HKUST JOCKEY CLUB
INSTITUTE FOR ADVANCED STUDY
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Preliminary Studies of Beam Polarization in CEPC

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Outline

- Background
- Questions&Answers about Beam Polarization

  (As a beginner)

1) What is Polarization?

2) Why Polarization?

3) How to...?

   ...

- My Work in the Future
- Summary

Background

- Accelerators in the world with polarized beam[1].

Institution	Location	Machine	Acronym
BINP	Novosibirsk, Russia	VEPP-(2, 2M, 3, 4)	Colliding Electron - Positron Beams
BNL	Upton, NY, USA	AGS	Alternating Gradient Synchrotron
		RHIC	Relativistic Heavy - Ion Collider
CERN	Geneva, Switzerland	LEP	Large Electron - Positron Project
DESY	Hamburg, Germany	HERA	Hadron - Elektron Ring Anlage
ELSA	Bonn, Germany	ELSA	Electron Stretcher Accelerator
KEK	Tsukuba, Japan	KEK-B	KEK B-Factory
		KEK-PS	KEK Proton Synchrotron
MIT-Bates	Middleton, MA, USA	SHR	South Hall Ring
Orsay	Gif-sur-Yvette, France	ACO	Anneau de Collisions d' Orsay
SLAC	Palo Alto, CA, USA	SLC	Stanford Linear Collider
		SPEAR	Stanford Positron Electron Asymmetric Rings
JLab	Newport News, VA, USA	CEBAF	Continuous Electron Beam Accelerator Facility
...			

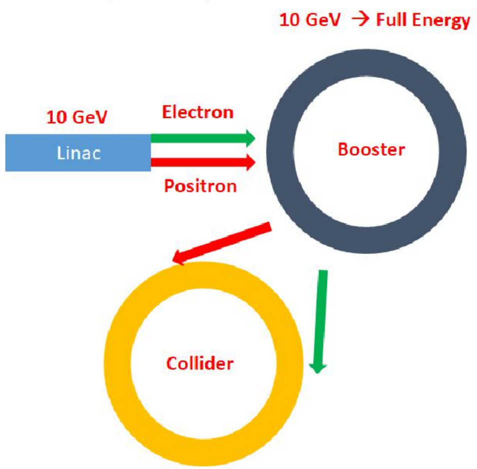
eRHIC,
FCC-ee,
JLEIC,
ILC,
Super-B,
Super-TC,
CEPC
...

[1]S R Mane et al 2005 Rep. Prog. Phys. 68 1997

Background

- **Nov 14,2018, The CEPC Study Group officially released the “CDR”.**

Mode	H($e^+e^-\to ZH$)	Z($e^+e^-\to Z$)	W($e^+e^-\to W^+W^-$)
Center-of-mass energy （GeV）	240	91	160
Luminosity ($cm^{-2}s^{-1}$)	3 $\times10^{34}$	32 $\times10^{34}$	10 $\times10^{34}$



CDR: Prof. Sergei A. Nikitin

Appendix 8: ” Opportunities for Polarization in the CEPC “

- **TDR in the future:**

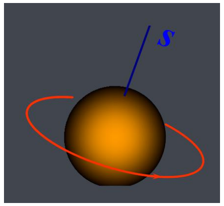
Scenario of obtaining and usage of polarization .

I got this opportunity: Research on key issues of beam polarization at CEPC.

What is Polarization?

All of the particle species accelerated in modern particle accelerators have spin. **Spin** is an intrinsic form of angular momentum .This immediately suggests the possibility of utilizing the particle spins as an additional experimental tool.

- **Spin & Polarization**



A spin **(S)**—a property of an individual particle.
Polarization **(P)** – a property of the entire beam.
i.e. The polarization vector is the statistical average of an ensemble of spin vectors. $\boldsymbol{P} = \langle \boldsymbol{s} \rangle.$

- **Analogy between Polarization& Emittances[2]**

Beam property	Damping	Diffusion	motion
Emittance	Radiation damping	Quantum excitation	Orbital motion
Polarization	Radiation polarization	Spin diffusion	Spin motion

Why polarization?

- **Transverse polarization**

Transversely polarized beams for energy calibration with resonant depolarization technique in precise experiment on Z-pole mass measurement .

