Study of Electron Spin Polarization in EIC: eRHIC Storage Ring (BNL)

Outline

• Radiative polarization and the eRHIC storage ring.
• Simulations of polarization in the eRHIC storage ring.
  – Effect of mis-alignments.
• Summary and Outlook.

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Radiative polarization and the eRHIC storage ring

Experiments require

- Large proton and electron polarization ($\gtrsim 70\%$)
- Longitudinal polarization at the IP with both helicities within the same store
- Energy
  - protons: between 41 and 275 GeV
  - electrons: between 5 and 18 GeV

While high proton polarization is routinely achieved in RHIC, electron beam polarization is a new field at BNL and studies for the storage ring were ranked as high priority by the 2017 panel:

<table>
<thead>
<tr>
<th>29</th>
<th>BNL</th>
<th>CoC</th>
<th>Completion of the ongoing CEC demonstration experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>BNL</td>
<td>RR-A-1</td>
<td>Beam-Beam Parameter Validation</td>
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<td>31</td>
<td>BNL</td>
<td>RR-A-2</td>
<td>Study of Electron Spin Polarization in the Storage Ring</td>
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<td>32</td>
<td>BNL</td>
<td>RR-A-3</td>
<td>Stability Study of Beams with Crab Cavities</td>
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</tbody>
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⇒
Because the experimenters call for storage of electron bunches with both spin helicities, Sokolov-Ternov effect is not an option but rather a nuisance!

- A full energy polarized electron injector is needed: electron bunches are injected into the storage ring with high vertical polarization ($\approx 85\%$) and the desired spin direction (up/down).

- In the storage ring the polarization is brought into the longitudinal direction at the IP by a couple of solenoidal spin rotators left and right of the IP.
The goal of my project funded first by NP Accelerator R&D Plan in July 2017 was to study the electron beam polarization in the eRHIC Storage Ring. In particular

- Investigating polarization lifetime for bunches with both helicity in the same store.
  - Assessing Sokolov-Ternov asymptotic polarization to be aimed for to avoid that the beam get quickly depolarized.

- Evaluating the impact of misalignments.
  - Putting in place countermeasures.

- Investigating the effect of the beam-beam force on the electron beam polarization.

The allocated NP funds were exhausted in March 2018.

For the remaining FY18, the project has been supported by a MPO (Memorandum Purchase Order) in place through March 2019.

Results shown here reflect the *current status* of the study, not only what funded by the 2017 award!
Sokolov-Ternov effect tends to polarize the electron beam in the eRHIC storage ring *upwards*.

In the planned energy range the minimum polarization time *nominally* is $\tau_p \simeq 30'$ at 18 GeV. At first sight a large time before Sokolov-Ternov effect reverses the polarization of the down-polarized electron bunches...

However the machine imperfections may quickly depolarize the *whole* beam, independently on polarization direction.
Polarization builds-up exponentially

\[ P(t) = P_\infty (1 - e^{-t/\tau_p}) + P(0)e^{-t/\tau_p} \]

In the presence of depolarizing effects it is

\[ P_\infty \simeq \frac{\tau_p}{\tau_{BKS}} P_{BKS} \quad \text{and} \quad \frac{1}{\tau_p} \simeq \frac{1}{\tau_{BKS}} + \frac{1}{\tau_d} \]

\( P_{BKS} \) and \( \tau_{BKS} \) are the Baier-Katkov-Strakhovenko generalization of the Sokolov-Ternov quantities when \( \hat{n}_0 \) is not everywhere perpendicular to the velocity. They may be computed “analytically”; for eRHIC storage ring at 18 GeV it is

- \( P_{BKS} \simeq 90\% \)
- \( \tau_{BKS} \simeq 30 \) minutes.
For instance, with $P_\infty=30\%$, after 5 minutes $P$ decays from 85\% to
- 60\% for *up* polarized bunches
  \[ <P> = 73\% \]
- −39\% for *down* polarized bunches
  \[ <P> = -61\% \]

No much gain pushing $P_\infty$ above $\approx 50\%$
for down polarized bunches...
\[ <P> = -70\% \rightarrow P_\infty = 80\% \]

