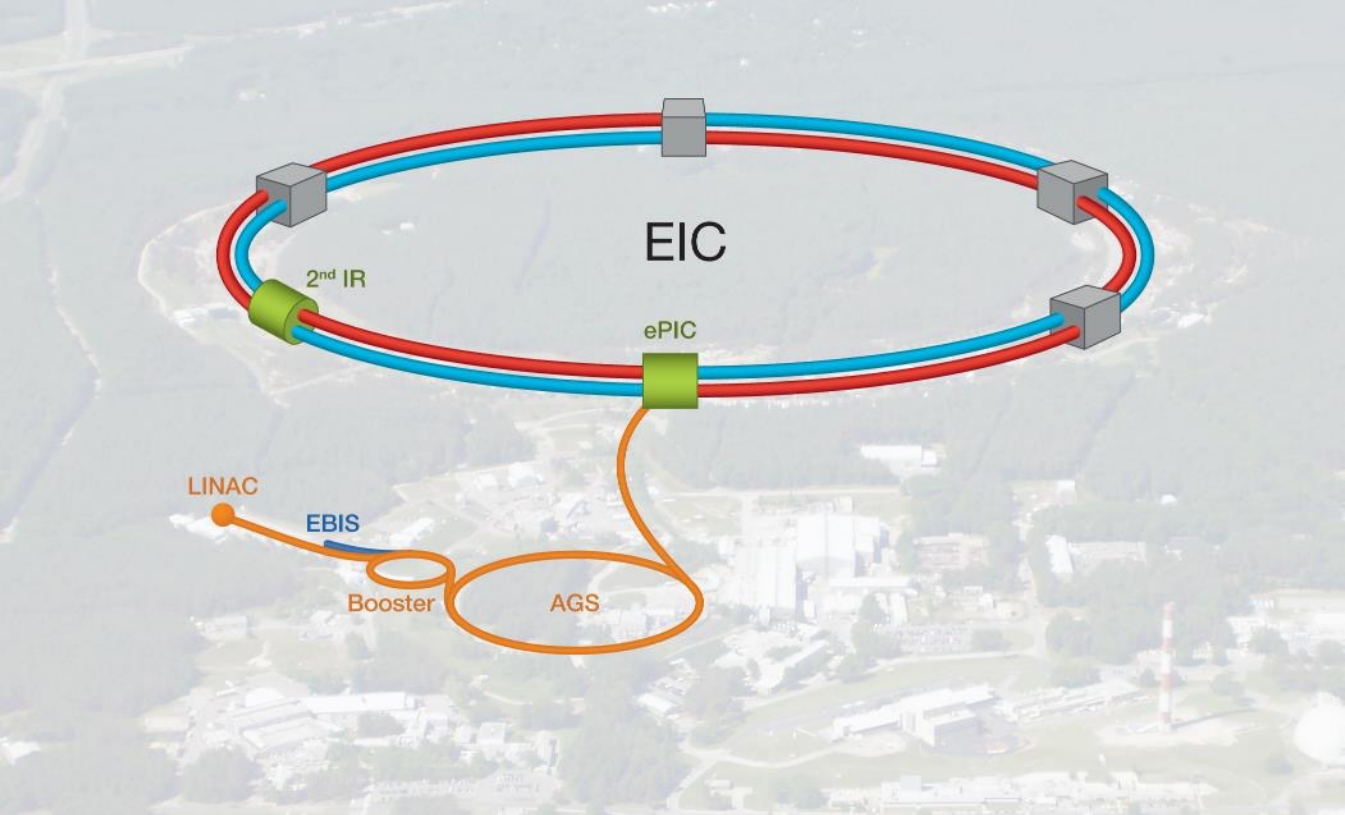
Electron Polarimetry at EIC

Dave Gaskell

Jefferson Lab



September 5, 2023

Polarization Time Dependence - electrons

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

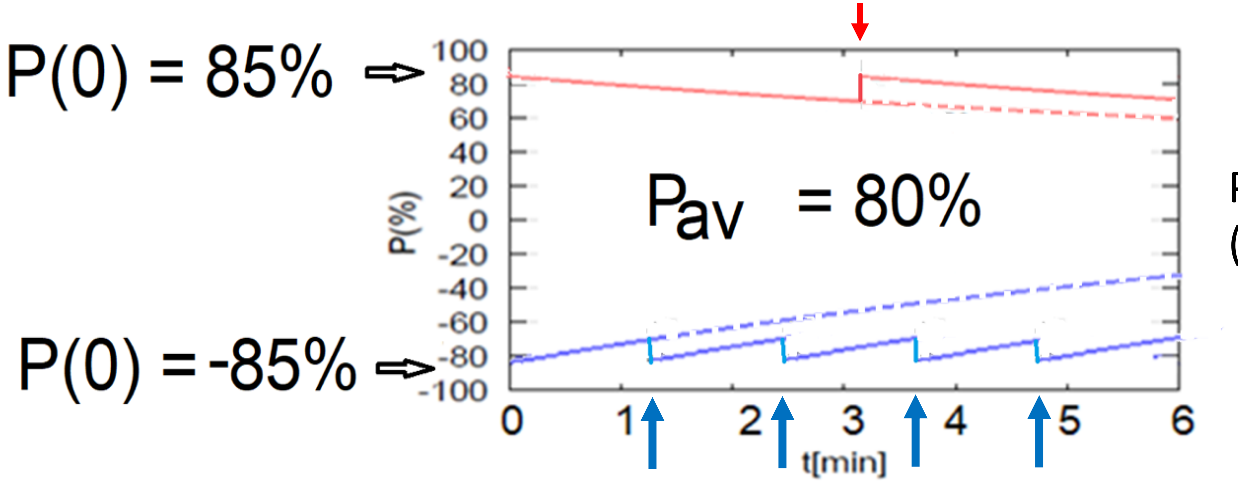
B P

Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

Re-injection



Re-injections

P_{∞}= 30%
(conservative)

Bunches will be replaced about every 50 minutes at 5 and 10 GeV
→ 1-3 minutes at 18 GeV

Sets requirement for measurement time scale

Figure from C. Montag (BNL)

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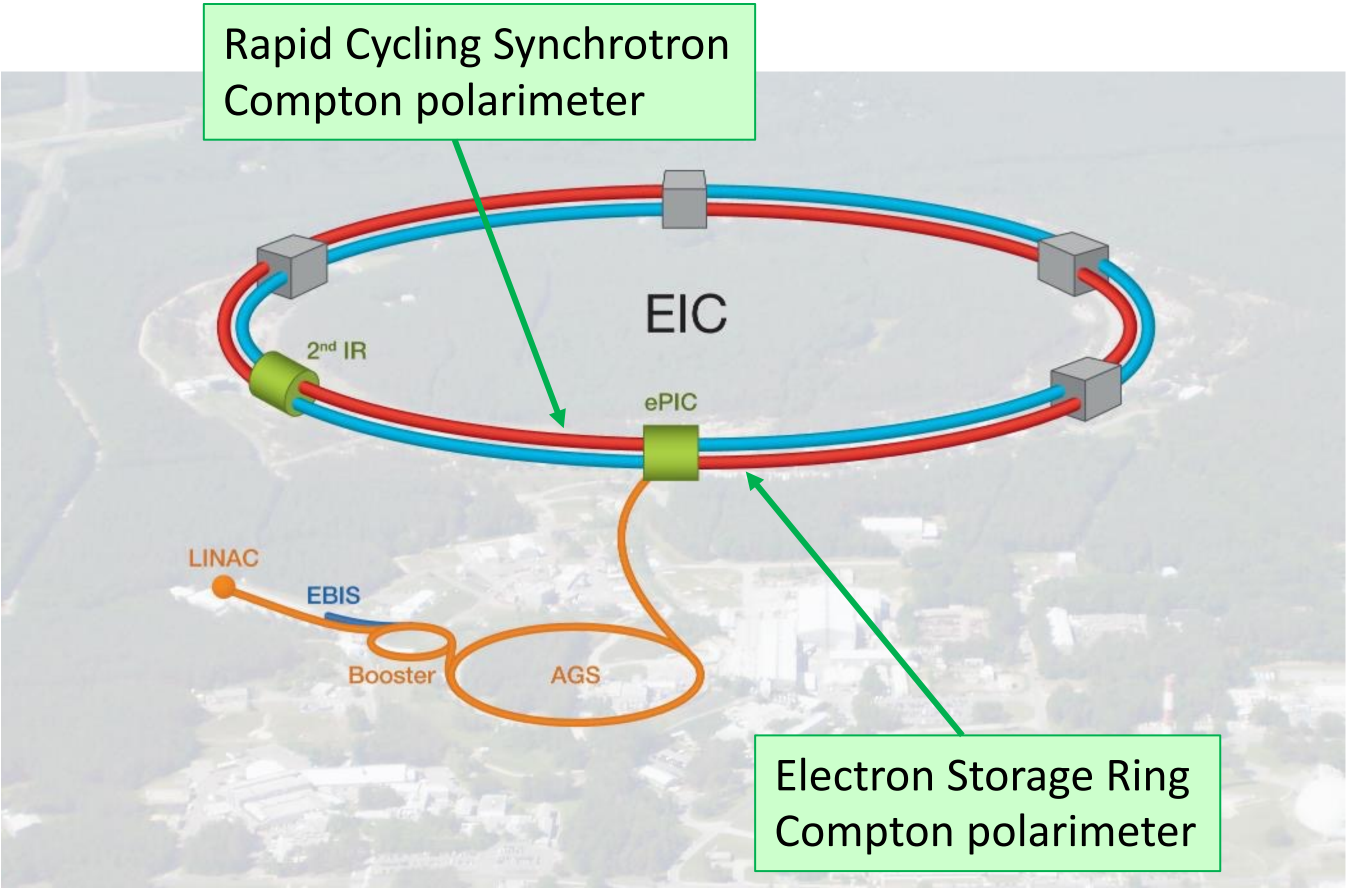
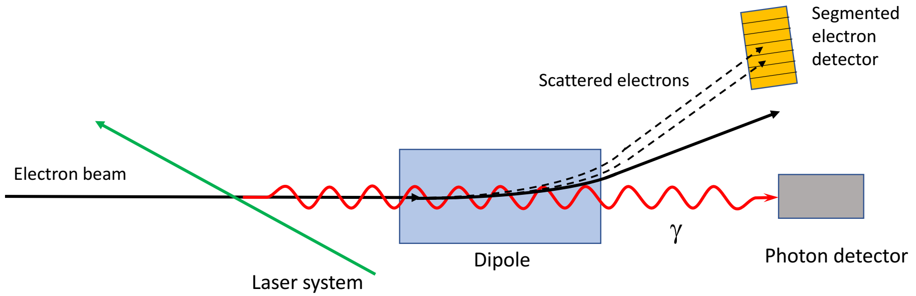
EIC Electron Polarimetry Map

