Longitudinally Polarized Beam Studies for BEPCII

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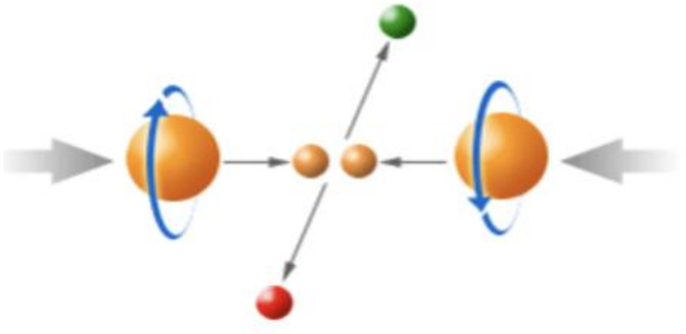
Polarized Electron Beam

- Spin polarization of electron beam $\vec{P} = \frac{1}{N}\sum_{i=1}^{N} \vec{S}_i$
- A critical technical foundation for high-energy physics experiments

  Vertical polarization: beam energy measurement

  Longitudinal polarized beam collision : expands the research potential of particle physics



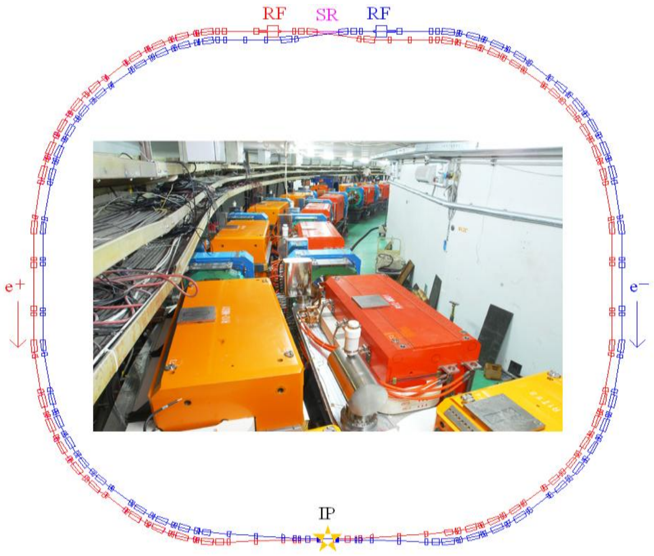
- Requires **polarization higher than 50%** for at least one beam

Collider	Particle Species	Energy (GeV)	Luminosity (cm^{-2}s^{-1})	Polarization	Polarized Beam Generation	Machine Status
SLC	e^-/e^+	46.2×46.2	3×10^{30}	e^-~66%	Pre-polarized(e^-)	Decommissioned
HERA	$e^\pm/p$	27.5×920	1.5×10^{31}	$e^\pm$ ~70%	Self-polarized	Decommissioned
ILC	e^-/e^+	91×91 to 1000×1000	1.8×10^{34}	e^-~80%	Pre-polarized	Planned
SuperKEKB	e^-/e^+	7.007×4.000	8×10^{35}	e^-~80%	Pre-polarized	In operation
CEPC	e^-/e^+	46.2×46.2 to 120×120	2.04×10^{34}	$e^- \geq 70\%$	Pre-polarized	Planned
EicC	e/p	3.5×19	1.1×10^{33}	e^-~80%	Pre-polarized	Planned
EIC	e/p	10×275	1.0×10^{34}	e^-~70%	Pre-polarized	Planned

Both high collision luminosity and high beam polarization !

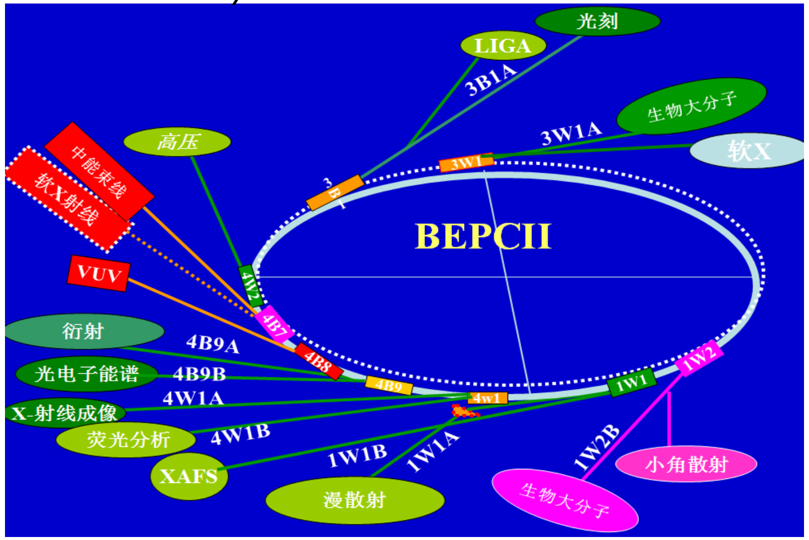
Beijing Electron Positron Collider (BEPC)

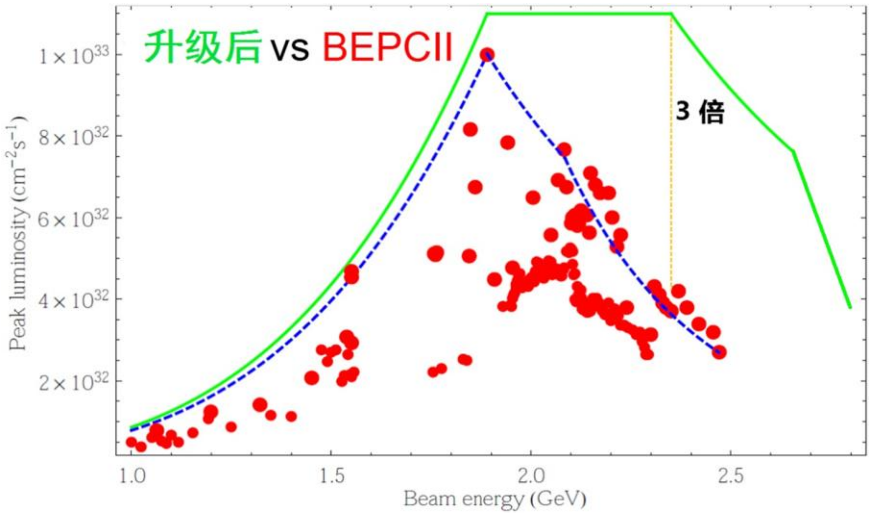
first large science facility in China (1988-2005)
BSRF: synchrotron light source operation (since 1990)



BEPCII: Single-ring -> double-ring collider (1.0 ~ 2.5 GeV)

- User operation since 2009, luminosity goal (*100) reached in 2016, now in routine operation





