Polarized Beams in Colliders

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Colliders with polarized beams

- Polarized e+e- colliders
  - As early as early 70s like ACO, VEPP-2
  - Most are circular and the polarization was built up during the store time via Sokolov-Ternov effect (ST effect)

The difference of probability between the two scenarios allows the radiative polarization build up.
The ST induced radiative polarization buildup is given

\[ P(t) = P_{ST}(1 - e^{-t/\tau_{ST}}), \]

where \( P_{ST} = \frac{8}{5\sqrt{3}} \approx 0.9237 \)

and

\[ \tau_{ST}^{-1} = \frac{\frac{5\sqrt{3}}{8}c\lambda e r_\gamma^5}{\rho^3} = 3654 \frac{R/\rho}{B[T]^3 E[GeV]^2} \text{ [sec}^{-1}] \]

S. Mane et al, Spin-polarized charged particle bams

For HERA, the estimated ST polarization buildup time for its 26.7 GeV electrons is about 43 mins
• In reality, the emission of a photon can yield a sudden change of the particle’s energy and induce a spin diffusion mechanism that leads to loss of polarization. The equilibrium polarization is the combination of the two effects

\[
P_{eq} = \frac{8}{5\sqrt{3}} \frac{\langle |\rho^{-3}| \hat{b} \cdot \hat{n} - \gamma \frac{\partial \hat{n}}{\partial \gamma} \rangle}{\langle |\rho^{-3}| \left[ 1 - \frac{2}{9} (\hat{\beta} \cdot \hat{n})^2 + \frac{11}{18} \gamma \frac{\partial \hat{n}}{\partial \gamma} \right]^2 \rangle}
\]

and the subsequent polarization buildup time is

\[
\tau_{eq}^{-1} = \tau_{ST}^{-1} + \tau_d^{-1}
\]

with

\[
\tau_d^{-1} = \tau_{ST}^{-1} \left[ -\frac{2}{9} (\hat{\beta} \cdot \hat{n})^2 + \frac{11}{18} \gamma \frac{\partial \hat{n}}{\partial \gamma} \right]^2 \]

In a planar circular accelerator
In a planar circular accelerator

- The radiative polarization buildup in HERA
  - Best achieved polarization is around 75%
  - Polarization buildup time ~ 1.5 hours

Fig. 19: Polarization $P$ versus the time $t$ in the storage ring HERA at 26.7 GeV.

J. Buon, J. P. Koutchouk, Polarization of Electron and Proton Beams
Spin Orbit Coupling

Thomas BMT Equation: (1927, 1959)

\[
\frac{d\vec{S}}{dt} = \frac{e}{\gamma m} \vec{S} \times [(1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_\parallel + \left(G - \frac{\gamma}{\gamma^2 - 1}\right) \frac{\vec{E} \times \vec{\beta}}{c}]
\]

\[
\frac{d\vec{S}}{ds} = \Omega(x, p_x, y, p_y, z, \delta) \hat{n} \times \vec{S}
\]

- stable spin direction \(\hat{n}\), an invariant direction that spin vector aligns to, when the particle returns to the same phase space

\[
\hat{n}(I_z, \phi_z, \theta) = \hat{n}(I_z, \phi_z + 2\pi, \theta)
\]

Here, \(I_z\) and \(\phi_z\) are the 6-D phase-space coordinates \((x, p_x, y, p_y, z, \delta)\)

- For particles on closed orbit, stable spin direction can be computed through one-turn spin transfer matrix. \(\hat{n}\) is also known as \(\hat{n}_0\)

Depolarizing mechanism in a synchrotron

- For particles not on closed orbit, since the betatron tunes are typically non-integer, \( \hat{n} \) can be significantly away from \( \hat{n}_0 \) when

\[
Q_s = k + k_x Q_x + k_y Q_y + k_z Q_z
\]

where \( k_x, k_y, k_z \) are horizontal, vertical and synchrotron tunes, respectively.

- These resonances contribute to the depolarization time and result to much less equilibrium polarization.
Depolarizing mechanism in a synchrotron

- For particles not on closed orbit, since the betatron tunes are typically non-integer, $\hat{n}$ can be significantly away from $\hat{n}_0$ when

$$Q_S = k + k_x Q_x + k_y Q_y + k_z Q_z$$

where $k_x$, $k_y$, $k_z$ are horizontal, vertical and synchrotron tunes, respectively.

