Proton R&D Plan

Storage Ring EDM Collaboration, 18 Nov. 2009

7. Spin Coherence Time (C.J.G. Onderwater)

Overview

The sensitivity with which an EDM can be sought for is to a good approximation given by

$$s_d \propto \frac{1}{PE\sqrt{N\,T_{tot}\tau}\,A}$$

Here P is the (transverse) polarization of the beam at the time of injection, E the effective electric field, N the number of particles stored per fill, T_{tot} the total running time of the experiment, τ a characteristic time scale and A the analyzing power of the polarimeter. The characteristic timescale depends on the lifetime of the beam in the storage ring, t_{beam}, which is predominantly determined by the extraction towards the polarimeter, and the polarization lifetime t_{pol}. Given a polarization lifetime the former can be tuned to yield optimal sensitivity, typically $t_{beam} \approx 2t_{pol}$. In this case τ is proportional to t_{pol}. The sensitivity is thus inversely proportional to (the square-root of) the polarization lifetime. Maximization of t_{pol} thus optimizes the sensitivity of the experiment.

The proposed experimental sensitivity is based on a projected polarization lifetime of 1000 seconds, i.e. $10^8 - 10^9$ particle revolutions. Such lifetimes are routinely achieved for the polarization component perpendicular to the beam orbit plane, i.e. *parallel* to the invariant spin field. This relies on the use of snakes, spin rotators, *etc*. Little experience is available with *transversely* polarized beams. Notable examples are the muon g-2 experiment at BNL (E821) and the measurement of the electron and positron anomalous magnetic moments at VEPP [I.B. Vasserman, *et al*., Phys.Lett. **B198** (1987) 302]. In the E821 experiment no depolarization was observed at the level of 10^{-4} for 140 spin turns. In the VEPP experiment a polarization lifetime of 10^7 spin revolutions was observed. Note that this paper also describes the use of a radial electric field to manipulate the spin precession frequency.

The polarization lifetime is determined by the spread in the average spin precession frequency, which is determined by the beam motion and storage ring lattice. To optimize the polarization lifetime detailed knowledge of the beam motion and storage ring are necessary.

Approach

The design of a storage ring with the required long polarization lifetime requires a staged approach. Three key issues need to be addressed prior to the final design of the EDM storage ring lattice.

Choice of Modeling tool(s)

The experiment is still in the design phase. Hence the analysis of the system is mainly done through computer simulation. The reliability of the simulation studies depend critically on the accuracy of the computer codes used. Such codes inevitably contain approximations and numerical inaccuracies. The essential question is thus how well the results of these codes represent actual physical phenomena.

The answer to this question is obtained by first carefully inspecting the codes themselves (approach, approximations and implementation). Shortcomings of otherwise well performing or promising tools can be improved. The level of precision is quantified by inspecting the level at which invariants are preserved, by comparing the simulated results to those of analytically solvable configurations, by inter-comparing the results obtained with different codes and by comparison with (existing) experimental results.

The final goal is to have a well-understood simulation tool that describes relevant physical phenomena with sufficient precision

Causes and cures of spin decoherence

The required polarization lifetime of 1000s corresponding to approximately 10^8 to 10^9 revolutions. The dominant causes for spin decoherence have been identified from analytical studies [see e.g. Eidelman, Shatunov, and Yakimenko, Nucl. Instrum. Meth. **A357**(1995)23 and Yuri Orlov [EDM note #61]. The results of these studies and those obtained by similar numerical simulation are necessary to formulate a strategy to eliminate or counteract those causes and to identify additional causes for spin decoherence. For all but the most straightforward ring configurations analytical studies become prohibitively complex. These studies are therefore limited to relatively simple configurations. Higher order non-linear behavior and effects such as fringe-fields, lattice defects and misalignments are best studied numerically. Through studies it should be investigated whether the developed strategy has sufficient flexibility to deal with these imperfections on an *ad hoc* basis.

