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ELECTRON POLARIZATION PRESERVATION IN THE EIC*

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Abstract

Polarization levels in the Electron Storage Ring (ESR) of the Electron-Ion Collider (EIC) must be maintained for a sufficient time before depolarized bunches are replaced. The depolarizing effects of synchrotron radiation can be minimized with spin matching, however the optics requirements for the ring must still be satisfied. Furthermore, the robustness of the polarization in the presence of misalignments, beam-beam effects, and the eventual insertion of a vertical emittance creator – necessary to match the electron and ion beam sizes at the interaction point – must be ensured. In this work, the results of various polarization analyses of the ESR lattices are presented, and their implications discussed; the necessity for a longitudinal spin match in the 18 GeV case is investigated, and vertical emittance creation schemes with minimal effects on polarization are analyzed.

INTRODUCTION

The Electron-Ion Collider (EIC) to be built at Brookhaven National Laboratory will provide polarized electron and light-ion collisions for a wide range of selected center-of-mass energies. The Electron Storage Ring (ESR) of the EIC will store polarized electron beam at roughly 5, 10, or 18 GeV, with the exact energies chosen so a half-integer closed-orbit spin tune, furthest away from the integer spin resonances, is obtained. Longitudinally polarized bunches for collisions will be achieved at each energy by employing a set of solenoidal spin rotators on either side of the interaction point (IP). The solenoid strengths may be chosen for each energy so that, paired with the spin precession in the bend modules, $\hat{n}_0$ is rotated from vertical in the arc to longitudinal at the IP, and then back to vertical in the arc. A schematic of the interaction region (IR) is shown in Fig. 1. Each solenoid "module" consists of two solenoids separated by either 5 or 7 quadrupoles for decoupling and spin matching.

Figure 1: Spin rotators in the interaction region of the ESR, with the spin precession angles in each module labelled [1].

Electron polarization evolution in a storage ring is defined primarily by two major effects: 1) the *Sokolov-Ternov (ST) effect* is an asymmetry in the spin flip during photon emission, and leads to a buildup of polarization antiparallel to the arc fields; 2) *spin diffusion* which depolarizes the bunch due to the stochasticity of synchrotron radiation [2–4]. These effects balance out over time, causing the polarization to asymptotically approach P_∞ as in Eq. (1). Neglecting kinetic effects, the rate τ_{eq}^{-1} is simply the sum of the ST rate τ_{st}^{-1} and the spin diffusion rate τ_{dep}^{-1} [5].

$$P(t) = P_\infty \left(1 - e^{-t/\tau_{\text{eq}}}\right) + P_0 e^{-t/\tau_{\text{eq}}}. \tag{1}$$

For the ESR, half of the electron bunches will have injected polarizations antiparallel to the arc fields (for positive longitudinal polarization at the IP), and half will have injected polarizations parallel to the arc fields (for negative longitudinal polarization at the IP). Once the time-averaged polarization for a bunch drops to ±70% (with sign chosen as the initial injected sign), it must be replaced. Therefore, due to the ST effect, the positively-polarized bunch replacement time T_+ will be greater than the negatively-polarized bunch replacement time T_-. These times can be numerically computed from the time-average of Eq. (1) after calculating P_∞ and τ_{eq}^{-1}. The long-term average bunch replacement time T may then be computed using Eq. (2) [6]. T must be at least greater than 2.4 min for the 18 GeV case [7]:

$$T = \frac{2T_+T_-}{T_+ + T_-}. \tag{2}$$

In order to minimize the spin diffusion, a strong synchro-beta spin match is desired across the IR (from arc-to-arc). Approximate horizontal and longitudinal spin matching conditions have been derived for the ESR, and simplified expressions are shown in Eq. (3) and Eq. (4) respectively [8]. H_i is a function of the transfer matrix $\mathcal{M}_i$ across the i-th solenoid module, ϕ_i is the spin precession in the i-th solenoid module, ψ_j is the spin precession in the j-th bend module, and $\vec{k}_0 = \hat{l}_0 + i\hat{m}_0$ in terms of the right-handed spin basis on the closed orbit $(\hat{n}_0, \hat{m}_0, \hat{l}_0)$. Horizontal spin matching is achieved by setting each $\mathcal{M}_i$ so that $H_i(\mathcal{M}_i) = 0$. With this condition satisfied for a given energy, by Eq. (4) a longitudinal spin match (LSM) is entirely determined by the spin precession in the solenoids (variable with solenoid length or field strength) and in the bends (variable with bend angle).