- These resonances contribute to the depolarization time and result to much less equilibrium polarization.

- Sources of these resonances
  - Miss-alignment of quadrupole
  - Devices that deviate $\hat{n}$ from $\hat{n}_0$
  - Other high order fields
Overcome depolarizing mechanism

- In general, the effect of these resonances grows with energy. For planar electron storage rings, a simply scaling law*

\[ p_{eq} \approx \frac{92.4\%}{1+\alpha^2E^2} \]

Where \( \alpha \) is the lattice related factor

- To overcome these resonances in a storage ring, it is critical to either break the resonance condition such as utilizing Siberian snakes, or adapt the lattice optics to minimize the spin orbit coupling strength

\[ \left| \gamma \frac{\partial \hat{n}}{\partial \gamma} \right|^2 \sim (1 + G\gamma)^2 \sum_k |c_k|^2 / (G\gamma - k)^2 \]

via spin matching

- Strong spin matching: full spin transparent at all harmonics
  - Practically very difficult

- Harmonic spin matching: minimize the driving term at the nearby harmonics
  - Has been implemented in various rings

Achieved Performance of Polarized e Beams

A Brief History of the LEP Collider, R. Assmann, M. Lamont, S. Myers for the LEP team
HERA polarization

- HERA was the 1st high energy collider, that employed local spin rotators to provide longitudinally polarized electron.

- A spin rotator consists of a sequence of horizontal and vertical orbit correctors that interleaves with each other to precess spin vector from vertical to longitudinal.
HERA polarization

- A spin rotator induces large orbital excursions in both planes and tilts the $\hat{n}$ away from vertical
HERA polarization

Vertical orbital bump ~ 20mm

HERA polarization

- A spin rotator induces large orbital excursions in both planes and tilts the $\hat{n}$ away from vertical

- Spin matching to make the section between spin rotators spin transparent to the 1$\text{st}$ order

- In addition, it is also critical to spin match at the entrance and exit of the rotator, respectively


Vertical orbital bump ~ 20mm
HERA polarization

- With the HEAR mini-rotator

- Polarization was later-on improved to 65% after a dedicated spin-match optics was implemented

HERA polarization

- With 3 pairs of rotators

Figure 1: Polarization optimizations with 3 pairs of spin rotators in HERA-e on the 1st of March 2003. A polarization of 54% was ultimately obtained.

Georg Hoffstaetter et al, Experiences with the HERA beams, ICFA Newsletter May 2003
Colliders with polarized beams

- Polarized hadron colliders:
  - RHIC@BNL: polarized protons

- Unlike the e+e- colliders, polarized beam starts from the source, and polarization need to survive through acceleration chain
  - Polarized ion source
  - Pre-Injector: LINAC, booster
  - Injector
  - Collider
Beam Polarization and Polarimetry @ EIC
June 26 – July 1, 2020

PHENIX (p)
AGS LINAC BOOSTER
Pol. H - Source
200 MeV Polarimeter

Siberian Snakes
Spin Rotators (longitudinal polarization)

RHIC pC Polarimeters

Absolute Polarimeter (H jet)

BRAHMS(p)

STAR (p)

Spin Rotators (longitudinal polarization)

Strong AGS Snake

AGS Polarimeters

Helical Partial Siberian Snake
Principle of full Siberian snake

- Use one or a group of snakes to make the spin tune to be at $\frac{1}{2}$
- Break the coherent build-up of the perturbations on the spin vector
Snake Depolarization Resonance

- **Condition**
  - even order resonance
    - Disappears in the two snake case if the closed orbit is perfect
  - odd order resonance
    - Driven by the intrinsic spin resonances

\[ mQ_y = Q_s + k \]

Snake resonance observed in RHIC

Setting for 2009 250 GeV run
Setting for 2011 250 GeV run
3/4 resonance
11/16 resonance
7/10 resonance
Blue, 2009
Yellow, 2009
BluePol1, 2011
BluePol2, 2011
YellowPol2, 2011
Polarization transmission efficiency (CNI #1)
vertical tune
How to avoid a snake resonance?

