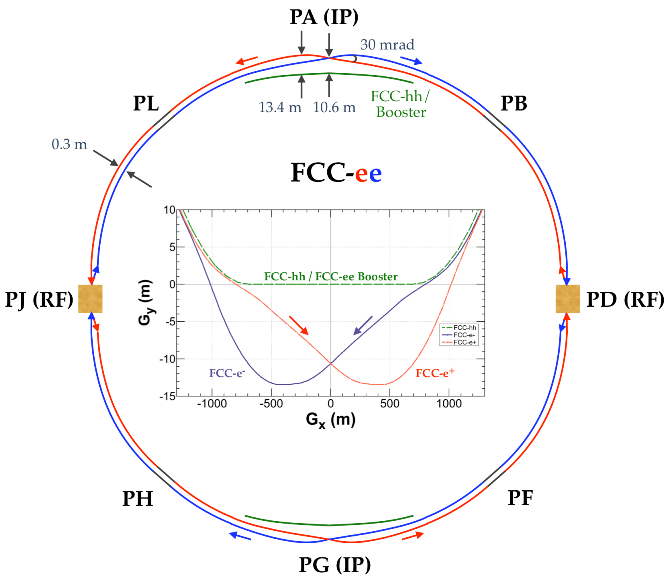
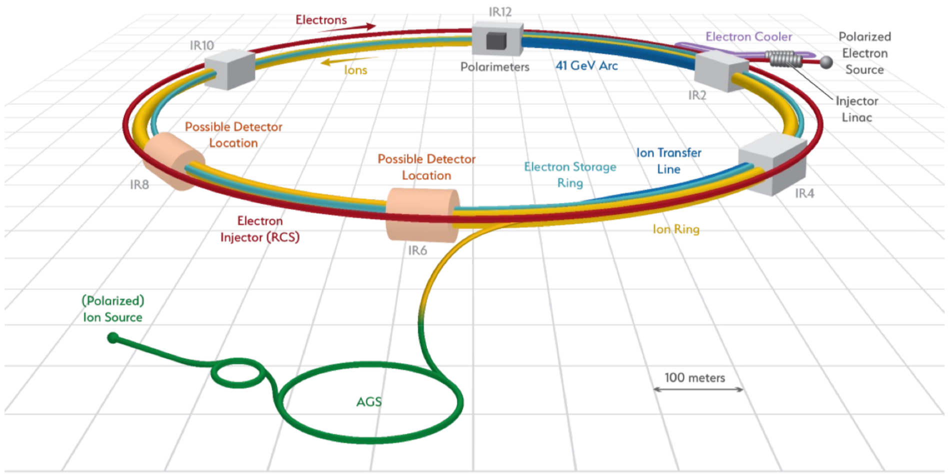
Electron Polarimetry: FCC-ee and EIC Synergies

Dave Gaskell

Jefferson Lab





Future Circular Collider (FCC) Workshop 2023

April 24–26, 2023

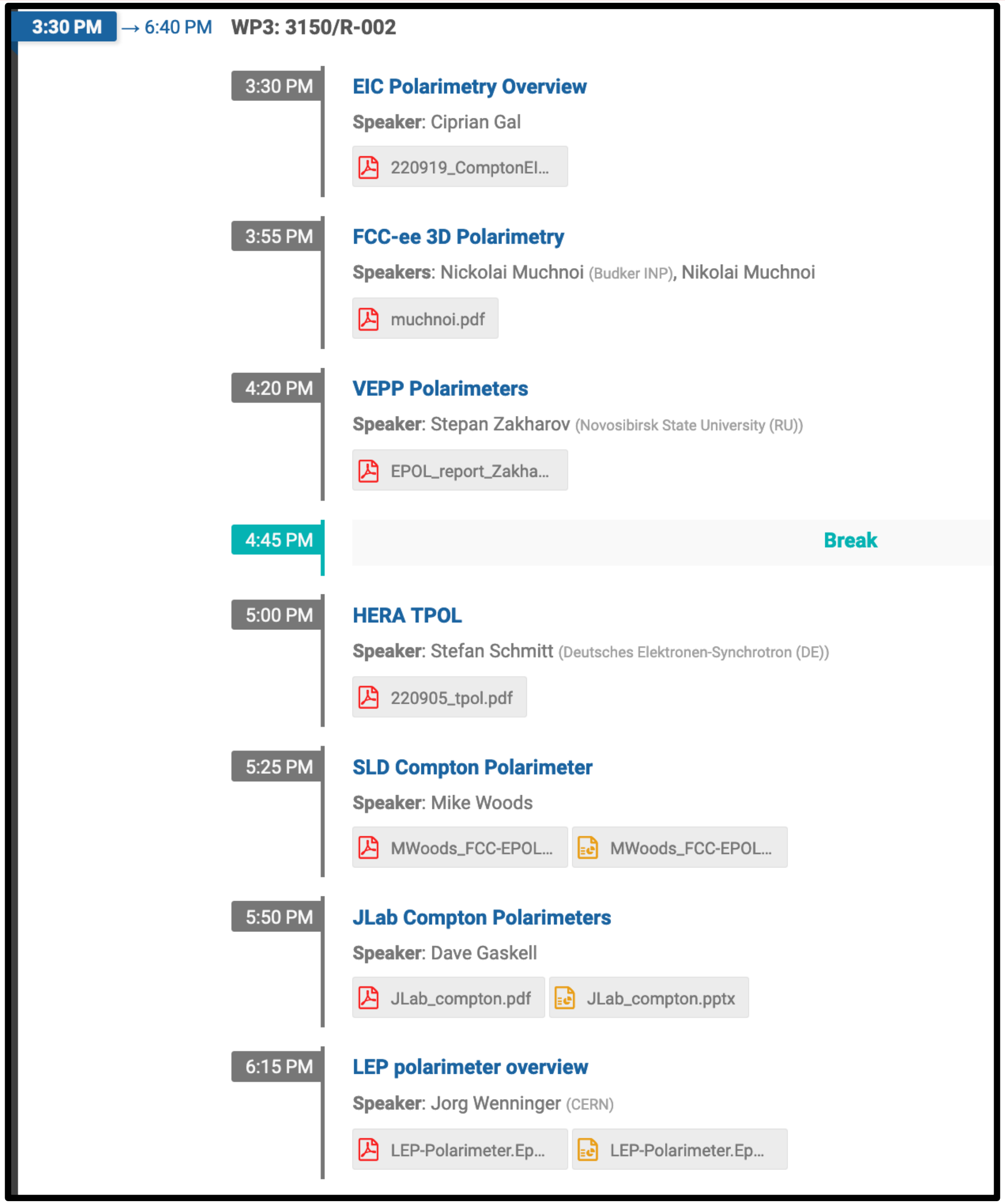
EIC and FCC-ee Polarimetry: areas of overlapping interest

