Longitudinally polarized colliding beams at CEPC

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On behalf of CEPC Beam Polarization Working Group

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Beam polarization working group

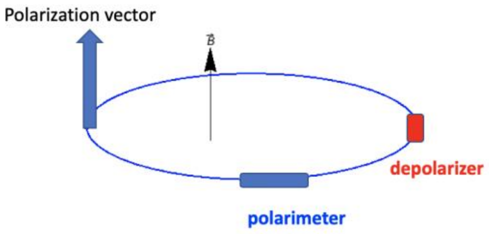
- Physics design:
  - Tao Chen, Zhe Duan, Hongjin Fu, Jie Gao, Sergei Nikitin (BINP), Dou Wang, Jiuqing Wang, Yiwei Wang, Wenhao Xia(graduated)
- Polarized electron source & linac:
  - Xiaoping Li, Cai Meng, Jingru Zhang
- Polarimeter:
  - Shanhong Chen, Yongsheng Huang, Guangyi Tang

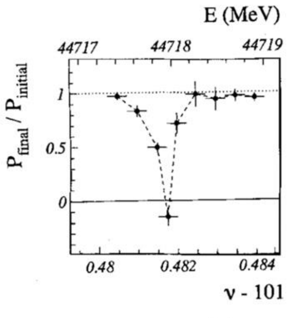
- Discussions with D. P. Barber (DESY) on polarization theories and simulations are illuminating.
- Helpful discussions with E. Forest (KEK) & D. Sagan (Cornell) on usage of Bmad/PTC are acknowledged.

Motivation of CEPC 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



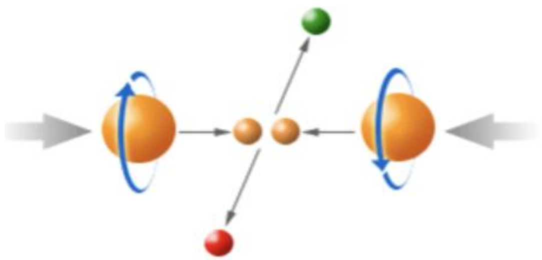


(a) $\Delta\nu_{scan}/\Delta t = 1.67 \cdot 10^{-4} s^{-1}$.

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



- Supported by National Key R&D Program 2018-2023 to design longitudinally polarized colliding beams at Z-pole.
- The study in this presentation is based on CEPC CDR lattice & parameters.
- Will be included as a Chapter in the Appendix in the CEPC TDR.

Self-polarization vs injection of polarized beams for the collider ring

- Decay mode
  - $P(t) = P_{\mathrm{ens,DK}}\left(1 - e^{-t/\tau_{\mathrm{DK}}}\right) + P_{\mathrm{inj}} e^{-t/\tau_{\mathrm{DK}}}$,
  - $\frac{1}{\tau_{DK}} = \frac{1}{\tau_{BKS}} + \frac{1}{\tau_{\mathrm{dep}}}$, $\frac{1}{\tau_{BKS}[\mathrm{s}]} \approx \frac{2\pi}{99} \frac{E[\mathrm{GeV}]^5}{C[\mathrm{m}]\rho[\mathrm{m}]^2}$,
  - $P_{\mathrm{ens,DK}} \approx \frac{92\%}{1+\tau_{BKS}/\tau_{\mathrm{dep}}}$
- Top-up injection
  - $P_{\mathrm{avg}} \approx \frac{P_{\mathrm{ens,DK}}}{1+\tau_{\mathrm{DK}}/\tau_{\mathrm{b}}} + \frac{P_{\mathrm{inj}}}{1+\tau_{\mathrm{b}}/\tau_{\mathrm{DK}}}$
    - If $\tau_b \gg \tau_{DK}$, then $P_{\mathrm{avg}} \approx P_{\mathrm{ens,DK}}$
    - If $\tau_{DK} \gg \tau_b$, then $P_{\mathrm{avg}} \approx P_{\mathrm{inj}}$

- In new e+e- circular colliders, a longer τ_b suggests a lower luminosity
- Injection of polarized beams is required to reach a high P_{avg} without sacrificing luminosity
  - Key: mitigate radiative depolarization (to achieve a longer τ_{dep}) to maintain $\tau_{DK} \gg \tau_b$
    - More challenging at higher beam energies at CEPC

CEPC CDR parameters	45.6 GeV (Z, 2T)	80 GeV (W)	120 GeV (Higgs)
τ_b (hour)	2.5	1.4	0.43
τ_{BKS} (hour)	256	15.2	2.0
$P_{\mathrm{ens,DK}}$ required to realize $P_{\mathrm{avg}} \geq 50\%$, if $P_{\mathrm{inj}} = 80\%$	0.6%	5%	11%

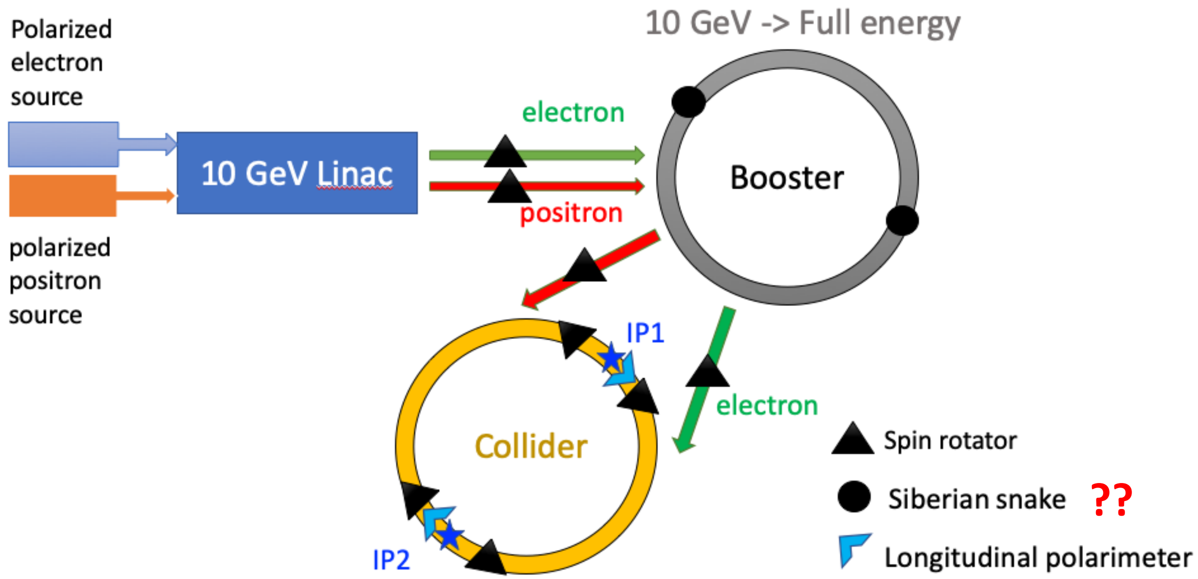
Longitudinal polarization @ CEPC

– In the injector: preparation and maintenance of highly polarized e- (e+) beam(s).

- Polarized source: polarized e- gun (specs defined), polarized e+ source (preliminary study)
- Booster: polarization maintenance (underway)
- Transfer lines: ensure the matching of polarization directions (to be studied)

– In the collider ring:

- spin rotators - > longitudinal polarization[1] (done)
- ensure $\tau_{DK} \gg \tau_b$, then $P_{\mathrm{avg}} \approx P_{\mathrm{inj}}$
- Compton polarimeter[2] (under way)



Polarized electron source

polarized positron source

10 GeV Linac

electron

positron

10 GeV -> Full energy

Booster

electron

Collider

IP1

IP2

▲ Spin rotator

● Siberian snake ??

◤ Longitudinal polarimeter

[1] W. H. Xia et al., RDTM (2022) doi: 10.1007/s41605-022-00344-2

[2] S. H. Chen et al., JINST 17, P08005, (2022)

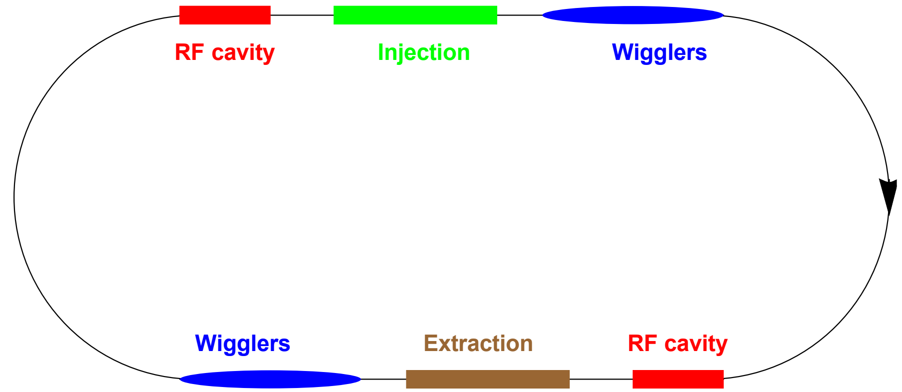
Polarized e-/e+ source for > 50% polarization

- Polarized e- source is matured technology

Parameter	ILC(TDR)	CLIC(3TeV)	CEPC
Electrons/microbunch	2×10^{10}	0.6×10^{10}	**>0.94×10^{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%**

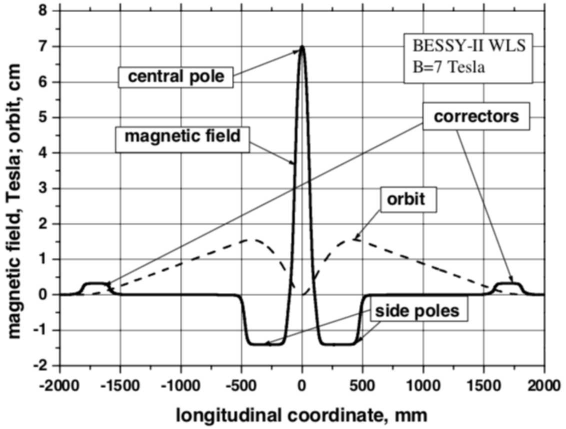
Parameters of CEPC polarized electron source	
Gun type	Photocathode DC Gun
Cathode material	Super-lattice GaAs/GaAsP
HV	150-200kV
QE	0.5%
Polarization	≥85%
Electrons/bunch	2×10^{10}
Repetition rate	100Hz
Drive laser	780nm (±20nm), 10μJ@1ns

