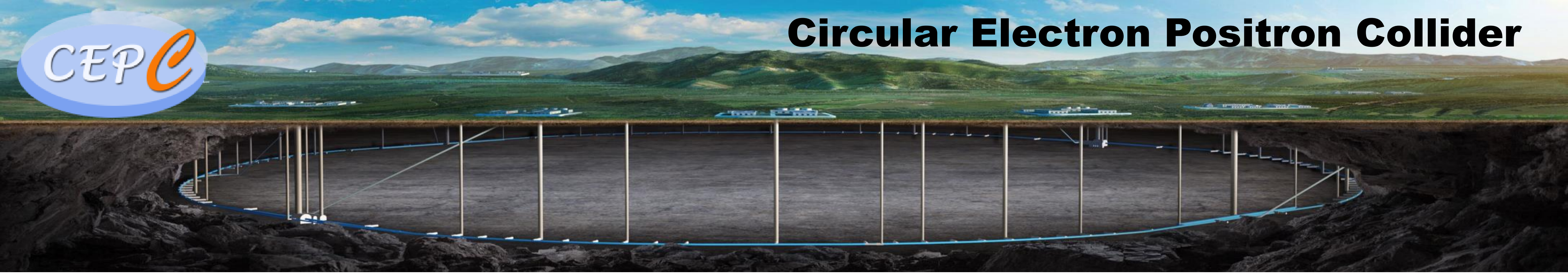

Beam polarization studies for CEPC

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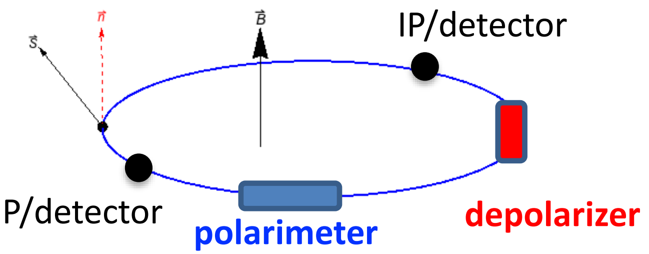
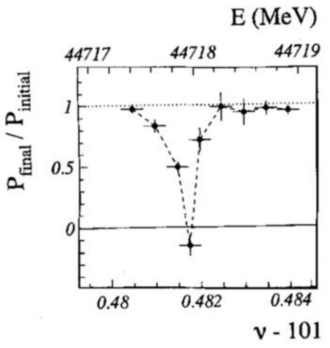
Motivation of CEPC polarized beam program

Vertical polarization for resonant depolarization

- Essential for precision measurements of Z and W properties
- > 5% ~ 10% polarization, for both e+ / e- beams



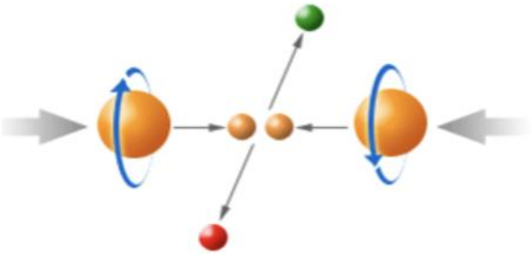


(a) $\Delta\nu_{scan}/\Delta t = 1.67 \cdot 10^{-4} s^{-1}$.

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

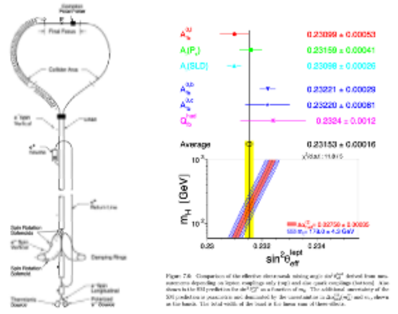
Longitudinal polarization for colliding beams

- Figure of merit: Luminosity * f(P_{e+}, P_{e-})
- 50% or more polarization is desired, for at least one beam; polarizing both beams is beneficial



Actively pursued in ILC, CLIC, EIC, STCF, SuperKEKB etc.

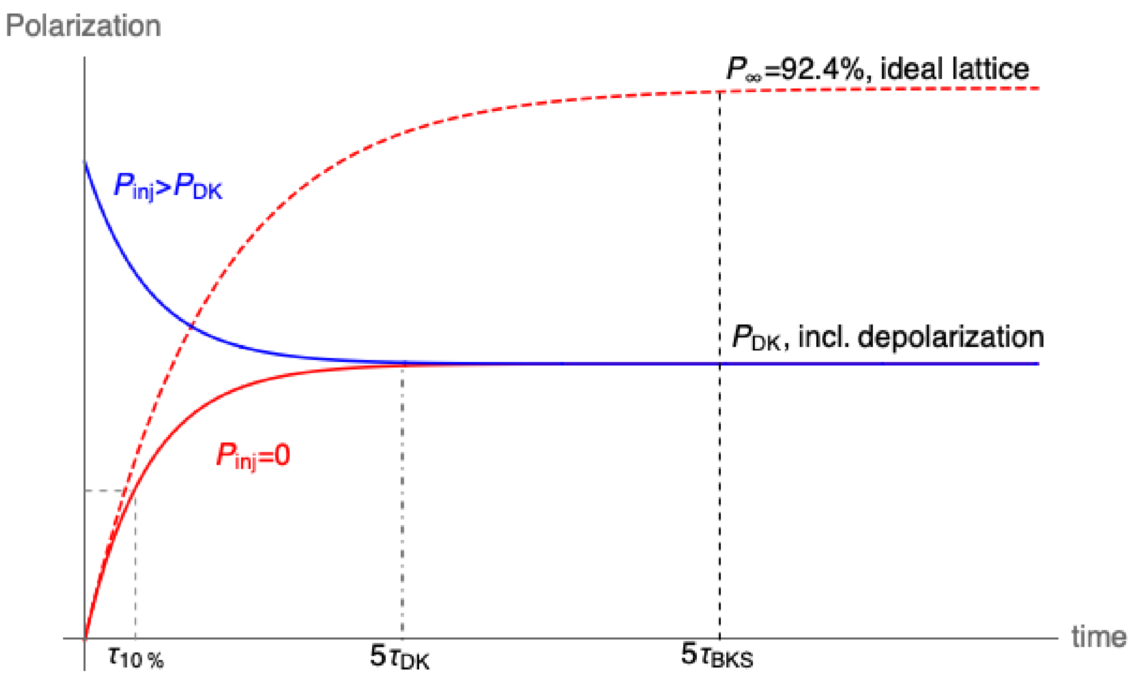
Most notably the measurement of the weak mixing angle @ SLC



	LEP	SLC
No. Z decays events	17 million	0.6 million
Longitudinal polarization	None	e- ~ 80%

- Supported by National Key R&D Program 2018-2023 to design longitudinally polarized colliding beams at Z-pole.
- **Summarized as a chapter in the Appendix of CEPC TDR.**

Self-polarization in the CEPC



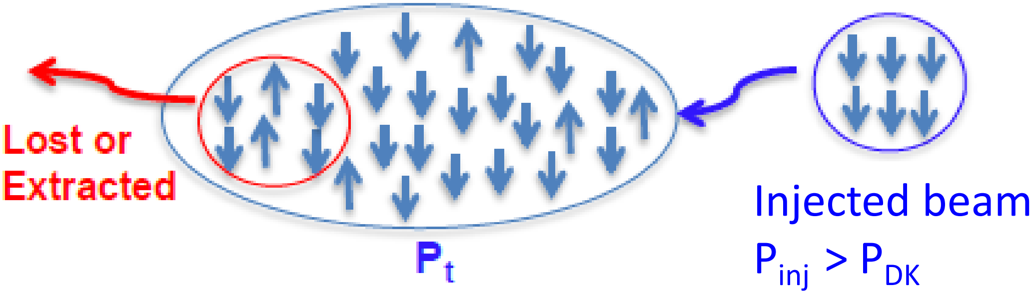
- e+/e- beams become "self-polarized" via the Sokolov-Ternov effect in a storage ring
  - $\tau_{BKS} \propto E^{-5}\rho^2 R$
- Beam polarization build-up rate much slower than the beam decay rate @ Z
  - Boosted with asymmetric wigglers in the Collider (FCC EPOL)
  - Hard to achieve a high-level polarization
  - In conflict with a high luminosity

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

How to achieve a high-level polarization?

