Polarimetry

Oleg Eyser
Brookhaven National Laboratory

CFNS Summer School on Physics of the Electron-Ion Collider
July 2022

Center for Frontiers in Nuclear Science

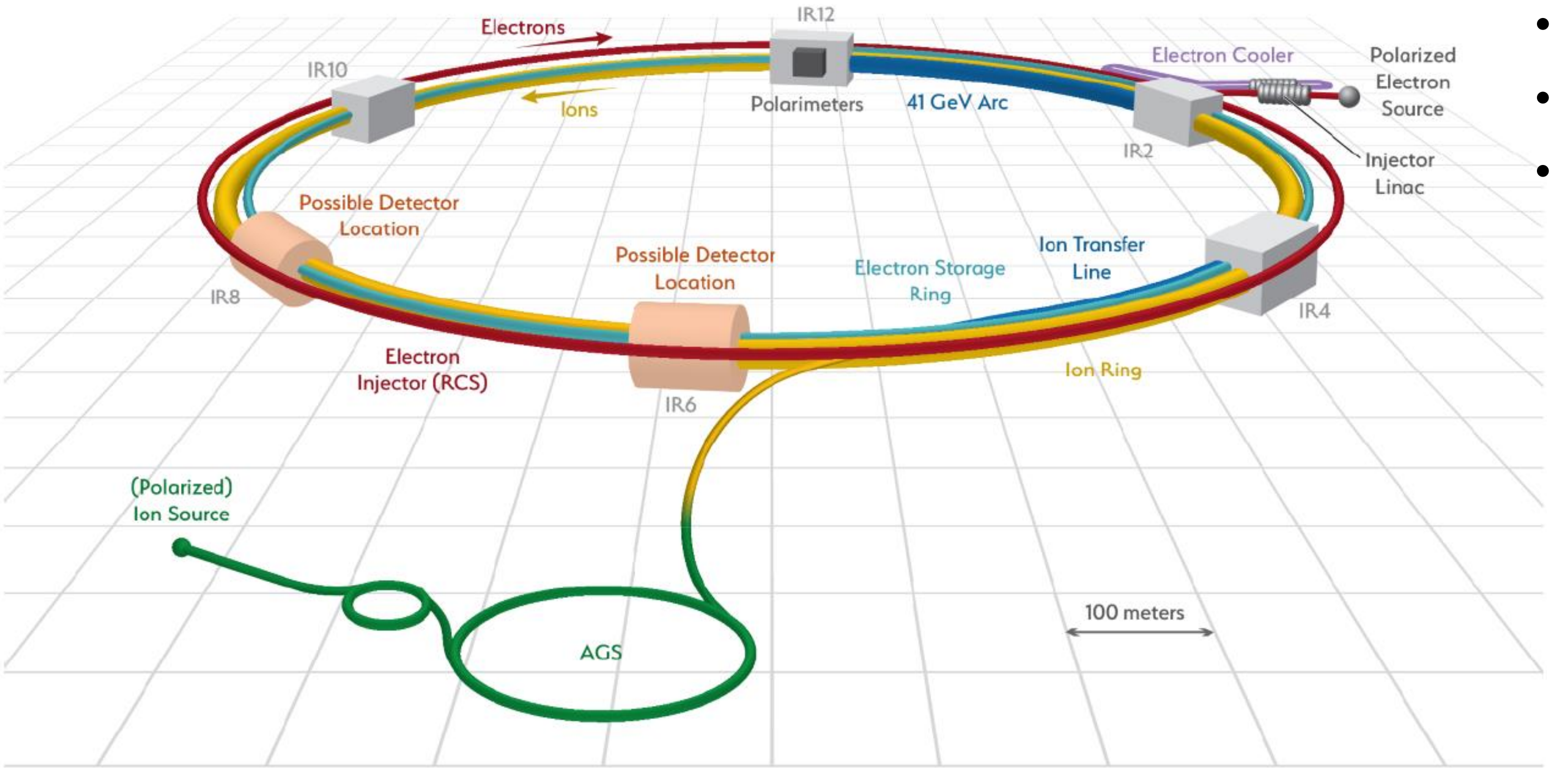
Brookhaven National Laboratory

Outline

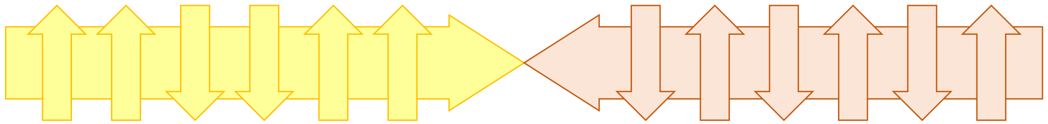
- Introduction: A Polarized Electron-Ion Collider
- I. Polarized Particle beams
- II. Proton Polarimetry
- III. Electron Polarimetry
- Conclusions

Polarimetry of High Energy Electron Beams

Recap: Requirements for Polarimetry



- Electron beam energies: $5 - 18$ GeV.
- Proton beam energies: $50 - 275$ GeV.
- Measure:
  - Absolute beam polarization $\Delta P/P \approx 1\%$
  - Polarization vector at experiment
  - Time-dependence (polarization decay)
  - Bunch-by-bunch polarization
  - Transverse polarization profile of bunches
  - Polarization during ramp (acceleration)



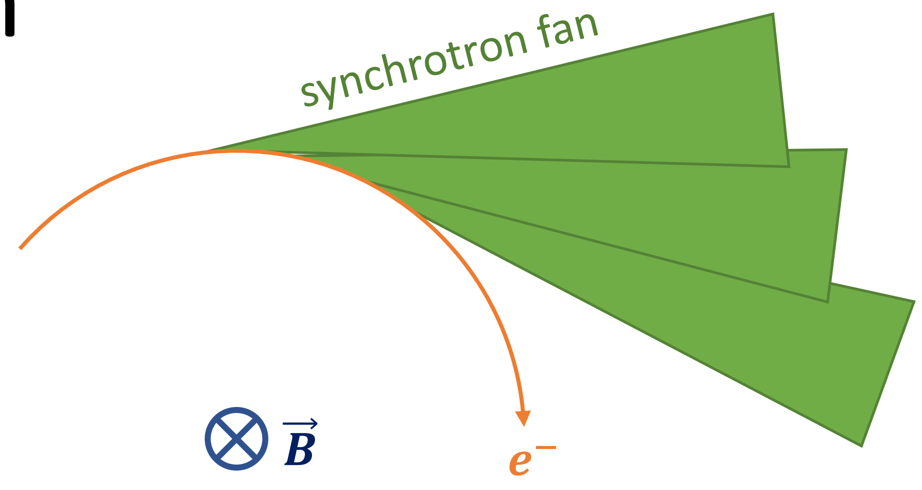
Remember Synchrotron Radiation

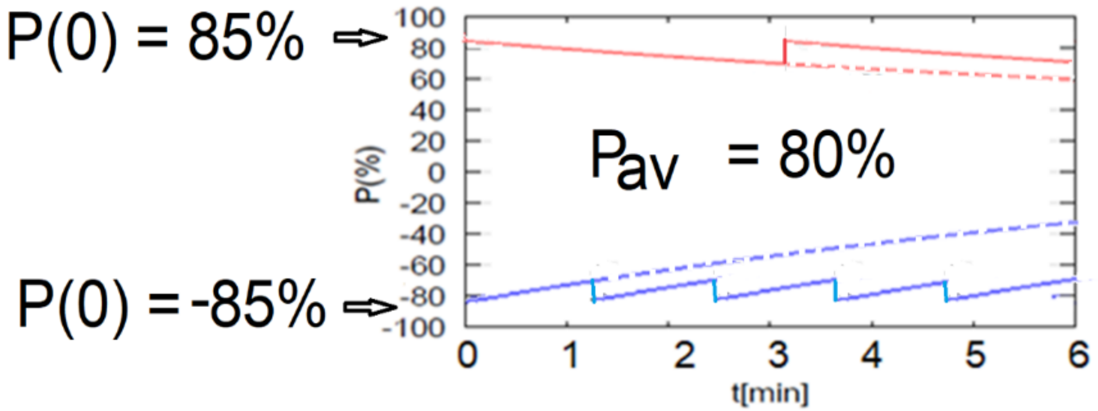
- The emission of synchrotron radiation leads to a self-polarizing of the beam (Sokolov-Ternov effect).

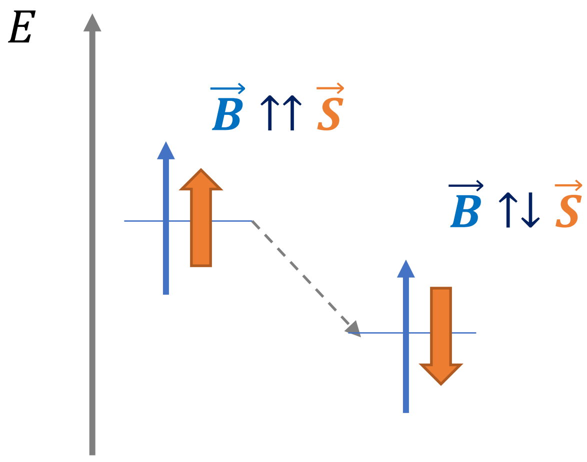
$$\xi(t) = A(1 - e^{-t/\tau})$$

$$\tau = A\frac{4\pi\epsilon_0\hbar^2}{mce^2}\left(\frac{mc^2}{E}\right)^2\left(\frac{B_c}{B}\right)^3$$

- After long enough time, the polarization limit should be reached: $A = 92.4\%$ (actually much smaller due to spin diffusion).
- But: the beam is bunched with alternating polarization directions.
- Polarized bunches need to be replaced every few minutes in order to ensure $|\langle P^{\uparrow}\rangle| = |\langle P^{\downarrow}\rangle|$

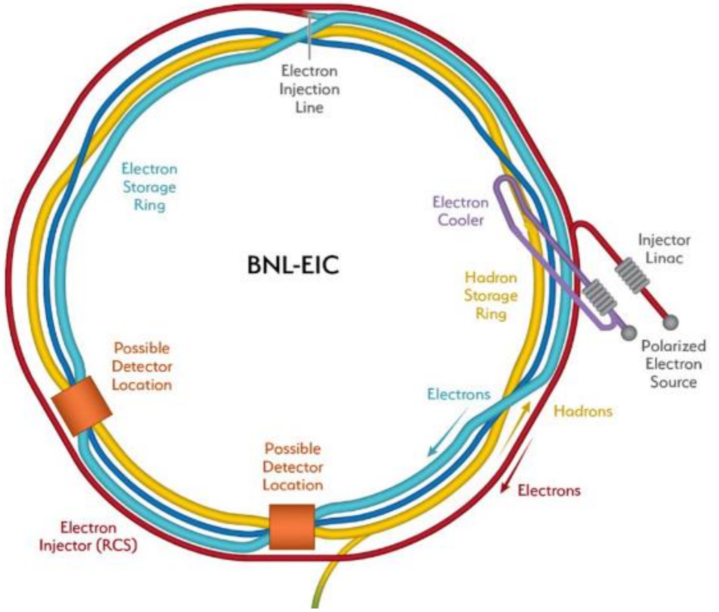




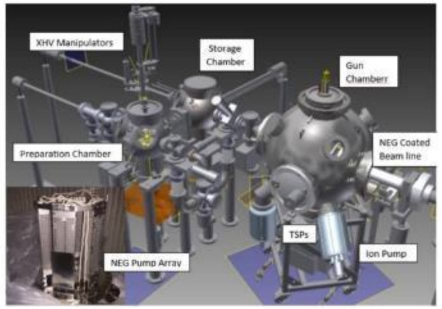


Electrons are not Hadrons

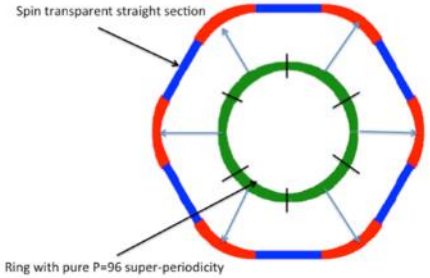
- The electron in deep-inelastic scattering is probing the nucleon.
- Interactions with the electron are through electromagnetic force.
    - Use electromagnetic field or photon to determine electron polarization
- Advantage EIC:
    - The acceleration of electrons happens in the Rapid Cycling Synchrotron.
    - The Electron Storage Ring has a fixed energy.



