THE POLARIZATION OF THE EIC ELECTRON BEAM*

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In this paper, the current status of the studies on the electron-beam polarization at the Electron–Ion Collider are summarized.

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1. Introduction

The Electron–Ion Collider (EIC), to be hosted in the RHIC tunnel at BNL, aims to collide polarized electrons with a variety of polarized hadron beams at various CM energies. The electron-beam energies at collision will be 5, 10, and 18 GeV. The highest luminosity, 10^{34} cm^{-2}sec^{-1}, is reached by colliding 10 GeV electrons with 275 GeV protons. Experiments require a time-averaged longitudinal polarization of 70%, with both helicity within the same store. Hadron beams will, to a large extent, exploit the already existing BNL facilities. A second ring for the e-beam will be accommodated inside the RHIC tunnel together with the Rapid Cycling Ring (RCS) e^- injector.

2. Radiative polarization

$e^\pm$ beams in storage rings may become spin-polarized through the Sokolov–Ternov effect [1]. In fact, an electron (or positron) moving on a plane perpendicular to a homogeneous constant magnetic field describes circular orbits and emits synchrotron radiation, a part of which is accompanied by a flip of the particle spin direction from parallel to anti-parallel to the field and the other way round. The two processes have slightly different probability and there is an exponential build-up of polarization with a rate

$$\tau_{\mathrm{ST}}^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\hbar}{m_0}\frac{\gamma^5}{|\rho|^3}$$

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and asymptotic value of 92.4%. The net polarization direction is anti-parallel to the field for electrons and parallel for positrons.

In storage rings, polarization, if any, is directed along the periodic solution, $\hat{n}_0(s)$, to the Thomas–BMT equation [2, 3] on the closed orbit. In a perfectly planar machine, without solenoids, $\hat{n}_0$ is everywhere vertical. In actual storage rings, by design and/or due to magnet misalignments, $\hat{n}_0(s)$ may be not everywhere perfectly vertical and the beam may have a finite vertical size. In these cases, photon emission leads to a randomization of the particle trajectories and spin direction (spin diffusion).

By using a semi-classical approach, Derbenev and Kondratenko [4] gave an analytical expression for asymptotic polarization and built-up constant in the presence of spin diffusion. Outside of resonances, the asymptotic polarization is oriented along $\hat{n}_0$ and its value is

$$P_{\mathrm{DK}} = P_{\mathrm{ST}} \frac{\oint \mathrm{d}s \left\langle \frac{1}{|\rho|^3} \hat{b} \cdot \left(\hat{n} - \frac{\partial \hat{n}}{\partial \delta}\right) \right\rangle}{\oint \mathrm{d}s \left\langle \frac{1}{|\rho|^3} \left[1 - \frac{2}{9} \left(\hat{n} \cdot \hat{v}\right)^2 + \frac{11}{18} \left(\frac{\partial \hat{n}}{\partial \delta}\right)^2\right] \right\rangle}$$

with $\hat{b} \equiv \hat{v} \times \dot{\hat{v}}/|\dot{\hat{v}}|$. The corresponding polarization rate is

$$\tau_{\mathrm{DK}}^{-1} = P_{\mathrm{ST}} \frac{r_e \gamma^5 \hbar}{m_0 C} \oint \left\langle \frac{1}{|\rho|^3} \left[1 - \frac{2}{9} \left(\hat{n} \cdot \hat{v}\right)^2 + \frac{11}{18} \left(\frac{\partial \hat{n}}{\partial \delta}\right)^2\right] \right\rangle .$$

The average is meant over the 6D phase space. The quantity $\partial \hat{n}/\partial \delta$, with δ being a relative energy deviation from the nominal machine energy, quantifies the effect on the particle spin direction of the trajectory perturbation after photon emission.

In a perfectly planar machine without solenoids, it is $\partial \hat{n}/\partial \delta = 0$. In general, $\partial \hat{n}/\partial \delta \neq 0$ and it is large on the spin-orbit resonances [5]

$$\nu_{\mathrm{s}} \pm m Q_x \pm n Q_y \pm p Q_s = \text{integer}$$

with ν_{s} being the spin tune, namely the number of precession per machine turn a spin performs around $\hat{n}_0$. In a perfectly planar machine without solenoids, it is $\nu_{\mathrm{s}} = a\gamma$, a being the electron gyromagnetic anomaly. In general, $\nu_{\mathrm{s}} \approx a\gamma$. The resonances are activated by the stochastic emissions of photons. Therefore, the resulting spin diffusion increases with energy. Spin rotators are introduced in the ring lattice for turning the direction of $\hat{n}_0$ locally. Their possible depolarizing effect can be minimized by a special optics design (spin matching). Tools for curing the effect of misalignments include the correction of closed orbit, vertical spurious dispersion, and betatron coupling.

