Polarized Beams: A Brief History and Future Prospects

Yaroslav Derbenev
Jefferson Laboratory, VA, USA

Mini-Workshop: Accelerator - Beam Polarization in Future Colliders
HKUST High Energy Physics Program
Hong Kong, January 17, 2019
Milestones of Polarized Beams History

I. Foundations and problems
- Polarization sources
- Thomas – BMT spin equations
- Spin in conventional rings
- Compensated spin rotators
- Resonance depolarization
- Crossing the spin resonances
- ZGS + AGS proton spin acceleration
- BST radiative polarization
- Orlov’s depolarization

II. Polarization canonical theory

III. Siberian Snakes
- SS idea and demonstration
- SS techniques
- SS utilization and success in RHIC
- Multiple SS for SSC

IV. Spin-compensated quads

V. Figure 8 synchrotron

VI. Polarized EIC
- Fixed orbit e-spin rotator and snake

VII. Future polarized beams
- Polarized LHC?
- Polarization ideas for CEPC:
  - Snakes
    - Bending snakes
    - Achromatic snakes
    - Flipping spin rotators
  - Polarization ideas for 75 TeV PPC
  - Many snakes
  - Spin-compensated quads
Thomas – BMT spin equation

\[ \vec{\mu} = \frac{e}{mc} (1 + G) \vec{S} = \frac{e\hbar}{2mc} (1 + G) \vec{\sigma} \]

With EM field in terms of rest frame (L. Thomas, 1925):

- \[ \frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}; \quad \vec{\Omega} = -\frac{e}{\gamma m} \left[ (1 + G) \vec{B}_{rest} + \frac{\gamma}{\gamma + 1} \vec{v} \times \vec{E}_{rest} \right] \]

With EM field in terms of the lab frame:

- \[ \frac{d\vec{S}}{dt} = \frac{e}{m} \vec{S} \times \left[ \left( \frac{1}{\gamma} + G \right) \vec{B}_\perp + \frac{1}{\gamma} (1 + G) \vec{B}_\parallel + \left( \frac{1}{\gamma + 1} + G \right) \vec{E} \times \vec{v} \right]. \]

/re-derived by Bargmann-Mishel-Telegdi (1956) on the background of the 4-fold covariant method and correspondence/
Polarized $e^\pm$ beams
Polarized $e^\pm$ sources and transport scenario options

**Electrons**

**Option I:** Use Polarized e-gun (electrons only…)
- Stacking and accelerating for injection to collider ring
- Acceleration and maintenance of PEB in the Collider Ring

**Option II:** BST polarization in the Collider Ring at injection energy **applying wigglers**
- Acceleration and Luminosity run at wigglers off

**Positrons**

- Produce and stack unpolarized positrons
- BST polarization in the Collider Ring at injection energy **applying wigglers**
- Acceleration and Luminosity run at wigglers off

Need Siberian Snakes (and spin rotators) for both…
Spin Rotators

- Simple bend
- Elements: dipoles (vertical and radial bends) + solenoids
- Fixed orbit non-commutative spin rotator of EIC
Spin Rotators for CEPC.1.

Fixed orbit SR on dipoles and solenoids for CEPC

\[
\begin{align*}
\alpha_{x1} & \quad \alpha_{y1} & \quad \varphi_{z1} & \quad \alpha_{x2} - \alpha_{x1} & \quad \alpha_{y2} & \quad \varphi_{z2} & \quad -\alpha_{x2} \\
(S_y = 1) & & & & & & (S_z = 1)
\end{align*}
\]

Рис. 9. Комбинированный ахроматический спиновый ротатор на поперечных полях с двумя соленоидами, переводящий вертикальное направление поляризации в продольное.
Максимальный интеграл поля в каждом из соленоидов составит примерно 35 и 60 Т·м, что при максимальном поле в соленоидах 5 Т потребует 7 и 12 м, соответственно.
Spin Rotators for CEPC. 2.

