Electron Polarimetry

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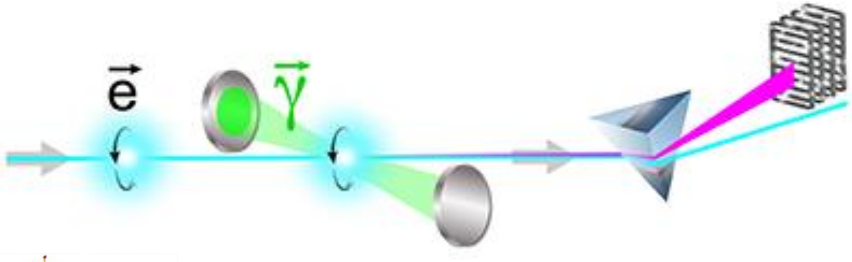

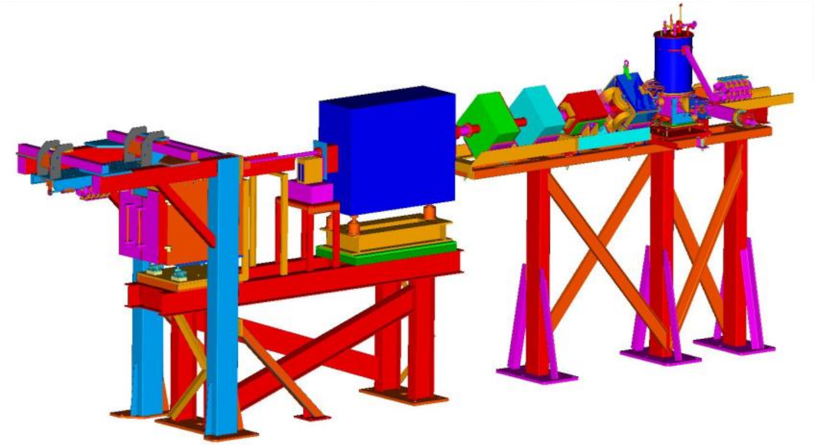

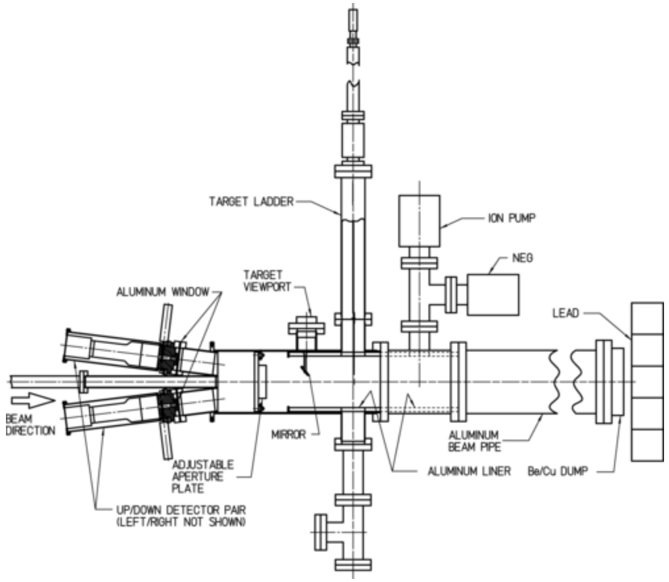

PSTP 2024

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Outline

- Introduction
- Common Electron Polarimetry Techniques
    - Mott Polarimetry
    - Møller Polarimetry
    - Compton Polarimetry
    - Analyzing power, advantages/disadvantages, examples for all the above
- Summary

Electron Beam Polarimetry

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

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

$A_{\mathrm{effective}}$ 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 (https://doi.org/10.1016/0168-9002(84)90119-0)
- Compton transmission polarimetry (https://doi.org/10.1016/j.nima.2024.169224)

Introduction – Towards 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%
- Future **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%

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

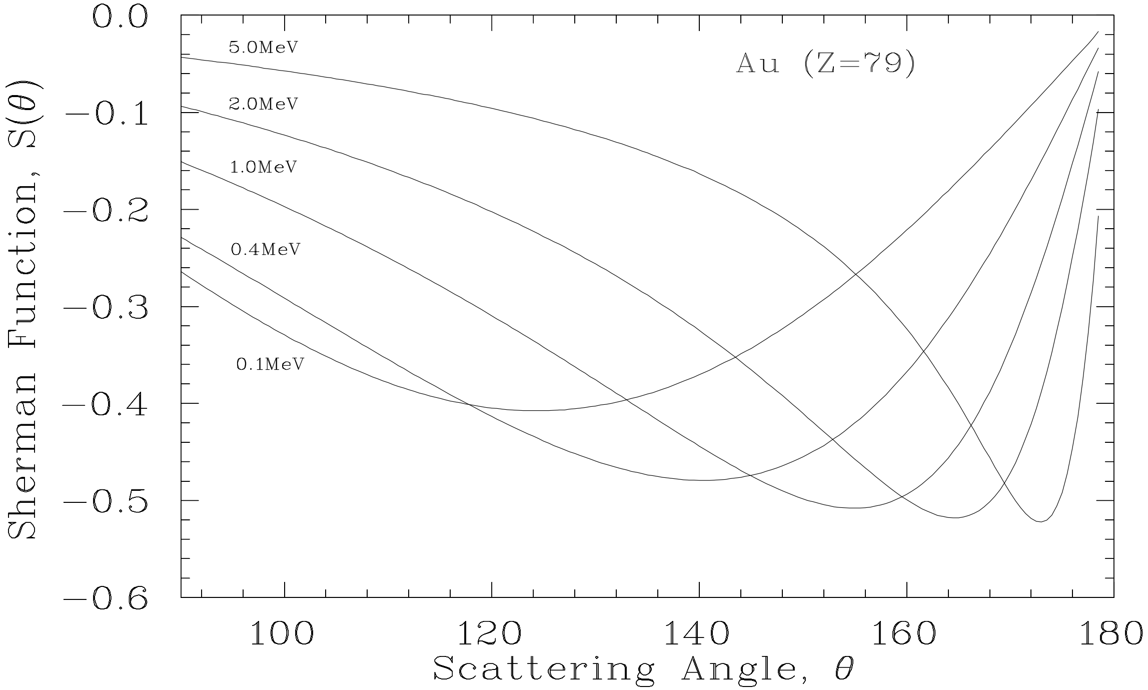
→ ~ 100 keV to 5 MeV

→ 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

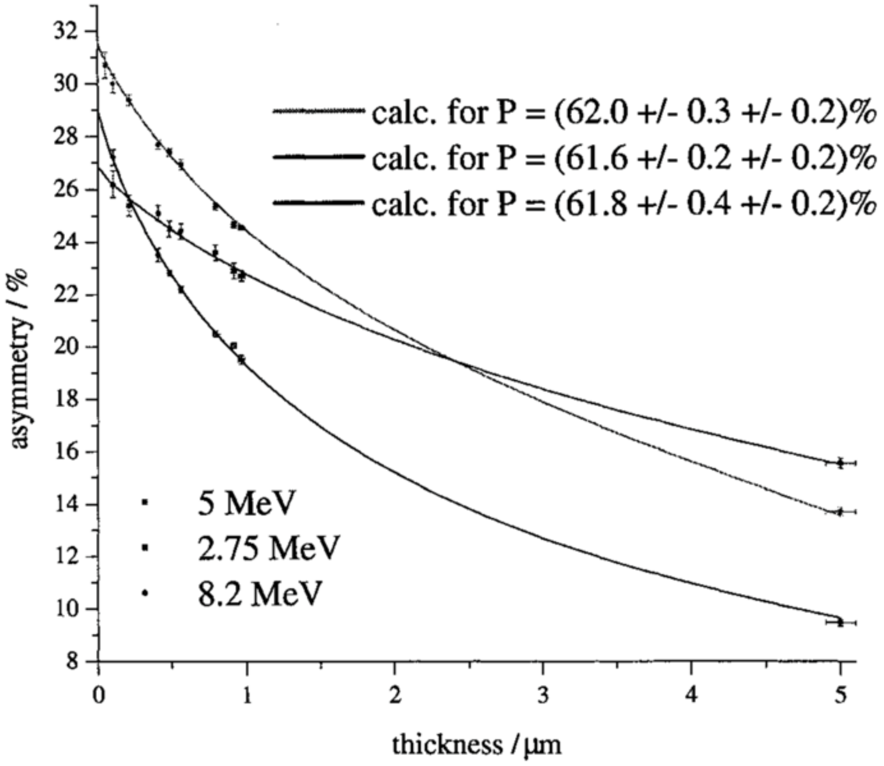
$$S(\theta) = i\frac{fg^* - gf^*}{f^2 + g^2}$$

Spin flip amplitude

Direct 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

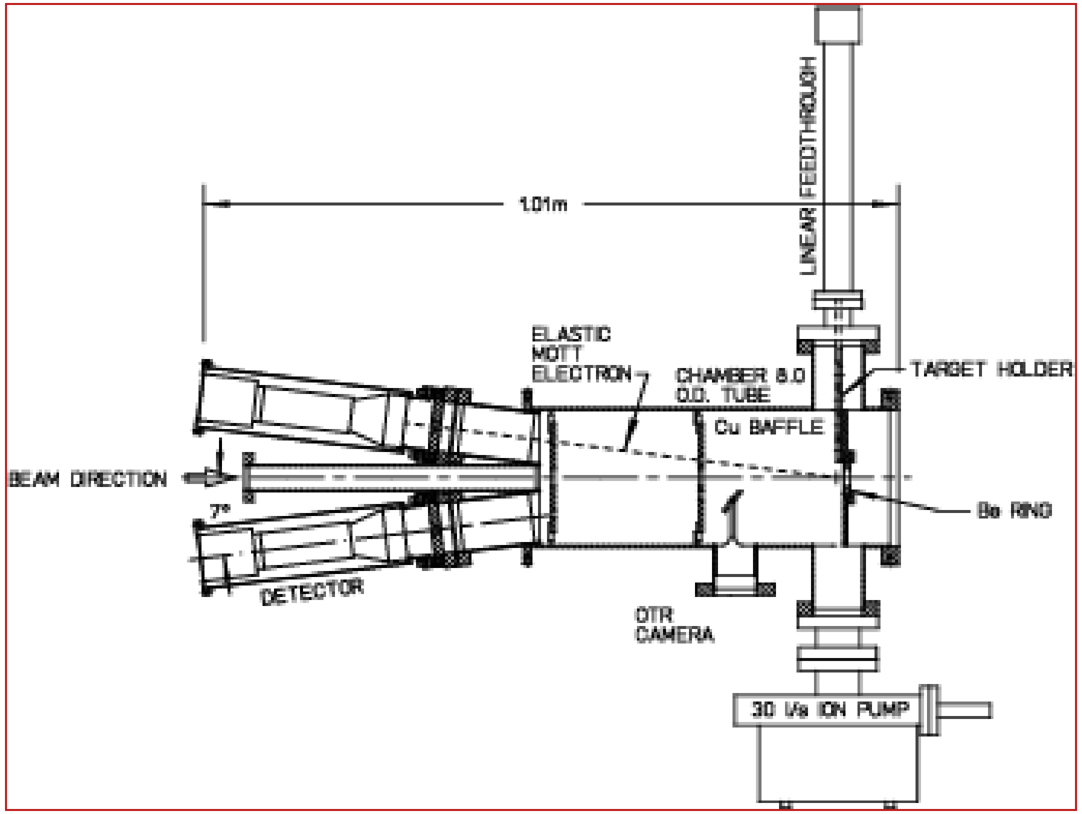


Finite thickness, electron may scatter more than once → Effective Sherman function
→ Measure at various foil thicknesses, extrapolate to zero

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 mm 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

Møller Scattering

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

Longitudinally polarized electrons/target:

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

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

→ At θ^*=90 deg. → -7/9

Transversely polarized electrons/target

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

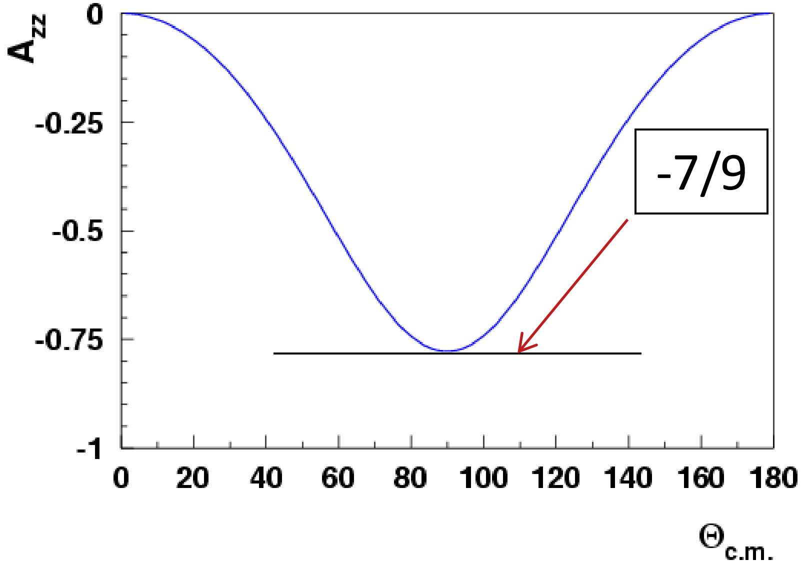
→ At θ^*=90 deg. → -1/9

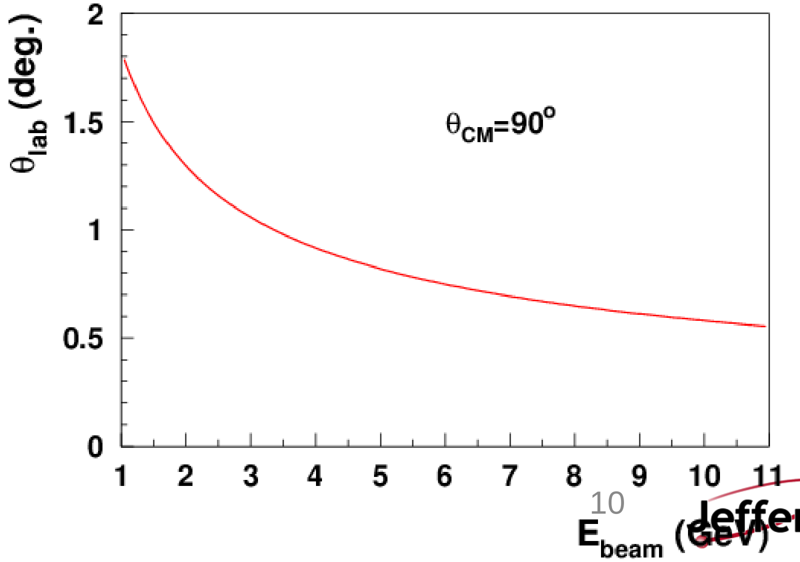
Maximum asymmetry independent of beam energy

