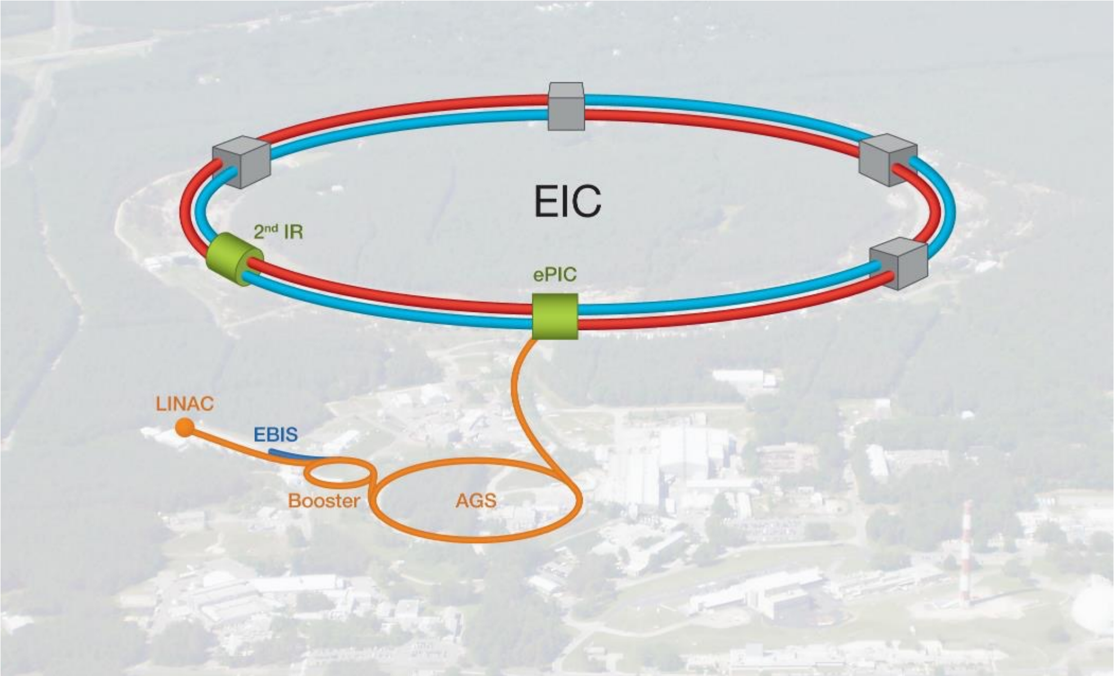
Electron Polarimetry at the Electron Ion Collider

Dave Gaskell

Jefferson Lab

- Polarimetry challenges at EIC
- EIC Electron Polarimeters
  - ESR Compton
  - RCS Compton
  - Mott Polarimeters



SPIN 2023

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EIC Beam Properties and Polarimetry Challenges

EIC will provide unique challenges for electron polarimetry

→ 10 ns between electron/hadron bunches at high luminosity configuration (~40 ns at higher CM configuration)

→ Intense beams (0.26 to 2.5 A)

  → Large synchrotron radiation for electron beams result in large effects at detectors

Requirements:

→ Bunch-by-bunch measurement of polarization

→ Simultaneous measurement of both P_L and P_T

→ Measurement fast enough to achieve 1% statistics for each bunch

→ Systematics ***dP/P = 1%*** or better

Electron energies = 5, 10, 18 GeV

Table 1.1: Maximum luminosity parameters.

Parameter	hadron	electron
Center-of-mass energy [GeV]	104.9	
Energy [GeV]	275	10
Number of bunches	1160	
Particles per bunch [10^{10}]	6.9	17.2
Beam current [A]	1.0	2.5
Horizontal emittance [nm]	11.3	20.0
Vertical emittance [nm]	1.0	1.3
Horizontal β-function at IP β_x^* [cm]	80	45
Vertical β-function at IP β_y^* [cm]	7.2	5.6
Horizontal/Vertical fractional betatron tunes	0.228/0.210	0.08/0.06
Horizontal divergence at IP $\sigma_{x'}^*$ [mrad]	0.119	0.211
Vertical divergence at IP $\sigma_{y'}^*$ [mrad]	0.119	0.152
Horizontal beam-beam parameter ξ_x	0.012	0.072
Vertical beam-beam parameter ξ_y	0.012	0.1
IBS growth time longitudinal/horizontal [hr]	2.9/2.0	-
Synchrotron radiation power [MW]	-	9.0
Bunch length [cm]	6	0.7
Hourglass and crab reduction factor [17]	0.94	
Luminosity [10^{34} cm^{-2} s^{-1}]	1.0	

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 have different lifetime depending on polarization
- Bunches must be replaced relatively often to keep average polarization high
- Bunch-by-bunch polarization measurement required

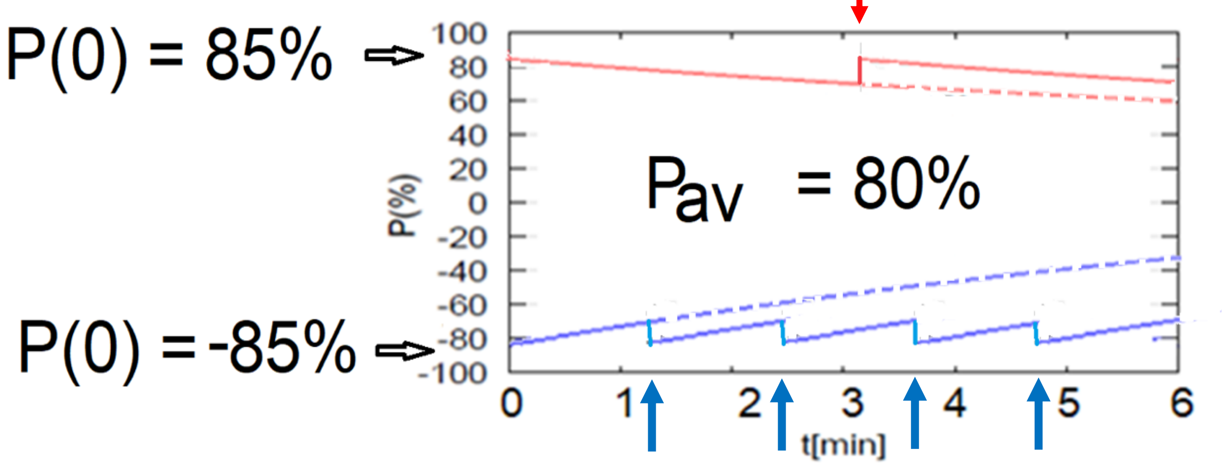
B P

Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

Re-injection



P_∞= 30%
(conservative)

Re-injections

Figure from C. Montag (BNL)

