CEPC polarization

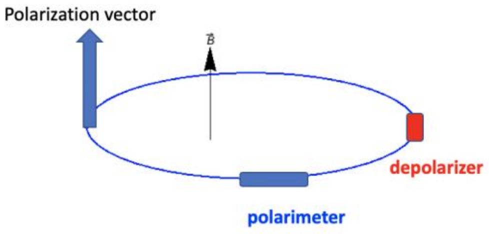
Zhe Duan
On behalf of CEPC Beam Polarization Working Group
2022. 01. 14

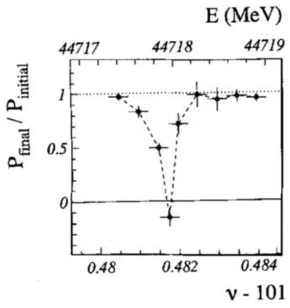
Mini-workshop on Accelerator Physics, IAS Program on High Energy Physics (HEP 2022)

Motivation of CEPC Z-pole polarized beam program

Vertically polarized beams in the arc

- Beam energy calibration via the resonant depolarization technique
- Essential for precision measurements of Z and W properties
- At least 5% ~ 10% vertical polarization, for both e+ and e- beams

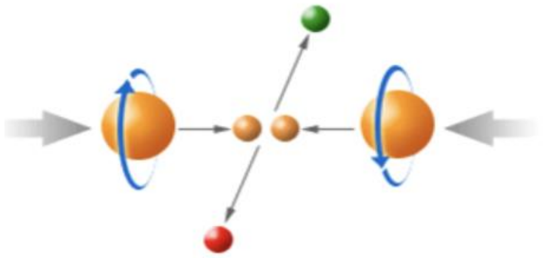




L. Arnaudon, et al., Z. Phys. C 66, 45-62 (1995).

Longitudinally polarized beams at IPs

- Beneficial to colliding beam physics programs at Z, W and Higgs
- Figure of merit: Luminosity * f(Pe+, Pe-)
- ~50% or more longitudinal polarization is desired, for one beam, or both beams



Final deliverable: a detailed design report of polarized beam operation @ Z-pole

Wish list and key questions

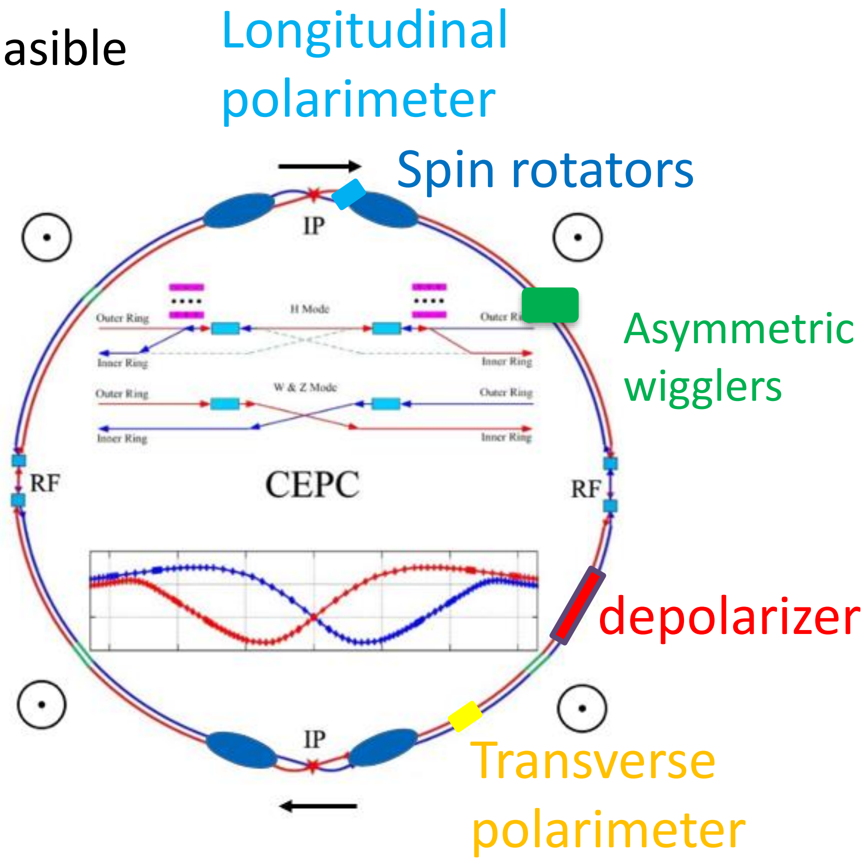
Wish list

- A small fraction of non-colliding bunches with at least 5% vertical polarization in the arc, depolarize one-by-one to carry out resonant depolarization measurements
- All colliding bunches have > 50% time-averaged longitudinal polarization at IPs
- Luminosity is not significantly affected
- Beam lifetime is sufficient long so that top-up injection is feasible

Key questions

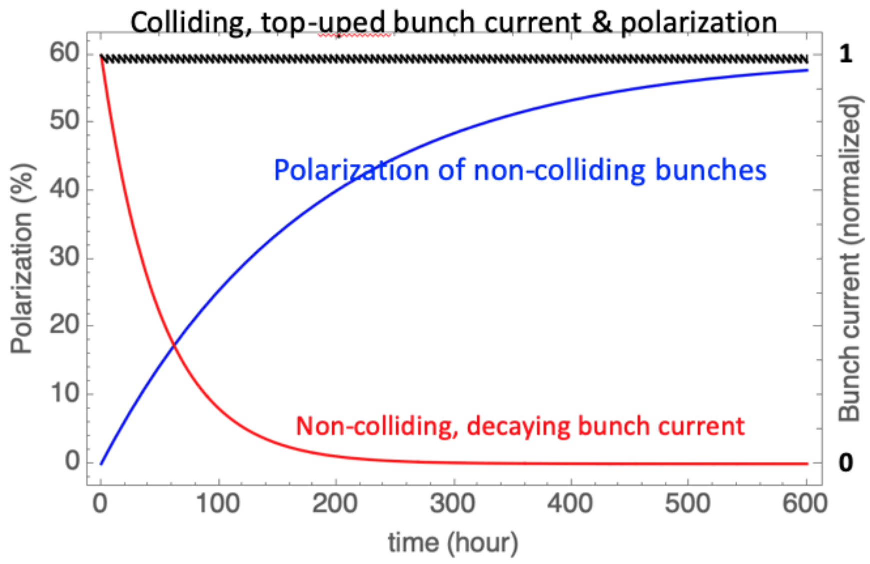
- How to polarize the beams?
- How to adjust the polarization direction?
- How to measure the polarization?
- How to reach a high luminosity, a high polarization and a reasonable beam lifetime?

Note: the current study is based on CEPC CDR parameters, to reach the first polarization specific design, then we'll update according to the CEPC TDR design parameters



How to polarize the e+/e- beam?

	Non-colliding bunches	Colliding bunches
Beam lifetime	20~100 hours, a high bunch current is not necessary	~2 hours
Injection frequency	Every 20~100 hours	Top-up injection, every ~ 10 seconds
Evolution of beam polarization	Exponential build-up Time scale ~ several hundred hours	Saw-tooth near the level of injected beam polarization
Usage	Resonant depolarization	Colliding beam experiments
Method to realize desired beam polarization	Use asymmetric wigglers to reduce self-polarization build-up time	Inject polarized beam



Note: injection of polarized beam for colliding experiments, enables resonant depolarization measurement of some colliding bunches, which could help reduce the systematic errors of RD on non-colliding bunches only.

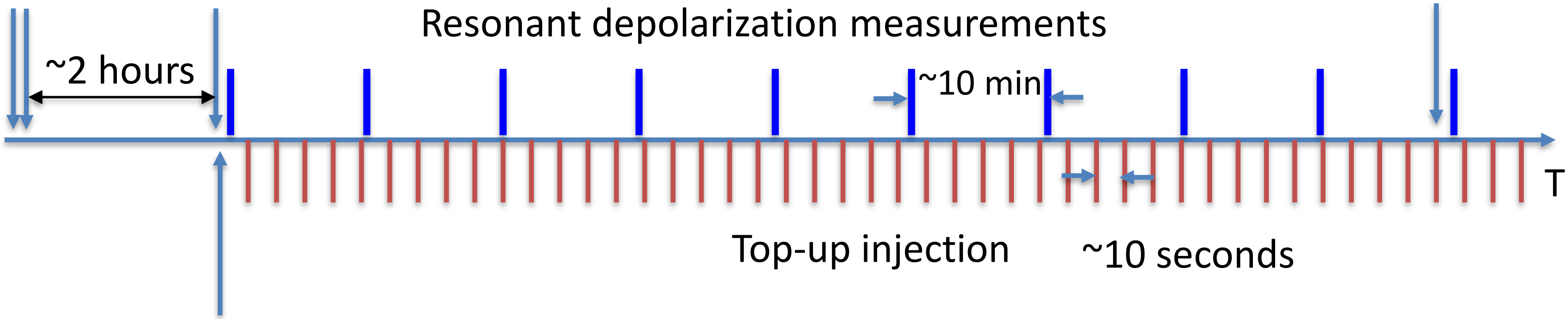
Basic operation scenario

Baseline assumptions:

- The injector can supply polarized e- beam (>50%), and unpolarized e+ beam (by default)
- Resonant depolarization requires a bunch polarization > 5%

- Inject ~100 unpolarized non-colliding beams
  - Turn-on asym. wigglers to boost self-polarization
    - Turn-off asym. wigglers