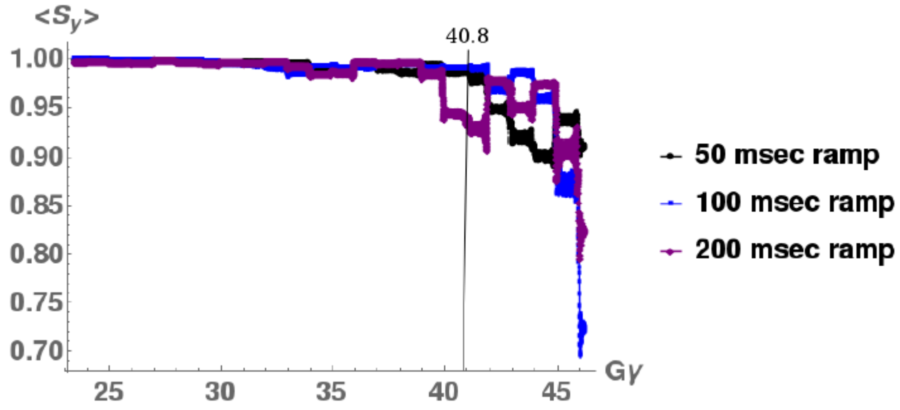
Polarized Electron Source (R&D Prototype)



RCS Design

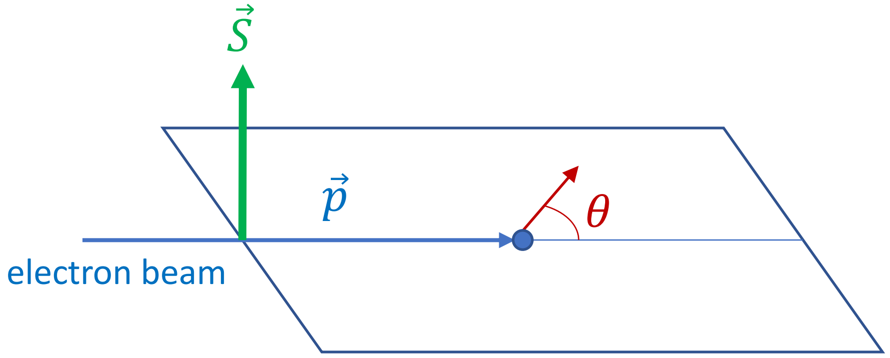


RCS Polarization Performance



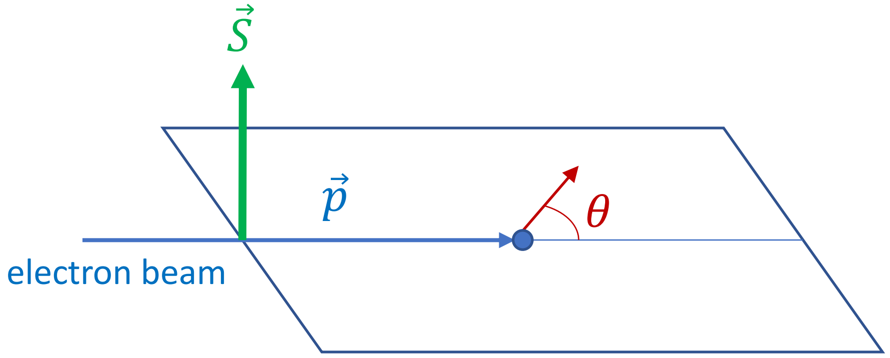
Mott Scattering

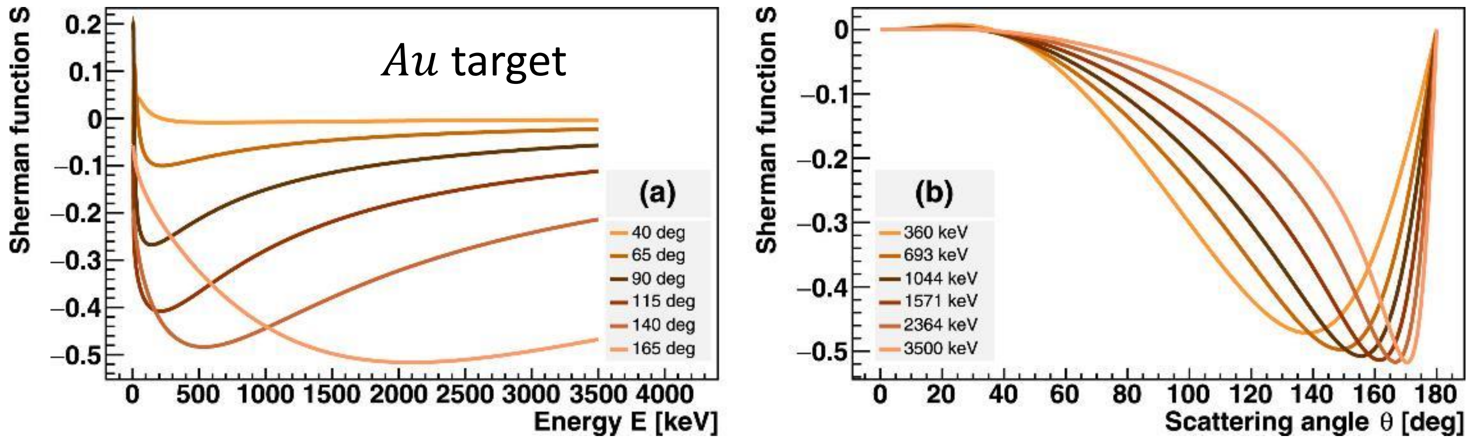
- Spin-orbit coupling of the electron passing through the electromagnetic field of a nucleus
- Electron experiences a magnetic field $\vec{B} \propto \frac{\partial U(r)}{\partial r} \vec{r} \times \vec{p}$
- $V_{SO} = \vec{\mu} \cdot \vec{B}$ changes the scattering probability to the left and right:
  - Sherman function $S(\theta)$
  - $A = PS(\theta)$
  - $S(\theta)$ depends on $\beta = v/c$



Mott Scattering

- Spin-orbit coupling of the electron passing through the electromagnetic field of a nucleus
- Electron experiences a magnetic field $\vec{B} \propto \frac{\partial U(r)}{\partial r} \vec{r} \times \vec{p}$
- $V_{SO} = \vec{\mu} \cdot \vec{B}$ changes the scattering probability to the left and right:
    - Sherman function $S(\theta)$
    - $A = PS(\theta)$
    - $S(\theta)$ depends on $\beta = v/c$





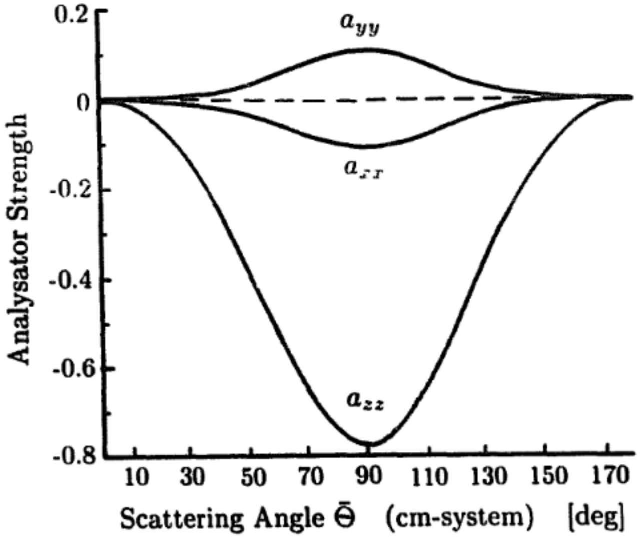
Nucl. Inst. & Meth. A 488 (2021) 37-42

- Asymmetries strongly energy dependent
    - Transverse polarization
    - Large asymmetries in backward direction
    - Useful for electron sources (keV to MeV)
    - Multiple scattering in target (systematics)
    - Heavy nuclei, destructive measurement

Møller Scattering

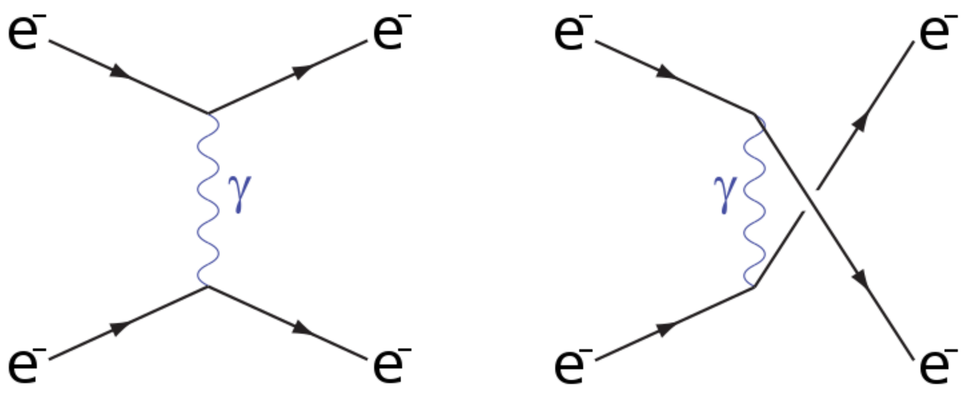
- Electron-electron scattering
    - Can be calculated in QED at tree level
    - Typically use electrons in fixed target
    - double-spin asymmetry:
      magnetized ferromagnetic foils

High energy limit of the analyzing power



Nucl. Inst. & Meth. A 294 (2990) 541

t-channel u-channel



$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_4 - p_2)^2$$
$$u = (p_1 - p_4)^2 = (p_3 - p_2)^2$$

