Electron Beam Polarimetry at Jefferson Lab

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CASA Beam Physics Seminar

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1. Motivation: Why do we care so much about polarimetry?
2. Overview of JLab polarimeters
3. Cross-polarimeter comparisons
4. Future directions

Precision Polarimetry

- A major motivation for precision polarimetry at JLab are for experiments that test the Standard Model
- The Standard Model is remarkably successful – but there is something "missing" → too many free parameters in the theory
- To search for physics beyond the Standard Model we either need to make measurements at:
  - Higher energies → LHC or,
  - Higher precision → JLAB
- Knowledge of beam polarization is a limiting systematic in precision Standard Model tests (Q_{Weak}, parity violation in Deep Inelastic Scattering)
  - Such experiments require 1% (or better) polarimetry
- Other, demanding nuclear physics experiments (strange quarks in the nucleon, neutron skin in nuclei) also benefit from precise measurements of beam polarization

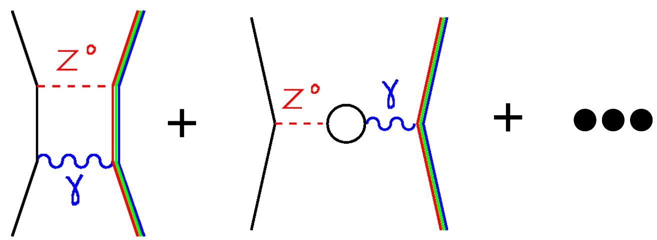
Testing the Standard Model

Weinberg-Salam theory of electro-weak interactions

$$L = \frac{g}{\sqrt{2}}\left(J_\mu^- W_\mu^+ + J_\mu^+ W_\mu^-\right) + \frac{g}{\cos\theta_W}\left(J_\mu^{(3)} - \sin^2\theta_W J_\mu^{e.m.}\right) Z_\mu + g\sin\theta_W J_\mu^{e.m.} A_\mu$$

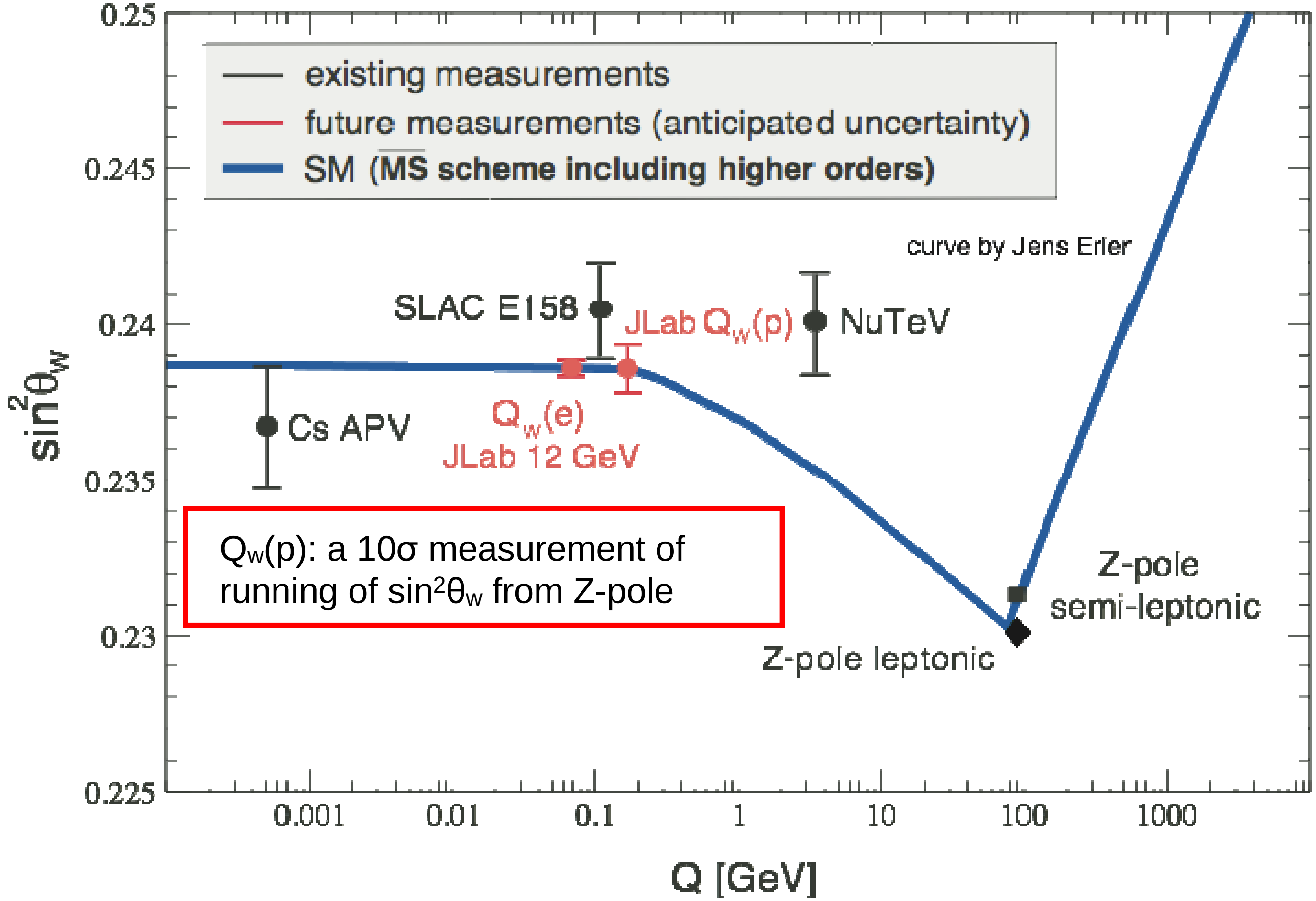
θ_W = weak mixing angle

The evolution of $\sin^2\theta_W$ with Q^2 can be predicted in the context of the Standard Model



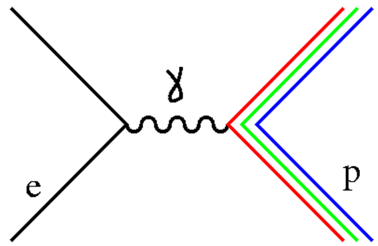
→deviations from this prediction are the signature of new physics, beyond the Standard Model (super-symmetry, Leptoquarks, etc.)

Running of $\sin^2\theta_W$

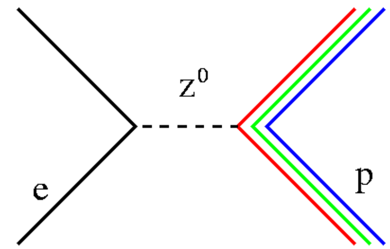


$Q_w(p)$: a 10σ measurement of running of $\sin^2\theta_W$ from Z-pole

Q_{Weak} in Hall C



As $Q^2 \rightarrow 0$



measures Q^p – proton's electric charge

measures Q^p_{weak} – proton's weak charge

The Q_{weak} experiment measures the parity-violating analyzing power *Az*

$$A_z \xrightarrow[\substack{Q^2 \to 0 \\ \theta \to 0}]{} \frac{-G_F}{4\pi\alpha\sqrt{2}}[Q^2 Q^p_{weak} + Q^4 B(Q^2)]$$

Contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$,
Extracted using global fit
of existing PVES experiments!

$$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072 \text{ (at tree level)}$$

Projected Uncertainties

Uncertainty	$\Delta A_z/A_z$	$\Delta Q_w/Q_w$
Statistical (2,544 hours at 180 μA)	2.1%	3.2%
Systematic:		2.6%
Hadronic structure uncertainties	---	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2 determination	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity correlated beam properties	0.5%	0.7%
Total:	2.5%	4.1%

Nominal error magnification due to the 33% hadronic dilution × 1.49. The enhancement for the Q^2 term is somewhat larger.

→ ***Polarimetry approaching limiting systematic uncertainty***

Experiments Requiring Precision Polarimetry

Q_{Weak} (Q^2 evolution of weak mixing angle)
→ 1% at 1 GeV

PREX (neutron distribution in Pb)
→ 1% at 850 MeV

Møller Scattering at 12 GeV* (more weak mixing angle)
→ 1% at 11 GeV

Parity Violation in Deep Inelastic Scattering (DIS-Parity)
→ 0.5% at 11 GeV

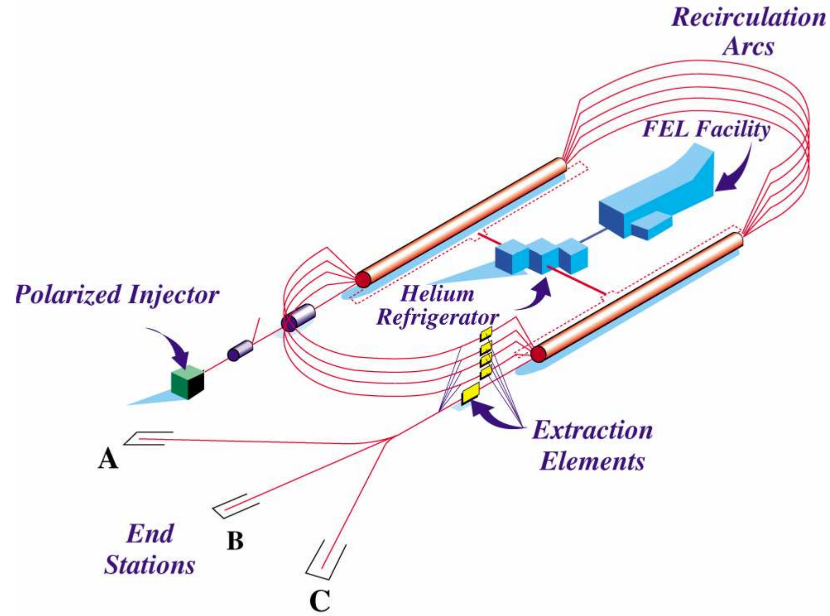
* = not yet officially proposed (but it will be)

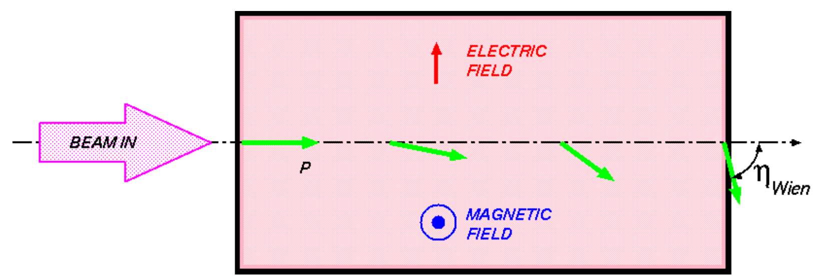
Polarized Electrons at Jefferson Lab

- Polarized electrons generated "at the source" using Superlattice GaAs photocathode
- Electrons polarized in the plane of the accelerator
  - → spin direction precesses as beam circulates (up to 5 times) through machine

$$\phi_{spin} = \frac{g-2}{2}\frac{E_{beam}}{m_e}\theta_{bend}$$

- Spin direction manipulated at source using Wien filter to get long. Polarization in Halls
- JLab now routinely provides electron beam polarizations >80% to experimental halls





JLab Polarimetry Techniques

- Three different processes used to measure electron beam polarization at JLab
  - Møller scattering: $\vec{e}+\vec{e} \to e+e$, atomic electrons in Fe (or Fe-alloy) polarized using by external magnetic field
  - Compton scattering: $\vec{e}+\vec{\gamma} \to e+\gamma$, laser photons scatter from electron beam
  - Mott scattering: $\vec{e}+Z \to e$, spin-orbit coupling of electron spin with (large Z) target nucleus
- Each has advantages and disadvantages in JLab environment

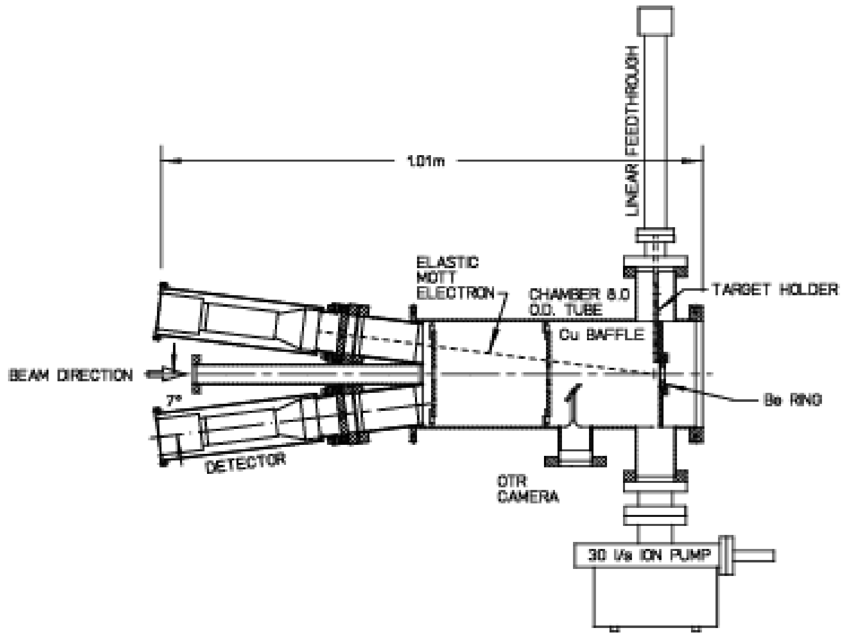
Method	Advantage	Disadvantage
Compton	Non-destructive	Can be time consuming, systematics energy dependent
Møller	Rapid, precise measurements	Destructive, low current only
Mott	Rapid, precise measurements	Does not measure polarization at the experiment

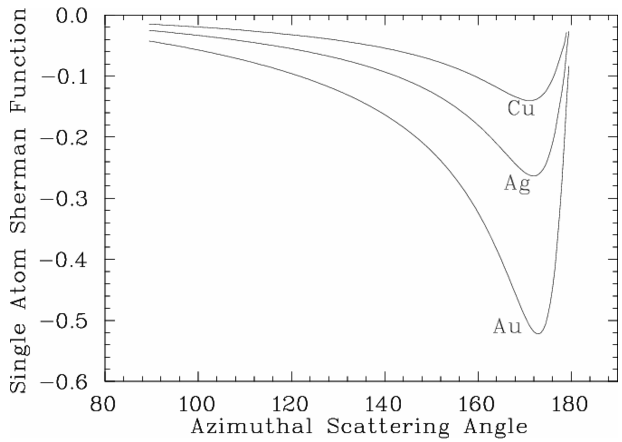
5 MeV Mott Polarimeter

- Mott polarimeter located in the 5 MeV region of the CEBAF injector
- Target must be thin, large Z material → 1 μm Au foil
- Asymmetry maximized near 172°, given by

$$A = \frac{N_r - N_l}{N_r + N_l} = P_{beam} S(\theta)$$

- *S(θ)* is the Sherman function → must be calculated from e-nucleus cross section
- Knowledge of Sherman function dominant systematic uncertainty ~ ***1.0%***

