The EIC Electron Polarimeters and Lessons for the FCC

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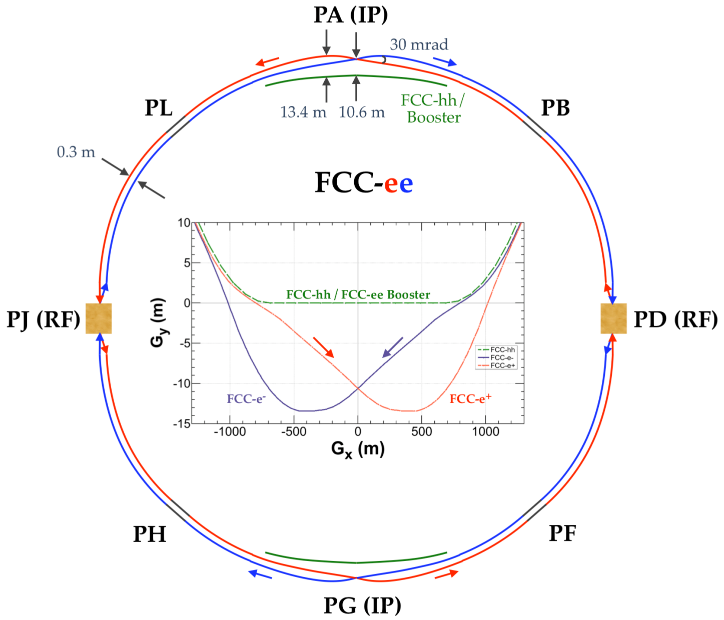
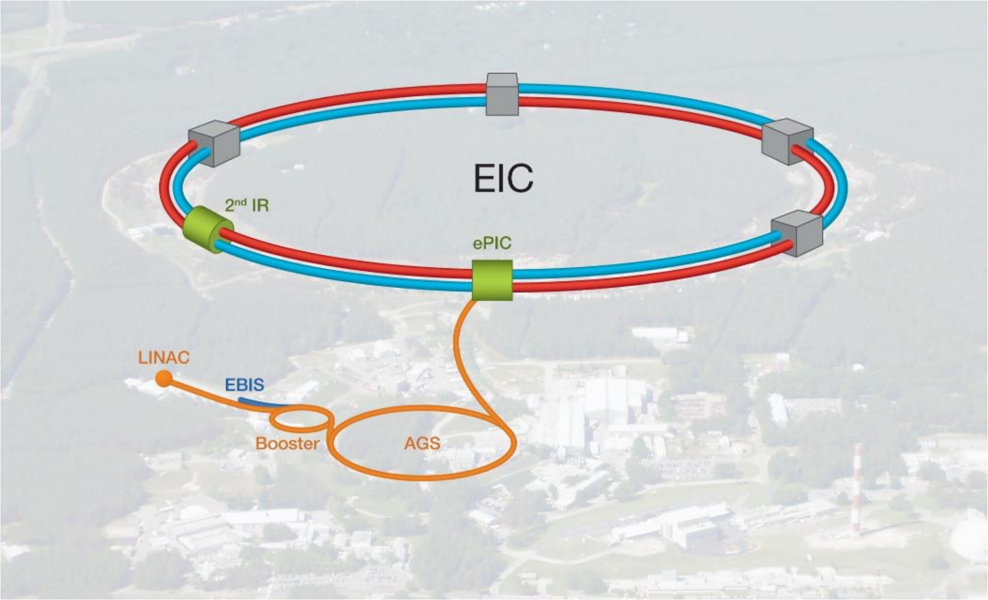




FCC Week 2024

June 10–14, 2024

EIC Electron Polarimeter Map and Requirements

RCS ramps electrons to full energy → injects into storage ring

→ Storage ring will have “top-off” injection

→ ESR polarimeter will function in counting mode (~ 1 backscattered photon/crossing)

→ RCS polarimeter will function in multi-photon mode (~1000 backscattered photons/crossing)

ESR Compton Requirements:

→ Bunch-by-bunch measurement of polarization

→ Simultaneous measurement of both $\boldsymbol{P_L}$ and $\boldsymbol{P_T}$

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

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

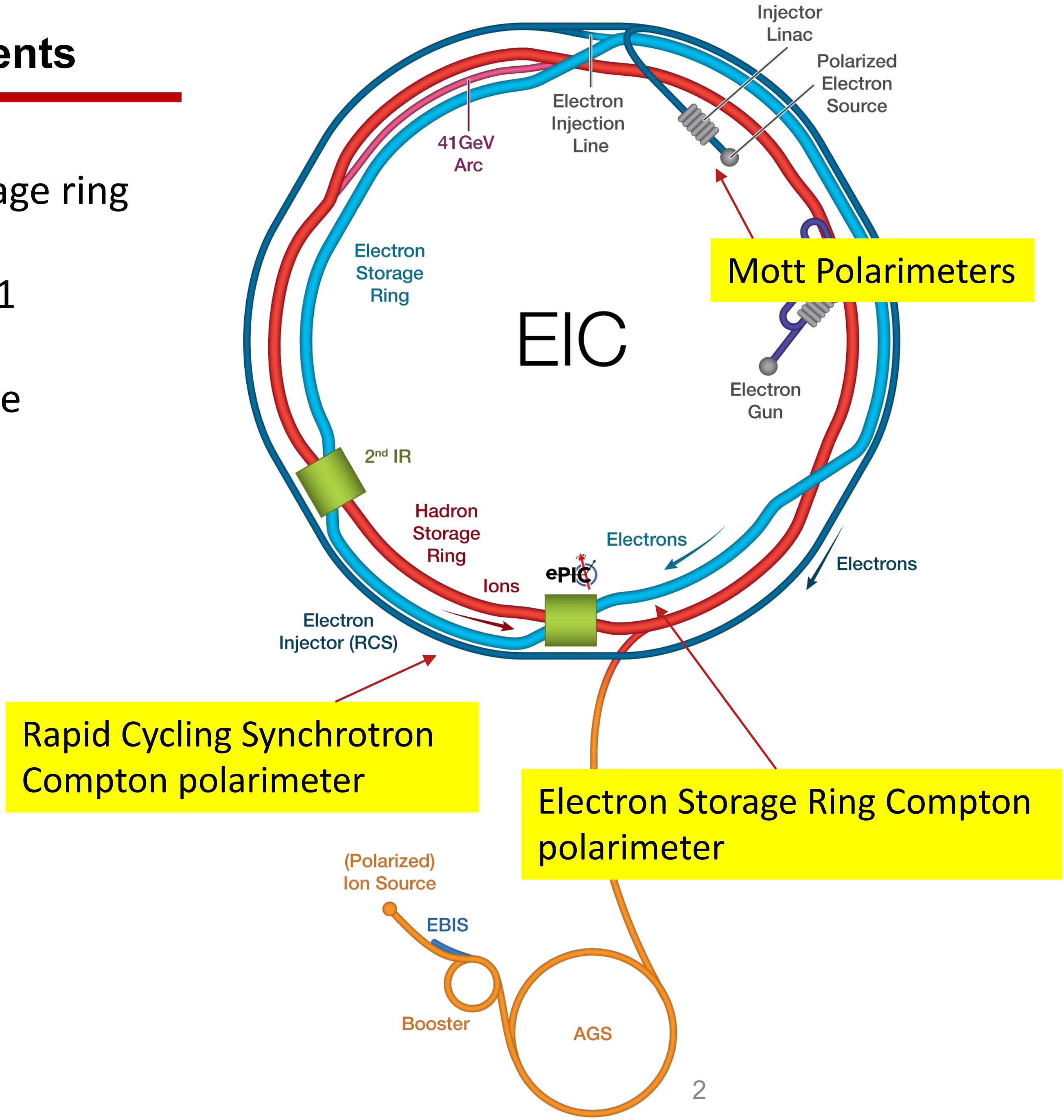
RCS Compton Requirements:

→ Polarization averaged over several bunches

→ Rapid measurement to facilitate accelerator setup

→ Modest requirements on absolute precision (~few %)