Møller Scattering

- Electron-electron scattering
  - Can be calculated in QED at tree level
  - Typically use electrons in fixed target
  - double-spin asymmetry: magnetized ferromagnetic foils

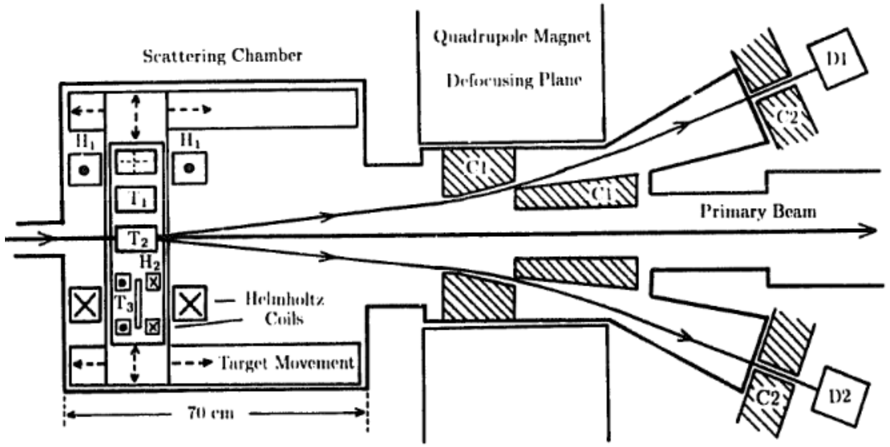
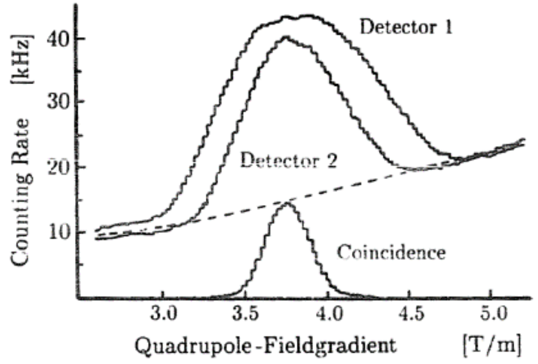
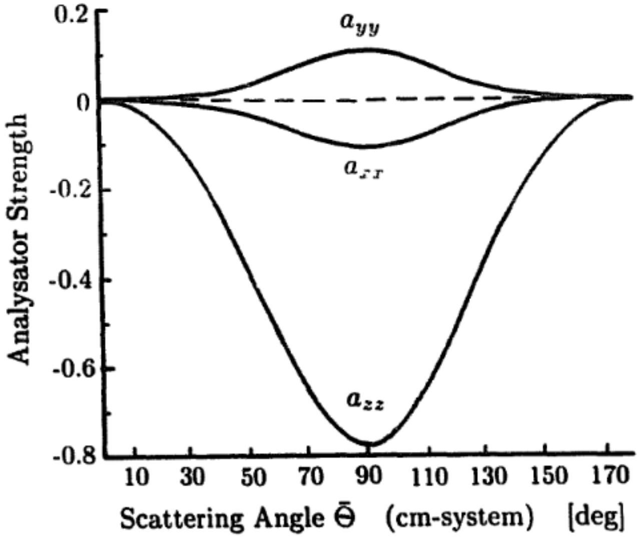


Fig. 3. Schematic Møller-polarimeter geometry.



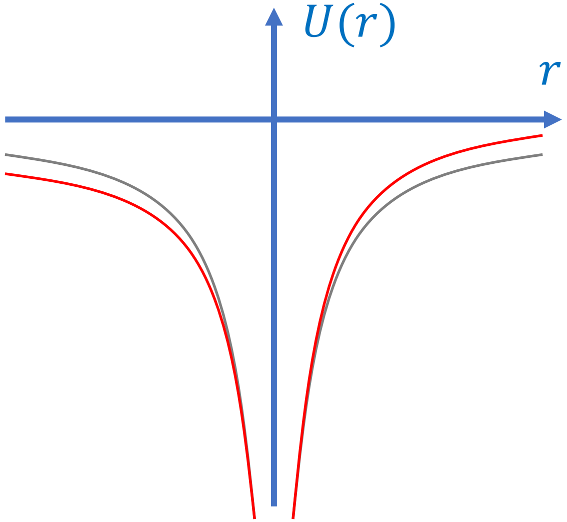
High energy limit of the analyzing power



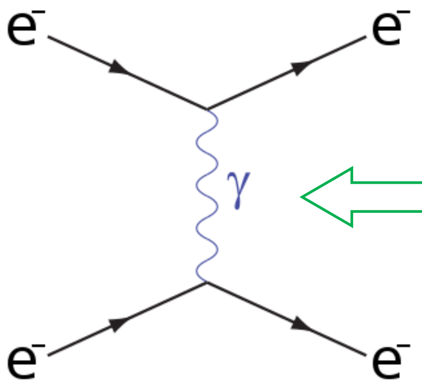
Nucl. Inst. & Meth. A 294 (2990) 541

- Maximum asymmetry at 90° in cms
  - Symmetric electron pair in lab frame: same energy, opposite angle
  - Target polarization can be changed by magnetic fields: “easy” magnetization → significant systematic uncertainty of polarization
  - Effective analyzing power for Fe is only 2/26
  - Work horse for fixed target experiments

Mott Scattering



Møller Scattering

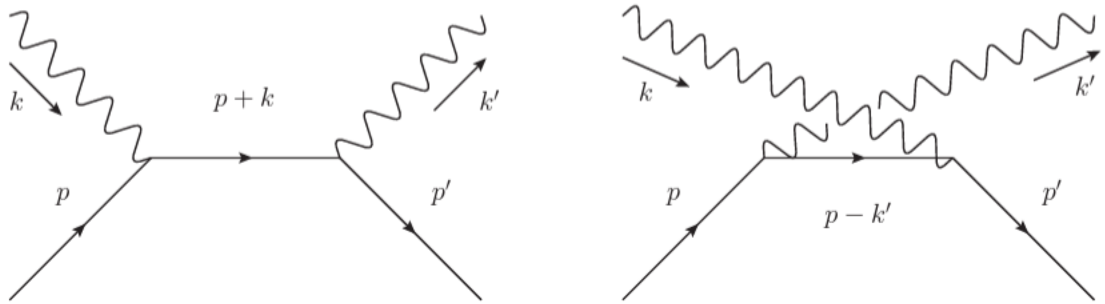


Anything else?

start here

Compton Scattering

- Cross section can be calculated at tree level in QED



- The cross section depends on the electron spin and photon helicity

$$\frac{d\sigma}{dy} = \frac{2\sigma_0}{x}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) + P\lambda rx(1-2r)(2-y)\right]$$

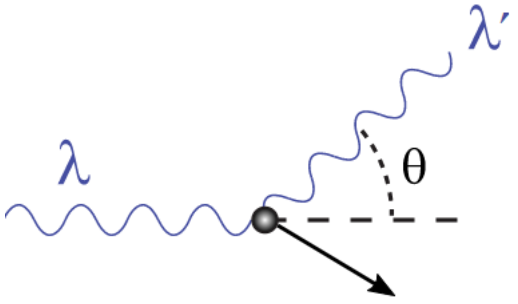
Electron/photon helicities

$$y = 1 - \frac{E}{E_0} = \frac{\omega}{E}$$

$$x = \frac{4E_0\omega_0}{m^2}\cos^2(\theta_0/2) \approx \frac{4E_0\omega_0}{m^2} \qquad r = \frac{y}{x(1-y)}$$

$$\sigma_0 = \pi r_0^2 = 0.2495 \text{ barn}$$

Target at rest



$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

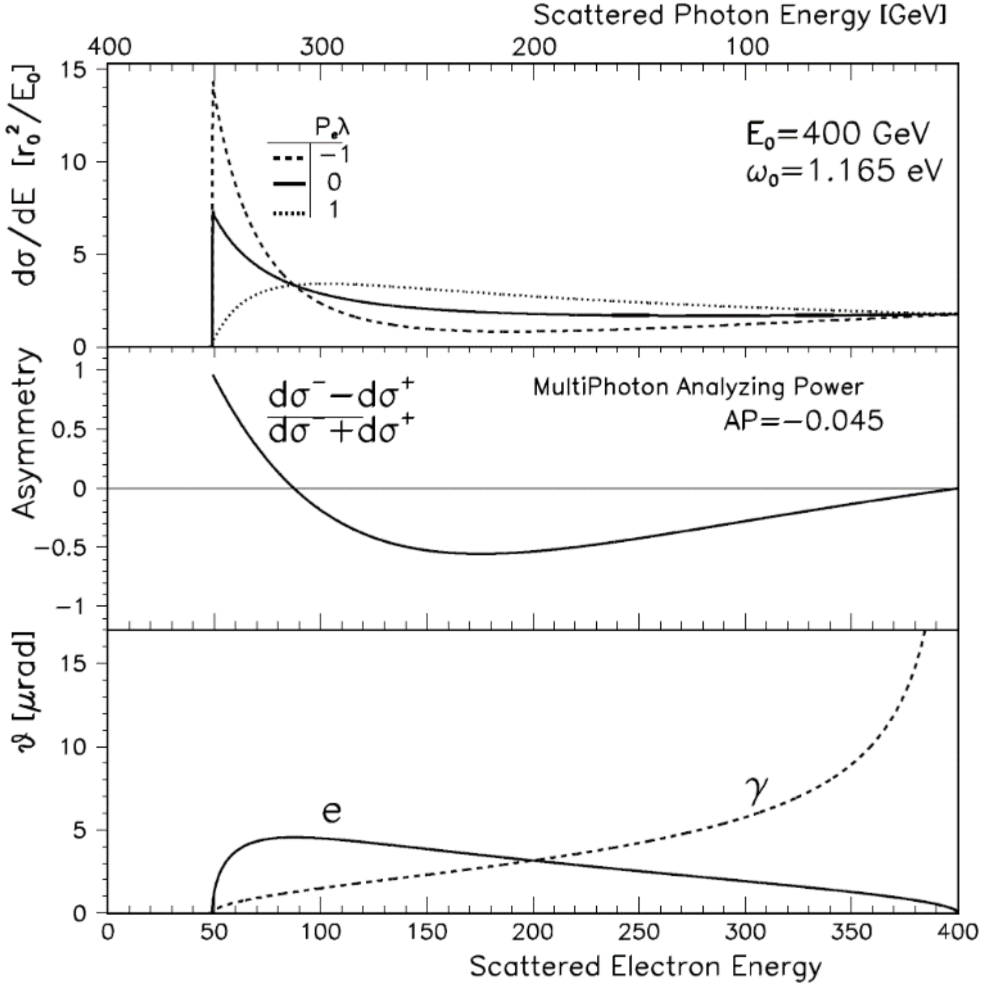
$$\omega_{max} = E_0\frac{x}{1+x} \qquad \theta_\gamma = \frac{m}{E_0}\sqrt{\frac{x}{y} - (x+1)}$$

