CEPC Polarization Study Status

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On behalf of CEPC Beam Polarization Working Group

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CEPC Beam polarization working group

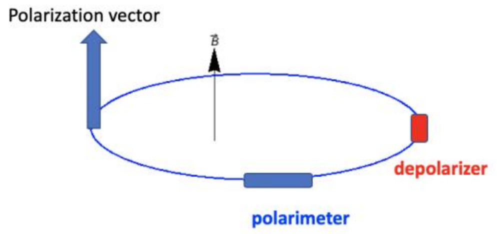
- Physics design:
  - Tao Chen, Zhe Duan, Hongjin Fu, Jie Gao, Sergei Nikitin (BINP), Dou Wang, Jiuqing Wang, Yiwei Wang, Wenhao Xia(graduated)
- Polarized electron source & linac:
  - Xiaoping Li, Cai Meng, Jingru Zhang
- Polarimeter:
  - Shanhong Chen, Yongsheng Huang, Guangyi Tang

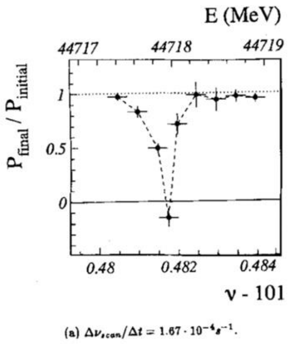
- Discussions with D. P. Barber (DESY) on polarization theories and simulations are illuminating.
- Helpful discussions with E. Forest (KEK) & D. Sagan (Cornell) on usage of Bmad/PTC are acknowledged.

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

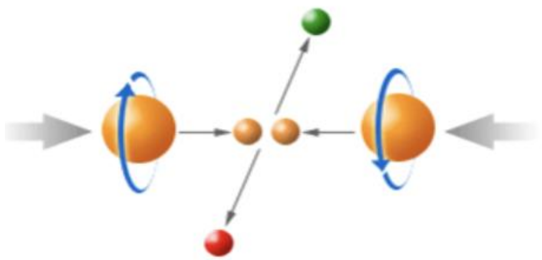




L. Arnaudon, et al., Z. Phys. C 66, 45-62 (1995).

Longitudinally polarized beams at IPs

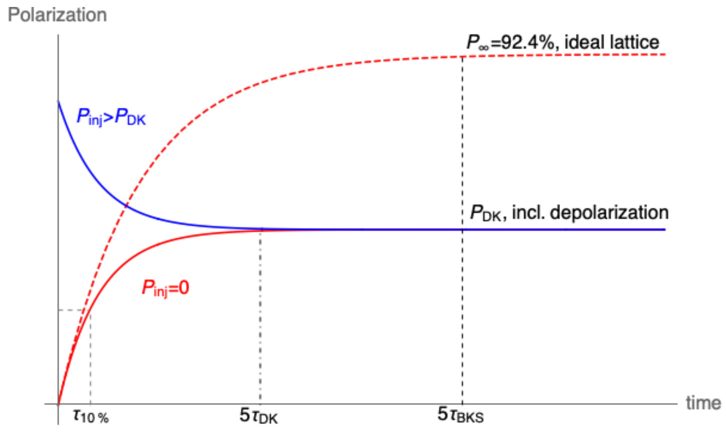
- Beneficial to colliding beam physics programs at Z, W and Higgs
- Figure of merit: Luminosity * f(Pe+, Pe-)
- ~50% or more longitudinal polarization is desired, for one beam, or both beams



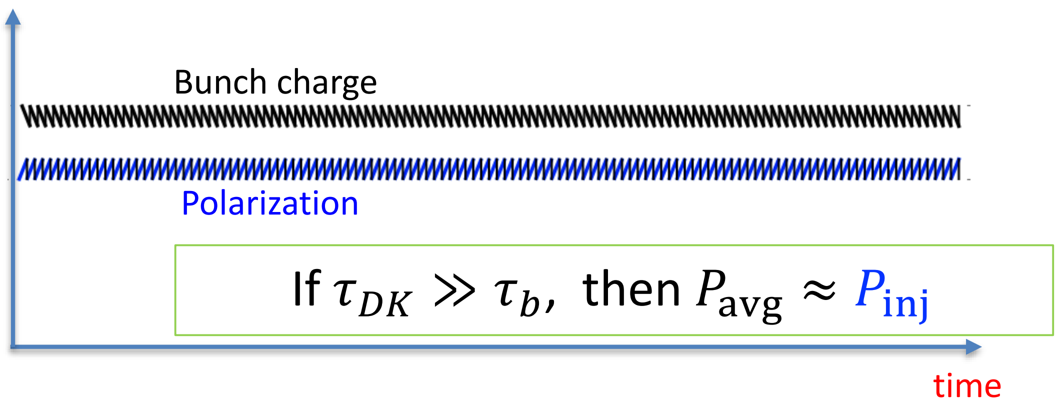
- Supported by National Key R&D Program 2018-2023 to design longitudinally polarized colliding beams at Z-pole.
- The study in this presentation is based on CEPC CDR lattice & parameters.
- Will be included as a Chapter in the Appendix in the CEPC TDR.

Beam polarization in the collider rings

- Non-colliding "pilot" bunch: decay mode



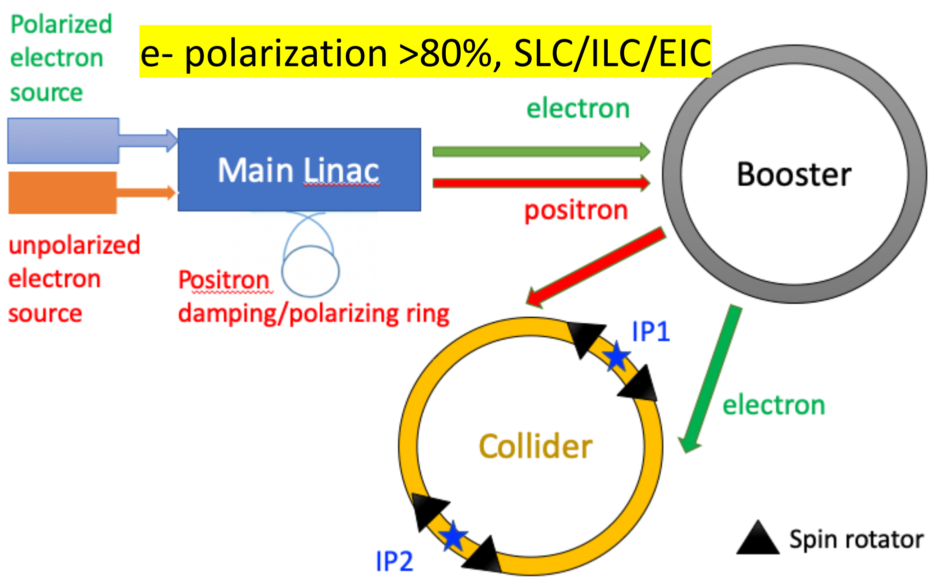
- Colliding bunch: top-up injection



- Injection of polarized beams is required
  - to achieve high-level longitudinal polarization without significantly sacrificing luminosity
  - also benefits resonant depolarization measurements w/ pilot bunches.