- Replenish one decayed unpolarized non-colliding bunch ~ every hour



Resonant depolarization

~2 hours

Resonant depolarization measurements

~10 min

Time of operation

Colliding beam experiments

Top-up injection

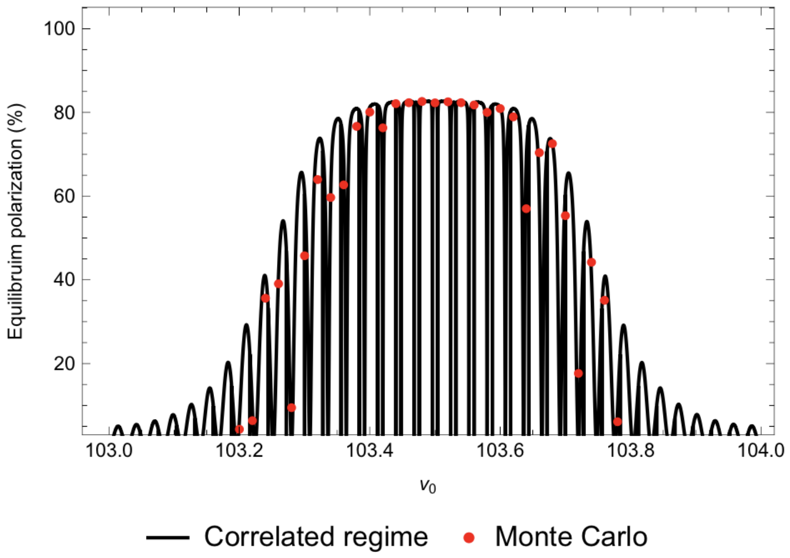
~10 seconds

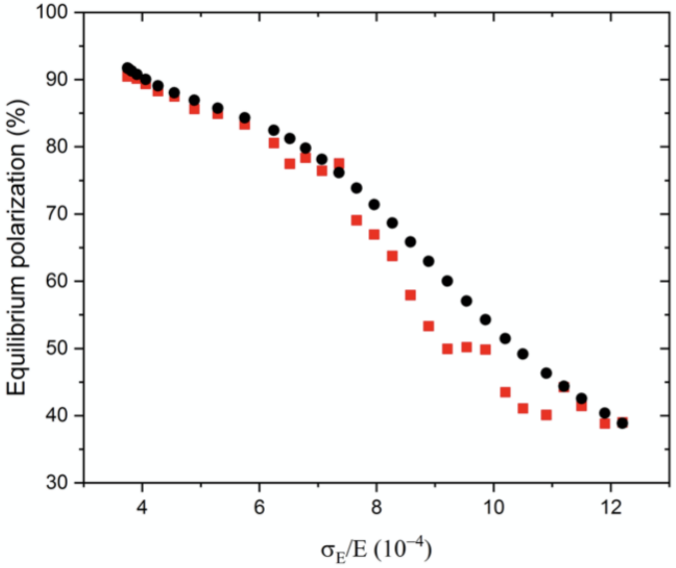
- Inject ~ 12000 polarized e- and unpolarized e+ bunches
- Start colliding beam experiments

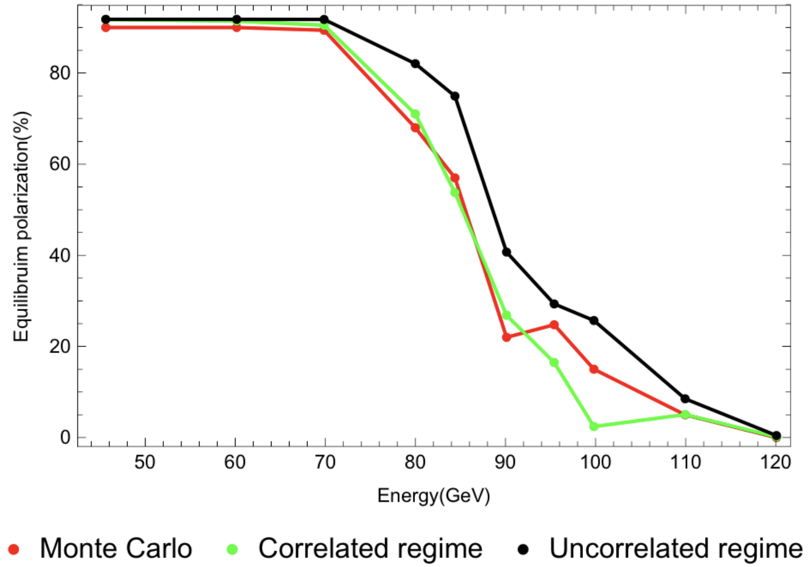
each fill could last many hours
Unless hardware failure occurs

Equilibrium beam polarization in the collider ring

- CEPC CDR lattices w/ errors & corrections are converted from SAD to BMAD/PTC
- Monte-Carlo simulations based on PTC, for evaluation of equilibrium beam polarization
- The depolarization effects at ultra-high energies are also explored.

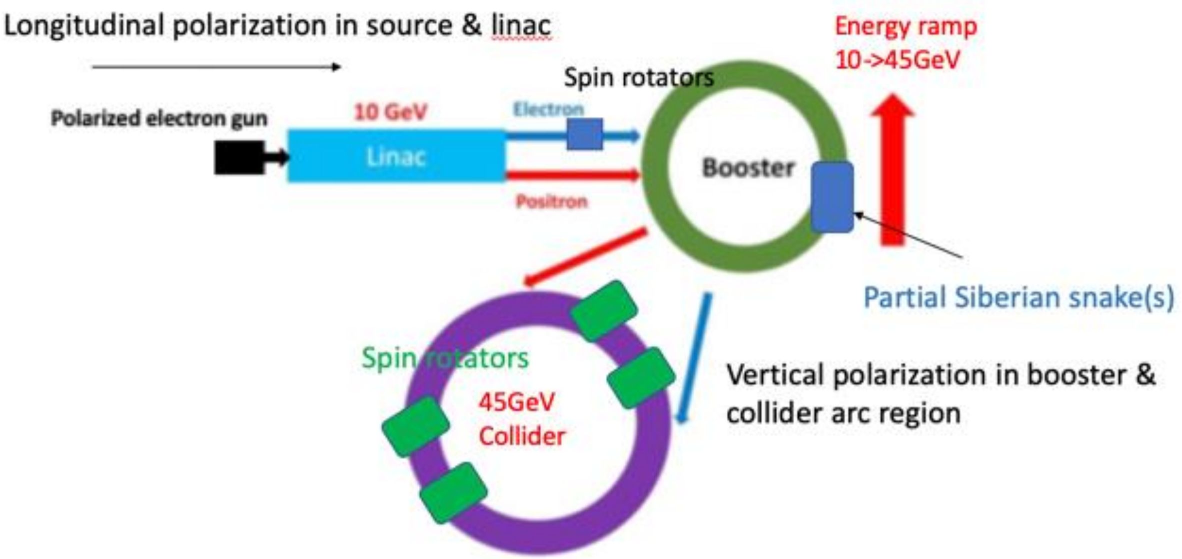




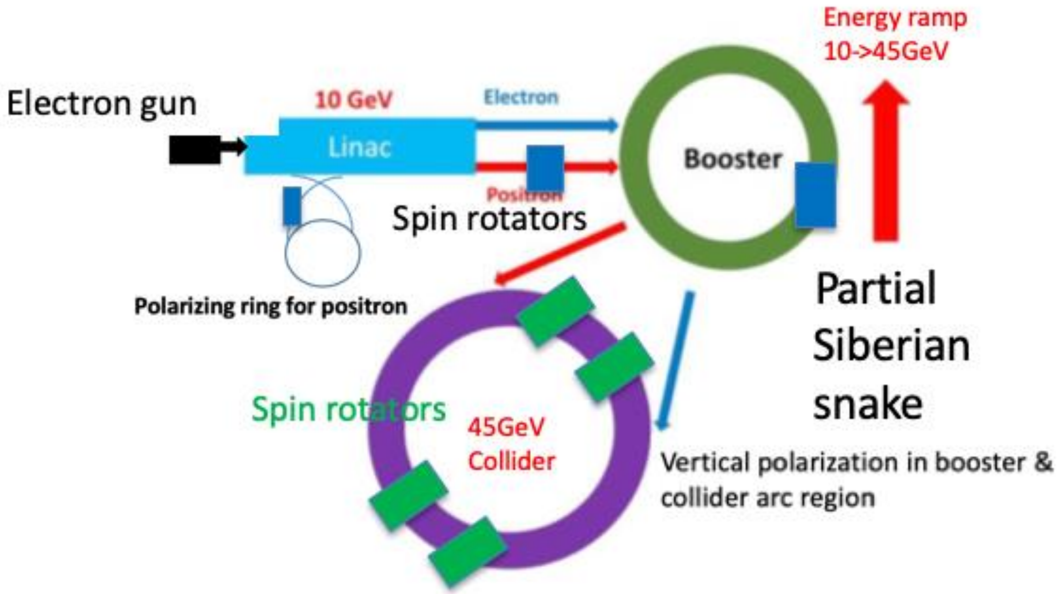


Injector chain to supply polarized e- beam

Injector modification for polarized e-



Injector modification for polarized e+ (optional)



Key research topics:

- Polarized electron source
- e+ polarizing ring
- Spin rotators in the linac-to-booster transport line
- Siberian snakes in the booster