- 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

EPOL Workshop

FCC EPOL workshop, September 2022

- Combined with joint EIC-FCC working meeting on e+/e- polarization
- Sessions on Compton polarimetry included experts from facilities (prior, existing, and planned) worldwide
- Significant EIC participation with respect to polarized sources, polarized beam tracking, etc.



3:30 PM → 6:40 PM WP3: 3150/R-002

3:30 PM **EIC Polarimetry Overview**
Speaker: Ciprian Gal
220919_ComptonEl...

3:55 PM **FCC-ee 3D Polarimetry**
Speakers: Nickolai Muchnoi (Budker INP), Nikolai Muchnoi
muchnoi.pdf

4:20 PM **VEPP Polarimeters**
Speaker: Stepan Zakharov (Novosibirsk State University (RU))
EPOL_report_Zakha...

4:45 PM **Break**

5:00 PM **HERA TPOL**
Speaker: Stefan Schmitt (Deutsches Elektronen-Synchrotron (DE))
220905_tpol.pdf

5:25 PM **SLD Compton Polarimeter**
Speaker: Mike Woods
MWoods_FCC-EPOL... MWoods_FCC-EPOL...

5:50 PM **JLab Compton Polarimeters**
Speaker: Dave Gaskell
JLab_compton.pdf JLab_compton.pptx

6:15 PM **LEP polarimeter overview**
Speaker: Jorg Wenninger (CERN)
LEP-Polarimeter.Ep... LEP-Polarimeter.Ep...

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 GeV0
  - Bunch spacing = 10 ns (5,10 GeV), 40 ns (18 GeV)
- Rapid Cycling Synchrotron
  - Accelerates bunches from 400 MeV to full energy in storage ring (5, 10, 18 GeV)
  - Bunch frequency → 2 Hz
  - 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)**

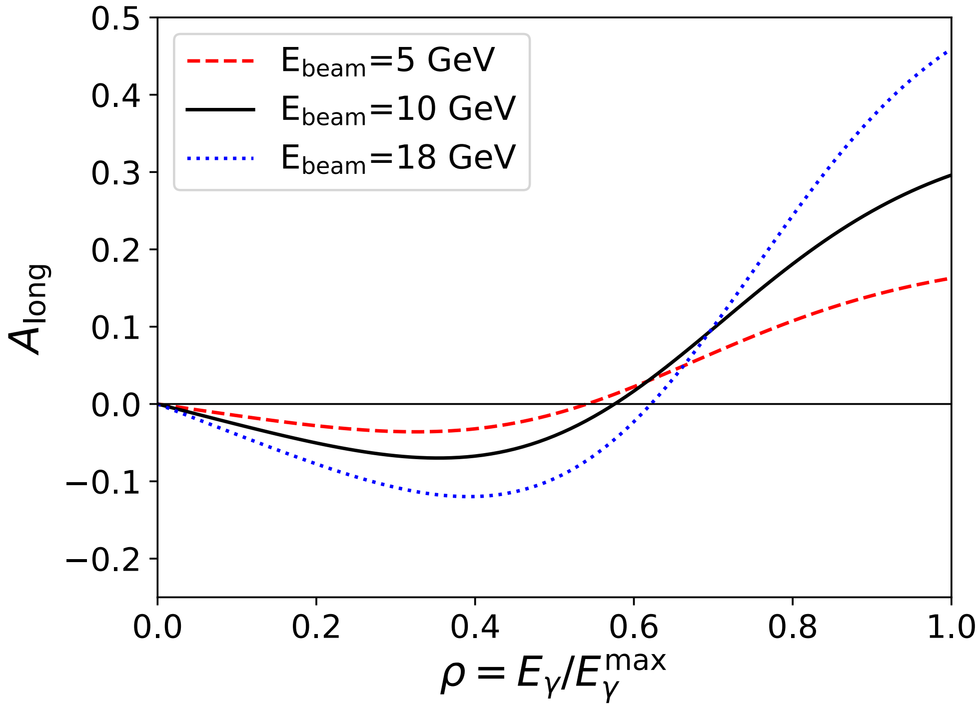
- FCC-ee
  - P=10% to ? → polarization from Sokolov-Ternov effect
  - 45.6, 80, 120, 182.5 GeV
  - Beam current = 1390, 147, 29, 5.4 mA
  - Bunch spacing = 19.6, 163, 994, 3396 ns (colliding bunches), 3 kHz (pilot bunches)
- **Polarimeter functions**
  - **Relative polarization of pilot bunches for Resonant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

