.

In addition to simulation codes the collaboration should consider working on the analytical theory of beam dynamics in electrostatic rings. Along with being a largely unexplored area of beam physics this approach will help us better understand the differences between magnetic and electric rings and improve intuition.
Several people from our collaboration are actively working on this subject.

Recommendations

In parallel to the present on-going code developments (TEAPOT, SPINK, RK4 methods), one might consider assessing the interest of, and possibly develop and use, existing stepwise integration based tracking tools (including Raytrace – which is used at C-AD and include spin, or SIMION which computes 3D electrostatic fields and can track, and was used at ELISA for instance, or other Zgoubi methods), and develop these further in view of achieving the required precision. At the present stage of the storage ring R&D, given the complexity of an electrostatic ring in terms of dynamics, the collaboration should consider the incorporation of precision stepwise ray-tracing tools in the on-going lattice design studies.

We agree. See response by A. Luccio.

Code development would strongly benefit from the involvement of graduate students, postdocs, and undergraduate students. A careful study of the analytic theory of beam dynamics in electrostatic rings would likely result in a high quality publication.

Indeed.

1.4 R&D:

Findings

The collaboration presented a prioritized list of R&D projects for this experiment:
1) beam position monitors,
2) spin coherence time tests and software development,
3) electric field tests for some of the storage ring components, and
4) polarimeter development.

Comments

The committee concurs with the list of proposed R&D projects based on the presentations and background material supplied.

R&D plans could include provision for systematic extensive multi-turn tracking of large number of particles, assuming a realistic assessment of and quantification of particle and spin distributions as part of the impact on the physics measurement. This strategy will possibly require the use of extensive parallel computing, CPU clusters, etc. It is also possible that this work will require an on-line model(s) of the ring, during the design stage, as is done for various on-going projects, such as the Neutrino Factory design, which consists of a muon dynamics code development, including code benchmarking and on-line code assessment in the frame of the muon accelerator prototyping experiment EMMA.

This is indeed a good idea.

Recommendations

The collaboration needs to move to CD0 as soon as possible to obtain new funding. Most of the important remaining tasks require a significant amount of money and/or people to complete, and the present (LDRD) funding is ending.
We agree.

1.5 Systematics:

Findings

At the current state of the project, no sufficient treatment of systematic issues such as effects that generate false signals, e.g. due to and sensitivity limiting effects, was presented.
We have included a number of effects the most serious of which (by several orders of magnitude) is a DC (i.e. the *N*=0 Fourier component around the ring) radial B-field.

Comments

Very careful treatment of systematic issues is crucial to estimate the potential gain of the experiment. A main focus of the strategy must be detailed simulations of ray tracing and spin tracking. As the requirements on components viewed from EDM-specific physics is likely to also have impact on the accelerator design and detailed simulations should have high priority.
In a storage ring the particles undergo 6D motion, which the particles integrate and average them out very effectively. The exceptions to them are effects like the geometrical phases, which are expected to be small.

Recommendations

Systematic effects that affect the EDM sensitivity should be identified and listed. This should include e.g. fringe fields, local magnetic residual fields, magnetic contaminations of electrodes, RF-noise frequencies and amplitudes at different positions of the ring, HV specific issues like HV ripple, discharges, mechanical deformations and vibrations of electrodes, beam kicker related effects, etc.
All thinkable effects should be explained and tested for their relevance. A possible classification could be in effects that could eventually mimic false EDMs (e.g. Ramsey-Bloch-Siegert shifts in residual local magnetic fields, potential geometric phases from the interaction of the wiper-method to align the spins with the motional B-field) and sensitivity limiting effects (e.g. angular spread of the spin distribution, beam divergence or size).
The RBS systematic error is minimized in the all-electric ring lattice. We have estimated it to be below our sensitivity level as it is of higher order. In addition, we are investigating the possibility of storing beams with spin directed in the radial direction, as those will be more sensitive to this effect by more than a factor of 10^2. We intend to spend approximately 1% of the effective running time in this configuration.

1.6 Magnetic fields, BPMs:

Findings

The use of beam position monitors for magnetic field measurement is an intriguing and interesting feature of the proposed experiment. Although a very challenging strategy, this should be followed up in the proposed way. However, a clear description of the required accuracy of the measurement (e.g. possible integration times vs. measurement bandwidth, connection to possible correlated and uncorrelated errors and possible feedback) is missing.
We agree that a more detailed measurement plan must be developed.