- A high-level polarization (time-averaged) P_{avg} in the Collider is attainable if
  - Top-up injection of highly polarized beam
  - Depolarization rate (τ_{DK}^{-1}) << beam loss rate (τ_b^{-1})

$$P_{\text{avg}} = \frac{P_{\text{inj}}}{1 + \frac{\tau_b}{\tau_{BKS}} \frac{P_\infty}{P_{\text{DK}}}} + \frac{P_{\text{DK}}}{1 + 1/\frac{\tau_b}{\tau_{BKS}} \frac{P_\infty}{P_{\text{DK}}}}$$



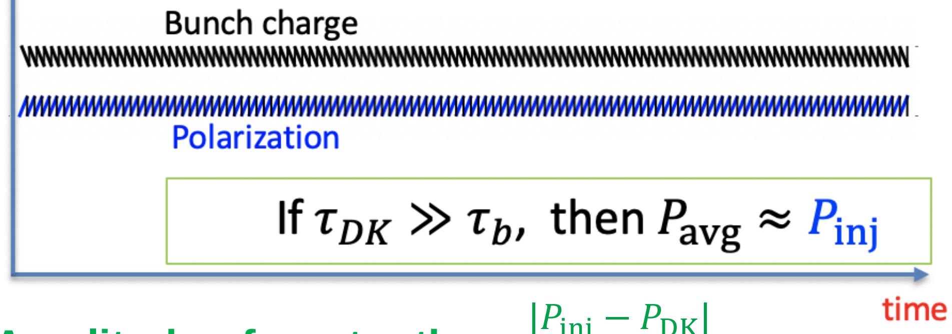
P_{DK} depends on machine imperfections, spin rotators

Assume $P_\infty = 90\%$

P_{avg} > 50% requires a minimum value of P_{DK}

	45.6 GeV (Z)	80 GeV (W)	120 GeV (Higgs)
P_{inj} = 50%	P_{DK}>50%	P_{DK}>50%	P_{DK}>50%
P_{inj} = 60%	P_{DK}>4%	P_{DK}>23%	P_{DK}>33%
P_{inj} = 70%	P_{DK}>2%	P_{DK}>15%	P_{DK}>25%
P_{inj} = 80%	P_{DK}>1%	P_{DK}>11%	P_{DK}>20%

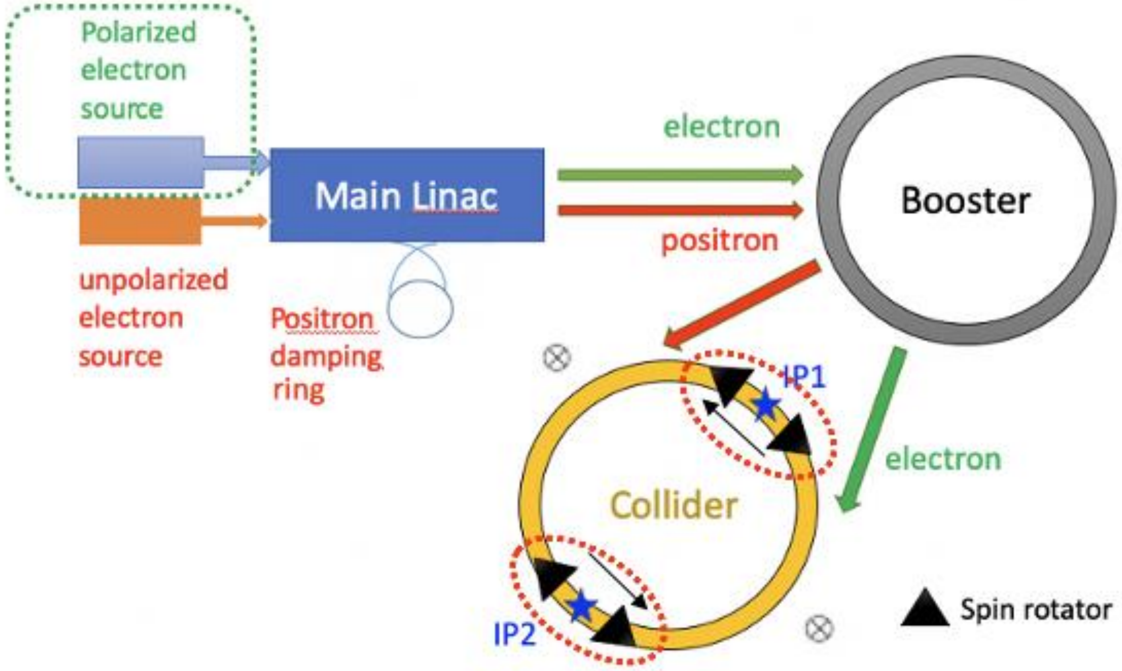
Sawtooth-shape evolution during top-up injection

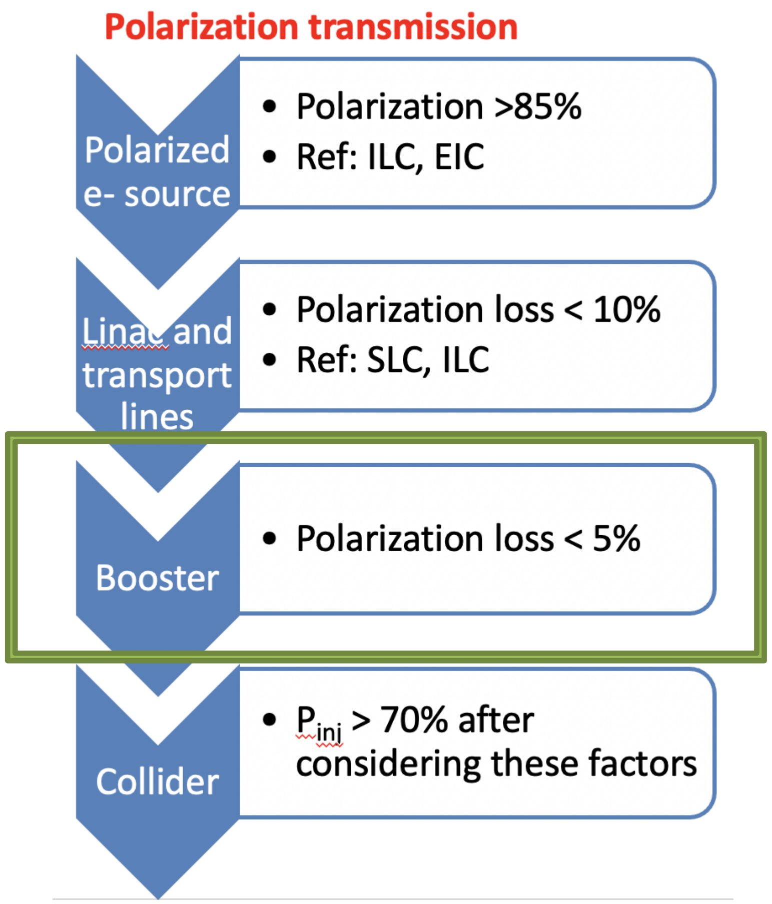


Amplitude of sawtooth ~ $\frac{|P_{\text{inj}} - P_{\text{DK}}|}{(\tau_b + \tau_{\text{DK}})/dt}$

A high-level longitudinal polarization @ Z-pole

- 50%-70% longitudinal polarization **for e- bunches** is a reasonable goal
  - **Over 70% injected e- beam polarization is possible.**
  - Polarized e+ source is challenging for CEPC [1],
    - self-polarization at a low energy e+ ring is possible, a tradeoff between the challenges & costs of the ring versus reduction injection rate & luminosity (need more study);
    - polarization transmission efficiency is similar otherwise.