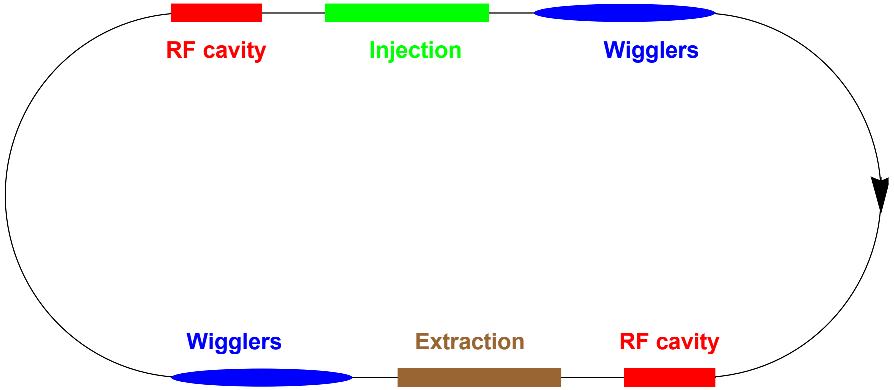
Polarized e+/e- source

- Polarized e- source is matured technology

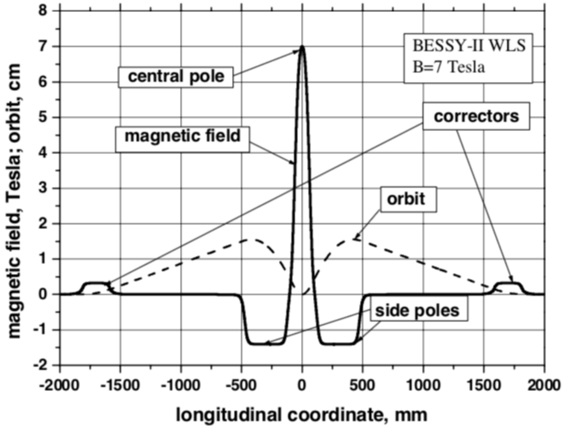
Parameter	ILC(TDR)	CLIC(3TeV)	CEPC
Electrons/microbunch	2×10^{10}	0.6×10^{10}	**$>0.94\times10^{10}$**
Charge / microbunch	3.2nC	1nC	**1.5nC**
Number of microbunches	1312	312	**1**
Macropulse repetition rate	5	50	**100**
Average current from gun	21μA	15μA	**0.15μA**
Polarization	>80%	>80%	**>80%**

Parameters of CEPC polarized electron source	
Gun type	Photocathode DC Gun
Cathode material	Super-lattice GaAs/GaAsP
HV	150-200kV
QE	0.5%
Polarization	≥85%
Electrons/bunch	2×10^{10}
Repetition rate	100Hz
Drive laser	780nm (±20nm), 10μJ@1ns

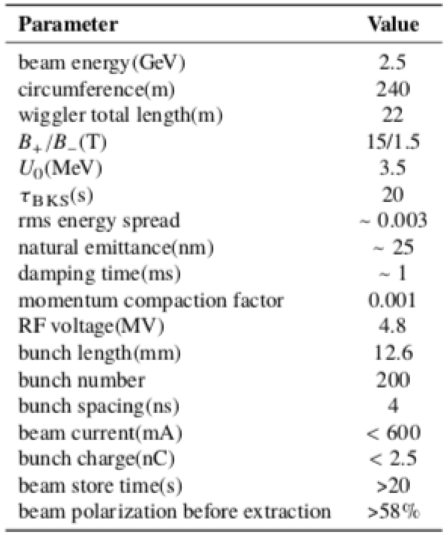
- A polarizing/damping ring for e+, using high-field asymmetric wigglers
  - Detailed design study is under way
    - Low-emittance lattice design w/ very strong wigglers



An asymmetric wiggler @BESSY-II as WLS,
A. M. Batrakov, et al., APAC 2001, pp251-253.



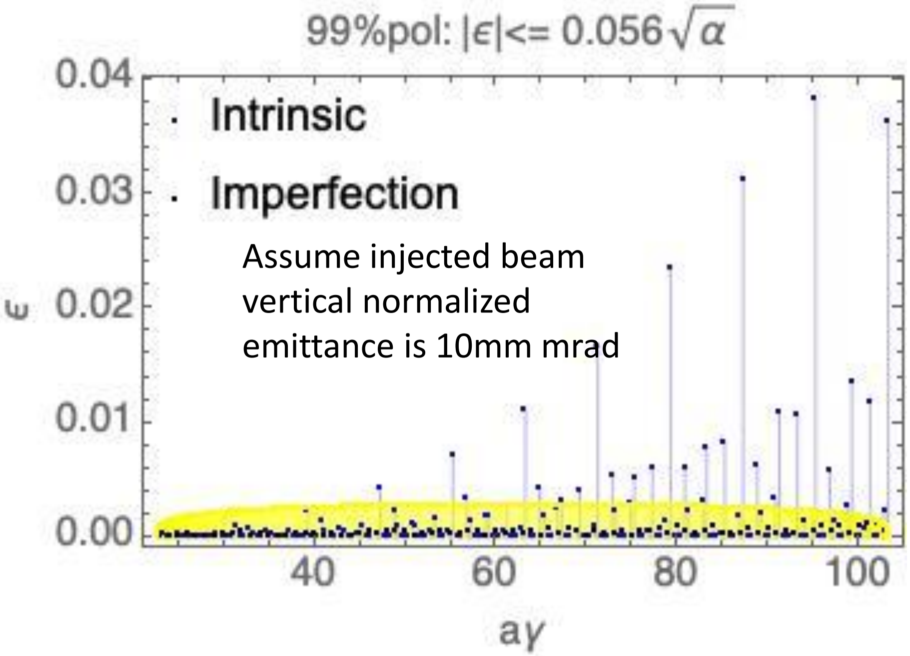
Tentative parameters



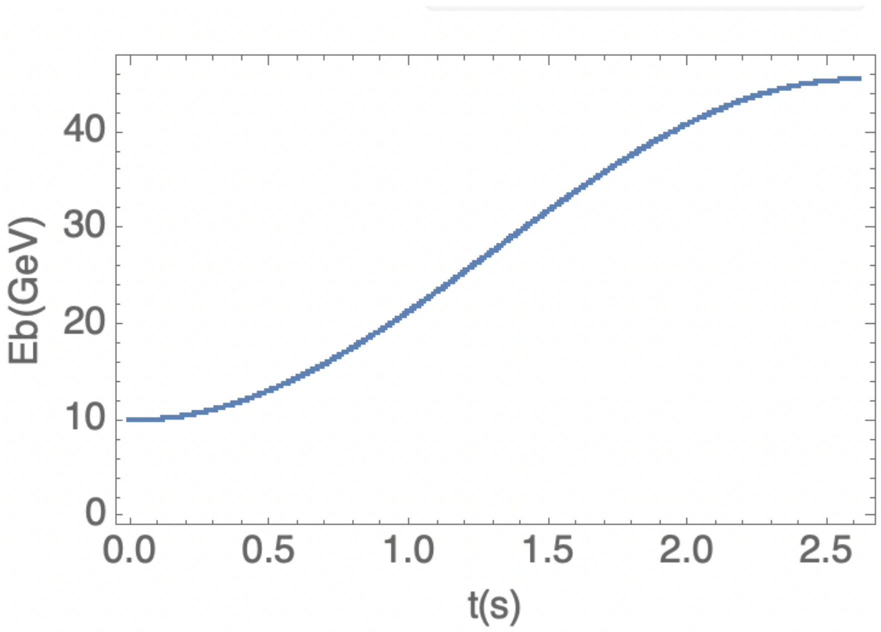
Parameter	Value
beam energy(GeV)	2.5
circumference(m)	240
wiggler total length(m)	22
B_+/B_-(T)	15/1.5
U_0(MeV)	3.5
τ_{BKS}(s)	20
rms energy spread	~ 0.003
natural emittance(nm)	~ 25
damping time(ms)	~ 1
momentum compaction factor	0.001
RF voltage(MV)	4.8
bunch length(mm)	12.6
bunch number	200
bunch spacing(ns)	4
beam current(mA)	< 600
bunch charge(nC)	< 2.5
beam store time(s)	>20
beam polarization before extraction	>58%

Depolarization in CEPC Booster

- The strongest spin resonance strength of CEPC booster is comparable to AGS
  - Single isolated spin resonances
- Ramping speed is ~100 times faster compared to AGS
  - It is unlikely to use jump quad or AC dipole schemes to mitigate depolarization
- Without special measures, the beam will get depolarized after acceleration to 45.5GeV