Achromatic Rotator on transverse fields

(1st Arc, $S_y = 1$) \[ \alpha_{x1}, \alpha_{y1}, \alpha_{x2} - \alpha_{x1}, \alpha_{y2} - \alpha_{x2} \] (IP, $S_z = 1$)

Орбитальные углы поворота в радиальных и вертикальных диполях:
\[
\begin{align*}
\alpha_{x1} &= -2.721 \text{ mrad}, \\
\alpha_{x2} &= -5.893 \text{ mrad}, \\
\alpha_{y1} &= 12.34 \text{ mrad}, \\
\alpha_{y2} &= 9.487 \text{ mrad}.
\end{align*}
\]
Spin dynamics canonical theory

- Quasi-classical Spin Hamiltonian
- Spin action $s_n$ and phase $\Psi$
  - $s_n = \vec{n}(\vec{p}, \vec{r}, \phi) \hat{s} = \text{inv}$;
- Form $\vec{n}(\vec{p}, \vec{r}, \phi)$ on definition satisfies same TBMT equation as spin vector
- Spin dispersion function (SDF) $\gamma \frac{\partial \vec{n}}{\partial \gamma}$ characterizes spin sensitivity to particle energy

**A theorem proved:**

On a periodic orbit, there is a unique periodic solution: $\vec{n}_0(z) = \vec{n}_0(z + C)$
and two (arbitrary chosen) “free” orthogonal to $\vec{n}_0$. Their arbitrary vector superposition describes general spin motion on the orbit… which is:

**Spin precession around** $\vec{n}_0(z)$ **with a global spin tune** $\nu_0$.

Deviation of $\vec{n}(\vec{p}, \vec{r}, \phi)$ from $\vec{n}_0(z)$ becomes large near resonances $\nu_0 = \nu_k$, where $\nu_k$ is a harmonic of the orbital motion.
Radiative polarization/depolarization of $e^\pm$

- Bagrov-Sokolov-Ternov polarization:

$$\tau_{bst}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 \hbar}{m_e |\rho|^3} \propto \gamma^2 B^3 ; \quad P_{bst} \Rightarrow \frac{8}{5\sqrt{3}}$$

- Orlov-Baier - D-K radiative depolarization rate: $\propto (\gamma \frac{\partial \hat{n}}{\partial \gamma})^2$

- Polarization rate:

$$\tau_{dk}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 \hbar}{m_e c} \oint d\rho \left( \frac{1-\frac{2}{9}(\hat{n} \cdot \hat{v})^2 + \frac{11}{18}(\gamma \frac{\partial \hat{n}}{\partial \gamma})^2}{|\rho(s)|^3} \right)_s$$

- Equilibrium polarization:

$$P_{dk} \Rightarrow - \frac{8}{5\sqrt{3}} \oint d\rho \left( \frac{1}{|\rho(s)|^3} \frac{1}{\hat{b} \cdot (\hat{n} - \gamma \frac{\partial \hat{n}}{\partial \gamma})} \right)_s$$
Spin Resonances
Problems with polarization in conventional rings

- Spin precession in vertical field: \( \frac{d\Psi}{dz} = (1 + \gamma G) \frac{d\alpha}{dz} \)
- On real trajectory: \( \vec{\Omega} = (\Omega_y ; \Omega_h) \)
- Spin tune in vertical field: \( \nu_{sp} = \gamma G \) (i.e. number of spin horizontal turns… over the orbit)

- Spin resonances take place at \( \gamma G \approx k; \ kN \pm k_x \nu_x \pm k_y \nu_y \pm k_s \nu_s \)
- …and depolarization happens: \( \frac{dS_h}{dt} - i\Omega_y S_h = i\Omega_h S_y \)
- About more than \( \gamma G \) resonances to be crossed at acceleration…
… a huge problem!
- Coherent spin maintenance during the luminosity run is other big problem…
- Radiative depolarization grows rapidly with energy due to the increasing of the spin tune spread
Spin resonance Crossing Culture

