ELECTRON POLARIZATION IN THE MEDIUM-ENERGY ELECTRON-ION COLLIDER AT JLAB*

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Abstract

A key feature of the Medium-energy Electron-Ion Collider (MEIC) at Jefferson Lab is high polarization (over 80%) of the electron beam at all collision points for the particle physics program. The equilibrium electron polarization is arranged to be vertical in the arcs of the figure-8 collider ring of the MEIC and anti-parallel to the arc dipole magnetic fields, in order to take advantage of the preservation of polarization by the Sokolov-Ternov (S-T) effect. Longitudinal polarization is achieved at collision points by utilizing energy-independent universal spin rotators each of which consists of a set of solenoids and dipoles placed at the end of an arc. The equilibrium beam polarization and its lifetime depend on competition between the S-T effect and radiative depolarization. The latter must be suppressed by spin matching. This paper reports on investigations of polarization in the MEIC electron collider ring and a preliminary estimate of beam polarization from calculations using the code SLICK.

INTRODUCTION

The MEIC electron ring at Jefferson Lab is designed to store, manipulate and preserve a highly polarized (over 80%) electron beam as required by the particle physics program. Many issues have to be carefully considered, such as a polarized source, self-polarization and depolarization, polarization time, and spin rotator, etc.

The main source of polarization of the MEIC electron beam is the CEBAF at Jefferson Lab. Currently, the electron polarization from the CEBAF at 6 GeV is above 85%. It is expected that a similarly high polarization will be achieved after completion of the 12 GeV upgrade. The S-T [1] effect will then help to preserve the electron polarization and improve the polarization lifetime.

The electron polarization is aligned in the vertical direction and anti-parallel to the magnetic field of the arc dipoles. To achieve longitudinal polarization at collision points, 90^0 spin rotators are required at each end of the two half arcs. Figure 1 illustrates the orientation of the polarization in various parts of the ring. Since the spin tune is energy dependent, one or more spin tuning solenoids are needed to control the closed orbit spin tune and keep it away from resonances [2]

$$\nu_{spin} = k_0 + k_x \nu_x + k_y \nu_y + k_z \nu_z. \qquad (1)$$

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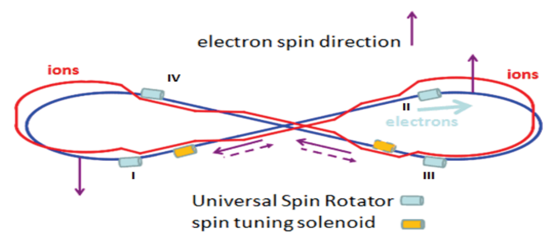

Figure 1: Illustration of the polarization orientation in the MEIC electron collider ring.

The spin rotators in the MEIC electron ring must perform correctly over an energy range of 3 to 11 GeV. Universal Spin Rotators (USR) [3] have been proposed recently for this task. They comprise interleaved solenoids and dipoles as shown in Fig. 2. The design orbit outside the rotators will be the same at all energies. To eliminate the transverse coupling introduced by the solenoids [4], each solenoid is split into two equal halves and five quadrupoles (in three families) are inserted between the halves. A block-diagonal 4×4 transport matrix is obtained by properly choosing the quadrupole strengths.

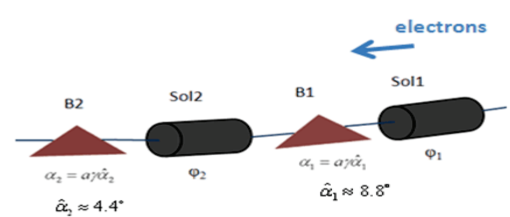

Figure 2: The schematic layout of a USR.

EQUILIBRIUM POLARIZATION AND POLARIZATION LIFETIME

In contrast to the spin dynamics of ions in a storage ring, where the evolution of a spin vector just follows from the Thomas-BMT equation, synchrotron radiation from electrons causes spin flip. This, the S-T effect, is purely quantum mechanical and since the transition rates for the two initial spin orientations differ, the polarization can build up to 92.4% in ideal circumstances. However, once radiative depolarization is taken into account, the equilibrium electron polarization is given by the Derbenev-Kondratenko (D-K) [2,5] formula

$$P_{dk} = \frac{8}{5\sqrt{3}} \frac{\oint ds \left\langle \frac{1}{|\rho(s)|^3} \hat{b} \cdot \left(\hat{n} - \frac{\partial \hat{n}}{\partial \delta} \right) \right\rangle_s}{\oint ds \left\langle \frac{1}{|\rho(s)|^3} \left(1 - \frac{2}{9} (\hat{n} \cdot \hat{s})^2 + \frac{11}{18} \left(\frac{\partial \hat{n}}{\partial \delta} \right)^2 \right) \right\rangle_s} , \qquad (2)$$

where $< >_s$ denotes an average over phase space at azimuth s, $\hat{s}$ is the direction of motion, $\hat{b}$ is a unit vector