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

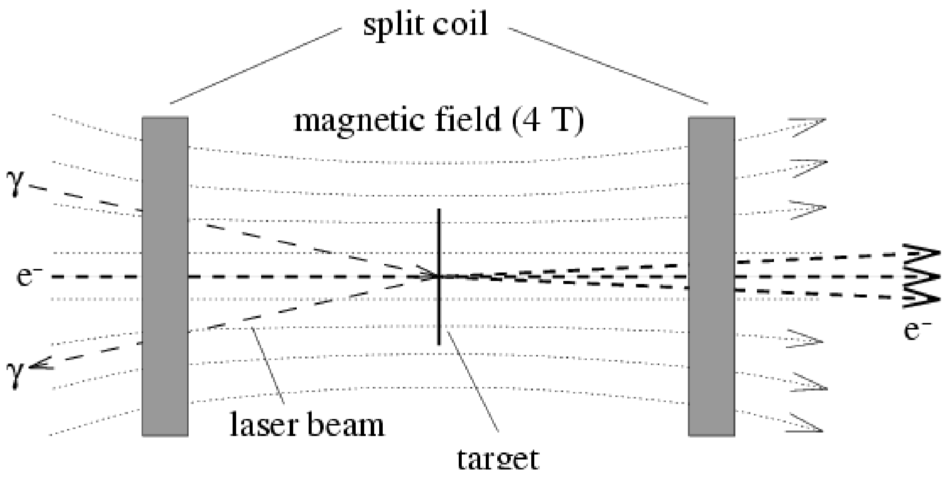
$$\vec{e}+\vec{e}\rightarrow e+e$$





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

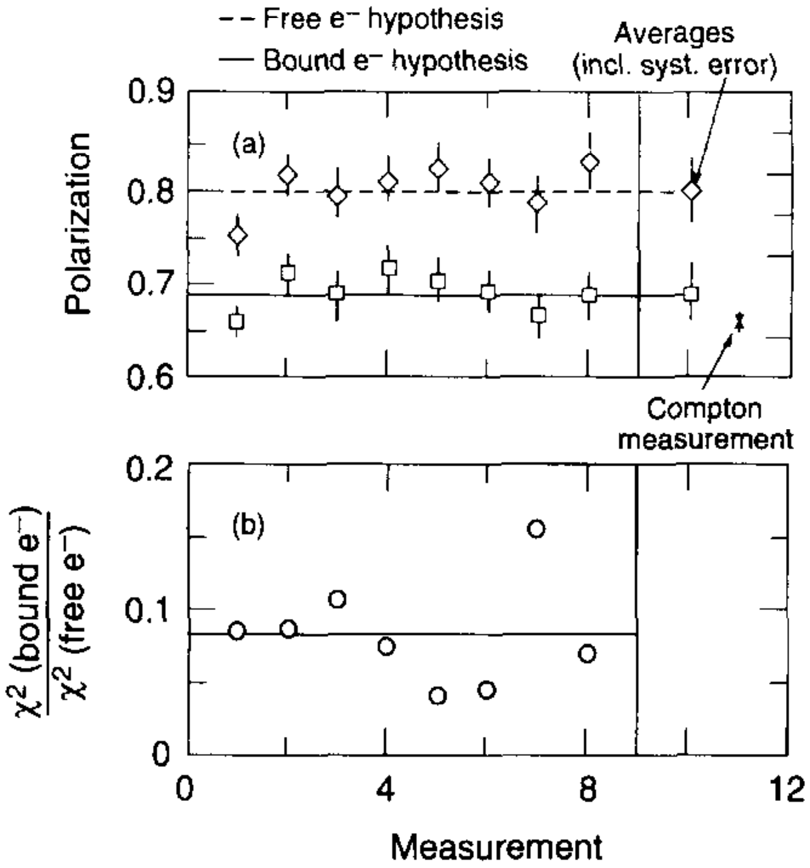


Effect	$M_s[\mu_B]$	error
Saturation magnetization (T→0 K,B→0 T)	2.2160	±0.0008
Saturation magnetization (T=294 K, B=1 T)	2.177	±0.002
Corrections for B=1→4 T	0.0059	±0.0002
Total magnetization	2.183	±0.002
Magnetization from orbital motion	0.0918	±0.0033
Magnetization from spin	2.0911	±0.004
Target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

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

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

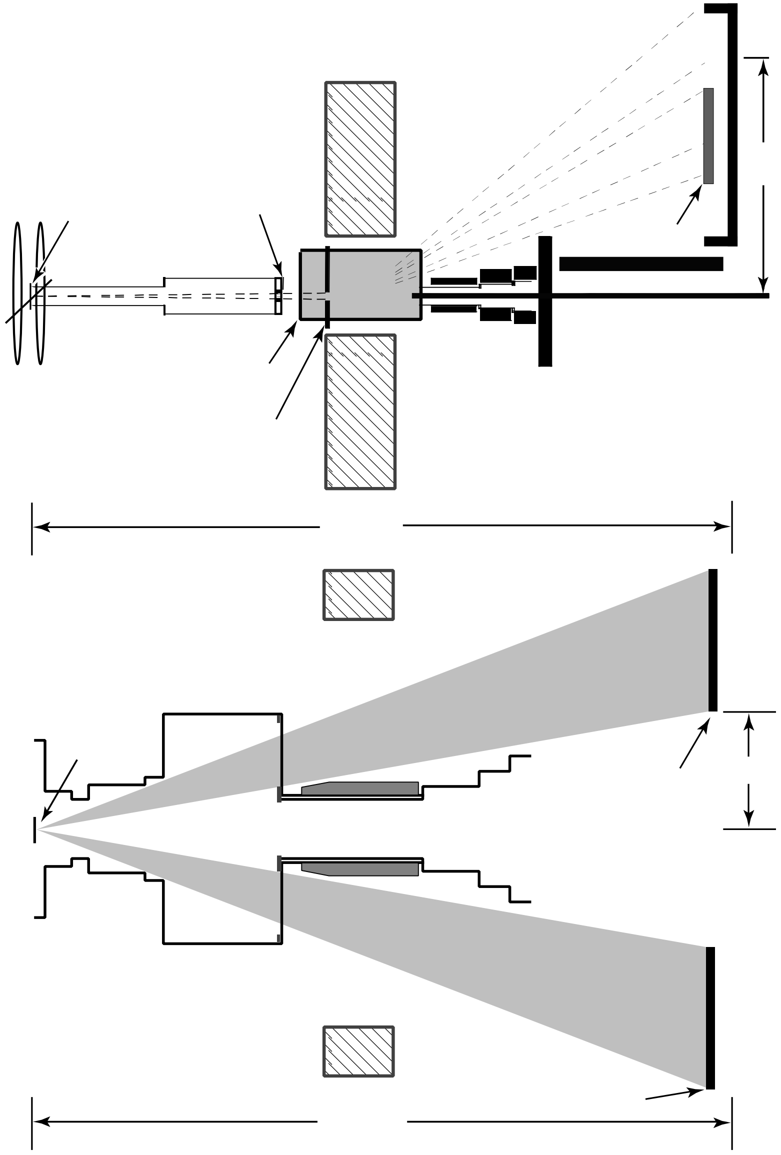


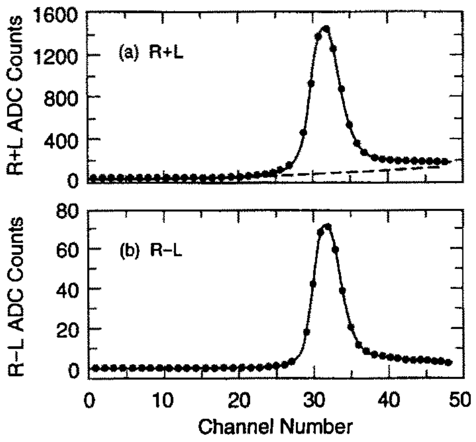
M. Swartz et al., Nucl. Instrum. Meth. A363 (1995) 526

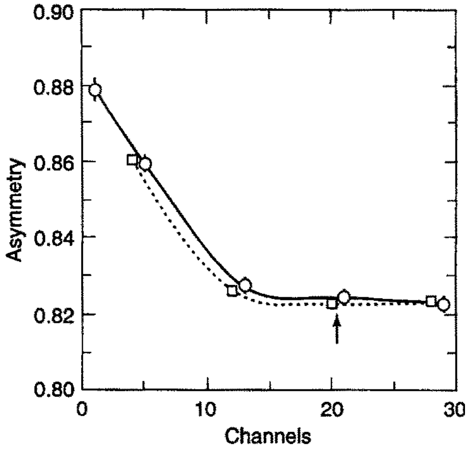
SLAC E154 Møller Polarimeter

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%)

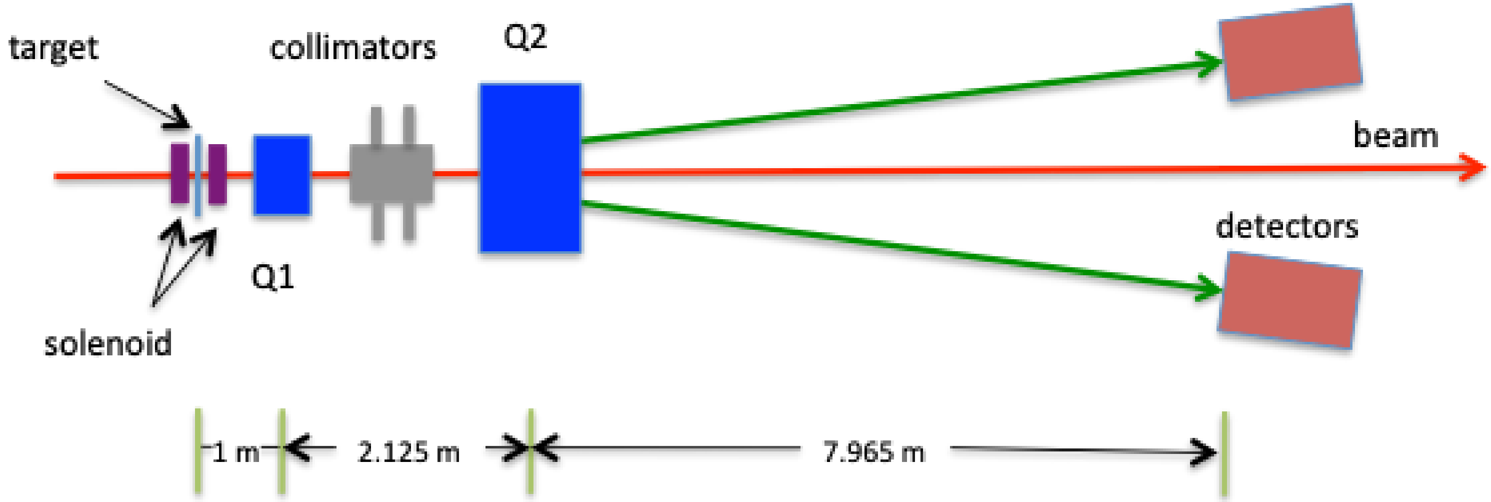






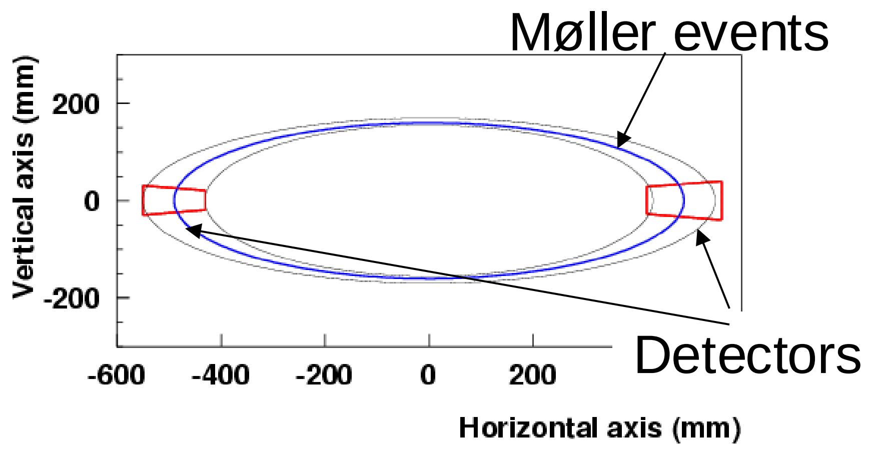
Hall C Møller Polarimeter at Jefferson Lab