- A polarizing/damping ring for e+, using high-field asymmetric wigglers [1]
  - Detailed design study is under way
    - Low-emittance lattice design w/ very strong wigglers

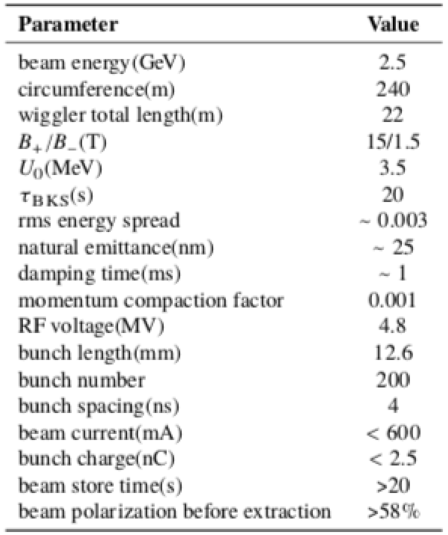


[1] Z. Duan et al., IPAC 2019, MOPMP012.

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



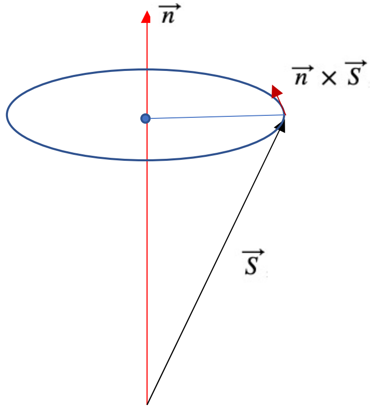
Tentative parameters

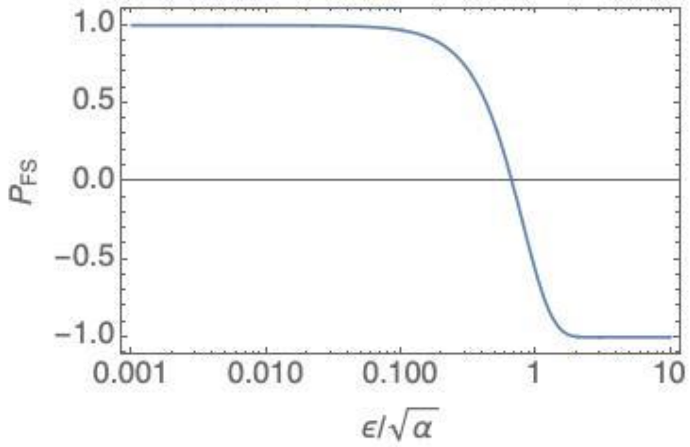


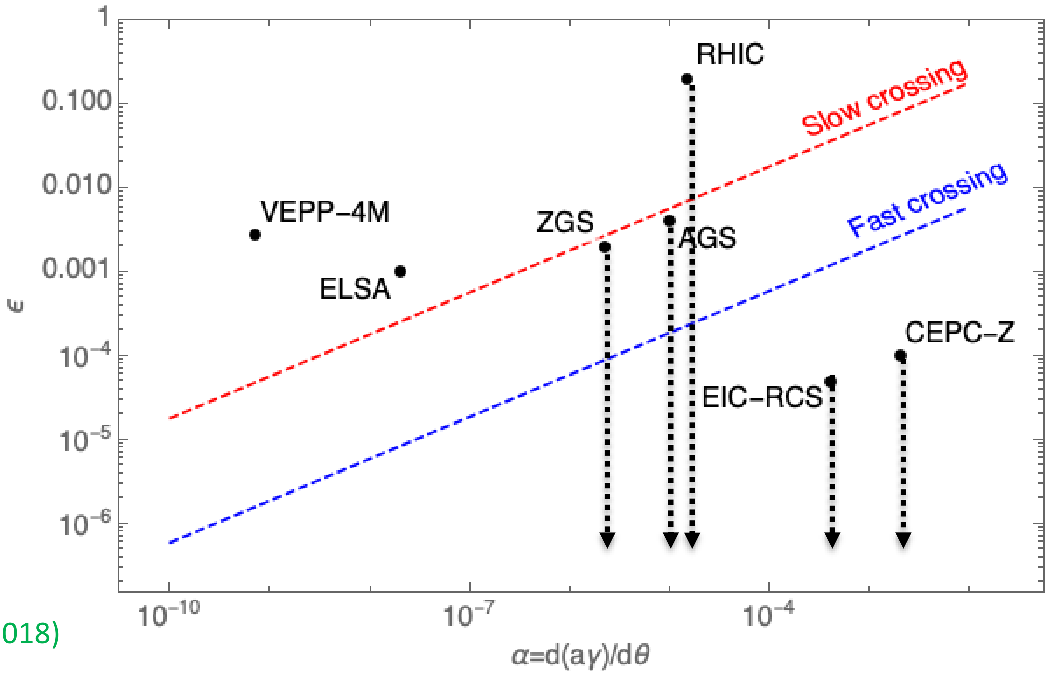
Parameter	Value
beam energy(GeV)	2.5
circumference(m)	240
wiggler total length(m)	22
B_+/B_-(T)	15/1.5
U_0(MeV)	3.5
τ_{BKS}(s)	20
rms energy spread	~ 0.003
natural emittance(nm)	~ 25
damping time(ms)	~ 1
momentum compaction factor	0.001
RF voltage(MV)	4.8
bunch length(mm)	12.6
bunch number	200
bunch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

Polarization maintenance in synchrotron/booster

- $J_s = \vec{S}\cdot\vec{n}$ is an adiabatic invariant
- $\upsilon_0 \approx a\gamma_0$ and $\vec{n}_0$ changes during acceleration. When crossing a spin resonance, $|J_s|$ could vary due to non-adiabaticity, leading to depolarization described by Froissart-Stora formula[1]:
  - Two factors: spin resonance strength ε and acceleration rate $\alpha \sim 10^{-6}\frac{dE}{dt}[\mathrm{GeV/s}]C[\mathrm{km}]$
  - Polarization is maintained (ΔP < 1%) if
    - Fast crossing: $\frac{\epsilon}{\sqrt{\alpha}} \ll 0.06$
    - Slow crossing: $\frac{\epsilon}{\sqrt{\alpha}} \gg 1.82$, spin flip







[1] Froissart and Stora, NIM 7, 297 (1960) [2] A. K. Barladyan, et al., PRAB 22, 112804, (2019)
[3] S. Nakamura, et al., NIM A 411, 93 (1998) [4] T. Khoe et al., Part. Accel. 6, 213 (1975)
[5] Configuration Manual: Polarized Proton Collider at RHIC, 2006 [6] V. Ranjbar, et al., PRAB 21, 111003 (2018)

Spin resonance structure

Parameter of CEPC CDR Booster	Value
P: number of periodicities	8
M: number of unit cells in each arc region (per period)	99
ν_y: total betatron phase advance/(2π)	261.2
ν_B: total betatron phase advance in arc regions/(2π)	198

- PM = 792, arc sections take up > 80% circumference
- About k * 2π betatron phase advance in each straight section & arc section

	Super strong	Less strong	Regular
Imperfection resonance	$\nu_0 = nPM \pm [\nu_B]$	$\nu_0 = nP \pm [\nu_y]$	ν_0 = n
Intrinsic resonance	$\nu_0 = nP \pm \nu_y$ near $nPM \pm [\nu_B]$	$\nu_0 = nP \pm \nu_y$	$\nu_0 = n \pm \nu_y$

$\varepsilon_{\text{RING}}$ = Enhancement Factor * $\varepsilon_{\text{arc cell}}$ + $\varepsilon_{\text{straight sections}}$

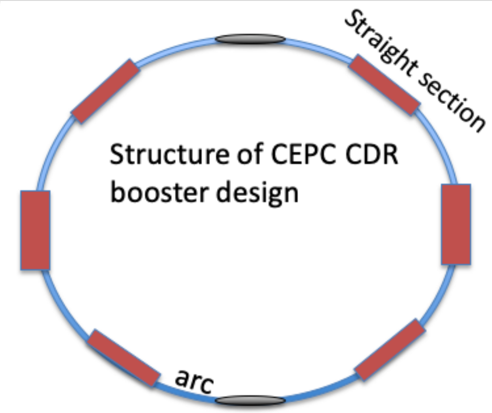
- Enhancement Factor : $\zeta_M(x) = \dfrac{\sin M\pi x}{\sin \pi x}$, when x = integer , $\zeta_M(x) = \mathrm{M}$

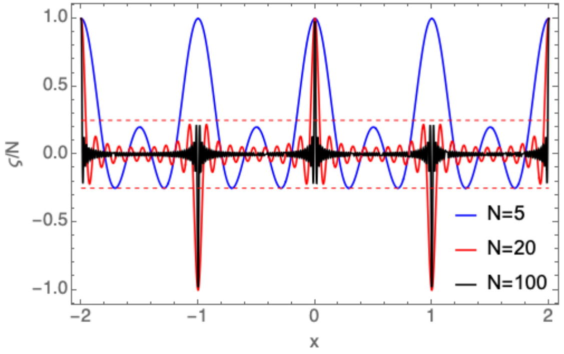
For intrinsic resonances

One FODO

$$\varepsilon_K \approx \frac{1+G\gamma}{2\pi}\sqrt{\frac{\varepsilon_N}{\pi\gamma}}\left\{E_P^+\left[E_M^+\left(\boxed{g_F\sqrt{\beta_F} - g_D\sqrt{\beta_D}e^{i\frac{K+\nu_B}{MP}}}\right) + X_{ins}\right] + E_P^-\left[E_M^-\left(\boxed{g_F\sqrt{\beta_F} - g_D\sqrt{\beta_D}e^{i\frac{K-\nu_B}{MP}}}\right) + X_{ins}\right]\right\}$$