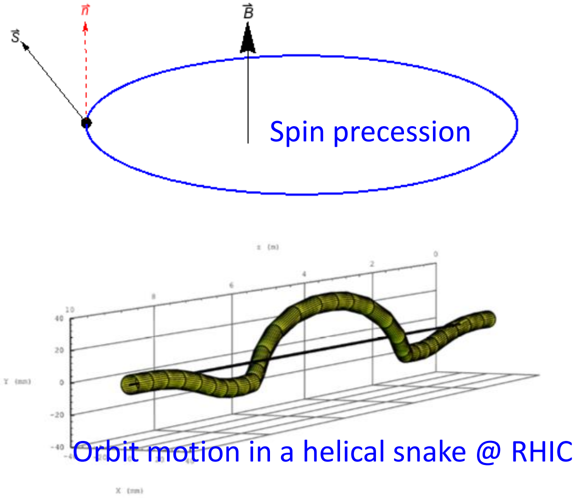


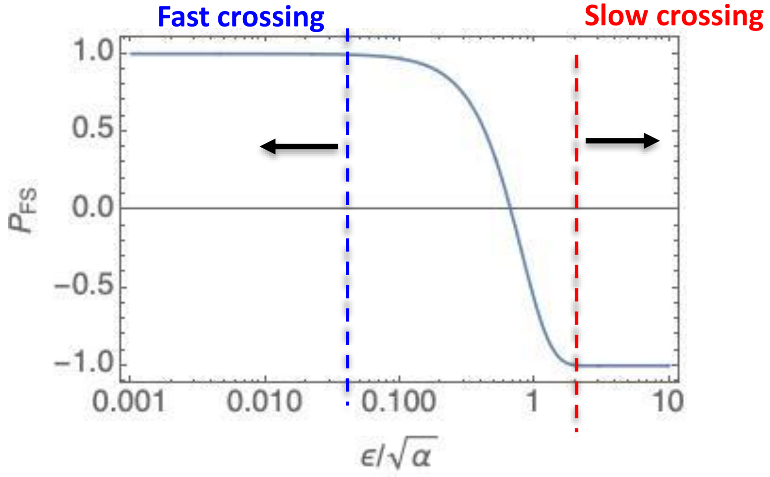


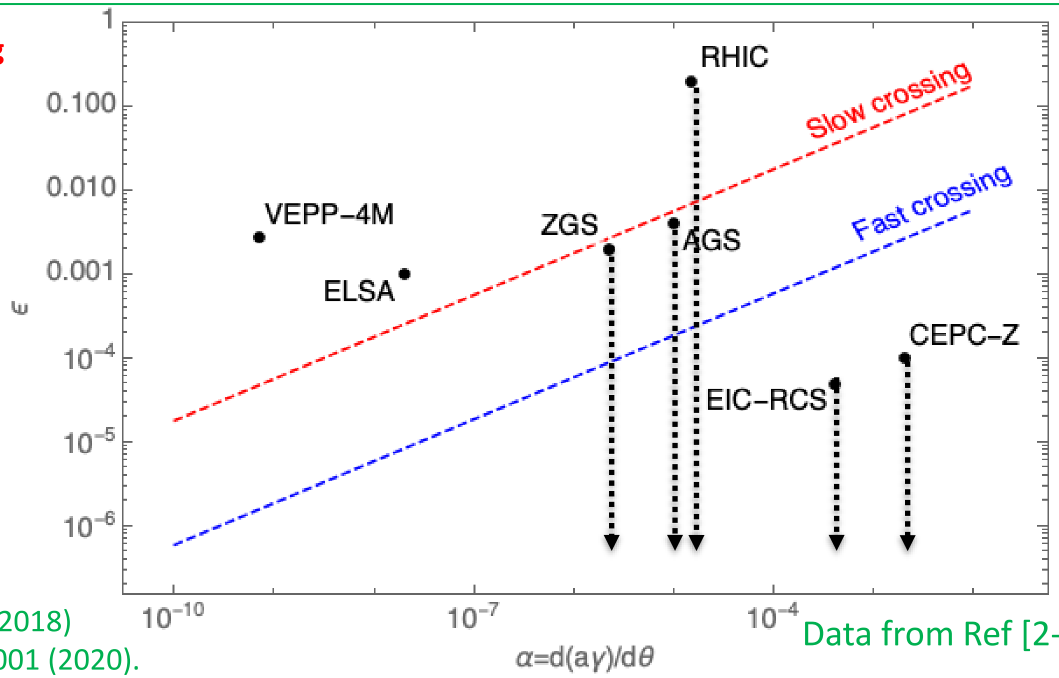
[1] P. Musumeci et al., Positron Sources for Future High Energy Physics Colliders, ArXiv:2204.13245 Phys. (2022).

Depolarization in the booster

- The spin tune $\nu_s \approx \nu_0 \approx a\gamma$ changes and could cross spin resonances $\nu_s = k + k_x\nu_x + k_y\nu_y + k_z\nu_z$
  - The spin resonances $\nu_0 = k$ 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 $\alpha \sim 10^{-6}\frac{dE}{dt}[\mathrm{GeV/s}]C[\mathrm{km}]$
  - $\Delta|P| < 1\%$ in the regimes of fast crossing & slow crossing
- Previous studies suggested using Siberian snakes to maintain polarization for future 100km-scale boosters[7]







Data from Ref [2-6]

[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)
[7] I. Koop et al., Phys. Part. Nucl. Lett. 13. 7 (2016); S. Nikitin, IJMPA 34, 1940004(2019); IJMPA 35, 2041001 (2020).

