Polarized Beams: A Brief History and Future Prospects

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Mini-Workshop: **Accelerator - Beam Polarization in Future Colliders**

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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' 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):

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

  magnetic part Thomas' precession

With EM field in terms of the lab frame:

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

/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**

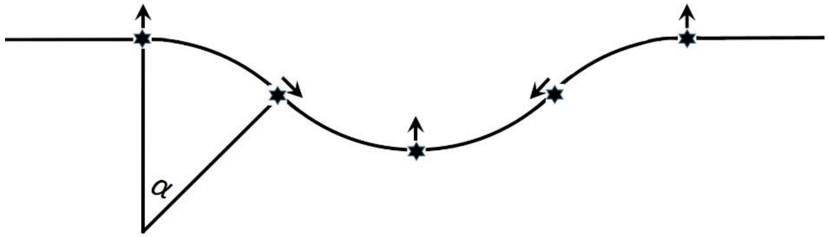
Positrons

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

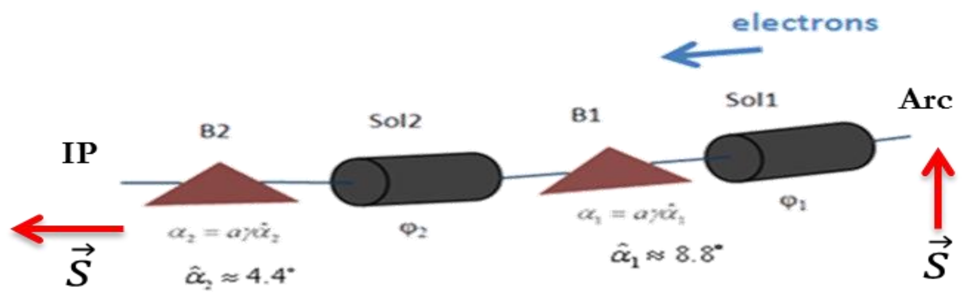
Need Siberian Snakes (and spin rotators) for both…

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

$(S_y = 1)$ | α_{x1} | α_{y1} | φ_{z1} | $\alpha_{x2} - \alpha_{x1}$ | α_{y2} | φ_{z2} | $-\alpha_{x2}$ | $(S_z = 1)$

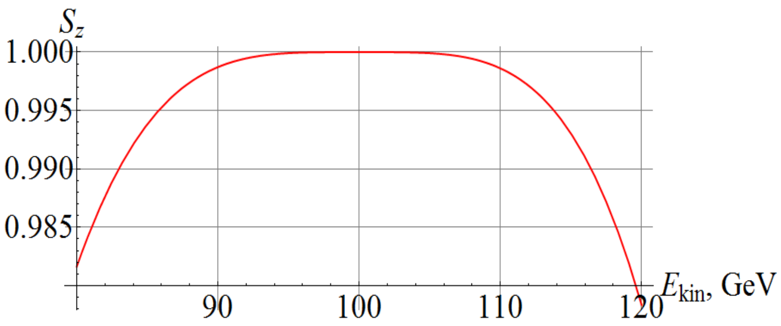
Рис. 9. Комбинированный ахроматический спиновый ротатор на поперечных полях с двумя соленоидами, переводящий вертикальное направление поляризации в продольное.

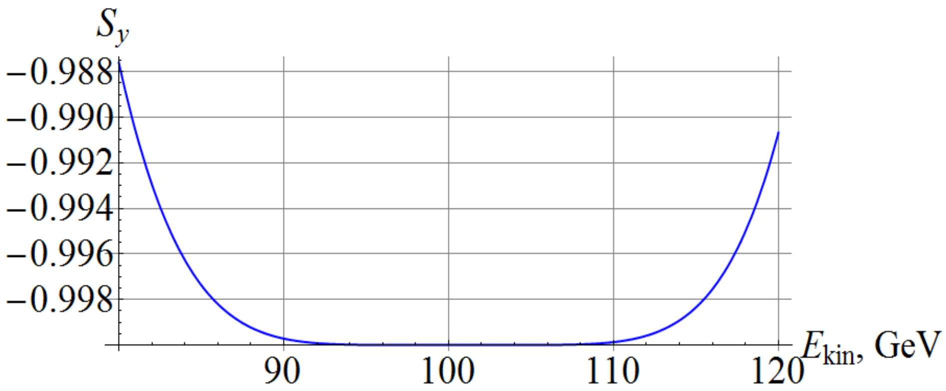
Максимальный интеграл поля в каждом из соленоидов составит примерно 35 и 60 T·m, что при максимальном поле в соленоидах 5 T потребует 7 и 12 m, соответственно.

Spin Rotators for CEPC. 2.