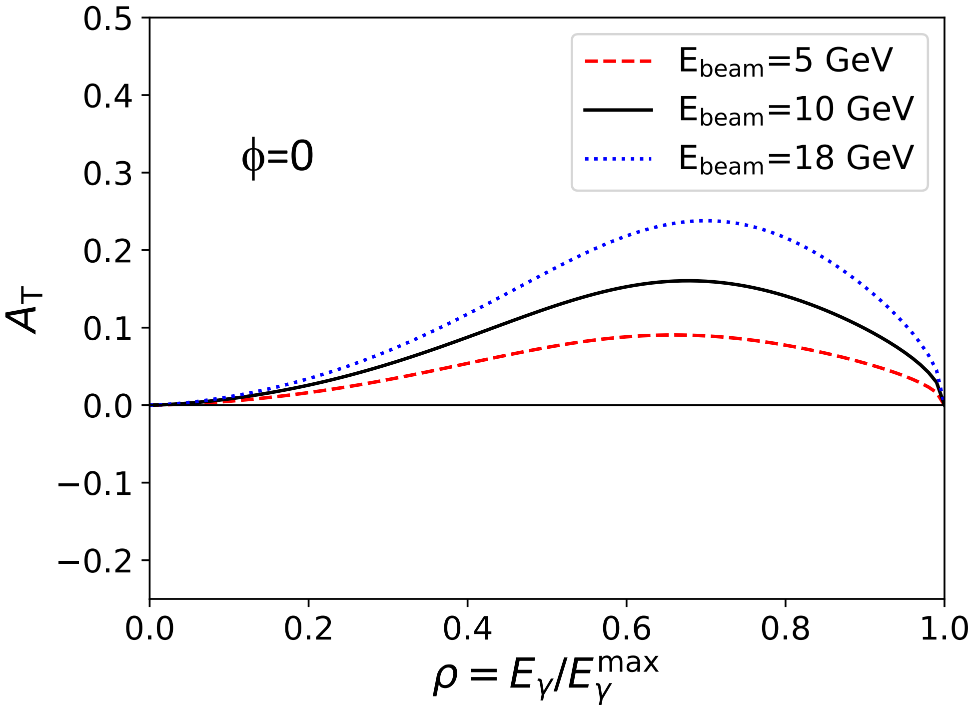
Polarization Measurement via Compton Polarimetry

Compton longitudinal and transverse analyzing powers

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

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





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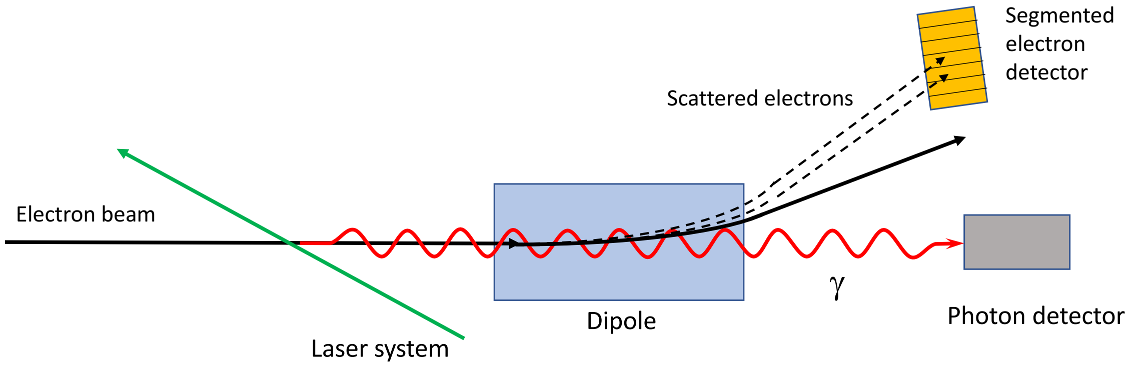
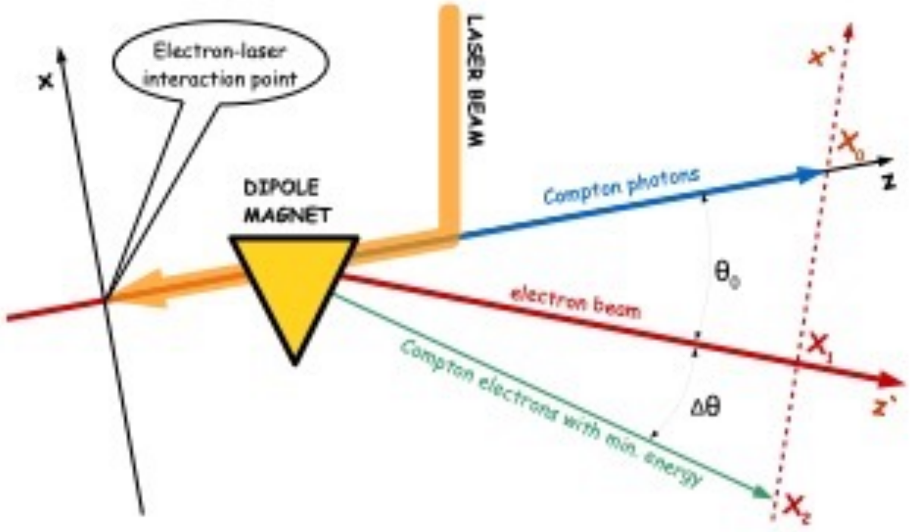
Generic Compton Polarimeter



