Summary of
Beam Polarization in Future Colliders
Mini-Workshop

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Conference at IAS Program of High Energy Physics,
Hong Kong University of Science and Technology
January 7-25, 2019

About Mini-Workshop

- **General topic**
  - “Polarized Beams: A Brief History and Future Prospect” by Yaroslav Derbenev (JLab)
- **Machine Overview**
  - “Introduction to CEPC “ by Jie Gao (IHEP)
- **e+e- colliders at low to medium energy**
  - “BINP's Polarization Proposal for Tau-Charm Factory” by Ivan Koop (BINP)
- **e+e- collider at energy frontier**
  - “Resonant Depolarization at Z and W Beam Energy” by Ivan Koop (BINP)
  - “Polarized Electron and Positron Beams in CEPC” by Zhe Duan (IHEP)
  - “Preliminary Studies of Beam Polarization in CEPC” by Wenhao Xia (IHEP)
- **e-p and e-A colliders**
  - “Beam Polarization in Future Colliders (eRHIC and FCC-ee)” by Eliana Gianfelice-Wendt (FNAL)
  - “JLEIC Electron Beam Polarization” by Yuhong Zhang (JLab)
  - “Spin Matching in Electron (Positron) Rings” by Vadim Ptitsyn (BNL)
- **Electron/positron sources**
  - “ILC Polarized Electron and Positron Sources” by Kaoru Yokoya (KEK)
- **Polarimetry**
  - “Overview of Electron Polarimetry” by David Gaskell (Jlab)
  - “Design of the Beam Polarimeter for FCC-ee” by Nikolai Muchnoi (BINP)
- **Code development and simulations**
  - “Code Development and Simulation Studies of Polarized Beams” by Francois Meot (BNL)
  - “Re-evaluation of Spin-Orbit Dynamics of Polarized e+e- Beams in High Energy Circular Accelerators and Storage Rings: Bloch Equation Approach” by Klaus Heinemann (Univ. of New Mexico)

"Polarized Beams: A Brief History & Future Prospects" by Ya. Derbenev (JLab)

I. Foundations and problems

- *Polarization sources*
- Thomas – BMT spin equations
- Spin in conventional rings
- Compensated spin rotators
- Resonance depolarization
- Crossing the spin resonances
- ZGS + AGS proton spin acceleration
- BST radiative polarization
- Orlov' depolarization

II. Polarization canonical theory

III. Siberian Snakes

- SS idea and demonstration
- SS techniques
- SS utilization and success in RHIC
- Multiple SS for SSC

IV. Spin-compensated quads

V. Figure 8 synchrotron

VI. Polarized EIC

- Fixed orbit e-spin rotator and snake

VII. Future polarized beams

- **Polarized LHC?**
- **Polarization ideas for CEPC:**

Snakes

Bending snakes

Achromatic snakes

Flipping spin rotators

- **Polarization ideas for 75 TeV PPC**

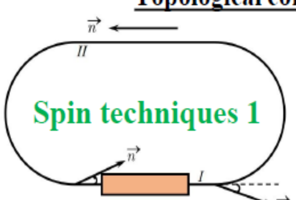
Many snakes

Spin-compensated quads

"Siberian Snakes": making *Spin Echo* in racetracks…

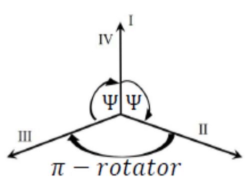
Cancellation idea of spin global precession over the racetrack orbit:
instead of reversing the arcs, let us make *reverse of spin*…!
by inserting local spin flip about a horizontal axis

Topological compensation of spin precession over arcs



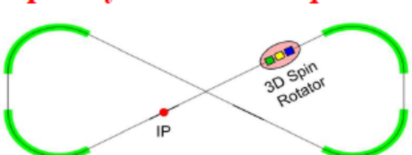
Solenoid as π – rotator

Spin echo effect is obviously extendable to any π – *rotator* around ***an arbitrary horizontal axis***

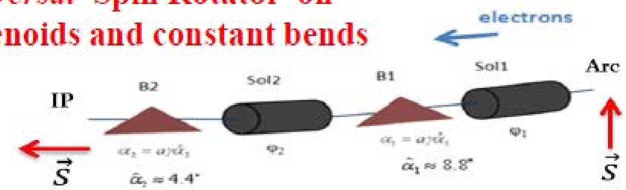


Spin Techniques 1

Twisted Spin Synchrotron: *Spin Echo*



Universal Spin Rotator on solenoids and constant bends



Thoughts on Beam Polarization delivery in CEPC

Option I: Use **Polarized e-gun (electrons only…)**

- Stacking and accelerating for injection to collider ring
- Acceleration and maintenance of PEB in the Collider Ring

Option II: **BST polarization in the Collider Ring (at injection energy…or in booster ring…?)**

- Takes Polarizing Wigglers to facilitate BST
- Luminosity run at wigglers off

Spin Rotators for CEPC.1.

Fixed orbit SR on dipoles and solenoids for CEPC

$(S_y = 1)$ | α_{x1} | α_{y1} | φ_{z1} | $\alpha_{x2} - \alpha_{x1}$ | α_{y2} | φ_{z2} | $-\alpha_{x2}$ | $(S_z = 1)$

Spin Rotators for CEPC. 2.