Spin resonance structure of a CEPC Booster lattice

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

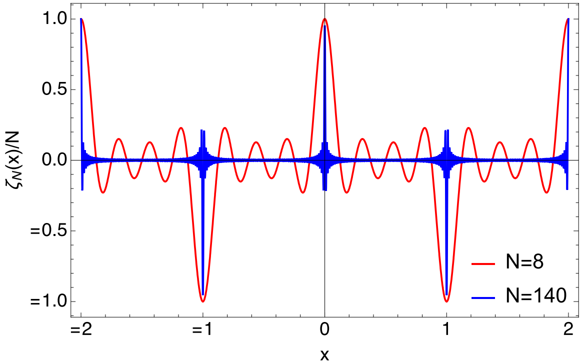
$$|\epsilon| \approx |\epsilon_{FODO}|\, E_P\, E_M$$

due to P superperiods

due to M identical FODOs in each arc

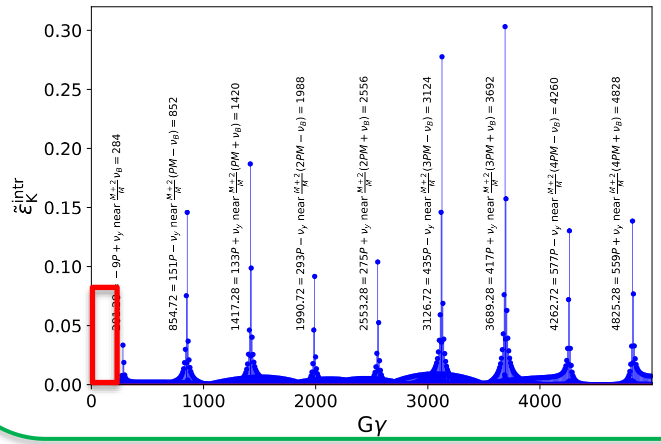
- Enhancement occurs near $\frac{mPM \pm \nu_B}{\eta_{arc}}$, ν_B is the total ν_y in all standard arc cells [2]

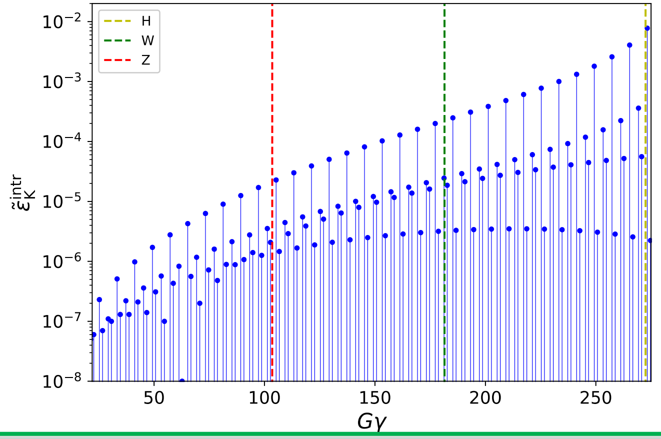
- Resonances at K<< ν_B tend to be weak due to cancellation [2]



Intrinsic resonances: $\upsilon_0 = K = k \pm \upsilon_y$

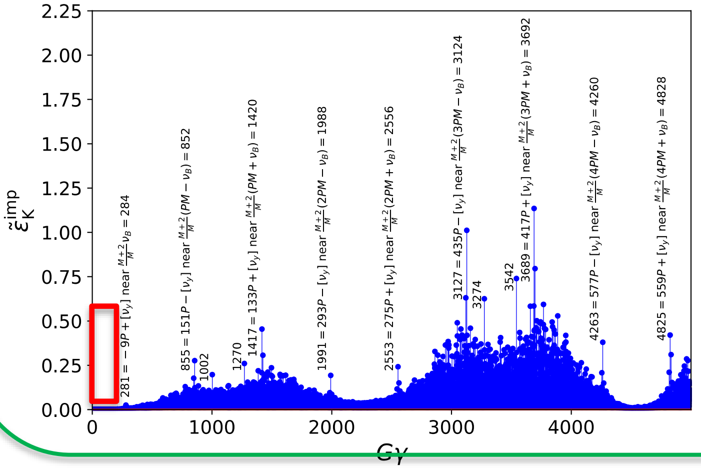
Super strong resonances: $K = nP \pm \nu_y, n \in \mathbb{Z}$ closest to $(mPM \pm \nu_B)/\eta_{\rm arc}, m \in \mathbb{Z}$

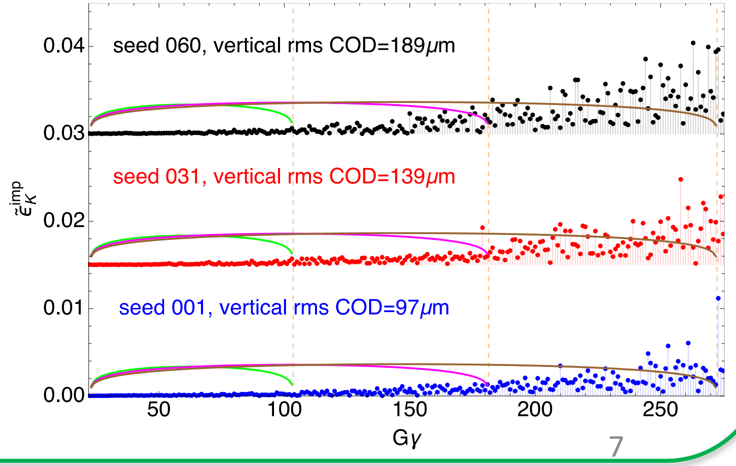




Imperfection resonances: $\upsilon_0 = K$

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





[1] S. Y. Lee, Spin dynamics and snakes in synchrotrons (World Scientific, 1997).
[2] T. Chen, Z. Duan, D. H. Ji, D. Wang, Phys. Rev. Accel. Beams, 26, 051003 (2023).

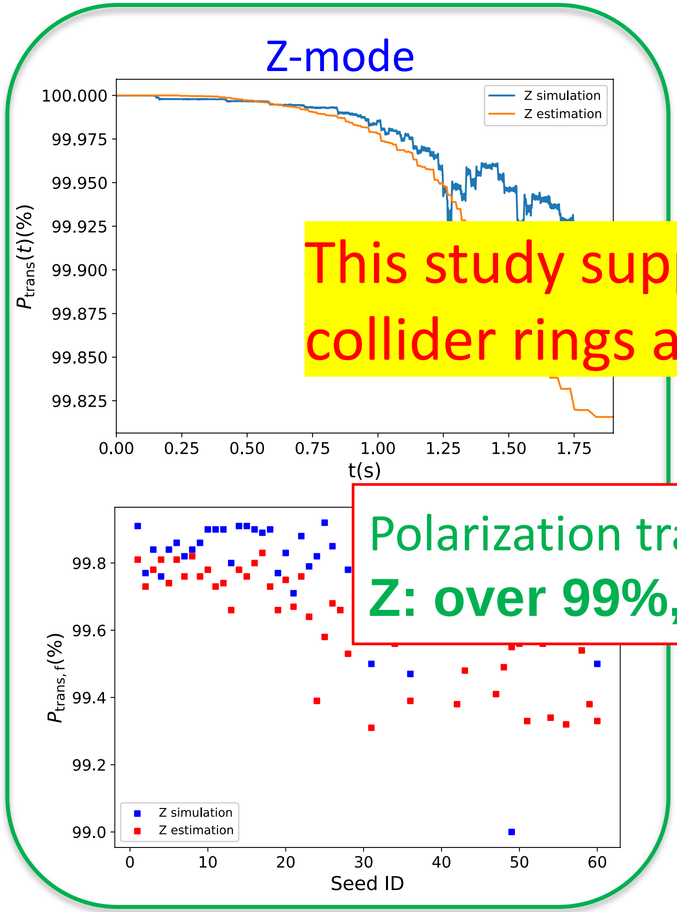
Depolarization effects: simulation vs. estimation

