Ph.D. Candidacy Exam: An Introduction to Electron Polarimetry

Greg Blume[1], Sylvain Marsillac[1], Joe Grames[2], Matt Grau[1], Yuan Zhang[1], Helmut Baumgart[1]

[1]Department of Physics, Old Dominion University, Norfolk VA, 23529 USA
[2]Thomas Jefferson National Accelerator Facility, Newport News VA, 23606 USA

Outline

- Introduction
- Mott Scattering Polarimeters
  - Theory
  - Retarding-Field Mott
  - Thin-Foil Mott
  - Experimental Results
- Compton Transmission Polarimeters
  - Theory
  - Compton Transmission
  - Experimental Results
- Comparison
- Conclusion

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Introduction

- Polarized electron beams are important for multiple applications

Material Science

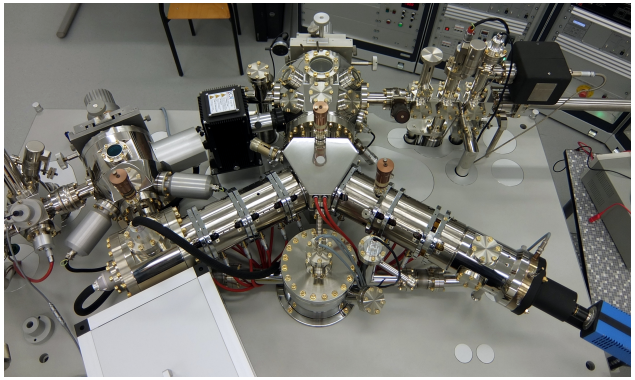
- Spin-polarized low energy electron microscopy (SPLEEM) is used to study magnetic micro-structures

Nuclear Physics

- Parity violation experiments at Jefferson Lab to explore and understand the Standard Model

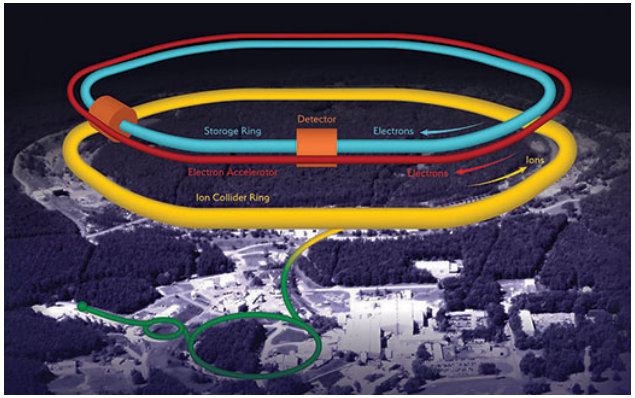
High Energy

- Studying spin effects on particle dynamics in high energy storage rings like the future EIC at BNL



UMCS, 2022

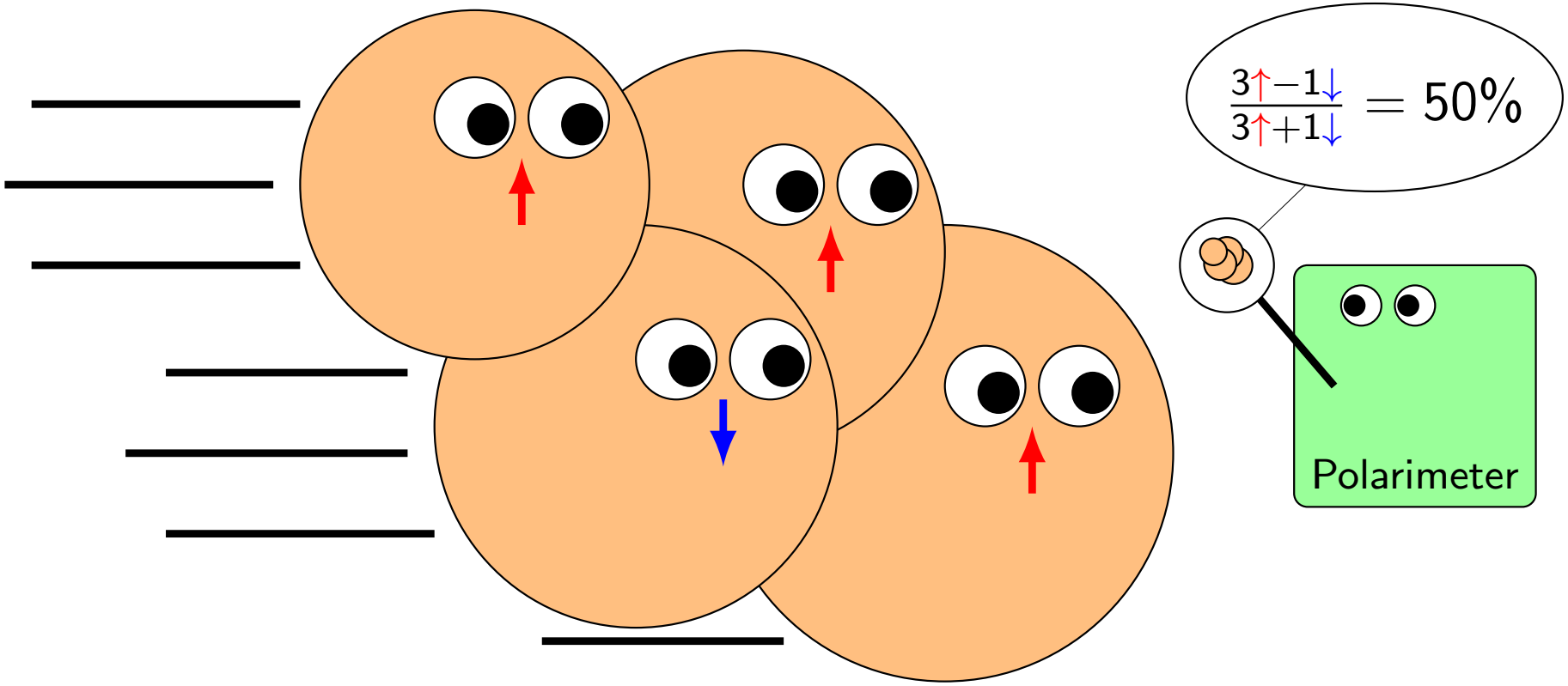
JLAB, 2021



BNL, 2023

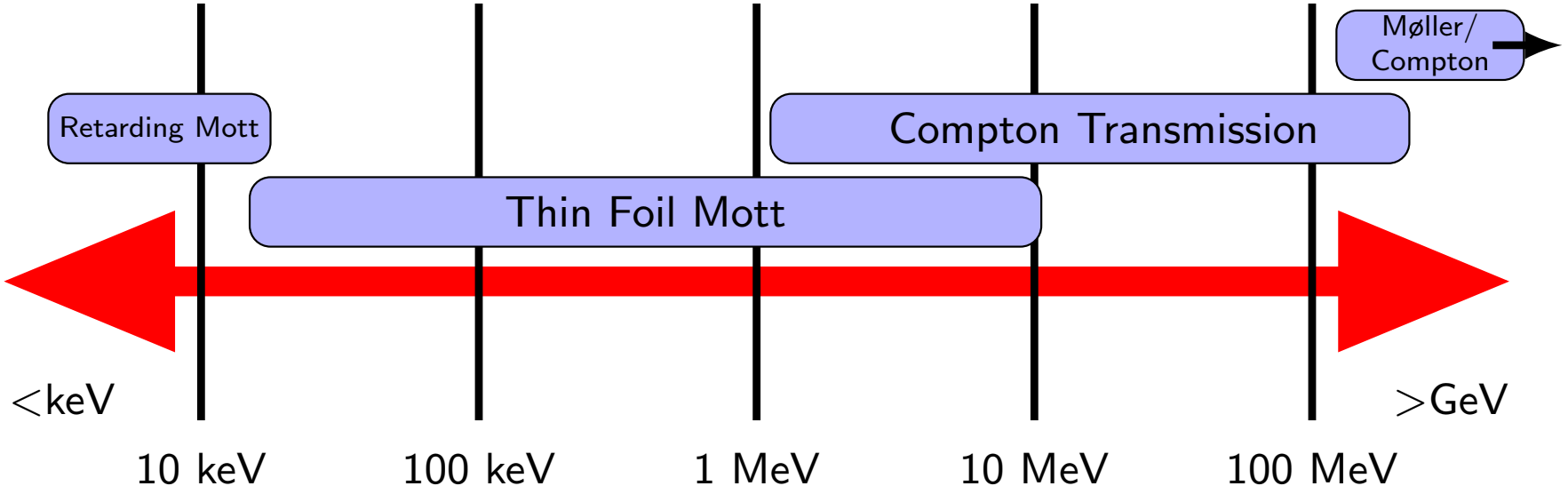
Introduction (cont.)

- Electron polarimeters measure the polarization of an electron beam



Introduction (cont.)