CEPC CDR parameters	45.6 GeV (Z, 2T)	80 GeV (W)	120 GeV (Higgs)
Polarization build-up time w/o radiative depolarization τ_{BKS} (hour)	256	15.2	2.0
Beam lifetime τ_b (hour)	2.5	1.4	0.43
$P_{\rm DK}$ required to realize $P_{\rm avg} \geq 50\%$ in top-up mode, if $P_{\rm inj} = 80\%$	0.6%	5%	11%

Preparation and injection of polarized beams

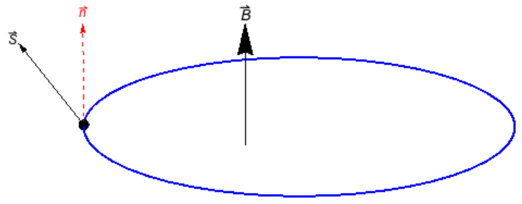


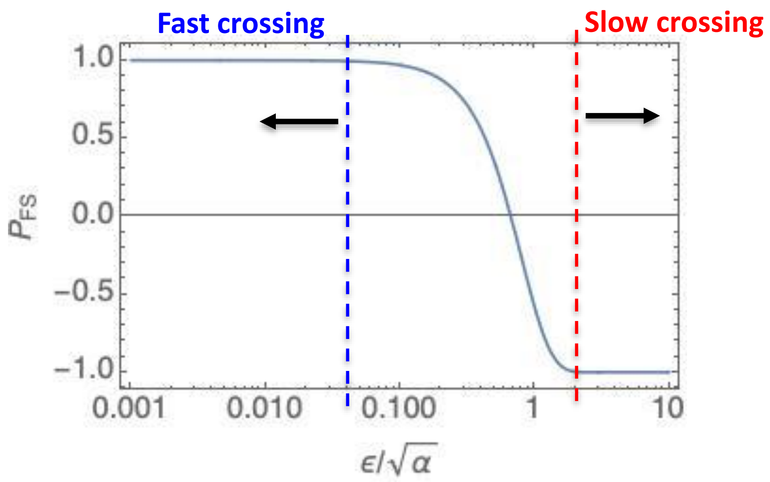
Aspect	Key issue	Pages in this presentation
Polarized beam acceleration in booster	How serious is depolarization, possible mitigation? [1,2]	6-10
Equilibrium beam polarization in collider rings	What are the mechanisms of radiative depolarization?[3]	11
Resonant depolarization	How to generate polarized e+ beam?[1]	12-14
Longitudinally polarized colliding beams	How to design spin rotators in the collider rings?[1,4]	15

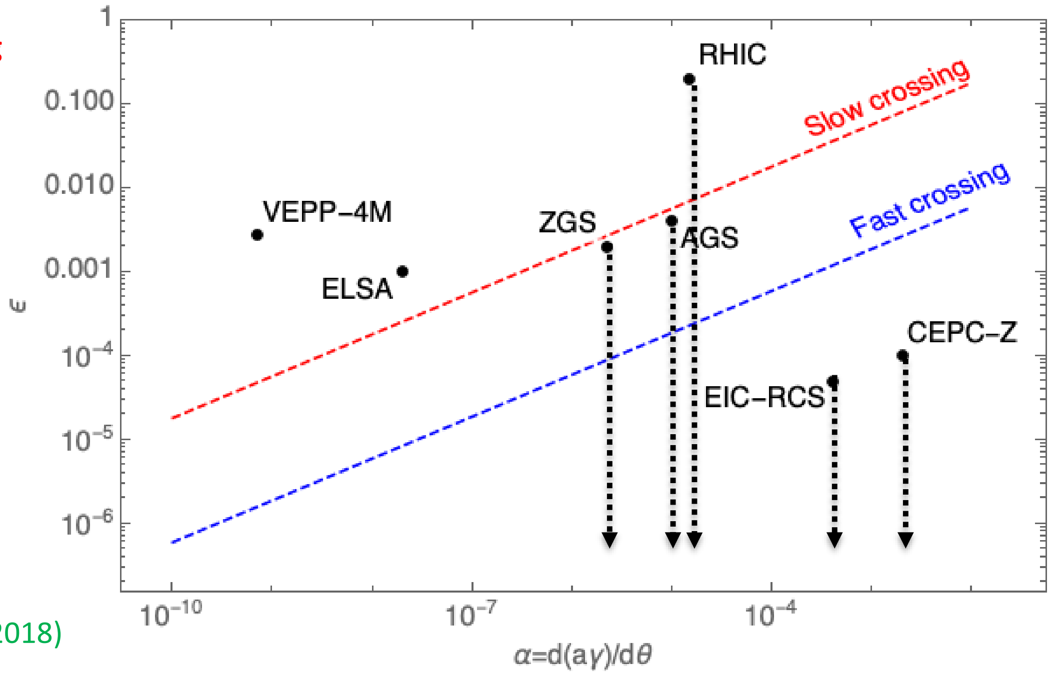
[1] Z. Duan, talk on eeFACT 2022, FCC EPOL Workshop 2022;
[2] T. Chen, Z. Duan, D. H. Ji, D. Wang, arXiv:2302.05321v1 [physics,acc-ph]
[3] W. H. Xia, Z. Duan, D. P. Barber, Y. W. Wang, B. Wang, J. Gao, arXiv:2204.12718v1 [physics.acc-ph], submitted to PRAB
[4]W. Xia, Z. Duan, J. Gao and Y. W. Wang, RDTM (2022) doi: 10.1007/s41605-022-00344-2

Depolarization in the booster

- The spin tune $\upsilon_s \approx a\gamma$ changes and could cross spin resonances $\upsilon_s = k + k_x\upsilon_x + k_y\upsilon_y + k_z\upsilon_z$
  - The spin resonances $\upsilon_0 = k$ are spaced by 440 MeV for e+/e-
- The non-adiabatic crossing could vary $J_s = \vec{S} \cdot \vec{n}$ and lead to depolarization [1]
  - Spin resonance strength ε
  - Acceleration rate $\alpha \sim 10^{-6} \frac{dE}{dt}[\mathrm{GeV/s}]C[\mathrm{km}]$
- Polarization is maintained (ΔP < 1%) for the regimes of fast crossing & slow crossing





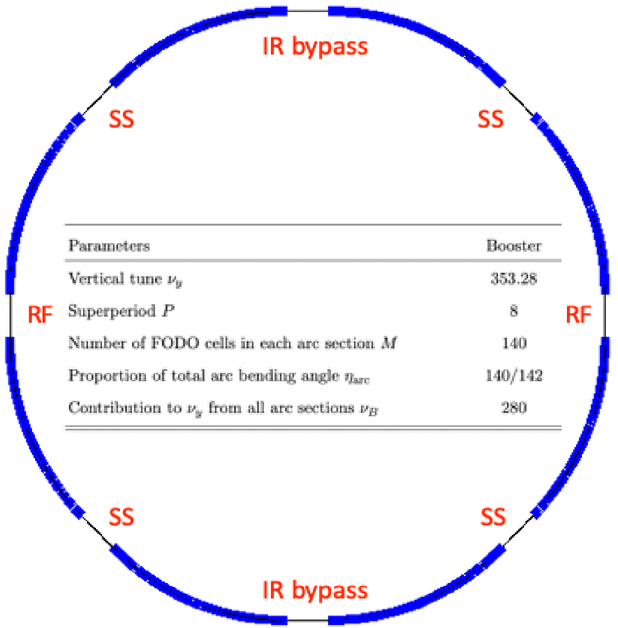


[1] Froissart and Stora, NIM 7, 297 (1960) [2] A. K. Barladyan, et al., PRAB 22, 112804, (2019)
[3] S. Nakamura, et al., NIM A 411, 93 (1998) [4] T. Khoe et al., Part. Accel. 6, 213 (1975)
[5] Configuration Manual: Polarized Proton Collider at RHIC, 2006 [6] V. Ranjbar, et al., PRAB 21, 111003 (2018)