Backup slides

- Fast crossing
- Adiabatic crossing
- Froissart-Stora process
- RF crossing
- Kondratenko’ transparent crossing
Backup slides

- Acceleration of polarized proton beam
- 12 GeV of ZGS (A. Krisch group in 70th)
- 24 GeV AGS (A. Krisch with collaborators in 80th)
Spin Echo: Twisted Spin and Siberian Snakes
Spin Techniques 1

Twisted Spin Synchrotron: Spin Echo

- Figure 8 synchrotron (booster or storage ring)
- Topological compensation for global spin precession
- TSS is the best solution for acceleration in boosters

However, degenerated spin dynamics is unstable…
- Stabilization by solenoid (or small spin rotators)
- TSS is solution for polarized d acceleration/maintenance in collider rings (EIC)
- TSS is a unique solution for acceleration and maintenance of polarized deuterons…!
“Siberian Snakes”: making *Spin Echo* in racetracks…

**Cancellation idea** of spin global precession over the racetrack orbit:

instead of reversing the arcs, let us make *reverse of spin*…!

by inserting local spin flip about a horizontal axis

**Topological compensation of spin precession over arcs**

Spin techniques 1

Solenoid as $\pi - rotator$

There is a unique periodic solution:

$$\vec{n}(z) = \vec{n}(z + C)$$

and two (arbitrary chosen) “semi-periodic” orthogonal to $\vec{n}$:

$$\vec{\eta}(z) = -\vec{\eta}(z + C)$$

Their arbitrary vector superposition describes general spin motion at a flat orbit which is:

spin precession around $\vec{n}(z)$ with global spin tune equal $\frac{1}{2}$ independent of the beam energy (!)
To insert solenoid is, in principle, the simplest way to utilize local spin flip around a horizontal (longitudinal) axis. It takes compensation for $x$ to $y$ coupling.

Demonstrated at IUCF (A. Krisch and T. Roser, 1989)

Solenoid as $\pi - rotator$

- SS technology 1

- However, use solenoid is impractical at high energies
"Longitudinal" SS on transverse fields
Takes 16 TM for protons
Spin techniques 4

"Radial" SS on transverse fields
Takes 16 TM for protons
Spin techniques 5

Helical snakes (1978)

Helical snakes for RHIC

Helical snake design for MI of FNAL
SS technology 2

SS utilization and success in RHIC
SS technology 3

Helical snake design for MI of FNAL
From single to two or more SS in a ring

Why two snakes?

- It may be convenient to have stable spin vertical in arcs.
- At very high energies single snake in a ring may not be sufficient to remove (suppress) resonance perturbations.
- In case of high energy $e^\pm$, BST polarization can be killed by high sensitivity of the horizontal periodic spin to energy in arcs.
Spin Techniques 6

Spin in a ring with two SS

With two snakes in a ring, periodical spin returns to be vertical in arcs
(but with inter-flipping polarity)

- However, at two identical symmetrically located snakes spin motion becomes degenerated... - equivalent to TSS!

There are two possible ways to remove degeneration:
1. Degeneration can be easily alleviated by a slight asymmetry in snakes location
2. There is no degeneration at all when two symmetrically located snakes distinguish in their axes direction relative the beam velocity:
   
   at angle $\varphi$ between two snake’ axes, global spin tune is equal to $\nu = \frac{\varphi}{\pi}$

- Spin Echo arrives thank to designed equity of the precession phases between snakes

What is achieved:
1. No spin resonances, no crossing them
2. Spin phase divergence still cancelled. No resonance quantum depolarization of $e^\pm$
3. Chromaticity of stable spin in arcs is avoided
   
   Issue: Intrinsic BST polarization is cancelled…but it can be return by wigglers.
Spin techniques 7

Multiple SS for High Energy hadron rings

26 pair of snakes for 20 TeV SSC

6 snakes for RHIC 300 GeV
Spin Techniques 8

Spin-compensated quads for very HE HC (1990) [A. Chao and Y.D.]