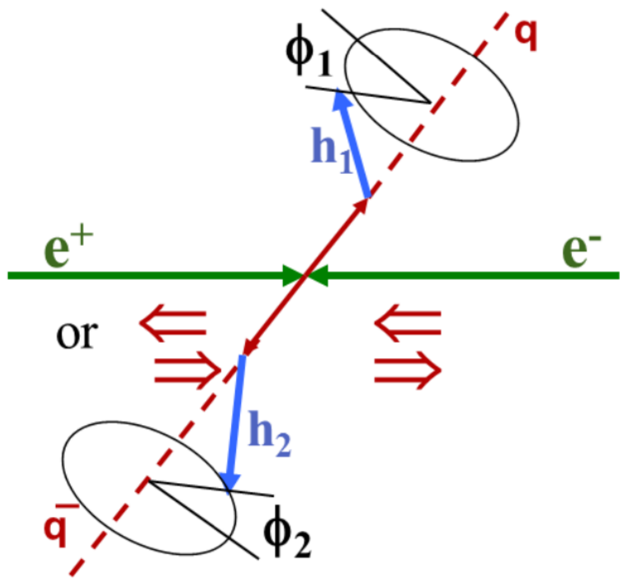
BEPCII-U (from mid-2024)

- Increase the energy reach (~2.8GeV) & luminosity at higher energies

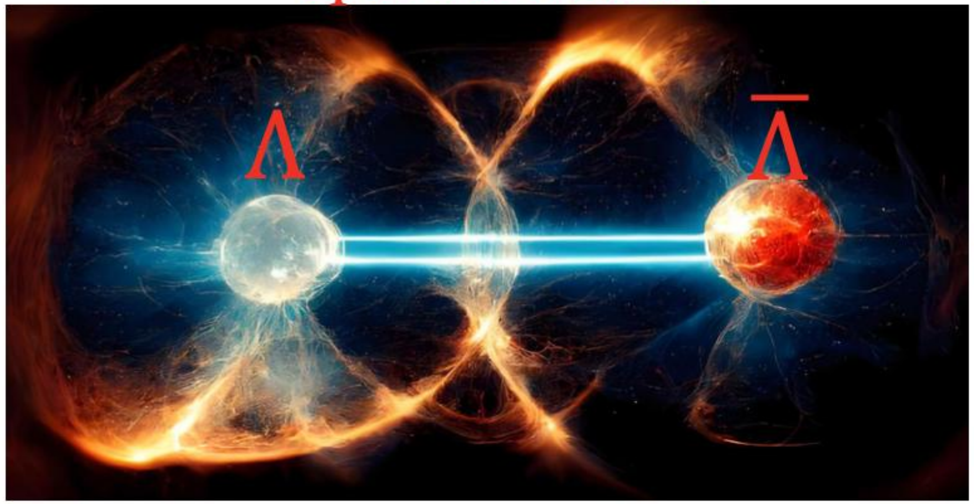
Motivation for Longitudinal Polarization at BEPCII

- BESIII spin physics has flourishes, focusing on polarization of final products of e+e- collisions
  - Nature,606,64-69,2022; PRL 116,042001, 2016; PRL 130, 231901, 2023; arXiv:2502.16084

- e- longitudinal polarization will **enhance the spin physics potential** at BESIII
  - Search for CP violation in production & decay of Hyperon-Antihyperon pairs (arXiv:2502.20274)
  - Spin dependent fragmentation function etc.

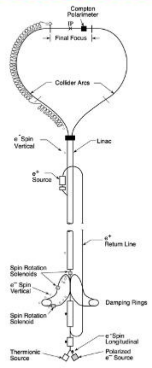


Spin correlation!

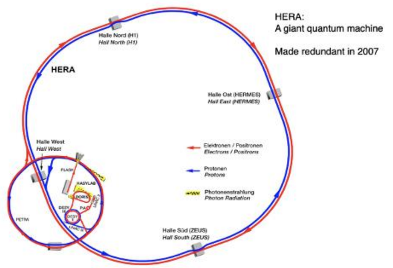


Motivation for Longitudinal Polarization at BEPCII

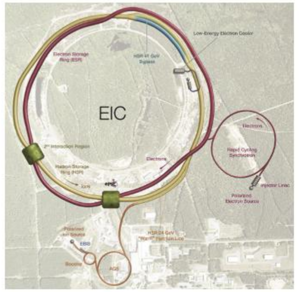
- **e- longitudinal polarization at BEPCII: a demonstrator for future colliders**
  - simultaneous achievement of high luminosity and high longitudinal polarization
  - swap-out injection applied to e+e- collider, already demonstrated at APS-U & HEPS
  - Long-term operation of polarized electron source
  - Precision Compton polarimetry



SLC : 77% pol e- vs unpol. e+, lumnosity~3e30



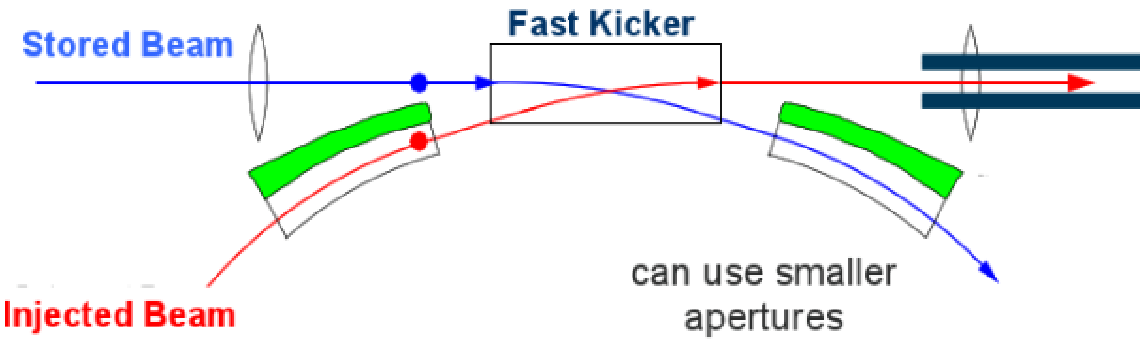
HERA : 65%pol e- vs unpol. proton lumnosity~7e31