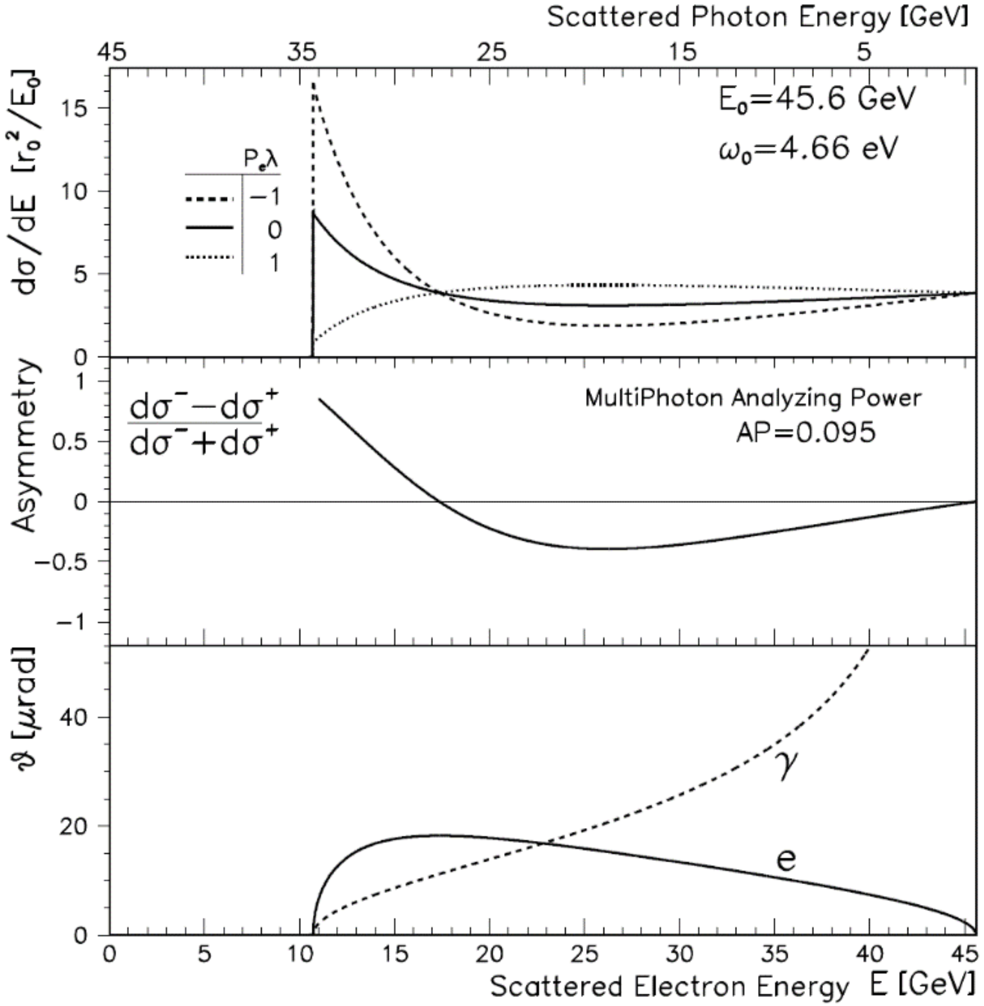
$$E_{min} = E_0\frac{1}{1+x} \qquad \theta_e = \frac{y}{1-y}\theta_\gamma$$

Polarized Compton Scattering at High Energies

- Example: International Linear Collider
  - Electron beam 250/400 GeV

V. Gharibyan, K. Meinert, P. Schüler.
"The TESLA Compton Polarimeter" LC-DET 2001-047

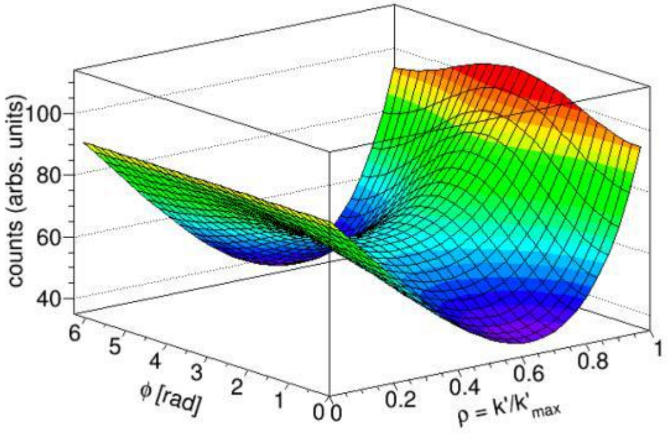




Transverse Electron Polarization

- Transverse electron polarization introduces an additional up/down asymmetry

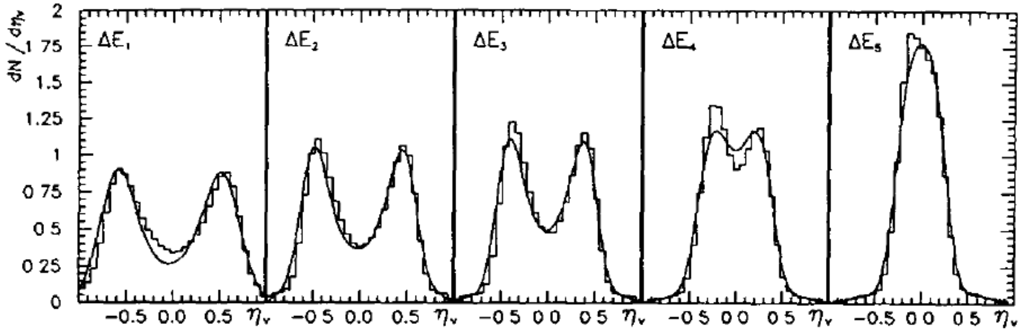
$$A_T = \frac{2\pi r_0^2 a}{d\sigma/d\rho} \cos\phi \left[\frac{\rho(1-a)\sqrt{4a\rho(1-\rho)}}{1-\rho(1-a))} \right] \qquad \rho = \omega/\omega_{max} \qquad a = \left(1 + \frac{4\gamma E_{laser}}{m_e}\right)^{-1}$$



$E_e = 20$ GeV

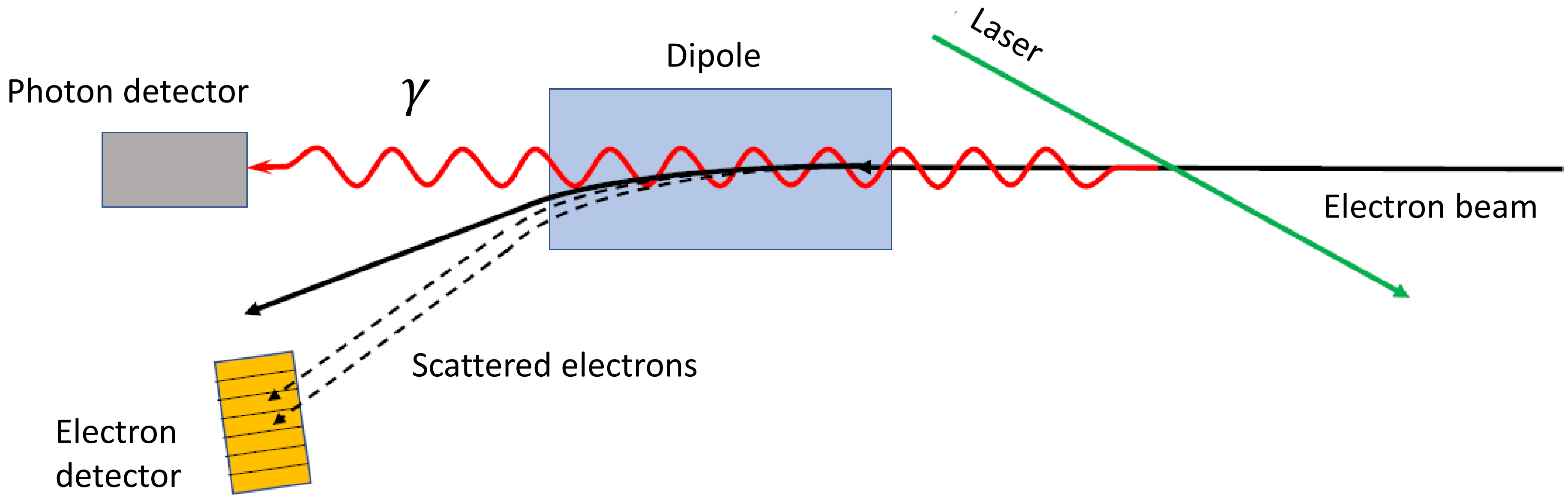
$\omega = 2.33$ eV

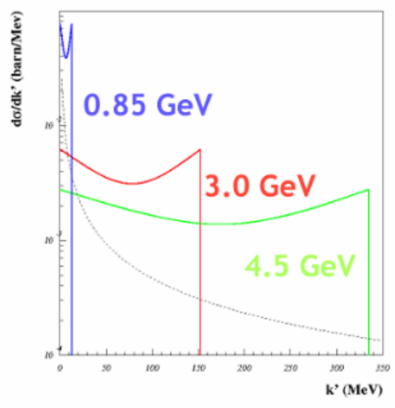
Early results from HERA (DESY)

