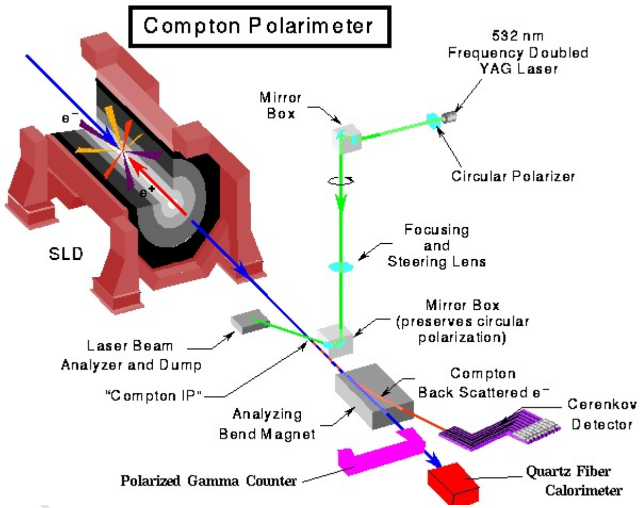
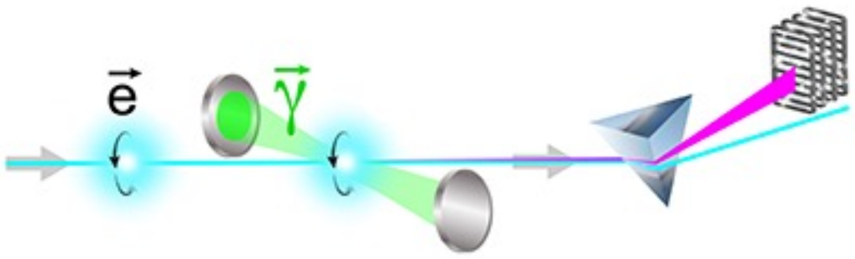
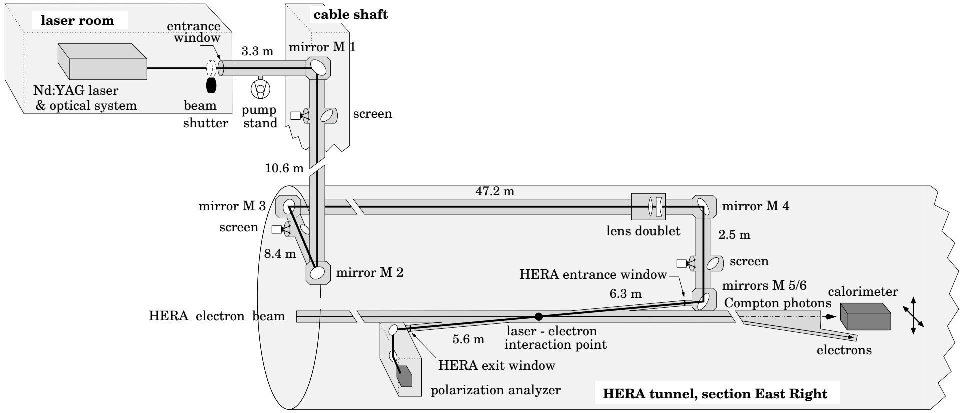
Polarimetry at EIC – Part 1

Dave Gaskell

Jefferson Lab







CFNS Summer School on the Physics of the Electron Ion Collider

August 9-20, 2021

A few references and resources

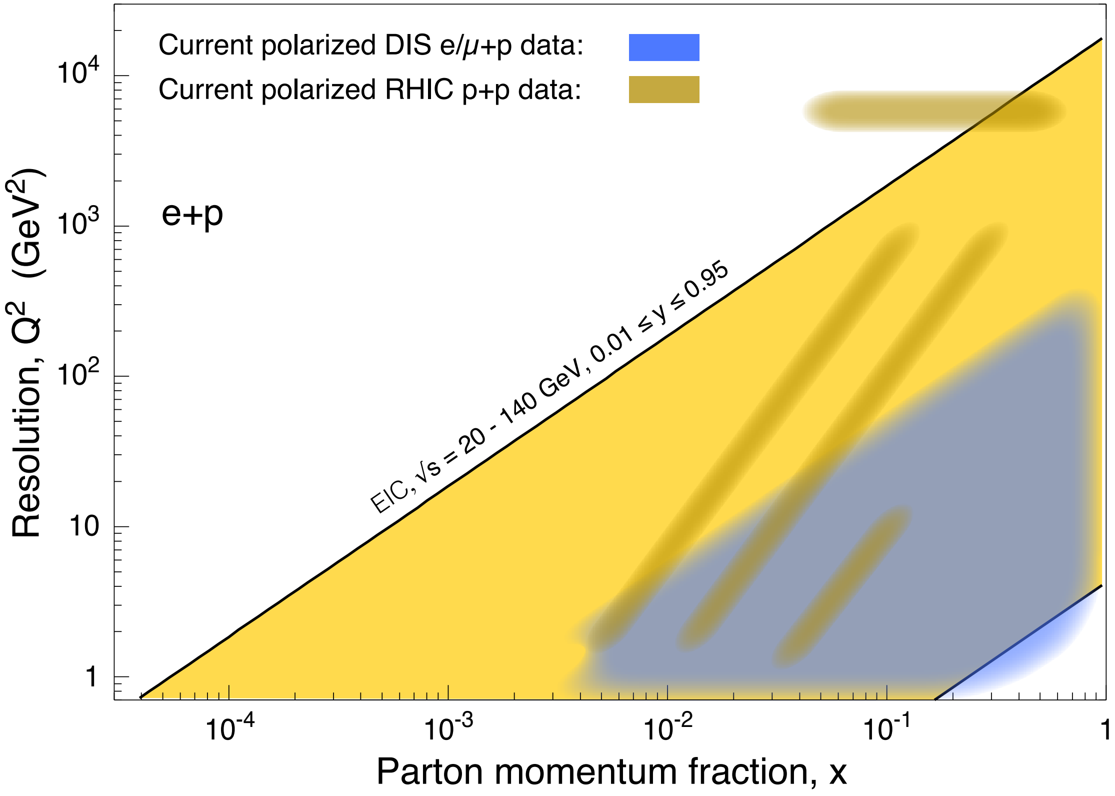
- CFNS Workshop on Beam Polarization and Polarimetry
  - https://indico.bnl.gov/event/7583/
- EICUG Working Group on Polarimetry and Ancillary Detectors (luminosity monitor)
  - https://indico.bnl.gov/category/280/
- Precision electron beam polarimetry for next generation nuclear physics experiments
  - *Int.J.Mod.Phys.E* 27 (2018) 07, 1830004, https://doi.org/10.1142/S0218301318300047
- “Conceptual Design Report of a Compton Polarimeter for Cebaf Hall A”, https://hallaweb.jlab.org/compton/Documentation/Technical/1996/proposal.ps.gz

Outline

- Polarimetry Requirements for EIC
  - Experiment requirements
  - Beam properties
- Electron Polarimetry
  - Overview of techniques
  - Compton polarimetry → in-depth look at previous polarimeters
  - Electron polarimetry at EIC
    - Mott (injector)
    - Electron Storage Ring (Compton)
    - Rapid Cycling Synchrotron
- Hadron Polarimetry
  - Experience from RHIC
  - Challenges at EIC
- Summary

Physics from Polarized Beams at EIC

- EIC will provided an enormous amount of information in many reaction channels to elucidate the quark/gluon structure of nucleons and nuclei
- Polarized beams a crucial requirement for achieving physics goals
- 1D polarized quark distributions via inclusive and SIDIS measurements (double-spin asymmetries)
- Access to transverse momentum distributions (TMDs) via SIDIS (single-spin, double-spin asymmetries)
- Total angular momentum in nucleon (GPDs) via exclusive reactions (single-spin, double-spin asymmetries)
- Physics beyond the Standard Model using PV processes



EIC will provide unprecedented statistical precision in many reaction channels due to its high luminosity
→ Require systematic precision to match

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Systematics and Luminosity Measurement

Collision luminosity measured via the Bremsstrahlung process: *ep* → *ep*γ

→ Successfully used at HERA – precisely known cross section, high rates

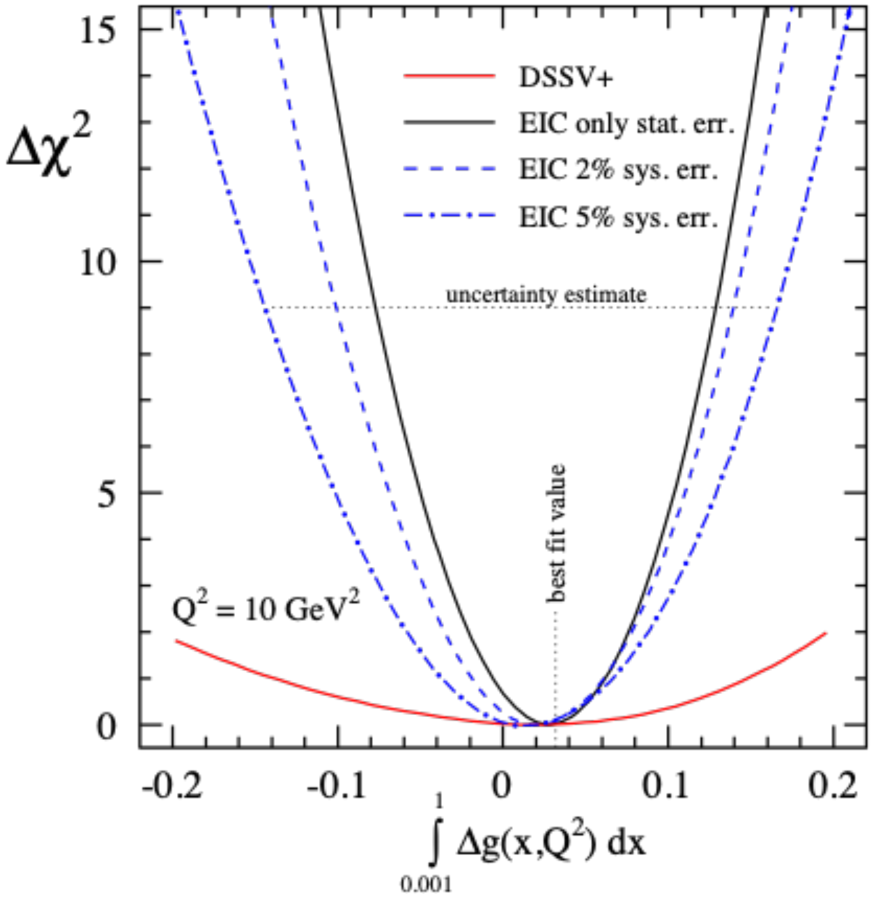
Unlike HERA, both beams polarized → results in a polarization dependent term:

$$\sigma_{Brems} = \sigma_0(1 + aP_eP_h)$$

Precision in luminosity measurement for double-spin asymmetries coupled to polarimetry

$$A_{\|} = \frac{1}{P_eP_h}\left[\frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}\right]$$

$$R = L^{++}/L^{+-}$$



Impact of systematic uncertainties on Δg

Polarimetry systematics:
Goal is ***dP/P = 1%*** or better for both electrons and hadrons

EIC Beam Properties

EIC will provide unique challenges for both electron and hadron polarimetry

Common challenge to both: small spacing between bunches
→ 10 ns between electron/hadron bunches at high luminosity configuration (~40 ns at higher CM configuration)
→ Intense beams
  → Large synchrotron radiation for electron beams result in large effects at detectors
  → Hadron beam intensity results in challenges for polarimeter targets

More detailed discussion later

Table 1.1: Maximum luminosity parameters.

Parameter	hadron	electron
Center-of-mass energy [GeV]	104.9	
Energy [GeV]	275	10
Number of bunches	1160	
Particles per bunch [10^{10}]	6.9	17.2
Beam current [A]	1.0	2.5
Horizontal emittance [nm]	11.3	20.0
Vertical emittance [nm]	1.0	1.3
Horizontal β-function at IP β_x^* [cm]	80	45
Vertical β-function at IP β_y^* [cm]	7.2	5.6
Horizontal/Vertical fractional betatron tunes	0.228/0.210	0.08/0.06
Horizontal divergence at IP $\sigma_{x'}^*$ [mrad]	0.119	0.211
Vertical divergence at IP $\sigma_{y'}^*$ [mrad]	0.119	0.152
Horizontal beam-beam parameter ξ_x	0.012	0.072
Vertical beam-beam parameter ξ_y	0.012	0.1
IBS growth time longitudinal/horizontal [hr]	2.9/2.0	-
Synchrotron radiation power [MW]	-	9.0
Bunch length [cm]	6	0.7
Hourglass and crab reduction factor [17]	0.94	
Luminosity [$10^{34}\,cm^{-2}\,s^{-1}$]	1.0	

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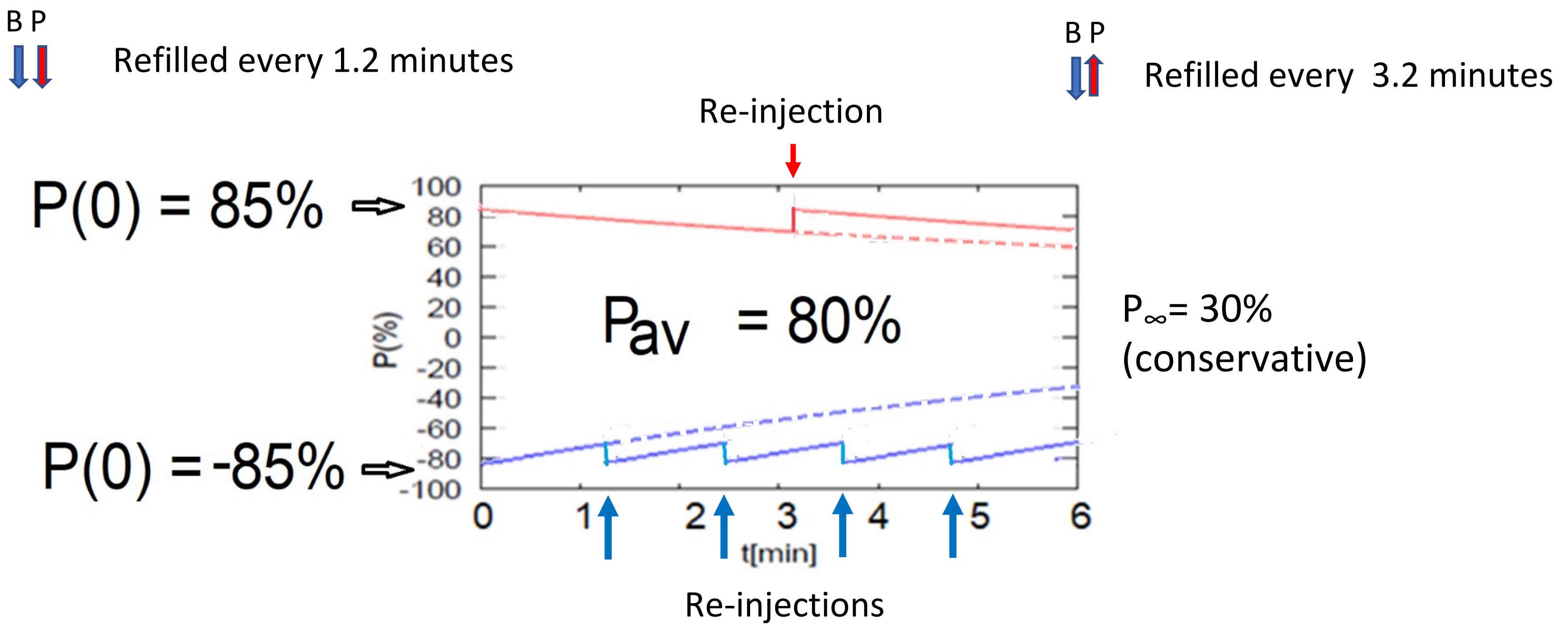
Polarization Time Dependence - electrons

- Electrons injected into the storage ring at full polarization (85%)
- Sokolov-Ternov effect (self-polarization) will re-orient spins to be anti-parallel to main dipole field → electrons will different lifetime depending on polarization
- Bunches must be replaced relatively often to keep average polarization high
- Bunch-by-bunch polarization measurement required



P_∞= 30%
(conservative)

Figure from C. Montag (BNL)

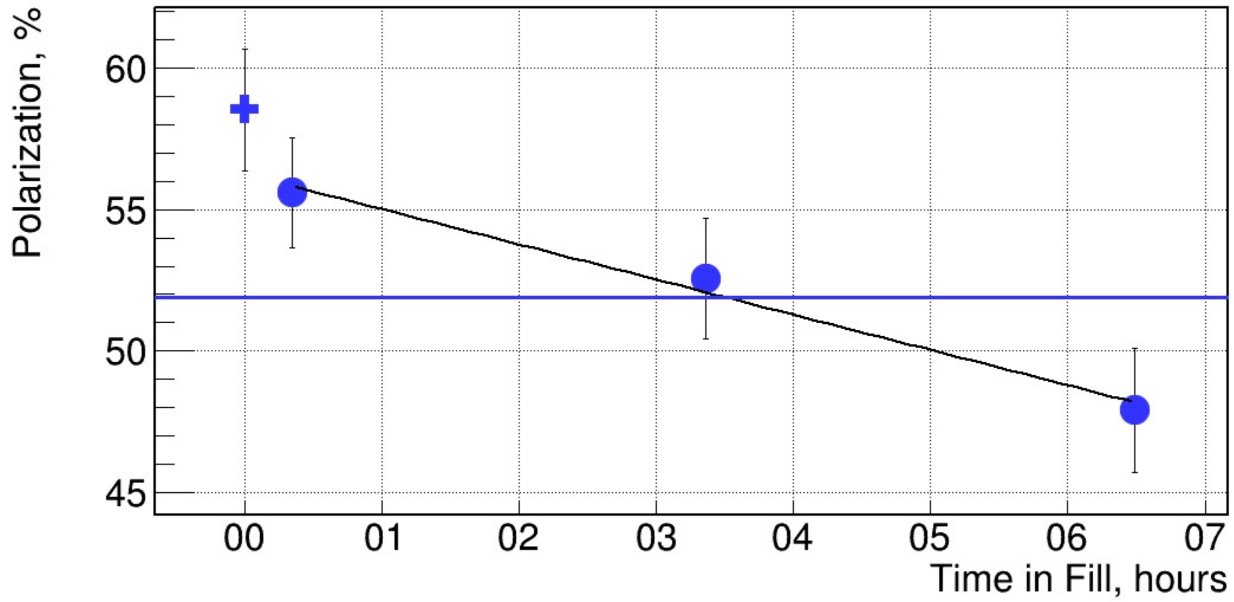
Bunches will be replaced about every 50 minutes at 5 and 10 GeV
→ 3 minutes at 18 GeV

Sets requirement for measurement time scale

Polarization Time Dependence - protons

Hadron polarization lifetime expected to be much longer than electrons
→ No need to replace bunches

Polarization will change with time, but much more slowly
→ Need sufficient statistical precision to track time dependence, but less stringent than electron beam requirements



Proton polarization for a fill @RHIC

Electron Beam Polarimetry

High Precision Electron Polarimetry

- Experiments have become ever more demanding in terms of electron beam polarization and required precision on knowledge of degree of polarization
- Hadronic physics experiments using polarized beams/targets dominated by knowledge of target polarization → usually on the order of 3-4%
  - Requirements on electron beam polarimetry correspondingly modest
- Precision in electron beam polarimetry has been driven by needs of parity violating electron scattering experiments
  - Precision of 1% or better desired
- Future PV experiments aim for precision better than 0.5%
- EIC will make measurements with highly polarized hadron beams
  - High precision polarimetry will become increasingly relevant for hadronic physics experiments

Experiment	Beam Energy	Polarization	Polarimetry Precision
JLab GEp/GMp (1999)	1-4 GeV	60%	3%
SLAC E154 DIS g1n (1997)	48 GeV	82%	2.4%
HERMES g1n DIS (2007)	30 GeV	55%	2.9%
SLAC 122 PV-DIS (1978)	16-22 GeV	37%	6%
Bates SAMPLE (2000)	0.2 GeV	39%	4%
MAMI PV-A4 (2004)	0.85 GeV	80%	2.1%
JLab Q-weak (2017)	1.2 GeV	88%	0.62%
SLD A_{LR} (2000)	46.5 GeV	75%	0.5%

Electron Beam Polarimetry

Beam polarization determined via measurement of scattering asymmetry with *known* analyzing power

$$A_{\rm measured} = P_{\rm beam} A_{\rm effective}$$

$A_{\rm effective}$ incorporates theoretical analyzing power, convoluted over polarimeter acceptance
→ May include additional corrections (radiative effects, "Levchuk" effect, etc.)

Process may rely on a double-spin or single-spin asymmetry

→ Double-spin measurements rely on knowledge of the target polarization
→ Single-spin asymmetry → no target polarization, but only one useful process (Mott scattering), can only be used at low energy
→ Electron polarimetry → for all useful processes, analyzing power known with high precision (QED)

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
- Møller scattering: $\vec{e} + \vec{e} \rightarrow e + e$, atomic electrons in Fe (or Fe-alloy) polarized using external magnetic field
  - Can be used at MeV to GeV-scale energies – rapid, precise measurements
  - Usually destructive (solid target) – non-destructive measurements possible with polarized gas target, but such measurements not common
- Compton scattering: $\vec{e} + \vec{\gamma} \rightarrow e + \gamma$, laser photons scatter from electron beam
  - Easiest at high energies
  - Non-destructive, but systematics are energy dependent

Other polarimetry techniques

- Spin-light polarimetry – use analyzing power from emission of synchrotron radiation
- Compton transmission polarimetry

Mott Polarimetry

Mott scattering: $\vec{e} + Z \rightarrow e$

→ Spin-orbit coupling of electron spin with (large Z) target nucleus gives single-spin asymmetry for transversely polarized electrons

Mott polarimetry useful at low energies

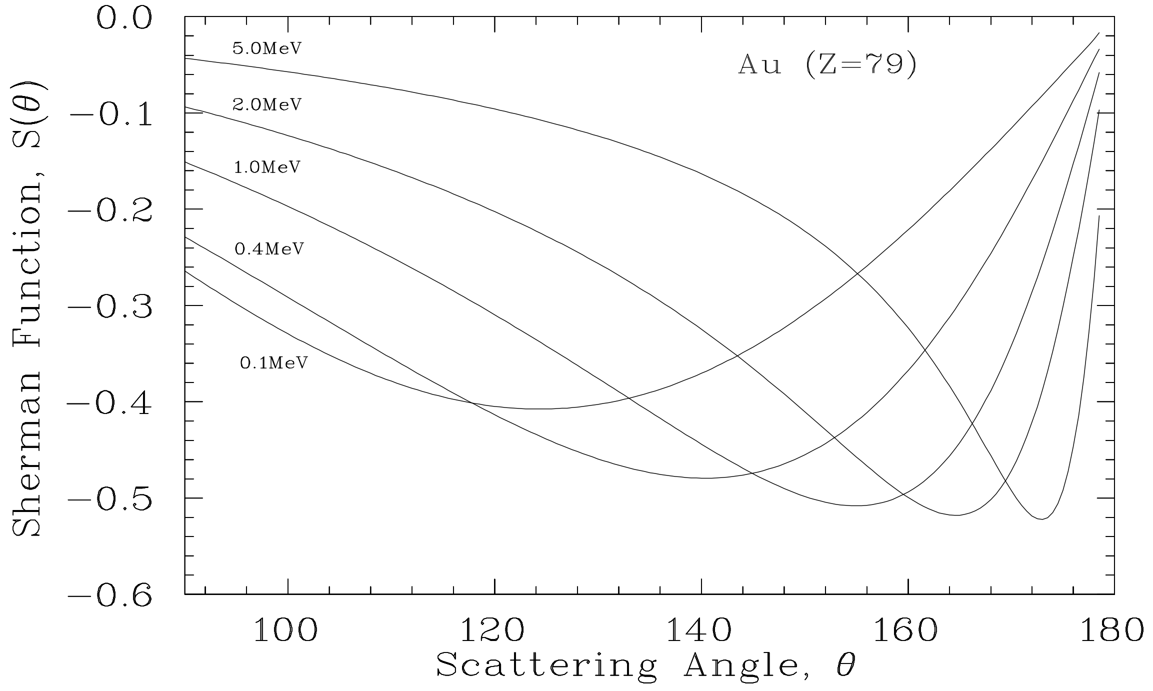
→ ~ 100 keV to 5 MeV

→ Ideal for use in polarized electron injectors

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

I(θ) → unpolarized cross section

$$I(\theta) = \left(\frac{Ze^2}{2mc^2}\right)^2 \frac{(1-\beta^2)(1-\beta^2 \sin^2 \frac{\theta}{2})}{\beta^4 \sin^2 \frac{\theta}{2}}$$



S(θ) is the Sherman function

→ must be calculated from electron-nucleus cross section

→ Dominant systematic uncertainty but controlled to better than 1%

Sherman Function

Sherman function describes single-atom elastic scattering from atomic nucleus

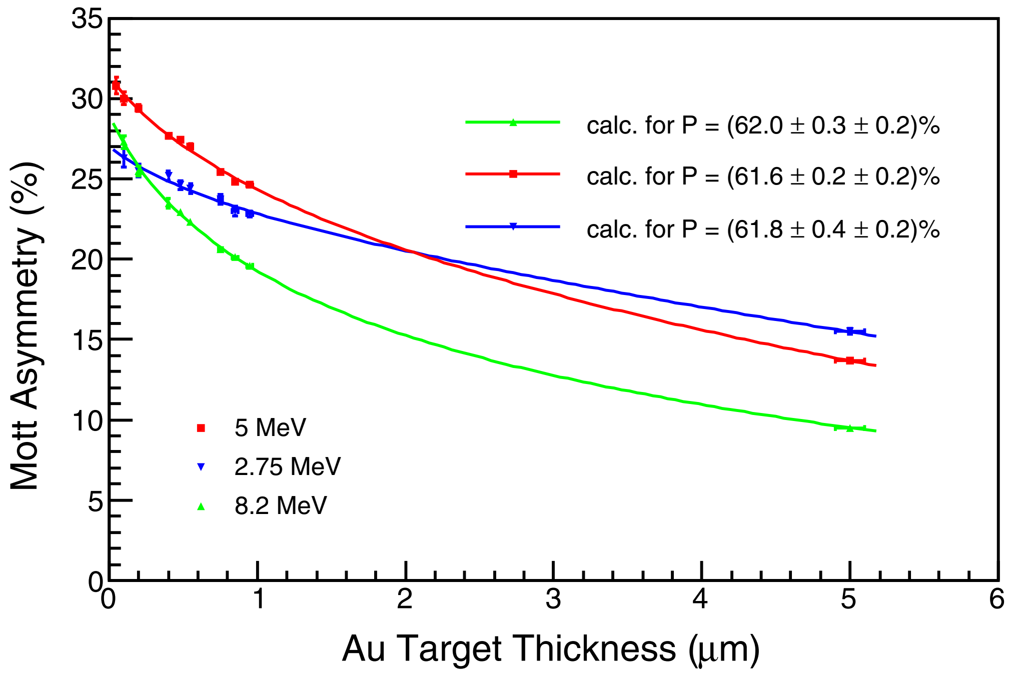
$$S(\theta) = i\frac{fg^* - gf^*}{f^2 + g^2}$$

Direct amplitude　　Spin flip amplitude

f and *g* can be calculated exactly for spherically symmetric charge distribution

Knowledge of nuclear charge distribution and atomic electron distribution leads to systematic error
→ Controlled better than 0.5% for regime 2-10 MeV

In target with finite thickness, electron may scatter more than once → Effective Sherman function
→ Controlled by making measurements at various foil thicknesses and extrapolating to zero



