Polarized electron and positron beams at CEPC

Zhe Duan

Institute of High Energy Physics, CAS

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中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

zhe.duan@ihep.ac.cn

Outline

- Motivation
- Prospect and challenges
- Equilibrium beam polarization simulations

Motivation

- Energy calibration with resonant depolarization technique was a major accomplishment at LEP
  - How much better precision can be done in CEPC?
- "Can we have polarized colliding beam experiments?" has been a must answer question in new linear/circular collider designs
  - How to implement longitudinally polarized e- (e+ ?) beam(s) for colliding experiments in CEPC?
  - Are there strong physics cases?
  - Would the design be cost effective?

Motivation

500

Chapter on polarization by Dr S. Nikitin in CEPC CDR

Appendix 8: Opportunities for Polarization in the CEPC

A8.1: Introduction

One of the future experiments at CEPC can be a precise measurement of the mass of the Z using resonant depolarization [1]. To achieve this goal one needs a method for obtaining polarized electron and positron beams. In this appendix we consider the major issues for obtaining the radiative self-polarization of particles with the current CEPC design parameters at 45 GeVand at 80 GeV.

Funding grant of MOST-2018 supports CEPC polarization studies in the coming 4 years, a more complete design of CEPC polarized beam operation at Z energy (and possibly also at W energy) is foreseen in the CEPC TDR.

Prospects and challenges

- Energy calibration with resonant depolarization
  - A detailed time diagram of operation with asymmetric wigglers
  - Complexities in energy calibration @ W
  - Estimation & simulation of the difference between the “measured energy” and the “CM energy” at IPs
- Longitudinally polarized e+/e- colliding beams
  - Polarized e+ source seems less matured at the moment
  - Maintenance of beam polarization in the booster
  - Spin rotator design
  - Spin matching
  - Equilibrium beam polarization w/ spin rotators, errors, & beam-beam

Equilibrium beam polarization simulations

The D-K formula

$$P_{\rm dk} = -\frac{8}{5\sqrt{3}}\frac{\alpha_-}{\alpha_+}$$

$$\alpha_- = \oint \mathrm{d}\theta \langle \frac{1}{|\rho|^3}\hat{b}\cdot(\hat{n} - \frac{\partial \hat{n}}{\partial \delta})\rangle$$

$$\alpha_+ = \oint \mathrm{d}\theta \langle \frac{1}{|\rho|^3}[1 - \frac{2}{9}(\hat{n}\cdot\hat{\beta})^2 + \frac{11}{18}(\frac{\partial \hat{n}}{\partial \delta})^2]\rangle$$

For Monte-Carlo simulation

$$P_{\rm eq} \approx \frac{P_\infty}{1+\lambda_d/\lambda_p}$$

$$P_\infty \approx -\frac{8}{5\sqrt{3}}\frac{\oint \mathrm{d}\theta \frac{1}{|\rho|^3}\hat{b}\cdot\hat{n}_0}{\oint \mathrm{d}\theta \frac{1}{|\rho|^3}[1-\frac{2}{9}(\hat{n}_0\cdot\hat{s})^2]}$$

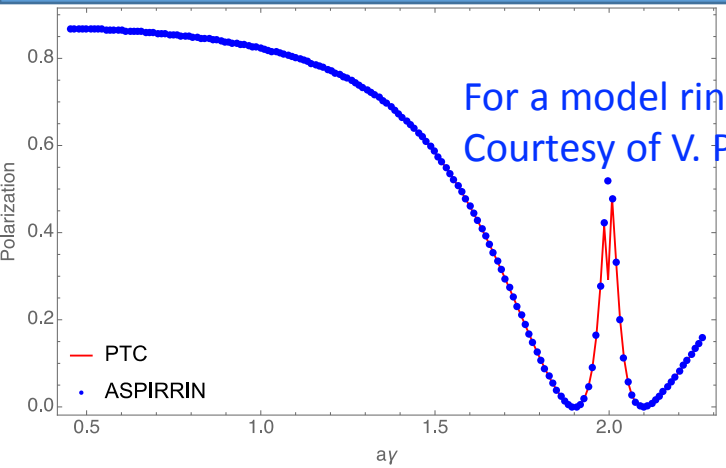
Simulation code: fortran scripts calling PTC[1] as a library

- Obtain $\hat{n}_0$ and $\frac{\partial \hat{n}}{\partial \delta}$ with a first order normal form[2], then apply DK formula (Contain effects due to first order spin resonance only)
- Monte-Carlo simulation of depolarization rate[3] (higher order spin resonances are also included)

Lattice modeling, including machine errors and corrections could be done in MAD-X / BMAD, and transformed to PTC readable format.