- 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]*

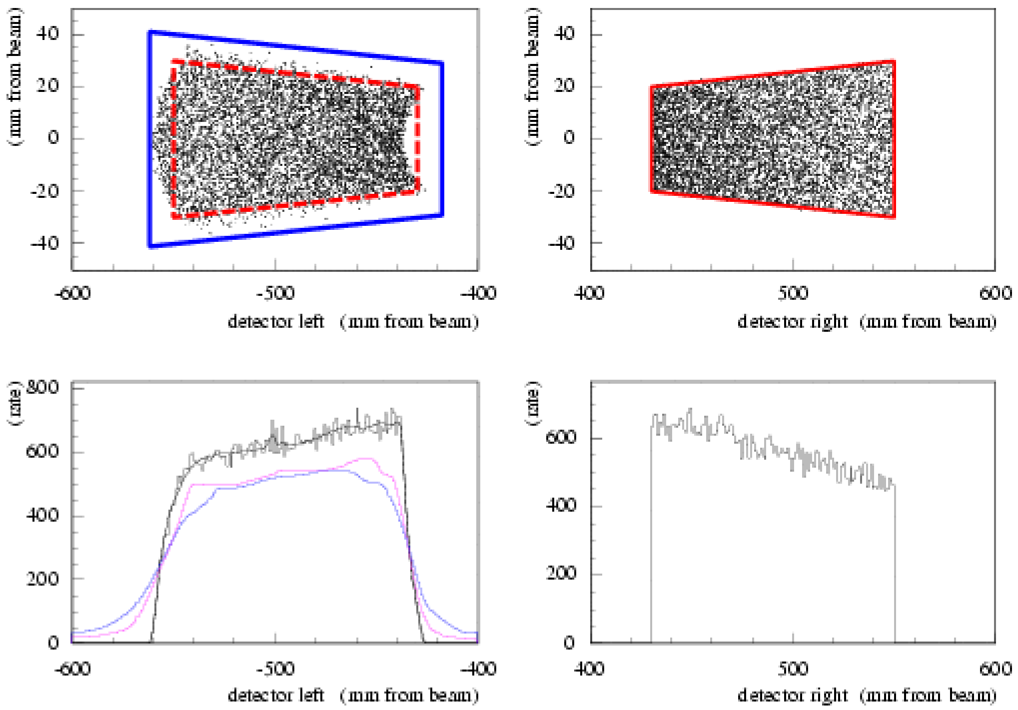


Hall C Møller Acceptance

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


Møller events

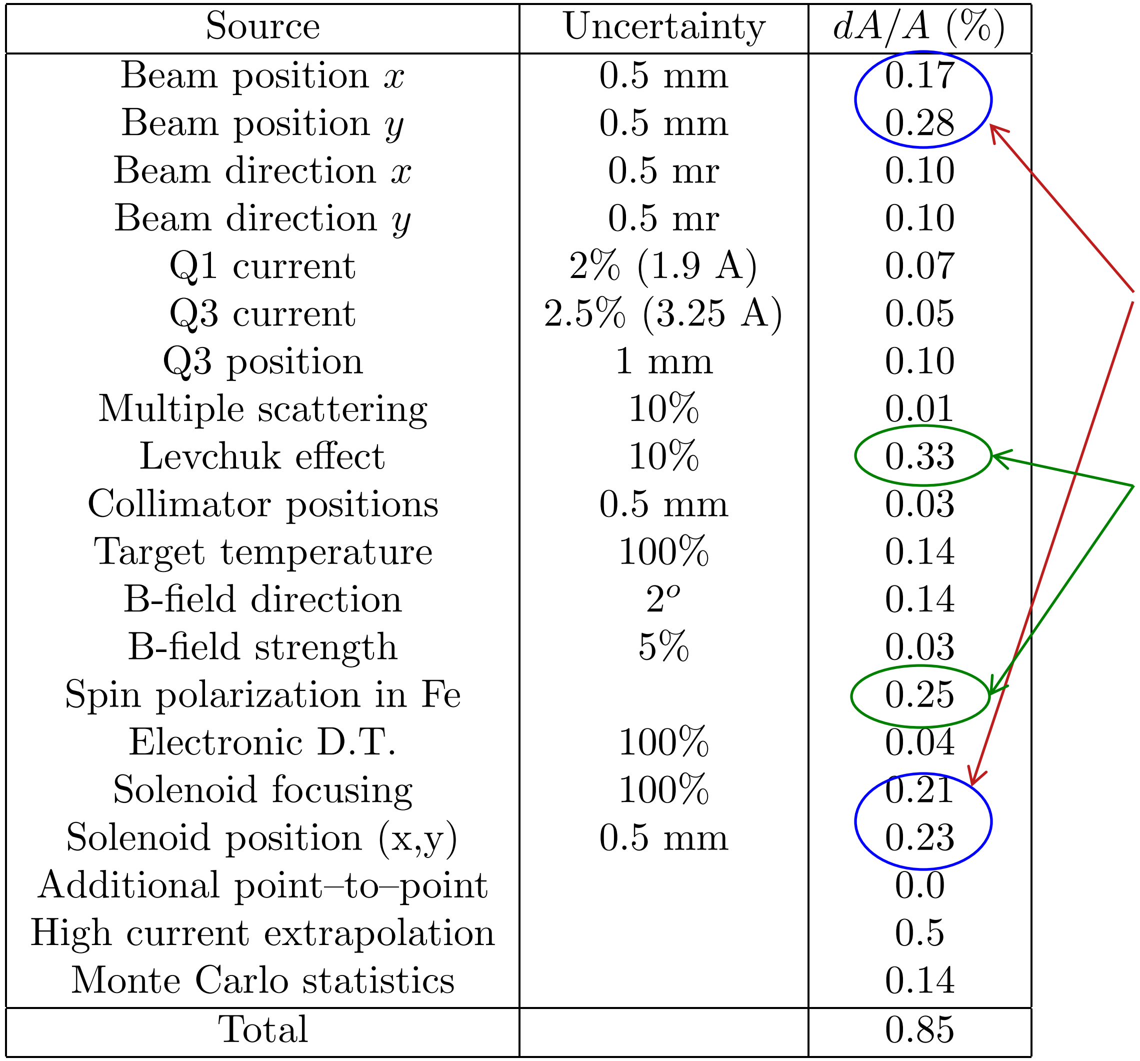
Detectors



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

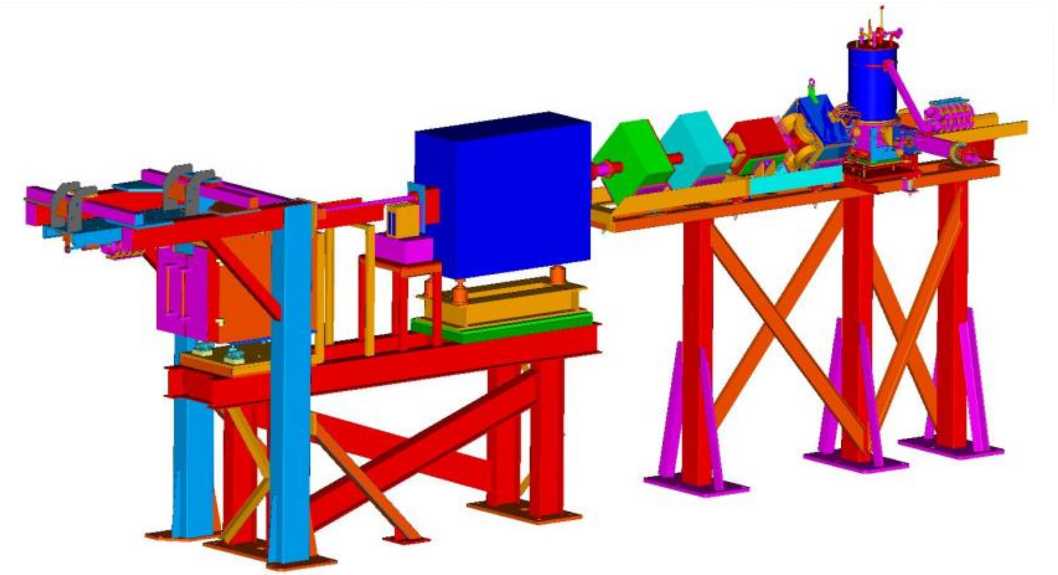
Total uncertainty less than 1%

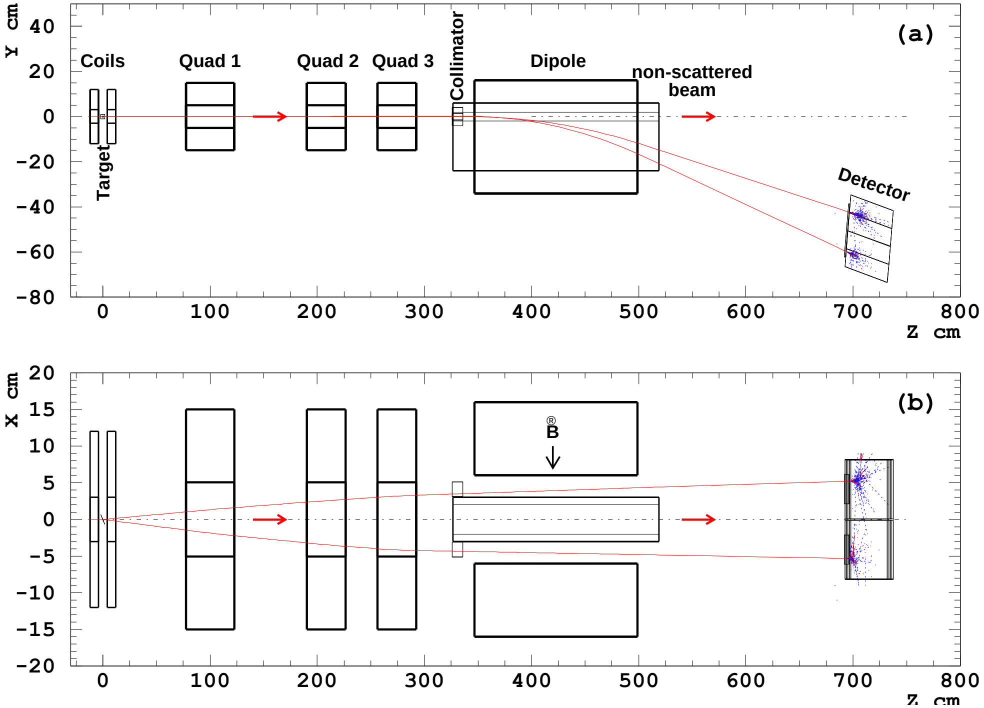
Hall A Møller Polarimeter at Jefferson Lab

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

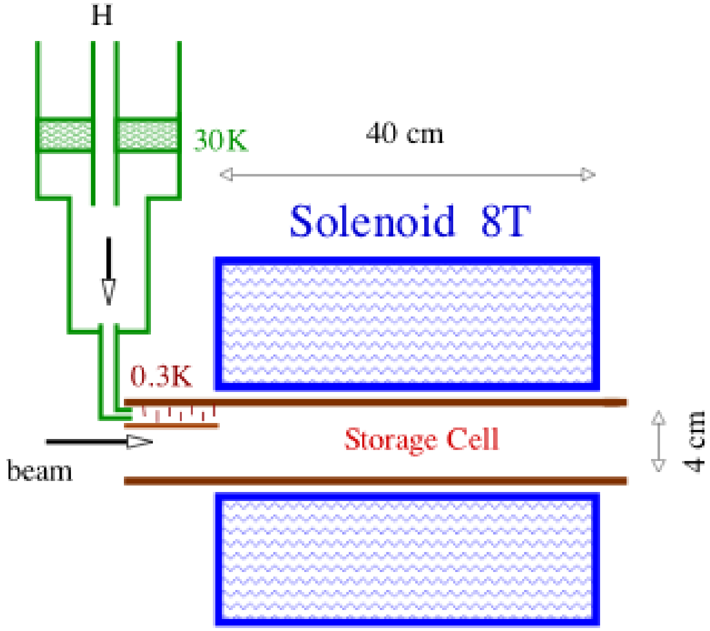
→at 300 mK, 8 T, P_e ~ 100%

→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



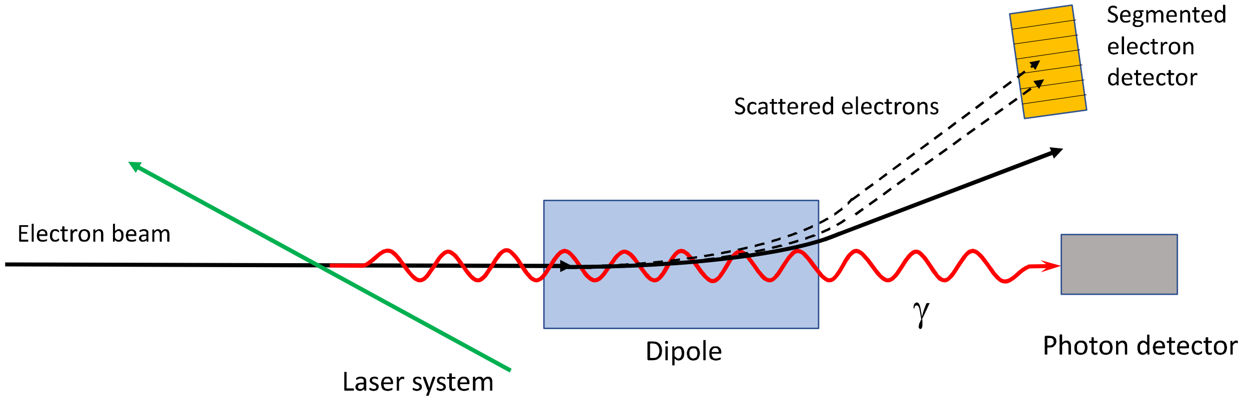
Application in storage rings?

