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POLARIZATION STUDIES FOR THE eRHIC ELECTRON STORAGE RING*

E. Gianfelice-Wendt†, Fermilab, Batavia, Illinois, USA
S. Tepikian, BNL, Upton, Long Island, New York, USA

Abstract

A hadron/lepton collider with polarized beams has been under consideration by the scientific community since some years, in the U.S. and Europe. Among the various proposals, those by JLAB and BNL with polarized electron and proton beams are currently under closer study in the U.S.

Experimenters call for the simultaneous storage of electron bunches with both spin helicity. In the BNL based Ring-Ring design, electrons are stored at top energy in a ring to be accommodated in the existing RHIC tunnel. The transversely polarized electron beam is injected into the storage ring at variable energies, between 5 and 18 GeV. Polarization is brought into the longitudinal direction at the IP by a couple of spin rotators.

In this paper results of first studies of the attainable beam polarization level and lifetime in the storage ring at 18 GeV are presented.

INTRODUCTION

2015 Nuclear Science Advisory Committee (NSAC) has recognized the realization of a high-energy, high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for nuclear science following the completion of the Facility for Rare Isotope Beams. EIC should be able of solving the nucleon spin puzzle and even explore the new quantum chromodynamics frontier of ultra-dense gluon fields.

The BNL based EIC design, eRHIC, exploits the already existing hadron complex. Because experimenters call for the simultaneous storage of electron bunches with both spin helicity, Sokolov-Ternov effect [1] is not an option for eRHIC but rather a nuisance even in a perfectly aligned machine, as it tends to polarize all bunches in the same direction, namely, for the clockwise rotating electrons, upwards.

Polarized electrons instead will be generated by a polarized electron source, accelerated in a 400 MeV Linac and in a Rapid Cycling Synchrotron (RCS) to up 18 GeV and injected at full energy into the electron storage ring. RCS and storage ring will be both accommodated into the 3835 m long RHIC tunnel. The longitudinal polarization of the electron bunches generated by the source is brought in the vertical direction by a spin rotator prior being injected into the RCS. Single bunches with ≈85% polarization, either up or down, are injected from the RCS into the storage ring where polarization is brought into the longitudinal direction at the Interaction Point (IP) through a couple of solenoidal spin rotators. In this way bunches with both spin helicities may be simultaneously stored. Bunches which polarization becomes too low must be replaced by fresh ones. The current overall design status is described in [2].

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† eliana@fnal.gov

STORAGE RING OPTICS

Various options are still under consideration for the electron storage ring optics in order to optimize the collider performance. The optics used for these studies is the so-called Achromatic Telescopic Squeezing (ATS) one. The ATS principle has been developed for the Large Hadron Collider upgrade studies [3]. The most relevant machine and beam parameters at 18 GeV are quoted in Table 1. The arcs consist of FODO cells with 90 degrees phase advance in both planes.

Table 1: Machine and Beam Parameters at 18 GeV

β_x^* [m]	β_y^* [m]	ξ_x^{nat}	ξ_y^{nat}	ϵ_x [nm]	ϵ_y [pm]
0.630	0.075	-106	-153	22.66	2.23

Storage Ring Spin Rotators

The IR requires spin rotators to precess the spin in the longitudinal direction for the detectors. A second spin rotator on the other side of the IP brings back polarization in the transverse direction. The eRHIC storage ring spin rotators must be able to operate on a wide energy range from 5–18 GeV. A dipole spin rotator would require too large an aperture at low energy. For this reason, the spin rotator of choice will use two solenoid modules and two dipoles modules as shown in Fig. 1. The lengths of the solenoids were chosen such that the field will not exceed 7 T. Rotators may cause large depolarization if not spin-matched. These modules can be made spin transparent as follows [4]: (1) split the solenoid into two equal magnets, (2) put five quadrupoles between these solenoids, and (3) ensure this module is in a zero dispersion section. Item (3) is accomplished by requiring the bending modules to have no dispersion at both ends. Strengths of the quadrupoles are then determined to have no coupling outside the module. The final beam transfer matrix

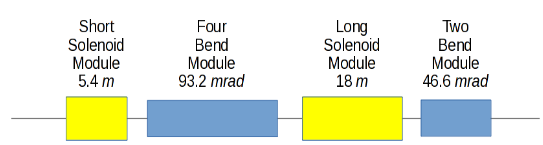

Figure 1: Schematic of the spin rotator section used on each side of the IP.