The level of polarization：
About 10% is sufficient

- **Longitudinal polarization**

Case[3]: (In the late 1980s)

	SLC(L-polarized)	LEP
Luminosity	3 x 10^{30}	1 x 10^{32} (each of the four experiments)
Z^0 decays	~500 k	~5 million(each of the four experiments)

The level of polarization:
At least 40%~50%

Both can improve precision measurements!! Necessary !

How is Spin moving?

- **Spin motion**

According to Thomas-BMT equation [4]

$$\frac{\mathrm{d}\boldsymbol{s}}{\mathrm{d}t} = \boldsymbol{\Omega} \times \boldsymbol{s}. \quad \Omega = -\frac{e}{mc}\left[\left(a+\frac{1}{\gamma}\right)\boldsymbol{B}_{\perp} + \frac{a+1}{\gamma}\boldsymbol{B}_{\parallel} - \left(a+\frac{1}{\gamma+1}\right)\beta \times \boldsymbol{E}\right]$$

Where $a = \frac{1}{2}(g-2)$: the magnetic moment anomaly, i.e , the anomalous part of the particle g-factor

In a perfect planar storage ring, where $B = Be_3$.

$$\Omega = -\frac{e}{mc}\left(a+\frac{1}{\gamma}\right)\boldsymbol{B} = (a\gamma + 1)\,\omega_{\text{rev}}$$

ω_{rev} :the orbital revolution frequency.

$$\boldsymbol{P} = \langle \boldsymbol{s} \rangle.$$

ONLY the e_3 -component of polarization is preserved.

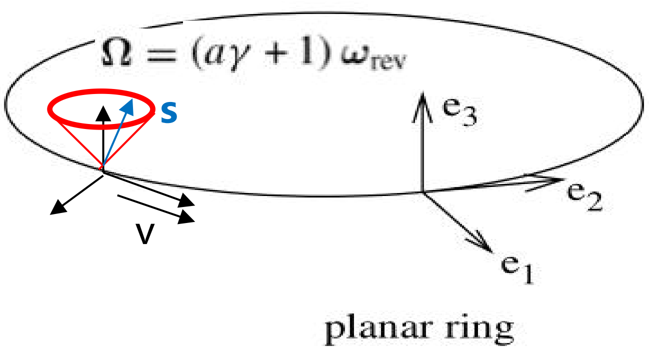
- **Spin tune**

The ratio of the spin precession frequency to the orbital revolution frequency.

In the "accelerator frame" , the spin precession is measured relative to the orbit , hence

$$\nu_{\text{spin}} = (\Omega - \omega_{\text{rev}})/\omega_{\text{rev}} = a\gamma$$

It is the simplest BUT most important equation in spin dynamics.



How to obtain polarization?

- **Polarized Particle Source**

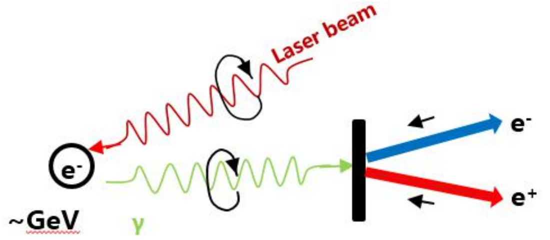
1) **Polarized electron source(R&D)**

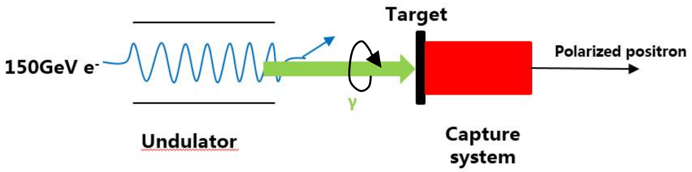
This polarized electron gun will enable the Linac to produce a high-intensity and low-emittance beam with high polarization.

Design parameters of CEPC polarized electron source[5] .