MAINZ MeV Mott

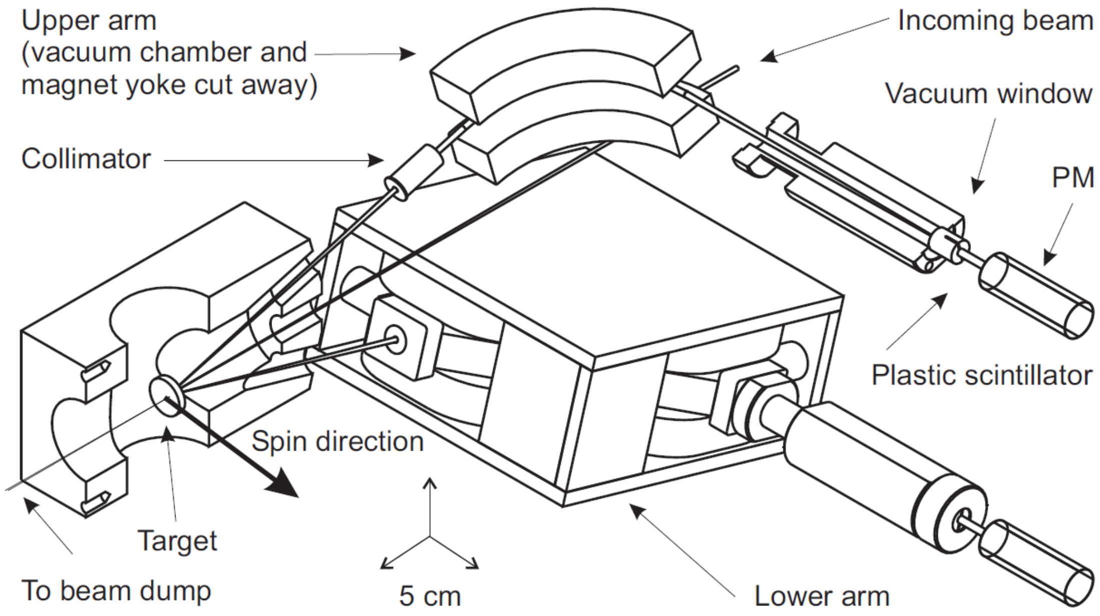
Mott polarimeter in MAMI accelerator at Mainz installed after injector linac

Scattering angle = 164 degrees
→ Sherman function peaks at 2 MeV

Background from dump suppressed by using deflection magnets to steer scattered electrons to detectors – no direct line of site to beam dump

Dominant systematics from Sherman function, zero-thickness extrapolation, background
→ GEANT simulations suggest backgrounds ~ 1%

Systematic uncertainty better than 1% achievable with some additional effort



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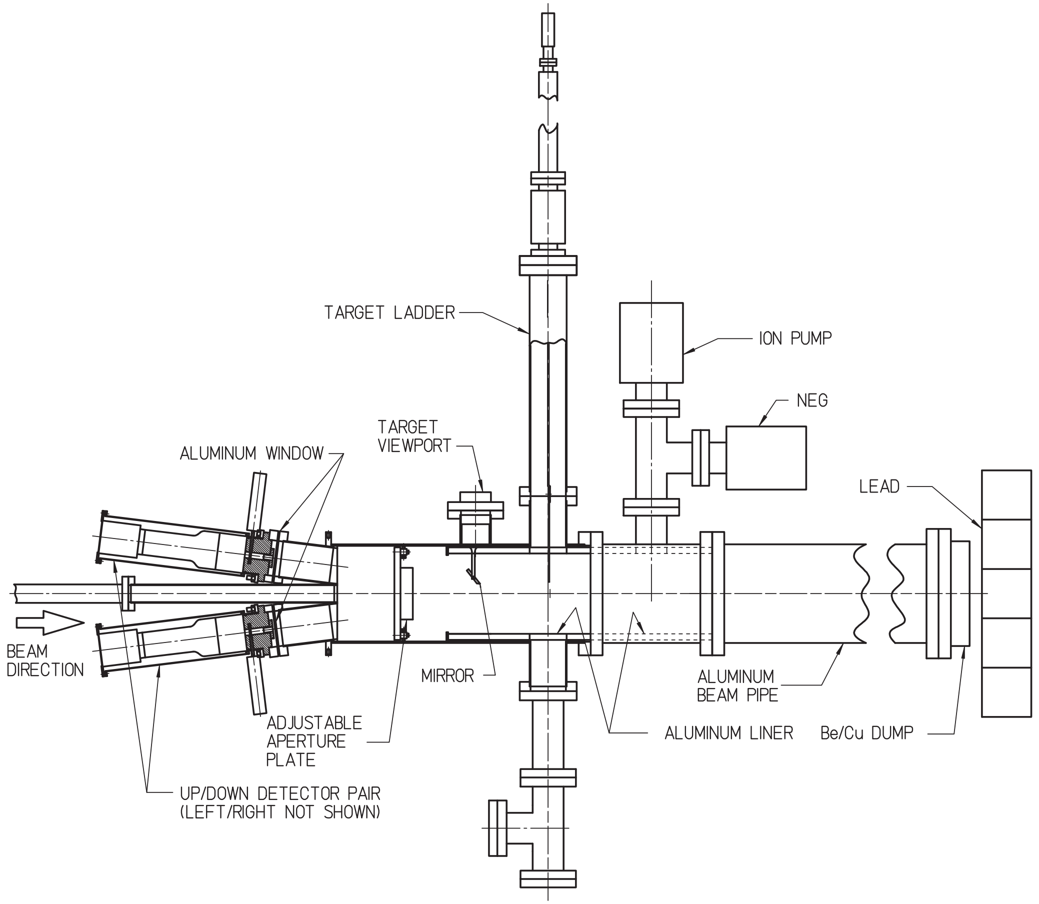
JLab 5 MeV Mott

Routinely used in CEBAF injector

- Optimized for operation at 5 MeV
    - Studied between 3-8 MeV
- Detectors at 172.7 degrees
    - Thin and thick scintillators
- Typically uses thin gold target (1 μm or less)
- Some backgrounds possible due to nearby beam dump
    - Has been studied using lower duty cycle beam + time of flight
- Recent extensive systematic studies yield overall systematic uncertainty < 1%



Jefferson Lab 5 MeV Mott Polarimeter

J.M. Grames et al, Phys.Rev.C 102 (2020) 1, 015501

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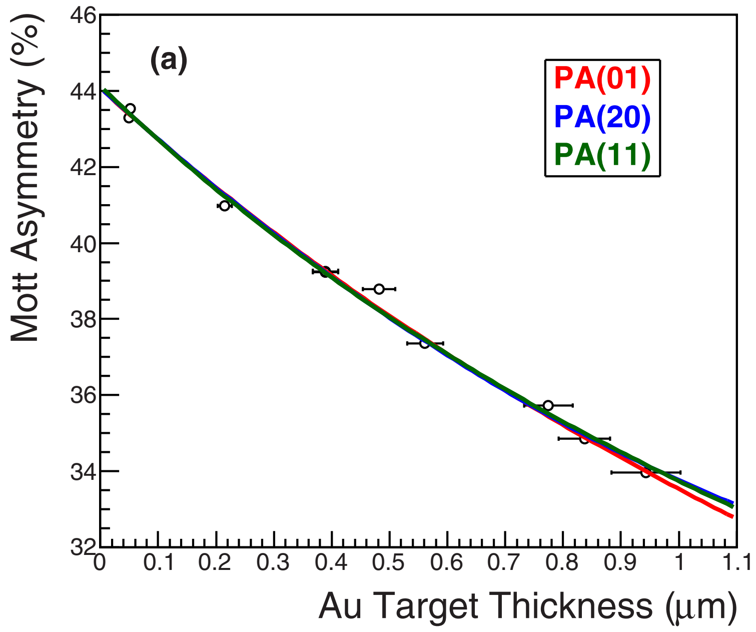
JLab 5 MeV Mott - Systematics

Much effort dedicated to demonstration of precision Mott polarimetry

→ Improved background rejection via time-of-flight cuts

→ Dedicated studies of Sherman function

→ GEANT4 simulations showed double-scattering in target foil is only source of dependence of analyzing power on target thickness



JLab 5 MeV Mott Systematic uncertainties

Contribution	Value
Sherman function	0.50%
Target thickness extrapolation	0.25%
Device-related systematics	0.24%
Energy cut (0.1%)	
Laser polarization (0.10%)	
Scattering angle/beam energy (0.20%)	
Total	**0.61%**

J.M. Grames et al, Phys.Rev.C 102 (2020) 1, 015501

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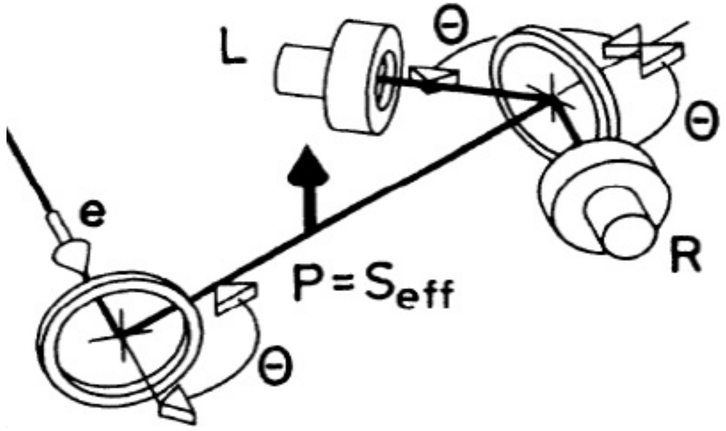
Double-Mott Polarimeter

Use double-scattering to measure effective Sherman function empirically

→ Unpolarized electrons scatter from target foil – resulting polarization: $P_{scatt} = S_{eff}$
→ Polarized electrons scatter from 2nd, ***identical*** foil

Resulting asymmetry : $A_{obs} = S^2_{eff}$



Double-Mott Polarimeter

Can also use modified version of this with polarized electron beam

→ Initial, auxiliary target no longer assumed to have same analyzing power as second target

→ Results in a system of 5 possible observables

$$A_1 = S_T S_{eff}$$

$$A_2 = P_0 S_{eff}$$

$$A_3 = P_{\uparrow} S_{eff}$$

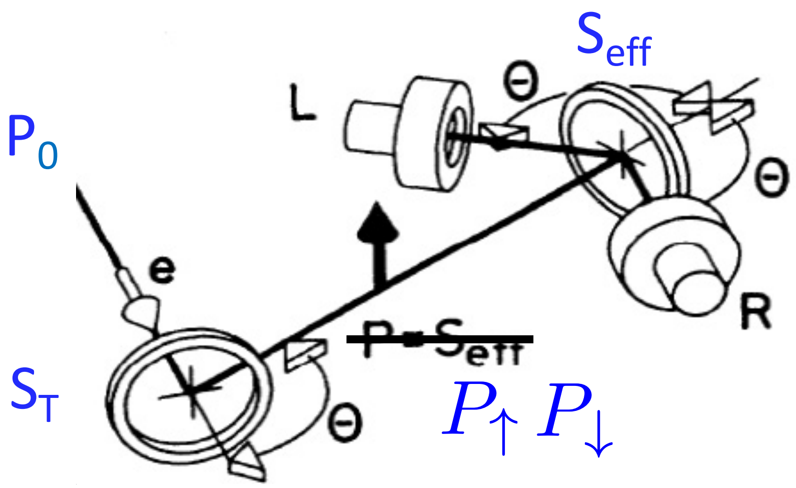
$$A_4 = P_{\downarrow} S_{eff}$$

$$A_5 = P_0 S_T$$

$$P_{\uparrow} = \frac{S_T + \alpha P_0}{1 + P_0 S_T}$$

$$P_{\downarrow} = \frac{S_T - \alpha P_0}{1 - P_0 S_T}$$

α= depolarization factor in auxiliary target



5 equations w/4 unknowns:

S_{eff}, S_T, P_0, α

Apparatus developed at U. Münster, transferred to Mainz → use w/MESA

Møller Scattering

Electron beam scatters from (polarized) atomic electrons in atom (typically iron or similar)

Longitudinally polarized electrons/target:

$$\frac{d\sigma}{d\Omega^*} = \frac{\alpha^2}{s}\frac{(3+\cos^2\theta^*)^2}{\sin^4\theta^*}\left[1+P_eP_tA_{\parallel}(\theta^*)\right]$$

$$A_{\parallel} = \frac{-(7+\cos^2\theta^*)\sin^2\theta^*}{(3+\cos^2\theta^*)^2}$$

→ At θ^*=90 deg. → -7/9

Transversely polarized electrons/target

$$A_{\perp} = \frac{-\sin^4\theta^*}{(3+\cos^2\theta^*)^2}$$

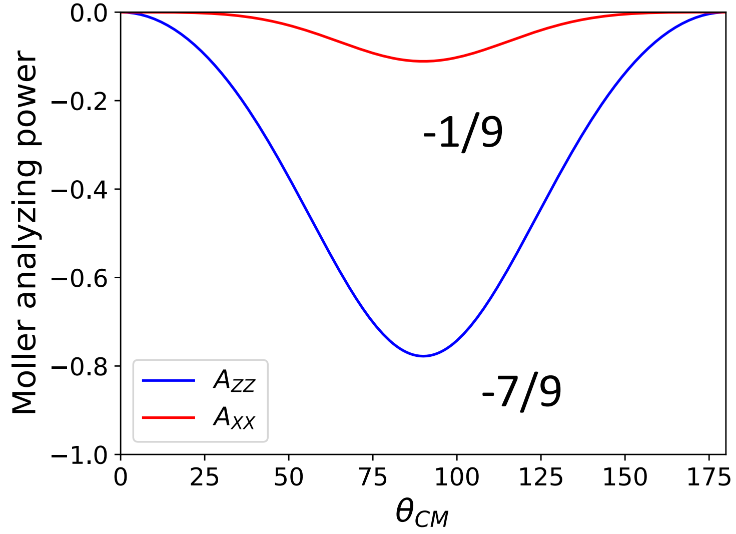
→ At θ^*=90 deg. → -1/9

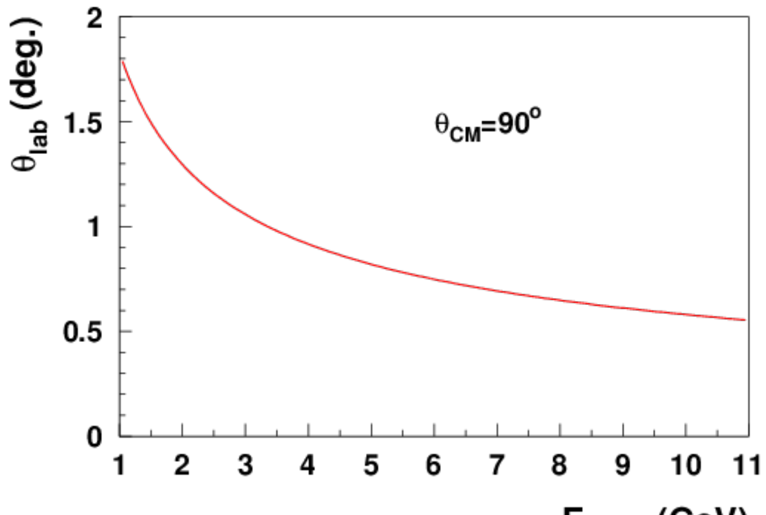
Maximum asymmetry independent of beam energy

Møller Polarimetry

- Møller polarimetry benefits from large longitudinal analyzing power → -7/9 (transverse → -1/9)
  → Asymmetry independent of energy
  → Relatively slowly varying near $\vartheta_{cm}=90^o$
  → Large asymmetry diluted by need to use iron foils to create polarized electrons
- Large boost results in Møller events near $\theta_{cm}=90^o$ having small lab angle
  → Magnets/spectrometer required so that detectors can be adequate distance from beam
- Dominant backgrounds from Mott scattering – totally suppressed via coincidence detection of scattered and recoiling electrons
- Rates are large, so rapid measurements are easy
- The need to use Fe or Fe-alloy foils means measurement must be destructive
- Foil depolarization at high currents

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





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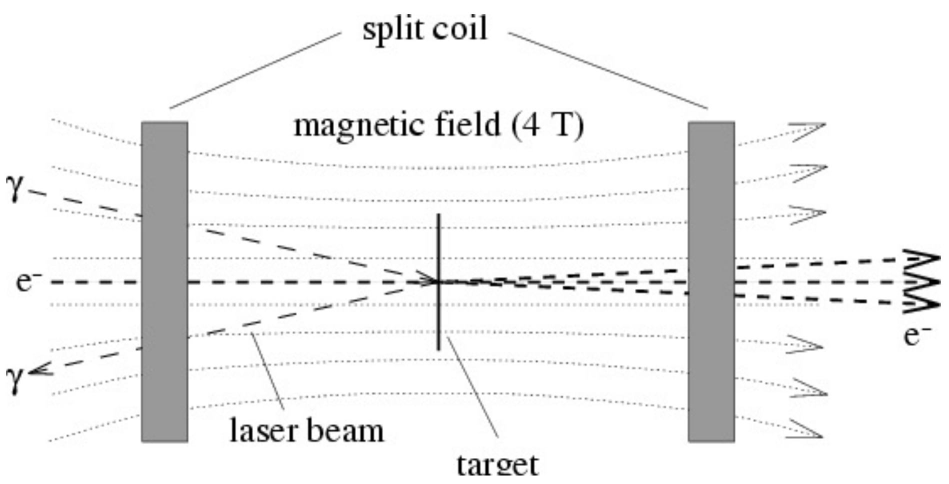
Polarized Target for Møller Polarimetry

- Originally, Møller polarimeters used Fe-alloy targets, polarized in plane of the foil
  - Used modest magnetic field
- In-plane polarized targets typically result is systematic errors of 2-3%
  - Require careful measurement magnetization of foil
- Pure Fe saturated in 4 T field
  - Spin polarization well known → 0.25%
  - Temperature dependence well known
  - No need to directly measure foil polarization

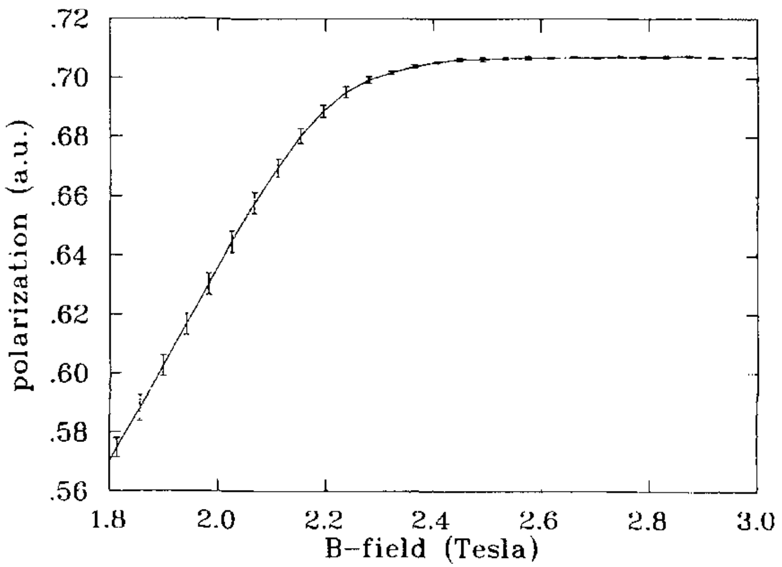


Effect	$M_s[\mu_B]$	error
Saturation magnetization (T→0 K,B→0 T)	2.2160	±0.0008
Saturation magnetization (T=294 K, B=1 T)	2.177	±0.002
Corrections for B=1→4 T	0.0059	±0.0002
Total magnetization	2.183	±0.002
Magnetization from orbital motion	0.0918	±0.0033
Magnetization from spin	2.0911	±0.004
Target electron polarization (T=294 K, B= 4 T)	0.08043	±0.00015

Saturated Iron Foil Target

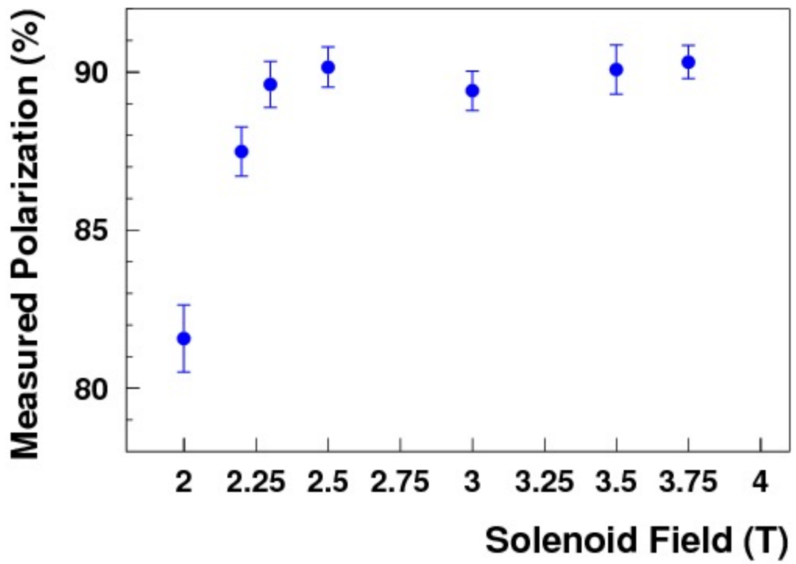
Polarization of target not directly measured when using iron foil driven to magnetic saturation
→ Rely on knowledge of magnetic properties of iron
→ One can test that foil is in magnetic saturation using magneto-optical Kerr effect (polarization properties of light change in magnetic medium)

Can also test dependence on foil angle (misalignment) and heating



Kerr effect measurement of foil saturation

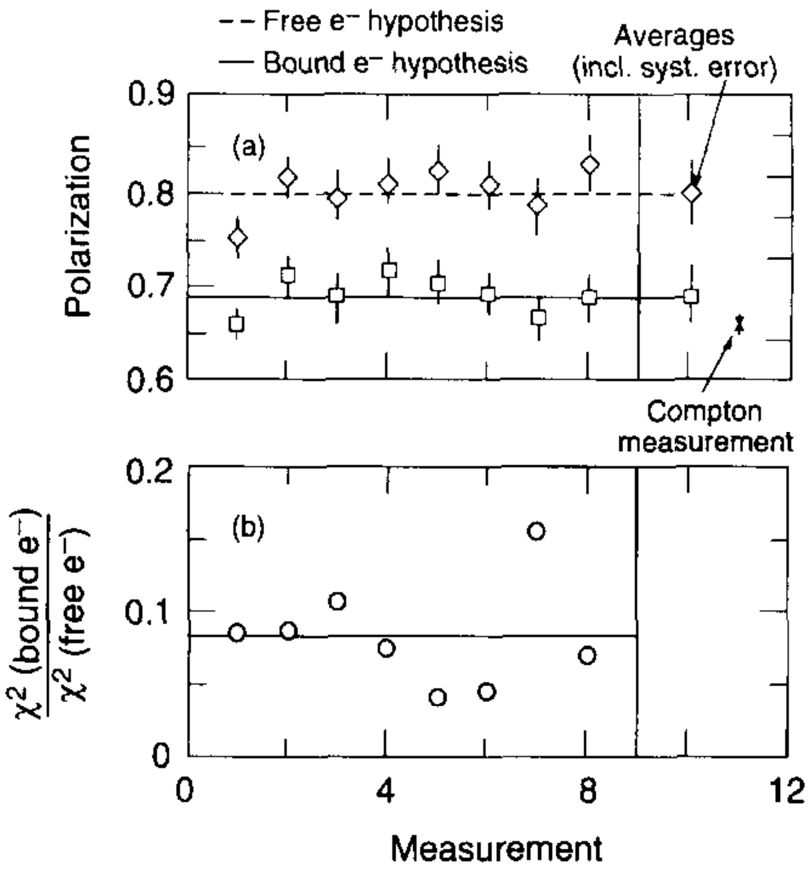
Example: Measure degree of saturation vs. applied magnetic field
→ This can also be tested with polarimeter directly



JLab measurements of asymmetry vs. applied field

Levchuk Effect

- On average, about 2 out of 26 atomic electrons in Fe atom are polarized
  - Polarized electrons are in outer shells
  - Inner shell, more tightly-bound electrons are unpolarized
- Electrons scattering from inner-shell electrons result in a ”smearing” of the correlation between momentum and scattering angle
- For finite acceptance detector, this can result in lower efficiency for detection of events scattering from more tightly bound (unpolarized) electrons
- Ignoring this “Levchuk*” effect can result in incorrect polarization measurements
- First observed experimentally at SLAC in 1995 – size of effect depends on detector acceptance



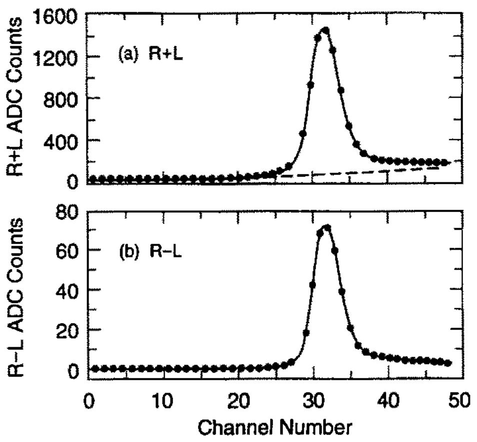
M. Swartz et al., Nucl. Instrum. Meth. A363 (1995) 526

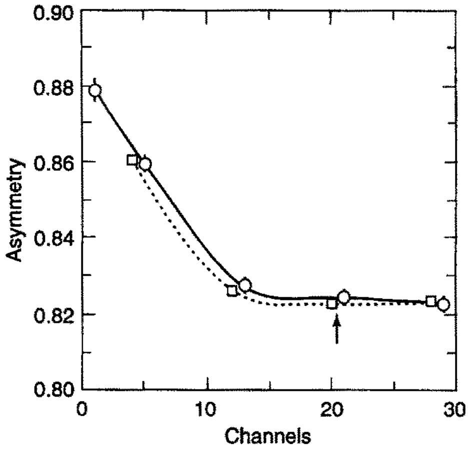
**L. G. Levchuk, Nucl. Instrum. Meth. A345 (1994) 496*

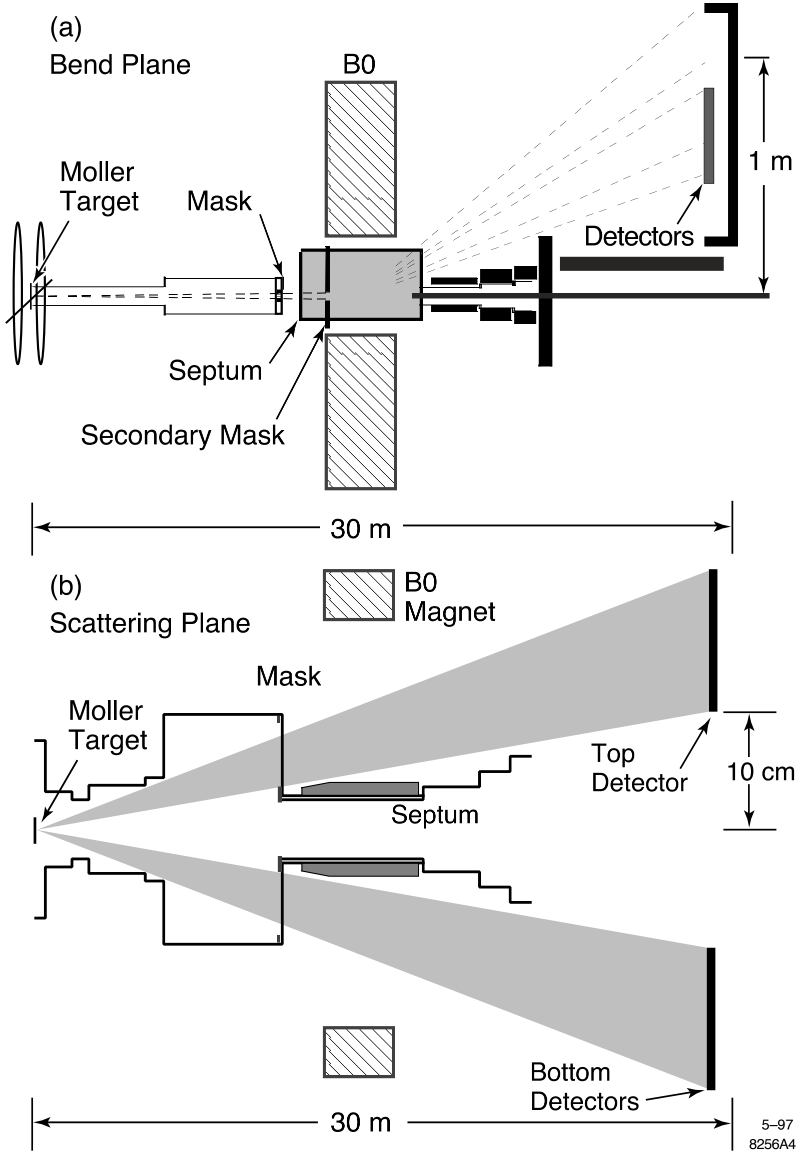
SLAC E154 Møller Polarimeter

Single-arm polarimeter used in End Station at SLAC in the 1990’s

→ Low field, in-plane polarized target
→ 2-detectors, but did not detect scattered and recoil electrons in coincidence
→ Scattered electrons steered to detectors using dipole – no focusing quads
→ Electrons detected with silicon strip detectors
→ Overall systematic uncertainty 2.4%, dominated by target polarization (1.7%) and background subtraction (2%)