Achromatic Rotator on transverse fields

$(1^{st}$ Arc, $S_y = 1)$ | α_{x1} | α_{y1} | $\alpha_{x2} - \alpha_{x1}$ | α_{y2} | $-\alpha_{x2}$ | (IP, $S_z = 1)$

“Polarized Beams: A Brief History and Future Prospects” by Ya. Derbenev

Thinking about Future 75 TeV Polarized Proton Beams. 1.

- **Figure 8 Booster in energy range below 30 GeV**
- **Snakes for the succeeding boosters**

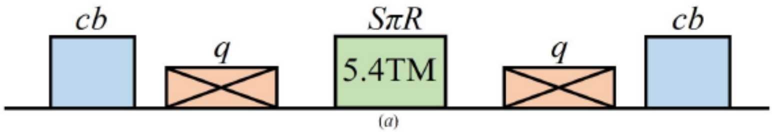
Options for the Collider Rings

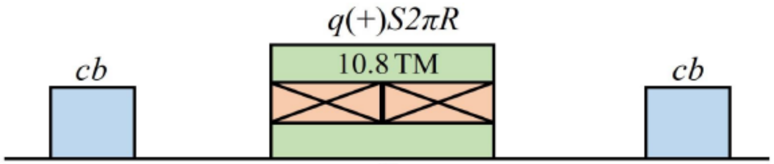
Option I **Many SS**

- Sufficient large chain of SS to suppress depolarizing impact of the superperiodic misalignment harmonics
- Spin tune ½
- Compensation of tune spread associated with beam emittance
- Spin response function to suppress the beam-beam depolarization

Thinking about Future 75 TeV Polarized Proton Beams. 2.

Option II: Spin-compensated quadrupoles





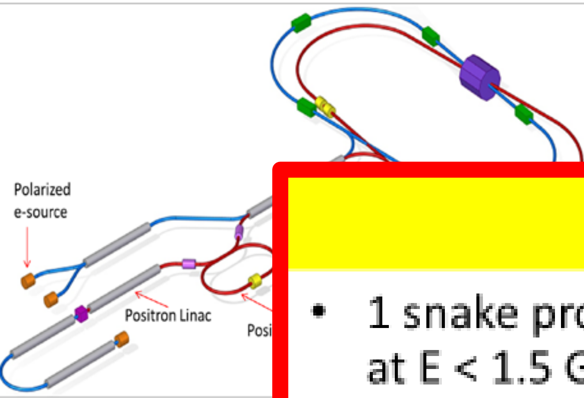
- **Two SS then will be enough to eliminate spin resonance crossing during the acceleration and stay away of the resonances through the luminosity run**
- **Think about spin flipping (if inquired); ideas on table…**

Thinking about Future 75 TeV Polarized Proton Beams. 1.

Preconclusion

- At this stage, our anticipation of successful design for future polarized beams is close to 100% optimism.

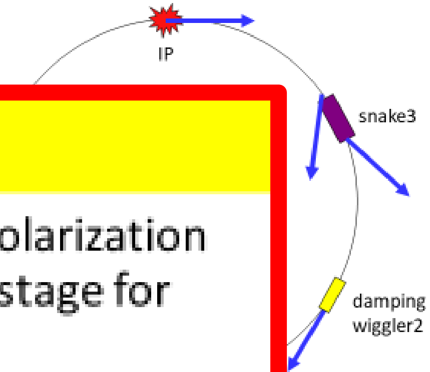
“BINP’s Polarization Proposal for Tau-Charm Factory” by I. Koop



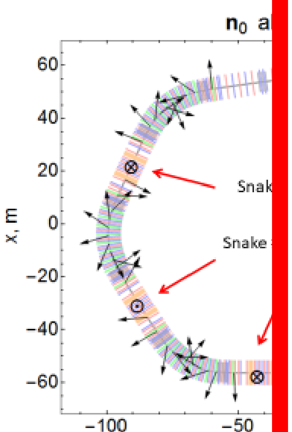
Outline

- BINP’s c-tau complex with the longitudinally polarized electrons.

Polarization scheme with 3 snakes (arc=120
+2 damping wigglers in the arc’s middle)