- Enhancement factor: $E_P^\pm \approx \zeta_P(\frac{K\pm\nu_z}{P})$; $E_M^\pm \approx \zeta_M(\frac{K\pm\nu_B}{PM})$





$g_{F/\mathrm{D}} = \frac{1}{f}$, For FODO cells with same phase shift: $\sin\frac{\phi}{2} = \frac{L}{2f}$

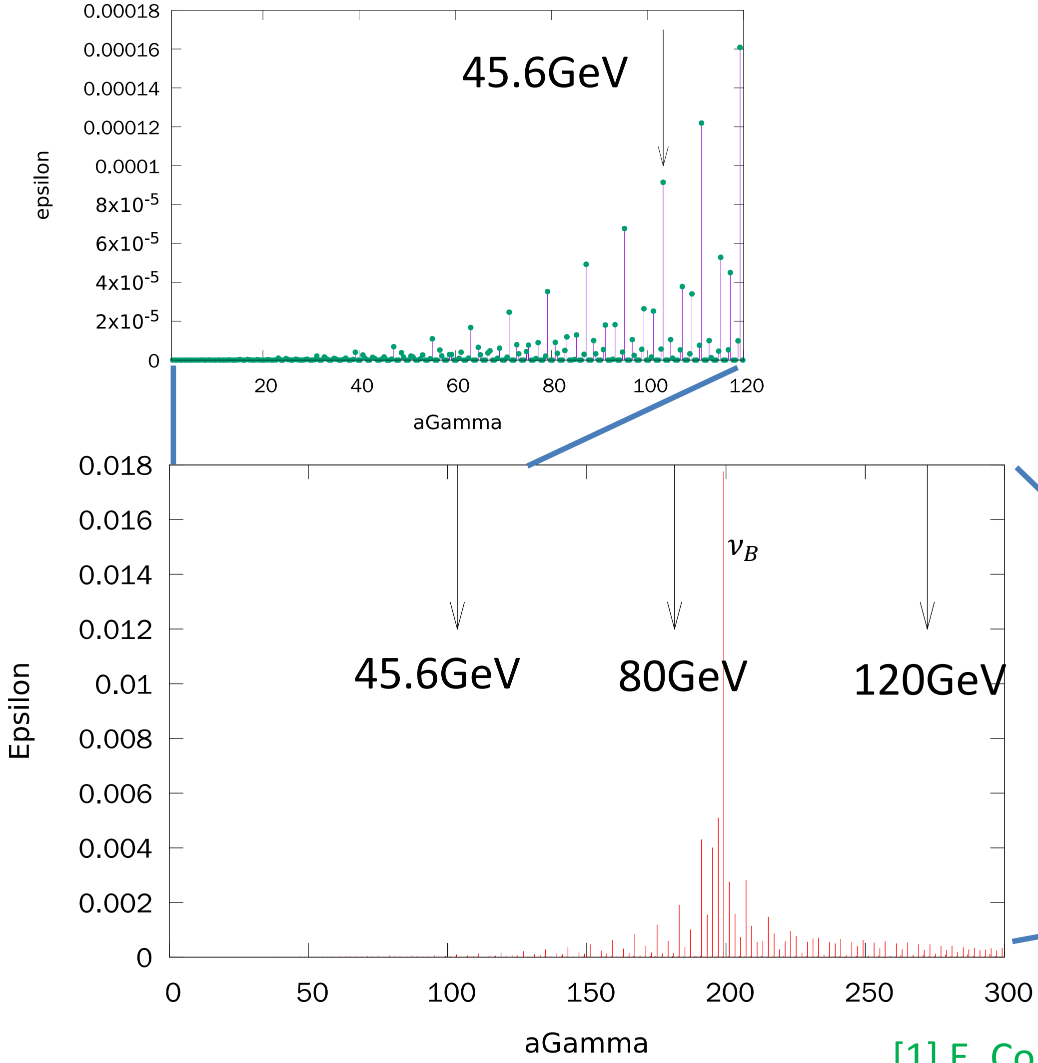
For large ring lake CEPC ,L is larger so $g_{F/\mathrm{D}}$ and resonance strength is smaller.

[1] S. Y. Lee, Spin Dynamics and snakes in synchrotrons, World Scientific, 1997, [2] V. Ranjbar, et al., PRAB 21, 111003 (2018)

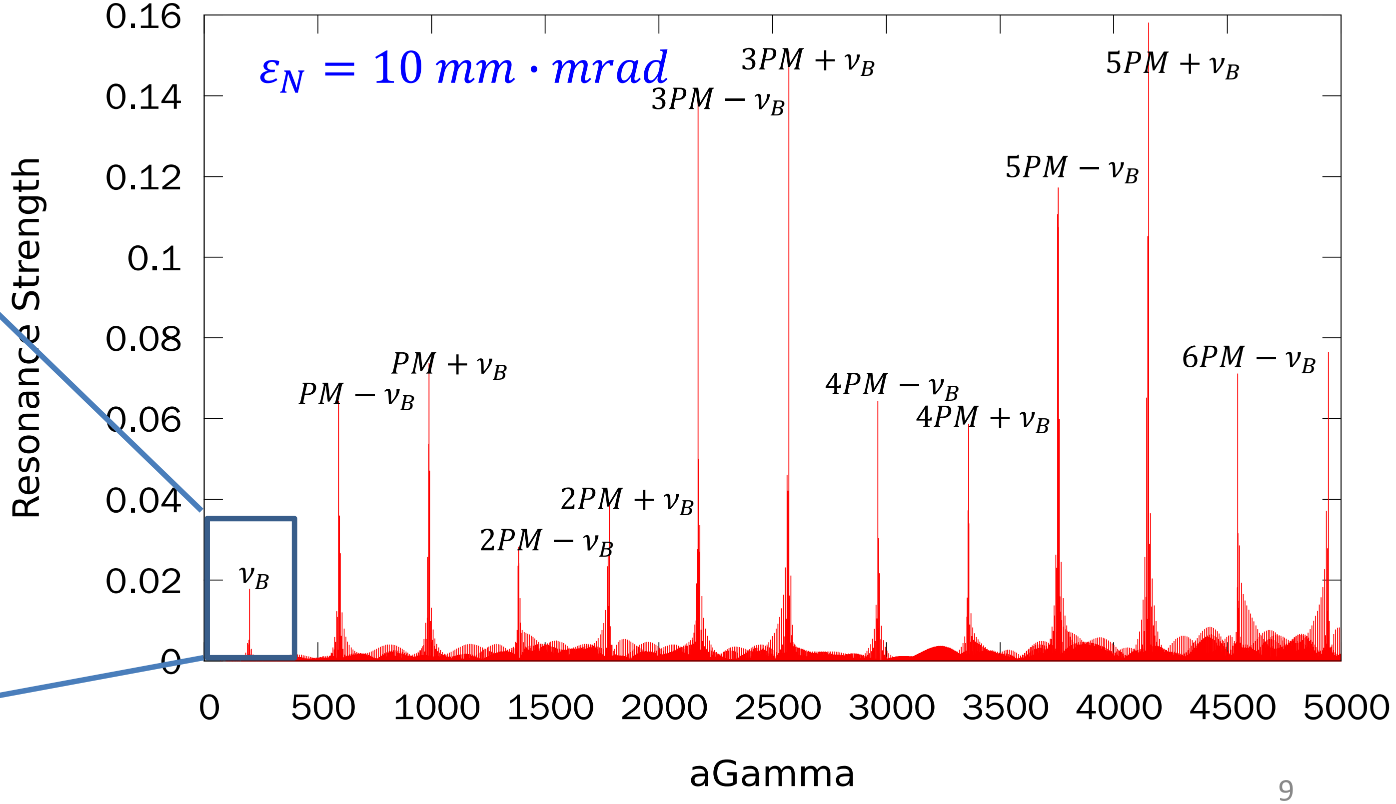
Intrinsic spin resonance structure

CEPC CDR Booster: $P = 8; M = 99; \nu_B = 198$

$\epsilon_{\text{K,intrinsic}} \sim \gamma \sqrt{\varepsilon_{\text{rms}}}$



Simulated with DEPOL [1]



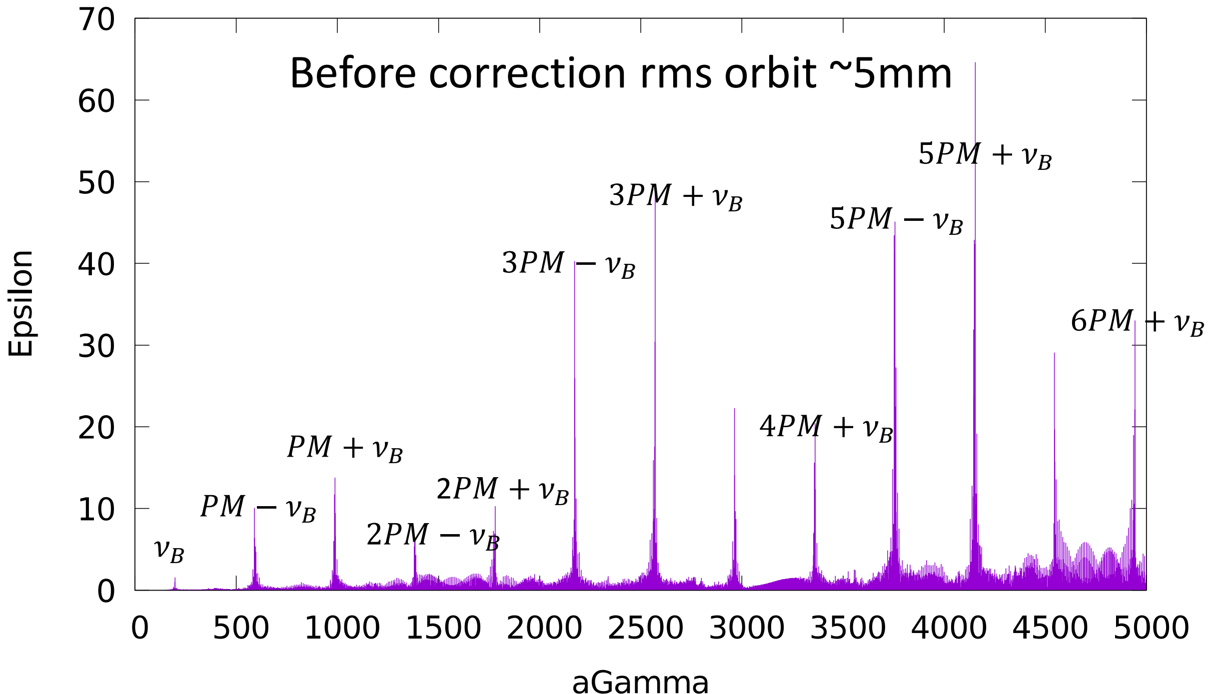
[1] E. Courant and R. Ruth, BNL-52170, 1980