EIC : 70%pol e- vs pol proton, luminosity ~1e34

Next generation e+e- colliders 1e34~1e36

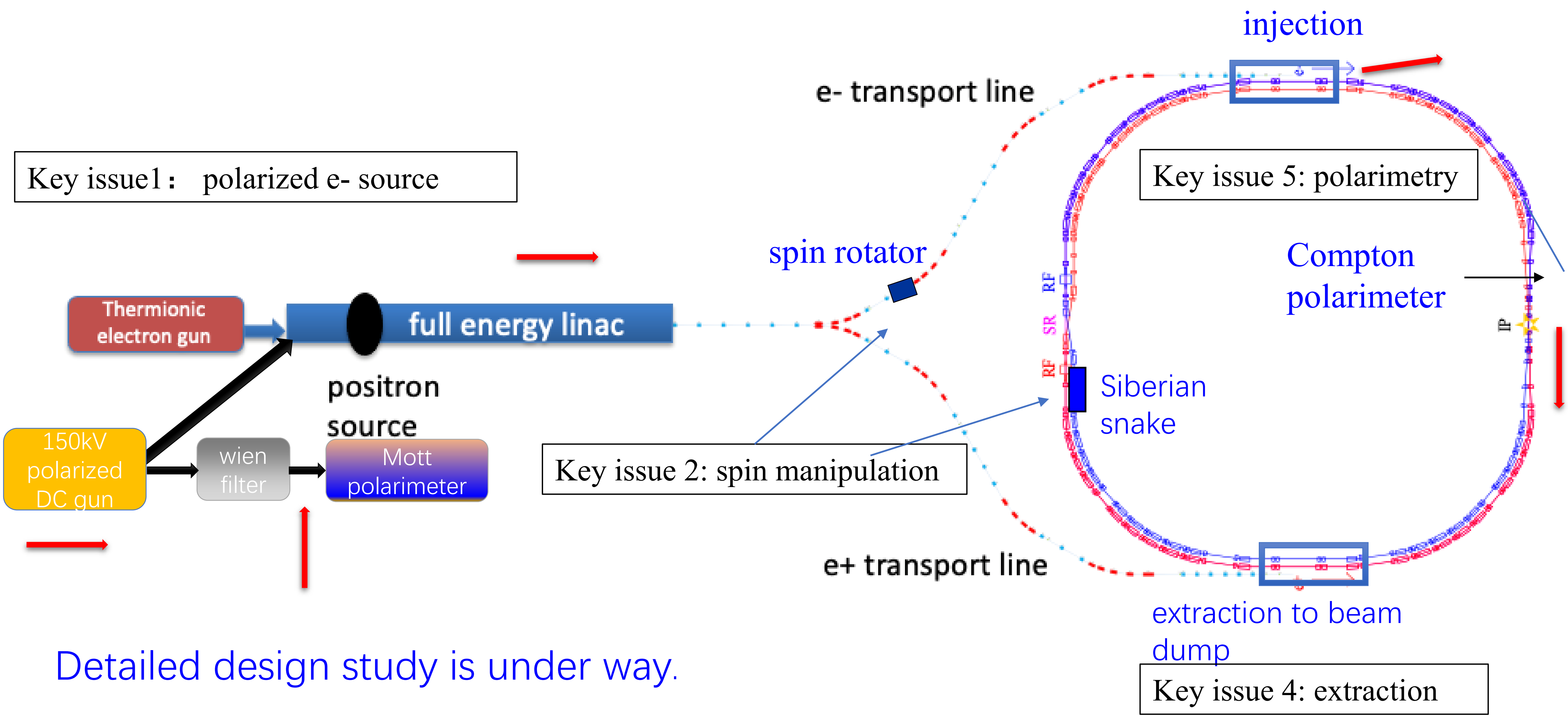
swap-out injection



Courtesy of C. Steier

Modified Layout for Longitudinal Polarization

- Self-polarization time ~ E^{-5}, 583 min @ 1.55 GeV

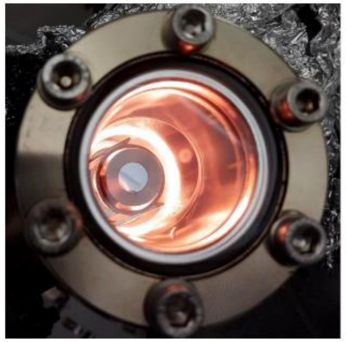


Detailed design study is under way.

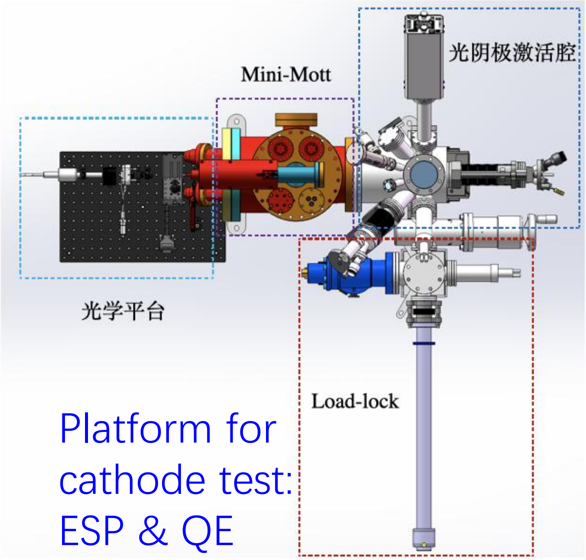
R&D on Polarized Electron Source

- **Superlattice GaAs cathode R&D (IHEP-JGU Mainz-Chongqing U)**
  - First test sample produced by Acken @ Suzhou 2025.6
  - Preliminary performance tests show promising results
    - Target: P > 85%, QE > 0.8%
    - Current: P~80%-82%, QE~0.1%--0.7%
  - A platform for cathode performance test under construction (pol & QE)
  - Second cathode sample to be tested
- **A polarized electron source for BEPCII is under design**

