Compact Electron Spin Rotator Design

Fanglei Lin

on behalf of

Vadim Ptitsyn, Holger Witte, Steven Tepikian (BNL), Uli Wienands (ANL), Desmond Barber (DESY), Vasily Morozov, Amy Sy (JLab), Oleksii Beznosov, Jim Ellison, Klaus Heinemann (UNM)

Outline:

• Introduction
• Compact Spin Rotator for EIC
• Summary and Outlook

CFNS Workshop on Beam Polarization and Polarimetry at EIC
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Electron Spin Rotator Design in the EIC

Spin rotation angles from solenoids and dipoles to rotate the spin from the vertical to the longitudinal satisfy:

\[ \tan \varphi_1 = \pm \frac{\cos \psi_2}{\sqrt{-\cos(\psi_1 + \psi_2) \cos(\psi_1 - \psi_2)}} \]

\[ \cos \varphi_2 = \cot \psi_1 \cot \psi_2 \]

\[ \theta_{1,2} \text{ are orbital bending angles:} \]

\[ \theta_1 = 76.89 \text{ mrad, } \theta_2 = 38.45 \text{ mrad} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Short solenoid module</th>
<th>Long solenoid module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field integral range [T \cdot m]</td>
<td>20-34</td>
<td>4-122</td>
</tr>
<tr>
<td>Solenoid length [m]</td>
<td>5.4</td>
<td>18.</td>
</tr>
<tr>
<td>Solenoid spin rotation angle at 18 GeV</td>
<td>32°</td>
<td>116°</td>
</tr>
<tr>
<td>Location in the RHIC tunnel</td>
<td>RHIC dipole 9-10</td>
<td>RHIC dipole 6-8</td>
</tr>
</tbody>
</table>

Optimization of current spin rotator design is continued considering the coverage of energy range, strength of depolarization effect and spin matching to extend the polarization relaxation time. (see Vadim’s talk)
Optics of Electron Spin Rotator Design

\[ \beta_s \approx 80 \text{ m} \quad \beta_s \approx 80 \text{ m} \]

Net zero bending angle

\[ 2.7 \text{ m} \quad 9 \text{ m} \]
Some Comments on the Current Spin Rotator Design

- Spin rotators, composed of solenoids and dipoles, are utilized in the electron storage ring in the EIC energy range 5-18 GeV. The solenoid field in the rotator
  - Pros:
    - has no synchrotron radiation or synchrotron radiation easily under control,
    - has no or negligible contribution to the emittances,
  - Cons:
    - introduces transverse orbit coupling
      - compensated using normal or skew quadrupoles
    - may have strong solenoid fields at the high beam energies because the spin effect over the solenoid is inversely proportional to the beam energy
      - requiring relatively long solenoids

Relative long spin rotator ~80m

Q: Is there a way to make the spin rotator compact in the EIC?
Origin of Compact Spin Rotator

- An interest has arisen to upgrade SuperKEKB to polarized electrons after the Hi-lumi program is complete.

- Question: “How do we get longitudinal polarization at the IP”?
  
  Answer: spin rotators up- and downstream of the IP

- Constraints:
  - A practical solution should not disturb the geometry of the lattice
  - Any practical solution cannot affect the emittance and beam dynamics too much
  - Highly desirable to be able to restore the present lattice by turning off the spin rotators
  - Spin rotators are placed in the High Energy Ring for polarized electrons only

- The concept of a compact spin rotator was explored and presented by Uli Wienands in the EIC Accelerator Collaboration meeting in 2019.

