Positron and electron polarimetry at modest beam energies

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Positron Working Group Meeting

March 7-8

Polarimetry in the Positron Injector

- Working assumptions
  - Beam energy = 120 MeV
  - Current for electrons = few mA
  - Current for positrons = few hundred nA
- Goals
  - Continuous, non-destructive
  - Precision 1% or better

- Usual techniques for absolute polarimetry
  - Mott: Scattered electrons/positrons of interest difficult to detect at 120 MeV?
  - Compton: small analyzing power at 120 MeV, but non-destructive, “symmetric” for e+/e-
  - Møller: Maybe easiest. High current an issue. Destructive. Spectrometer an issue?

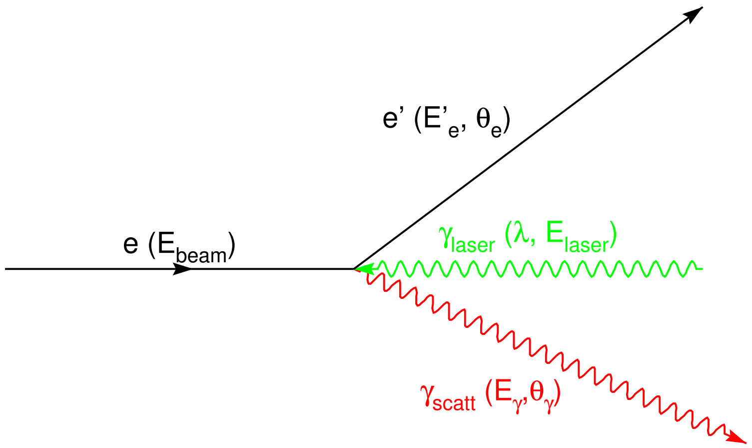
Helpful discussion can be found in Eugene Chudakov’s talk from the PEB (Polarized Electron Beams) Workshop at MIT in 2013

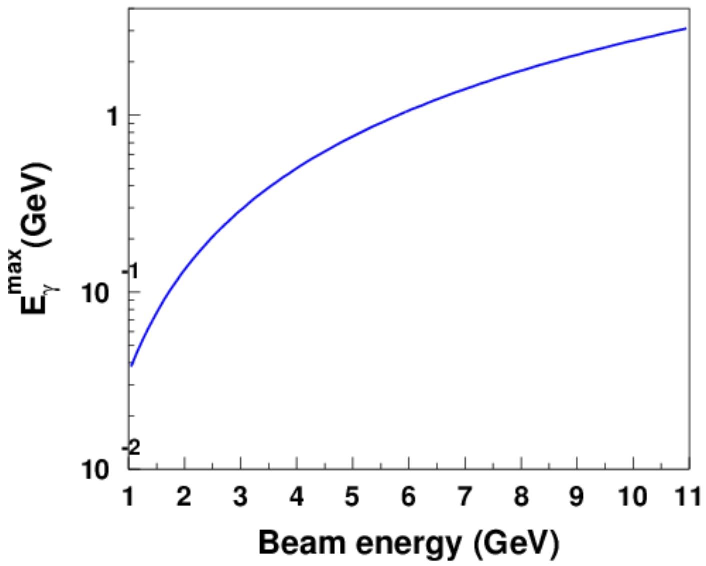
Compton Scattering - Kinematics

Laser beam colliding with electron beam nearly head-on

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

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





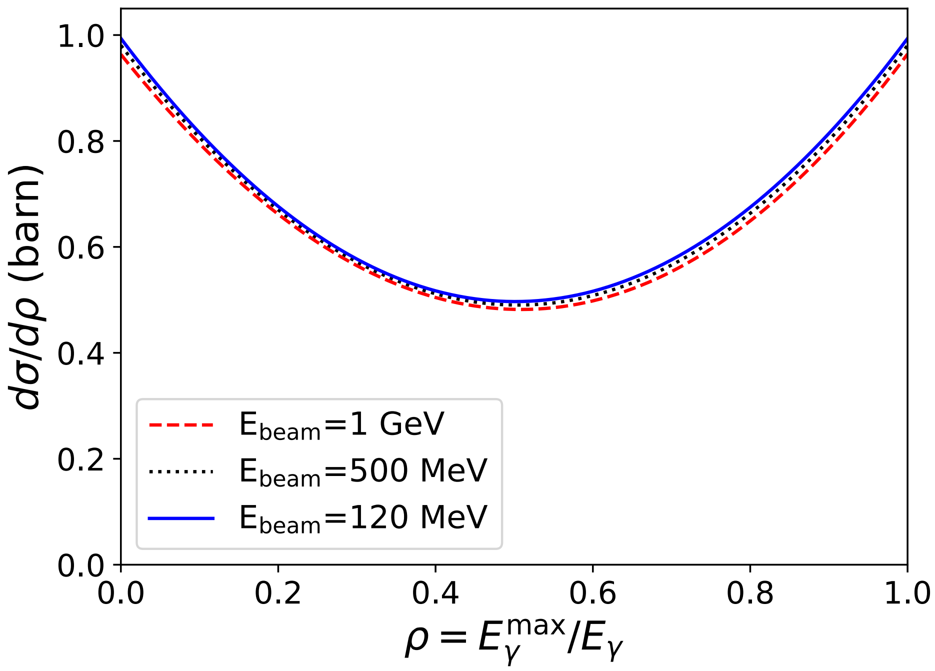
Maximum backscattered photon energy at θ=0 degrees (180 degree scattering)