Bunches will be replaced about every 50 minutes at 5 and 10 GeV

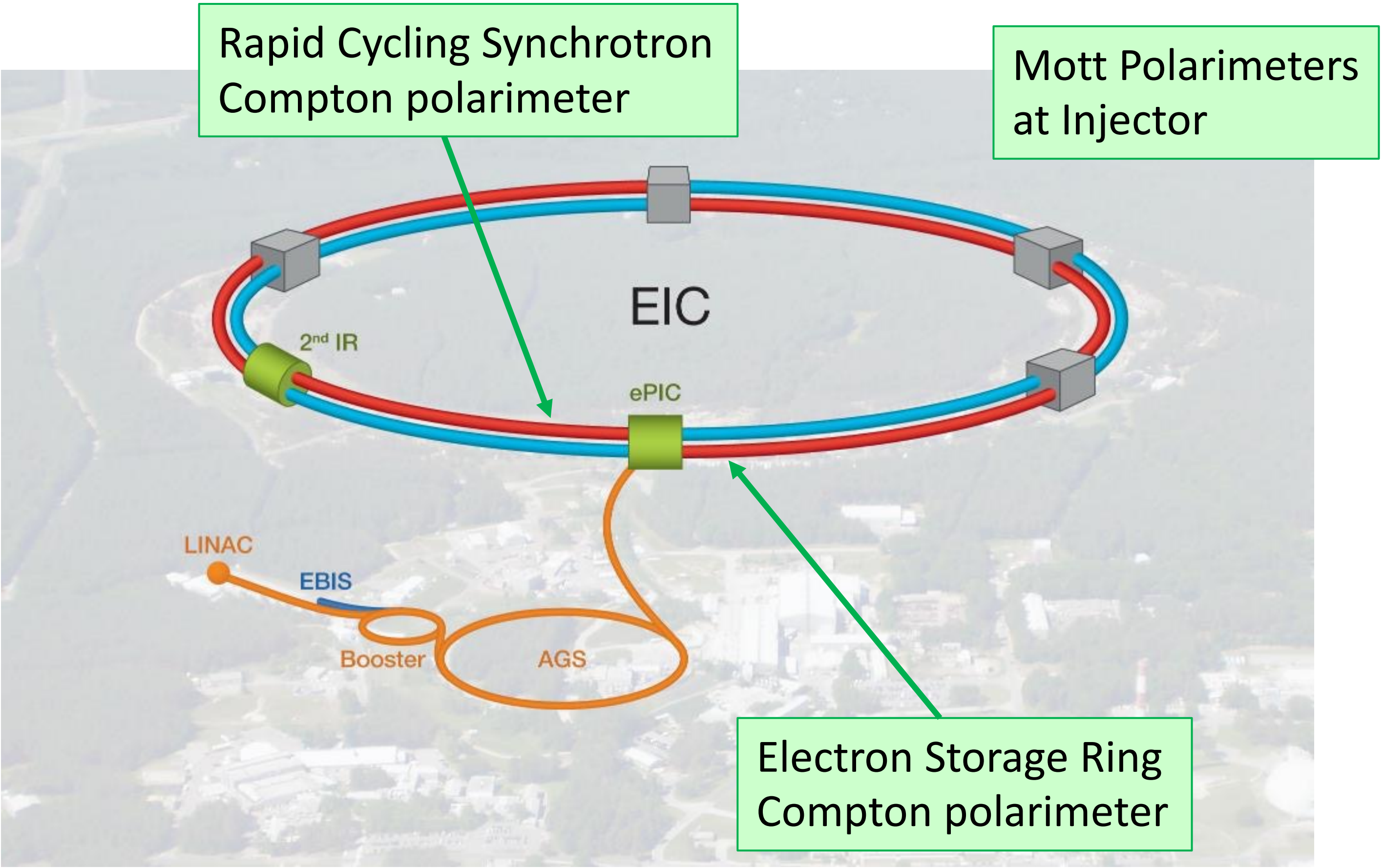
→ **1-3 minutes at 18 GeV**

Sets requirement for measurement time scale

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
→ Beam should be 100% transversely polarized
→ Detect backscattered photons, multi-photon mode
→ Average over several bunches



Electron Storage Ring (ESR) Compton Polarimeter

Compton polarimeter will be upstream of upstream of 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%

Polarization Components at Compton

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

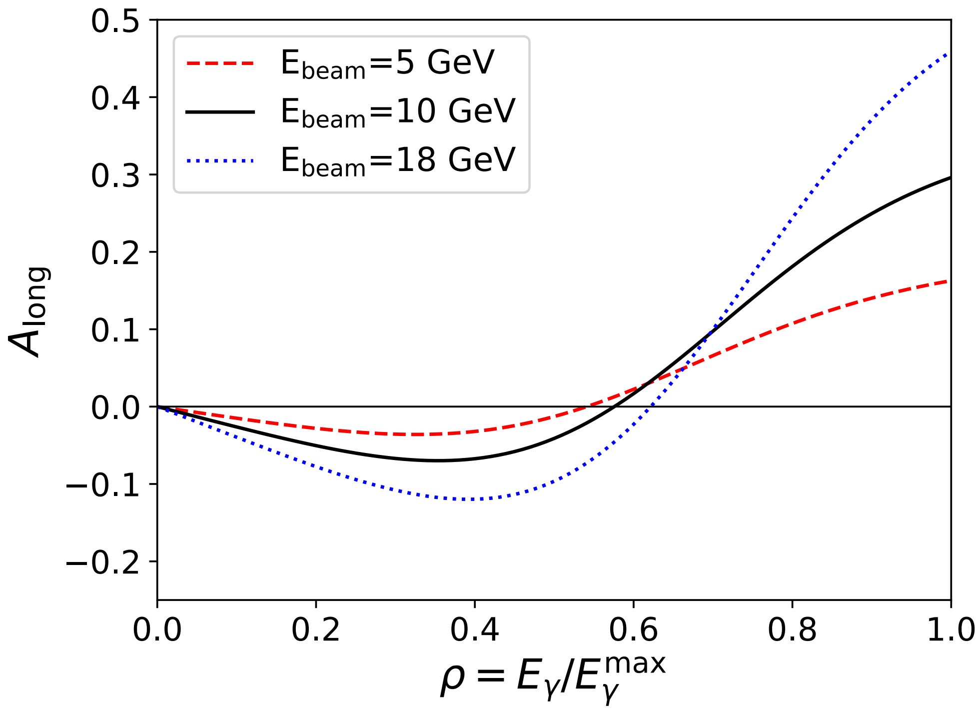
EIC Compton will provide first **high precision** measurement of P_L and P_T at the same time

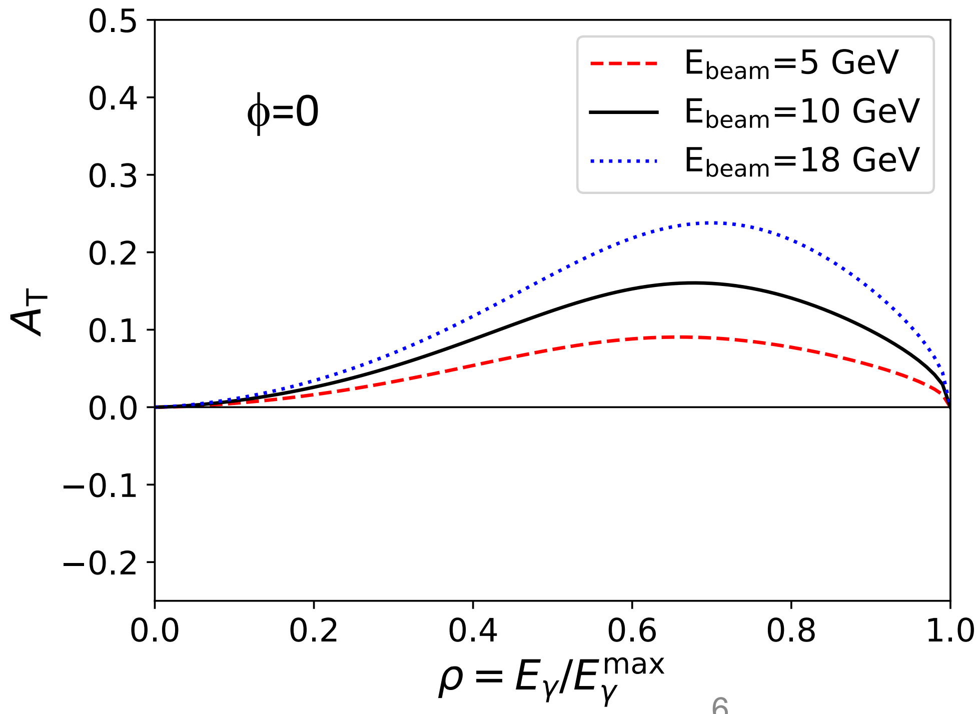
Polarization Measurement via Compton Polarimetry

Compton longitudinal and transverse analyzing powers

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

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





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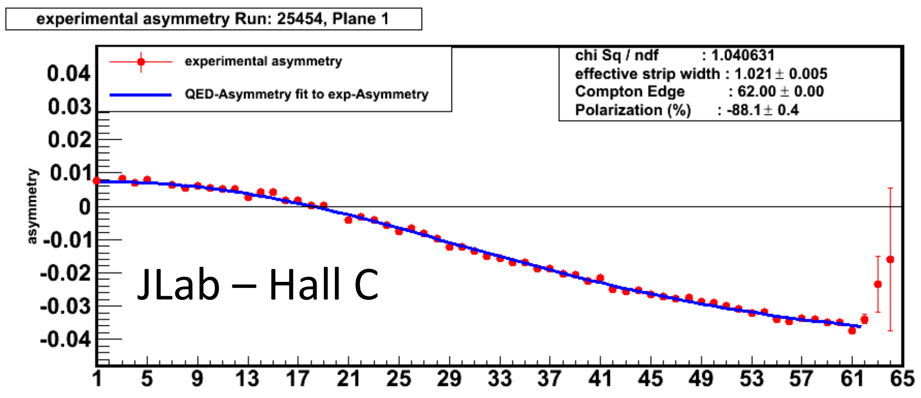
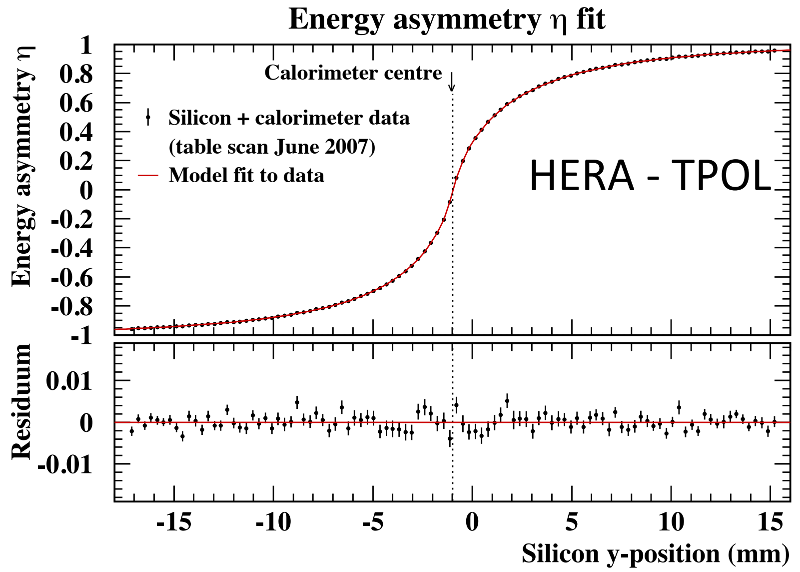
Compton polarimetry – lessons from previous devices