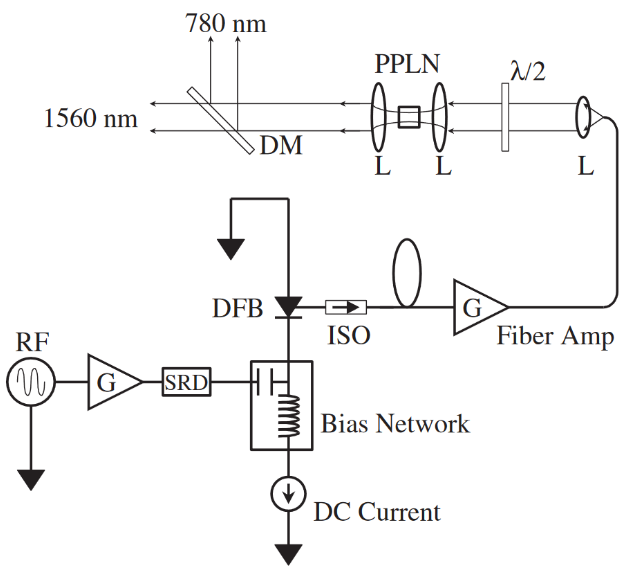


Key systems:
→ Laser
→ Photon and electron detector
→ Dipole

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

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

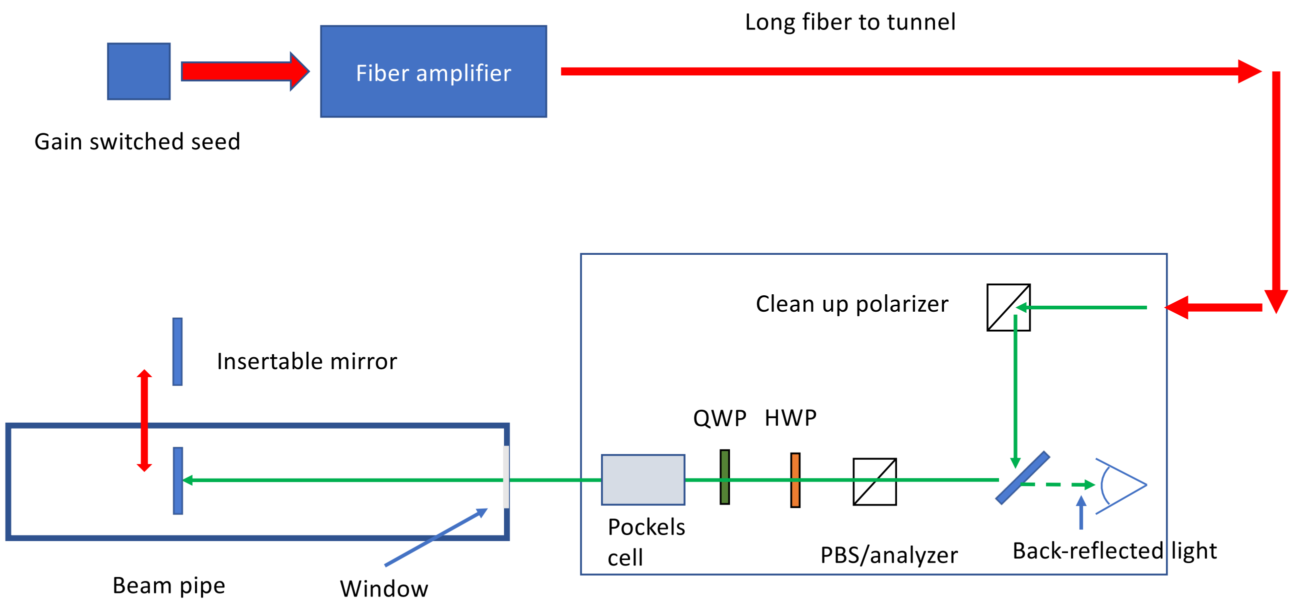


JLab injector laser system

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 (C. Gal, JLab)

Laser systems for FCC-ee

technology	Q-switch	modelock Yb	modelock Yb
bunch type	pilots	pilots	colliding
$f_{\text{rep.}}$	3 kHz	3 kHz	30 kHz
U	1 mJ	1 mJ	$10 \times 50\ \mu$J
P	3 W	3 W	15 W
σ_t	3 ns	30 ps	30 ps
$\sigma_{x/y,l}$	1.5 mm	1.5 mm	1.5 mm
θ	2 mrad	3 deg	3 deg
$n_{\text{int.}}$/crossing	45	50	60
$n_{\text{int.}}/s$	$1.4 \times 10^5 \text{s}^{-1}$	$1.5 \times 10^5 \text{s}^{-1}$	$1.8 \times 10^7 \text{s}^{-1}$

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

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 (?)

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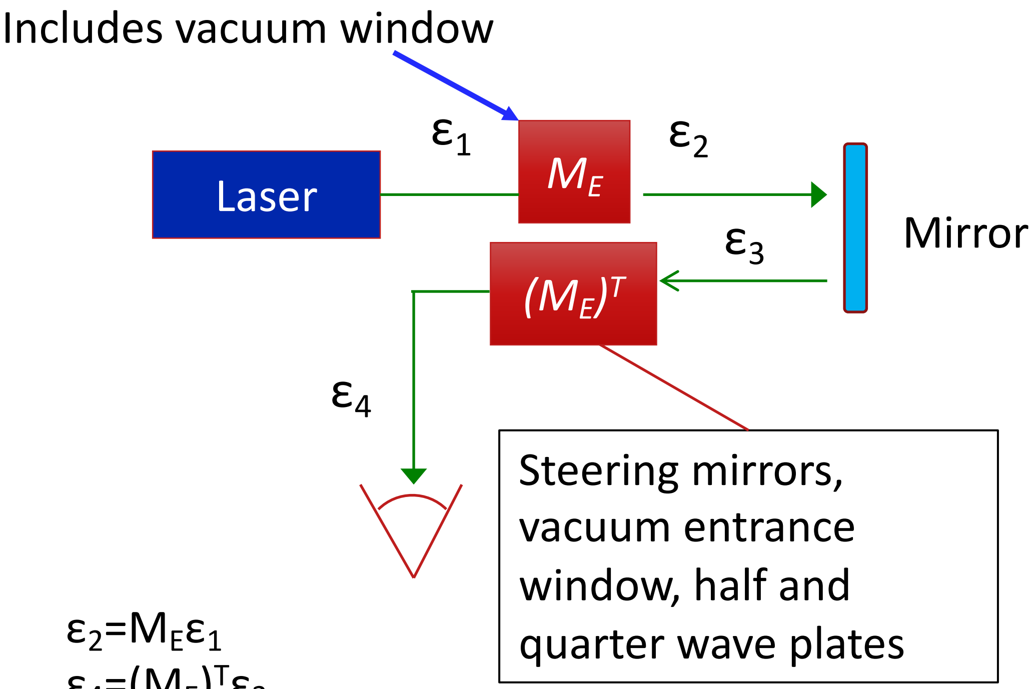
Laser Polarization – experience at JLab/DESY → EIC and FCC?