DC Gun	
Gun type	Photocathode DC gun
Cathode	Super-lattice GaAs photocathode
High Voltage of Anode	200~350kV
Polarization	>80%
Electron per bunch	2×10^{10}
Quantum efficiency	0.5%
Repetition rate	50Hz
Drive laser	790nm（±20nm），10μJ@1ns

2) **Polarized positron source(R&D)**



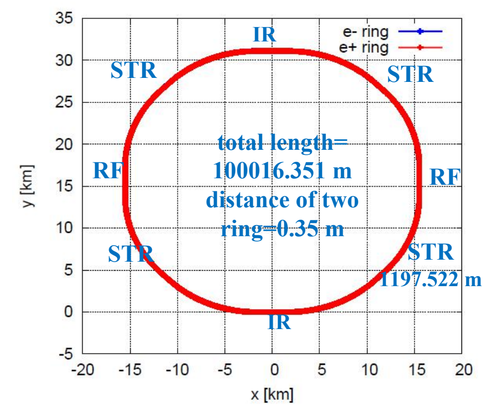


How to obtain polarization?

- **Radiative self-polarization**

According to Sokolov-Ternov effect[6], relativistic electrons in a storage ring emit synchrotron radiation. A very small fraction of the radiated photons cause spin flip.

In a perfect planar storage ring, for a beam initially unpolarized, the time dependence for build-up to equilibrium is ($\hat{n}$ is the direction of equilibrium beam polarization)



$$P(t) = P_0(1 - e^{\frac{-t}{\tau_p}})$$

$$\hat{n} = -\hat{e}_3$$

$$spin\_tune = a\gamma$$

$$P_0 = 92.38\%;$$

The time constant $\tau_p^{-1} = \frac{5\sqrt{3}}{8} c \lambda\!\!\!^{-}_e r_e \frac{\gamma^5}{\rho^3}$**, CEPC @Z-pole(w/o dep.),**

Straight lines ⟶ $\frac{1}{\rho^3} \rightarrow \oint \frac{1}{|\rho(\theta)|^3} \frac{d\theta}{2\pi} = \frac{1}{2\pi R} \oint \frac{1}{|\rho(s)|^3} ds$, isomagnetic fileds

$$R = 15.9 \times 10^3 m, (\text{the average machine radius})$$

$$\rho = 10.9 \times 10^3 m, (\text{bending radius})$$

$$\tau_p \approx 2.74 \times 10^{-2} \frac{\rho^2[m]R[m]}{E^5[GeV]} \approx 262.53h$$

That is a long time. We need to speed up it.

[6]A.A. Sokolov, I.M. Ternov, Sov. Phys. Dokl. 8 No.12 (1964) 1203.

How to speed up polarization?

- **Wiggler magnets @CEPC Z-pole[7]($B_0 \approx 0.013\mathrm{T}, < B_0 > \approx 0.01\mathrm{T}$)**

1) Polarization time with N_w wigglers

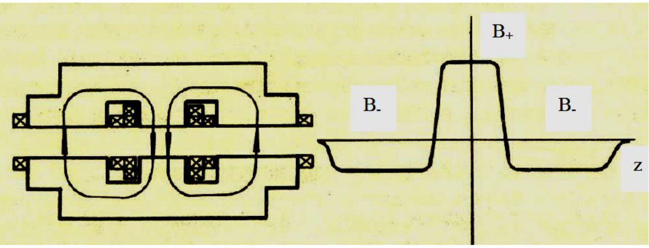
$$\tau_p^w = \tau_p \left[1 + N_w \frac{B_+^3 L_+ + 2|B_-|^3 L_-}{2\pi R \langle B_0 \rangle B_0^2} \right]^{-1}$$

2)Fraction of radiation energy loss enhancement

$$u = N_w \frac{B_+^2 L_+ + 2B_-^2 L_-}{2\pi R \langle B_0 \rangle B_0}$$

3) Factor of beam energy spread enhancement

$$\frac{\Delta E_w}{\Delta E} = \left[\frac{\tau_p}{\tau_p^w} \cdot \frac{1}{1+u} \right]^{1/2}$$



$$\int B_w dl = 0, \quad \int B_w^3 dl \neq 0, |B_+|^3 >> |B_-|^3$$

N_w	B_+	L_+	B_-	L_-	$\frac{\tau_p}{\tau_p^w}$	u	$\frac{\Delta E_w}{\Delta E}$	$\frac{P_0^w}{P_0}$
10	0.6T	1m	0.15T	2m	13.4	0.34	3.2	0.99

4) Equilibrium beam polarization with N_w wigglers

$$P_0^W = \frac{e}{|e|} \frac{8}{5\sqrt{3}} \frac{\oint ds/\rho^3(s)}{\oint ds/|\rho^3(s)|} = \frac{1 + N_w \frac{B_+^3 L_+ + 2B_-^3 L_-}{2\pi R \langle B_0 \rangle B_0^2}}{1 + N_w \frac{B_+^3 L_+ + 2|B_-|^3 L_-}{2\pi R \langle B_0 \rangle B_0^2}}$$

5)

$$P(t) = P_0^w (1 - e^{\frac{-t}{\tau_p^w}})$$

$$\tau_p^w = 19.6h, t = 2.3h, P_0^w = 0.913,$$

$$P(t) = 10\%$$

10% polarization is enough for energy calibration .