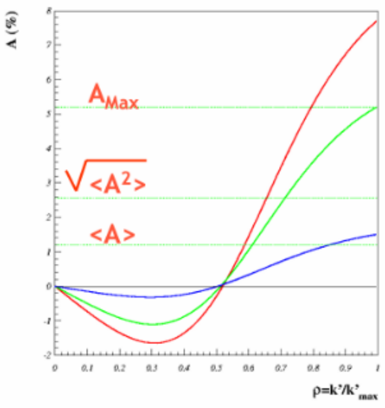


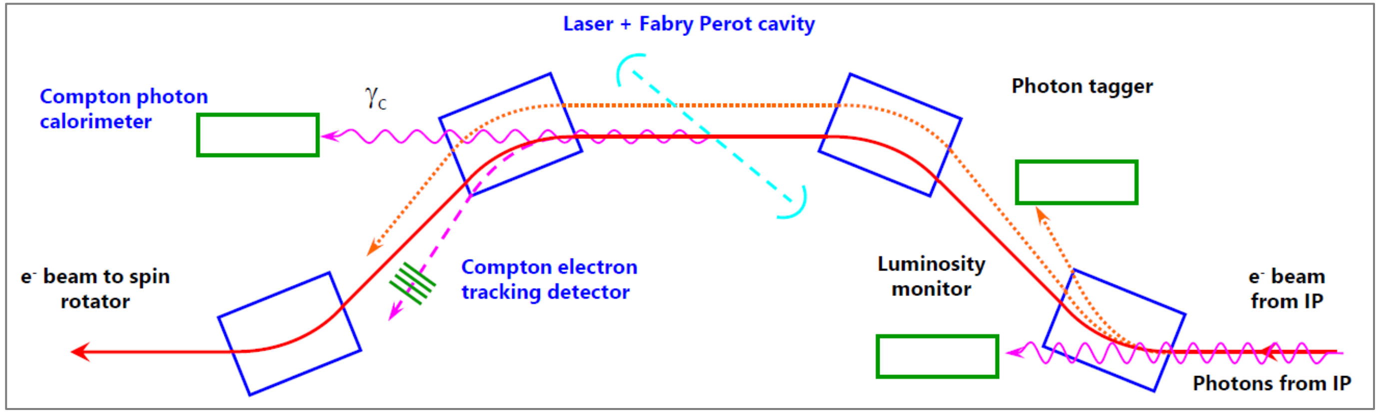
D. Barber et al. NIM A 329 (1993) 79

Components for Compton Measurements



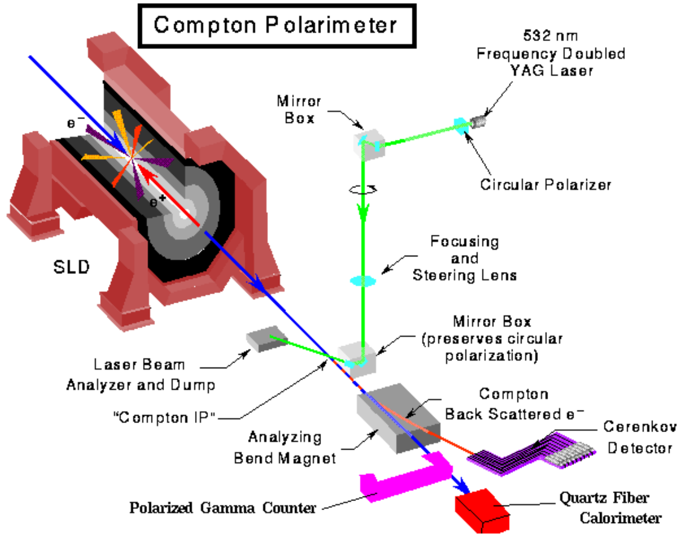




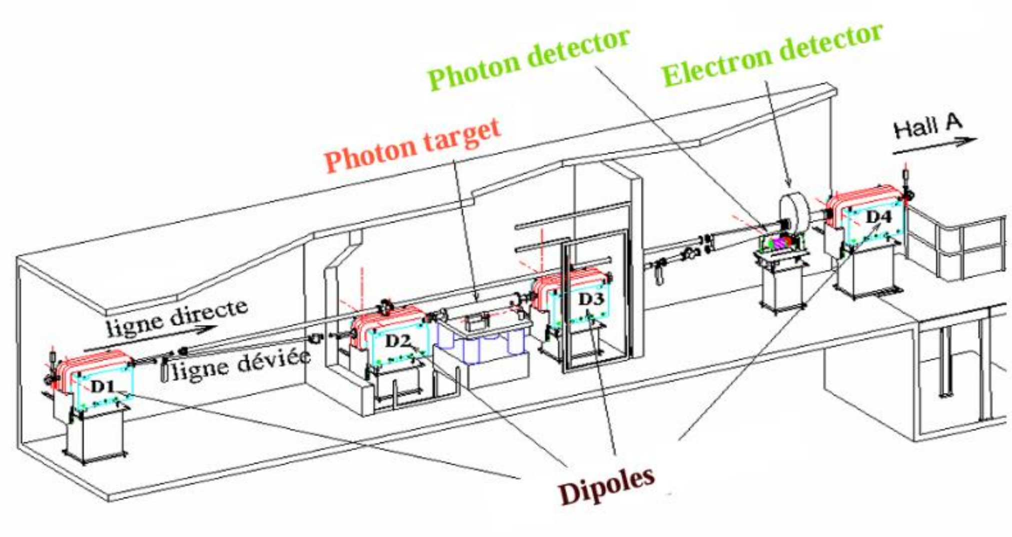


Compton Polarimeters

SLAC



JLAB



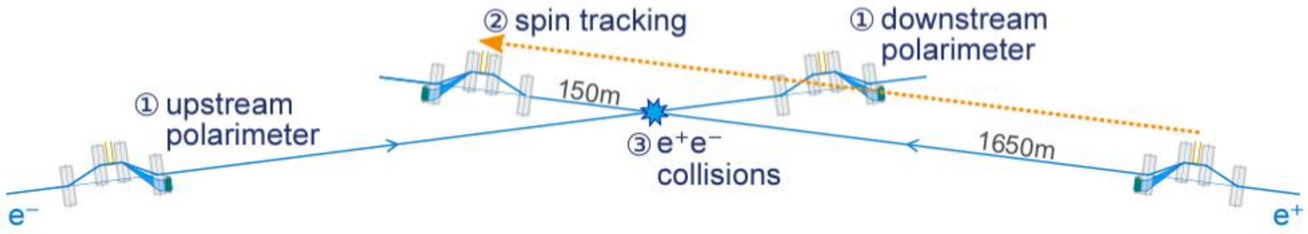
- Electron measurement seems easier to extract
- Dipole magnets (chicane) are less problematic in linear accelerator
- Every magnet creates synchrotron radiation

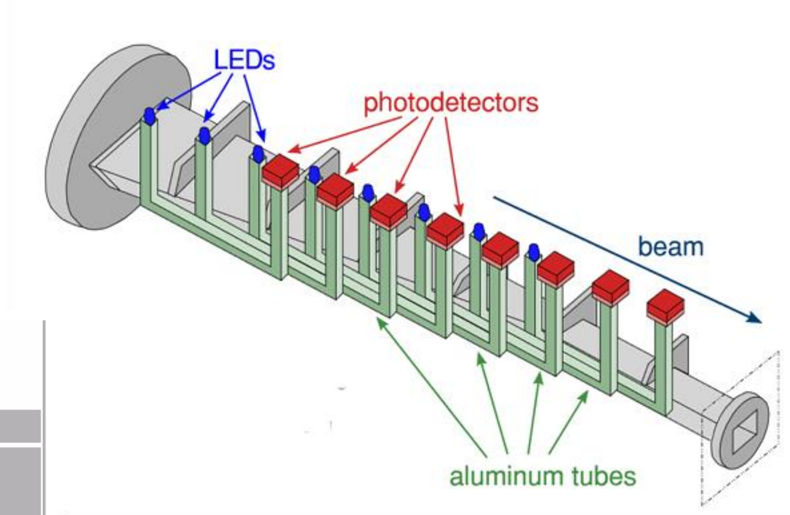
Experiment	Beam energy	Polarization	Polarimetry precision
JLab GEp/GMp (1999)[5]	1–4 GeV	60%	3%
SLAC E154 DIS $g1n$ (1997)[13]	48 GeV	82%	2.4%
HERMES $g1n$ DIS (2007)[14]	30 GeV	55%	2.9%
SLAC 122 PV-DIS (1978)[7]	16–22 GeV	37%	6%
Bates SAMPLE (2000)[15]	0.2 GeV	39%	4%
MAMI PV-A4 (2004)[16]	0.85 GeV	80%	2.1%
JLab Qweak (2017)[11]	1.2 GeV	88%	0.62%
SLD A_{LR} (2000)[17]	46.5 GeV	75%	0.5%

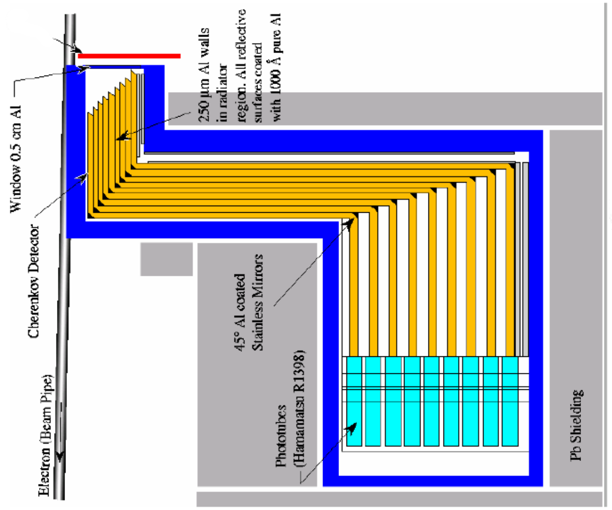
K. Aulenbacher, E. Chudakov, D. Gaskell, J. Grames, and K. D. Paschke,
"Precision electron beam polarimetry for next generation nuclear physics experiments,"
Int. J. Mod. Phys. E, vol. 27, no. 07, p. 1830004, 2018.

ILC Design

- International Linear Collider will use longitudinally polarized electron beams
  - $\sqrt{s} = 500\ \mathrm{GeV}$
  - Beam-beam interaction will significantly affect the polarization: measure before and after
  - High rate for fast measurement, $O(10^3)$ events per bunch
- Cerenkov detector
  - Position translates into energy
  - Multi-electron measurement with simple counting