The total integration time is of order 10^7 s, from 10^4 stores of 10^3 s. In each store, we are required to determine the radial magnetic field to an accuracy of 20 pG. Given the long integration times, large time constants/settling times can be used, so a measurement bandwidth of 1 Hz (or less) about the vertical tune modulation frequency should be possible.

Regarding correlated and uncorrelated noise sources, the pickup coils of the SQUID BPMs will be sensitive to magnetic field noise in the local environment. The closest shields will dominate the noise at the modulation frequency, which will be of the order of a cm away. BPM pickup coils with spacings greater than a few cm will largely see uncorrelated magnetic field noise. The electronic noise in the rest of the SQUID electronics should be uncorrelated as well. The system will be designed with a S/N>>1 so that unanticipated correlation between noise sources (which reduces the efficacy of averaging) will not limit the overall pEDM sensitivity. If feedback is only applied between stores, the integration time will be the storage time.

Careful investigations for the R&D towards beam position monitors have been performed. BPMs are a key component of the measurement and the choice of SQUID magnetometers seem to be the right choice for this problem (especially compared with atomic magnetometers). Suitable sensors and measurement schemes have been identified.

The bpm system requires the betatron tune to be modulated during the measurement process. The tune variation causes any vertical separation between the beams to be modulated at the same frequency. Reducing this modulated signal is the method for performing fine orbit correction.

Comments

Although in laboratory environments magnetic fields can be measured on the level of 1 fT/sqrt(Hz) with state of the art sensors by experienced groups, the accuracy of SQUIDs in an accelerator may be significantly worse due to residual RF and Johnson noise (e.g. due to thermal shielding), and an estimated accuracy of 10 fT/sqrt(Hz) looks more realistic.

The BPM magnetometers are the high-risk system of this experiment. They need to succeed and we plan to build them to the required specs. We also find it necessary to include one more stage to those already presented: include a “string test” where the RF as well as the operating E-field plates are included to demonstrate that we can operate the BPMs under realistic conditions.

The BPM magnetic shielding configuration will be nearly identical to systems achieving 1 fT/sqrt(Hz) at 35 Hz. We will operate significantly above 35 Hz (perhaps several hundred Hz), where the noise should be even less. The modulation frequency will be chosen where noise is a minimum.

The additional RF noise in the accelerator environment will be screened by thin layers of Al surrounding the pick-up coils. The noise from this material has been estimated, and will not limit the measurement. For B_φ fields, thickness less than a skin-depth are needed. For other B field components, several skin depths will be required. The noise from these thin shields may require us to work at modulation frequencies above 200 Hz or so.

RF noise leaking into the SQUID electronics through cables and other pathways is a serious issue. We will investigate and reduce these with a ``string-test'' including RF generating elements.

A medium-to-high risk factor is magnetic shielding, especially for BPMs. While the level required has been demonstrated in a small dedicated experiments, it will be much more challenging to achieve on an accelerator scale. Also, no concept of the shielding was presented for the rest of the machine. More effort is needed to assure that required level of magnetic shielding is achievable.

See attachment by Bill Morse and David Kawall. The passive B-field shielding factor is estimated by Amuneal to be of order 10^5. Another factor of 3×10^3 needs to be achieved by a combination of internal and external feedback system.

The BPM sections will have additional shielding beyond that in the rest of the storage ring to bring the magnetic field noise at the vertical tune modulation frequency to the 1 fT/sqrt(Hz) level. (We anticipate a few extra layers of mu-metal, a ferrite shield, and very thin Al shields around the BPM pickup coils). Estimates of the noise based on experimental data and calculations suggest this level of noise is achievable. The modulation frequency can be increased into the kHz range if required to be in a suitably low noise environment. This system needs to undergo extensive testing, which is planned. We also intend to map the storage ring radial B field with atomic magnetometers. Sensors with fT/sqrt(Hz) sensitivity, which can run between the 3 cm electrode gaps, should be available commercially within a year.

While it is clear that a radial magnetic field will split the beams vertically and that this split will modulate with the betatron tune, it is not clear that the extreme precision required for the average vertical displacement will not be swamped by the inevitable random errors associated with other magnetic harmonics. Remember that not only the average orbit but all orbital harmonics will vary as the betatron tune is modulated.

The effect of the higher harmonics diminishes very fast as its dependence is $\sim 1/(Q_y^2 - N^2)$, making clear the significance of the low vertical tune value. Q_y is the vertical tune (planned to be kept around 0.1), and N is the Fourier component of the radial B-field around the ring with the $N=0$ being the most dangerous one. The $N=1$ is about 10^2 times less effective and the $N=10$ about 10^4 times less effective.