- Beam energy is the largest deciding factor



- Three methods are applicable below 10 MeV
- Discuss theory, operation, and results of each method at Jefferson Lab

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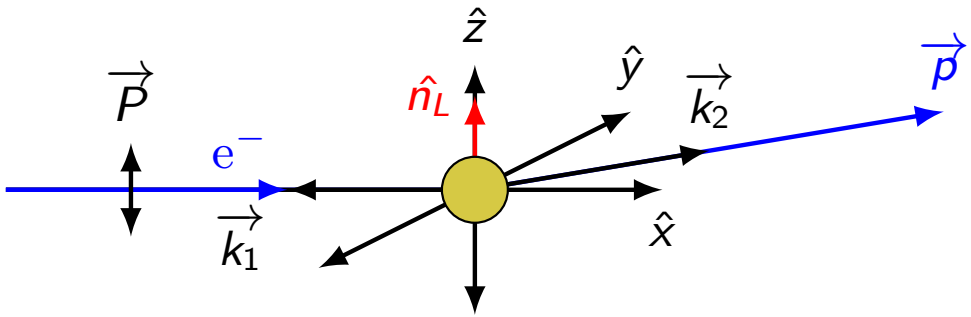
Mott-Scattering Polarimetry

- Mott scattering makes use of electrons scattered elastically off the Coulomb field of a high-Z target like gold (Z= 79)

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

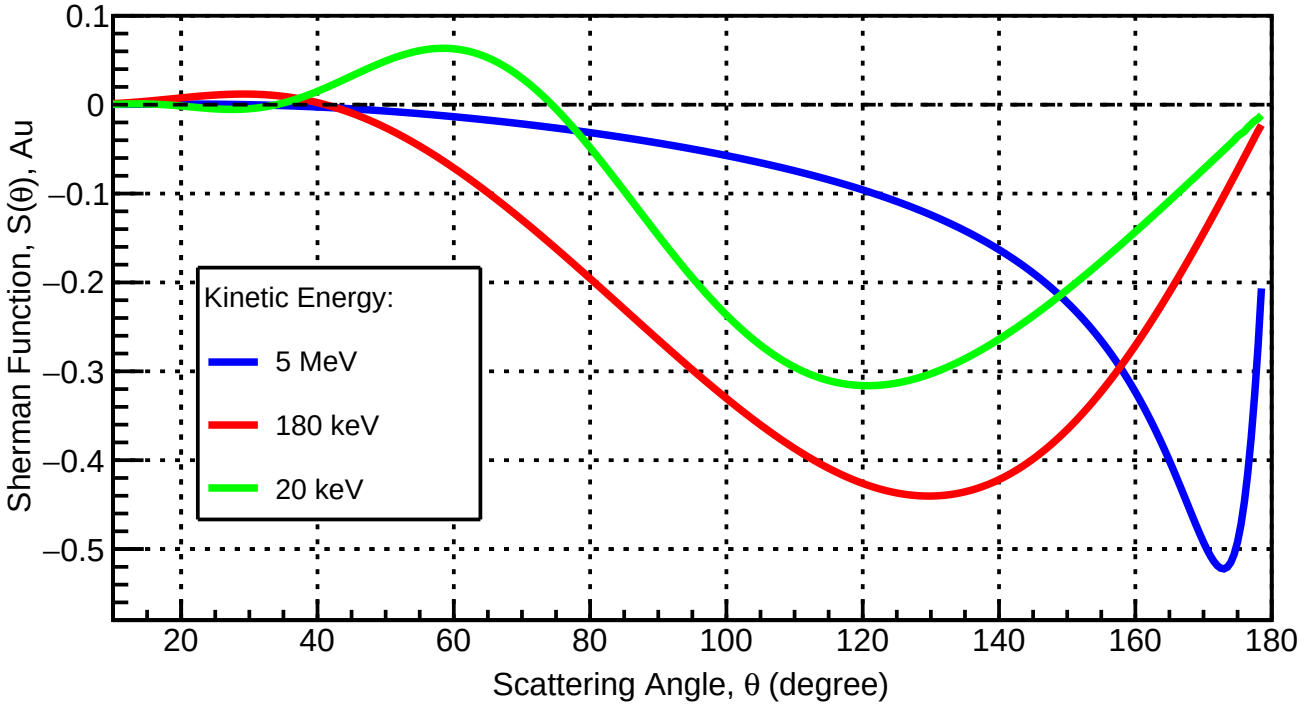
- An electron beam transversely polarized to the scattering plane will generate an asymmetry at θ



- Detectors placed at $\pm\theta$ will have a count of electrons that corresponds to either $1 + PS(\theta)$ or $1 - PS(\theta)$

Mott-Scattering Polarimetry (cont.)

- Detectors are placed at the maximum of $S(\theta)$

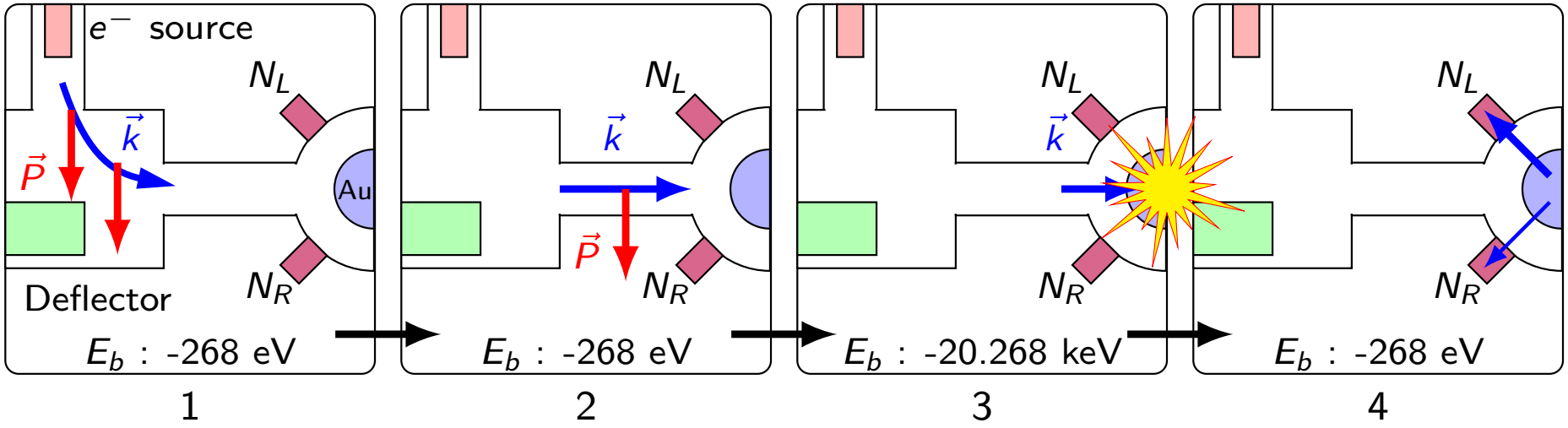


- Count asymmetry between $\pm\theta$

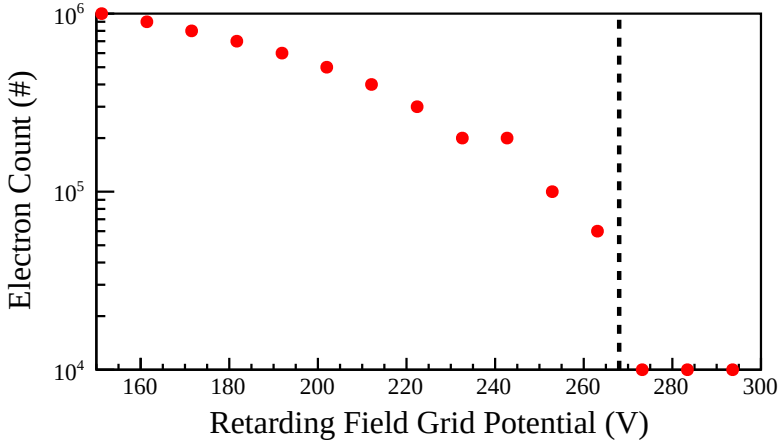
$$A = \frac{N_L - N_R}{N_L + N_R} = \frac{1 + PS(\theta) - 1 - PS(\theta)}{1 + PS(\theta) + 1 - PS(\theta)} = \frac{2PS(\theta)}{2} = PS(\theta)$$