How to use polarization?

- **Resonant depolarization technique**

Resonant depolarization is the most accurate method of calibrating the beam energy **in storage rings** with vertical polarized beams.

According to Froissart–Stora formula[8]

$$\frac{P_f}{P_i} = 2\,e^{-\pi\epsilon^2/(2|\alpha|)} - 1.$$

This formula shows the exact analytical solution for the depolarization of a spin polarized beam caused by the crossing of a single resonance driving term.where ε is the resonance strength, and α is the crossing speed.

Types of resonances(@CEPC booster 10~45GeV/440.65MeV)

Imperfection resonances:

$$a\gamma = \nu_{spin} = k,$$

Intrinsic resonances:

$$a\gamma = \nu_{spin} = k \pm \nu_y,$$

$$a\gamma = \nu_{spin} = k \pm \nu_x$$

(Snake resonances ...)

About 80 imperfection spin resonances and 320 intrinsic resonances on way from 10 to 45GeV .

[8]Froissart M and Stora R 1960 Nucl. Instrum. Methods A 7 297–305 (in French).

How to use polarization?

Symbol	Anomaly $a = \frac{1}{2}(g-2)$	Accuracy	Mass (MeV)	$\Delta E = mc^2/a$ (MeV)
$e^{\pm}$	$1.159\,652\,1859 \times 10^{-3}$	$\pm 3.8 \times 10^{-12}$	510.9989×10^{-3}	440.65
$\mu^{\pm}$	$1.165\,9208 \times 10^{-3}$	$\pm 6.0 \times 10^{-7}$	105.658	90 622.24
p	1.792 847 351	$\pm 2.8 \times 10^{-8}$	938.272	523.34
d	−0.142 9878	$\pm 5.0 \times 10^{-7}$	1875.613	13 117.30

- **Resonant depolarization technique**

The basic idea is as follows:

$$\nu_{\text{spin}} = a\gamma$$

Since the values of **a** are known to great accuracy[9], by measuring the spin tune, one can deduce the value of γ to a high precision. From a knowledge of the electron mass, one can then calibrate the beam energy to high accuracy.

Specific steps:

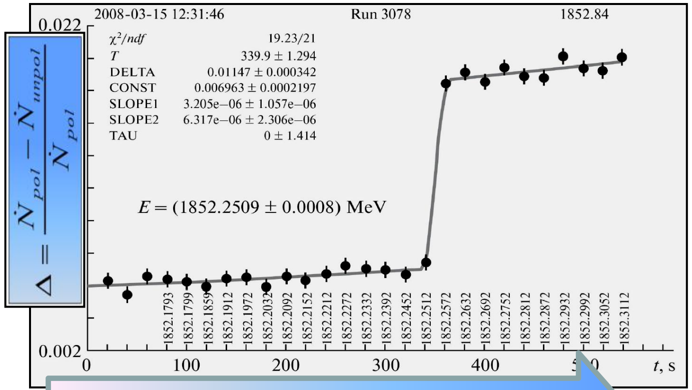
A radio-frequency magnetic field is applied in the horizontal plane to kick the spins. The frequency for the kicks to act coherently on the spins is one of the two possibilities

$$f_{\rm rf}^{+} = (a\gamma - k)\, f_{\rm c}, \qquad f_{\rm rf}^{-} = (k - a\gamma)\, f_{\rm c}$$

Where k is an integer . f_c is the orbital revolution frequency.

The frequency of the kicker $f_{\rm rf}$ is swept across the resonant value, when the kicker frequency is close to the resonant frequency, depolarization occurs.

How this does at VEPP-4M



Scanning the depolarizer frequency

Resonant depolarization= Imperfection resonances

=External spin resonance+aγ

[9]S R Mane et al 2005 Rep. Prog. Phys. 68 1997

How to measure polarization?

