Different approaches of polarimetry

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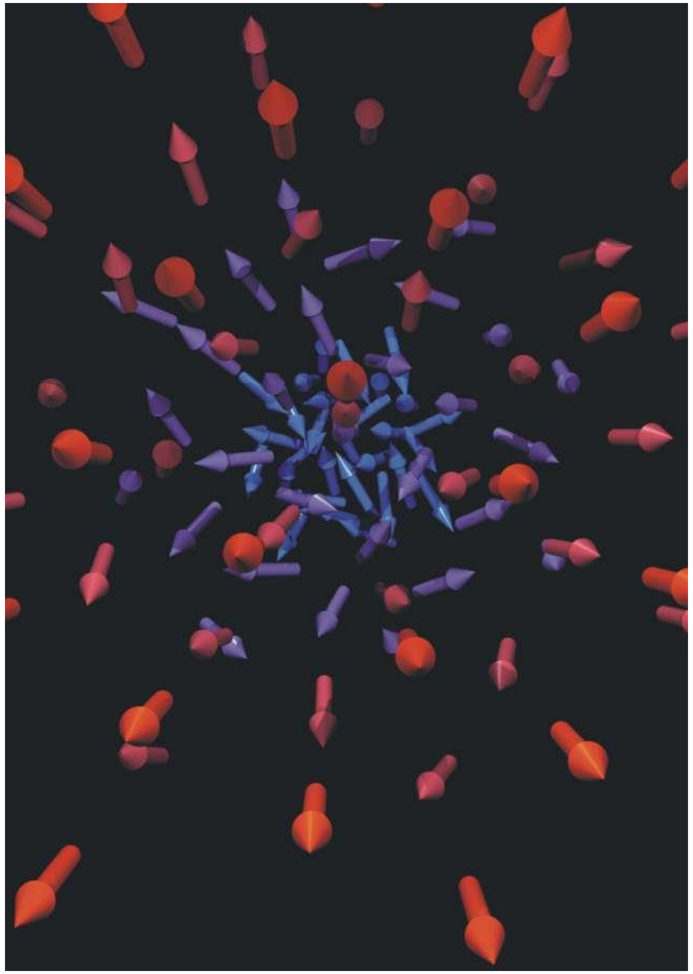
Outline

- Motivation of the measurement of polarization
- Techniques
  - Principle
  - Application
- Discussion & Conclusion

Introduction of polarization

➢ Polarization of spin-1/2 particles



- Spin is an entirely non-classical property of particles
- For electron/positron, Quantum number of spin is : $\pm 1/2$
- Relation to Anomalous magnetic moment(G) and nuclear physics, nuclear structure

- Beam polarization is an observable and is the ensemble average of a beam of spin-1/2 particles, e+, e-, etc.

Sokolov-Ternov effect: electrons gradually polarize in storage rings due to sustained transverse acceleration while orbiting. The mechanism is the emission of spin-flip synchrotron radiation:

- The degree of the polarization is defined:

$$P = \left| \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \right|$$

$N_{\uparrow}$ $N_{\downarrow}$:is the “up” and “down” state

Ref: [1] Leemann SC. 2002. Precise Energy Calibration Measurement at the SLS Storage Ring by Means of Resonant Spin Depolization[D]: Switzerland: Swiss Federal Institute of Technology, 5-18

Motivation

Transverse polarization

1. valuable probes for exploring new physics by the observation of CP violation[1]
2. distinguishing between different models of the extra dimensions in indirect searches for massive gravitons[2].
3. for the resonant depolarization technique(RDP)[3]to calibrate the beam energy,
   - high-precision measurements of Z mass
   - the momentum compaction factor
   - the monitoring of the machine stability[2, 4].

Longitudinal polarization

1. longitudinal polarized beam is a powerful probe for the anomalous couplings in the electroweak physics
2. suppress background noise in new physics searches[5, 6].

Ref: [1] Ananthanarayan B, Rindani S D. CP violation at a linear collider with transverse polarization[J]. Physical Review D, 2004, 70(3): 036005.
[2] Moortgat-Pick G, Abe T, Alexander G, et al. Polarized positrons and electrons at the linear collider[J]. Physics Reports, 2008, 460(4-5): 131-243.
[3] Arnaudon L, Dehning B, Grosse-Wiesmann P, et al. Accurate determination of the LEP beam energy by resonant depolarization[J]., 1995, 66(1): 45-62.
[4] Steier C, Byrd J, Kuske P. Energy calibration of the electron beam of the ALS using resonant depolarization[C]. Proceedings of EPAC. 2000:1566-1568.
[5] Moortgat-Pick G, Steiner H. Physics opportunities with polarized e − and e + beams at TESLA[J]. EPJ direct, 2001, 3(1): 1-27.
[6] Moortgat-Pick G, Abe T, Alexander G, et al. Revealing fundamental interactions: the role of polarized positrons and electrons at the Linear Collider[R], 2005.

Method

- Touschek lifetime measurement
- Spin-light polarimeter
- Scattering method
  - Mott scattering
  - Moller scattering
  - Compton scattering

Office AI

对撞机束流极化是高能物理领域中的重要研究方向之一。束流极化可以为物理实验提供独特的信息，有助于精确测量物理现象。目前，测量对撞机束流极化的方法主要有三种：

1. 第一种方法基于光电大致仪的束流极化测量法。该方法是利用极化光的光电效应对束流极化进行分析。当束流通过大致仪时，光电子因极化效应而具有不同的能量分布。通过光电大致仪可以观测到不同的能量分布，从而得到束流的极化信息。
2. 第二种方法基于散射偏振度的束流极化测量法。该方法是利用荷电粒子在反应过程中的散射偏振现象进行束流极化分析。当束流与靶相互作用时，散射出的粒子具有极化效应。通过测量散射偏振度可以推断束流的极化状态。
3. 第三种方法基于电离谱的束流极化测量法。该方法是利用离子化过程中的自旋成分变化进行束流极化分析。当束流与激发态原子相遇时，电离过程中发生的自旋成分变化可以反映束流自身的极化状态。通过测量电离谱可以推断束流的自旋极化方向。

总之，测量对撞机束流极化的方法比较多样化，但也具有一定难度。需要结合不同的实验条件和测量方法，以达到更高的精度和可靠性。在未来的研究中，需要不断探索和发展新的束流极化测量方法，以满足高能物理研究的需要。

Beam lifetime

- 束流寿命
  - 束团中电子数目的丢失，称之为束流寿命

$$I(t) = I_0 \exp(-t/\tau)$$

$I(t)$: t 时刻的束流流强
I_0：初始时刻的束流流强
τ是束流的寿命，即束流流强衰减到原来的1/e所用的时间

  - 影响束流寿命的因素很多，例如量子激发、气体散射和拖歇克效应等，各种因素影响程度不同，总的束流寿命是各种影响因素的综合造成的，表示为：

$$\tau = \left(\sum_i \frac{1}{\tau_i}\right)^{-1}$$

- 如果造成电子丢失的因素是量子激发效应，则称这种寿命为束流的量子寿命；
- 如果造成电子丢失的因素是电子和真空管道内剩余气体分子（或原子）的散射，则称这种寿命为束流的气体散射寿命。也称为真空寿命；
- 束团内部电子之间的弹射散射会使得电子的纵向能量发生变化，如果超出了能量接受度就会造成电子丢失，这种寿命成为束流的托歇克寿命。

Touschek lifetime measurement

- Touschek lifetime is the result of single large-angle Coulomb scattering between particles in the beam. The cross section is related to the polarization state.
- The Polarized beam’ s Touschek lifetime is longer than no-polarized beam.

$$\frac{d\sigma(P)}{d\Omega} = \frac{d\sigma(0)}{d\Omega}(1 - \frac{sin^2\theta}{1+3cos^2\theta}P^2)$$

$\frac{d\sigma(P)}{d\Omega}$和$\frac{d\sigma(0)}{d\Omega}$分别是含极化和不含极化的微分截面。P是束流的横向极化度。