→ Gas heating by radiation drops density

→Beam creates fields that may trap positive ions

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

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%
JLab Hall A	2 GeV	0.36%

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

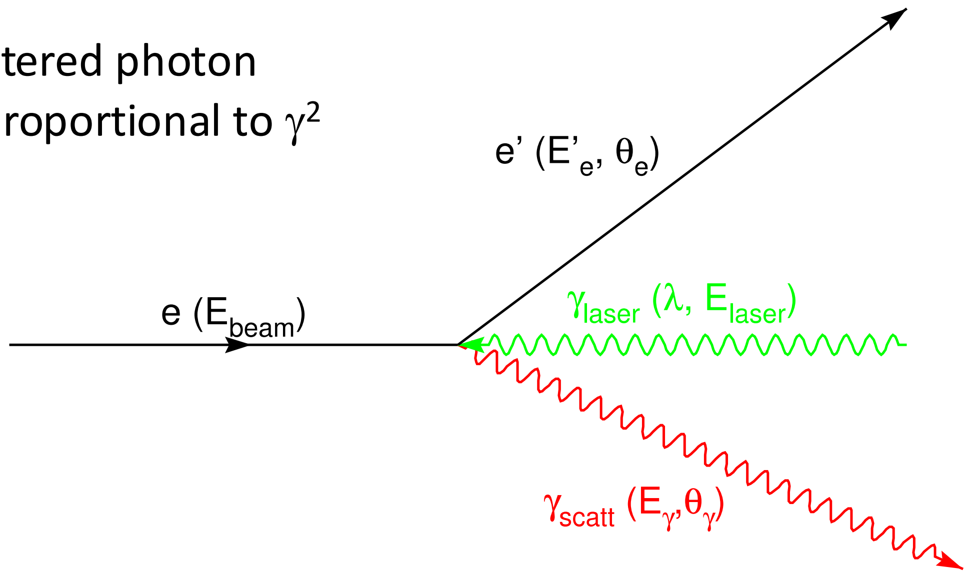
Compton Scattering - Kinematics

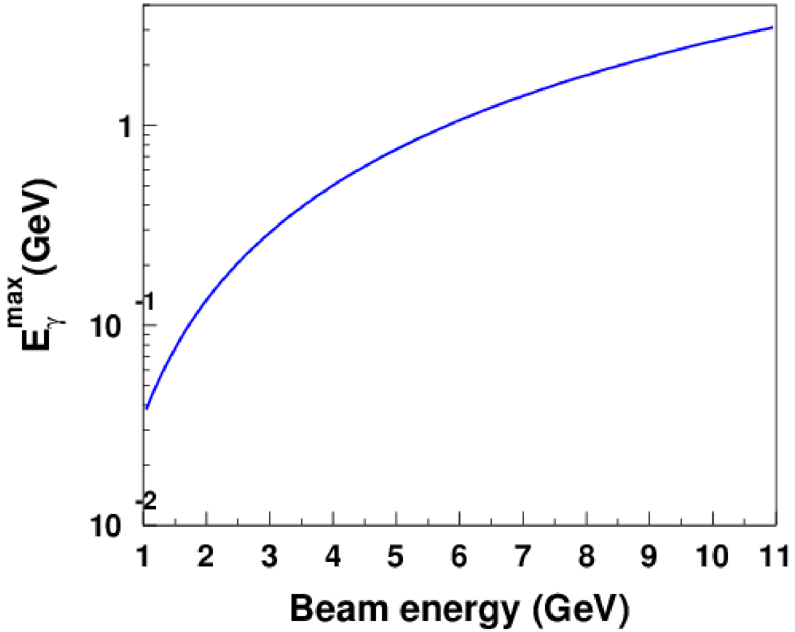
Laser beam colliding with electron beam nearly head-on

Backscattered photon
Energy proportional to γ^2

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

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





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

For green laser (532 nm):

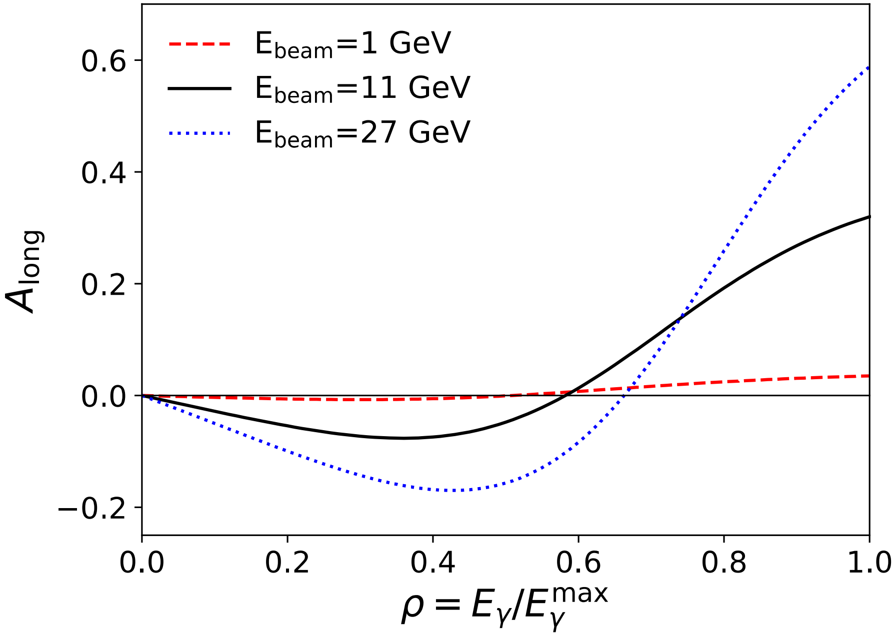
→E_γ^{max} = 34.5 MeV at E_{beam}=1 GeV
→E_γ^{max} = 3.1 GeV at E_{beam}=11 GeV

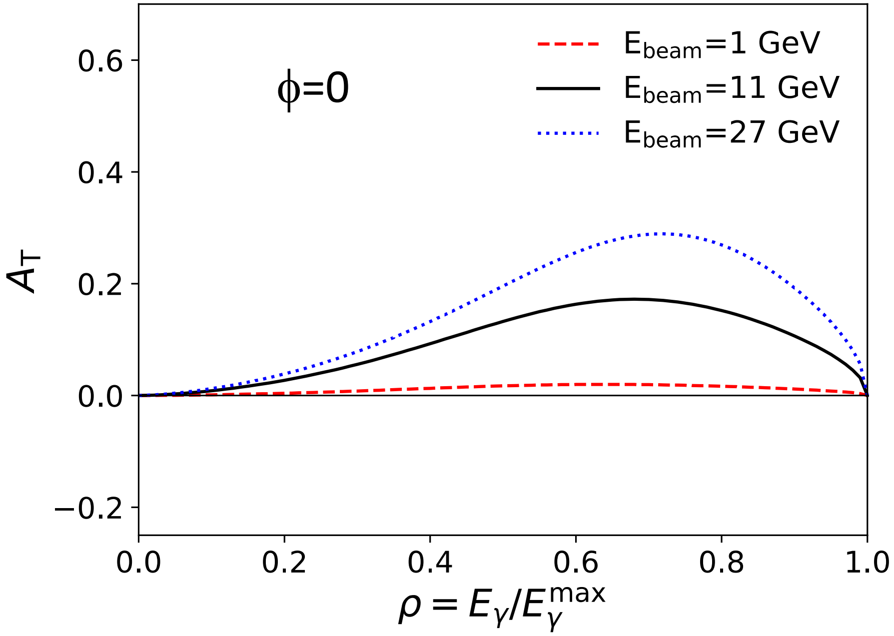
Polarization Measurement via Compton Polarimetry

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

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

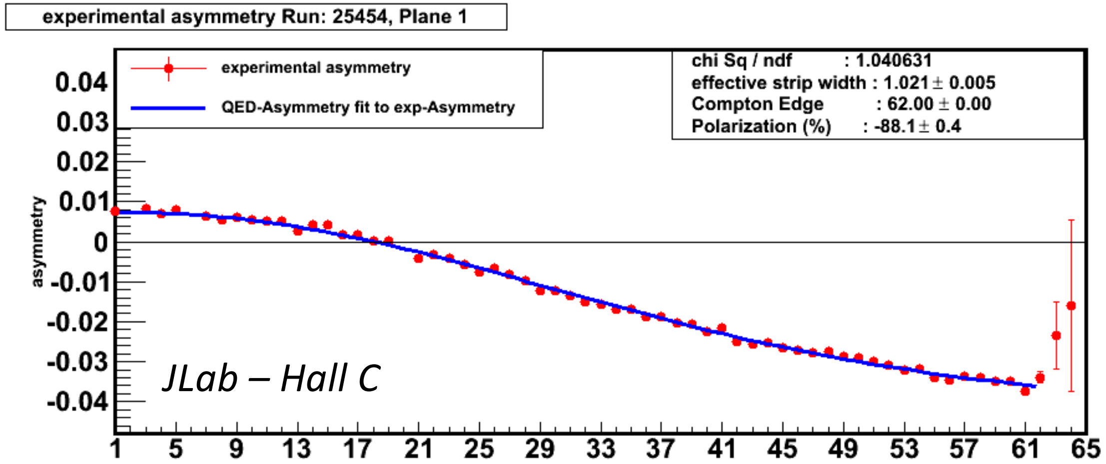
$$A_{\text{T}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}\cos\phi\left[\rho(1-a)\frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))}\right]$$





Polarization Measurement via Compton Polarimetry

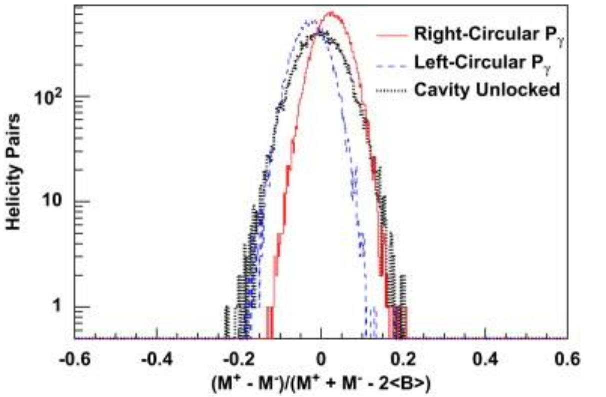
Longitudinal polarization measured via counting asymmetry vs. energy, or energy-integrated asymmetry



JLab – Hall C

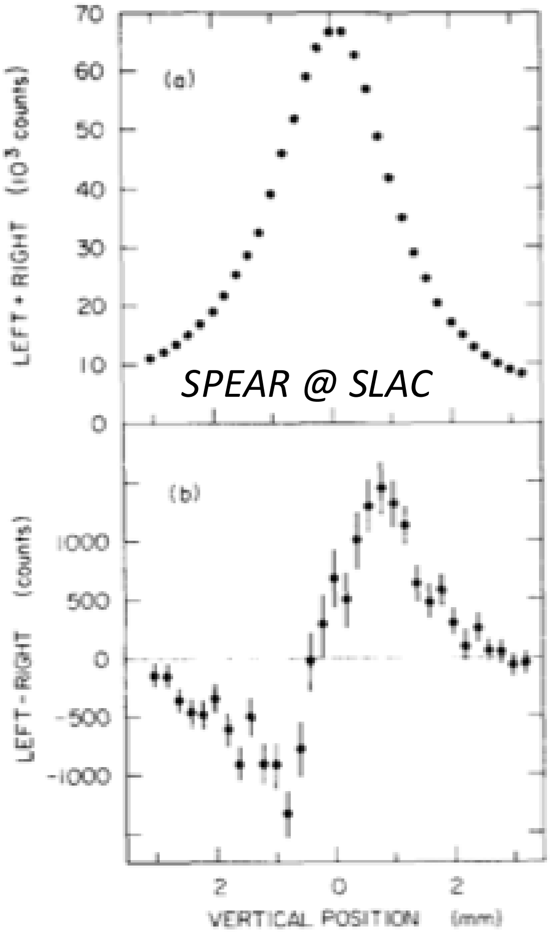
Detector strip # → Scattered electron energy

