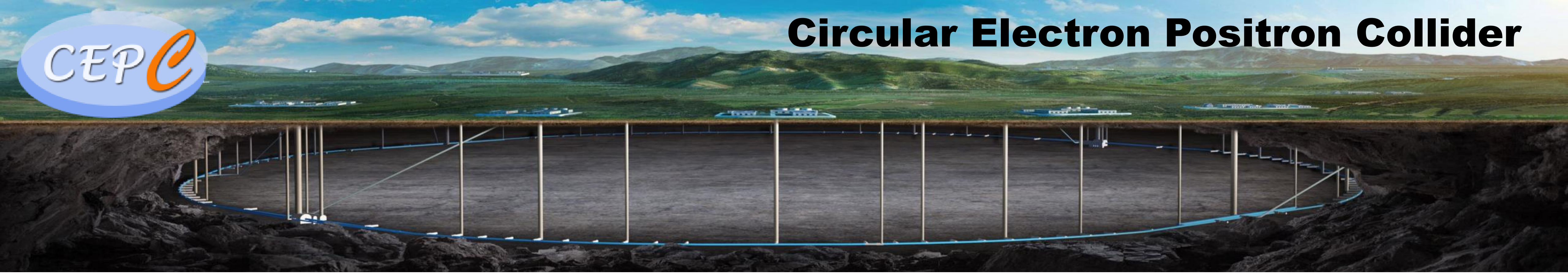


Polarized injectors for CEPC

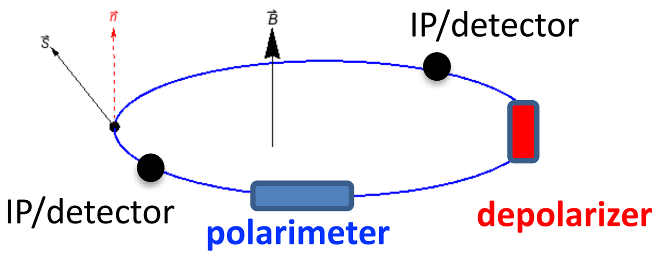
Zhe Duan
On behalf of the CEPC Polarization Working Group

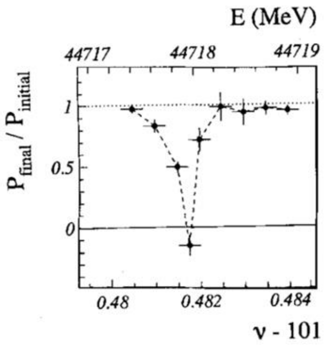
Institute of High Energy Physics, CAS

Motivation of CEPC polarized beam program

Vertical polarization for resonant depolarization

- Essential for precision measurements of Z and W masses
- > 5% ~ 10% polarization



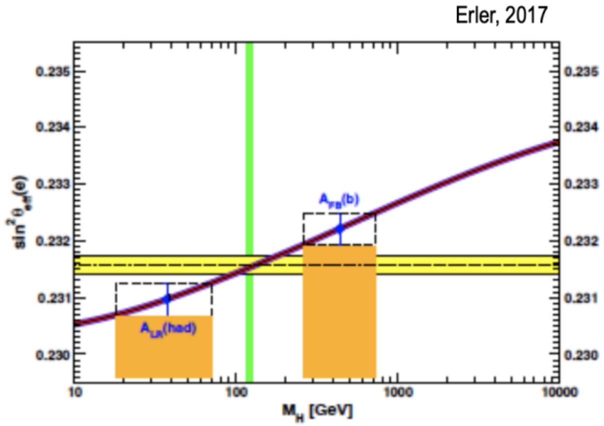


(a) $\Delta\nu_{scan}/\Delta t = 1.67 \cdot 10^{-4} s^{-1}$.

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

Longitudinal polarization for colliding beams

- Measurements of A_{FB} and A_{LR} @ Z-pole in the same experiment
- > 50% polarization with a high luminosity



LEP: unpolarized e+/e-
$\sin^2\theta_{eff}(A_{FB}^{b})$= 0.23221±0.00029

SLC: polarized e- & unpolarized e+
$\sin^2\theta_{eff}(A_{LR})$= 0.23098±0.00026

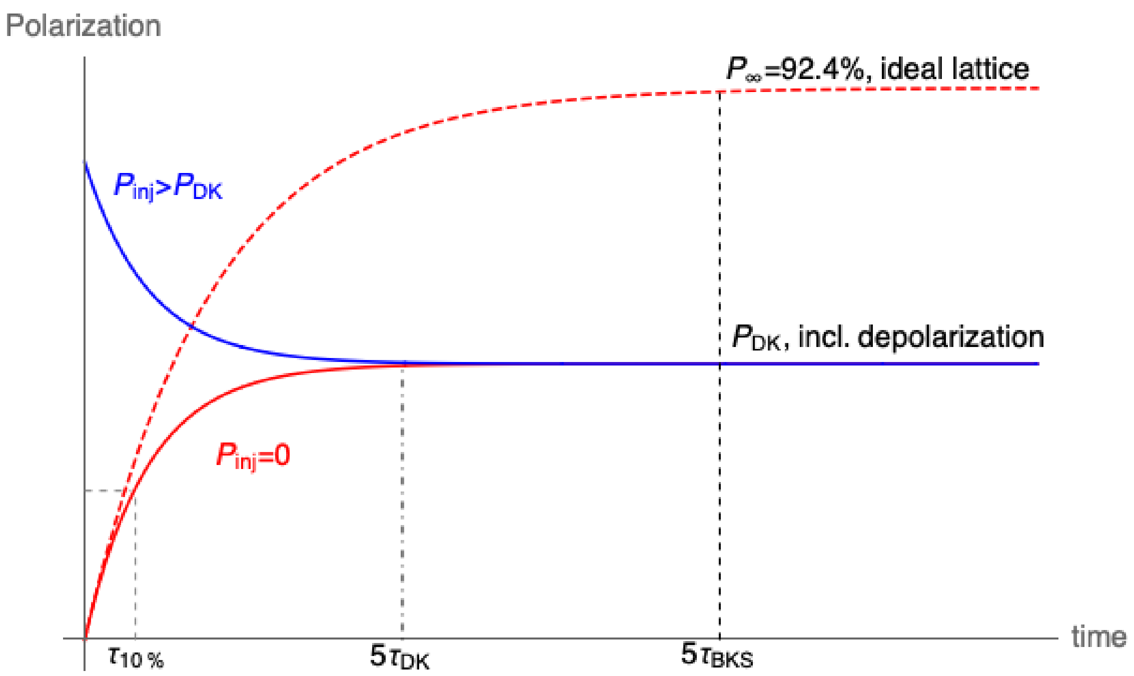
Current central values:
$\sin^2\theta_{eff}$ = 0.23105±0.00087 (LHC)
0.23179±0.00035 (Tevatron)

➡ **Discrepancy between the most precise measurements**
Central value has large impact on physics predictions!

G. Moortgat-Pick's talk on CEPC Workshop EU @ Marseille, 2024 April

- **Summarized as a chapter in the Appendix of CEPC TDR.**

Self-polarization in the CEPC



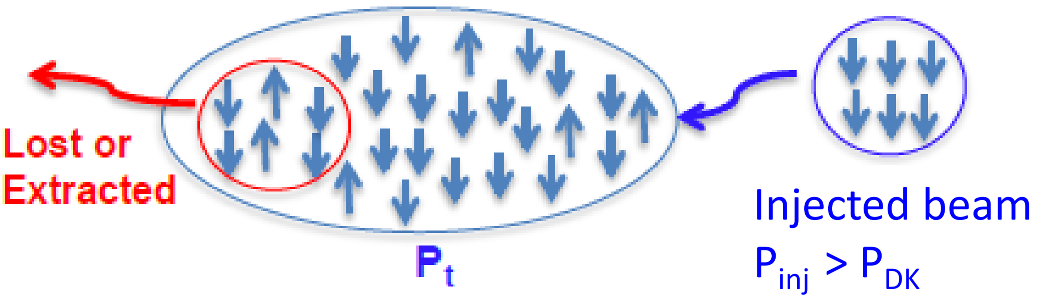
- e+/e- beams become "self-polarized" via the Sokolov-Ternov effect in a storage ring
  - $\tau_{BKS} \propto E^{-5}\rho^2 R$
- Beam polarization build-up rate much slower than the beam decay rate @ Z-pole
  - Boosted with asymmetric wigglers in the Collider (FCC EPOL)
  - Hard to achieve a high-level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