Electron Storage Ring Compton (ESR)
→ Upstream of IP6, between IP and spin rotating solenoid
→ Will measure polarization for each bunch
→ Measure both transverse and longitudinal beam polarization
→ Detect backscattered photon and scattered electron

Rapid Cycling Synchrotron Compton (RCS)
→ Primarily for machine setup – less stringent precision requirements
→ Detect backscattered photons, multi-photon mode
→ Average over several bunches



ESR Compton Polarimeter



EIC Electron Beam Properties

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

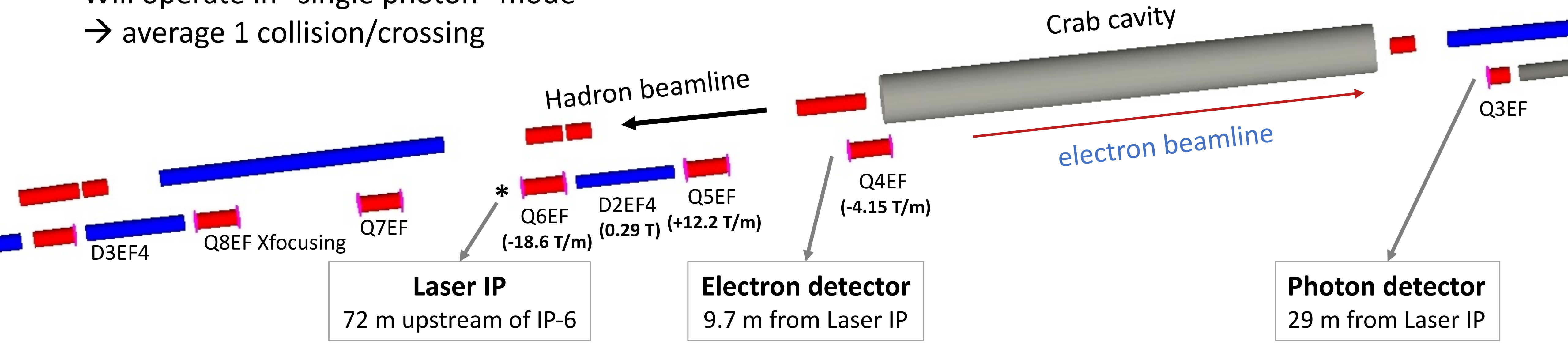
Primary electron polarimetry technique in ESR will be Compton → lessons learned from earlier polarimeters shape design of EIC Compton

Requirements:
1. dP/P = 1% (or better)
2. Bunch-by-bunch polarization measurements → 10 ns bunch spacing
3. Measurement time compatible with electron bunch lifetime in ring (~2 minutes at 18 GeV)

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

Electron Storage Ring Compton

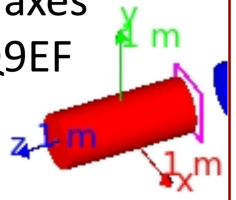
- Will operate in "single photon" mode
  → average 1 collision/crossing



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

Sim axes at Q9EF



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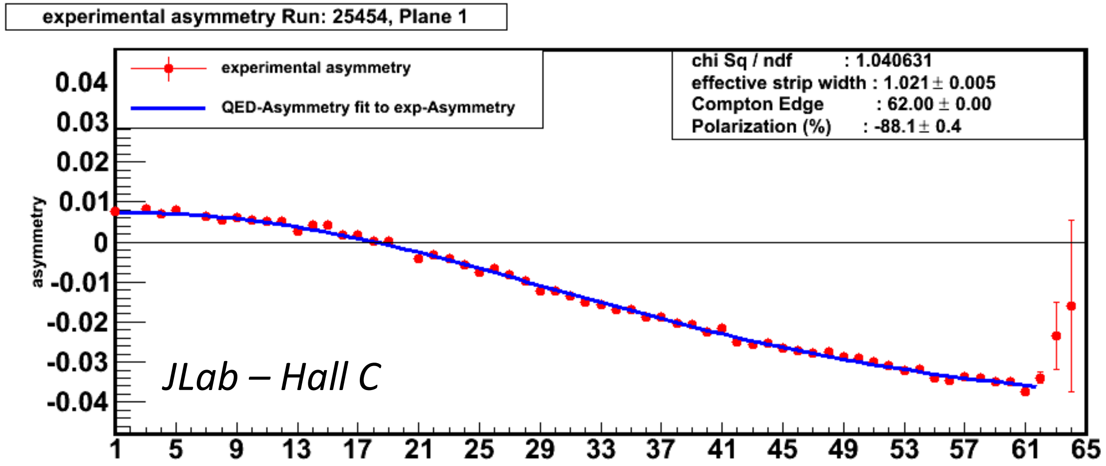
Polarization Measurement via Compton Polarimetry

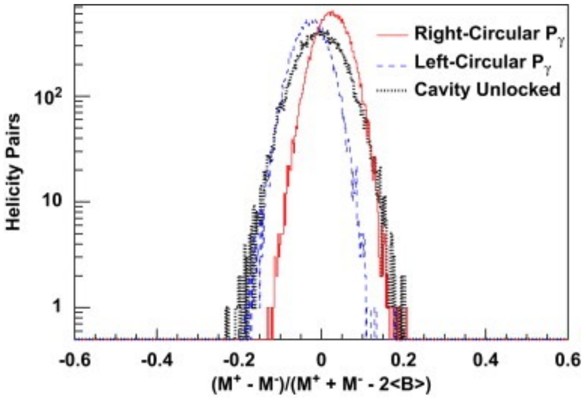
Longitudinal polarization measured via counting asymmetry vs. energy, or energy-integrated asymmetry



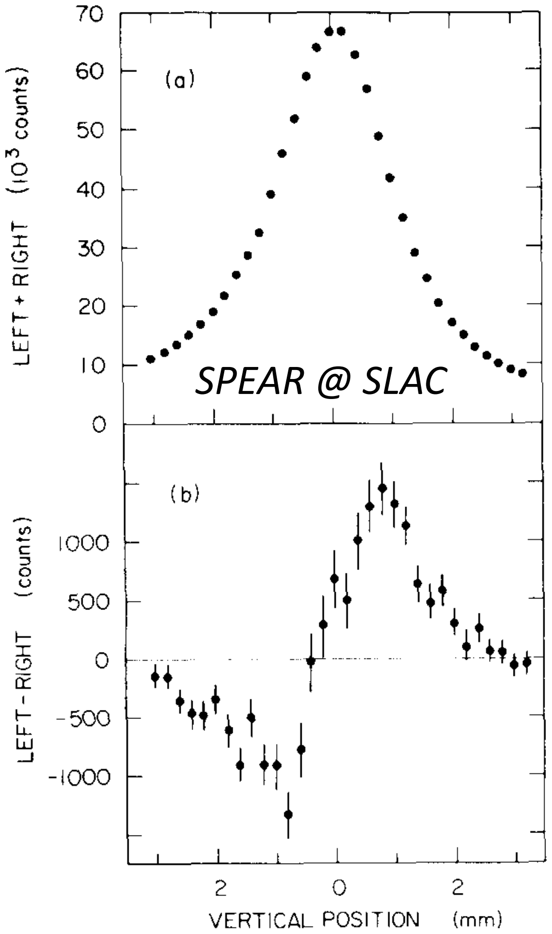
Detector strip # → Scattered electron energy

Photon-energy weighted asymmetry

JLab – Hall A



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



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Simultaneous Longitudinal and Transverse Electron Polarization Measurement

Planned Compton polarimeter location upstream of detector IP
→ Significant transverse components at Compton location → spin rotation before arrival at detector IP

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

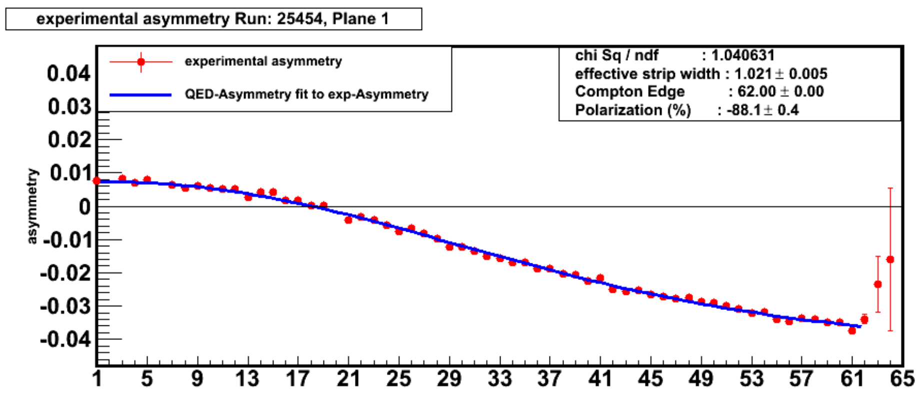
Beam energy	P_L	P_T
5 GeV	96.5%	26.1%
10 GeV	86.4%	50.4%
18 GeV	58.1%	81.4%