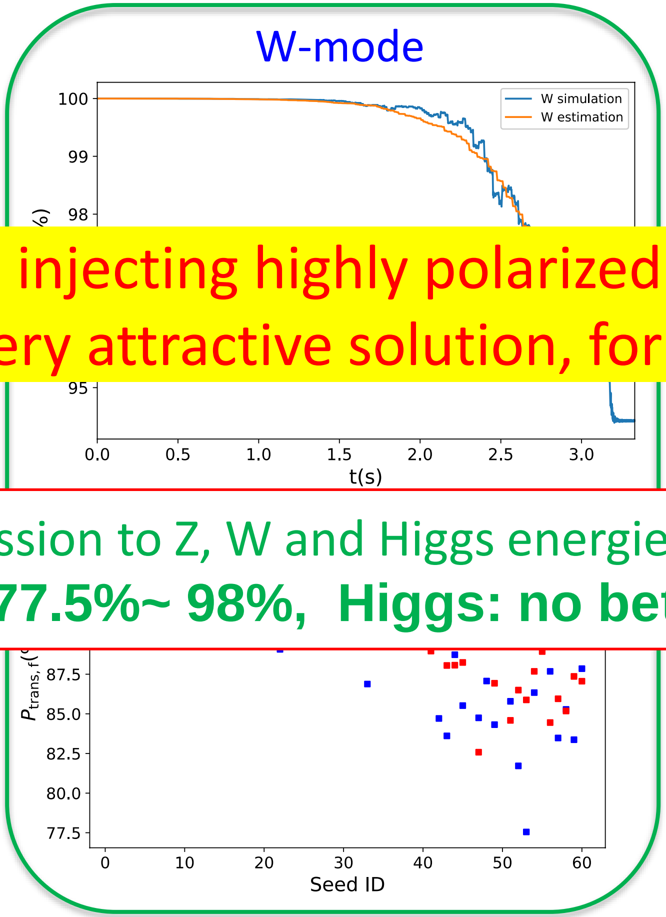
In the acceleration to Z & W

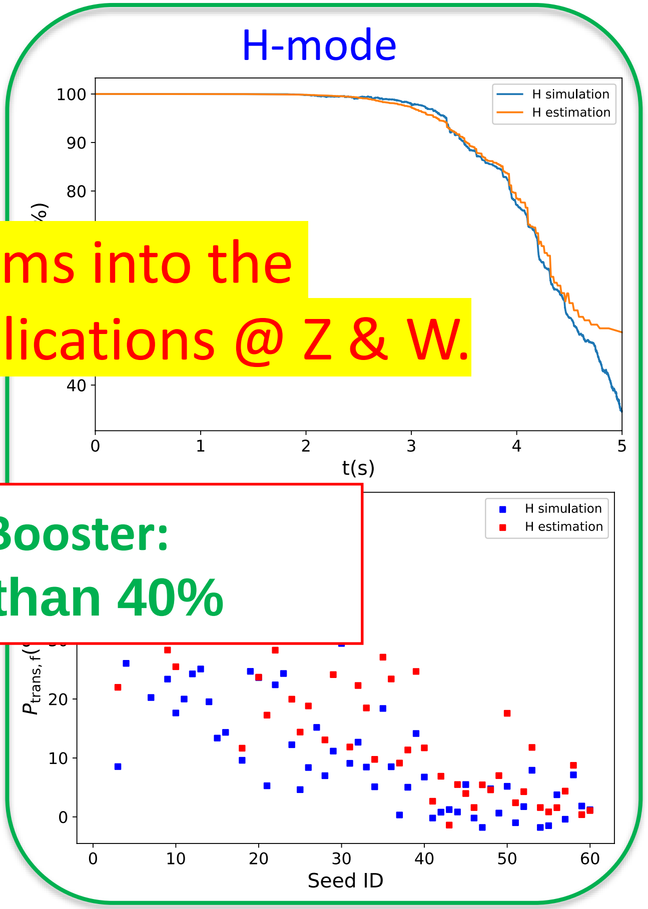
- The spin resonances are generally weak
- Polarization is mostly maintained
- Estimations agree fairly well with simulations

In the acceleration to H

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







This study supports injecting highly polarized beams into the collider rings as a very attractive solution, for applications @ Z & W.

Polarization transmission to Z, W and Higgs energies in **Booster:**

Z: over 99%, W: 77.5%~ 98%, Higgs: no better than 40%

[1] T. Chen, Z. Duan, D. H. Ji, D. Wang, Phys. Rev. Accel. Beams, 26, 051003 (2023).

A high-level longitudinal polarization @ Z-pole

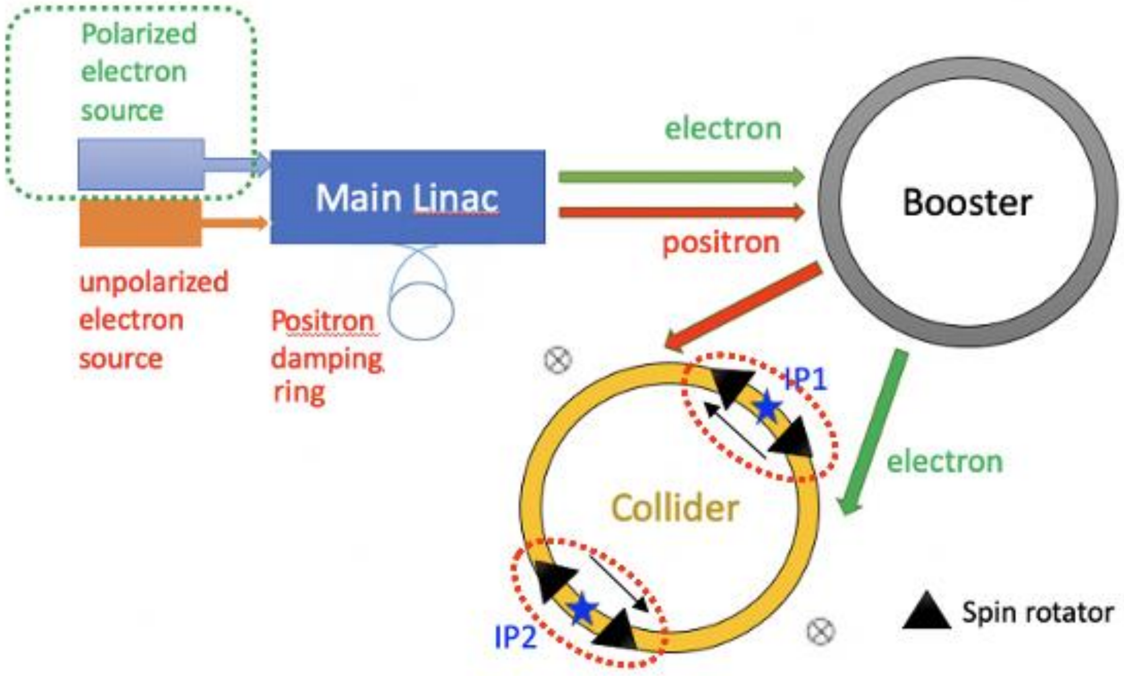
- 50%-70% longitudinal polarization for **e- bunches** is a reasonable goal

• Over 70% injected e- beam polarization is possible.