The final goal is to identify all relevant causes for spin decoherence and to apply this knowledge to develop a strategy that provides guides on how to prepare a storage ring lattice with the longest possible spin coherence time.

Experimental verification

The imperfections found in a practical storage ring are often not or not sufficiently well known. Therefore the resulting effects on the stored beam cannot be predicted precisely. The level of accuracy at which these imperfections manifest themselves can be quantified by studying a representative storage ring such as the COSY ring at the Germany research laboratory in Jülich. Certain imperfections may be exposed by manipulating the ring lattice such that their effect is greatly enhanced, e.g. by bringing it close to a resonance. By matching the observed enhanced effect the much smaller effect under optimized conditions may be estimated.

Existing storage rings usually have limited room to manipulate the lattice. Within the possibilities, the corresponding spin coherence time can be predicted through simulations and subsequently be measured. Following the strategy developed in the previous stage, the lattice for optimal spin coherence can be predicted and experimentally confirmed.

The primary goal is to demonstrate that the strategy for prolonging the spin coherence time developed in the previous step is robust despite the necessarily limited knowledge of an actual storage ring. A secondary goal is the development of the tools to expose small imperfections.

Progress, Status and Plans

I. Model Selection & Improvement

Generally, beam simulation codes fall into two categories. One category includes ray tracing codes which use numerical integrators to determine the trajectories of individual rays through external and possibly internal electromagnetic fields. The core of such a code is quite robust and easy to set up; for many applications, however, certain important information cannot be directly extracted from the mere values of ray coordinates. Furthermore, this type of code is often quite slow and does not allow extensive optimization. The other category of codes are the map codes, which compute Taylor expansions to describe the action of the system on phase space. These codes are usually faster than integration codes, and the expansion coefficients often provide more insight into the system.

We have evaluated the performance of several tracking codes, including tracking via Monte-Carlo integration, the beam dynamics simulation codes MadX and UAL each combined with the spin tracking module SPINK and COSY-Infinity.

Raytracing via Monte-Carlo integration allows for arbitrarily complicated configurations of electromagnetic fields. To reach sufficient precision a high-level numerical integration scheme must be employed (Runge-Kutta 5 or better) in addition to making small time steps (of the order of picoseconds). This leads to impractically long simulation times. Furthermore, for reliable results the field must obey Maxwell's equations. Therefore, interpolation of calculated fields on a grid should be done with great care. Interaction between particles can in principle be incorporated by tracing multiple particles at the same time.

The **MAD-X** (Methodical Accelerator Design) program is a general purpose accelerator and lattice design program [http://mad.web.cern.ch/mad/]. It can handle very large and very small accelerators and solves various problems on such machines. For the calculations, the elements can be defined either as so-called thick lenses with a finite length or as so-called thin lenses with zero length. In the latter case, the effects of an element (e.g. a magnet) on the beam are represented as impulses (kicks) at a fixed value s on the reference orbit. This simplifies the treatment since it allows to treat the machine as a series of linear transformations separated by the ”kicks” at the positions of the thin elements. This method is very fast and symplectic by construction and it is therefore best suited for particle tracking. The disadvantage is the loss of precision when the magnets are very long (compared to the size of the machine) or when fringe fields are important. Part of this precision can be recovered by sub-dividing the magnets into slices , i.e shorter sections, each representing a thin lens. Particle tracking in MAD-X is only possible using thin lenses. A lattice defined with thick elements has to be converted to thin lenses. MAD-X cannot track spin. For spin tracking the resulting lattice solution has to be used in a external program, e.g. SPINK.

As an alternative to MAD the use of the Unified Accelerator Libraries (**UAL**), in particular the module TEAPOT (Thin Element Accelerator Program for Optics and Tracking) was studied [http://www.ual.bnl.gov]. It provides similar functionality, but also lacks the ability to track spin.