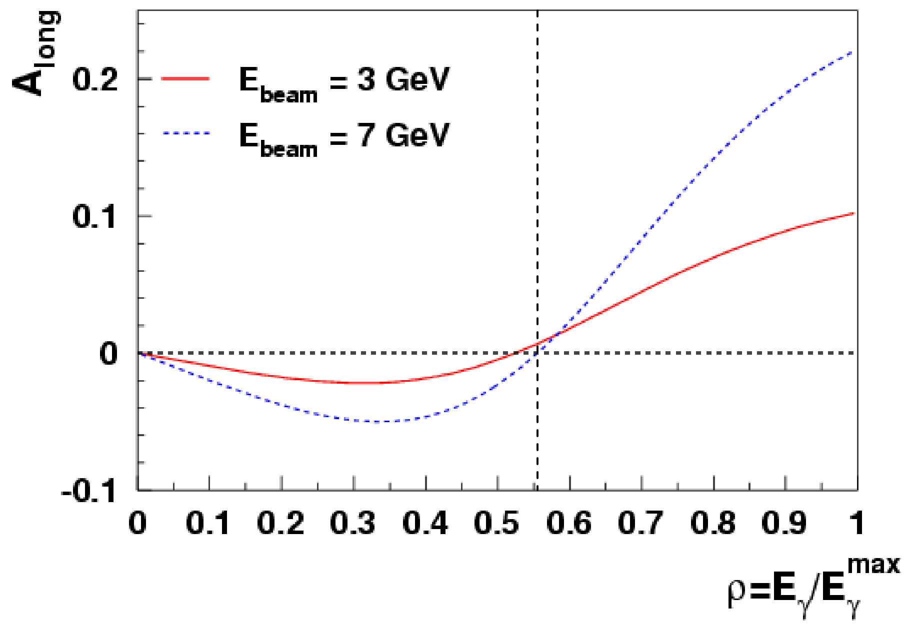




Compton Polarimetry at JLab

Two main challenges for Compton polarimetry at JLab

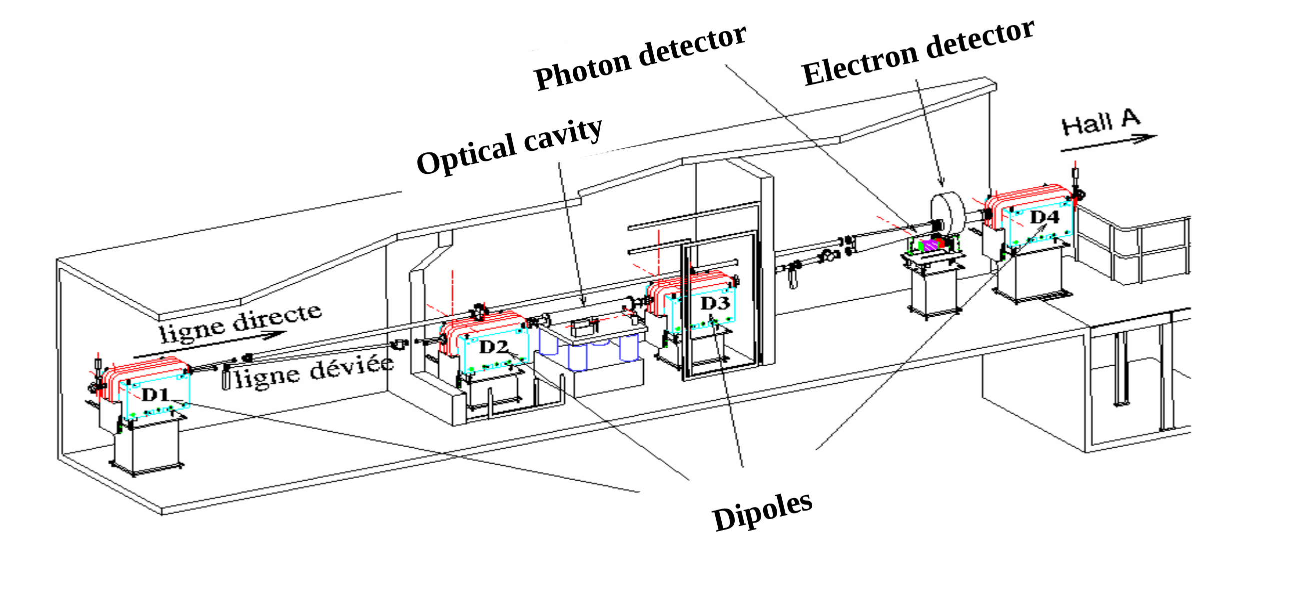
- Low beam currents (~100 μA)
  - Measurements can take on the order of hours
  - Makes systematic studies difficult
- Relatively small asymmetries
  - Smaller asymmetries lead to harder-to-control systematics



- Strong dependence of asymmetry on E_γ is a challenge
  → Understanding of detector response crucial

Hall A Compton Polarimeter

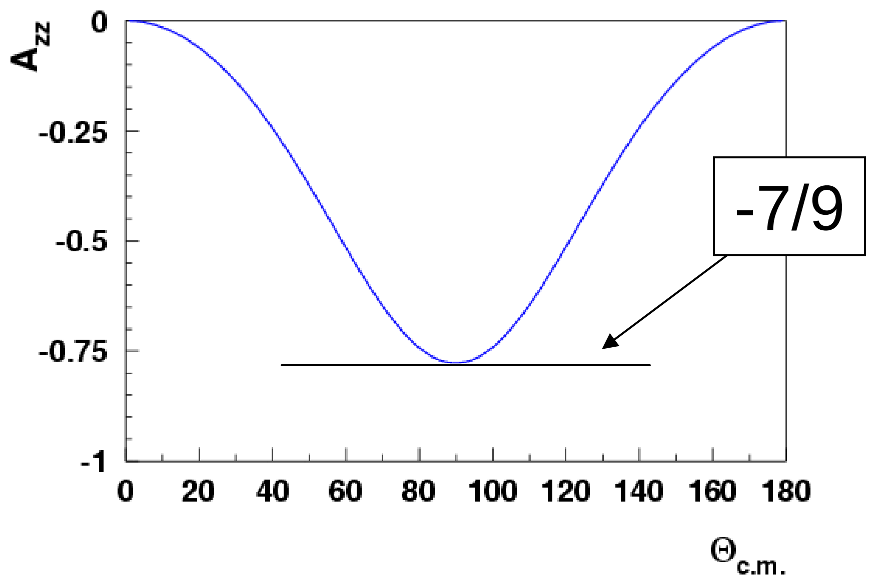
- Hall A Compton polarimeter uses high gain Fabry-Perot cavity to create ~ 1 kW of laser power in IR (1064 nm)
- Detects *both* scattered electron and backscattered $\gamma \rightarrow$ 2 independent measurements, coincidences used to calibrate γ detector
- Systematic errors quoted at ***1%*** level for recent HAPPEx experiments @ 3 GeV *[PRL 98 (2007) 032301]*



Møller Polarimetry at JLab

- Møller polarimetry benefits from large long. asymmetry → -7/9
  - Asymmetry independent of energy
  - Relatively slowly varying near $\theta_{cm}=90^o$
  - Large asymmetry diluted by need to use iron foils to create polarized electrons

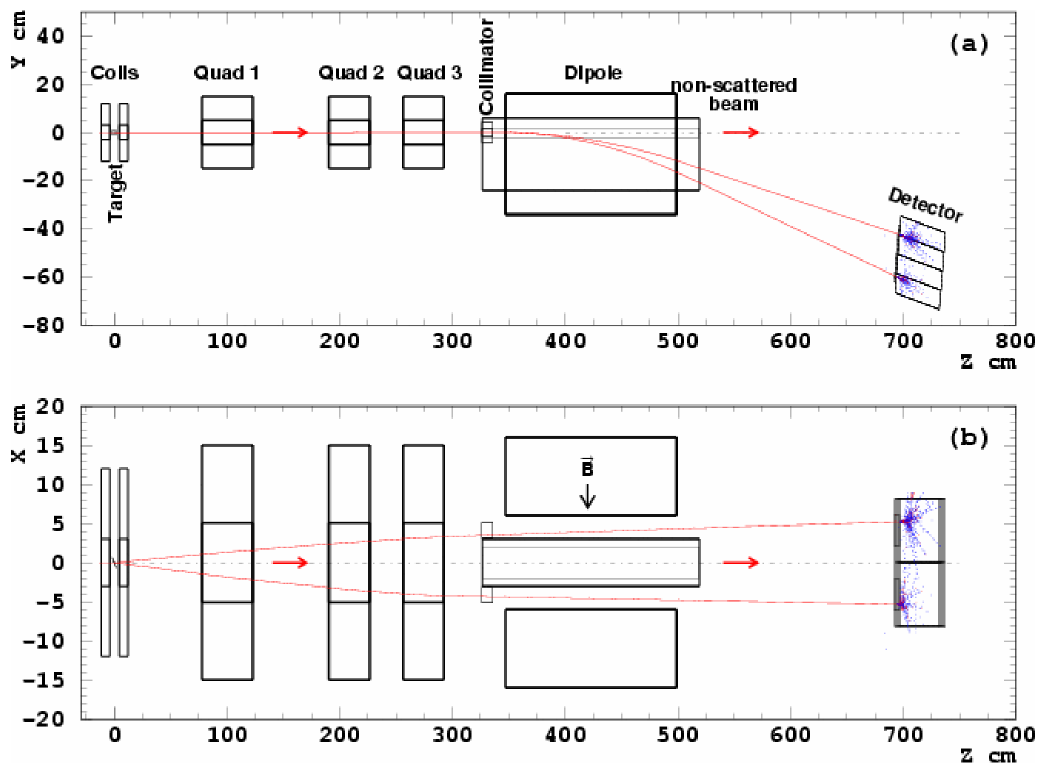
    → $P_e \sim 8\%$
- Rates are large, so rapid measurements are easy
- Need to use Fe or Fe-alloy foils means measurement must be destructive



- Making measurements at high beam currents challenging

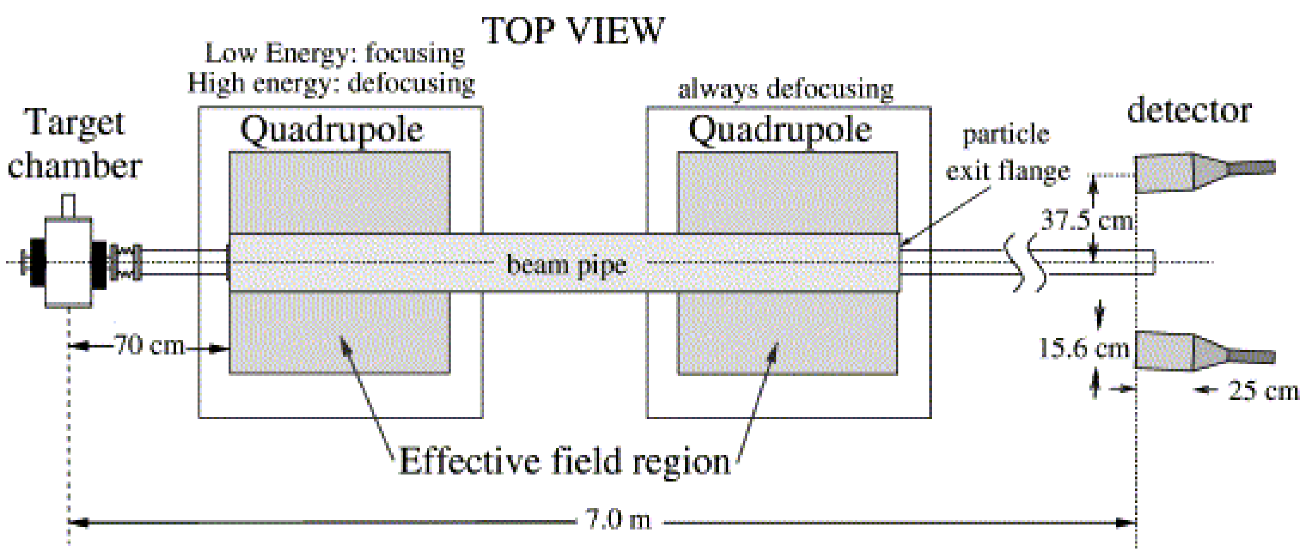
Hall A Møller Polarimeter

- Target =supermendeur foil, polarized in-plane
  - Low field applied (240 G)
  - Tilted 20º relative to beam direction
  - Target polarization known to ~ ***2%*** → *this will improve*
- Large acceptance of detectors mitigates potentially large systematic unc. from Levchuk effect (atomic Fermi motion of bound electrons)
- Large acceptance also leads to large rates - dead time corrections cannot be ignored, but are tractable



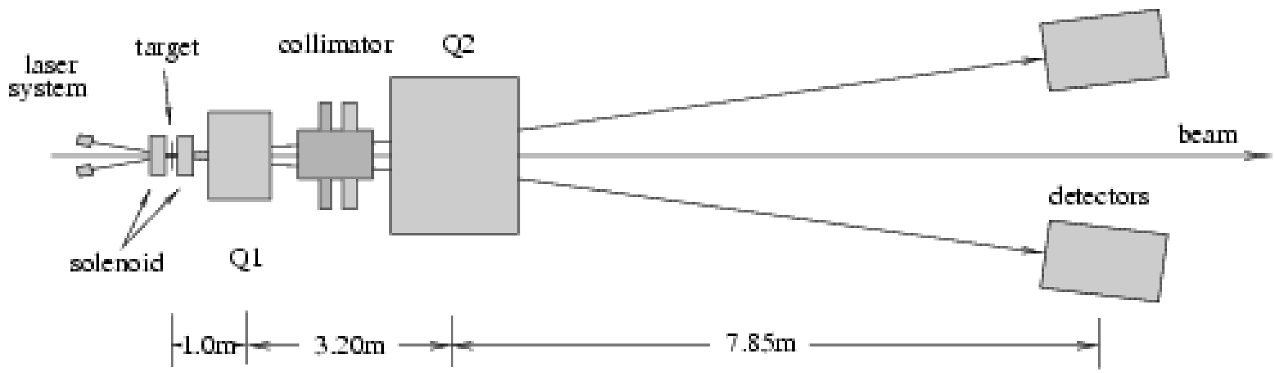
Hall B Møller Polarimeter

- Hall B Møller uses similar target design as Hall A → Fe alloy in weak magnetic field
- Two-quadrupole system rather than QQQD
- Detector acceptance not as large – Levchuk effect corrections important
- Dominant systematics *[NIM A 503 (2003) 513]*
  - Target polarization ~ ***1.4%***
  - Levchuk effect ~ ***0.8%***



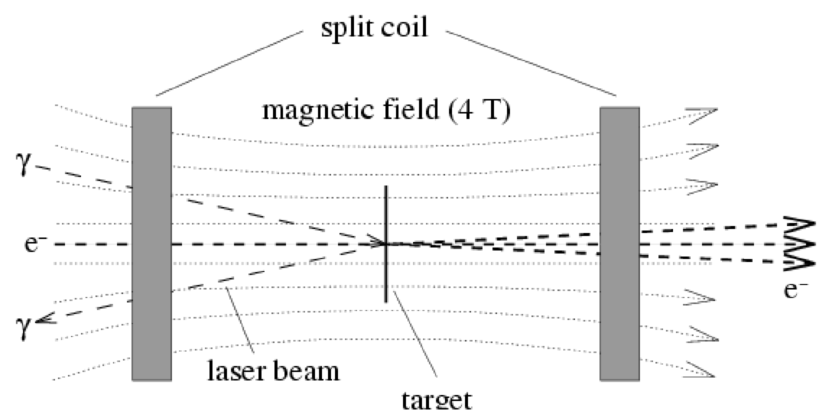
Hall C Møller Polarimeter

- 2 quadrupole optics maintains constant tune at detector plane
- “Moderate” (compared to Hall A) 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
- Total systematic uncertainty = ***0.47%*** *[NIM A 462 (2001) 382]*