Those with lower than mHz frequency dependence are the most dangerous. Those are also the easier ones to cancel by applying a correction signal at the end of the storage time.

We plan to spend ~20% of the time probing and checking for systematic errors during data taking including using a magnetometer on a trolley to map out the fields and confirm the integrity of the system. For E821 (the muon g-2 experiment) we spend ½ a shift every 2 to three days for a trolley run.

Recommendations

A feasibility study of the implementation and operation of SQUID sensors and cryogenics in vicinity of the beam will require a dedicated test setup and R&D that should start promptly. Probably knowledge can be obtained by inviting groups with expertise in the field. SQUID magnetometry at cryogenic temperatures must be carefully compared to the accelerator vacuum environment (e.g. superinsulation foil in clean vacuum, anti-static handling of SQUIDs, surface charges on insulating components, discharges...). The effect of EM noise could strongly depend on the actual implementation of SQUIDs in vicinity of the beam. These issues should be carefully investigated already at an early stage of the BPM design.
We agree.

A realistic estimate of the rms orbit difference between the cw and ccw beams needs to be made. This then must be translated into required linearity in the bpms and necessary accuracy in the knowledge of the lattice functions. Without this it will be necessary to correct all the harmonics of the radial magnetic field. In fact it would probably be worthwhile to consider correcting at least a few low harmonic numbers just to reduce the necessary dynamic range.
Indeed, we believe correcting a few low order B-field harmonics will prove to be necessary. The BPM linearity needs to be good at the 0.1-1% level. We will be applying a net radial B-field to cancel the buildup of the vertical spin component during storage. At the end of the storage time (10^3s) our statistical sensitivity will be only 10^2 times worse than the final sensitivity of the experiment. We will very careful to keep the SQUIDS within their dynamic range.

1.7 RF system:

Findings

The RF system as presented is at a rudimentary stage of development.

As well as the drift tube linac assumed in the earlier proposal the alternate lattice assumes a conventional RF-cavity.

Comments

More effort is required on RF system questions, especially on how to manage RF fields so they do not produce high levels of EMI for beam instrumentation and the EDM experiment detectors. The lattice is finely tuned so that the second derivative of revolution frequency with respect to beam energy vanishes: $\frac{d^2T}{dE^2} = 0$. The RF frequency controls the average beam energy that must be 232.8 MeV to very high accuracy.

See note by R. Talman. The RF will need to keep the beam to its magic momentum with very high accuracy. The only way to achieve this is with feedback from the polarimeter probing the horizontal transverse spin component. This feedback should keep the spin within certain limited angle with respect to the momentum vector in a “windshield wiper” fashion.

Recommendations

Begin to develop a conceptual RF system design. It is necessary to verify that $\frac{d^2T}{dE^2} = 0$ and that the average energy is sufficiently close to the magic value. The necessary RF requirements should be included in the conceptual design. Lattice tuning knobs and measurements that can be used for tuning should also be considered.

We will develop a realistic RF-system after CD0 and R&D support materializes, as our current resources are limited.

1.8 EM Shielding:

Findings

No clear numbers on the required reduction of electromagnetic noises at different frequencies could be shown at this point of the development. A reduction of few 10^8 for DC (magnetostatic) disturbances is extremely difficult for this geometry and the collaboration is looking at a compromise of acceptable disturbances and applied corrections. The basic idea of using cylinders seems in principle suitable. However, the longitudinal and transverse shielding capability of a toroidal mu-metal shield should be estimated in an early stage.
Once we obtain CD0 we will ask the company to produce a 3-D B-field mapping of the expected shielding factors.

Comments

In the presented strategy for DC magnetic shielding, mu-metal may perform significantly worse if placed in a magnetically stabilized environment. Furthermore, (static) residual fields caused by the mu-metal will likely be on the few 10 nT level at the position of the beam (randomly distributed) and will be hard to remove by demagnetization due to mechanical features of the assembly. Also, any time dependent effects (temperature changes, sparks, HV noise,...) will affect the shield. This may have several consequences for the performance of the EDM experiment, which should also be investigated with simulations and probably by a test setup. Sufficient RF shielding based just on the vacuum system might need special consideration due to the RF sensitivity of the BPMs (SQUIDs).
See attachment by Bill Morse and David Kawall. Several good ideas are expressed over here. A “string test” will be able to adequately address those concerns.

An intelligent conceptual design of electrodes for the new ring has been established. However, their potential systematic effects on the EDM measurements must still be carefully investigated.
We agree.