The tracking code **SPINK** [see e.g. SPIN PHYSICS: 18th International Spin Physics Symposium. AIP Conference Proceedings, Volume 1149, pp. 759-762 (2009)] was written for the RHIC SPIN project at Brookhaven to study the behavior of polarized protons in the Relativistic Collider during injection, acceleration and storage at fixed energy. From the output of MAD SPINK reads the first order matrices for each machine element and the second order transport maps as well as the Twiss functions along the lattice. Work is in progress to incorporate a SPINK module in UAL. A disadvantage of SPINK is that it calculates the spin rotation matrices for a collection of kicks, i.e. for thin elements. To reach high precision for a thick elements requires fine “slicing” of these elements.

The beam simulation program **COSY-Infinity** [K. Makino, M. Berz, Nuclear Instruments and Methods A558 (2005) 346-350] uses differential algebraic techniques that allow it the compute Taylor maps for arbitrarily complicated fields and to arbitrary order. Tracking of the spin is an integral part of the code. Fringe fields can be included at different levels of sophistication. System parameters can be incorporated seamlessly. The maps generated by COSY were used inside the ROOT analysis framework for tracking studies.

The results obtained with COSY-Infinity (version 9) using the muon g-2 ring as a trail-setup were numerically equivalent to those obtained using Monte-Carlo ray-tracing. Also the comparison between COSY-Infinity and Mad-X and UAL-based simulations showed no discrepancies. All programs were found to be able to store a set of trial particles for millions of turns. This demonstrates the insignificance (at this level of precision) of numerical round-off errors and model truncation errors. Furthermore, the resulting synchrotron, betatron and spin precession frequencies were compared and found to be compatible.

For COSY-Infinity the symplectic error in the one-turn map for a complex setup (in this case the COSY storage ring) was studied as a function of the order of the Taylor approximation. Non-symplecticity may result from truncation of the Taylor map and round-off errors. The numerical precision of COSY-Infinity is limited by the precision of double-precision floating point arithmetic, i.e. 10^{-15} per number. This uncertainty propagates into each coefficient of the transfer map. This results in a symplectic error in the 6D transfer map which grows from $2\text{x}10^{-15}$ at first order (21 non-zero coefficients) to $2\text{x}10^{-13}$ at eighth order (9142 non-zero coefficients). Slightly smaller errors are found for the non-orthogonality error of the spin rotation matrix (which has 13085 non-zero coefficient at eighth order approximation).

An overview of this work was presented at the ICAP2009 conference and [F. Lin et al, *Overview of (some) computational approaches in spin studies*, Proceedings of the 10th International Computational Accelerator Physics Conference, San Francisco (ICAP 2009), 03.09.2009].

The results of the combination of UAL+SPINK, as well as those of COSY-Infinity are sufficiently precise. Both packages will be used side-by-side for further studies. No further development of COSY-Infinity is necessary at this time. The Spink module for UAL needs to be further developed.

II. Analytical & Numerical Studies on "Simple" Lattices

A first trial case that was studied is the so-called pitch effect found, e.g., in the muon g-2 storage ring. It leads to a change in the spin precession frequency that depends quadratically on the vertical betatron amplitude. For comparison purposes the (average) spin precession frequencies for two trial particles with y'=0 and y'=1mrad (and x,x',y,dp/p and φ all zero) at t=0 are determined. Tracking results were obtained for Monte-Carlo ray tracing, COSY-Infinity and UAL/Spink. All three approaches give the same result of $\Delta\omega/\omega=(7.40\pm0.02)\cdot10^{-8}$, in agreement with analytical estimations.

Studies are presently focused on a first design of an electrostatic storage ring. The lattice consists of a set of unit-cells build from two cylindrically symmetric electric field sections separated by a *magnetic* quadrupole sandwiched between two thin sextupoles. The polarity of these sandwiches are alternating between horizontally and vertically focusing.
A set of longitudinally polarized particles is traced for an initial horizontal or vertical displacement ranging from -1cm to 1cm. The spin precession frequency is determined from the (linear) growth rate of the transverse spin component. It was found that $\omega=-0.081\cdot x_0^2$ for horizon displacements and $\omega=-0.59\cdot y_0^2$ for vertical displacements (x_0 and y_0 both in meters). There is a large *instantaneous* dependence of ω on the particle's energy offset. However, no *net* growth is observed. First studies show that the sextupoles can be used effectively to cancel this slow spin precession. Work on this continues.