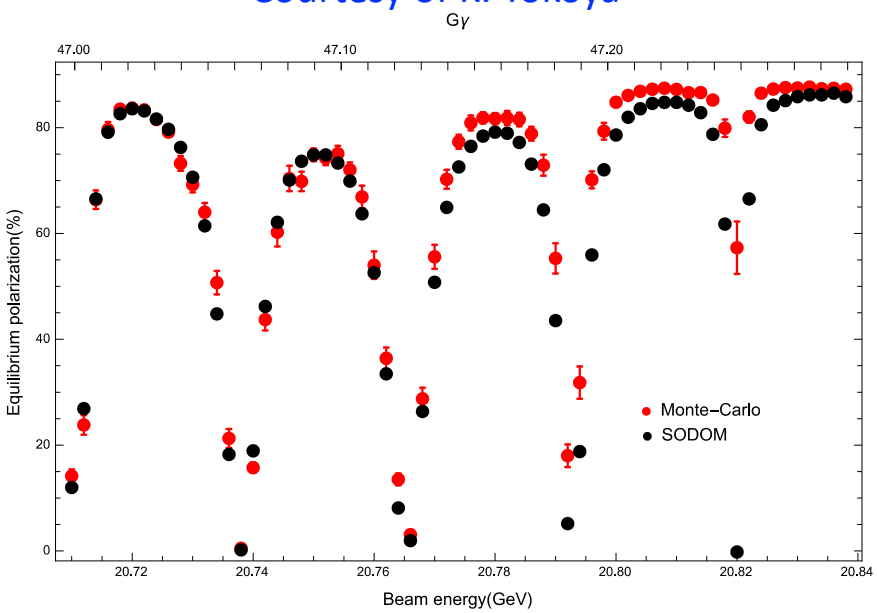
[1] F. Schmit, E. Forest and E. McIntosh, CERN-SL-2002-044, 2002.
[2] E. Forest, KEK Report KEK-2010-39, 2010.
[3] Z. Duan, M. Bai, D. P. Barber and Q. Qin, NIM A793 (2015) 81.