→ Transverse polarization measurement only



Mott Polarimeters

Rapid Cycling Synchrotron Compton polarimeter

Electron Storage Ring Compton polarimeter

EIC and FCC-ee comparisons

- EIC Electron Storage Ring
  - P=75-85% → electrons fully polarized at injection
  - E = 5, 10, 18 GeV
  - Beam current = **2.5 A** (5, 10 GeV), 0.26 A (18 GeV)
  - Bunch spacing = **10 ns** (5,10 GeV), **40 ns** (18 GeV)
- EIC Rapid Cycling Synchrotron
  - Accelerates bunches from 400 MeV to full energy in storage ring (5, 10, 18 GeV)
  - Bunch injection frequency → 2 Hz (76 kHz in ring)
  - Bunch charge → up to 28 nA
  - Ramping time = 100 ms
- **Polarimeter functions**
  - **High precision absolute polarization measurements for ESR (experiment)**
  - **Modest precision absolute polarization measurements in RCS (beam tune-up)**

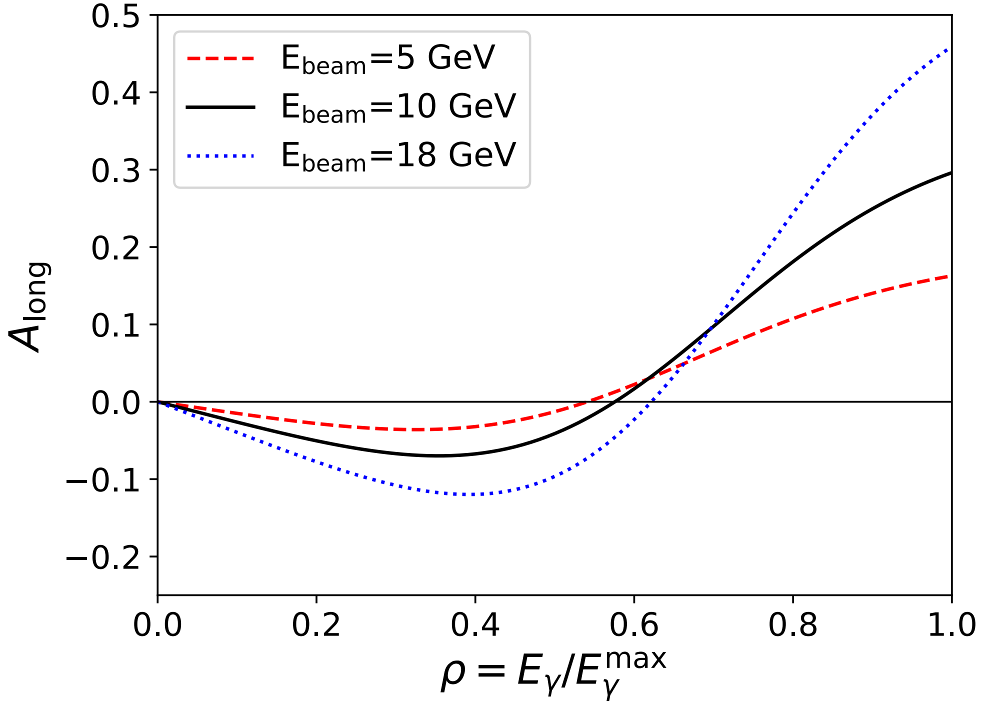
- FCC-ee
  - P=10% to ? → polarization from Sokolov-Ternov effect
  - E = 45.6, 80, 120, 182.5 GeV
  - Beam current = **1390**, 147, 29, 5.4 mA
  - Bunch spacing = **19.6**, 163, 994, 3396 ns (colliding bunches), 3 kHz (pilot bunches)
- **Polarimeter functions**
  - **Relative polarization of pilot bunches for Resonant Depolarization (RDP) measurement or Free Spin Precession (FSP)**
  - **Monitor longitudinal polarization of colliding bunches → stringent upper limits**

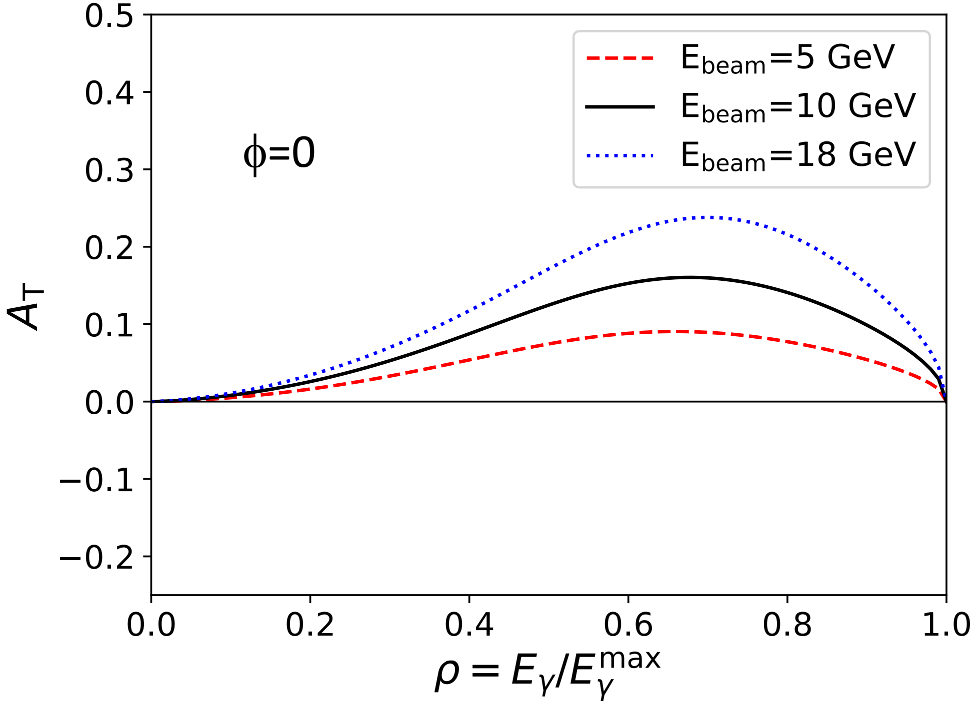
Polarization Measurement via Compton Polarimetry

Compton longitudinal and transverse analyzing powers

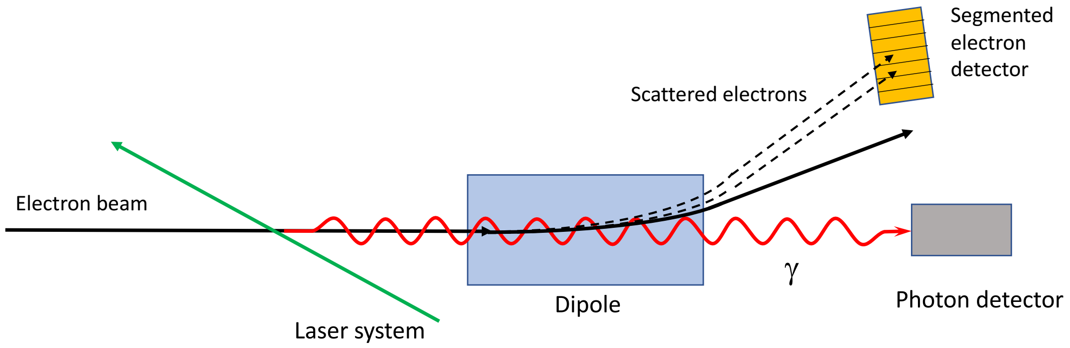
$$A_{\text{long}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}(1-\rho(1+a))\left[1-\frac{1}{(1-\rho(1-a))^2}\right]$$

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





Generic Compton Polarimeter



Key systems:
- → Laser
- → Photon and electron detectors
- → Dipole

Beam interfaces:
- → Vacuum chambers, windows
- → Beam diagnostics → size, trajectory
- → Background mitigation → collimators, synchrotron absorbers