Achromatic Rotator on transverse fields

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





Орбитальные углы поворота в радиальных и вертикальных диполях:

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

$\alpha_{y1} = 12.34$ mrad, $\alpha_{y2} = 9.487$ mrad.

Spin dynamics canonical theory

- Quasi-classical Spin Hamiltonian
- Spin action s_n and phase Ψ
- $s_n = \vec{n}(\vec{p}, \vec{r}, \varphi)\vec{s} = inv;$
- Form $\vec{n}(\vec{p}, \vec{r}, \varphi)$ on definition satisfies same TBMT equation as spin vector
- Spin dispersion function (SDF) $\gamma \dfrac{\partial \vec{n}}{\partial \gamma}$ characterizes spin sensitivity to particle energy
- **<u>A theorem proved</u>**::

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** $\boldsymbol{\nu_0}$**.**

Deviation of $\vec{n}(\vec{p}, \vec{r}, \varphi)$ from $\vec{n}_0(z)$ becomes large near resonances $\boldsymbol{\nu_0 = \nu_k}$,
where $\boldsymbol{\nu_k}$ is a harmonic of the orbital motion.

Radiative polarization/depolarization of $e^{\pm}$

- Bagrov-Sokolov-Ternov polarization:

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

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

$$\tau_{dk}^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m_e C}\oint ds\,\langle\frac{1-\frac{2}{9}(\hat{n}\cdot\hat{v})^2+\frac{11}{18}(\gamma\frac{\partial\hat{n}}{\partial\gamma})^2}{|\rho(s)|^3}\rangle_s,$$

  - Equilibrium polarization:

- $$P_{dk} \Longrightarrow -\frac{8}{5\sqrt{3}}\frac{\oint ds\langle\frac{1}{|\rho(s)|^3}\hat{b}\cdot(\hat{n}-\gamma\frac{\partial\hat{n}}{\partial\gamma})\rangle_s}{\oint ds\langle\frac{1}{|\rho(s)|^3}\left[1-\frac{2}{9}(\hat{n}\cdot\hat{s})^2+\frac{11}{18}\left(\gamma\frac{\partial\hat{n}}{\partial\gamma}\right)^2\right]\rangle_s}$$

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: $\vec{\Omega} = (\Omega_y \,;\, \vec{\Omega}_h)$
- Spin tune in vertical field: $\nu_{sp} = \gamma G$ (i.e. number of spin horizontal turns… over the orbit)

- Spin resonances take place at $\gamma G \approx k; \quad kN \pm k_x\nu_x \pm k_y\nu_y \pm k_s\nu_s$
- …and depolarization happens: $\frac{dS_h}{dt} - i\Omega_y S_h = i\Omega_{hk} S_y$
- About more than γG 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

ZGS + AGS proton spin acceleration

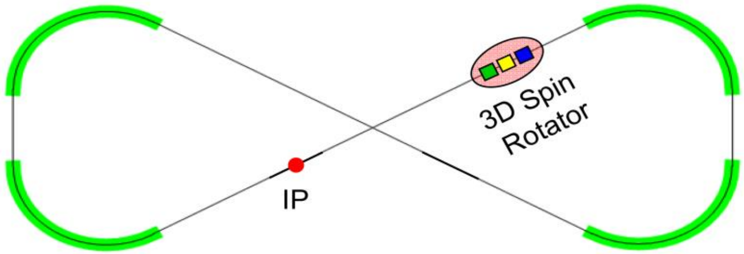
Backup slides

- 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… !

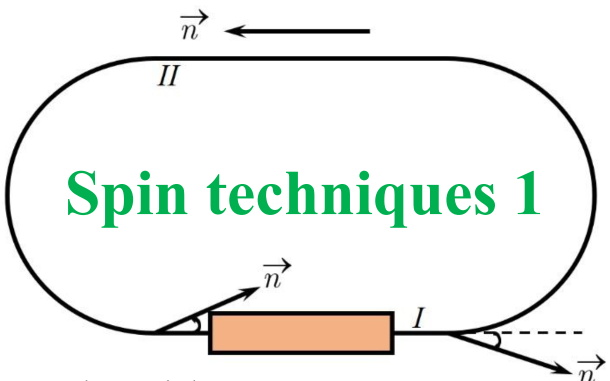
"Siberian Snakes": making *Spin Echo* in racetracks…

Cancellation idea of spin global precession over the racetrack orbit:

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

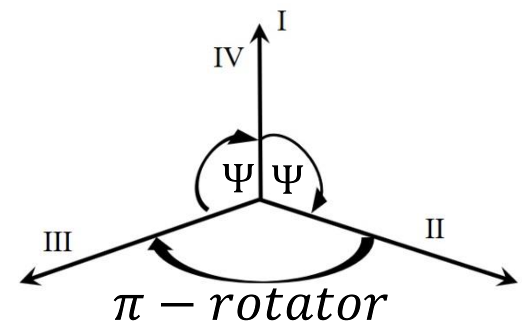
by inserting local spin flip about a horizontal axis