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becomes:

$$M = \begin{pmatrix} 0 & -2/K_{sol} & 0 & 0 \\ K_{sol}/2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2/K_{sol} \\ 0 & 0 & -K_{sol}/2 & 0 \end{pmatrix}$$

where $K_{sol} = B_{sol}/B\rho$. Figure 2 shows the layout of the rotator on the r.h.s.of the IP and the coupling matrix elements.

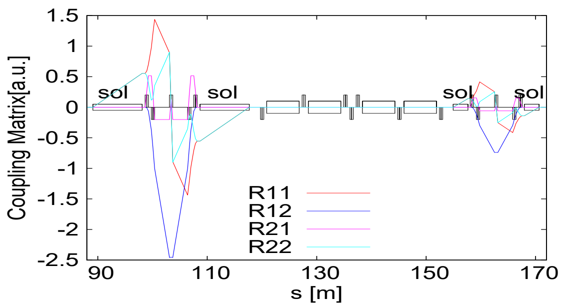

Figure 2: Right rotator layout and coupling matrix elements.

POLARIZATION IN THE STORAGE RING

The self-polarization time for an eRHIC storage ring placed in the present RHIC tunnel and with ρ_b=242 m in the FODO cells, is quite long over the entire energy range, except approaching 18 GeV where it drops to about 30 minutes. At first sight a large time before Sokolov-Ternov effect reverses the polarization of the downwards polarized electron bunches. Actually, while the Sokolov-Ternov effect is a slow process, stochastic photon emission in the storage ring in the presence of misalignments and spin rotators may quickly destroy the polarization of the injected beam, thus requiring a continuous replacement of the depolarized bunches.
Polarization varies with time as

$$P(t) = P_\infty \left[1 - \exp^{-t/\tau_p}\right] + P(0)\exp^{-t/\tau_p} \quad (1)$$

where P_∞, $1/\tau_p$ and $P(0)$ are the asymptotic polarization, the polarization rate, and the initial polarization, respectively. It holds (see for instance [5])

$$P_\infty \simeq \frac{\tau_p}{\tau_{\rm BKS}} P_{\rm BKS} \qquad \frac{1}{\tau_p} \simeq \frac{1}{\tau_{\rm BKS}} + \frac{1}{\tau_{\rm d}} \quad (2)$$

where $1/\tau_{\rm d}$ is the spin diffusion rate, $P_{\rm BKS}$ and $1/\tau_{\rm BKS}$ are respectively the Baier-Katkov-Strakhovenko asymptotic polarization and polarization rate [6]. For the eRHIC storage ring at 18 GeV it is $P_{\rm BKS}$ ≃90% and $\tau_{\rm BKS}$ ≃30 minutes. Resorting to Eqs. 1 and 2 we can evaluate that for instance in order to deliver an average polarization of about 70% in the first 5 minutes after injection it must be $P_\infty \simeq 27\%$ for the upwards polarized bunches and $P_\infty \simeq 80\%$ for the downwards ones. Figure 3 shows polarization after 5 minutes and the average polarization vs. P_∞ with $P(0)$=-85%. The benefit of increasing P_∞ saturates above ≈50%. It is important to show that a large value of P_∞ is feasible in the storage ring in presence of realistic misalignments and countermeasures as this determines the frequency of bunch