3. Assessing the needed asymptotic polarization P_∞

Experiments require both helicity in the same store, while the Sokolov–Ternov effect tends to polarize the e^- beam upwards in the EIC Electron Storage Ring (ESR). For this reason, a full energy injector is needed for filling the ring with up- and down-polarized bunches whose polarization is turned into the longitudinal direction at the Interaction Point (IP) by a pair of solenoidal spin rotators. Nevertheless, the Sokolov–Ternov effect impacts the bunch polarization, especially at high energy. Polarization builds-up exponentially

$$P(t) = P_\infty \left(1 - \mathrm{e}^{-t/\tau_p}\right) + P(0)\,\mathrm{e}^{-t/\tau_p}\,.$$

From the Derbenev–Kondratenko formulas, it is

$$\frac{1}{\tau_p} \simeq \frac{1}{\tau_{\rm BKS}} + \frac{1}{\tau_d} \qquad \text{and} \qquad P_\infty \simeq \frac{\tau_p}{\tau_{\rm BKS}} P_{\rm BKS}\,.$$

$P_{\rm BKS}$ and $\tau_{\rm BKS}$, the Baier–Katkov–Strakhovenko [6] generalization of the Sokolov–Ternov quantities are known for the nominal lattice, while τ_d, and thus P_∞, depend on the actual machine and therefore are unknown. Figure 1 shows the polarization evolution of a 10 GeV polarized beam with starting polarization $P(0) = \pm 85\%$ assuming that $P_\infty = 30\%$. Polarization decays slowly even for the initially downward-polarized bunches. Figures 2 and 3 show the polarization evolution at 18 GeV for $P_\infty = 50\%$ and 30% respectively.

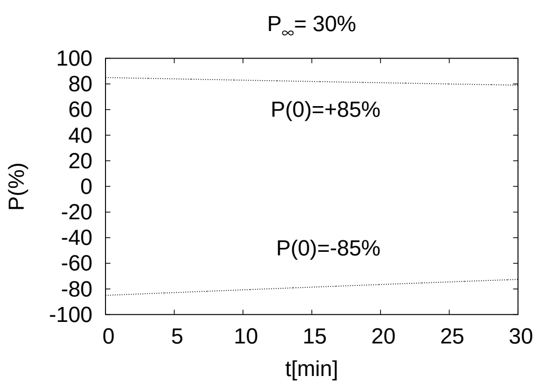

Fig. 1. Polarization *vs.* time for $P(0) = \pm 85\%$ and $P_\infty = 30\%$ at 10 GeV (ESR optics version 5.0).

At 18 GeV, the decay is faster, in particular for the initially downward-polarized bunches, and it is clear that the largest P_∞ slower the decay.

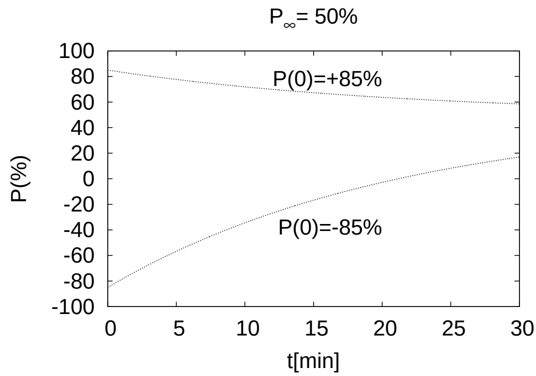

Fig. 2. Polarization *vs.* time for $P(0) = \pm 85\%$ and $P_\infty = 50\%$ at 18 GeV (ESR optics version 5.6).