Split quadruple with simple $\pi$ rotator in between
$cb$ – correcting bends

Quad combined with $2\pi$ rotator along

Two “normal” SS installed in HE ring can then provide acceleration of polarized protons in range of about 1000 TeV (!)
Spin Techniques 9

Bending Rotators and Snakes on tilted dipoles (1995)
Future Prospects
Universal Spin Rotator and SS for EIC

Universal Spin Rotator on solenoids and constant bends

Electron spin rotators for JLEIC

R&S for electrons in eRHIC

JLEIC

CEBAF
Thinking about polarized CEPC
Thoughts on Beam Polarization delivery in CEPC

**Option I:** Use Polarized e-gun (electrons only…)  
- Stacking and accelerating for injection to collider ring  
- Acceleration and maintenance of PEB in the Collider Ring

**Option II:** BST polarization in the Collider Ring  
(at injection energy…or in booster ring…?)  
- Takes Polarizing Wigglers to facilitate BST  
- Luminosity run at wigglers off

Need SS (and spin rotators) in both…
Spin Techniques 11

Achromatic Rotator and Snake on transverse fields for CEPC

(1\textsuperscript{st} Arc, $S_y = 1$)
\[
\begin{align*}
\alpha_{x1} & \quad \alpha_{y1} & \quad \alpha_{x2} - \alpha_{x1} & \quad \alpha_{y2} & \quad -\alpha_{x2}
\end{align*}
\]

(IP, $S_z = 1$)

(2\textsuperscript{nd} Arc, $S_y = -1$)
\[
\begin{align*}
-\alpha_{x2} & \quad -\alpha_{y2} & \quad \alpha_{x2} - \alpha_{x1} & \quad -\alpha_{y1} & \quad \alpha_{x1}
\end{align*}
\]

Орбитальные углы поворота в радиальных и вертикальных диполях:

$\alpha_{x1} = -2.721 \text{ mrad}, \alpha_{x2} = -5.893 \text{ mrad},$

$\alpha_{y1} = 12.34 \text{ mrad}, \quad \alpha_{y2} = 9.487 \text{ mrad}.$
Fixed orbit SR and SS on dipoles and solenoids for CEPC

\[(S_y = 1) \quad \alpha_{x1} \quad \alpha_{y1} \quad \varphi_{z1} \quad \alpha_{x2} - \alpha_{x1} \quad \alpha_{y2} \quad \varphi_{z2} \quad -\alpha_{x2} \quad (S_z = 1)\]

First estimations:

- Maximum TM of solenoids are 35 and 60 (7 and 12 M at 5 T)
- Total length of snake about 200 meters. (transverse field about 0.2 KGs)
Spin Matching and Tolerances

To be explored:

• Solenoids
• Snakes and arcs alignments
Thinking about Future 75 TeV Polarized Proton Beams. 1.

- Figure 8 Booster in energy range below 30 GeV
- Snakes for the succeeding boosters

**Options for the Collider Rings**

**Option I  Many SS**

- Sufficient large chain of SS to suppress depolarizing impact of the superperiodic misalignment harmonics
- Spin tune $\frac{1}{2}$
- Compensation of tune spread associated with beam emittance
- Spin response function to suppress the beam-beam depolarization
Thinking about Future 75 TeV Polarized Proton Beams. 2.

**Option II:** Spin-compensated quadrupoles

- Two SS then will be enough to eliminate spin resonance crossing during the acceleration and stay away of the resonances through the luminosity run
- Think about spin flipping (if inquired); ideas on table…
Preconclusion

• At this stage, our anticipation of successful design for future polarized beams is close to 100% optimism.

Thank you for your attention!
Backup slides