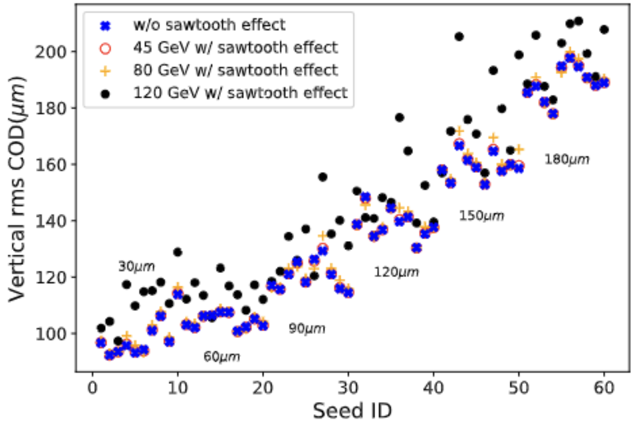
Setup of CEPC booster lattice

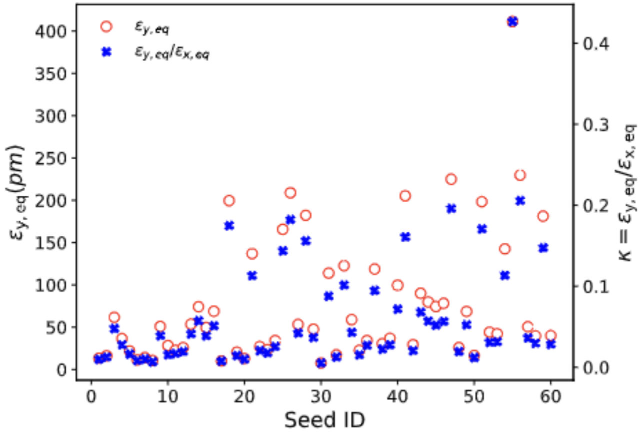
- General structure of the CEPC booster lattice
  - 8 arcs each containing 140 FODO cells
  - interleaved with 8 straight sections
- 60 imperfection lattice seeds
  - Misalignment error & field error, scan BPM offset
  - Closed orbit correction & tune correction
- Multi-particle tracking in Bmad
  - Energy and RF ramping in the whole process
  - Element-by-element tracking with radiation damping & quantum excitation

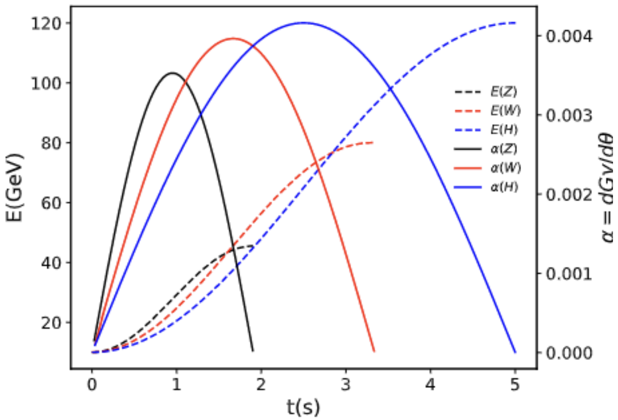
Arc region covers ~ 80% of circumference

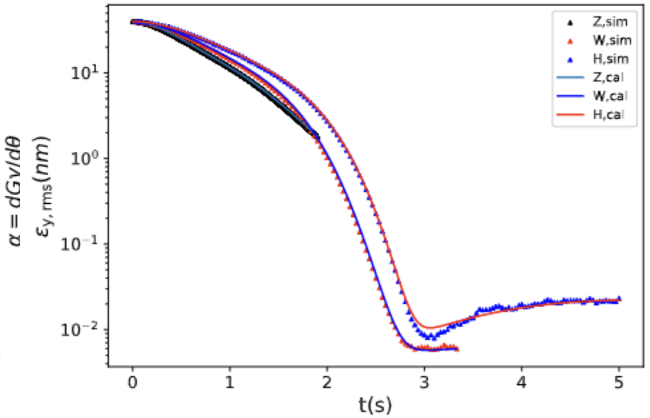


Parameters	Booster
Vertical tune ν_y	353.28
Superperiod P	8
Number of FODO cells in each arc section M	140
Proportion of total arc bending angle η_{arc}	140/142
Contribution to ν_y from all arc sections ν_B	280









Spin resonance structure of CEPC Booster

- Strength of intrinsic & imperfection resonances can be approximated by[1]

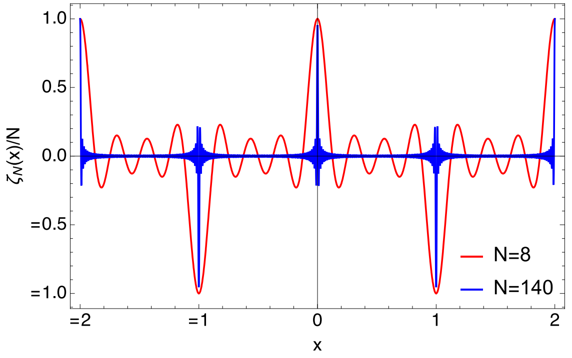
$$|\epsilon| \approx |\epsilon_{FODO}|\, E_P\, E_M$$

due to P superperiods

due to M identical FODOs in each arc

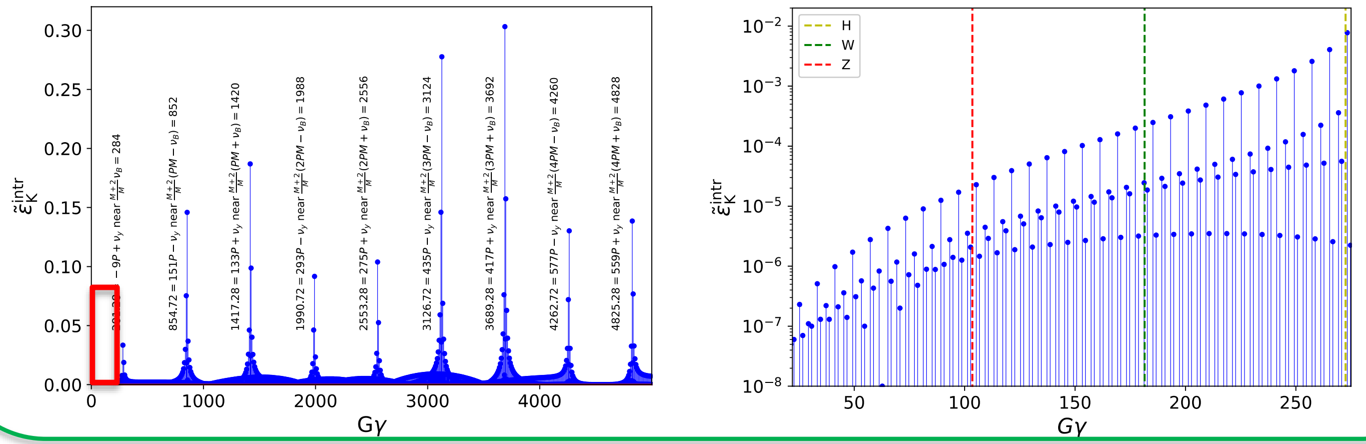
- Enhancement or cancellation occurs when specific conditions are met or not

- Resonances are generally weak within working beam energies of CEPC.