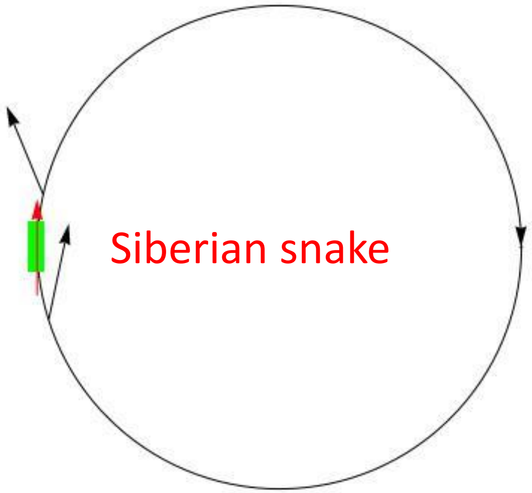


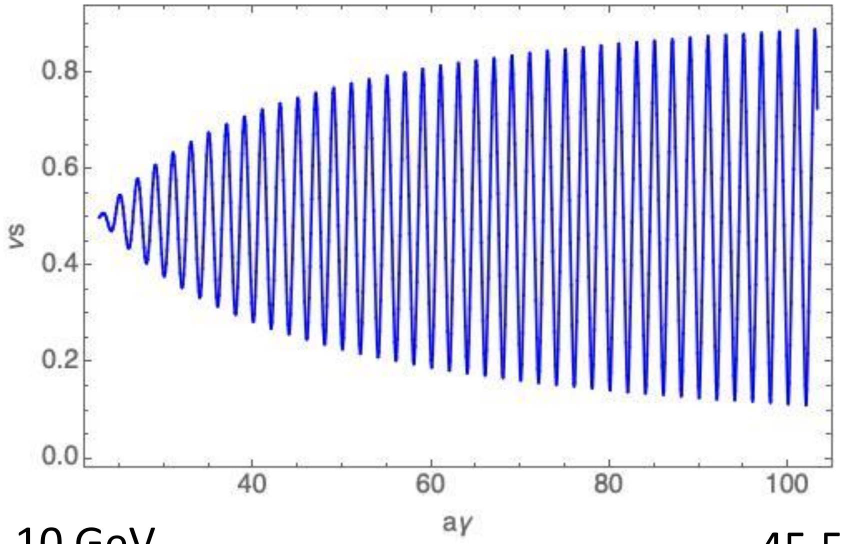
Assume injected beam vertical normalized emittance is 10mm mrad



Maintenance of beam polarization in CEPC Booster

- Depolarization during acceleration can be mitigated with Siberian snake(s)
- Solenoid-based Siberian snake
  - $\int B_{\mathrm{SOL}} dl \simeq \frac{10.479}{1+a} p \left(\frac{\mathrm{GeV}}{c}\right)$: Full snake: 105 T · m @ 10GeV ~ 476T · m@ 45.5GeV
  - One potential cost-effective solution: superconducting solenoids fixed in strength
    - full snake at injection, partial snake at higher energy
  - Alternative schemes will also be explored

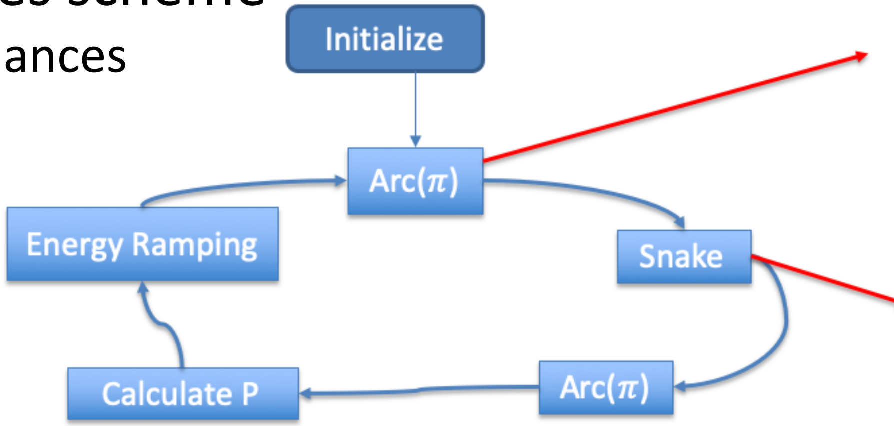




10 GeV 45.5 GeV

Lattice independent simulations

- Launch lattice-independent simulations for fast evaluation of the effectiveness of the snakes scheme
  - Single-isolated spin resonances
  - One (partial) snake

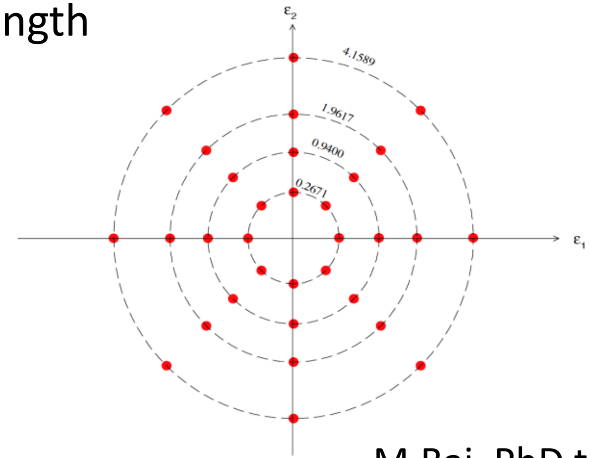


Arc module uses constant $a\gamma$ model in which arc and resonance are considered together:

$$\psi(\theta_f) = e^{-\frac{i}{2}K\theta_f\sigma_3} e^{\frac{i}{2}[\delta\sigma_3+\epsilon_R\sigma_1-\epsilon_I\sigma_2](\theta_f-\theta_i)} e^{\frac{i}{2}K\theta_i\sigma_3}\psi(\theta_i) \equiv t(\theta_f,\theta_i)\psi(\theta_i)$$

Siberian snake is placed at π from the observation point

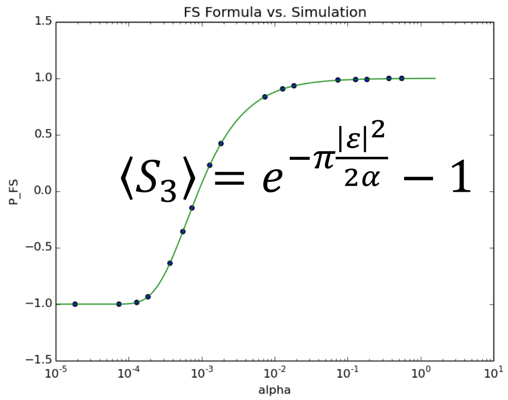
Launch a beam of 32 particles to account for amplitude dependence of intrinsic resonance strength



M.Bai, PhD thesis, 1998

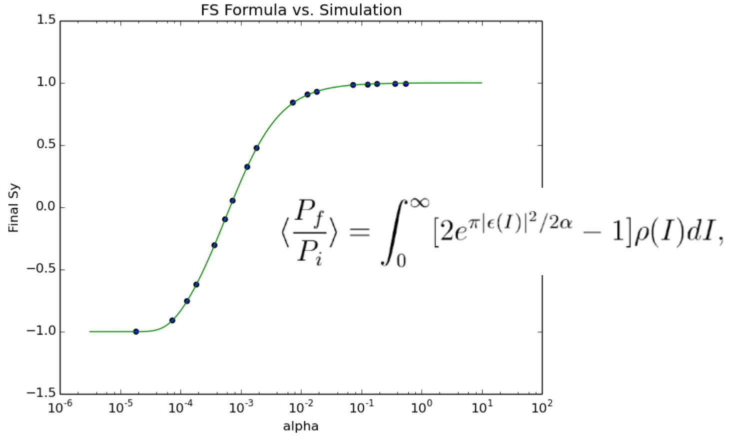
Benchmark: single spin resonance: $|\varepsilon| = 0.02$, $K = 30$. scan ramping rate α