<u>Topological compensation of spin precession over arcs</u>



Solenoid as $\pi - rotator$

Spin echo effect is obviously extendable to any $\pi - rotator$ around ***an arbitrary horizontal axis***



There is a unique periodic solution: $\vec{n}(z) = \vec{n}\,(z + C)$

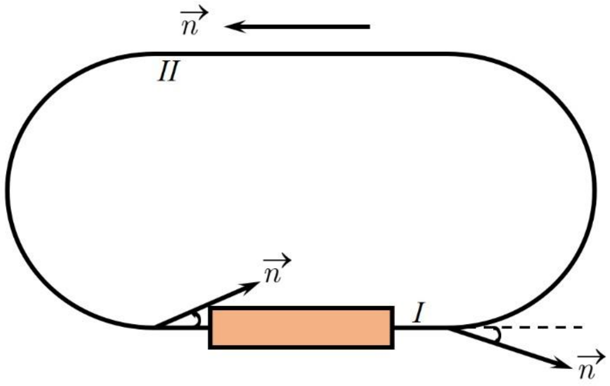
and two (arbitrary chosen) "semi-periodic" orthogonal to $\vec{n}$: $\vec{\eta}(z) = -\vec{\eta}(z + C)$

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 ½ independent of the beam energy (!)

SS technology 1

To insert solenoid is, in principle, the simplest way to utilize local spin flip around a horizontal (longitudinal) axis



Solenoid as $\pi - rotator$

It takes compensation for x to y coupling

Demonstrated at IUCF

(A. Krisch and T. Roser, 1989)