V. Tyukin (JGU Mainz) sliced the SL wafer @ Acken

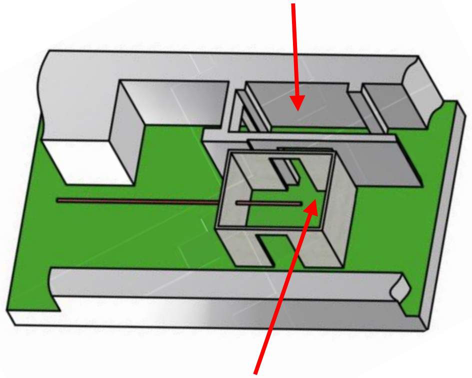


SL cathode in load-lock chamber @ Mainz

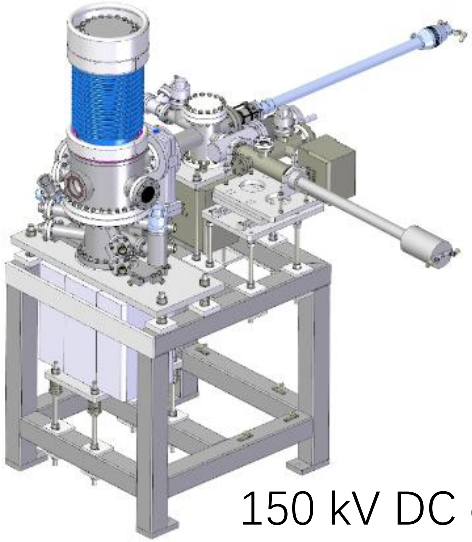


Platform for cathode test: ESP & QE

Space for polarized electron source



Existing unpolarized source @ BEPCII



150 kV DC gun

Solenoid Siberian Snake

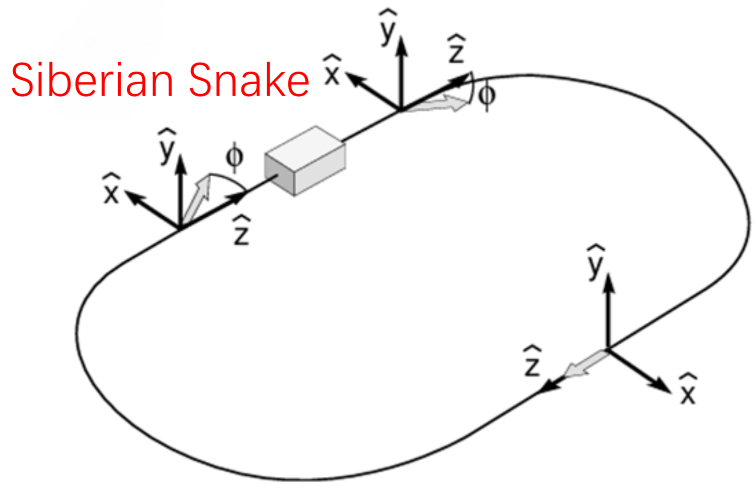
- **Siberian Snake Mechanism**: net effect on the spin of a particle is to rotate it by π around the z-axis as it passes through the device
- **The opposite side of the Siberian Snake** can serve as the interaction point for longitudinally polarized beams.

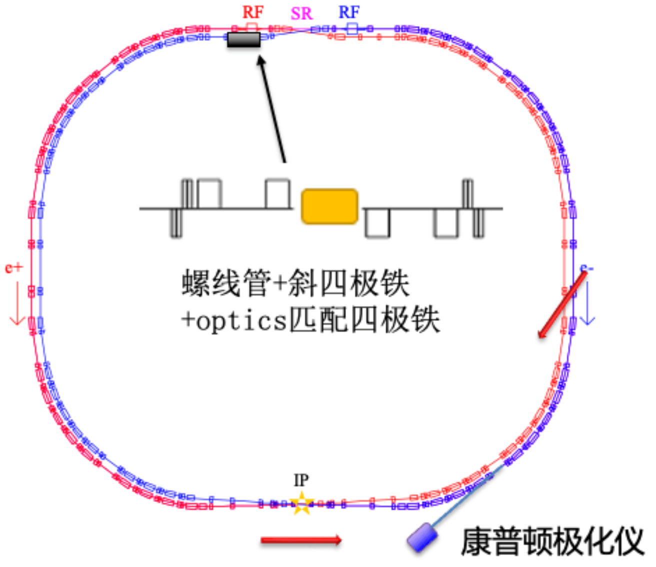
$$M_{\text{tot}} = -i\sigma_z$$

$$\hat{n} = \frac{i}{2}\,\text{tr}\left(M_{\text{tot}}\vec{\sigma}\right) = \hat{z}$$

$$\cos(\pi\nu_0) = \frac{1}{2}\text{tr}(M_{\text{tot}}) = 0,$$

$$\Rightarrow \quad \nu_0 = \frac{1}{2}.$$



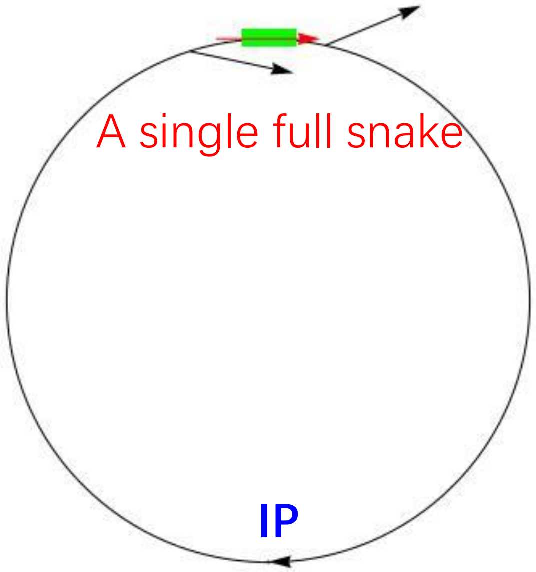


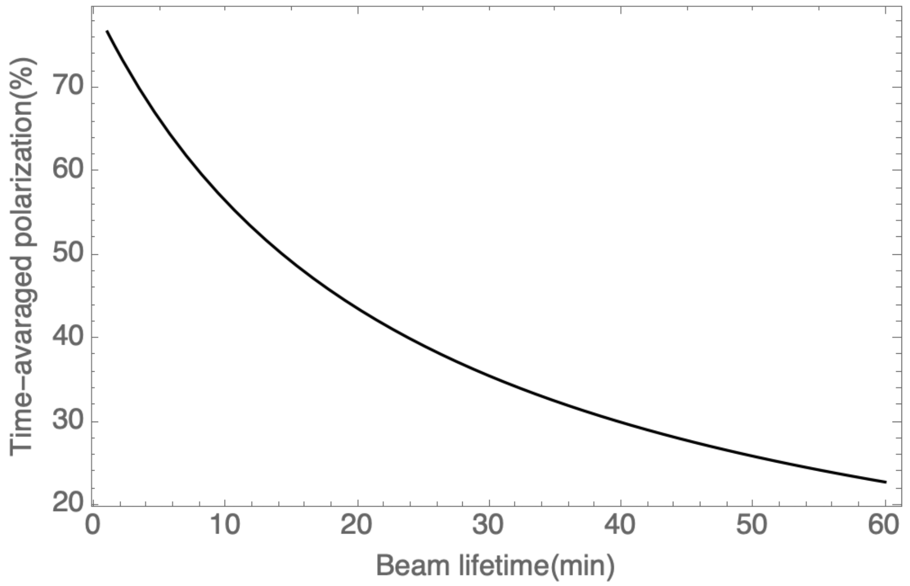
- **Space**: no ring circumference increment;
- **Detector**: the snake device can be arranged far from the detector region;
- …

A. W. Chao, Special topics in accelerator physics(2022)

Longitudinal Polarization Scheme @ BEPCII

- Longitudinal polarized e- versus unpolarized e+
- Inserting a Siberian snake to attain longitudinal polarization at IP
  - Superconducting solenoid, BL[T·m]=10.467E[GeV], ~20T·m @ 1.89GeV
  - Depolarization time ~ E^{-7}, 24 min @ 1.55 GeV (for spin matched snake)
- **top-up injection:** frequently **refill** depleted depolarized bunches with fresh polarized bunches
  - Polarized electron source can deliver injected beam polarization > 80%
  - A shorter beam lifetime -> higher time-averaged beam polarization