- Longitudinal polarimetry
  - Electron detector – needs sufficient segmentation to allow self-calibration
  - Photon detector – integrating technique provides most robust results – perhaps not practical at EIC? → lower the threshold as much as possible
- 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 (optical reversibility theorems)





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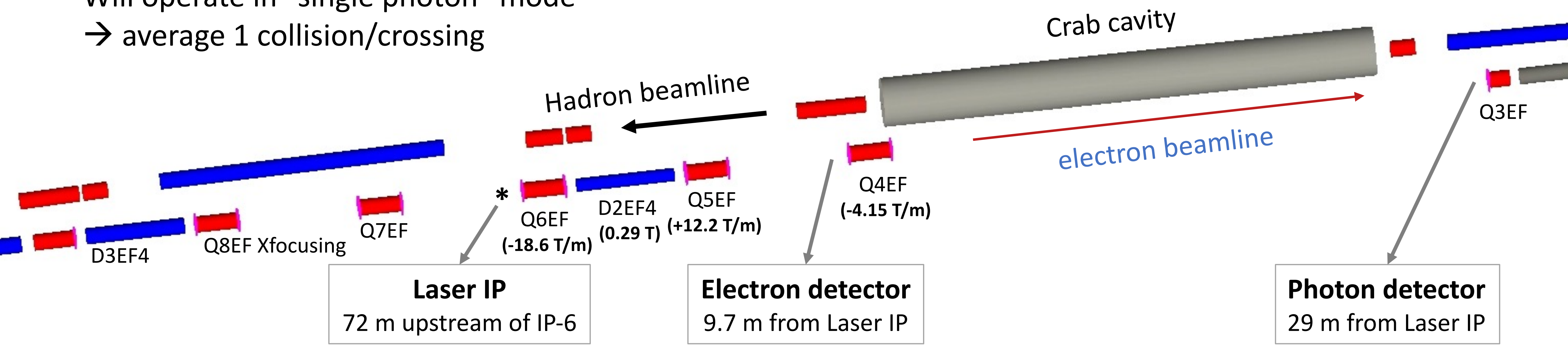
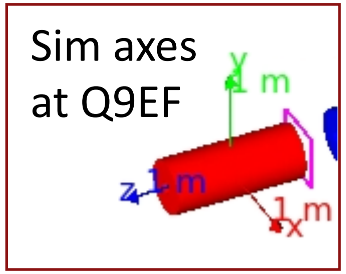
Electron Storage Ring Compton

- 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



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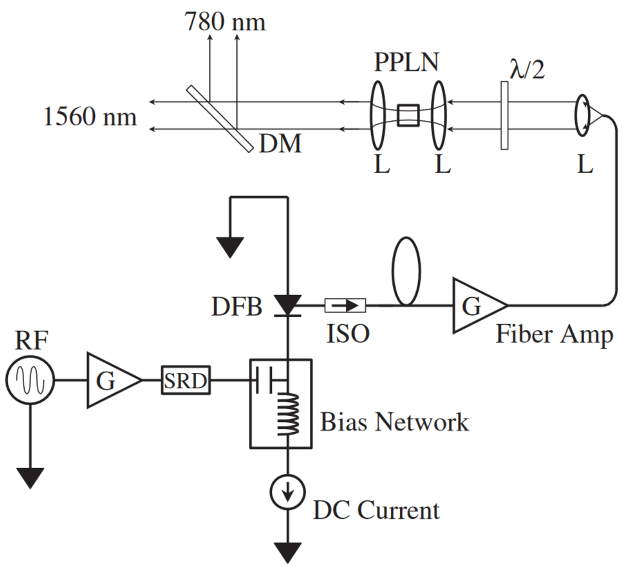
Compton Polarimeter Laser System

Average of 1 backscattered photon/bunch crossing will allow Compton measurements on the ~1 minute time scale → can be achieved with pulsed laser system that provides about 5 W average power at 532 nm

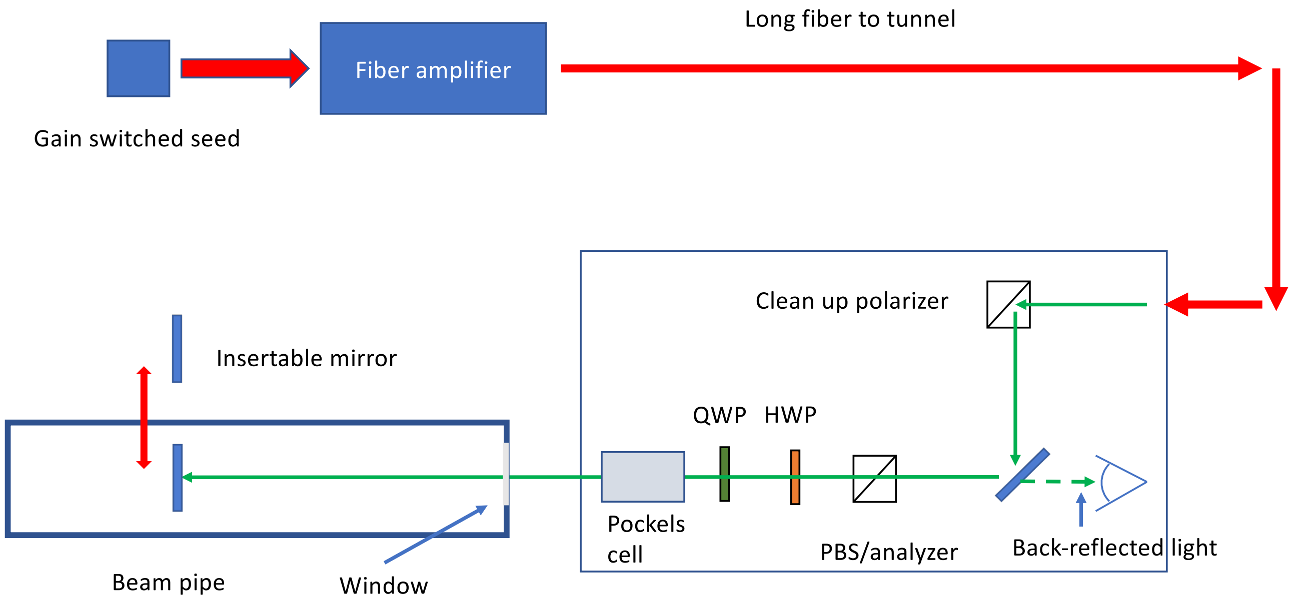
Proposed laser system based on similar system used in JLab injector and LERF

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)
4. Insertable in-vacuum mirror for laser polarization setup



JLab injector laser system

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



Prototype system under development (C. Gal, JLab)

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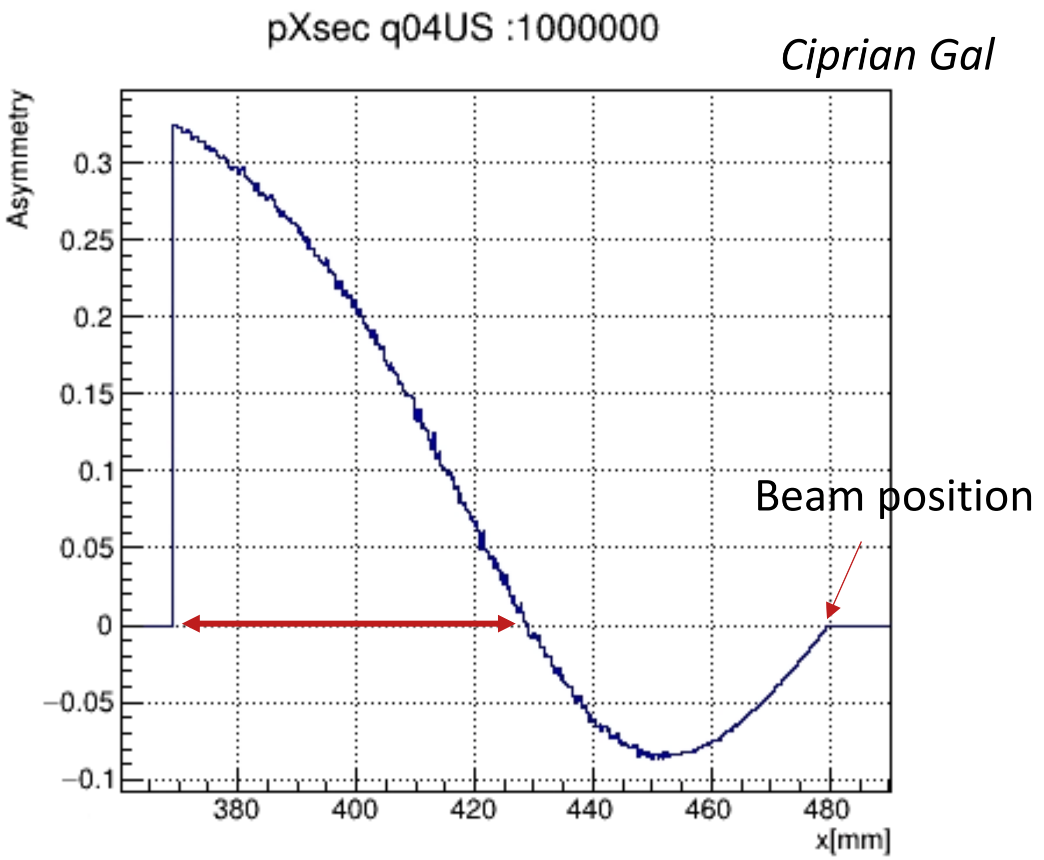
Electron Detector Size and Segmentation