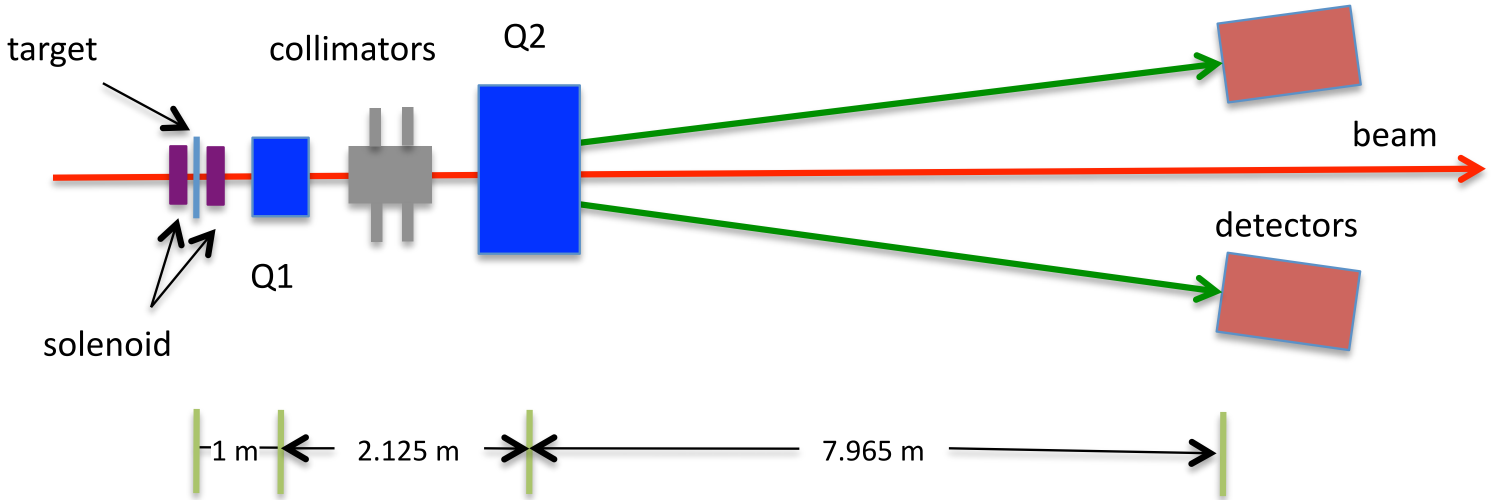






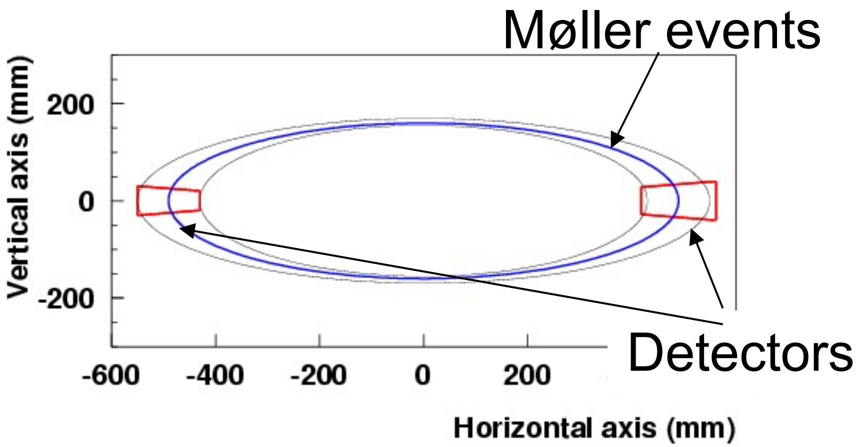
Hall C Møller Polarimeter at Jefferson Lab

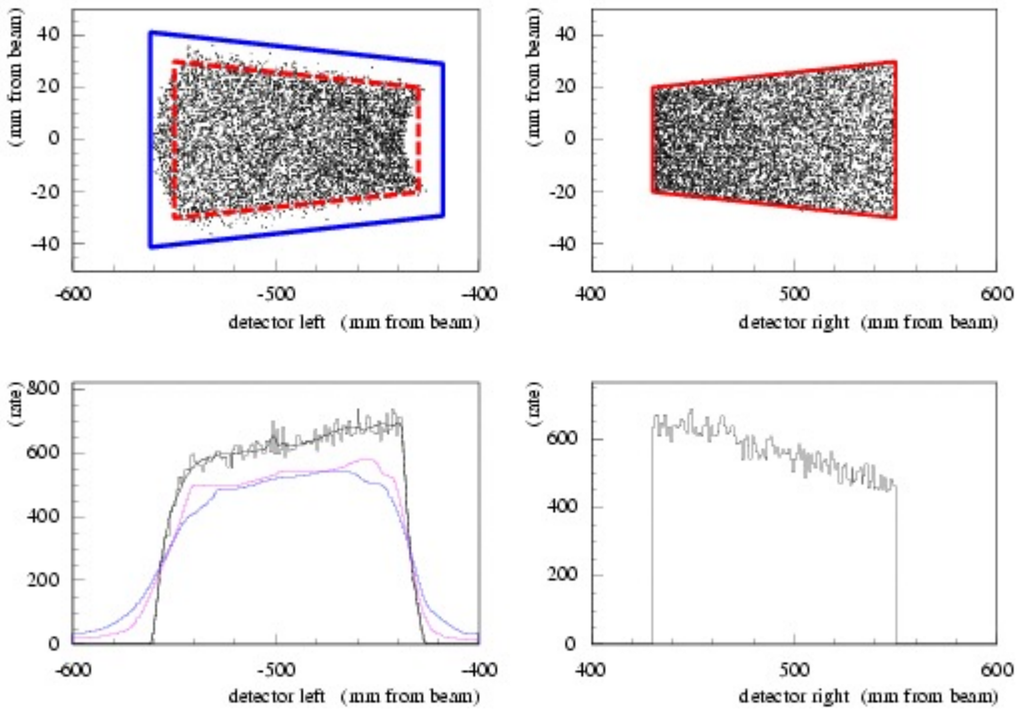
- First polarimeter to use high field, out-of-plane polarized target
- Detects scattered and recoil electron in coincidence
- 2 quadrupole optics maintains constant tune at detector plane, independent of beam energy
- "Moderate" acceptance mitigates Levchuk effect → still a non-trivial source of uncertainty
- Target = pure Fe foil, brute-force polarized out of plane with 3-4 T superconducting magnet
- Target polarization uncertainty = ***0.25%*** *[NIM A 462 (2001) 382]*



Hall C Møller Acceptance

Optics designed to maintain similar acceptance at detectors independent of beam energy





Collimators in front of Pb:Glass detectors define acceptance

One slightly larger to reduce sensitivity to Levchuk effect

Møller Systematic Uncertainties

Source	Uncertainty	dA/A (%)
Beam position x	0.5 mm	0.17
Beam position y	0.5 mm	0.28
Beam direction x	0.5 mr	0.10
Beam direction y	0.5 mr	0.10
Q1 current	2% (1.9 A)	0.07
Q3 current	2.5% (3.25 A)	0.05
Q3 position	1 mm	0.10
Multiple scattering	10%	0.01
Levchuk effect	10%	0.33
Collimator positions	0.5 mm	0.03
Target temperature	100%	0.14
B-field direction	2^o	0.14
B-field strength	5%	0.03
Spin polarization in Fe		0.25
Electronic D.T.	100%	0.04
Solenoid focusing	100%	0.21
Solenoid position (x,y)	0.5 mm	0.23
Additional point–to–point		0.0
High current extrapolation		0.5
Monte Carlo statistics		0.14
Total		0.85

Systematic error table from Q-Weak (2nd run) in Hall C (2012)

→ Some uncertainties larger than usual due to low beam energy (1 GeV)

→ Levchuk effect, target polarization same at all energies

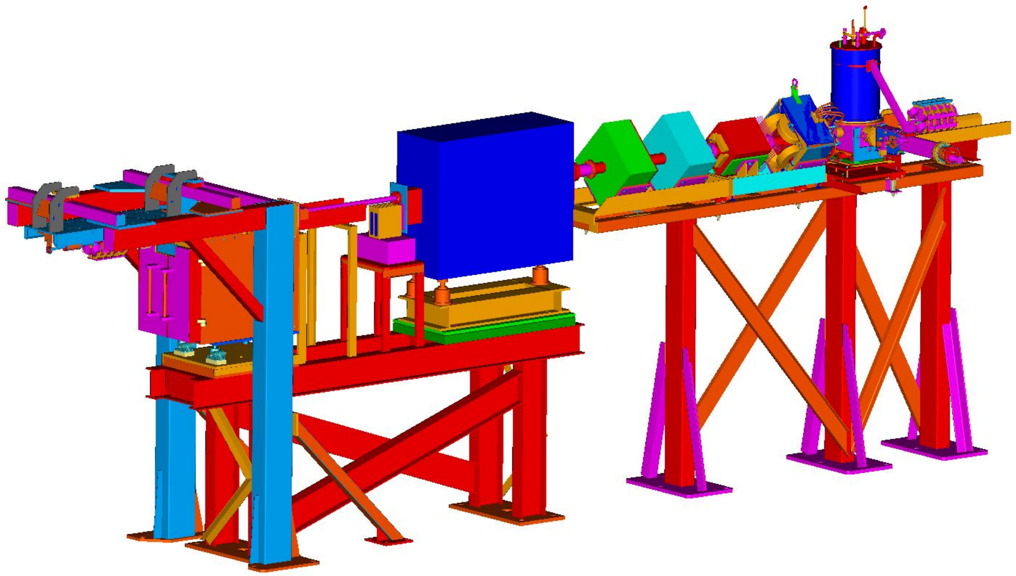
Total uncertainty less than 1%

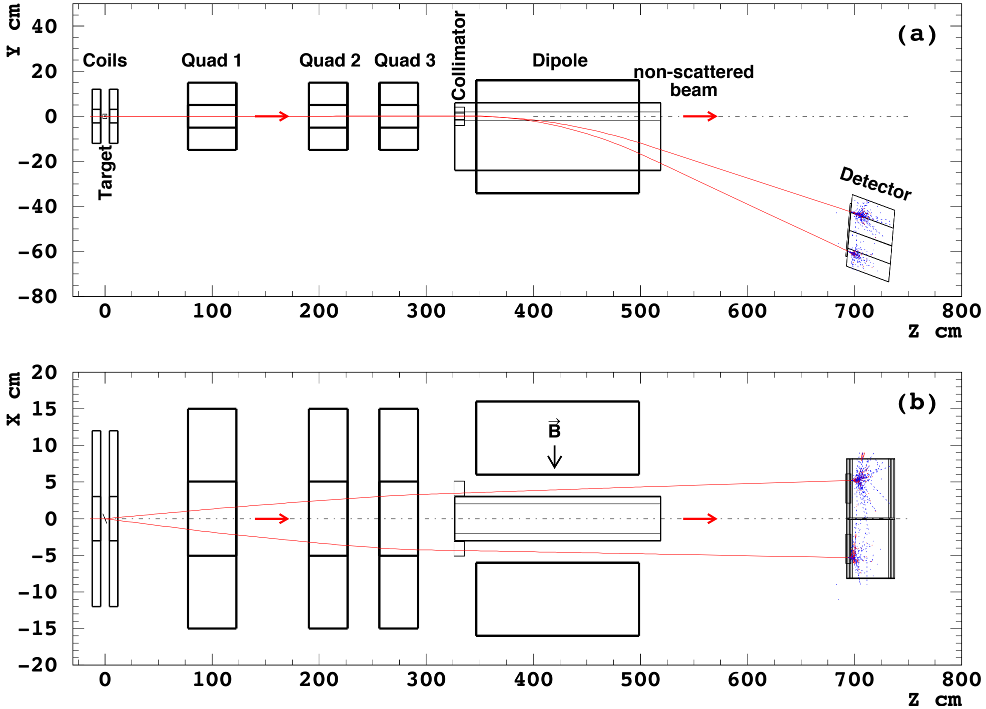
Hall A Møller Polarimeter at Jefferson Lab

Like Hall C, uses high field target polarized out-of-plane

→ Initially used low field target, but upgraded to achieve higher precision

→ Large detector acceptance to mitigate Levchuk effect





→ Optics uses combination of 3(4) quadrupoles + dipole

→ Same tune cannot be used for all energies – each energy requires new solution

→ Overall systematic uncertainties comparable to Hall C

Møller Polarimetry with an Atomic Hydrogen Target

Proposal to use atomic hydrogen as target; operates at full beam current, non-destructive measurement

→at 300 mK, 8 T, P_e ~ 100%

→density ~ 3 10^{15} cm^{-3}

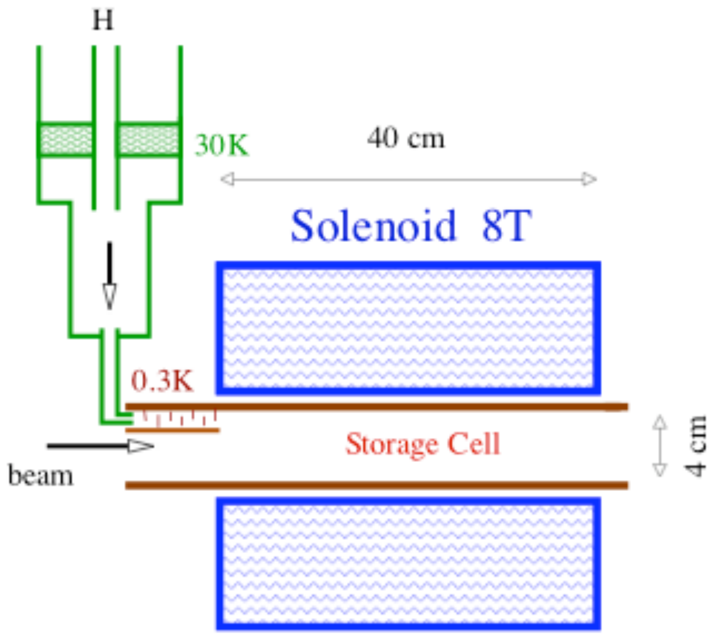
→lifetime >1 hour

→Expected precision < 0.5%!

Contamination, depolarization expected to be small → < 10^{-4}

Such a target allows measurements concurrent with running experiment, mitigates Levchuk effect

System is under development for use at MAINZ for the P2 experiment → polarization measurements expected within the next couple years



Application at EIC?

→ Gas heating by radiation drops density by factor ~ 100 to 1000

→Beam creates field 0.2-2 kV/cm – traps positive ions

Maybe some kind of H jet target can be used instead?

Jefferson Lab

Møller Polarimetry with Jet Targets

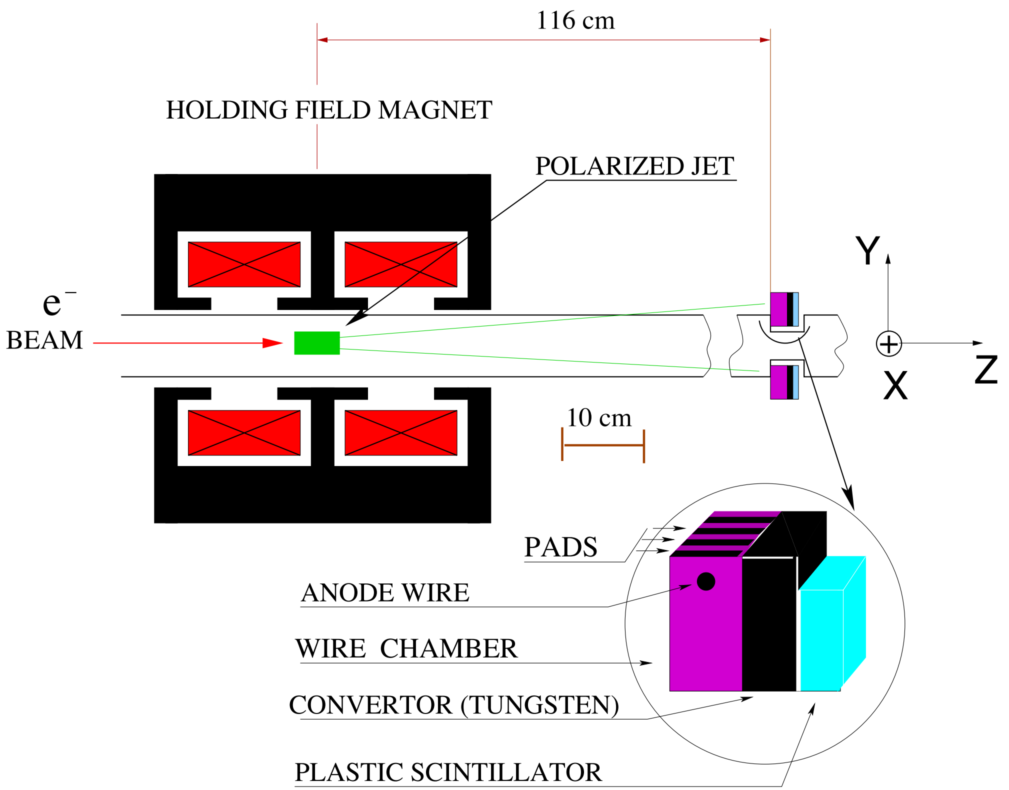
Møller not typically used in storage rings since commonly used targets are destructive to the beam → iron and iron-alloy foils

→Jet target would be non-destructive – some measurements with jet targets have been done at VEPP-3

What precision on target polarization can be achieved with jet targets?

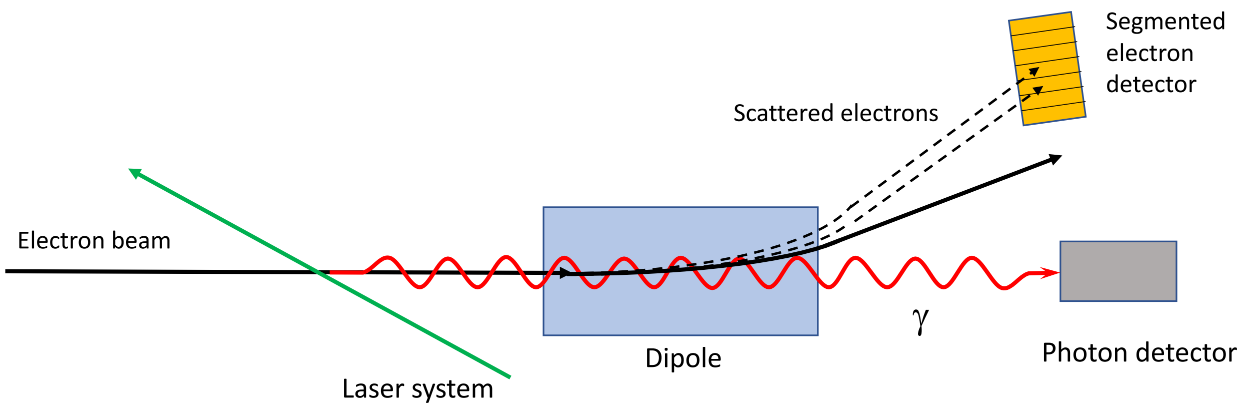
→RHIC H-JET target polarization known to better than 1%

Some R&D would be required, but precision Møller polarimetry in storage rings may be feasible



A. Grigoriev et al, *Proceedings of EPAC 2004*

Compton Polarimetry



Polarimeter	Energy	Sys. Uncertainty
CERN LEP*	46 GeV	5%
HERA LPOL	27 GeV	1.6%
HERA TPOL*	27 GeV	2.9%
SLD at SLAC	45.6 GeV	0.5%
JLAB Hall A	1-6 GeV	1-3%
JLab Hall C	1.1 GeV	0.6%

* Transverse

Compton polarimetry has been used extensively in both fixed-target and collider environments – standard technique in storage rings since it is non-destructive

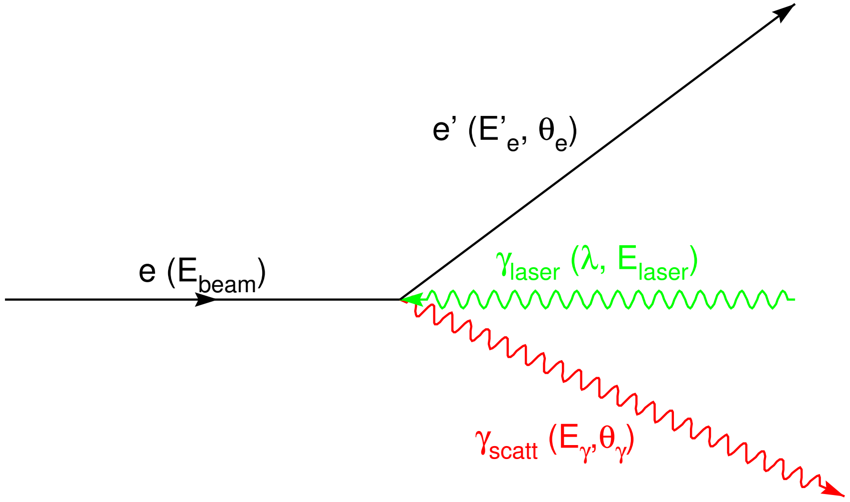
→ Highest precision has been achieved using electron detection, for longitudinally polarized electrons

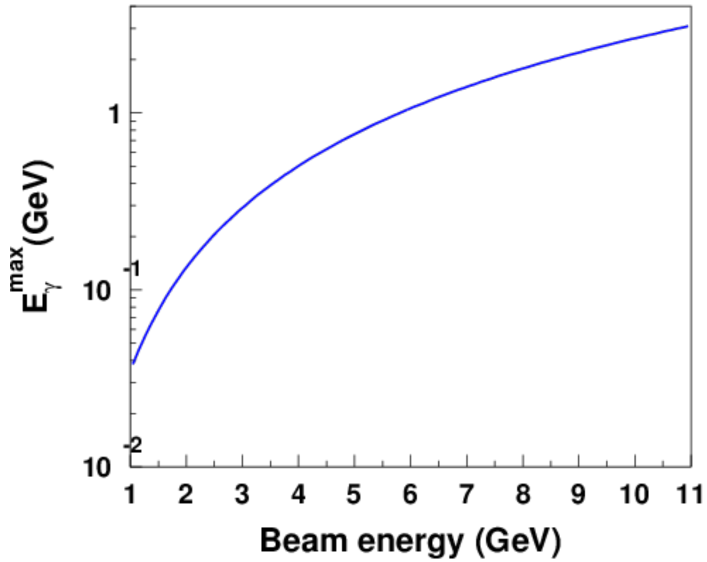
Compton Scattering - Kinematics

Laser beam colliding with electron beam nearly head-on

$$E_\gamma \approx E_{\mathrm{laser}} \frac{4a\gamma^2}{1 + a\theta_\gamma^2\gamma^2}$$

$$a = \frac{1}{1 + 4\gamma E_{\mathrm{laser}}/m_e}$$





Maximum backscattered photon energy at θ=0 degrees (180 degree scattering)

For green laser (532 nm):

→ E_γ^{max} ~ 34.5 MeV at E_{beam}=1 GeV

→ E_γ^{max} = 3.1 GeV at E_{beam}=11 GeV

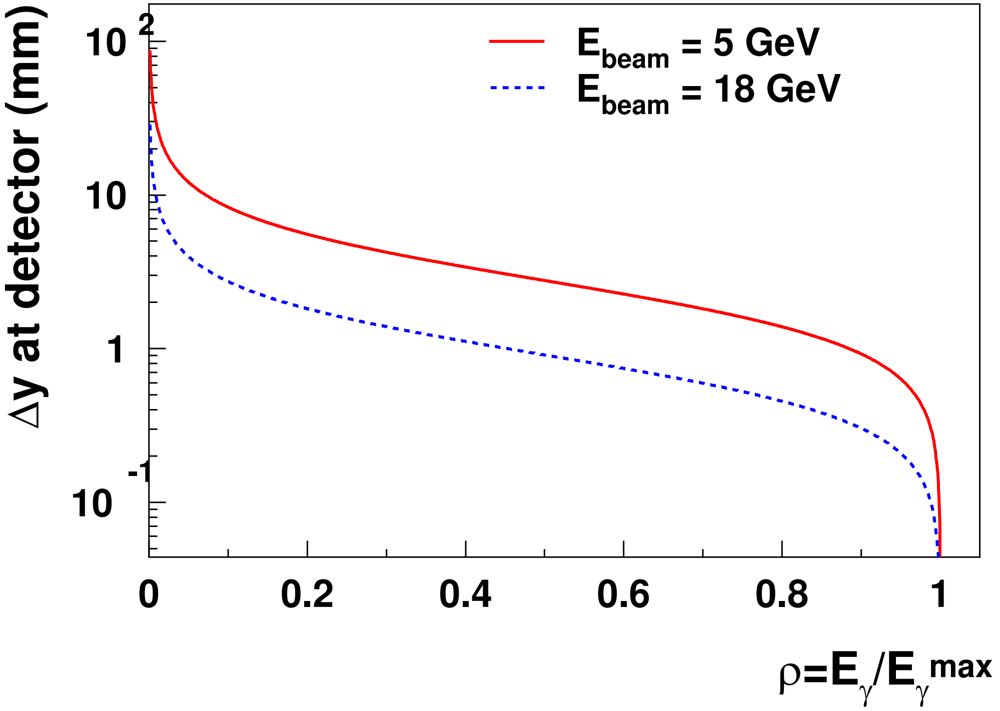
Compton Scattering – Backscattered Photon Angle

$$\cos\theta_\gamma = \frac{E_{beam} + E_{laser} - 2E_{laser}E_{beam}/E_\gamma}{E_{beam} - E_{laser}}$$

Backscattered photons emitted in a narrow cone

For measurements of longitudinal polarization, helpful in that detector can be compact

→ Measurements of transverse polarization require measurement of spatial dependence of asymmetry – high granularity detectors needed



Backscattered photon position vs. energy at hypothetical detector 25 m from collision point