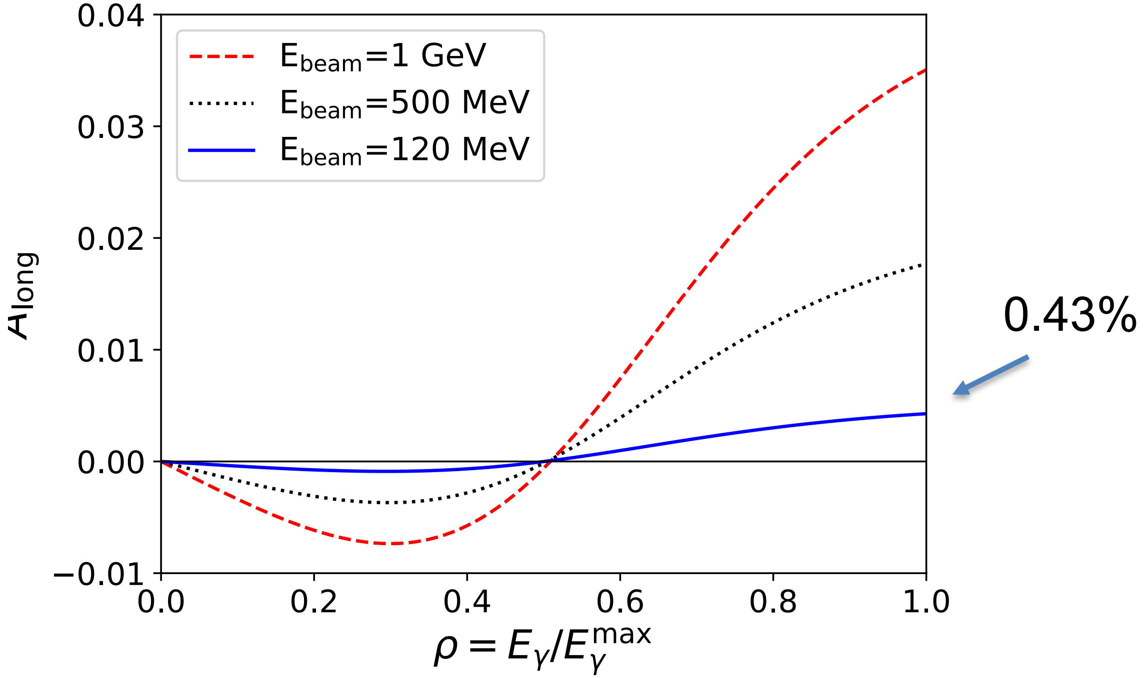
<u>For green laser (532 nm):</u>

→ E_γ^{max} ~ 34.5 MeV at E_{beam}=1 GeV
→ E_γ^{max} = 3.1 GeV at E_{beam}=11 GeV
→ **E_γ^{max} = 0.5 MeV at E_{beam}=120 MeV**

Compton Scattering – Cross Section and Asymmetry

$$\rho = \frac{E_\gamma}{E_\gamma^{\max}} \quad \Rightarrow \quad \frac{d\sigma}{d\rho} = 2\pi r_o^2 a \left[\frac{\rho^2(1-a)^2}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)} \right)^2 \right]$$

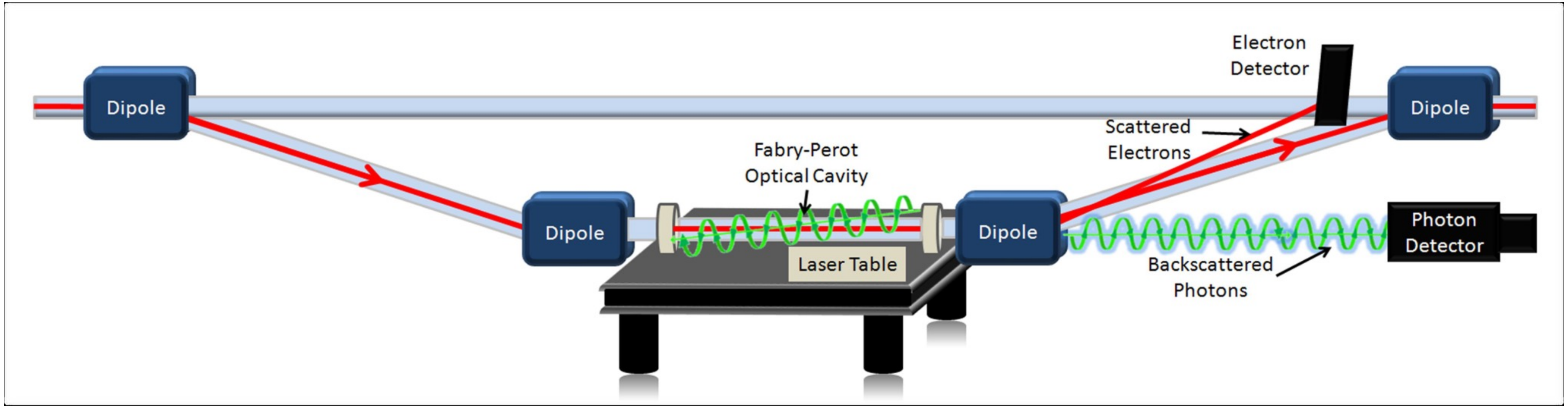




$$A_{\text{long}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} (1-\rho(1+a)) \left[1 - \frac{1}{(1-\rho(1-a))^2} \right]$$

Jefferson Lab

Compton Polarimeter Example (Halls A and C)



Components:

1. 4-dipole chicane: Deflect electron beam
2. Laser system: Fabry-Perot cavity pumped by CW laser → few kW stored power
3. Photon detector: PbWO4 or GSO – operated in integrating mode
4. Electron detector: segmented strip detector

Compton Polarimetry for Positrons and Electrons

- Compton polarimetry can be applied (easily?) to both positron and electron beams
  - Cross sections, analyzing power identical
  - Polarimeter layout (dipole chicane, detectors, etc.) needs no modifications → ***just need to flip polarity of dipoles in chicane***
- Challenges
  - Small analyzing power at low energy → 0.43% at endpoint
  - Low rates for positrons (~100 nA) → typically run at 10's of μA in experimental halls
  - Small backscattered photon energy → different detector technology than we typically use for Compton polarimeters at JLab

Compton Measurement Times

Luminosity for Compton scattering at non-zero crossing angle (CW laser):

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

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:

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

Measurement time depends on square of analyzing power

This can be average analyzing power, energy-weighted

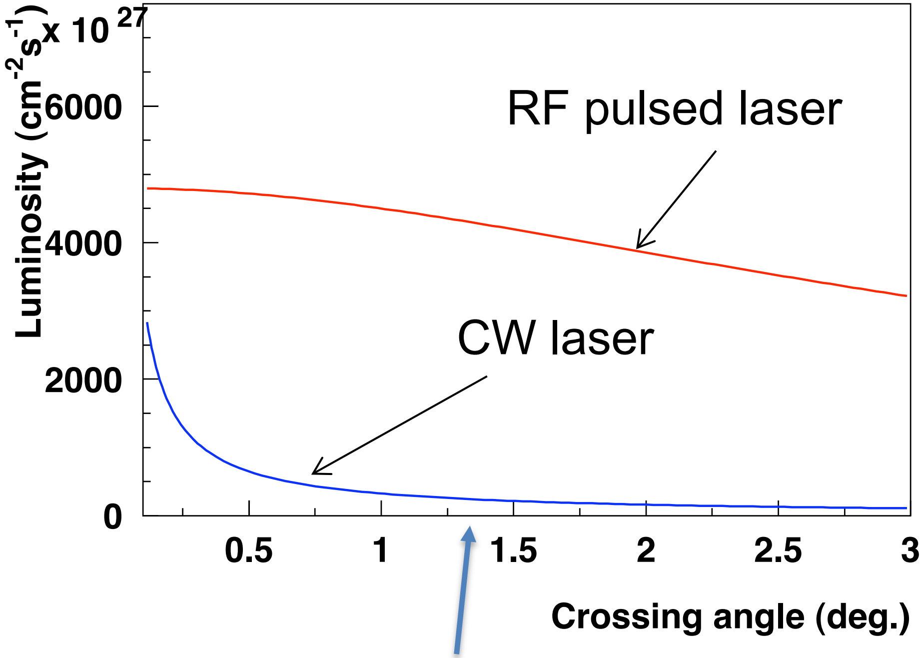
Measurement time estimates

- Assumptions:
  - Fabry-Perot cavity similar to Hall A/C Compton polarimeters
    - 1.3 deg. crossing angle
    - stored laser power 4 kW @ λ=532 nm
  - Laser/beam spot sizes: $\sigma_x=\sigma_y=100\ \mu m$
- Time to achieve statistical precision of 1%
  - Electrons @ 2 mA: t= 6-8 minutes, backscattered photon rate = 7.2 MHz
  - Positrons @ 200 nA: t=60,000-80,000 minutes → order 1000 hours!