Imperfection spin resonance structure

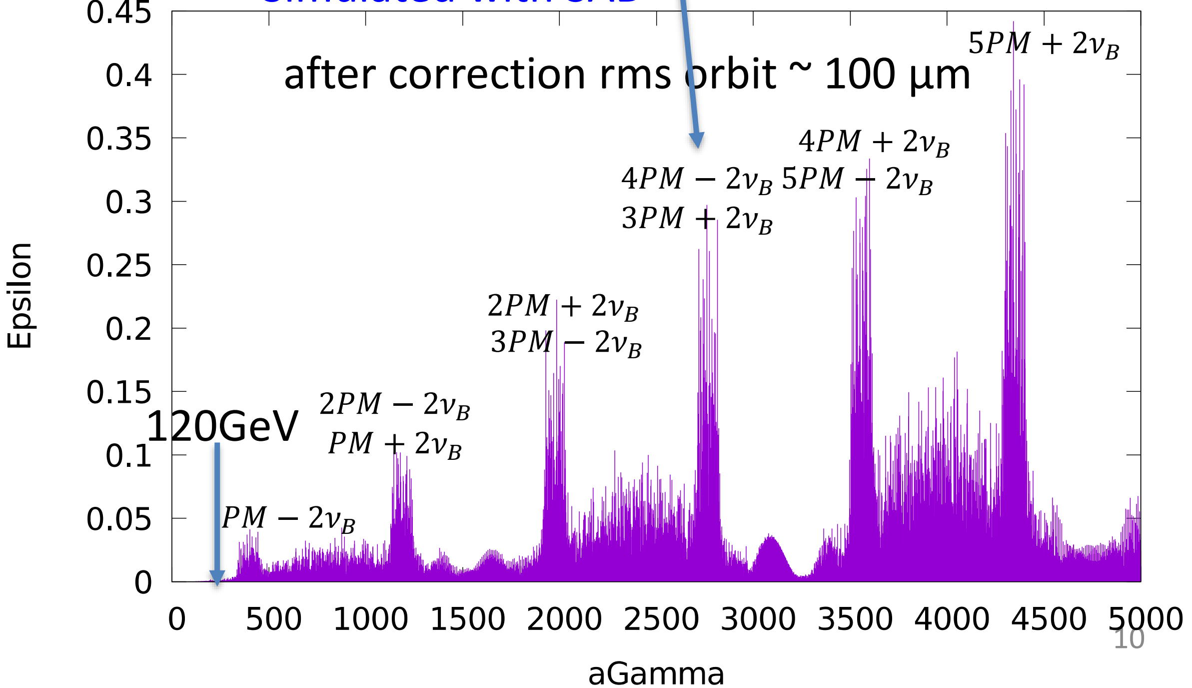
Closed orbit: $z_{\mathrm{co}}(s) = \beta_z^{\frac{1}{2}}(s)\sum_{-\infty}^{\infty}\frac{\nu_z^2 f_k e^{ik\phi(s)}}{\nu_z^2-k^2}$

- The orbit correction eliminates f_k near$[\nu_z]$
- Imperfection resonance strength: $\epsilon_K = \frac{1+G\gamma}{2\pi}\sum_{-\infty}^{\infty}\boxed{\frac{\nu_z^2 f_k}{\nu_z^2-k^2}}\, e^{i\frac{P-1}{P}(k+K)\pi}\zeta_P\left(\frac{k+K}{P}\right)\times\{\zeta_M(\boxed{\frac{K+k\frac{\nu_B}{\nu_z}}{MP}})\times\left[g_D\beta_z^{\frac{1}{2}}(\mathrm{D}) - g_F\beta_z^{\frac{1}{2}}(\mathrm{F})e^{-\frac{i\left(K+\frac{k\nu_B}{\nu_z}\right)\pi}{MP}}\right] + X_I\}$

The position of the peak is shifted and the preceding and following peaks are coincident



Simulated with SAD



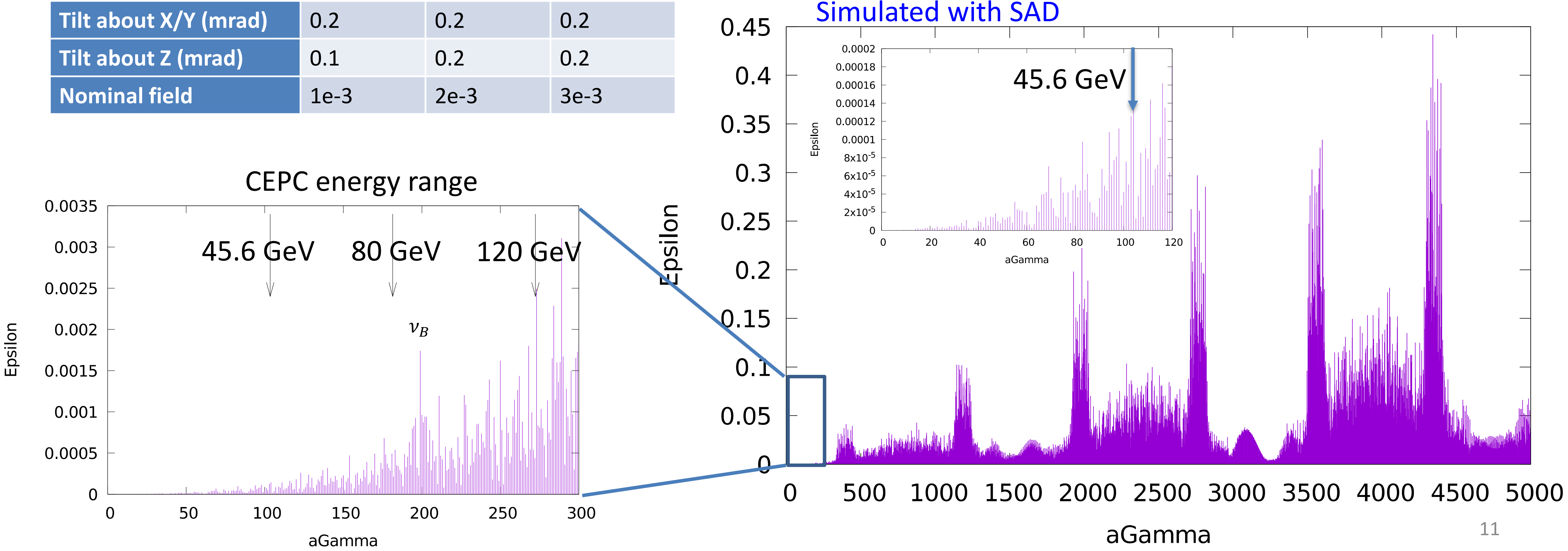
Imperfection spin resonance structure

Error setting in the lattice, rms vertical closed orbit is ~ 100 µm in this seed

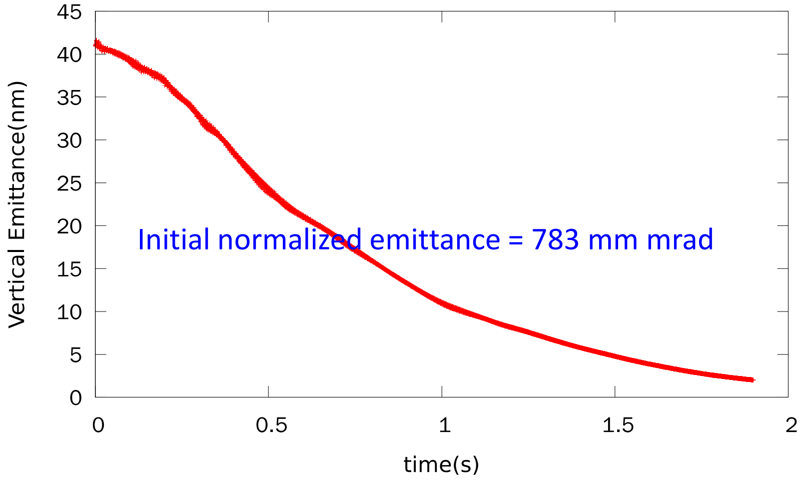
	Dipole	Quadrupole	Sextupole
Transverse shift X/Y (µm)	100	100	100
Longitudinal shift Z (µm)	100	150	100
Tilt about X/Y (mrad)	0.2	0.2	0.2
Tilt about Z (mrad)	0.1	0.2	0.2
Nominal field	1e-3	2e-3	3e-3