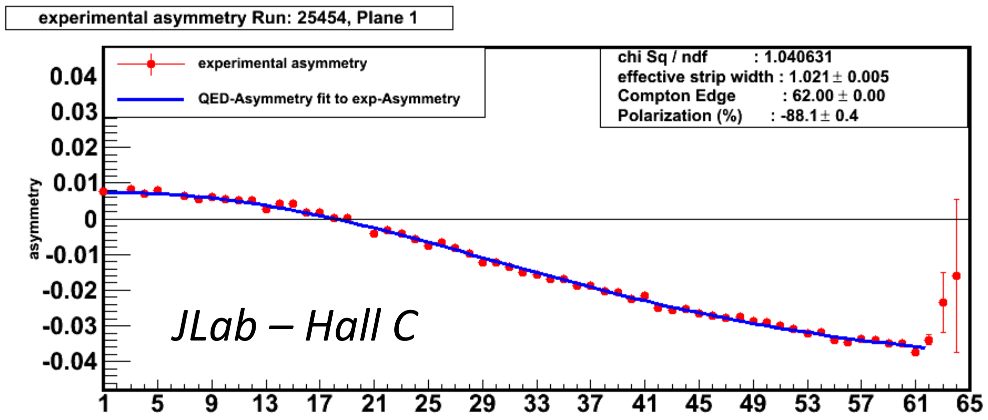
Mode of operation determines detailed design

- Low intensity at JLab requires high gain Fabry-Perot cavity to increase effective laser power
  - Higher intensities in storage rings allow single-pass laser systems
- Longitudinal measurements can rely on energy-dependent asymmetry (photons)
  - Measurement of scattered electrons requires position sensitive detector
- Transverse measurements **require** measurement of spatial dependence of asymmetry

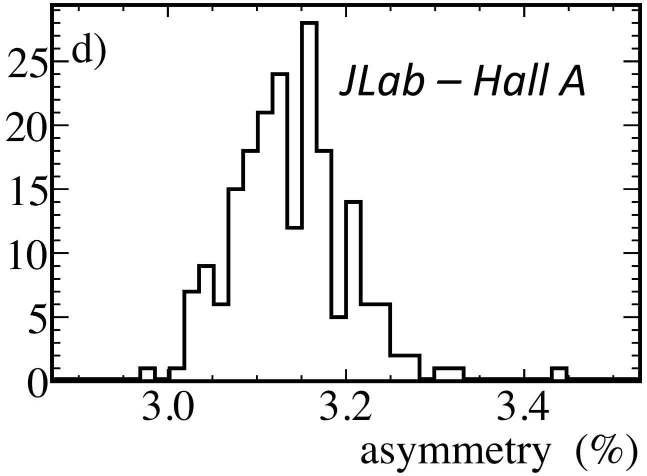
Polarization Measurement Methods

Actual extraction of polarization can be achieved in a variety of ways:

Longitudinal



Fit the asymmetry energy spectrum (photons or electrons)

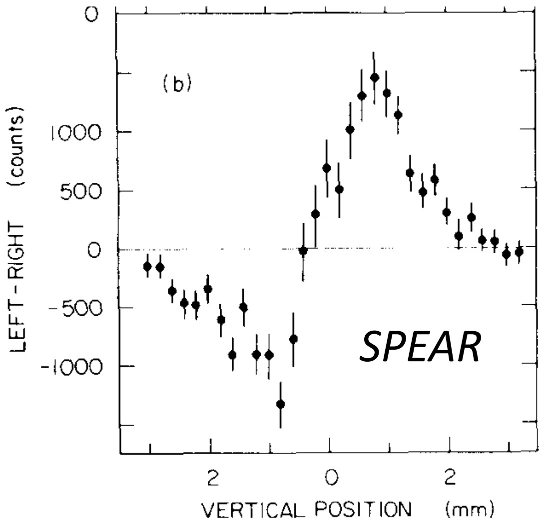


Energy-weighted integral

$$A = \frac{\Sigma^+ - \Sigma^-}{\Sigma^+ + \Sigma^-}$$

$\Sigma^\pm$ = energy deposited for +/- beam helicity

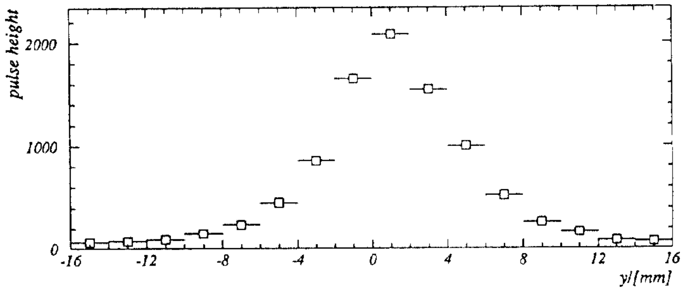
Transverse



Fit/measure up-down asymmetry distribution

Up-down energy asymmetry (HERA –TPOL)

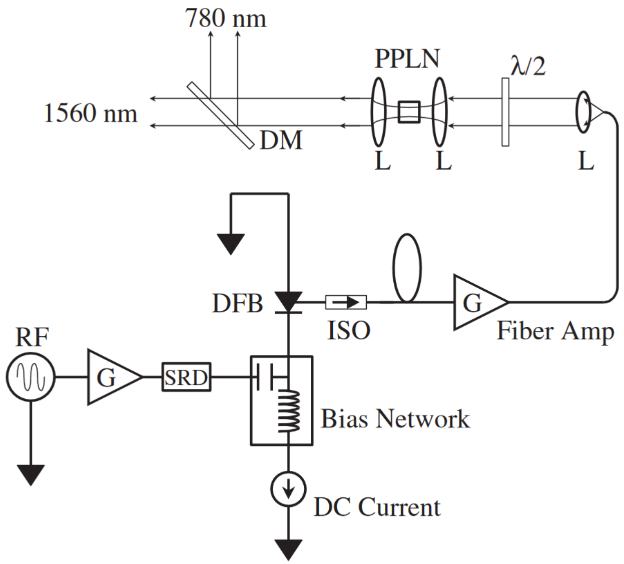
$$\eta = \frac{E_{up} - E_{down}}{E_{up} + E_{down}}$$



Change in average vertical position, <ΔY> (LEP)

EIC ESR 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

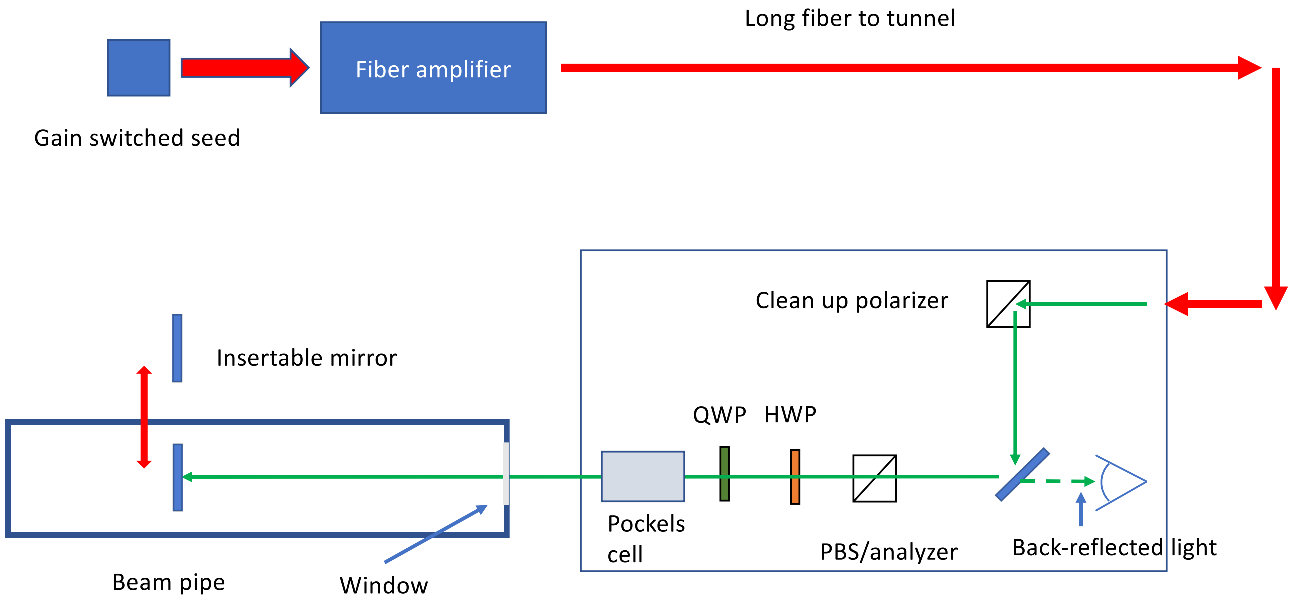


JLab injector laser system

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

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



Prototype system under development at JLab (C. Gal, D.G., Shukui Zhang JLab)