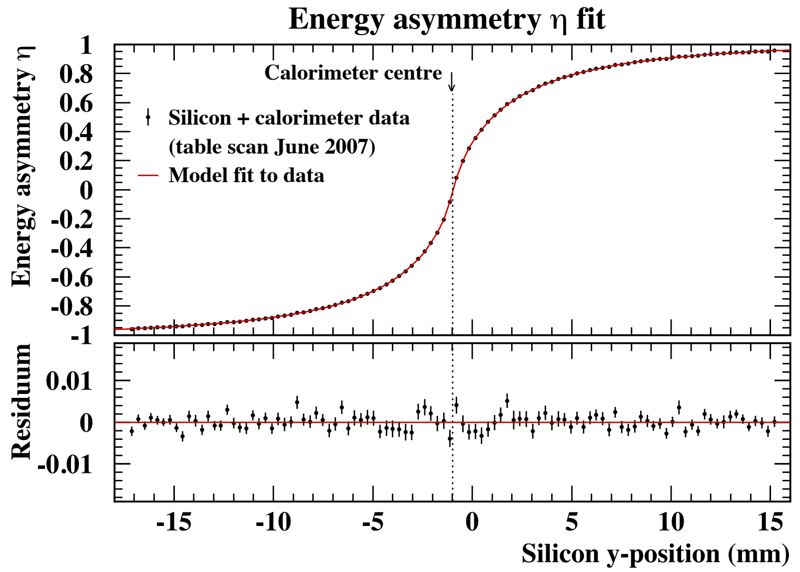
Beam polarization will be fully longitudinal at detector IP, but accurate measurement of absolute polarization will require simultaneous measurement of P_L and P_T at Compton polarimeter

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

Compton polarimetry – lessons from previous devices

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





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Compton Laser System Requirements

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

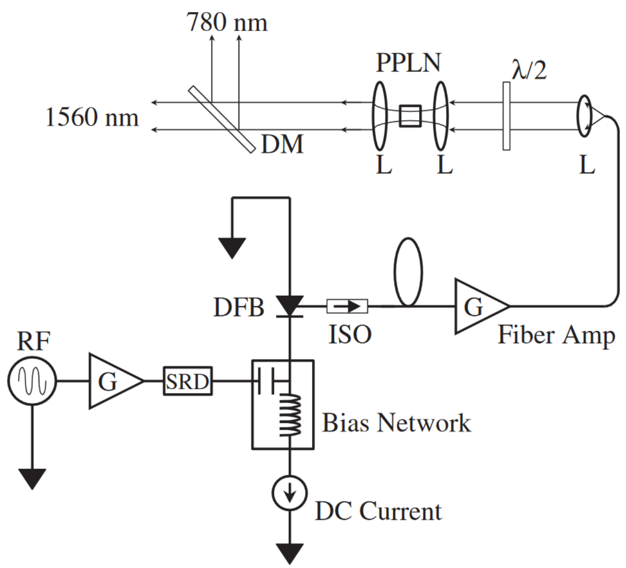
Ciprian Gal

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

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

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

Compton Laser System

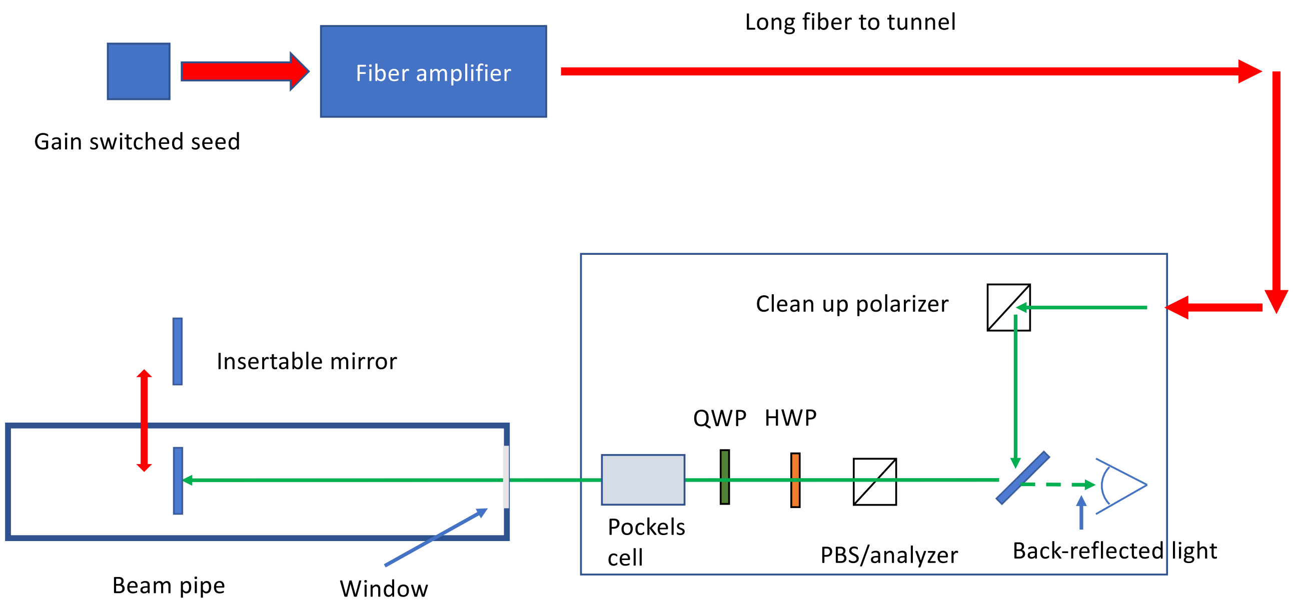


JLab injector laser system

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

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

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



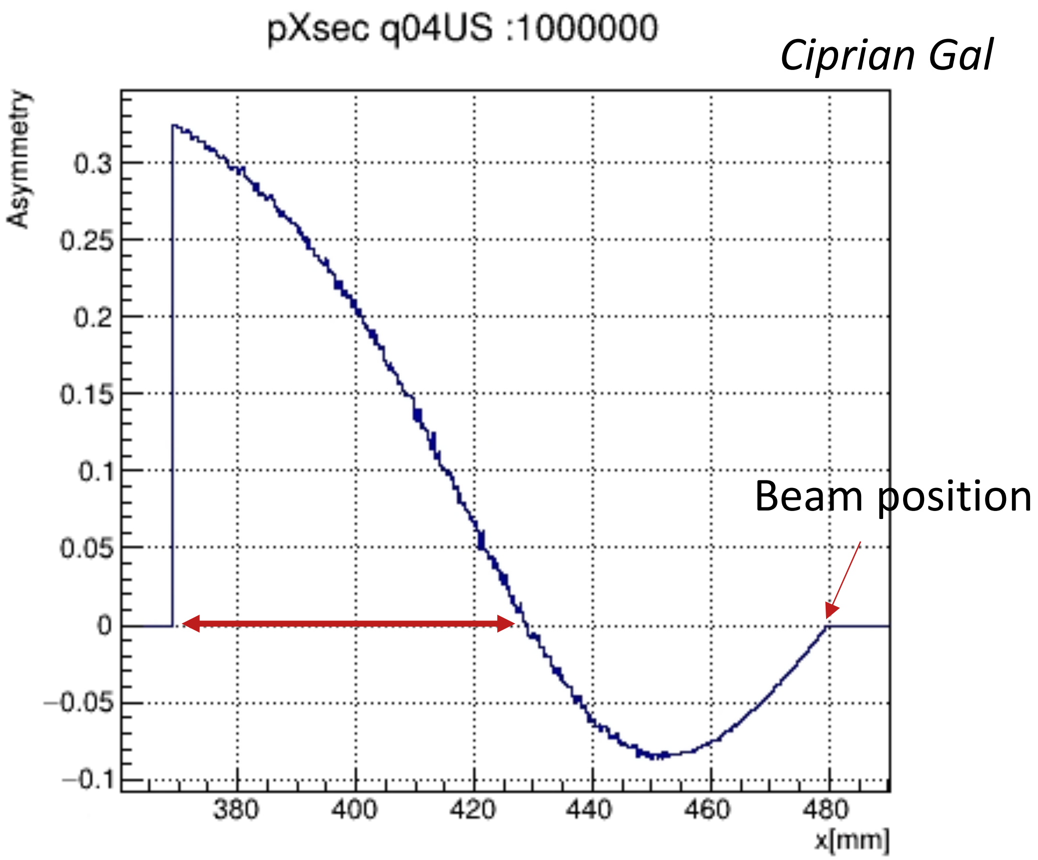
Prototype system under development (C. Gal, started under old EIC eRD program, now underway at JLab)

Electron Detector Size and Segmentation

- Electron detector (horizontal) size determined by spectrum at 18 GeV (spectrum has largest horizontal spread)
  - Need to capture zero-crossing to endpoint → detector should cover at least 60 mm

- Segmentation dictated by spectrum at 5 GeV (smallest spread)
  - Scales ~ energy → 17 mm
  - Need at least 30 bins, so a strip pitch of about 550 μm would be sufficient

- At 18 GeV, zero-crossing about 3 cm from beam
  - 5 GeV → 8-10 mm – this might be challenging



Asymmetry at electron detector @18 GeV

Transverse Polarization Measurement with Electron Detector

At Compton location – significant transverse beam polarization

→ Unfortunately, this transverse polarization is in the horizontal direction

→ Same coordinate as momentum-analyzing dipole

In the absence of the dipole, the transversely polarized electrons would result in a left-right asymmetry