Benchmark against other codes

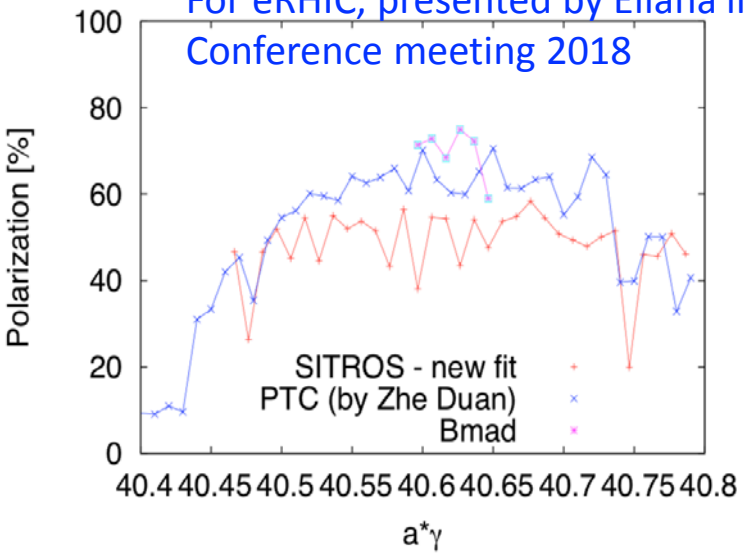


For a model ring of VEPP-2000
Courtesy of V. Ptitsyn

For a model ring with vertical bends
Courtesy of K. Yokoya



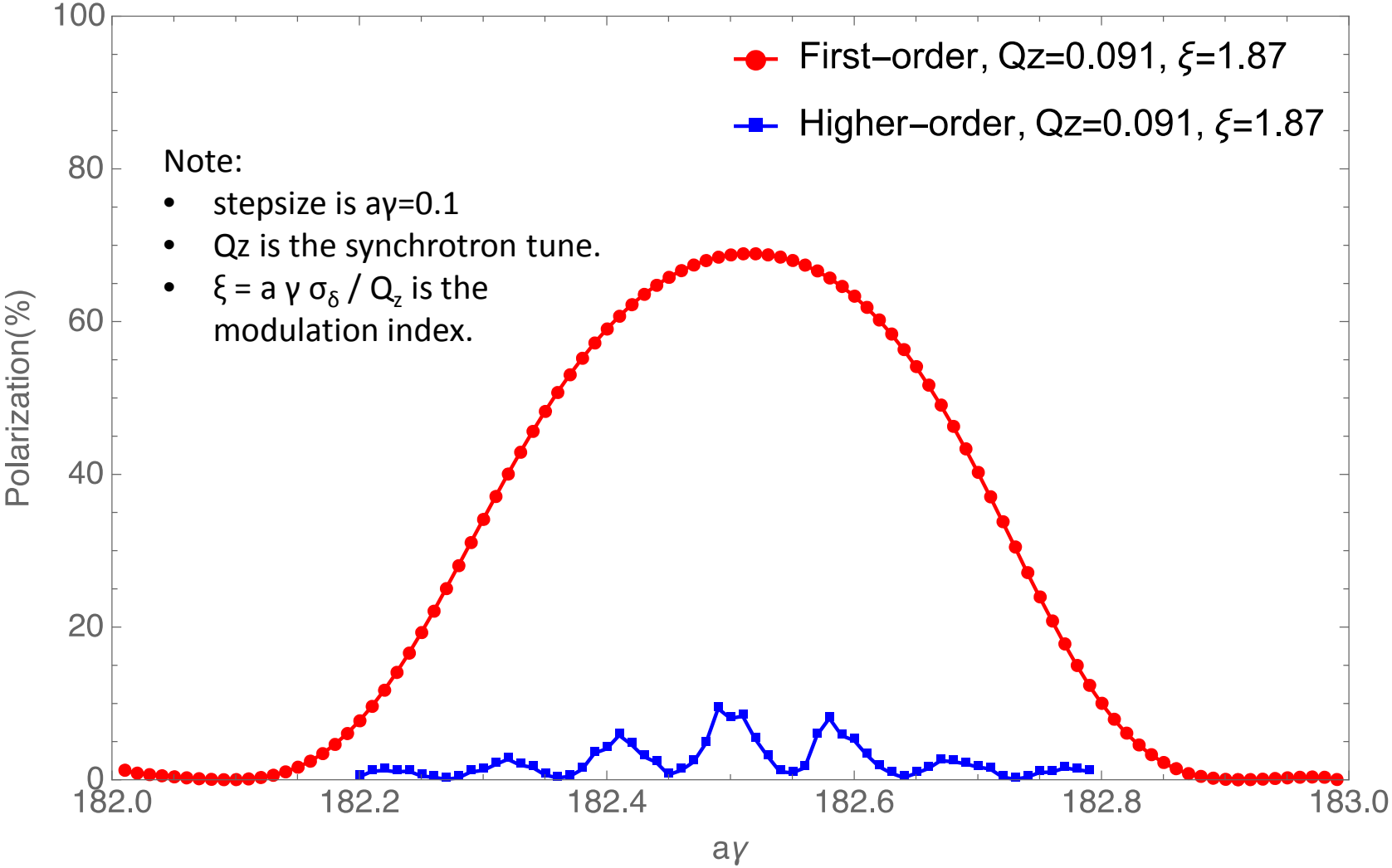
For eRHIC, presented by Eliana in EIC
Conference meeting 2018