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



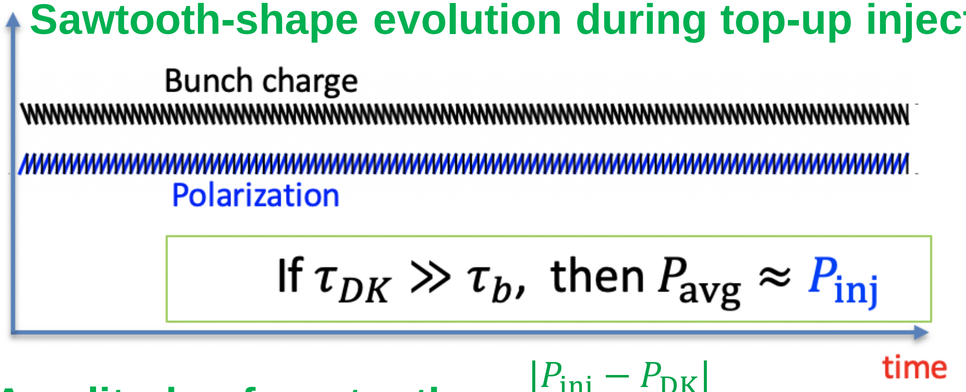
P_{DK} depends on machine imperfections, spin rotators

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%

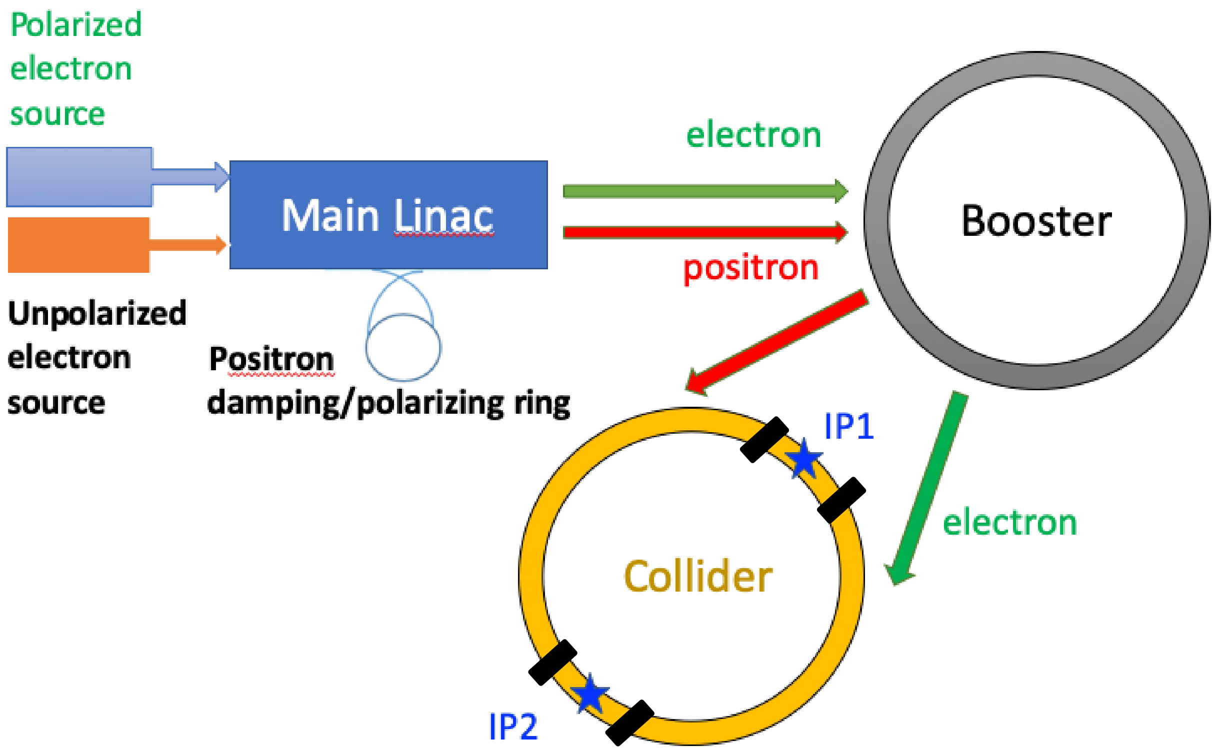
Sawtooth-shape evolution during top-up injection



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

Polarized injector for CEPC

- Polarized source
  - PES
  - Positron damping/polarizing ring
- Linac & Transport lines
  - spin direction matching @ injection/extraction
  - helicity adjustment for e+



- Booster
  - free from intrinsic spin resonances
- Collider
  - solenoid spin rotators

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

Polarized electron source

- Polarized electron source based on HV DC gun w/ superlattice AsGa/AsGaP cathode can deliver >80% beam polarization
- CEPC parameters less challenging than ILC, EIC
- R&D towards converting a HV photocathode DC gun @ PAPS to a polarized electron source

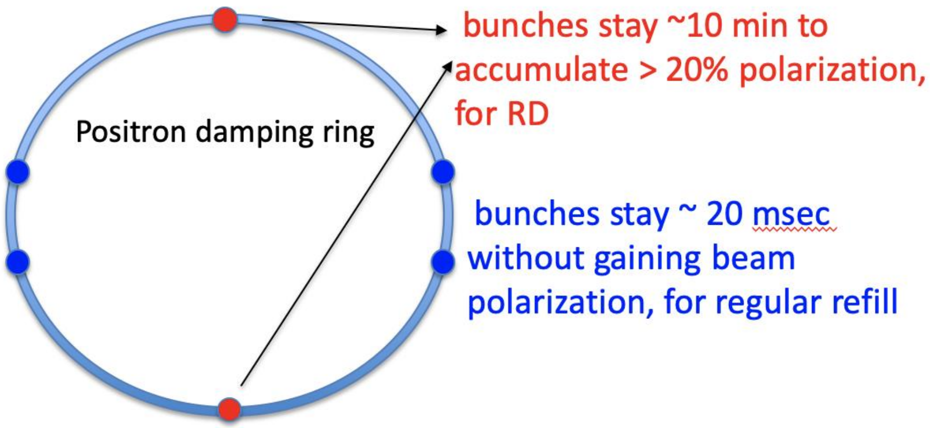
Parameter	CEPC	SLC	ILC	CLIC	EIC
Polarization [%]	>80	85	>80	>80	85
Bunch charge [nC]	3.3	9-16	3.2	1	7
Number of microbunches	1	1	1312	312	8
Repetition rate [Hz]	100	120	5	50	100
Average current from gun [μA]	0.33	1.1-1.9	21	15.6	5.6

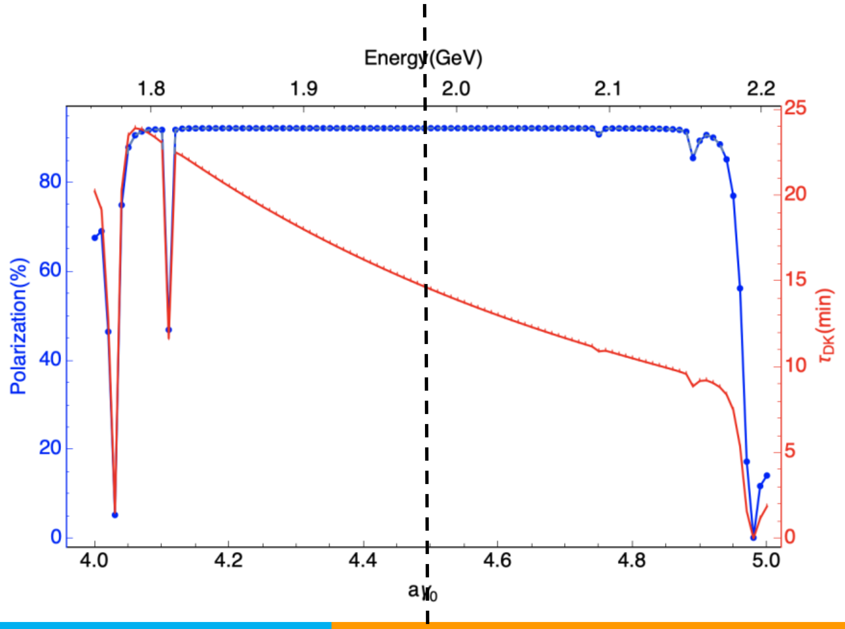
Table A8.2.2: Specifications of polarized electron gun for CEPC

Parameter	Specification
Gun type	Photocathode DC gun
Cathode material	Superlattice GaAs/GasAsP
Voltage	150-200kV
Quantum Efficiency	0.5%
Polarization	>85%
Bunch population	2.1×10^{10}
Drive laser	780 nm ($\pm$20 nm), 10μJ@1ns