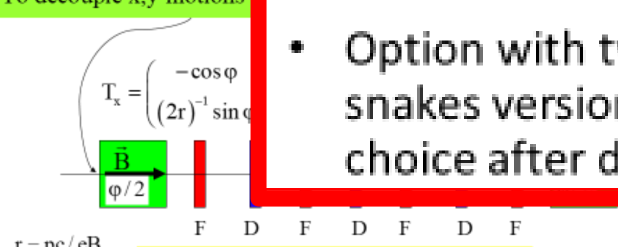


Polarization vector in B



Transparent sp

To decouple x,y-motions

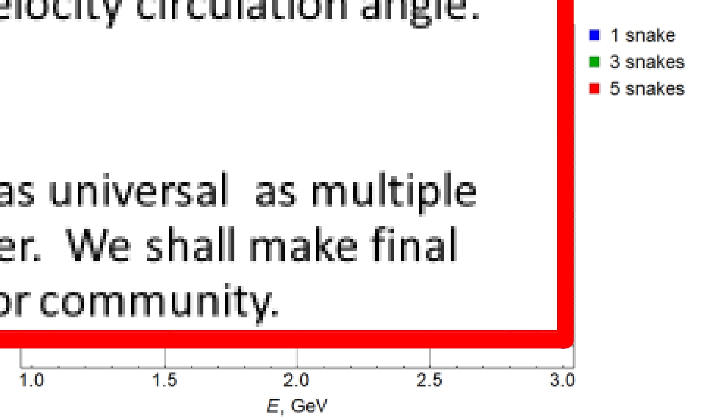


Two solenoids rotate spin by the total angle φ

Conclusion

- 1 snake provides up to 80% - 90% of the longitudinal polarization at E < 1.5 GeV. This option can be considered as a first stage for polarization program.
- 3 snakes provide sufficiently high polarization degree, about 75-90% in the energy range E < 2.5 GeV and only about 50% at 3 GeV. Currently this is the main scenario because it fulfils to the main physics program requirements.
- 5 snakes option requires different optimization of a ring layout to place snakes uniformly in terms of the velocity circulation angle. Now not under consideration.
- Option with two 90^0 spin rotators is not as universal as multiple snakes version, but its price is much lower. We shall make final choice after discussions with the detector community.

, τ_{rad}



"Resonant Depolarization at Z and W Beam Energy" by I. Koop

Outline

- Resonance Depolarization studies by spin tracking
- Spi
- Self
- Pro

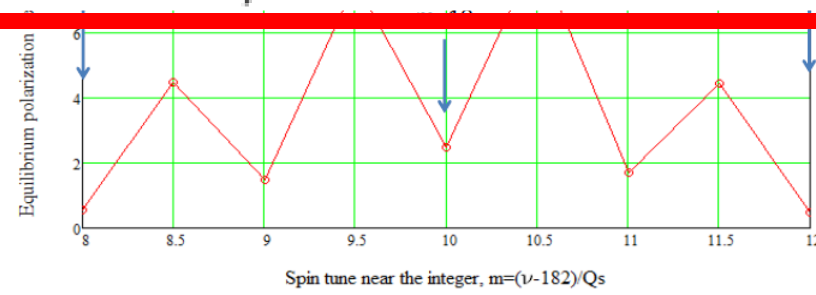
- Beam emittances in CEPC/FCCee are so small that all resonances with betatron frequencies are suppressed and their influence on the spin motion is negligible

Spi

Res

Conclusion

- Spin tracking of a motion of a single particle reveals the dependence of the spectrum line width from the synchrotron tune and other beam parameters.
- This width becomes very large for chosen synchrotron tune Qs=0.05 at W and the standard RD procedure becomes not applicable.
- The discussed above new RD procedure (by steps) works well even in cases when a width of the spin resonance became very large. That is just the case with Qs=0.05. Still the accuracy of a method needs to be studied further.
- Second order terms in orbital motion also contribute to the line width (I.Koop, Yu.Shatunov, in proc. EPAC 1988, Rome, p.738-739). See also the talk on systematic errors from A.Bogomyagkov: tomorrow, WG7.



Polarized electron and positron beams at CEPC by Zhe Duan

Outline
- Motivation
- Prospect and challenges
- Equilibrium beam polarization simulations

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Prospects and challenges
- Energy calibration w/ resonant depolarization
  - A detailed time diagram of operation with asymmetric wigglers
  - Complexities in energy calibration @ W
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Discussions

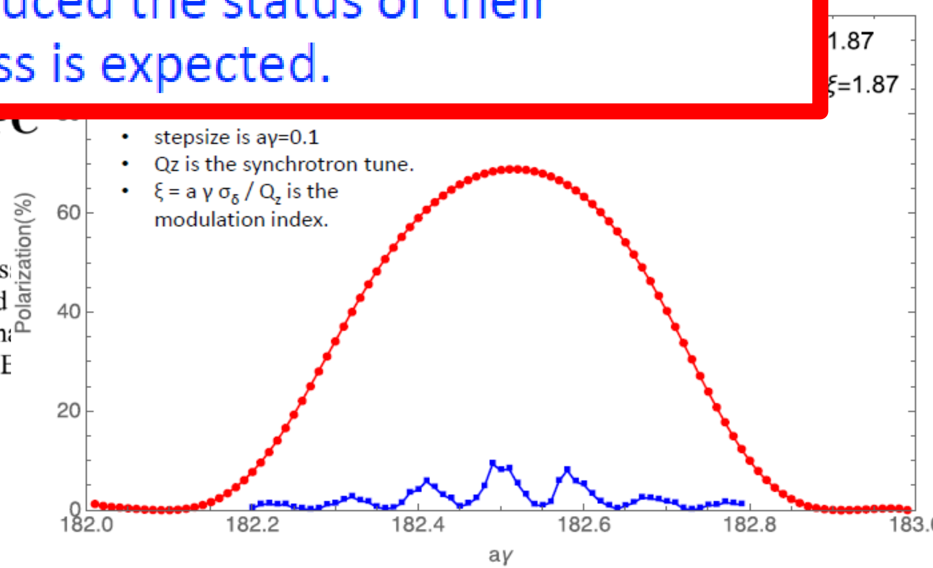
- The simulation results support the theory of uncorrelated regime at ultra-high beam energies, CEPC@120 GeV is expected to be within this regime.
- This study shows there are some open questions to be answered theoretically, Klaus's talk introduced the status of their investigation, and more progress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

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 mas the Z using resonant depolarization [1]. To achieve this goal one needs a method obtaining polarized electron and positron beams. In this appendix we consider the ma issues for obtaining the radiative self-polarization of particles with the current CE design parameters at 45 GeVand at 80 GeV.