- If it works, such a compact spin rotator will make the geometric layout much easier and more flexible in the EIC design.
SuperKEKB Spin Rotator

- Three of these make up the whole rotation
  - Solenoid strengths: two 26.37 Tm, one 5.27 Tm
  - With solenoids and skew quads off the rotators reduce to pure dipoles
- The ring magnets make up the horizontal rotation
- It turns out the three solenoids give flexibility in the rotator location as well as ability to tune the spin angle at the IP
- Sketch of rotator magnet

Using Bmad (David Sagan (Cornell))

- Solenoid ≤ 4.45 T, dipole 0.28 T, quads ≤ 35 T/m
Overall Effects of SuperKEKB Spin Rotator

- Some noticeable effect on emittances
- Not acceptable chromaticity growth
  - Turns out there are sextupoles within the rotator that need retuning

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Without Rotator</th>
<th>With Rotator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emittance_x</td>
<td>$4.44 \times 10^{-9}$</td>
<td>$5.42 \times 10^{-9}$</td>
</tr>
<tr>
<td>Emittance_y</td>
<td>$1.88 \times 10^{-12}$</td>
<td>$9.70 \times 10^{-12}$</td>
</tr>
<tr>
<td>Alpha Damp_x</td>
<td>$1.79 \times 10^{-4}$</td>
<td>$2.54 \times 10^{-4}$</td>
</tr>
<tr>
<td>Alpha Damp_y</td>
<td>$1.79 \times 10^{-4}$</td>
<td>$1.81 \times 10^{-4}$</td>
</tr>
<tr>
<td>Damping Partition x</td>
<td>0.999667</td>
<td>1.420164</td>
</tr>
<tr>
<td>Damping Partition y</td>
<td>1.001851</td>
<td>1.013181</td>
</tr>
<tr>
<td>Chromaticity_x</td>
<td>3.953515</td>
<td>-82.933671</td>
</tr>
<tr>
<td>Chromaticity_y</td>
<td>6.595477</td>
<td>-17.182644</td>
</tr>
<tr>
<td>Momentum Compaction</td>
<td>$4.54 \times 10^{-4}$</td>
<td>$4.58 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
A Compact Spin Rotator in the EIC?

- **Idea:**
  - It is a compact solenoid-dipole field spin rotator
  - The combined-function magnets with solenoid, dipole and/or quadrupole fields may reduce the physical length, taking advantage of the superconducting technology (BNL “Direct Winding” technique)
    - Spin rotation from solenoid and dipole fields
    - Decoupling of transverse motions by (skew) quadrupoles

- **Constraints**
  - Rotate the spin between vertical and longitudinal directions in the EIC energy range
  - Keep the geometry fixed
  - Maximum solenoid field 7 T
Simulation Environments

• Tools: ZGOUBI + tune (external optimizer)
• Procedure:
  – Code ZGOUBI is used to generate a combined-function magnet composed of solenoid and dipole fields and track the orbital and spin motions.
  – Code tune is utilized to optimize solenoid and/or dipole field components in the combined-function magnet to achieve the desired spin rotation between vertical and longitudinal directions.
Examination of Orbit in Pure Dipole Magnets

Six 2m-long dipoles (with 20 cm drifts between them)

Three 2m-long dipoles (with 20 cm drifts between them)

- "CHANGREF" is set correctly in the "TOSCA"
- Short dipoles are chosen to have a small sagitta, which may help to have a relatively small magnet aperture.
- Dipole length and bending angle should be optimized for a reasonably large synchrotron radiation density.
### Solution with Scaled Dipole Field + Two Solenoid Fields

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>5</th>
<th>10</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of combined-function magnet 1</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>0.21</td>
<td>0.43</td>
<td>0.77</td>
</tr>
<tr>
<td>Dipole length (m)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dipole radius (m)</td>
<td>78.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sol1 (T)</td>
<td>1.65</td>
<td>3.47</td>
<td>-26.67</td>
</tr>
</tbody>
</table>

| Number of combined-function magnet 2 | 3   |
| Dipole field (T) | 0.21 | 0.43 | 0.77 |
| Dipole length (m) | 2   |
| Dipole radius (m) | 78.13 |
| Sol2 (T) | 4.50 | 18.14 | 15.81 |

- **Conclusion:**
  - Solenoid fields are too strong when scaling the dipole fields with the beam energy