Hall C Møller Target

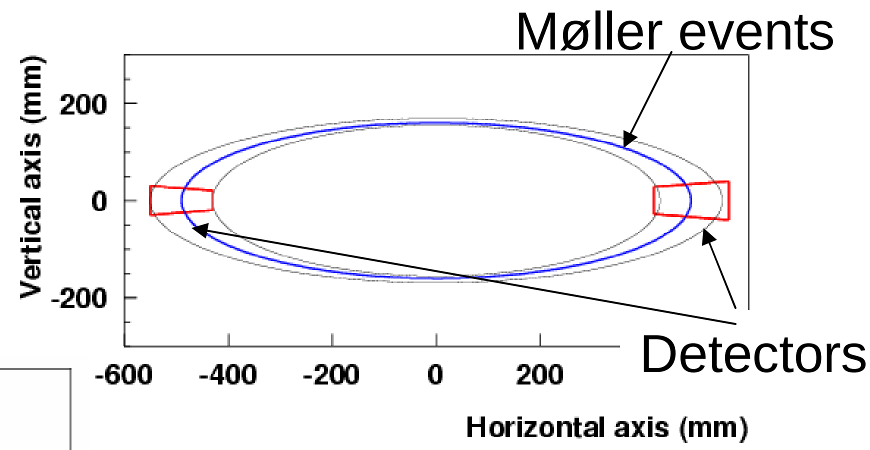
- Fe-alloy, in plane polarized targets typically result is systematic errors of 2-3%
  - Require careful measurement magnetization of foil
- Pure Fe saturated in 4 T field
  - Spin polarization well known → 0.25%
  - Temperature dependence well known
  - No need to directly measure foil polarization

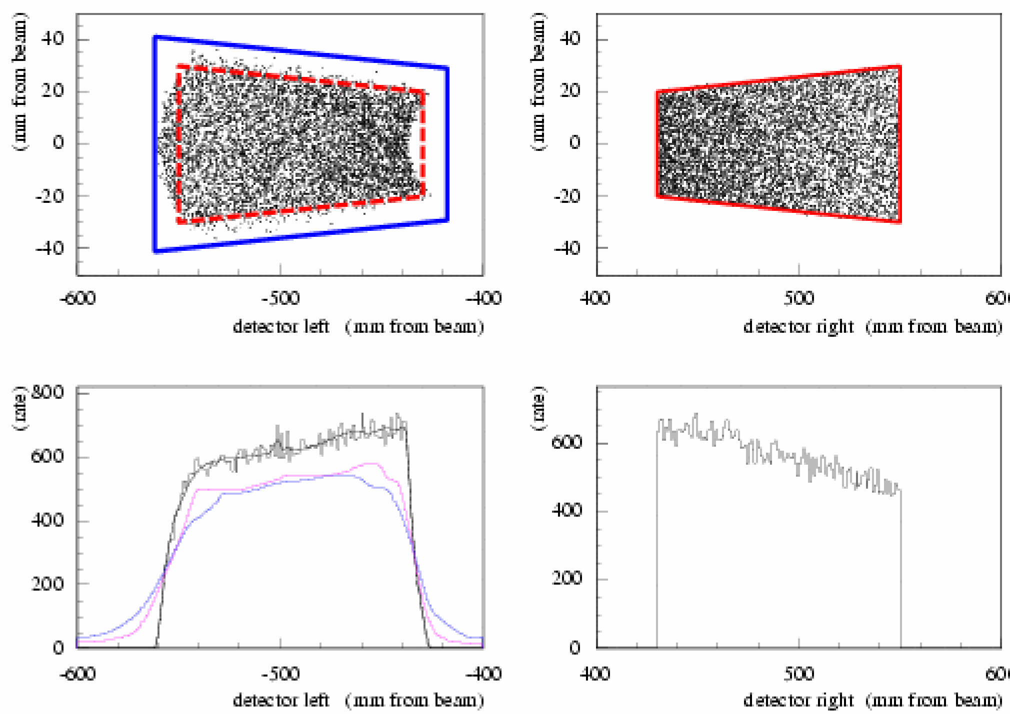


Effect	$M_s[\mu_B]$	error
Saturation magnetization (T→0 K,B→0 T)	2.2160	±0.0008
Saturation magnetization (T=294 K, B=1 T)	2.177	±0.002
Corrections for B=1→4 T	0.0059	±0.0002
Total magnetization	2.183	±0.002
Magnetization from orbital motion	0.0918	±0.0033
Magnetization from spin	2.0911	±0.004
Target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

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

Hall C Møller Systematics (I)

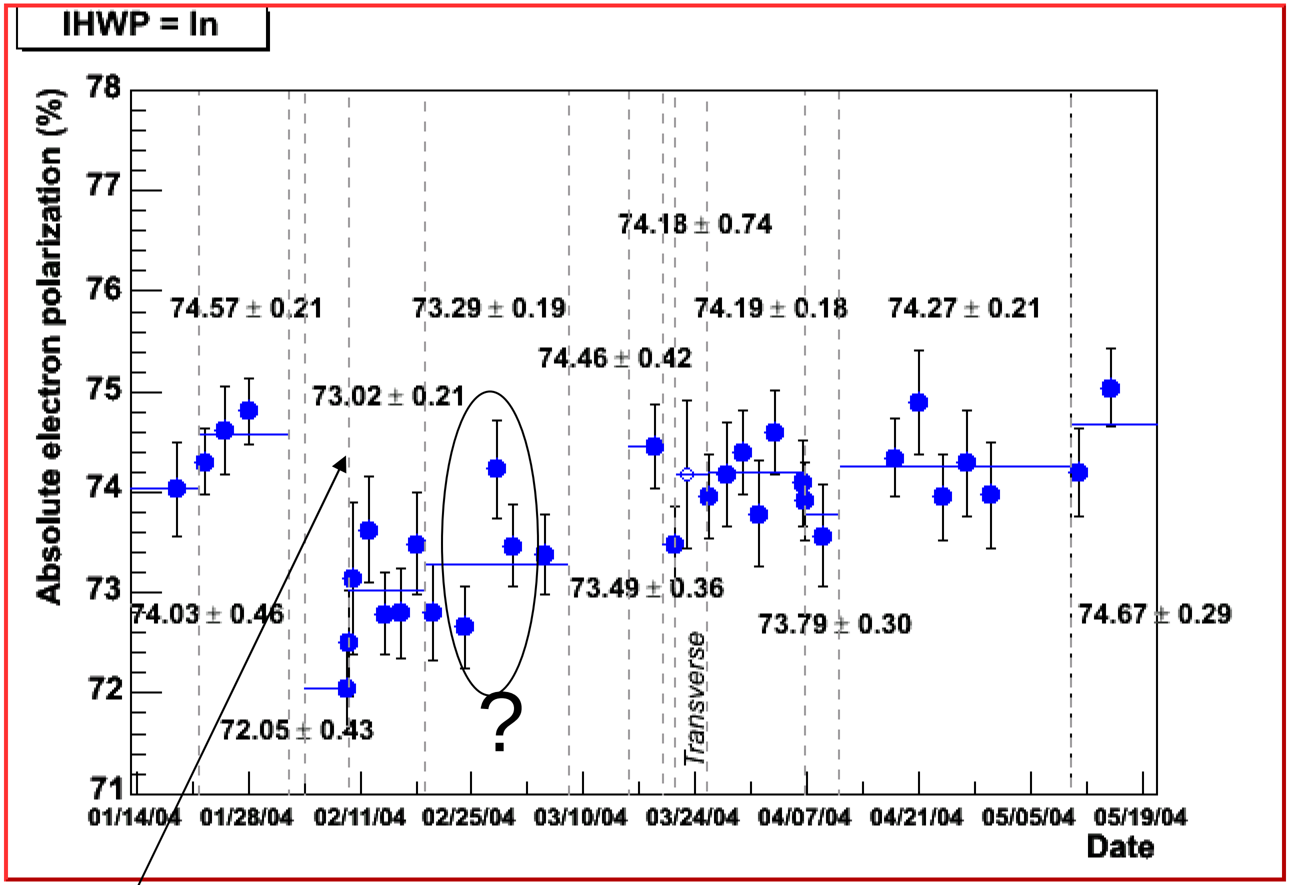
Systematic error budget from NIM article

Idealized?

A particular measurement under specific conditions may approach this level of uncertainty – ***but we want the polarization for the same conditions as the experiment!***

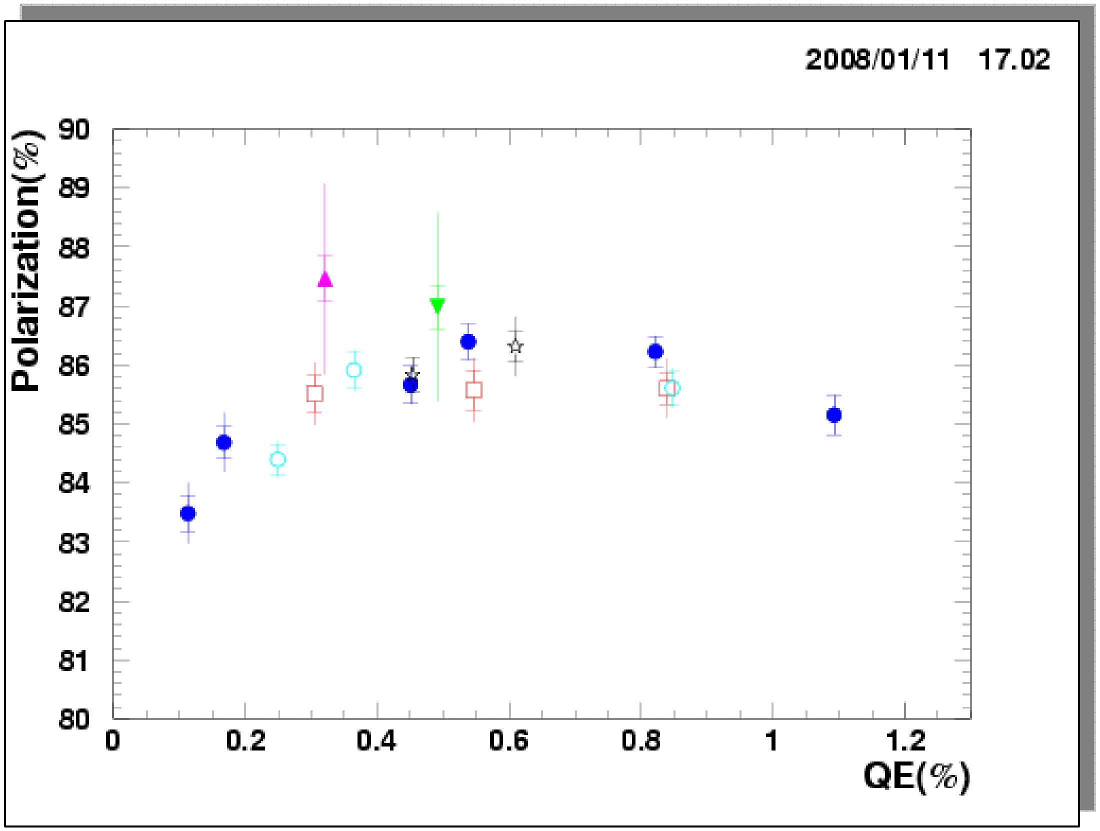
Source	Uncertainty	dAsy./Asy. (%)
Beam position x	0.5 mm	0.15
Beam position y	0.5 mm	0.03
Beam direction x	0.15 mr	0.04
Beam direction y	0.15 mr	0.04
Q1 current	2%	0.10
Q2 current	1%	0.07
Q2 position	1 mm	0.02
Multiple Scattering	10%	0.12
Levchuk effect	10%	0.30
Collimator positions	0.5 mm	0.06
Target temperature	50%	0.05
B-field direction	2^o	0.06
B-field strength	5%	0.03
Spin polarization in Fe		0.25
Total		**0.47**

Hall C Møller during G0 Forward Angle



Each dashed line corresponds to an "event" that *may* have impacted the polarization in machine

Hall C Møller during GEp



Some hint of dependence of polarization on QE!

Hall C Møller Systematics (II)

Systematic error budget from G0 Forward Angle expt.

dP/P = 1.32%

Source	Uncertainty	dAsy./Asy. (%)
Beam position x	0.5 mm	0.15
Beam position y	0.5 mm	0.03
Beam direction x	0.15 mr	0.04
Beam direction y	0.15 mr	0.04
Q1 current	2%	0.10
Q2 current	1%	0.07
Q2 position	1 mm	0.02
Multiple Scattering	10%	0.12
Levchuk effect	10%	0.30
Collimator positions	0.5 mm	0.06
Target temperature	50%	0.05
B-field direction	2º	~~0.06~~ **0.37**
B-field strength	5%	0.03
Spin polarization in Fe		**0.25**
Leakage	*30 nA*	***0.2***
High current extrap.	*1%/40 uA*	***1.0***
Solenoid focusing	*100%*	*0.1*
Elec. DT.	*100%*	*0.04*
Charge measurment		*0.02*
Monte Carlo Statistics		***0.28***
Unknown accelerator changes		***0.5***
Total		**1.32**

JLab Polarimeter Roundup

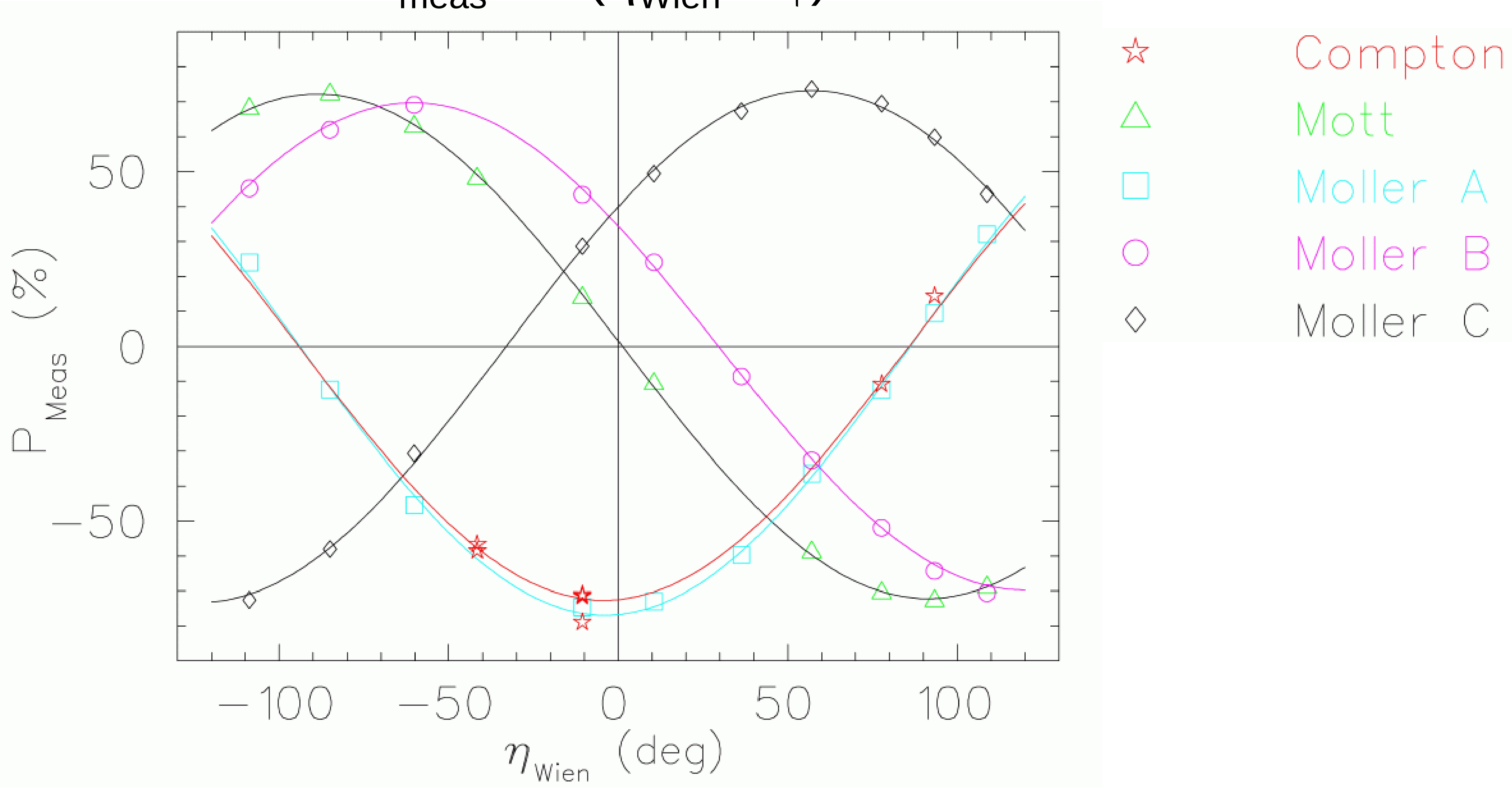
Polarimeter	Relative precision	Limiting systematic
5 MeV Mott	~1%	Sherman function
Hall A Møller	~2-3%	Target polarization
Hall B Møller	1.6% (?)	Target polarization, Levchuk effect
Hall C Møller	0.5% (→1.3%)	Target polarization, Levchuk effect, high current extrapolation
Hall A Compton	1% (@ > 3 GeV)	Detector acceptance + response