Questions to be answered are:
1. What are the sources of spin decoherence at second and higher order?
2. What is the magnitude of each of these sources?
3. Does electric or magnetic focusing lead to the smallest spin decoherence?
4. To what level can sextupoles and higher multipoles (at practical strengths) reduce spin decoherence?
5. What is the effect of fringe fields?
6. How can two counter propagating beams be accommodated?
7. What is the effect of beam heating (necessary for polarimetry)?
8. What are the (quantitative) effects of lattice imperfections?

Once these questions are answered the strategy to prolong the spin coherence can be formulated and tested.
Efforts are concentrated on this stage.

III. Experimental Studies at Existing Facilities (e.g. COSY)

Experimental studies of the spin coherence are planned at the cooler synchrotron COSY at the German research center in Jülich. Preliminary studies are being made to understand the present lattice, the resulting spin coherence time and ways to improve the coherence using the current setup [A. Luccio et al., Proc. PST'09 Conference].
The measurement of short coherence times is difficult. The coherence time is determined by the spread in the spin tune. This spread can be deduced from the measurements made by the Spin@COSY collaboration. They try to induce a spin-flip in a vertically vector polarized deuteron beam using an RF solenoid. For a long solenoid-on time at a fixed frequency, the width of the observed resonance is determined by the spin tune spread. First results suggest a resonance width for a bunched beam of several Hz (FWHM). Hence the corresponding coherence time is of the order of 100ms. The final goal is the quantitative description of these results, as well as those obtained when sweeping the RF frequency (Froissart-Stora sweep), using a model.
This stage is still in its infancy.

Risk & Effort

Spin decoherence needs to be controlled by three orders of magnitude compared to what is presently available for high energy stored beams. Whether such control is possible *in principle*, *i.e.* in a model, needs to be demonstrated first. *Practical* demonstration hinges on the ability to develop a successful strategy to (a) expose the dominant sources for decoherence and (b) to correct for them. These two conditions must be fulfilled successfully prior to the final design of the EDM ring.

The first stage of this program has mostly been completed. Current efforts are focused on the second stage. First exploratory steps are made for the third stage. For the last few years this project has greatly benefited from the concentrated effort made possible by the funding for a postdoc (Fanglei Lin). This funding has now run out. To guarantee continued progress a new dedicated postdoc position needs to be funded to complete the second stage of this program. The experimental program considered for COSY is expected to cover several years, extending beyond the typical “lifetime” of a postdoc. It includes modeling, experiment preparation, running and analysis. It makes for an ideal Ph.D. student project. Other members of the spin coherence study team are Alfredo Luccio (BNL), Nikolay Malitsky (BNL), Bill Morse (BNL), Gerco Onderwater (KVI), Yuri Orlov (Cornell), Vadim Ptitsyn (BNL), Yannis Semertzidis (BNL), Richard Talman (Cornell).

Funding request

The cost for the spin coherence time R&D program is driven by cost for personnel and travel expenses for the experimental part of the program. In the table below the amount requested for a 3 year R&D program is listed.

Item	Amount requested [k$]	Comments
Postdoc	300	
Graduate student	135	
Stationing	105	
Travel to BNL	45	6 person-trips per year
Travel to COSY	25	3 expt's / 2wks / 3 people
Conference visits	15	2 people-conf. / year
Computing & DAQ facilities	35	Computer + electronics
Sub-total	705	
Miscellaneous (30%)	210	Overheads, unforseen
Total	**916**	

It is assumed that small modifications to the COSY ring can be provided by COSY (as they did for the polarimeter work). So we do not ask for any money here.