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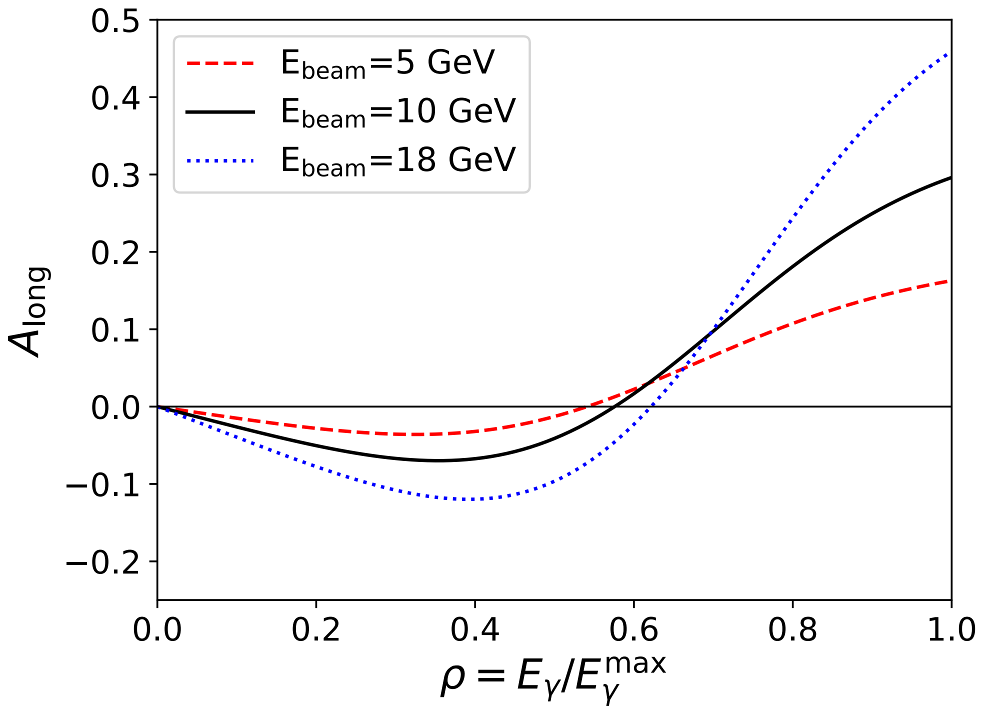
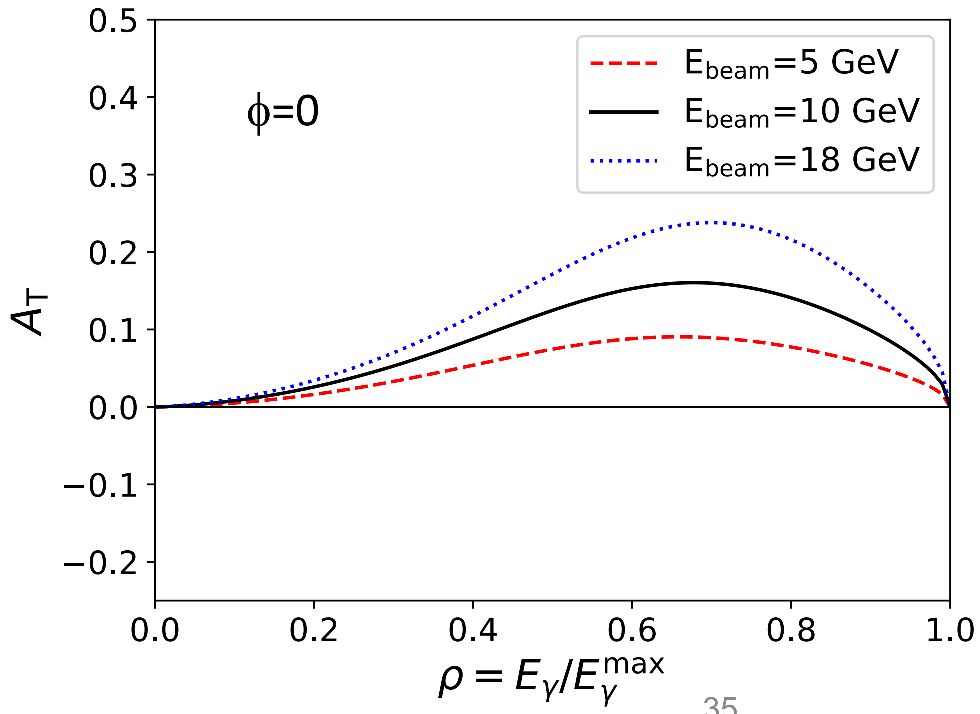
Polarization Measurement via Compton Polarimetry

Compton polarimetry can be used to measure both longitudinal and transverse electron beam polarization

$$A_{\text{long}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}(1-\rho(1+a))\left[1-\frac{1}{(1-\rho(1-a))^2}\right]$$

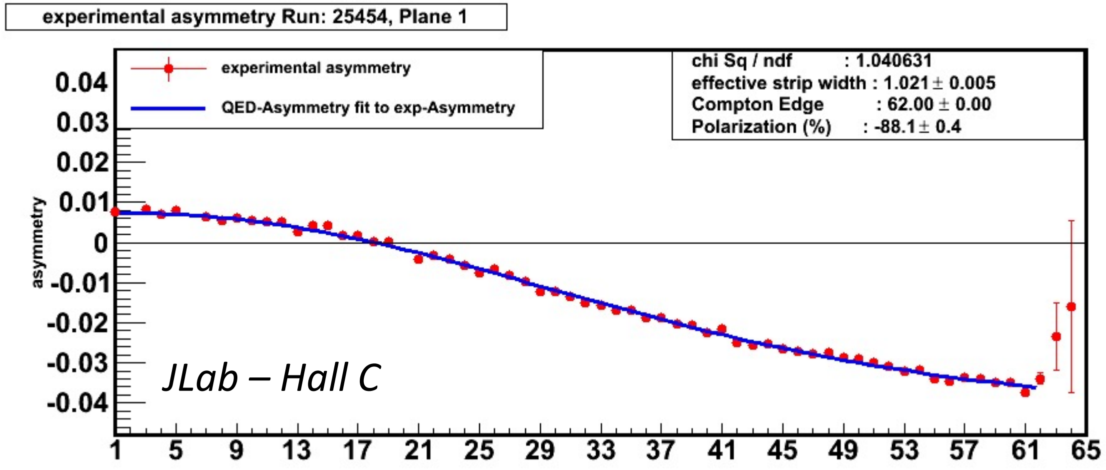
$$A_{\text{T}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}\cos\phi\left[\rho(1-a)\frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))}\right]$$





Polarization Measurement via Compton Polarimetry

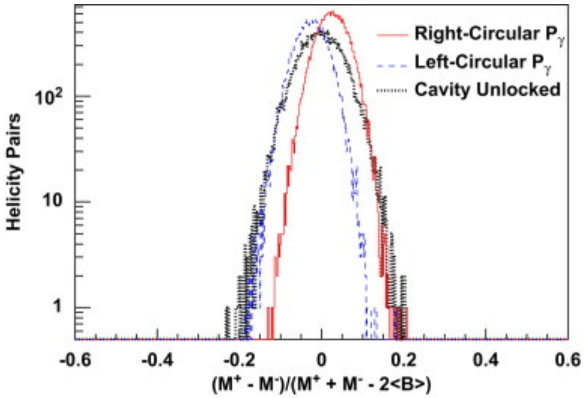
Longitudinal polarization measured via counting asymmetry vs. energy, or energy-integrated asymmetry



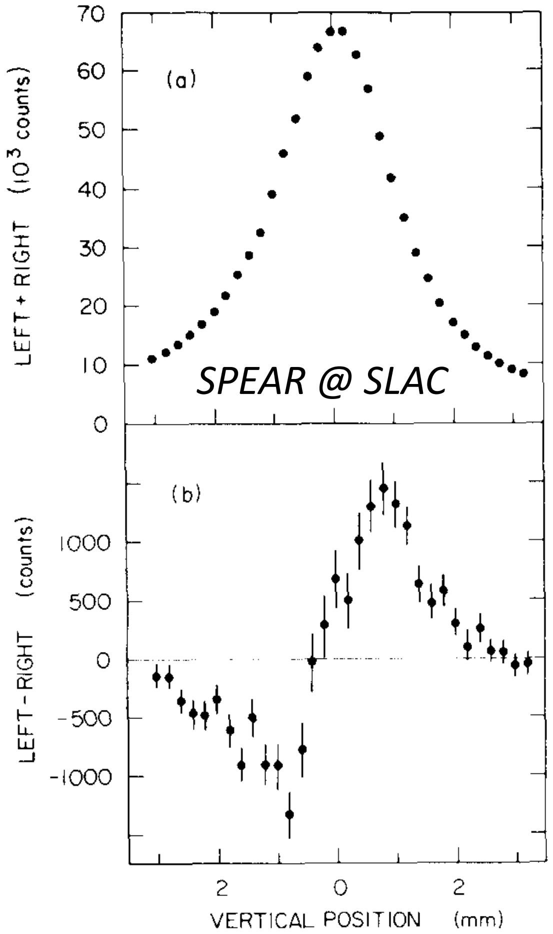
Detector strip # → Scattered electron energy

Photon-energy weighted asymmetry

JLab – Hall A



Transverse polarization typically measured via spatial dependence (up-down) of asymmetry



Luminosity

Luminosity for CW laser colliding with electron beam at non-zero crossing angle:

$$\mathcal{L} = \frac{(1+\cos\alpha_c)}{\sqrt{2\pi}} \frac{I_e}{e} \frac{P_L \lambda}{hc^2} \frac{1}{\sqrt{\sigma_e^2 + \sigma_\gamma^2}} \frac{1}{\sin\alpha_c}$$

Pulsed laser:

$$\mathcal{L} = f_{coll} N_\gamma N_e \frac{\cos(\alpha_c/2)}{2\pi} \frac{1}{\sqrt{\sigma_{x,\gamma}^2 + \sigma_{x,e}^2}} \frac{1}{\sqrt{(\sigma_{y,\gamma}^2 + \sigma_{y,e}^2)\cos^2(\alpha_c/2) + (\sigma_{z,\gamma}^2 + \sigma_{z,e}^2)\sin^2(\alpha_c/2)}}$$

$N_{\gamma(e)}$ = number of photons (electrons) per bunch

Assumes beam sizes constant over region of overlap (ignores “hourglass effect”)

Beam size at interaction point with laser dictates luminosity (for given beam current and laser/electron beam crossing angle)

Luminosity

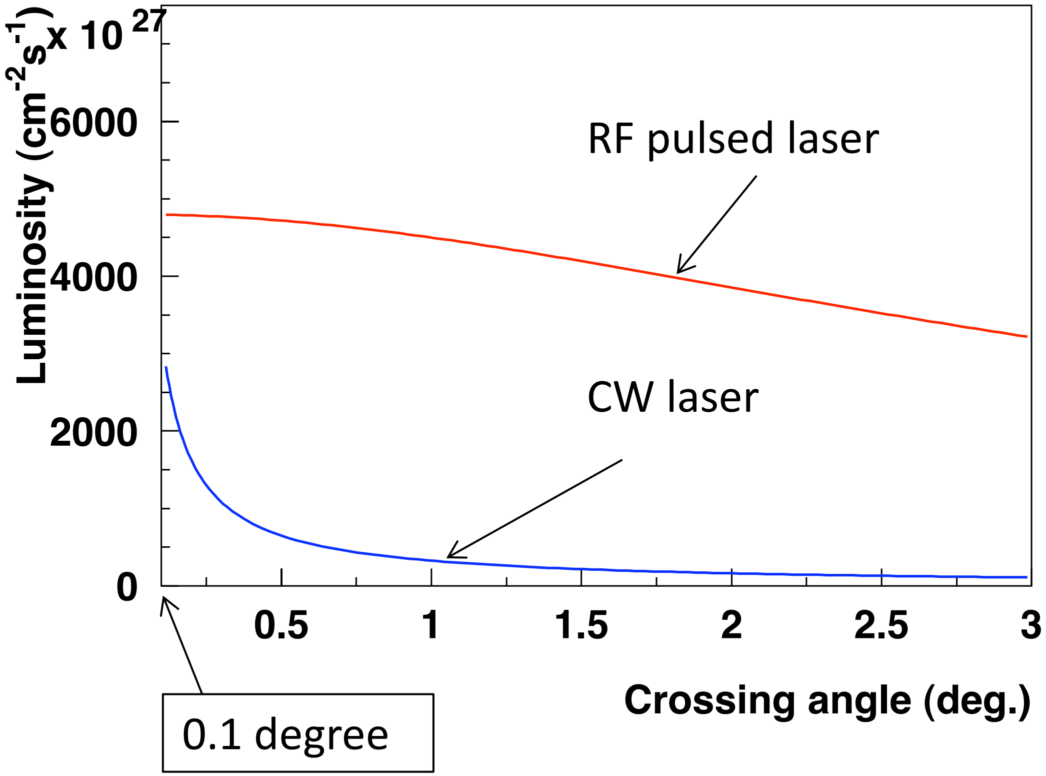
Pulsed laser provides higher luminosity than CW lasers (for pulsed beams)

→ As crossing angle gets smaller, improvement in rates become more comparable

→ Main advantage at small crossing angle in using pulsed laser is identification of beam bunch and ability to measure polarization profile

→ Laser beam bunch length smaller than beam bunch will allow extraction of polarization vs. time in bunch (center vs. tails)

JLab beam → 499 MHz, $\Delta\tau$~0.5 ps



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Analyzing Power and Measurement Times

Measurement time depends on luminosity, analyzing power, and measurement technique

$$t^{-1} = \mathcal{L}\sigma \left(\frac{\Delta P}{P}\right)^2 A^2_{method}$$

Average analyzing power: $A^2_{method} = \langle A \rangle^2$ → Average value of asymmetry over acceptance

Energy-weighted: $A^2_{method} = \left(\frac{\langle EA \rangle}{\langle E \rangle}\right)^2$ → Energy deposited in detector for each helicity state

Differential: $A^2_{method} = \langle A^2 \rangle$ → Measurement of asymmetry bin-by-bin vs. energy, etc.

$$\langle A \rangle^2 < \left(\frac{\langle EA \rangle}{\langle E \rangle}\right)^2 < \langle A^2 \rangle$$

HERA Longitudinal Compton Polarimeter

HERA Longitudinal polarimeter installed in long straight section near HERMES experiments

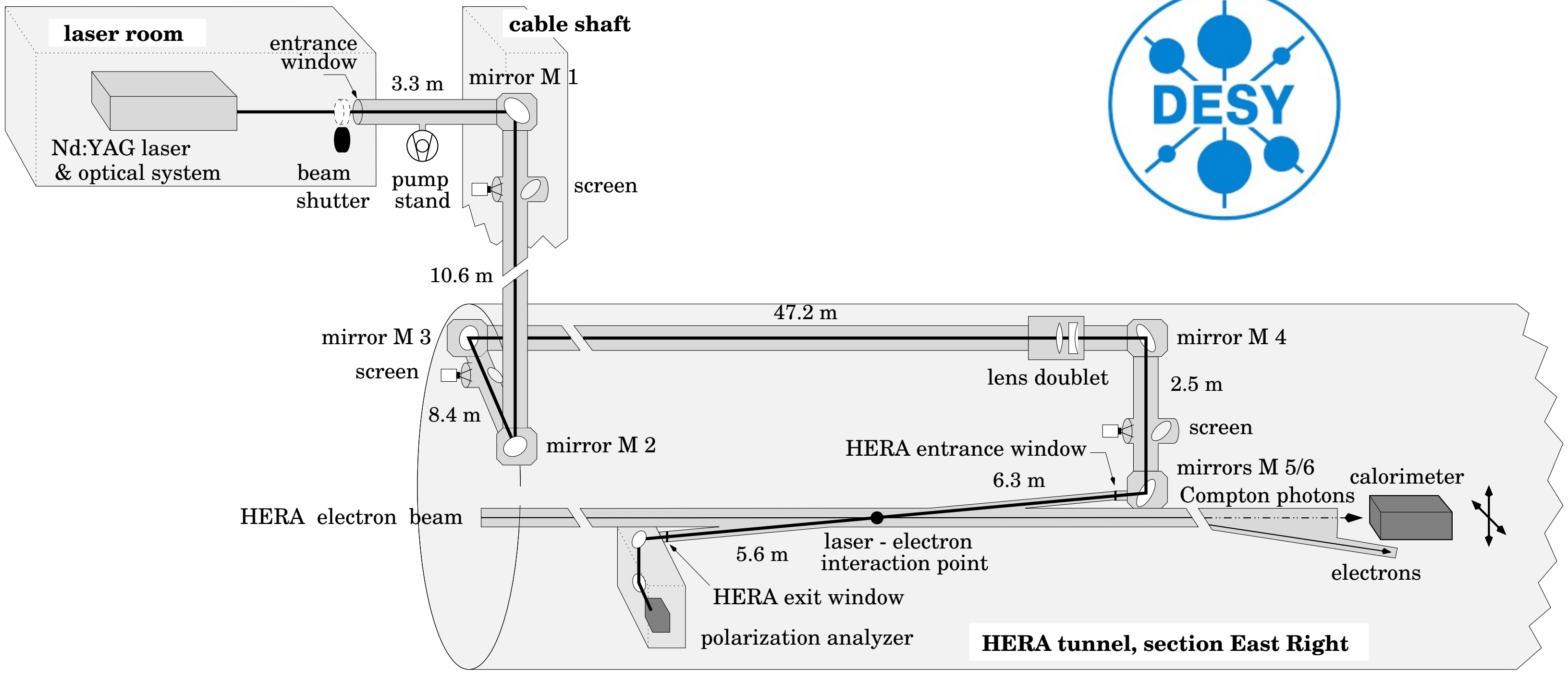
→ Laser system: single pass, pulsed laser synced to beam frequency

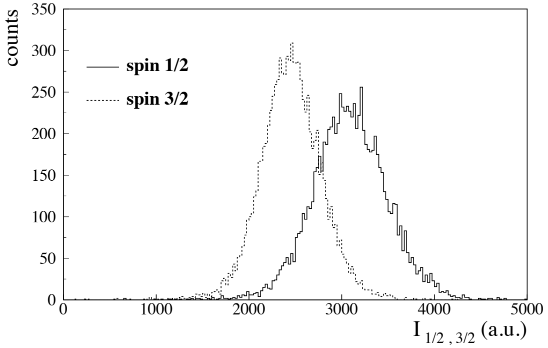
→ Backscattered photons detected in sampling calorimeter

→ Operated in “multi-photon” mode – up to thousand photons produced per laser pulse

→ Polarization extracted using energy integrated asymmetry

→ Total systematic uncertainty = 1.6%, dominated by detector response





$$\Sigma^{\pm} = \int (\frac{d\sigma}{dE_\gamma})^{\pm} E_\gamma dE_\gamma$$

$$A = \frac{\Sigma^+ - \Sigma^-}{\Sigma^+ + \Sigma^-}$$

M. Beckmann et al, NIM A479 (2002) 334-348

HERA Transverse Polarimeter

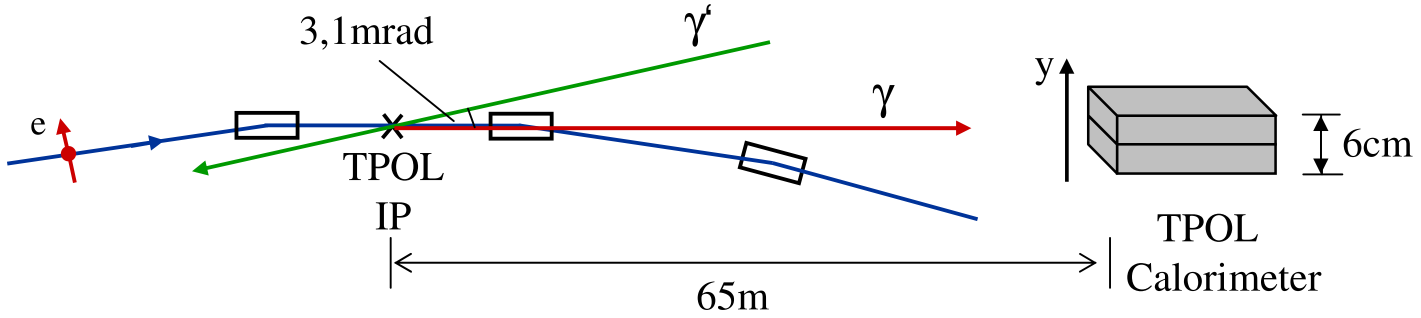
Transverse Compton polarimeters used at several accelerators

→ Primarily beam diagnostic – look for depolarizing resonances

→ HERA TPOL one of few that quote absolute polarization w/uncertainty

→ Most precise transverse Compton to-daye

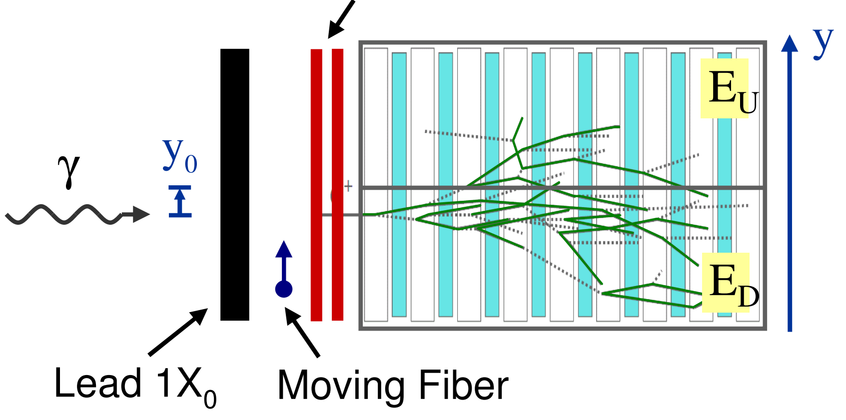
TPOL layout



HERA TPOL operated in single-photon mode w/CW laser

→ Used calorimeter segmented into upper and lower halves

→ Up-down energy asymmetry serves as proxy for up-down position asymmetry



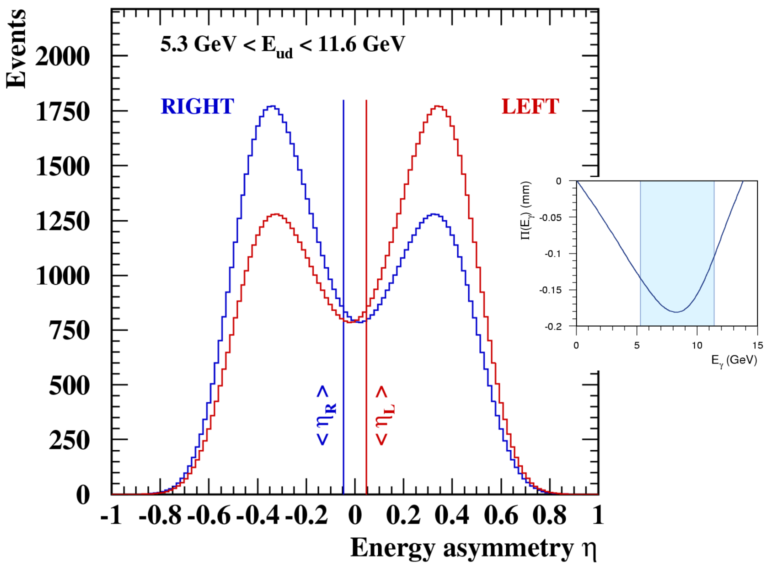
$$\eta = \frac{E_U - E_D}{E_U + E_D}$$

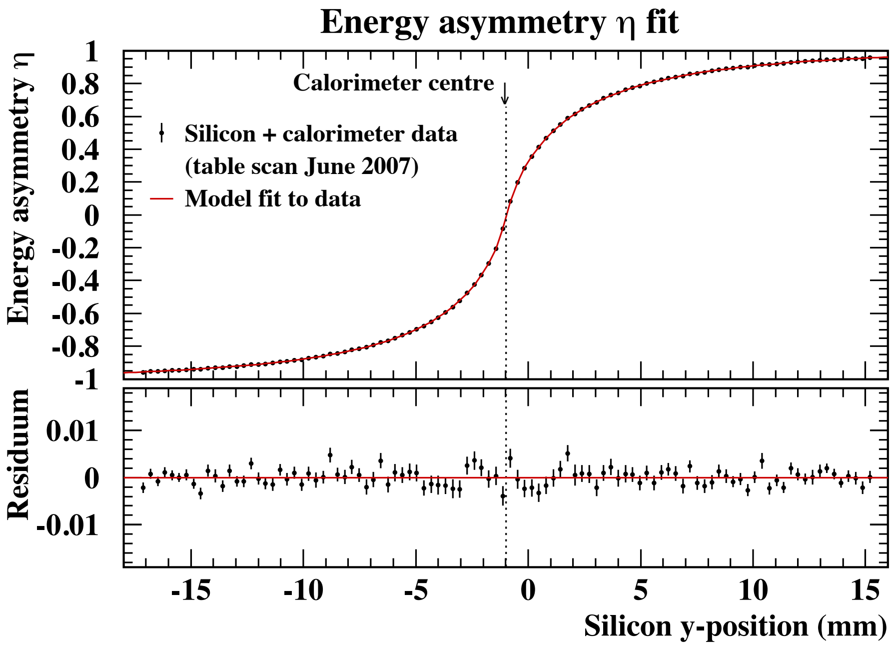
B. Sobloher, PSTP 2009

HERA Transverse Polarimeter

Key systematic uncertainty related to mapping energy asymmetry to position
→ Measured in-situ with position sensitive strip detector
→ Systematic uncertainty in η-y calibration dominated by strip pitch → 0.5%

Other significant contributions to systematic uncertainty include:
→ Beam optics and position
→ Detector energy resolution





B. Sobloher, PSTP 2009

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HERA Transverse Polarimeter

<u>Dominant Systematic uncertainties</u>

- Beam properties
  - Extracted polarization very sensitive to laser/beam collision point, electron beam size – impacts resolution/distribution of up-down asymmetry
- Calorimeter response
  - Calibration of up-down energy asymmetry in calorimeter to position
- Calorimeter energy resolution
  - Up-down asymmetry evaluated for different bins in photon energy

Contribution	Value
Beam properties	1.14%
Calorimeter response	0.60%
Calorimeter energy resolution	0.70%
Other	1.16%
Total uncertainty	**1.87%**

Systematics could be reduced with improved beam diagnostics and different detector scheme