- Adequate number of snakes

\[ N_{snk} > 4 \left| k_{\max} \right| \]

\[ Q_s = \sum_{k=1}^{N_{snk}} (1)^k \]

\( k \) is the snake axis relative to the beam direction

- Minimize number of snake resonances to gain more tune spaces for operations

He-3 with dual snake

He-3 with six-snake
Avoid polarization losses due to snake resonance

- Adequate number of snakes

\[ N_{snk} > 4 \left| k_{\text{max}} \right| \]

\[ Q_s = \sum_{k=1}^{N_{snk}} (1)^k \]

\( k \) is the snake axis relative to the beam direction

- Keep spin tune as close to 0.5 as possible

- Source of spin tune deviation
  - Snake configuration
  - Local orbit at snakes as well as other spin rotators. For RHIC,

angle between two snake axes

\[ Q_s = \frac{1}{\sum \text{angle between two snakes}} + (1+G) \]

- Source of spin tune spread
  - momentum dependence due to local orbit at snakes
    - equalize the dispersion primes at both snakes
  - betatron amplitude dependence
How to avoid a snake resonance?

- Adequate number of snakes

- Keep spin tune as close to 0.5 as possible

- Precise control of the vertical closed orbit

- Precise optics control
  - Choice of working point to avoid snake resonances
  - Minimize the linear coupling to avoid the resonance due to horizontal betatron oscillation
Precise Beam Control

- Tune/coupling feedback system: acceleration close to 2/3 orbital resonance
- Orbit feedback system: rms orbit distortion less than 0.1mm
RHIC Polarization Performance

- Commissioning of OPPIS, snakes, rotators
- Operation modes developments
- Improvement of injectors, beam controls and polarimeters
RHIC, the world’s 1st high energy pp collider

Polarized protons

Integrated polarized proton luminosity $L$ [pb$^{-1}$]

- 250/255 GeV
- 100 GeV

2017 $P = 53\%$
(L peak limited by STAR)
2013 $P = 53\%$

2012 $P = 52\%$
2015 $P = 55\%$
2009 $P = 34\%$
2012 $P = 59\%$
2011 $P = 48\%$
2009 $P = 56\%$
2006 $P = 55\%$
2005 $P = 47\%$
2003 $P = 34\%$

Time [weeks in physics]
Beam-beam Effect on Polarization

- Beam-Beam force on spin motion
- For a Gaussian round beam, particle from the other beam sees

\[
\vec{E} = \frac{qN}{2} \int_0^l \left[ 1 - \exp\left( \frac{r^2}{2s^2} \right) \right] \hat{r}
\]

\[
\vec{B} = \frac{1}{c} \rightarrow \vec{E}
\]

The effect is much weaker than the spin perturbations from the lattice.

- beam-beam parameter 0.01
- beam emittance \(15\pi \text{ mm-mrad}\)
- \(\beta^* = 0.7\text{m}\) and beam energy at \(G\gamma = 487\)
- Beam-Beam induces tune shift of $\frac{N_{r_0}^*}{4g_s^2}$, as well as incoherent tune spread.
- Both HERA and LEP observed the beam-beam effect on the electron beam polarization.
- RHIC has observed very mild to moderate polarization loss during store.

Polarization of positrons colliding/not colliding with protons at HERA.

D.P. BARBER, arXiv:physics/9901040v1
Summary

- Polarized beams have been successfully used for exploring high energy particle and nuclear physics
- The upcoming EIC, as well as future high energy collider proposals (FCC-ee, ILC, CEPC, etc) requires
  - High luminosity with high polarized lepton and hadron beams
  - Polarized beams at very high energy
- The challenges ahead
  - Novel techniques in overcoming depolarizing effects
    - Existing spin orbit tracking and simulation codes, i.e. SLIM, SITROS, SLICKTRACK, PTC@Bmad, zgoubi etc met challenges in balancing computation power and accuracy
    - Innovative spin orbit tracking and simulation such as the latest discovery of a complete system of spin-orbit stochastic ODEs by K. Heinemann et al
      - More robust and fast spin matching algorithms
  - Novel techniques in spin manipulation
Look forward to polarized EIC!!!

- Highly polarized beams
  - Proton 80%
  - Electron 85%
  - Polarized Helium

- High luminosity
  - $1.3 \times 10^{34}$ cm$^{-2}$s$^{-1}$