Møller polarimeter

The scattering cross-section is spin-dependent, hence the particle loss rate depends on the beam polarization. The particle loss rate is linear in P^2 **[10]**

$$\dot{N} = -\frac{N^2 c}{\sqrt{2} V \gamma^2 \sigma_{x'} \sigma_{y'}} (a + bP^2)$$

Here **N** is the total number of particles in the beam, **V** the volume of the beam and **a** and **b** are suitably defined functions. $\sigma_{y'}$ is the vertical rms divergence . the radial rms divergence is $\sigma_{x'}$

VEPP-2, ACO, VEPP-2M, VEPP-4, VEPP-4M …

Compton polarimeter:

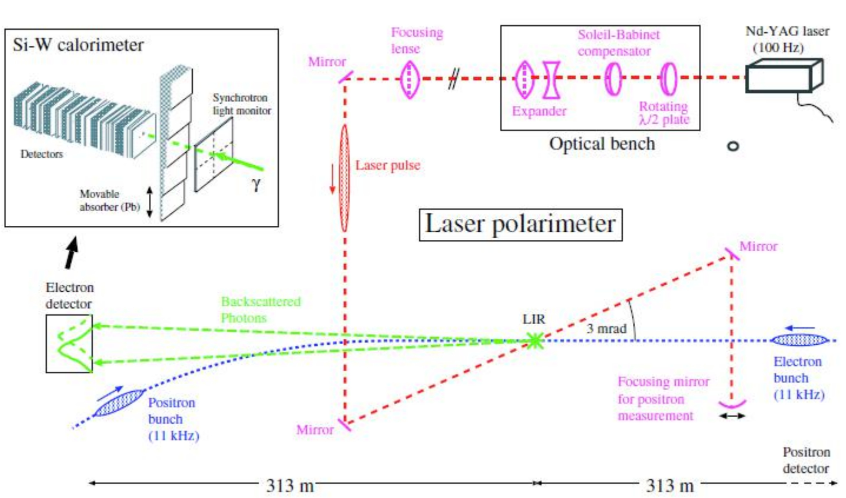
Laser polarimeter:

SPEAR , VEPP-4, LEP →→→ →

→→→ → **FCCee, CEPC**

A beam of circularly polarized laser photons is shot at the electron (or positron) beam, and the backscattered photons are detected.

Figure:Schematic of the LEP polarimeter



How to rotate spin?

- **Siberian snakes**

A Siberian Snake is theoretically defined as a device which rotates a particle spin through 180 ◦ around an axis in the horizontal plane, while leaving the orbital motion unaffected. It can overcome resonances.

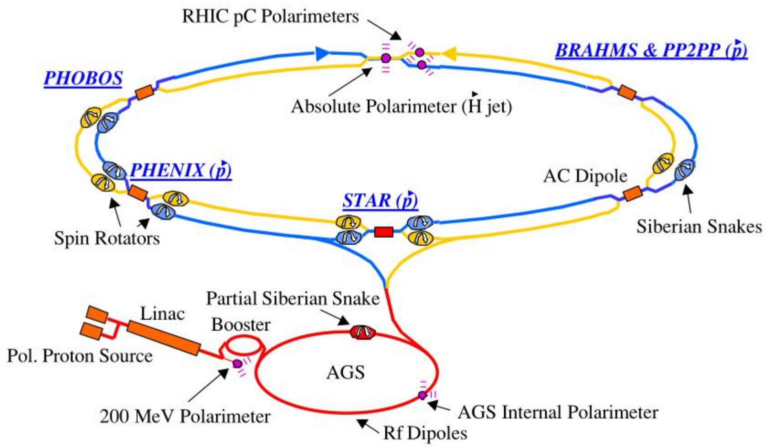
Why are such devices so named?

Firstly, the basic idea was proposed by Derbenev and Kondratenko who were then at the Institute of Nuclear Physics at Novosibirsk in **Siberia** .