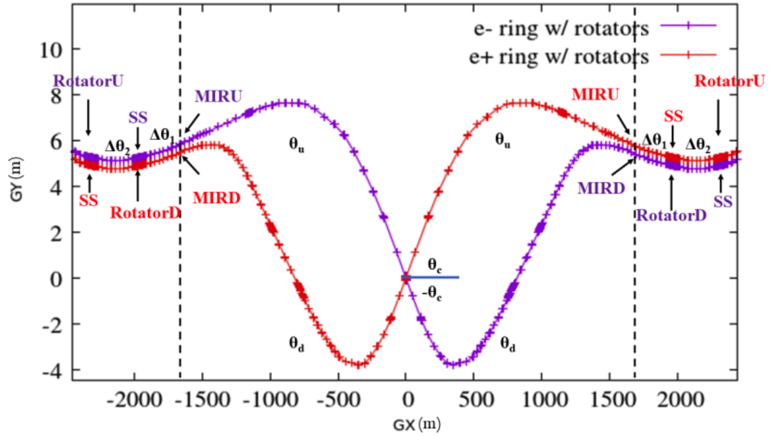
• **Simulated equilibrium longitudinal polarization > 70%,**

>> the minimum $P_{\rm DK}$ =2% to attain $P_{\rm avg}$ > 50%

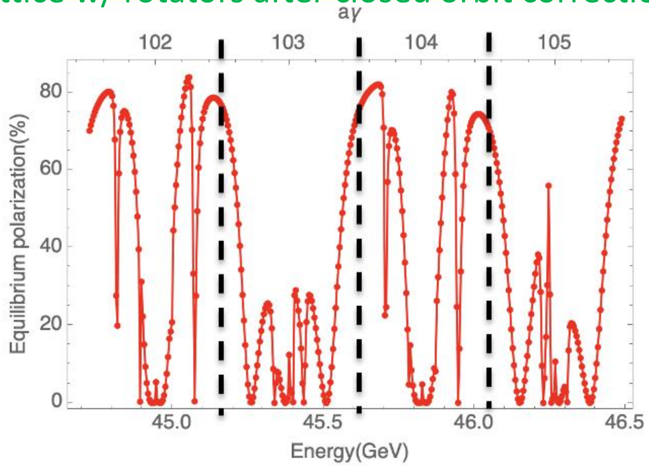
leaving a large margin for effects not yet covered.



Implementation of the spin rotators adjacent to the IR



Simulated equilibrium polarization for an imperfect lattice w/ rotators after closed orbit correction

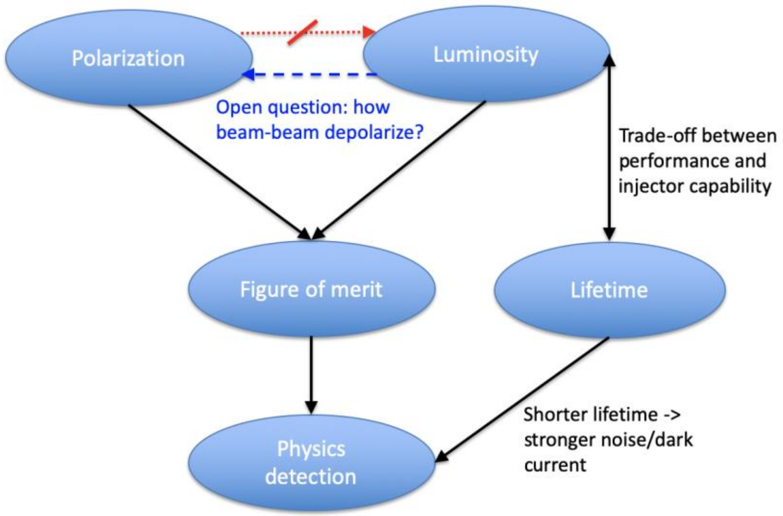


Polarization, luminosity and beam lifetime

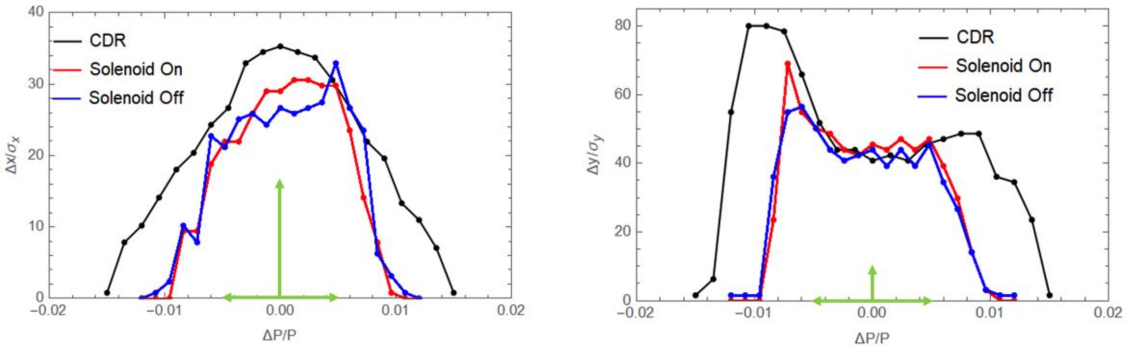
- It is possible to attain 50%-70% e- longitudinal polarization at the **nominal luminosity** and simultaneously with a decent lifetime @ Z-pole

Two pairs of spin rotators

- **240 T·m solenoid each**
- Occupy a space of 2.8 km, can be optimized
- **No interference with the complicated IR design**
- Influence to DA & beam lifetime can be recovered by dedicated sextupole optimization.



Comparison of the dynamic aperture



Contributors to the beam lifetime

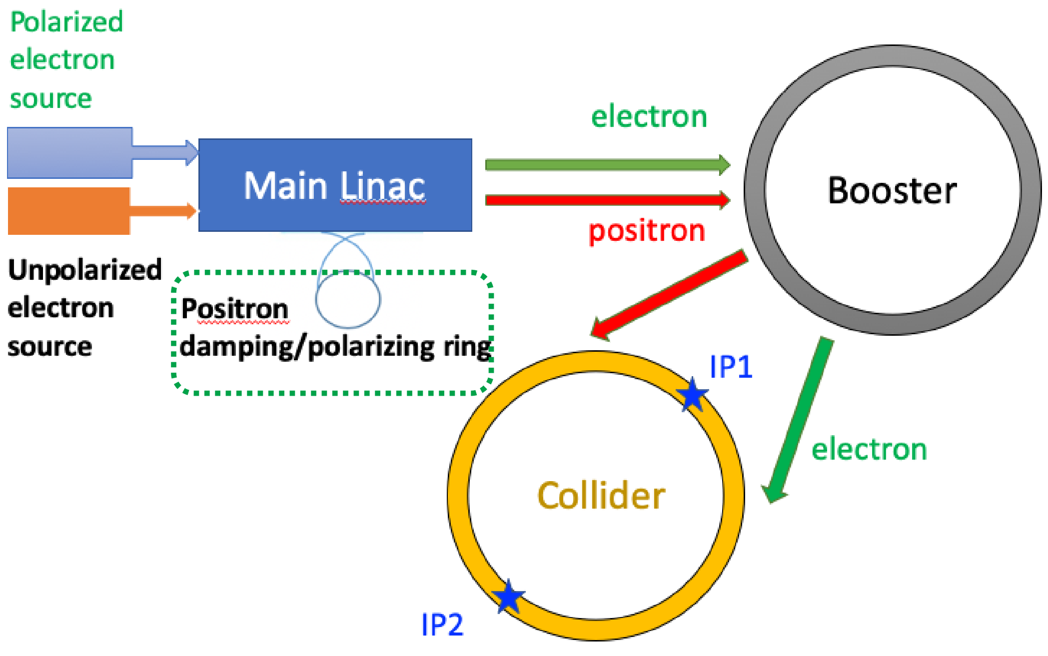
Beam lifetime contribution	CDR lattice w/ spin rotators	Comments
Radiative Bhabha	2.9 hour	ref: CEPC TDR
Vacuum lifetime	3 hour	ref: CEPC TDR
Touschek lifetime	4.63 hour	
Lifetime limited by dynamic aperture	**> 9.53 hour**	**no loss in 100 k turns in the tracking simulations**
Total beam lifetime	**> 1 hour**	