Longitudinal Polarization Scheme @ BEPCII

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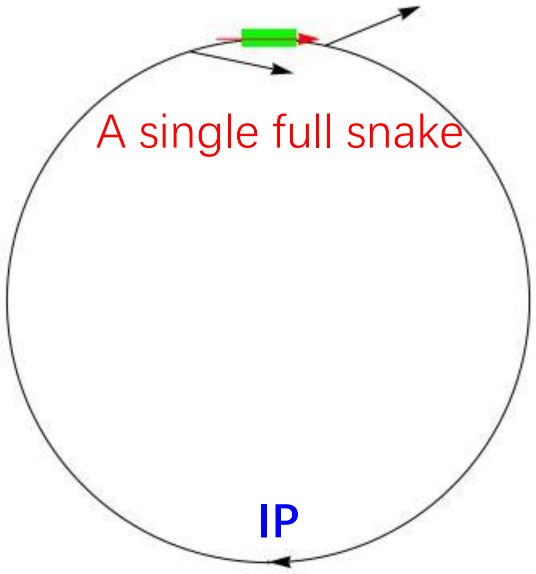
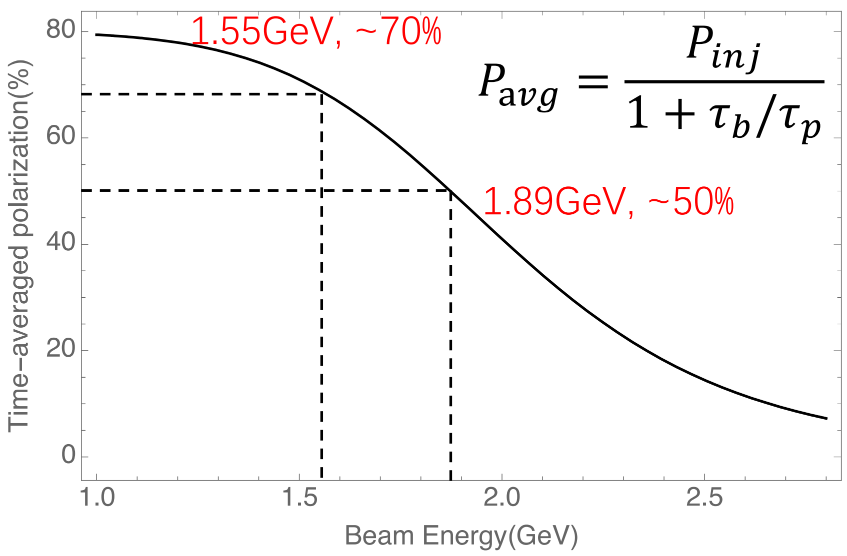
  - Superconducting solenoid, BL[T·m]=10.467E[GeV], ~20T·m @ 1.89GeV
  - Depolarization time ~ E^{-7}, 24 min @ 1.55 GeV (for spin matched snake)
- **Swap-out injection:** frequently **dump** depolarized bunches and **replace** with fresh polarized bunches
  - Polarized electron source can deliver injected beam polarization > 80%
  - e.g. replace 1/12 of all 120 bunches every 20 seconds, corresponding to a beam lifetime of ~ 4min



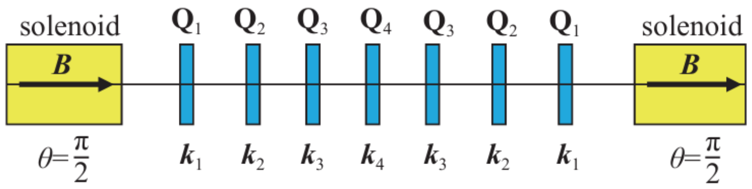


Orbit Coupling Compensation for Solenoids

- Solenoids will introduce **coupling of transverse orbit motions**, which causes the growth of vertical emittance and consequently degrades collision luminosity.

- **Coupling compensation scheme**: Alternate arrangement of solenoids together with quadrupoles or skew quadrupoles.

$$\begin{pmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{pmatrix}$$



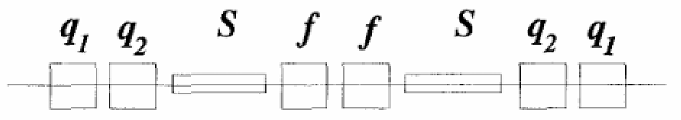
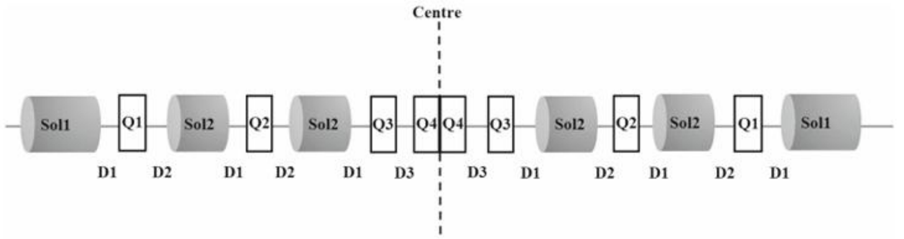


Figure. 3. Siberian Snake scheme

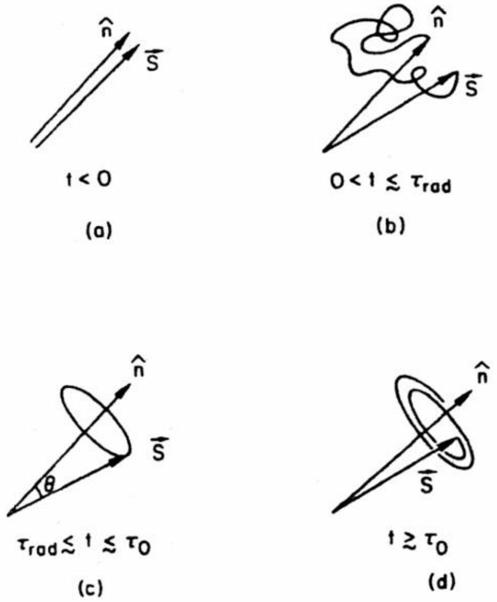


Spin-orbit Coupling Vector in Circular Accelerators

- **Spin matching**—to minimize **the spin-orbit coupling vector:** $\mathbf{d} = \mathrm{Re}(iD\hat{\eta}^*)$
- Two components of the spin-orbit coupling vector

$$D = D_\gamma + D_\beta$$

\- D_γ correlated with synchrotron oscillations: 24min@1.55GeV ($\propto E$^(−7))
\- D_β associated with betatron oscillations, triggers **spin resonances** (can be suppressed with an appropriate matching scheme).