- 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

Ciprian Gal



Asymmetry at electron detector @18 GeV

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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

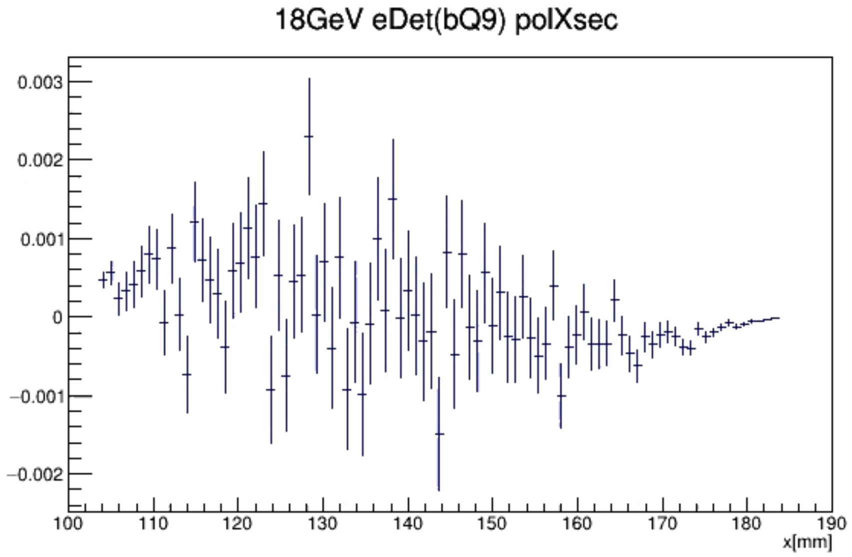
In the absence of the dipole, the transversely polarized electrons would result in a left-right asymmetry
→ The ”scattered electron cone” is much smaller than the photons
→ Left-right asymmetry is spread over much smaller distance (μm vs mm)

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



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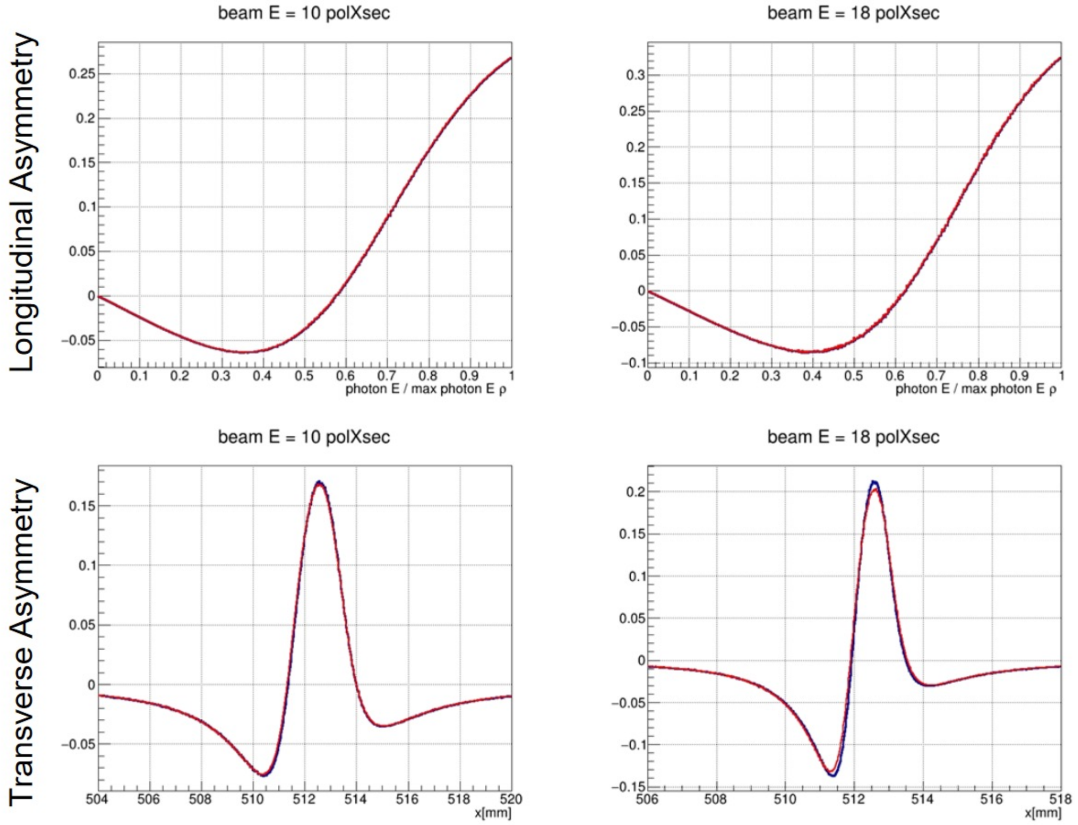
Polarization Measurement with Photon Detector

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%



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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

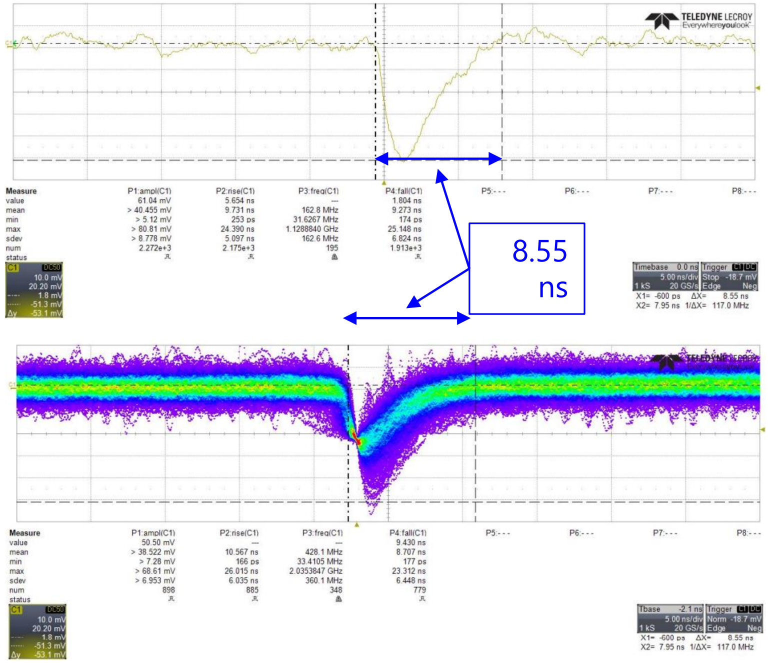
- Requirements for position sensitive detectors
  - Radiation hard
  - Fast response (needed for bunch-by-bunch measurements)
  - High granularity (down to 25 μm pitch)

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

Diamond strip detectors have been used successfully at JLab in Compton polarimeters

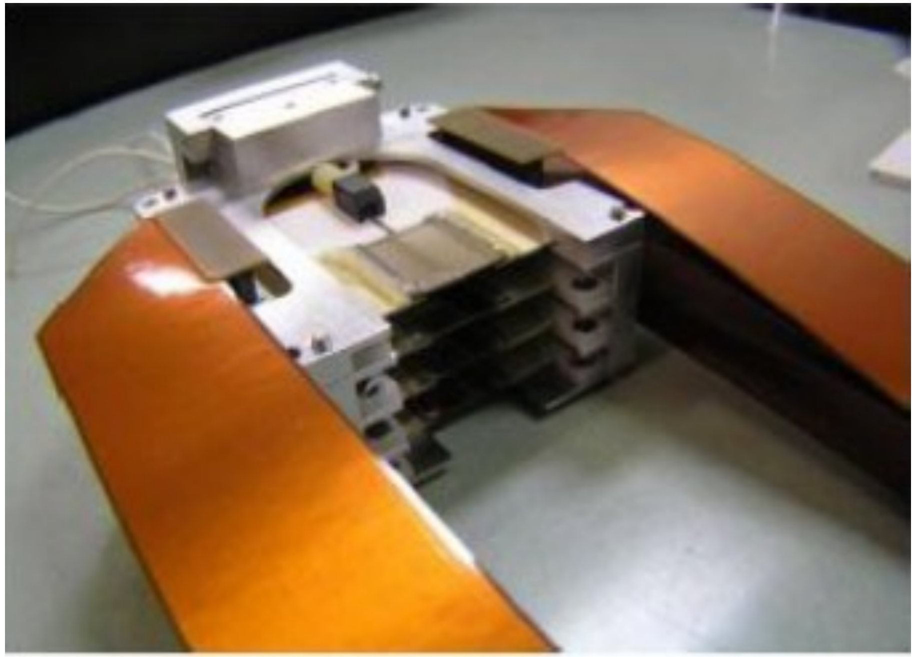
→ No performance degradation after 10 Mrad dose during Q-Weak experiment @ JLab