→ The "scattered electron cone" is much smaller than the photons

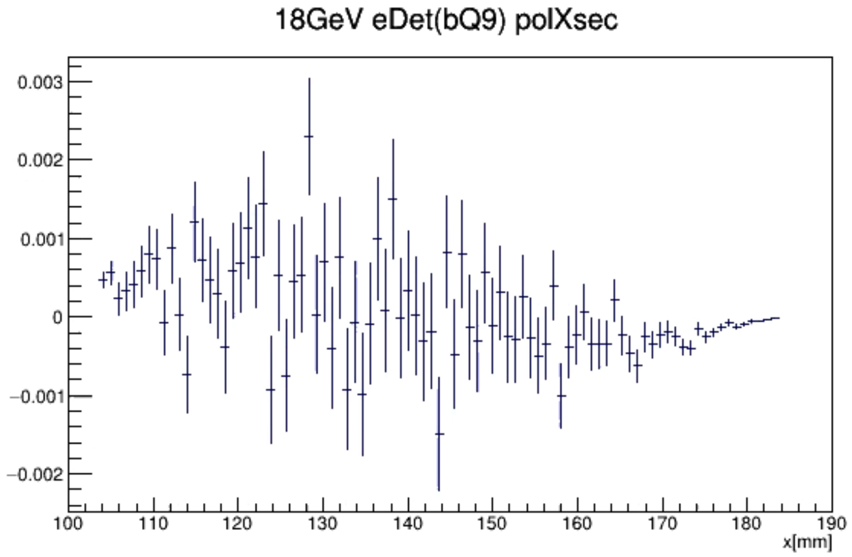
→ Left-right asymmetry is spread over much smaller distance (μm vs mm)

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

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

Beam energy	P_L	P_T
5 GeV	96.5%	26.1%
10 GeV	86.4%	50.4%
18 GeV	58.1%	81.4%

100% transversely polarized beam



Ciprian Gal

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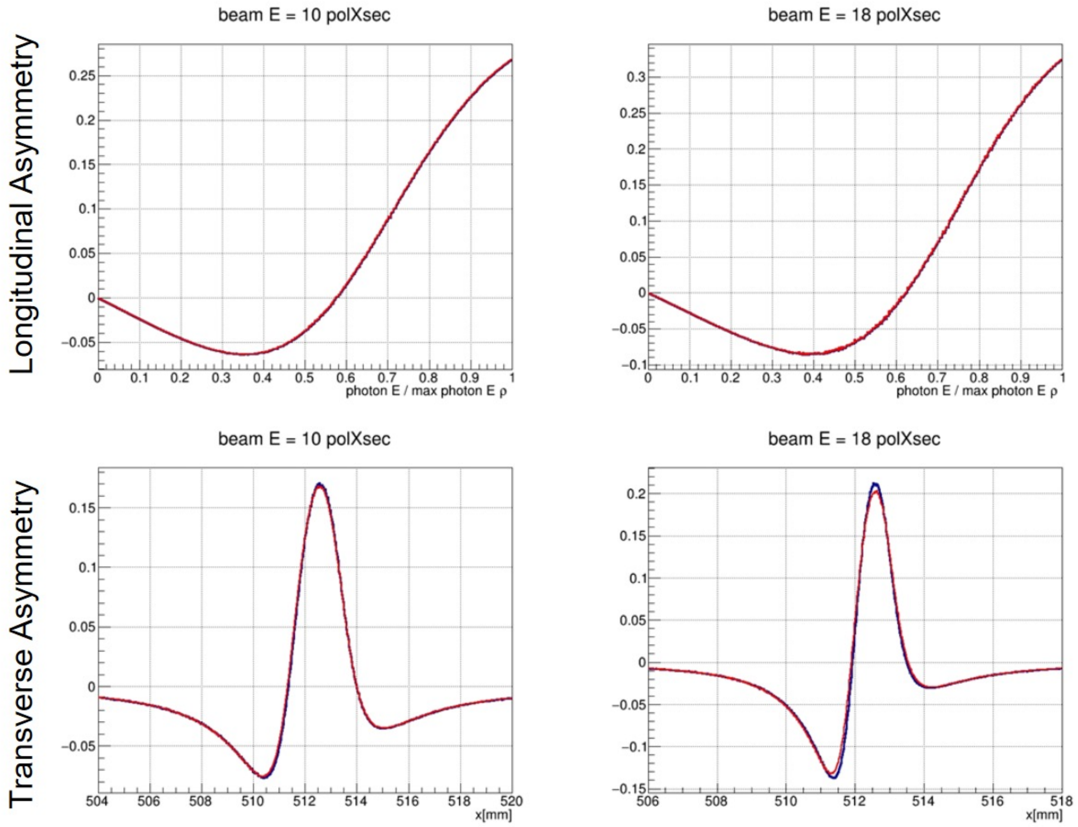
Polarization Measurement with Photon Detector

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

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

Beam energy	P_L	P_T
5 GeV	96.5%	26.1%
10 GeV	86.4%	50.4%
18 GeV	58.1%	81.4%



Ciprian Gal

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

→ +/- 2 cm adequate at 5 GeV

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

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

→ PbWO4 a possible candidate (slow component may be an issue)

Position sensitive detector segmentation determined by highest energy → 18 GeV

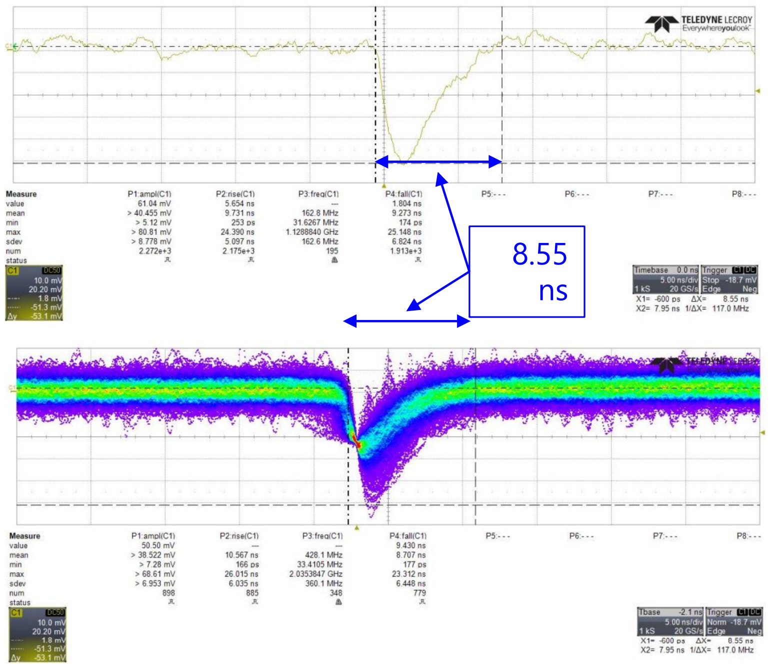
→ More investigation needed, but segmentation on the order of 100-400 μm should work

Position Sensitive Detectors

- Requirements for position sensitive detectors
  - Radiation hard
  - Fast response (needed for bunch-by-bunch measurements)
  - High granularity (down to 100 μm pitch)

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

Diamond strip detectors have been used successfully at JLab in Compton polarimeters
→ No performance degradation after 10 Mrad dose during Q-Weak experiment @ JLab
→ Intrinsic time response is fast, but small signals require significant amplification – custom electronics/ASIC will be required



500 μm pCVD diamond w/TOTEM electronics

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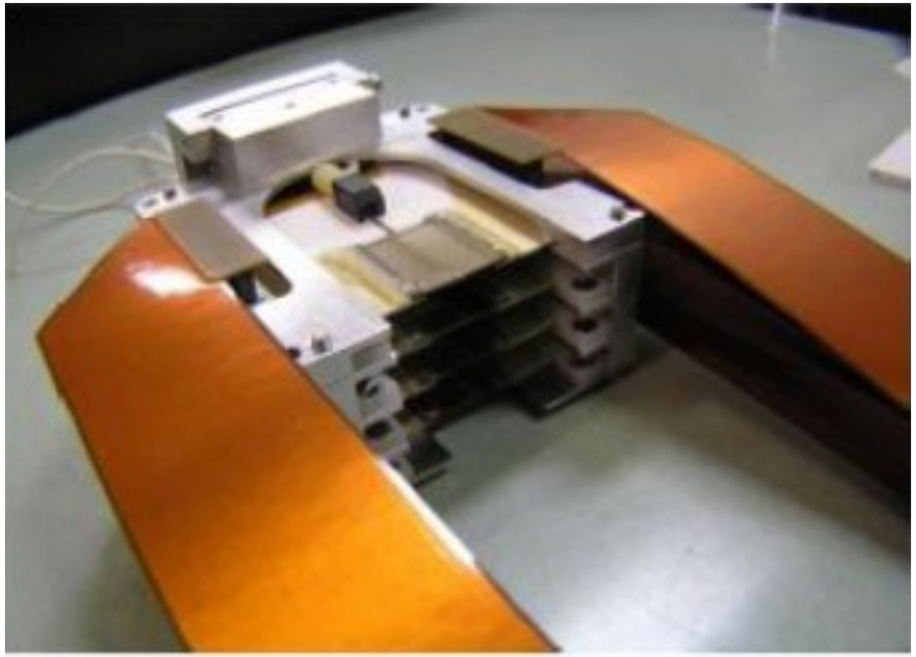
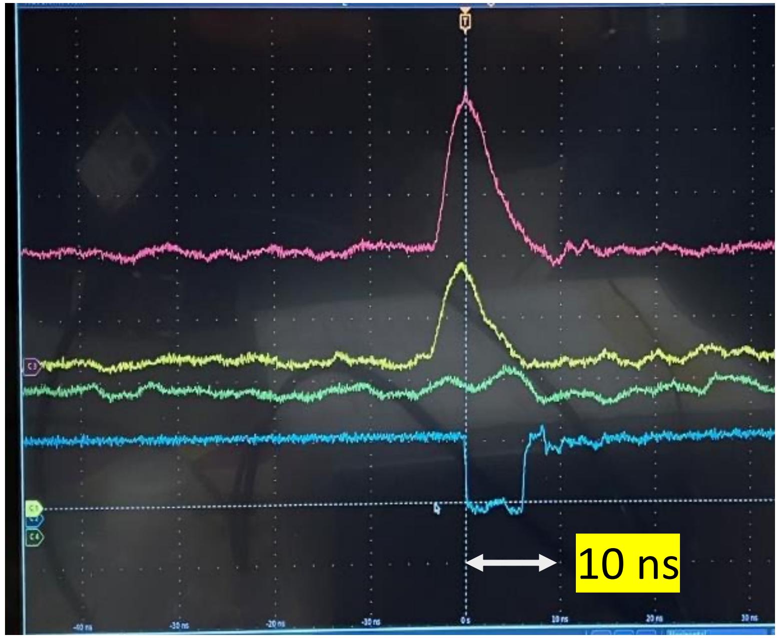
Diamond strip detectors @ JLab