自旋轨道耦合矢量用来衡量同步辐射带来的自旋扩散

Spin Resonances Introduced by Siberian Snake

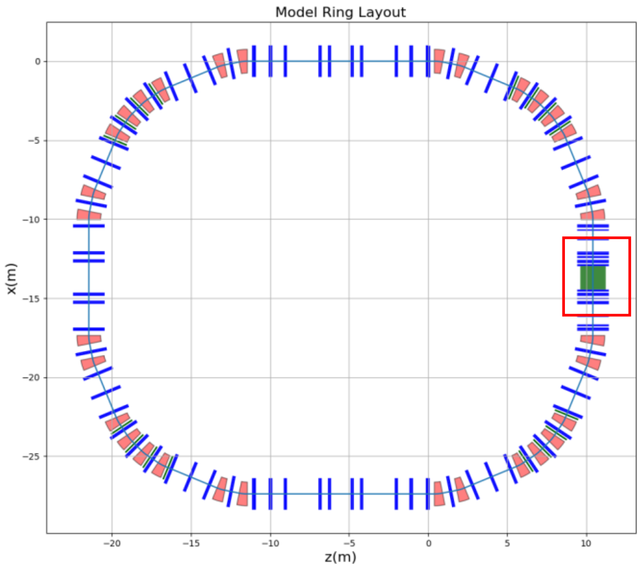
- In high-luminosity colliders with a single interaction point, the transverse tunes are typically set near half-integer values to suppress beam-beam effects and enhance luminosity.
- **Spin resonances** $\nu_0 \pm \nu_x = k$ **at** $\nu_x = 0.5$ introduced by Siberian Snake

Parameter	BEPCII-U @2.35GeV
RF voltage [MV]	3.3
SR power [kW]	250
Beam current [mA]	900
β_x^*/β_y^* [m]	1.0/0.013
ν_x/ν_y	7.5056/5.5758
Bunch current [mA]	7.5
Bunch number	120
ξ_y	0.036
Emittance [nm·rad]	152
Coupling [%]	0.35
ν_s	0.04
Bucket height	0.011
σ_{z0} [cm]	1.04
σ_z [cm]	1.3
Peak luminosity [10^{32}cm^{-2}s^{-1}]	11

Geng, Huiping et al. Beam physics design for BEPCII upgrade, Radiat. Det. Tech. Meth. (2026)

Spin Resonances Introduced by Siberian Snake

- In high-luminosity colliders with a single interaction point, the transverse tunes are typically set near half-integer values to suppress beam-beam effects and enhance luminosity.
- **Spin resonances** $\nu_0 \pm \nu_x = k$ **at** $\nu_x = 0.5$ introduced by Siberian Snake
- Simulation on a Model Ring@1.2GeV 100.252m

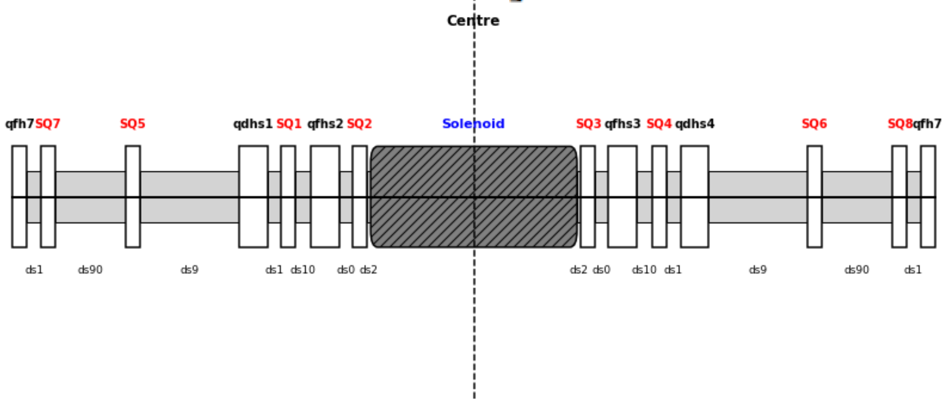


	ν_x	ν_y	ν_z	ν_0(spin tune)
with snake	6.496	6.808	0.051	0.500
without snake	6.398	6.418	0.051	0.673

Model Ring Spin Matching

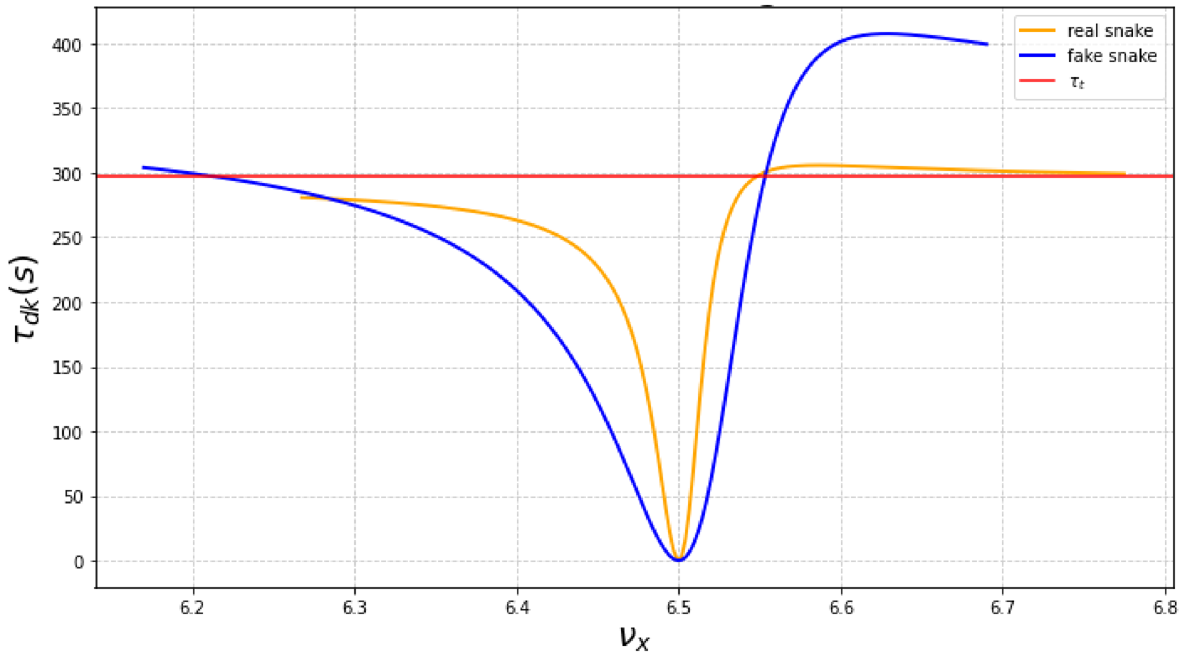
- **Single solenoids snake**： $f_I'^* \neq 0$， resonances cannot be eliminated entirely, while the snake structure is capable of suppressing the resonance width to a certain extent.