RF pulsed FP Cavity

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

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



Hall A/C FP cavities

Luminosity from pulsed laser drops more slowly with crossing angle than CW laser

→ FP cavity pumped by mode-locked laser at beam frequency could yield significantly higher luminosity

→ More complicated system – R&D required

RF pulsed cavities have been built – this is a technology under development for ILC among other applications

JLab beam structure, nominal laser system, luminosity increase is about a factor of 55

Measurement time estimates

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  - ~~Positrons @ 200 nA: t=60,000-80,000 minutes → order 1000 hours!~~
  - Positrons @ 200 nA, pulsed FP cavity → 18 hours
    - Still too long!
    - May be able to reduce by factor of 2 with higher gain/finesse cavity
    - Lower precision goals (factor of 4 is we go for 2% instead of 1%)
    - Combining both of the above → 2.3 hours

Compton at 120 MeV – photon detector

Photon detector
→ Maximum backscattered photon energy = 0.5 MeV – this is a very different regime than what we are used to!
→ Need sufficient energy resolution to measure Compton photon energy spectrum

→ Will need different type of photon detector (PbWO4, GSO not good enough)
→ HPGe?
→ Tried HPGe detector with Compton test in late 90's without great success – backgrounds were an issue

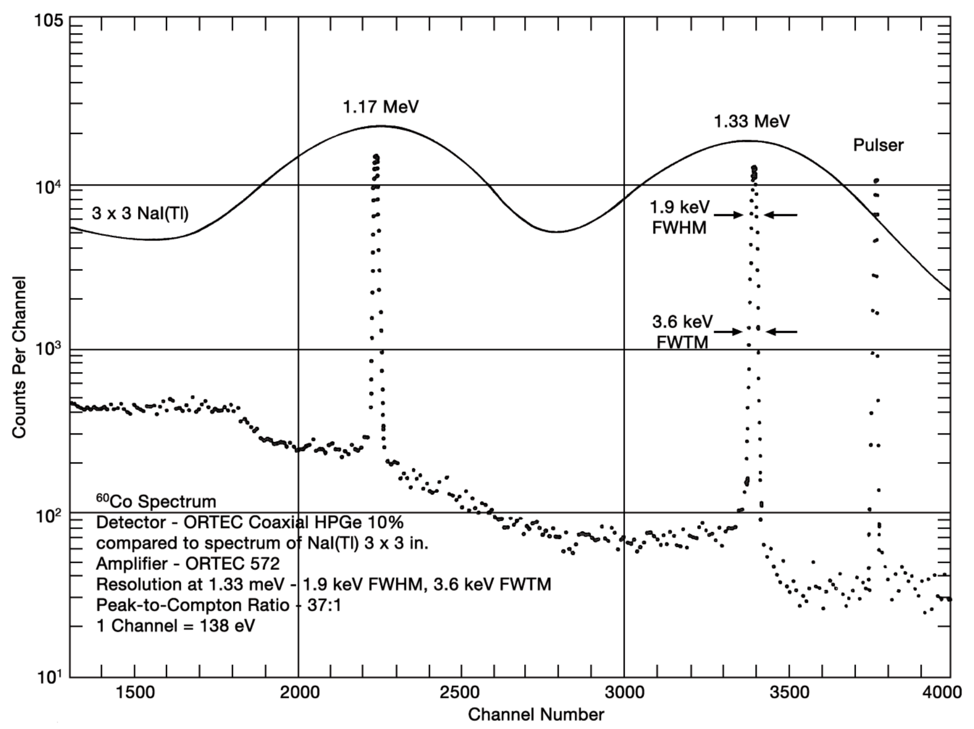


Fig. 7.1. A Portion of a ^{60}Co Spectrum, Illustrating the Energy Resolutions and Peak-to-Compton Ratios for a Coaxial HPGe Detector Compared to a NaI(Tl) Detector.

High-Resolution Gamma-Ray Spectroscopy - Ortec

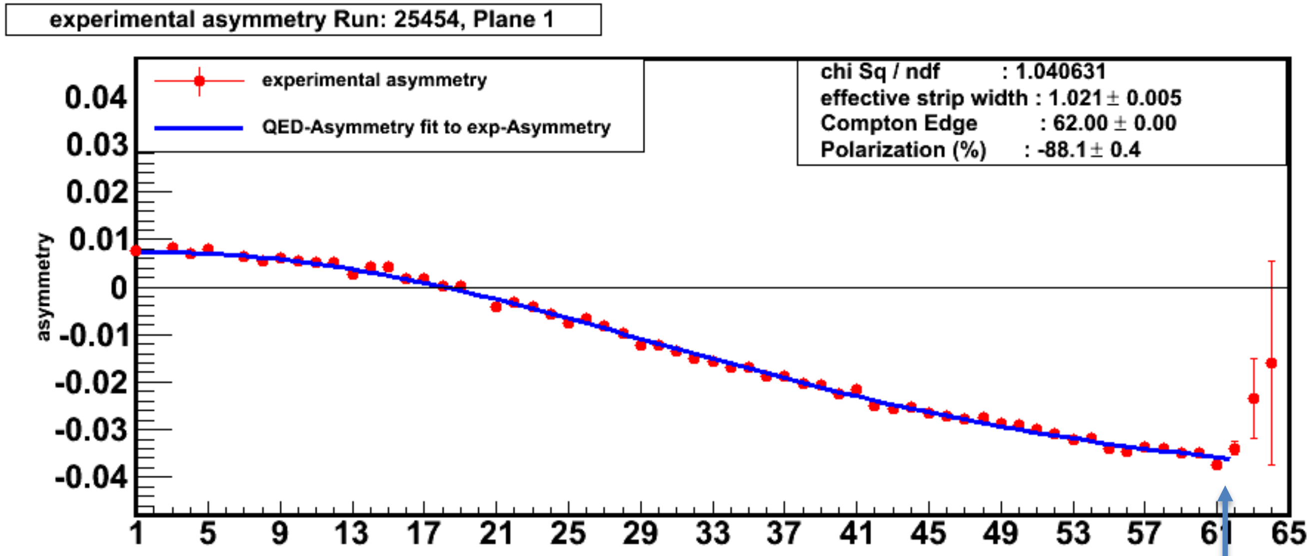
Compton at 120 MeV –electron detector

Scattered electrons deflected away from main beam by dipole
→ Higher energy backscattered photons → lower energy electrons → larger distance from beam

Hall A/C chicanes designed to allow detection of scattered electrons to zero crossing