B. Sobloher et al, DESY-11-259 , arXiv:1201.2894

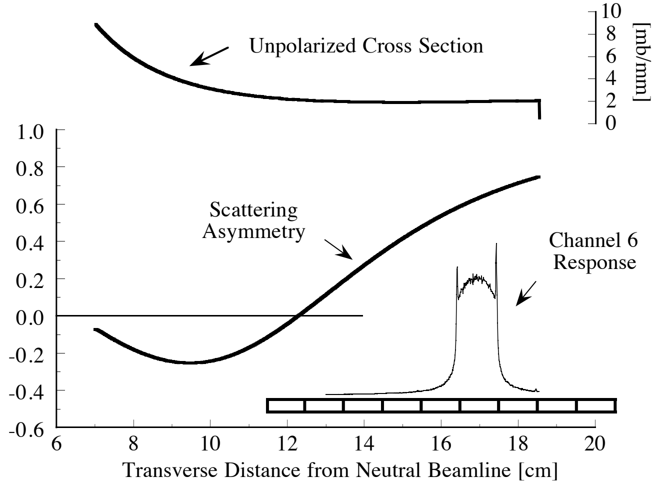
SLAC SLD Compton Polarimeter

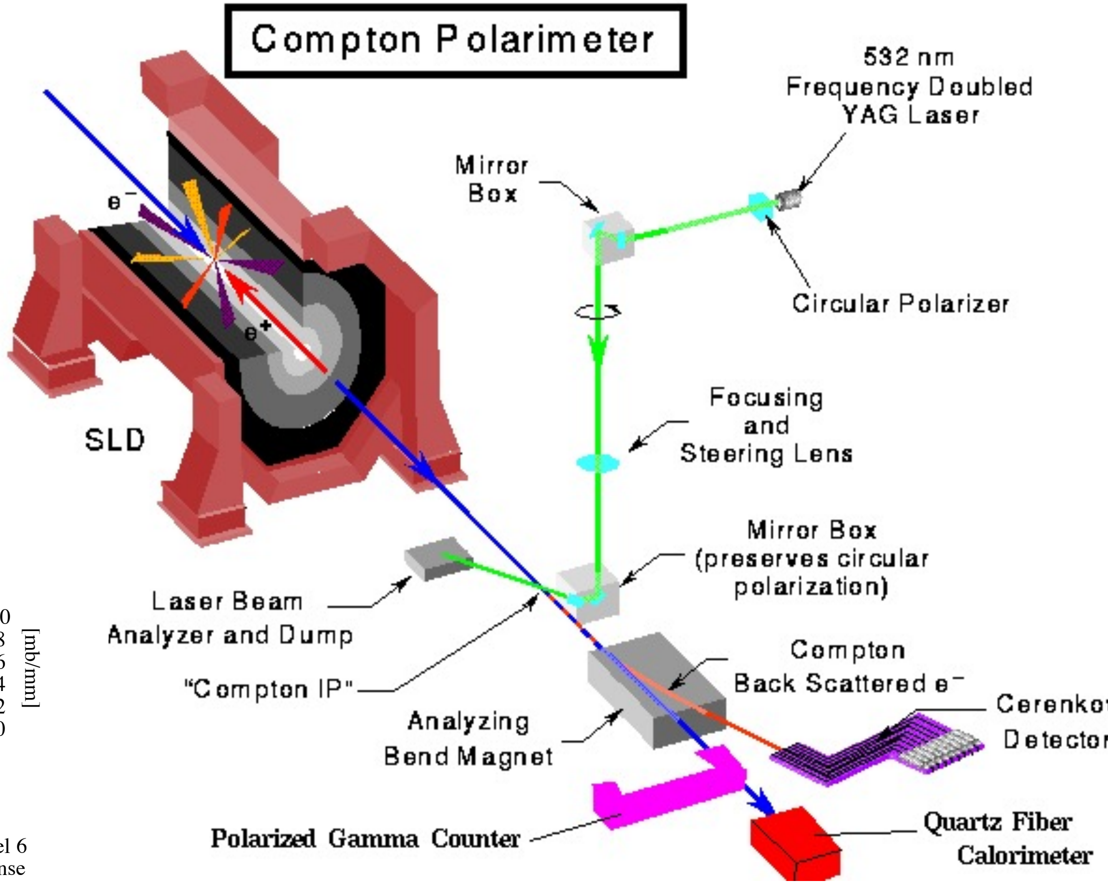
Highest precision achieved with Compton polarimetry → dP/P = 0.5%

Operated at 45 GeV → endpoint analyzing power was very large: ~ 75%

Used single-pass, pulsed laser – excellent control of laser polarization at interaction point

Multichannel gas Cherenkov detector → electrons ~ 10 cm from nominal beam path

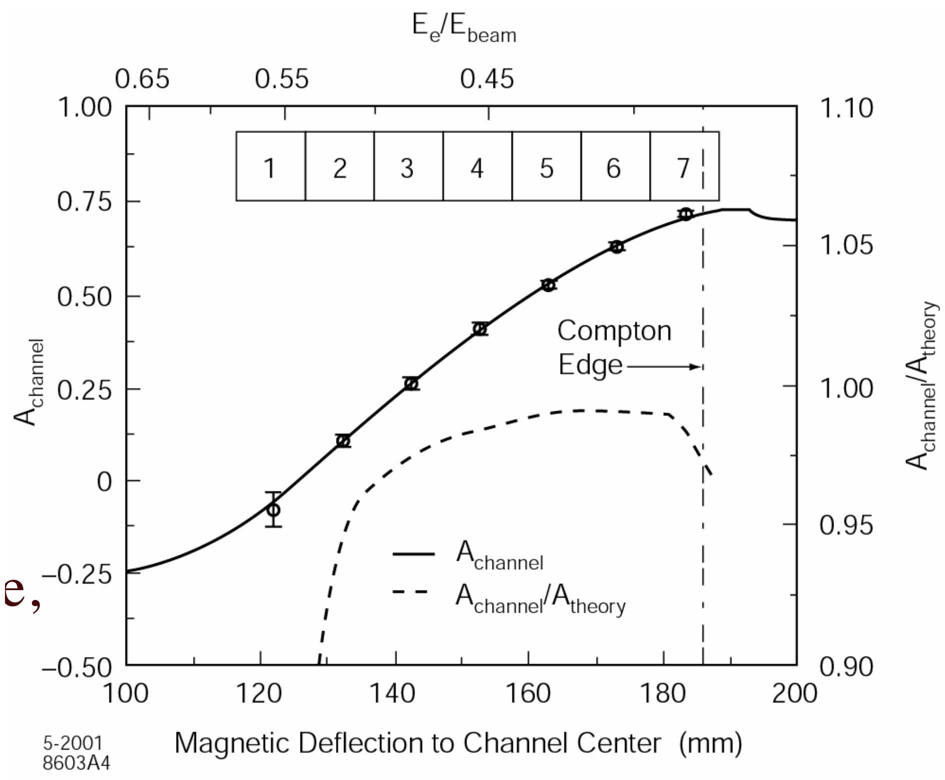




M. Woods - SLAC-PUB-7319

SLD Compton Systematics

Systematic	Value
Laser polarization	0.1%
Detector linearity	0.2%
Analyzing power	0.4%
Laser pickup	0.2%
Luminosity-weighting	0.15%
Total	**0.52%**

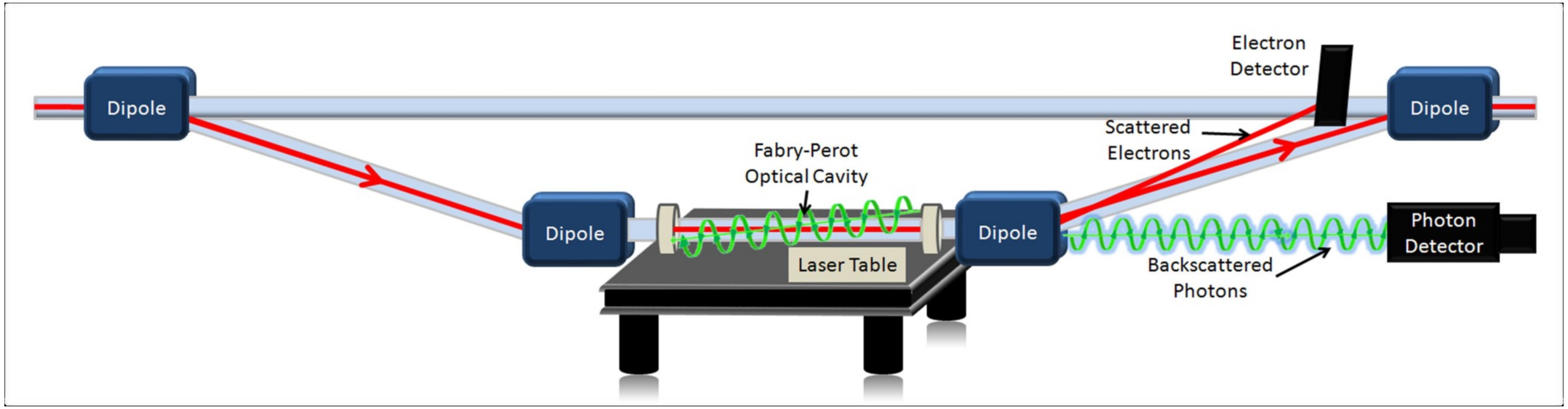


- → Pulsed laser operated in multi-photon mode – several scattered electrons/pulse
- → Cerenkov detector response (linearity) key systematic
- → Detector coarsely segmented – small correction to theoretical asymmetry in each bin/channel

Detector position scans used to determine position of Compton edge

Mike Woods, SLAC, JLab Polarimetry Workshop, 2003

Compton Polarimeters in Halls A and C at Jefferson Lab



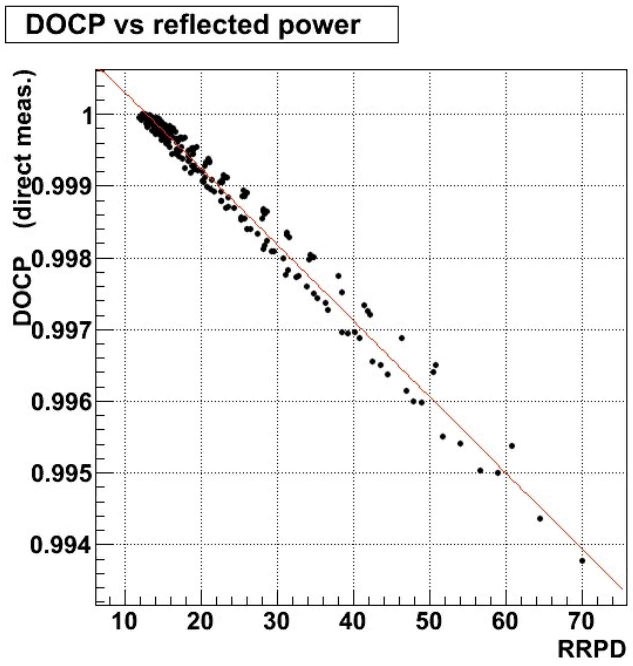
Compton polarimeters in Hall A and C:

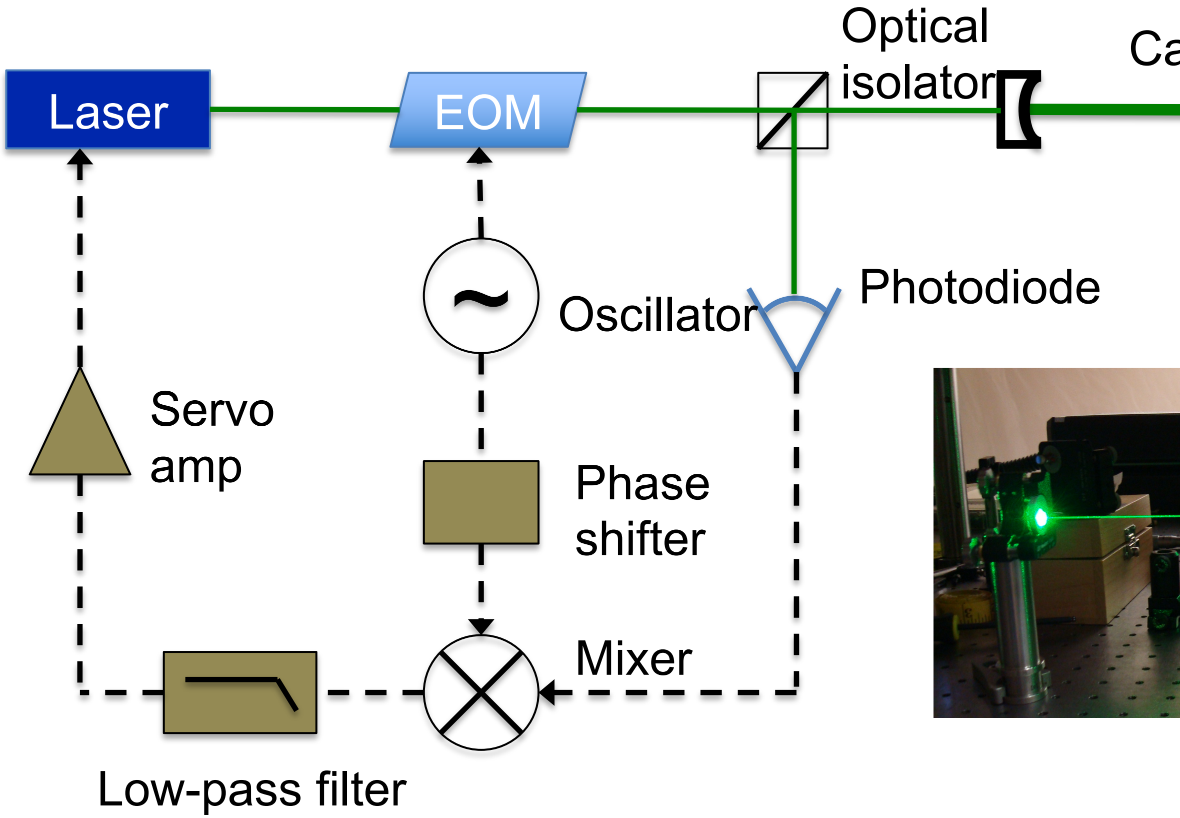
1. 4 dipole chicane to deflect beam to laser system
2. Fabry-Perot cavity to provide kW level CW laser power
3. Diamond/silicon strip detectors for scattered electrons
4. Photon detectors operated in integrating mode

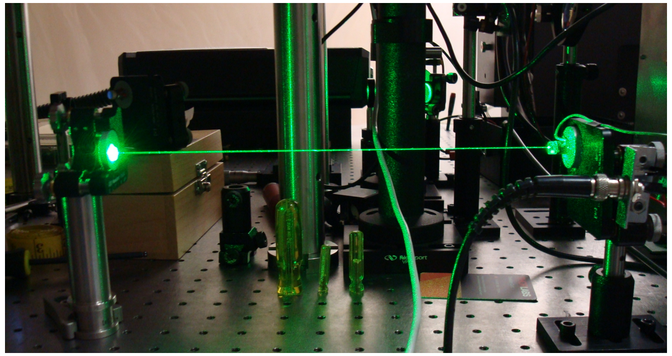
→ Hall C has achieved dP/P=0.6% (electron detector)
→ Hall A has achieved dP/P=0.9% (photon detection)

Fabry-Perot Cavity Laser System

Due to relatively low intensity of JLab electron beam, need higher laser power
→ Use external Fabry-Perot cavity to amplify 1-10 W laser to 1-5 kW of stored laser power







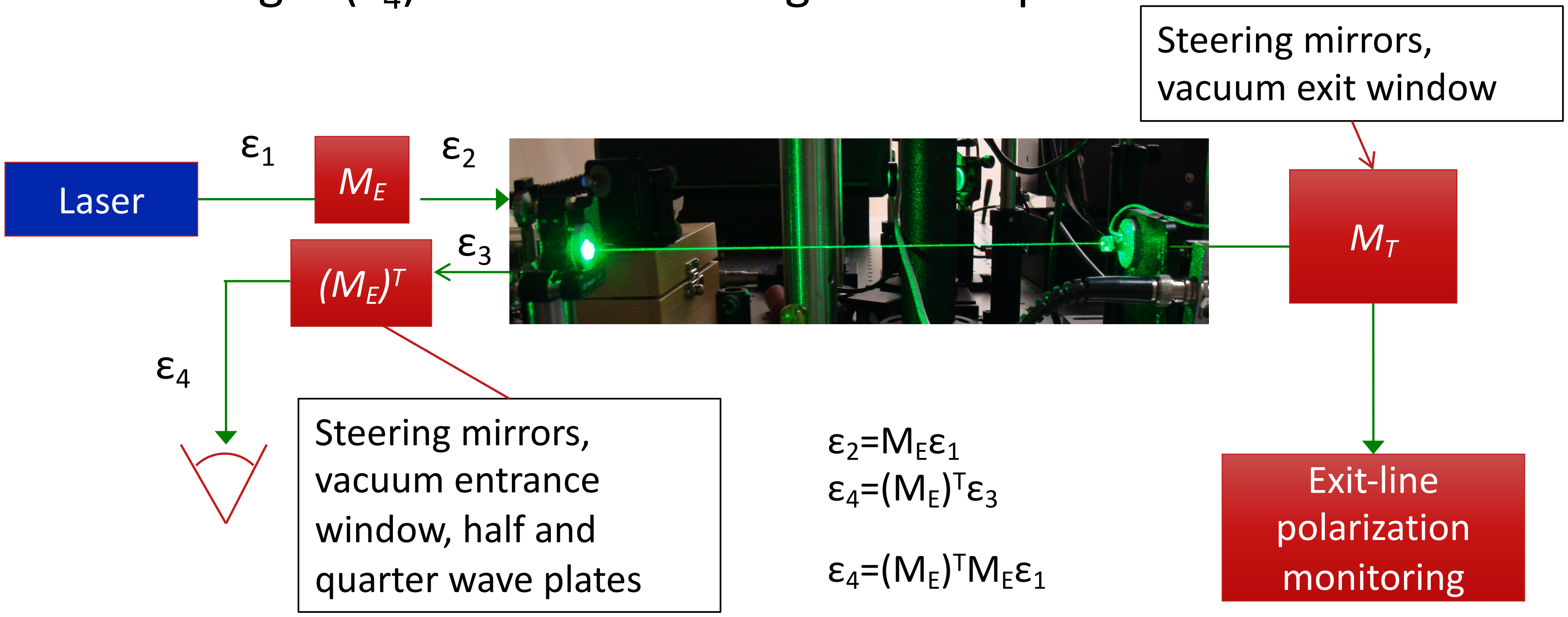
Key systematic: Laser polarization in Fabry-Perot cavity
→ Constrain by monitoring light reflected back from cavity and measurement of cavity birefringence

Laser Polarization

Propagation of light into the Fabry-Pérot cavity can be described by matrix, $\boldsymbol{M_E}$

→Light propagating in opposite direction described by transpose matrix, $\boldsymbol{(M_E)^T}$

→If input polarization (ε_1) linear, polarization at cavity (ε_2) circular only if polarization of reflected light (ε_4) linear and orthogonal to input*



$\varepsilon_2 = M_E \varepsilon_1$

$\varepsilon_4 = (M_E)^T \varepsilon_3$

$\varepsilon_4 = (M_E)^T M_E \varepsilon_1$

JINST 5 (2010) P06006

*J. Opt. Soc. Am. A/Vol. 10, No. 10/October 1993

Laser Polarization

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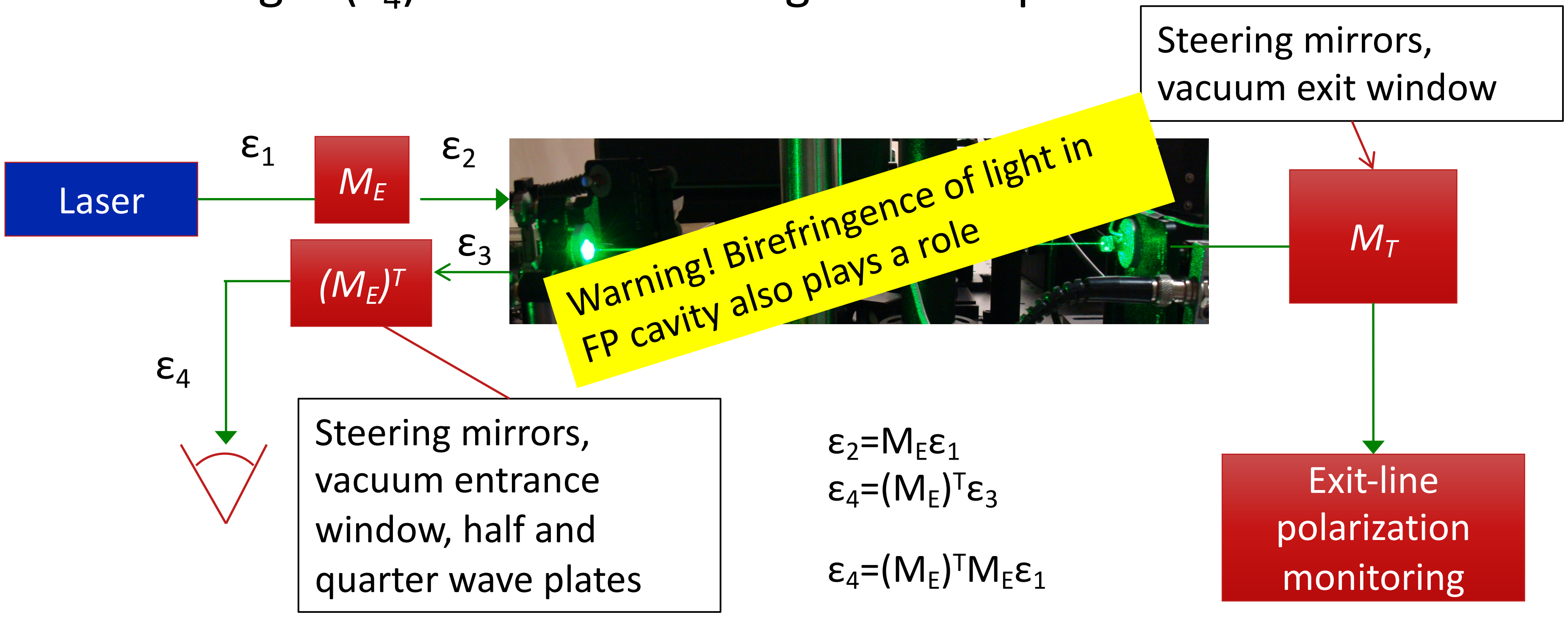

$\varepsilon_2 = M_E \varepsilon_1$

$\varepsilon_4 = (M_E)^T \varepsilon_3$

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JINST 5 (2010) P06006

*J. Opt. Soc. Am. A/Vol. 10, No. 10/October 1993

Polarization at Cavity Entrance via Reflected Power

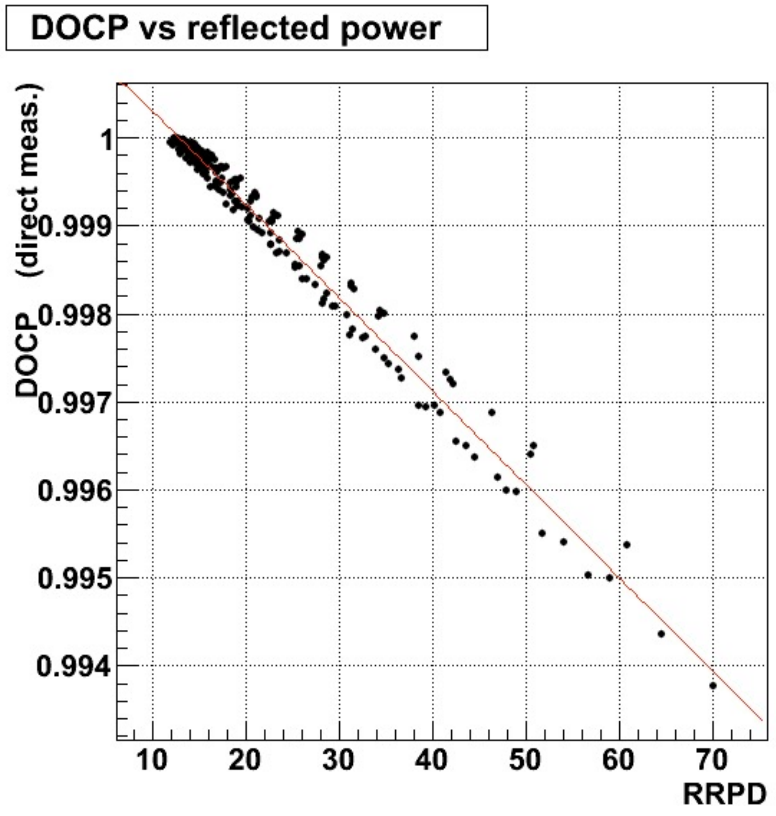
"If input polarization (ε_1) linear, polarization at cavity (ε_2) circular only if polarization of reflected light (ε_4) linear and orthogonal to input"

→ In the context of the Hall A Compton, this means that the circular polarization at cavity is maximized when retro-reflected light is minimized

→ Optical reversibility allows configuring system to give 100% DOCP at cavity entrance, even when the system is under vacuum, just by minimizing signal in one detector

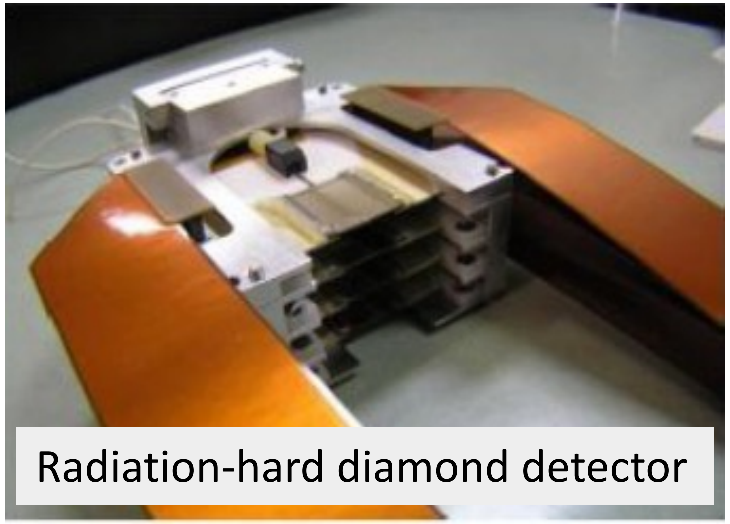
→ In addition, response of whole system can be modeled by sampling all possible initial state polarizations

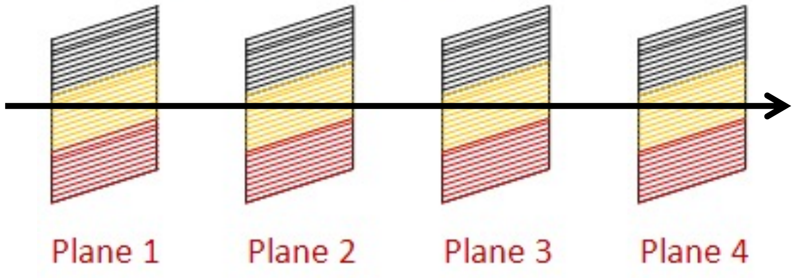
Technique applicable to any Compton polarimeter → eliminates uncertainties due to birefringence in vacuum windows (very difficult to control)

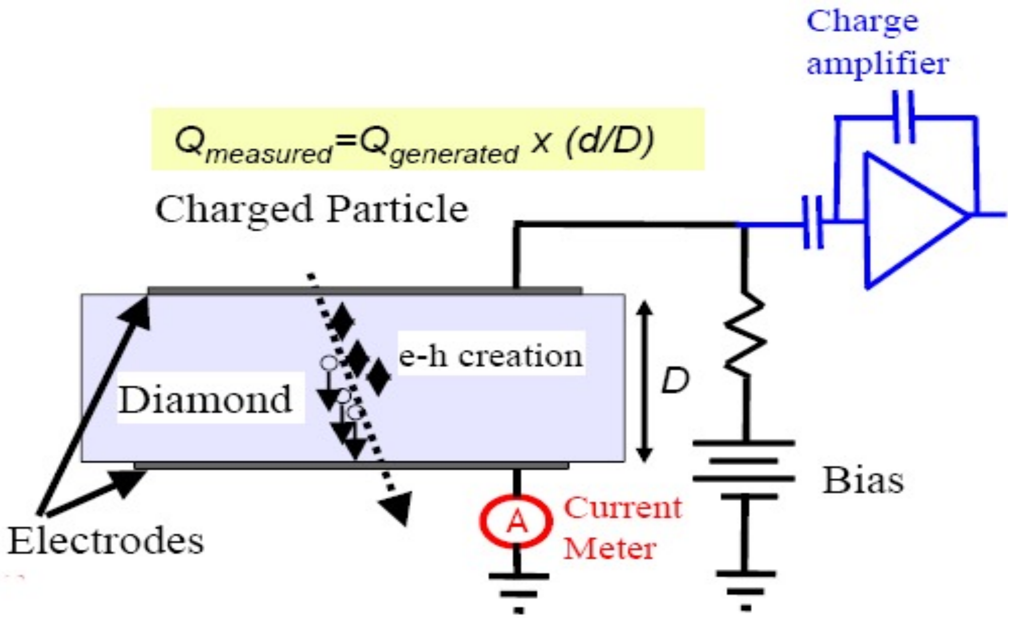


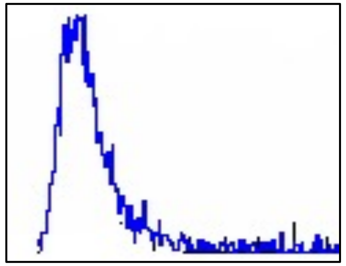
Hall C Compton Diamond Electron Detector