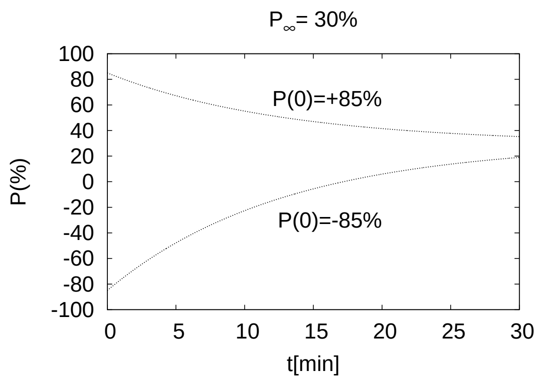

Fig. 3. Polarization *vs.* time for $P(0) = \pm 85\%$ and $P_\infty = 30\%$ at 18 GeV (ESR optics version 5.6).

4. Polarization in the ESR with v5.6 optics

The Linac is expected to deliver (longitudinally) polarized bunches with $P = 90\%$ to the Rapid Cycling Synchrotron (RCS) [7, 8]. Their polarization is rotated into the vertical direction prior injection in the RCS.

The ESR will receive upwards- and downwards-polarized bunches from the RCS. Polarization is turned into the longitudinal direction in the ESR by a pair of solenoid-based left and right rotators of the IP. The starting polarization is expected to be $\approx \pm 85\%$ [8].

In the following, only results for the most demanding 18 GeV case will be shown. The optics considered here is version 5.6 with one IP. A second IP is a still open option. The expected polarization and r.m.s. value of $\delta\hat{n}_0$ *vs.* $a\gamma$ are shown in Figs. 4 and 5, respectively, for the design optics. The calculations are done by SITF [9] with linearized spin motion. In this case, only first-order resonances may appear.

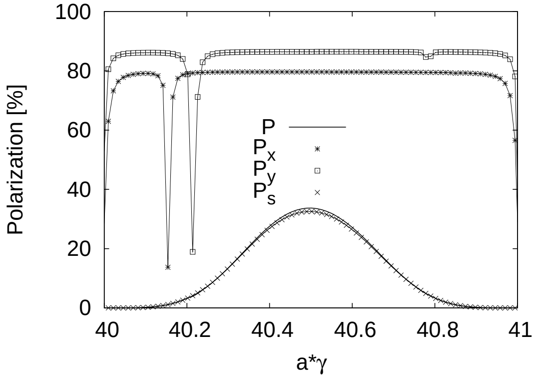

Fig. 4. Polarization *vs.* $a\gamma$ for the design ESR optics version 5.6 (linear spin motion).

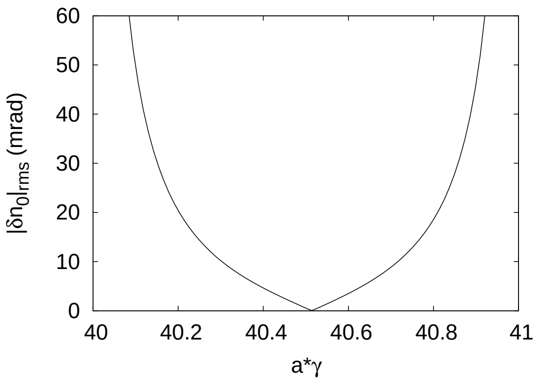

Fig. 5. R.m.s $|\delta\hat{n}_0|$ *vs.* $a\gamma$ for the design ESR optics version 5.6.

The three lines designated as P_x, P_y, and P_s show the polarization related to the purely radial, vertical, and longitudinal motion respectively. We see that the resonances related to the longitudinal motion are very strong and limit the maximum polarization. The large spin diffusion related to the synchrotron motion may originate in the Interaction Region (IR), which in the v5.6 optics is not spin matched for synchrotron motion, and/or in the arcs due to the large $\delta\hat{n}_0$ away from $a\gamma = 40.5$. Figure 6 shows the polarization computed by SITROS [9] tracking where the spin motion is not linearized. The computations have been repeated after introducing random misalignments of the quadrupoles with r.m.s. value of 200 μm for the horizontal and vertical offsets, and of 200 μrad for the roll angle. For measuring and correcting the closed orbit, a dual reading beam position monitor (BPM) and a vertical corrector have been inserted near each vertical focusing quadrupole and a horizontal corrector near each horizontal focusing one, with the ex-