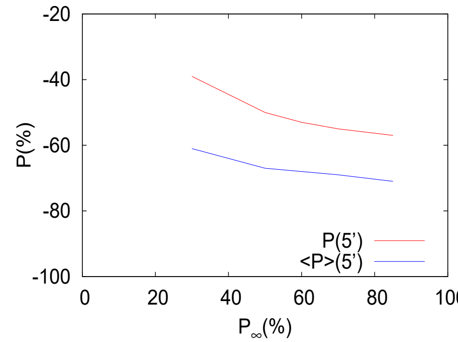

Figure 3: Variation vs. P_∞ of $P(\tilde{t})$ and $<P>$ $(\tilde{t})$ for $\tilde{t}$=5 minutes and $P(0)$=-85% .

injection. Following simulations are based on the MAD-X [7] misalignment/correction tool kit. The resulting optics is dumped into a file which can be read by the SITROS package [8] which is used for polarization calculations.

Polarization in the Unperturbed Ring

Figure 4 shows polarization in linear approximation for the unperturbed machine with luminosity tunes Q_x=60.08, Q_y=56.06 and Q_s=0.046 and in presence of one pair of spin rotators, vs. $a\gamma$ (a electron gyromagnetic anomaly), which is the spin tune for a planar machine w/o solenoids. The red, magenta and cyan lines refer to the polarization related to the radial, vertical and longitudinal motion respectively. During the scan the settings of the solenoid are fixed; however $\delta\hat{n}_0$ is relatively small over the whole energy range (see Fig. 5).

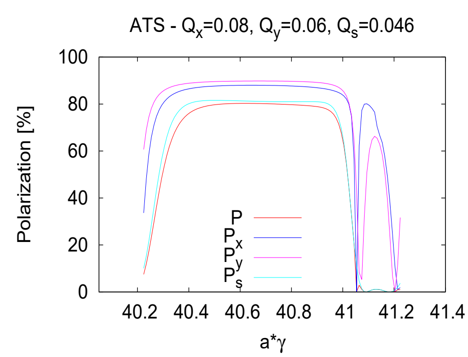

Figure 4: Linear polarization vs. $a\gamma$ for the unperturbed lattice as computed by SITF [8].

Figure 6 shows polarization as computed by the tracking code SITROS. It can be expected that, manifesting the presence of higher order resonances and synchrotron side-bands, tracking calculations give lower polarization than calculations with linearized spin motion. However the discrepancy seems exceedingly large in this case. This may be related to the fact that the vertical emittance as computed by the tracking is about 8 times larger than expected or to the fact that the IR optics is not fully spin matched.

Polarization in Presence of Misalignments

494 Beam Position Monitors (BPMs), measuring the beam position in both planes, have been added close to each quadrupole together with 494 vertical and 494 horizontal

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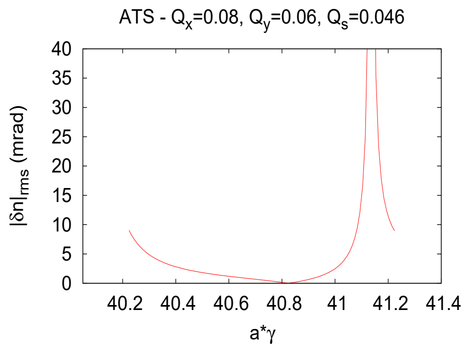

Figure 5: RMS value of $\delta\hat{n}_0$ vs. $a\gamma$ for the unperturbed lattice (SITF).

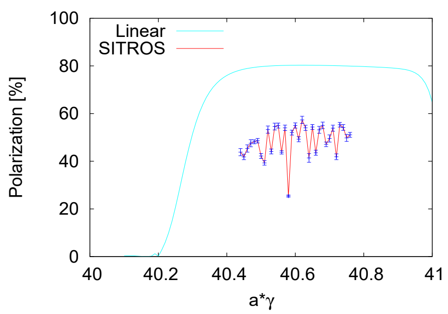

Figure 6: Polarization vs. $a\gamma$ for the unperturbed lattice from SITROS tracking. The cyan line is the linear polarization.

correctors. The RMS values of the quadrupole misalignment assumed are δx=δy=200 µm and a roll angle $\delta\Psi$=200 µrad. BPMs errors have not been included yet.