$$\sum_{i=1}^{4\text{ sol}} H_i(\mathcal{M}_i) = 0 \tag{3}$$

$$a\gamma_0 \sum_{i=1}^{4\text{ sol}} H_i(\mathcal{M}_i) + \sum_{i=1}^{4\text{ sol}} \phi_i k_{0s,i} - \sum_{j=1}^{4\text{ bend}} \psi_j k_{0y,j} = 0 \tag{4}$$

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Table 1: Solenoid and bend module spin precession angles for the 18 GeV ESR versions analyzed in this work.

	Solenoids		Bends	
	$\phi_{1,4}$	$\phi_{2,3}$	$\psi_{1,4}$	$\psi_{2,3}$
ESR v5.3 (LSM)	30°	120°	180°	90°
ESR v5.6 (No LSM)	0°	90°	180°	90°
ESR v6.0 (No LSM)	0°	90°	227°	90°

All energies for the ESR are horizontally spin matched. Calculations of the depolarization times with Monte Carlo tracking have shown that a LSM does not appear necessary for the lower energy cases. However, at 18 GeV the effects of a LSM are much more significant. Furthermore, the eventual insertion of a vertical emittance creator in the ESR - necessary to match the electron and ion beam sizes - will have detrimental effects on polarization unless carefully implemented. We present the importance and feasibility of achieving a LSM for the 1-IP and 2-IP 18 GeV cases of the ESR. We also present the results of a vertical chicane as a vertical emittance creator, and the effects on polarization.

The preliminary ESR lattice versions analyzed in this work are titled v5.3, v5.6, and v6.0, where v5.3 is the oldest lattice version and v6.0 is the latest version. Table 1 shows the spin precession angles in the solenoid and bend modules for each version at 18 GeV, with each ϕ_i and ψ_j as labelled in Fig. 1. Each ESR version has both a 1-IP lattice (with only the 6 o'clock IR active) and a 2-IP lattice (with both 6 o'clock and 8 o'clock IRs active).The v5.3 and v5.6 supported a low energy case of 6 GeV instead of the current 5 GeV, geometrically allowing for both short ($\phi_{1,4}$) and long ($\phi_{2,3}$) solenoid modules to be on at 18 GeV and still achieve longitudinal $\hat{n}_0$ at the IP. The latest version, v6.0, has a low energy case of 5 GeV which is more desirable to experimenters, but no possibility for a longitudinal spin match.

LONGITUDINAL SPIN MATCH

Significance and Feasibility

The longitudinal spin match was originally dropped going from v5.3 to v5.6 due to various undesirable nonlinear effects, including low polarization [9], that resolved when turning off the short solenoid module (thus losing the LSM) and setting the dispersion to zero in the long solenoid module. These effects were later determined to be caused by a 2^{nd} order synchrobeta resonance excited by vertical dispersion in quadrupoles - as is the case when entering a solenoid module with nonzero horizontal dispersion. By changing the tunes, the effects may be resolved; the nonlinear polarization can have excellent agreement with the analytical calculation [10]. While this finding led to a change in the working point, it also re-opened the question of whether or not a LSM should be achieved in the ESR.

In the analytical calculations of P_∞ and τ_{dep}^{-1}, one of the modes of spin-orbit coupling can be ignored by zeroing the amplitude of that mode's spin eigenvector in the calculation of $\frac{\partial \hat{n}}{\partial \delta}$ [11]. This provides a good diagnostic of the effects of spin matching a particular mode. Figure 2 shows an energy scan of the average bunch replacement times for the v5.3 1-IP and v5.6 1-IP lattices, and their values when ignoring the longitudinal (c) mode.

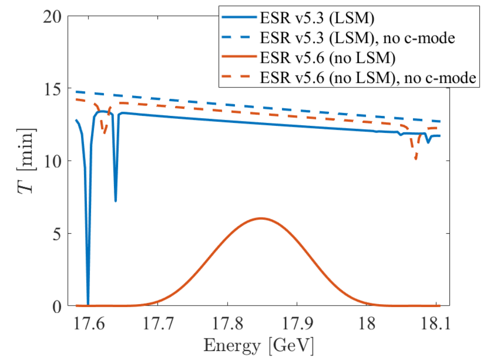

Figure 2: Average bunch replacement times for the v5.3 (LSM) and v5.6 (no LSM).