Imperfect resonance



$$\langle S_3\rangle = e^{-\pi\frac{|\varepsilon|^2}{2\alpha}} - 1$$

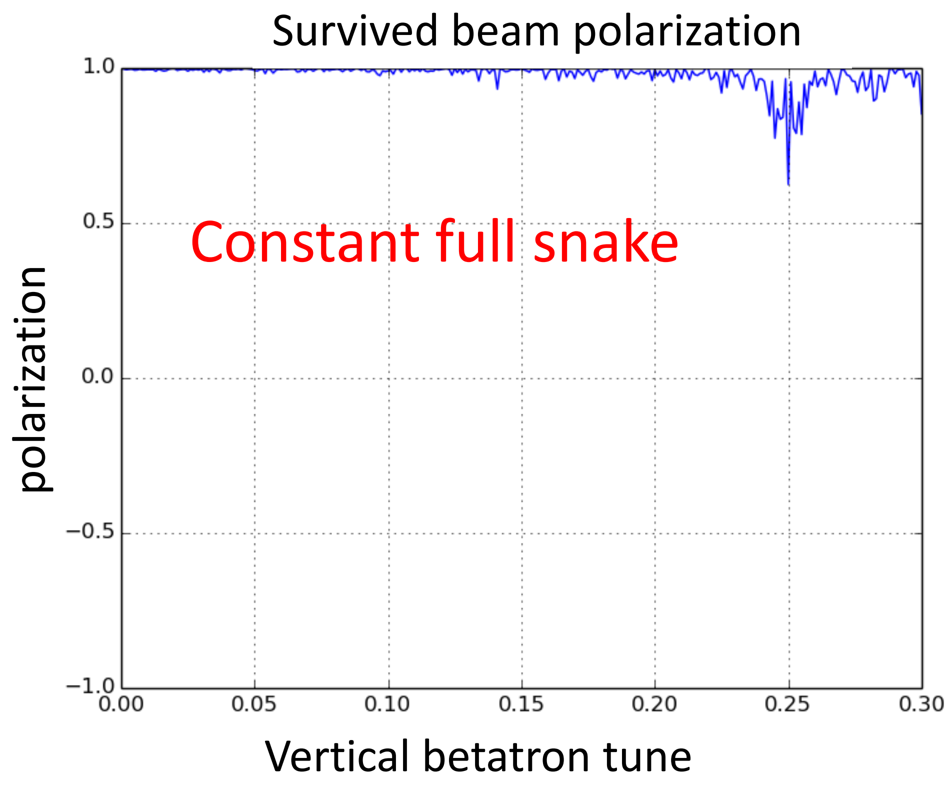
Intrinsic resonance



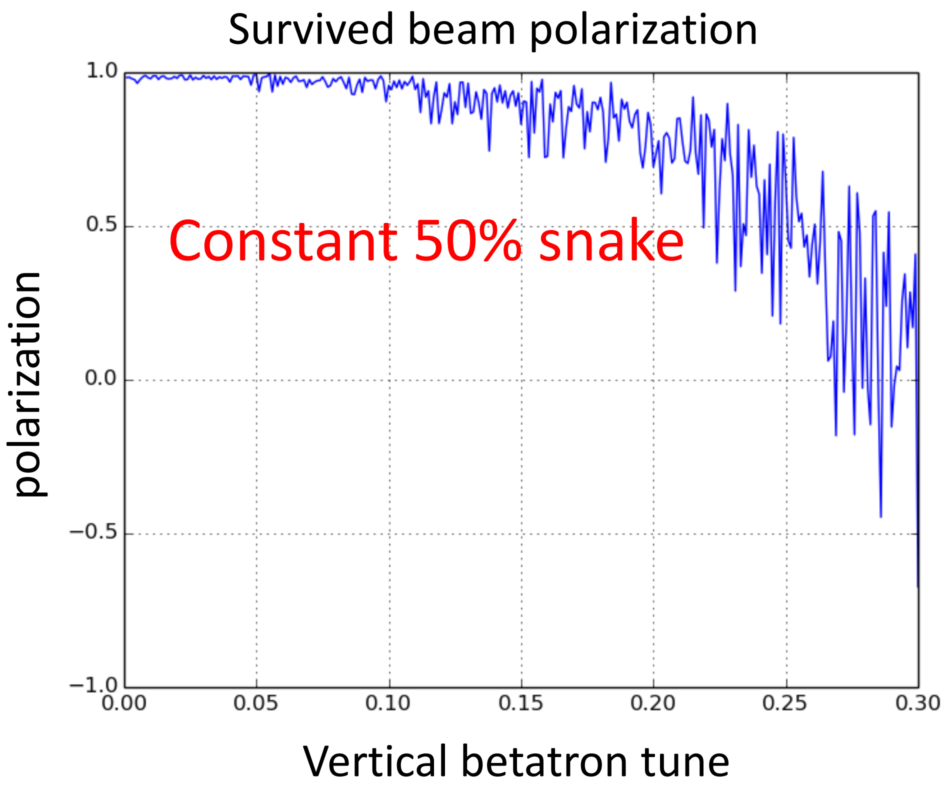
$$\langle\frac{P_f}{P_i}\rangle = \int_0^\infty [2e^{\pi|\epsilon(I)|^2/2\alpha} - 1]\rho(I)dI,$$

Lattice independent simulations

- 10GeV -> 45.5GeV acceleration simulation
  - Assume a 100% polarized injected beam
  - Injected beam particles are matched to the \vec{n} of the booster
  - Realistic ramping curve (10GeV -> 45.6 GeV: 2.62 second), w/o SR effects



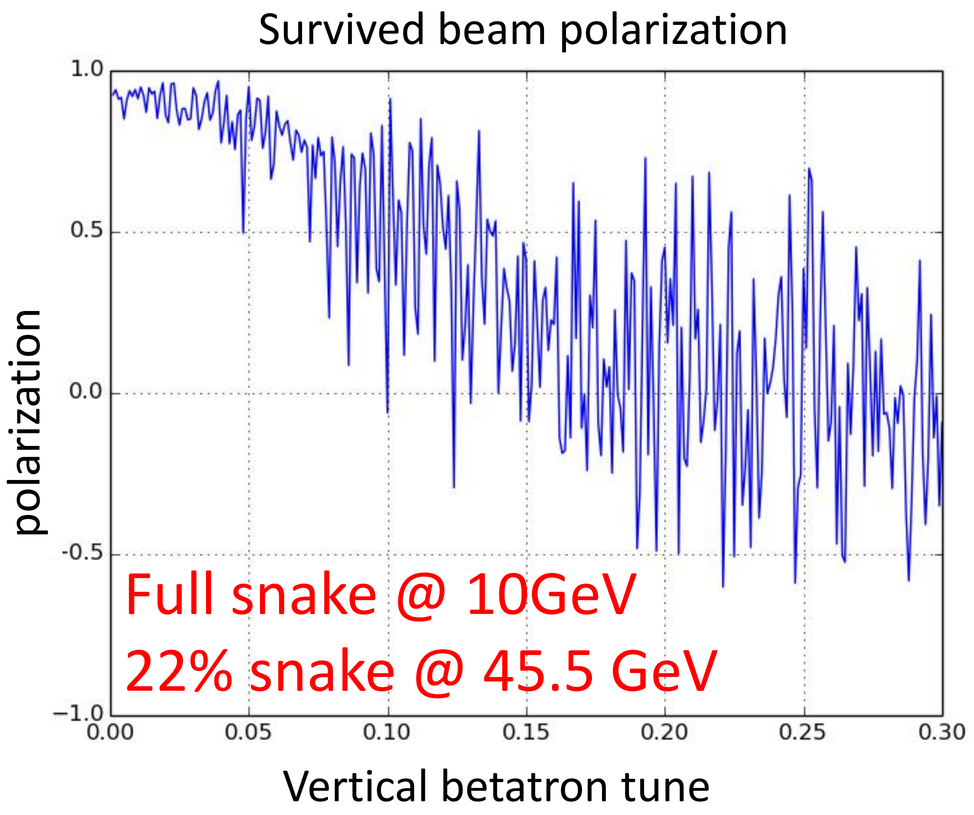
Constant full snake

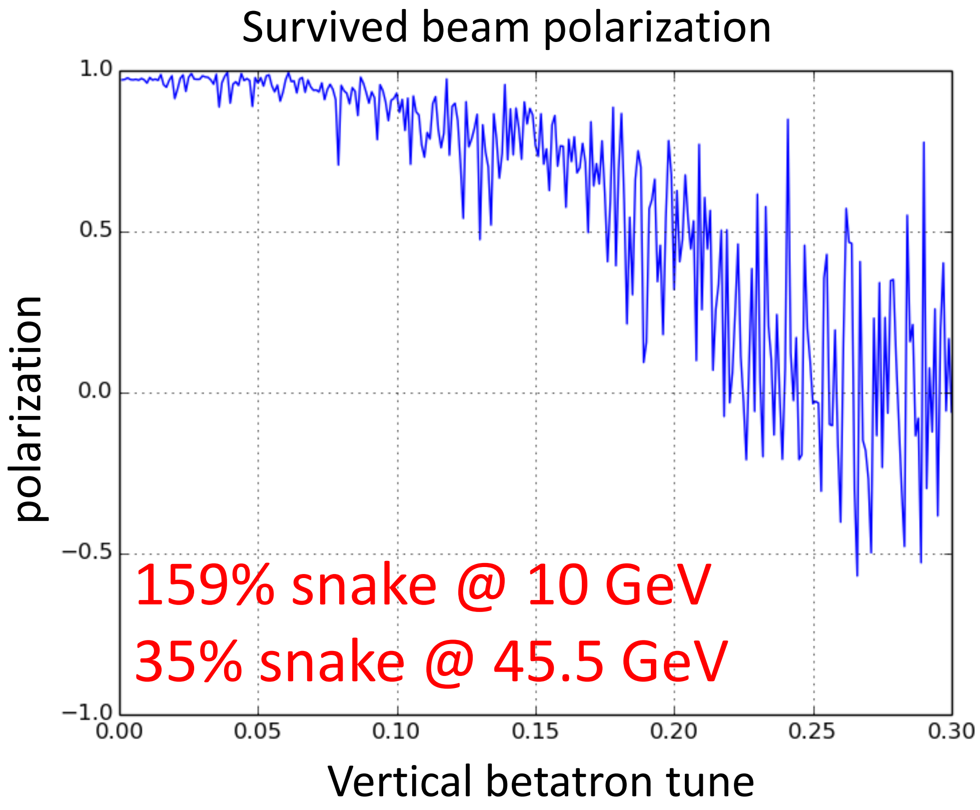


Constant 50% snake

Lattice independent simulations

- 10GeV -> 45.5GeV acceleration simulation
  - The partial snake scheme on the right looks better
  - Vertical betatron tune needs to be moved to <0.07, to ensure > 80% polarization transmission
  - Next, will launch lattice-dependent simulations to verify this conclusion
  - Design of the snake is in line with the spin rotators in the collider ring