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along the magnetic field, $\hat{n}$ is a 1-turn periodic unit 3-vector field over the phase space satisfying the Thomas-BMT equation along particle trajectories $u(s)$, and $\delta = \Delta E/E$ is the relative energy deviation. The first two terms in the parenthesis in the denominator of Eq.(2), come from the generalization by Baier and Katkov [6] of the original S-T expression to an arbitrary magnetic field. The third term contains the *spin-orbit coupling function* $\frac{\partial\hat{n}}{\partial\delta}$, which quantifies the radiative depolarization. The beam polarization points along the unit vector $\hat{n}_0$. This is the 1-turn periodic solution of the Thomas-BMT equation on the closed orbit: $\hat{n}_0 = \hat{n}(u = 0; s)$. To obtain high polarization, we need $\left|\frac{\partial\hat{n}}{\partial\delta}\right|^2 \ll 1$ in dipole magnets where $1/|\rho(s)|^3$ is large. Correspondingly, the inverse polarization time constant for this build-up of equilibrium polarization in the presence of radiative depolarization [2] is

$$\tau_{dk}{}^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m_e c}\frac{1}{C}\oint ds\ \langle\frac{(1-\frac{2}{9}(\hat{n}\cdot\hat{s})^2+\frac{11}{18}\left(\frac{\partial\hat{n}}{\partial\delta}\right)^2)}{|\rho(s)|^3}\rangle_s, \quad (3)$$

which implies that due to the self-polarization effect, the equilibrium polarization, P_{dk}, will be achieved after several polarization lifetimes, τ_{dk}.

Instead of relying on self-polarization, one can inject an electron beam with a polarization higher than the equilibrium value P_{dk}. Then the polarization will approach this value with the characteristic time τ_{dk}. Since the S-T polarization time is inversely proportional to the 5th power of the beam energy, injecting a pre-polarized beam is the only solution if the required energy of the stored beam is so low that τ_{dk} is impractically large. It is also practical if the lifetime of the stored beam is small: full polarization is immediately available while the luminosity is still high. Since CEBAF can usually provide a polarization higher than the equilibrium polarization, this would be important at high energy if the depolarization rate were high, as happens when $\left|\frac{\partial\hat{n}}{\partial\delta}\right|^2$ in Eq.(3) is large compared to 1. The detail will be discussed in the next section.

Estimating the equilibrium polarization and lifetime, with inclusion of high order resonances, requires evaluating $\hat{n}$ and $\frac{\partial\hat{n}}{\partial\delta}$ all over the orbital phase space and this can require large amounts of computer power. However, valuable first impressions can be obtained easily and quickly by linearizing the spin motion as in the SLIM [7] algorithm. This is implemented in the thick-lens code SLICK. For details of these matters see [2]. The linearization entails assuming that the angle between $\hat{n}$ and $\hat{n}_0$ is small all over phase space. The formalism only exhibits the first order spin-orbit resonances but that suffices in the first steps.

The first estimates of equilibrium polarization and the polarization time for the baseline design of the MEIC electron ring at 5 GeV using SLICK are 7% and 13 minutes, respectively. So the depolarization is significant in the current design. The situation can be worse if magnet misalignments are also considered. Since pre-polarized electrons would be injected from CEBAF, the polarization time τ_{dk} should be as large as possible to ensure that the polarization remains large for as long as possible.

SPIN MATCHING

Then, as already mentioned, the optics and layout must be chosen so that $\left|\frac{\partial\hat{n}}{\partial\delta}\right|^2$ is small where $1/|\rho(s)|^3$ is large.

Although we prefer to calculate and discuss within the D-K framework, the essence of depolarization can be understood heuristically as follows. When a photon in the synchrotron radiation is emitted from an electron, the subsequent orbital motion of the electron is perturbed. Since the quadrupole fields are non-uniform and since the photon emission is a stochastic process, the coupling of the spins to the trajectories by the Thomas-BMT equation causes the spins to drift stochastically away from the equilibrium polarization direction, namely $\hat{n}_0$, so that polarization can be reduced. The depolarization can be strong when the integrated spin-orbit coupling is large, as for example in interaction regions where $\hat{n}_0$ is horizontal in order to get longitudinal polarization, or when $\hat{n}_0$ is tilted from the vertical in the arcs due to closed orbit distortion.