- 进而，对于具有横向极化的束流，由托歇克效应引起的电子束损失率可以表示为：

$$\frac{1}{\tau_t} = a \cdot D(\xi)$$

$$D(\xi) = \xi^{3/2} \int_{\xi}^{\infty} \frac{1}{u^2} \left[\frac{u}{\xi} - 1 - \frac{1+P^2}{2} \ln \frac{u}{\xi}\right] \exp(-u) du$$

$$a = -\frac{N}{\gamma^2} \frac{r_e^2 c}{8\pi\sigma_x\sigma_y\sigma_s} \frac{1}{(\Delta p/p)^3}; \quad \xi = \left(\frac{\Delta p/p}{\gamma} \frac{\beta_x}{\sigma_x}\right)^2$$

$\sigma_{x,y,z}$ 是束团尺寸，β_z 是物理对撞点的水平 β 函数，$\frac{\Delta p}{p}$ 是动量接受度。

Touschek lifetime measurement

对全环取平均，可以得到托歇克寿命与束流横向极化度的依赖关系，并且托歇克寿命随着束流极化度的增加而增加。

$$\frac{\tau_t(P)-\tau_t(0)}{\tau_t(P)} = -\frac{\langle aF(\xi)\rangle}{\langle aC(\xi)\rangle}P^2 \tag{5-15}$$

其中，

$$\begin{aligned} C(\xi) &= \xi^{3/2}\int_{\xi}^{\infty}\frac{1}{u^2}\left[\frac{u}{\xi}-1-\frac{1}{2}\ln\frac{u}{\xi}\right]\exp(-u)du \\ F(\xi) &= -\frac{\xi^{3/2}}{2}\int_{\xi}^{\infty}\frac{1}{u^2}\ln\frac{u}{\xi}\exp(-u)du \end{aligned} \tag{5-16}$$

- Advantage: does not need a complicated setup
- Disadvantage:
  - 1. Touschek lifetime is the main (beam energy E < 2 GeV)
  - 2. require a highly stable beam, a relatively variable lifetime
  - 3. an accurate measurement of beam lifetime
  - 4. stable and repeatable operation of the machine

Application of Touschek polarimeter

- Touscheck polarimeter in VEPP of BINP

- [1] Blinov, V.E. (2016). High precision energy calibration with resonant depolarization at the VEPP-4M collider. Nuclear and Particle Physics Proceedings. 273-275. 210-218. 10.1016/j.nuclphysbps.2015.09.028.

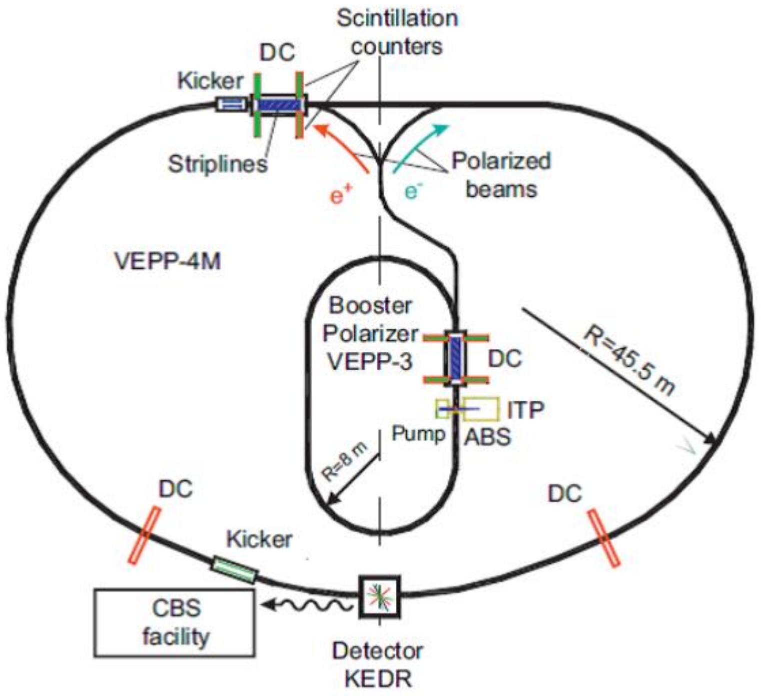


Figure 1: The VEPP-4 Complex with the elements of the Touschek polarimeter (*DC* , the counters of the distributed system of Touschek particle registration), the MØller polarimeter based on the internal polarized target (*ITP*), the depolarizer kickers as well as the Compton Back Scattering monitor (*CBS*).

- Touschek polarimeters are the natural choice to measure the polarization of circulating beams
- Have been studied in colliders: VEPP、BESYY-I/II、ALS、SLS……

Classical theory of SR

单个电子在磁场中运动的瞬时辐射功率:
The total radiative power is given by Larmor formula

$$P_{clas} = \frac{2}{3}\frac{e^2\gamma^4 c}{R^2}$$

The angular distribution of the radiated power is given by

$$\frac{dP_{clas}}{d\boldsymbol{\Omega}} = \frac{dP_{clas}}{d\theta d\phi} = \frac{e^2\gamma^4 c}{4\pi R^2}\frac{(1-\beta cos\theta)^2-(1-\beta^2)sin^2\theta cos^2\phi}{(1-\beta cos\theta)^5}$$

Angle (θ, ϕ) are measured with respect to the direction of electron's motion.

➢ Properties of SR

- SR is strongly linearly polarized.
- For highly relativistic electrons, the radiation with an opening angle $\theta \approx 1/\gamma$.
- Critical frequency:

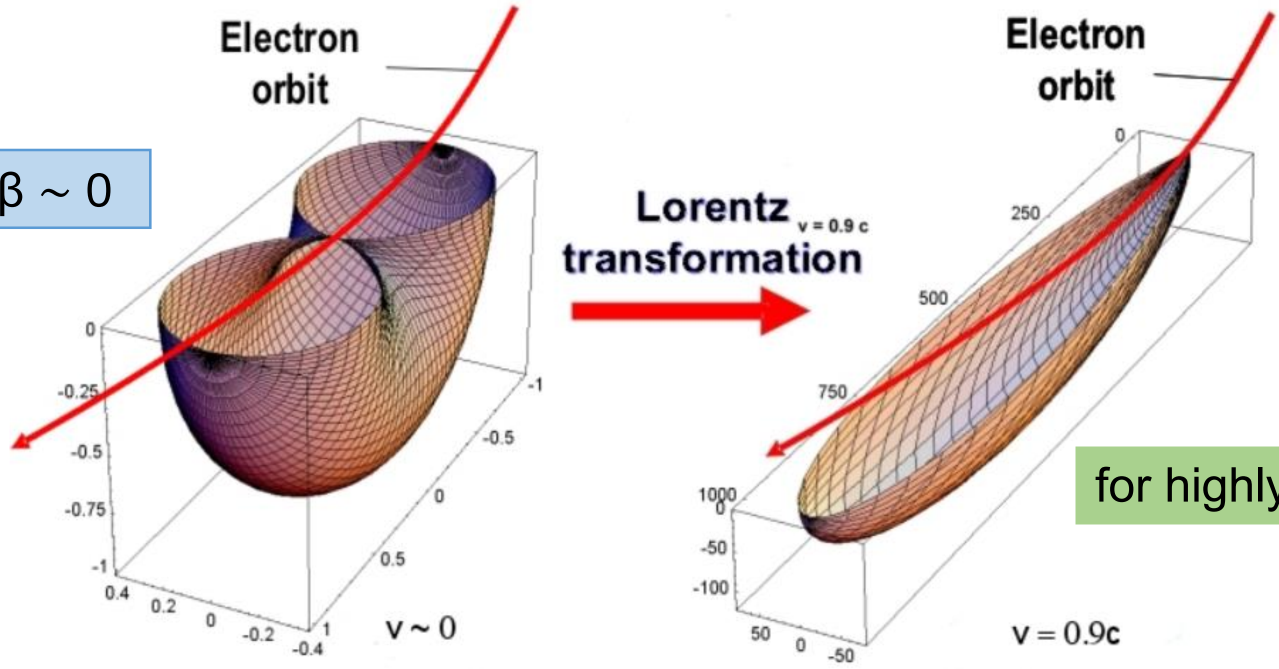
$$w_c = \frac{3}{2}\gamma^3 c/R$$

- Critical energy:

$$E_c = m_e c^2\sqrt{\frac{m_e cR}{\hbar}}$$

Quantum Theory of SR

for slow electrons, β ~ 0



for highly relativistic electrons, β ~ 1

Angular distribution of synchrotron radiation shown for the bottom half of the electron's orbital plane.