Laser systems for FCC-ee

Laser param.	**1 pilot (1.6nC)**	**1 pilot v2 (1.6nC)**	**colliding bunches (38nC, at Z)**
Repetition rate	3 kHz	3 kHz	30 kHz
Pulse energy	1 mJ	1 mJ	10x0.5mJ
Pulse duration	5 ns	5 ps	5 ps
Average power	3 W	3 W	150 W
Scattering rate	2×10^5/s	3×10^5/s	4×10^8/s
Scattering rate per bunch	2×10^5/s	3×10^5/s	4×10^6/s

Collide with ~100 bunches – change phase to sample all bunches in ring

Note: very high rates

Aurélien Martens (IJCLab Orsay), FCC E-POL meeting, March 6, 2023

Q-switched laser meets requirements for pilot bunches, but mode-locked Yb offers ability to measure both pilot and (a subset of) the colliding bunches

→ Mode-locked laser solution is similar to the EIC gain-switched solution → gain-switched system may offer more flexibility, *no need to change phase to sample all bunches*

Laser Entrance/Exit Window Effects

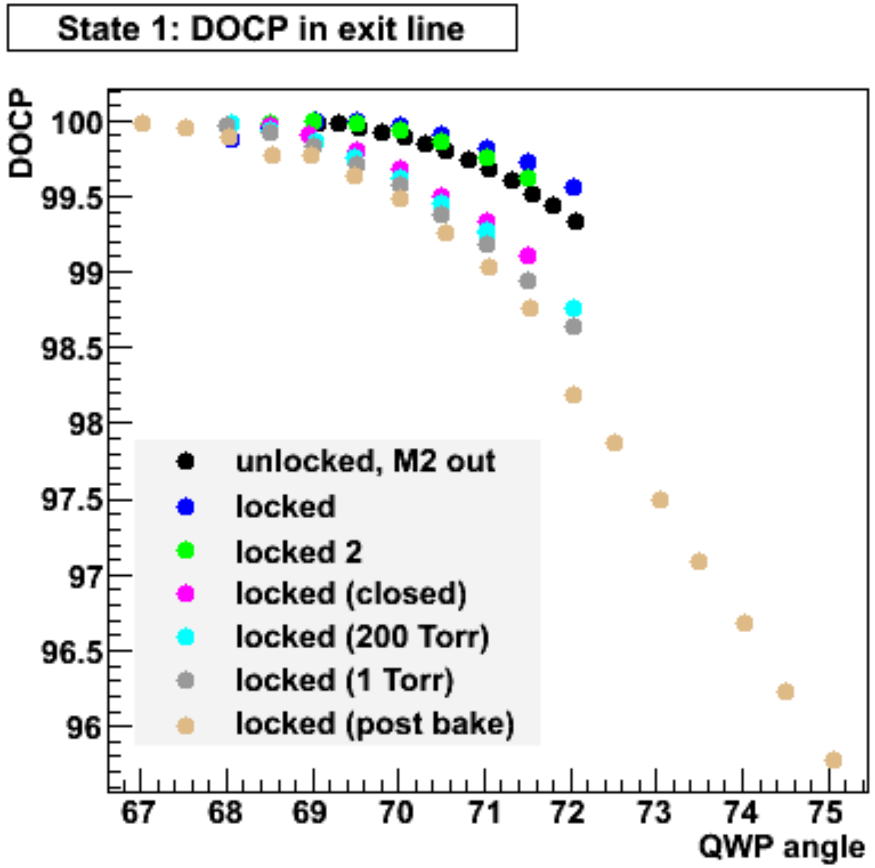
Key systematic uncertainty is polarization of laser at collision point

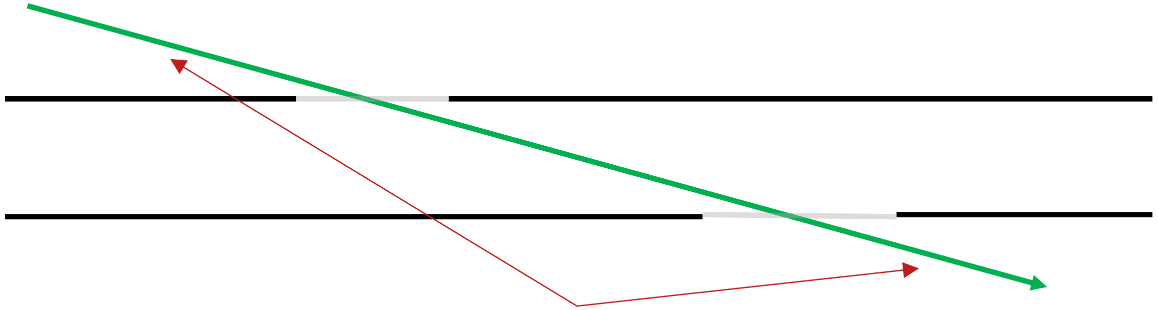
→ No easy way to measure laser polarization in vacuum

→ Must rely on measurements before and after vacuum windows

→ Mechanical effects, vacuum stresses can impact window birefringence

→ Tests at JLab (Hall C) – measured exit line polarization before and after connecting/bolting flanges, while pumping down





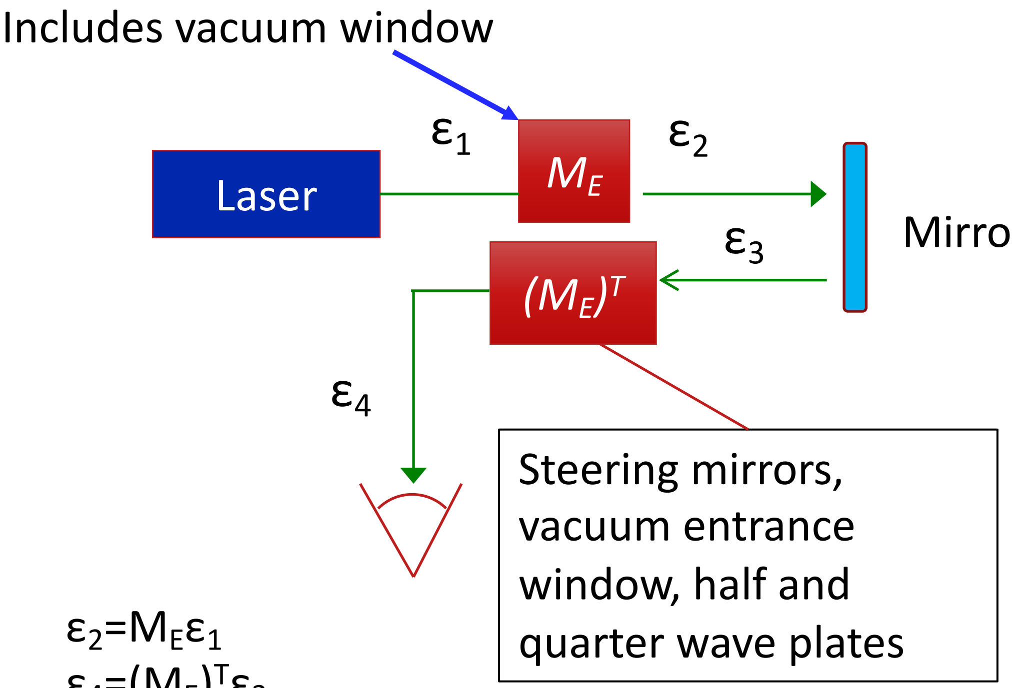
Laser measurement points

Constraining Laser Polarization using back-reflection → EIC and FCC?