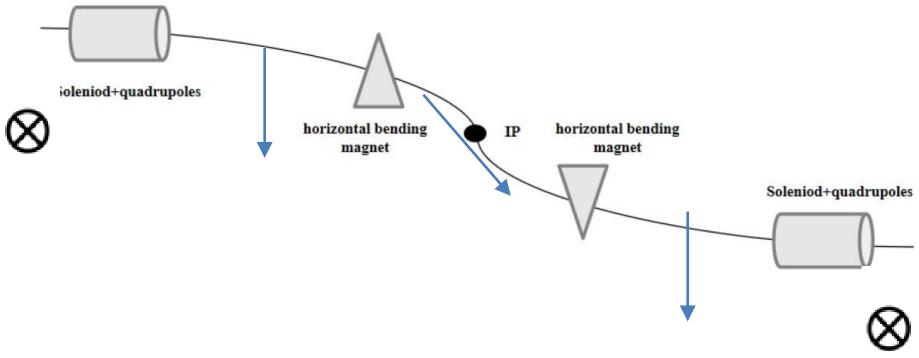

Survived beam polarization

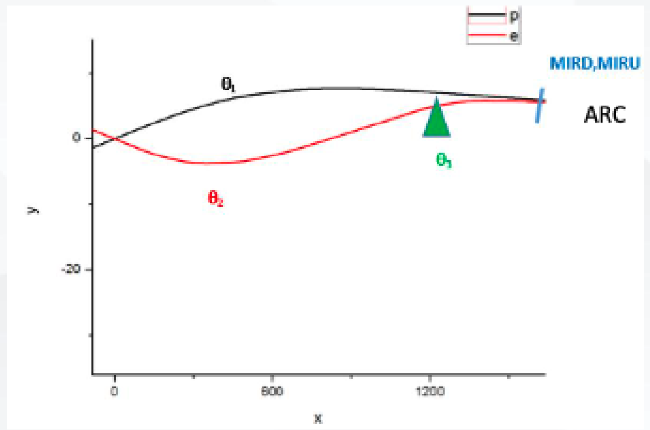

Survived beam polarization

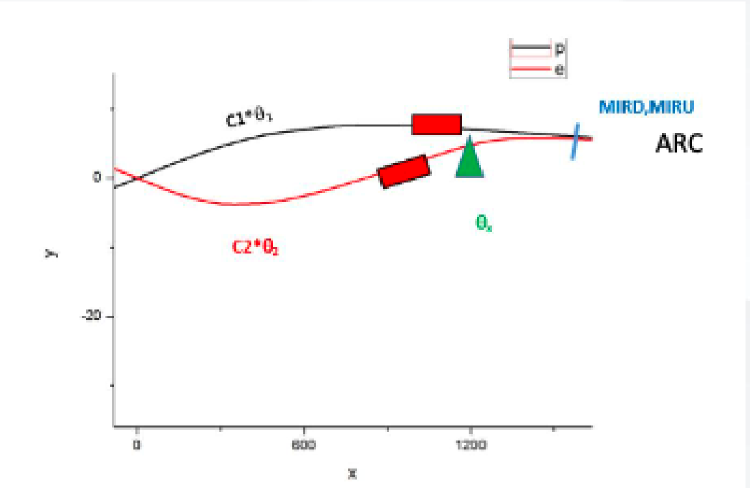
Spin rotators in the CEPC CDR lattice

First attempt to implement spin rotators into the collider ring lattice

- Solenoid spin rotators is implemented at the first short straight sections next to IR
- Modified the ring layout -> $\theta_{\text{bend}} = 15\text{mrad}$
  - Keep the IR geometry
  - Keep the transverse distance between e+ and e- rings D=0.35m
  - Scale the bending angle before and after the short straight section



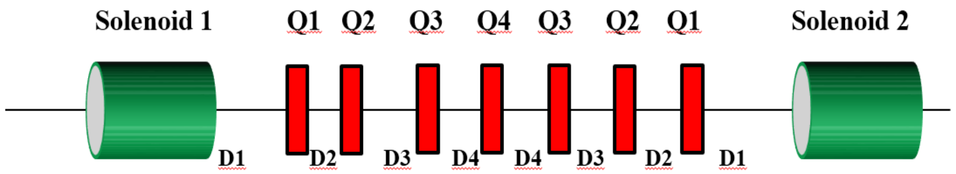




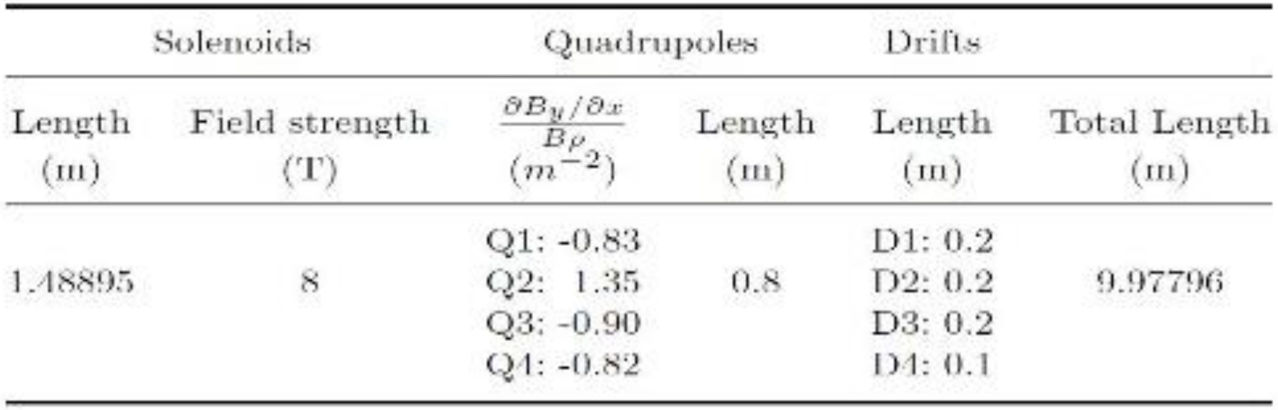
Spin rotators in the CEPC CDR lattice

First attempt to implement spin rotators into the collider ring lattice

- Each spin rotator $\int B_{\mathrm{SOL}} dl \simeq 240\ \mathrm{T \cdot m}$
- Assume each solenoid is 8 T, ~1.5m
- Each decouple unit cell contains two solenoids and matching quads, total length ~ 10 m
- Replace the existing drifts in the lattice by such unit cells
- Each spin rotator consists of 10 unit cells



Decouple unit

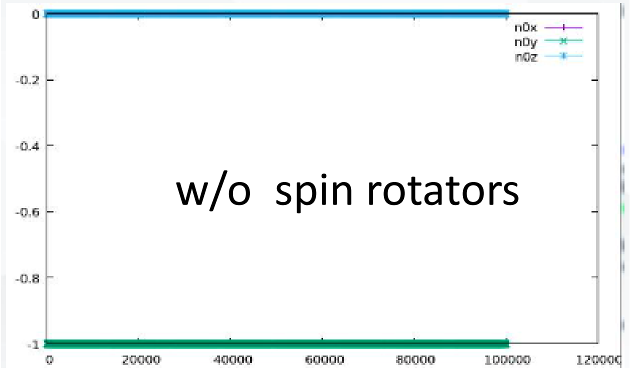


Solenoids		Quadrupoles		Drifts	
Length (m)	Field strength (T)	$\frac{\partial B_y/\partial x}{B\rho}$ (m^{-2})	Length (m)	Length (m)	Total Length (m)
1.48895	8	Q1: -0.83 Q2: 1.35 Q3: -0.90 Q4: -0.82	0.8	D1: 0.2 D2: 0.2 D3: 0.2 D4: 0.1	9.97796

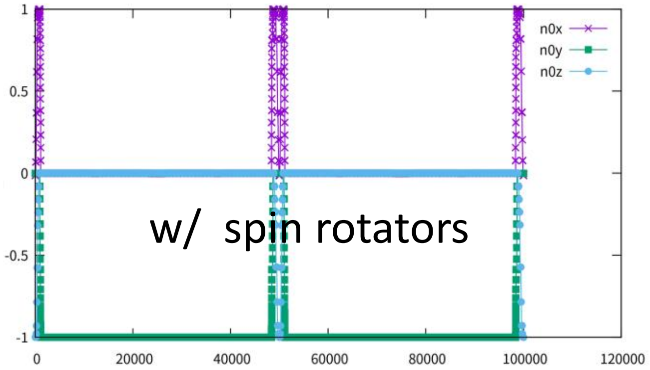
Spin rotators in the CEPC CDR lattice

First attempt to implement spin rotators into the collider ring lattice

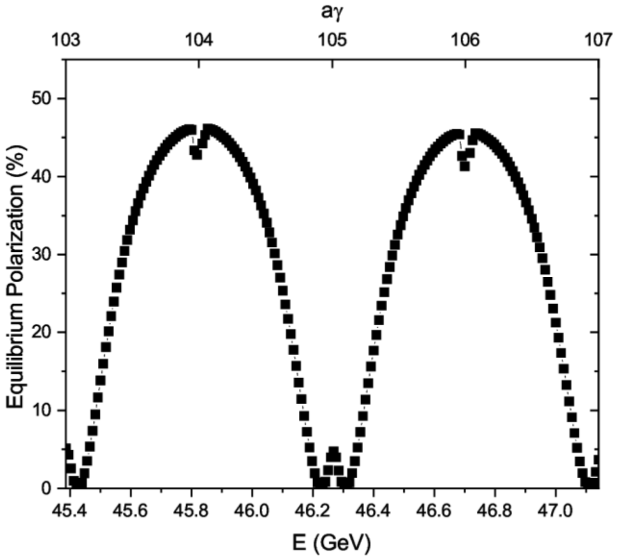
- The spin rotators do rotate the spin direction as expected
- SLIM simulation shows $\tau_{DK} \gg \tau_b$, then $P_{avg} \approx P_{inj}$ during top-up injection
- The compact design leads to uncomfortably large local chromaticities