It turns out that due to the large coupling in the solenoid sections, the orbit can't be corrected in a satisfactory manner in the two planes separately in the whole machine as done by the MAD-X correction module. One way out was correcting both planes simultaneously with an "external" code and read back the corrections with MAD-X. A second problem arose by setting the luminosity tunes which are close to the integer and to the linear coupling resonance.

Recent beam-beam simulations showed that it should be possible to rise the fractional part of the betatron tunes to q_x=0.12 and q_y=0.10. For sake of space results for this working point only are shown. Corrections have been not re-optimized for the new working point. Figure 7 shows the polarization for the perturbed machine after orbit correction by a SVD using all BPMs and correctors available. In Table 2 the beam sizes at the IP are quoted.

Table 2: Beam Size at IP

	σ_x [mm]	σ_y [µm]	σ_ℓ [mm]
Analytical	0.115	15.29	7.022
SITROS	0.121	16.81	6.918

46 independently powered skew quadrupoles, inserted at high $D_x\sqrt{\beta_y}$ and $\sqrt{\beta_x\beta_y}$ locations, are used for correcting

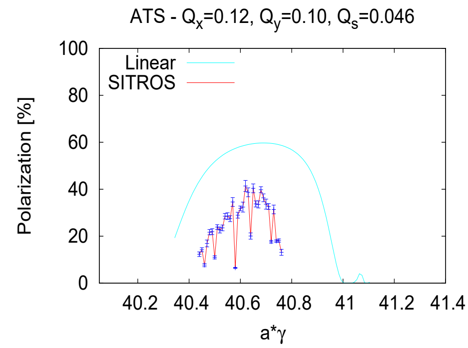

Figure 7: Polarization vs. $a\gamma$ for the perturbed lattice with q_x=0.12 and q_y=0.10.

spurious vertical dispersion and betatron coupling [9] which are large due to the vicinity of the working point to the linear coupling difference resonance. The resulting polarization is shown in Fig. 8 for the same error realization of Fig. 7. In Table 3 the beam sizes at the IP are quoted.

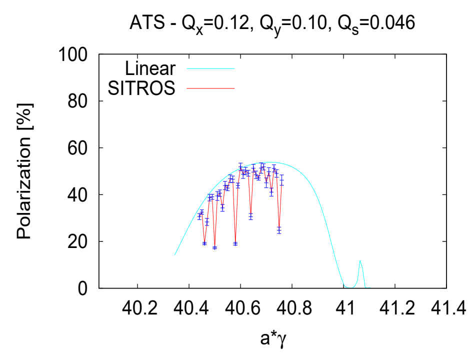

Figure 8: Polarization vs. $a\gamma$ for the perturbed lattice with q_x=0.12 and q_y=0.10. Spurious vertical dispersion and betatron coupling corrected by using 46 skew quadrupoles.

Table 3: Beam Size at IP with Skew Quads Correction

	σ_x [mm]	σ_y [µm]	σ_ℓ [mm]
Analytical	0.121	1.72	6.974
SITROS	0.145	2.44	6.999

CONCLUSION

Polarization studies for the eRHIC storage ring have started for the 18 GeV case. With conservative errors $P_\infty \approx$50% seems within reach. This means that for *upwards* polarized bunches (anti-parallel to the guiding field), $<P>\approx$ 80% over 5 minutes if $P(0)$=85%; for bunches polarized *downwards* the average polarization drops to 67%. BPMs errors need to be included, as well as beam-beam effects. If the orbit is not very well corrected, the polarization axis $\hat{n}_0$ needs a dedicated correction [10, 11]. New luminosity working point will ease orbit correction (and stability). Spurious vertical dispersion and betatron coupling must be corrected. Here the benefits of a local correction using 46 skew quadrupoles have been shown.

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