→ Intrinsic time response is fast, but small signals require significant amplification – custom electronics/ASIC will be required



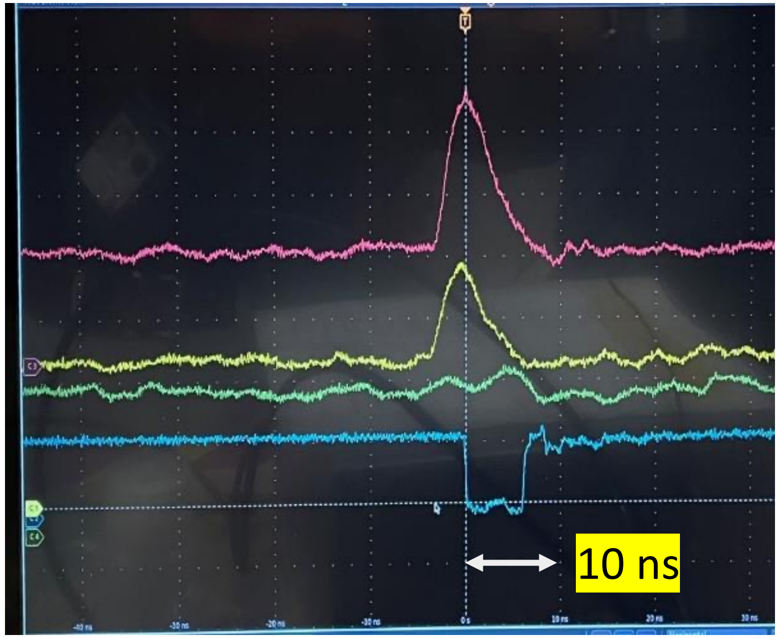
500 μm pCVD diamond w/TOTEM electronics

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

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

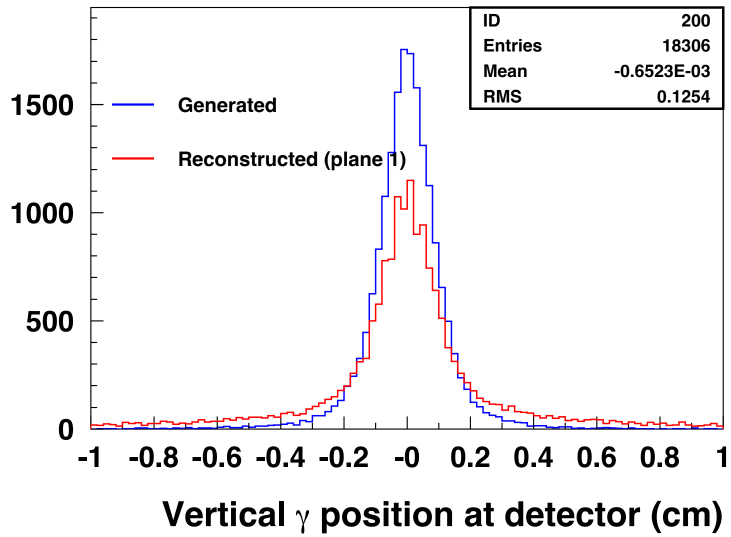
Table 2. Measured luminescence properties of doped $PbWO_4$ scintillator crystals on our apparatus for a mean energy deposited of 432 keV. Y_{xx} stands for photo-electron yields, τ_{XX}, for scintillation time constants. The Cherenkov contribution to yield, 0.80 photo-electron, is included in the total 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

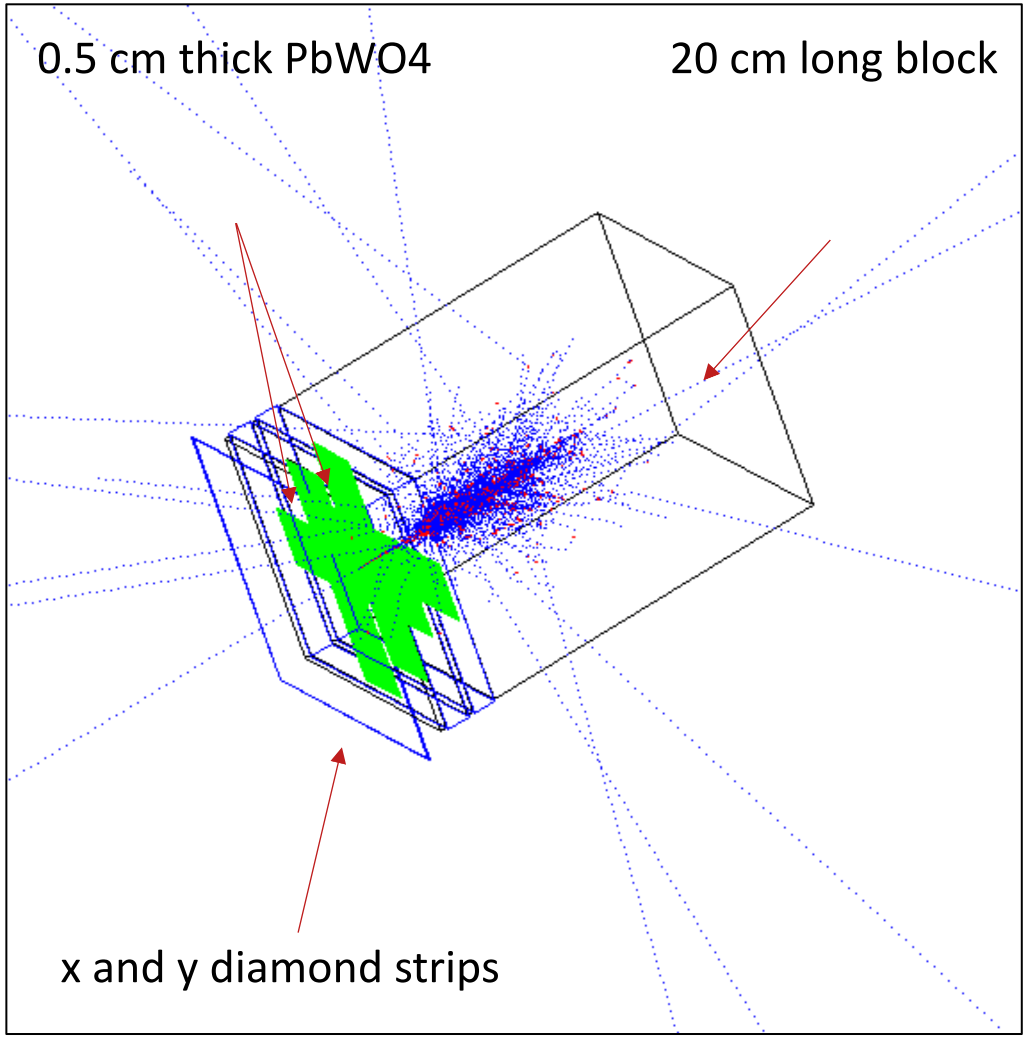
M. Follin et al 2021 JINST 16 P08040

Detector Simulations

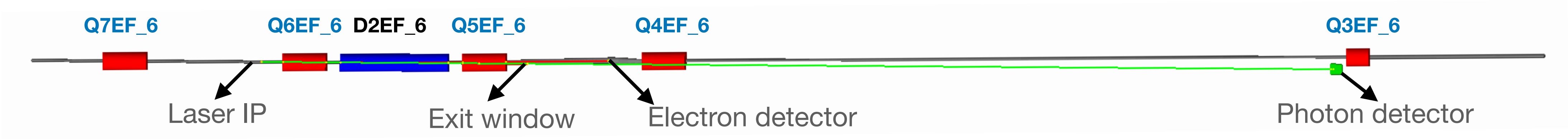
- → Need high position resolution for backscattered photons for transverse polarization measurement
- → Best results from longitudinally segmented calorimeter with (x-y) diamond strips



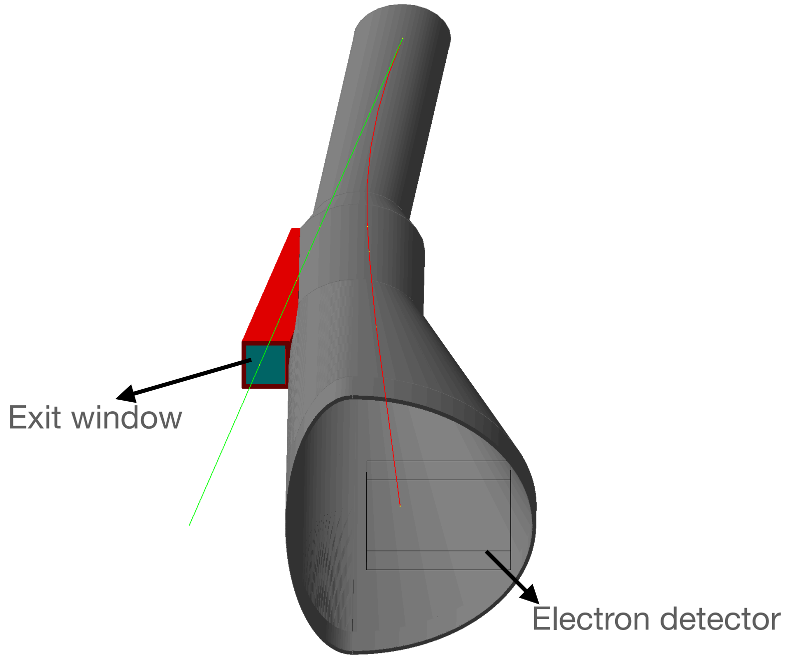
Overall efficiency 60% w/adequate resolution