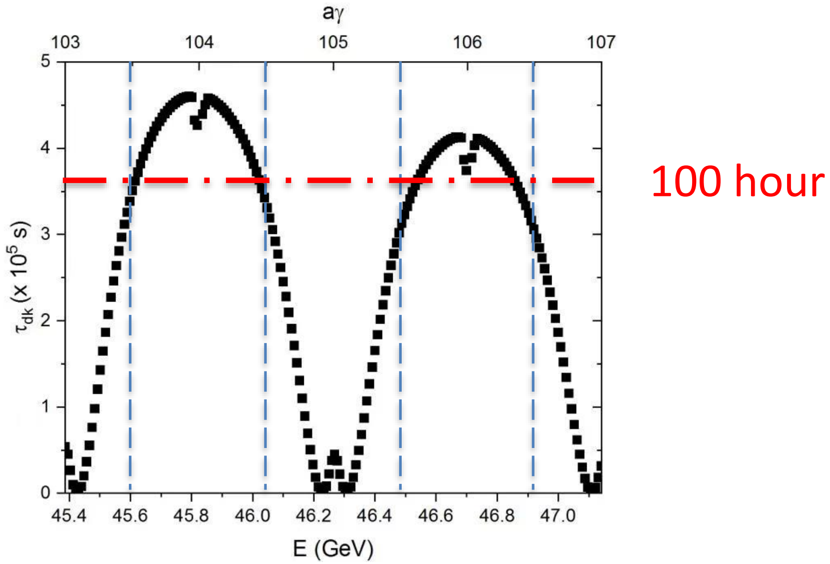


w/o spin rotators



w/ spin rotators



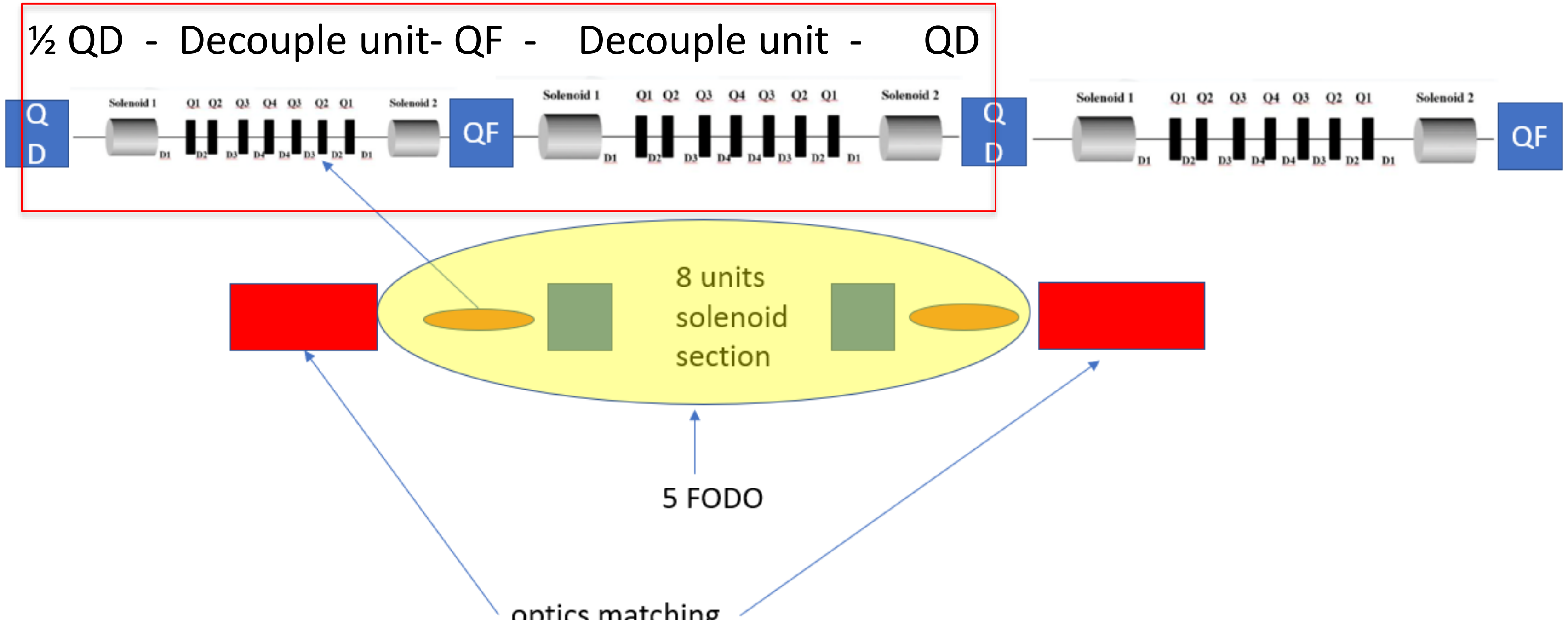


	SPIN ROTATOR 1， 3	SPIN ROTATOR 2， 4	Final focus Quads
X chromaticity	−2107. 72	−1767. 22	−125. 188
Y chromaticity	−2526. 059	−8016. 724	−3754. 209

New design of spin rotators

Redesign of the spin rotators and implementation into lattice

- A new version of CEPC lattice is under design
  - The geometric requirement is built-in
  - A space of ~300m is reserved for each spin rotator, in a long straight section near IR
- A new modular design of spin rotator is also under way
  - Decouple unit => Drift; FODO: O is replaced by Decouple unit;



½ QD - Decouple unit- QF - Decouple unit - QD

8 units solenoid section

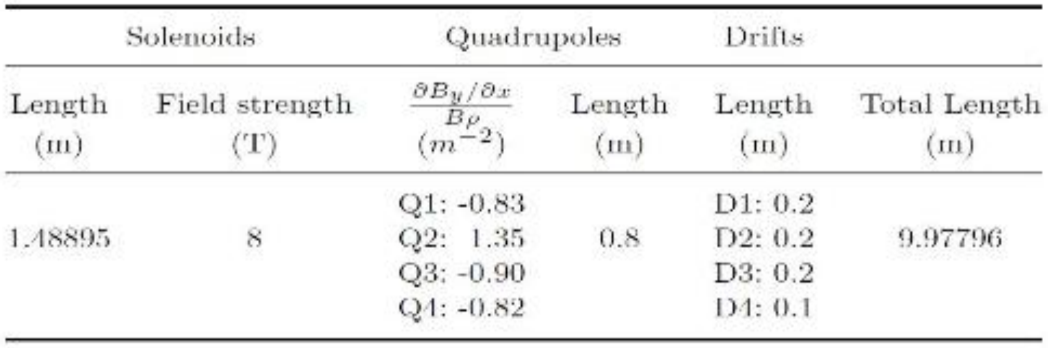
5 FODO

optics matching

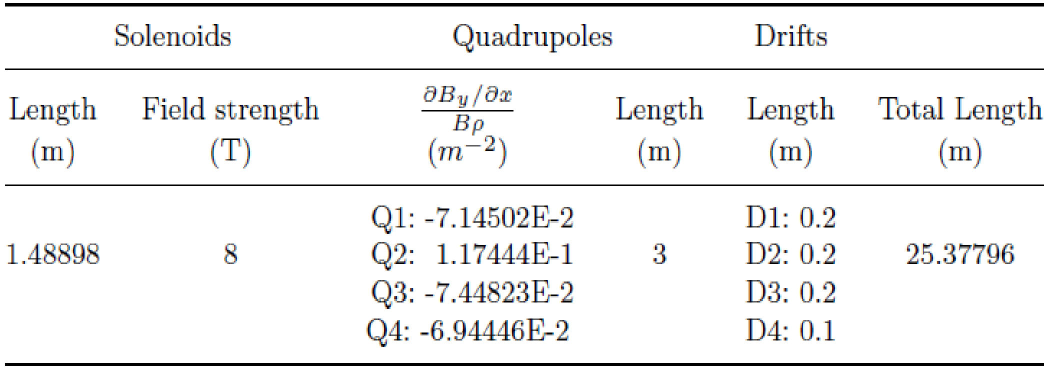
New design of spin rotators

Redesign of the spin rotators

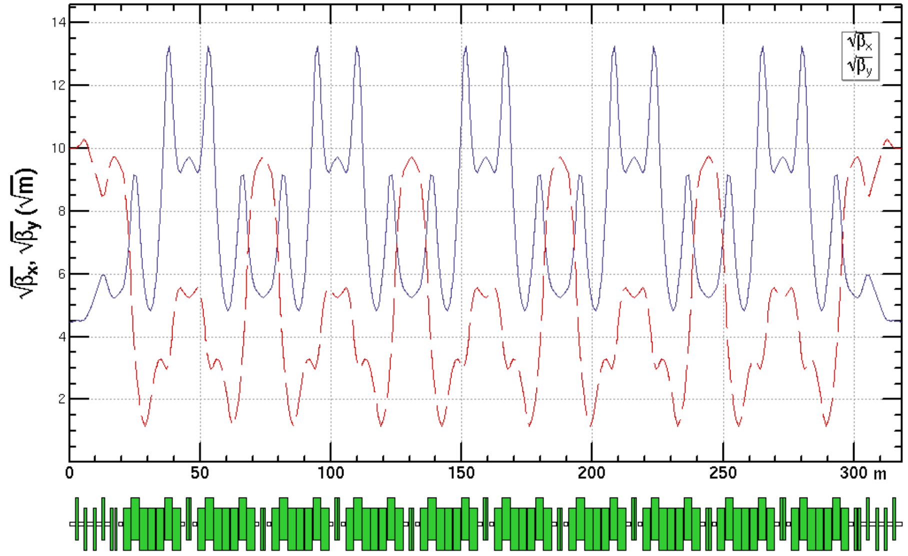
- Unit cell length is streched from 10 m -> 25 m
- max gradient of quads is reduced by a factor of 10
- Optics matching : betax/betay=20m/100m, alpha=0
- Will be integrated into the new lattice and investigate the influence on spin & obital motion