Hall C diamond strip detector

Signals from CALYPSO/FLAT32 prototype



New diamond strip detectors under development for JLab/Hall A MOLLER experiments
→ Size optimized for 11 GeV operation
→ Q-Weak detector had amplifier discriminator outside vacuum – will use ASIC chip mounted on detector board

New “FLAT32” chip based on “CALYPSO” (used at LHC) under development – already meets EIC requirements

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Photon Calorimeter

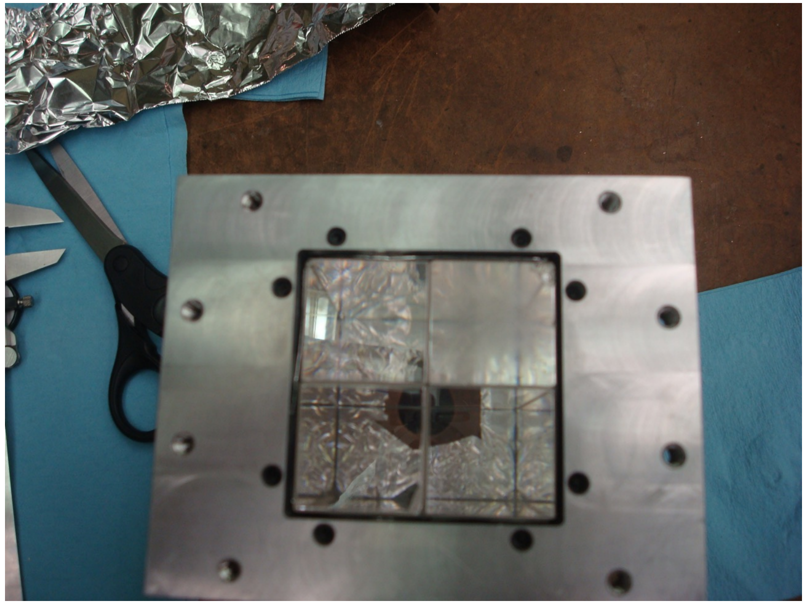
- Good energy resolution required for longitudinal polarization measurements, but fast time response required for bunch-by-bunch measurements
- Tungsten-powder calorimeter (similar to STAR Forward Upgrade) satisfies timing requirements for Compton polarimeters
  - Scintillating fiber embedded in tungsten powder
  - Ample experience with such detectors at BNL
- Detector size 16 x 16 mm^2
- Initially, thought long time component ruled out lead-tungstate
  - Recent publication suggests time response at room temperature may be acceptable

Table 2. Measured luminescence properties of doped $PbWO_4$ scintillator crystals on our apparatus for a mean energy deposited of 432 keV. Y_{xx} stands for photo-electron yields, τ_{XX}, for scintillation time constants. The Cherenkov contribution to yield, 0.80 photo-electron, is included in the total luminescence Yield. Second part: computed values of systematic errors on measurements (see paragraph 6)

Temp. (°C)	Y_{Total} (PE)	Y_{Fast} (PE)	τ_{Fast} (ns)	Y_{slow} (PE)	τ_{slow} (ns)
CRYTUR - Panda II					
20	15.2 ± 0.5	8.45 ± 0.1	1.80 ± 0.06	6.0 ± 0.3	6.4 ± 0.2
5	22.3 ± 0.5	8.9 ± 0.1	2.20 ± 0.06	12.7 ± 0.4	8.0 ± 0.2
−10	34.8 ± 0.5	7.6 ± 0.1	2.31 ± 0.06	26.4 ± 0.6	10.5 ± 0.2
−25	54.5 ± 1.7	7.05 ± 0.2	2.8 ± 0.22	46.5 ± 1.9	16.5 ± 0.5
SICCAS - CMS					
20	14.1 ± 0.5	8.0 ± 0.1	1.71 ± 0.06	5.3 ± 0.3	5.8 ± 0.2
5	20.7 ± 0.5	7.8 ± 0.1	2.0 ± 0.06	12.1 ± 0.4	6.9 ± 0.2
−10	31.7 ± 0.5	7.2 ± 0.1	2.33 ± 0.06	23.7 ± 0.6	9.8 ± 0.2
−25	51.5 ± 1.7	6.5 ± 0.2	2.6 ± 0.22	44 ± 1.9	15.9 ± 0.5
SICCAS - Y Doped					
20	15.0 ± 0.5	8.75 ± 0.1	1.67 ± 0.06	5.4 ± 0.3	6.6 ± 0.2
5	22.2 ± 0.5	9.7 ± 0.1	2.06 ± 0.06	11.65 ± 0.4	7.9 ± 0.2
−10	33.0 ± 0.5	8.8 ± 0.1	2.37 ± 0.06	23.4 ± 0.6	10.2 ± 0.2
−25	53.5 ± 1.7	7.5 ± 0.2	2.65 ± 0.22	45.5 ± 1.9	15.5 ± 0.5
Systematic uncertainities - All doped Crystals					
20	±0.8	±0.55	±0.1	±0.9	±0.1
5	±1.1	±0.55	±0.1	±1.2	±0.1
−10	±1.7	±0.5	±0.2	±1.7	±0.1
−25	±2.7	±0.5	±0.2	±2.2	±0.1

M. Follin et al 2021 JINST 16 P08040

Lead Tungstate in Hall A Compton

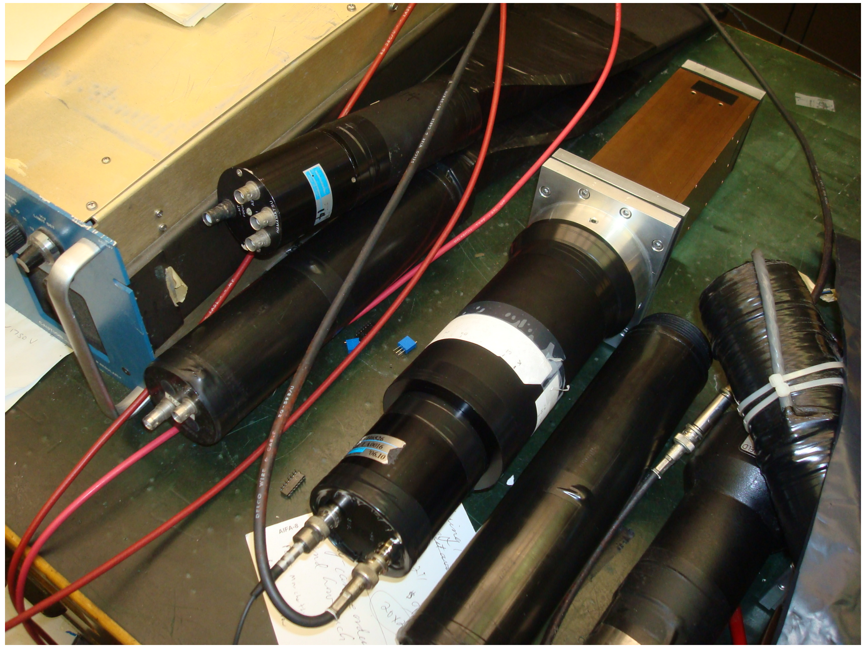


Hall A, 2015-2016: 4-block, lead-tungstate detector was used during DVCS/GMp experiments
→ Initially used “found” PMT + base
→ Summer of 2015 – base was replaced/optimized to provide better linearity

Crystal size = 3 x 3 x 20 cm

Read out using single PMT

Detector assembled, PMT optimized by CMU (B. Quinn)



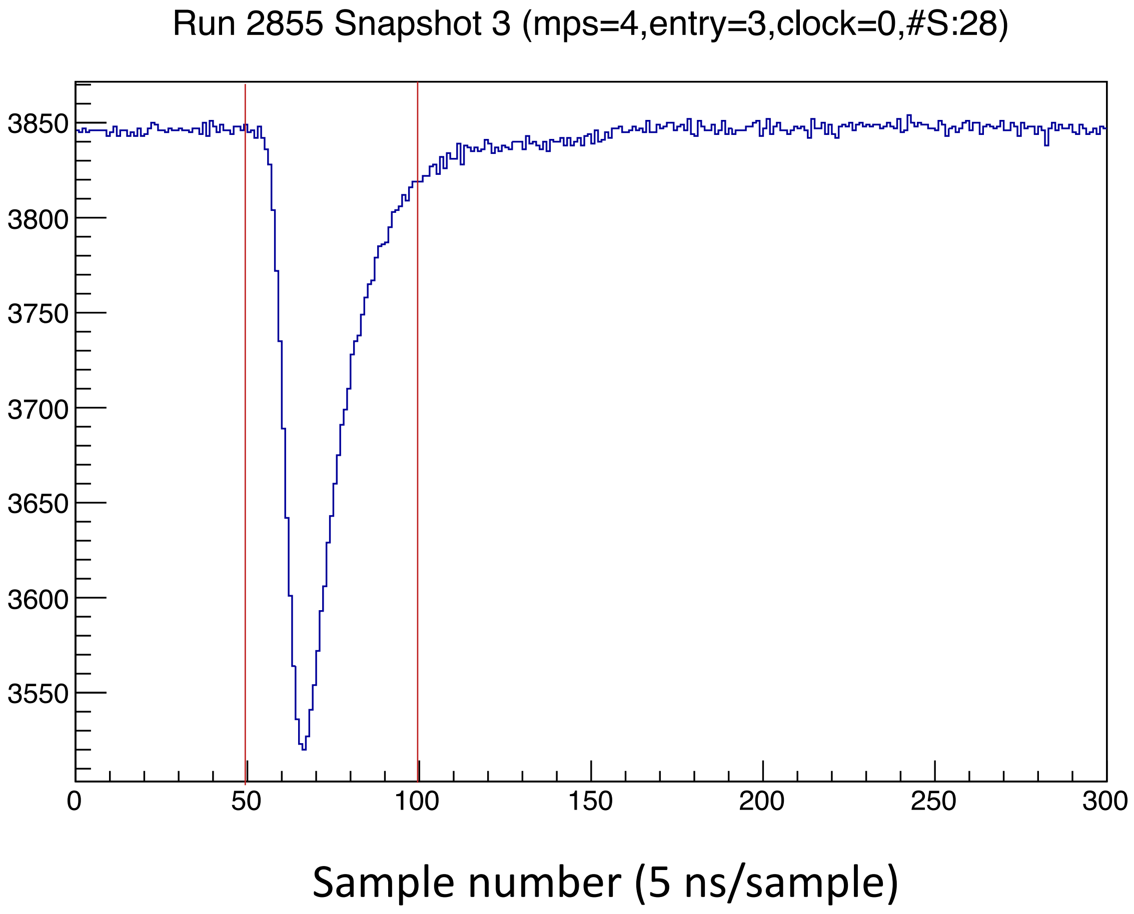
Lead Tungstate Time response

Hall A detector was operated at room temperature
→ Primarily operated in integrating mode, but snapshots also available
→ 200 MHz FADC