Retarding Field Mott Polarimeters

- Grid bias linear extrapolation used to exclude inelastic events

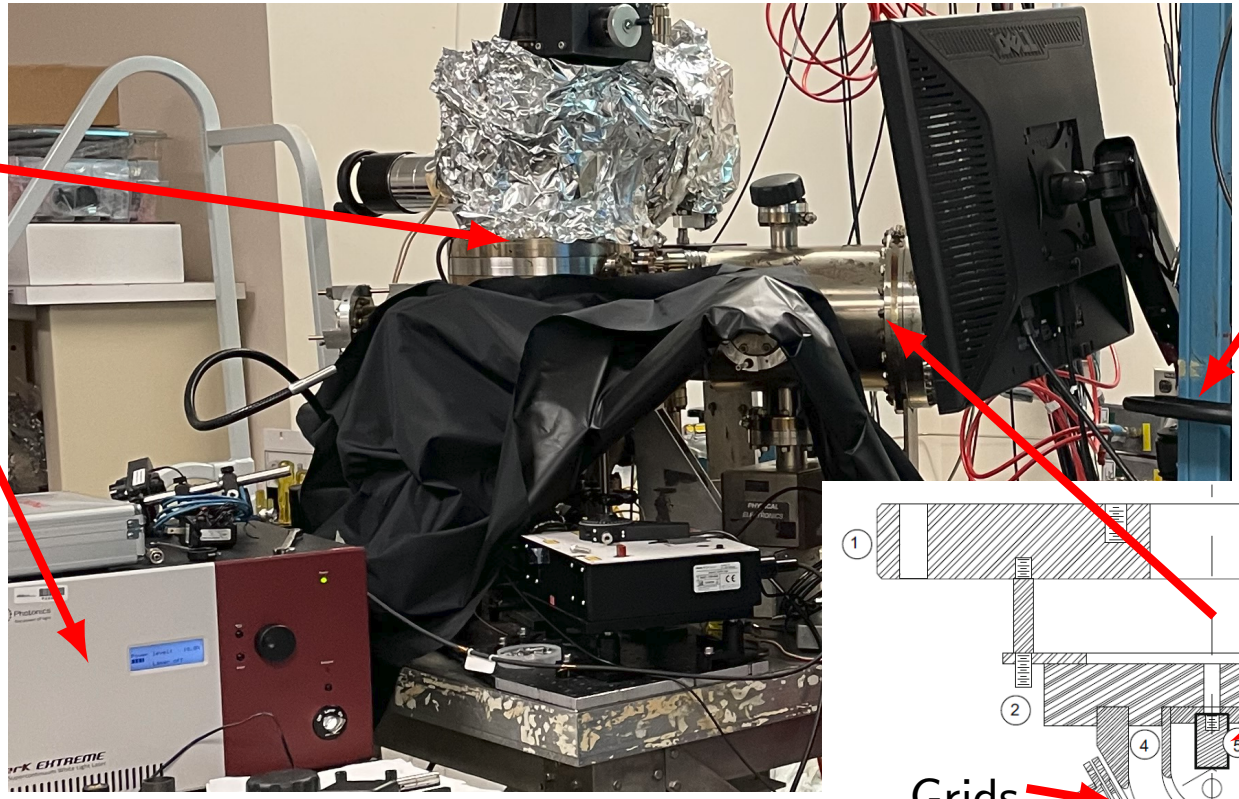


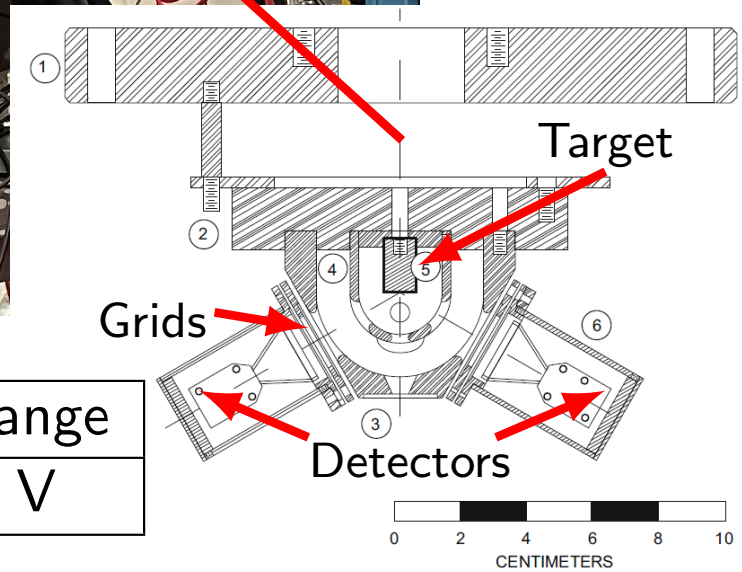
- Electron count continues to decrease approaching initial beam energy
- Counts diminishes by an order of magnitude after threshold



Results — Retarding Field Mott Polarimeter

- Gold target retarding field Mott polarimeter at Jefferson Lab

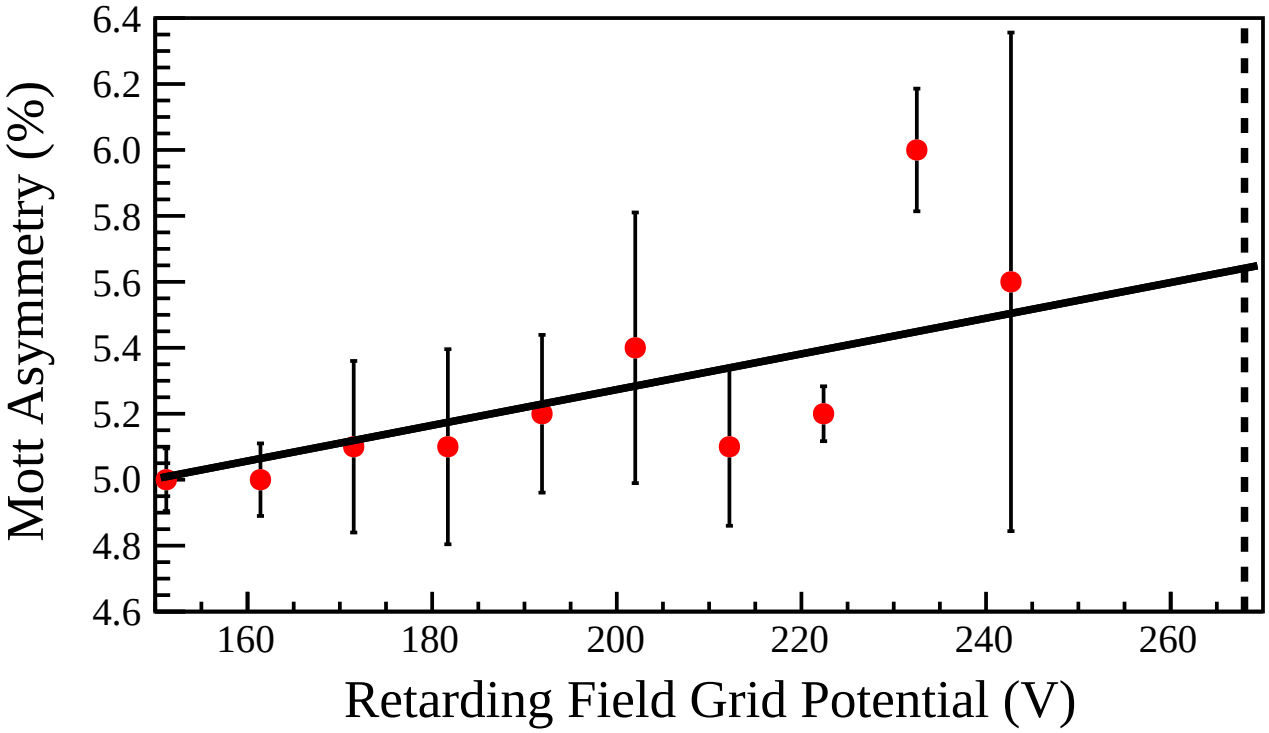




Beam Energy	Target Bias	Grid Bias Range
–268 eV	20 kV	150 - 320 V

Results — Retarding Field Mott Polarimeter

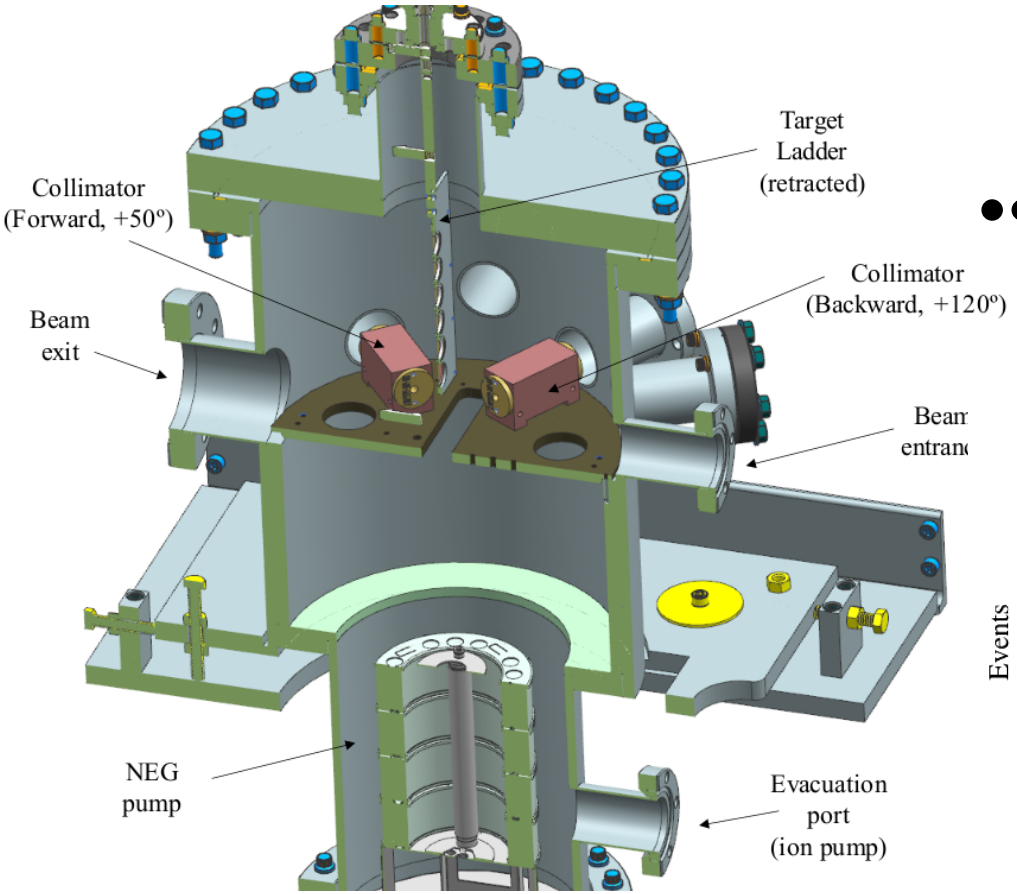
- Linear extrapolation to isolate elastic scattering