Quantum Theory of SR

- QED corrections give electrons spin dependence in the radiated power.
- Ternov and et. al. provide the Dirac equation.

Taylor expanded:

$$P = P^{clas}\left[\left(1-\frac{55\sqrt{3}}{24}\xi+\frac{64}{3}\xi^2\right)\right.$$

$$-\left(\frac{1+jj'}{2}\right)\left(j\xi+\frac{5}{9}\xi^2\frac{245\sqrt{3}}{48}j\xi^2\right) \rightarrow \text{Spin dependent term}$$

$$\left.+\left(\frac{1-jj'}{2}\right)\left(\frac{4}{3}\xi^2+\frac{315\sqrt{3}}{432}j\xi^2\right)+\dots\right] \rightarrow \text{Spin-flip dependent term}$$

- Classic SR
- Thomas Precession
- Larmor precession
- Interaction between Larmor and Thomas precession
- Radiation from intrinsic magnetic moment.

j: spin orientations with respect to the magnetic field

- 极化的电子束流与无极化的电子束流辐射功率之差为：which is called “spin-light”

$$P^{spin} = P^{pol} - P^{unpol} = -j\xi P^{cals}\int_0^\infty \frac{9\sqrt{3}}{8\pi} y^2 K_{1/3}(y)dy$$

Quantum Theory of SR

- Polarized electron beams have longitudinal (P_z), transverse horizontal (P_y) and transverse vertical (P_x) components relative to the beam direction.

➢ Transverse polarization

ignoring spin flip terms and other terms of order ξ^2

$$P_\gamma(tran) = \frac{9n_e}{16\pi^3}\frac{ce^2}{R^2}\gamma^5\int_0^\infty \frac{y^2dy}{(1+\xi y)^4}\oint d\Omega(1+\alpha^2)^2 \times\left[K_{2/3}^2(z)+\frac{\alpha^2}{1+\alpha^2}K_{1/3}^2(z) - (+)p_{x(y)}\xi y\frac{1}{\sqrt{1+\alpha^2}}K_{1/3}(z)K_{2/3}(z)\right], \quad (6)$$

公式中，α = γφ
上述表达式中的极化相关项是φ角的偶函数，因此，当在所有角度上积分时，它使总SR功率与自旋相关。因此，通过测量总辐射功率中的自旋依赖性，可以测量横向极化电子束的极化。

➢ Longitudinal polarization

ignoring spin flip terms and other terms of order ξ^2

$$P_\gamma(long) = \frac{9n_e}{16\pi^3}\frac{ce^2}{R^2}\gamma^5\int_0^\infty \frac{y^2dy}{(1+\xi y)^4}\oint d\Omega(1+\alpha^2)^2 \times\left[K_{2/3}^2(z)+\frac{\alpha^2}{1+\alpha^2}K_{1/3}^2(z) + p_z\xi y\frac{\alpha}{\sqrt{1+\alpha^2}}K_{1/3}(z)K_{2/3}(z)\right], \quad (7)$$

上述表达式中的极化相关项是φ角的奇函数，在所有的角度上积分等于0，总的SR辐射对于纵向极化而言是自旋无关的。然而，空间上方($0 < \varphi < \pi/2$)的辐射功率和空间下方($-\pi/2 < \varphi < 0$)的辐射功率在电子的轨道平面是不同的，依赖于自旋。因此通过测量spatial asymmetry,就可以测量电子束流的纵向极化。

Quantum Theory of SR

➢ Longitudinal polarization

辐射到有限水平角的光子总数可表示为:

$$N_\gamma = \frac{3}{4\pi^2}\frac{1}{137}\frac{I_e}{e}\gamma\Delta\theta\int_{y_1}^{y_2} y dy \int_{-\alpha}^{\alpha}(1+\alpha^2)^{3/2} \times\left[K_{2/3}^2(z)+\frac{\alpha^2}{1+\alpha^2}K_{1/3}^2(z)\right]d\alpha, \tag{8}$$

电子轨道上方和下方空间中辐射的光子通量之差由下式给出:

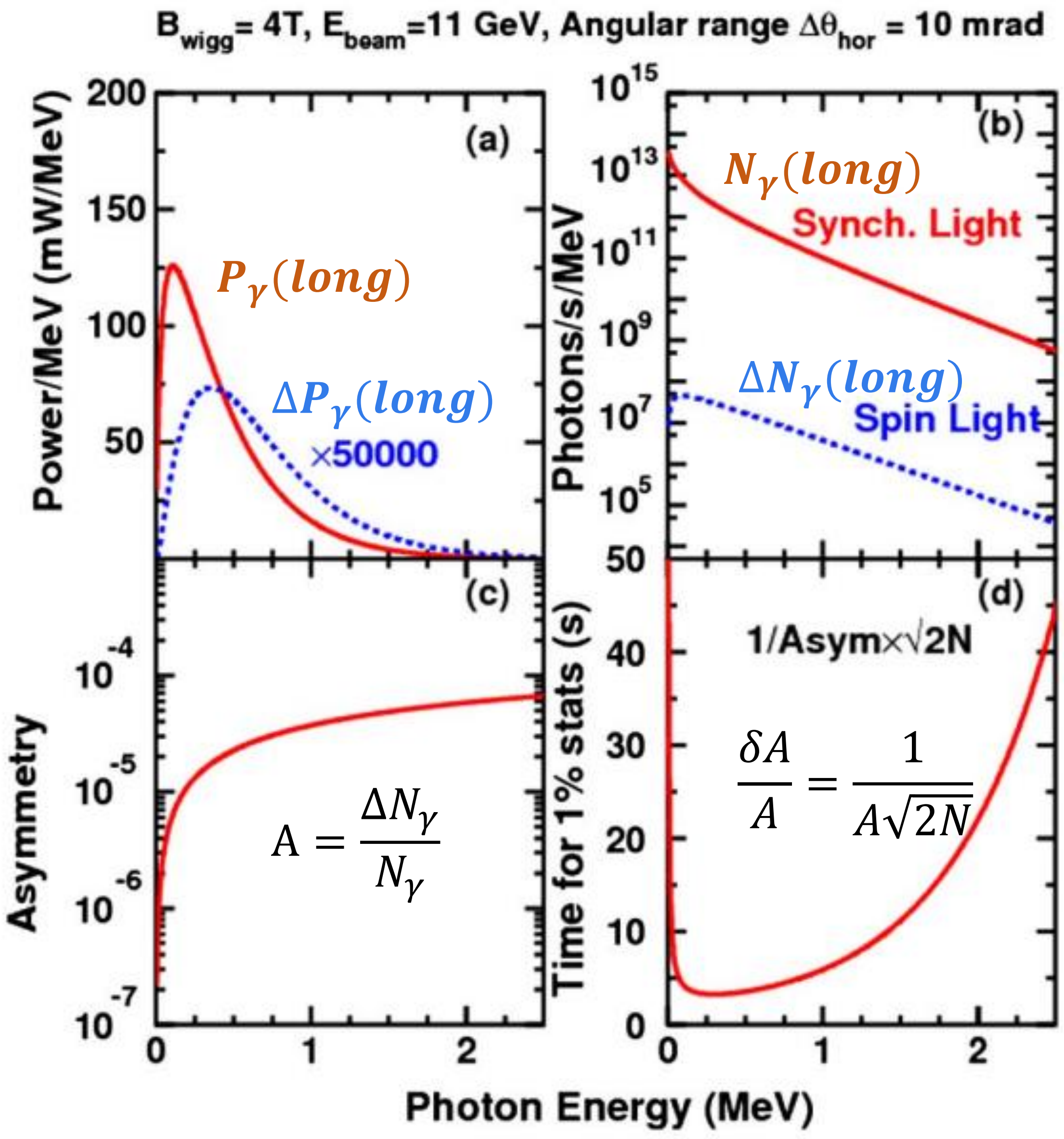
$$\Delta N_\gamma(p_z) = \frac{3}{\pi^2}\frac{1}{137}\frac{I_e}{e}p_z\xi\gamma\Delta\theta\int_{y_1}^{y_2} y^2 dy\int_0^{\alpha}\alpha(1+\alpha^2)^{3/2} \times K_{1/3}(z)K_{2/3}(z)d\alpha \tag{9}$$