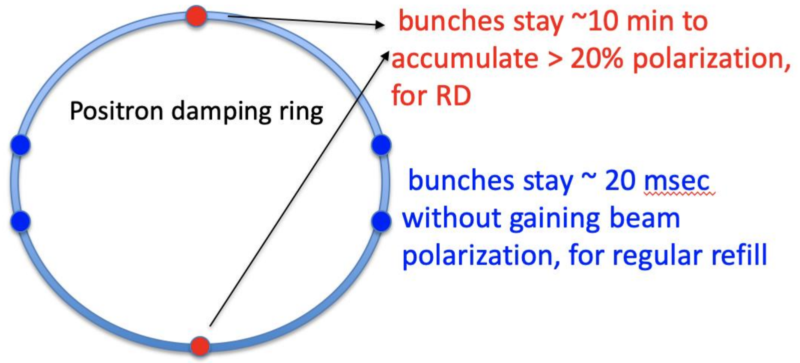
W. Xia et al., Investigation of spin rotators in CEPC at the Z-pole, Radiat. Det. Tech. Meth. 6:490 (2022).

Resonant Depolarization at Z

- It's possible to inject > 20% polarized beams to enable RD measurements at Z-pole
  - **No dead time for physics, a few pilot bunches**
  - Polarized e+ source ?   Dual-purpose damping/polarizing ring (could accommodate both e+/e- beams to gain sufficient polarization)

Approaches		Self-polarization in the collider	Injection of polarized beams
Hardware	Polarized electron gun	None	Yes
	Asymmetric wigglers	In the colliders	In the e+ damping ring or None
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 at lower bunch charge





One typical design:
beam energy ~ 2 GeV, circumference ~ 150 m
polarization build-up time ~ 14.5 min
Extracted beam polarization @ 10min ~ 44%

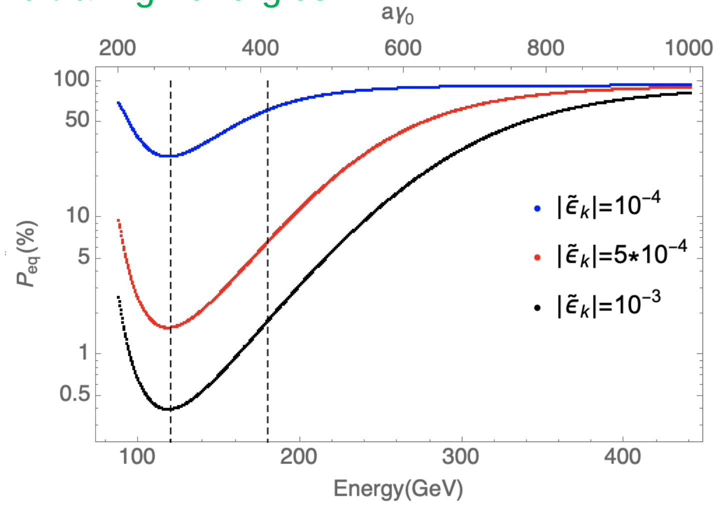
Prospects of Z-pole polarization for CEPC

- Injecting polarized beam(s) to the Collider
- 50%-70% longitudinal polarization for e- versus unpolarized (or lower polarization) e+
  - Polarized e+ source needs more study;
- Spin helicity adjustment
  - e- : changing laser helicity at polarized e- source
  - e+ : a solenoid spin rotator (21 T·m for 2 GeV) in the transport line following the polarizing ring, or a programmed spin flip in the polarizing ring prior to extraction
- RD measurements w/ a few pilot non-colliding bunches, no physics deadtime
- Accurate 3D polarimetry is needed
  - Inside the IR -> deduce longitudinal polarization @ IP
  - Outside the IR -> RD measurements

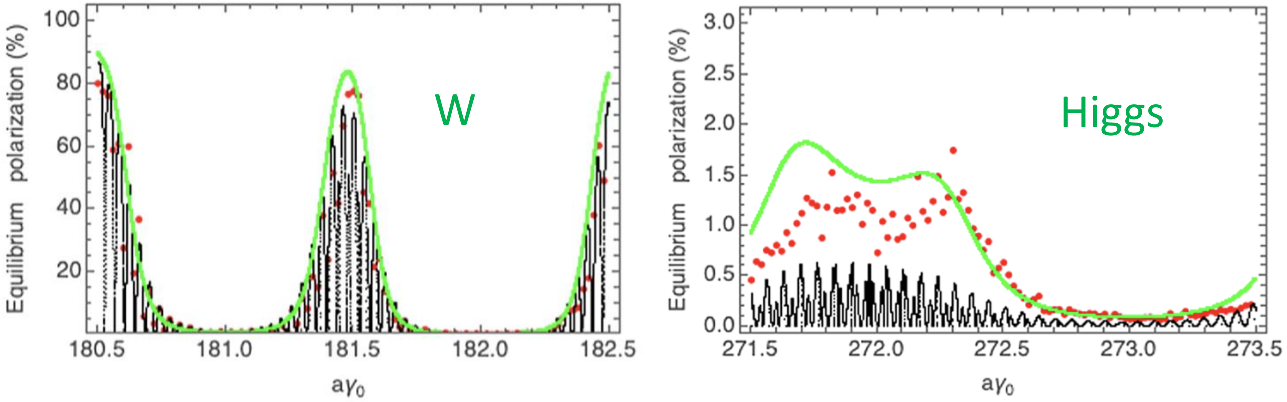
Longitudinal polarization at W & Higgs?

- A good chance for >50% e- longitudinal polarization at W
  - Assume injected polarization > 60%, then P_{DK} needs to be above 23%
- More challenging at Higgs (Under study)
  - Simulated injected polarization < 30% -> improvements in Booster lattice design & mitigation to machine imperfections
  - Simulated equilibrium polarization ~ 1% -> mitigate depolarization by harmonic spin matching, cancellation of Sokolov-Ternov effect
- Strength of solenoid spin rotators scales linearly with energy

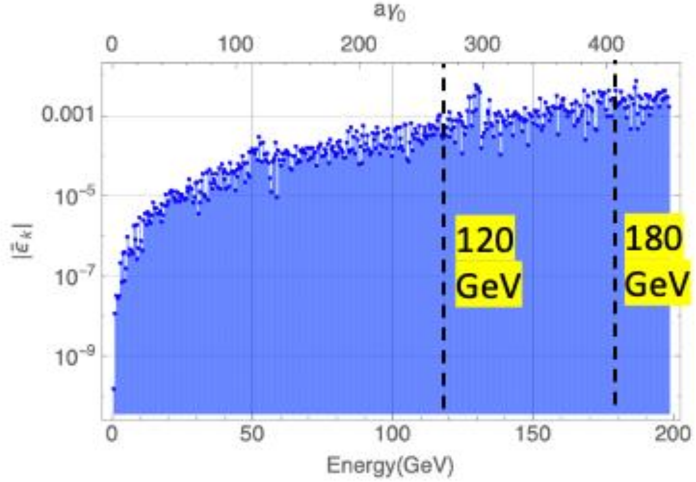
Prediction of resonant spin diffusion theory at ultra-high energies