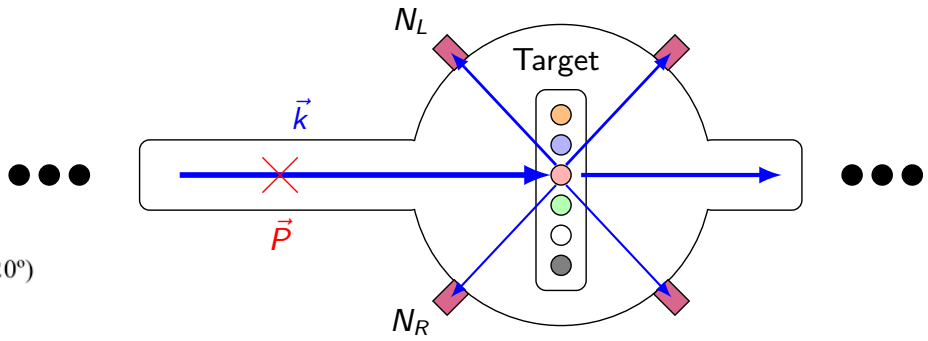


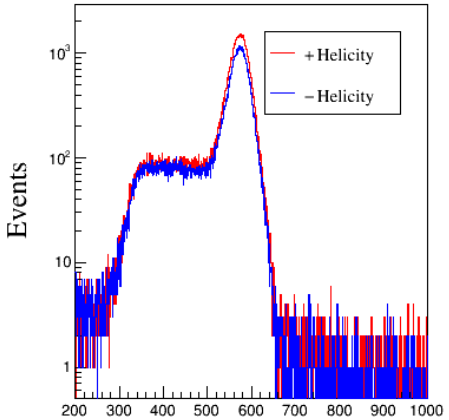
A: 5.6 ± 0.3 %	$S(\theta)$: 20.1 ± .4 %	P: 28.1 ± 1.3 %

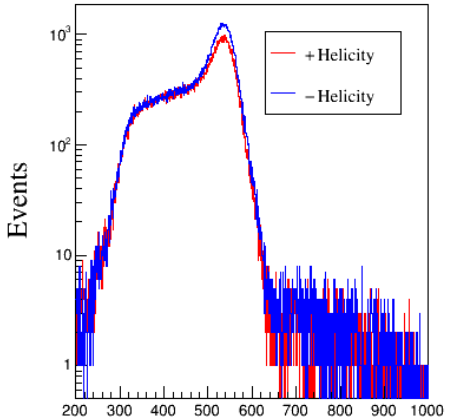
Thin-Foil Mott Polarimeters

- Nanometer thick target used to generate the Left-Right asymmetry



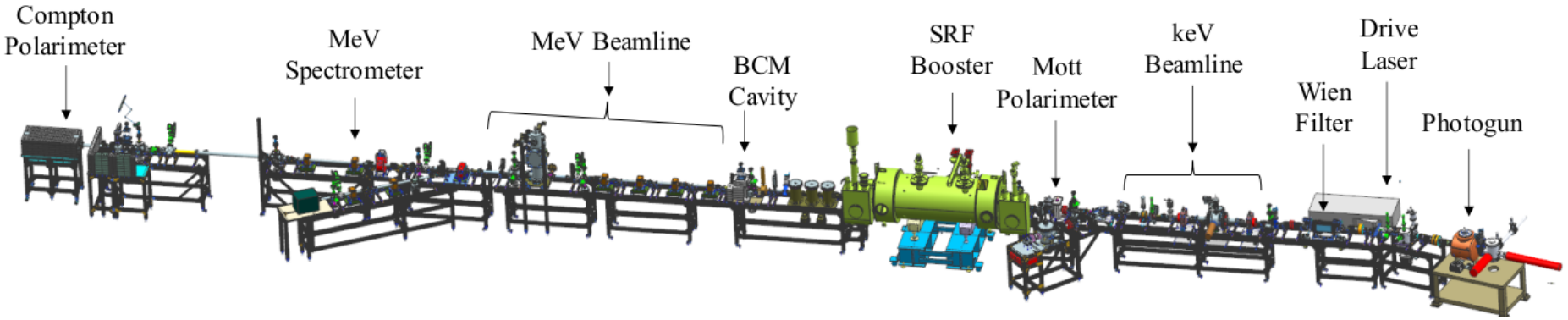


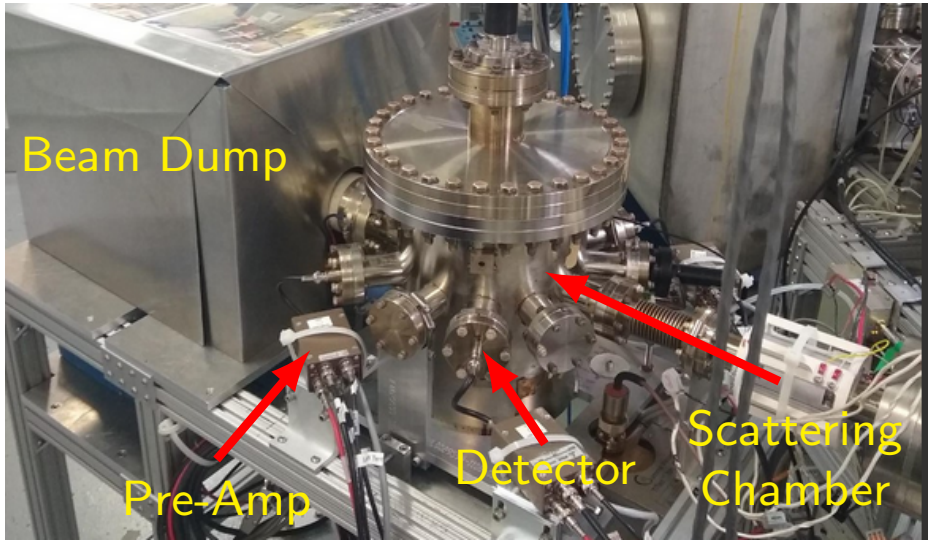


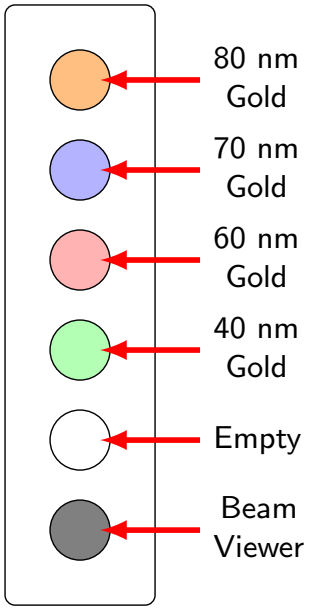


Results — Thin-Foil Mott Polarimeter

- Thin foil Mott polarimeter at the UITF beam-line







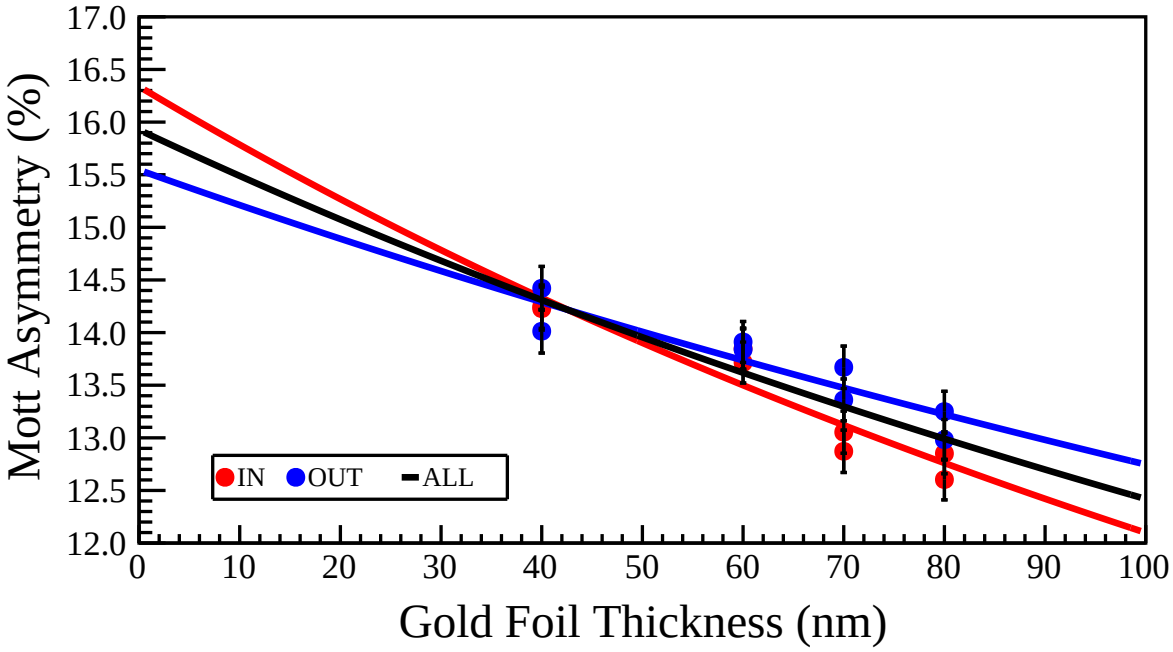
Results — Thin-Foil Mott Polarimeter

Asymmetry is a function of target thickness

Zero thickness asymmetry

$$A(t) = \frac{A_E(t{=}0)}{(1.0{+}\beta t)}$$

Thickness increases secondary scattering



Zero-thickness Asymmetry	15.9 ± 0.4 %
β	(0.0028 ± 0.0004) 1/nm
Sherman Function	42.6 %
Beam Polarization	37.4 ± 0.8 %