Positron damping/polarizing ring

- Using the self-polarization to generate polarized e+ beams
  - For Resonant depolarization (very promising)
    - polarization build-up time ~ 14.5 min
    - extracted beam polarization @ 10min ~ 44%
    - could be designed to also pre-polarize e- beams
  - for polarized colliding beams (under study)
    - Higher energy and/or asymmetric wigglers
    - More bunches

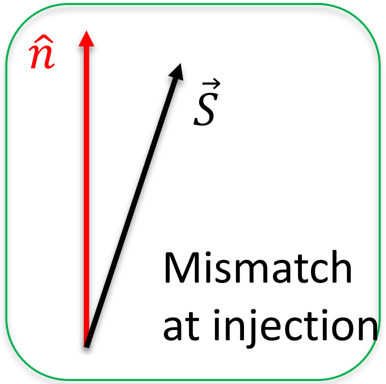




DR V4.0	unpolarized e+	polarized e+
Energy (Gev)	1.983	
Circumference (m)	144.2	
Number of trains	2(4)	
Number of bunches/trian	1(2)	
Total current (mA)	12.4	
Dipole strength B_0 (T)	1.92	
U_0 (kev/turn)	397.9	
Damping time x/y/z (ms)	4.8/4.8/2.4	
Momentum compaction	0.0078	
Storage time	20 ms	10 min
δ_0 (%)	0.0917	
ε_0 (mm.mrad)	132	
injection σ_z (mm)	6	
Extract σ_z (mm)	6.7	6.6
ε_{inj} (mm.mrad)	2500	
$\varepsilon_{ext\ x/y}$ (mm.mrad)	133/13	132/13
$\delta_{inj}/\delta_{ext}$ (%)	0.18 /0.092	
RF acceptance (%)	1.85	
Longitudinal tune	0.025	

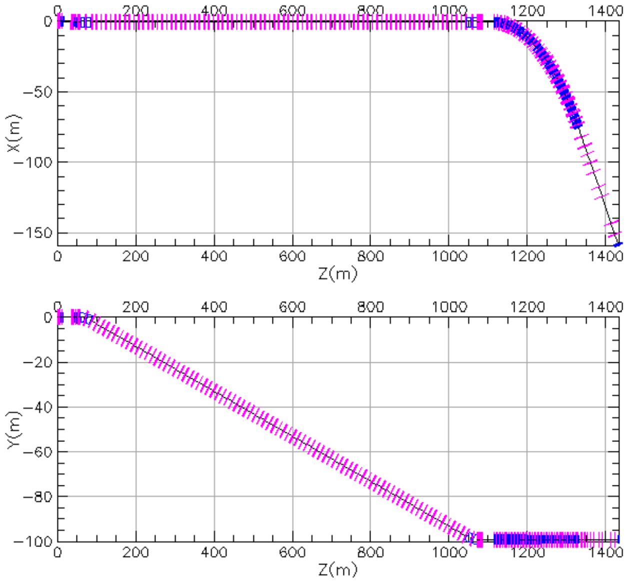
Linac & transport lines

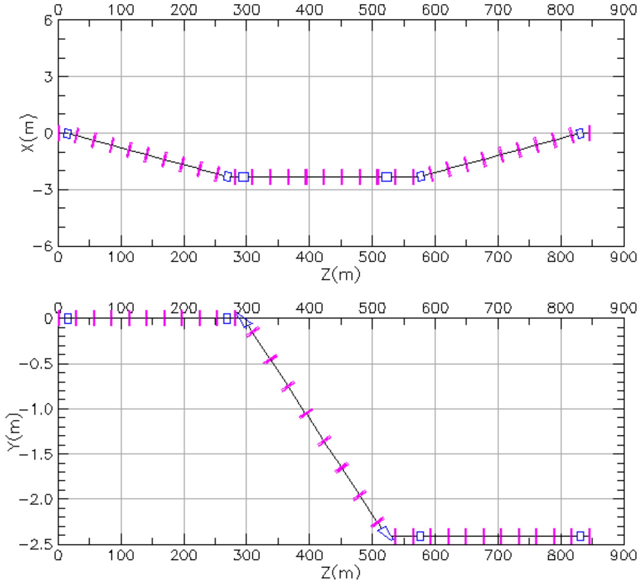
- Depolarization in the linac is expected to be negligible[1,2].
- Transport lines
  - Non-interleaved horizontal & vertical bending
  - Typical errors without trajectory correction -> polarization loss < 10%

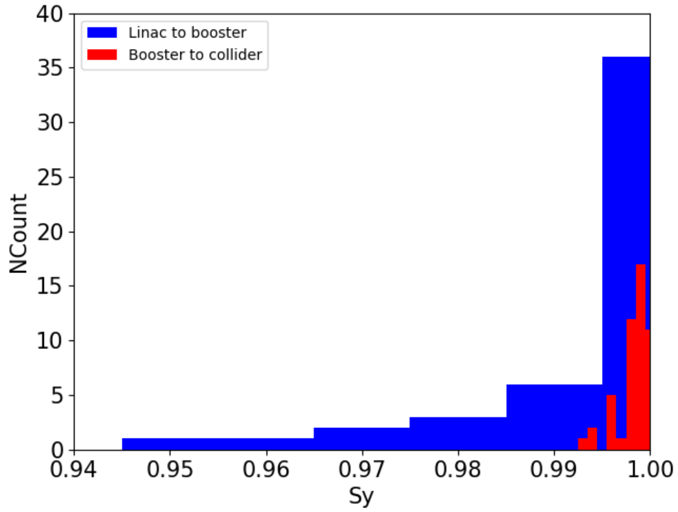


Linac to booster transport line

Booster to ring transport line



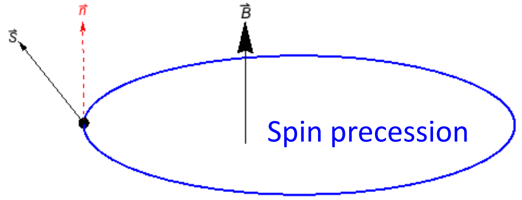


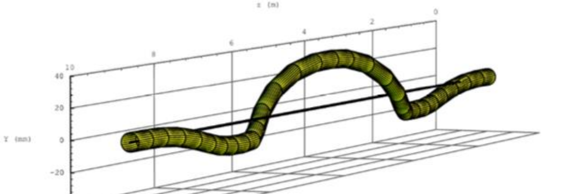


[1] G. Moortgat-Pick, et al., Polarized positrons and electrons at the linear collider, Physics Reports 460 (2008) 131-243.
[2] M. Woods, The polarized electron beam for the SLAC Linear Collider, arXiv:heps-ex/9611006v1, 1996