Calculated using one corrected lattice with error

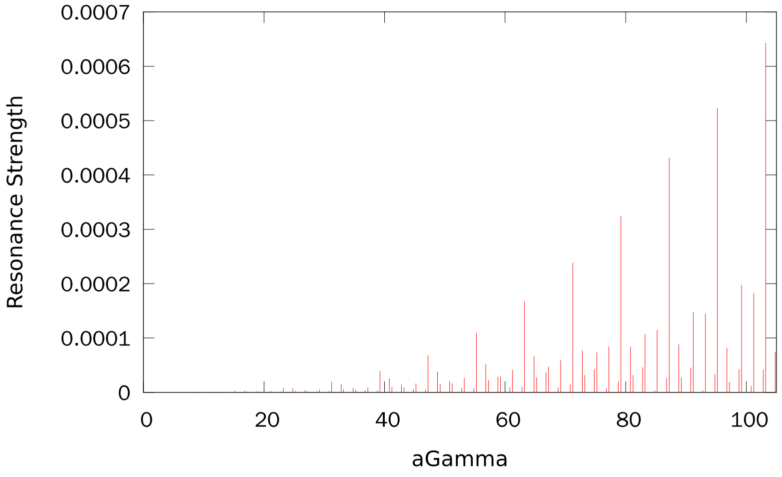
$$\epsilon_K = -\frac{1+a\gamma}{2\pi}\oint z'' e^{iK\theta} ds \approx -\frac{1+a\gamma}{2\pi}\sum_i (z'_{i+1}-z'_i)e^{iK\theta_i}$$

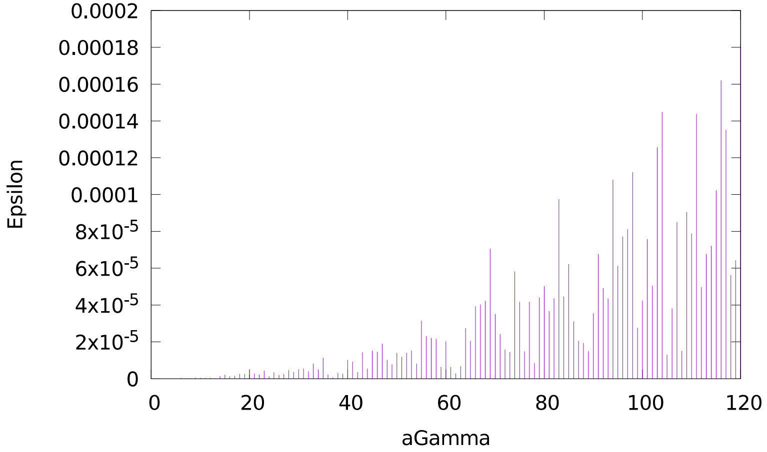


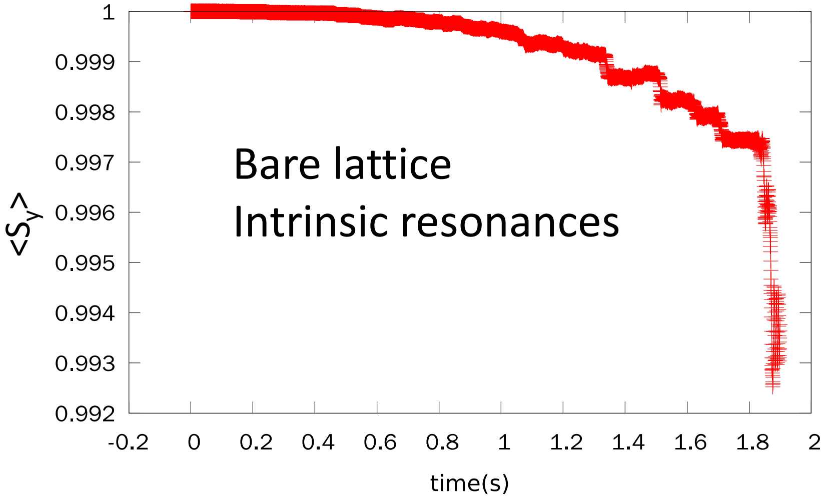
Simulation of polarization transmission to 45.6 GeV


Evolution of vertical rms emittance

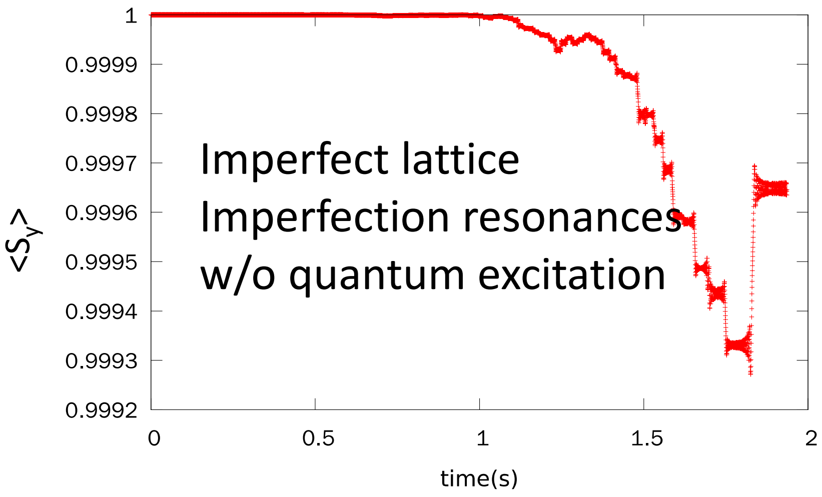
Initial normalized emittance = 783 mm mrad


Intrinsic resonance strength scaled with emittance

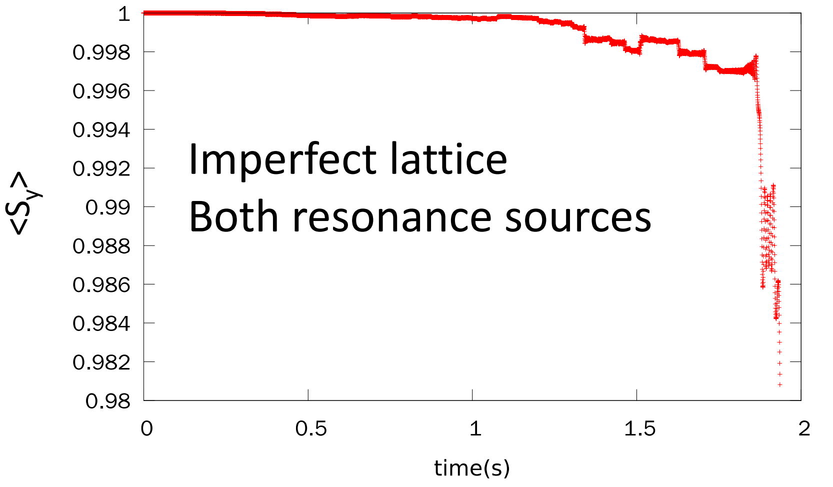

Imperfection resonance strength


200 particles ,initial vertical emittance 40nm

Bare lattice
Intrinsic resonances


On the closed orbit

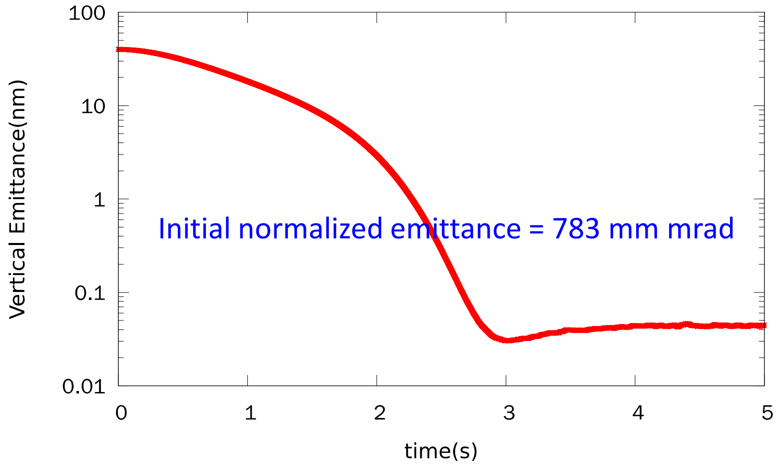
Imperfect lattice
Imperfection resonances
w/o quantum excitation


200 particles ,initial vertical emittance 40nm

Imperfect lattice
Both resonance sources

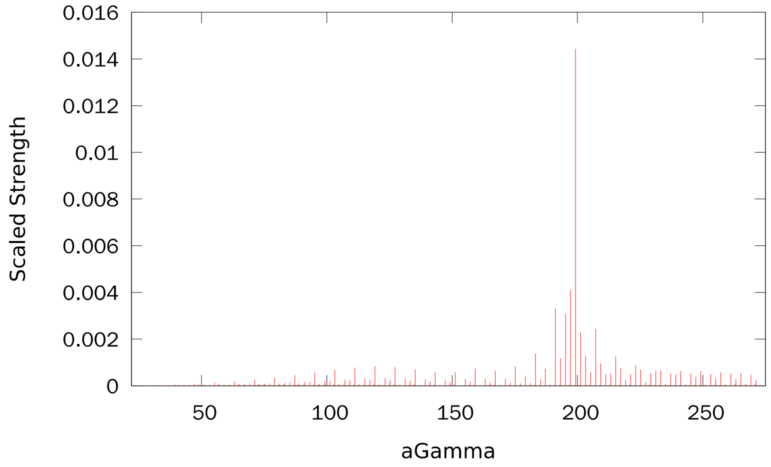
Simulation of polarization transmission to 120 GeV