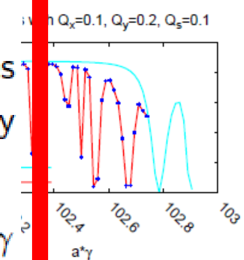
S. Nikitin

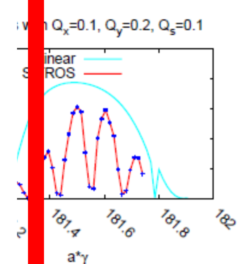


Beam P… eRHIC

Summary for FCCee

- Due to the demanding IR optics design and the machine size, establishing a closed orbit and keeping a stable machine look challenging.
  - Even for an extremely well corrected orbit polarization may reserve surprises, however means have been found for meeting polarization requirements at 45 and 80 GeV beam energy.
- The long τ_p at 45 GeV and short lifetime in collision call for a strategical plan for polarization measurement (see M.Koratzinos IPAC15 contribution):
  - Use of *non-colliding bunches*.
  - Wigglers turned on for the time needed for polarizing the non-colliding bunches while the machine is filled.
  - Exhausted pilote bunches must be immediately replaced (top-up injection needed anyway) so that they get naturally polarized.
- It must be proven that the required calibration precision can be reached. This implies a careful review of all possible biases (see Amsterdam FCC week contributions by A.Bogomyagkov and T.Tydecks):
  - Experiment solenoids, vertical closed orbit and electric fields break the $\nu_s = a\gamma$ relationship.
  - Sawtooth effect.
  - Difference between the energy of non-colliding and colliding bunches.
  - Difference between measured energy and CM energy.
- Energy needs to be monitored routinely.
- Double ring $\rightarrow$ both beams energy needs to be monitored.





Preliminary Studies of Beam Polarization in CEPC by Wenhao XIA

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

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.

Beam Polarization in Future Colliders: FCC-ee and eRHIC
by Eliana Gianfelice-Wendt

Schematic view of the eRHIC electron accelerators chain

Simulations for the eRHIC storage ring

Summary for eRHIC storage ring

Polarization studies for the eRHIC storage ring are going on.

- With conservative errors $P_\infty \approx 50\%$ seems within reach:
  - for *upwards* polarized bunches (anti-parallel to the guiding field), $<P>\approx$ 80%., over 5 minutes if $P(0)$=85%;
  - for bunches polarized *downwards* the average polarization drops to 67%: they must be replaced more often.
- Luminosity working point requires linear coupling correction. Here the benefits of a *local correction* using 46 skew quadrupoles have been shown, but
  - the use of correctors for dispersion and of (fewer?) skew quads for betatron coupling correction is an alternative to be tried;
  - implementation of a knob for controlling the vertical beam size at IP w/o affecting polarization seems feasible.
- Comparisons with different codes (Bmad, PTC) are going on.
- Beam-beam effects need to be addressed.

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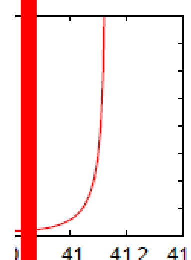
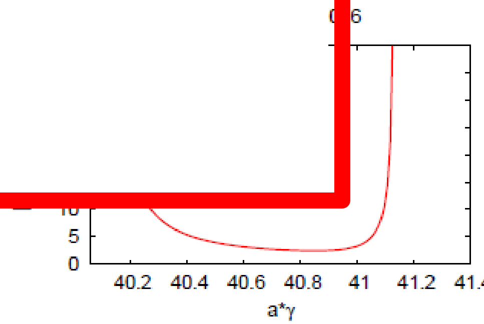
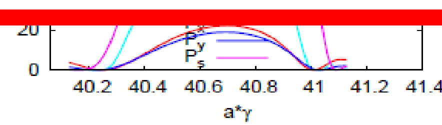
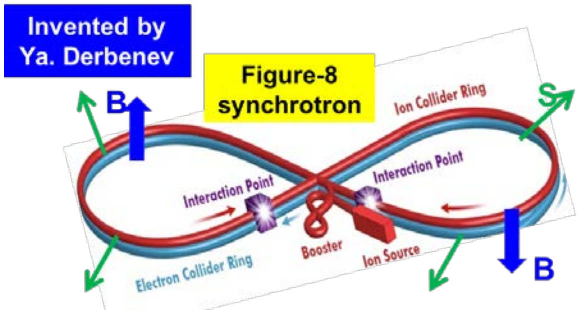


luminosity





JLEIC Electron Beam Polarization by Yuhong Zhang



Design concepts

- Figure-8 topology ➔ *Enabled by a green field collider ring design*
- Spin precessions in the left & right parts of a figure-8 ring *exactly cancelled* ➔ spin tune is *zero*
- Does not cross spin resonance during energy ramp
- Spin can be controlled and stabilized by compact spin rotators, no need of Siberian Snakes

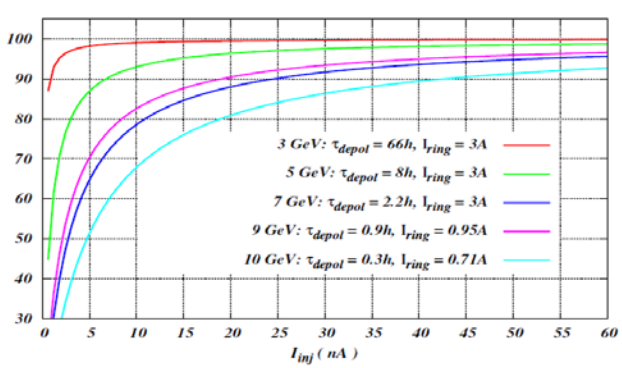
Summary

- JLEIC booster and collider rings have adopted a figure-8 shape for better preservation and control of polarization by taking advantage of a spin transparency mode
- Ion and electron polarization schemes have been designed.
- Spin tracking validated figure-8 based polarization control schemes for the whole JLEIC complex
  - Both ion and electron polarizations > 80% can be reached
- Spin transparency mode will be studied in RHIC