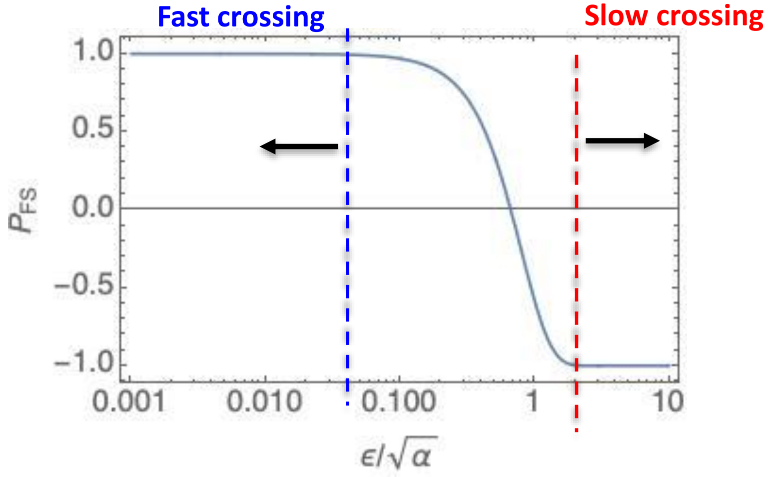
Depolarization in the booster

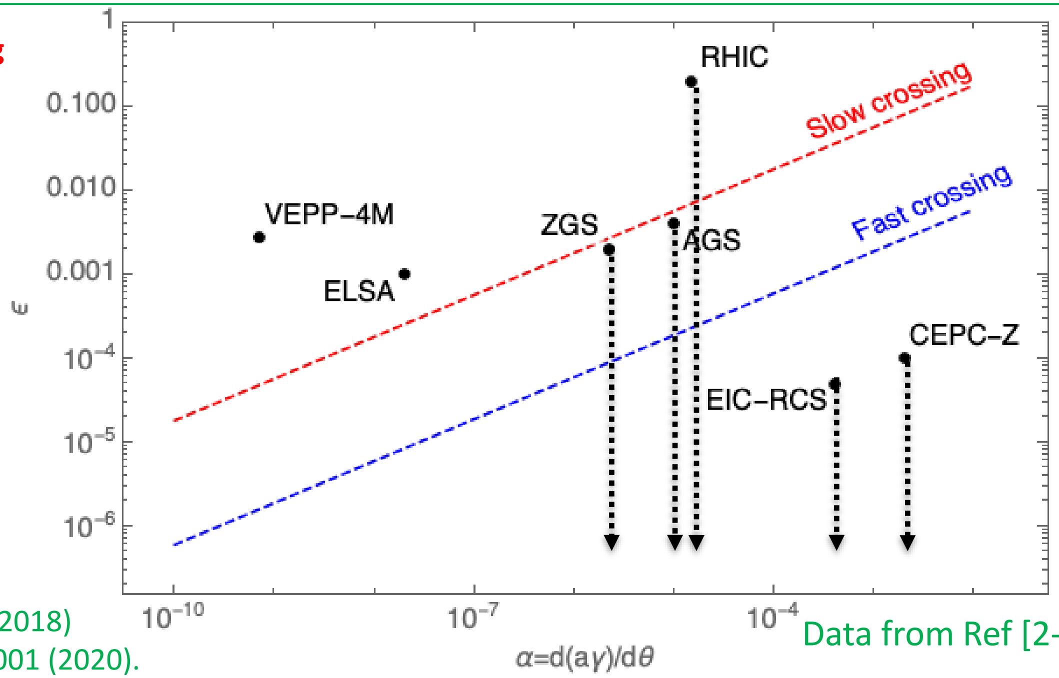
- The spin tune $\upsilon_s \approx \upsilon_0 \approx a\gamma$ changes and could cross spin resonances $\upsilon_s = k + k_x\upsilon_x + k_y\upsilon_y + k_z\upsilon_z$
  - The spin resonances $\upsilon_0 = k$ are spaced by 440 MeV for e+/e-
- The non-adiabatic crossing could vary $J_s = \vec{S} \cdot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





Orbit motion in a helical snake @ RHIC





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]

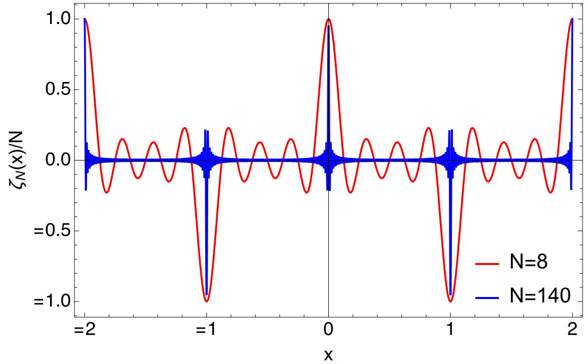
$$|\epsilon| \approx |\epsilon_{FODO}|\, E_P\, E_M$$

due to P superperiods

due to M identical FODOs in each arc

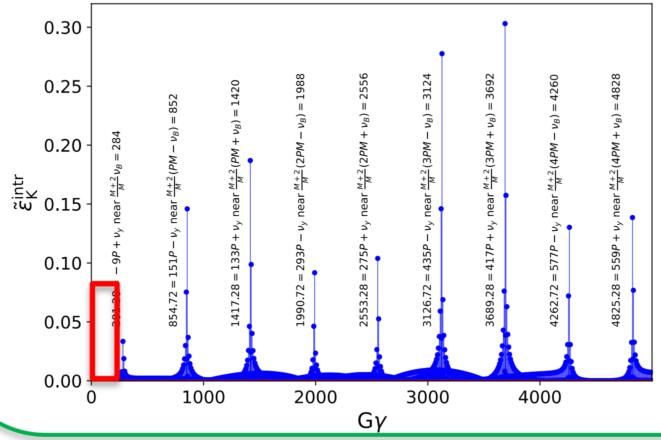
- Enhancement occurs near $\frac{mPM \pm \nu_B}{\eta_{arc}}$, ν_B is the total ν_y in all standard arc cells [2]

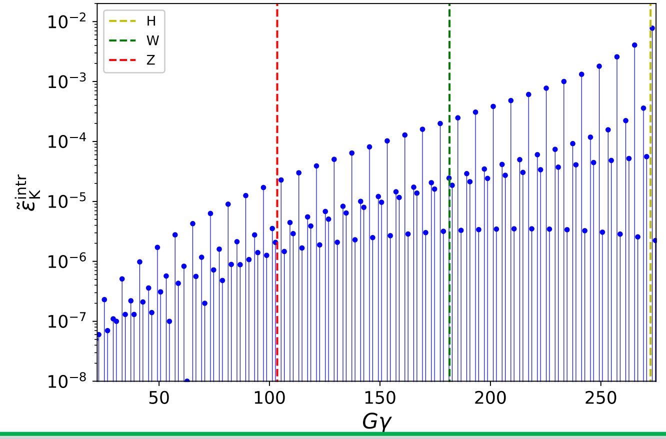
- Resonances at $K \ll \nu_B$ tend to be weak due to cancellation [2]



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

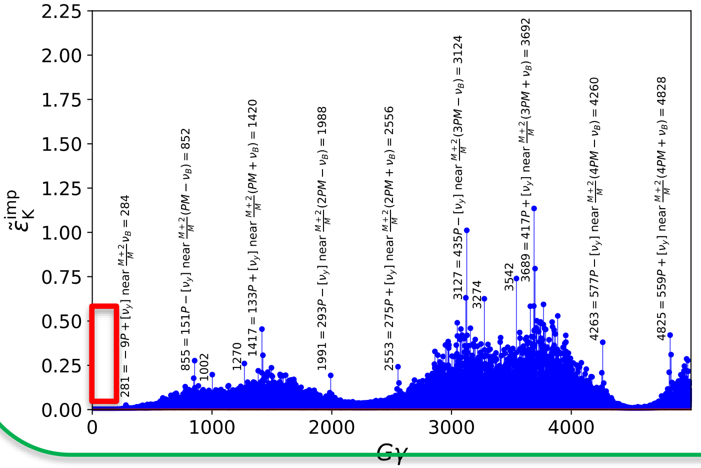
Super strong resonances: $K = nP \pm \nu_y, n \in \mathbb{Z}$ closest to $(mPM \pm \nu_B)/\eta_{\text{arc}}, m \in \mathbb{Z}$

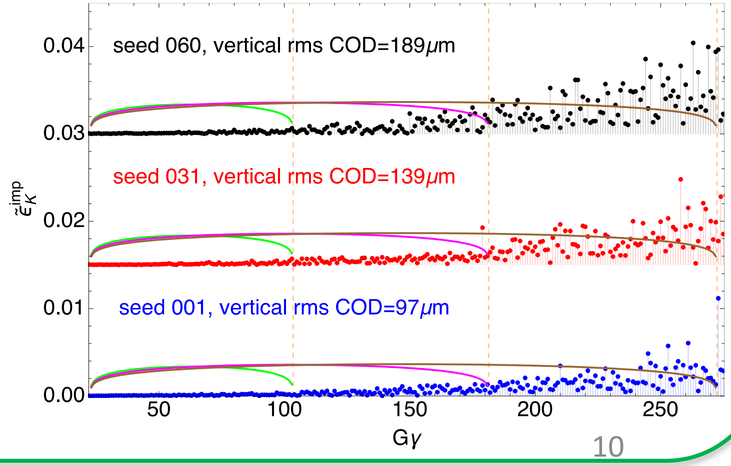




Imperfection resonances: $\upsilon_0 = K$

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





[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).