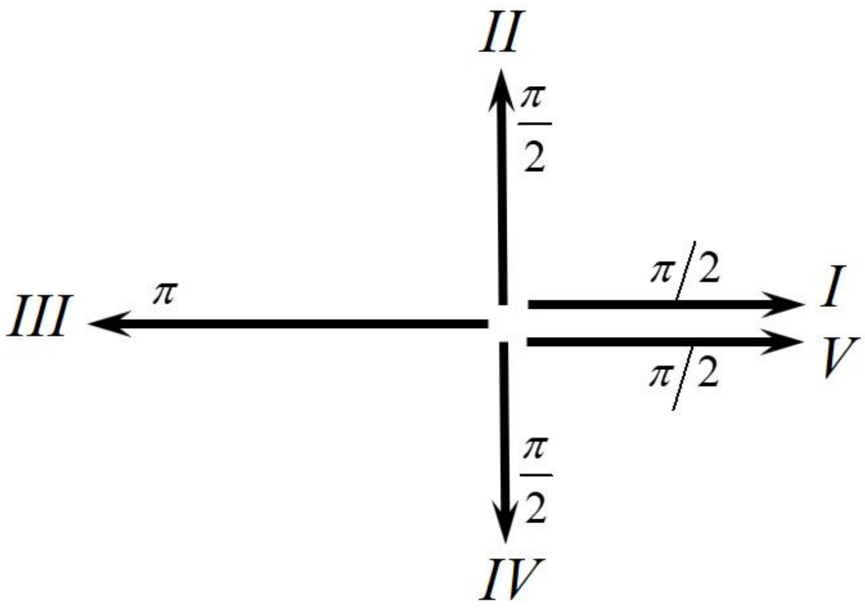
- SS technology 1

- However, use solenoid is impractical at high energies

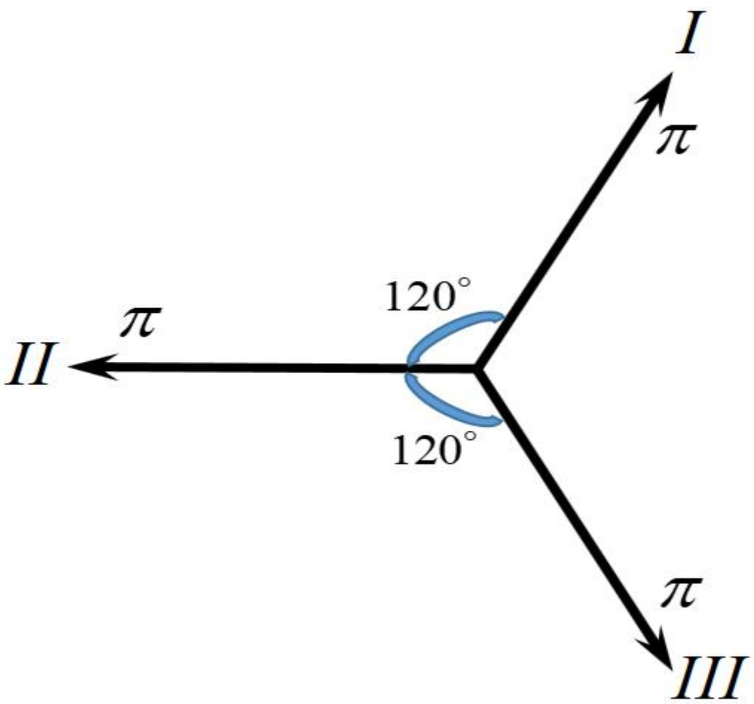
Spin Techniques 3

"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

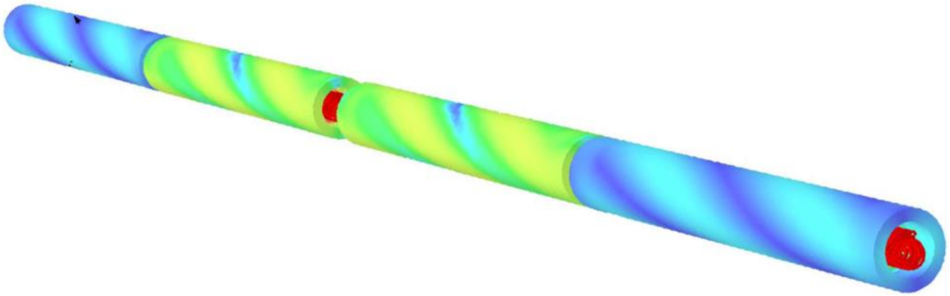
Helical snakes (1978)