– Rotate spin to longitudinal in straights using spin rotators

- **Universal spin rotator**
  - Fixed orbit, energy independent, optics independent

Energy (GeV)	3	5	7	9	12
Lifetime (hours)	116	9	1.7	0.5	0.1



ILC Polarized Electron and Positron Sources by Kaoru Yokoya

Summary

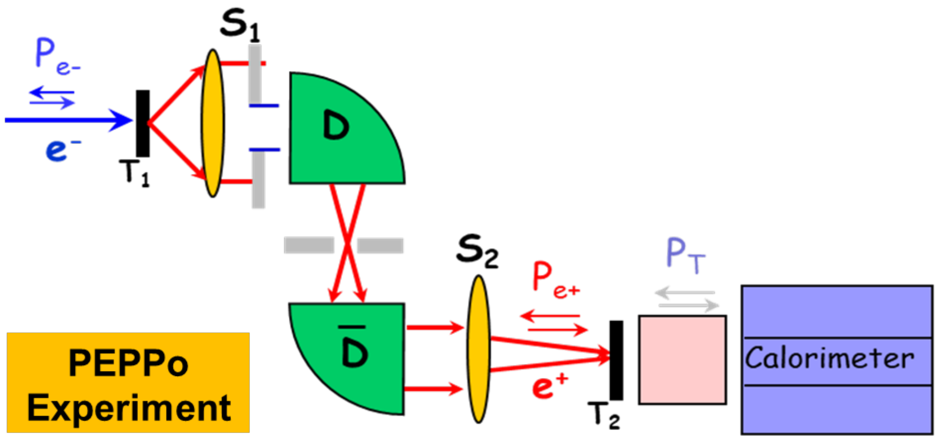
- Electron source
  - In good shape
  - ~90% polarization can be expected
  - Need some study on the laser
- Positron (undulator)
  - Many issues still remain
  - Water-cooled target → radiation-cooled target
  - FC → QWT
    - Serious design of QWT needed
  - Photon dump
  - Must select undulator or e-driven in early 2021
- Report by Positron WG (May 2018)
  - http://edmsdirect.desy.de/item/D00000001165115

Polarized Electrons for Polarized Positrons (PEPPo)

$\vec{e}^- \to \overset{\circlearrowleft}{\gamma} \to \vec{e}^+ \,(+\, \vec{e}^-)$

E.G. Bessonov, A.A. Mikhailichenko, EPAC (1996)
A.P. Potylitsin, NIM A398 (1997) 395

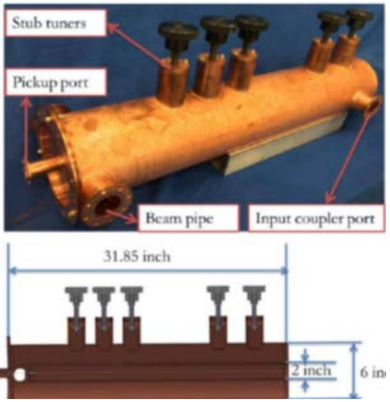
E.A. Kuraev, Y.M. Bystritskiy, M. Shatnev, E.Tomasi-Gustafsson, PRC 81 (2010) 055208

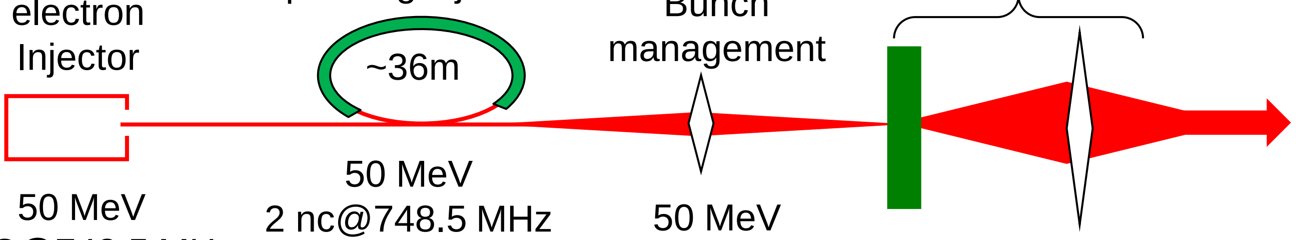


PEPPo Experiment

- PEPPo provides a new option for polarized positrons in a 10-100 MeV range
  - Pro: low neutron radiation
  - Con: low position yield (10^{-5} to 10^{-3})
- Mitigation of low current: Accumulation
  - "hot" positrons after conversion: hard to accumulate with large phase space distribution
  - "cold" electrons before conversion: easy to accumulate

Harmonic RF Kicker





Polarized electron Injector	Compact accumulator ring w/ 500-turn phase space painting injection	Bunch management	Positron conversion and collection	
50 MeV 4 pC@748.5 MHz 85% polarization	50 MeV 2 nc@748.5 MHz 85% polarization	50 MeV 2 nC@17 MHz 80% polarization	10^{-5} - 10^{-3} efficiency >60% in polarization	~30 MeV e^+ 1 pC @ 17 MHz > 60% polarization