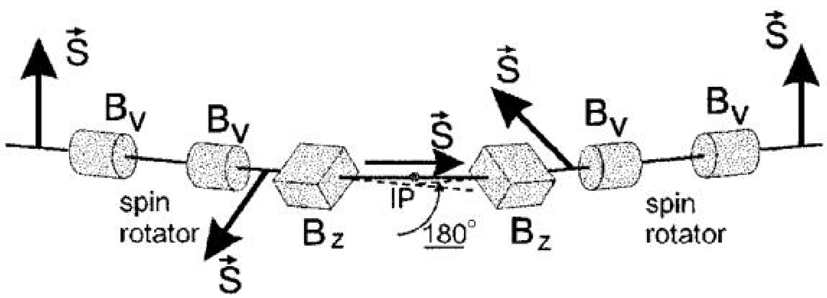
Secondly, the orbit excursions twist like a **snake** in this device.

- **Spin rotators**

Spin rotators are used to rotate the polarization direction from the vertical to the horizontal plane, and back again. Most particle physics experiments with polarized beams in colliding beam accelerators require longitudinally polarized beams.



Schematic layout of BNL complex for polarized proton operations.[11]



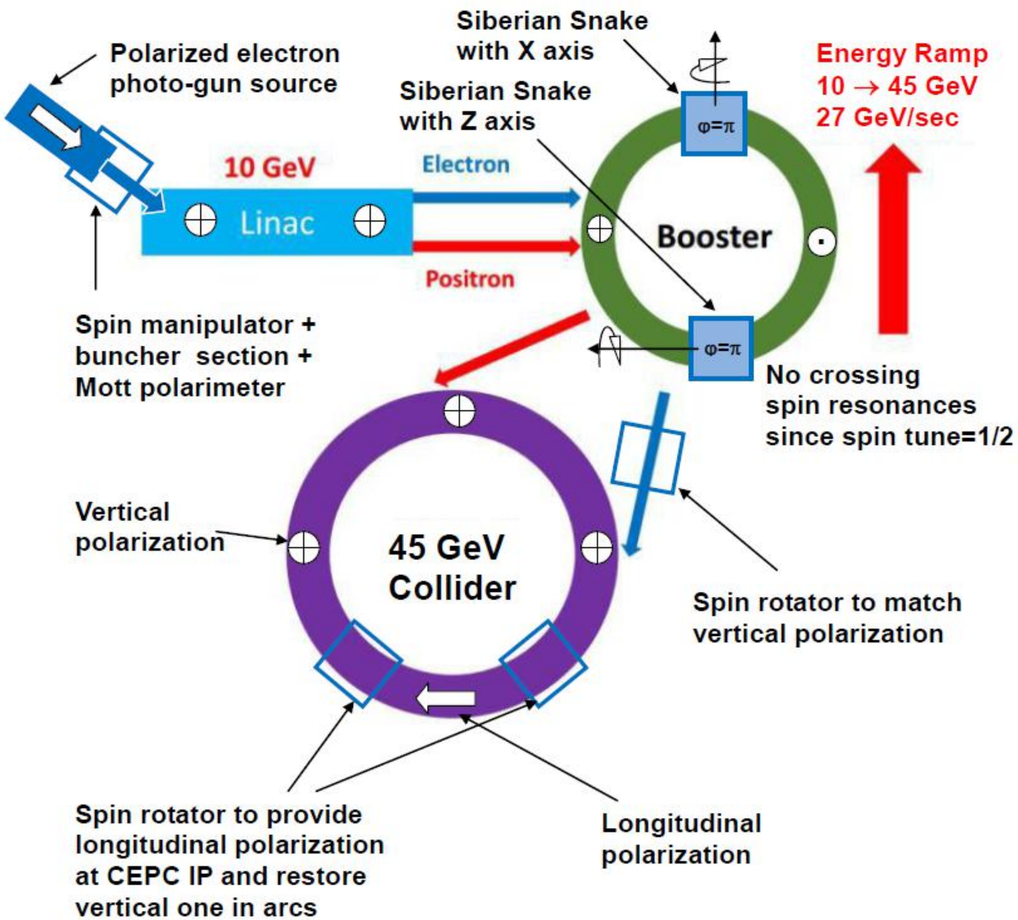
Schematic design of a proposed solenoid spin rotator for e + e − colliding beams at VEPP-4.[12]

[11]T. Roser, AIP Proc. 1149 (2009) 180; H. Huang et al, ibid. 767.

[12]Derbenev Ya S et al 1977a Proc. 5th Russian Conf. on Charged Particle

My work in the future

- **Cardinal Option of longitudinal polarization[13]**



1) A source of polarized electron beam is required.
Beam intensity may be lower.