Solenoids		Quadrupoles		Drifts	
Length (m)	Field strength (T)	$\frac{\partial B_y/\partial x}{B\rho}$ (m^{-2})	Length (m)	Length (m)	Total Length (m)
1.48895	8	Q1: -0.83 Q2: 1.35 Q3: -0.90 Q4: -0.82	0.8	D1: 0.2 D2: 0.2 D3: 0.2 D4: 0.1	9.97796



Solenoids		Quadrupoles		Drifts	
Length (m)	Field strength (T)	$\frac{\partial B_y/\partial x}{B\rho}$ (m^{-2})	Length (m)	Length (m)	Total Length (m)
1.48898	8	Q1: -7.14502E-2 Q2: 1.17444E-1 Q3: -7.44823E-2 Q4: -6.94446E-2	3	D1: 0.2 D2: 0.2 D3: 0.2 D4: 0.1	25.37796



chromaticity	New	Final focus Quads
X	-290.4	-125.2
Y	-168.3	-3754.2

Summary

- The overall operation scheme of polarized beam CEPC-Z is outlined.
- The injector chain of the polarized beams is being studied, in particular the maintainance of polarized beam in the booster using Siberian snakes has been simulated.
- Solenoid-based spin rotators were implemented in CEPC CDR lattices, they rotate the spin direction as expected, a new modular design shows promising results.
- Alternative subjects in the to do list
  - Understand the influence of beam-beam interaction on beam polarization in the collider ring
  - Spin rotators in the transport lines
  - Detailed design of e+ polarizing ring

Thank you for your attention!

Backup

Formulas

Beam polarization evolution in an electron storage ring between injections

$$P(t) = P_{\mathrm{ens,DK}}\left(1 - e^{-t/\tau_{\mathrm{DK}}}\right) + P_0 e^{-t/\tau_{\mathrm{DK}}}, \quad \frac{1}{\tau_{DK}} = \frac{1}{\tau_{BKS}} + \frac{1}{\tau_{\mathrm{dep}}}, P_{\mathrm{ens,DK}} \approx \frac{92\%}{1+\tau_{BKS}/\tau_{\mathrm{dep}}}$$

$$\tau_0^{-1}[\mathrm{s}^{-1}] \approx \frac{2\pi}{99}\frac{E[\mathrm{GeV}]^5}{C[\mathrm{m}]\rho[\mathrm{m}]^2}$$

Time-averaged beam polarization in an electron storage ring during top-up injection

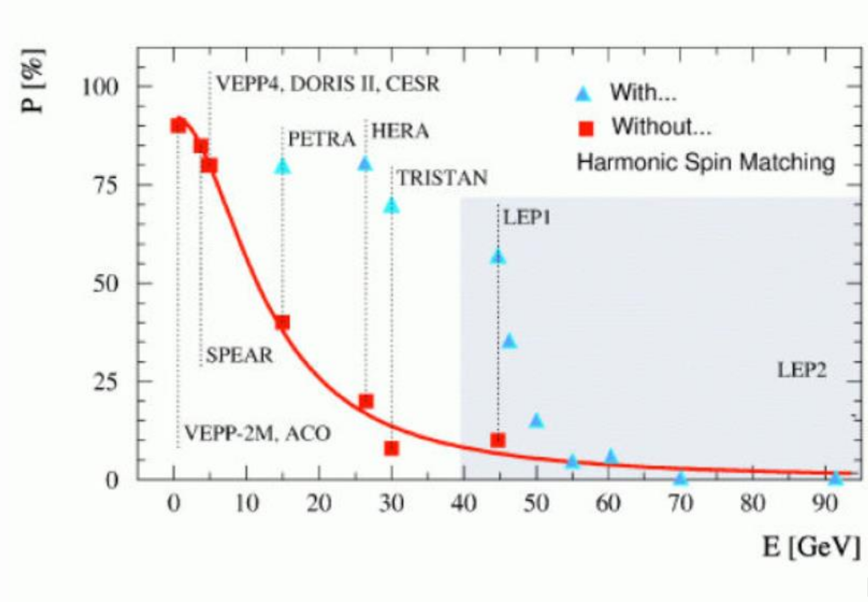
Self-polarization: equilibrium beam polarization in the ring

Injected beam polarization

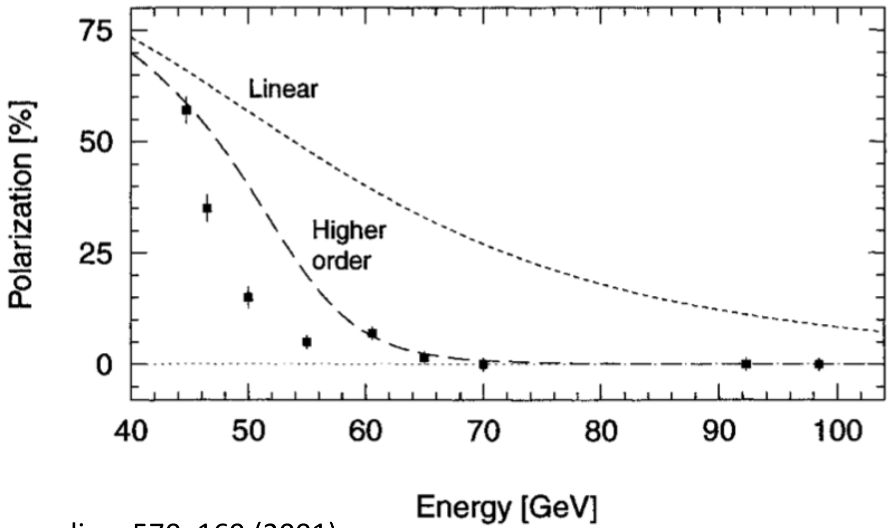
$$P_{\mathrm{avg}} = \frac{P_{\mathrm{ens,DK}}}{1 + \tau_{\mathrm{DK}}/\tau_{\mathrm{b}}} + \frac{P_{\mathrm{inj}}}{1 + \tau_{\mathrm{b}}/\tau_{\mathrm{DK}}}$$

Competition between beam decay/injection and polarization build-up in the ring

Scaling with beam energy



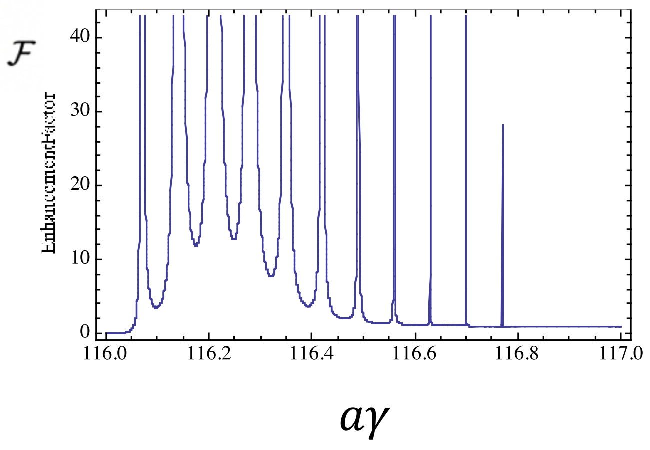
LEP measured beam polarization



R. Assmann, et al, AIP Conference Proceeding, 570, 169 (2001).

$$P = \frac{P_{ST}}{1 + (\alpha E)^2 \mathcal{F}}$$

$$\mathcal{F} = \left\langle \left| \frac{\partial \zeta}{\partial \varepsilon} \right|^2 \right\rangle \Big/ \left\langle \left| \frac{\partial \zeta}{\partial \varepsilon} \right|^2 \right\rangle_{\sigma=0} = [(\Delta\nu)^2 - Q_s^2]^2 \sum_{m=-\infty}^{\infty} \frac{e^{-\sigma^2}\, I_m(\sigma^2)}{[(\Delta\nu + mQ_s)^2 - Q_s^2]^2}$$



$\sigma = a\gamma\sigma_\varepsilon / Q_s$ $\mathcal{F}$ becomes remarkable at higher beam energy

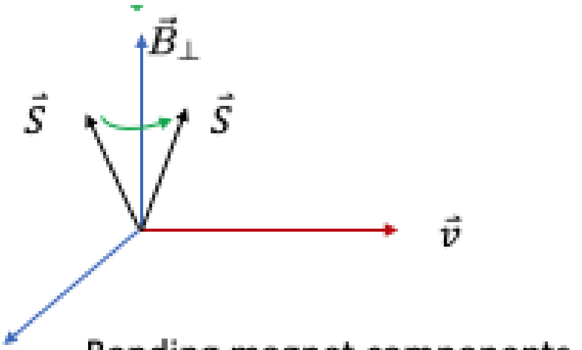
[1] Derbenev, Kondratenko, Skrinsky, PA 9 247, 1979. [2]S. R. Mane, arXiv:1406.0561.

How to adjust the polarization direction?

Devices to rotate spin around a direction in horizontal plane by a certain angle θ

Transverse magnetic field (Not favored for CEPC energies)

- $\int B_\perp \, dl$ independent of energy (approximately)
- Vertical orbit excursion $\propto 1/\gamma, \ \propto L$
- synchrotron radiation power $\propto \gamma^2, \propto 1/L$
- Examples: helical dipole, interleaved H&V bends



Bending magnet components

Longitudinal magnetic field(Under study)

- No orbit excursion, no radiation problem
- $\int B_\perp \, dl \propto 1/\gamma$
- Need quadrupoles to decouple the beam