Evolution of vertical rms emittance

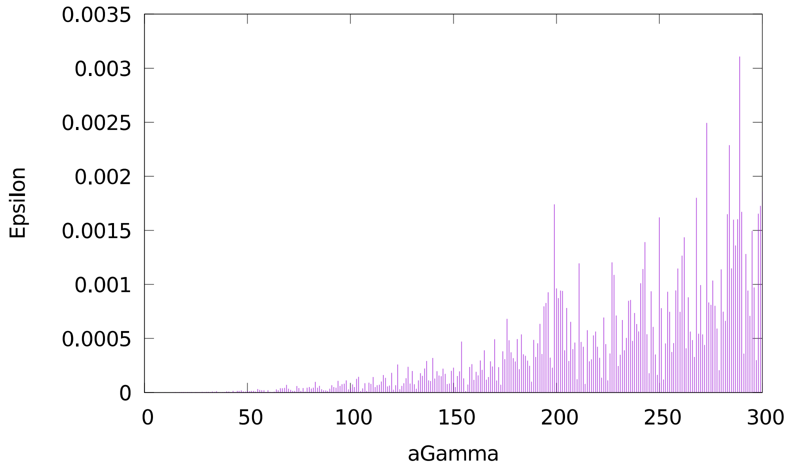


Initial normalized emittance = 783 mm mrad

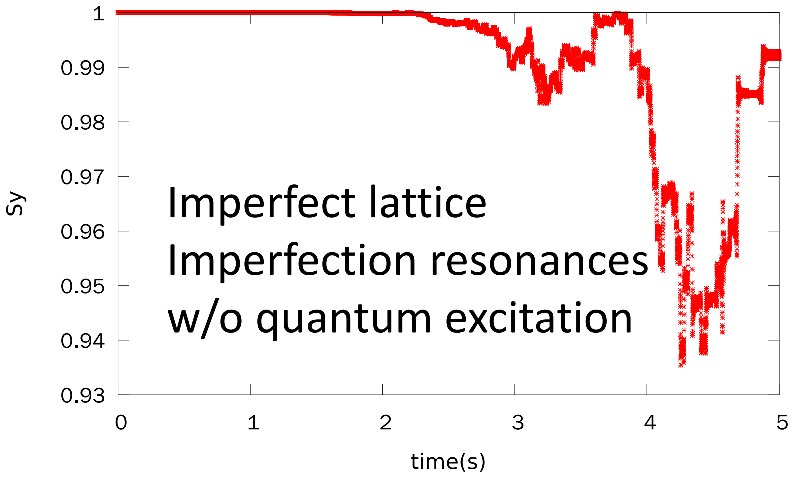
Intrinsic resonance strength scaled with emittance



Imperfection resonance strength

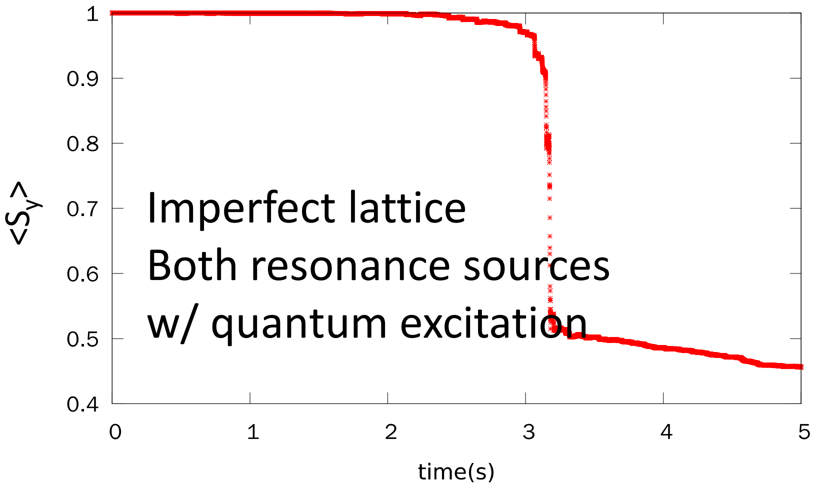


On the closed orbit

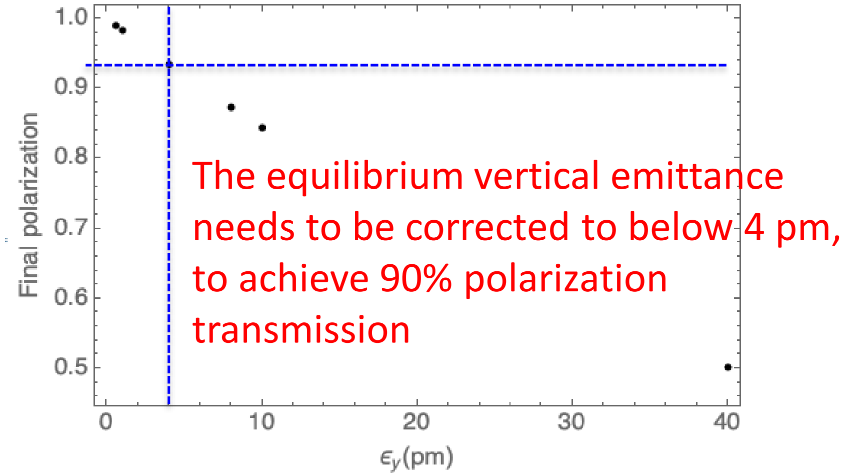


Imperfect lattice
Imperfection resonances
w/o quantum excitation

5000 particles, initial vertical emittance 40nm



Imperfect lattice
Both resonance sources
w/ quantum excitation



The equilibrium vertical emittance needs to be corrected to below 4 pm, to achieve 90% polarization transmission

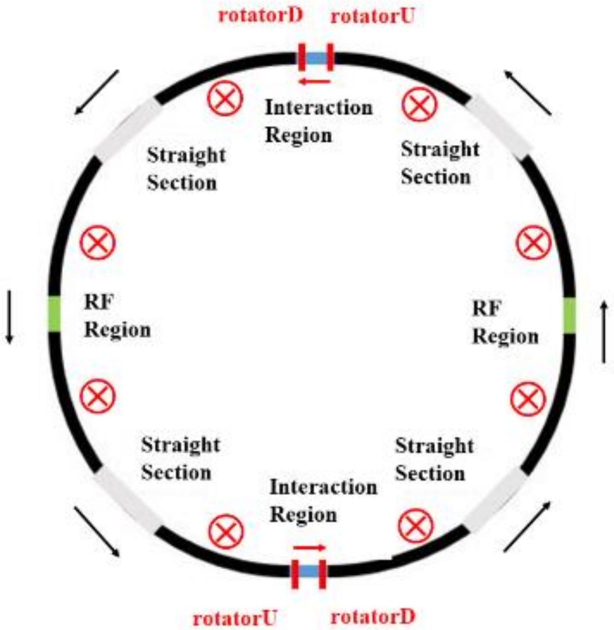
Short summary on polarization maintenance in booster

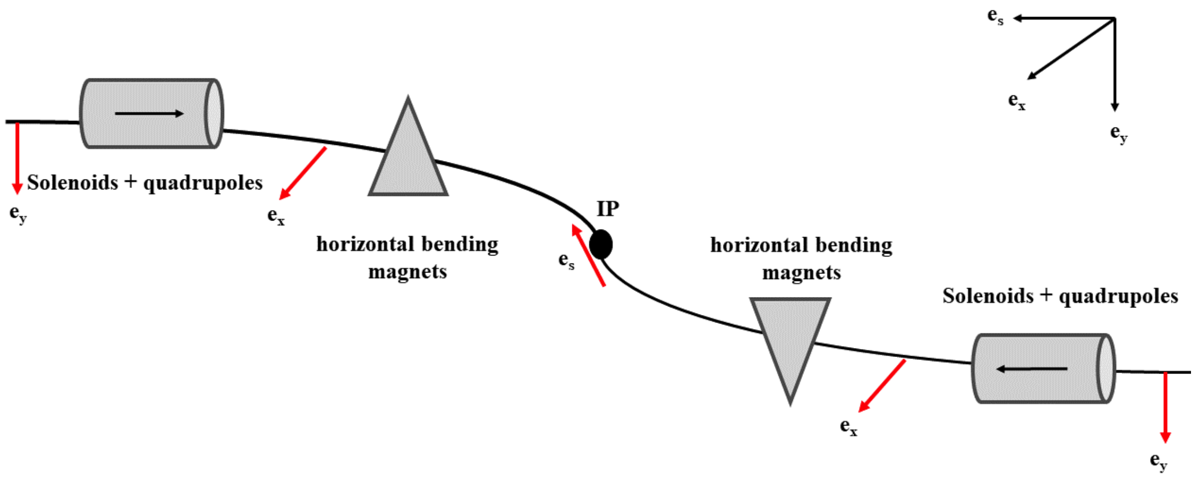
Findings:

- A large ramping rate of spin precession frequency α, due to the large circumference
- Spin resonances are generally weak, due to the high periodicity & cancellation
- Depolarization is negligible, in the fast crossing regime $\frac{\epsilon}{\sqrt{\alpha}} \ll 0.1$, up to 45.6 GeV
- The strong intrinsic resonance at ~ 87 GeV leads to large depolarization, and hurts the polarization transmission up to 120 GeV, potential mitigations:
  - A new lattice with the first strong intrinsic resonance larger than 120 GeV
    - The above study used the lattice of CDR， In the new design of TDR the condition is satisfied.
  - Control the vertical equilibrium beam emittance to below ~ 4 pm (coupling ~ 0.1%)
- Further research is needed on the tolerance of the highly efficient polarization transmission to the corrected closed-orbit amplitude

Spin rotators in the collider ring at Z-pole

- Solenoid-based spin rotator + anti-symmetric arrangement [1,2,3] (W. Xia et al., RDTM (2022) doi: 10.1007/s41605-022-00344-2)
  - Successfully implemented in the collider ring lattice
  - Now focus on Z-pole, extendable to cover higher beam energies using interleaved solenoid+dipole scheme [4]

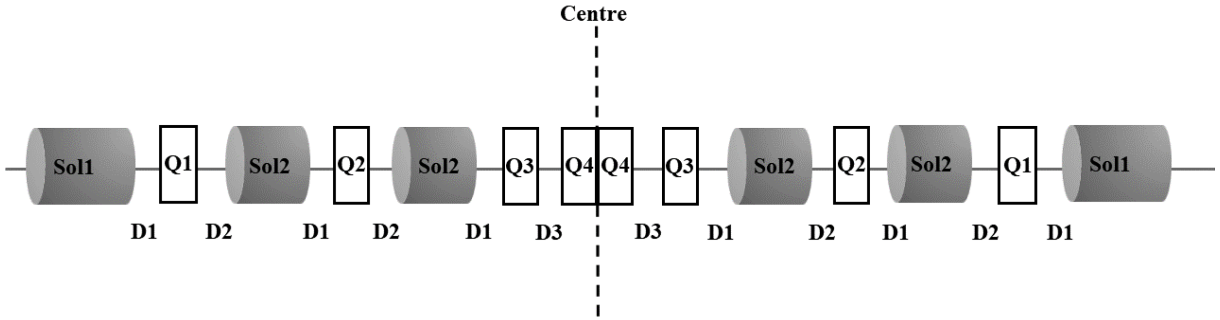




[1] D. Barber, et al., A solenoid spin rotator for large electron storage rings. Part. Accel. 17 (1985) 243.
[2] I. Koop, Longitudinally polarized electron in SuperB, eeFACT'08
[3] M. Biagini et al., Super-B lattice studies, IPAC 2010, TUPEB004.
[4] P. Chevtsov et al., Universal synchronous spin rotators for Electron-Ion Colliders, arXiv:1606.02419.