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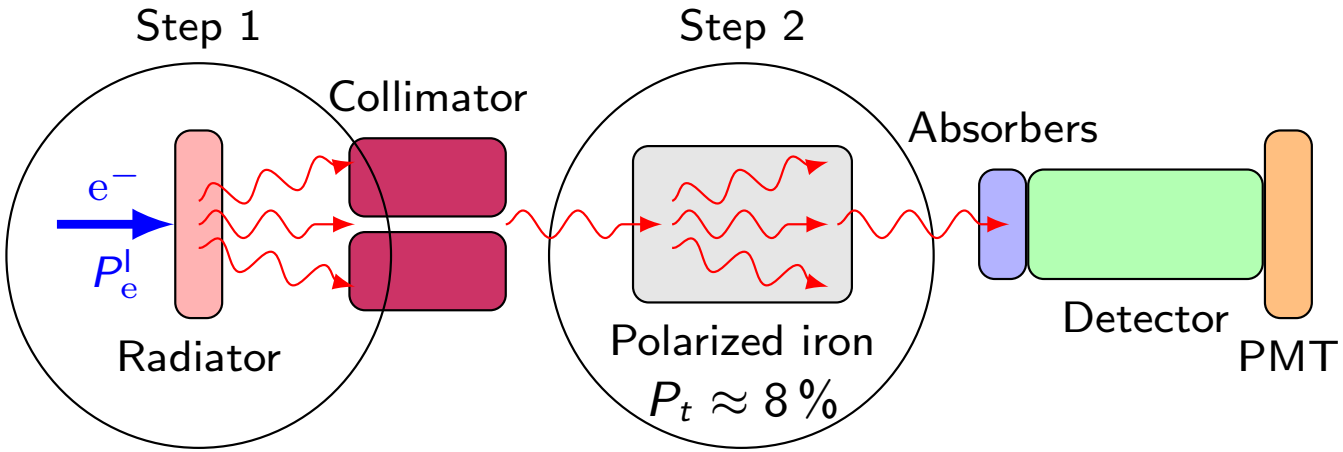
Compton Transmission Polarimetry

- Polarized photons created from the polarized electron beam are used to measure a transmission asymmetry

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{d}^2\sigma^0}{\mathrm{d}\Omega}\left[1 + P_\mathrm{t} P_\gamma^\mathrm{c} A_\mathrm{C}(\theta)\right] = \frac{\mathrm{d}^2\sigma^0}{\mathrm{d}\Omega}\left[1 + P_\mathrm{e}^\mathrm{l} \mathcal{A}_\mathrm{eff}\right]$$

$$\mathcal{A}_\mathrm{eff} = P_\mathrm{t} \mathcal{T} A_\mathrm{C}(\theta)$$

- At small angles $A_\mathrm{C}(\theta) \approx \mu_1 L$

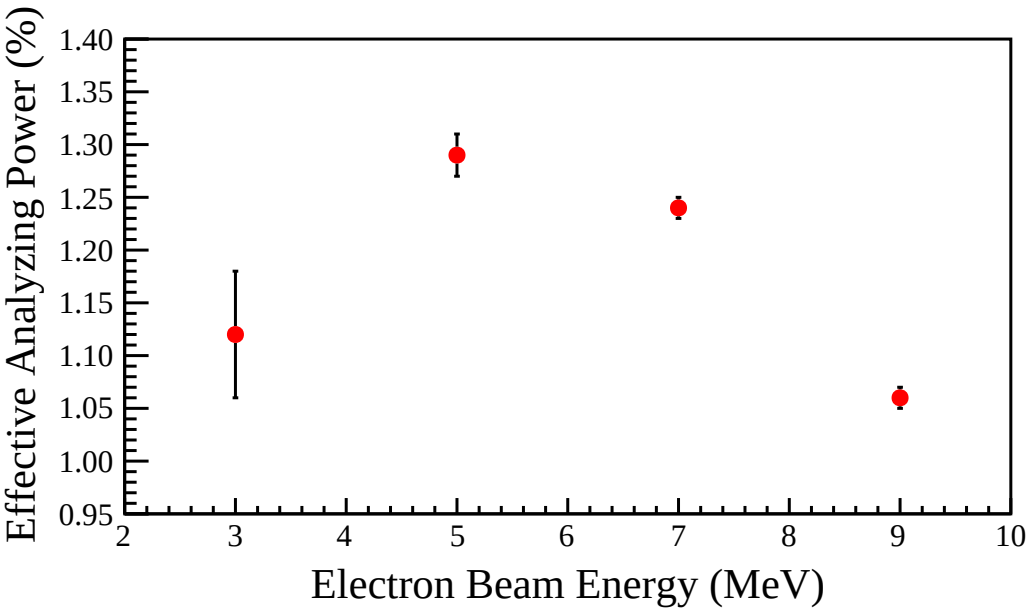


Compton Transmission Polarimetry (cont.)

- Bremsstrahlung photons scattering in the polarized target cause the transmission asymmetry

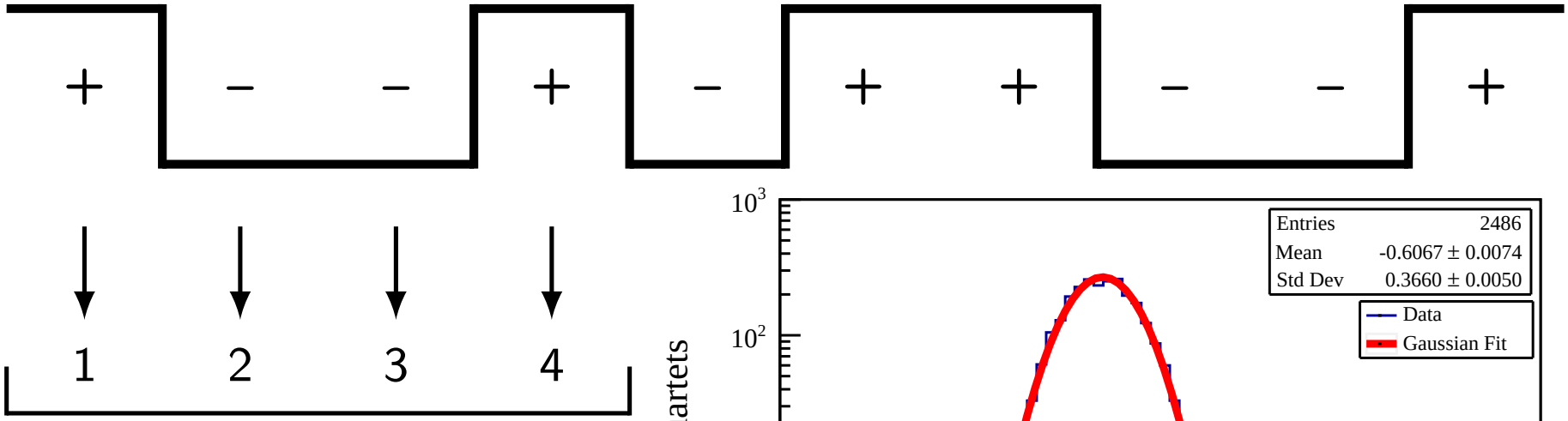
$$A_{\mathrm{T}} = \frac{N^{+} - N^{-}}{N^{+} + N^{-}} \approx P_{\mathrm{e}}^{\mathrm{l}} P_{\mathrm{t}}\, \mu_1 \mathcal{T}\, L = P_{\mathrm{e}}^{\mathrm{l}} \mathcal{A}_{\mathrm{eff}}$$

- $\mathcal{A}_{\mathrm{eff}}$ is very geometry dependent which makes is computationally difficult