- Try to vary the dipole field, in addition to solenoid fields
### Solution with One Dipole and Two Solenoid Fields

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Number of combined-function magnet 1</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>0.172</td>
<td>0.169</td>
<td>0.167</td>
</tr>
<tr>
<td>Dipole length (m)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dipole radius (m)</td>
<td>97.12</td>
<td>197.16</td>
<td>358.57</td>
</tr>
<tr>
<td>Dipole 1 bending angle (deg)</td>
<td>1.17</td>
<td>0.58</td>
<td>0.32</td>
</tr>
<tr>
<td>Sol1 (T)</td>
<td>2.27</td>
<td>4.68</td>
<td>8.63</td>
</tr>
<tr>
<td>Number of combined-function magnet 2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>0.172</td>
<td>0.169</td>
<td>0.167</td>
</tr>
<tr>
<td>Dipole length (m)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dipole radius (m)</td>
<td>97.12</td>
<td>197.16</td>
<td>358.57</td>
</tr>
<tr>
<td>Sol2 (T)</td>
<td>1.01</td>
<td>1.19</td>
<td>1.01</td>
</tr>
</tbody>
</table>

#### Orbit

- **5 GeV**
  - Radial/Vertical Orbit
  - Spin Components

- **10 GeV**
  - Radial/Vertical Orbit
  - Spin Components

- **18 GeV**
  - Radial/Vertical Orbit
  - Spin Components

#### Spin

- **Sz**: Vertical
- **Sx**: Longitudinal

### Conclusion:
- Dipole Dipole fields are almost constant in the whole energy range. This leads to:
  - Total bending angle is inversely proportional to the energy
  - Either change the geometry to keep small orbit excursion in the magnets (shown on the orbit plots), or keep a fixed geometry but with large orbit excursions up to ~1m in the magnets
- The first solenoid fields are almost proportional to the energy
Configuration of Spin Rotator with a Fixed Geometry

18 GeV
22 dipole magnets
8 CF magnets (sol_1 + dipole)
2 CF magnets (sol_2 + dipole)

10 GeV
14 dipole magnets
16 CF magnets (sol_1 + dipole)
2 CF magnets (sol_2 + dipole)

5 GeV
16 CF magnets (sol_1 + dipole)
8 CF magnets (sol_2 + dipole)
8 CF magnets (sol_3 + dipole)
### Solution with A Fixed Geometry and Three Solenoid Fields

<table>
<thead>
<tr>
<th>energy (GeV)</th>
<th>5</th>
<th>10</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>dipole field (T)</td>
<td>0.044</td>
<td>0.088</td>
<td>0.167</td>
</tr>
<tr>
<td>dipole radius (m)</td>
<td>380</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dipole bending angle (deg)</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sol1 (T)</td>
<td>1.23</td>
<td>2.16</td>
<td>6.99</td>
</tr>
<tr>
<td>Sol2 (T)</td>
<td>-0.93</td>
<td>-3.61</td>
<td>1.73</td>
</tr>
<tr>
<td>Sol3 (T)</td>
<td>-0.45</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Number of pure dipole magnets</td>
<td>0</td>
<td>14</td>
<td>22</td>
</tr>
<tr>
<td>Number of combined function magnets</td>
<td>32</td>
<td>18</td>
<td>10</td>
</tr>
</tbody>
</table>

#### Conclusion:
- Dipole fields are scaled with the beam energy, so the geometry is fixed
- Orbit excursion in the magnets < 2 mm
- Maximum solenoid field < 7 T

#### IF the spin rotator covers spin rotation in the whole energy range, the effective length may not be too compact.
Summary and Outlook

• Study of the feasibility of a compact spin rotator in the EIC is carried out
• A few design scenarios have been explored considering the orbit and spin motions and applicability at different beam energies
• Future work
  – continue the optimization in the design to reduce the length of the spin rotator
  – consider to include radial dipole fields while control the vertical emittance contribution

Thank You for Your Attention!