Hall A chicane: 2.3 degree bend, ~20 cm beam displacement at laser

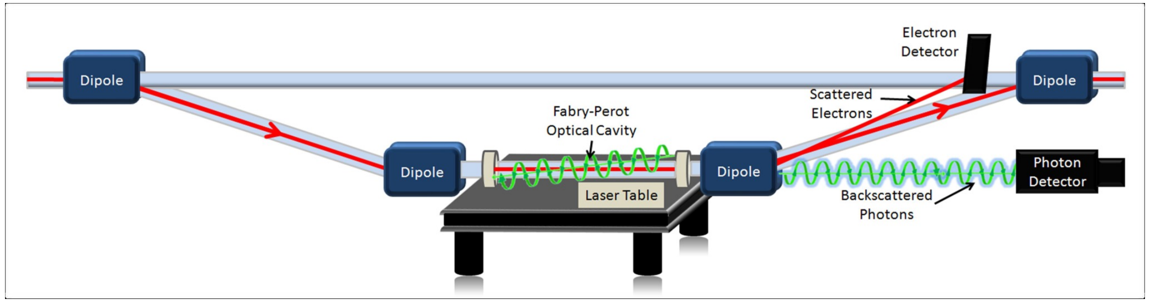
To get scattered electrons ~ 1 cm from beam at 120 MeV – need 20-degree bend → **beam displacement = 3 m!**



Beam

Distance from beam

Compton endpoint



Compton Summary

- Compton polarimetry in principle possible at 120 MeV, but several challenges
  - Small analyzing power significantly increases measurement time (problem for positrons in particular)
  - Kinematics requires much larger footprint for chicane if electron detector used
  - Photon detection requires different detector technology
- Other considerations
  - Compton polarimetry generally requires non-trivial analysis time → can get online results, but final results take more work
  - Can be used continuously, but then requires significant attention → during PREX/CREX, a team of 3-4 people were regularly monitoring the Compton laser system, detectors and results

Møller Polarimetry

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

Electrons

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

Positrons

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

Longitudinally polarized electrons/target:

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

→ 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

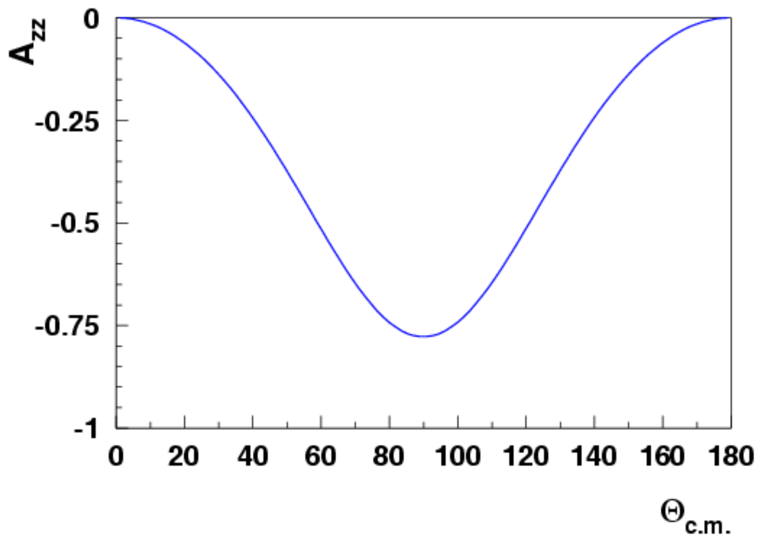
Maximum asymmetry independent of beam energy

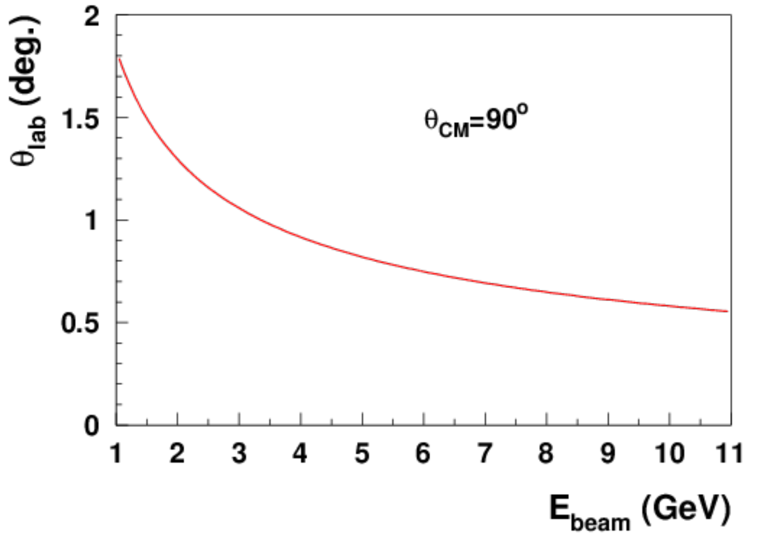
Møller Polarimetry

Møller polarimetry benefits from large longitudinal 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 ~ 8%

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





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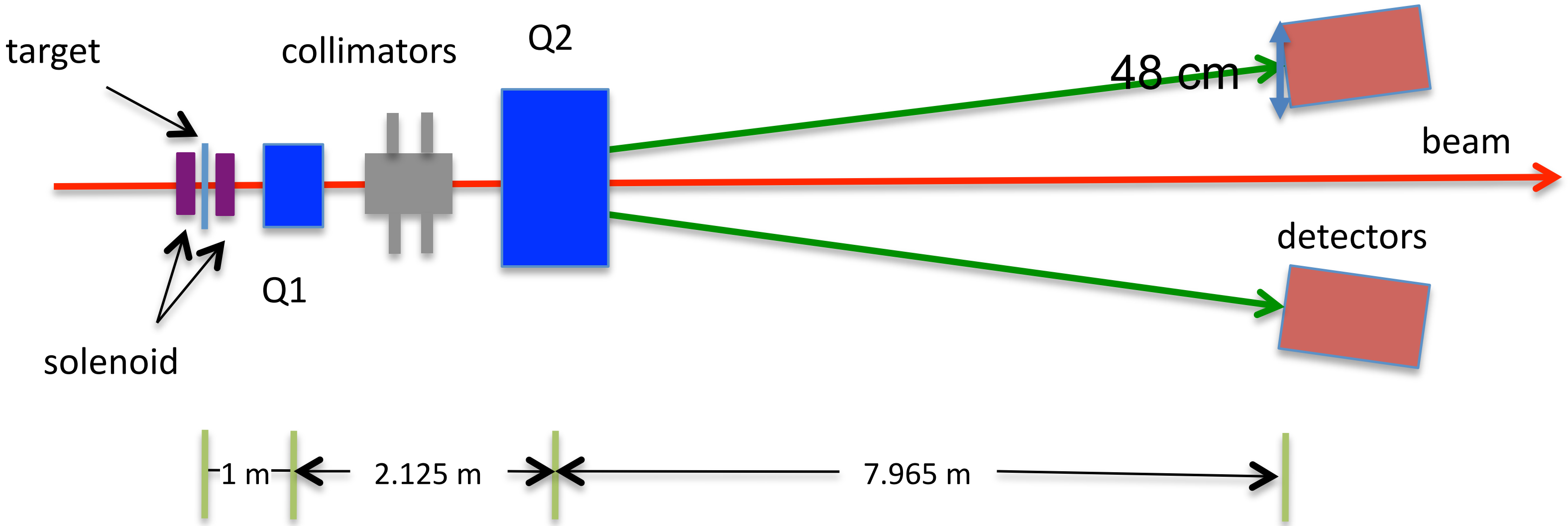
Example: Hall C Møller Polarimeter