The asymmetry is defined:

$$\mathrm{A} = \frac{\Delta N_\gamma}{N_\gamma}$$

Performance of spin-light polarimeter

(a)The total SR power and the spin-dependence power. Integrated over a horizontal angular acceptance of $\Delta\theta$=10 mrad

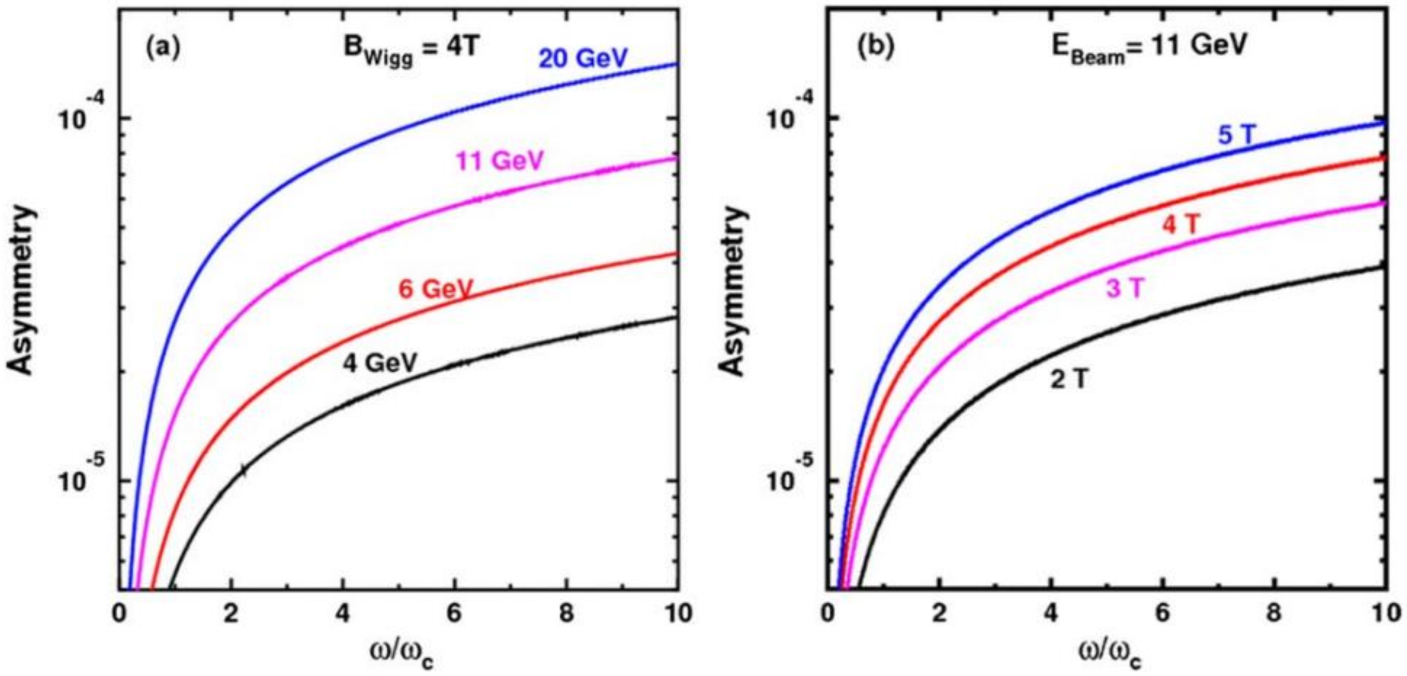


(b) The number of SR photons $\boldsymbol{N_\gamma}$, and the spin-light photons $\Delta \boldsymbol{N_\gamma}$

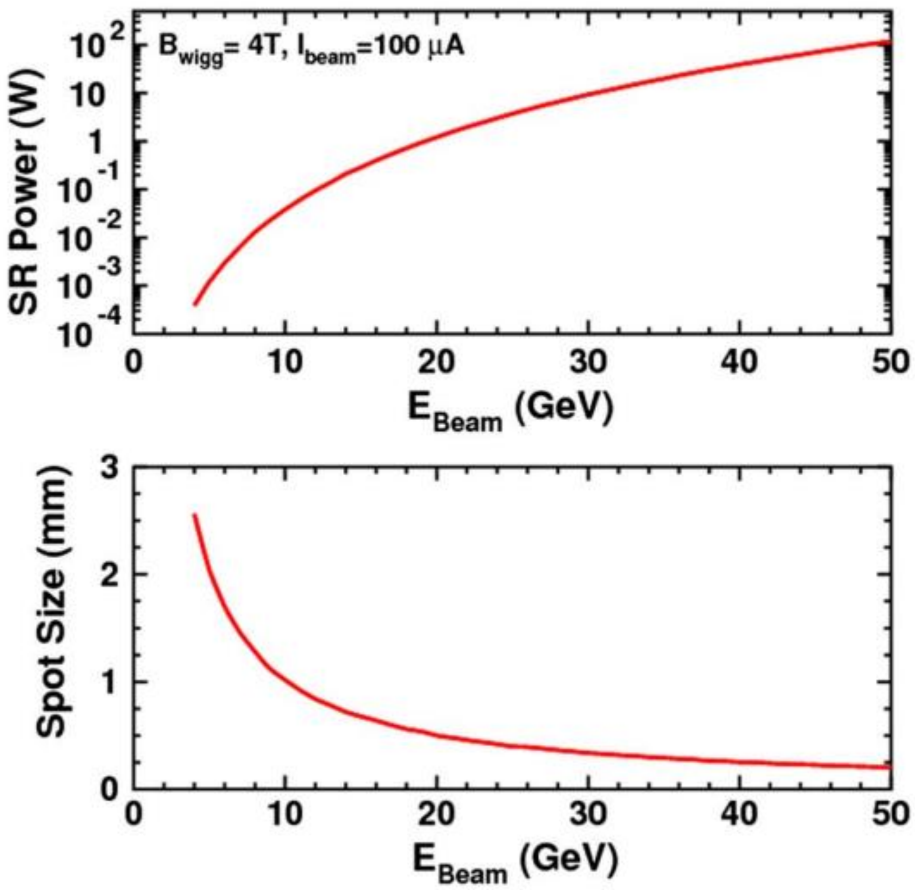
(c) One should measure the hard tail of the SR spectrum ($E_\gamma > 500keV$)

(d) 1% statistical error within few tens of seconds.

Performance of spin-light polarimeter



(a) The energy dependence of the asymmetry for beam energy is 4-20 GeV
(b) The spin dependent asymmetry for magnetic field B = 2-5 T

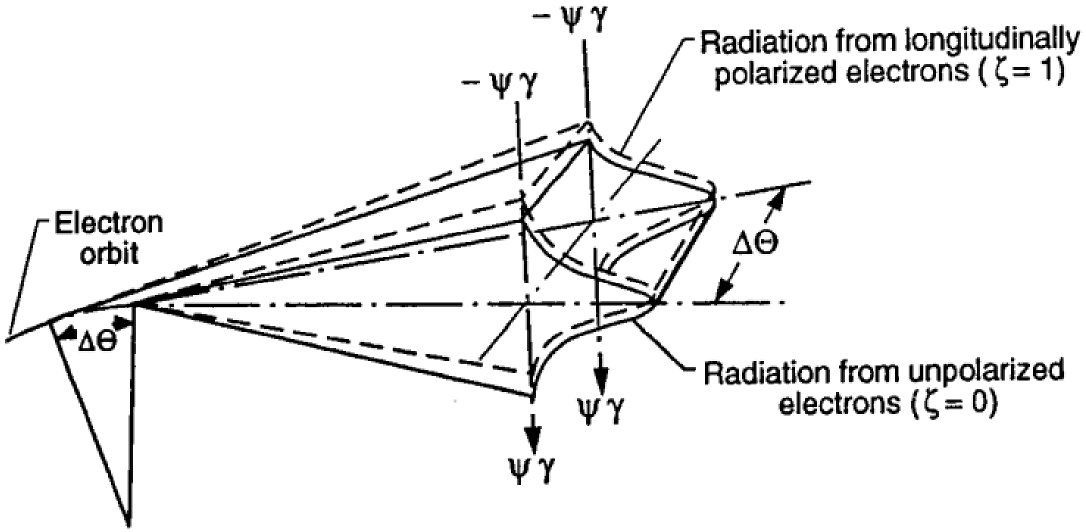


(top) The total SR power as a function of the electron beam energy
(bottom) The vertical size of the SR beam spot vs the electron beam energy