Overview of Electron Polarimetry by Dave Gaskell (JLab)

Outline

- Overview of common electron polarimetry te
  - Mott scattering
  - Møller scattering

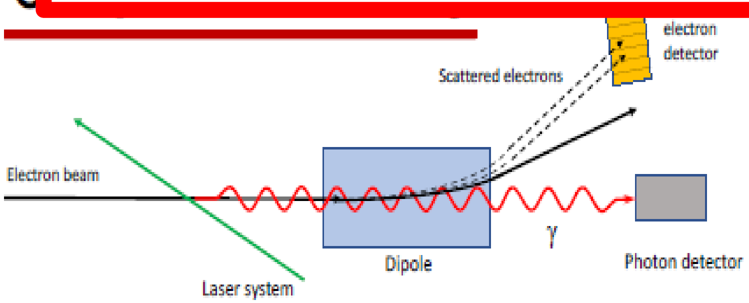
Electron Polarimetry Techniques

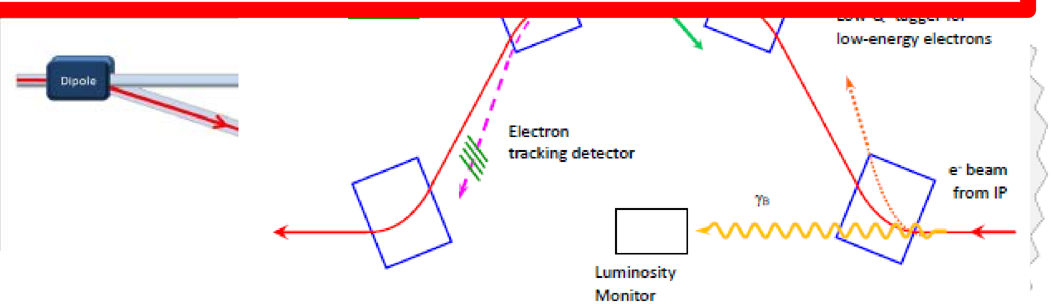
Common techniques for measuring electron beam polarization

- Mott scattering: $\vec{e} + Z \rightarrow e$, spin-orbit coupling of electron spin with (large Z) target nucleus
  - Useful at MeV-scale (injector) energies

Summary

- Several useful techniques for electron polarimetry
  - Compton polarimetry is commonly used in storage rings/colliders
  - Møller polarimetry may be possible using jet targets, but likely more R&D is required
- High precision has been achieved with Compton polarimetry with several devices in different accelerators
  - In general, highest precision has used electron detection for longitudinal polarization
  - High precision is possible for transverse Compton polarimeters, but less experience
- EIC will require precise measurements of both electron and hadron polarization
  - Compton polarimeter design for EIC will draw on experience from earlier devices
  - JLEIC (longitudinal) Compton polarimeter design based on successful JLab polarimeters
  - eRHIC Compton polarimeter will measure transverse polarization – important experience from HERA TPOL will prove valuable





Design of the FCC-ee Beam Polarimeter by Nickolai Muchnoi

Excerpts from FCC-ee CDR

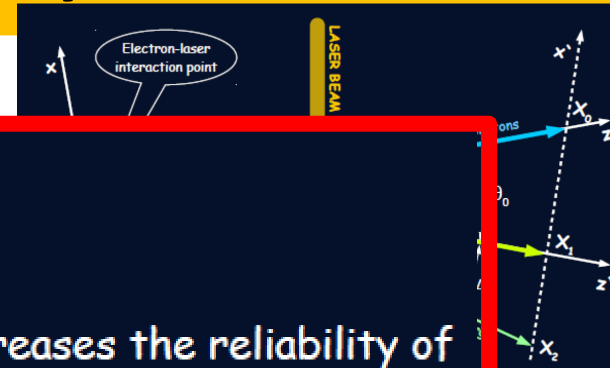
- Beam er… precise… ~100 ke…
- About 2… frequen…
- It is im… energy … asympt…
- E_{cm} nea… reconst… of the …

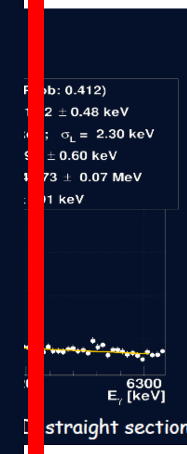
Polar…

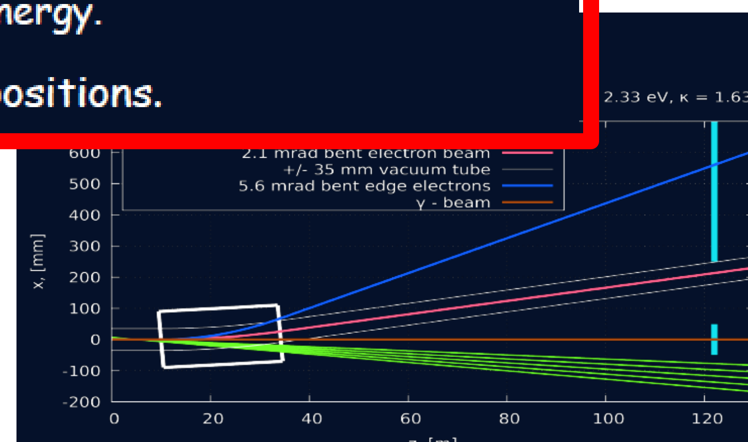
- Fast m… energy…
- Positiv…
- Known … polariz…
- Inverse Compton scattering is used for direct beam energy calibration at low-energy $e^{\pm}$ colliders: VEPP-4M, BEPC-II, VEPP-2000.
- Extend the latter experience for high energy colliders?