- Spectrometer (2 quads) needed to steer scattered + recoiling electrons to detectors
- Target is typically some kind of metallic foil → destructive to beam. Measurements must be made intermittently
- Hall C target = pure Fe foil, brute-force polarized out of plane with 3-4 T superconducting magnet
- Beam currents limited to 1-2 μA → higher currents lead to foil depolarization
- Systematic uncertainties <1%
  - Typically dominated by target polarization, but Hall C high-field target reduces this to ~0.25%



Møller Polarimetry at 120 MeV

In experimental halls, **spectrometer** required to get sufficient separation between electrons/positrons and beamline

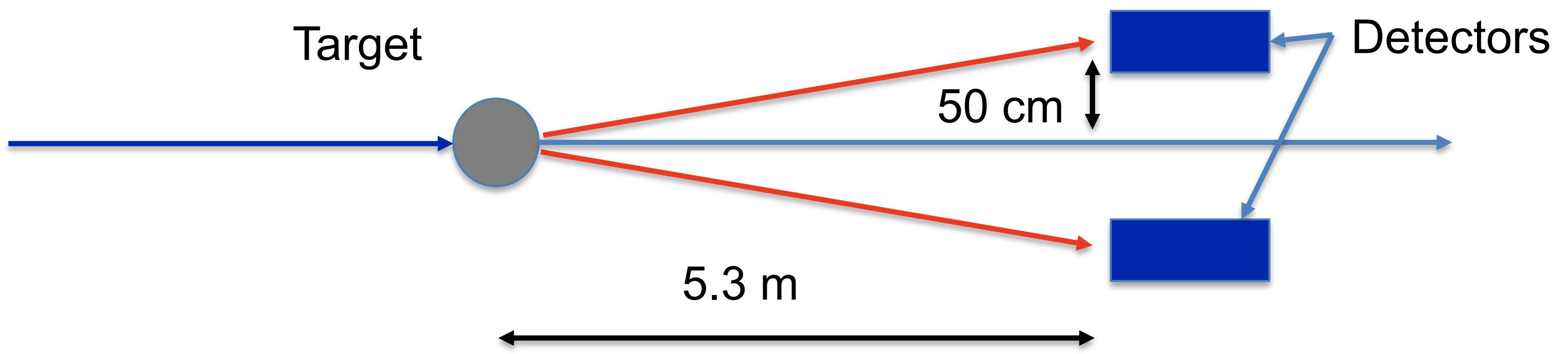
→ Challenging for polarimeter intended for both electrons and positrons:

- → For electron beam, spectrometer must deflect 2 particles with same charge to detectors
- → For positron beam, spectrometer must deflect 2 oppositely charged particles to detectors
- → Can't use identical setup for both electrons and positrons (see JPOS17 talk)

At 120 MeV, lab scattering angle is large → 5.3 degrees!

→ This is big enough that a spectrometer likely isn't needed

→ For detectors 50 cm from beamline, need 5.3 m drift



Møller Polarimetry at 120 MeV

- Advantages
  - No spectrometer required at these low energies – not so much space along beamline
  - Works equally well for electrons and positrons (modulo target magnet focusing)
  - Measurement times for 100-200 nA can be on the order of 20-30 minutes for 1% statistical precision
- Disadvantages
  - Destructive – measurement must be made intermittently
  - Beam currents for electrons must be reduced → 2 mA too high
  - ***High precision (~1%) requires high field target magn***et → steering may be challenging!

Non-destructive Møller Measurement?

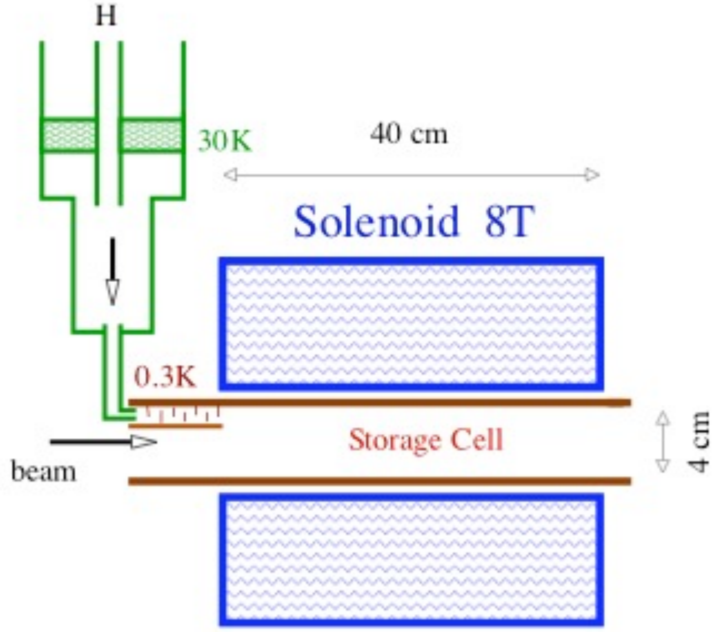
Proposal to use atomic hydrogen as target; operates at full beam current, non-destructive measurement

→at 300 mK, 8 T, $P_e \sim 100\%$

→density ~ 3 10^{15} cm^{-3}
→lifetime >1 hour
→Expected precision < 0.5%!