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*



$\varepsilon_2=M_E\varepsilon_1$

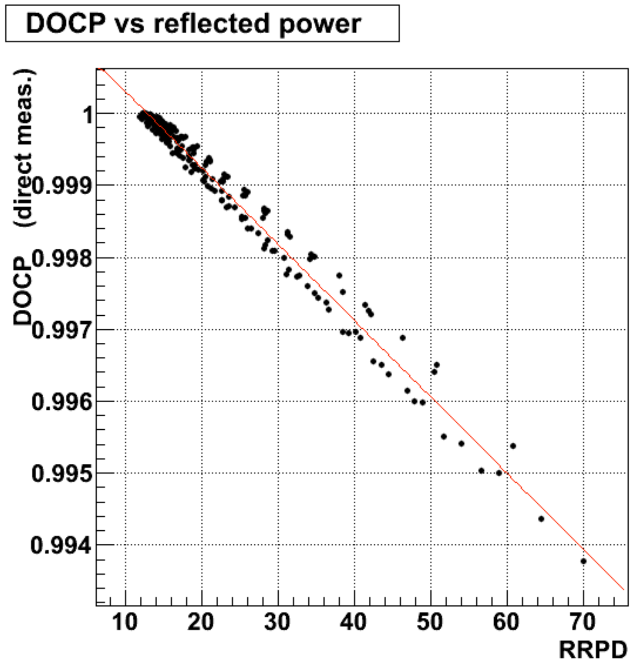
$\varepsilon_4=(M_E)^T\varepsilon_3$

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

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%

→ **FCC will require 0.01% level** precision to meet requirements for minimizing P_L



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

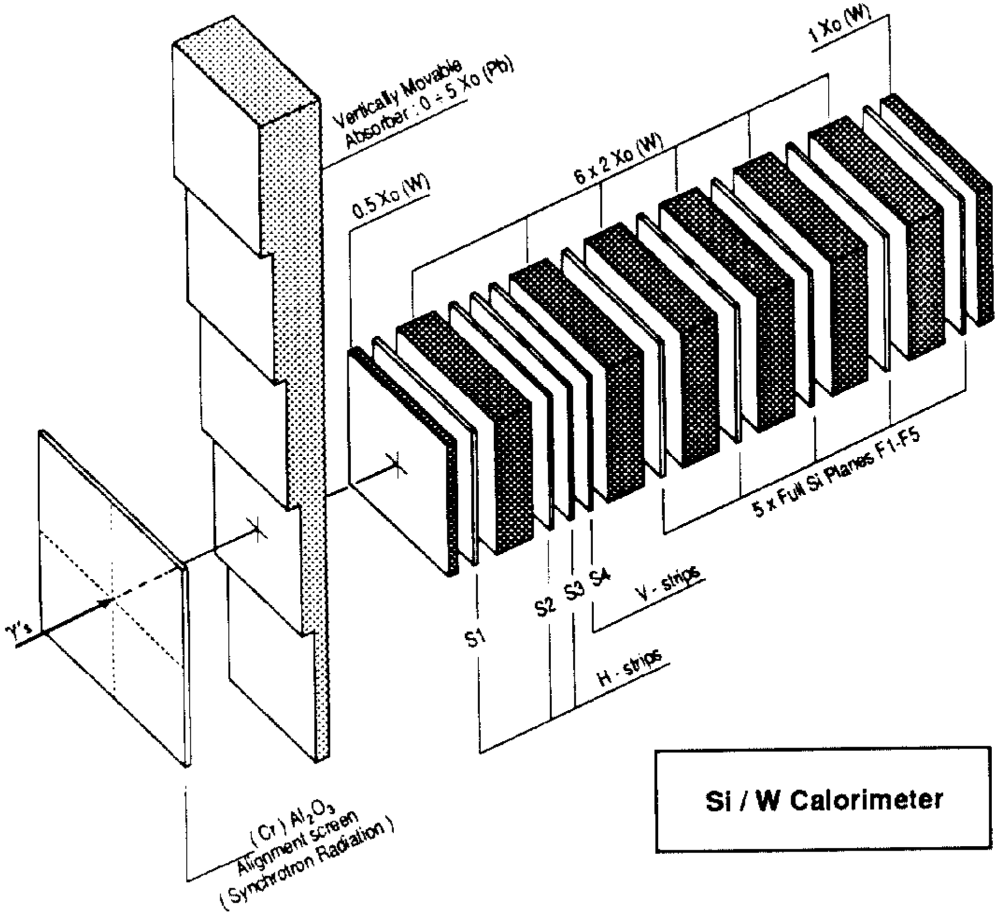
Detectors

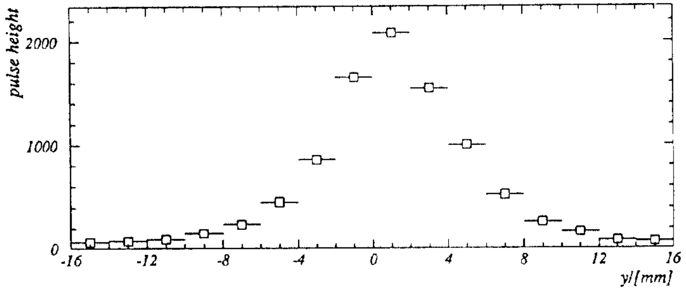
- EIC ESR Compton will operate in single-photon mode with short times between bunches
- EIC RCS will operate in multi-photon mode with many backscattered photons between bunch crossing
- In both cases, need to measure position dependent asymmetry to extract transverse polarization

FCC-ee polarimeter will operate in multi-photon mode like RCS, but with bunch separation similar to ESR Compton

Both EIC-RCS and FCC-ee will use some sort of pixel or strip detector, operating in integrating mode
→ Perhaps common detector technology possible

LEP Transverse Compton Detector





Position Sensitive (strip or pixel) Detectors

Key requirement for EIC is time response (~10 ns) and segmentation (100-400 μm)

→ Silicon detectors (e.g. AC-LGADs) can easily meet these requirements and are planned for use in several systems in EIC main detector

→ Compton polarimeter will see much higher event rates than main detector and receive ***higher radiation dose***

> "The state of the art silicon strip and pixel detectors used at experiments at LHC retain close to 100% detection efficiency for minimum ionizing particles at hadron fluences in excess of 10^{15} cm^{-2} and ionization doses of 1 MGy. "
> -*Solid State Detectors for High Radiation Environments*, Gregor Kramberger

EIC electron detector in storage ring will receive 1 MGy dose in about **1-2 weeks**

→ Diamond has higher radiation hardness, adequate time response

→ Used successfully at JLab (Hall C) → improved system under development for use in Hall A and C

→ New "FLAT32" ASIC will allow low noise, high efficiency readout, with very fast time response

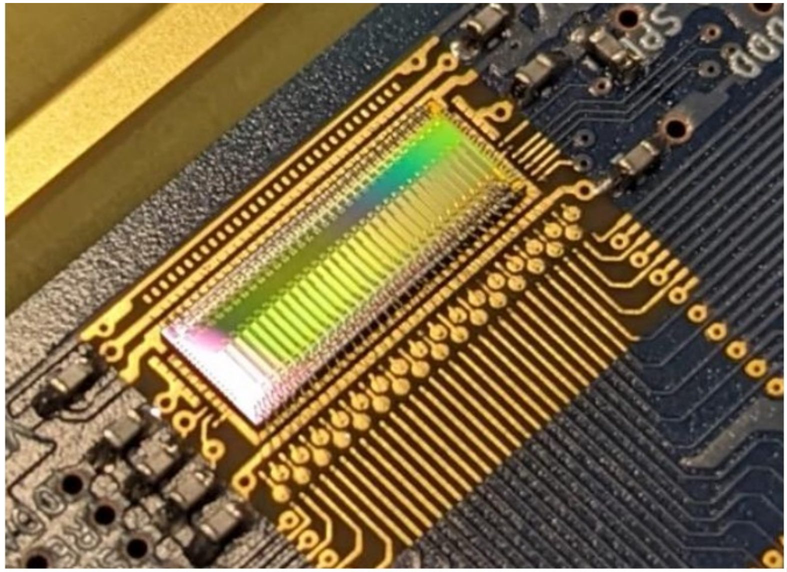


Figure 2: Wire bonded FLAT-32 on the test PCB.