Some simulations for CEPC-50 km model ring

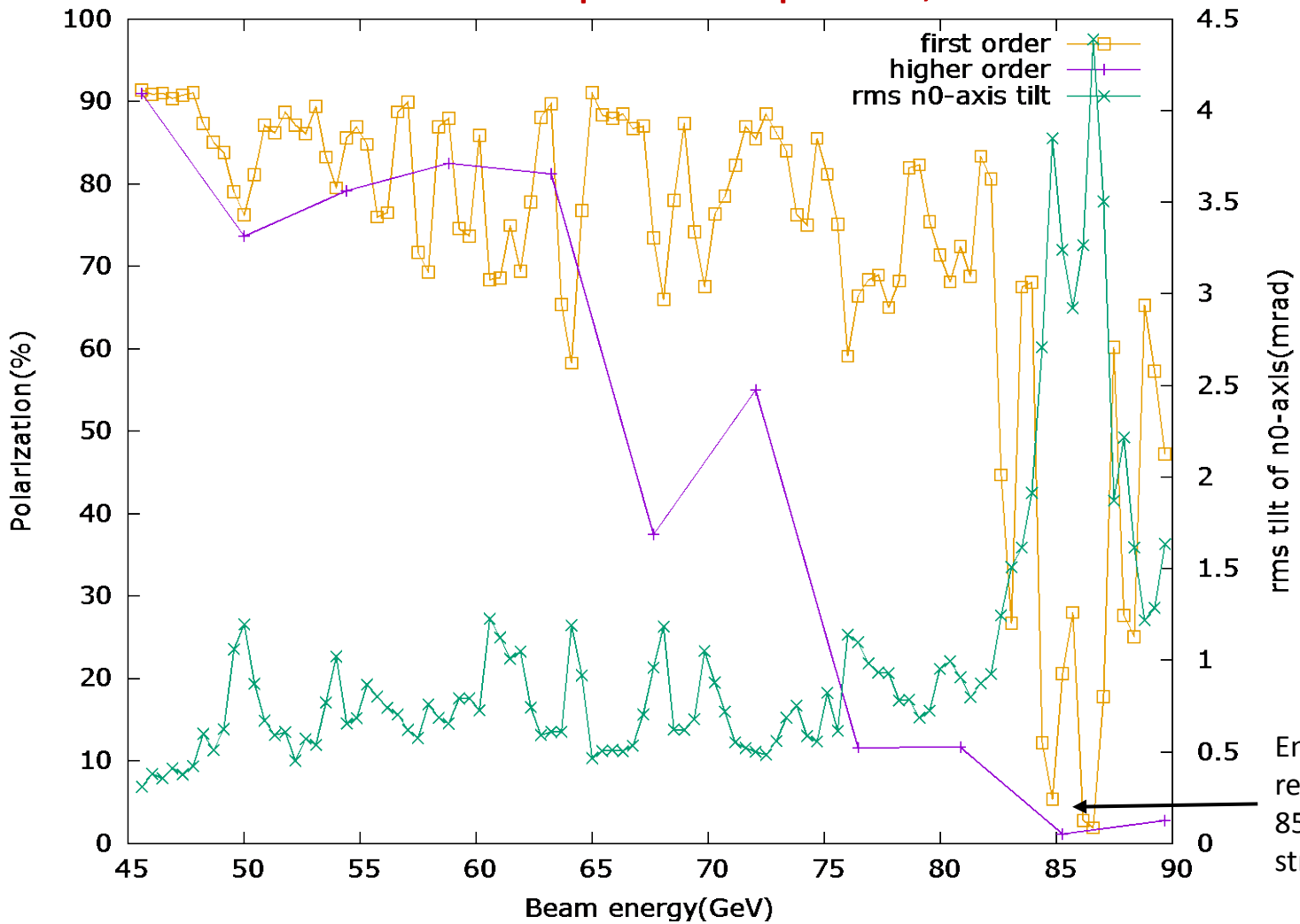
- Arc FODO cells of phase advances 60/60 degrees, connected by straight FODO cells; Periodicity: 4. Circumference: 57436.8m. No polarization wigglers.
- Initially all quads are vertically misaligned by 50 μm rms, then corrected with MICADO using 300 correctors.
- rms vertical closed orbit = 57.9 μm.
- rms vertical closed orbit @ quadrupoles = 56.6 μm.
- (vx, vy)=(268.124, 268.261)
- rms tilt of n0-axis = 0.98 mrad @ aγ=182.5

Polarization around 80 GeV



Polarization scan over energy

Fix fractional part of aγ = 0.5, Qz = 0.11



Enhanced imperfection resonances around 85 GeV due to optics structure.

DKS theory at ultra-high beam energy

Away from spin resonances (DK1973)

$$P_{\rm dk} = -\frac{8}{5\sqrt{3}}\frac{\alpha_-}{\alpha_+}$$

$$\alpha_- = \oint d\theta \langle \frac{1}{|\rho|^3}\hat{b}\cdot(\hat{n} - \frac{\partial \hat{n}}{\partial \delta})\rangle$$

$$\alpha_+ = \oint d\theta \langle \frac{1}{|\rho|^3}[1 - \frac{2}{9}(\hat{n}\cdot\hat{\beta})^2 + \frac{11}{18}(\frac{\partial \hat{n}}{\partial \delta})^2]\rangle$$