Summary

- Detecting both scattered photons & electrons increases the reliability of beam polarization measurement.
- FCC-ee polarimeter provides $\simeq 1$ % / s accuracy for $\zeta_\perp$.
- The beam energy spectrometer option does not require mandatory neither the B-field measurement nor the BPMs data:
  - statistical precision $\Delta E/E \simeq 100$ ppm / 10 sec;
  - systematic effects estimation requires further studies: yet no limitations;
  - test of the approach does not require high beam energy and should be performed with low emittance beam at low energy.
- Polarimeter allows to measure beam sizes & positions.







Blue bars – 2D silicon pixel detectors for scattered electrons & photons.

Code Development and Polarized Beam Simulation Studies by Francois Meot (BNL)

Contents

1 ZGOUBI
2 Hadron polarization at RHIC complex
3 Electron polarization in eRHIC
4 Hadron polarization in eRHIC
5 JLEIC EIC
6 Cornell-BNL CBETA FFAG ERL

Numerical integrator

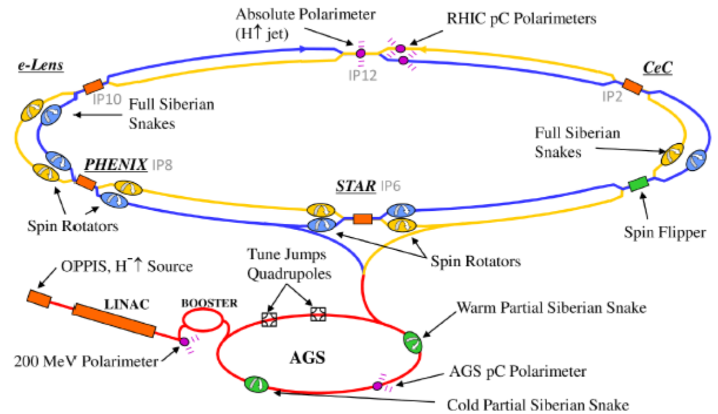
$$\frac{d(m\tilde{v})}{dt} = q\,\tilde{v} \times \tilde{b}$$

$$\frac{d\tilde{S}}{dt} = \frac{q}{m}\tilde{S} \times \tilde{\omega}$$

$$\left(\tilde{\omega} = (1+\gamma G)\tilde{b} + G(1-\gamma)\tilde{b}_{//}\right)$$

◇ Zgoubi was first written in 1972... 45^{+}yrs !

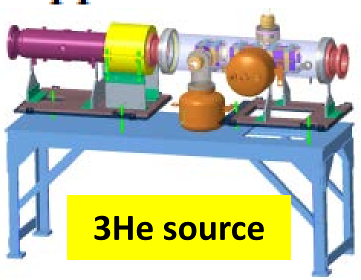
◇ Installed in sourceforge in 2007



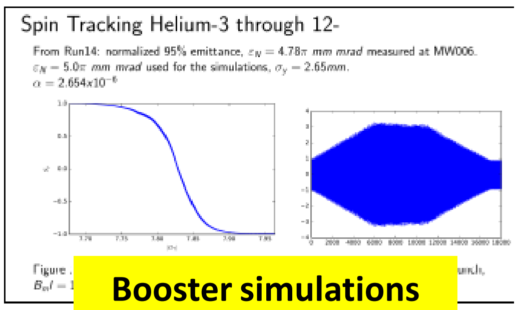
2 Hadron polarization at RHIC complex

- include p, He3
- start at the booster, and include AGS, AtR, RHI

support the eRHIC polarized ^{3}He project

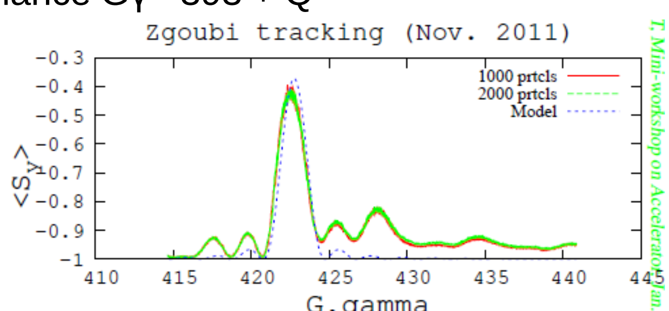


3He source



Booster simulations

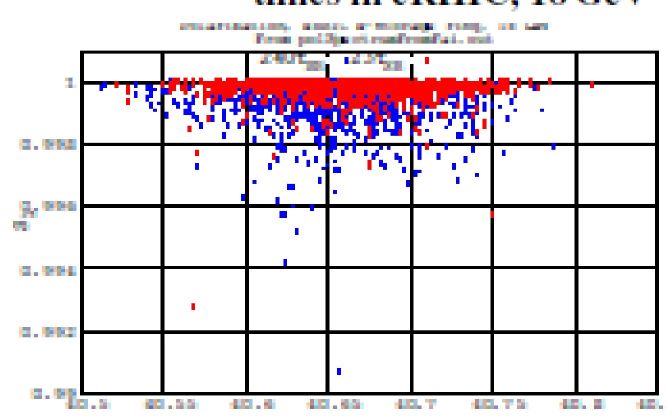
- Used over past 10 yrs to study polarization in RHIC.
- A benchmarking example: crossing the strong snake resonance Gγ =393 + Q