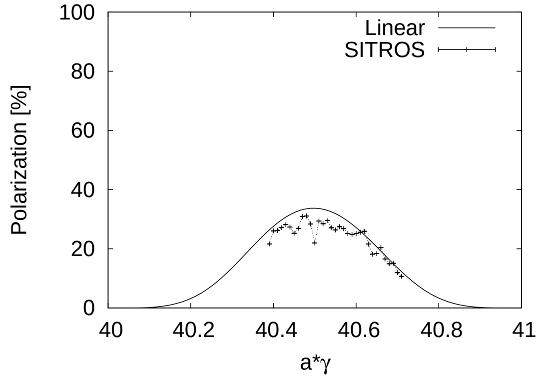

Fig. 6. Polarization *vs.* $a\gamma$ for the design ESR optics version 5.6 in linear approximation and by tracking.

ception of the IR where each quadrupole is equipped with a dual reading BPM and a horizontal and vertical corrector. It is assumed that the BPMs are integrated in the near quadrupole. In addition, residual r.m.s. errors of 20 μm and 20 μrad are superimposed and an r.m.s. calibration error of 1% assumed. The polarization (linear) and $\delta\hat{n}_0$ are shown in Figs. 7 and 8 for one particular error seed. Figures 9 and 10 show polarization in a linear approximation and $\delta\hat{n}_0$ after adding the correction of $\delta\hat{n}_0$ by "harmonic bumps" [10]. Figure 11 shows the corresponding polarization computed by the tracking. The vertical beam size at the IP, σ_y^*, computed by the tracking is 4 μm. Simulations, confirmed by HERA experience, show that e^- and hadron beam sizes must be matched at the IP. For the 18 GeV case, this means that the e^- beam σ_y^* must be about 10 μm. The simplest way for

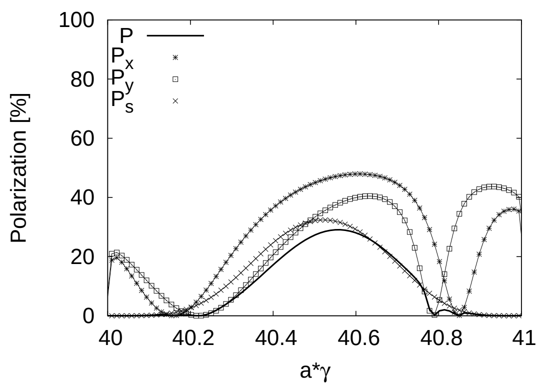

Fig. 7. Polarization *vs.* $a\gamma$ for the ESR optics version 5.6 in presence of misalignments after orbit correction (linear spin motion).

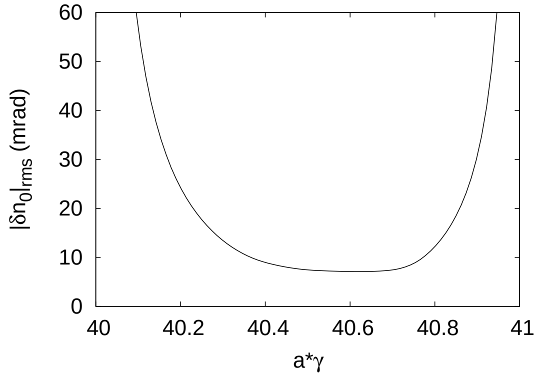

Fig. 8. R.m.s $|\delta\hat{n}_0|$ *vs.* $a\gamma$ for the ESR optics version 5.6 in presence of misalignments after orbit correction.

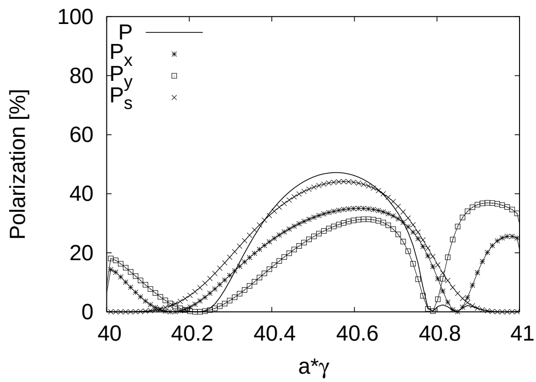

Fig. 9. Polarization *vs.* $a\gamma$ for the ESR optics version 5.6 in presence of misalignments after orbit and $\delta\hat{n}_0$ correction (linear spin motion).