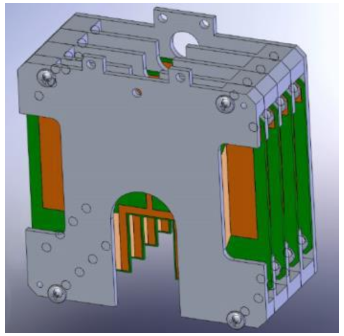


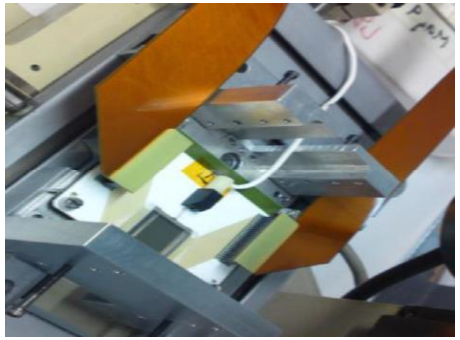


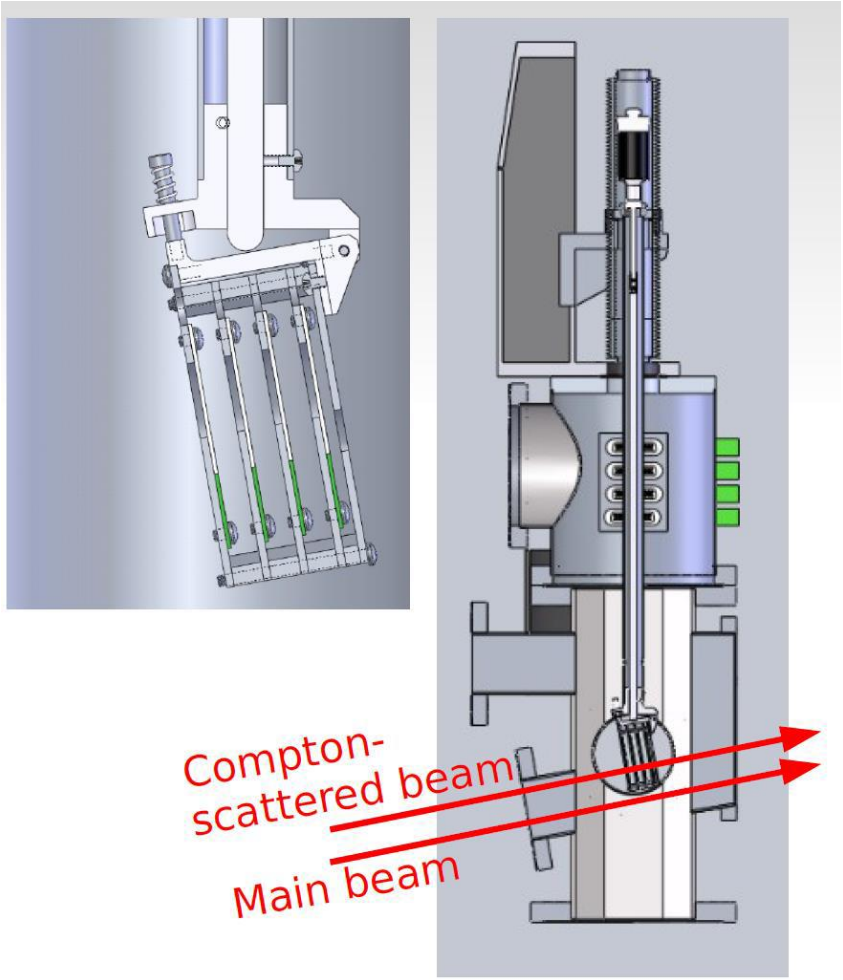
Based of SLD design

JLAB Hall C Compton Electron Detector

- Solid state detector on a movable arm
  - Similar to Roman Pot detector
  - Can get very close to the beam
- Silicon or diamond strips
  - Fine segmentation (≈ 200 strips with small pitch)
- Zero crossing of asymmetry (calibration/alignment)

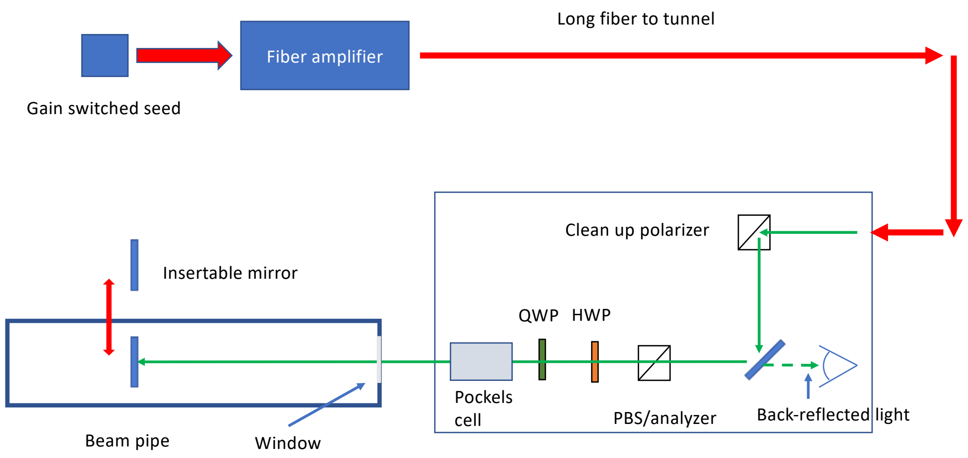




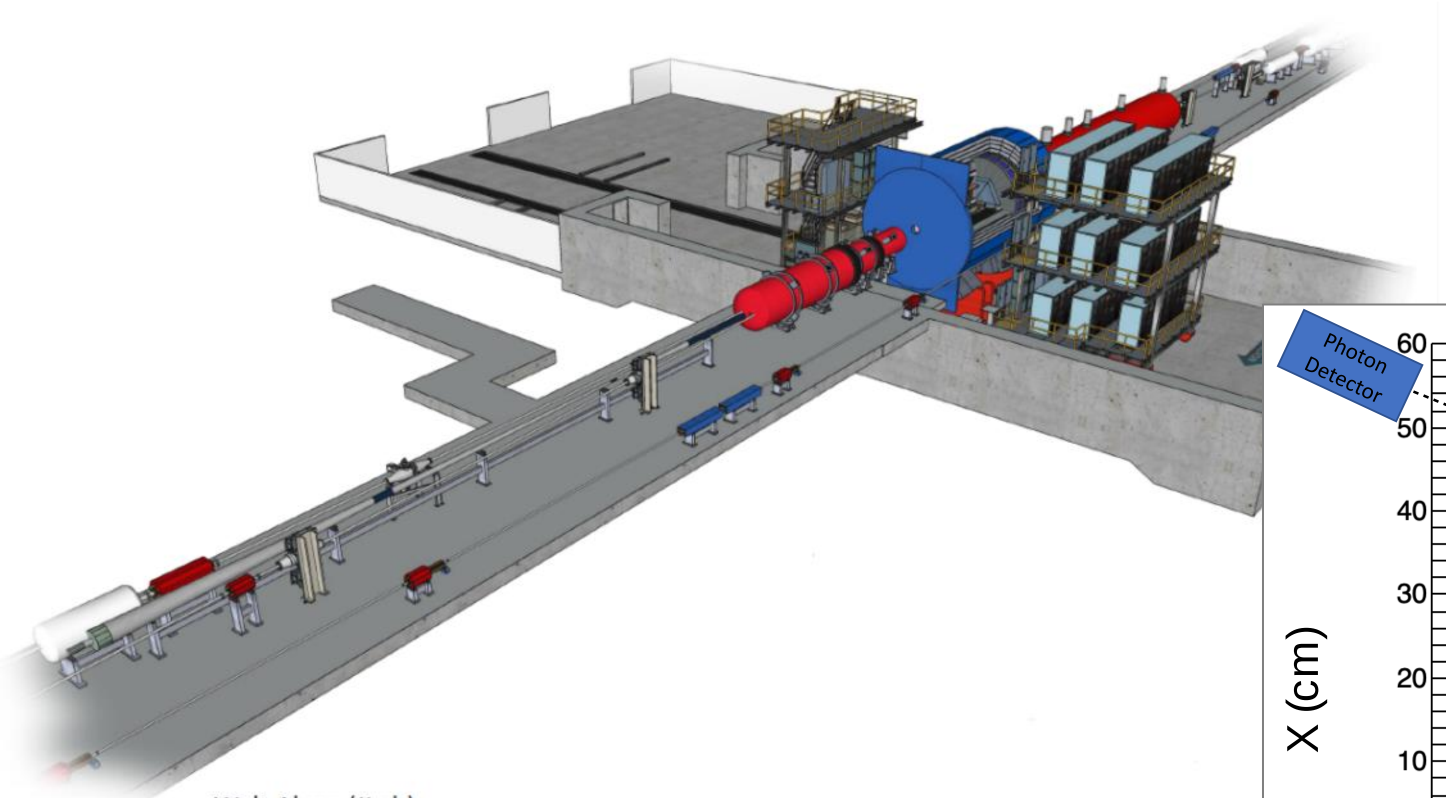


LASER Requirements

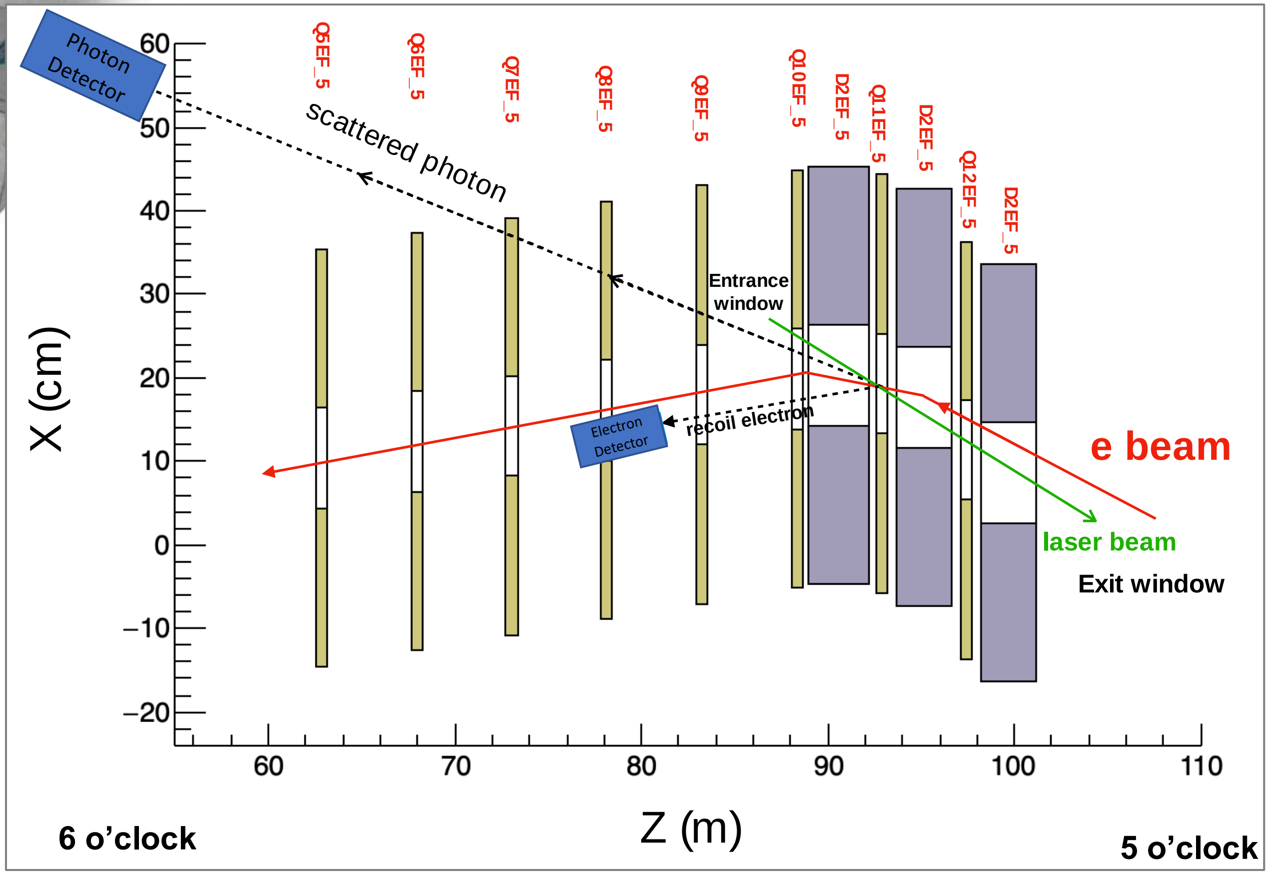
- Analyzing power depends on the photon energy.
- Components:
    - Gain-switched seed laser (1064 nm)
    - Fiber amplifier
    - Frequency doubling system (532 nm)
    - Laser polarization setup and diagnostics
- The laser power needs to match the beam intensity to meet the statistical demand.
- Pulsed laser at RF frequency of electron beam (25 and 100 MHz)
    - Average power = 10-20 W
    - Narrow bunch-width (10-15 ps)
- Laser power scaled from JLAB experiments