No assumption regarding proximity to spin resonances (DK1975)

$$\alpha_+ = \left\langle \frac{5\sqrt{3}}{8}\lambda\left[1 - \frac{2}{9}(\mathbf{n}\mathbf{v})^2 + \frac{11}{18}\left|\gamma\frac{\partial}{\partial\gamma}\sum_k \frac{w_k \exp i\psi_k}{\nu - \nu_k - i0}\right|^2\right] + \pi\sum_k |w_k|^2\delta(\nu - \nu_k)\right\rangle,$$

$$\alpha_- = \left\langle \lambda\frac{[\dot{\mathbf{v}}\mathbf{v}]}{|\dot{\mathbf{v}}|}\left[\mathbf{n} - \mathrm{Re}(\mathbf{e}_1 + i\mathbf{e}_2)\gamma\frac{\partial}{\partial\gamma}\sum_k \frac{w_k \exp i\psi_k}{\nu - \nu_k - i0}\right]\right\rangle,$$

Spin diffusion by uncorrelated crossing of spin resonances

Correlated and noncorrelated regimes (DKS1979)

The spread in spin phase in a synchrotron oscillation period $\kappa = \frac{11}{18}\nu_0^2\tilde{\lambda}_p/\nu_z^3.$

- If κ << 1, the successive passages of the spin resonance due to synchrotron oscillation are correlated
- Otherwise, if at the same time the rms spread of the spin-precessing frequency $\sigma_\nu = \nu_0\sigma_\delta \gg \nu_z$

It is claimed that synchrotron oscillation drives the uncorrelated resonance crossings, and the depolarization rate is

$$\lambda_d' = \pi\sum_k \langle |\omega_k|^2\delta(\nu_s - \nu_k)\rangle.$$

CEPC CDR Parameters

Parameters	Higgs	W	Z
beam energy(GeV)	120	80	45.5
radius of curvature(km)	10.7	10.7	10.7
circumference(km)	100	100	100
bunch number	242	1524	12000
momentum compaction factor	1.11e-5	1.11e-5	1.11e-5
Natural rms energy spread	1e-3	6.6e-4	3.8e-4
synchrotron tune Q_z	0.065	0.04	0.028
polarization build-up time(hour)	2	15.2	256
spread of spin precessing rate $\sigma_\nu = a\gamma\ \sigma_\varepsilon$	0.27	0.12	0.04
modulation index $\sigma = \sigma_\nu / Q_z$	4.19	3.0	1.40
Correlation index κ	1.21	0.30	0.017

$$\kappa = \frac{11}{18}\nu_0^2 \tilde{\lambda}_p / \nu_z^3.$$

How to test this theory?

Correlated regime

Calculation the equilibrium polarization with only the first order spin resonances -> obtain the synchrotron sidebands -> sum over contributions from different spin resonances

DKS1979, K. Yokoya 1983

The synchrotron sideband resonances of an integer resonance are $\nu_0 = k + m\nu_z$, with the contribution to $\lambda_d^0/\tilde{\lambda}_p$ [40]

$$\frac{\lambda_d^0}{\tilde{\lambda}_p} = A \sum_{m=-\infty}^{\infty} \left[\frac{\Delta\nu}{(\Delta\nu + m\nu_z)^2 - \nu_z^2} \right]^2 e^{-\alpha} I_m(\alpha), \qquad (9)$$

$$P_{\rm eq} \approx \frac{P_0}{1 + \sum_{\nu_k} \left(\frac{\lambda_d^0}{\tilde{\lambda}_p} \right)_{\nu_k}}$$

Uncorrelated regime

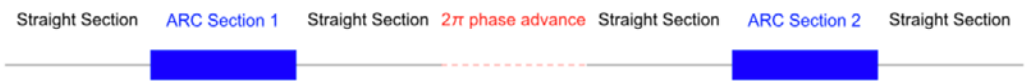
Calculation of the first order spin resonances width with a normal form -> calculate the depolarization rate directly