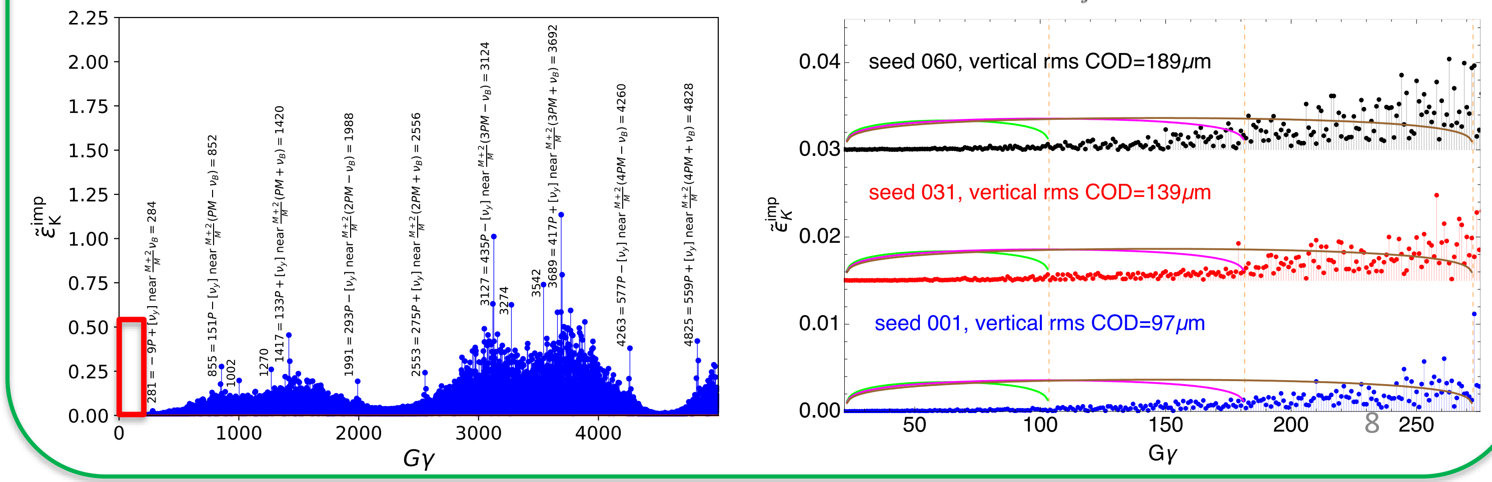
Intrinsic resonances: $\nu_0 = K \pm \nu_\nu$

Super strong resonances: $K = nP \pm \nu_y, n \in \mathbb{Z}$ closest to $(mPM \pm \nu_B)/\eta_{\mathrm{arc}}, m \in \mathbb{Z}$



Imperfection resonances: $\nu_0 = K$

Super strong resonances: $K = nP \pm [\nu_y], n \in \mathbb{Z}$ and $K = [(mPM \pm [\nu_y]\frac{\nu_B}{\nu_y})/\eta_{\mathrm{arc}}]$



[1] S. Y. Lee, Spin dynamics and snakes in synchrotrons (World Scientific, 1997).

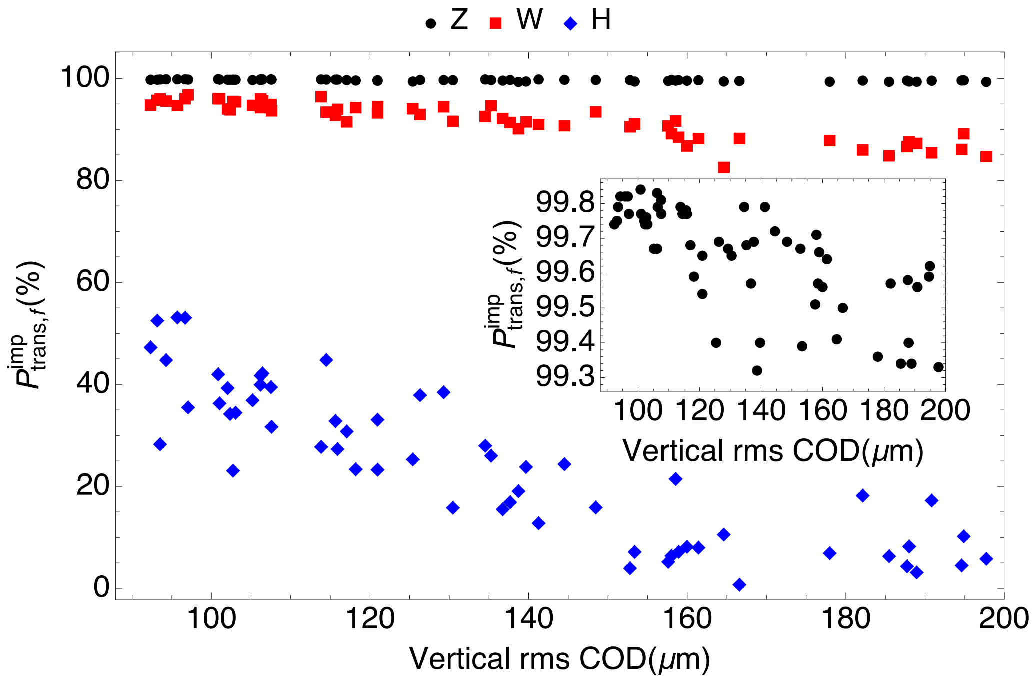
Estimation of depolarization with Froissart-Stora formula

$$P_{\mathrm{trans}}^{\mathrm{imp}}(t) \approx \prod_{K \leq G\gamma(t)} \frac{P_f}{P_i}(K,\alpha)$$