<table>
<thead>
<tr>
<th>$P(0)$</th>
<th>$P_\infty$ [%]</th>
<th>$t$ [min]</th>
<th>$&lt;P&gt;$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-85</td>
<td>50</td>
<td>4</td>
<td>70</td>
</tr>
</tbody>
</table>
Simulations for the eRHIC storage ring

- Energy: 18 GeV, the most challenging.
- BNL files must be modified for mis-alignment simulations and compatibility with SITROS, used for the polarization studies → conversion codes.
- First simulations with now obsolete optics/tunes.
- Results shown here are for the “ATS” optics with
  - $90^0$ FODO for both planes;
  - $\beta^*_x=0.7 \text{ m}$ and $\beta^*_y=9 \text{ cm}$.
  - $Q_x=60.12$, $Q_y=56.10$, $Q_s=0.046$

Tools:
- MAD-X for simulating quadrupole misalignments and orbit correction.
- SITROS package for computing the resulting polarization.
  - Tracking code with 2nd order orbit description and fully non-linear spin motion.
  - It has been used for HERA-e.
  - It contains SITF for polarization computation with linearized spin motion.
Two problems

- Large equilibrium $\epsilon_y$.
- Unusual large difference between linearized calculation and tracking.

\[ \text{For comparison: Hera-e with 3 rotators.} \]
**Bmad** (by D. Sagan) implemented on a MAC laptop for cross-checking SITROS results. 300 particles tracked over 6000 turns (typical SITROS parameters) with SR and stochastic emission with Bmad “standard” tracking.

The large $\epsilon_y$ is not a SITROS artifact. Also confirmed by MAD8 and MADX-PTC.
Add spins following SITROS path:

- Once equilibrium is reached particles coordinates are dumped on file.
- Spins parallel to $\hat{n}_0(0)$ are added and tracking re-started.

The spin tracking is very slow: 300 particles and 3000 turns take over 24 hours for one single energy point!

D. Sagan is speeding up the tracking with spin.
Machine with misalignments

- 494 BPMs (h+v) added close to each quadrupole.
- 2x494 correctors (h+v) added close to each quadrupole.
- Magnet misalignments and orbit correction simulated by MAD-X.
- Optics with errors and corrections dumped into a SITROS readable file.

**Strategy**

- switch off sextupoles;
- move tunes to 0.2/0.3;
- introduce errors;
- correct orbit (MICADO/SVD);
- turn on sextupoles;
- tunes back to luminosity values.

**Assumed quadrupole RMS misalignments**

<table>
<thead>
<tr>
<th></th>
<th>( \delta x^Q )</th>
<th>( \delta y^Q )</th>
<th>( \delta \psi^Q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal offset</td>
<td>200 ( \mu m )</td>
<td>200 ( \mu m )</td>
<td>200 ( \mu rad )</td>
</tr>
<tr>
<td>vertical offset</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>roll angle</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
MAD-X fails correcting the orbit!

Example with only $\delta y^Q \neq 0$ and sexts off. Large discrepancy between what the correction module promises...

\[
\begin{array}{cccc}
\text{average [mm]} & \text{std.dev. [mm]} & \text{RMS [mm]} & \text{peak-to-peak [mm]} \\
\hline
\text{before correction: 0.763587} & 18.408777 & 18.424607 & 216.307978 \\
\text{after correction: 0.000241} & 0.015902 & 0.015903 & 0.213275 \\
\end{array}
\]

\[\uparrow\] Effect on horizontal plane with sextupoles off

Separate horizontal and vertical orbit correction inadequate in the rotator sections → “external” program used for correcting horizontal and vertical orbits simultaneously.
One error realization

- after orbit correction
- with $Q_x=60.10$, $Q_y=56.20$ (HERA-e tunes).
Same error realization, betatron tunes moved to $Q_x=60.12$, $Q_y=56.10$ for luminosity operation; w/o skew quads, $|C^-| \approx 0.01$. 