Recommendations

The parameter space for a compromise of a minimum required shielding and the largest acceptable corrections should be further investigated. Perhaps the amount of shielding can be reduced. In previous cases, some realizations of connected cylinders of mu-metal did not show reasonable performance.
We will study this recommendation very carefully before we commit to the number of shielding layers.

Problems that limit the sensitivity or mimic false EDMs in other EDM experiments are e.g. magnetic dipole contaminations in stainless steel, HV noise that cause currents in the electrodes, vibrations, deformations due to HV, alignment issues, thermally or tension induced currents that change with time or Johnson noise. High order effects diminish very fast. The most dangerous are the low order ones with the DC being the most dangerous one by several orders of magnitude. Those will also induce a beam splitting that our BPMs should be able to probe with high accuracy.

1.9 Polarimetry

Findings

The polarimeters play a key role in the pEDM experiment, both to measure the pEDM signal and also to monitor and feedback information on beam dynamics.

Beam polarimetry is proposed by extraction of the beam onto a thick, fixed carbon target, with measurement of azimuthal asymmetries in the resultant scattering (elastic plus low Q-value inelastic). The extraction will be achieved by either decreasing the vertical focusing or applying small random vertical electric fields to the beams.

Detectors will be placed on either side of the carbon target to simultaneously record the polarizations for both the clockwise and counter-clockwise rotating beams (scattered from the same target). The predicted efficiency (integrated over 2π in φ) and analyzing power are ~1 % and ~0.6, respectively.

Concentrating the polarimeter measurements early and late in the "fill" or "store" was shown to give a significant improvement in the precision by simulations.

Measurements performed at COSY, using deuteron beams and the EDDA detector for a polarimeter, have been very successful. Considerable progress has been made in understanding and verifying the parameters that would contribute to systematic uncertainties in the pEDM polarization determination. The results of these measurements suggest that it is feasible to obtain a vertical polarization sensitivity of 10^{-6} or better in the experiment, which is the stated goal.

The COSY results were obtained at a slightly different momentum, and at lab angles from 9 – 20°, instead of the planned 5 – 20°. This resulted in considerably lower rates than anticipated in the pEDM experiment. Nevertheless, rate effects were observed in the EDDA detector scintillation counters. Other types of detectors are planned for the pEDM polarimeter.

Comments

The pEDM collaboration is to be commended for its work at COSY on polarimetry.

The present design is an improvement over the two-polarimeter scheme proposed in the previous review.
The purpose of the two polarimeters was to probe the *N*=1 geometrical effect. We may still find it necessary so that we do include it at a later ring lattice design.

Time will be required at the startup of the pEDM experiment to calibrate the polarimeter with normal-transversely polarized beam and possibly with sideways polarized beam with momentum slightly different from the "magic" value. Corrections will also need to be studied for beam offsets, etc. as has been done at COSY.
We expect to spend most of the first year of running on systematic errors, calibrations, etc. and a significant fraction of the time on that in subsequent years.

It is planned to use a different detector technology for the pEDM polarimeter than scintillation counters (EDDA). Also, the angular acceptance will increase to smaller angles, thus significantly increasing the detected rates. The alternate technologies (resistive plate chambers, micro-megas chambers, GEM chambers) appear reasonable choices.

Tests will need to be performed to verify that the rate corrections to the polarization developed for the EDDA data will still be adequate.
After CD0 we expect to be testing those polarimeters at COSY.

At the end of a “fill” or “store”, the collaboration mentioned that the beam momentum could be moved slightly away from the “magic” value. The time variation of the sideways-transverse polarization would then permit determination of the longitudinal beam polarization just before the momentum change. This might also be achieved by using the solenoid to precess the spin direction back to normal-transverse. Tests with both schemes might be useful.
There are several options available and we will study them further.

Recommendations

New measurements at COSY should include at least some proton beam runs. It was stated that the sensitivity of some of the coefficients of the Taylor series expansion of the asymmetry formula is higher for proton than for deuteron beams, for example. There are also fewer coefficients for proton beams due to the lack of tensor analyzing powers. Finally, the proton data will permit reliable simulations necessary for the final design of the pEDM polarimeter.
See attachment by Ed Stephenson. Studying proton beams at COSY is in order in due time.

The present polarimeter design would not sample the beam uniformly. Studies of the polarization profiles (normal- and sideways-transverse, as well as longitudinal) of the beams should be considered. This may involve temporarily replacing the thick carbon target. Provision for this measurement should be made in the polarimeter (and perhaps storage ring) design.

See attachment by Ed Stephenson and Bill Morse. This is a potential polarimeter-specific systematic error and one way of addressing it is by reducing the time period between early and late time measurements.

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