Summary: it is best suited for the 4 - 20 GeV energy range for currents less than 100 mA

Application of Spin-light polarimeter

CEBAF (electron energy E = 4 GeV and 100 pA beam current)



https://ieeexplore.ieee.org/document/308883

Electron Ion Collider (EIC)

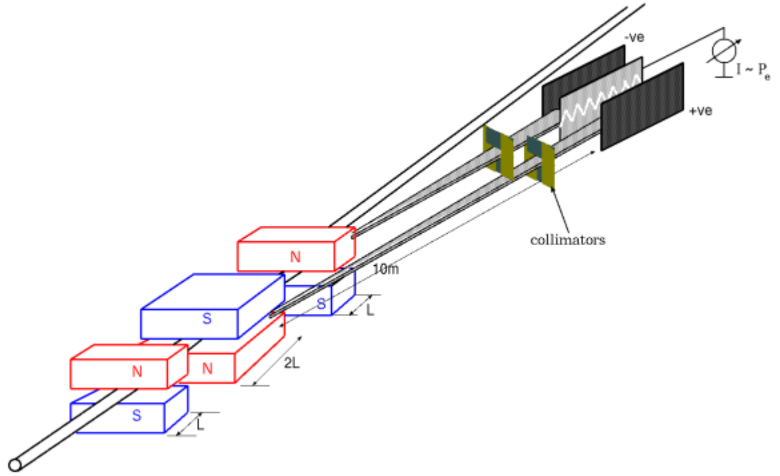
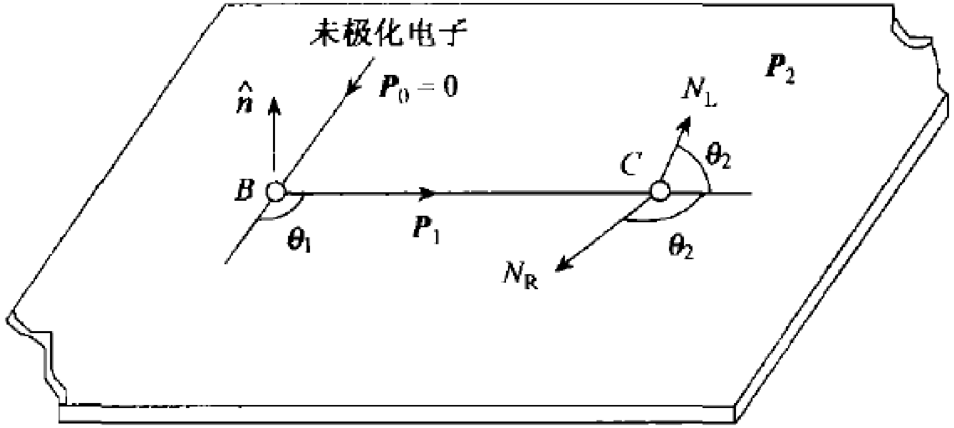


Figure 27: Schematic diagram of the entire Differential Spin Light Polarimeter (The only visible difference between the absolute and relative polarimeters in the schematics is the difference in collector plate bias).

https://arxiv.org/abs/1401.6744

Mott polarimeter

- 散射实验被广泛应用在探究粒子的性质中，例如可以通过莫特（Mott）散射、 穆勒（Møller）散射和康普顿（Compton）散射测量电子的极化。
- 莫特散射：极化的电子束被未极化的核子散射
- 穆勒散射：极化的电子束与极化的电子束散射
- 康普顿散射：极化的电子束与极化的激光光子散射



- 莫特散射的截面可表示为：

$$\sigma(\theta,\varphi) = I(\theta)[1 + S(\theta)\vec{P}\cdot\hat{n}]$$

$I(\theta)$是不含极化的截面；
$\vec{P}$是电子束流的极化；
$\hat{n}$是散射电子平面内的单位矢量
$S(\theta)$称之为Sherman 函数，也是analyzing power

Mott polarimeter

莫特极化仪旨在测量散射前后粒子的分布的不对称性：

$$P(\theta_1) = \left|\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right| = \left|\frac{[1 + S(\theta_1)] - [1 - S(\theta_1)]}{[1 + S(\theta_1)] + [1 - S(\theta_1)]}\right| = S(\theta_1)$$