![Graph of Polarization vs $a^\gamma$](image1)

![Graph of $|\delta n|_{\text{rms}}$ vs $a^\gamma$](image2)
Coupling and vertical dispersion correction with skew quads

Vertical dispersion due to a skew quad

\[ \Delta D_y(s) = \frac{1}{2\pi \sin \pi Q_y} D_{skq}^{skq} \beta_y(s) \cos (\pi Q_y - |\mu_y - \mu_{y^{skq}}|) (K\ell)_{skq} \]

Coupling functions

\[ w_{\pm}(s) \propto \sqrt{\beta_{skq}^{skq}(s)} \]

Introduced 46 independently powered skew quadrupoles in arc locations where

\[ D_{skq}^{skq} \beta_y(s) \quad \text{and} \quad \sqrt{\beta_{skq}^{skq}(s)} \]

are large.
Same error realization, luminosity betatron tunes with optimized skew quads, $|C^-| \approx 0.002$. 

<table>
<thead>
<tr>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
<th>$\sigma_\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[mm]</td>
<td>[\mu m]</td>
<td>[mm]</td>
</tr>
<tr>
<td>SITF</td>
<td>0.121</td>
<td>1.718</td>
</tr>
<tr>
<td>SITROS</td>
<td>0.138</td>
<td>3.126</td>
</tr>
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Adding $\hat{n}_0$ correction by *harmonic bumps*

Effect on vertical orbit
Level of polarizations is as for the *unperturbed* optics. However: BPMs errors must be included and some statistics is needed!
The beam vertical emittance is 1.7 pm, corresponding to $\sigma_y^* \simeq 0.4 \mu$m. A larger beam size at the IP may be needed.

The e-beam $\epsilon_y$ may be efficiently increased by anti-symmetric bumps around low $\beta_y$ locations.

As a test such a bump has been introduced around the IP. Effect on polarization is detrimental. For $\epsilon_y = 3$ nm there is no polarization!
Delivered in summary

• Beam polarization in the eRHIC storage ring has been studied.
• ATS lattice has been modified to include BPMs, correctors and skew quadrupoles.
• With conservative errors $P_\infty \approx 50\%$ seems within reach:
  – for \textit{upwards} polarized bunches (anti-parallel to the guiding field),
    \[ <P> \approx 80\% , \text{ over 5 minutes if } P(0) = 85\%; \]
  – for bunches polarized \textit{downwards} the average polarization drops to 67\%.
• Luminosity working point requires linear coupling correction. Here the benefit of a \textit{local correction} using 46 skew quadrupoles has been shown.
• Harmonic bumps for the $\hat{n}_0$ axis correction have been implemented.
• Comparisons with different codes (Bmad, PTC) have started.

<table>
<thead>
<tr>
<th>July 2017 - March 2018</th>
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<tbody>
<tr>
<td>Funds allocated by NP Acc. R&amp;D FOA</td>
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<tr>
<td>Actual costs to March 2018</td>
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The work is currently funded by a MPO.
To-do-list

• BPMs errors must be included in the mis-alignments simulation.
• Some statistics must be gained.
• Independent correction of betatron coupling and vertical spurious dispersion must be tried.
• A knob for controlling the vertical beam size at IP w/o affecting polarization is needed.
• Beam-beam effects need to be addressed.
• The work must be repeated for the other 2 energy values.
It is difficult to evaluate how much time will be needed to complete the work, because for some items it depends on the outcome.

**Tentative Schedule**

<table>
<thead>
<tr>
<th></th>
<th>hours</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPMs errors + statistics</td>
<td>140</td>
<td>easy</td>
</tr>
<tr>
<td>betatron coupling and dispersion</td>
<td>140</td>
<td>easy</td>
</tr>
<tr>
<td>$\epsilon_y$ knob</td>
<td>160</td>
<td>the wished $\epsilon_y$ may be incompatible with polarization $\rightarrow$ upper limit</td>
</tr>
<tr>
<td>beam-beam</td>
<td>180</td>
<td>using SITROS</td>
</tr>
<tr>
<td>beam-beam</td>
<td>?</td>
<td>Bmad/PTC</td>
</tr>
</tbody>
</table>