If there is enough flexibility in the optics and the layout, $\left|\frac{\partial\hat{n}}{\partial\delta}\right|^2$ can be appropriately reduced by "*spin matching*". This is described in detail in [2] and it relies heavily on the linearization in the SLIM formalism. Briefly, "*strong synchrobeta spin matching*" is applied to the optics of a perfectly aligned ring, in particular to the interaction regions and the rotators, and "*harmonic closed orbit spin matching*" is applied to soften the effect of misalignments by adjusting the closed orbit to reduce the tilt of $\hat{n}_0$ from the vertical in the arcs. Because the misalignments and the closed orbit are usually not known with a precision sufficient to predict the tilt of $\hat{n}_0$, the closed orbit is adjusted empirically while the polarization is measured. At this stage of our studies only strong synchrobeta spin matching is being developed. A section of a ring for which strong synchrobeta spin matching has been achieved is said to be "*spin transparent*".

As a first step it is necessary to understand the sources of depolarization in the perfectly aligned ring. Except for the two regular arcs, the MEIC electron collider ring has the rotators and the sections between them. These latter include the final-focus regions near the interaction points and the sections for chromaticity compensation etc. In general, the rotators and the sections between them are the main source of depolarization and this is confirmed by calculations with SLICK. Within the SLIM formalism these sections should be considered as a whole. Thus a single quadrupole will not be spin transparent, but by suitable choice of optics it might be possible to make the

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whole region from the entrance of the first solenoid to the exit of the last solenoid spin transparent. Dominant contributions can often be discovered by switching off the spin-orbit coupling for chosen sections. By this means it is found that the dominant source of depolarization comes from the energy (δ) dependence of the spin precession in the longitudinal fields of the solenoids. This produces strong first order spin-synchrotron resonances.

Within the heuristic view sketched above, spin transparency of a section is achieved when, in linear approximation, kicks to a spin away from $\hat{n}_0$ due to the magnetic fields of quadrupoles, solenoids and dipoles are zero for a particle entering the section at any position u in phase space.

Spin matching can be a tedious task since an optic developed for spin matching must also be practical for the orbital motion. For example, the orbital tunes, the chromaticities and the beta functions must be acceptable. Moreover, in order to utilize the S-T effect to preserve the electron polarization, the directions, $\hat{n}_0$, of the equilibrium polarization must be opposite and anti-parallel to the magnetic field in the two half arcs of the figure-8 ring. Thus in the current design, the rotators on each side of an Interaction Point (IP) have the same direction of magnetic field (i.e. same polarity) in the solenoids and opposite directions of the magnetic field (i.e. opposite polarity) in the dipoles. So the integral of the solenoid fields does not vanish for the whole stretch between the entrance of the first spin rotator and the exit of the second. Hence at the first order there is net spin perturbation from non-zero δ in the solenoids [8]. This is the source of the depolarizing effect of the solenoids mentioned above. Thus the spin matching may also involve redesigning the spin rotators.

A first calculation of polarization time was carried out by switching off the spin-orbit coupling inside the spin rotators. SLICK shows that at 5 GeV in the MEIC electron baseline lattice and with perfect alignment, the polarization lifetime can reach 1.7 hours with 35% equilibrium polarization. Furthermore, by switching off all orbit-spin coupling inside and between the spin rotators, the polarization lifetime will be 126 hours with 84% equilibrium polarization, which is below 92.4% because $\hat{n}_0$ is perpendicular to the fields in the dipoles between the rotators around the same IP. Self-polarization will be essential for reaching high polarization when unpolarized electrons are injected. In these cases spin matching is likely to be essential. However, for a continuously injected high polarization electron beam, for example from CEBAF, the demand for the spin matching is relatively mild. As long as the polarization can be maintained for a reasonable time period, such as half an hour, the electron beam can be dumped and re-injected without burdening the source too much.

CONCLUSION

We have described our first studies of electron polarization in the MEIC collier ring at 5 GeV for the current baseline optics. Using the thick-lens code SLICK, the calculated equilibrium polarization and lifetime show significant depolarization with perfect alignment. First calculations confirm that the spin rotators and the sections between them are the main source of depolarization. Spin matching will be performed by manipulating the optics and layout of the lattice to achieve spin transparency between the two spin rotators.

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