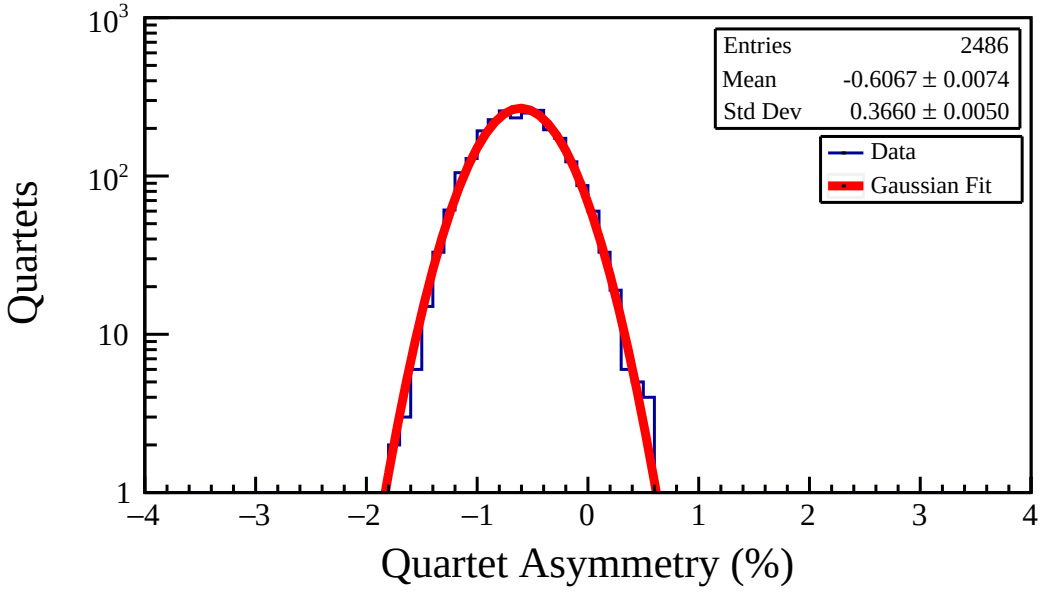


Compton Transmission Polarimeters

- Asymmetry is found between helicity states
- Event rate is too high to resolve individual events
- Resolution — integrate over the time of one helicity state



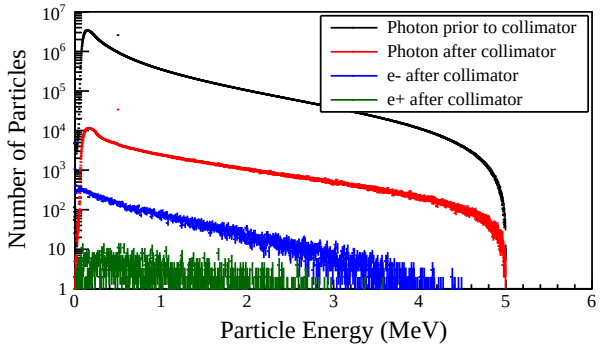
$$A_T^{\pm} = \frac{\pm(w_1+w_4)\mp(w_2+w_3)}{w_1+w_2+w_3+w_4}$$

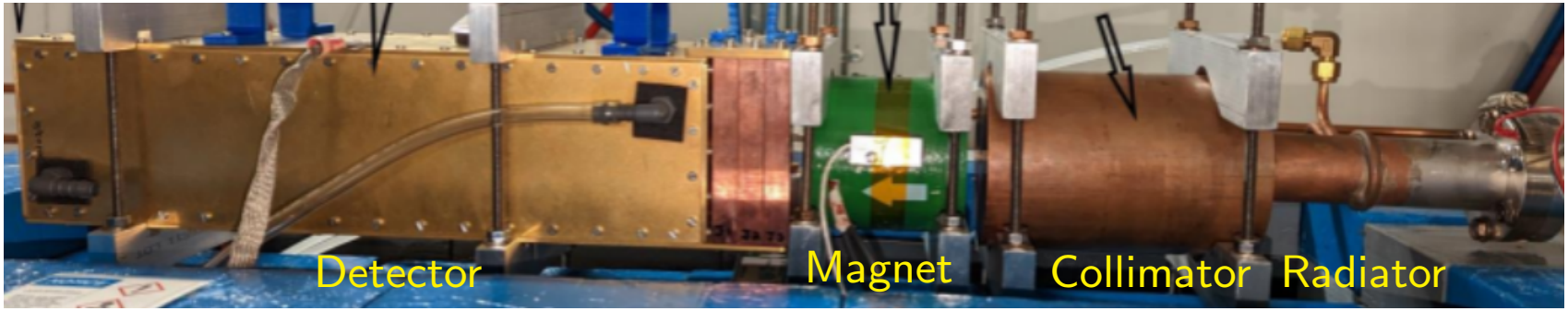


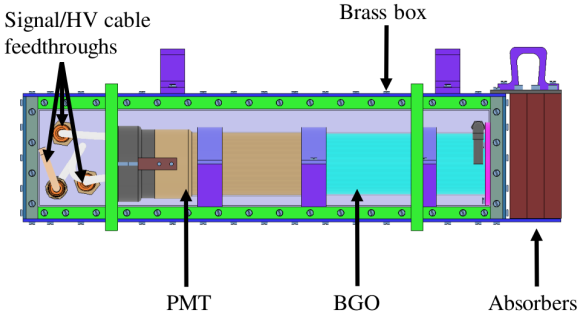
Calibration — Compton Transmission Polarimeter

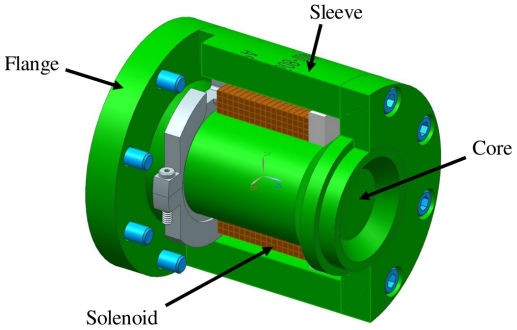
- Compton Transmission polarimeter at Jefferson Lab

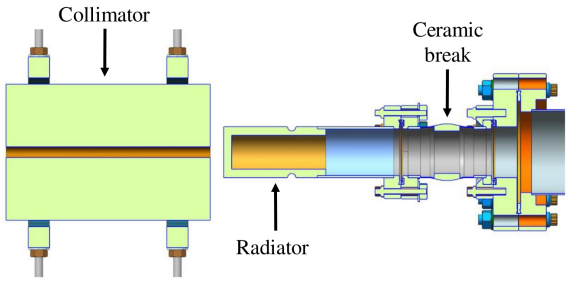
Radiator	0.6 cm thick Cu
Collimator	14.6 cm Cu w/ 0.8 cm bore
Analyzing Magnet	7.5 cm Fe Core
Detector	$Bi_4Ge_3O_{12}$





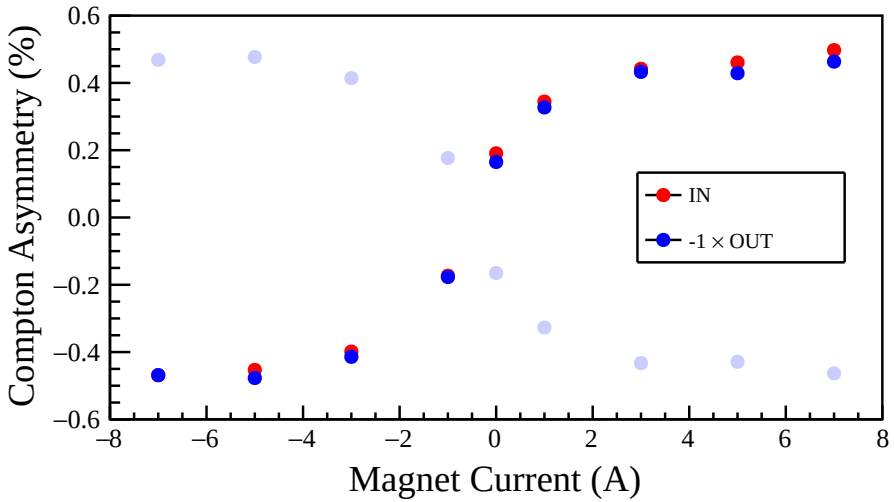


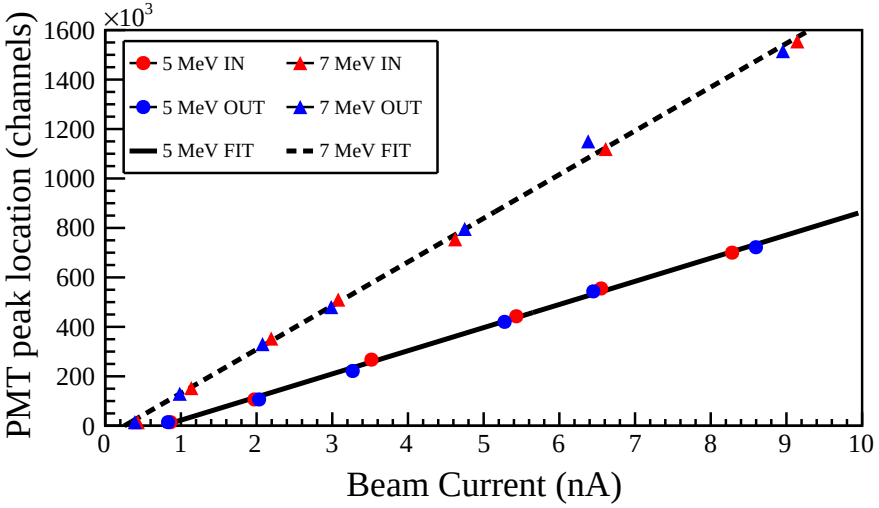




Calibration — Compton Transmission Polarimeter (cont.)