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*



$\varepsilon_2 = M_E \varepsilon_1$

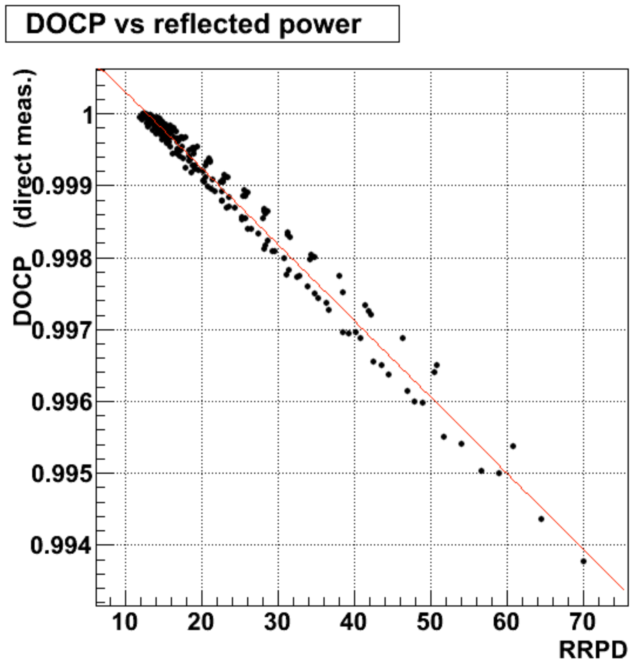
$\varepsilon_4 = (M_E)^T \varepsilon_3$

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

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

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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

→ Need to measure position dependent asymmetry to extract transverse polarization

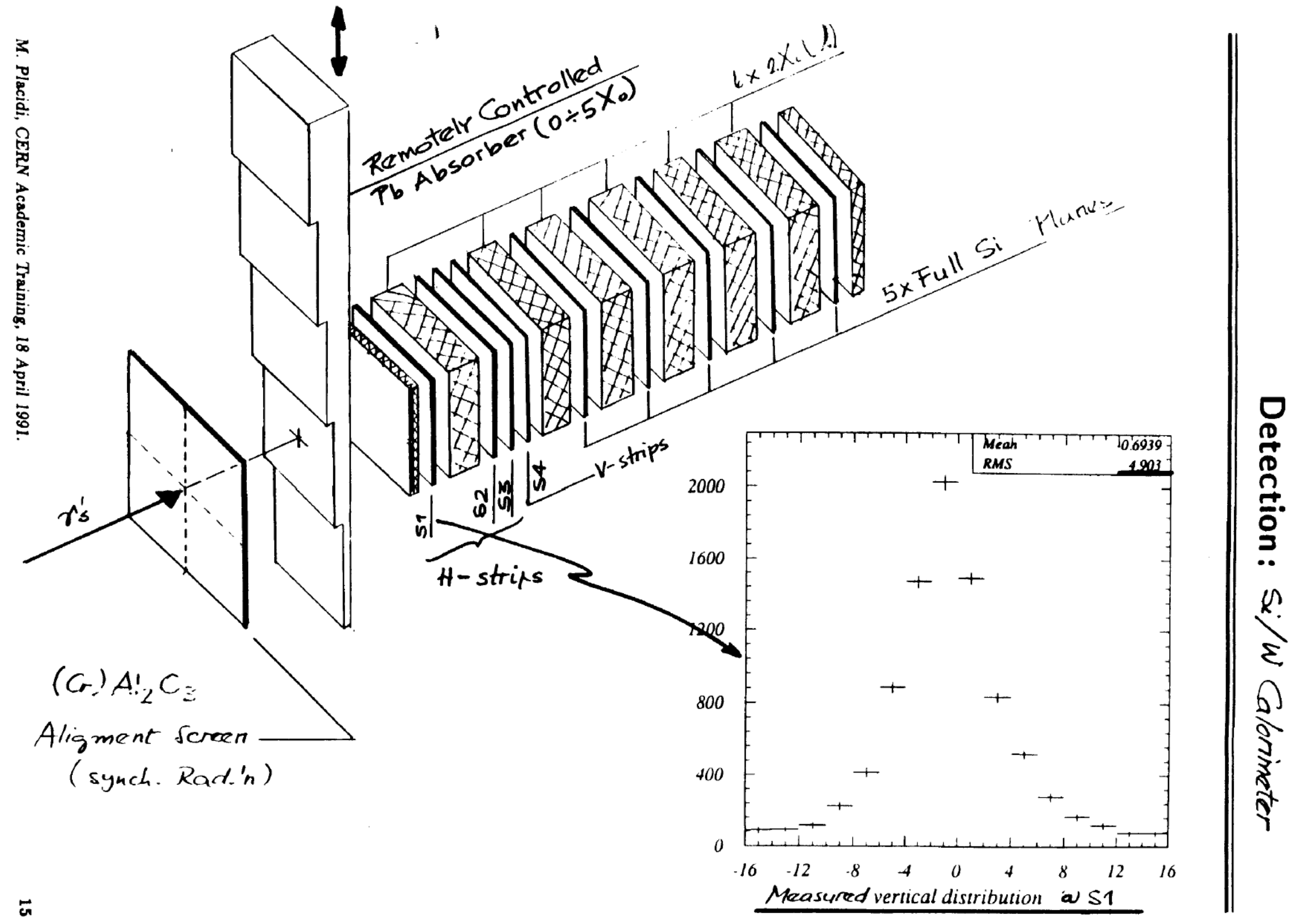
→ FCC-ee polarimeter will operate in fashion similar to RCS