Electron polarization in eRHIC

Polarization lifetime in eRHIC storage ring

- Spins tracked over 240 damping times in eRHIC, 18 GeV



Re-evaluation of Spin-Orbit Dynamics of Polarized e+e− Beams in High Energy Circular Accelerators and Storage Rings: Bloch equation approach by Klaus Heinemann (Univ. New Mexico)

Outline

- Topic: Is polarization possible in high energy electron storage rings like proposed Circular Electron Positron Collider (CEPC) and Future Circular Collider (FCC-ee)?
- Review standard approach: Derbenev-Kondratenko formulas
- Derbenev-Kondratenko formulas rely, in part, on plausible assumptions grounded in deep physical intuition [2]
- Question: Do Derbenev-Kondratenko formulas, even with correction terms, tell full story?

- Alternative approach: Bloch equation for polarization density [3]
- Bloch equation allows for assessment of Derbenev-Kondratenko formulas
- Numerical approach to Bloch equation suggests Method of Averaging for getting effective Bloch equation
- Hope: Bloch equation teaches us domain of applicability of Derbenev-Kondratenko formulas

Derbenev-Kondratenko-formula

$$P_{\rm DK}(\theta) = P_{\rm DK}(+\infty)(1 - e^{-\theta/\tau_{\rm DK}}) + P_{\rm DK}(0)e^{-\theta/\tau_{\rm DK}}$$

$$P_{\rm DK}(+\infty) = \frac{\tau_0^{-1}}{\tau_{\rm DK}^{-1}}$$

$$\tau_{\rm DK}^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m}\frac{C}{4\pi^2}\int_0^{2\pi} d\theta \frac{1}{|\rho(\theta)|^3}\left\langle 1 - \frac{2}{9}(\vec{n}\cdot\hat{\beta})^2 + \frac{11}{18}\left|\frac{\partial\vec{n}}{\partial z_6}\right|^2\right\rangle$$

1. $\tau_0^{-1} = \frac{r_e\gamma^5\hbar}{m}\frac{C}{4\pi^2}\int_0^{2\pi} d\theta \frac{1}{|\rho(\theta)|^3}\left\langle \hat{b}\cdot\left[\vec{n} - \frac{\partial\vec{n}}{\partial z_6}\right]\right\rangle_\theta$

1. Fokker-Planck equation for phase space density:

$$\partial_t f_{\rm lab} = \underbrace{L_{\rm lab}(t,r,p) f_{\rm lab}}_{\text{Liouville \& damping \& diffusion}} \qquad ($$

2. Bloch equation for polarization density:

$$\partial_t \vec{\eta}_{\rm lab} = \underbrace{L_{\rm lab}(t,r,p)\vec{\eta}_{\rm lab}}_{\text{Liouville \& damping \& diffusion}} \underbrace{+\vec{\Omega}_{\rm lab}(t,r,p)\times\vec{\eta}_{\rm lab}}_{\text{T}-\text{BMT}-\text{terms}}$$
$$\underbrace{+G_{\rm lab}(t,r,p)\vec{\eta}_{\rm lab} + \vec{g}_{\rm lab}(t,r,p) f_{\rm lab}}_{\text{spin}-\text{flip terms}} \qquad ($$

- Description of electron bunch by spin-1/2 Wigner function $\rho_{\rm lab}$:

$$\rho_{\rm lab}(t,r,p) = \frac{1}{2}[f_{\rm lab}(t,r,p)I_{2\times 2} + \vec{\sigma}\cdot\vec{\eta}_{\rm lab}(t,r,p)]$$

- Bloch equation is PDE describing linear driven oscillator with damping and diffusion
- Task: Find equilibrium polarization vector $\vec{P}_{\rm lab}(\infty)$
- Bloch equation generalizes Baier-Katkov-Strakhovenko ODE to include phase-space effects [8]

Future work

- Further development of Bloch equation approach (numerical and theoretical)
- Comparing the Bloch equation approach with Derbenev-Kondratenko-formula approach
- Better understanding/modification of Derbenev-Kondratenko-formula approach
  1. Study of correction term to $\tau_{\rm DK}^{-1}$ in terms of RBE
  2. Replacing the invariant spin field $\vec{n}$ by "radiative invariant spin fiel
     $\vec{p} \Longrightarrow \left|\frac{\partial\vec{n}}{\partial z_6}\right|^2$ replaced by $\left|\frac{\partial\vec{p}}{\partial z_6}\right|^2$ [20]

Personal Impression and Prospect

- There is a theoretical framework of beam polarization and good understanding
- There were successful experiences in dealing beam polarizations in collider
  - Lepton beam polarization in HERA
  - Hadron beam polarization in RHIC
- Very challenging beam polarization requirements in future colliders
  - ~10% polarization for both e- and e+ beams in z (and even W) energy
  - >70% polarization for both electron and proton/light ion beams in EIC
- More challenges in delivering physics: spin flip
- Technical systems: polarized sources (ILAC, Super Tau-Charm, EIC)
- Technical system: polarimetry
- There are good simulation tools, still need improvements (physics and computing)
- A small community, international collaboration should be very helpful