Photon-energy weighted asymmetry



JLab – Hall A

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

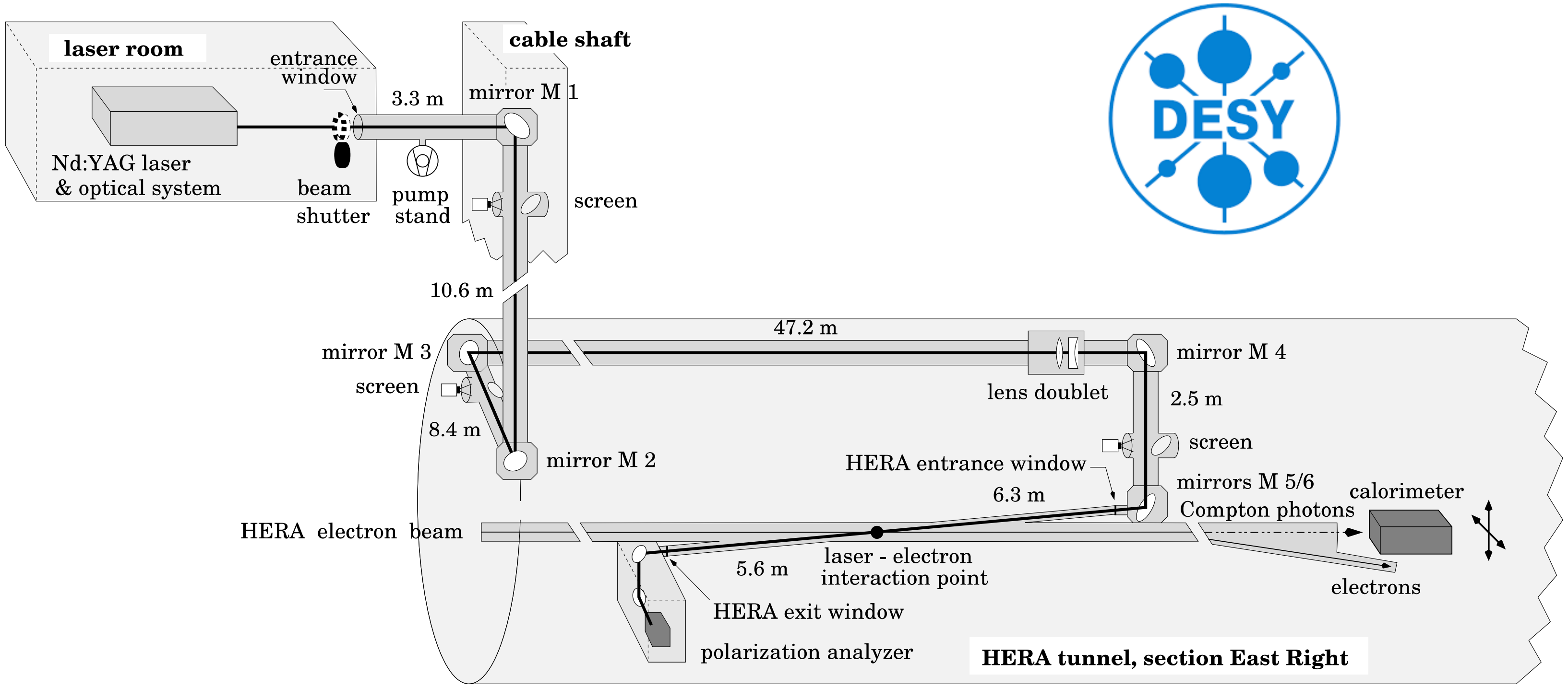


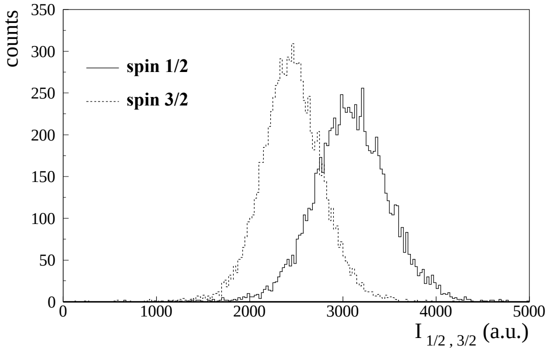
SPEAR @ SLAC

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





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

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

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

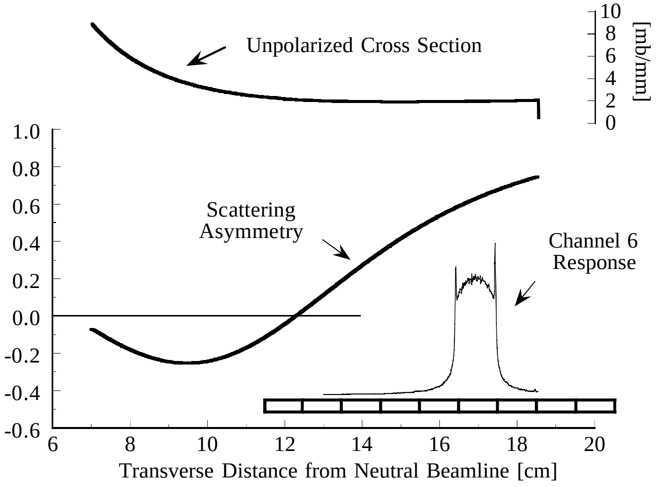
SLAC SLD Compton Polarimeter

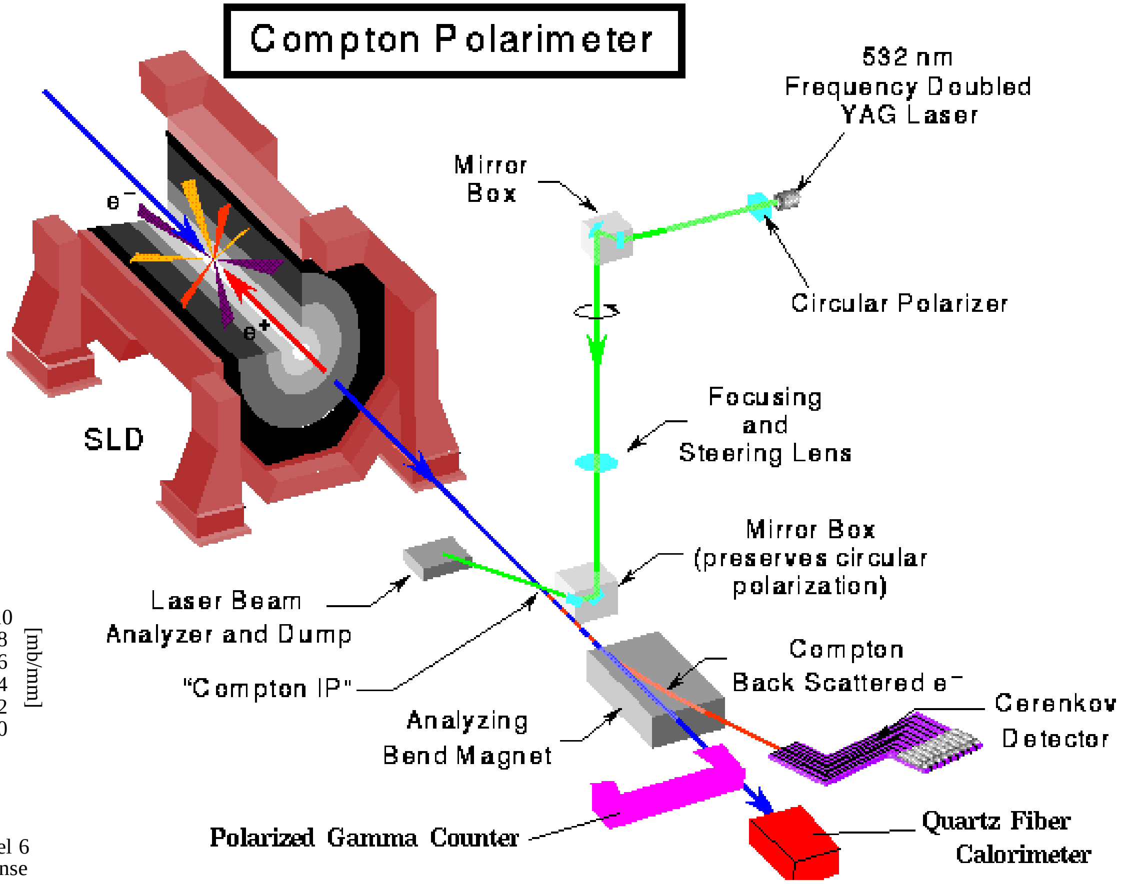
Highest precision achieved with Compton polarimetry → dP/P = 0.5%

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

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

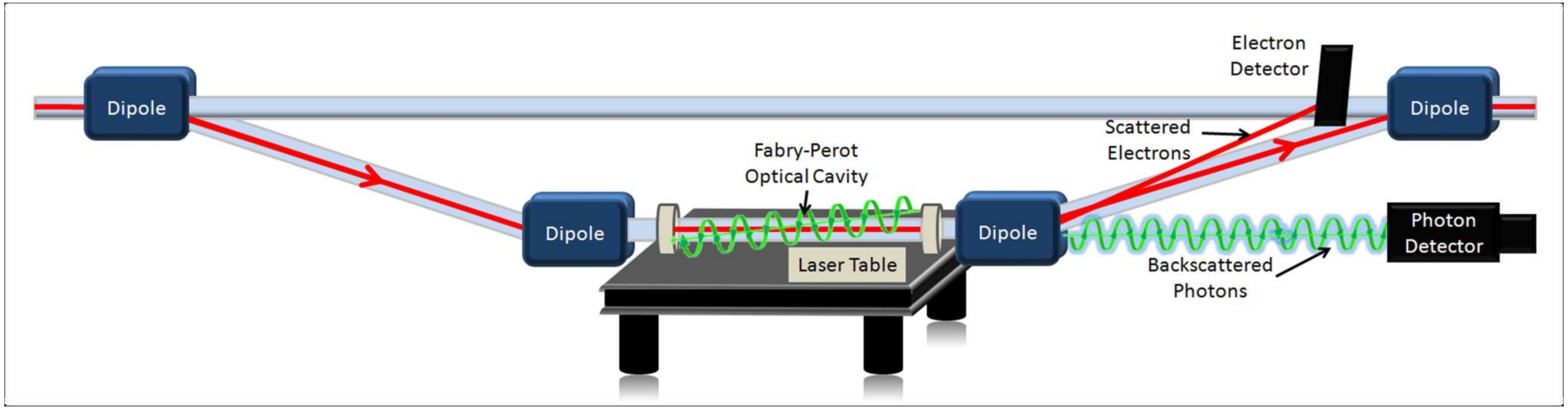
Multichannel gas Cherenkov detector → electrons ~ 10 cm from nominal beam path





M. Woods - SLAC-PUB-7319

Compton Polarimeters in Halls A and C at Jefferson Lab



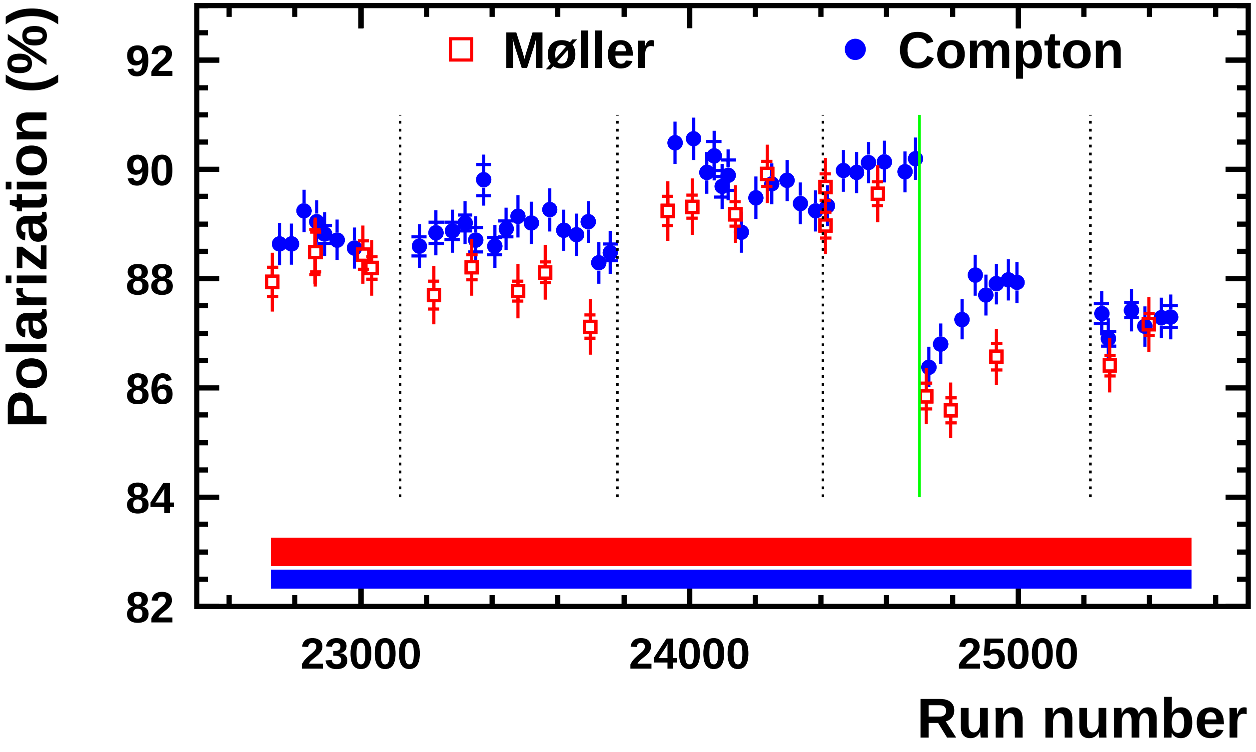
Compton polarimeters in Hall A and C:

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)

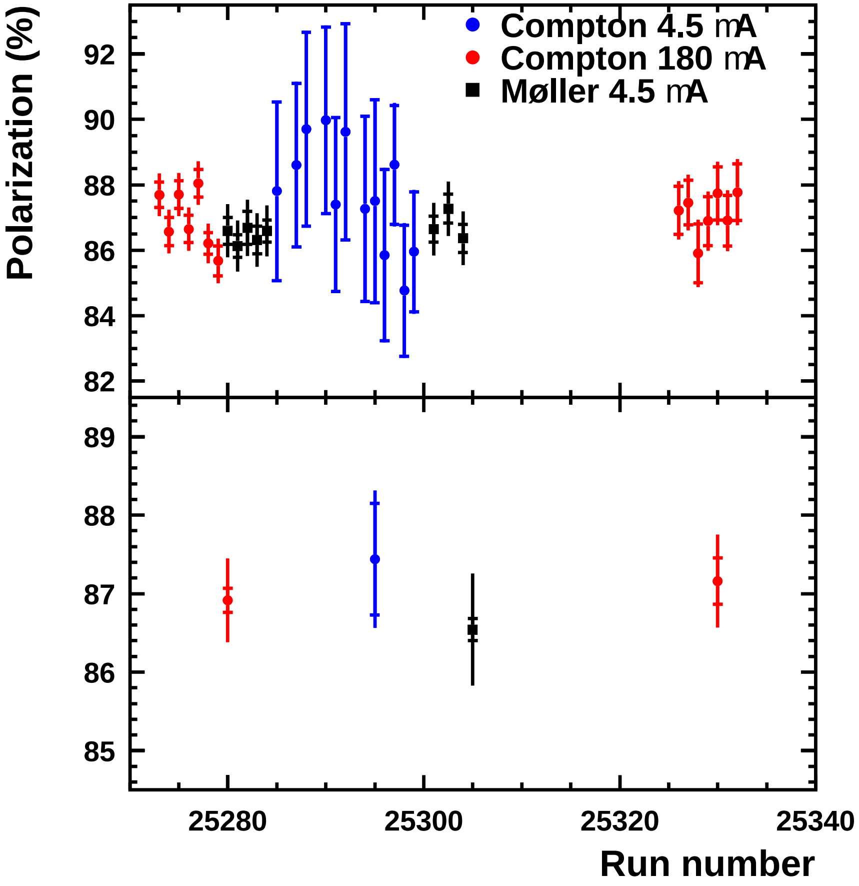
→ Hall A has achieved dP/P=0.36% (photon detection)