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

→ Timing requirements also similar

→ Perhaps common detector technology possible

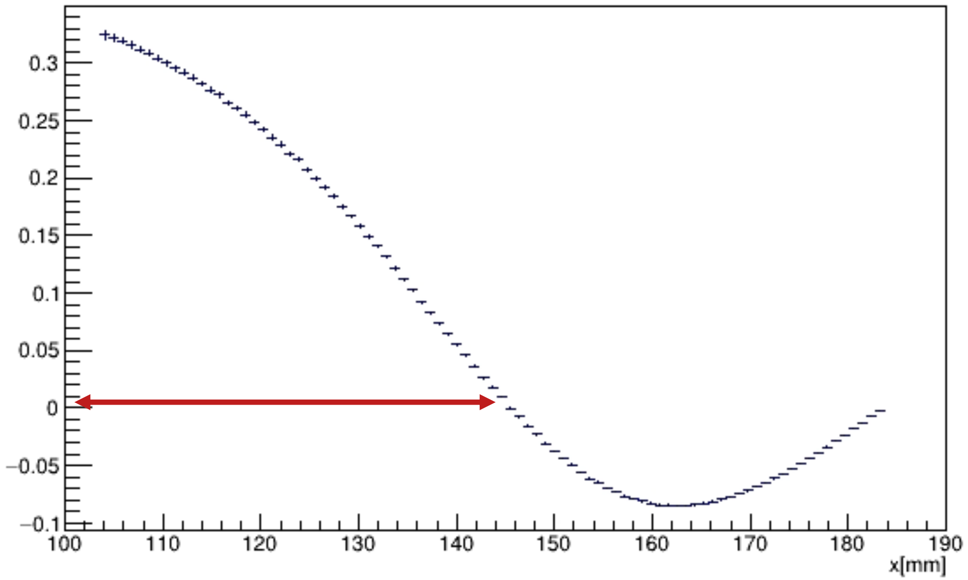
LEP Transverse Compton Detector



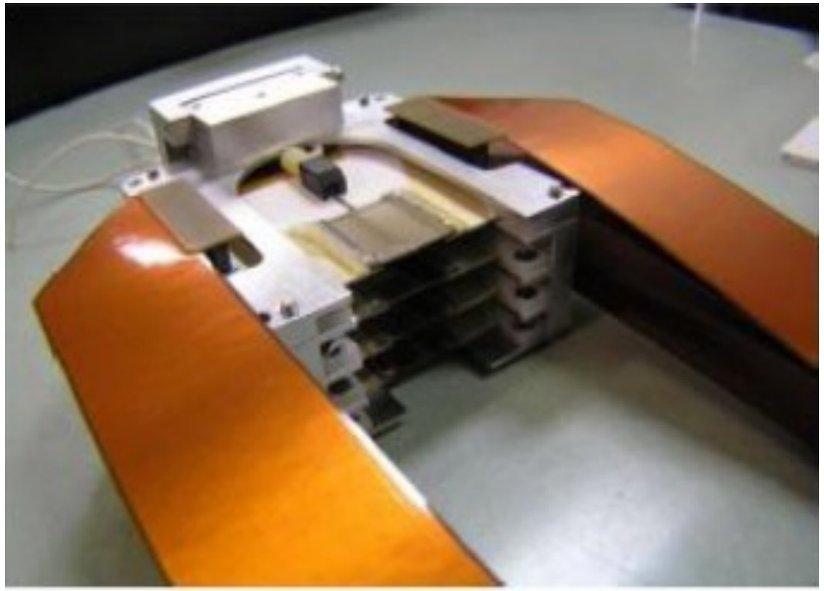
Detector Requirements – EIC Electron Detector

Detector size: capture (longitudinal) asymmetry zero crossing and kinematic endpoint → this will be largest at highest energy (18 GeV) → 4.5 cm

Detector segmentation: at least 30 bins from endpoint to zero crossing to allow ”self-calibration” → 400 um



JLab Hall C diamond detector



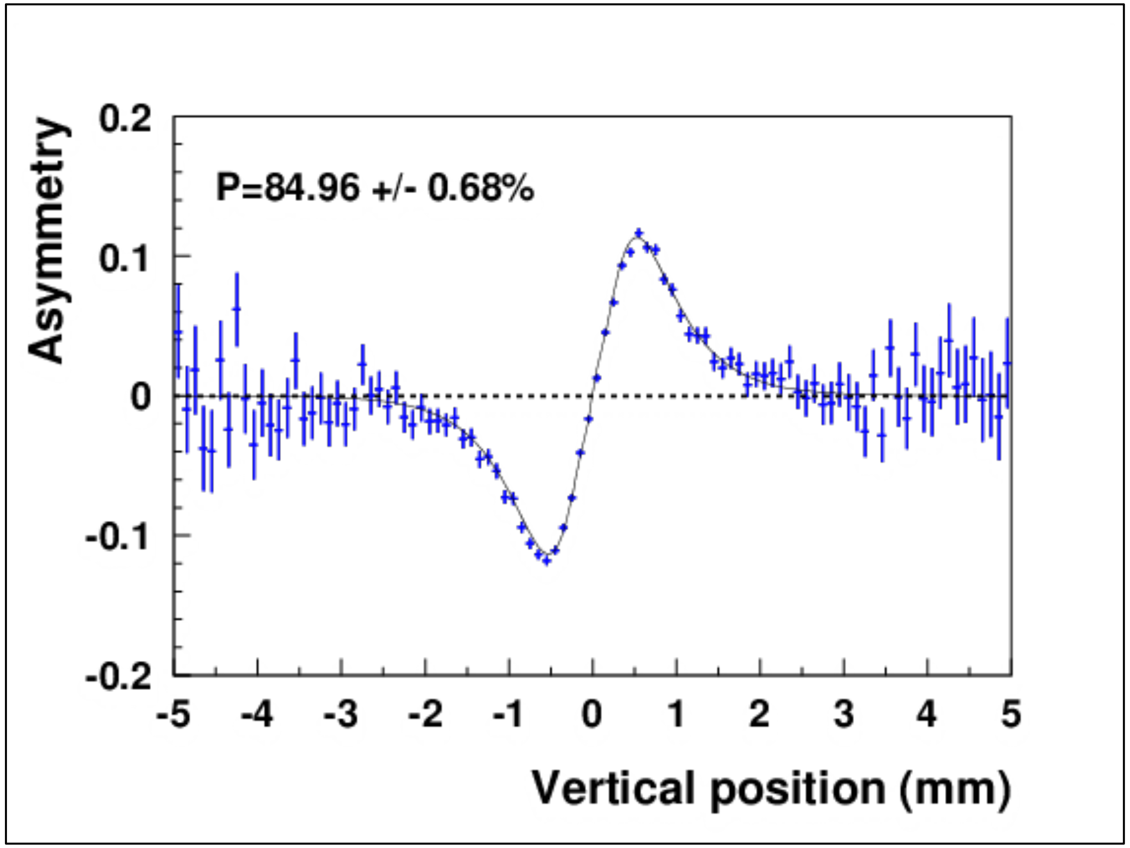
Additional requirements
→ Fast - resolve 100 MHz beam bunch structure
→ Radiation hard → large integrated dose in normal running