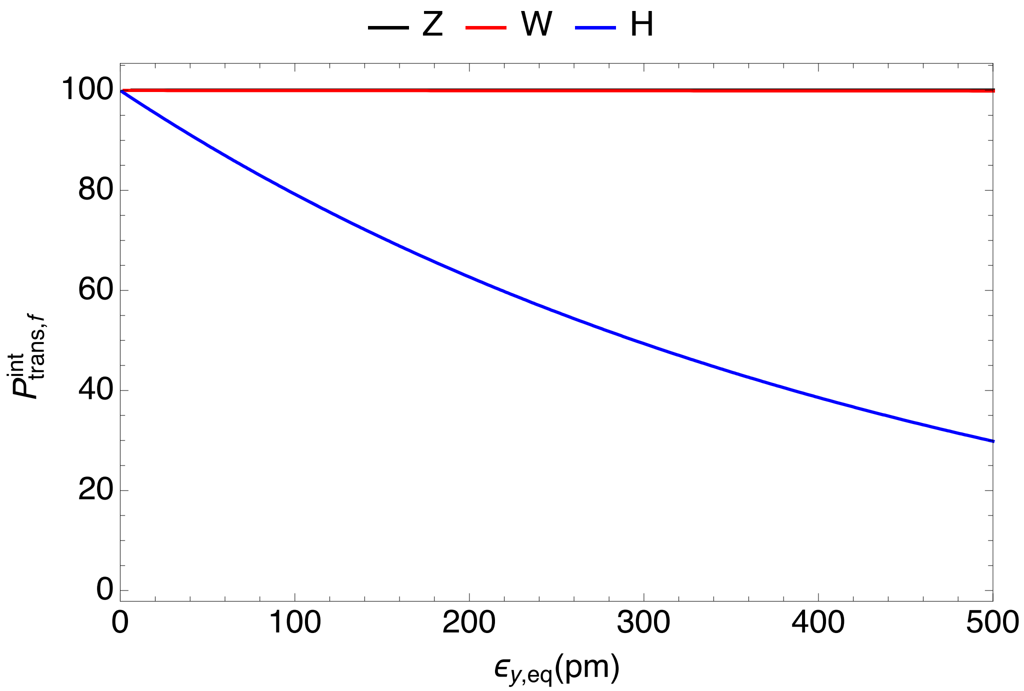
Assumption:

- single crossing of imperfection & intrinsic resonances
- there are no interference between resonance crossings

- Imperfection resonance



- Intrinsic resonance



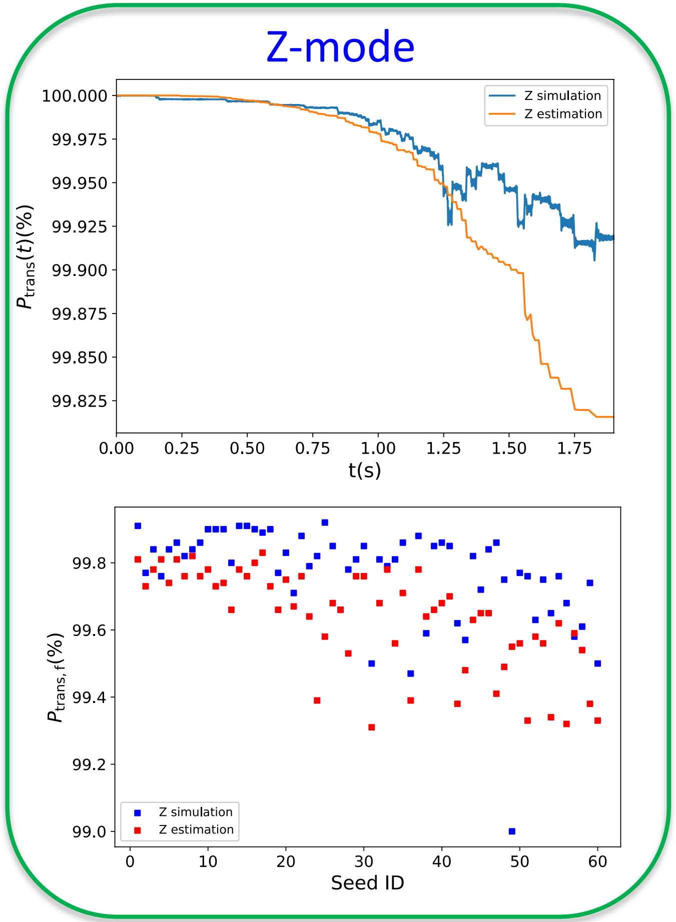
Depolarization effects: simulation vs. estimation

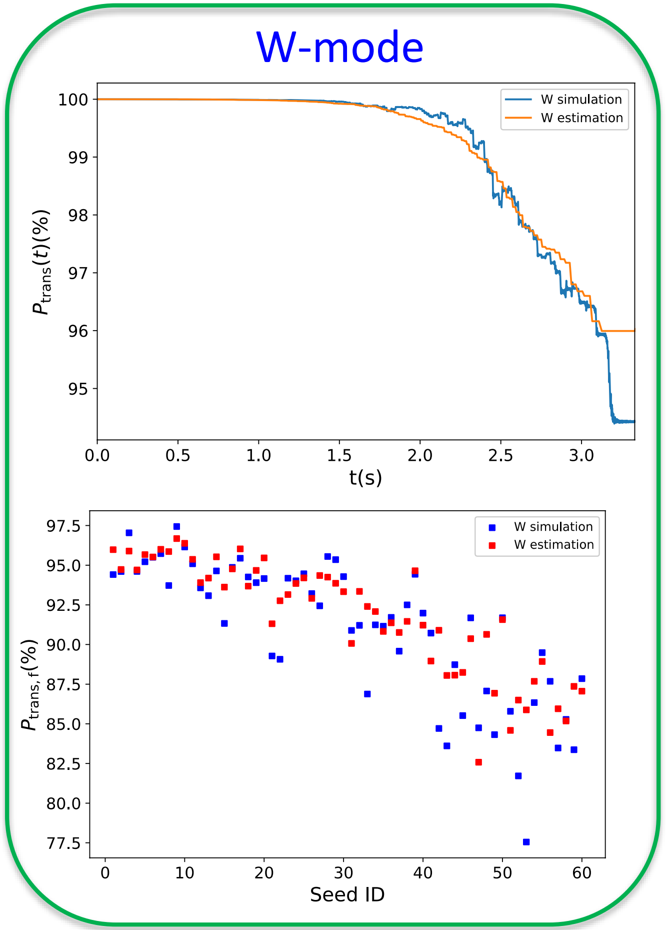
In the acceleration to Z & W

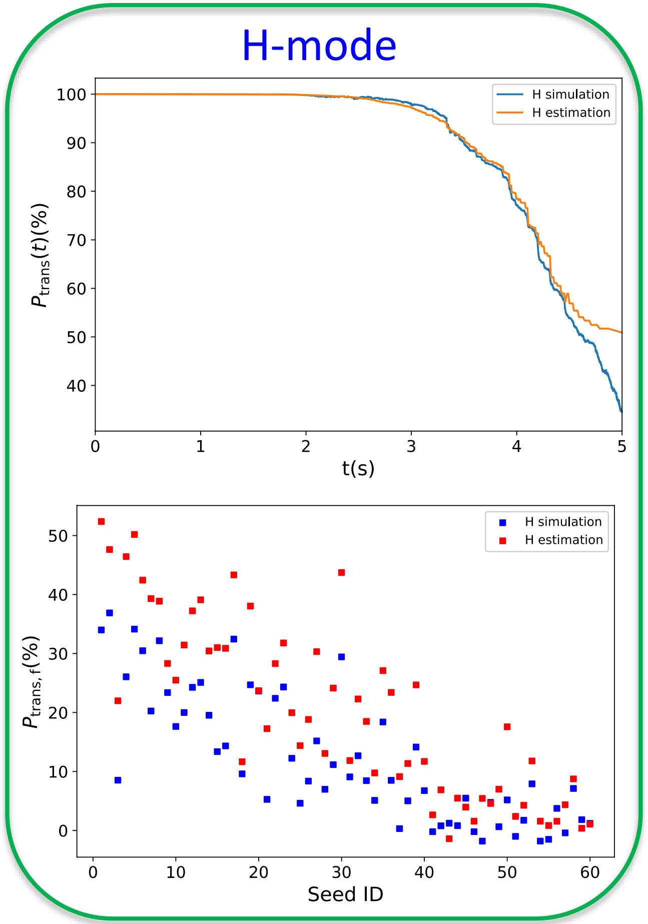
- The spin resonances are generally weak
- Polarization is mostly maintained
- Estimations agree fairly well with simulations