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

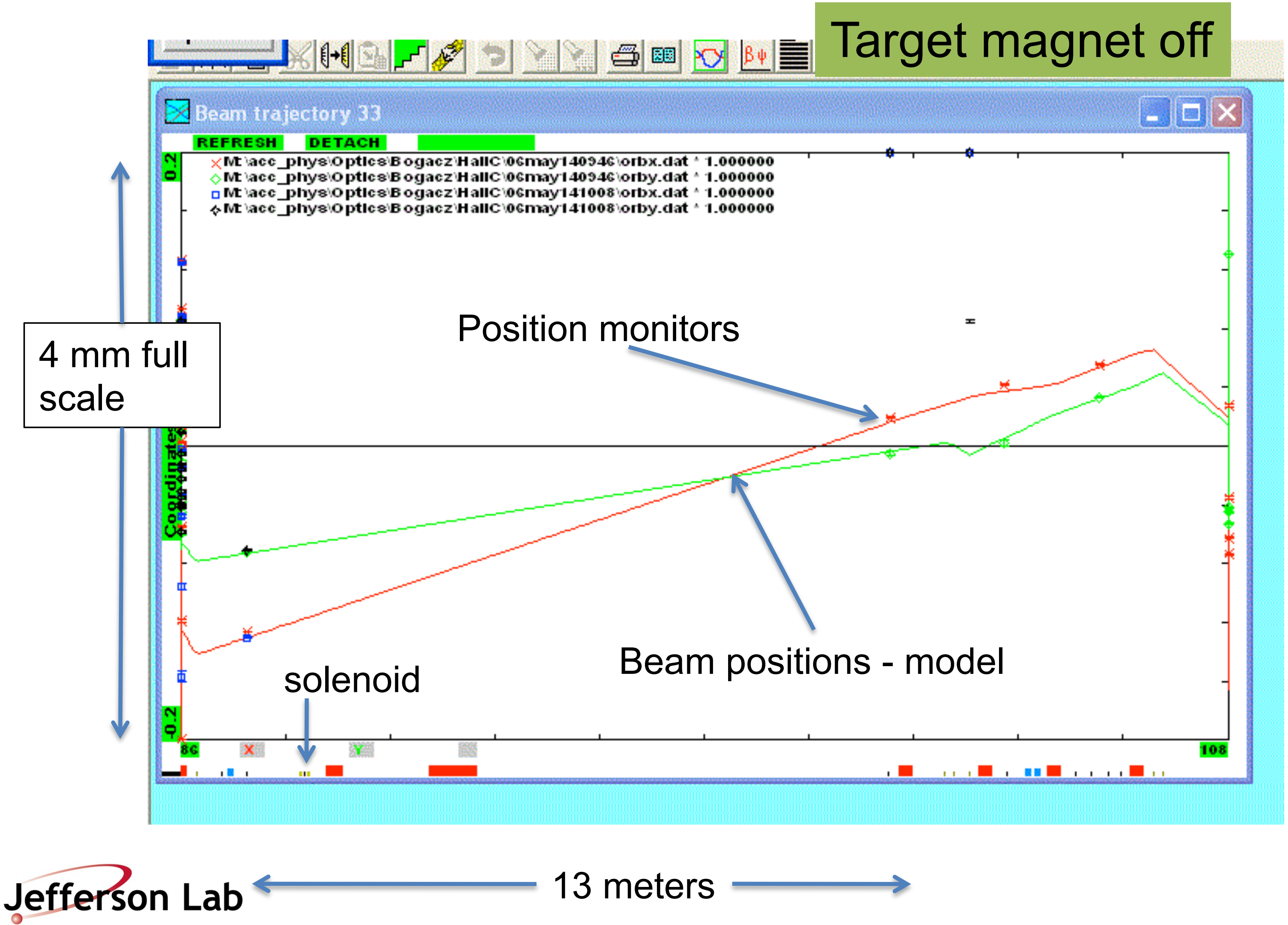
Such a target allows measurements concurrent with running experiment, mitigates Levchuk effect

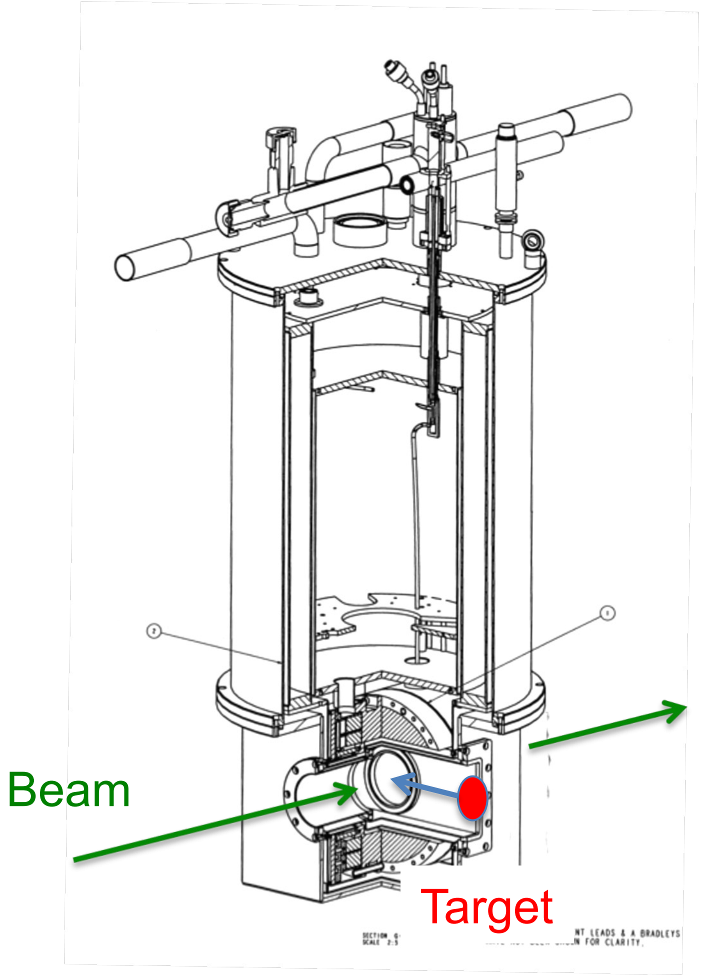


System is under development for use at MAINZ for the P2 experiment

Very technically challenging – requires significant investment and development!