Default solution = diamond
→ In use at JLab, but with more modest timing requirements
→ CALYPSO electronics (modified version under development for Hall A) already nearly meets the EIC requirements

Detector Requirements – 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 (filter slow components)
- ***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 → still investigating optimal detector technology



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

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Detector Requirements – FCC-ee

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

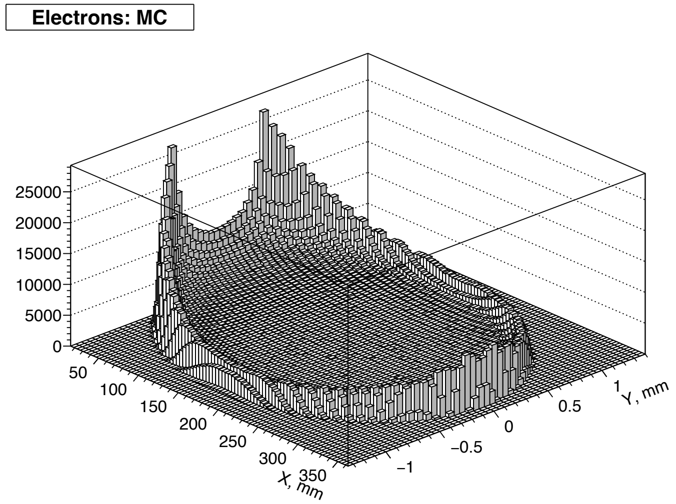
Detector	Size ($X \times Y$)	Npix ($X \times Y$)	Pixel size ($X \times Y$)
Photons	10×10 mm	100×100	100×100 μm
Electrons	400×4 mm	1600×80	250×50 μm

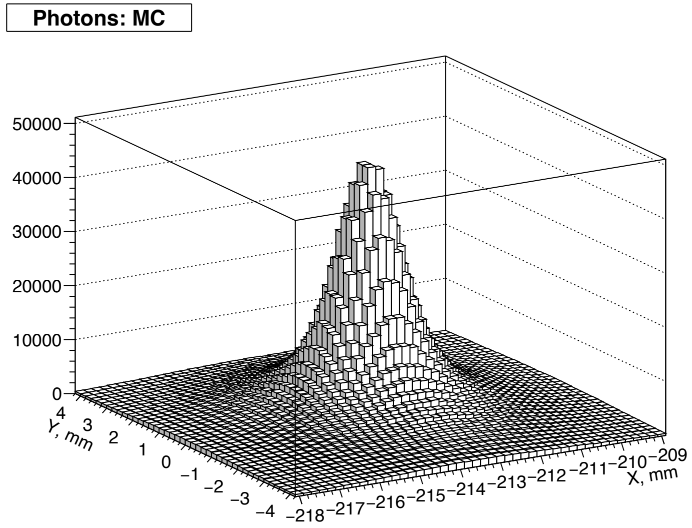
Simulations of photon/electron distributions exist:
For example, *N. Yu. Muchnoi*, *JINST* 17 (2022) 10, P10014

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 4 kHz
→ Emphasis on transverse polarization → modest energy resolution calorimeter adequate?





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Polarimeter Simulations

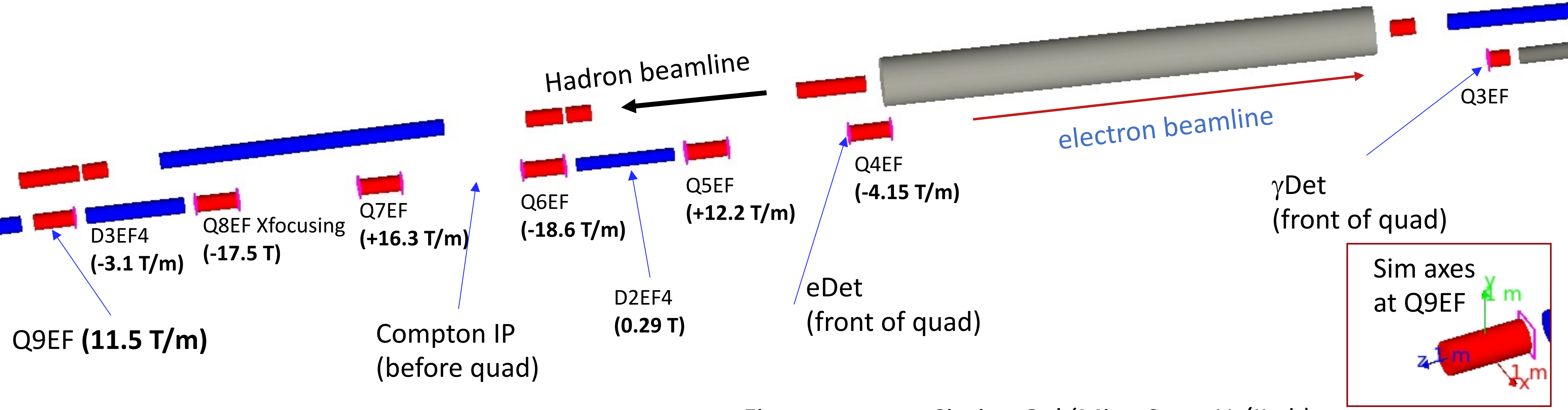


Figure courtesy Ciprian Gal (Miss. State U./JLab)

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.