In the acceleration H

- The spin resonances become stronger at higher energies
- Severe depolarization occurs
- Mitigation methods to be explored







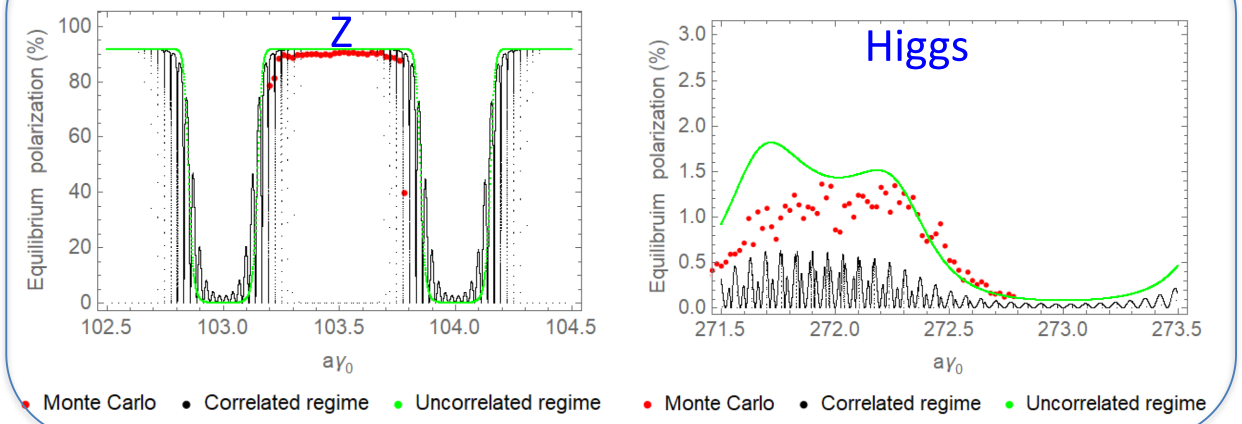
Radiative depolarization in the collider rings

- Two distinct spin diffusion mechanisms were proposed in [1] in 1970s, regarding the regimes of spin resonance crossing, in the combined effects of synchrotron oscillation and synchrotron radiation

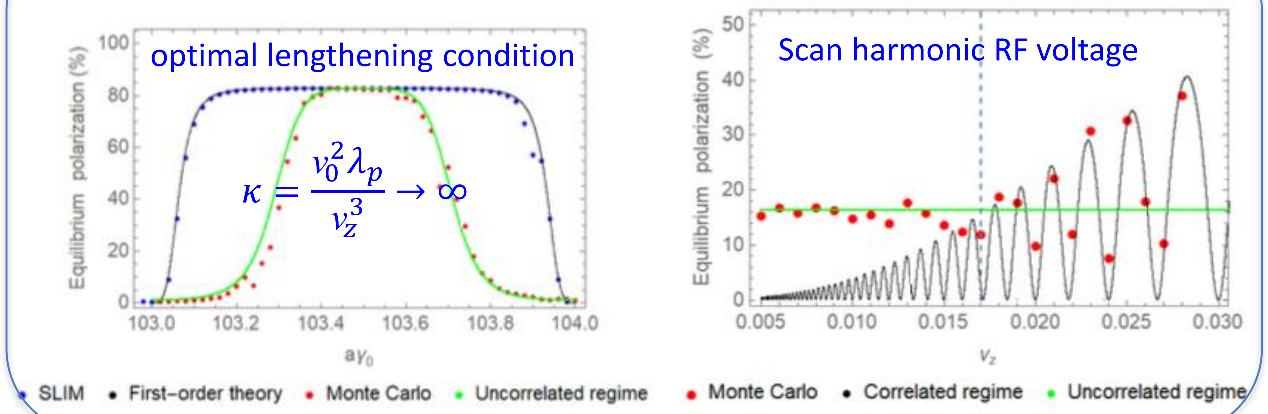
Regime	Correlated regime	Uncorrelated regime
Condition	$\kappa = \frac{\nu_0^2 \lambda_p}{\nu_z^3} \ll 1$	$\kappa = \frac{\nu_0^2 \lambda_p}{\nu_z^3} \ll 1$ is violated and $\frac{\nu_0 \sigma_\delta}{\nu_z} \gg 1$
Theory	Non-resonant spin diffusion & perturbative treatment of $\frac{\partial \hat{n}}{\partial \delta}$	Resonant spin diffusion
Depolarization effect	Higher-order synchrotron sideband spin resonances	No dependence on ν_z, weaker depolarization

- Monte-Carlo simulations were compared with these theories[2], showing a gradual evolution from the correlated regime to the uncorrelated regime in parameter scan, suggesting existing theories are incomplete, requiring further development