Table 2: Solenoid Strengths for LSM vs. no LSM

	B_{short} [T]	B_{long} [T]
ESR v5.6 w/ LSM	11.1	11.3
ESR v6.0 (No LSM)	7.4	8.5

The v5.6 at the half-integer spin tune has an average replacement time of 6.0 min, vs. the v5.3 with 12.6 min. However, ignoring longitudinal spin-orbit coupling, the replacement times are very similar. This strongly suggests that the lack of a LSM in the v5.6 is the primary cause for the large reduction. While a LSM is significant and desired at 18 GeV, the feasibility must also be considered. Given the bend angles, the v5.6 may still gain a LSM by adjusting the solenoid strengths to give the spin precession angles as for the v5.3 in Table 1. The solenoid strengths to achieve a LSM in the v5.6 vs. dropping the LSM altogether and adopting the v6.0, which also supports a low energy of 5 GeV instead of 6 GeV, are shown in Table 2. The solenoid field strengths necessary for a LSM are simply too high to realistically engineer, and even without a LSM, T is still reasonably above the minimum 2.4 min.

Partial LSM Using the 2nd Interaction Region

While a full LSM over a single IR is not feasible, it may be possible to achieve a partial LSM around the ring; for the 1-IP case, using the solenoids in the 2^{nd} IR we can attempt to spin match from the start of the 6 o'clock IR to the end of the last active solenoid in the 8 o'clock IR. The spin matching condition for this case looks the same as that in Eq. (4), but the solenoid sums are now over 8 solenoid modules and the bend sum is over 9 bend modules (including the bend between IR-6 and IR-8, ψ_5). Thus, with horizontal spin matching $H_i(\mathcal{M}_i) = 0$ and assuming a constant geometry (constant ψ_i's), the goal is to minimize g in Eq. (5) where

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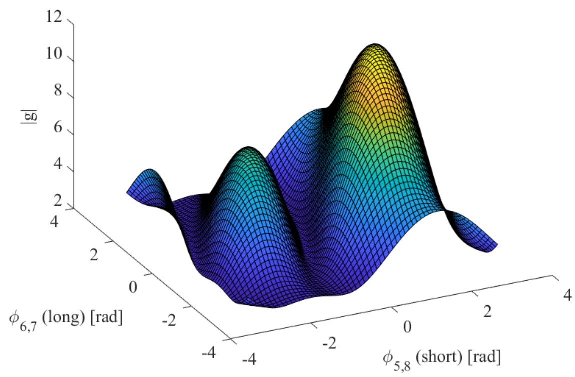

Figure 3: $|g(\phi_5, \phi_6)|$ with $\phi_5 = \phi_8$ and $\phi_6 = \phi_7$ (case 1) for the ESR v5.6.

ϕ_5, ϕ_8 are the IR-8 short solenoid module precession angles and ϕ_6, ϕ_7 the long solenoid module precession angles.

$$g(\phi_5, \phi_6, \phi_7, \phi_8) = \sum_{i=1}^{8\text{ sol}} \phi_i k_{0s,i} - \sum_{j=1}^{9\text{ bend}} \psi_j k_{0y,j} \quad (5)$$

Each ϕ_i must be chosen so that $\hat{n}_0$ returns to vertical. For the v6.0, due to the bend module precession angles, this leaves only $\phi_{5,8} = 0$ and $\phi_6 = \phi_7$. For the v5.6, there are three simple cases: 1) $\phi_5 = \phi_8$ and $\phi_6 = \phi_7$; 2) $\phi_5 = \phi_6$ and $\phi_7 = \phi_8$; 3) $\phi_5 = -\phi_7$ and $\phi_6 = -\phi_8$. We start with the v5.6. For each of the three cases, surfaces of $|g|$ like Fig. 3 may be generated. With the IR-8 solenoids all off, $|g| = \pi$. Because the choice of angles for minimum $|g|$ is not unique, the angles which minimize the length of the section we attempt to partially LSM are selected as optimal.