其理论基础是 “Sherman-function”，又称之为分析本领（anglayzing power），决定了被测量的不对称性和电子束流极化之间的关联。

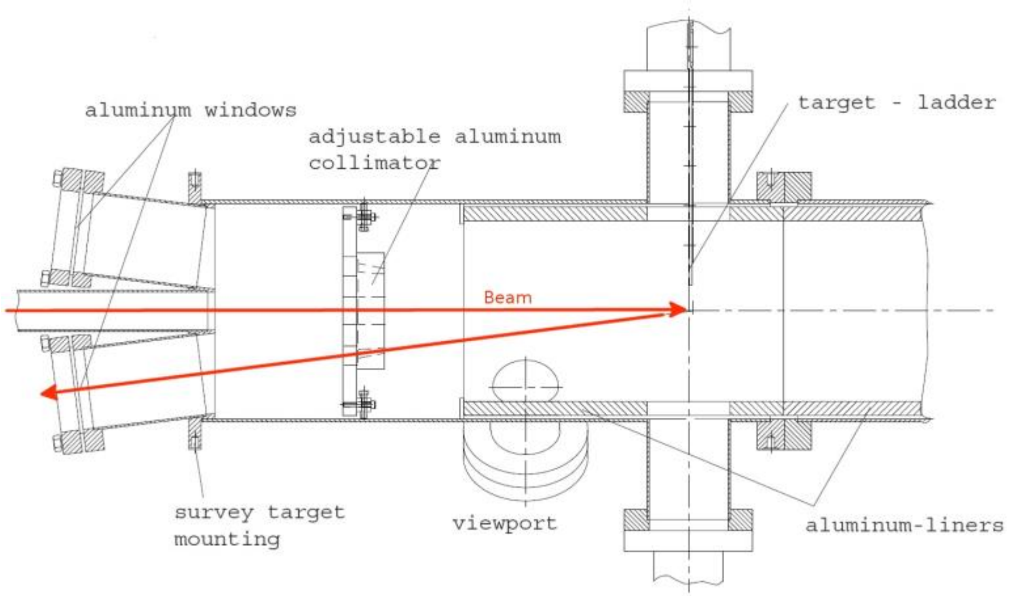
该函数依赖于散射角，束流能量和靶材料的核电荷数。

莫特极化仪要想保证其测量的精度，有以下限制条件

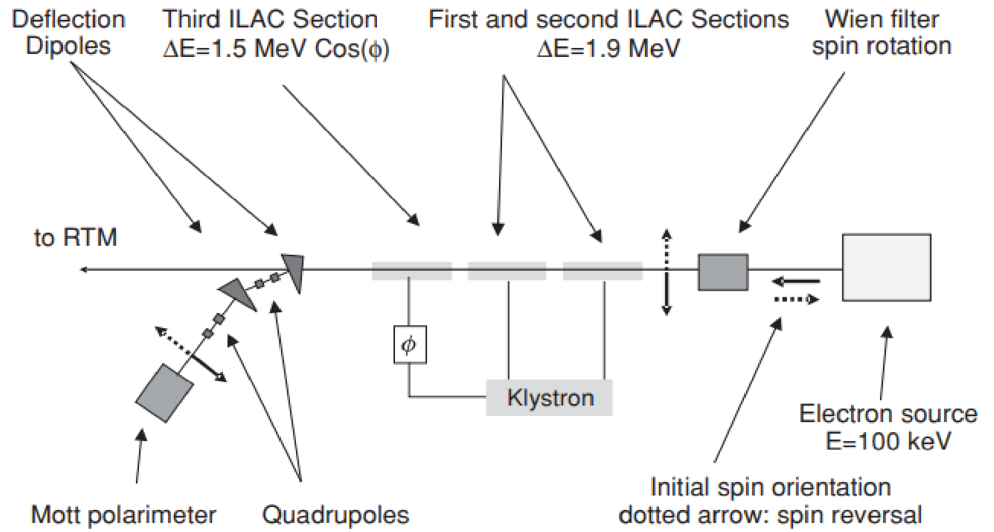
- 关于Sherman-function的理论计算要足够精确
- 通过获得高质量的能谱来正确测量每个靶发生散射后的不对称性
- 该系统通常被限制在束流10 MeV以下，因为横截面随着束能量的增加而减小，通常在加速到最高能量之前在束源附近使用。
- 莫特散射仪仅可以测量束流的横向极化度。

Application of Mott polarimeter -1

CEBAF in JLab



2 - 8 MeV energy range



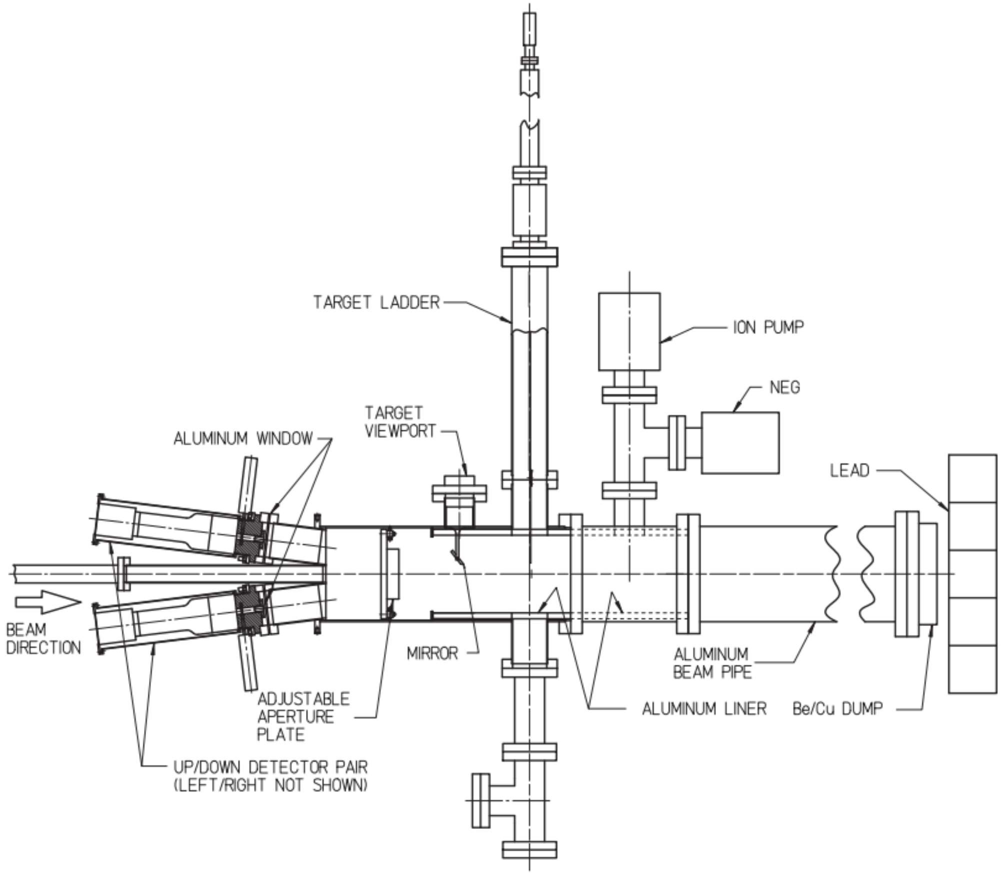
Mott polarimeter at the 3.5 MeV injector of the MAMI RTM cascade.

https://www.researchgate.net/publication/281111680

REVIEW OF SCIENTIFIC INSTRUMENTS 82, 033303 (2011)

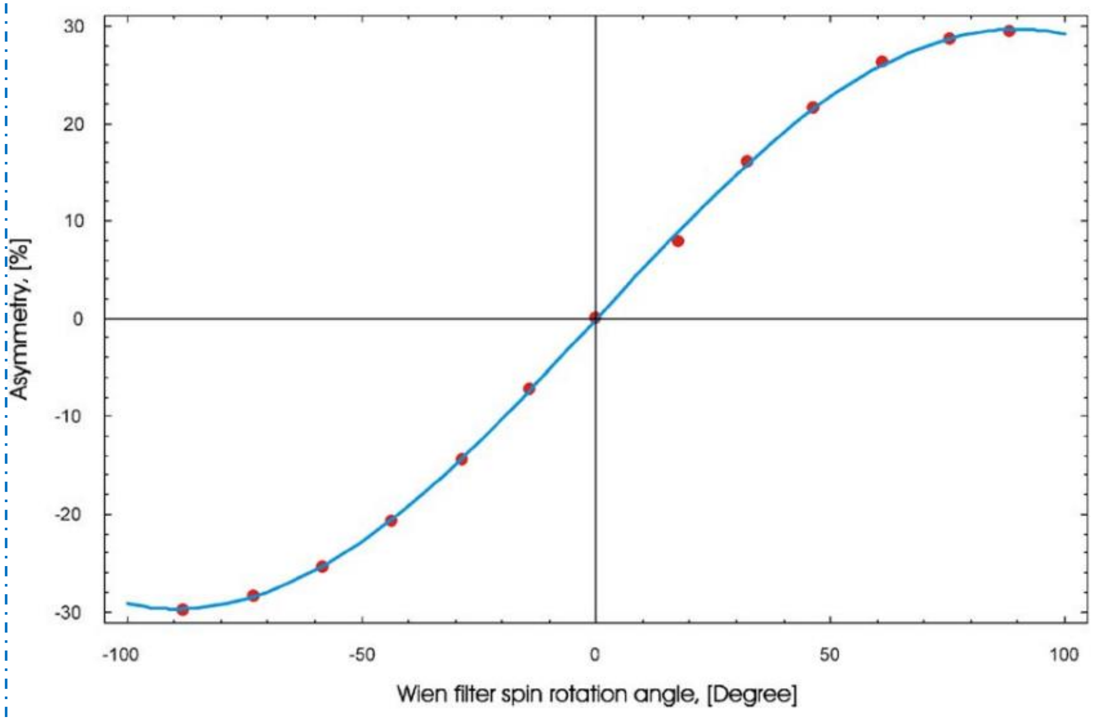
Application of Mott polarimeter - 2

High precision 5 MeV Mott polarimeter in CEBAF



Elevation view of the Mott polarimeter, including the beam line from the dipole magnet which steers the beam into the polarimeter.

Signal from the Mott-polarization monitor behind the 3.5MeV injector of MAMI for different Wien-filter settings.



V. Tioukine, K. Aulenbacher / Nuclear Instruments and Methods in Physics Research A 568 (2006) 537–542

PHYSICAL REVIEW C 102, 015501 (2020)

Moller polarimeter

- Moller polarimeters exploit the asymmetry in scattering a polarized electron beam off of a polarized electron target.