The EIC Compton Polarimeter

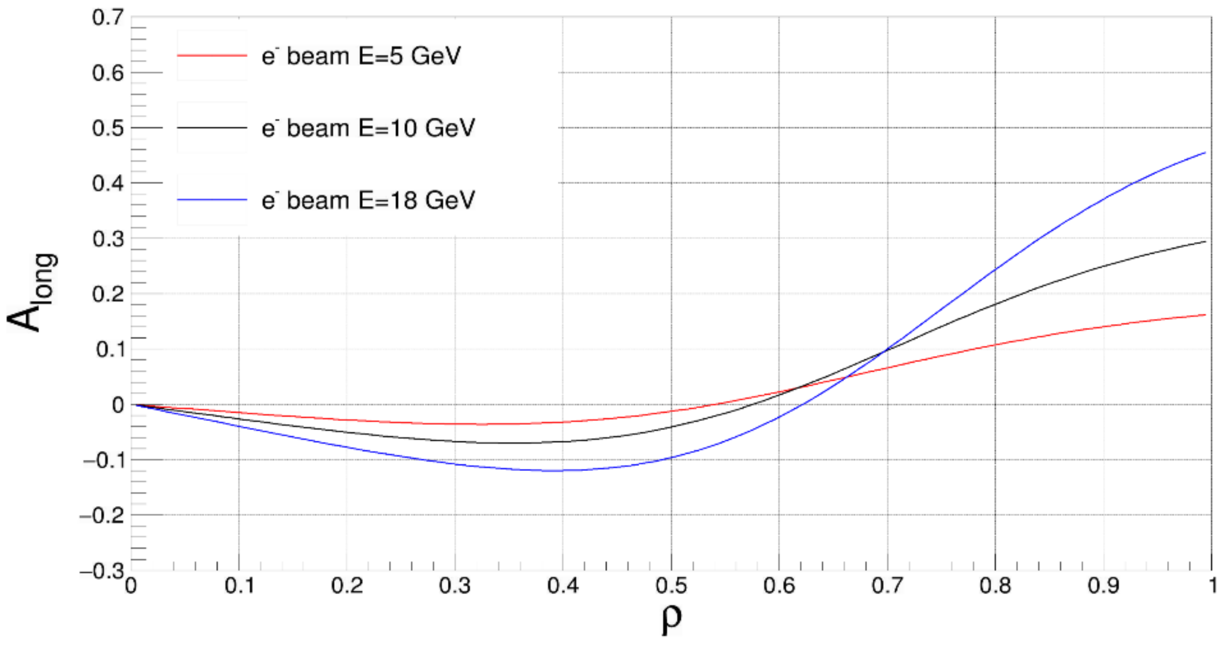


Walt Akers (JLab)