2) Polarimeters are required.

3) Siberian Snakes are needed during beam acceleration .

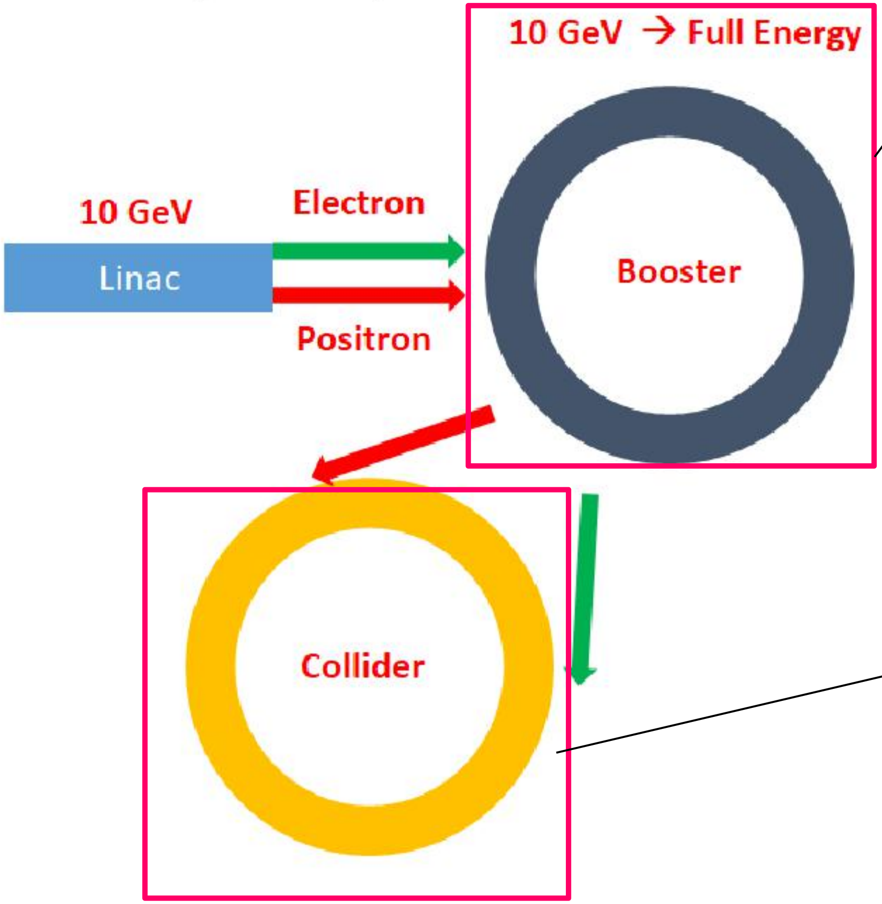
4) Spin rotators are needed to provide longitudinal polarization at IP.

(My work in the future)

[13]S.A. Nikitin "On opportunities to obtain and use polarization at CEPC" ,2017

My work in the future

- **Questions to be answered**



- **To overcome/avoid depolarization during acceleration:**

1) How many Siberia Snakes?
2) Which type of Snakes?
3) Where to insert Snakes?
4) How to overcome higher-order spin resonances?
5) How to minimize orbit excursion in the Snakes?
6) …

- **To speed up the process of radiate self-pol:**

1) How many wigglers ?
2) What are the parameters of wigglers?
3) Where to insert wigglers?
4) …

- **Longitudinal Polarization at IPs:**

1) Which type of Spin rotators?
2) Where to insert rotators?
3) …

Summary

- Polarized electron/positron beams are needed at CEPC to do beam energy calibration and polarization-dependent physics experiments.

- I have learnt some basic theoretical knowledge about beam polarization. For example , Thomas-BMT equation , Sokolov-Ternov effect , Froissart–Stora formula and so on.

- I did some simple calculations with parameters of CEPC. It takes a lot of time to obtain polarization with radiative self-polarization. Special wiggler magnets can speed up this progress.

- My work in the future:

1. To insert wigglers into the collider ring to speed up radiative self-polarization progress for beam energy calibration .
2. To overcome/avoid depolarization during acceleration at booster.
3. To realize the collision of the longitudinally polarized beams at the IPs.

A lot of work need to be done. Work hard!

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Thank you for your attention!