Spin Dance 2000

- In July 2000, a multi-hall "Spin Dance" was performed at JLab
- Wien filter in the injector was varied from -110^{o} to 110^{o}, thus varying degree of longitudinal polarization in each hall
- Purpose was 2-fold
  - Allow precise cross-comparison of JLab polarimeters
  - Extract measurement of beam energy using spin precession through machine
- Results can be found in: *Phys. Rev. ST Accel. Beams* ***7****, 042802 (2004)*

Spin Dance 2000 Data

$P_{meas}\cos(\eta_{Wien} + \phi)$



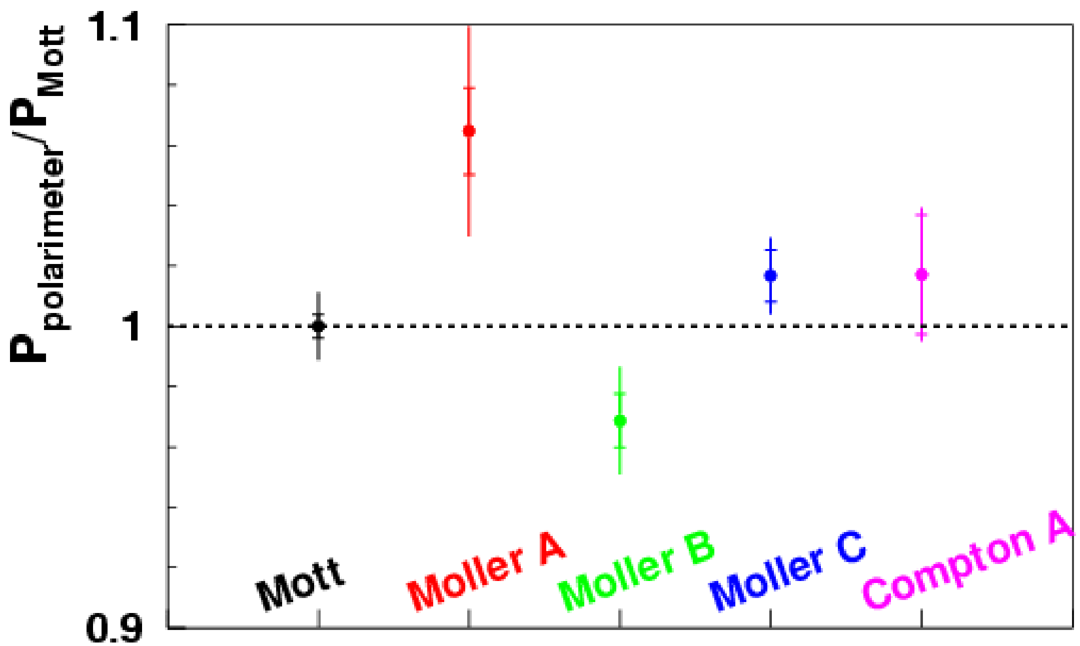
Polarization Results

Results shown include statistical errors only
→some amplification to account for non-sinusoidal behavior

Statistically significant

Systematics shown:

Mott Møller C Compton	1%
Møller B	1.6%
Møller A	3%



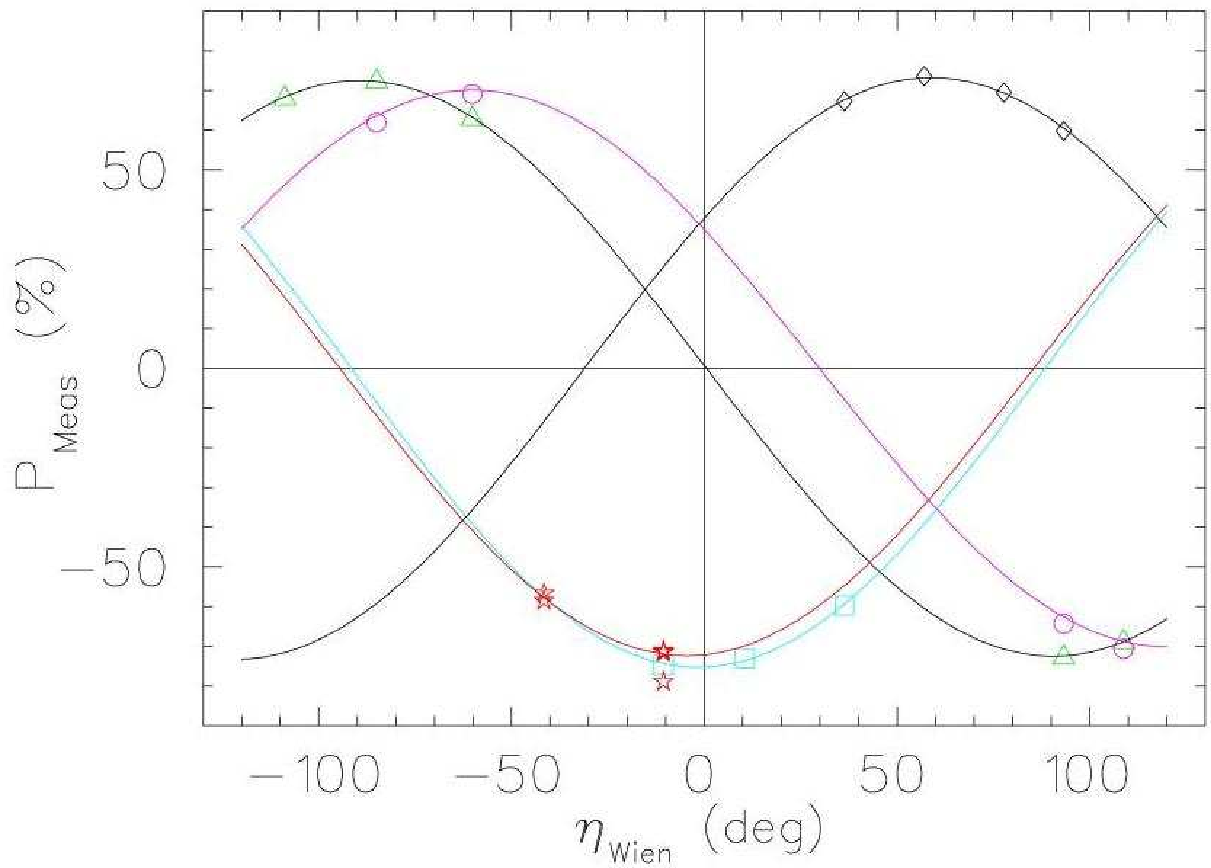
Even including systematic errors, discrepancy still significant

Reduced Data Set

Hall A, B Møllers sensitive to transverse components of beam polarization

Normally – these components eliminated via measurements with foil tilt reversed, but some systematic effects may remain

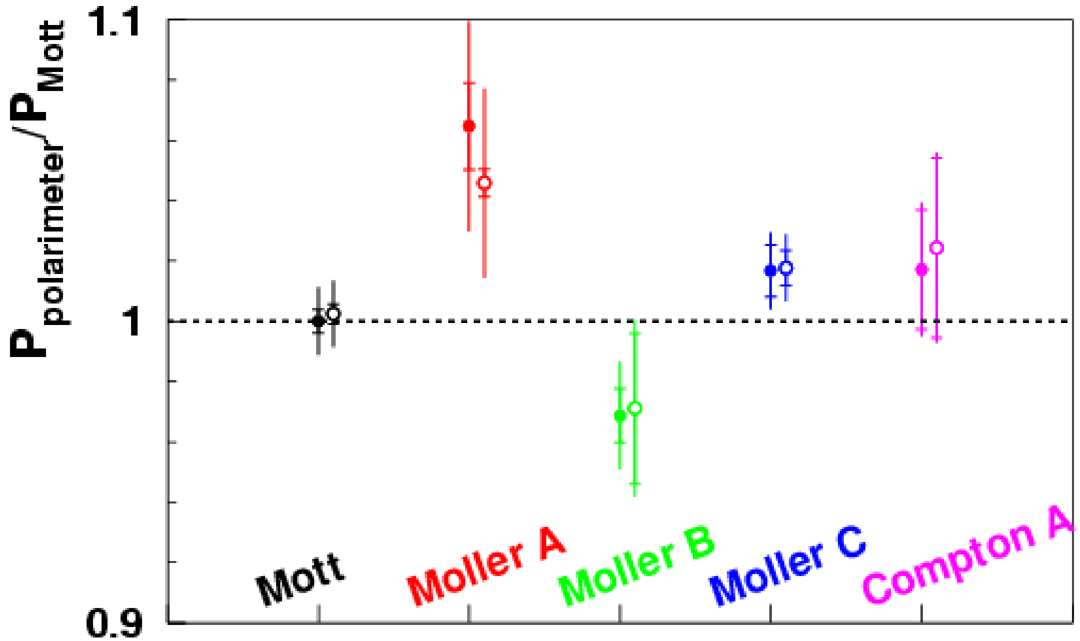
Fit was redone with data only within 20% of total polarization



Polarization Results – Reduced Data Set

Agreement improves, but still statistically significant deviations
→ when systematics included, discrepancy less significant

Further study in Hall A suggests measured foil polarization too big by 1-1.5%



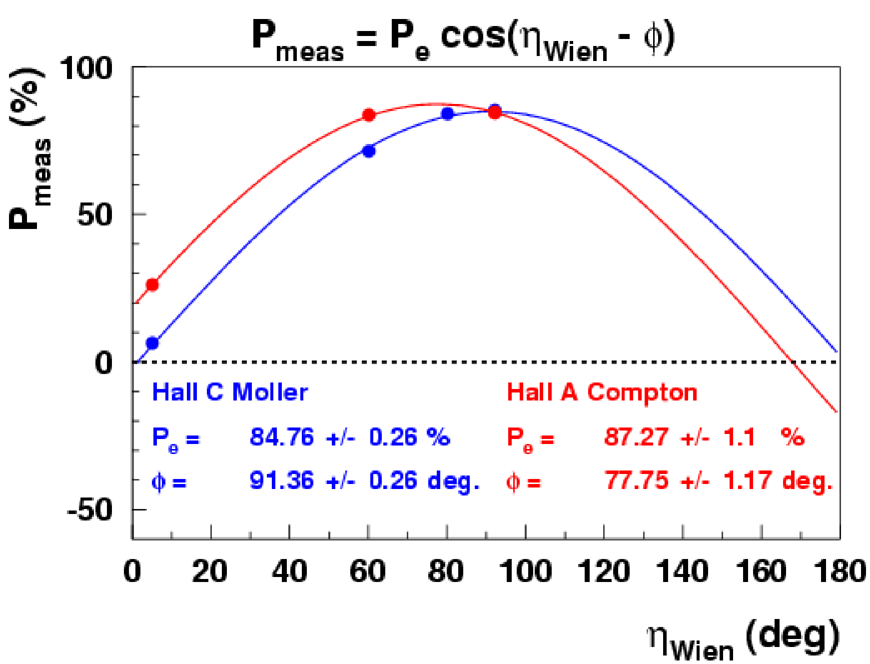
closed circles = full data set
open circles = reduced data set

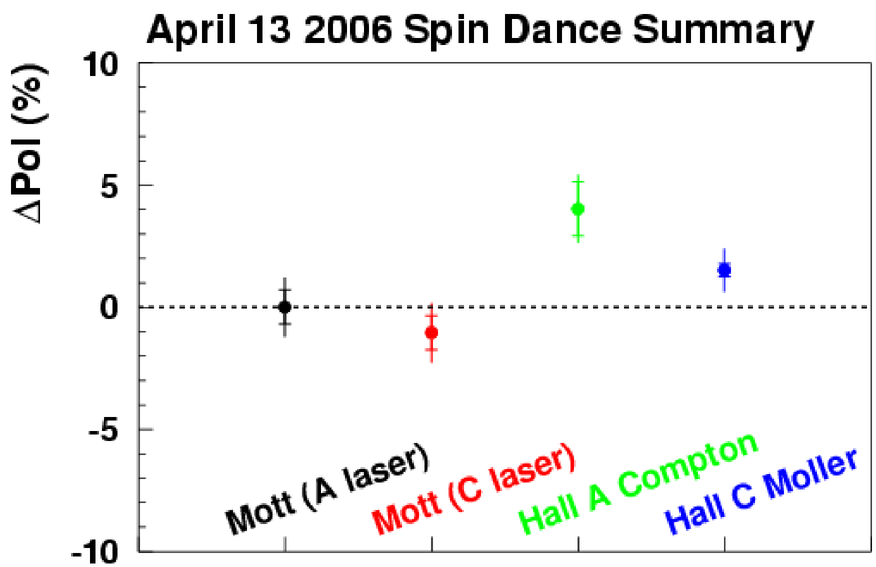
Spin Dance 200X?