Improved Diamond Electron Detector @ JLab → EIC

Primary drawback of first JLab diamond detector was trip-to-strip variation in efficiency → needed high thresholds to suppress noise

→ Diamond signals were not large, signals propagated to electronics far from detector (outside the vacuum chamber)

→ New diamond detector will have amplifier-discriminator electronics mounted on carrier board → FLAT-32

FLAT-32 development by SenseIC

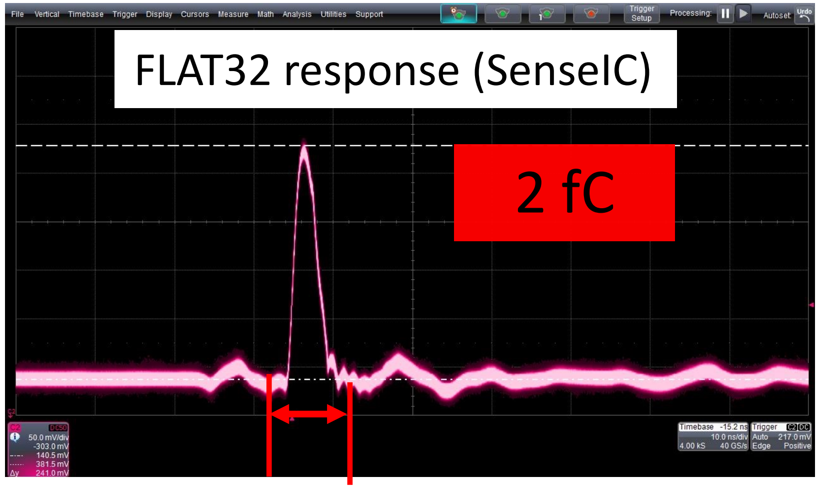
→ 32 channel version of CALYPSO electronics

→ Low noise, fast

→ Choice of analog or LVDS output

Testing underway at SenseIC

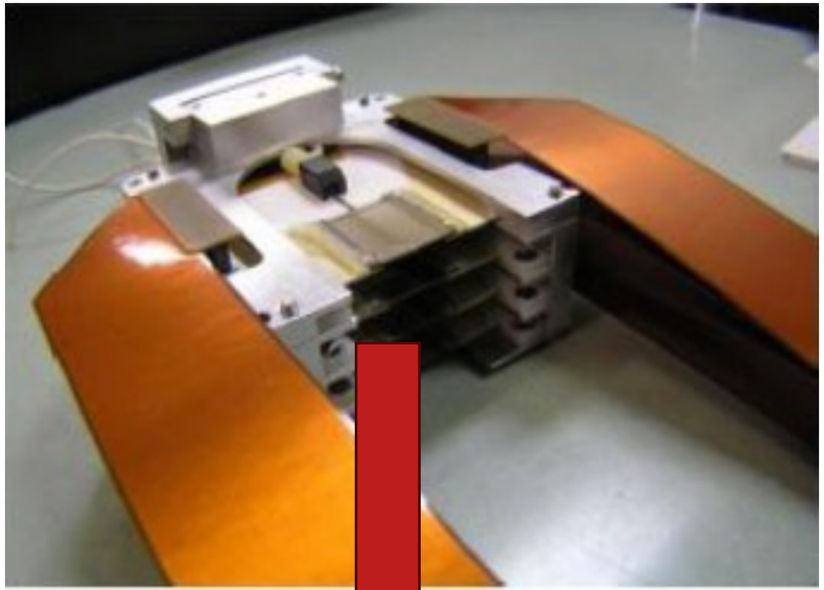
To be deployed in next couple years → may already meets EIC needs

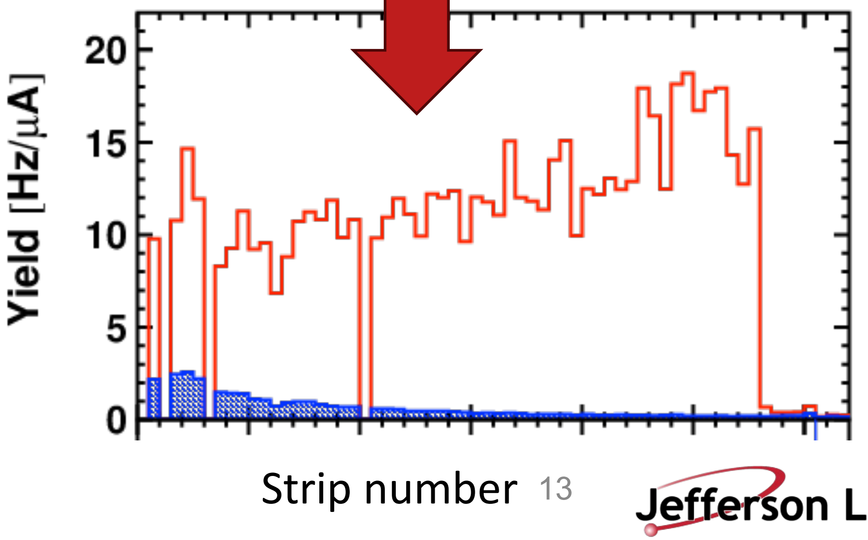

FLAT32 response (SenseIC)