Spin rotators @ Z-pole

- Solenoid-based spin rotators
  - Integral solenoid field strength = 240 T m @ 45.6 GeV
  - Utilize the solenoid decoupling model developed for HERA [1]
  - Each solenoid section contains two modules (~100 m total length)



Solenoid:

Sol1: L= 5.0 (m) , B= 5.97 (T) ;
Sol2: L= 2.5 (m) , B= 5.97 (T) ;

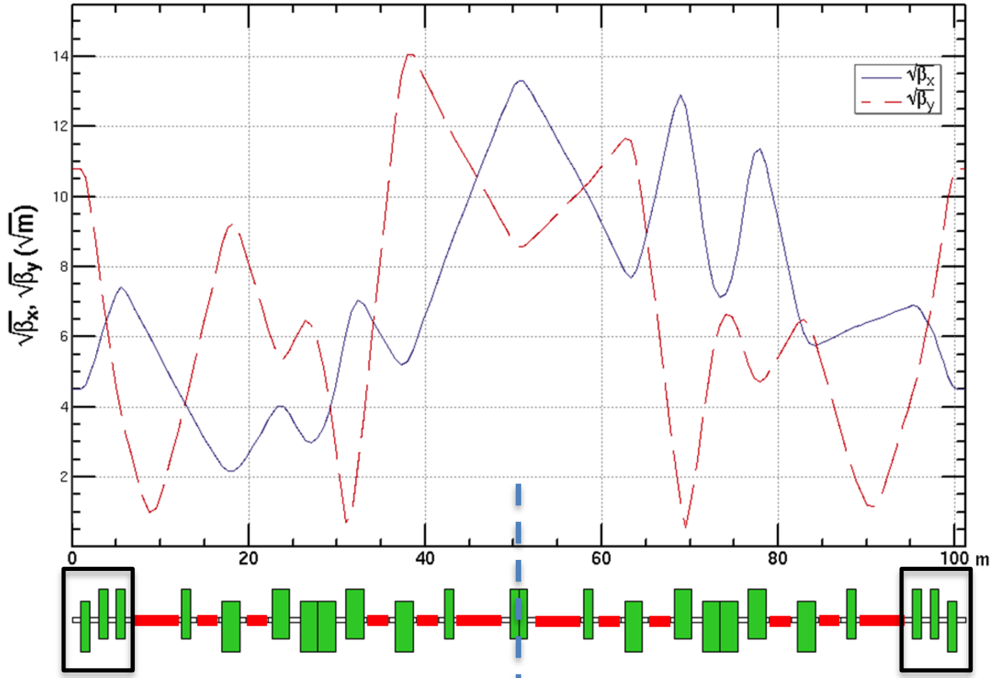
Drift:

D1: L= 0.4 (m) ;
D2: L= 0.7 (m) ;
D3: L= 1.2 (m) ;

Quadrupole:

Q1: L= 1.0 (m) , K= 0.007 (m^{-2}) ;
Q2: L= 2.0 (m) , K= -0.104 (m^{-2}) ;
Q3: L= 2.0 (m) , K= 0.124 (m^{-2}) ;
Q4: L= 2.0 (m) , K= -0.116 (m^{-2}) ;

$$M = \begin{pmatrix} 2.23 & 51.83 & 0 & 0 \\ 0.08 & 2.23 & 0 & 0 \\ 0 & 0 & 0.60 & -7.64 \\ 0 & 0 & 0.08 & 0.60 \end{pmatrix}$$



Optics matching

Optics matching

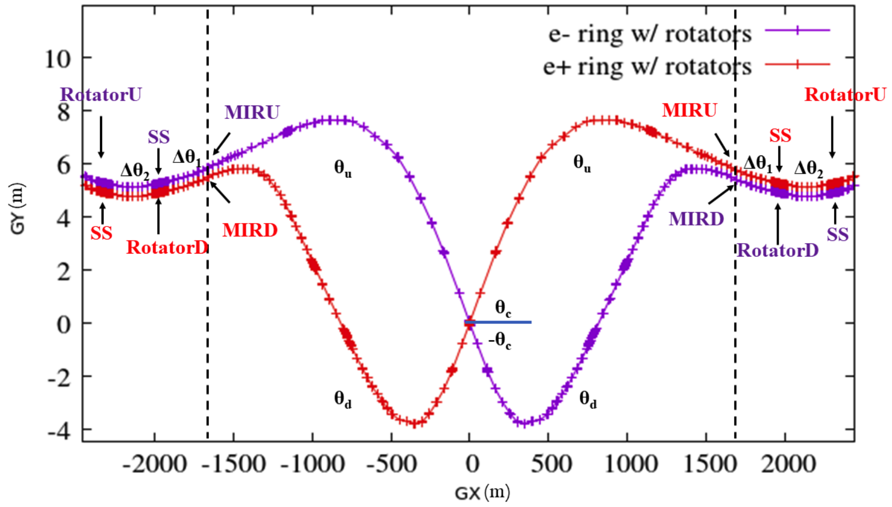
[1] D. Barber, et al., A solenoid spin rotator for large electron storage rings. Part. Accel. 17 (1985) 243.

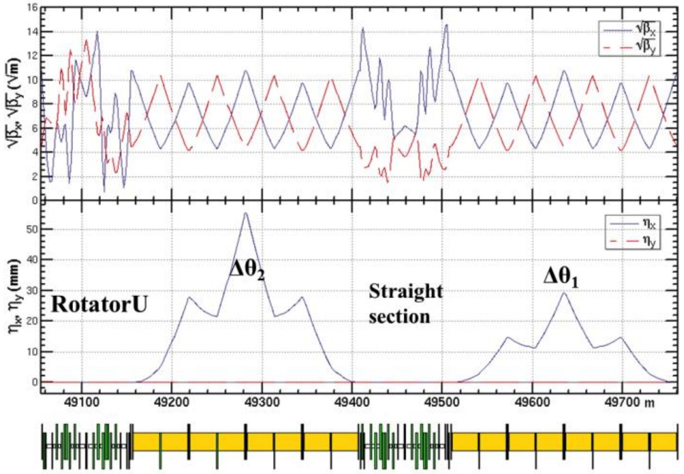
Spin rotators @ Z-pole

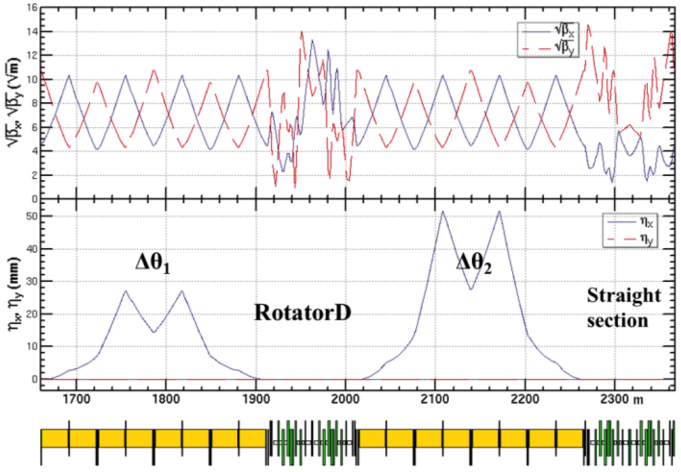
- Anti-symmetric arrangement [1,2,3]
  - θ_c=2*16.5 mrad, rather than the ideal value 2*15.17 mrad
  - Angle compensation sections $\Delta\theta_1$(1.39mrad) and $\Delta\theta_2$(2.65mrad)

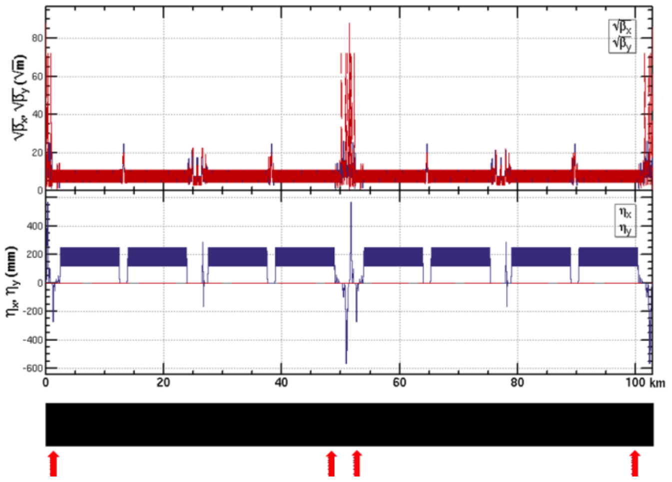
$$\begin{aligned} a\gamma(\theta_u + \Delta\theta_1 + \Delta\theta_2) &= -\frac{\pi}{2} \\ a\gamma(\theta_d + \Delta\theta_1) &= \frac{\pi}{2}. \end{aligned}$$

  - Straight sections (SS) w/o solenoids









[1] I. Koop, Ideas for longitudinal polarization at the Z/W/H/top factory, eeFACT 2018.
[2] S. Nikitin, Opportunities to obtain polarization at CEPC, IJMPA, 34, 194004 (2019)
[3] S. Nikitin, Polarization issues in circular electron-positron super-colliders, IJMPA, 35 (2020).