- Since Spin Dance 2000, there has not been another full-blown, cross-hall, polarimeter comparison
- Dedicated time for these measurements difficult to obtain – beam time is precious and there is enormous pressure to complete as much of the physics program as possible
- There are sometimes opportunities for multi-hall comparisons, but usually only when experiments are using polarized beam and polarimeters are already commissioned
- PREX and Q_{Weak} will be running in the next few years → this may be an excellent opportunity to push for further studies
- In particular, Hall A Møller implementing Hall C style target
  - Systematics due to target polarization *identical*
  - Comparison (if done carefully) would isolate instrumental effects

Additional Cross-Hall Comparisons

- During G0 Backangle, performed “mini-spin dance” to ensure purely longitudinal polarization in Hall C
- Hall A Compton was also in use, so they participated as well





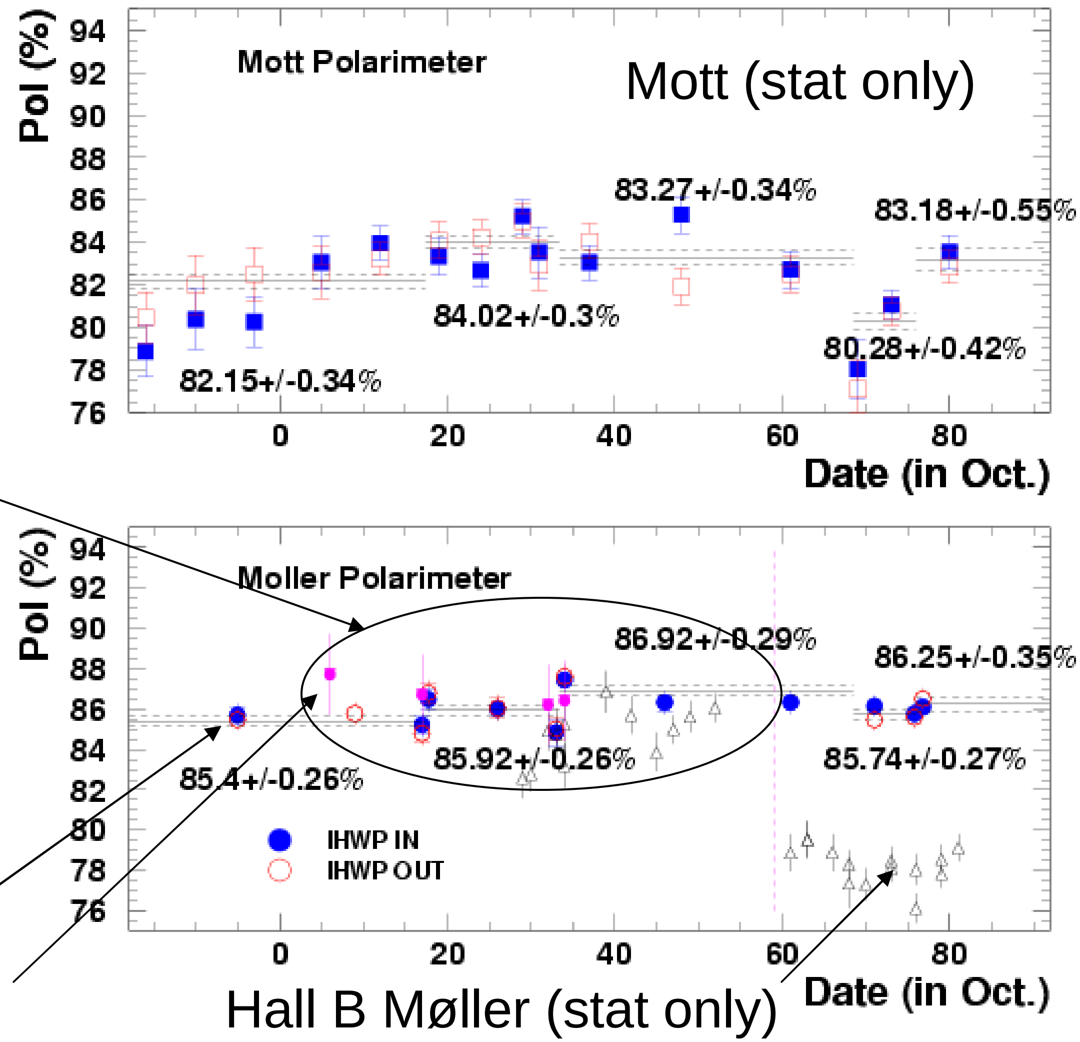
- Relatively good agreement between Hall C Møller and Mott and between Hall C Møller and Compton
- Hall A results are “online” only even though I show 1% syst.

  → Compton takes significant offline analysis

Comparisons During Fall 2006

Fall 2006, CEBAF was at “magic energy”
→allows longitudinal polarization to all halls for some passes

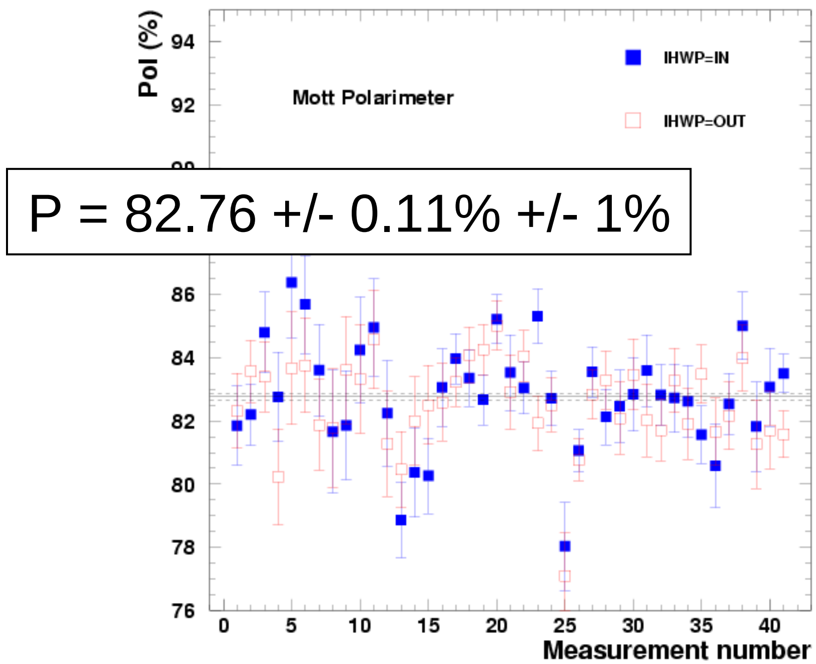
During this period A, B, C agreement quite good
→ some unexplained variation in B measurements

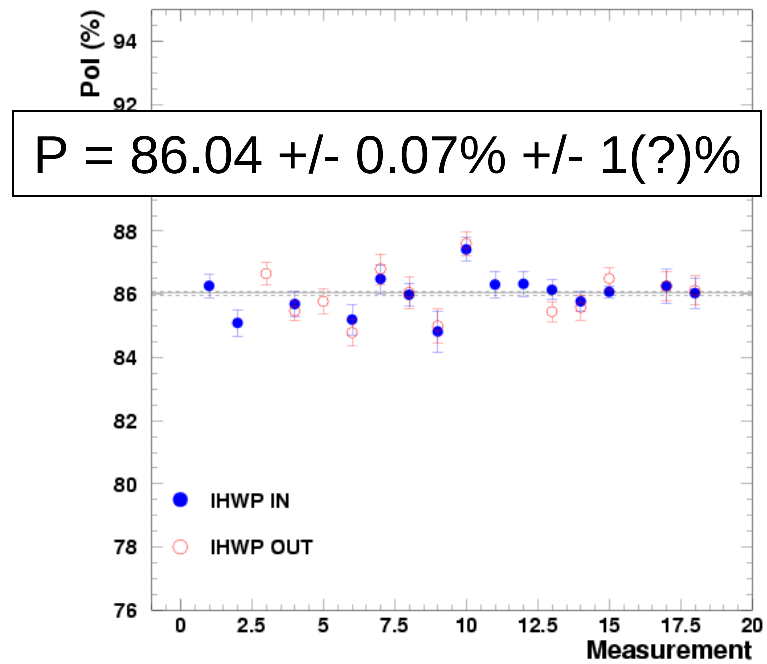


Hall C Møller (stat only)

Hall A Møller (+2% sys.)

Hall C Møller and Mott Discrepancy





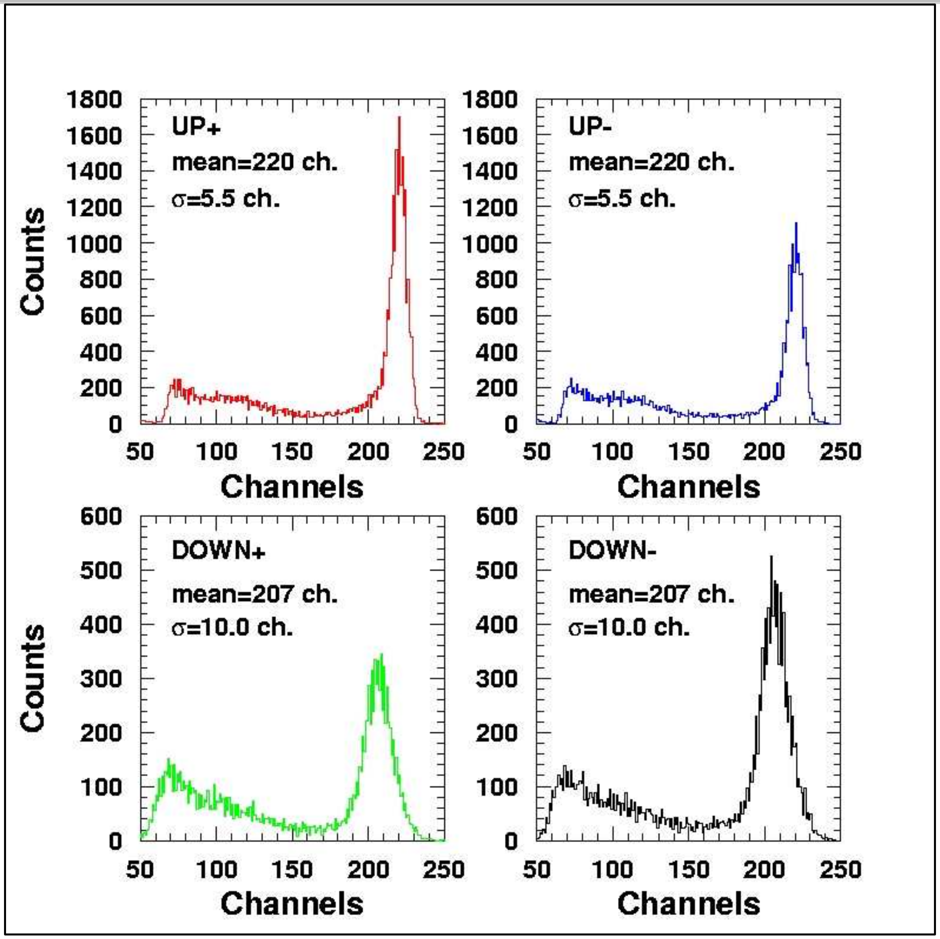
- Historically, Hall C Møller and Mott have agreed to 1.5-2%
- Measurements made during G0 Backangle indicate this difference has grown → 4%!

Mott Detector Resolution

Resolution of DOWN detector in Mott polarimeter has worsened

→Background under elastic peak may no longer be identical between UP and DOWN detectors

→Simulation of background + resolution effects increases polarization extracted by Mott



Mott/Møller discrepancy: 4% → 2.5%

Polarimetry Goals

- Halls A and C are the primary drivers for precision polarimetry
- Hall C has "highest precision" polarimeter at JLab
  - dP/P ~ 0.5%*
  - Limited to low currents, destructive measurement
- Hall A the only experimental Hall with 2 electron beam polarimeters
  - Hall A Compton: dP/P = 1% for E_{beam}>3 GeV
  - Hall A Møller: dP/P = 2-3%, limited by knowledge of target polarization
- ***Both Halls would like 2 polarimeters capable of polarization measurements yielding dP/P=1%***

Polarimetry Upgrade Plans

- Hall A
  - Upgrade Møller to use saturated foil target like Hall C
  - *Pursue extending reach of Møller to high currents*
  - Upgrade Compton to achieve high precision at low energy
- Hall C
  - *Pursue extending reach of Møller to high currents*
  - Build new Compton polarimeter to allow continuous non-destructive polarization measurements

Møller Polarimetry Improvements

- Primary limitation of Hall A Møller polarimeter is knowledge of target foil polarization
  - For PREX, Hall A will use old Hall C superconducting solenoid to make use of saturated foil technique
  - Identical targets in Halls A and C will allow direct comparison of ***other*** polarimeter systematics (Levchuk effect, etc.)
- Limitation in both Halls A ***and*** C is maximum current on foil target

Is P_e @ 2 μA = P_e @ 100 μA ?

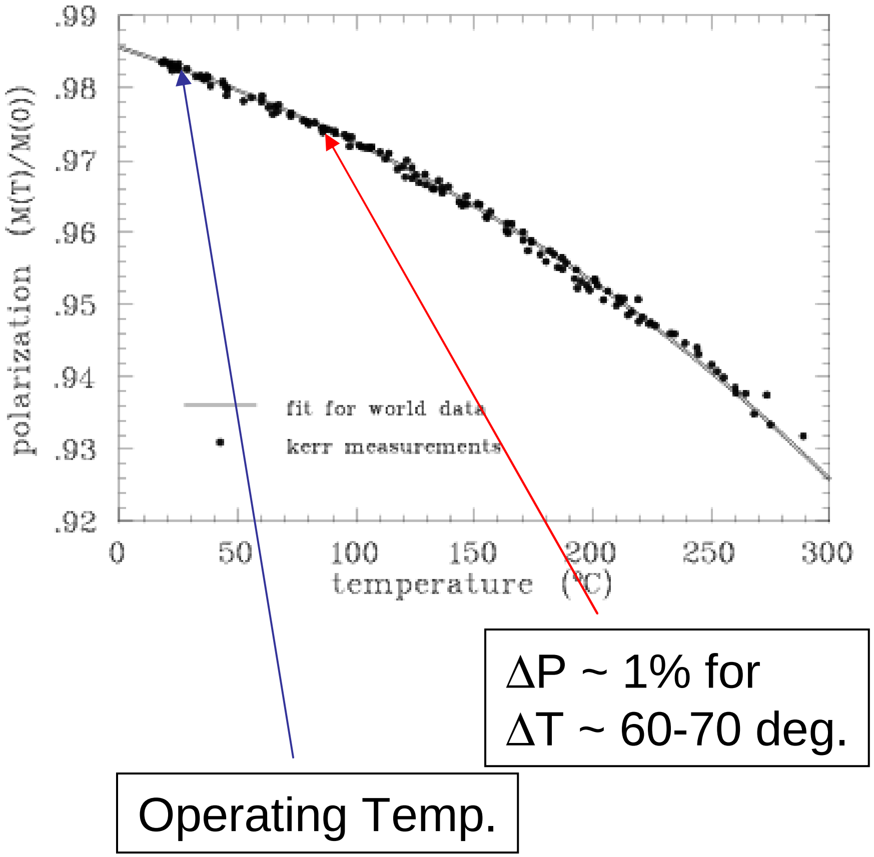
Hall C Møller at High Beam Currents

In general Møller limited to low beam currents to avoid foil depolarization

Since 2003, have been pursuing tests with a fast “kicker” magnet and various targets

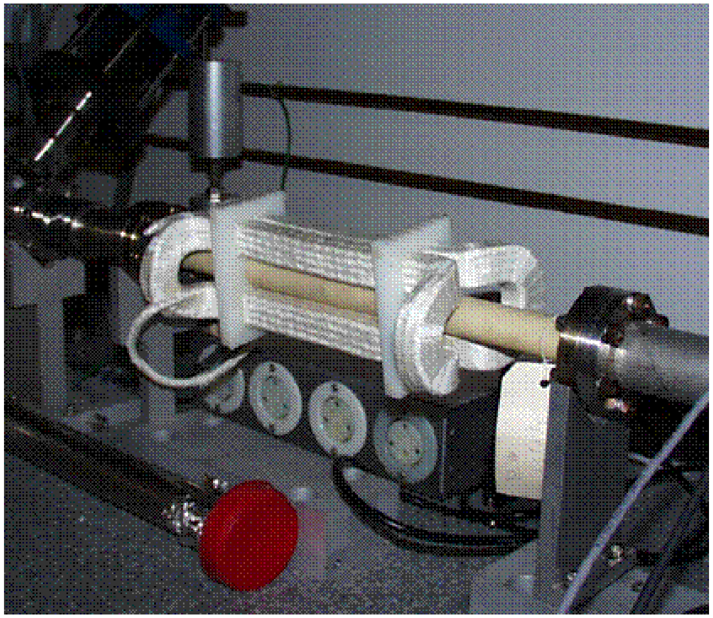
Minimizing time of beam on target and allowing enough time between “kicks” will mitigate foil heating