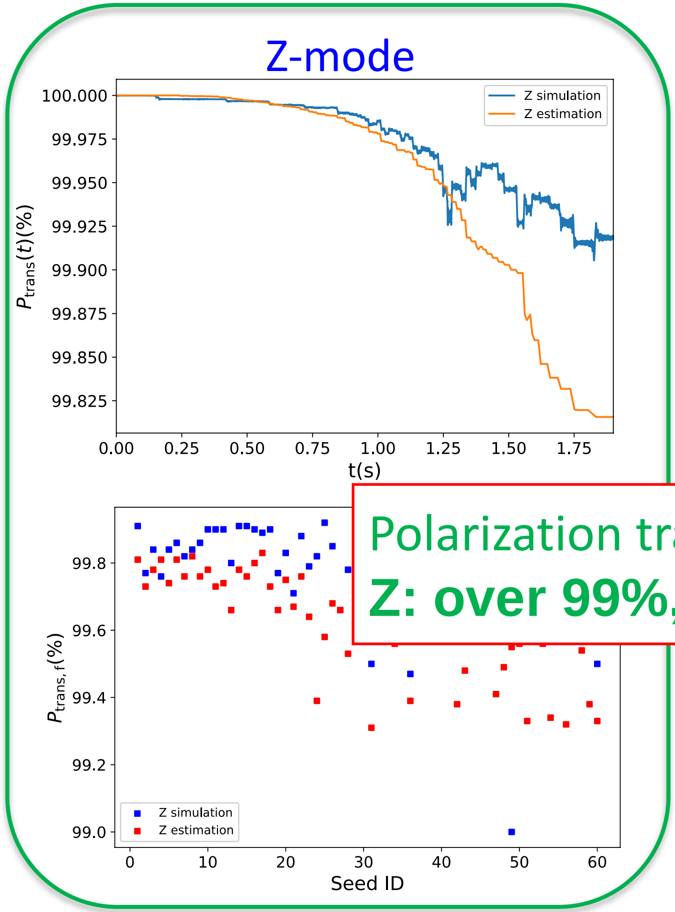
Depolarization effects: simulation vs. estimation

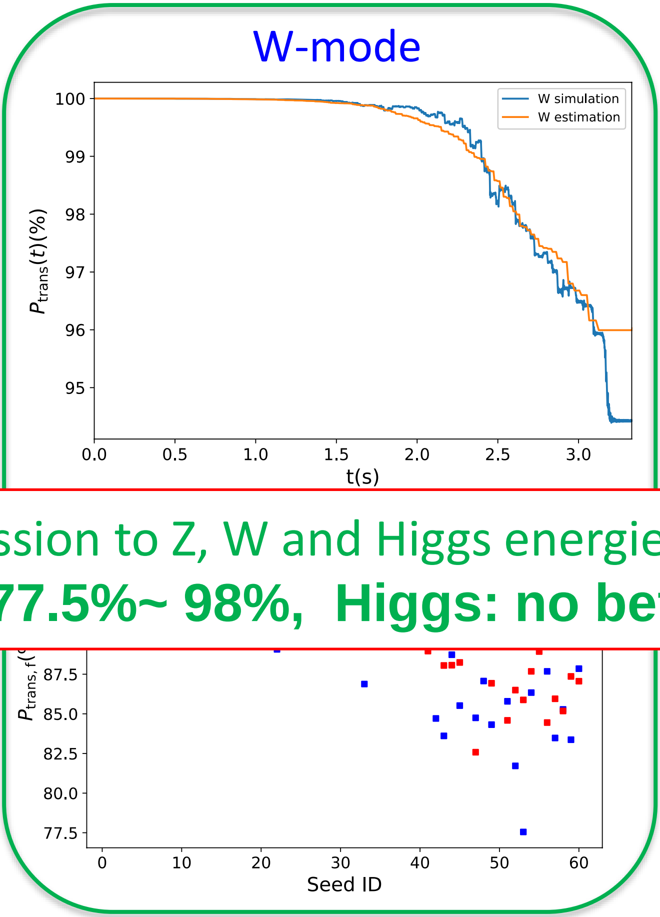
In the acceleration to Z & W

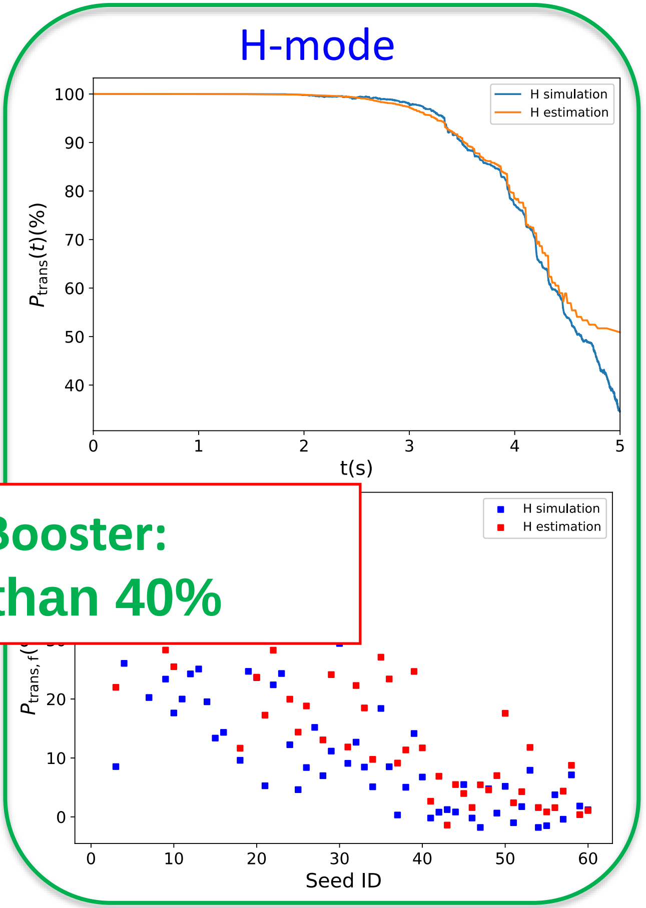
- The spin resonances are generally weak
- Polarization is mostly maintained
- Estimations agree fairly well with simulations

In the acceleration to H

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







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).

CEPC TDR lattice and more optimizations

- The CEPC 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
  - Vary lattice vertical focusing
  - Study lattice sensitivity to imperfection resonances
- More to address
  - – influence of the smoothed 3D closed curve of the accelerator after alignment

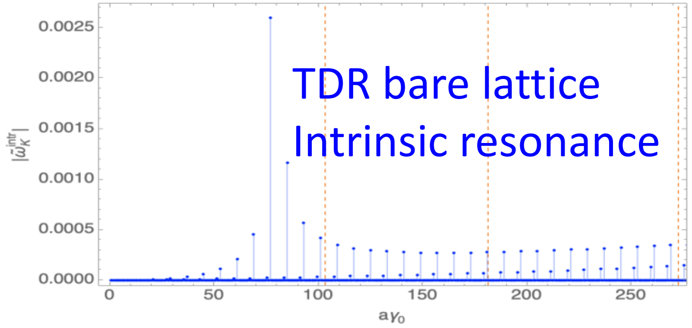
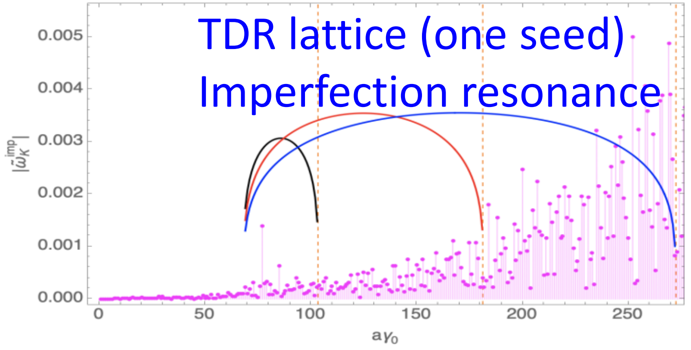


Table A8.3.1 Parameters relevant for the spin resonance structure

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



Our study for FCC HEB show similar results: 179th & 182nd FCC-ee optics meeting

Beam polarization transmission in the injector

An estimate based on the CEPC TDR booster, further optimization is under way

Polarized e-

Polarized e- source
- Polarization >80%
- Ref: ILC, EIC

Linac and TLs
- Polarization loss < 10%
- Ref: SLC, ILC

Booster
- Polarization loss < 20%

Collider
- P_{inj} ~ 60% after considering these factors

Polarized e+

e+ polarizing ring
- Polarization >40%
- e+ damping/polarizing ring

Linac and TLs
- Polarization loss < 10%
- Ref: SLC, ILC

Booster
- Polarization loss < 50%

Collider
- P_{inj} ~ 20% after considering these factors

Summary

- Injecting pre-polarized beams to the Colliders is promising
  - RD measurements w/ a few pre-polarized (e- > 50%, e+ ~ 20%) pilot non-colliding bunches, no physics deadtime, robust towards machine faults & much higher integrated luminosity (J. Heron's talk)
  - Longitudinal polarization @ Z-pole: > 50% polarized e- at nominal luminosity, more powerful polarized e+ source is under study.
- Polarized beam applications towards higher energies (W, Higgs etc) can also be envisaged.