$$D_\beta = -\frac{a\gamma\pi}{2\cos(\pi\nu_x)}\left[\cos(\pi a\gamma)\,\mathrm{Im}\left(e^{i\pi\nu_x}J(\theta)f_{Iy0}'^*\right) - i\,\mathrm{Im}\left(e^{i\pi\nu_x}J(\theta)f_{Ix0}'^*\right)\right]$$



$$M = \begin{bmatrix} -0.991 & -0.548 & 0.000 & 0.000 \\ 0.030 & -0.991 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.416 & -1.453 \\ 0.000 & 0.000 & 0.569 & 0.416 \end{bmatrix}$$

V. Ptitsin et al., Siberian snakes for electron storage rings, Proceedings of the 1997 Particle Accelerator Conference, pp. 3500-3502 vol.3(1997)



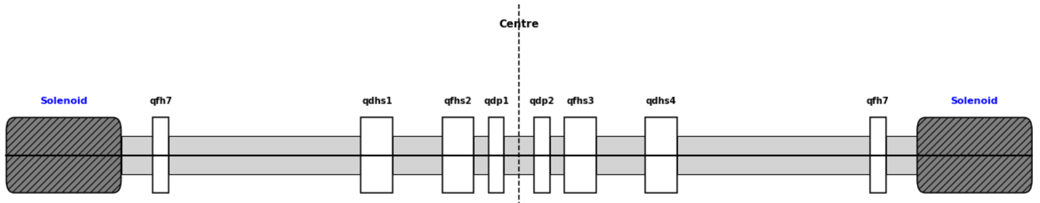
$\nu_x - \tau_{dk}$scanning carried out via **Bmad**

Yellow： orbit map+spin map

Blue ： spin map only

Model Ring Spin Matching

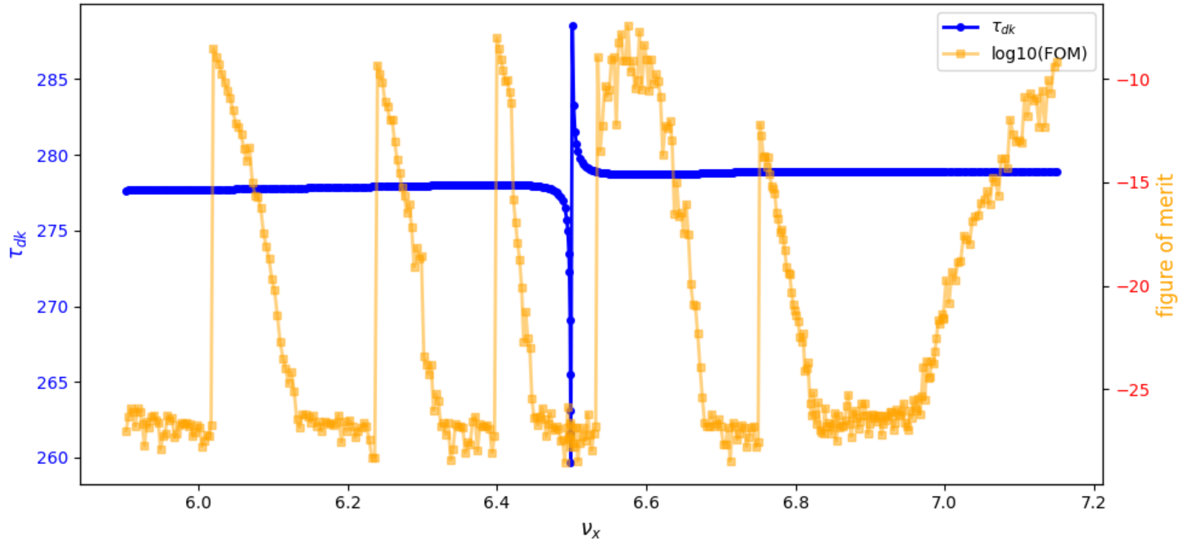
- **Double solenoids snake**: to cancel out the D_β oscillatory term ,the transfer matrix of the entire snake device $\begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$




```
Solenoid:
sol: L = 0.731 (m), B = 8.590(T);

Drift:
ds1: L = 0.200 (m);
ds2: L = 1.227 (m);
ds3: L = 0.315 (m);
ds4: L = 0.094 (m);
ds0: L = 0.191 (m);
```

```
Quadrupole:
qfh7:  L = 0.103 (m), k1 = 13.919 (m⁻²);
qdhs1: L = 0.101 (m), k1 = -6.564 (m⁻²);
qfhs2: L = 0.100 (m), k1 = 5.256 (m⁻²);
qfhs3: L = 0.100 (m), k1 = 5.265 (m⁻²);
qdhs4: L = 0.101 (m), k1 = -6.558 (m⁻²);
qdp1:  L = 0.100 (m), k1 = 0.447 (m⁻²);
qdp2:  L = 0.100 (m), k1 = 0.424 (m⁻²);
```



$\nu_x - \tau_{dk}$scanning carried out via **Bmad**

$@\nu_x = 6.496\,,\ \tau_{dep}: 12.12s \rightarrow 291.10s$

V. Ptitsin et al., Siberian snakes for electron storage rings, Proceedings of the 1997 Particle Accelerator Conference, pp. 3500-3502 vol.3(1997)

Model Ring Spin Matching

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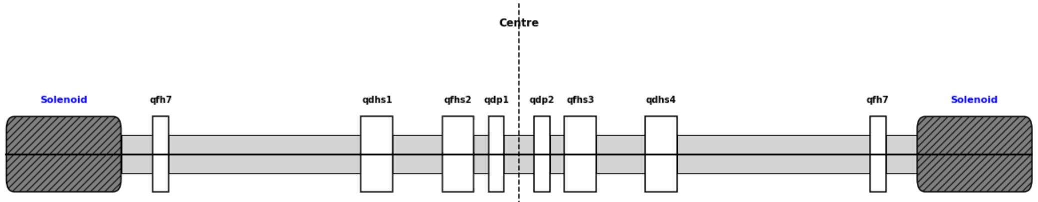