$$\lambda_d' = \pi \sum_k \langle |\omega_k|^2 \delta(\nu_s - \nu_k) \rangle.$$

$$P_{\rm eq} \approx \frac{P_\infty}{1 + \lambda_d/\lambda_p}$$

Model Ring

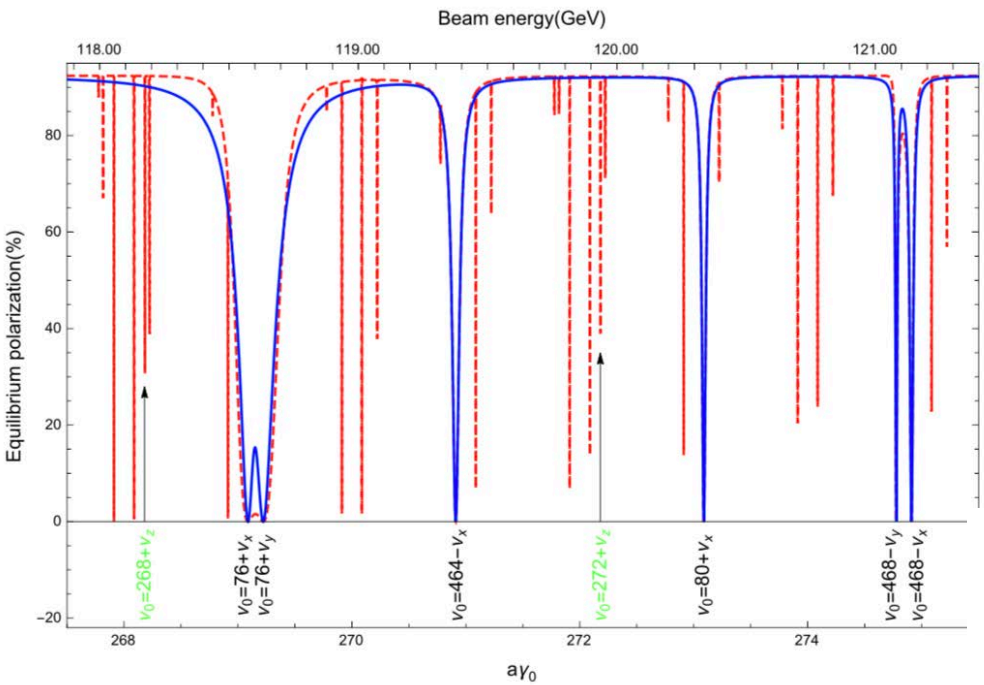
A ring of arc FODO cells connected by FODO straight sections, Periodicity = 4.
Four skew quads are symmetrically inserted to drive horizontal & vertical spin resonances. No lattice imperfections.