Thank you for your attention!

Two lattices studied for FCC HEB

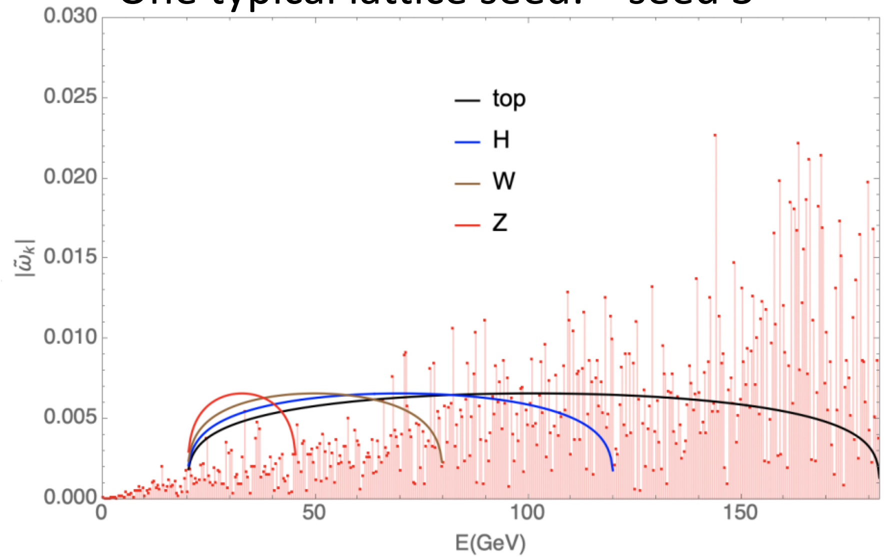
	FODO 90 deg (provided by B. Dalena)	HFD (provided by A. Chance)
Number of arcs (P)	8	8
Number of standard arc cells (M)	175	175
Total bending angle of standard arc cells ($2\pi * \eta_{arc}$)	0.745 rad * 8 = 2π * 0.9486	0.745 rad * 8 = 2π * 0.9486
Vertical betatron tune ν_y	416.29	382.29
Vertical betatron tune from standard arc cells ν_B	¼ * 175 * 8 = 350	~ 40 * 8 = 320
ν_B/η_{arc}	~ 369 (corresponding to a beam energy of 162.6 GeV)	~ 337 (corresponding to a beam energy of 148.5 GeV)

Note:

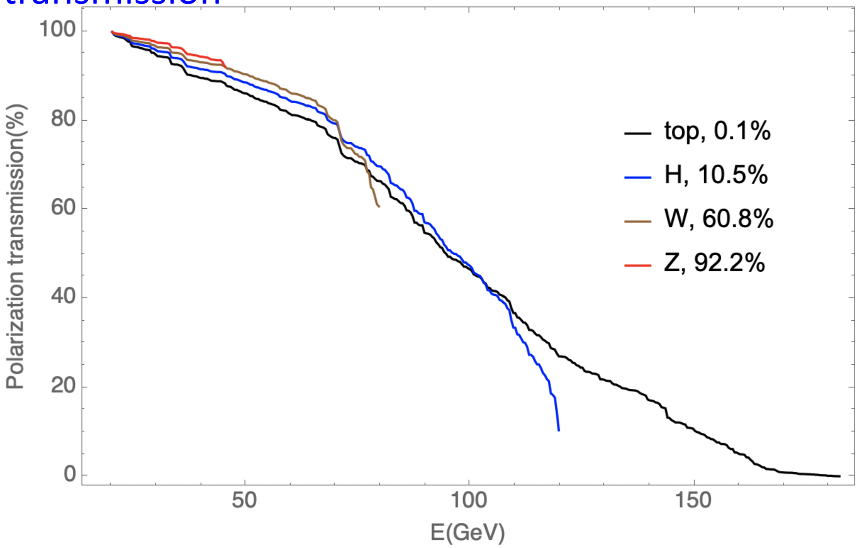
- Superstrong intrinsic resonances are located at $\upsilon_0 = K = nP \pm \upsilon_y$ that are closest to $\frac{mPM \pm \upsilon_B}{\eta_{arc}}$
- The superstrong intrinsic resonance at the lowest beam energy is near $\upsilon_0 = \upsilon_B/\eta_{arc}$

Polarization transmission for FODO 90 degree lattice

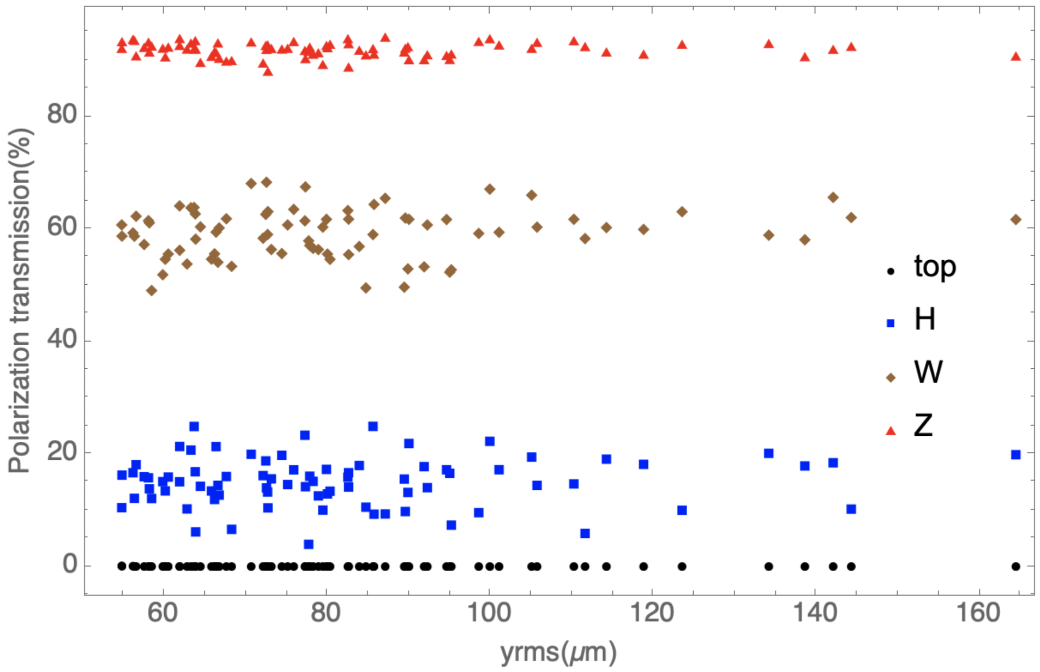
One typical lattice seed: seed 3



Above figure: the curves show the strength w/ 99% polarization transmission



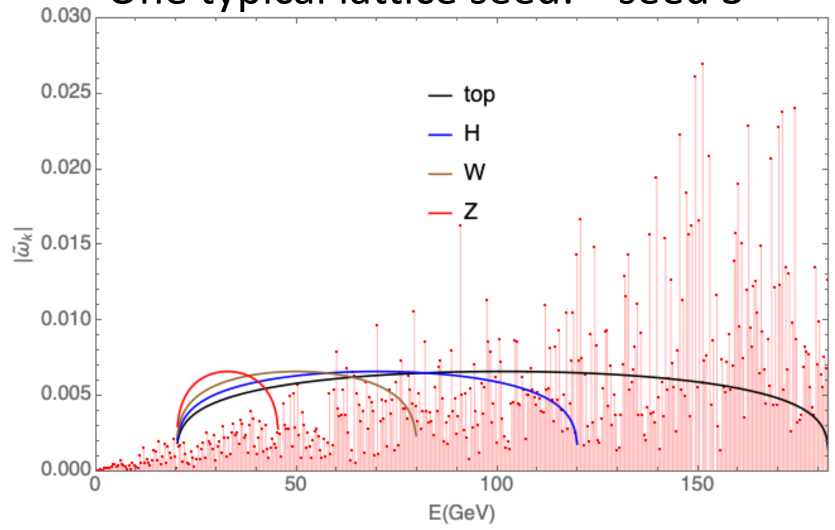
All 79 successfully corrected seeds out of 100