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)

Rapid Cycling Synchrotron (RCS) Compton Polarimeter

RCS properties

- RCS accelerates electron bunches from 0.4 GeV to full beam energy (5-18 GeV)
- Bunch frequency → 2 Hz
- Bunch charge → up to 28 nA
- Ramping time = 100 ms

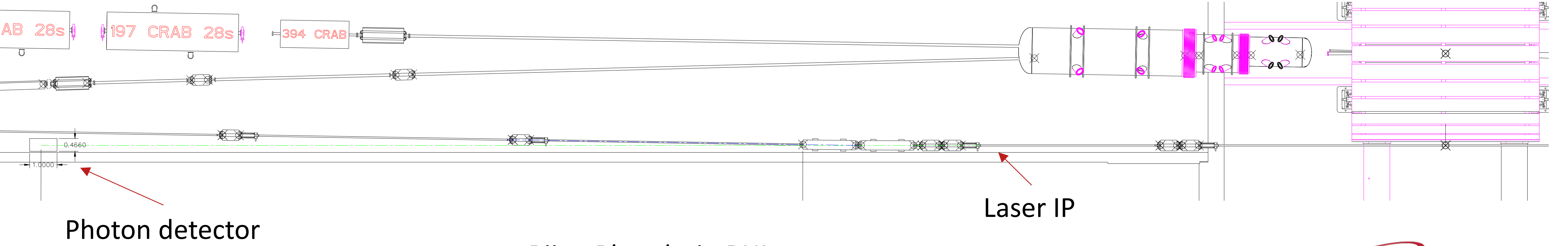
Polarimetry challenges

- Analyzing power often depends on beam energy
- Low average current
- Bunch lifetime is short

Compton polarimeter can also be used for measurement of polarization in RCS

→ Measurements will be averaged over several bunches – can tag accelerating bunches to get information on bunches at fixed energy

→ Requires measurement in multiphoton mode (many backscattered photons/electron bunch)

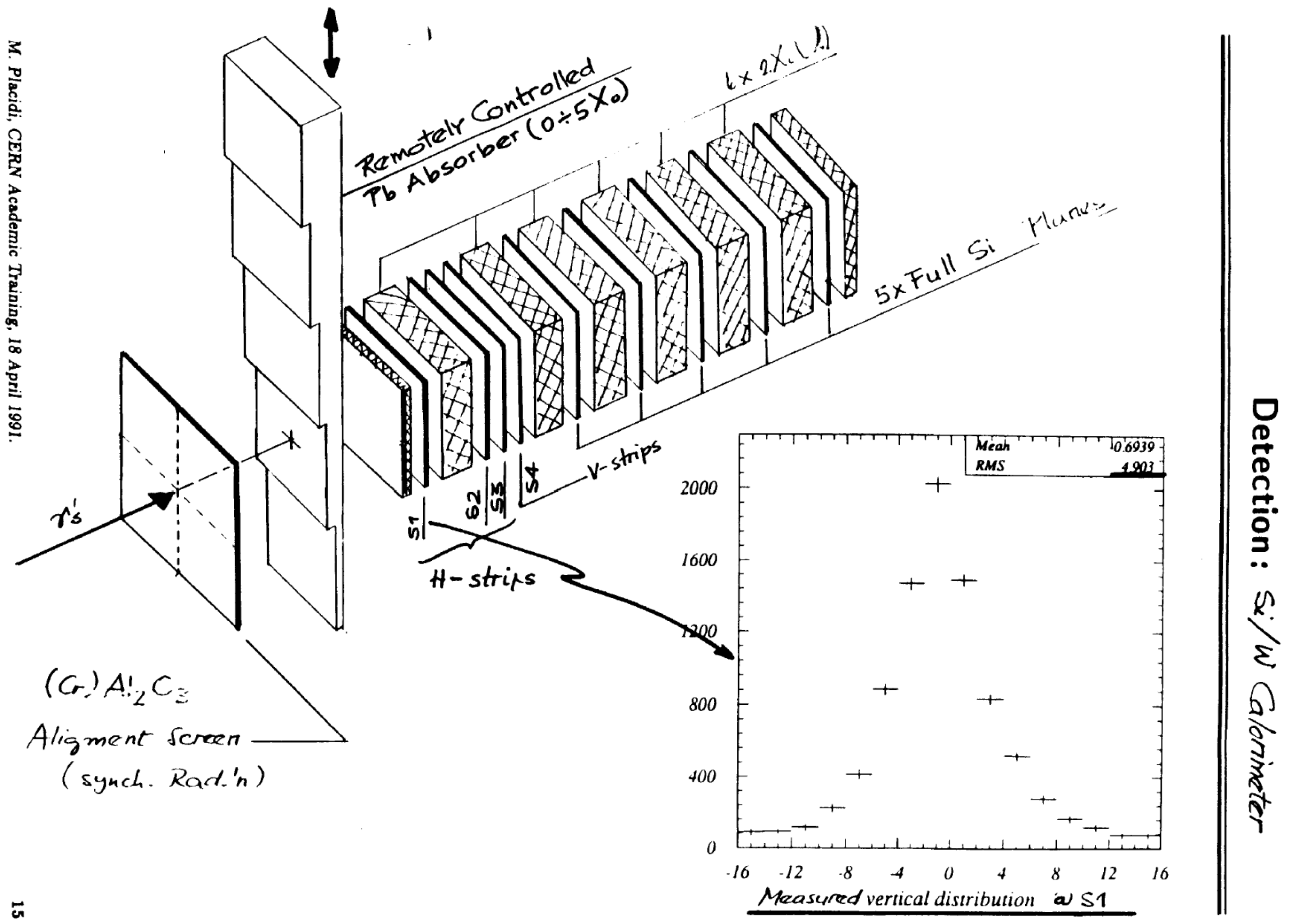


Transverse Polarimetry in Multi-photon mode

Highest precision transverse Compton polarimeter operated in **single photon** mode (HERA)
→ RCS requires position sensitive measurement in **multi-photon** mode

Need highly segmented detector sensitive to signal size (not just counts above threshold)

→ LEP polarimeter operated in this fashion, although with relatively low precision

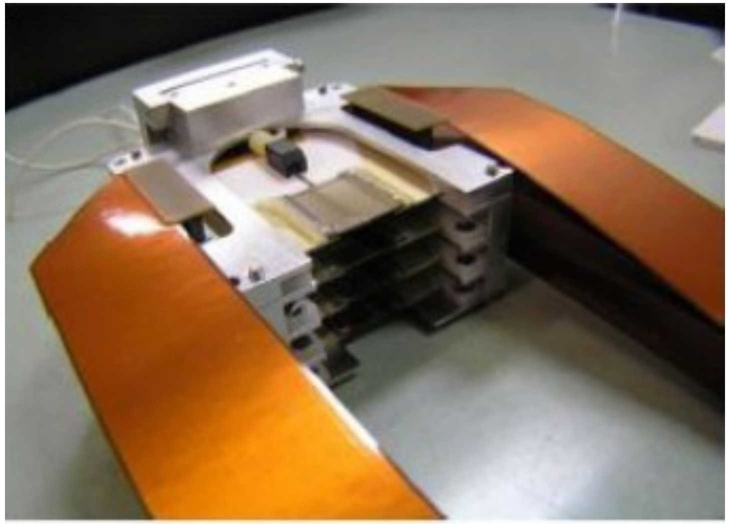


Summary

- Electron polarimetry at EIC has challenging requirements
  - Bunch-by-bunch polarization measurement with short times between bunches (as low as 10 ns)
  - High precision: dP/P=1% (or better)
  - Simultaneous measurement of longitudinal and transverse components
- EIC Compton polarimeter in storage ring must meet all these requirements
  - Simultaneous detection of the backscattered photons and scattered electrons will allow high precision for both longitudinal and transverse polarization
  - Fast detectors required due to bunch structure
- RCS Compton polarimeter needed to provide information on electron polarization during acceleration
  - Will operate in multi-photon mode (several thousand photons/bunch crossing)
  - Less stringent requirements for absolute precision

EXTRA

ESR Compton Detector Technology



JLab Hall C diamond detector

Tungsten-powder calorimeter

Several choices feasible for position sensitive detectors
→ Diamond strip detectors are baseline choice

- Radiation hard
- Fast time response
- Compatible with segmentation requirements
- ASIC under development for LHC diamond detectors compatible with EIC timing requirements