Diamond microstrips used to detect scattered electrons
→ Radiation hard: exposed to 10 MRad without significant signal degradation
→ Four 21mm x 21mm planes each with 96 horizontal 200 µm wide microstrips.
→ Rough-tracking based/coincidence trigger suppresses backgrounds

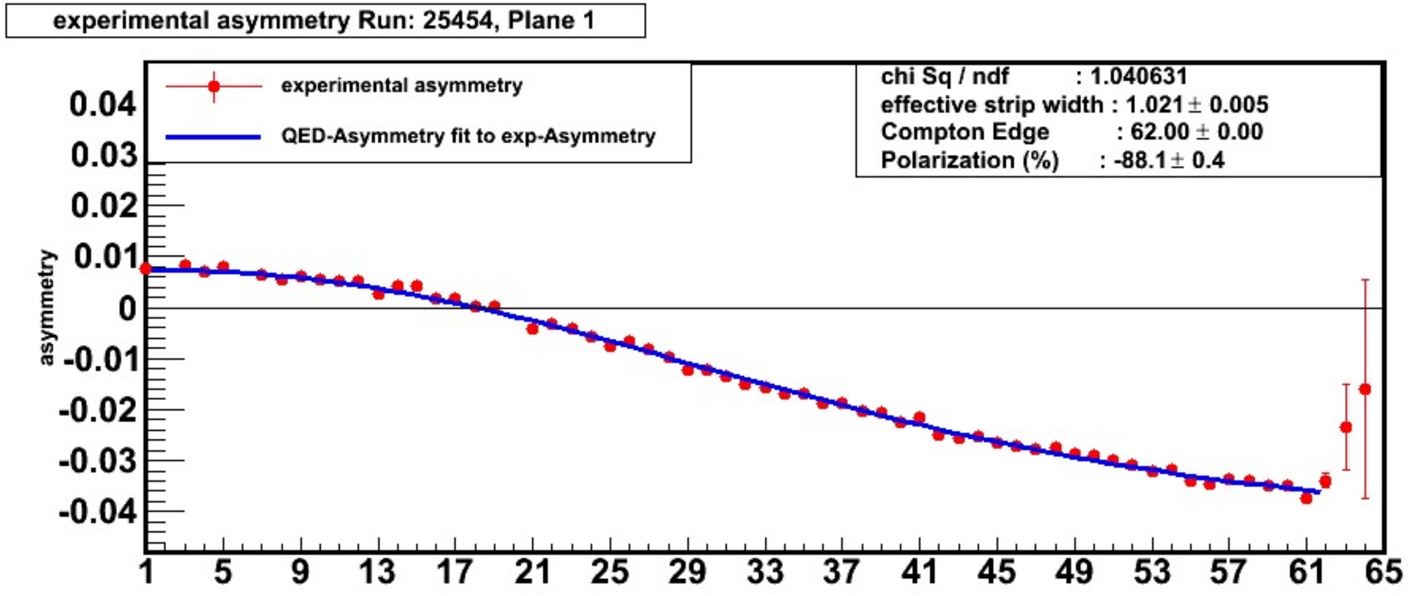

Radiation-hard diamond detector







Electron Detector Polarization Extraction



An “integrating” technique can be employed by fitting asymmetry zero-crossing
→ Worked well for earlier Hall A experiments yielding 1% level results
→ Drawback: extremely sensitive to strip/detector efficiency

Hall C Compton employed a 2 parameter fit (polarization and Compton edge) to the differential spectrum
→ This has yielded good results → strip width (resolution) is important
→ Zero-crossing must be in acceptance to constrain the fit well
→ Systematic uncertainty dP/P = 0.6%

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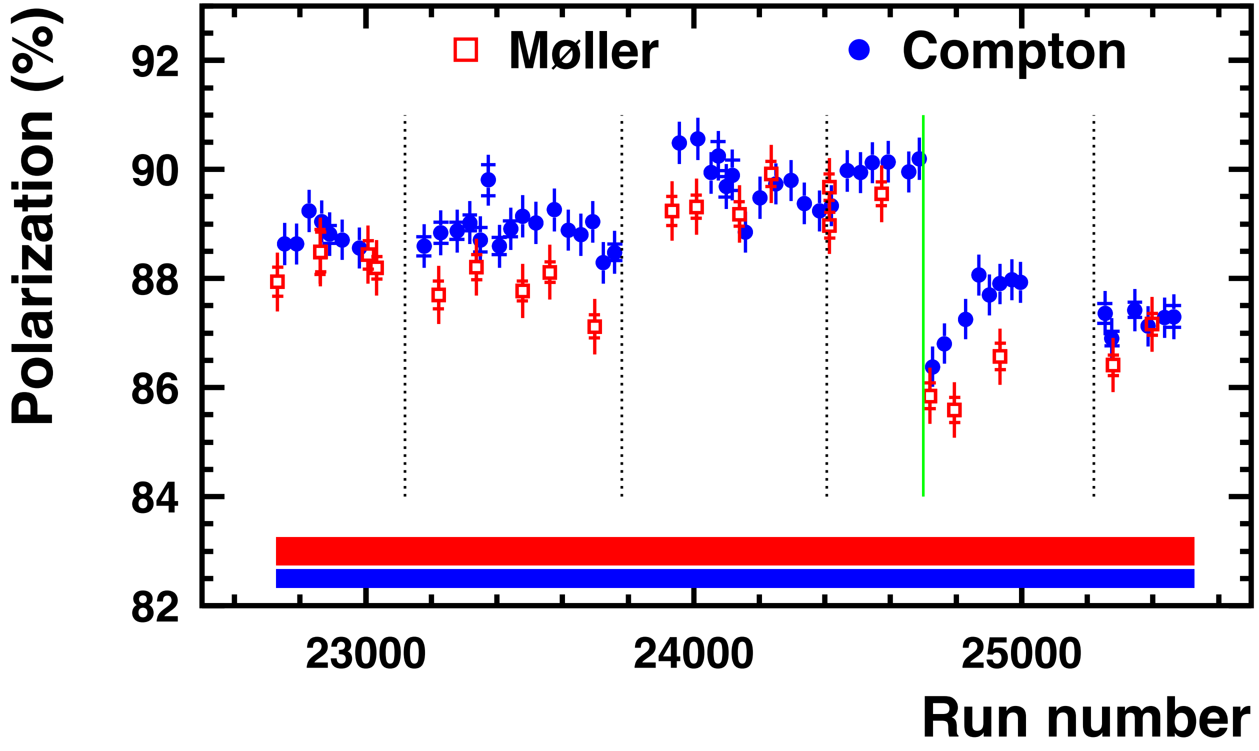
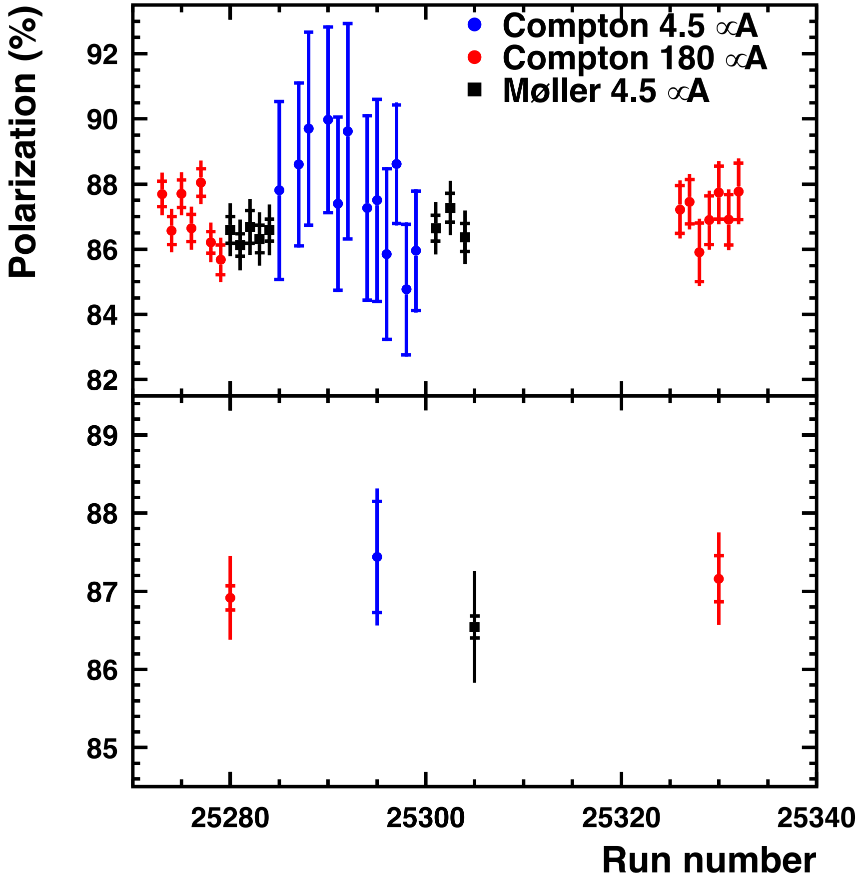
Polarimeter Comparisons: Hall C Møller and Compton





Compton measurements at 180 μA concurrent with experiment

Møller measurements taken intermittently, at 1 μA

Dedicated test with both Møller and Compton at 4.5 μA

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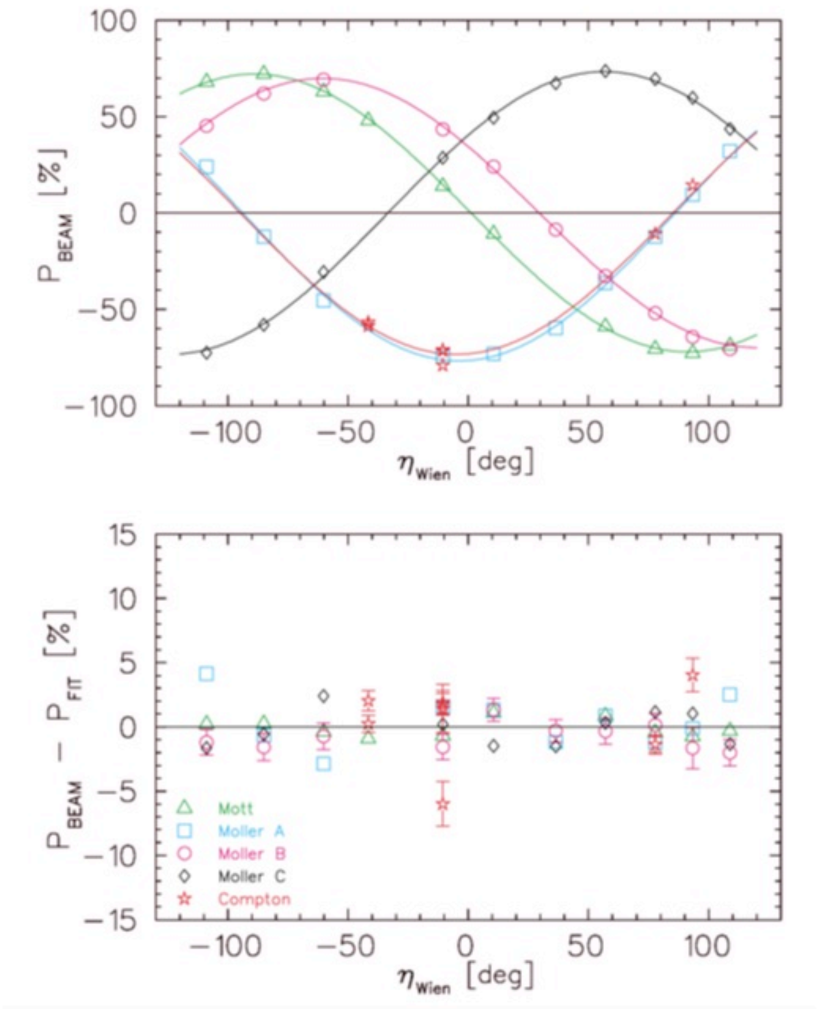
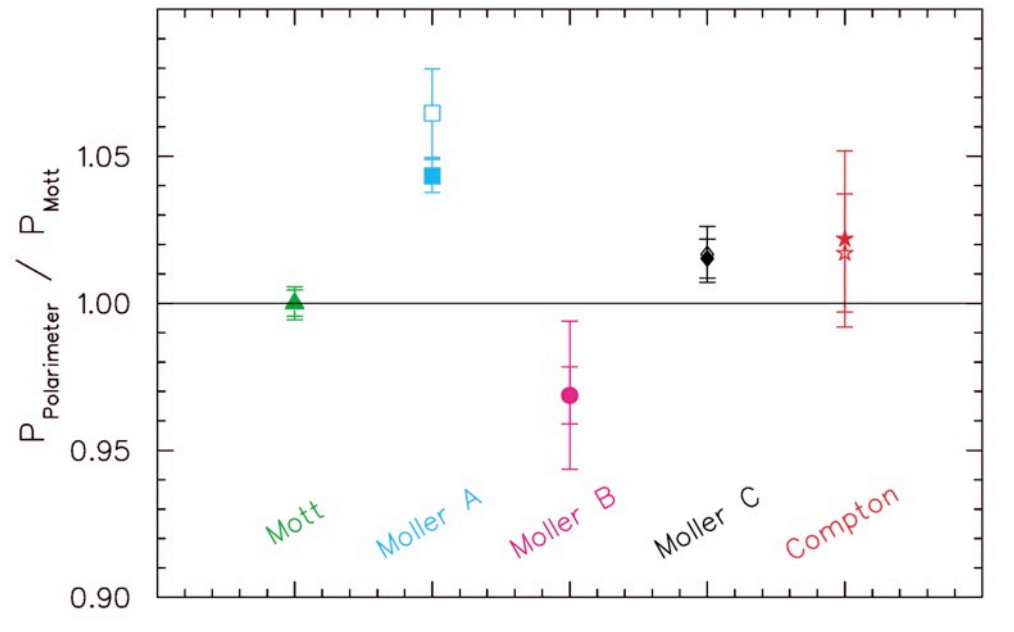
Jefferson Lab Polarimeter Comparisons: Spin Dance



Compared electron polarimeters in Halls A, B, C by taking measurements at several Wien angles – compare maximum polarization

→ Discovered unexpected systematic in Hall A Møller

→ Updated multi-hall Spin Dance would be beneficial since polarimeters have improved since original results from 2004



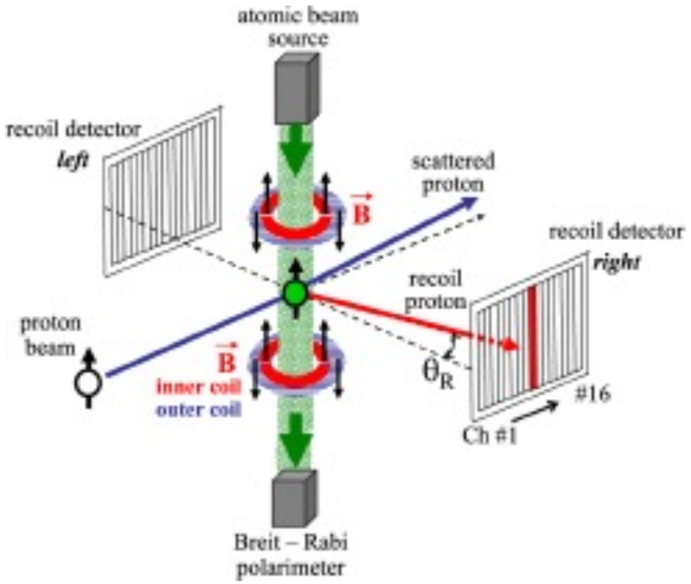
Summary (Part 1)

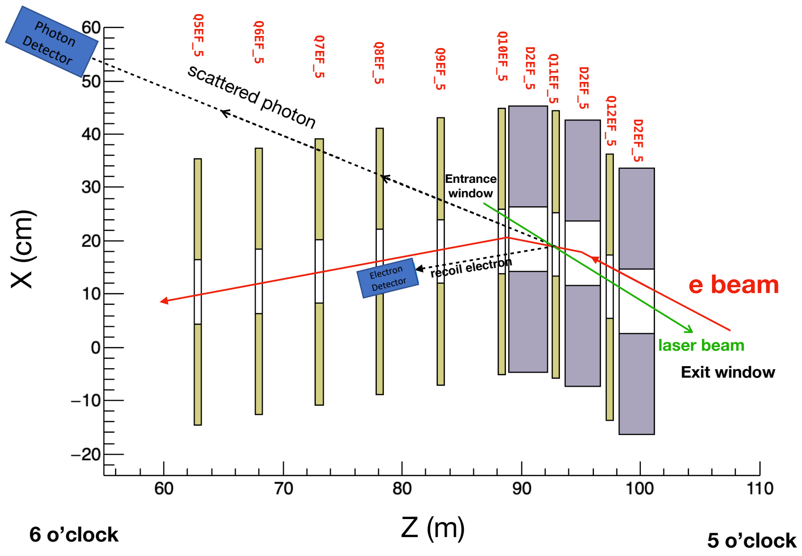
- Precision polarimetry at EIC – key to full leveraging potential of physics program
  - Couples to luminosity measurements as well through double-spin asymmetry in Bremsstrahlung cross section
- Electron polarimetry techniques
  - Mott → high precision achieved (<1%). Only suitable up to MeV-scale energies (injectors)
  - Møller polarimetry → high precision, rapid measurements. Destructive (not good for storage rings)
  - Compton polarimetry → default technique for storage rings. Challenges due to energy dependence of analyzing power
  - Comparisons with multiple devices and techniques powerful tool for reducing systematic uncertainties

Polarimetry at EIC – Part 2

Dave Gaskell

Jefferson Lab



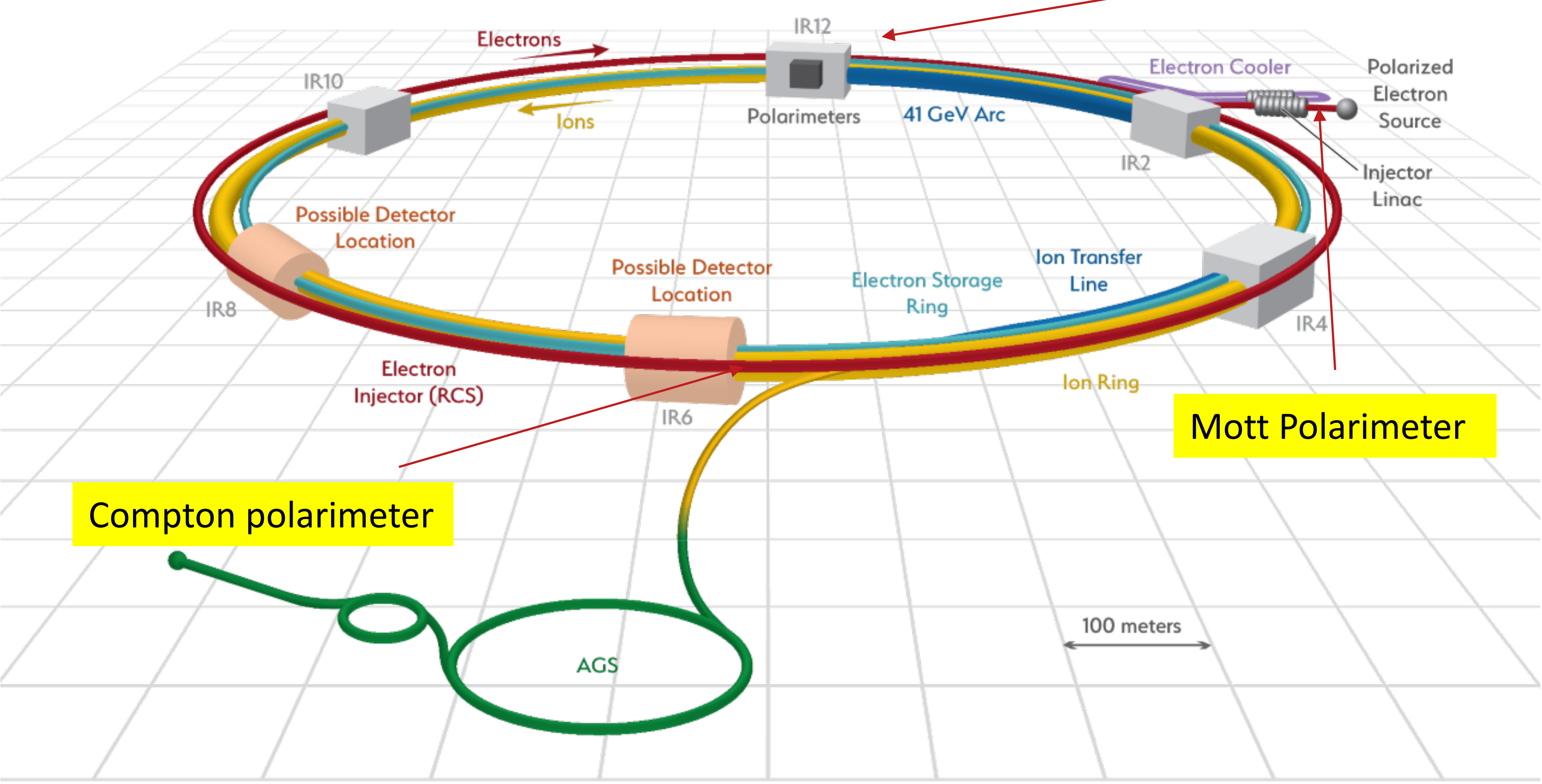


CFNS Summer School on the Physics of the Electron Ion Collider

August 9-20, 2021

EIC Electron Polarimetry

EIC Electron Polarimetry Map

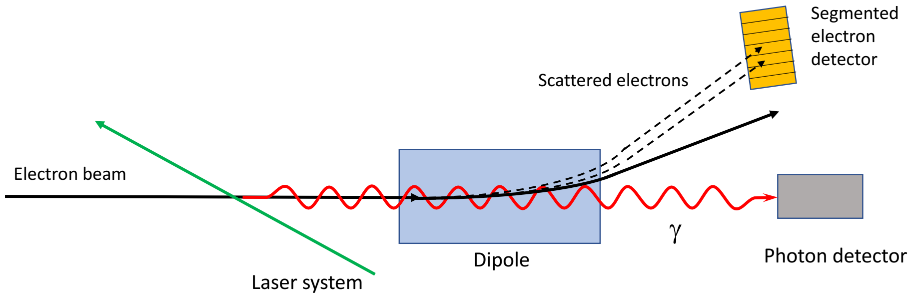


RCS: Møller Polarimeter or Compton

Mott Polarimeter

Compton polarimeter

Development of a Compton Polarimeter for EIC



EIC Electron Beam Properties

Energy (GeV)	Current (A)	Polarization (%)	Frequency (MHz)
5	2.5	70	99
10	2.5	70	99
18	0.26	70	25

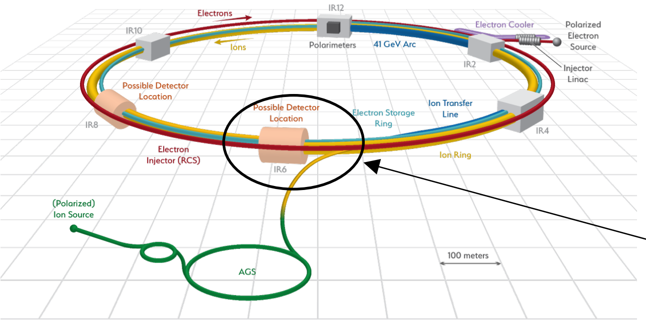
Primary electron polarimetry technique in ESR will be Compton → lessons learned from earlier polarimeters will shape design of EIC Compton

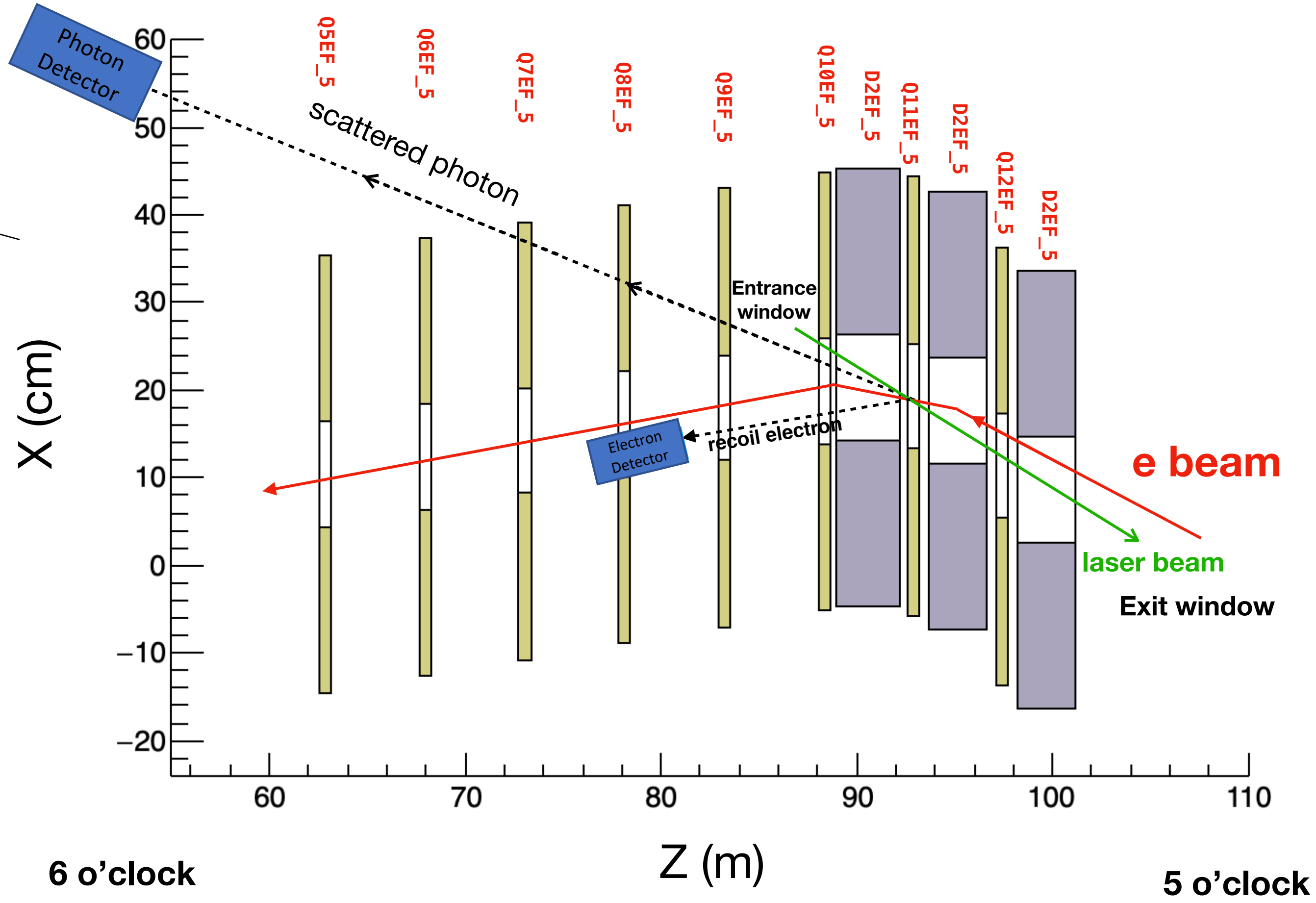
Requirements:

1. dP/P = 1% (or better)
2. Bunch-by-bunch polarization measurements
3. Measurement time compatible with electron bunch lifetime in ring (~2 minutes at 18 GeV)

Elke Aschenauer, Alexandre Camsonne, Ciprian Gal, Josh Hoskins, Caryn Palatchi , Richard Petti, Zhengqiao Zhang

EIC Compton Polarimeter Location





Initially considered placing Compton at IP12
→ Far from detector IP @ 6 o'clock
→ Not sufficient space in that region (hadron polarimetry, etc.)