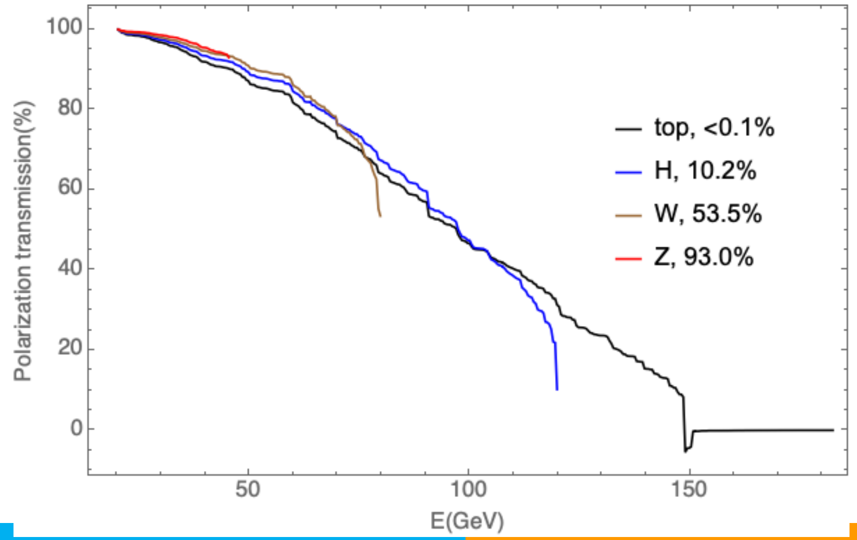
- More dangerous imperfection resonances are crossed in the higher energy modes
- Assuming 100% polarization @ injection, the final polarization transmission after acceleration is typically ~90% (Z), ~60%(W), ~15%(H) and zero (top)

Polarization transmission for HFD lattice

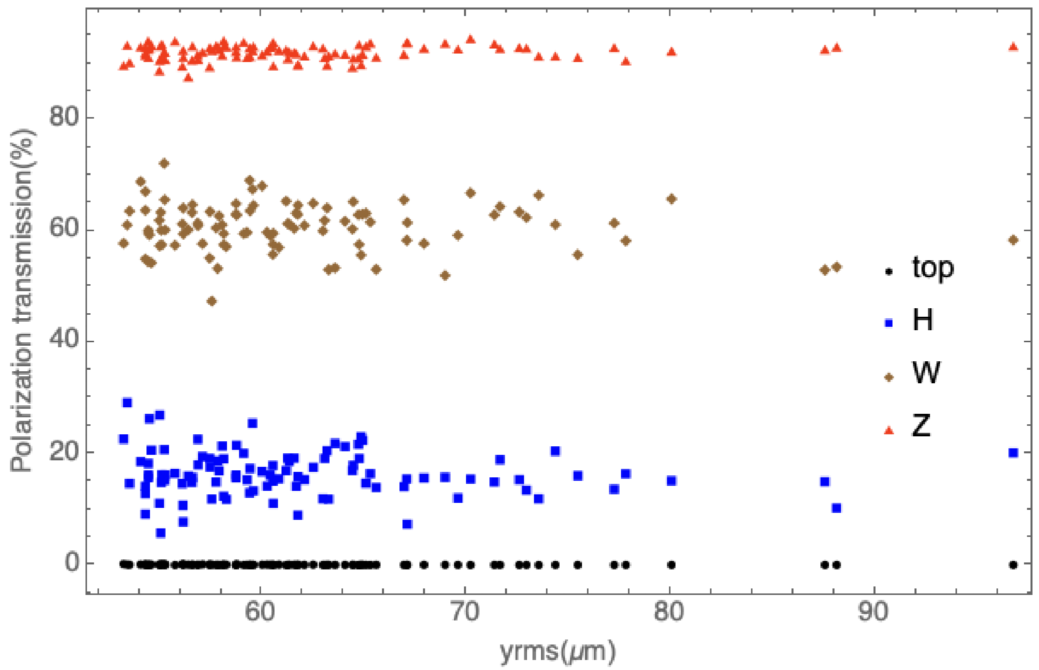
One typical lattice seed: seed 3



Above figure: the curves show the strength w/ 99% polarization transmission



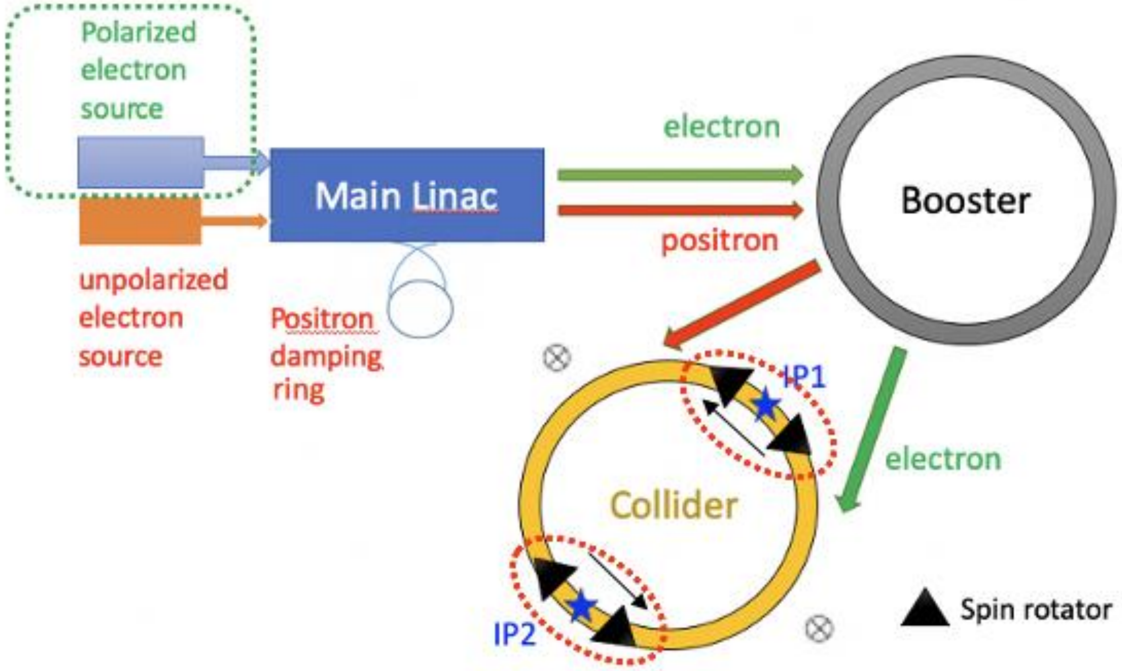
All 100 successfully corrected seeds out of 100

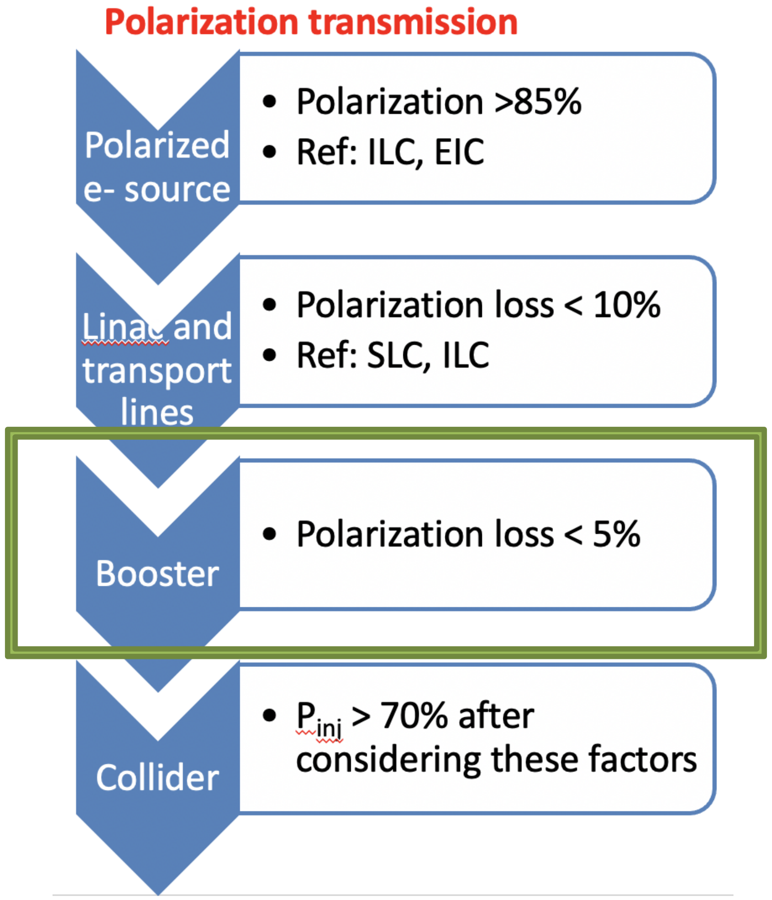


- More dangerous imperfection resonances are crossed in the higher energy modes
- Assuming 100% polarization @ injection, the final polarization transmission after acceleration is typically ~90% (Z), ~60%(W), ~15%(H) and zero (top)

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).