Simulated equilibrium polarization of Collider at W & Higgs



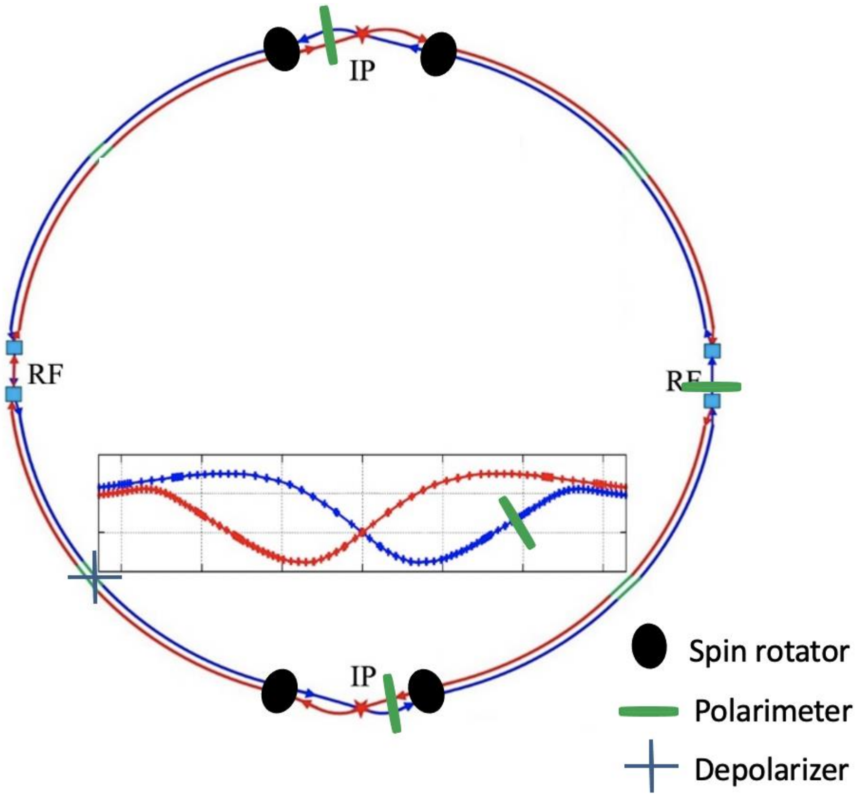
The key is to reduce the spin resonance strength by a factor of 10



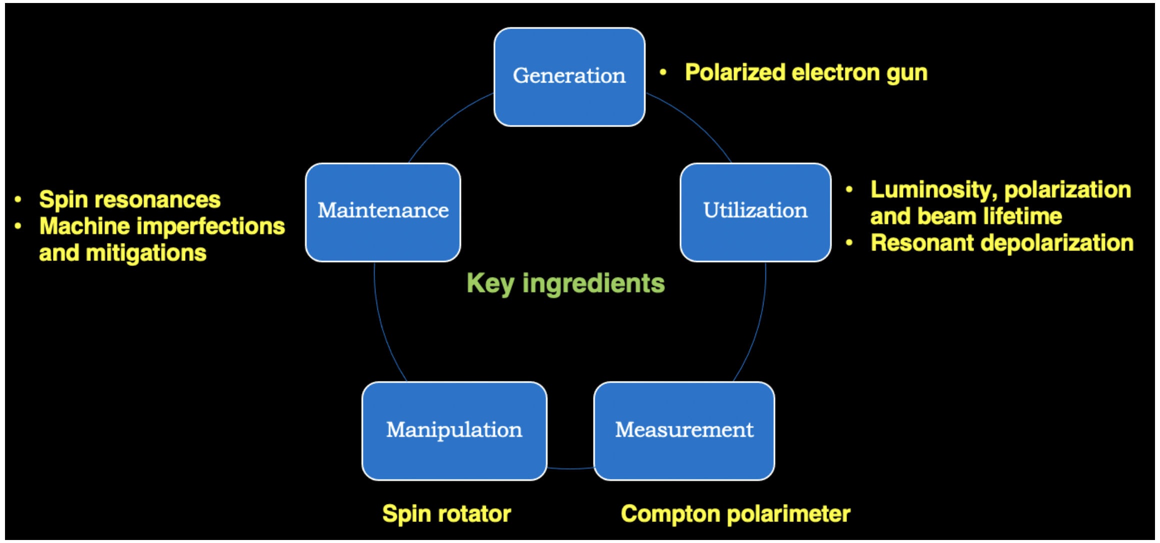
W. H. Xia, et al, Evaluation of radiative depolarization in the future circular electron-positron collider, Phys. Rev. Accel. Beams, 26, 091001, (2023).

Polarization R&D plan in the CEPC EDR Phase

- Implement the spin components in the post-TDR lattice designs
- Study the polarization utilities at Higgs and W energies
- Polarization-related key hardware R&D



Modify the PAPS photocathode DC gun to a Polarized Electron Source



RD @ BEPCII

R&D of high-field SC solenoids

A vertical polarimeter for BEPCII

Summary

- Injecting polarized beams is promising for longitudinal polarization and RD measurements.
- 50%-70% longitudinally polarized e- versus unpolarized e+ at Z with nominal luminosity is a reasonable goal.
- Further studies of polarized beams towards higher energies as well as related hardware R&D are planned for the CEPC EDR phase.
- International collaborations are warmly welcome.

Thank you for your attention!

Booster lattice optimization for better polarization transmission

- The TDR lattice suffers from super-strong resonances before Z energy
  - Injected vertical emittance 6.5nm -> Polarization transmission~ 50% @ Z & W, 20% @ Higgs
  - Injected vertical emittance 1.5 nm -> Polarization transmission~ 80% @ Z & W, 30% @ Higgs
- Potential optimization:
  - Further reduce vertical emittance of injected beam
  - Increase vertical focusing
  - Mitigation of imperfection resonances
    - Reduce lattice sensitivity
    - Harmonic spin matching, how to do it in the ramping?

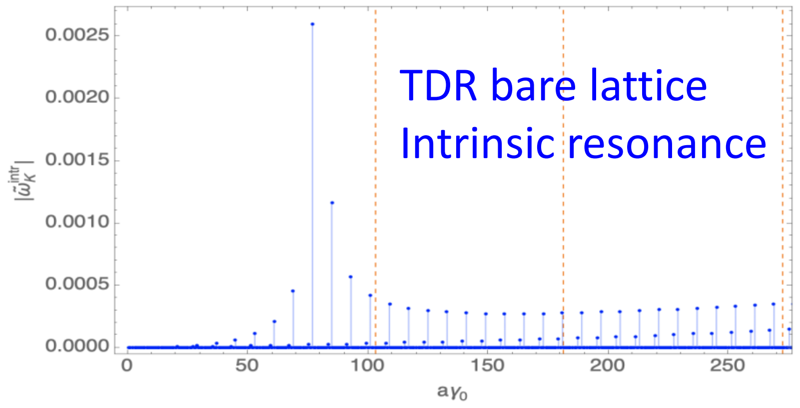


Table A8.3.1 Parameters relevant for the spin resonance structure

Parameters	TDR	CDR	Alternative
ν_y	116.83	261.2	353.28
Basic arc cell structure	TME	FODO	FODO
Vertical phase advance per arc cell	28 degree	90 degree	90 degree
P	8	8	8
M	126	97	140
η_{arc}	126/127	97/99	140/142
ν_B	78.4	194	280
PM	1008	776	1120
ν_B/η_{arc}	79.0	198	284