2 fC

10 ns

JLab Hall C diamond detector

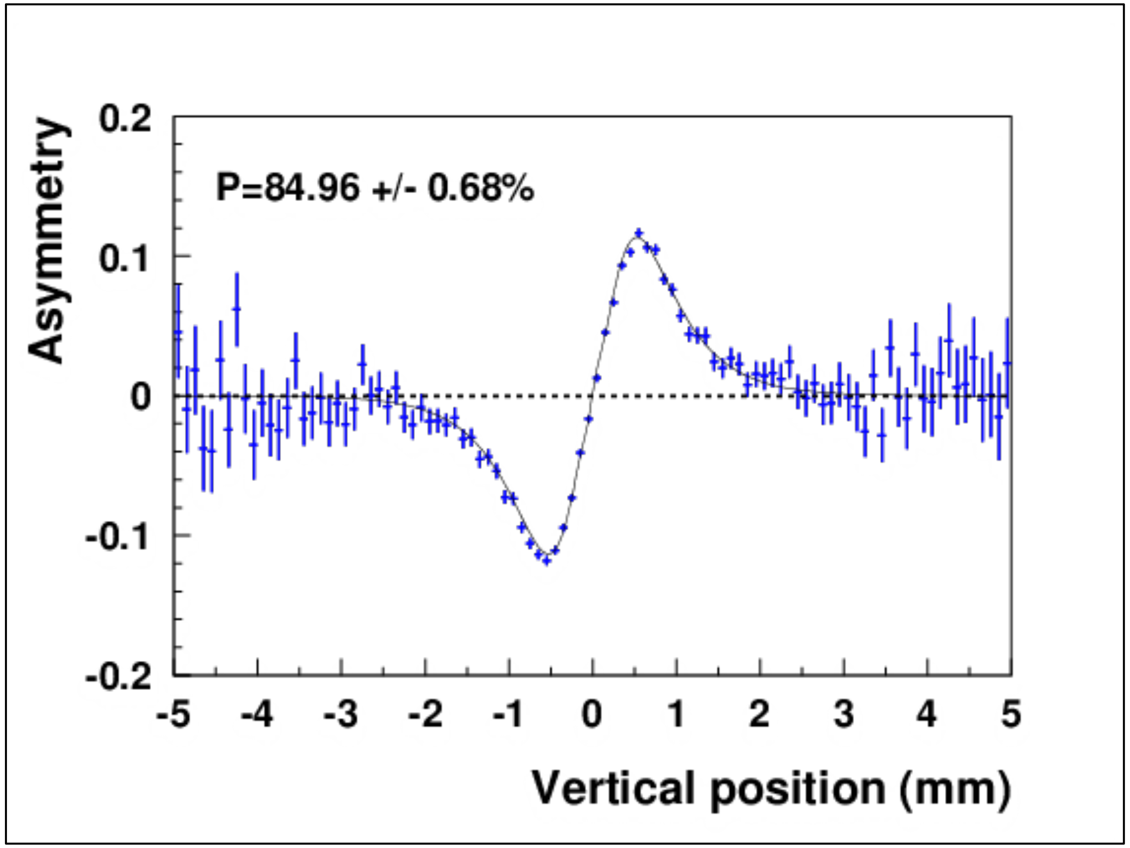




EIC Photon Detectors

- ESR photon detector must measure longitudinal and transverse polarization
- Same timing requirements as electron detector – 10 ns spacing
- ***P_L*** from energy spectrum → need high resolution crystal calorimeter
  - BaF2 or PbWO4? Slow components and radiation hardness an issue
- ***P_T*** from spatial asymmetry (left-right/up-down)
  - 10 ns bunch spacing → diamond strips (x-y)
  - 100-200 μm strips to allow "self calibration" – fit asymmetry and offset

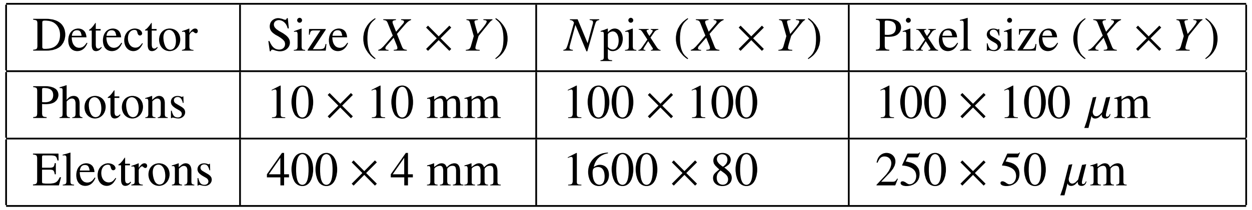
- RCS will primarily measure transverse polarization
  - Larger bunch spacing – so can be slower than ESR detectors
  - Like ESR, need 100-200 μm segmentation, operated in integrating/multi-photon mode



Fit to simulated "ideal spectrum" → offset allowed to float

Detector Requirements – FCC-ee

Table 3. Detectors: geometry, number of pixels, size of pixels.



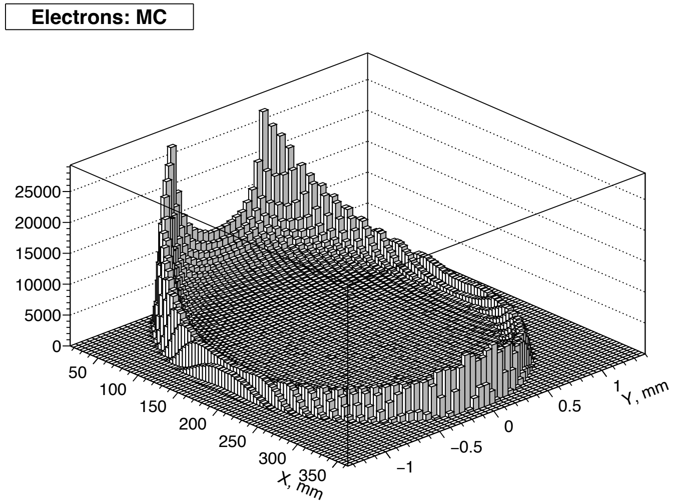
Detector	Size $(X \times Y)$	Npix $(X \times Y)$	Pixel size $(X \times Y)$
Photons	10×10 mm	100×100	100×100 μm
Electrons	400×4 mm	1600×80	250×50 μm

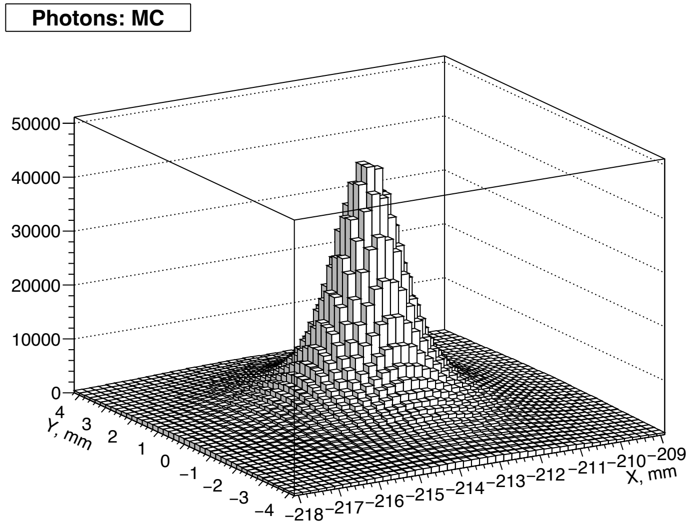
Simulations of photon/electron distributions exist:
For example, *N. Yu. Muchnoi, JINST* 17 (2022) 10, P10014

Expect 40-60 backscattered photons/scattered electrons per laser-beam bunch crossing → *must operate in integrating/multi-photon mode*

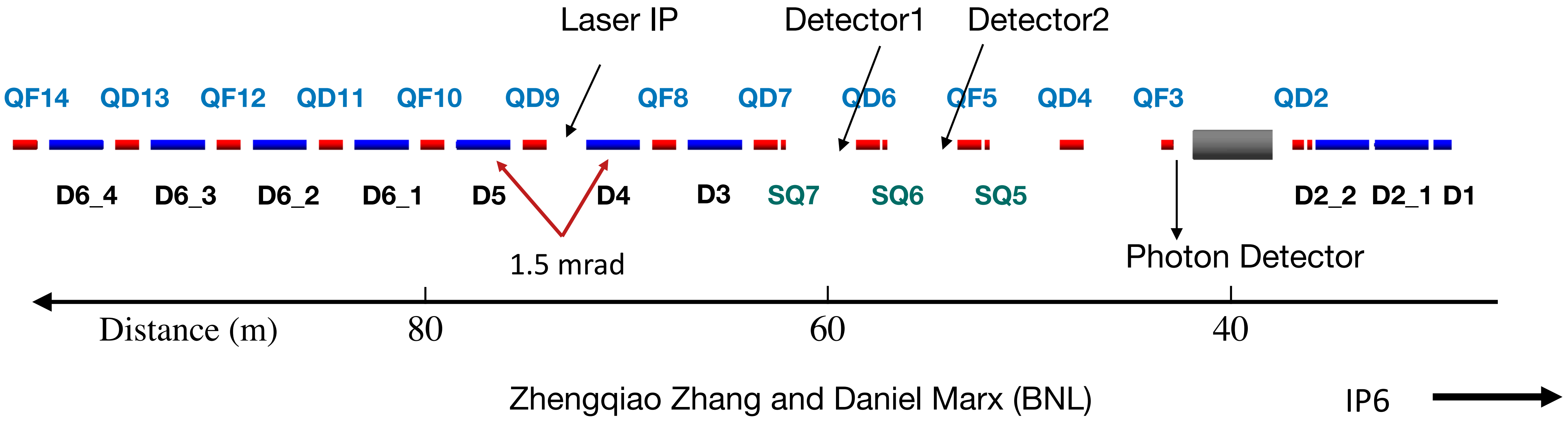
Required segmentation requires further study, but easily achievable pitch sizes appear adequate

→ Less stringent timing requirements → maximum laser repetition rate 30 kHz
→ Similar radiation hardness issues as EIC? → 400 MHz at 45.6 GeV
→ *Diamond also preferred for FCC?*





ESR Compton Beamline Design and Synchrotron Radiation



Zhengqiao Zhang and Daniel Marx (BNL)