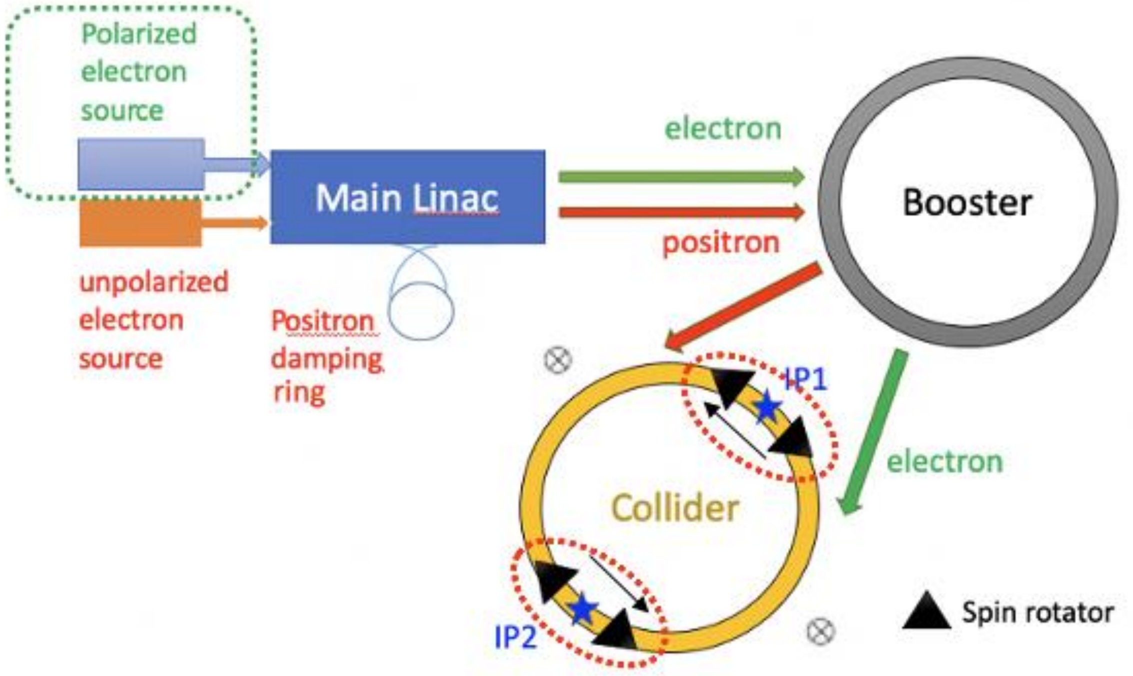
A high-level longitudinal polarization @ Z-pole

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

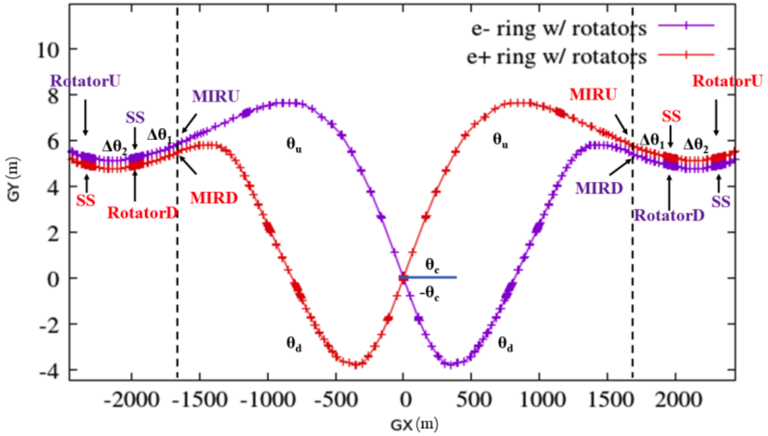
- Over 70% injected e- beam polarization is possible.
- **Simulated equilibrium longitudinal polarization > 70%,**

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

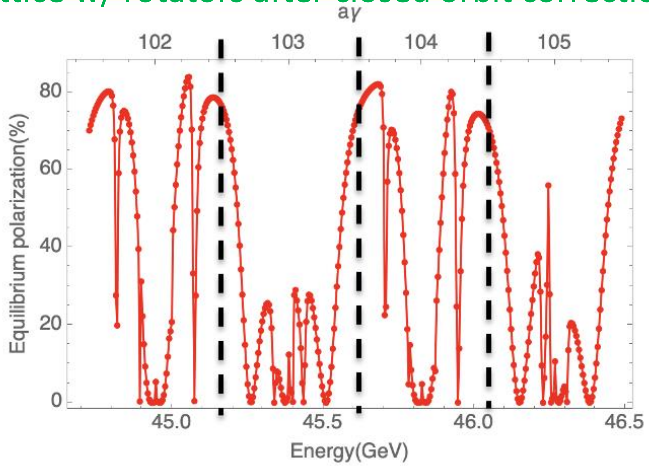
leaving a large margin for effects not yet covered.



Implementation of the spin rotators adjacent to the IR



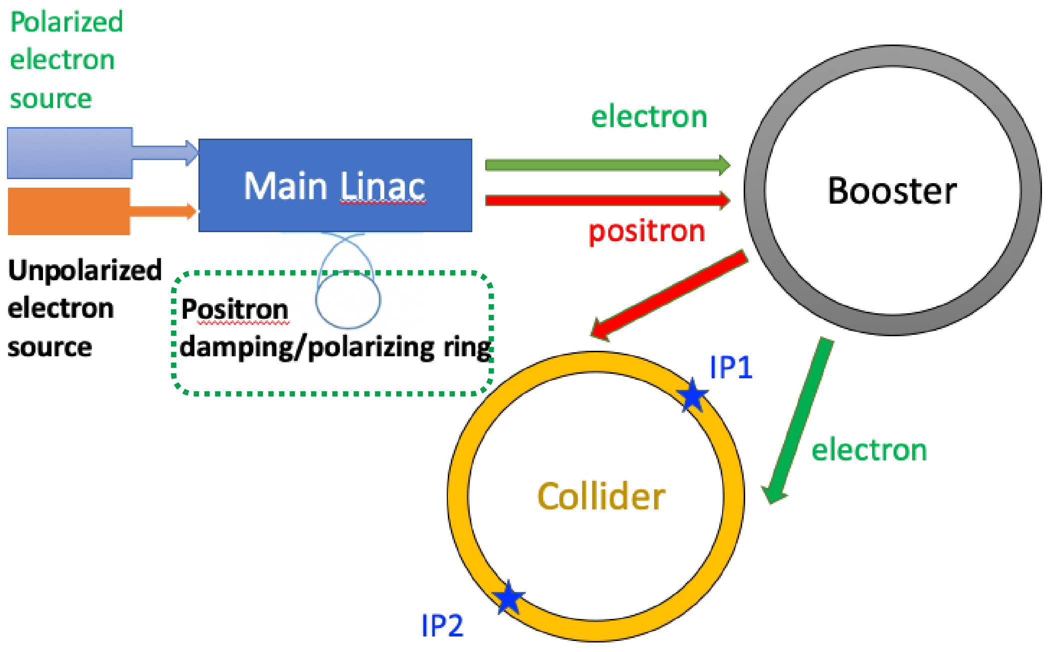
Simulated equilibrium polarization for an imperfect lattice w/ rotators after closed orbit correction

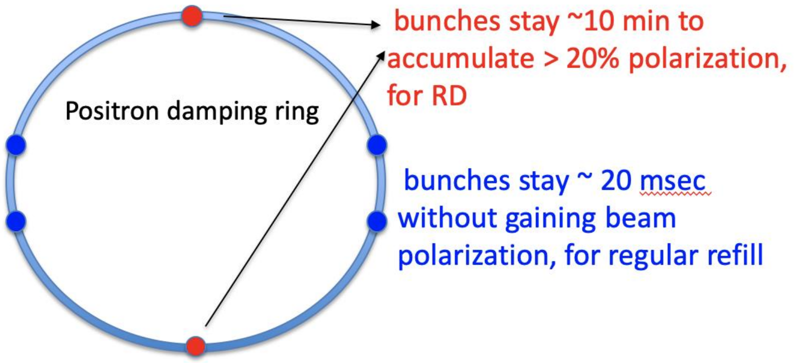


Resonant Depolarization at Z

- 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%