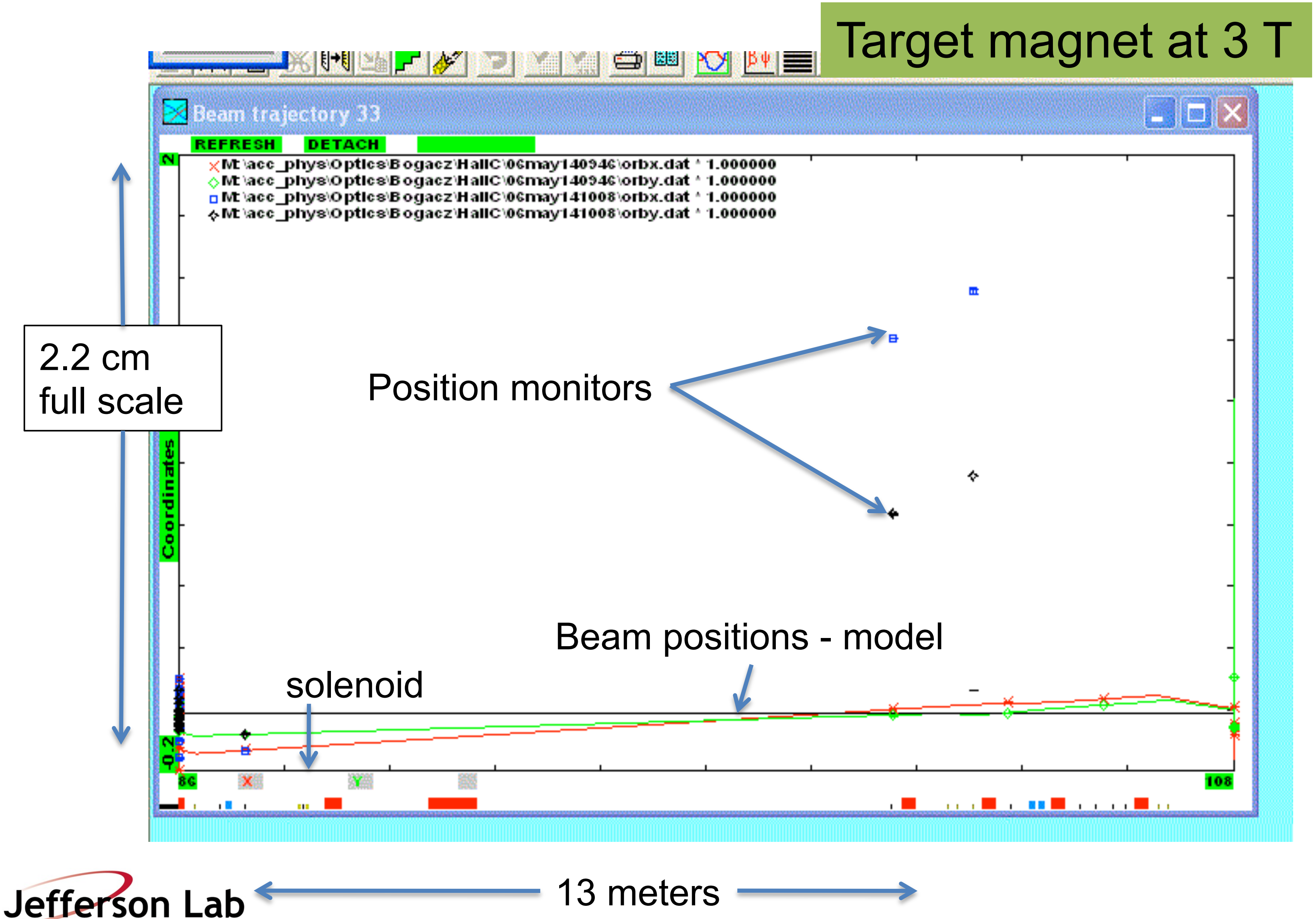
Hall C Target Magnet Steering at 687 MeV

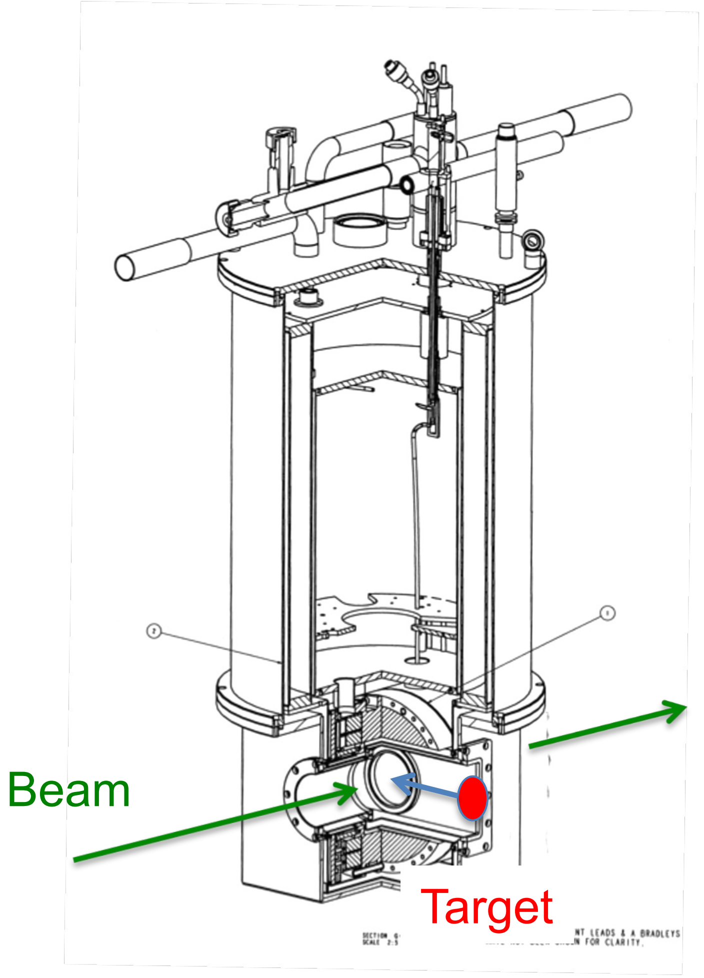




Beam test performed during G0

Hall C Target Magnet Steering at 687 MeV





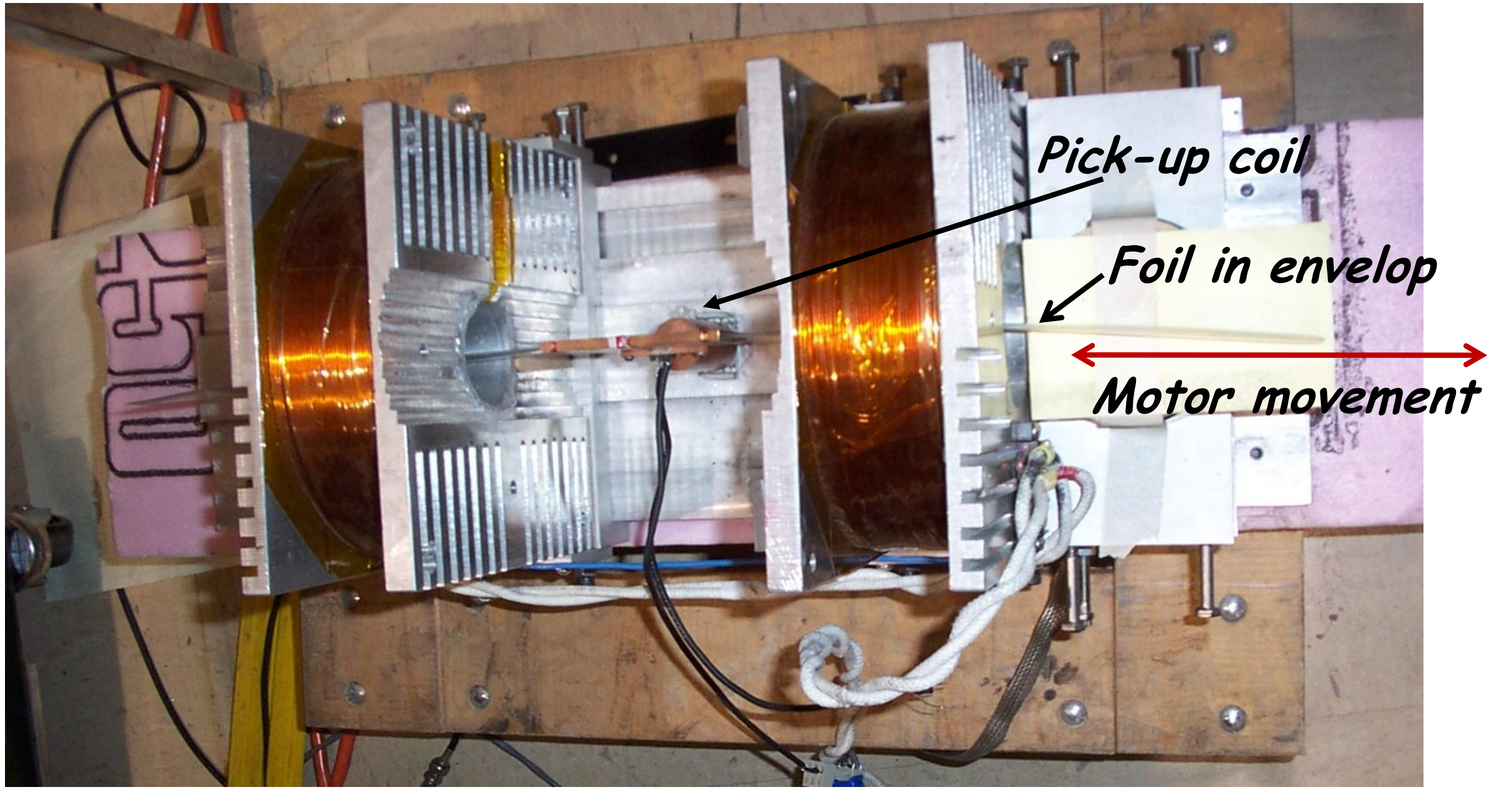
Magnet misalignment (2 mm) had huge impact