The same minimum value $|g_{\min}| = 2.2561$ was obtained for each case, and is dependent on the spin precession angle in the bend between IR-6 and IR-8 (ψ_5). In fact, if $\psi_5 = n\pi$, $n \in \mathbb{Z}$, then $g_{\min} = 0$ and thus a full LSM using the 2$^{\text{nd}}$ IR is achievable. Unfortunately, this is not the case, and such geometry changes to make $\psi_5 = n\pi$ are not feasible. We determined the best scheme to be one of case 2 with $\phi_{7,8} = 0$, so that only the first set of solenoids before IP-8 are on; this achieves a partial LSM at the earliest point in the lattice. The scheme was implemented into a Bmad lattice and both optics matched and horizontally spin matched. The resulting increase in T was 0.4 min, as shown in Table 3. For the v6.0, which has only one valid solenoid setting ($\phi_{5,8} = 0$ and $\phi_6 = \phi_7$), $|g_{\min}| = 2.2564$. Thus, we expect the result to be similar to that for the v5.6.

For the 2-IP v5.6, where both IR-6 and IR-8 have the same solenoid settings, $|g| = 5.7858$. By flipping the polarity of the IR-8 solenoids (and thus the sign of the polarization at IP-8), $|g| = 2.45$. This simple change significantly improves T, as shown in Table 3. A similar result is seen in the v6.0, and so this solution will be adopted for the 2-IP lattice.

Table 3: Replacement Times for 18 GeV ESR Lattices

18 GeV ESR Lattices	T_+ [min]	T_- [min]	T [min]
v5.3 1-IP, LSM	77.8	6.9	12.6
v5.3 2-IP, LSM	29.2	6.4	10.6
v5.6 1-IP, no LSM	11.0	4.1	6.0
v5.6 1-IP, partial LSM	11.5	4.4	6.4
v5.6 2-IP, no LSM	4.0	2.5	3.1
v5.6 2-IP, flip IR-8 polarity	7.8	3.9	5.2
v6.0 1-IP, no LSM	9.8	3.8	5.5
v6.0 2-IP, no LSM	4.7	2.8	3.5
v6.0 2-IP, flip IR-8 polarity	7.5	4.0	5.2

VERTICAL EMITTANCE CREATION

A scheme must be implemented in the ESR that gives $\epsilon_y \sim 0.1\epsilon_x$ while also maintaining sufficient polarization and satisfying the optics requirements. Vertical emittance can be created by photon radiation in the vertical direction, radiation in the horizontal direction in regions with vertical dispersion, and coupling the horizontal emittance into the vertical. There are many different ways to do each, or a mix, of these. One method is to insert a vertical chicane as a closed vertical dispersion bump. This was done in the v5.6 in the longest, dispersion-free (to minimize $\frac{\partial \hat{n}}{\partial \delta}$) drift. Four dipoles - up, down, down, up - with the same chord length as the arc dipoles were used, and the bend angle varied so that $\epsilon_y = 0.1\epsilon_x$. The field strength necessary to achieve this ratio was $B = 0.657$ T, which is impractical. Furthermore, T dropped to 2.8 min; this is too close to the minimum 2.4 min, and so spin matching will be necessary. Finally, with this scheme, the emittance ratio will not be maintained at 5 GeV due to the use of superbends at that energy.

We are currently investigating vertical closed orbit bumps through sextupoles so that delocalized coupling is excited, paired with harmonic closed orbit spin matching to fix the tilt of $\hat{n}_0$ in the arc.

CONCLUSIONS

The significance of achieving a longitudinal spin match in the ESR at 18 GeV was presented, with analytical calculations suggesting a 6.6 min difference in the average bunch replacement time. However, both the infeasibility of a LSM due to the required solenoid field strengths, as well as a 6 GeV low energy case instead of the desired 5 GeV, supports the adopting of a new ESR lattice with no possibility for a LSM. A study to achieve a partial LSM using the 2$^{\text{nd}}$ IR was also performed, but only a marginal gain in the average replacement time was observed. For the 2-IP lattice, flipping the polarity of the 2$^{\text{nd}}$ IR solenoids proved highly beneficial to polarization, and will be adopted. Finally, the use of a vertical chicane as a vertical emittance creator in the ESR was ruled out due to the necessity for spin matching, excessively high field strengths, and inability to maintain $\epsilon_y \sim 0.1\epsilon_x$ for the 5 GeV case which uses superbends.

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