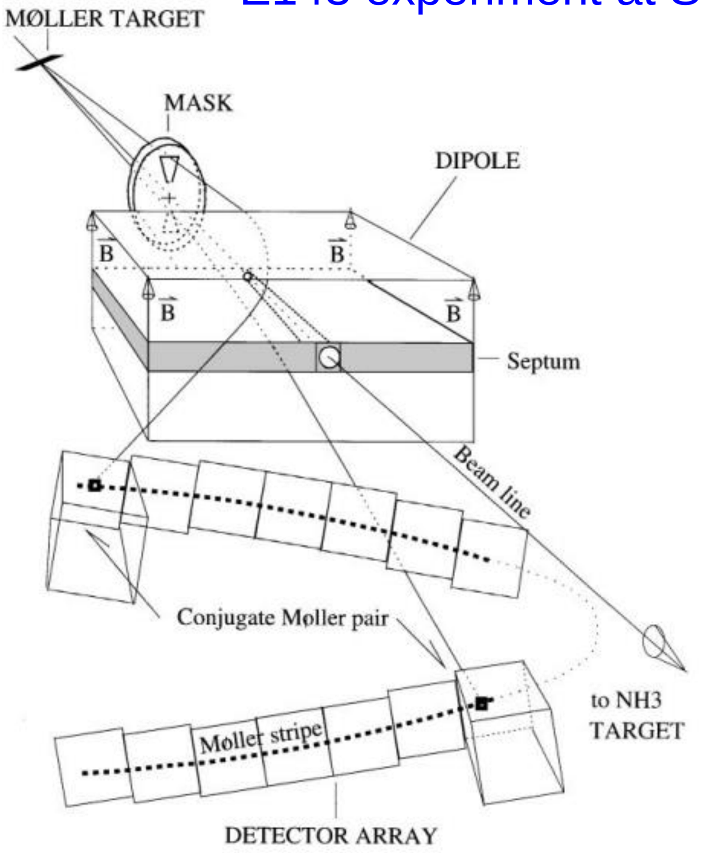
$$\vec{e} + \vec{e} \rightarrow e + e$$

利用一个极化的电子束与另一个极化的电子靶散射，测量散射后电子分布的不 对称性
可反推束流的横向或者纵向极化

- Advantage: relative accurate. Since this is a pure QED process, its cross-section can be calculated to very high precision.
- Disadvantage:
  1. due to a solid target being used and that the beam current at which the measurement is done is limited a few μA to avoid depolarization effects due to target heating.

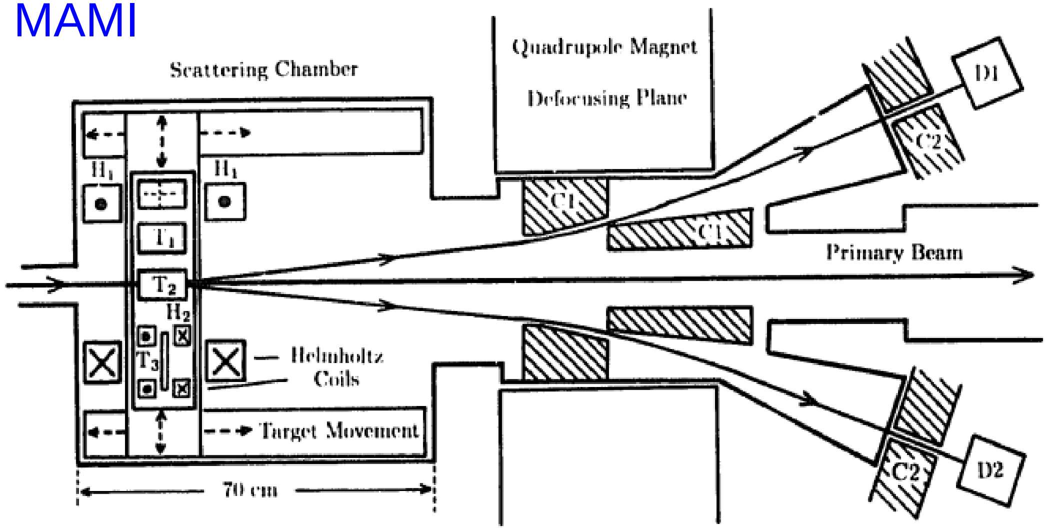
Application of Moller polarimeter

E143 experiment at SLAC



NIMA 419 (1998) 105—120

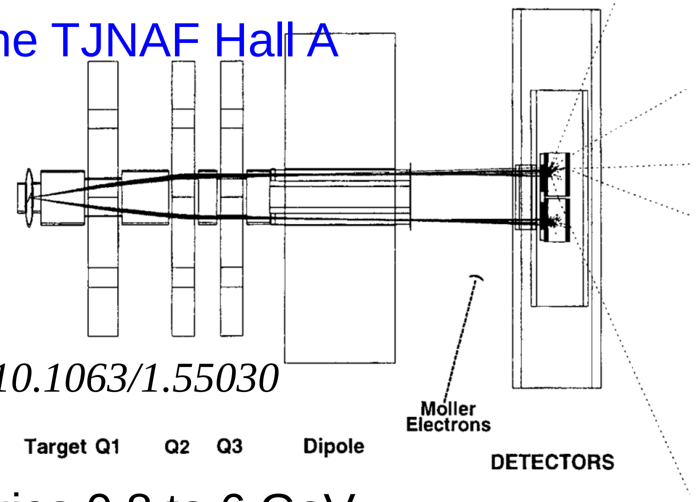
MAMI



25 and 185 MeV

NIMA294 (1990) 541-548

Top view of the TJNAF Hall A



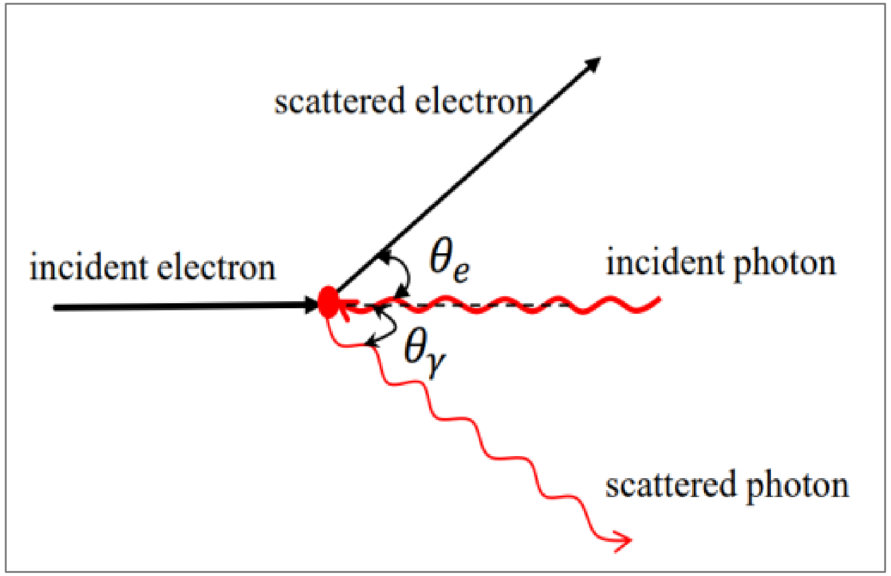
https://doi.org/10.1063/1.55030

Beam energies 0.8 to 6 GeV

Compton polarimeter

- Compton polarimeters

$$e^- + \gamma \rightarrow e^- + \gamma$$



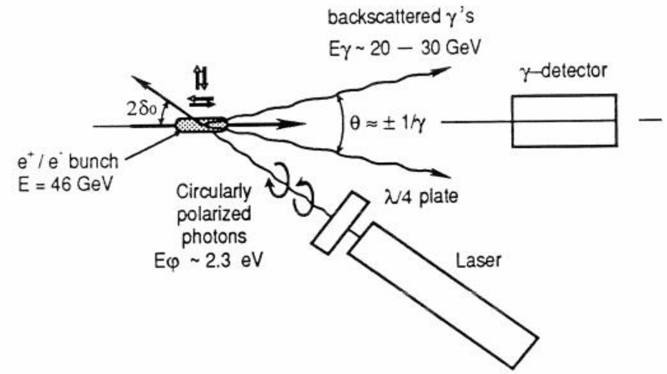
- Advantage: non-invasive
- Can be measured spatial position / energy of the scattered particles.