Full width of pulse ~ 250 ns → factor of 25 too large

PMT was optimized for linearity, not time response

Same detector/PMT now deployed in Hall A – further tests possible



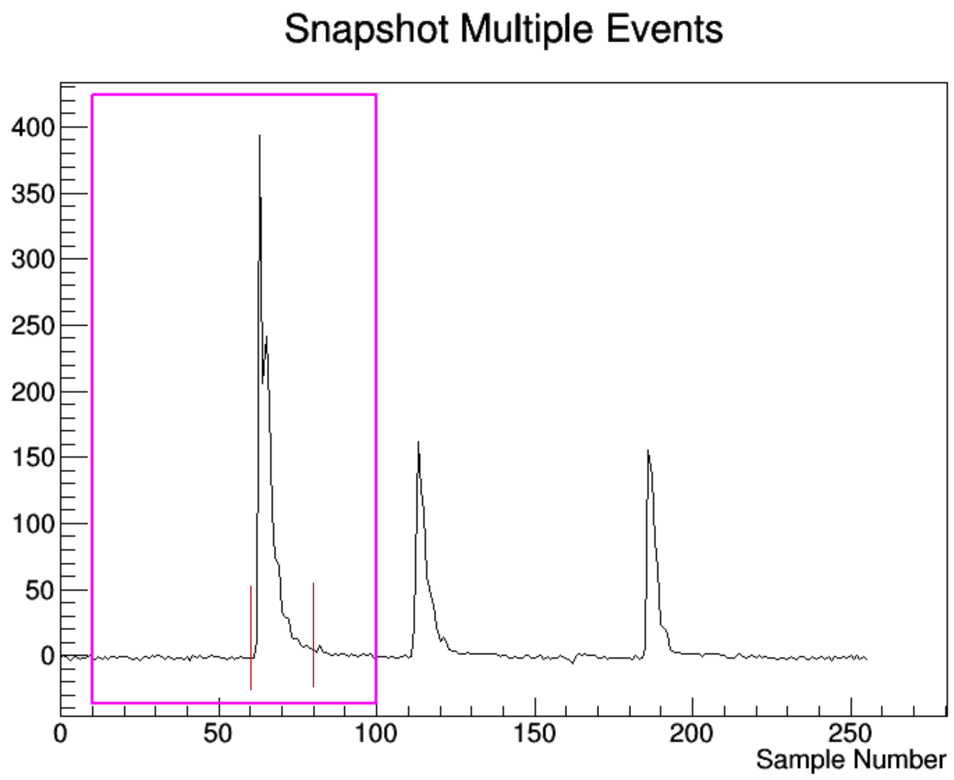
Q-Weak Lead Tungstate

Q-Weak experiment in Hall C used lead-tungstate crystals from same batch
→ Same configuration (2x2 array)
→ Different PMT

Time response appears to be a bit faster
→ 30 samples → 150 ns

Further improvement with different PMT?
Separate PMT for each crystal?

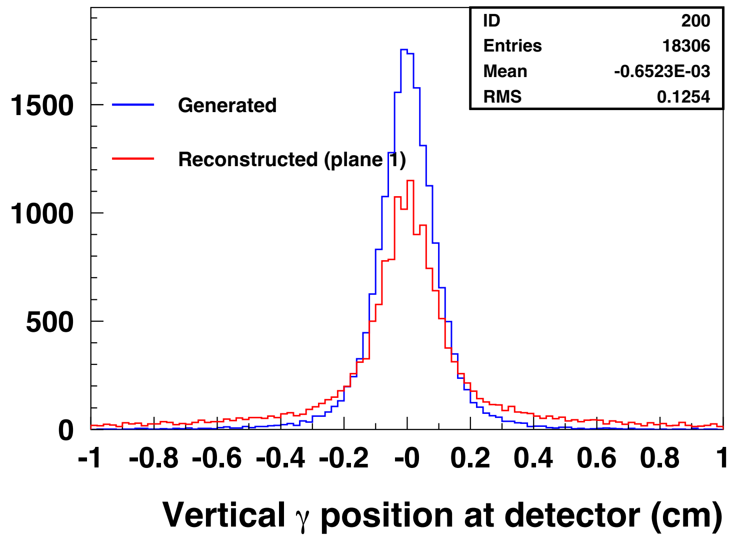
Lead-tungstate deployed for NPS experiment in Hall C appears to have ~ 40 ns pulse width



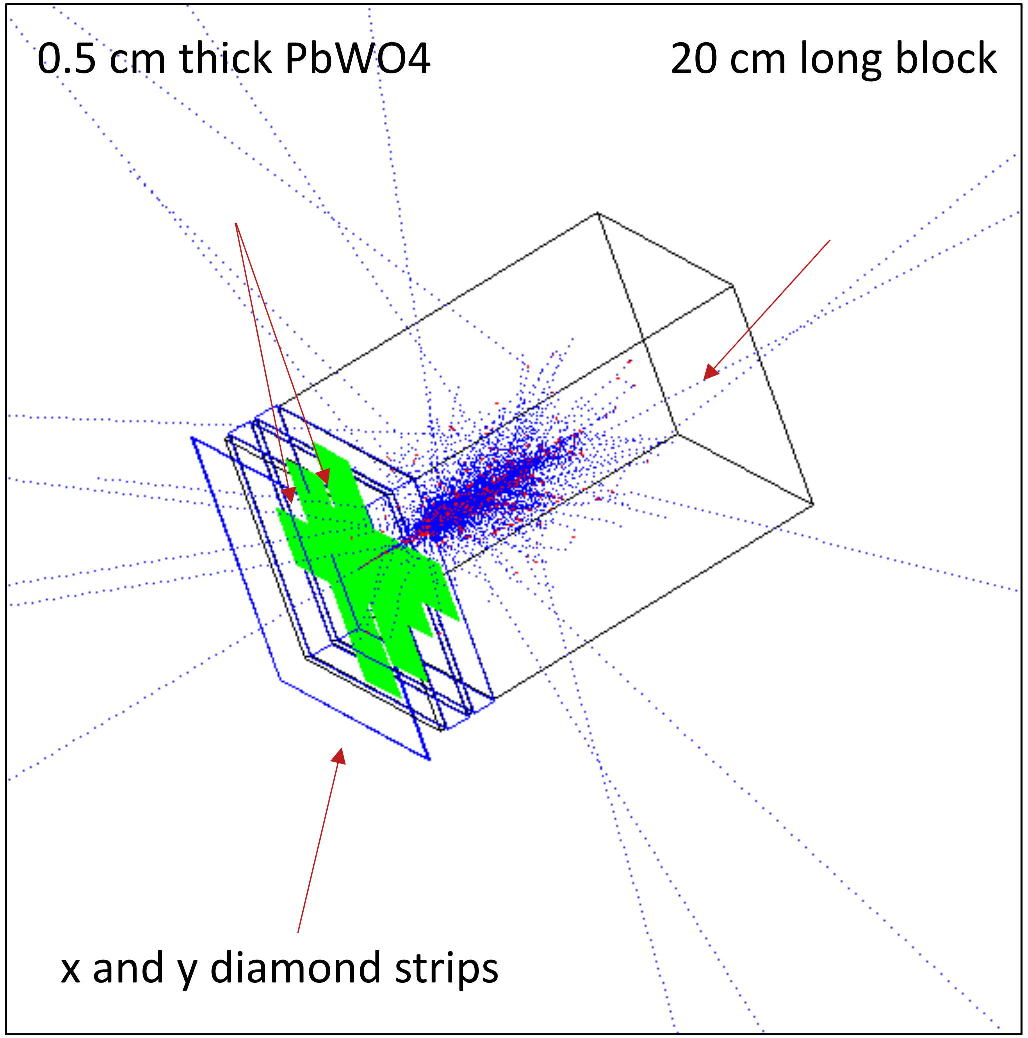
Q-Weak lead-tungstate response

Detector Simulations

→ Need high position resolution for backscattered photons for transverse polarization measurement
→ Best results from longitudinally segmented calorimeter with (x-y) diamond strips