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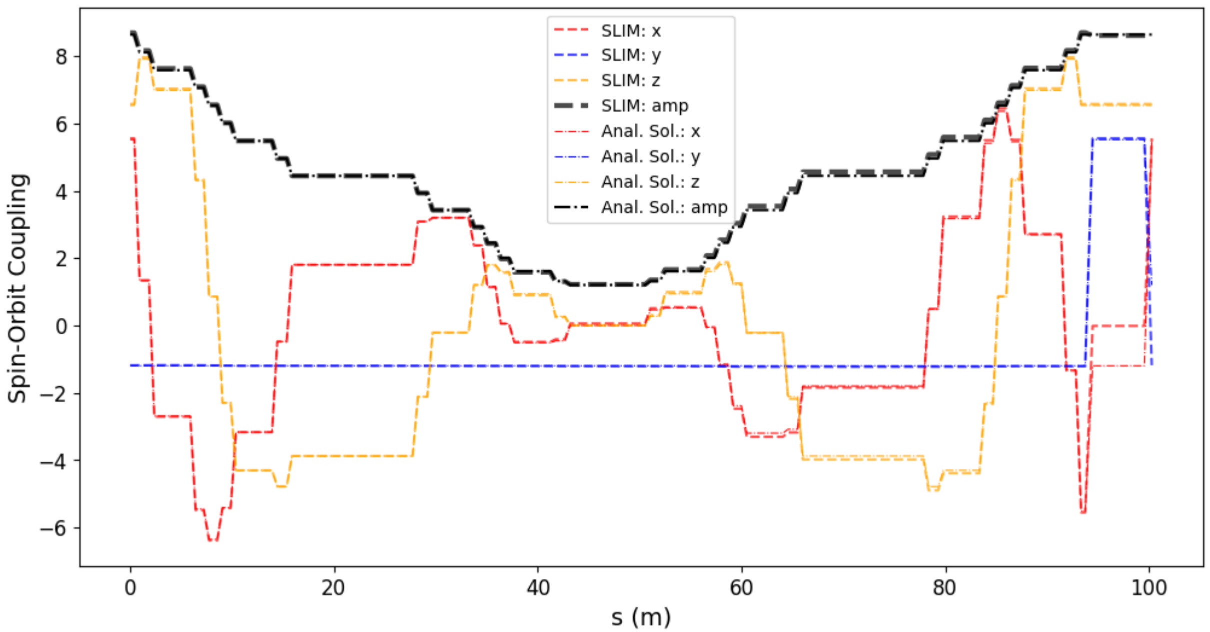

$$D = D_\gamma + \cancel{D_\beta}$$

$$D_\gamma = -\frac{\pi}{2}\sin(\pi a\gamma) + ia\gamma\left(\pi - \int_0^\theta \frac{H_y}{\langle H_y\rangle} d\theta'\right)$$

Compared with the numerical solution from Bmad, the D_β term is cancelled out

V. Ptitsin et al., Siberian snakes for electron storage rings, Proceedings of the 1997 Particle Accelerator Conference, pp. 3500-3502 vol.3(1997)

Model Ring Spin Matching

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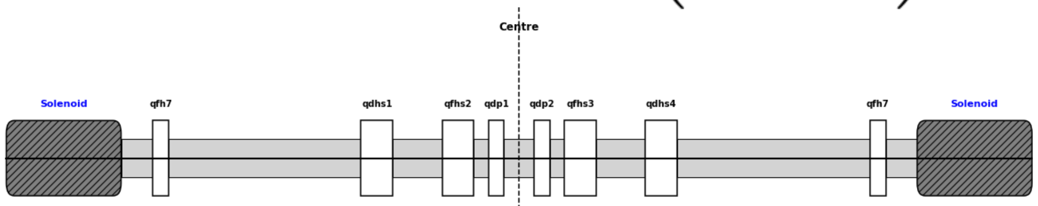


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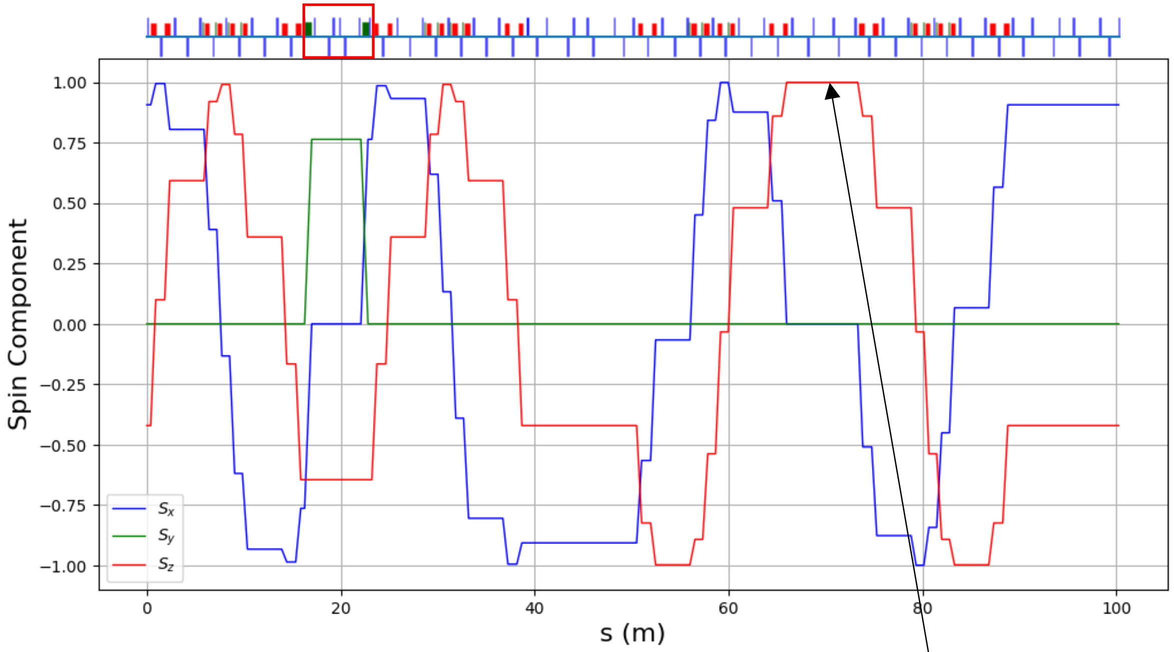

Spin at the opposite side of the Siberian Snake is longitudinal.

V. Ptitsin et al., Siberian snakes for electron storage rings, Proceedings of the 1997 Particle Accelerator Conference, pp. 3500-3502 vol.3(1997)

TO DO LIST

- More compact schemes are currently under investigation.
- The corresponding scheme will be extended to BEPCII in subsequent work.
- Comprehensive performance evaluation covering polarization and collision luminosity.

Summary

- Researches on polarized sources and polarization manipulation techniques are being carried forward continuously.

- The performance of polarized cathodes remains improvable; a test and optimization platform for polarized cathode characteristics is under construction.

- Solenoid Siberian snakes are selected as the key elements to establish longitudinal beam polarization in the storage ring.

- Numerical simulations verify feasible schemes to compensate spin resonances at half-integer working points, which will be further validated and tested on the BEPCII storage ring in subsequent studies.

Thank you!