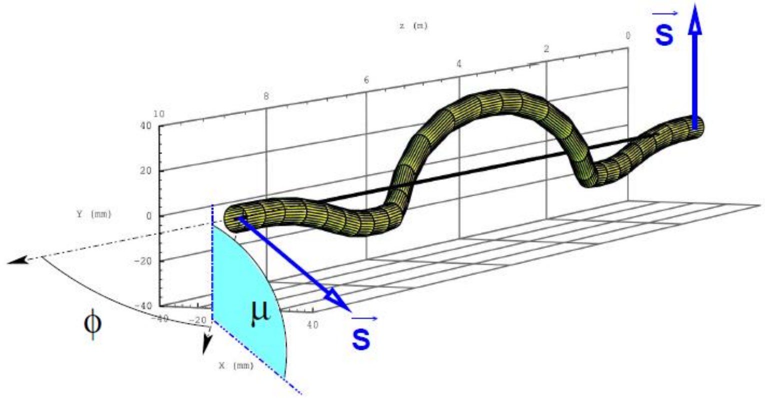
Helical snakes for RHIC

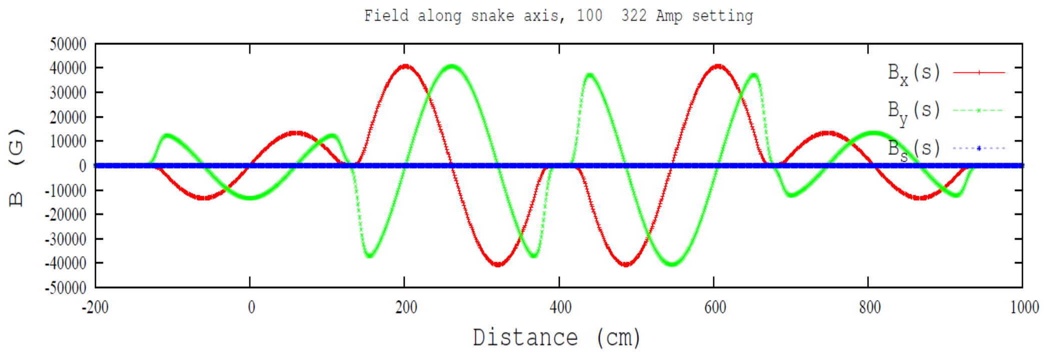
Helical snake design for MI of FNAL

SS technology 2

SS utilization and success in RHIC

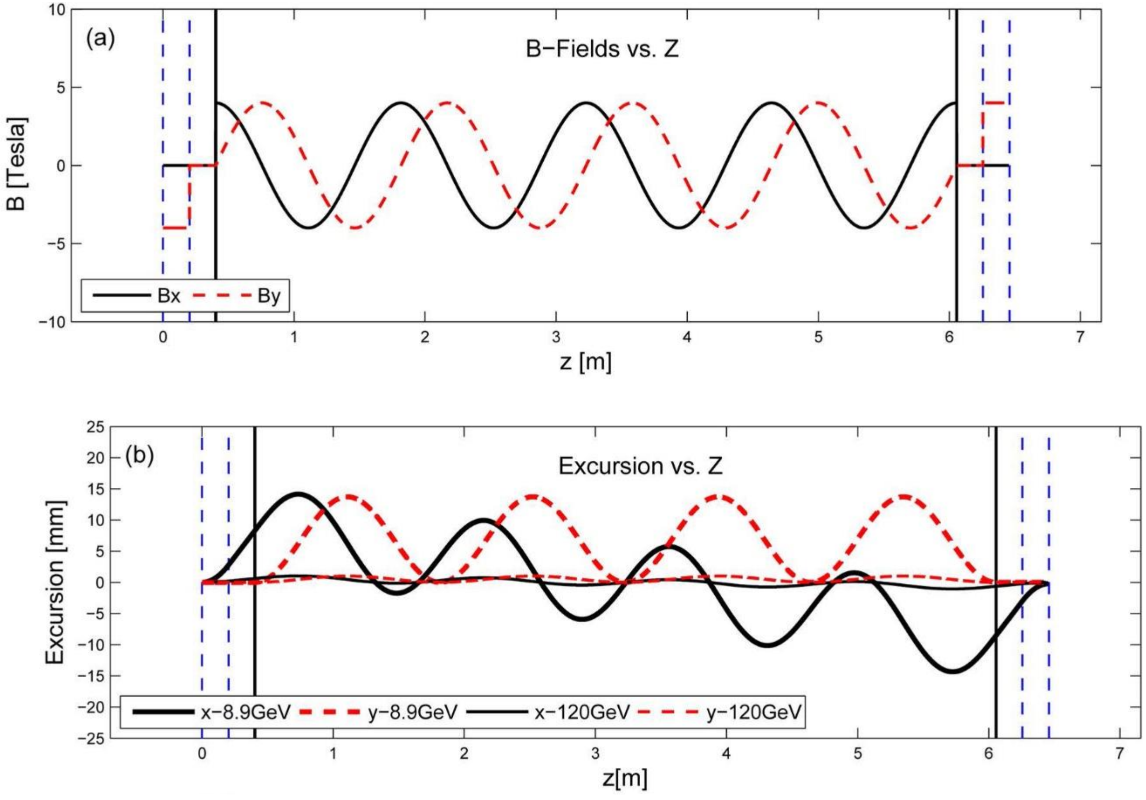






SS technology 3

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

<u>With two snakes in a ring, periodical spin returns to be vertical in arcs</u>

<u>(but with inter-flipping polarity)</u>

- 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 φ between two snake' axes, global spin tune is equal to $\nu = \frac{\varphi}{\pi}$

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

<u>What is achieved</u>:

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

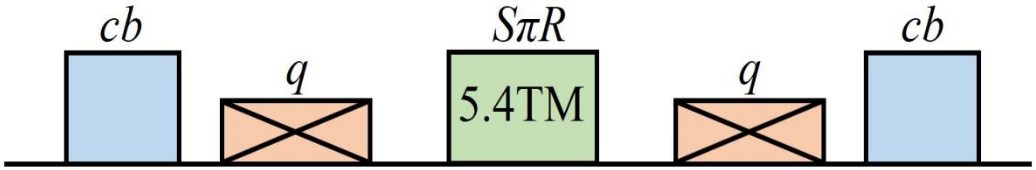
Multiple SS for High Energy hadron rings