Overall efficiency 60% w/adequate resolution



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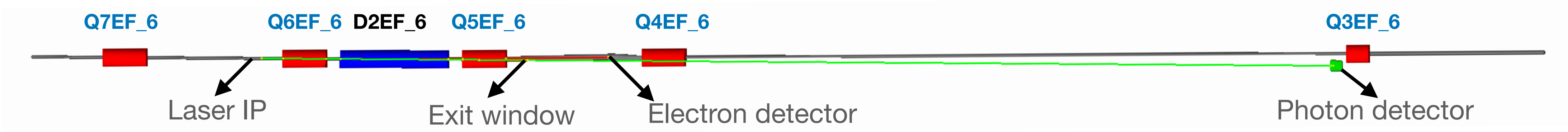
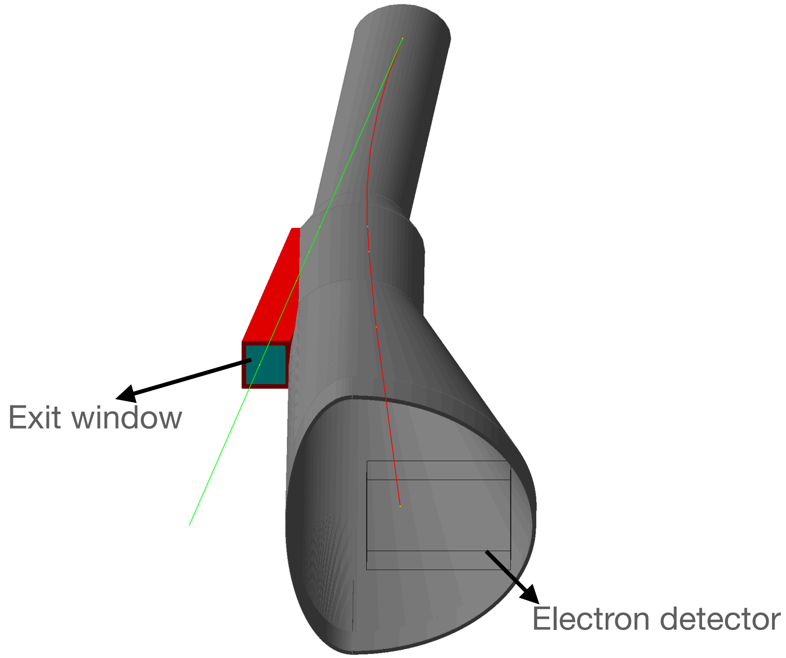
Beamline Design and Synchrotron Backgrounds



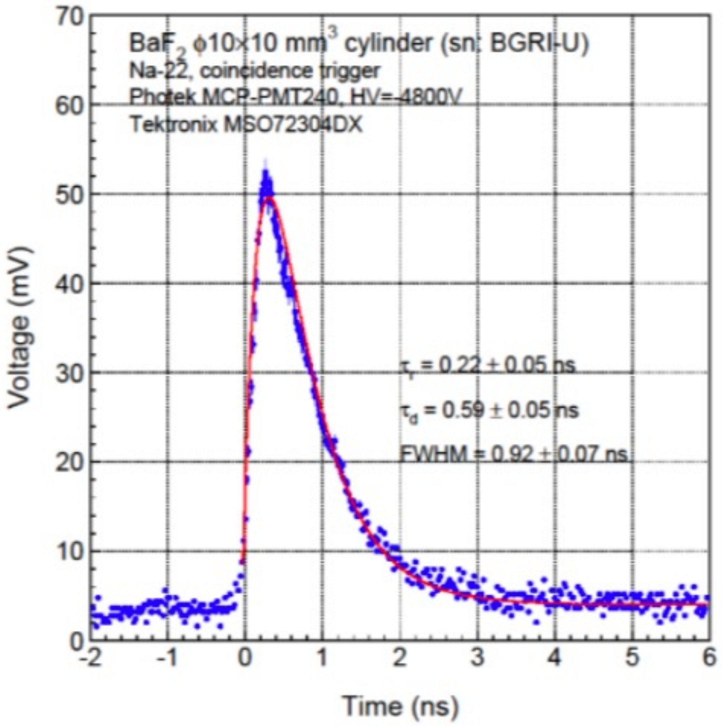
- Beampipe design for region downstream of laser-electron beam collisions underway
- Need photon exit window and room to accommodate scattered electrons and electron detector
- Impedance likely an issue – electron detector may need to be outside beam pipe, but this could limit how much of the spectrum we can detect
- Synchrotron backgrounds at 18 GeV require **2 cm tungsten shield!** → Although polarimeter location has been chosen, need to iterate with machine group to minimize synchrotron backgrounds (dipole bend too large)



Zhengqiao Zhang (BNL)

Summary

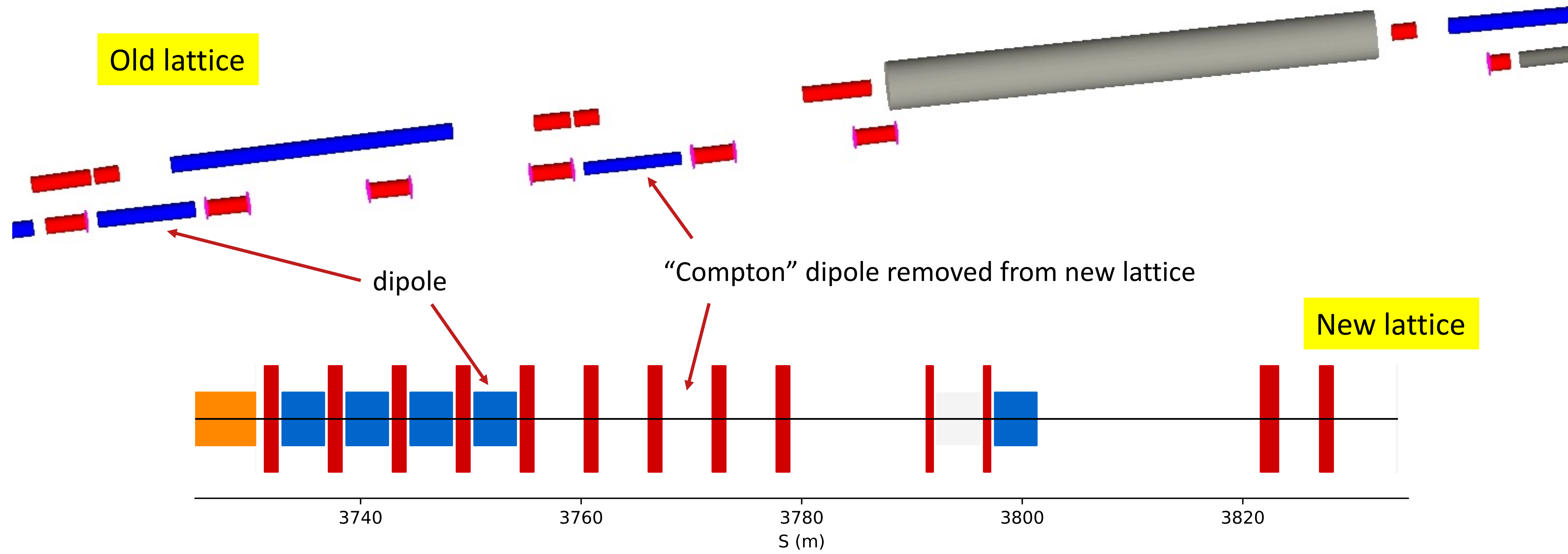
- ESR Compton requires bunch-by-bunch measurements of polarization
- Time response requirements particularly challenging
- Diamond strip detectors + FLAT32 ASIC should be adequate
- Working towards higher resolution photon calorimeter with adequate time response
  - Not discussed: BaF2 with optical filters (suggested by A. Martens for superKEKB photon detector)
- Synchrotron backgrounds a significant issue
  - Still need to work on mitigation



Ren-Yuan Zhu 2019 *J. Phys.: Conf. Ser.* **1162** 012022

EXTRA

ESR Lattice Update



New ESR lattice not compatible with existing Compton design
→ Not clear new lattice can accommodate Compton requirements

Luminosity

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

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

Pulsed laser:

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

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

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

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

Luminosity

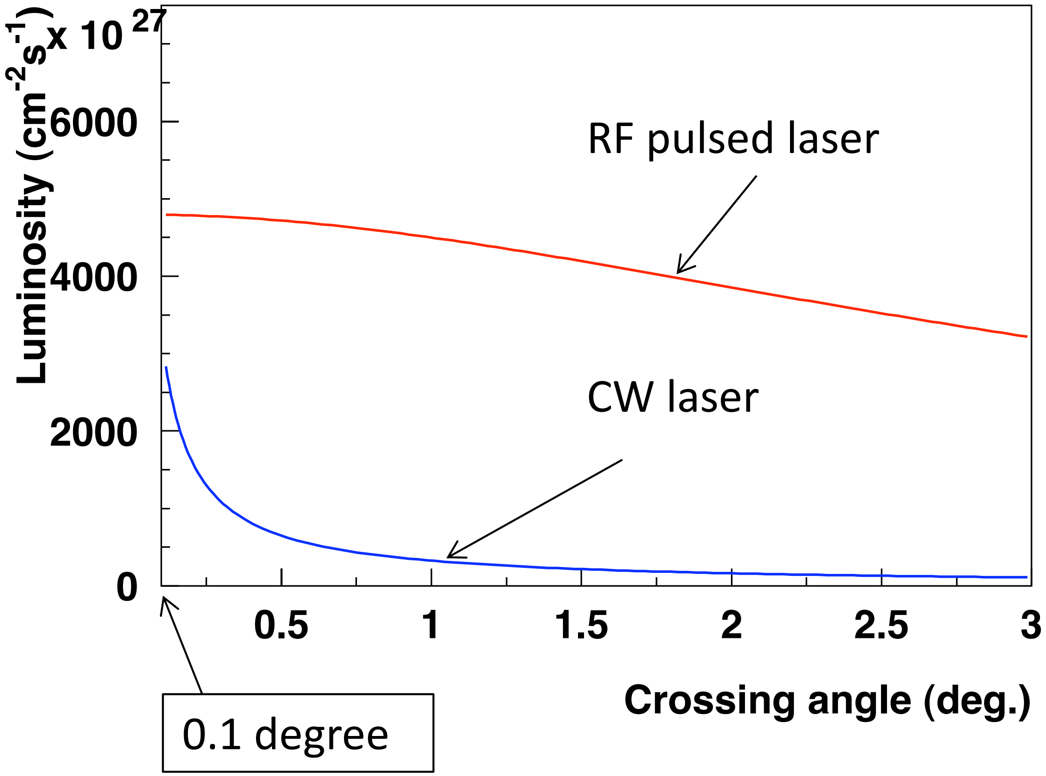
Pulsed laser provides higher luminosity than CW lasers (for pulsed beams)