Low-field Møller

Prior to use of high-field/saturated iron targets, Møller polarimeters used magnetic alloy, tilted at small angle relative to low field Helmholtz coils

→ Foil saturation/target polarization had to be measured in situ with pickup coil
→ Hall A eventually reduced systematic error on target polarization to 1.5%

If this larger systematic uncertainty is acceptable, would make operation much easier



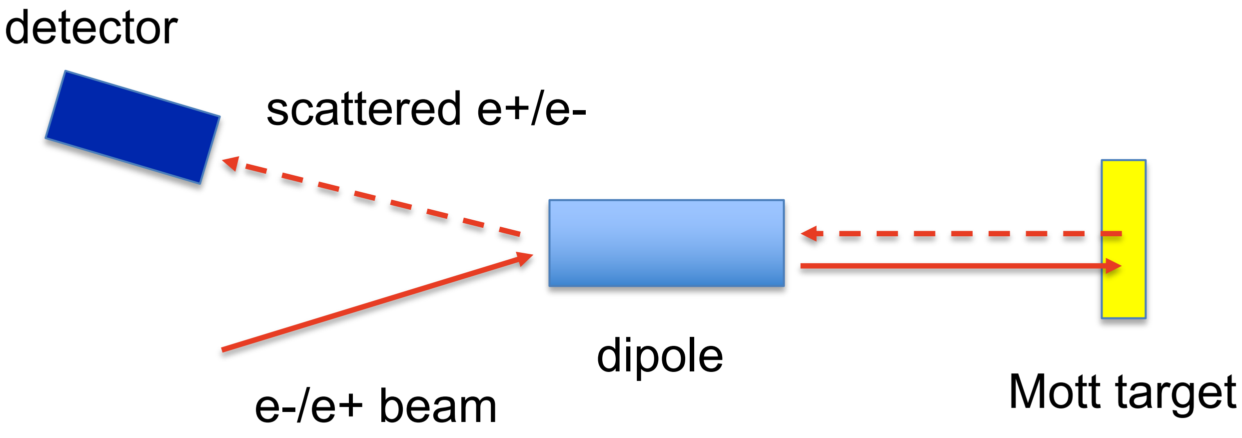
(old) Hall A Møller Polarimeter target system

Summary

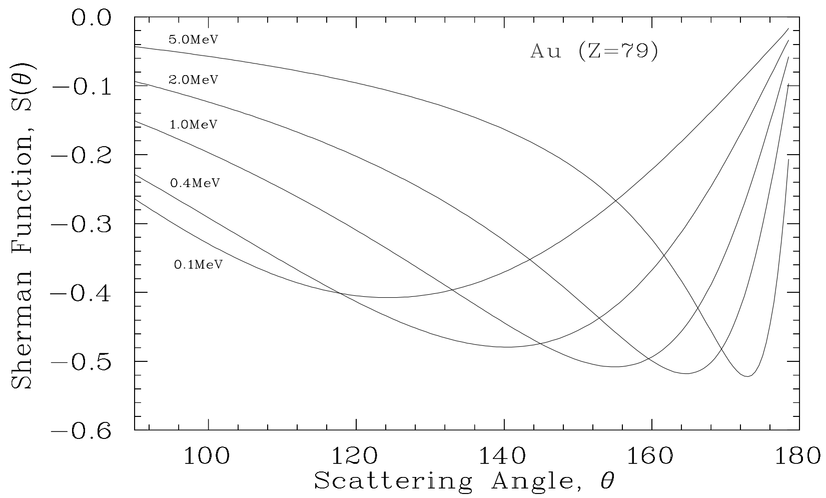
- Easiest path is likely intermittent Møller measurements with low-field target
  - If high precision is really required, high-field target can be deployed
  - Careful studies of beam steering at low energies should be carried out before committing to this plan (i.e. G0 experience at low energies)
  - Møller with atomic hydrogen target theoretically possible, but very technically challenging
- Compton polarimetry is borderline feasible
  - Would require significant resources → laser development, detector studies, chicane
  - Even in best case, measurement for positrons will take a very long time → of order 1 shift for 1% statistical uncertainty

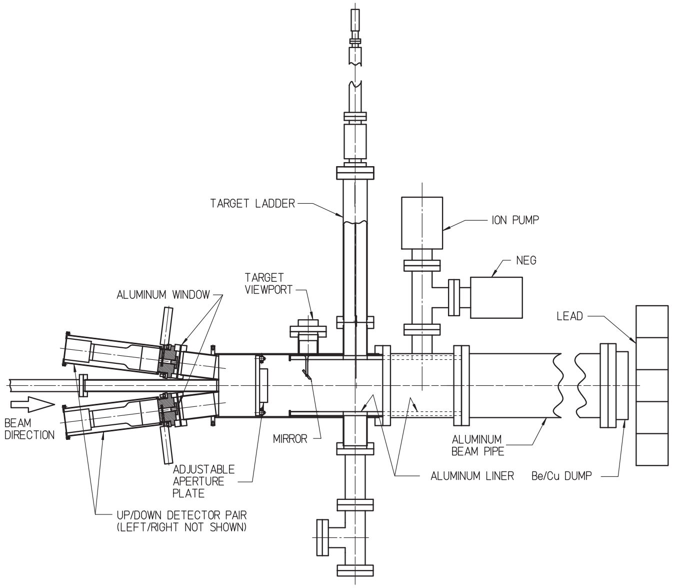
White-board discussion with Joe (Mott Polarimetry)

Mott polarimetry at higher energy becomes increasingly difficult at higher energy
→ Scattered electrons (positrons) of interest get too close to beam direction – no way to separate from incoming beam



Dipole used to steer beam to Mott target can be used to deflect scattered particles to detector





JLab 5 MeV Mott