26 pair of snakes for 20 TeV SSC

6 snakes for RHIC 300 GeV

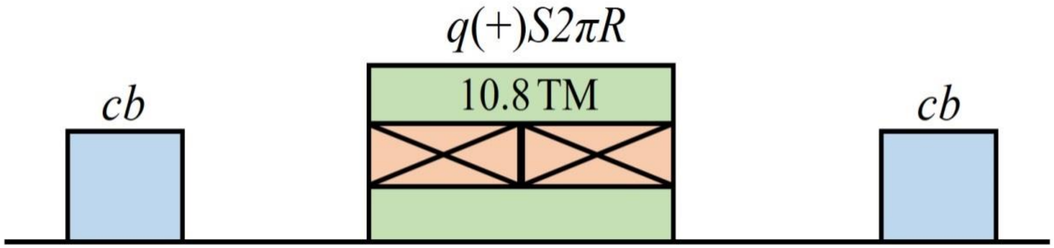
Spin Techniques 8

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



Split quadruple with simple π *rotator* in between

cb – correcting bends

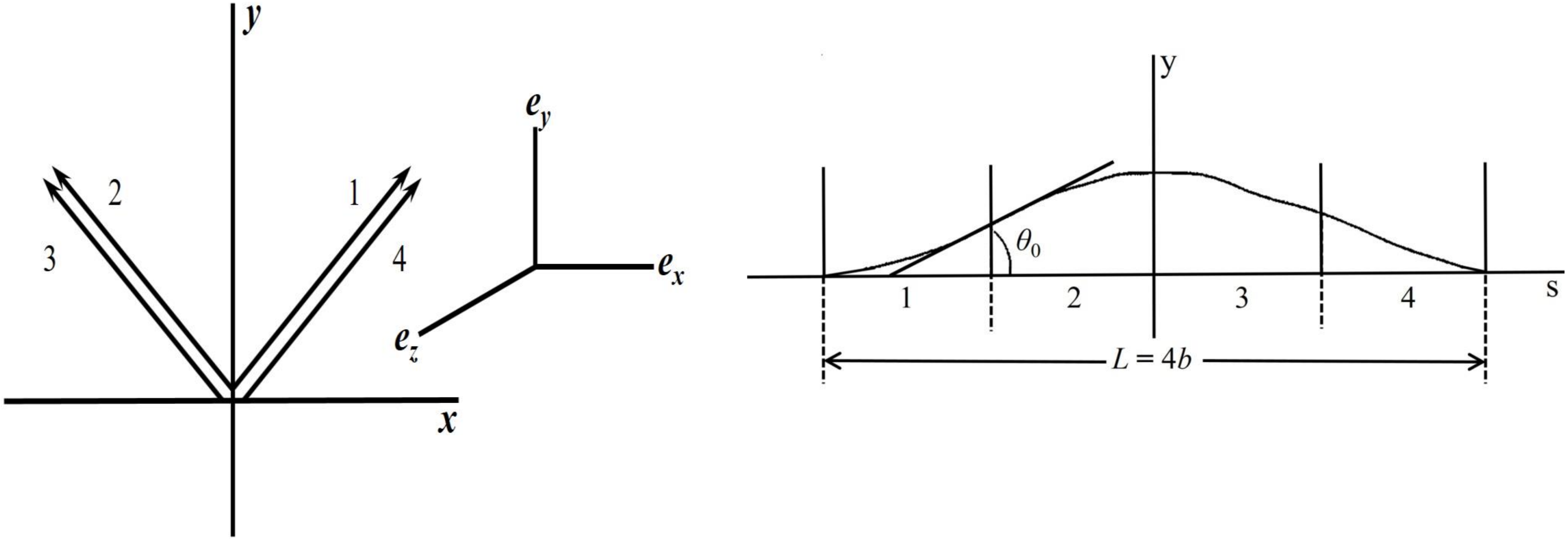


Quad combined with 2π *rotator* along

Two "normal" SS installed in HE ring can then provide acceleration of polarized protons in range of about 1000 TeV (!)

Spin Techniques 9

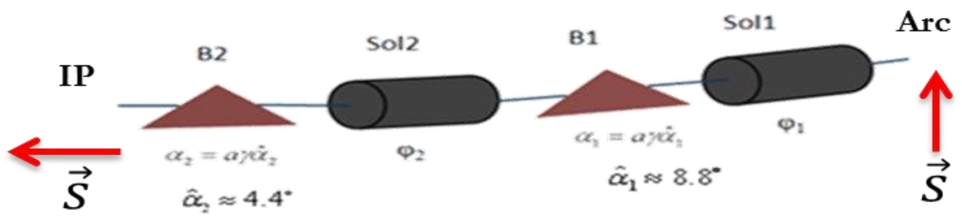
Bending Rotators and Snakes on tilted dipoles (1995)