Case A: dependence on beam energy

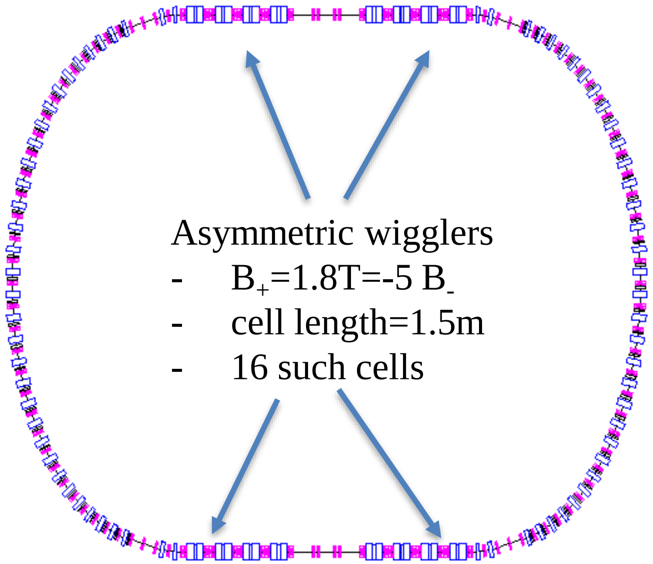


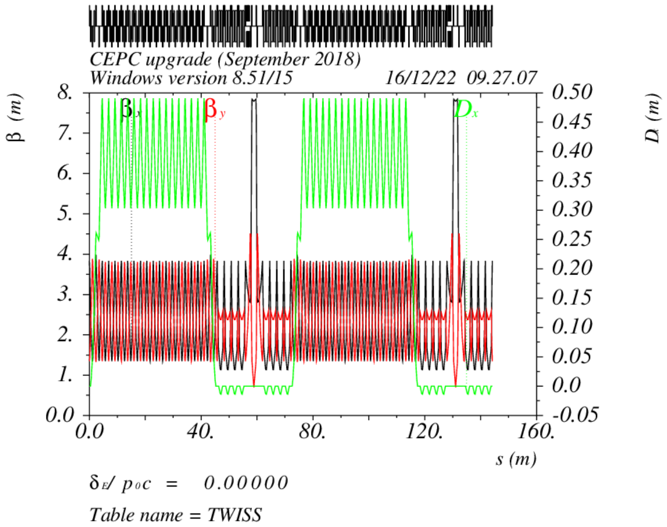
Case B: influence of harmonic RF cavity



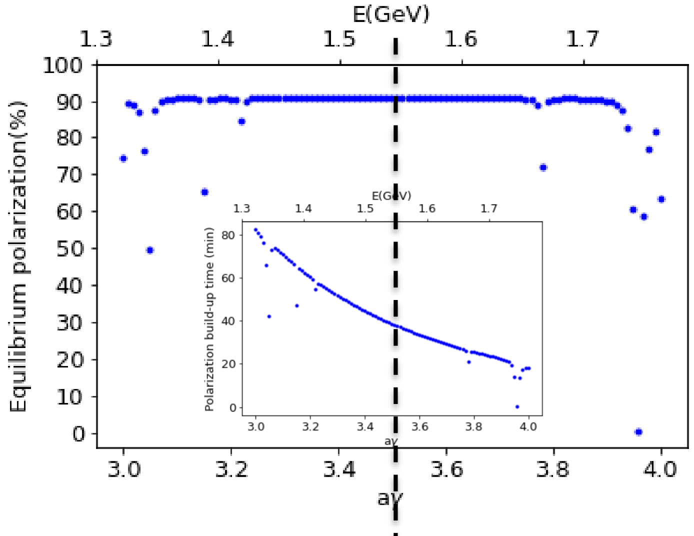
[1] Derbenev, Kondrantenko and Skrinsky, Part. Accel. 9, 247 (1979) [2] W. H. Xia, Z. Duan, D. P. Barber, Y. W. Wang, B. Wang, J. Gao, arXiv:2204.12718v1 [physics.acc-ph], submitted to PRAB

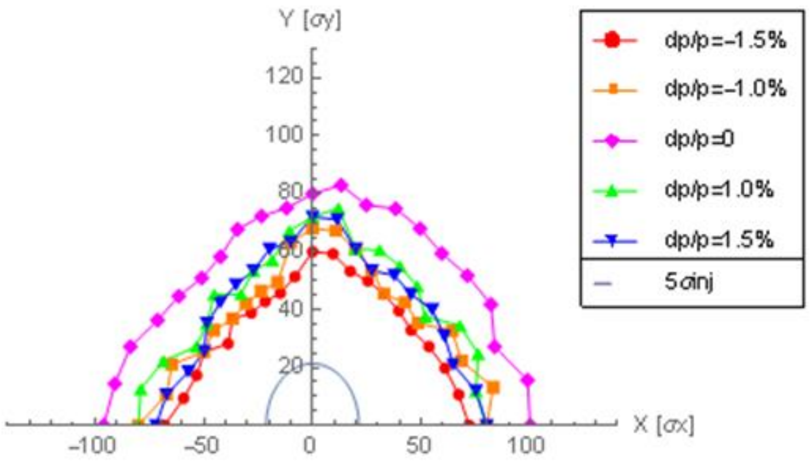
e+ damping/polarizing ring



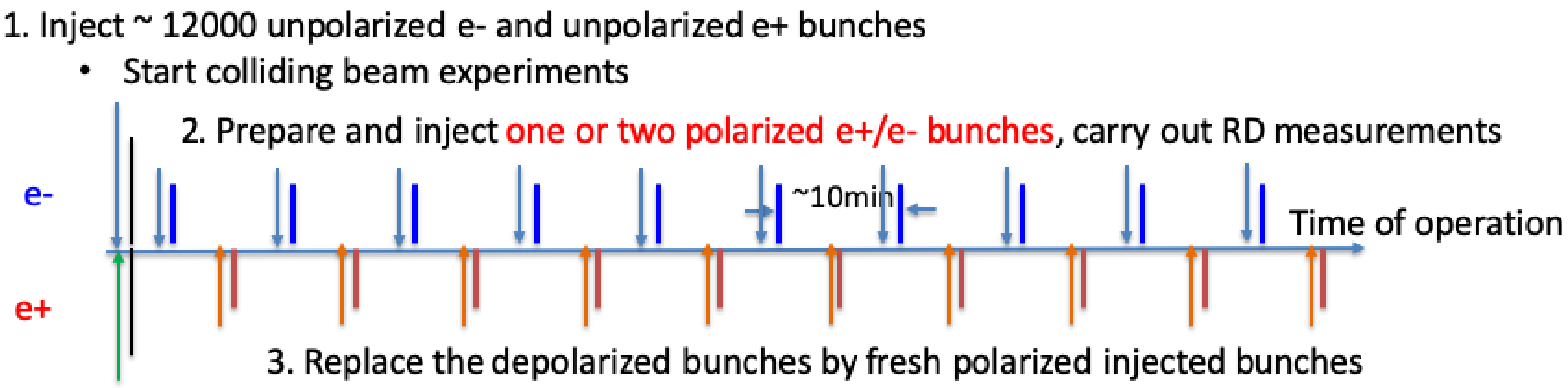


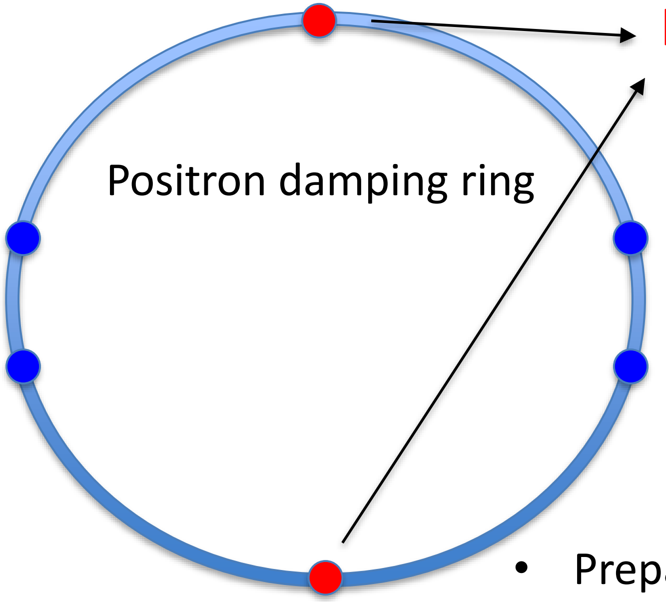
DR V4.0	unpolarized e+	polarized e+
Energy (Gev)	1.542	
Circumference (m)	144.2	
Number of trains	2(4) **+1(2)**	
Number of bunches/trian	1(2)	
Total current (mA)	12.4	
Bending radius (m)	3.44	
Dipole strength B_0 (T)	1.07	
Wiggler strength B_+ (T)	1.8	
Wiggler cell length (m)	1.5	
U_0 (kev/turn)	190.9	
Damping time x/y/z (ms)	7.77/7.77/3.89	
Momentum compaction	0.015	
Storage time	20 ms	10 min
δ_0 (%)	0.072	
ε_0 (mm.mrad)	138	
injection σ_z (mm)	6	
Extract σ_z (mm)	5.7	5.6
ε_{inj} (mm.mrad)	2500	
$\varepsilon_{ext\ x/y}$ (mm.mrad)	151/15	138/14
$\delta_{inj}/\delta_{ext}$ (%)	0.18 /0.072	
RF acceptance (%)	1.8	
f_{RF} (MHz)	650	
V_{RF} (MV)	3.95	
Longitudinal tune	0.044	





RD scenario & e+ damping/polarizing ring





bunches stay ~10 min to accumulate ~ 20% polarization, for RD

bunches stay ~ 20 msec without gaining beam polarization, for regular refill

- Preparation and injection of polarized e+/e- bunches alternates with unpolarized bunches.