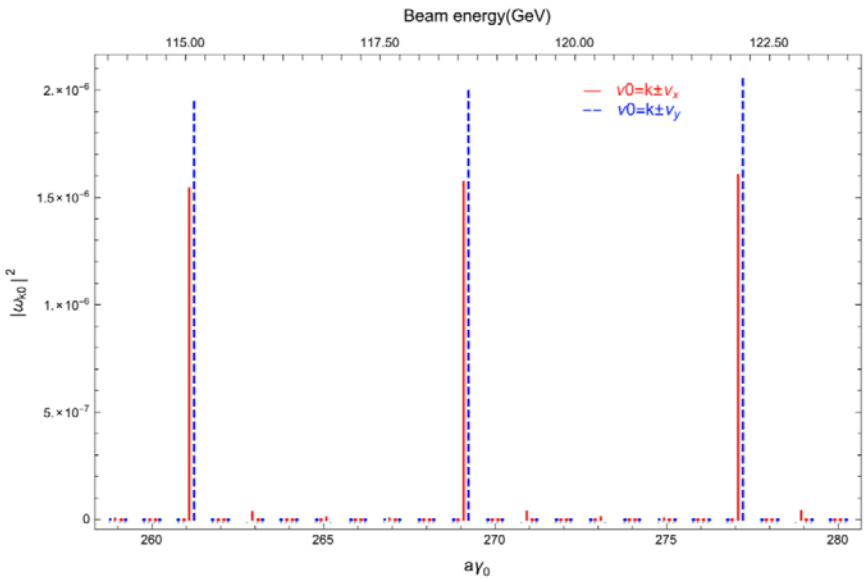


One superperiod

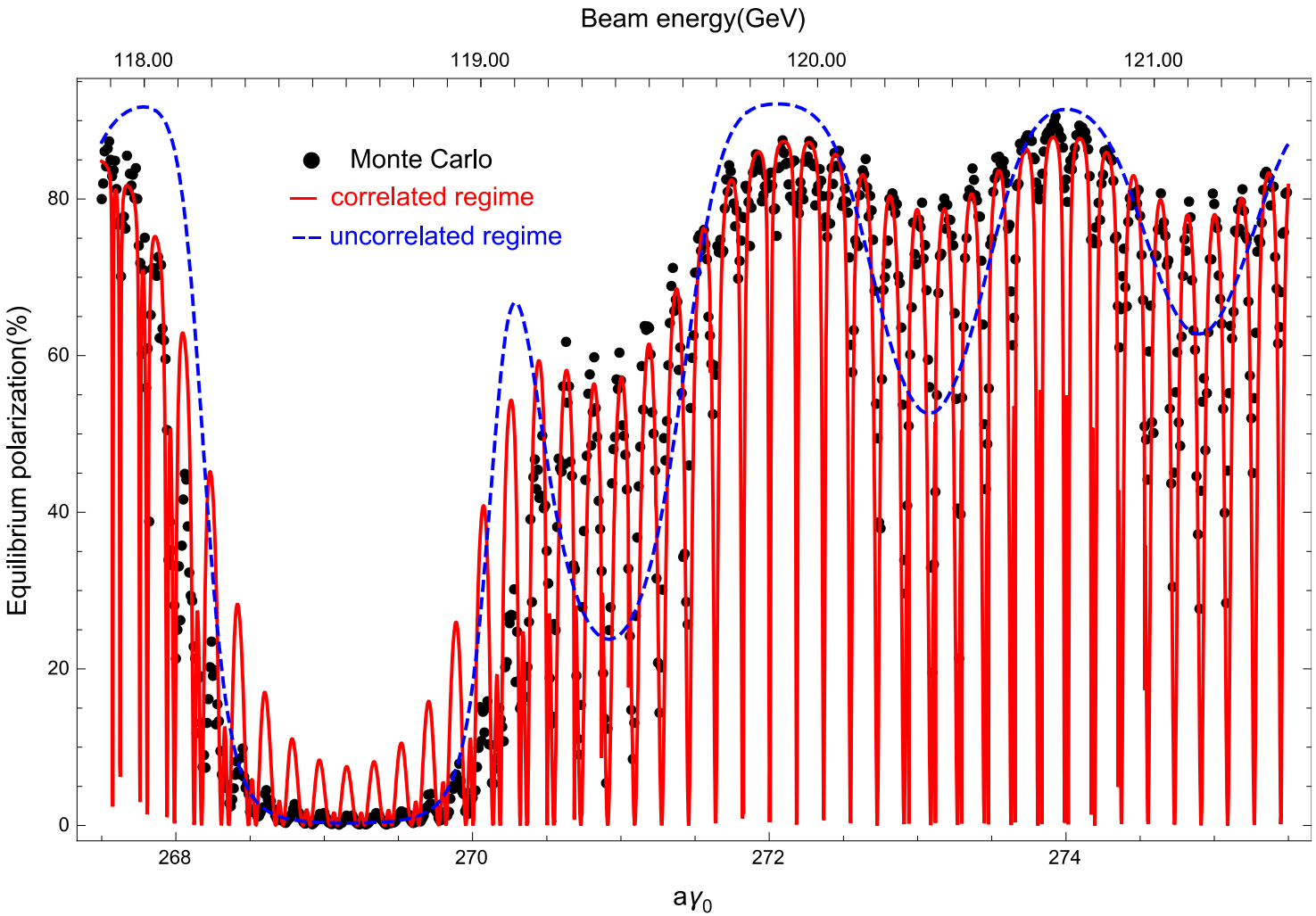
Parameter	Case 1	Case 2
Circumference(m)	54752	54752
Beam energy(GeV)	120	150
$\nu_x/\nu_y/\nu_z$	193.084/193.218/0.181	193.088/193.216/0.162
Relative energy spread	1.3×10^{-3}	1.64×10^{-3}
damping time(turns)	80/80/41	41/41/21
emittance(mm·mrad)	$6.26 \times 10^{-3}/1.92 \times 10^{-5}/2.8$	$9.78 \times 10^{-3}/2.92 \times 10^{-5}/4.9$
Sokolov-Ternov time(τ_p)(minute)	21.4	7.0
rms spin precession frequency spread(σ_ν)	0.358	0.560
modulation index(α)	3.921	11.986
correlation index(κ)	0.174	1.160