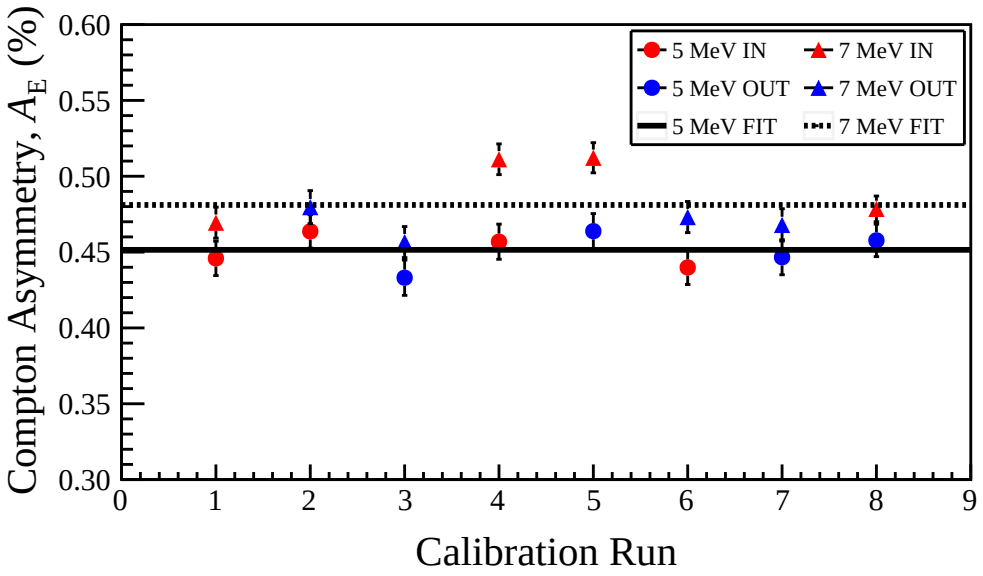
- Target Saturation is found > 5 A — required for consistent analyzing power
- Linearity is required for an $\mathcal{A}_{\text{eff}}$ that is **NOT** current dependent





Calibration — Compton Transmission Polarimeter (cont.)

- Calibration runs are performed to extract the asymmetry



$$\mathcal{A}_{\text{eff}}^{5\,\text{MeV}} = \frac{(0.452 \pm 0.004)\%}{(37.4 \pm 0.8)\%} = 1.20 \pm 0.03\%$$

$$\mathcal{A}_{\text{eff}}^{7\,\text{MeV}} = \frac{(0.481 \pm 0.007)\%}{(37.4 \pm 0.8)\%} = 1.29 \pm 0.04\%$$

- $\mathcal{A}_{\text{eff}}$ is functionally equivalent to the Sherman function

Beam Current	6 nA	Beam Size	~0.2 mm

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- **Comparison**
- Conclusion

Comparison

	20 keV Retarding Field Mott†	180 keV Thin Foil Mott*	5 MeV Thin Foil Mott‡	5-7 MeV Compton Transmission*
Effective Analyzing Power (%)	20.1	38.0	39.2	1.2-1.3
Figure of Merit ($\%^2$ nA)	$\sim 10^2$	$\sim 10^3$	$\sim 10^6$	$\sim$10
Spin Direction	Transverse	Transverse	Transverse	Longitudinal
Target Polarization	No	No	No	Yes
Beam Energy (keV)	20	180	5000	5000-7000
Beam Current (nA)	10	5	1000	6
Detection	Primary (e^-)	Primary (e^-)	Primary (e^-)	Secondary (γ)

References: *(Blume et al., 2023) A Compton transmission polarimeter for DC and SRF electron photo-injectors
†(McCarter et al., 2010) A low-voltage retarding-field Mott polarimeter for photocathode characterization
‡(Grames et al., 2020) High precision 5 MeV Mott polarimeter

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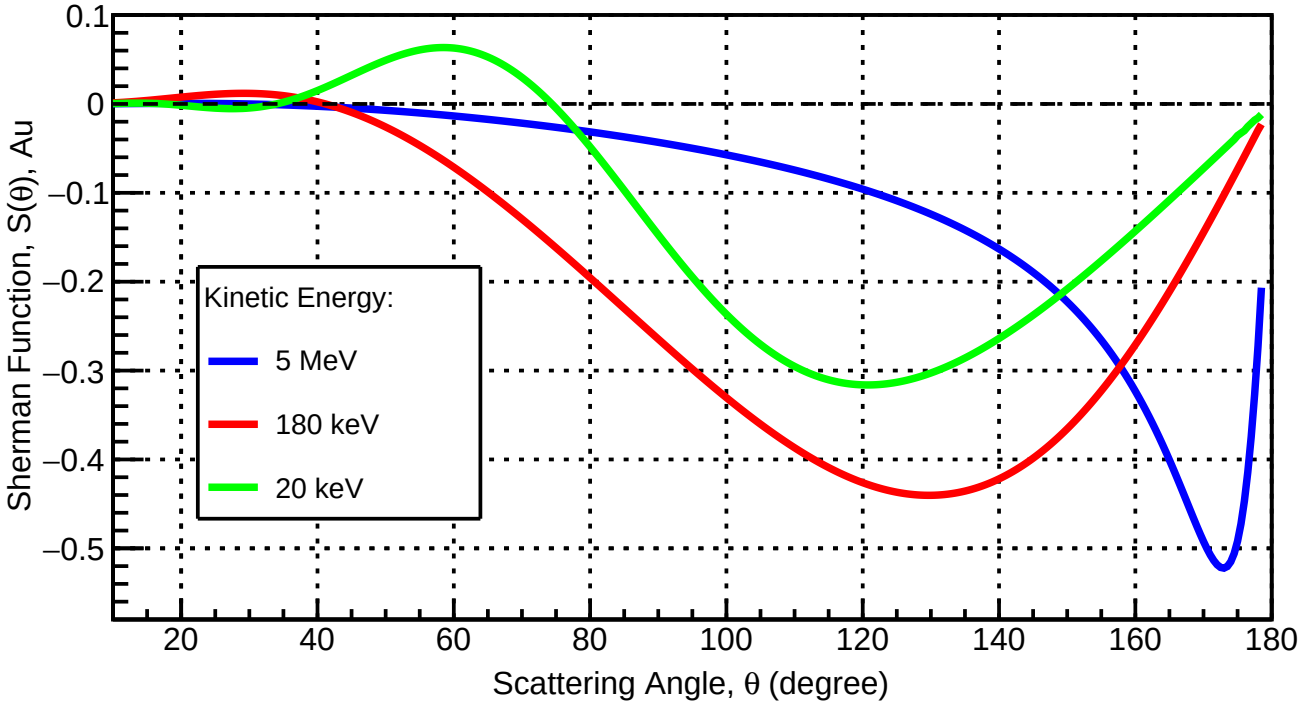
Conclusion

- Electron polarimetry is an important tool in the measurement of spin polarization of electron beams
- Many different methods exist depending on the criteria of the experiment
- $<$ 10 MeV the choices are limited to Retarding Field Mott, Thin Foil Mott, and Compton Transmission polarimeters
- Selecting the appropriate technique is key in making a good measurement
- Jefferson Lab has all 3 types of polarimeters and we have discussed the pros and cons of each polarimeter
- We are publishing a paper on the calibration of a Compton transmission polarimeter

Question?

Thank you for listening!

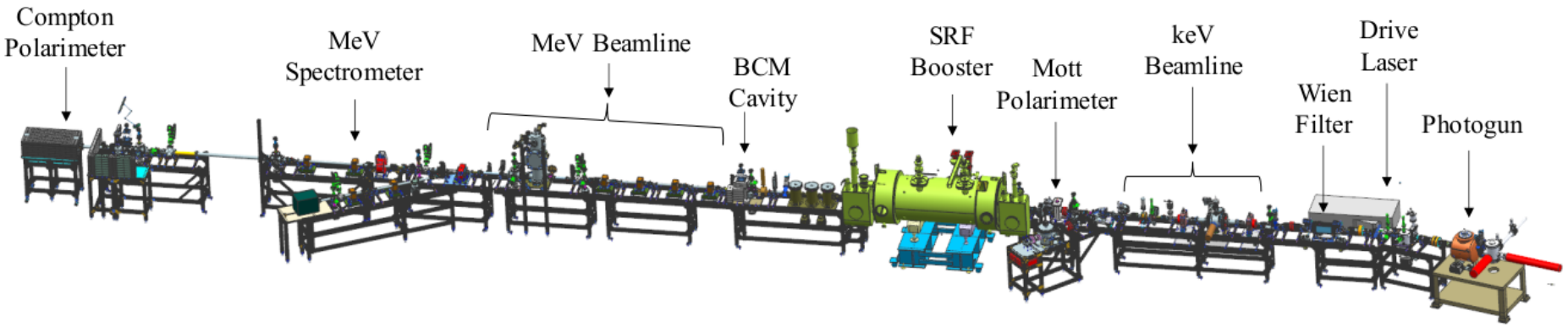
Back-up


0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
Sherman Function, S(θ), Au
20
40
60
80
100
120
140
160
180
Scattering Angle, θ (degree)
Kinetic Energy:
5 MeV
180 keV
20 keV