Performance evaluation: orbital motion

- Changes in optics parameters
  - Increase of circumference ~ 2.8 km, can be optimized.
  - Increase of integer betatron tunes by 18 units

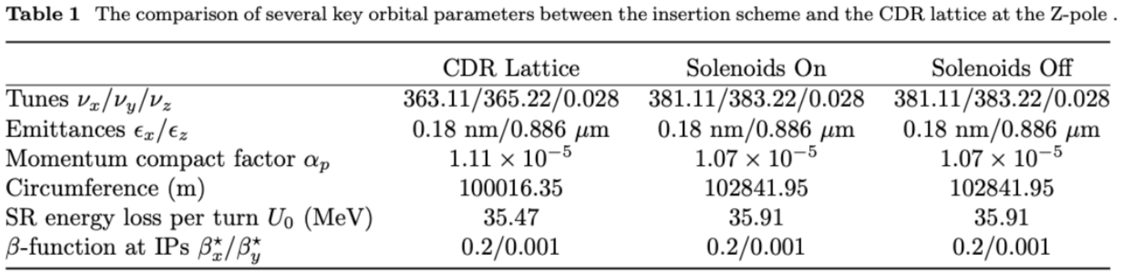
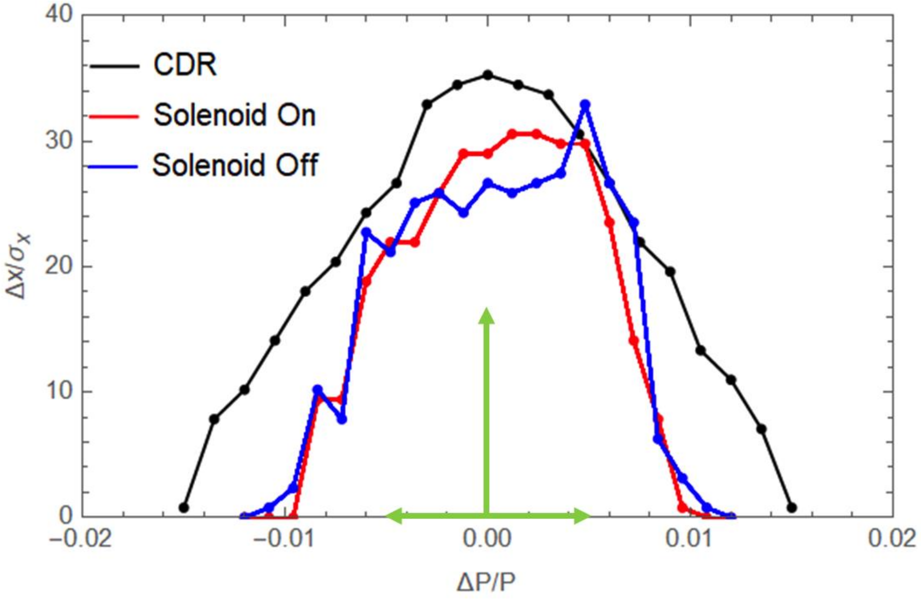
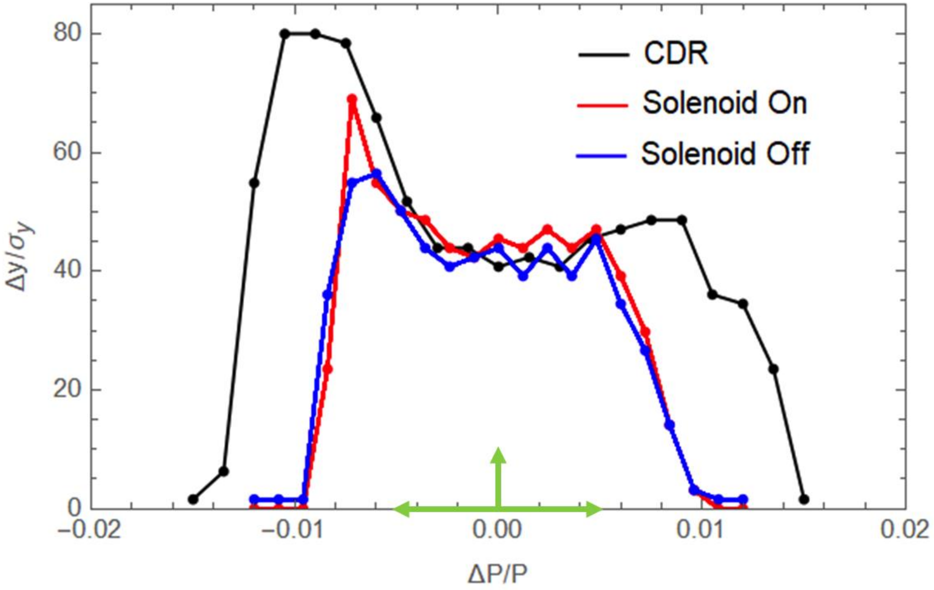


Table 1 The comparison of several key orbital parameters between the insertion scheme and the CDR lattice at the Z-pole .

	CDR Lattice	Solenoids On	Solenoids Off
Tunes $\nu_x/\nu_y/\nu_z$	363.11/365.22/0.028	381.11/383.22/0.028	381.11/383.22/0.028
Emittances ϵ_x/ϵ_z	0.18 nm/0.886 μm	0.18 nm/0.886 μm	0.18 nm/0.886 μm
Momentum compact factor α_p	1.11×10^{-5}	1.07×10^{-5}	1.07×10^{-5}
Circumference (m)	100016.35	102841.95	102841.95
SR energy loss per turn U_0 (MeV)	35.47	35.91	35.91
β-function at IPs $\beta_x^\star/\beta_y^\star$	0.2/0.001	0.2/0.001	0.2/0.001

- Dynamic aperture shrinks a bit, but further optimization using more sextupole families could help recover.

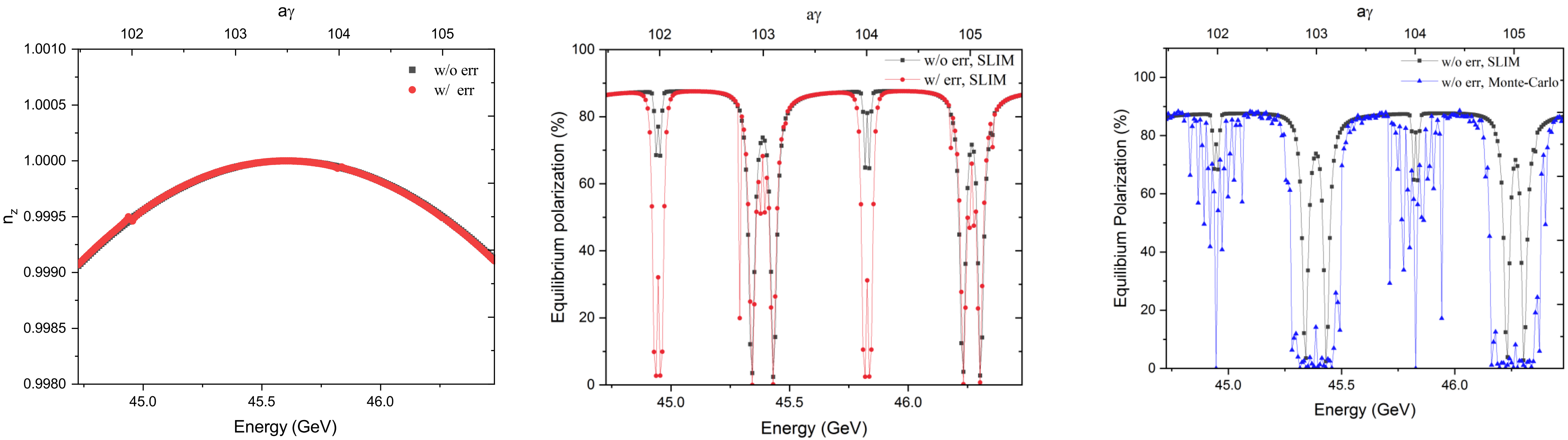




Performance evaluation: polarization

Bmad/PTC simulations show:

- Weak dependence of $\hat{n}_0$ over energy in the working energy range
- Errors in solenoid sections lead to enhanced but acceptable depolarization near first-order spin resonances
  - Rms relative field error of 5e-4 for solenoids & quadrupoles, roll error of 1e-4 for quadrupoles.
- A sufficient large safe region exists, that enables $\tau_{DK} \gg \tau_b$ thus $P_{\text{avg}} \approx P_{\text{inj}}$, when higher-order spin resonances are also considered
  - $P_{\text{avg}} \approx P_{\text{inj}}/(1 + \frac{92\%}{P_{\text{eq}}}\frac{\tau_b}{\tau_{BKS}})$, $\tau_b \sim 2$ hours, $\tau_{BKS} \sim 260$ hours, if P_{eq}=7%, then $P_{\text{avg}} \approx P_{\text{inj}}/1.1$



Summary

- First-order issues to realize longitudinal polarized colliding beams at CEPC-Z (45.6 GeV) have been addressed
  - Beam polarization can be well preserved in the booster, without additional hardware
  - Spin rotators implemented in the collider ring, shows promising performance
  - This also provides an alternative scenario for resonant depolarization applications
- The current studies will be extended to higher beam energies, for example CEPC-Higgs (120 GeV), many issues to be solved
  - Polarization maintanance in the booster
  - Spin rotator design in the collider ring
  - Radiative depolarization due to machine imperfections in the collider ring

Thank you for your attention!