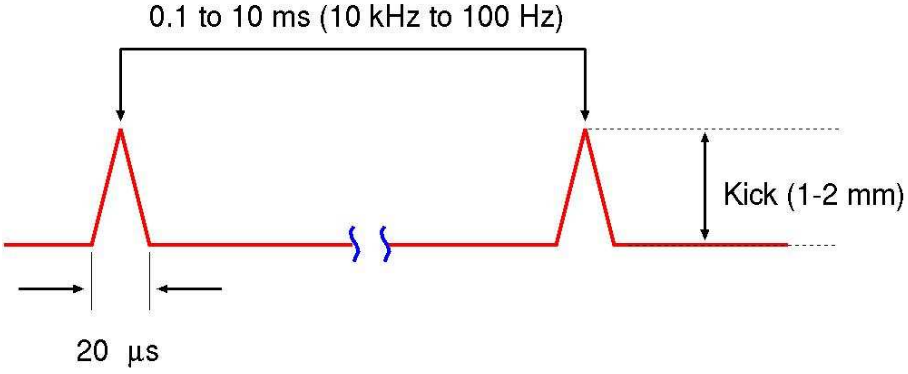
Fe Foil Depolarization



Kicker Magnet for High Current Møller Polarimetry

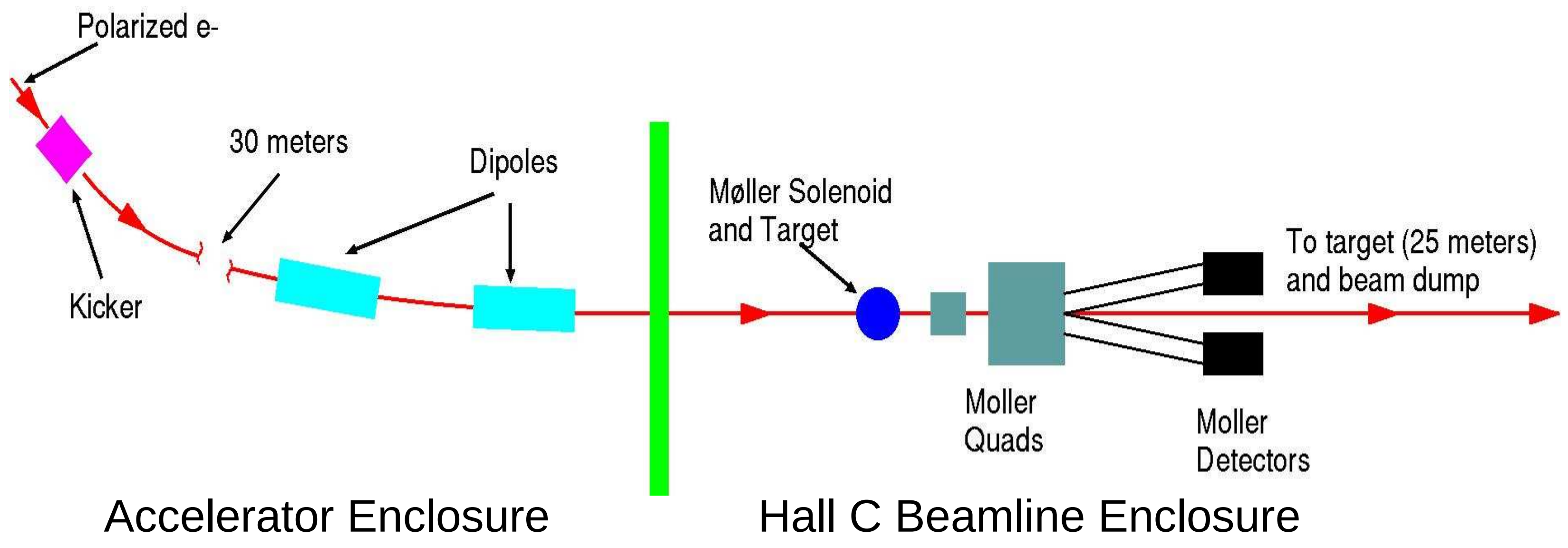
- We can overcome target heating effects by using a fast kicker magnet to scan the electron beam across an iron wire or strip target
- Kicker needs to move beam quickly and at low duty cycle to minimize time on iron target and beam heating
- First generation kicker was installed in Fall 2003 (built by Chen Yan, Hall C)





Kicker + Møller Layout

- Kicker located upstream of Møller target in Hall C beam transport arc
- Beam excursion ~ 1-2 mm at target
- The kick angle is small and the beam optics are configured to allow beam to continue cleanly to the dump



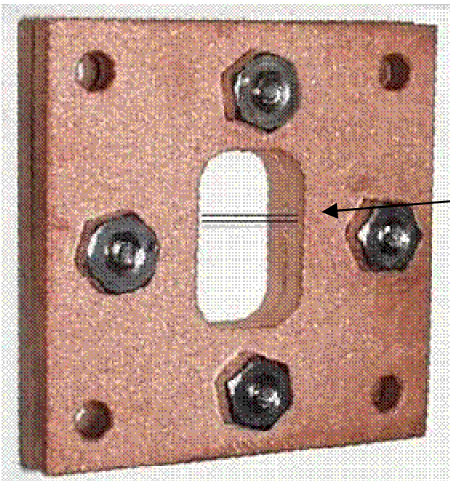
Kicker and Iron Wire Target

- Initial tests with kicker and an iron wire target were performed in Dec. 2003
- Many useful lessons learned
  - 25 μm wires too thick
  - Large instantaneous rate gave large rate of random coincidences

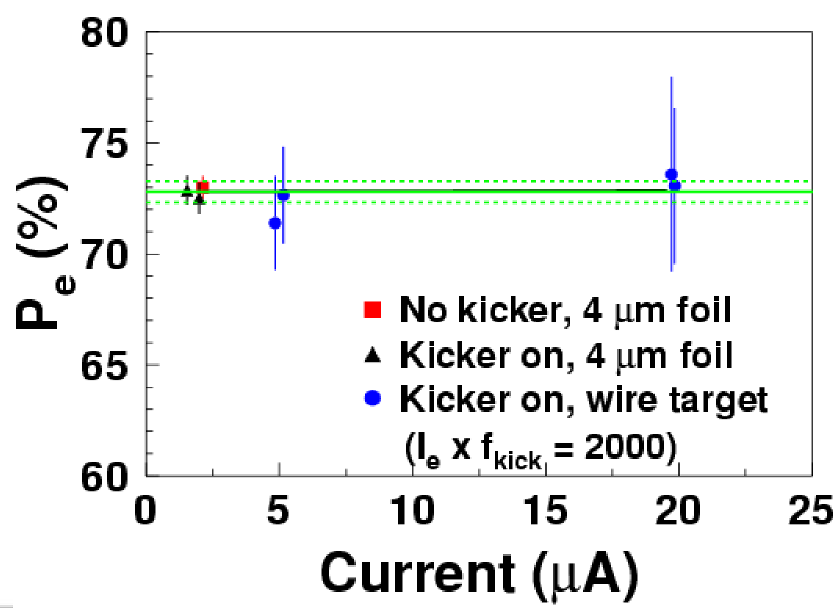
$N_{coincidence}$ ~ target thickness

N_{random} ~ (target thickness)^2

- Nonetheless, we were able to make measurements at currents up to 20 μA (large uncertainties from large random rates)

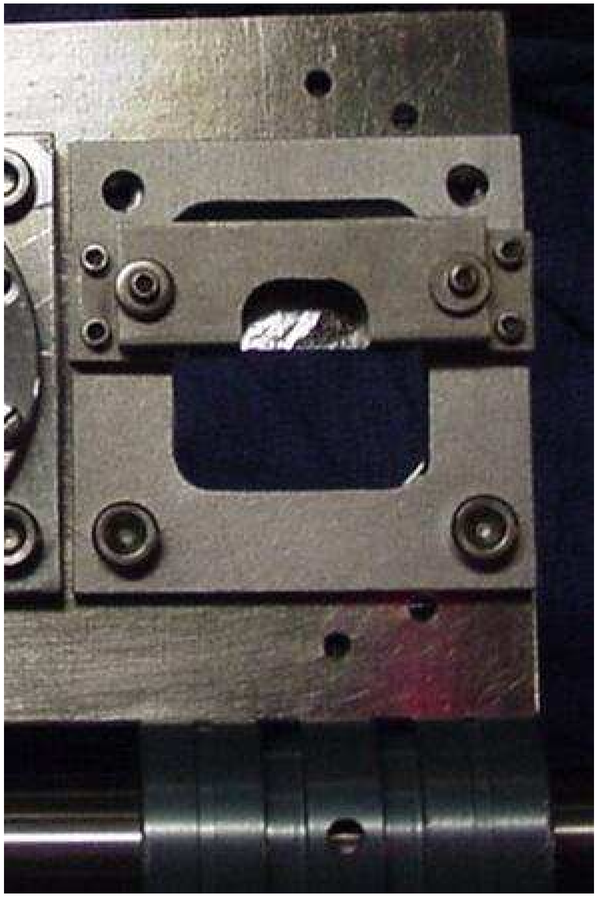


Target built by
Dave Meekins
JLab Target Group



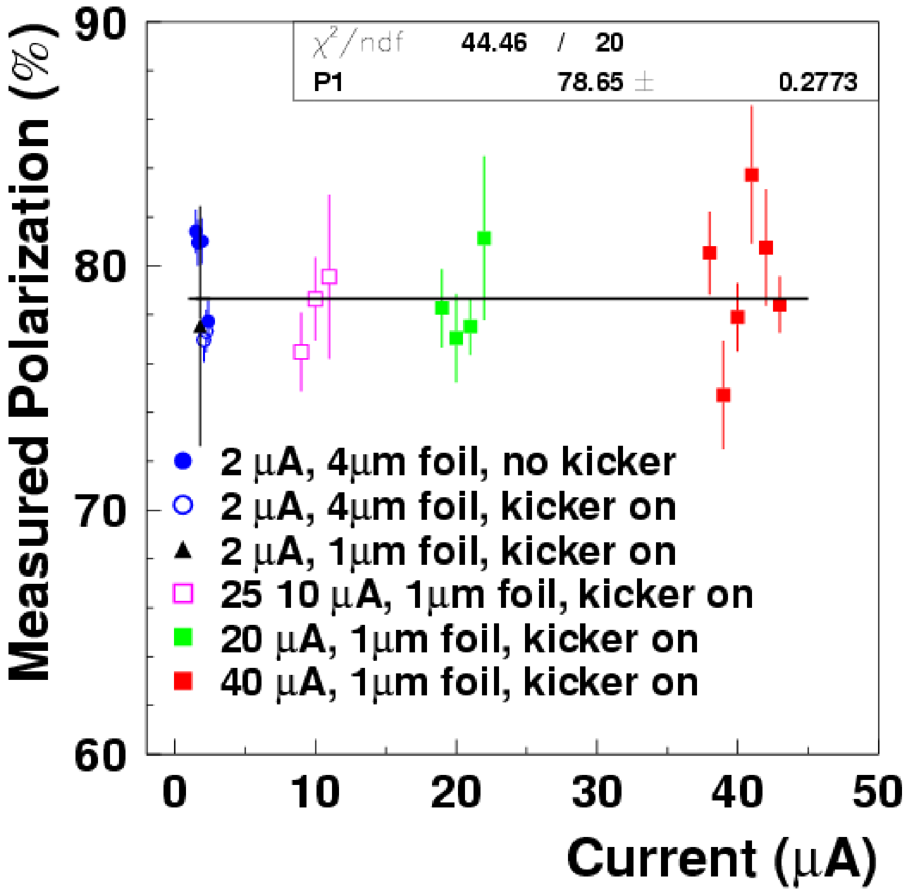
Tests With a 1 μm "Strip" Target

- The only way to keep random coincidences at an acceptable level is to reduce the instantaneous rate
- This can be achieved with a 1 mm foil
  - $N_{real}/N_{random} \approx 10$ at 200 μA at a few GeV
- Replaced iron wire target with a 1 μm thick iron "strip" target
- Conducted more tests with this target and slightly upgraded kicker in December 2004



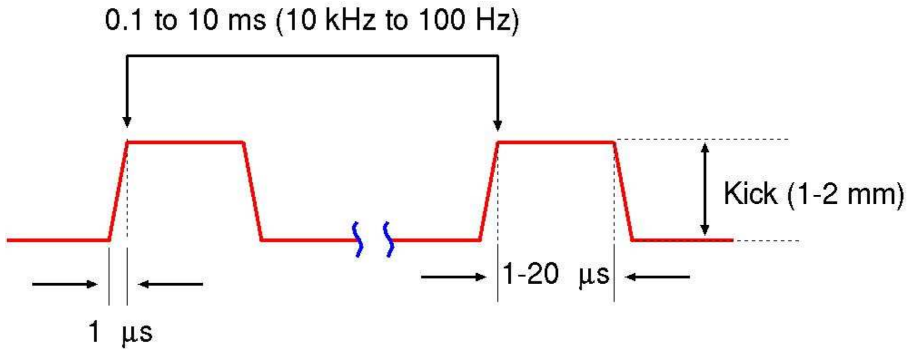
December 2004 Kicker Test Results

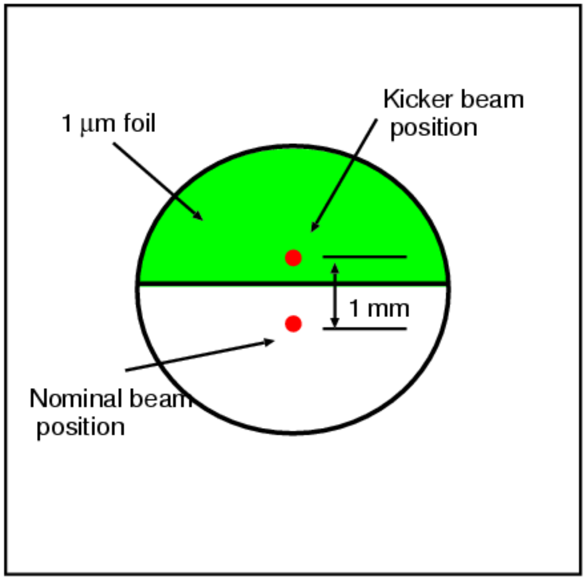
- Short test – no time to optimize polarized source
  - Tests cannot be used to prove 1% precision
- Took measurements up to 40 μA
  - Ion chamber trips prevented us from running at higher currents
  - Lesson learned: need a beam tune that includes focus at Møller target AND downstream
- Demonstrated ability to make measurements at high currents – good proof of principle



Optimized Kicker with “Half-Target”

- The ideal kicker would allow the beam to dwell at a certain point on the target for a few ms rather than continuously move across the foil
- To reach the very highest currents, the kick duration must be as small as 2 μs to keep target heating effects small
- The 1 μm target is crucial – we need to improve the mounting scheme to avoid wrinkles and deformations