First order spin resonances

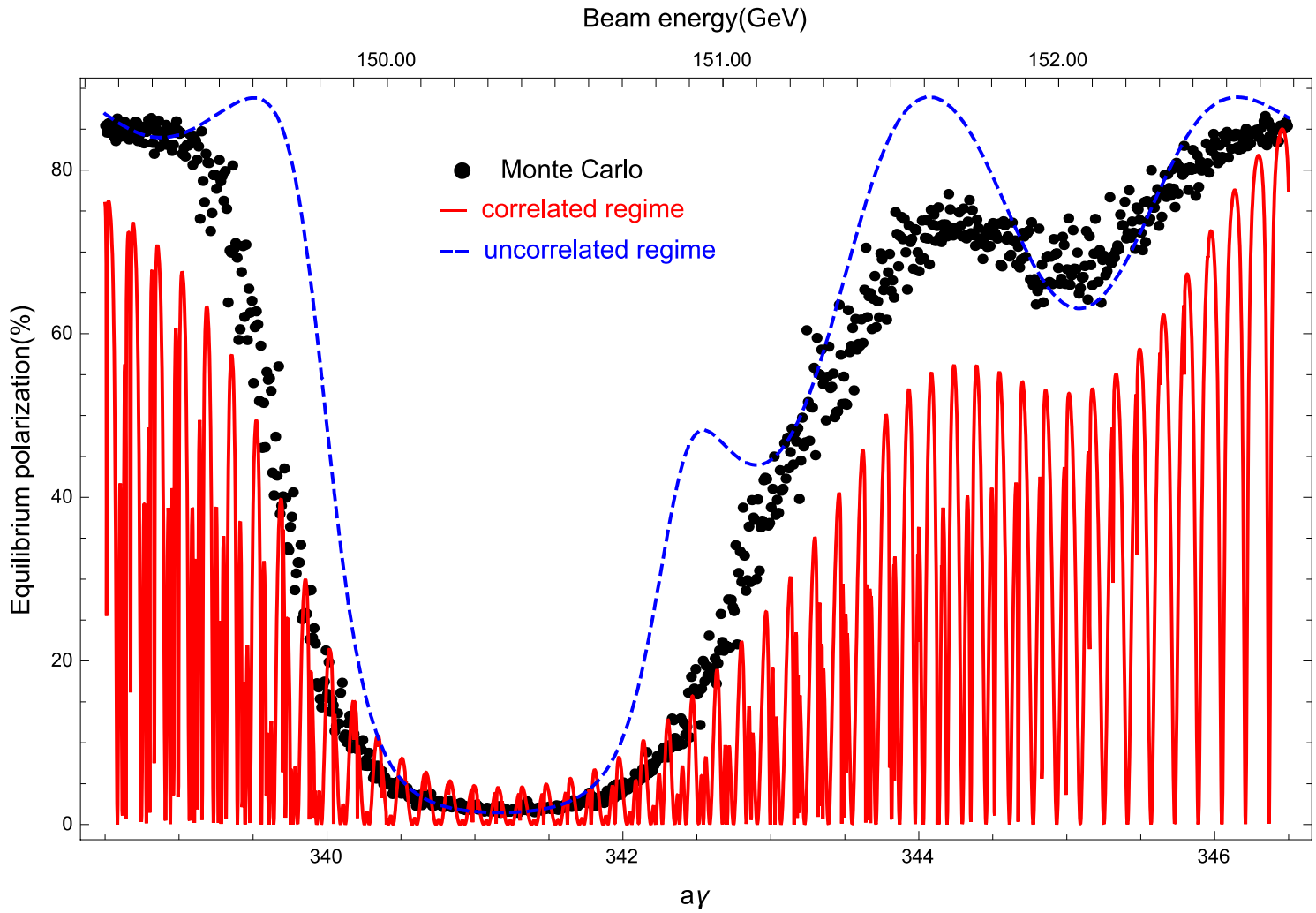




For Case 1, κ << 1


Beam energy(GeV)
118.00
119.00
120.00
121.00
Monte Carlo
correlated regime
uncorrelated regime
Equilibrium polarization(%)
0
20
40
60
80
268
270
272
274
$a\gamma_0$

For Case 2, κ > 1


Beam energy(GeV)
150.00
151.00
152.00
Monte Carlo
correlated regime
uncorrelated regime
Equilibrium polarization(%)
0
20
40
60
80
340
342
344
346
aγ

Discussions

- The simulation results support the theory of uncorrelated regime at ultra-high beam energies, CEPC@120 GeV is expected to be within this regime.
- This study shows there are some open questions to be answered theoretically, Klaus's talk introduced the status of their investigation, and more progress is expected.

Summary

- We've just started the CEPC polarized e+/e- program, and some key issues have been highlighted.
- I personally learned a lot in this workshop, and hopefully we could have more fruitful discussions in the future.