Compton will be placed just upstream of IP6
→ Much of beamline occupied – little free space. Integration will be challenging

Simultaneous Longitudinal and Transverse Electron Polarization Measurement

Planned Compton polarimeter location upstream of detector IP
→ Beam polarization mostly longitudinal, but some spin rotation remains before arrival at detector IP

At Compton interaction point, electrons have both longitudinal and transverse (horizontal) components
→ Longitudinal polarization measured via asymmetry as a function of backscattered photon/scattered electron energy
→ Transverse polarization from left-right asymmetry

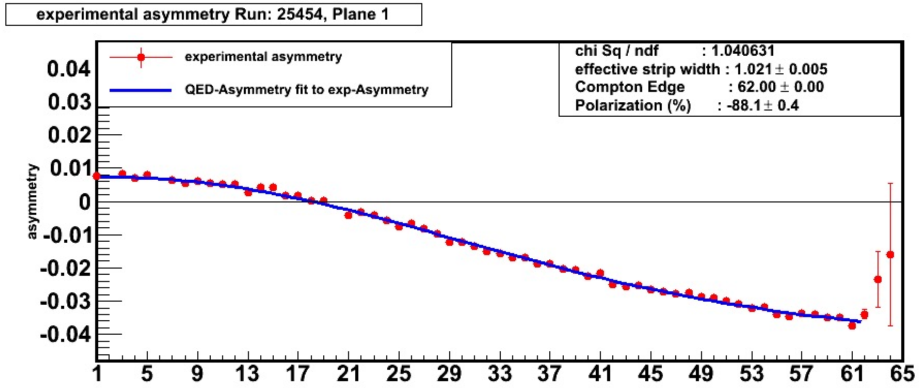
Beam energy	P_L	P_T
5 GeV	97.6%	21.6%
10 GeV	90.7%	42.2%
18 GeV	70.8%	70.6%

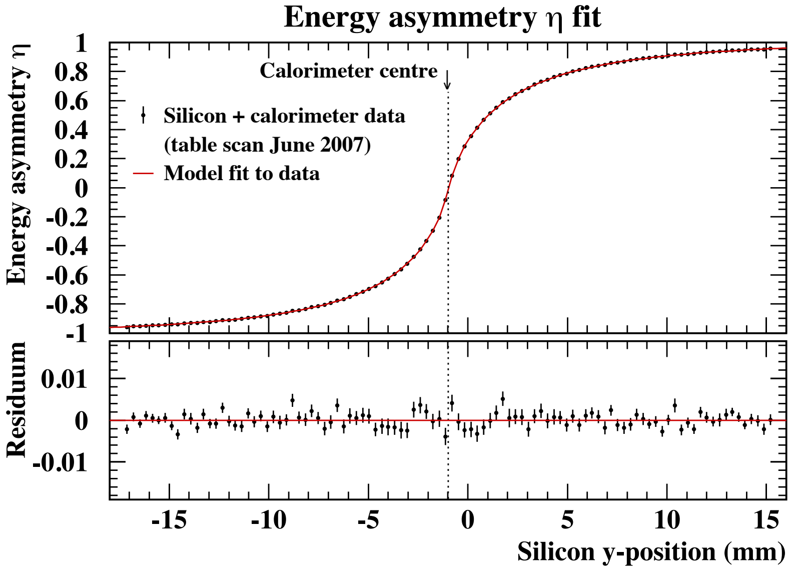
Beam polarization will be fully longitudinal at detector IP, but accurate measurement of absolute polarization will require simultaneous measurement of P_L and P_T at Compton polarimeter

EIC Compton will provide first high precision measurement of P_L and P_T at the same time

Compton polarimetry – lessons from previous devices

- Longitudinal polarimetry
  - Electron detector – needs sufficient segmentation to allow self-calibration "on-the-fly"
  - Photon detector – integrating technique provides most robust results – perhaps not practical at EIC? → lower the threshold
- Transverse polarimetry
  - Remove η-y calibration issue – use highly segmented detectors at all times
  - Calorimeter resolution → integrate over all energy?
  - Beam size/trajectory important – build in sufficient beam diagnostics
- Common to both
  - Birefringence of vacuum windows can impact laser polarization → use back-reflected light





Compton Laser System Requirements

8	Configuration	Beam energy [GeV]	Unpol Xsec[barn]	Tot Unpol Xsec[barn]	Apeak [not used]	<A^2>	L	1/t(1%)	t[s]	t[min]
9	laser:532nm, photon long	18	0.432	0.432	0.310	2.07E-02	1.81E+05	1.17E-01	9	0.14
10	laser:532nm, photon trans	18	0.432	0.432	0.210	3.62E-03	1.81E+05	2.05E-02	49	0.81
11	laser:532nm, electron	18	0.301	0.432	0.320	4.57E-02	1.81E+05	1.80E-01	6	0.09
12										
13	laser:532nm, photon long	10	0.503	0.503	0.270	1.54E-02	1.55E+05	8.69E-02	12	0.19
14	laser:532nm, photon trans	10	0.503	0.503	0.170	2.15E-03	1.55E+05	1.21E-02	83	1.38
15	laser:532nm, electron	10	0.340	0.503	0.270	3.05E-02	1.55E+05	1.17E-01	9	0.14
16										
17	laser:532nm, photon long	5	0.569	0.569	0.160	5.82E-03	1.37E+05	3.29E-02	30	0.51
18	laser:532nm, photon trans	5	0.569	0.569	0.110	1.63E-03	1.37E+05	9.19E-03	109	1.81
19	laser:532nm, electron	5	0.323	0.569	0.160	1.14E-02	1.37E+05	3.65E-02	27	0.46

Ciprian Gal

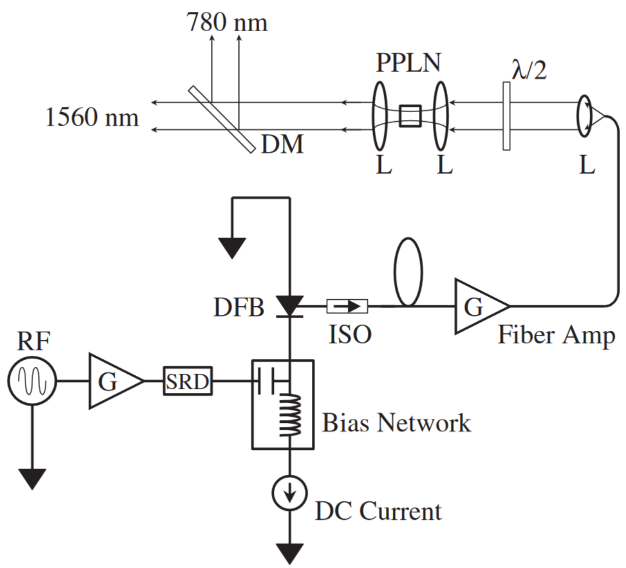
Laser power constraint: sufficient power to result in ~ 1 backscattered photon/bunch-laser crossing
→ Want to make "single photon" measurements – not integrating

532 nm laser with ~5 W average power at same frequency as EIC electron bunches sufficient

Resulting measurement times (for differential measurement, dP/P=1%) as noted above – easily meets beam lifetime constraints

Jefferson Lab

Compton Laser System

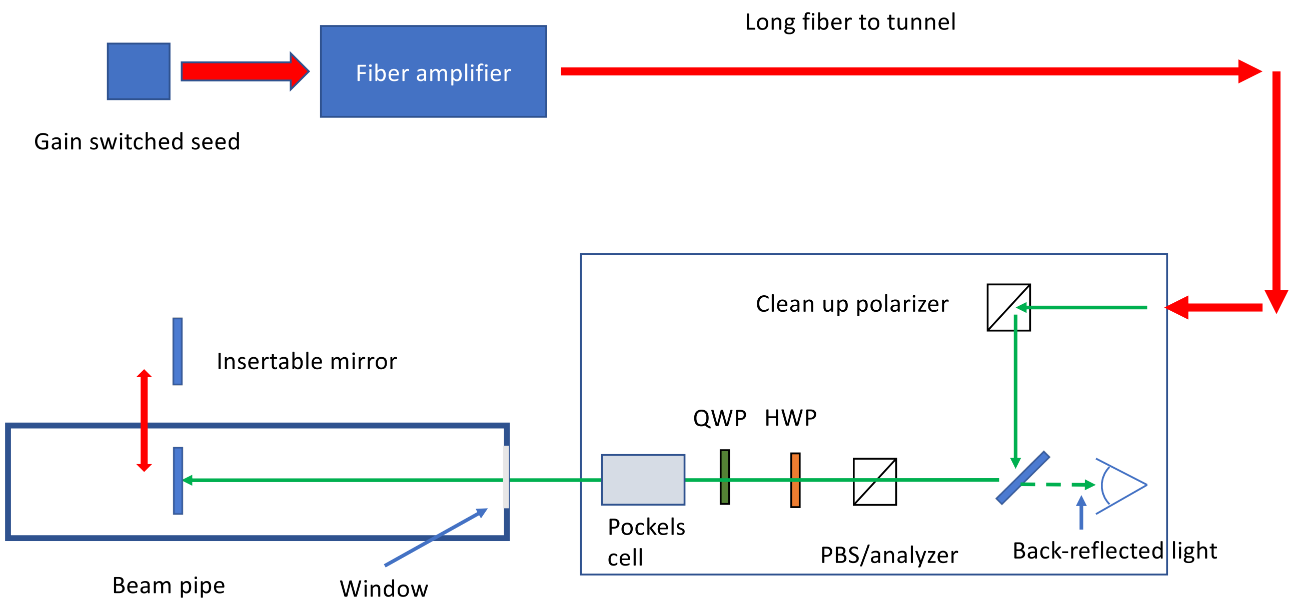


JLab injector laser system

Proposed laser system based on similar system used in JLab injector and LERF

1. Gain-switched diode seed laser – variable frequency, few to 10 ps pulses @ 1064 nm
   - ➢ Variable frequency allows optimal use at different bunch frequencies (100 MHz vs 25 MHz)
2. Fiber amplifier → average power 10-20 W
3. Optional: Frequency doubling system (LBO or PPLN)

Polarization in vacuum set using "back-reflection" technique
→ Requires remotely insertable mirror (in vacuum)

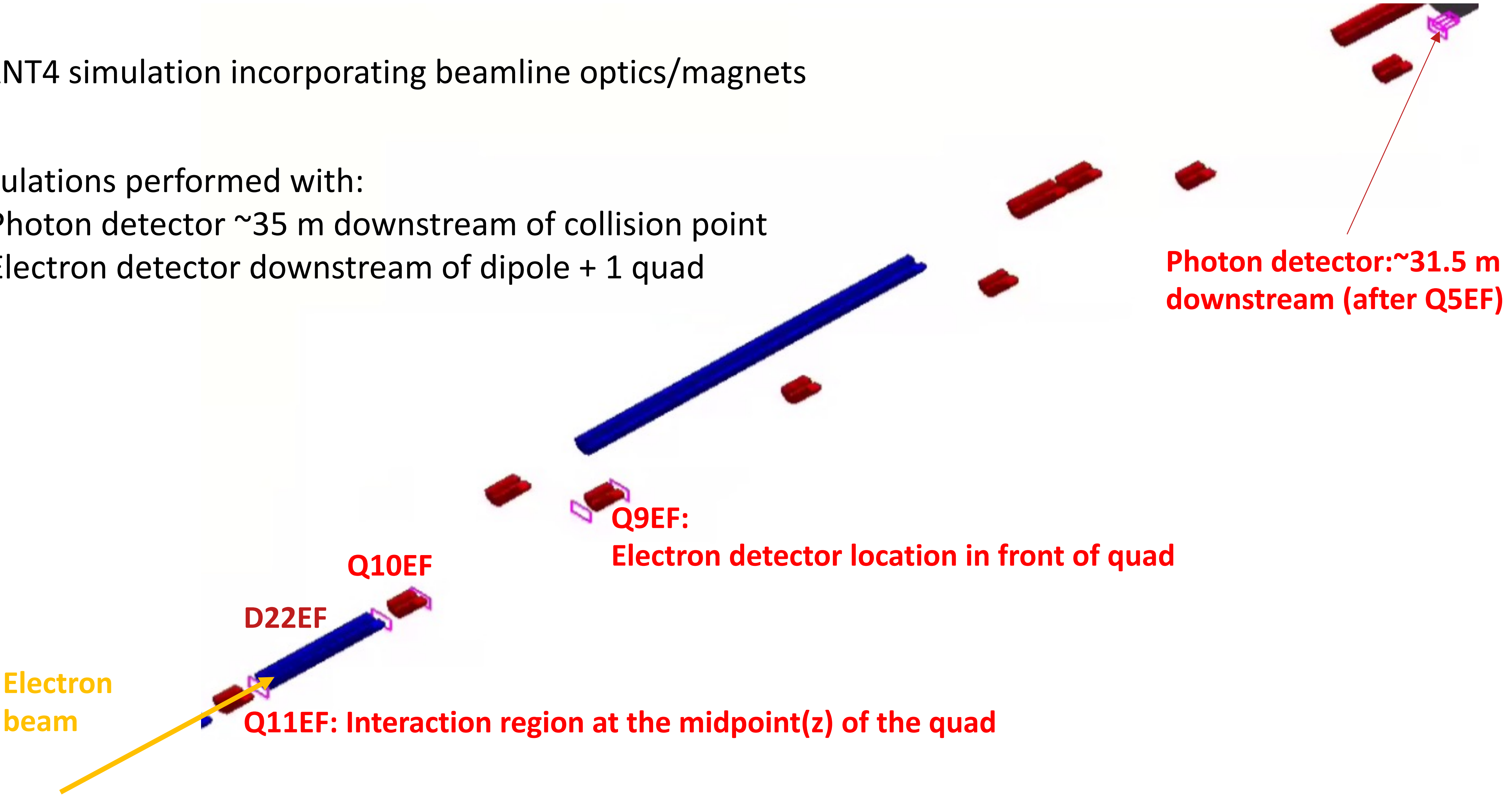


Prototype system under development (C. Gal, eRD26)

Compton Detectors and Simulations

GEANT4 simulation incorporating beamline optics/magnets

Simulations performed with:
→ Photon detector ~35 m downstream of collision point
→ Electron detector downstream of dipole + 1 quad



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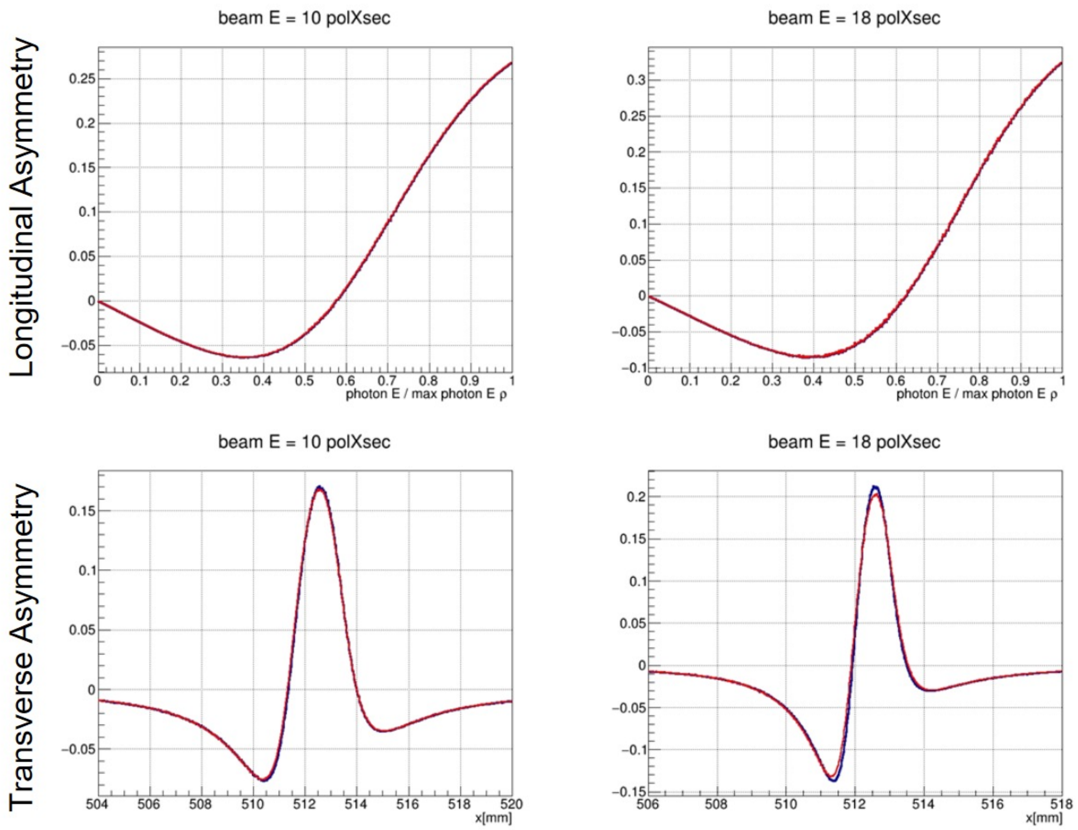
Polarization Measurement with Photon Detector

Photon detector needs 2 components to measure both longitudinal and transverse polarization

- Calorimeter → asymmetry vs. photon energy (P_L)
- Position sensitive detector → left-right asymmetry (P_T)

Beam energy	P_L	P_T
5 GeV	97.6%	21.6%
10 GeV	90.7%	42.2%
18 GeV	70.8%	70.6%



Transverse size of detectors determined by backscattered photon cone at low energy

→ +/- 2 cm adequate at 5 GeV

→ Longitudinal measurement requires good energy resolution from ~0 (as low as possible) to 3 GeV

→ Fast time response also needed (10 ns bunch spacing)

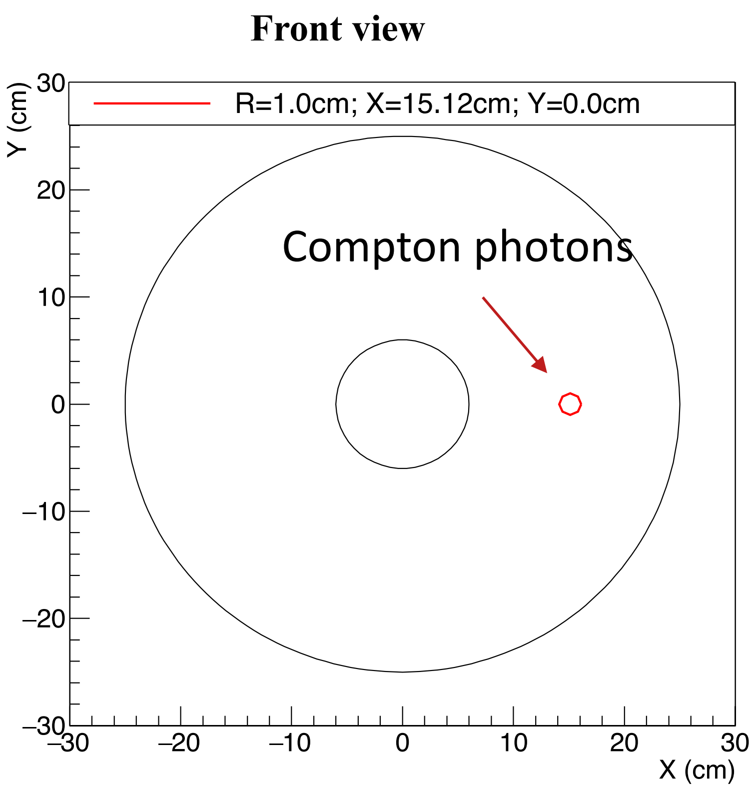
→ PbWO4 a possible candidate

Position sensitive detector segmentation determined by highest energy → 18 GeV

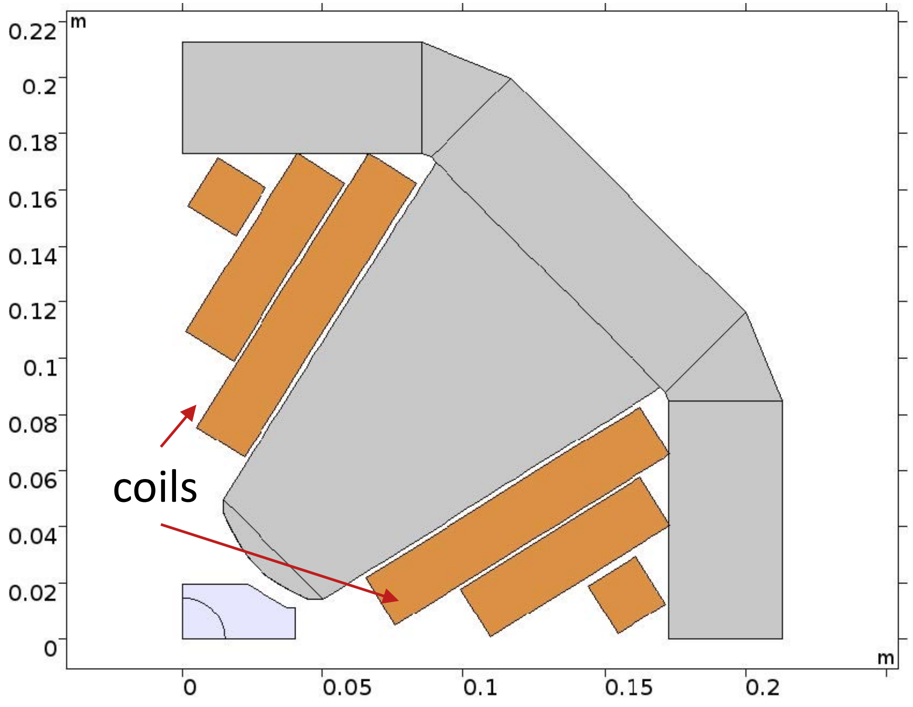
→ More investigation needed, but segmentation on the order of 200-400 μm

Backscattered photons vs. Beamline magnets

Photons will not clear beamline magnet apertures in some cases



Q8EF_5



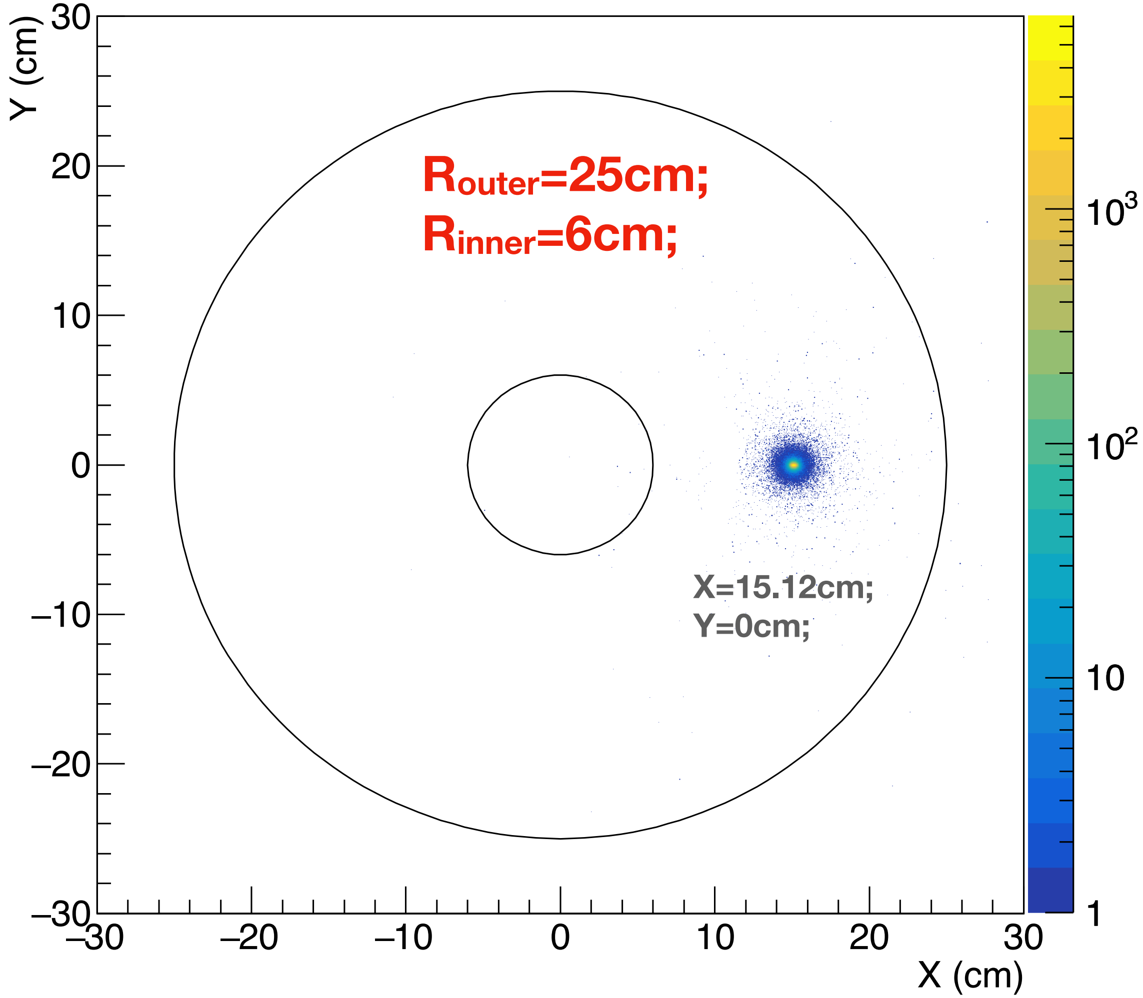
Quad cross-section

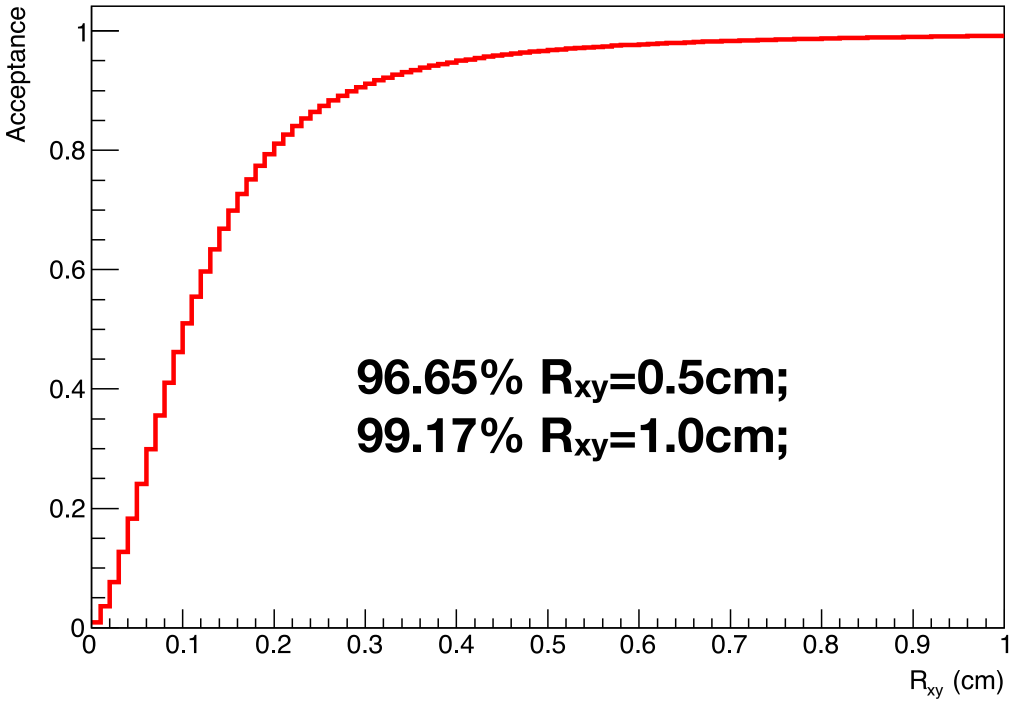
For 2 of 3 quads, backscattered photons traverse iron-free region – coils can likely/hopefully be modified to accommodate