High electron beam currents (2.5 A @ 5,10 GeV, 0.26 A @ 18 GeV) imply large amount of synchrotron radiation

→ Beamline in Compton area recently re-designed

→ Synchrotron mitigated by inserting weak bending dipoles before stronger dipoles to reduce synchrotron with line-of-sight to the photon detector

Dipoles near Compton:

D4 and D5: bend = 1.5 mrad
D6: bend = 11.9 mrad
D3: bend = 13.0 mrad

L=2.726 m

Only ~ 1 mm of tungsten shielding needed for photon detector

Rapid Cycling Synchrotron (RCS) Compton Polarimeter

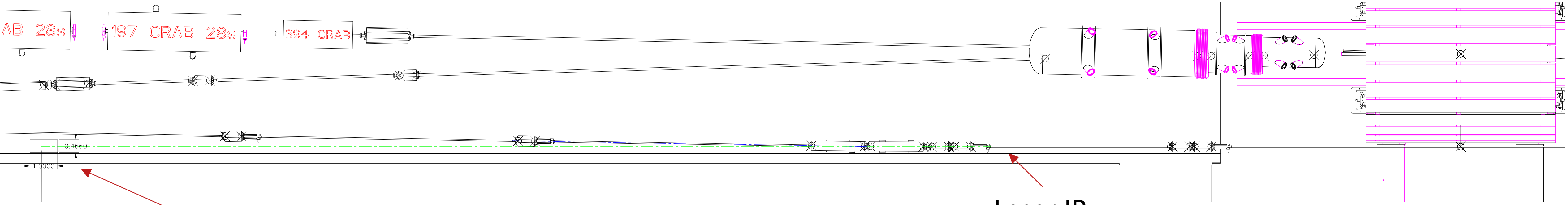
RCS properties

- RCS accelerates electron bunches from 0.4 GeV to full beam energy (5-18 GeV)
- Bunch injection frequency → 2 Hz
- Bunch rotation frequency → 76 kHz
- 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

RCS Compton will operate very differently than ESR Compton
→ Measurement of bunch-by-bunch polarization not practical
→ 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)



Photon detector

Laser IP

Summary

- Despite significant difference in energy regime, several common issues faced by EIC and FCC polarimeters
  - Beam structure: short times between bunches in some cases
  - Synchrotron radiation issues
  - Laser diagnostics
- Use of laser back-reflection (HERA → JLab → EIC) eliminates nearly all uncertainty in determination of laser circular polarization at interaction point
- EIC planning to use diamond detectors in ESR Compton
  - Fast response (new ASIC), segmentation, radiation hard
- Careful design of ESR Compton region has mitigated synchrotron radiation issues
  - Even larger issue at FCC due to higher energy
- Not addressed today: beamline diagnostics (beam size, position, direction, intensity) crucial for accurate polarization measurements

Extra

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

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

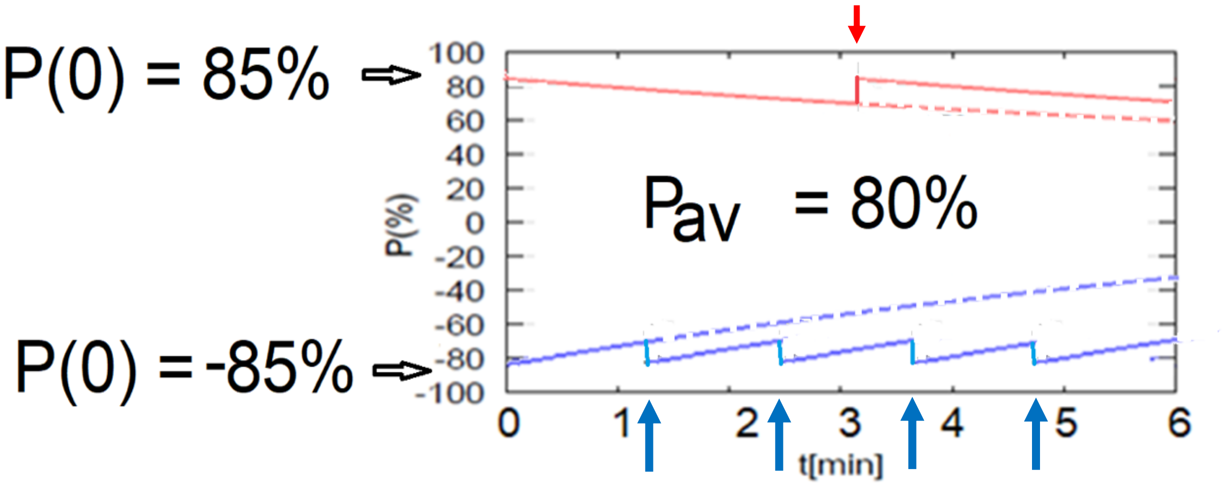
B P

Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

Re-injection



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

Re-injections

Figure from C. Montag (BNL)

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	99.3%	11.8%
10 GeV	97.3%	23.0%
18 GeV	91.4%	40.5%

Polarization Components at Compton *(December 2023 lattice)*

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

EIC and FCC-ee Polarimetry: areas of overlapping interest

- The Electron Ion Collider (EIC) at BNL and FCC-ee will operate in different energy regimes, but face some common issues with respect to electron polarization measurements
- Compton polarimeters are very sensitive to beam properties
  - Beam size and stability
  - Beam-related backgrounds (synchrotron, Bremsstrahlung, halo-induced)
- Laser technologies and polarization measurement techniques
- Detectors
- Simulations

Polarimeter Simulations

Older lattice – simulation geometry has been updated

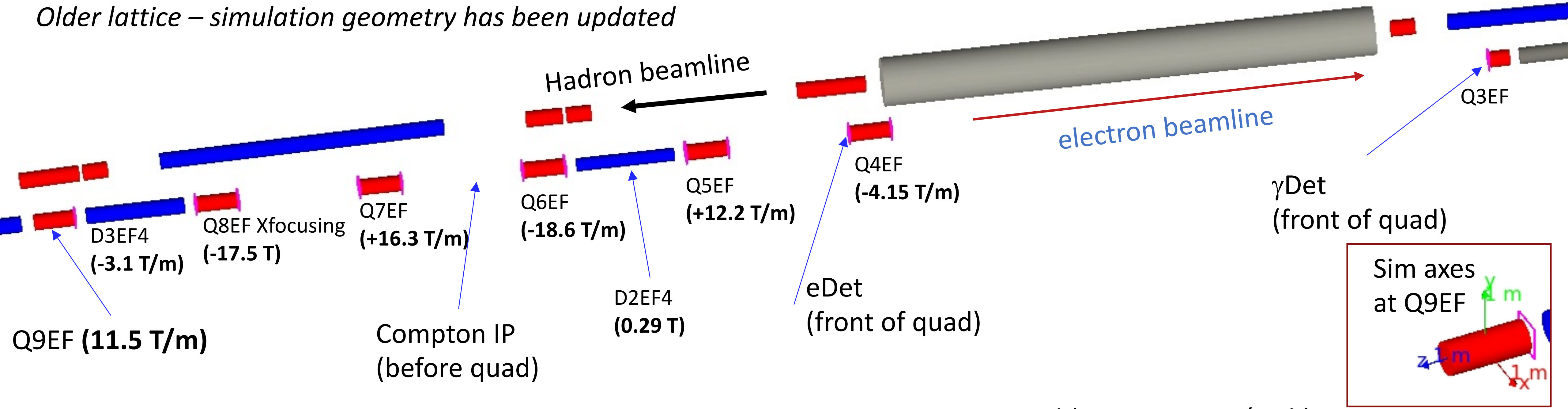


Figure courtesy Ciprian Gal (Miss. State U./JLab)

EIC has GEANT4 simulation of ESR Compton, including Compton event generation, beamline geometry, and detectors
→ Framework could be easily adapted for other polarimeters → in use for some KEKb related simulations (U. Manitoba)

Has been used for studies of beam-related backgrounds, beam size sensitivity, detector requirements, etc.

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 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)