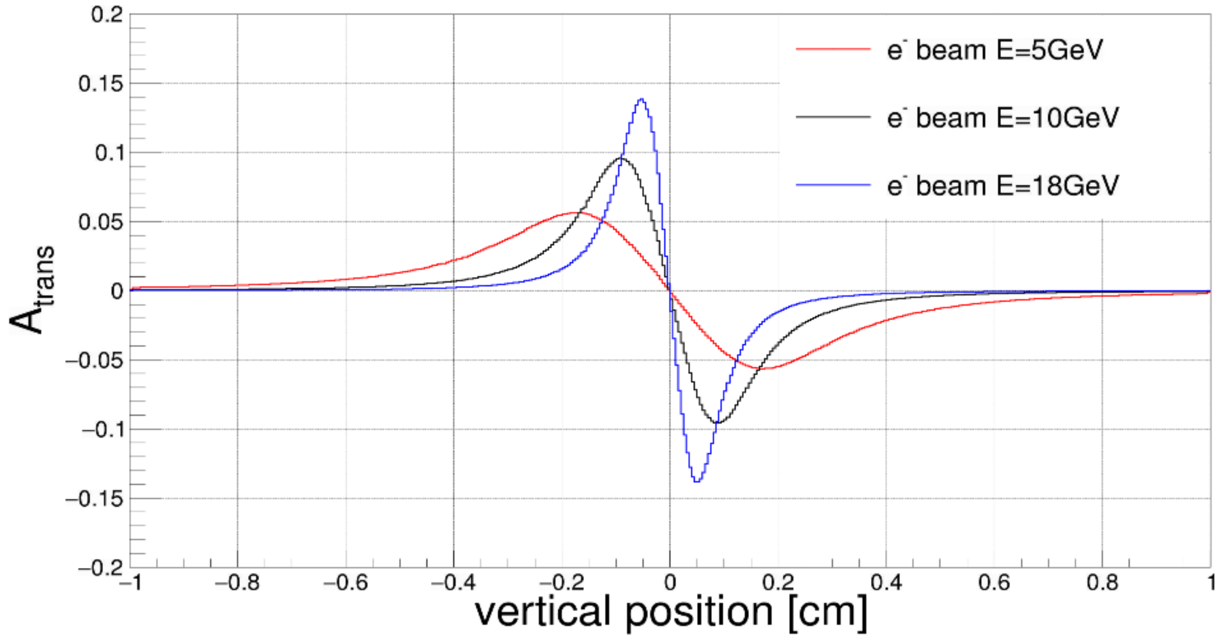


Compton Asymmetries at the EIC

Longitudinal electron polarization



Transverse electron polarization



Moderate energy resolution needed

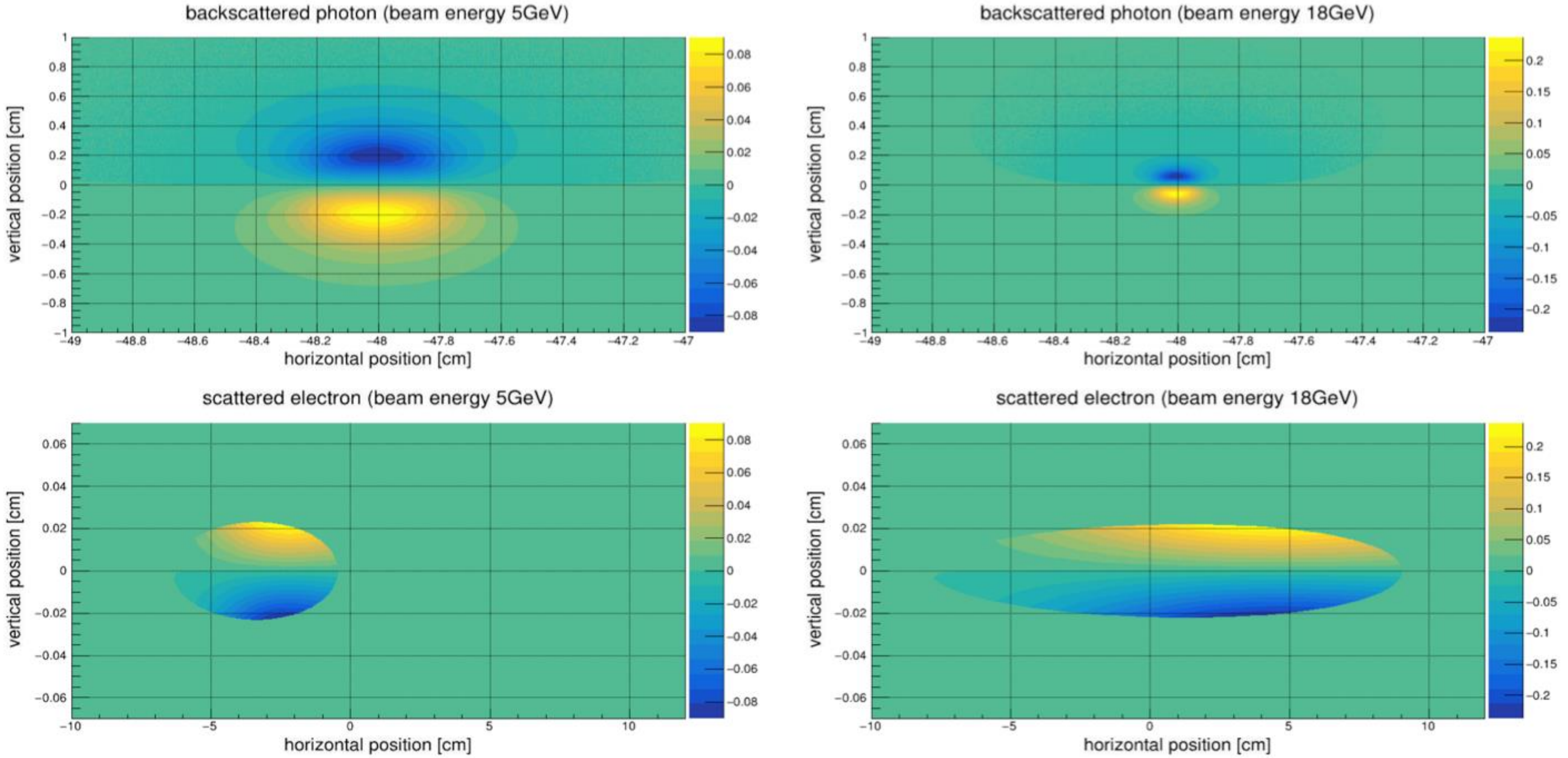
Vertical segmentation is vital

Transverse Polarization

$E_{beam} = 5 \text{ GeV}$ | $E_{beam} = 18 \text{ GeV}$

recoil photon

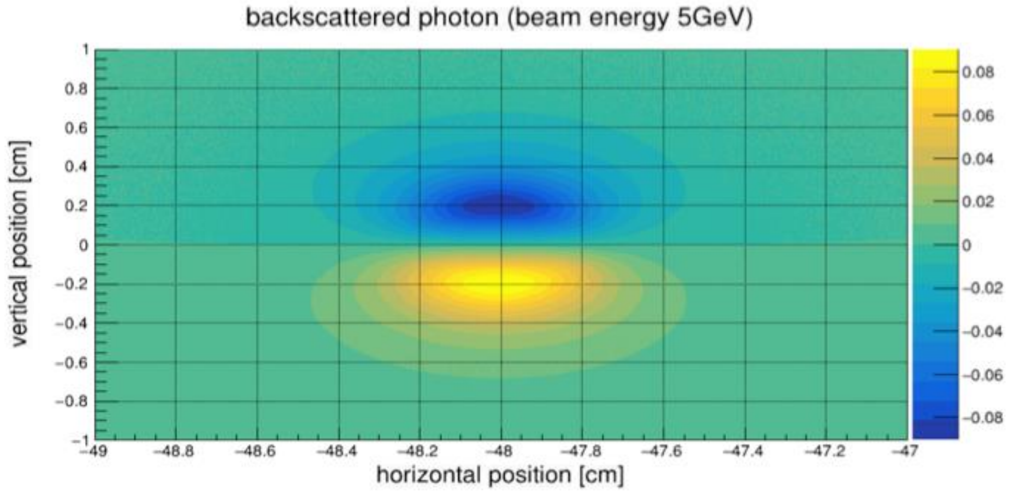
scattered electron



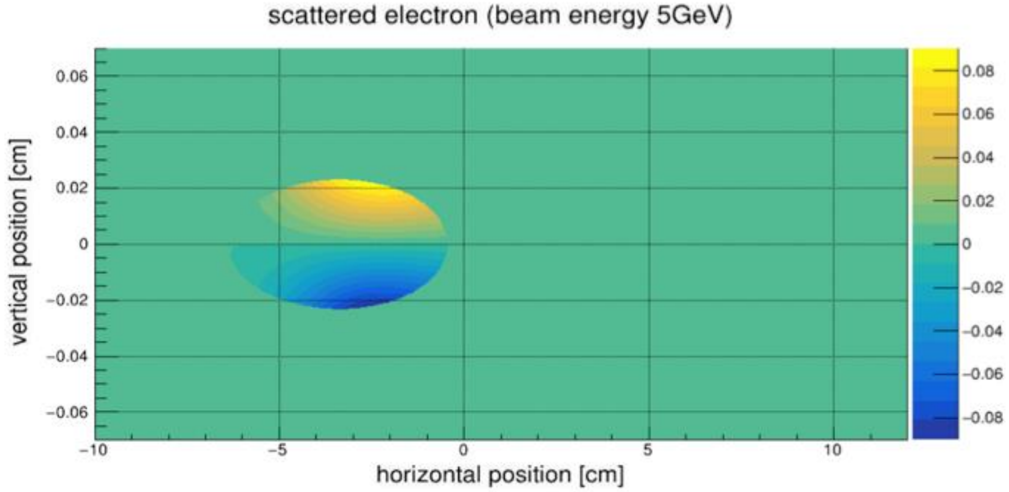
The Full Picture

$E_{beam} = 5 \text{ GeV}$

recoil photon



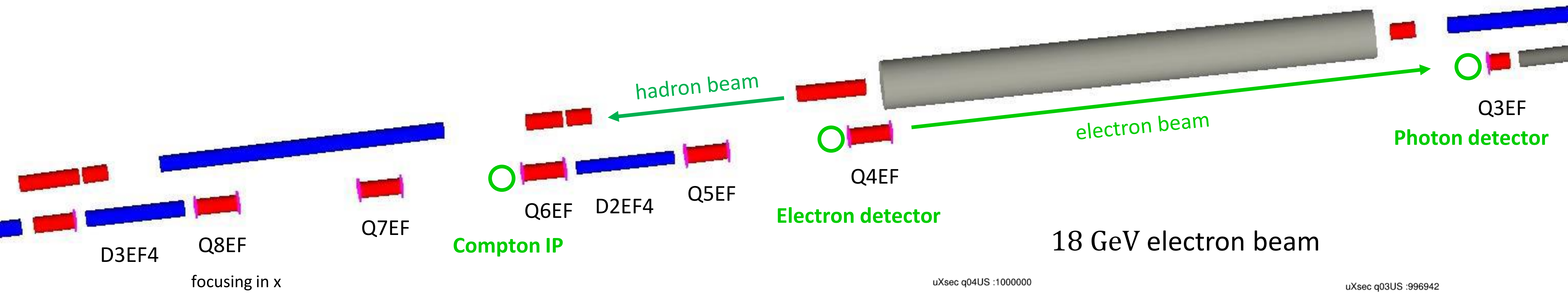
scattered electron



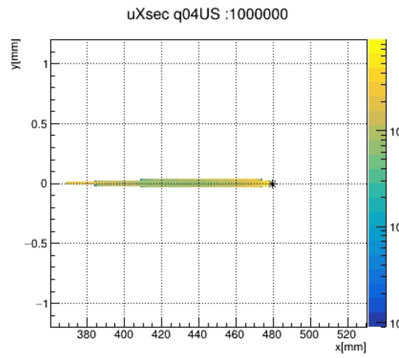
- Electromagnetic calorimeter
  - single or multiphoton mode
- Diamond strip detectors
- Radiation hard
- Fast response (needed for bunch-by-bunch measurements)
- Size determined by 5 GeV hit distributions, segmentation by 18 GeV distributions

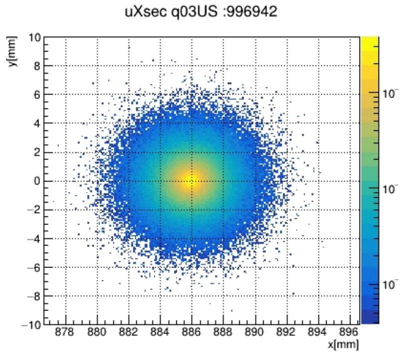
- Photon detector:
  - 16 x 16 mm^2, 100 μm pitch (vertical only)
- Electron detector:
  - 10 cm x 1 mm, few mm x 25 μm pitch

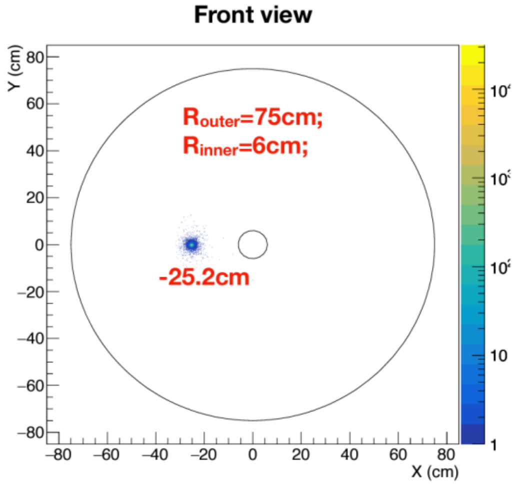
Detailed Simulations

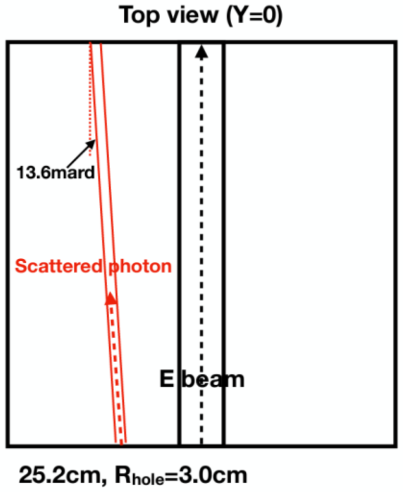


18 GeV electron beam





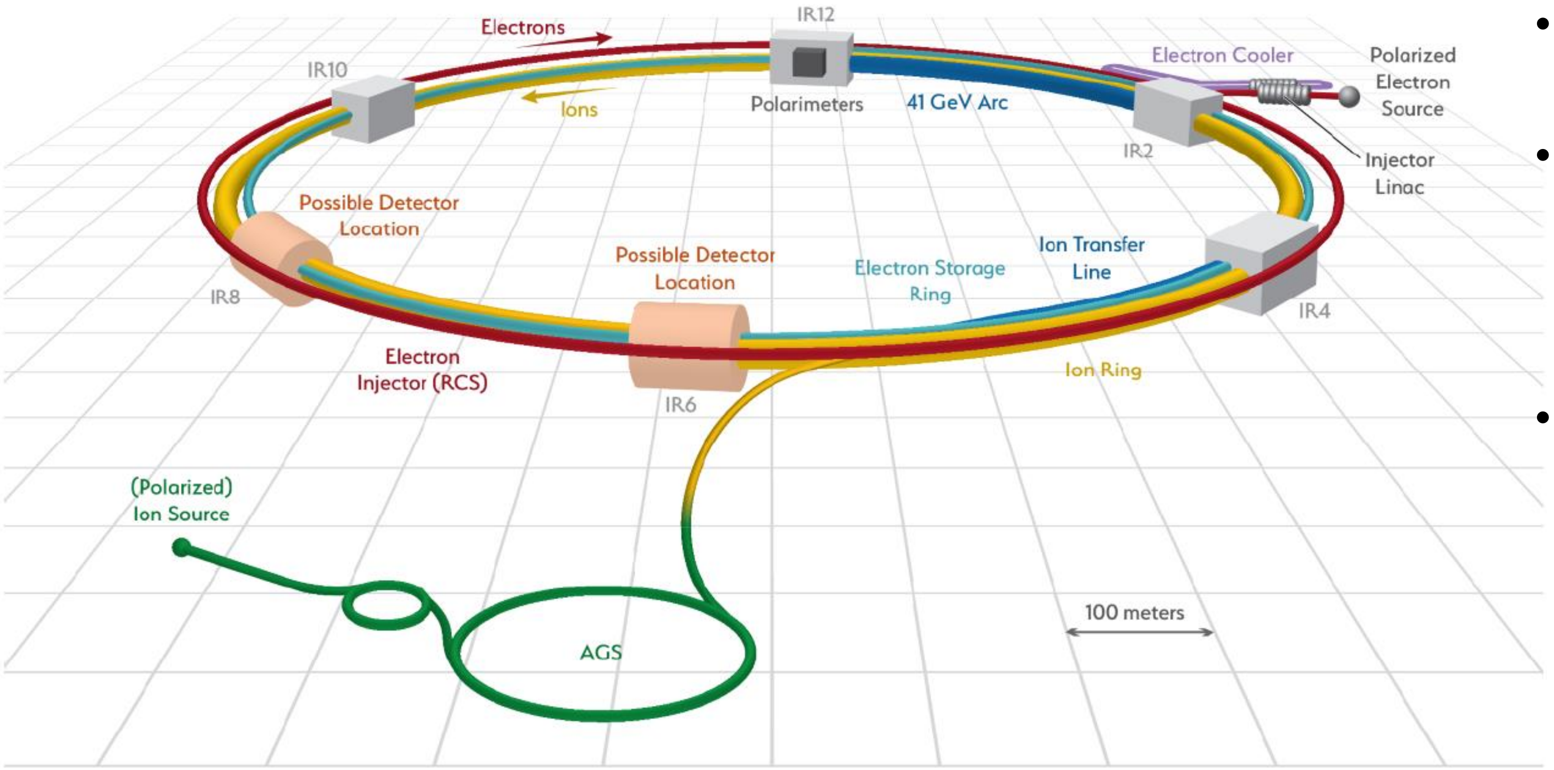


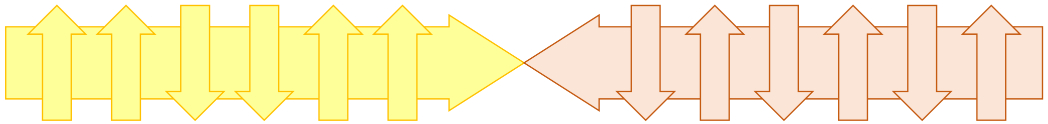


Vertical spread is a challenge for the transverse polarization measurement

Conclusions

A Polarized Electron-Ion Collider





- The EIC will be the first dedicated polarized electron-ion collider.
- Polarimetry is an integral part of the collider design to meet the demands of the physics goals.

- EIC-UG Polarimetry group:

  eicug-polarimetry@eicug.org