Polarimeter Comparisons: Hall C Møller and Compton



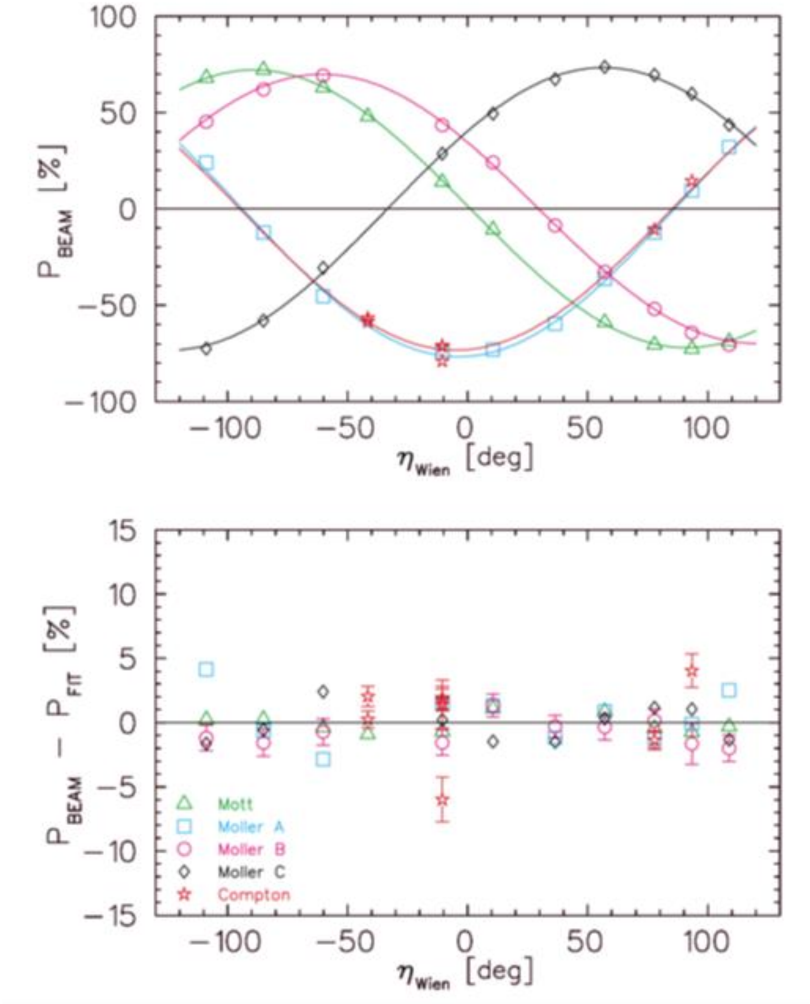
Compton measurements at 180 μA concurrent with experiment

Møller measurements taken intermittently, at 1 μA



Dedicated test with both Møller and Compton at 4.5 μA

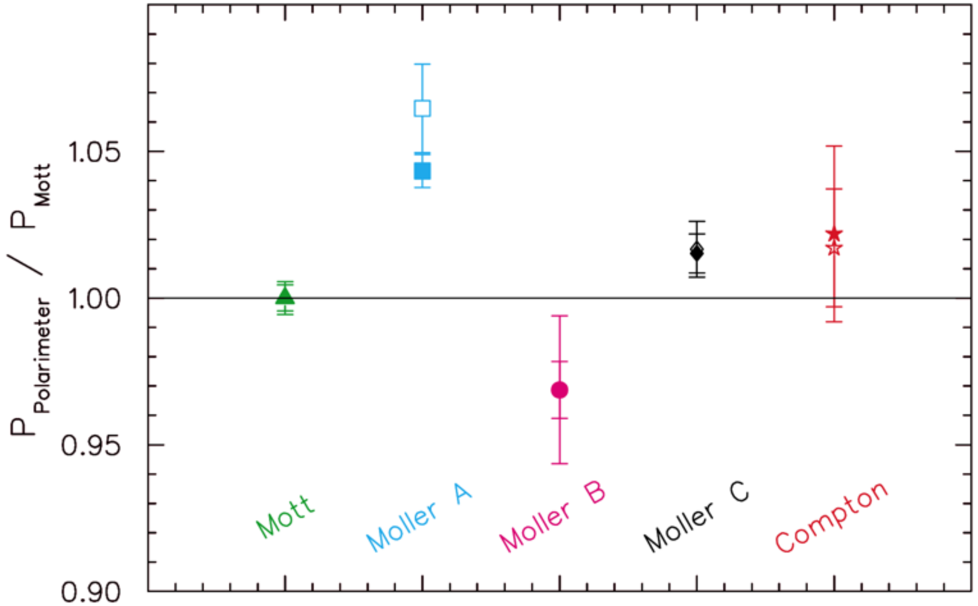
Jefferson Lab Polarimeter Comparisons: Spin Dance



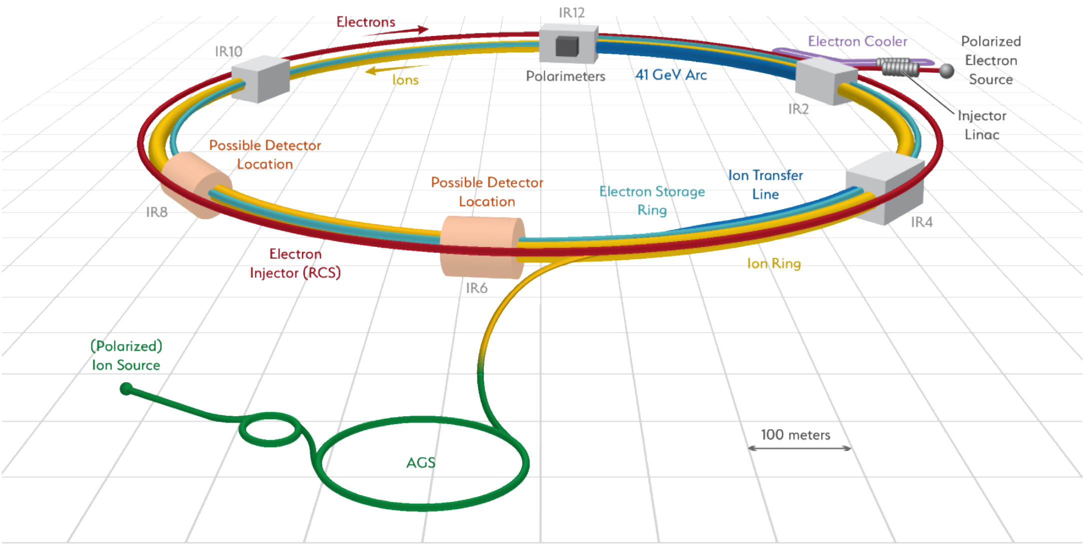
Compared electron polarimeters in Halls A, B, C by taking measurements at several Wien angles – compare maximum polarization

→ Discovered unexpected systematic in Hall A Møller

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



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

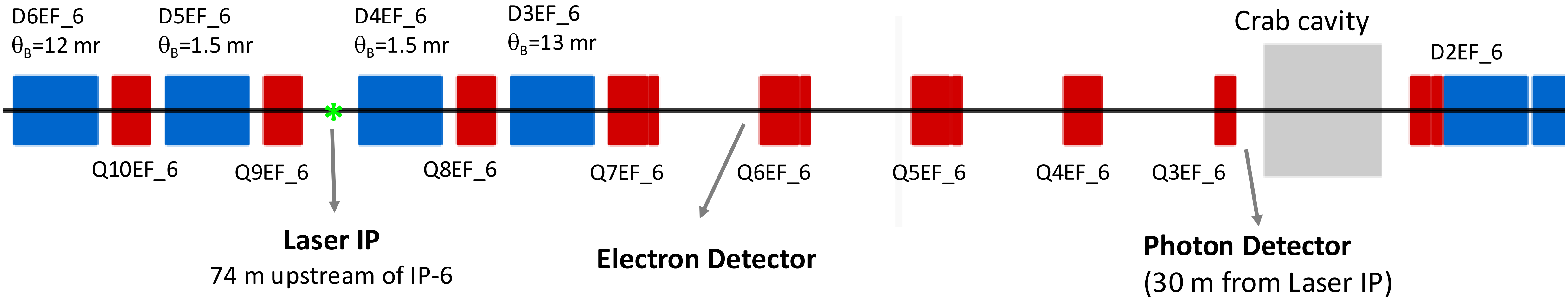
Electron-ion collider in U.S. → Highly polarized electron and proton/light ion beams and high luminosities

→ Physics measurements will have high statistical precision. Excellent control of systematic uncertainties needed to fully leverage potential of the EIC

→ Precise polarimetry (both electron and hadron) will be important

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

Compton Polarimetry at EIC



Laser IP
74 m upstream of IP-6

Electron Detector

Photon Detector
(30 m from Laser IP)

Polarization components at Laser IP

Beam energy	P_L	P_T
5 GeV	99.1%	13.2%
10 GeV	96.5%	26.2%
18 GeV	89.0%	45.6%

Polarimeter Components:

1. RF-pulsed laser system (under development)
2. Position sensitive detectors (diamond strips) for scattered electrons and backscattered photons
3. Calorimeter for backscattered photons

Will operate in single-photon mode

High precision measurement of P_L and P_T required!

Summary

- Several useful techniques for absolute electron polarimetry
  - Mott polarimetry used primarily at/near electron beam injector
  - Møller polarimetry used in fixed-target facilities but could possibly be employed in colliders/rings – R&D would be required
  - Compton polarimetry most commonly employed in colliders, but increasingly useful at relatively low intensity fixed target facilities
- High precision has been achieved with all three techniques discussed here
  - In general, highest precision has been achieved for measuring longitudinal polarization
- Comparison between multiple devices with different systematic errors provides confidence in measurements and improved precision
- EIC will require precise measurements of both electron and hadron polarization
  - Compton polarimeter design for EIC draws on experience from earlier devices
  - EIC Compton polarimeter will need to be able to measure longitudinal and transverse electron polarization simultaneously

Extra

MAINZ MeV Mott

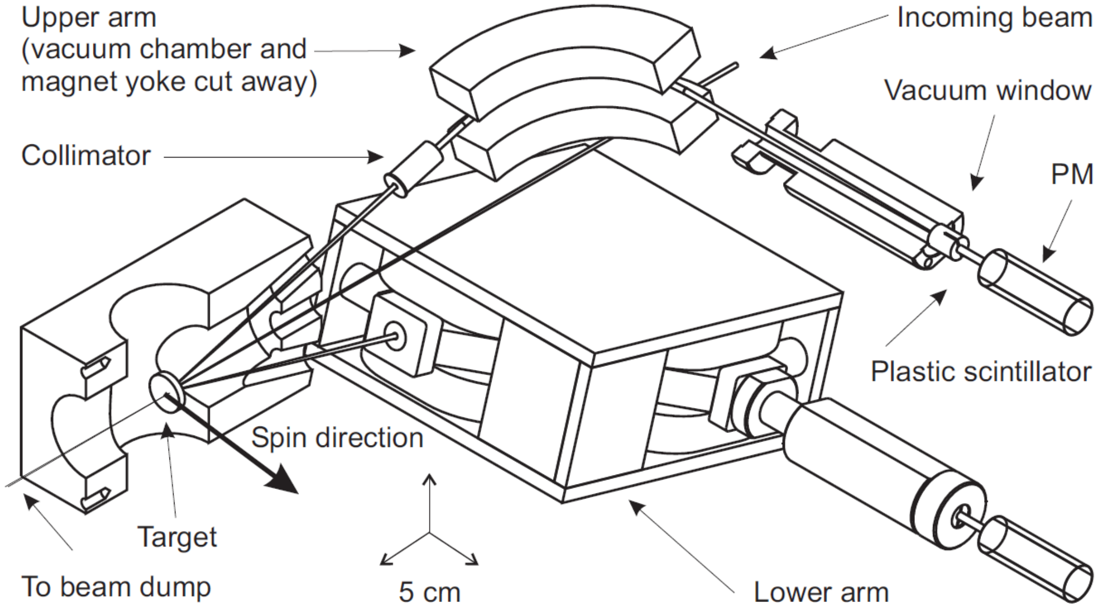
Mott polarimeter in MAMI accelerator at Mainz installed after injector linac

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



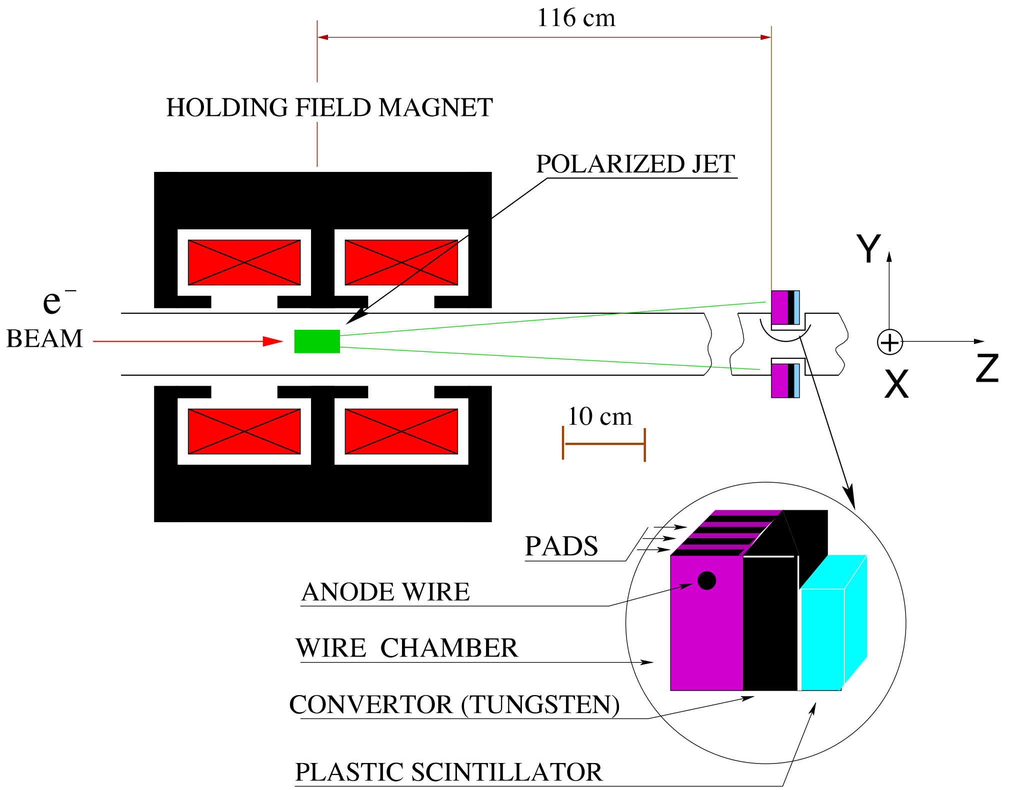
Møller Polarimetry with Jet Targets

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*

Polarization Measurement Times

Luminosity for Compton scattering at non-zero crossing angle:

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

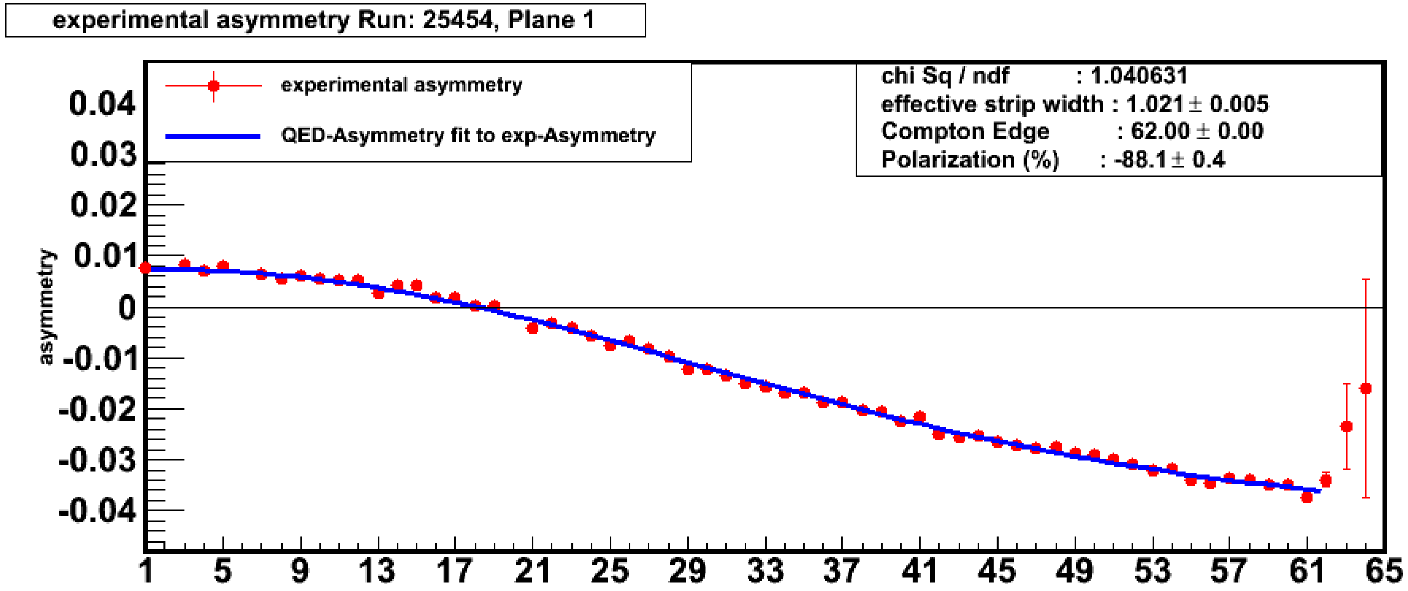
Beam size at interaction point with laser dictates luminosity (for given beam current and laser/electron beam crossing angle)

Time for measurement of precision ΔP/P:

$$t^{-1} \approx \mathcal{L}\sigma \left(\frac{\Delta P}{P}\right)^2 P_e^2 < A^2 >$$

→ Time required for measurement can vary significantly with beam energy due to changing asymmetry
→ Lower energies/beam currents can require novel laser solutions

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

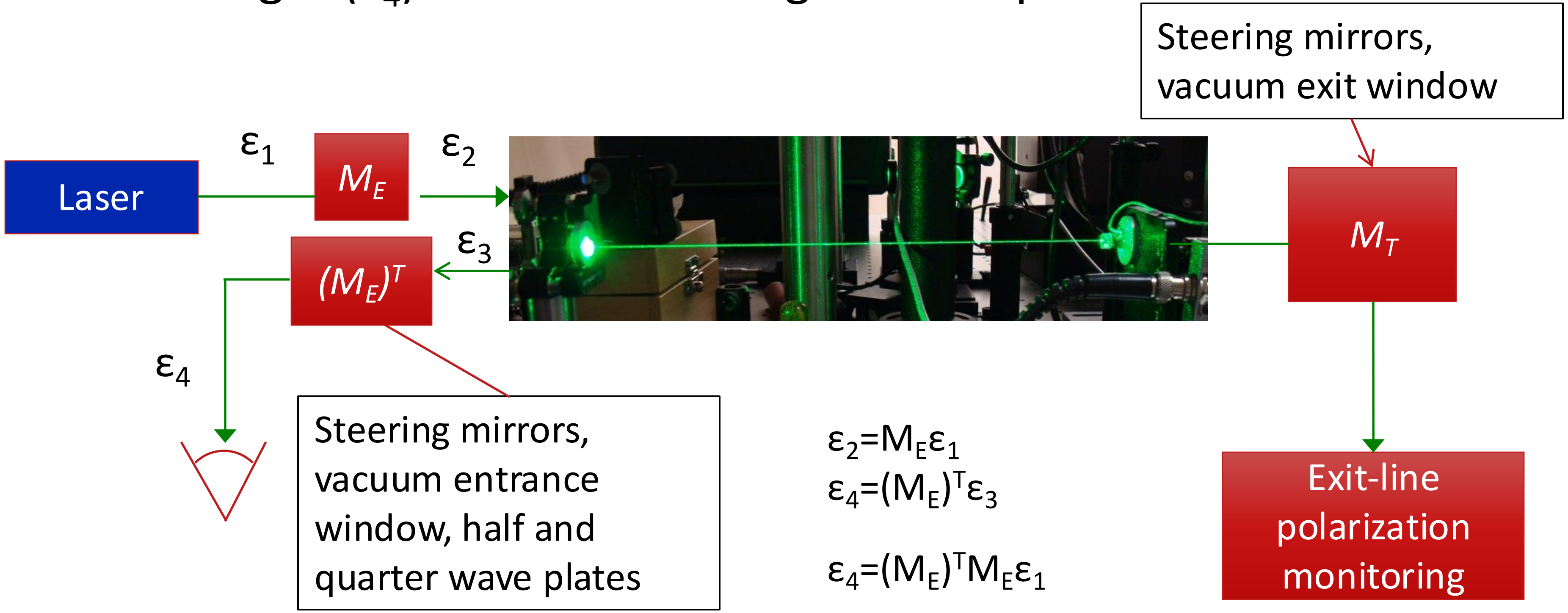
Hall C Compton employed a 2-parameter fit (polarization and Compton edge) to the differential spectrum
→ This has yielded good results → strip width (resolution) is important
→ Zero-crossing must be in acceptance to constrain the fit well
→ Systematic uncertainty dP/P = 0.6%

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*



Steering mirrors, vacuum exit window

Laser

ε_1

M_E

ε_2

ε_3

$(M_E)^T$

M_T

ε_4

Steering mirrors, vacuum entrance window, half and quarter wave plates

Exit-line polarization monitoring

$\varepsilon_2=M_E\varepsilon_1$

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

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

JINST 5 (2010) P06006

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

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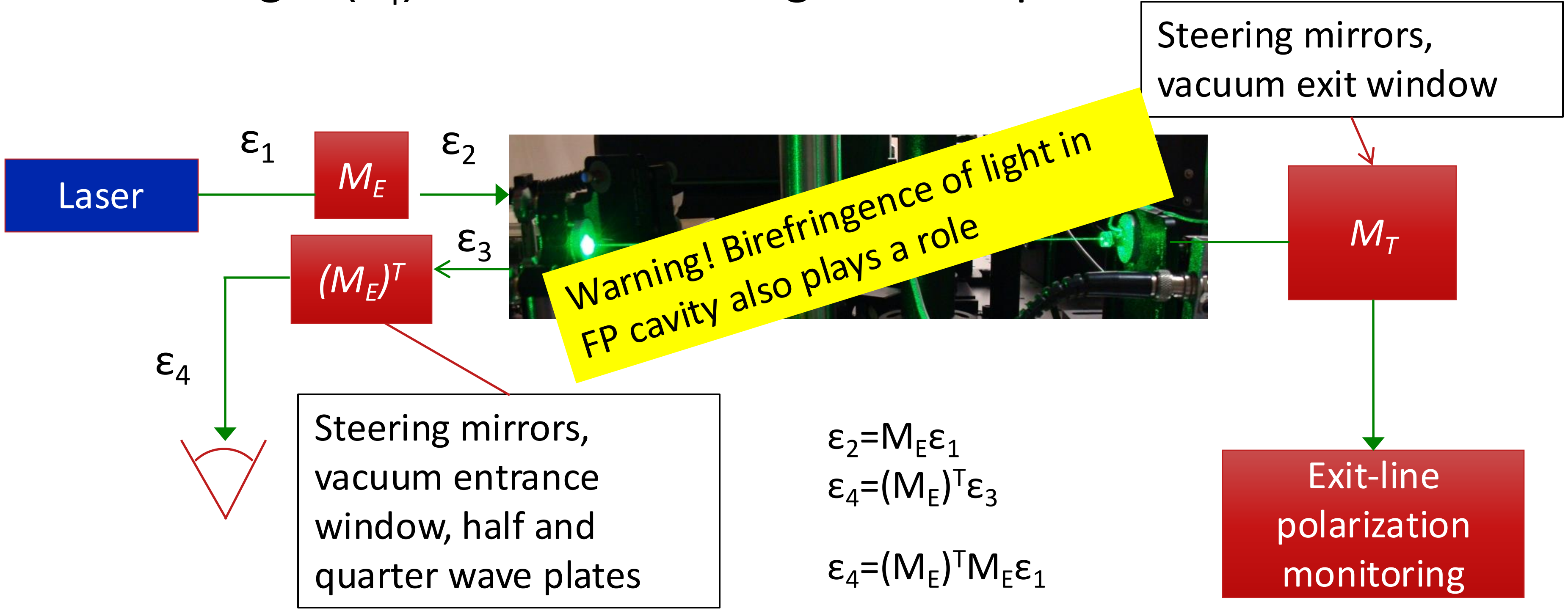

Steering mirrors, vacuum exit window

Warning! Birefringence of light in FP cavity also plays a role

Steering mirrors, vacuum entrance window, half and quarter wave plates

$\varepsilon_2 = M_E \varepsilon_1$

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

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

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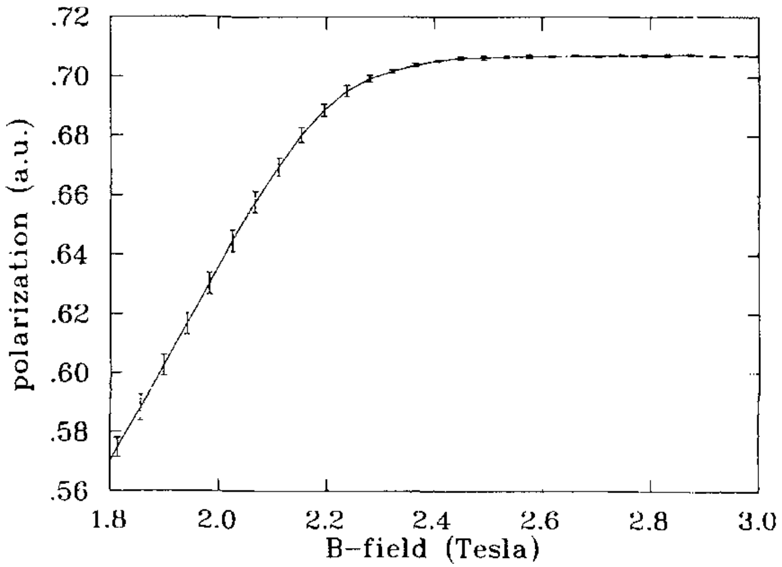
Saturated Iron Foil Target

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)

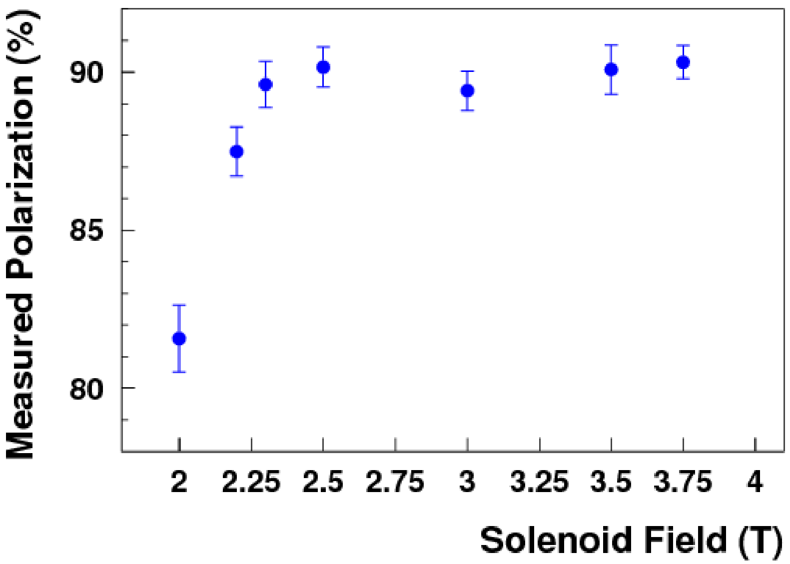
Can also test dependence on foil angle (misalignment) and heating



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

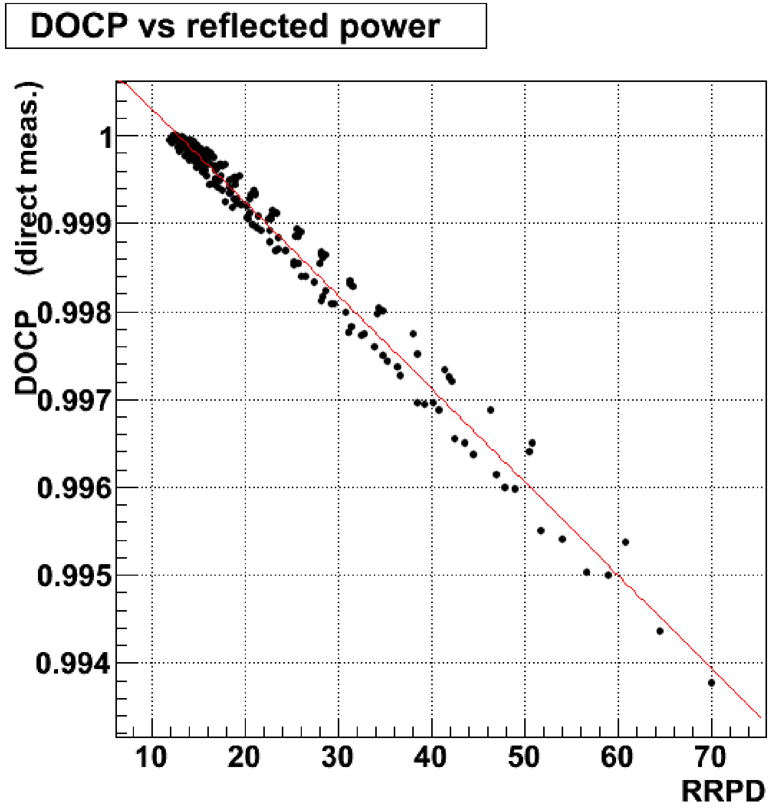
Polarization at Cavity Entrance via Reflected Power