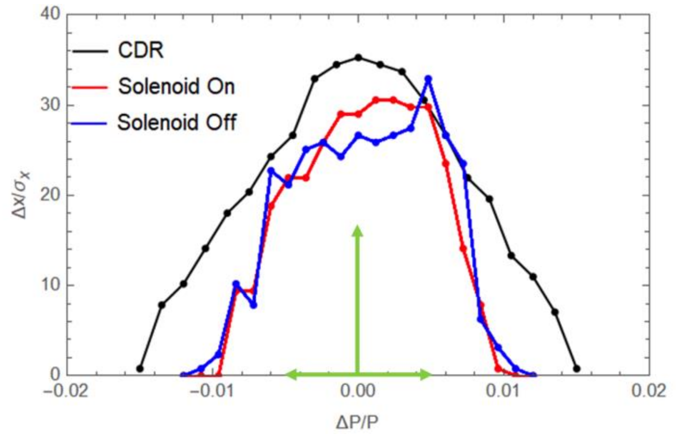
What we can gain from injecting polarized beams for RD?

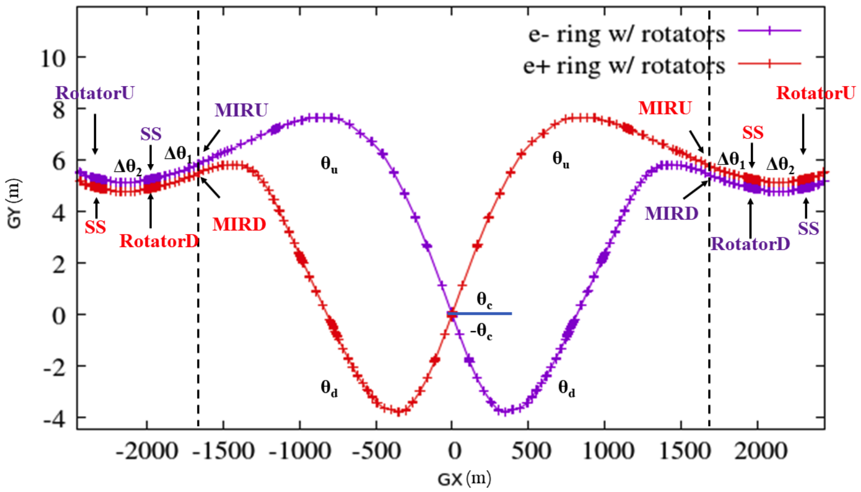
Scenarios of polarized beam generation		Self-polarization in the collider[1]	Injection of polarized beams[2]
Hardware	Polarized electron gun	None	Yes
	Asymmetric wigglers	In the collider	In the positron damping ring
Polarization level		5% ~ 10%	> 70% for e-, > 20% e+
Dead time for physics		Initial 1~2 hours in each fill	None
Frequency of RD measurements		Every ~10 min per beam	More frequent for e- beam
RD on colliding beams		None	Possible, especially at lower bunch charge
Horizontal polarization for free spin precession method		Strong spin flipper in the collider	Spin rotator in the transfer line; much higher polarization

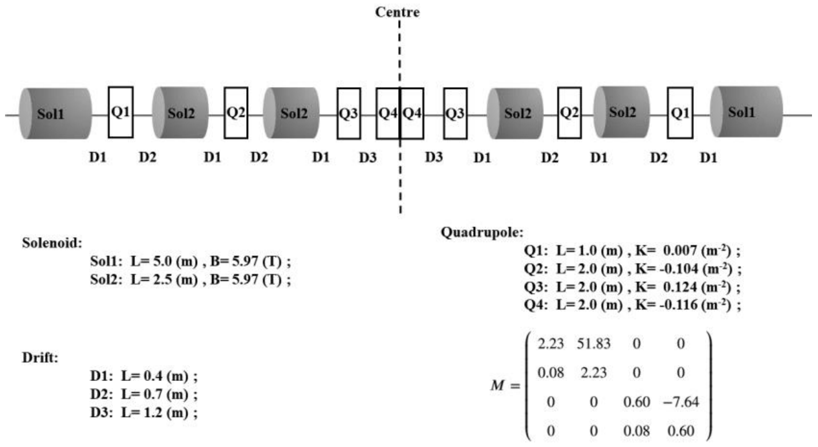
[1] The FCC-ee Energy and Polarization Working Group, arXiv:1909.12245v1, 2019.
[2] Zhe Duan, talk on 2nd EPOL Workshop, Sep 29, 2022

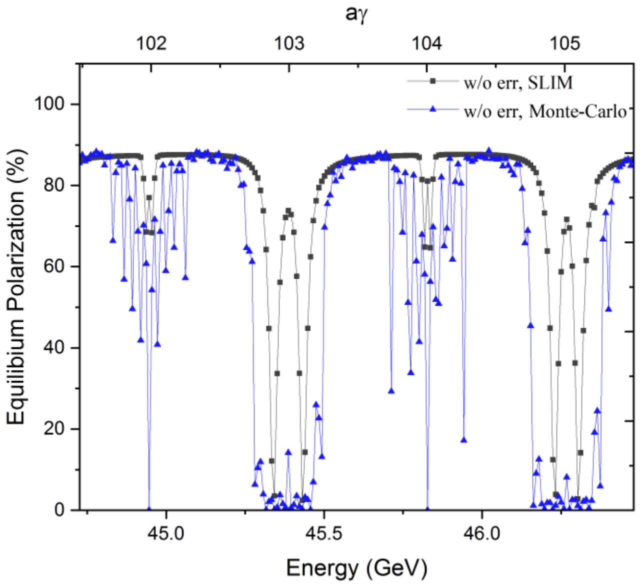
Spin rotators in the collider ring @ Z-pole

- Solenoid-based spin rotators
  - interleaved solenoid + quads [1] to cancel coupling effects
- Anti-symmetric insertion just outside interaction region [2,3,4]
- Influence[4]
  - Increase of circumference ~ 2.8 km, can be optimized
  - DA shrinks but still sufficient, can be further optimized
  - Depolarization is relatively weak near 45.6 GeV, confirmed by simulations
    - Cancellation of energy dependence with the anti-symmetric design









[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] S. Nikitin, IJMPA 34, 1940004 (2019), IJMPA 45, 2041001 (2020).
[4] . W. Xia, Z. Duan, J. Gao and Y. W. Wang, RDTM (2022) doi: 10.1007/s41605-022-00344-2

Summary

- For polarized beam applications at CEPC, we've studied the possibility of generating polarized beams from the source and injecting into the collider rings. Some key issues have been addressed
  - Beam polarization can be mostly preserved in the booster up to 45.6 GeV and 80 GeV.
  - Polarized e+ beam can be generated in the e+ damping/polarizing ring, for RD measurements.
  - Spin rotators have been implemented into the collider rings @Z-pole, with promising performance.
- Mechanisms of radiative depolarization effect still require further investigation.

Thank you for your attention!