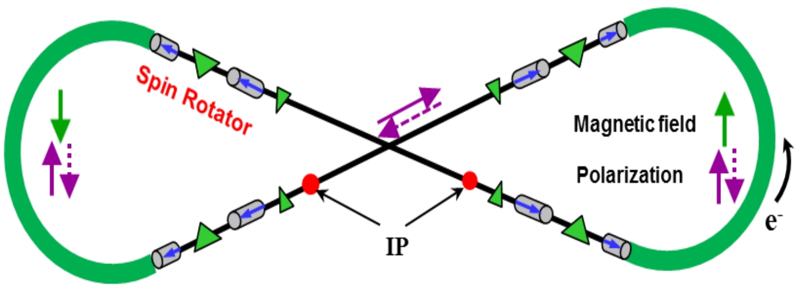
Future Prospects

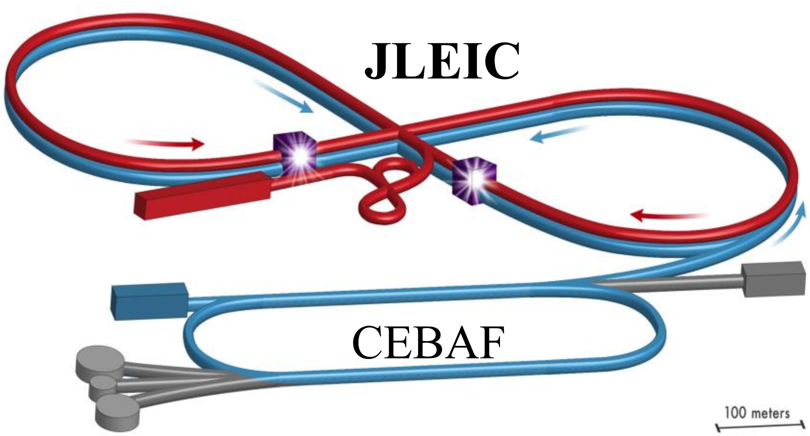
Universal Spin Rotator and SS for EIC

Universal Spin Rotator on solenoids and constant bends

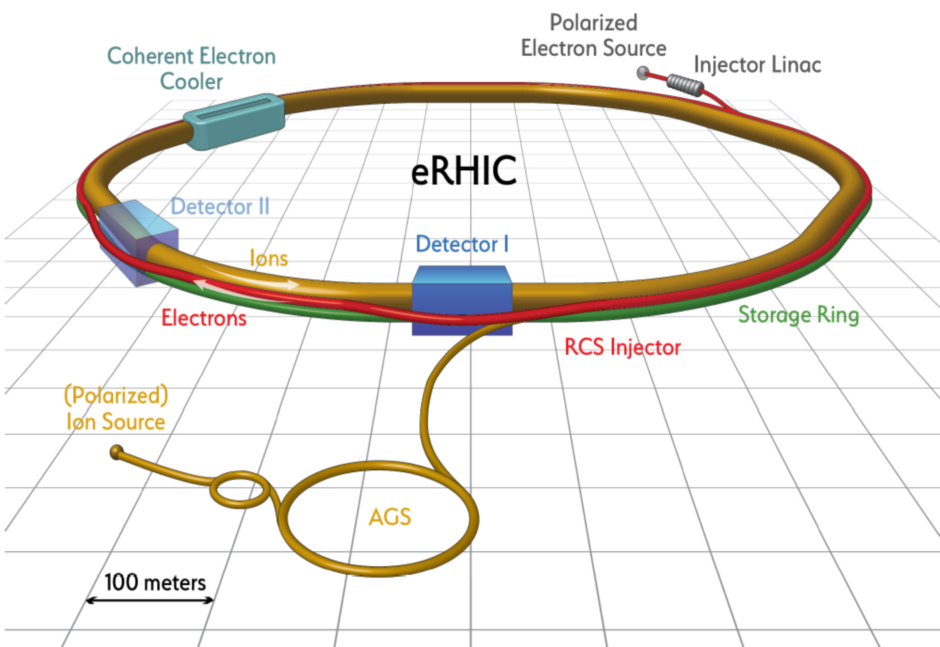


Electron spin rotators for JLEIC





R&S for electrons in eRHIC



Thinking about polarized CEPC

Thoughts on Beam Polarization delivery in CEPC

<u>Option I</u>: Use Polarized e-gun (electrons only…)

- Stacking and accelerating for injection to collider ring
- Acceleration and maintenance of PEB in the Collider Ring

<u>Option II</u> : BST polarization in the Collider Ring

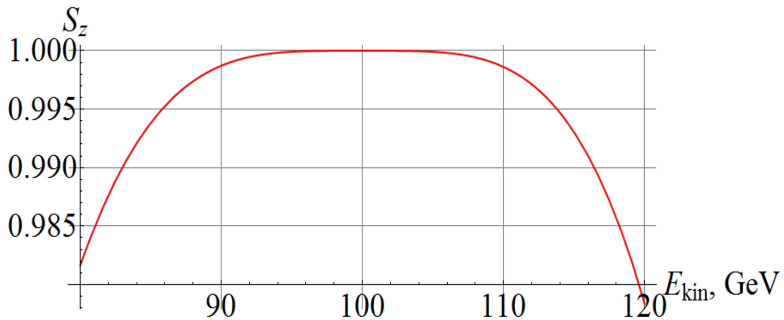
(at injection energy…or in booster ring…?)

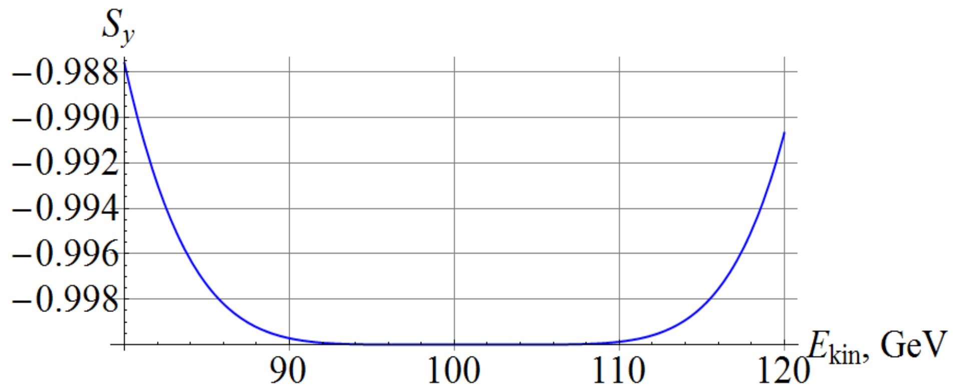
- Takes Polarizing Wigglers to facilitate BST
- Luminosity run at wigglers off