Compton polarimeter in colliders

Techniques	Storage ring	parameters	results
Scattered energy of photons	NIKHEF	$E_{beam} = 440MeV$ $\lambda = 514nm$	$P_L = 61.6\% \pm 1.4\%(statistical)$ $\text{time} = 90\text{min}$
	HERA	$E_{beam} = 27.5GeV$	$\Delta P_L = 1\%\sim 2\%(statistical)$ $\text{time} = 1\text{min}$ $2\%(\text{systematic uncertainty})$
	TRISTAN	$E_{beam} = 29GeV$ $E_\lambda = 2.41eV$	
vertical position of photons	HERA	$E_{beam} = 27.5GeV$	$\Delta P_T = 2\sim 3\%(statistical)$ $\text{time} = 1\text{min}$ $2.9\%(\text{systematic uncertainty})$
	LEP	$E_{beam} = 55GeV$ $\lambda = 523nm$	$\Delta P_T = 1\%(statistical)$ $\text{time} = 1\text{min}$
	SPEAR	$E_{beam} = 3.7GeV$ $E_\lambda = 2.41eV$	$\Delta P_T = 5\%(statistical)$ $\text{time} = 2\text{min}$
	TRISTAN	$E_{beam} = 29GeV$ $E_\lambda = 2.41eV$	
Spatial position of electrons	FCC-ee	$E_{beam} = 45.6GeV$ $E_\lambda = 2.33eV$	$\Delta P_T = 1\%(statistical)$ $\Delta P_L = 1\%(statistical)$ $\text{time} = 1\text{min}$
	ILC	$E_{beam} = 250GeV$ $E_\lambda = 2.33eV$	$\Delta P_T \sim 0.5\%(statistical)$ $0.2\%(\text{systematic uncertainty})$
	SLC	$E_{beam} = 45.6GeV$ $E_\lambda = 2.34eV$	$\Delta P_T \sim 1\%(statistical)$(3 mim)

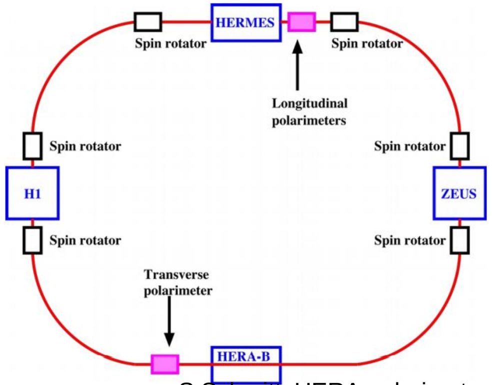
Application of Compton polarimeter

CERN LEP 46GeV



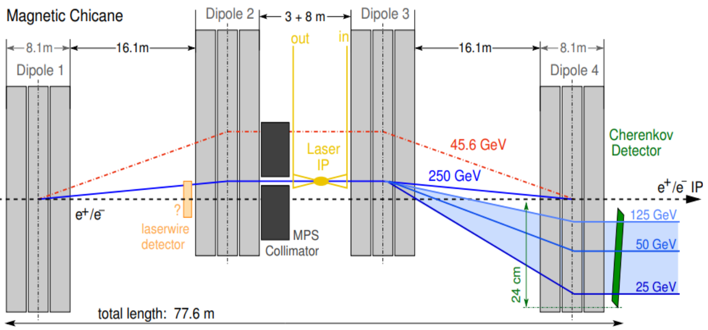
R.Schmidt. CERN SL/91-51(BI), 1991.

HERA 27GeV



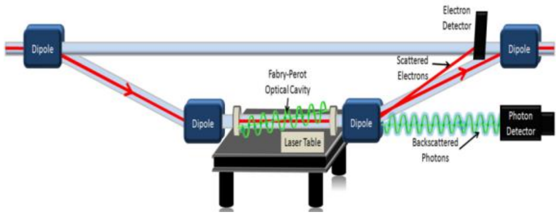
S.Schmitt, HERA polarimeter review

ILC



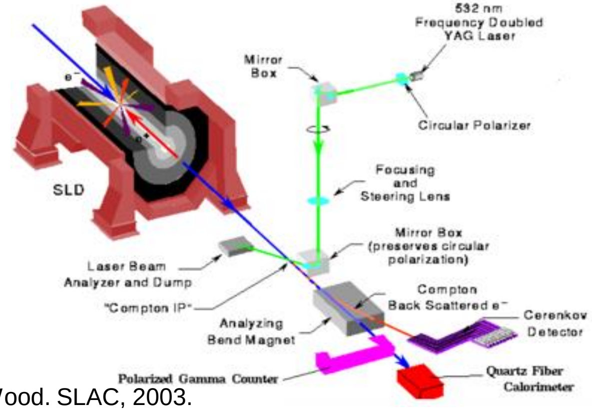
Jenny List, ILC Polarimetry,2020

JLab Hall C 1.16GeV



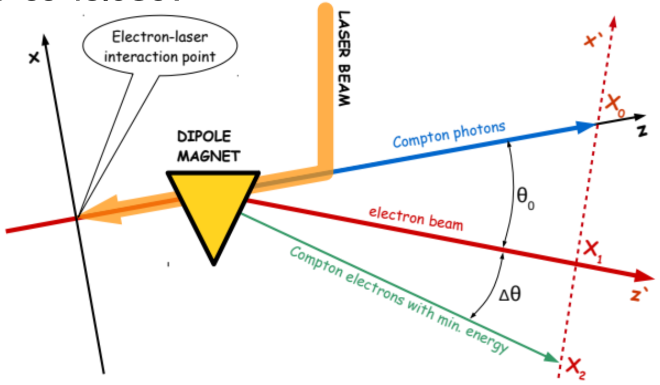
Donald Jones, Compton Polarimetry, PSTP 2013.

SLD at SLAC 45.6GeV



M.Wood. SLAC, 2003.

FCC-ee 45.6GeV



Nickolai Muchnoi, 2018

- Compton polarimeters are the natural choice to measure the polarization of circulating beams
- Have been successfully used in colliders: HERA、SLD、EIC、LEP、JLab、FCC-ee、ILC…CEPC

Summary

Technique	Principle	Requirements	Device
Touscheck lifetime measurement	$\frac{\tau_t(P)-\tau_t(0)}{\tau_t(P)} = -\frac{< aF(\xi) >}{< aC(\xi) >} P^2$	• A highly stable and repeatable machine of the polarized and unpolarized beam • A more accurate measurement of the change of the lifetime	Duke storage ring
"spin-light" polarimeter	Measure the total SR power (transverse polarization) or the spatial asymmetry of the SR (longitudinal-spin dependent)	• Best suited for the 4 - 20 GeV energy range, for current less than mA	VEPP-4 JLab
Mott polarimeter	Elastic scattering asymmetry of electron incident on the nuclei of a thin target foil	• Operate in beam energy below 10 MeV	CEBAF, MAMI
Moller polarimeter	$e + e \rightarrow e + e$	• Low beam current • Suitable for energy 100 MeV ~ 50 GeV.	MAMI, SLAC(E143), TJNAF(hall A)
Compton polarimeter	$e + \gamma \rightarrow e + \gamma$	• In theory, the scattered electrons and photons can be independently measured to obtain the polarization • " non-invasive " cross-section is small	TRISTAN, NIKHEF, HERA, LEP, JLab(Hall C), ILC, FCC

backup

Compton	Spin-Light	Møller
non-invasive, continuous	non-invasive, continuous	invasive
analyzing power energy dependent	analyzing power energy dependent	analyzing power energy independent
high currents	moderately high currents	low currents
target is 100% polarized (requires stable laser)	no target needed	target is $< 10\%$ polarized
electron & photon detection are two independent measurements	beam left & right detectors provide two independent measurements	no independent measurements possible
high precision absolute polarimeter	high precision relative polarimeter	high precision absolute polarimeter
Best reported [3] instrumental uncertainty: 0.4%	expected instrumental uncertainty: 0.6%	Best reported [1] instrumental uncertainty: 0.47%
Best reported [3] absolute uncertainty: 0.5%	estimated absolute uncertainty: $\sim$2.5%	Best achieved [2] absolute uncertainty: 0.85%