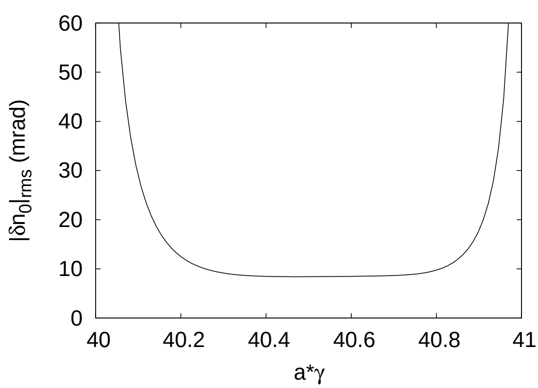

Fig. 10. R.m.s $|\delta\hat{n}_0|$ *vs.* $a\gamma$ for the ESR optics version 5.6 in presence of misalignments after orbit and $\delta\hat{n}_0$ correction.

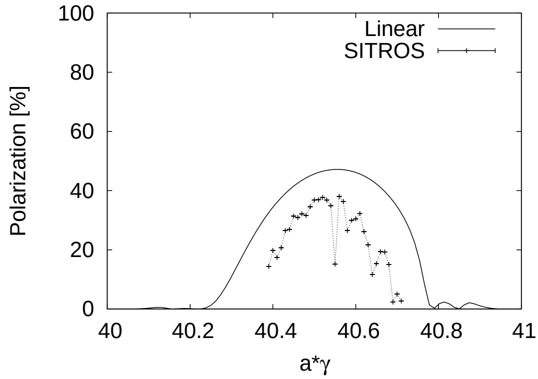

Fig. 11. Polarization *vs.* $a\gamma$ for the ESR optics version 5.6 in linear approximation and by tracking in presence of misalignments after orbit and $\delta\hat{n}_0$ correction.

increasing σ_y^*, although not the most convenient one for polarization[1], is to introduce a long vertical orbit bump in the arcs which increases the vertical emittance through the betatron coupling excited by the vertical offset in the sextupoles. Figure 12 shows the expected polarization when such a bump is added. The maximum polarization is 29%. Table 1 shows the run duration for $\langle P \rangle = \pm 70\%$ with $P_\infty = 29\%$: downwards-polarized bunches must be replaced after ≈ 3.5 minutes, while the upwards-polarized ones each ≈ 8 minutes. This is well within the injector capability.

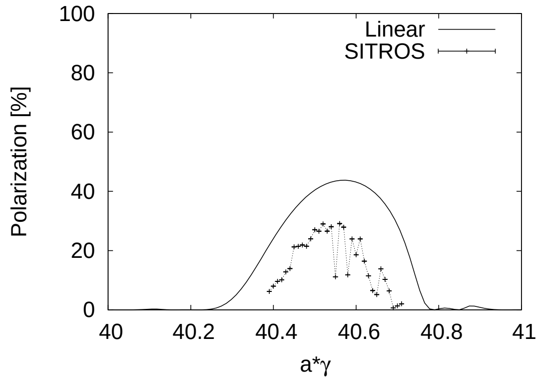

Fig. 12. Polarization *vs.* $a\gamma$ for the ESR optics version 5.6 in linear approximation and by tracking in presence of misalignments after orbit and $\delta\hat{n}_0$ correction. A long vertical bump has been added to get $\sigma_y^* = 10\ \mu$m.

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[1] Exciting local betatron coupling at the IP has been ruled out by beam–beam simulations, while introducing a dispersion bump by vertical dipoles in a dedicated quadrupole free spin matched section is not an easily tunable knob and complicates layout and optics.

Table 1. Down and up polarized bunches replacement time for $\langle P \rangle = \mp 70\%$ with $P_\infty = 29\%$.

P_∞	$P(0)$	$\langle P \rangle_{3.6'}$	$P(3.5')$	$P(0)$	$\langle P \rangle_{8'}$	$P(8')$
$+29\%$	-85%	-70%	-56%	$+85\%$	$+70\%$	$+58\%$

5. Summary and outlook

Although the polarization for the new optics design is relatively low, even for the unperturbed ring, the goal of $\langle 70 \rangle\%$ polarization can be met with the baseline injection rate (2 bunches/s for filling the ESR with 290 bunches at 18 GeV). However, larger statistics is needed and dipole rolls and beam–beam interaction must be included in the simulations. If necessary, the injection rate may be doubled.

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