Need SS (and spin rotators) in both…

Spin Techniques 11

Achromatic Rotator and Snake on transverse fields for CEPC





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

(IP, $S_z = 1$) | $-\alpha_{x2}$ | $-\alpha_{y2}$ | $\alpha_{x2} - \alpha_{x1}$ | $-\alpha_{y1}$ | α_{x1} | **(2nd Arc, $S_y = -1$)**

Орбитальные углы поворота в радиальных и вертикальных диполях:

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

$\alpha_{y1} = 12.34$ mrad, $\alpha_{y2} = 9.487$ mrad.

Spin techniques 12

Fixed orbit SR and SS on dipoles and solenoids for CEPC

$(S_y = 1)$ | α_{x1} | α_{y1} | φ_{z1} | $\alpha_{x2} - \alpha_{x1}$ | α_{y2} | φ_{z2} | $-\alpha_{x2}$ | $(S_z = 1)$

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**

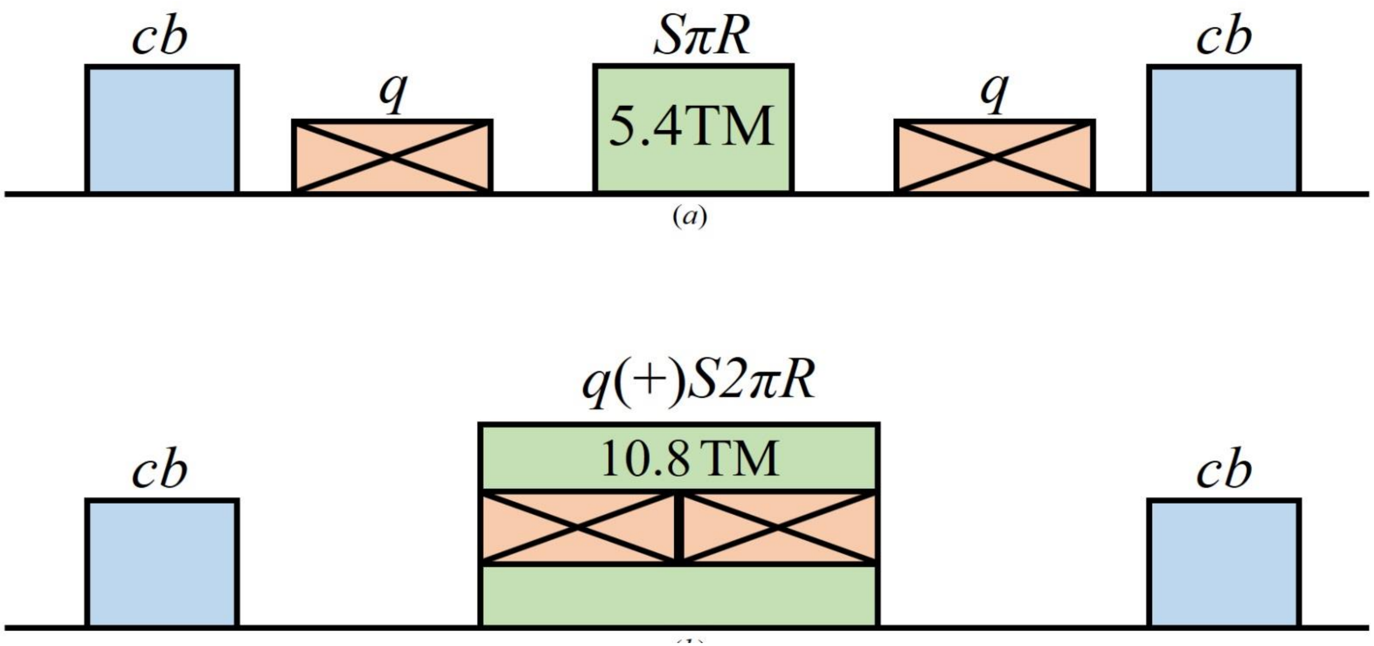
<u>Options for the Collider Rings</u>

<u>Option I</u>   Many SS

- Sufficient large chain of SS to suppress depolarizing impact of the superperiodic misalignment harmonics
- Spin tune ½
- 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.

<u>Option II</u>: **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 four attention!

Backup slides