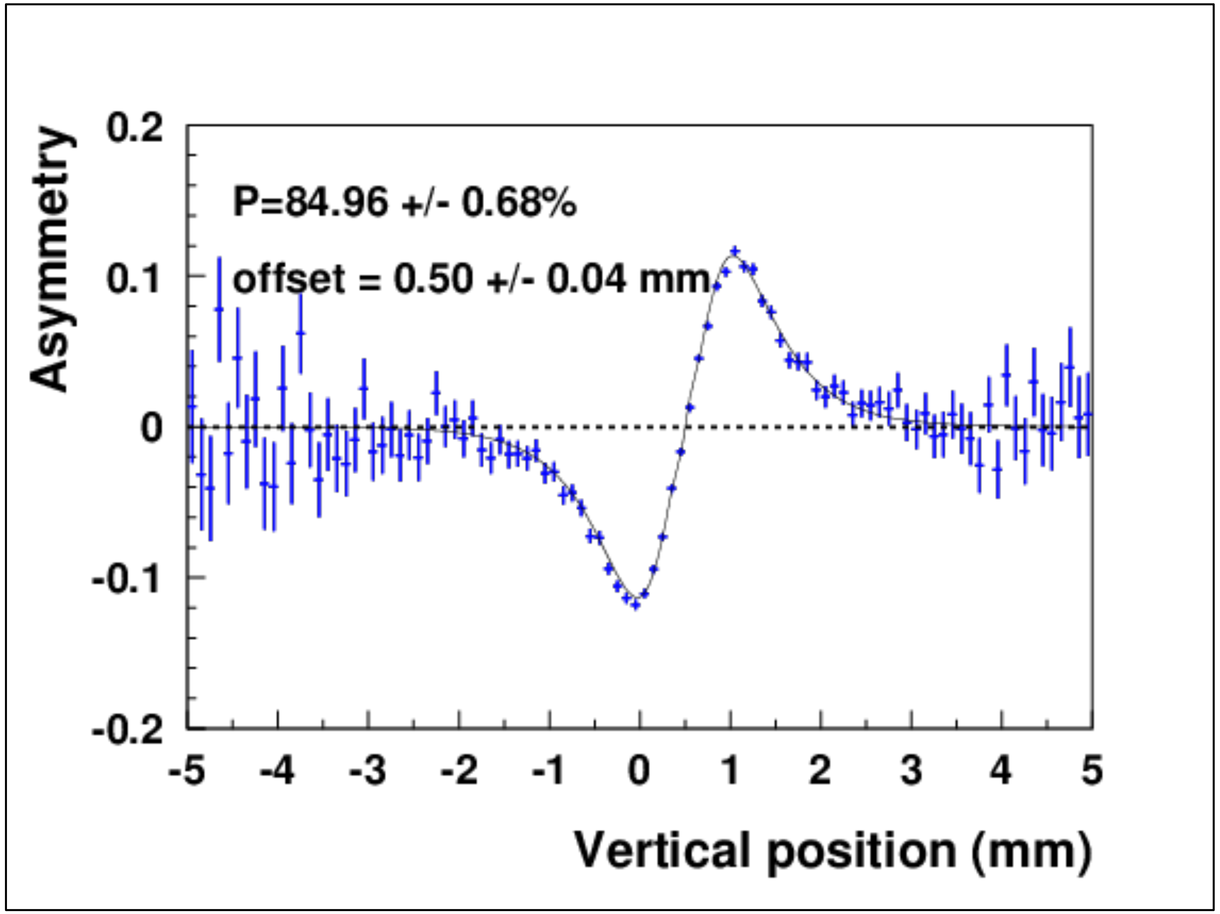
Photon calorimeter more challenging
→ Timing requirements suggest lower resolution calorimeter must be used
→ OK for transverse measurement, but reduces precision on longitudinal

Differential Asymmetry measurement

Differential measurement of asymmetry vs. position at detector allows us to incorporate offsets in the fit

Example using Toy MC for integrating mode asymmetry vs. y assuming 0.1 mm segmentation (240 bunches)
→ Sufficient position resolution would allow determination of arbitrary offset in spectrum

→ Requires detector operating in integrating mode (~10,000 photons/bunch) with signal proportional to number of photons in each channel



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

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Laser power constraint: sufficient power to provide ~ 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

Backscattered photons vs. Beamline magnets

Photons will not clear beamline magnet apertures in some cases

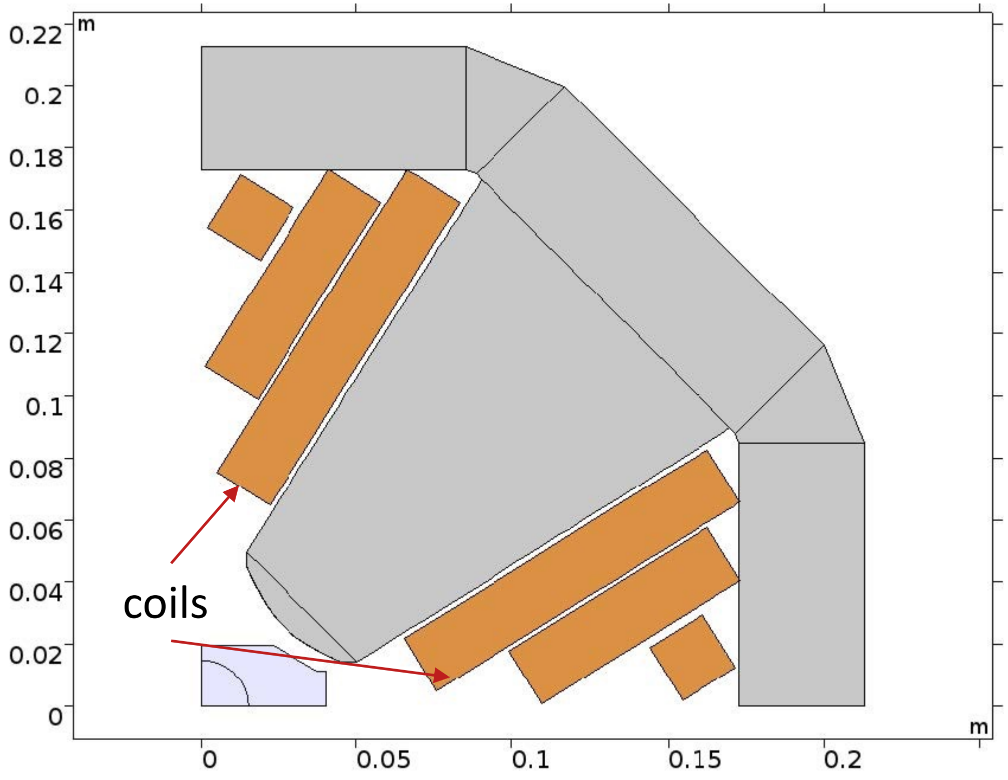
→ Quad inner aperture: R= 6 cm

→ Quad outer radius = 25 cm

Depending on final layout, will need to modify one or more quads to allow clear aperture for backscattered photons

If backscattered photons traverse iron-free region – coils can likely/hopefully be modified to accommodate

→ For 1st option, one quad may require a hole in the iron – but this should not have large impact on quad performance



Quad cross-section

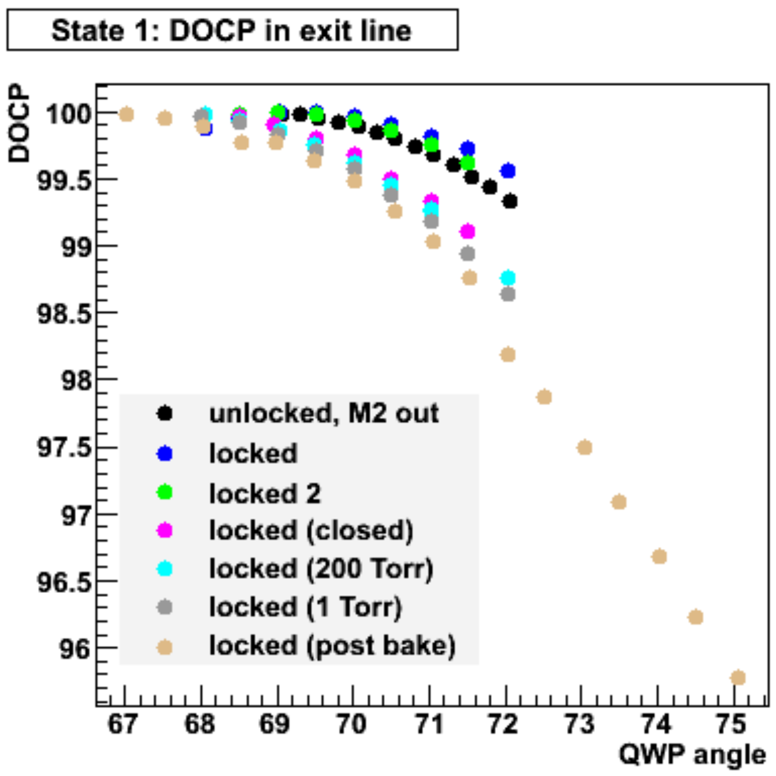
Laser Polarization

Relatively straightforward to prepare/determine laser polarization before entering beamline