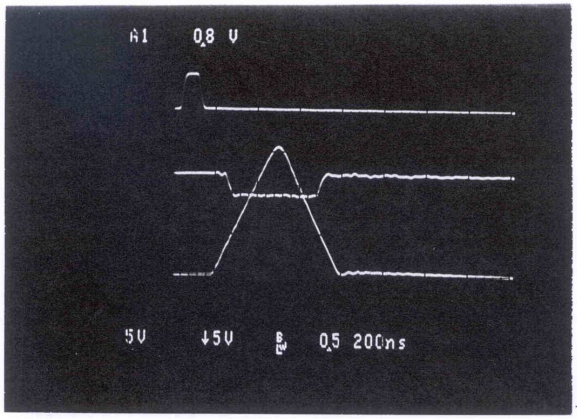


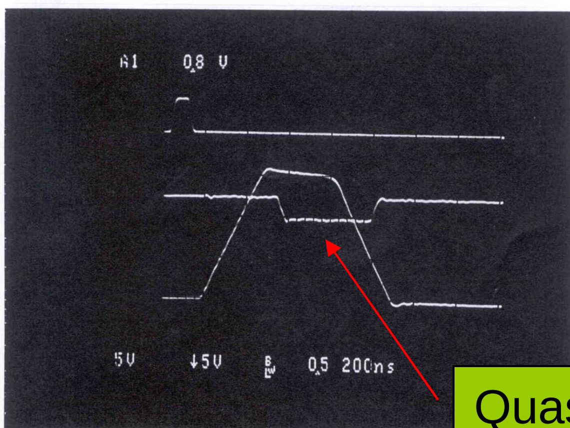


Kicker R&D

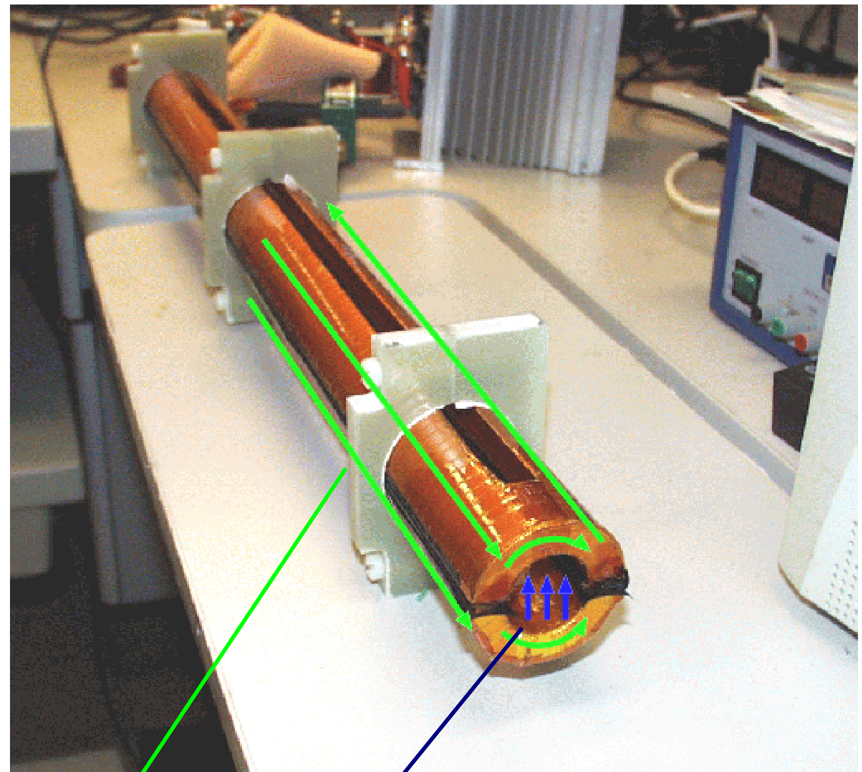
Kicker Current Waveform from Pearson Probe

Base width ~ 600 ns, Reputation ~ 5 kHz, I_{peak} ~ 100 A





Quasi-flat top kicker interval



Current flow

Magnetic field

“Two turn” kicker –
2 μs total dwell time!

Møller Polarimetry Using “Pulsed” Beam

- Use electron beam in “pulsed” mode
  - 0.1-1 μs pulses at 30 to 120 Hz
  - Low average current, but for the duration of the pulse, same current as experiment conditions (10s of μA)

- Using a raster (25 kHz) to blow up the effective beam size, target heating can be kept at acceptable levels

Target Heating vs. Time for one beam pulse

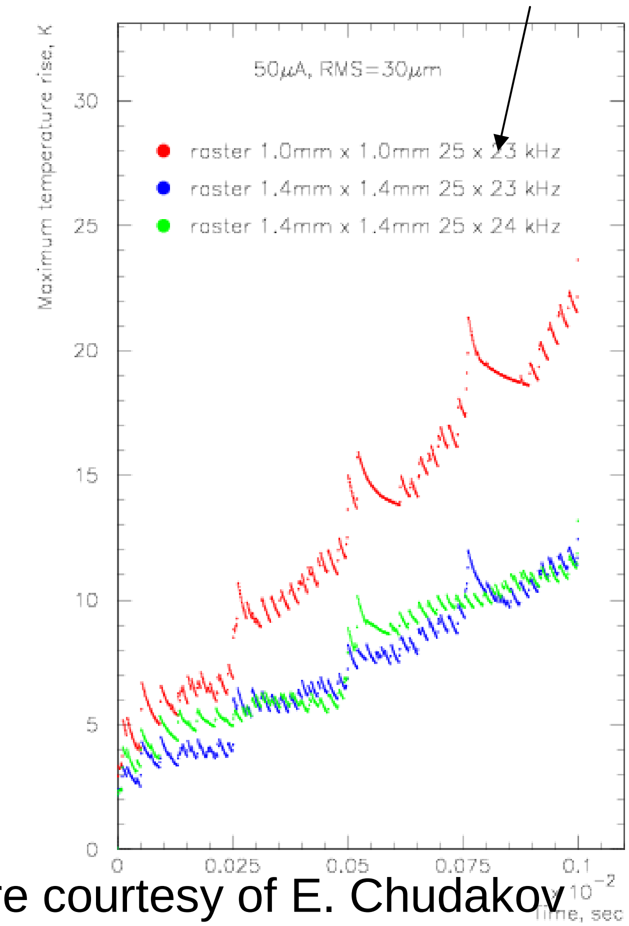


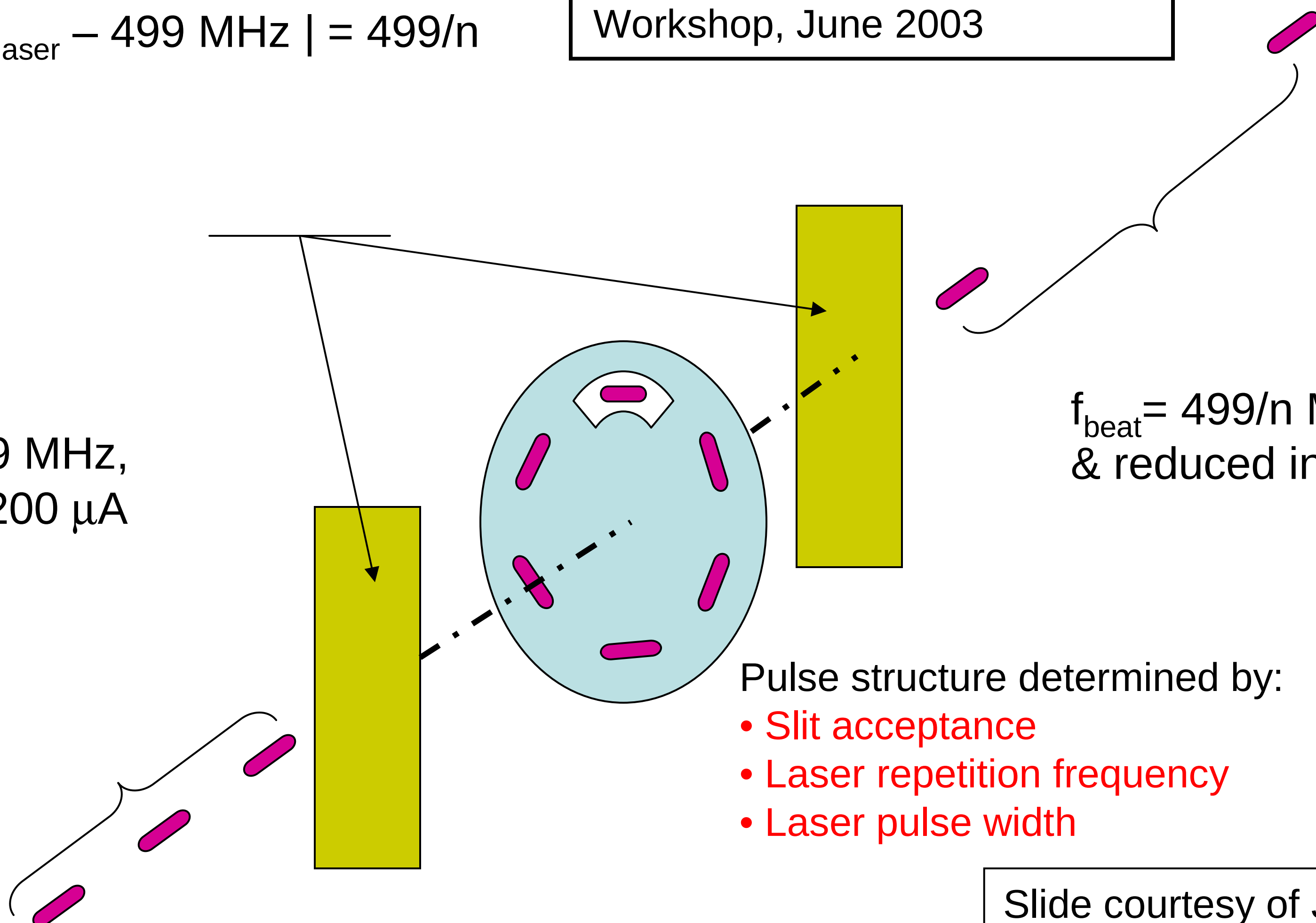
Figure courtesy of E. Chudakov

Generation of 31 MHz Beam Structure

RF beam & chopping

$f_{beat} = | f_{laser} – 499 \text{ MHz} | = 499/n$

Proposed at JLAB Precision Electron Beam Polarimetry Workshop, June 2003



$f_{laser} \neq 499$ MHz,
but I_{ave}=200 μA

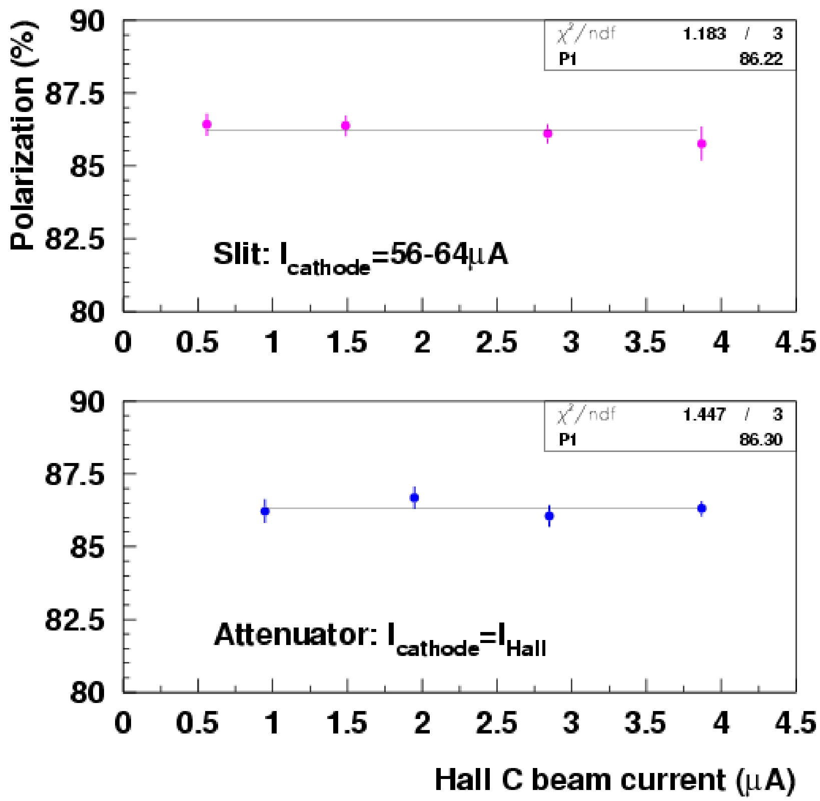
f_{beat}= 499/n MHz,
& reduced intensity

Pulse structure determined by:
- Slit acceptance
- Laser repetition frequency
- Laser pulse width