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

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

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

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



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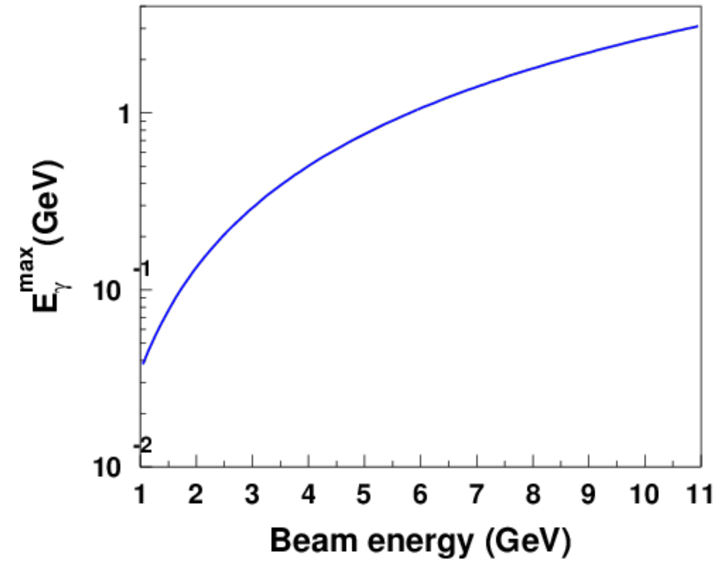
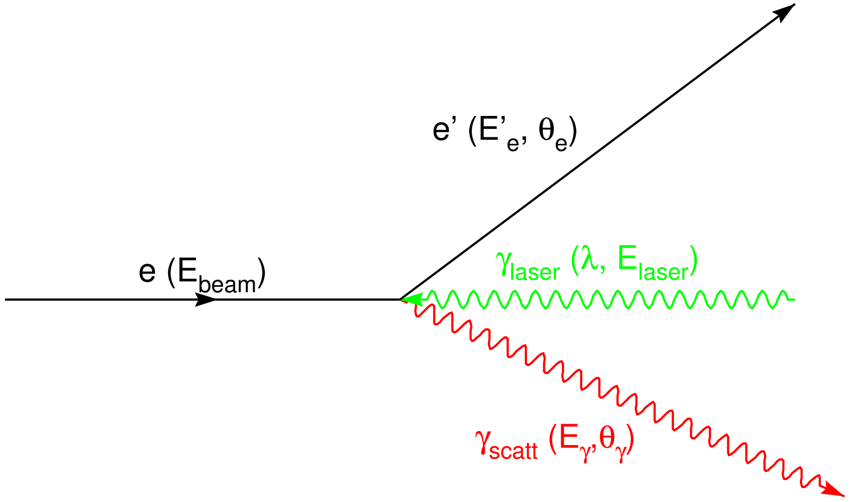
Compton Scattering - Kinematics

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

Jefferson Lab

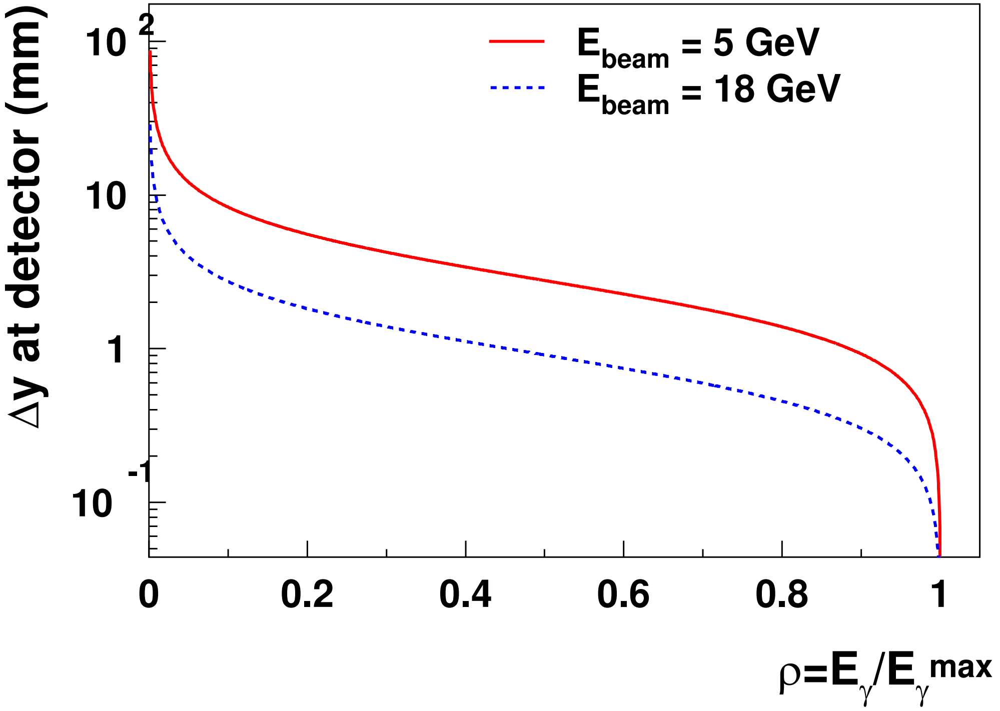
Compton Scattering – Backscattered Photon Angle

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

Backscattered photons emitted in a narrow cone

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

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



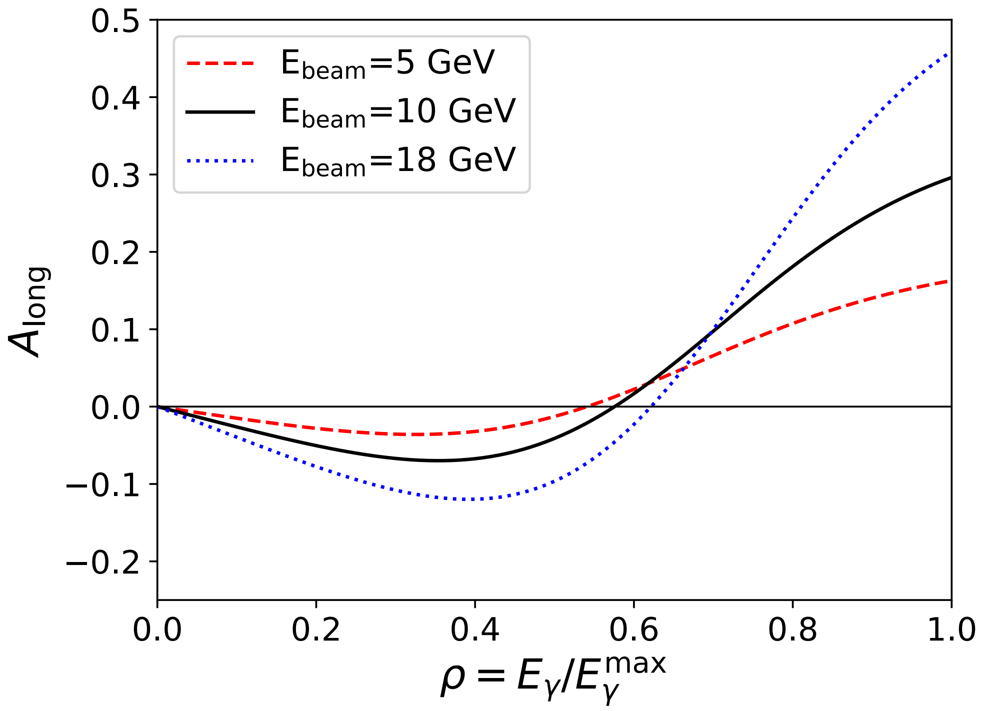
Backscattered photon position vs. energy at hypothetical detector 25 m from collision point

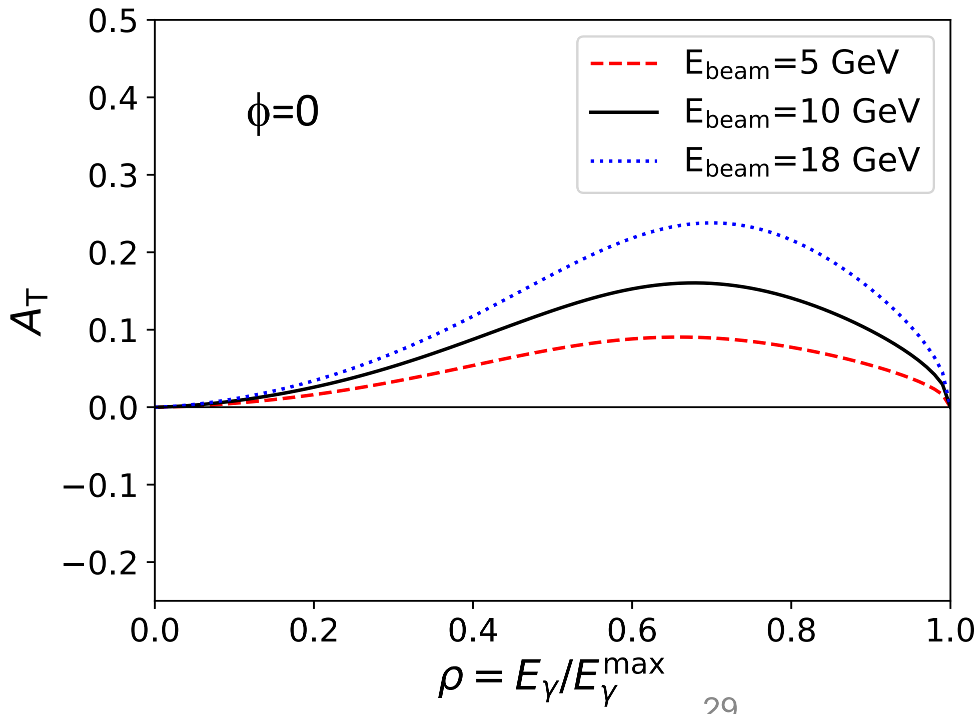
Polarization Measurement via Compton Polarimetry

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

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

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





Analyzing Power and Measurement Times

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

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

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

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

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

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