→Stress on entrance window can introduce significant birefringence

→Nearly impossible to measure directly without significant instrumentation in vacuum

Measurements at JLab suggest these effects can't be ignored



JLab laser polarization measurements through 2 vacuum windows
→ Tightening bolts on flanges, vacuum stress has significant impact

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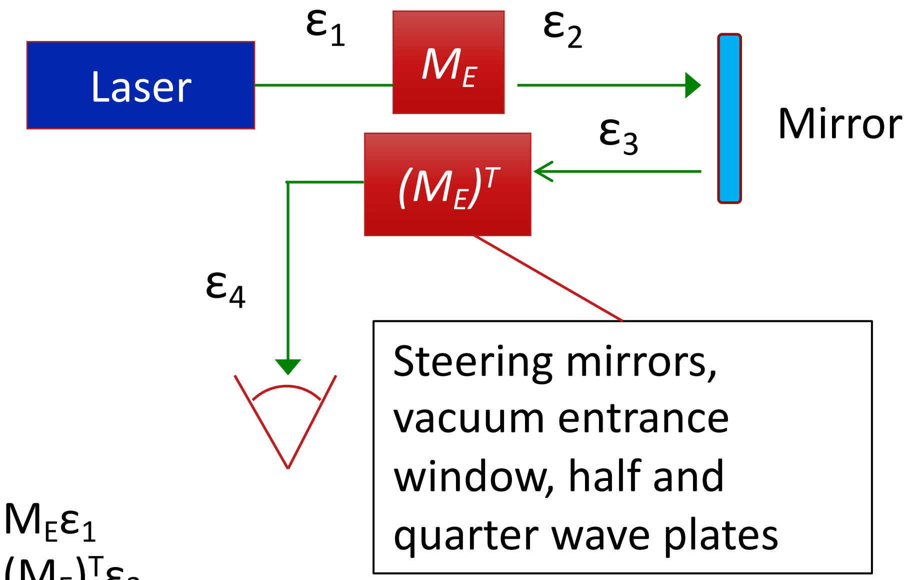
Laser Polarization – Optical reversibility theorems

Propagation of light through the vacuum window to the IP 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*



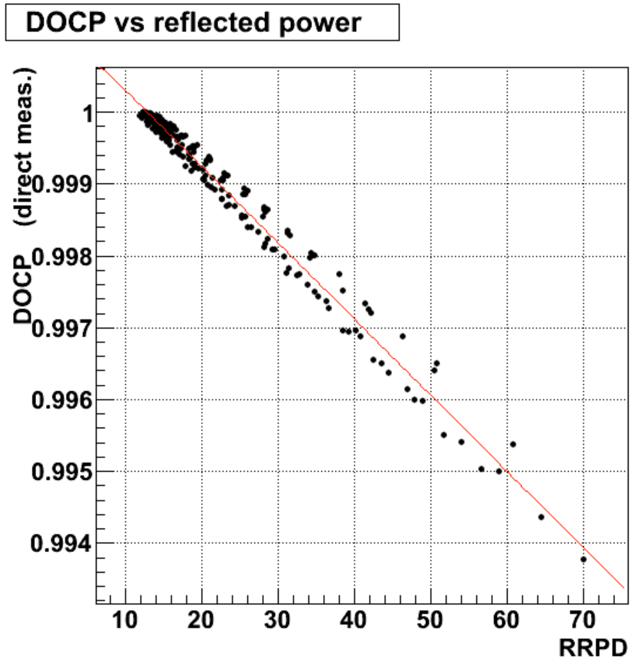
$\varepsilon_2 = M_E \varepsilon_1$

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

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

Laser polarization at a mirror (inside vacuum) can be set/determined by monitoring the back-reflected light in a single photodiode

→ Used this technique at JLab to constrain laser polarization to ~0.1%



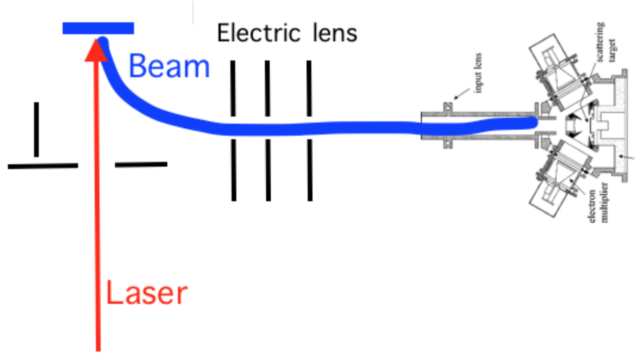
*J. Opt. Soc. Am. A/Vol. 10, No. 10/October 1993

Mott Polarimetry at EIC

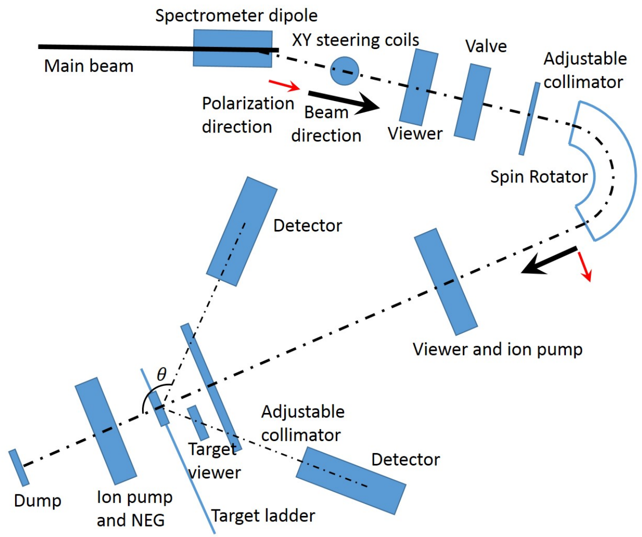
EIC will make use of two Mott polarimeters to measure the electron polarization from the source

1. Low voltage Mott polarimeter
→ Measure polarization at 20 keV immediately after photocathode

2. High voltage Mott polarimeter
→ Measure at 300 keV, in the beamline, before electron bunching
→ Requires spin rotator to change electron from longitudinal to transverse spin



Low voltage Mott polarimeter

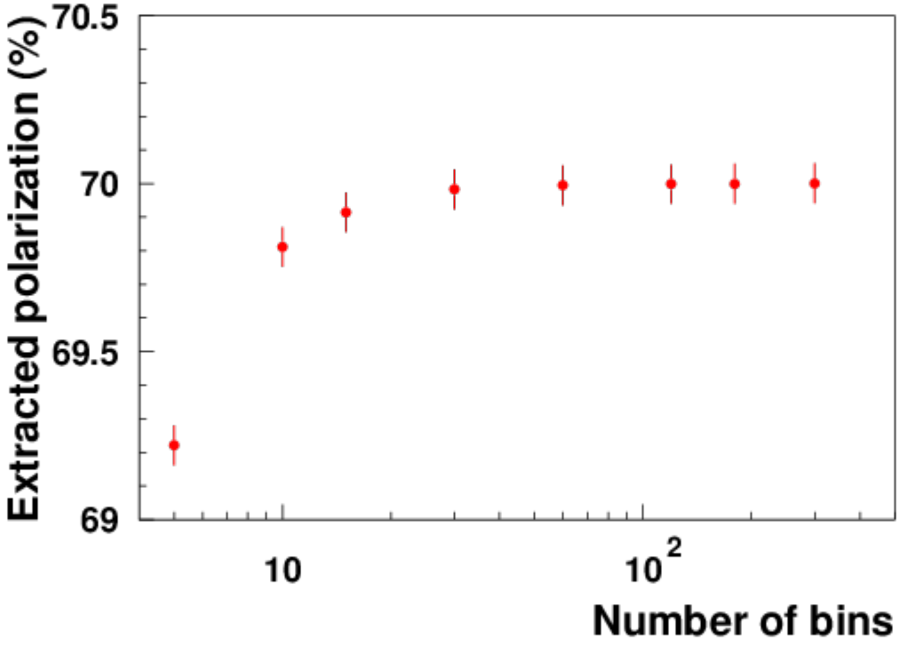


High voltage Mott polarimeter

Detector Segmentation – Electron Detector

Detector segmentation driven by requirement to be able to extract polarization (fit asymmetry) without any corrections due to detector resolution (see SLD Compton)

→ Studies with toy Monte Carlo suggest that about 30 bins (strips) between asymmetry zero crossing and endpoint results in corrections <0.1%



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)

Electron Polarimetry Systematics

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

State of the art for Compton polarimetry:

Longitudinal:

SLD @ SLAC: dP/P=0.5% → Electron detector in multi-photon mode

Q-Weak in Hall C @ JLab: dP/P=0.59% → Electron detector, counting mode

CREX in Hall A @ JLab: dP/P=0.44% → Photon detector, integrating mode

Transverse:

TPOL @ HERA: dP/P=1.87% → Photon detector in counting mode

Total polarization extraction will rely on two quasi-independent measurements

While 0.5% for P_L is plausible, P_T is less certain → 1%?

At 18 GeV this results in dP/P=0.86% at 18 GeV