"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

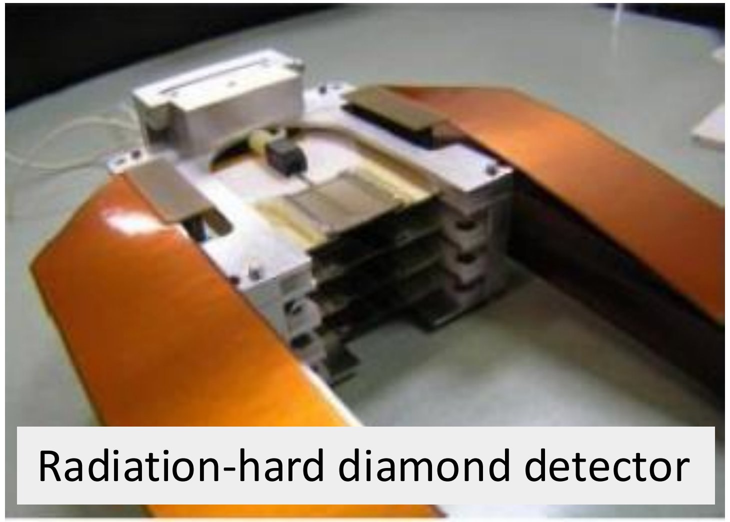
Technique applicable to any Compton polarimeter
→ eliminates uncertainties due to birefringence in vacuum windows (very difficult to control)

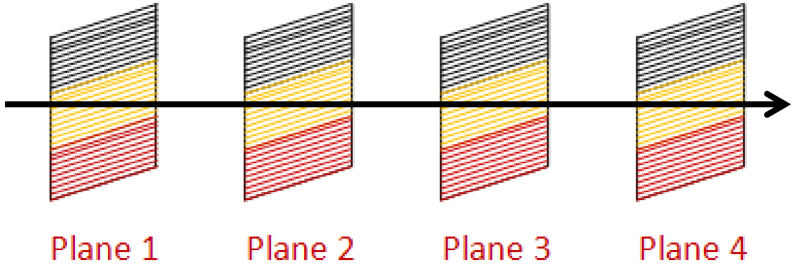


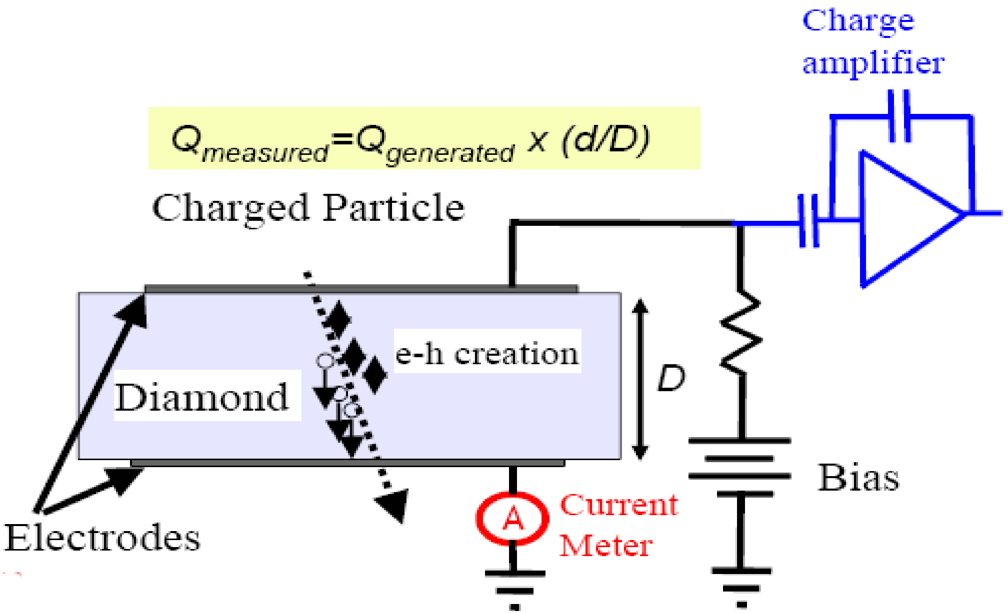
Jefferson Lab

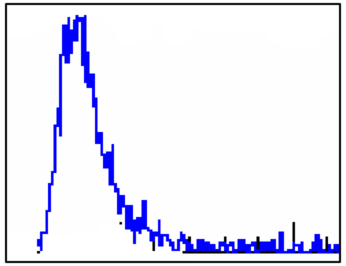
Hall C Compton Diamond Electron Detector

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



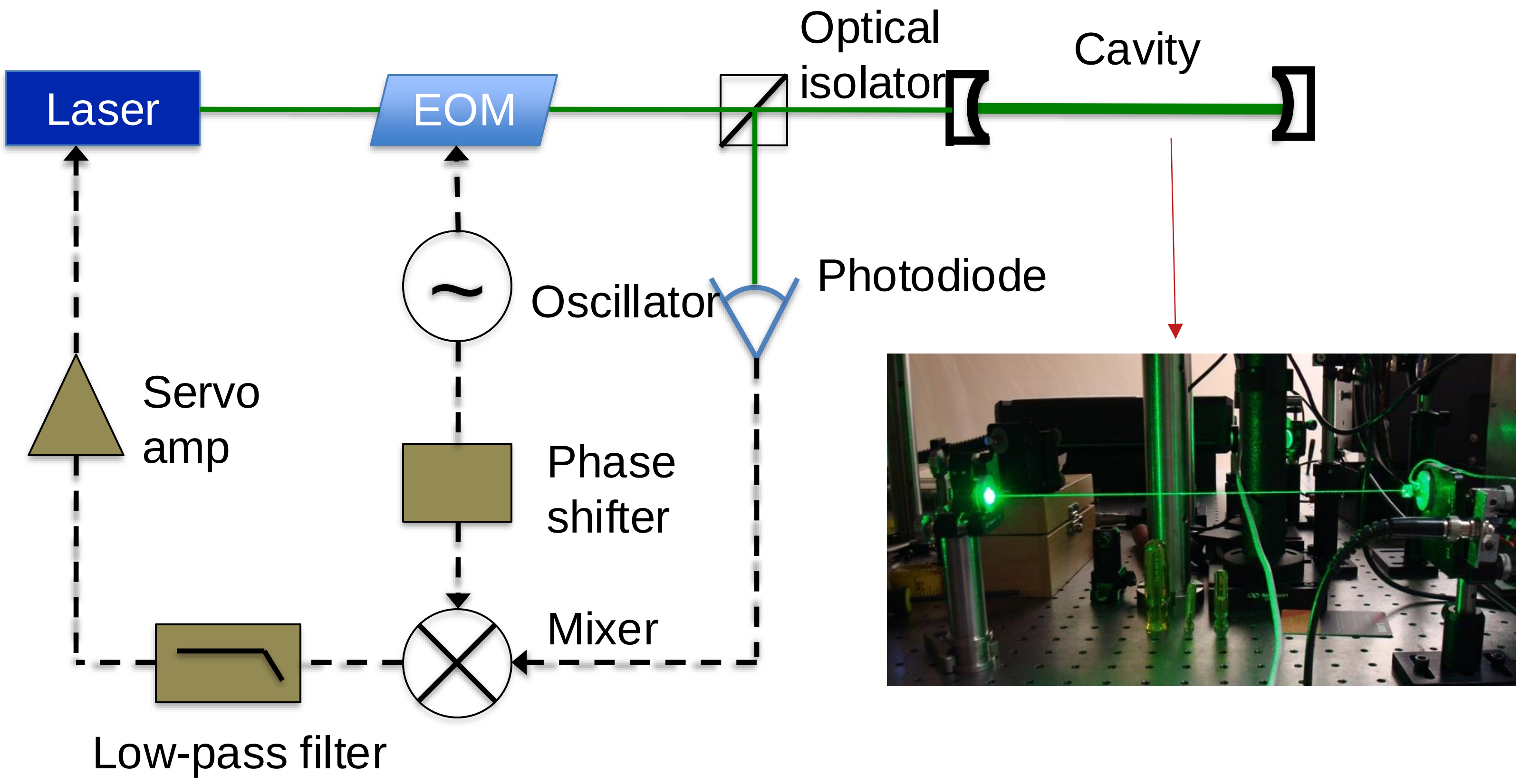

$Q_{measured} = Q_{generated} \times (d/D)$

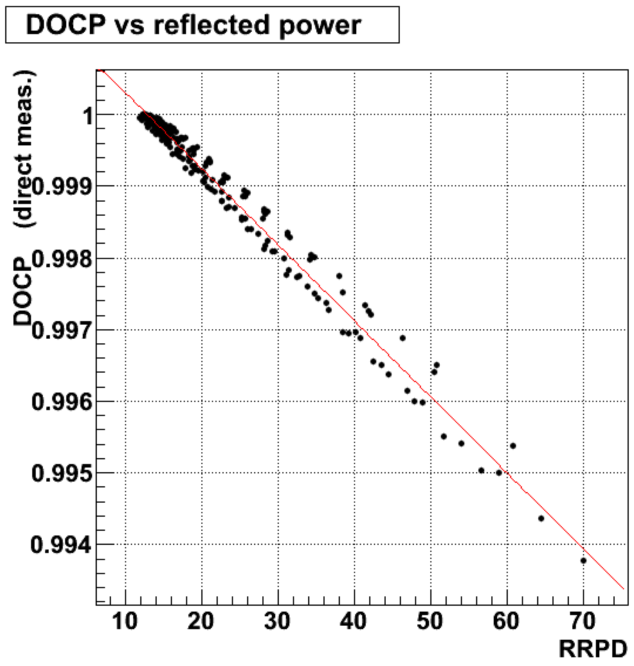


Fabry-Perot Cavity Laser System

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





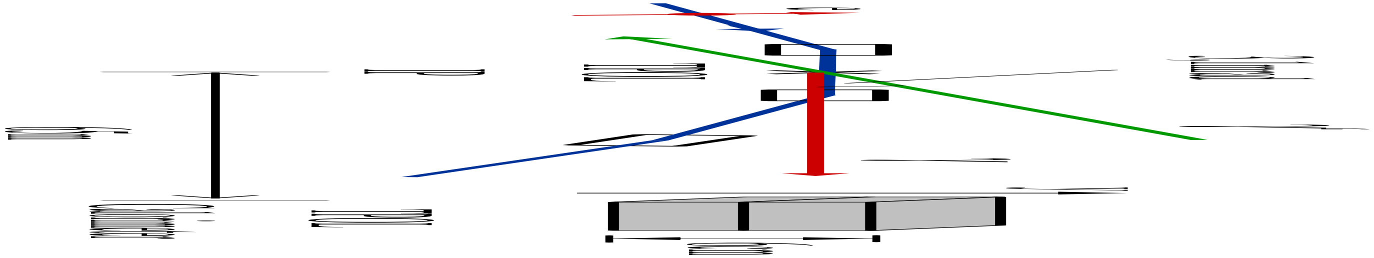
Key systematic: Laser polarization in Fabry-Perot cavity

→ Constrain by monitoring light reflected back from cavity and measurement of cavity birefringence

Jefferson Lab

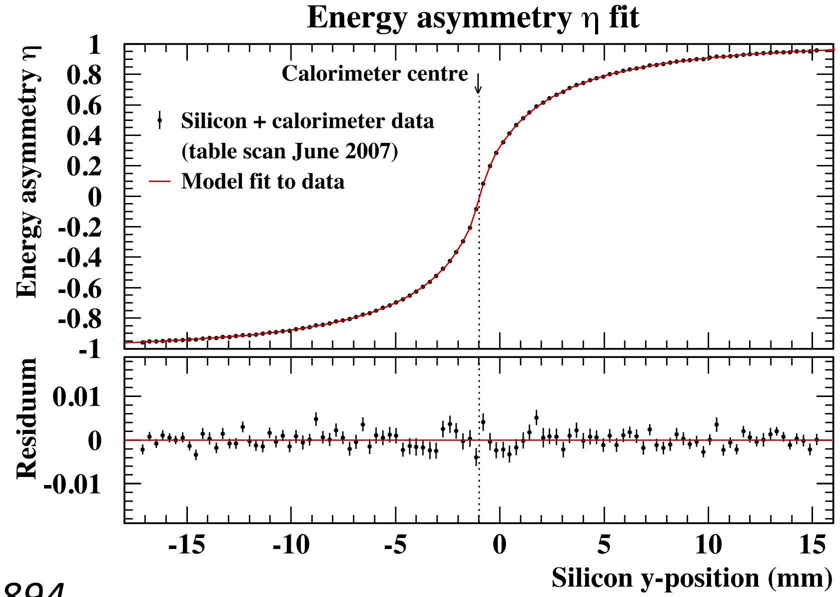
HERA Transverse Compton Polarimeter

Transverse Compton at **HERA** was used to provide absolute polarization measurements with 2-3% precision
→ Transverse Compton polarimeters have been relatively common, but not typically used as absolute devices
→ Key difference from longitudinal case is need to measure spatial dependence of asymmetry



Used a sampling calorimeter with top and bottom optically isolated:
→ Polarization measured via up-down energy asymmetry

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



Key systematic uncertainty is understanding the $\eta(y)$ transformation function
→ Strip detectors provide can be used to help calibrate the detector response

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