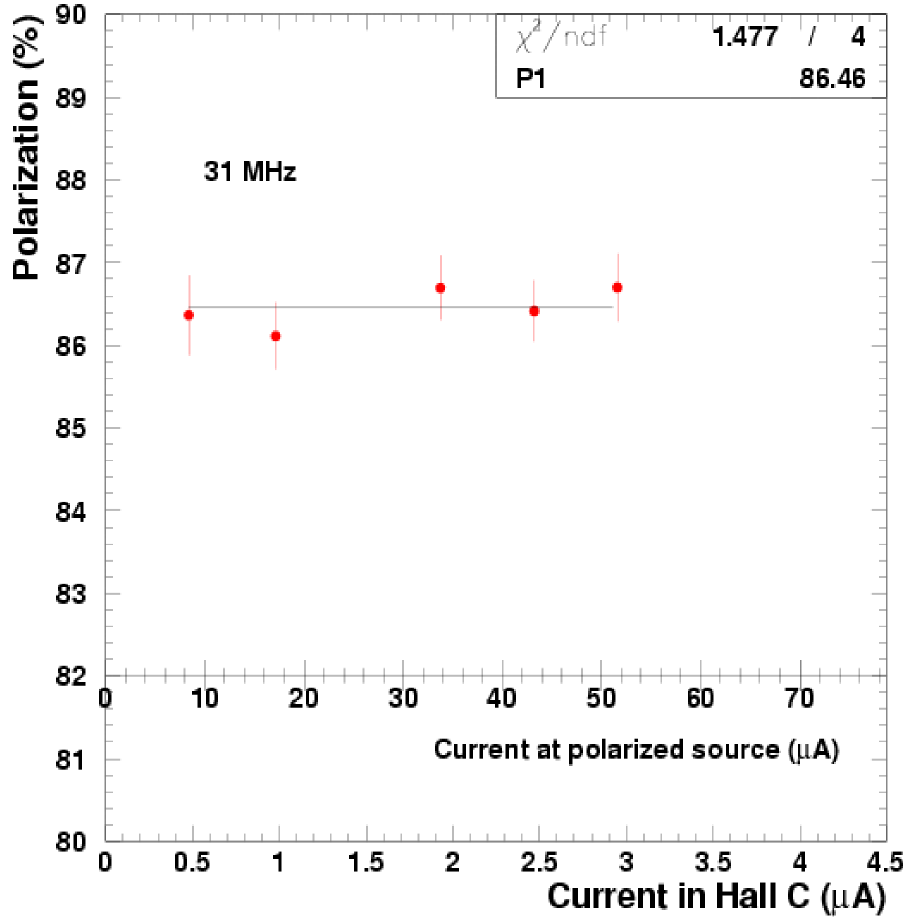
Slide courtesy of Joe Grames

31 MHz Test in Hall C

499 MHz – current reduced using slit or attenuator



31 MHz

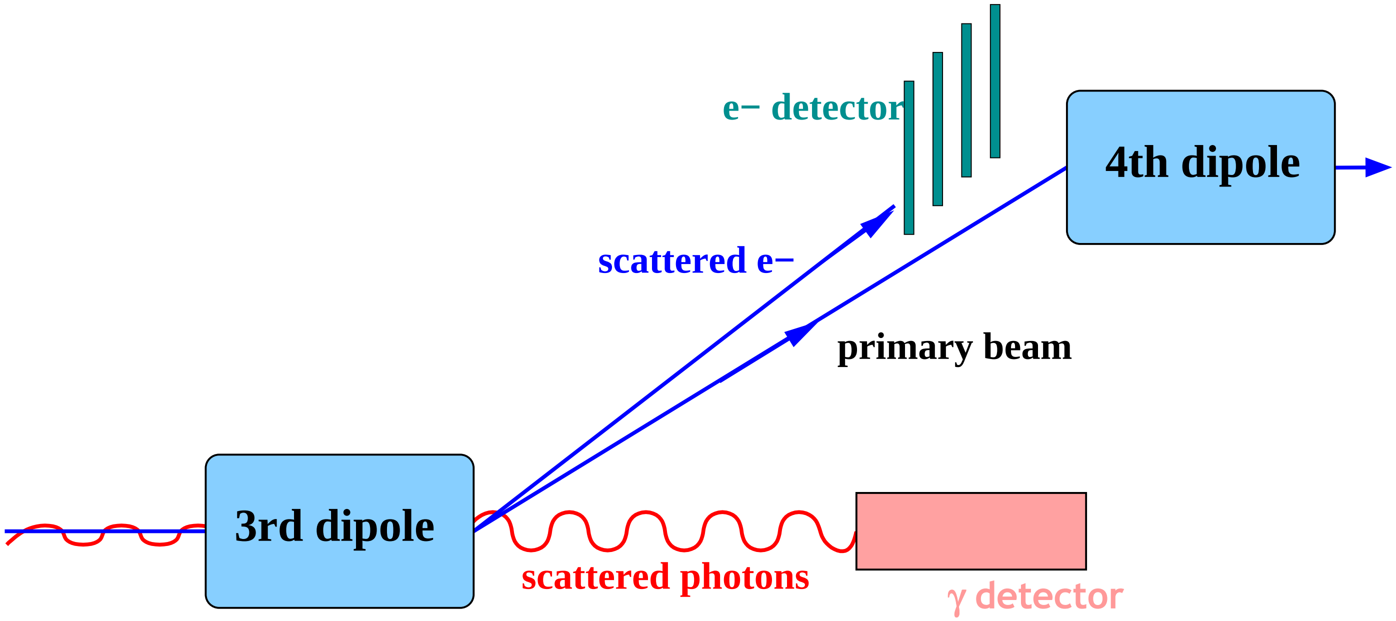


Error bars statistical only

Compton Polarimetry Plans

- Hall C has no Compton Polarimeter
  - Previous experience (G0, GEp) has shown us it is at best difficult to track the polarization over time using “periodic” measurements
  - To achieve dP/P of 1% ***for the experiment***, a continuous measurement is required
- Hall A has a Compton Polarimeter that quotes dP/P=1% at a few GeV
  - For PREX, 1% is required down to 850 MeV
  - There are fundamental issues that limit the systematic error of the existing device at low energy
  - Hall A will upgrade their Compton to achieve dP/P=1% down to 850 MeV

Hall A Compton Polarimeter



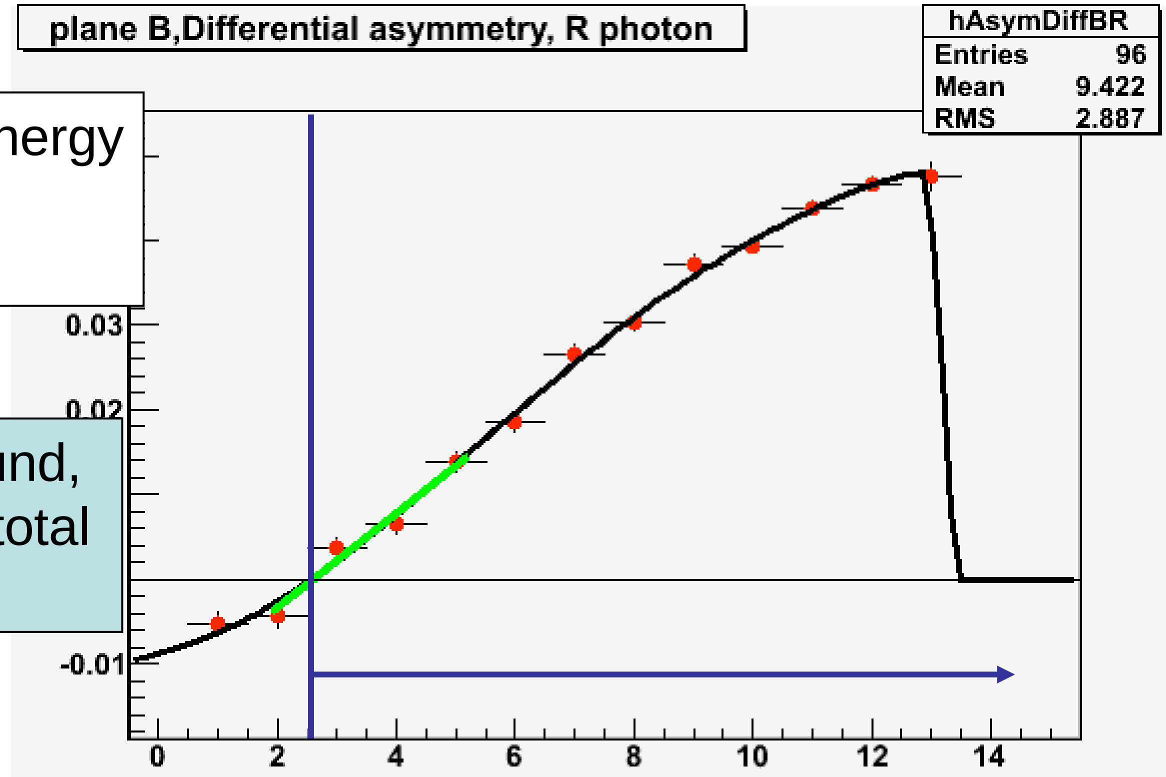
Hall A Compton detects scattered electron and backscattered photon simultaneously

→Uses high gain IR cavity to increase luminosity

→Best precision typically achieved using electron detector analysis

Electron Detector

2 points of well defined energy
→End point
→Zero-crossing



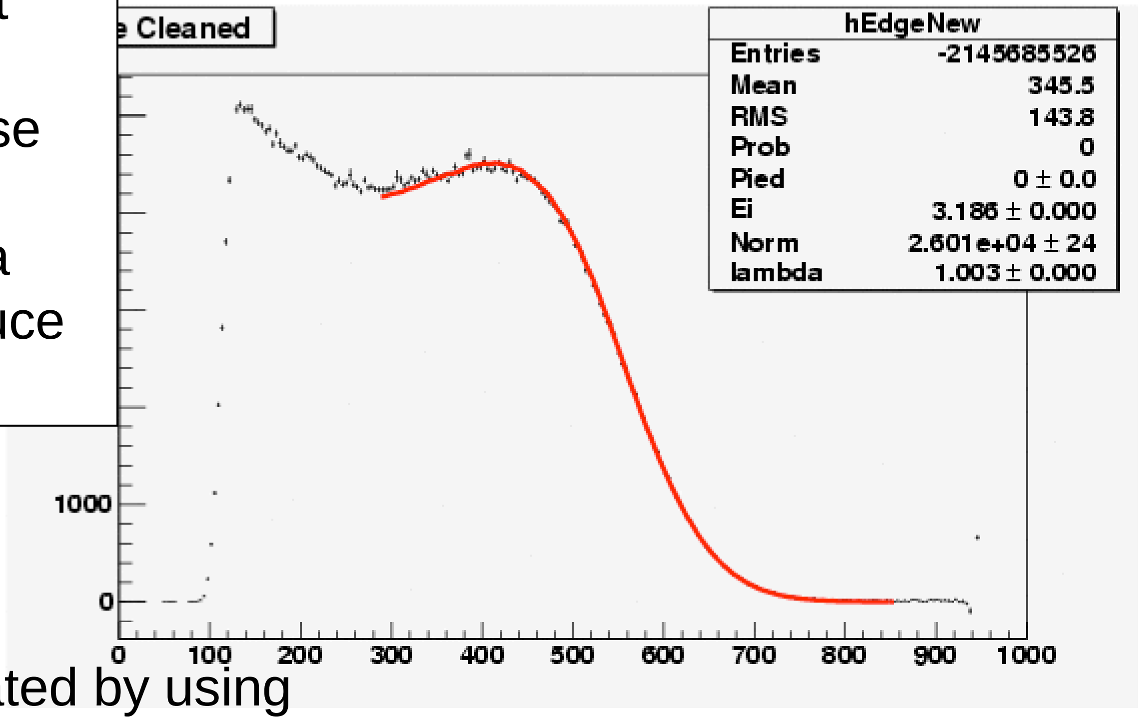
Once zero-crossing is found, relatively easy to extract total analyzing power

At low energy – zero-crossing not in the acceptance
→This can be fixed by switching from IR to green laser
→Green laser also has the advantage of yielding larger asymmetry
→Upgrade will also increase granularity to improve resolution

Photon Detector

Extracting analyzing power for photon detector more difficult

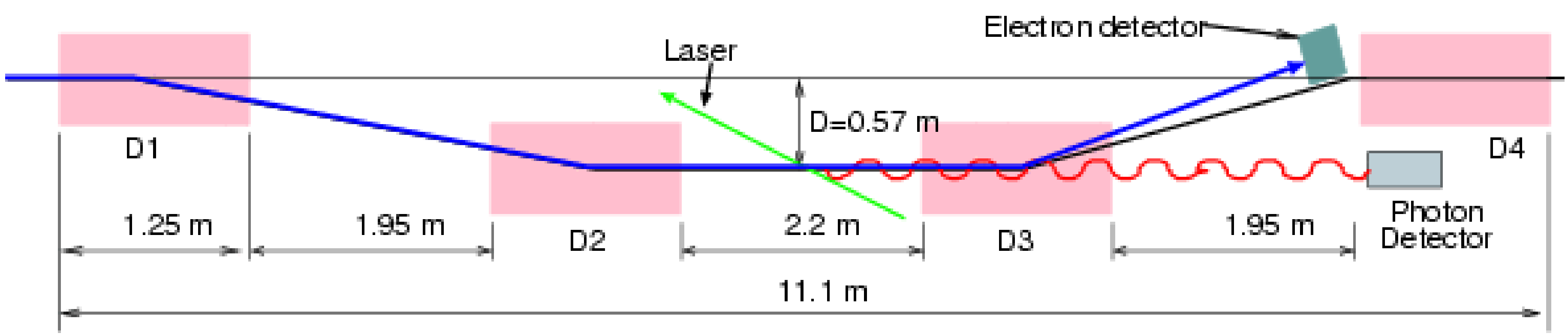
→Need to know the "response function", *R(ADC,k)*
→*R(ADC,k)* = probability of a photon of energy "*k*" to produce a signal in channel "ADC"



This can be somewhat alleviated by using "integrating" method → less sensitive to thresholds and absolute response
→ Integrating method (in combination with new photon detector) will be pursued for PREX

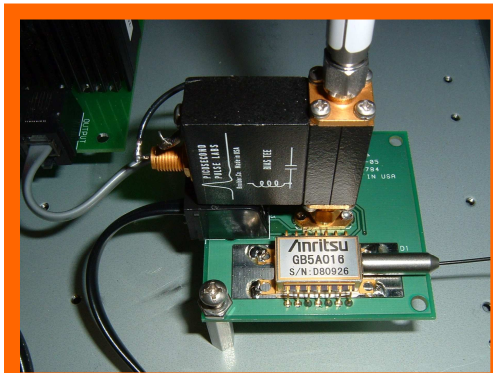
Hall C Compton Polarimeter

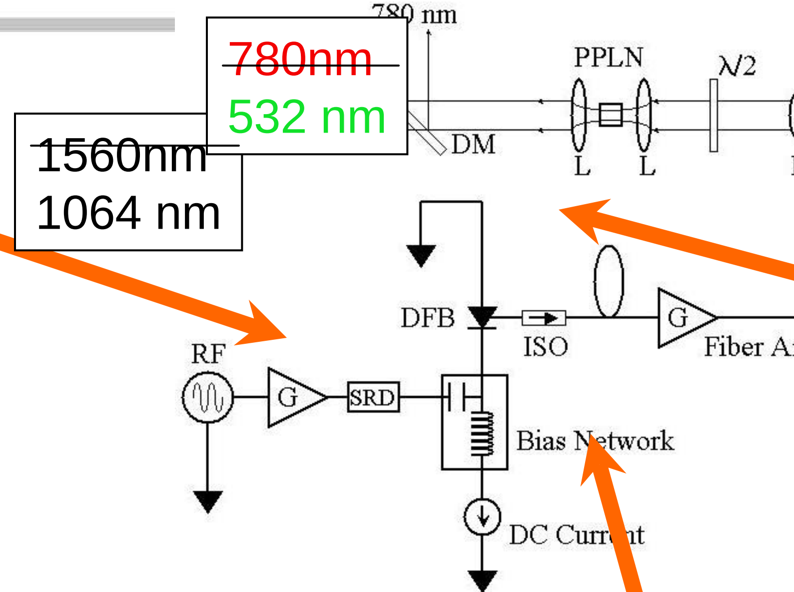
- The Hall C Compton polarimeter will be very similar to the Hall A Compton with some differences in the details
  - Chicane → vertical drop = 57 cm (30 cm in Hall A) → larger separation between scattered electron and beam
  - Electron detector → diamond strip detector with 200 μm pitch (silicon strip in Hall A)
  - Photon detector → Lead-tungstate for now
  - RF pulsed 20 W green laser (high gain cavity in Hall A)



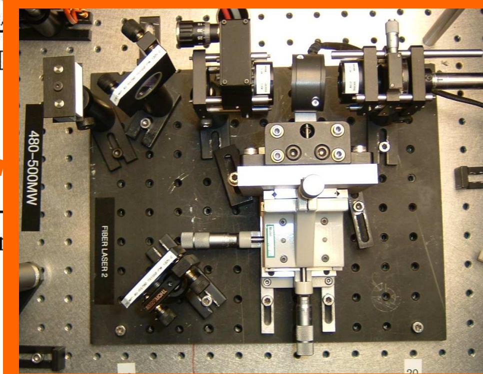
Fiber-Based Drive Laser

Gain-switched seed





Frequency-doubler



ErYb-doped fiber amplifier

Luminosity from Fiber Laser

- Average power from fiber laser modest (20 W) → Hall A will have high gain cavity with 1 kW of green power
- How can we live with this relatively low laser power?
  - For laser pulsed at electron beam repetition rate (499 MHz) and comparable pulse width (on the order of ps), the luminosity is increased by a factor:

$$\frac{L_{pulsed}}{L_{CW}} \approx \frac{c}{f\sqrt{2\pi}}\left(\sqrt{\sigma^2_{c\tau,laser}+\sigma^2_{c\tau,e}+\frac{1}{\sin^2(\alpha/2)}\left(\sigma_e^2+\sigma^2_{laser}\right)}\right)^{-1}$$

- For typical JLab parameters, this yields about a factor of 20 improvement in luminosity for α = 20 mrad

20 W RF pulsed laser ~ 400 W CW laser

Hall C Compton Project

- Laser → EGG+Shukui Zhang+UVa+Hall C
- Electron Detector → U. Winnipeg + Miss. State
- Photon Detector → Yerevan + Hampton U.
- Dipole chicane → MIT-Bates
- Beamline overhaul → JLAB

Everything must be ready at to be installed simultaneously with Q_{weak} → Fall 2009!

Systematic goal = 1%: this will take significant effort and time. Initially we will cross-calibrate to Møller

Polarimetry at JLab

- Measuring the electron beam polarization at JLab is an industry with many contributors from EGG, and the experimental Halls
- Availability of multiple polarimeters using multiple techniques at JLab is a real advantage and strength
- To achieve 1% (and better) polarimetry, 2 things are required
  – More time: Experimenters want 1%, but they don't want to pay the price. It is hard to get beam time for systematic tests.
  – Better coordination between halls: As hard as it is to get time in 1 hall for polarimetry tests, it is harder to get time for 2 halls! (at the same time)