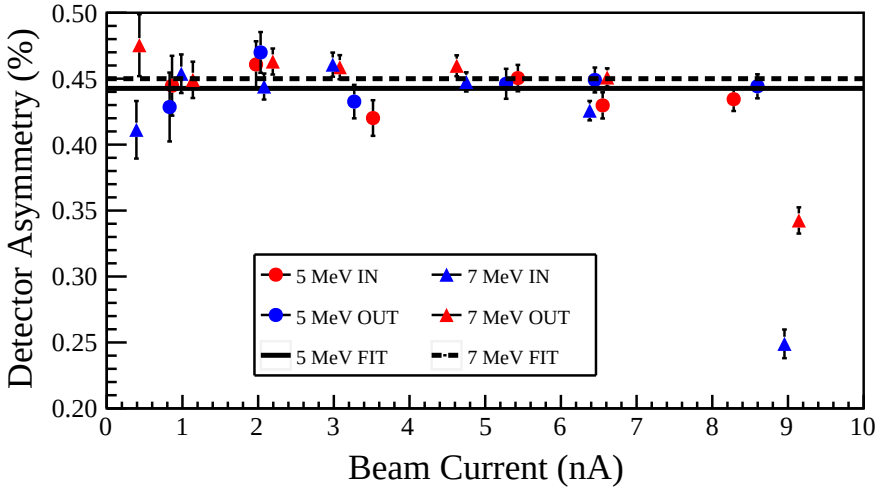
Back-up

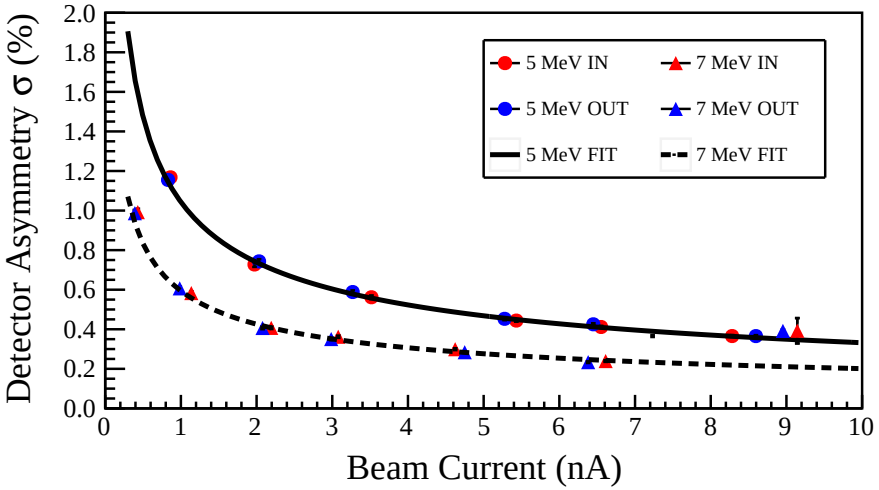
Pockels cell's allow for rapid helicity reversal. Thus, 4 asymmetry states can be observed.

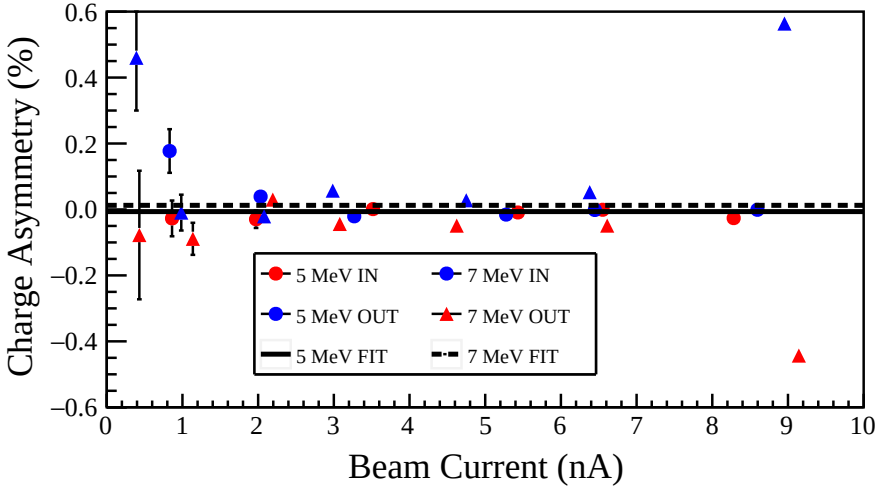
$$A = \frac{\sqrt{N_{l,d}N_{r,u}} - \sqrt{N_{l,u}N_{r,d}}}{\sqrt{N_{l,d}N_{r,u}} + \sqrt{N_{l,u}N_{r,d}}} \tag{1}$$

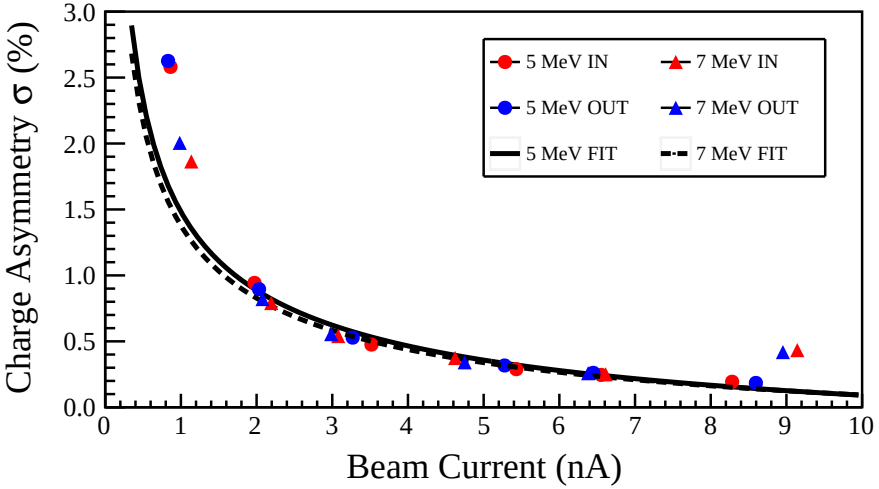


Back-up

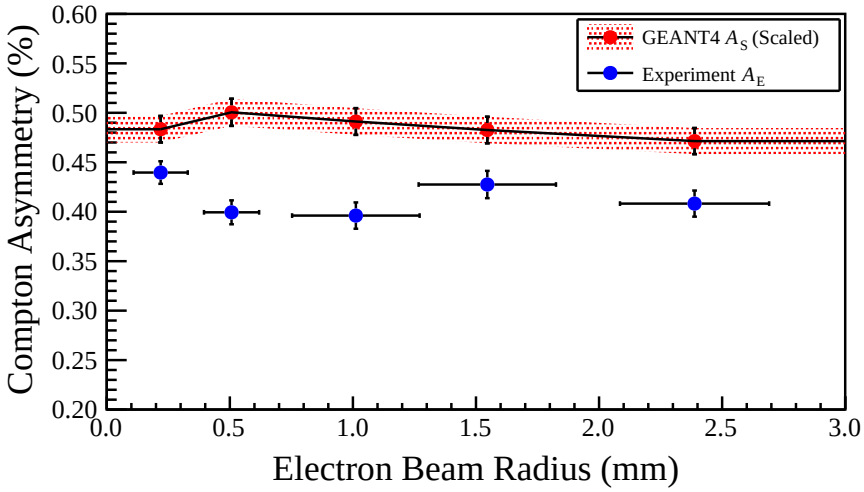

Detector Asymmetry (%)
Beam Current (nA)
5 MeV IN
7 MeV IN
5 MeV OUT
7 MeV OUT
5 MeV FIT
7 MeV FIT

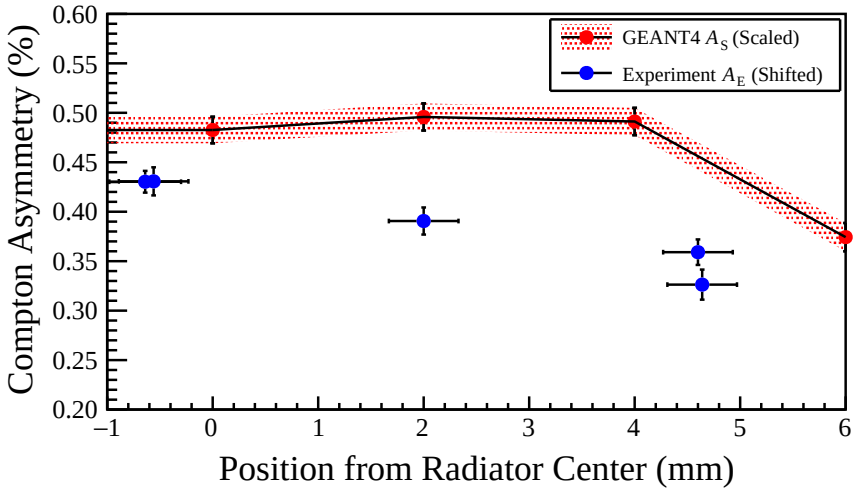

Detector Asymmetry σ (%)
Beam Current (nA)
5 MeV IN
7 MeV IN
5 MeV OUT
7 MeV OUT
5 MeV FIT
7 MeV FIT


Charge Asymmetry (%)
Beam Current (nA)
5 MeV IN
7 MeV IN
5 MeV OUT
7 MeV OUT
5 MeV FIT
7 MeV FIT


Charge Asymmetry σ (%)
Beam Current (nA)
5 MeV IN
7 MeV IN
5 MeV OUT
7 MeV OUT
5 MeV FIT
7 MeV FIT

Back-up


Compton Asymmetry (%)
Electron Beam Radius (mm)
GEANT4 A_S (Scaled)
Experiment A_E
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Compton Asymmetry (%)
Position from Radiator Center (mm)
GEANT4 A_S (Scaled)
Experiment A_E (Shifted)
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
−1
0
1
2
3
4
5
6