→ Last quad (Q7EF_5) will probably require a hole in the iron – but this should not have large impact on quad performance

Zhengqiao Zhang (BNL)

Backscattered photons vs. Beamline magnets





1 cm radius required to capture 99% of spectrum

Q9_EF5 → 0.5 cm

Q7_EF5 → 1.25 cm

Initial studies done at 18 GeV → apertures will need to be larger at lower energies (5-10 GeV)

Zhengqiao Zhang (BNL)

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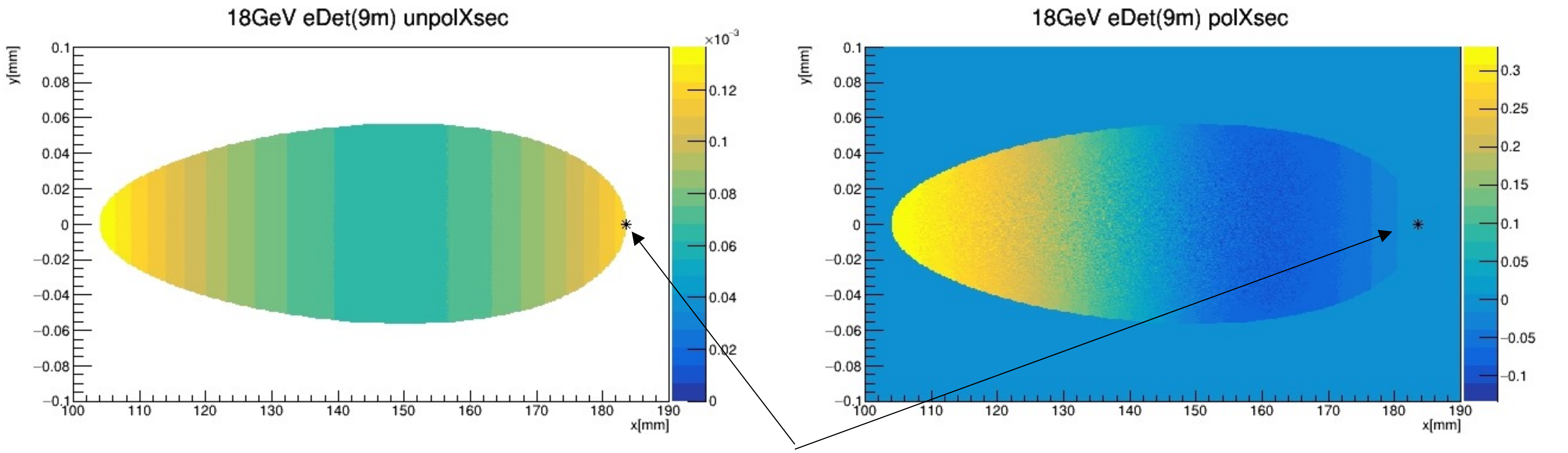
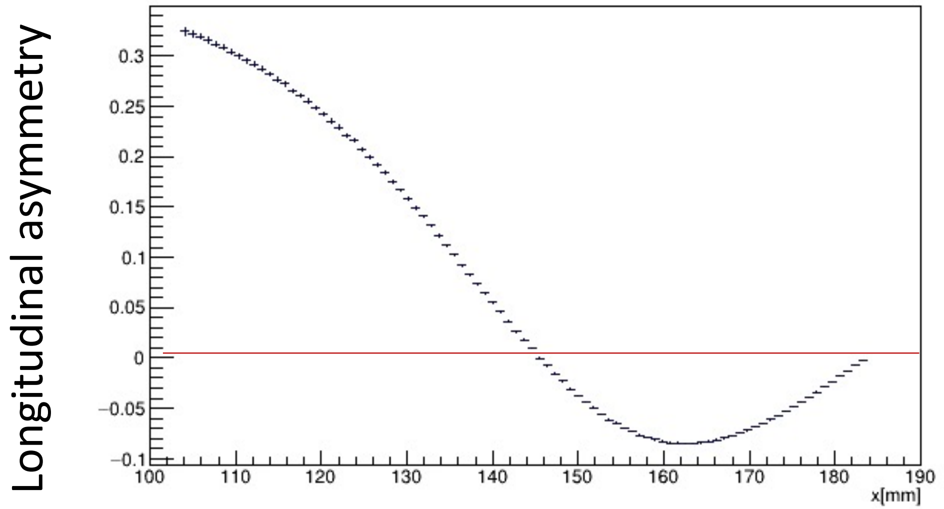
Detector Size – Electron Detector



Un-scattered beam



Scattered electrons will be dispersed horizontally by dipole after interaction → larger energy loss, further from beam → Vertical size dominated by scattering angle – very small

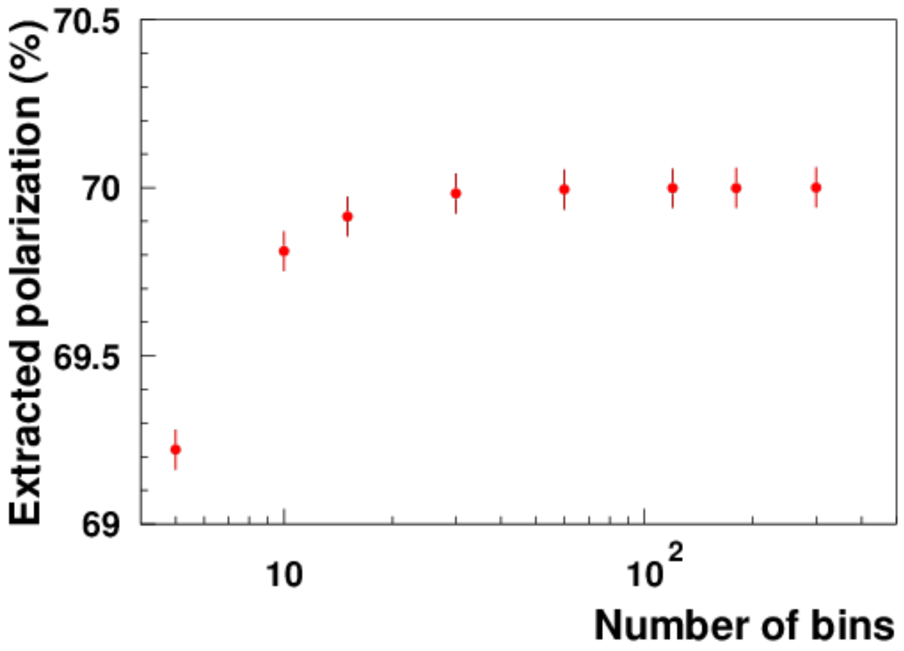
Detector size: capture (longitudinal) asymmetry zero crossing and kinematic endpoint → this will be largest at highest energy (18 GeV)

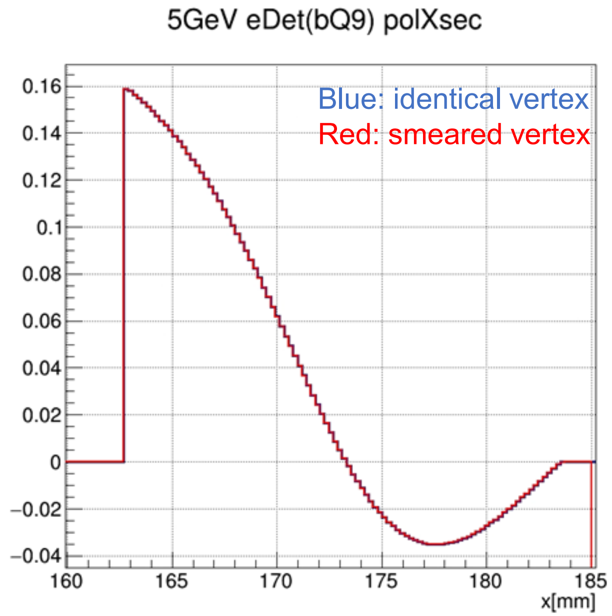
→ Implies detector size of at least 4.5 cm (6 cm would better)

Detector Segmentation – Electron Detector

Detector segmentation driven by requirement to be able to extract polarization (fit asymmetry) without any corrections due to detector resolution (see SLD Compton)

→ Studies with toy Monte Carlo suggest that about 30 bins (strips) between asymmetry zero crossing and endpoint results in corrections <0.1%





EIC Compton: separation between zero crossing and endpoint smallest at 5 GeV
→ 12 mm, implies needed segmentation of about 400 μm

Easily achievable with silicon or diamond strip detectors

Note: at 5 GeV, asymmetry zero crossing only 8-10 mm from beam!

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Transverse Polarization Measurement with EDET

At Compton location – significant transverse beam polarization
→ Unfortunately, this transverse polarization is in the horizontal direction
→ Same coordinate as momentum-analyzing dipole

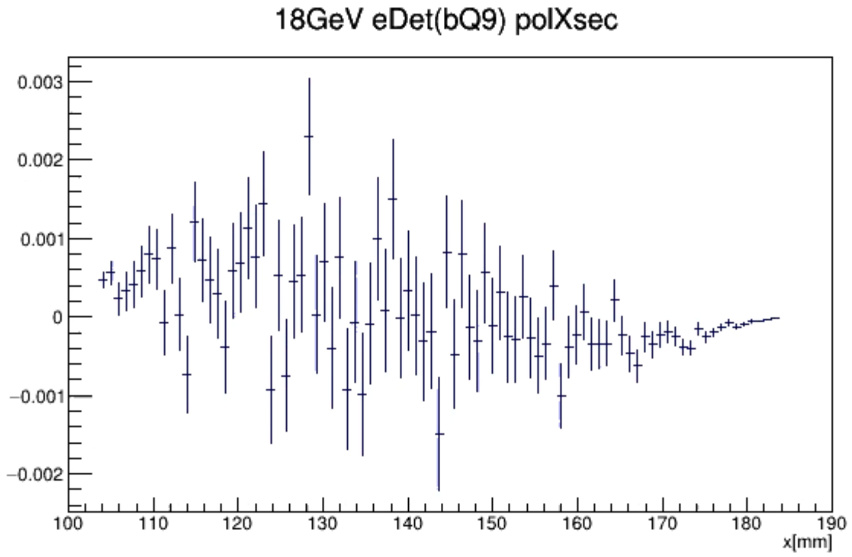
In the absence of the dipole, the transversely polarized electrons would result in a left-right asymmetry
→ The "scattered electron cone" is much smaller than the photons
→ Left-right asymmetry is spread over much smaller distance (μm vs mm)

The large dispersion induced by the dipole makes measurement of the left-right asymmetry impossible

Electron detector can only be used for measurements of $\boldsymbol{P_L}$

Beam energy	P_L	P_T
5 GeV	97.6%	21.6%
10 GeV	90.7%	42.2%
18 GeV	70.8%	70.6%

100% transversely polarized beam

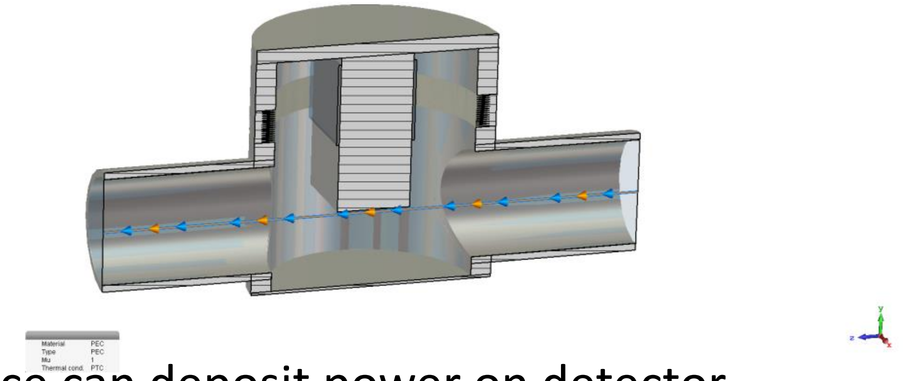


Electron detector considerations

Electron detector likely cannot live in vacuum directly – needs to be housed in a structure similar to Roman Pot

→ Preliminary wakefield calculations (alternate configuration) suggest power deposited manageable

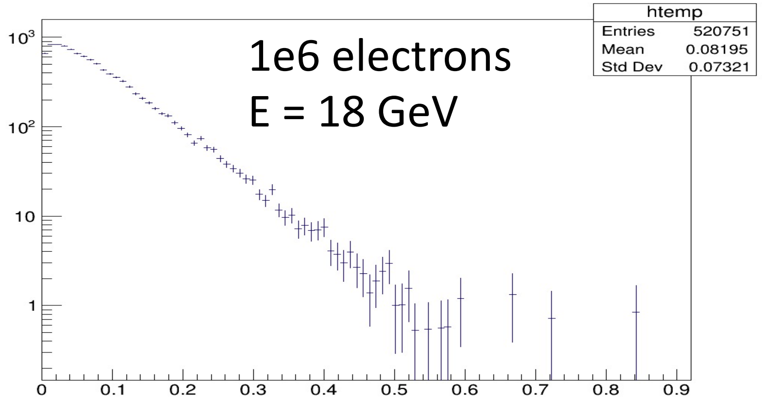
→ This needs to be updated for latest EIC layout



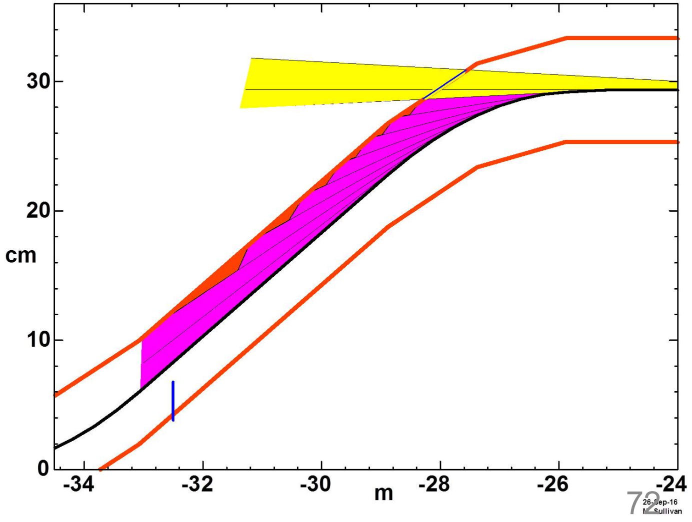
Electron detector out of direct synchrotron fan, but single-bounce can deposit power on detector

→ Studies by Mike Sullivan (for different configuration) suggested large power deposition

→ Updated studies with GEANT4 for latest layout suggests that synchrotron backgrounds may not be a problem – work in progress



Sync photon energy [MeV]



Mike Sullivan

Position Sensitive Detectors

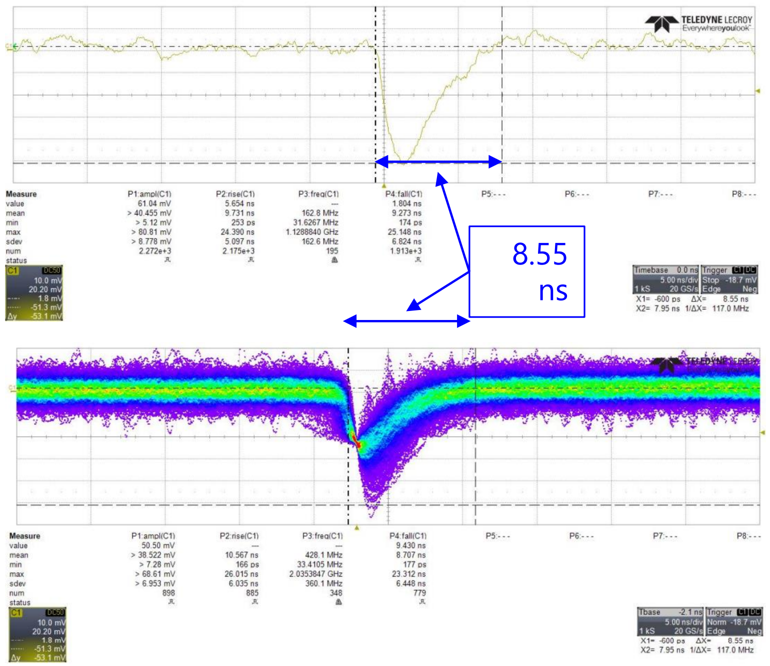
- Requirements for position sensitive detectors
  - Radiation hard
  - Fast response (needed for bunch-by-bunch measurements)
  - High granularity (down to 25 μm pitch)

Size determined by 5 GeV hit distributions, segmentation by 18 GeV distributions

Diamond strip detectors have been used successfully at JLab in Compton polarimeters

→ No performance degradation after 10 Mrad dose during Q-Weak experiment @ JLab

→ Intrinsic time response is fast, but small signals require significant amplification – custom electronics/ASIC will be required

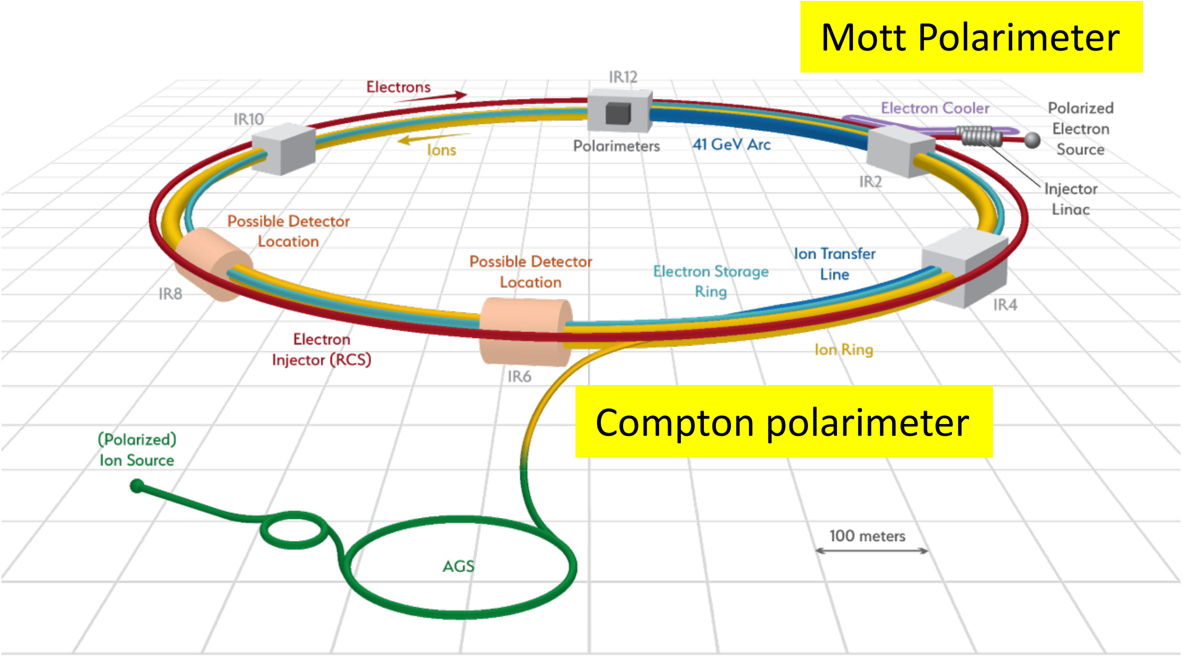


500 μm pCVD diamond w/TOTEM electronics

Polarimetry at RCS

EIC electrons: source to storage ring

1. Ga-As polarized electron source→ Mott polarimeter
2. Low energy transfer line (0.4 MeV)
3. Electron linac (400 MeV)
4. Rapid Cycling Synchrotron (0.4-18 GeV)
5. High energy transfer line to ESR (5-18 GeV)
6. ESR → Compton polarimeter



RCS is a Key location to check beam polarization

→ High polarization verified at source w/Mott polarimeters

→ Polarization measured in ESR with Compton polarimeter

→ If low polarization observed at Compton, difficult to isolate problem location

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Polarimetry for RCS

RCS properties

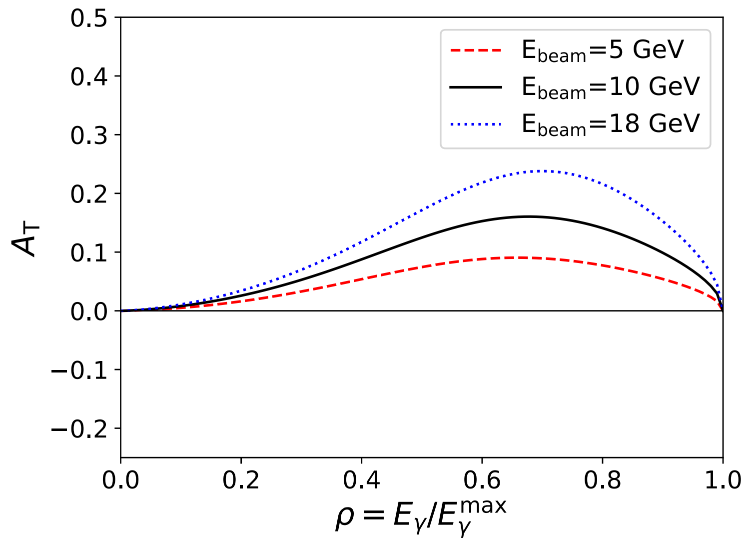
- RCS accelerates electron bunches from 0.4 to full beam energy (5-18 GeV)
- Bunch frequency → 2 Hz
- Bunch charge → up to 28 nA
- Ramping time = 100 ms

Polarimetry challenges

- Analyzing power often depends on beam energy
- Low average current
- Bunch lifetime is short

Options

- Compton polarimeter in RCS
  - Analyzing power depends on energy ✗
  - Measurement times for a single bunch on the order of minutes (too long) ✗
- Møller in RCS
  - Analyzing power nearly constant ✓
  - Requires spectrometer ✗
  - Destructive ✗
- Measurement in RCS → ESR transfer line



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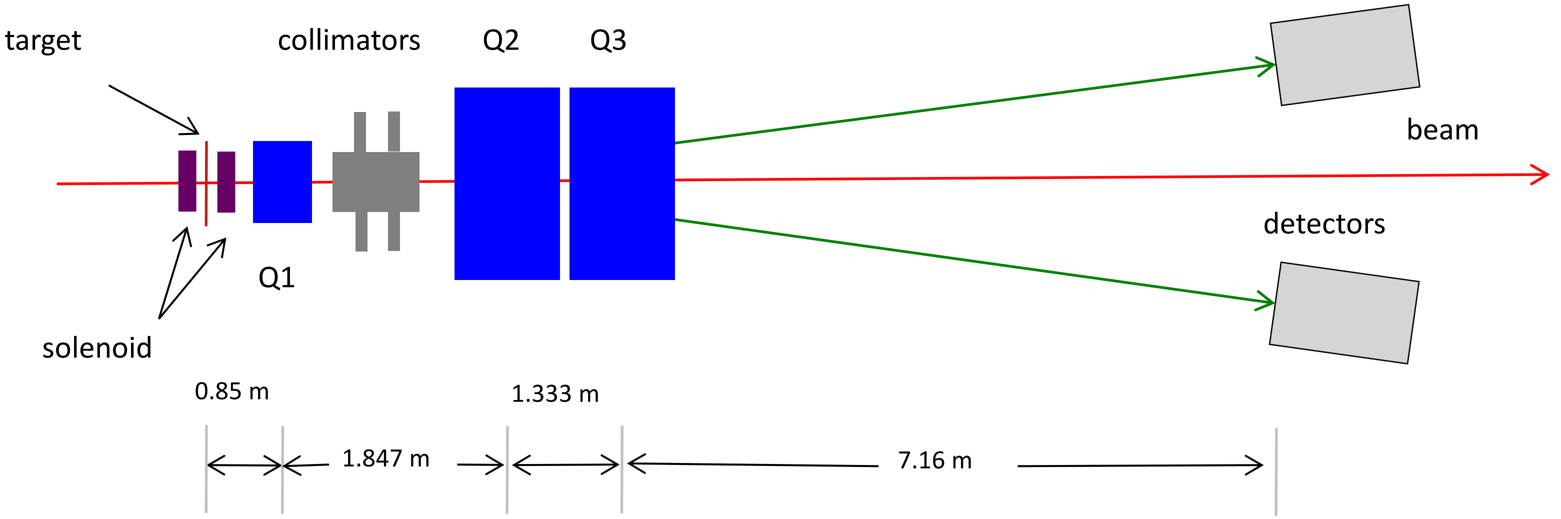
Measurement Time

In general, Møller measurements faster than Compton
→ Destructive measurements OK for dedicated polarization checks



Time estimates scaled from experience in Hall C @11 GeV
→ 15 minutes for 1% measurement of P_L at 1 μA, 4 μm iron target

RCS: average (extracted) current ~ 56 nA (28 nC bunch at 2 Hz)
→ Transverse analyzing power smaller by factor of 7, ***figure of merit worse by factor of 49***
→ Time estimate for 1% measurement of beam from RCS: 15 min * (1/0.056) * 49 = too long
→ ***Thicker foil (30 μm), reduced precision (10%): Measurement time = 17.5 minutes***

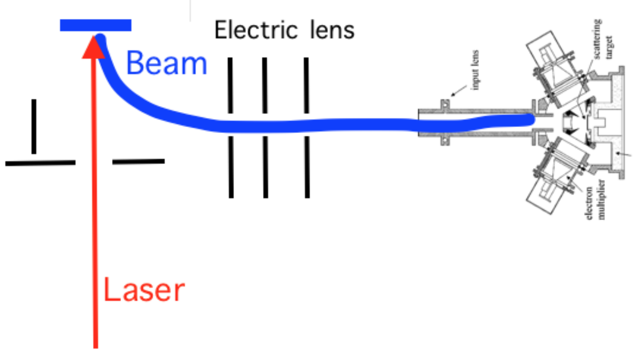
Some discussion of running at larger bunch charge for these measurements

Mott Polarimetry at EIC

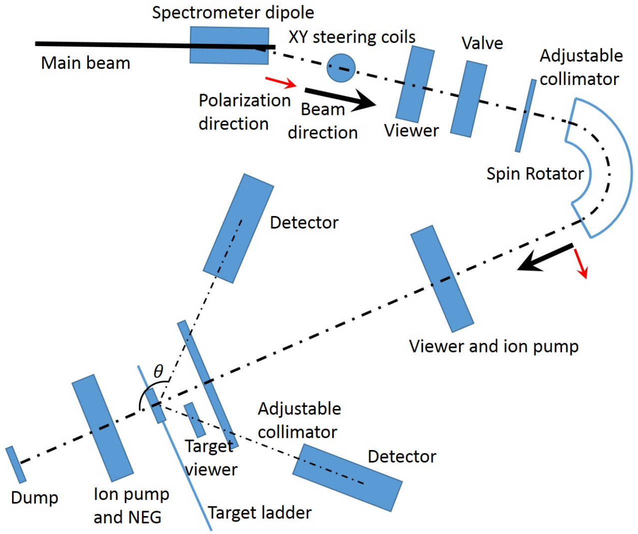
EIC will make use of two Mott polarimeters to measure the electron polarization from the source

1. Low voltage Mott polarimeter
→ Measure polarization at 20 keV immediately after photocathode

2. High voltage Mott polarimeter
→ Measure at 300 keV, in the beamline, before electron bunching
→ Requires spin rotator to change electron from longitudinal to transverse spin



Low voltage Mott polarimeter



High voltage Mott polarimeter

Summary (Part 2)

- EIC will require multiple polarimeters and techniques to fully characterize electron beam polarization throughout the accelerator complex (source → ESR)
- Compton polarimeter will be primary device used by experimenters
  - Mott and RCS polarimeter also important, but precision can be somewhat more relaxed
- EIC Compton design in progress
  - Location determined
  - Laser and detector technologies consistent with required performance have been identified, but options are still being explored
  - Still work to be done on integration with beamline, background studies