Summary

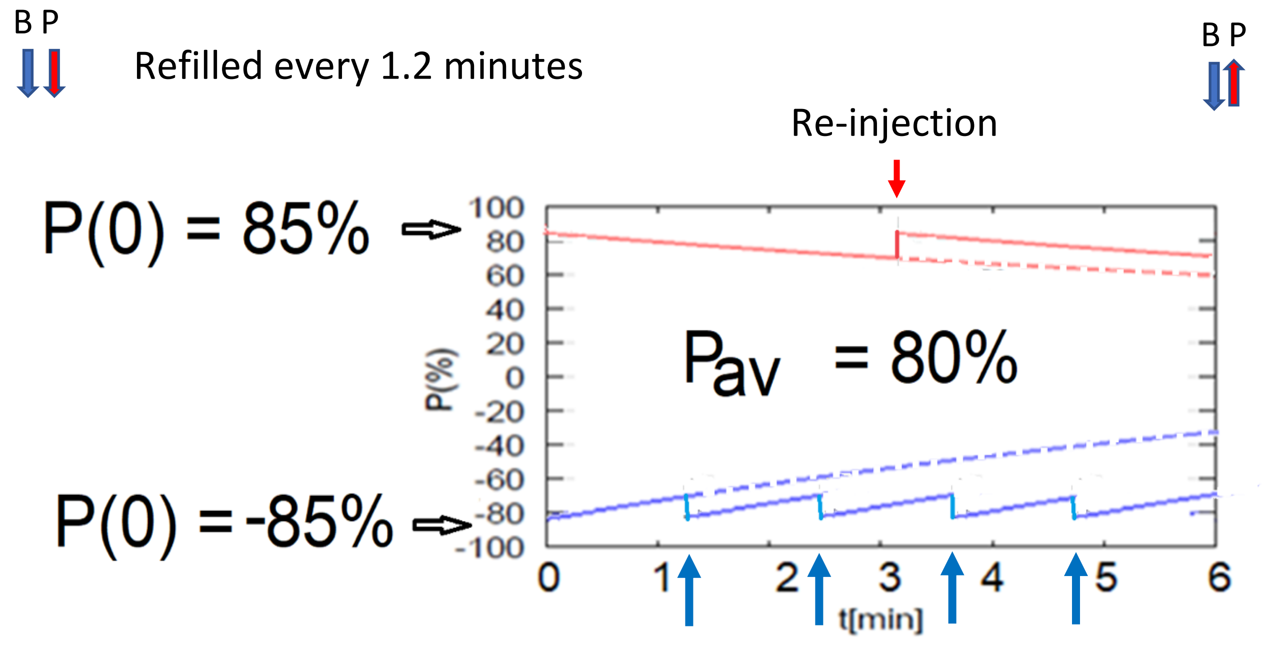
- Communication between EIC electron polarimetry group and FCC EPOL group already underway
  - Participation of EPOL members in EIC Polarimetry Working Group meetings and vice versa
- EPOL workshop in 2022 emphasized many of our common issues and goals
  - Example: EIC laser system already benefitting from valuable input from FCC EPOL group
- Several areas of common interest – will work to maintain communication and collaboration

Extra

ESR 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



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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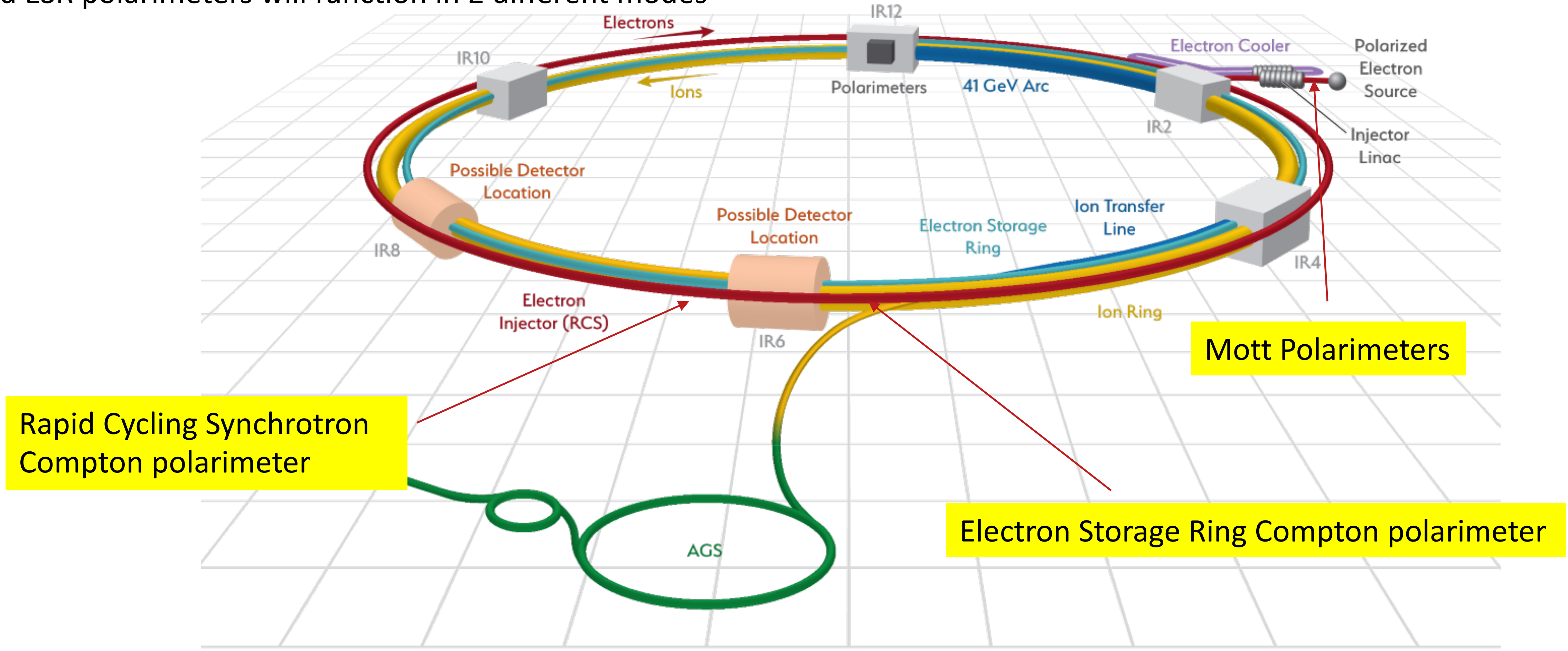
EIC Electron Polarimeter Map

RCS ramps electrons to full energy → injects into storage ring
Storage ring will have "top-off" injection
RCS and ESR polarimeters will function in 2 different modes



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

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

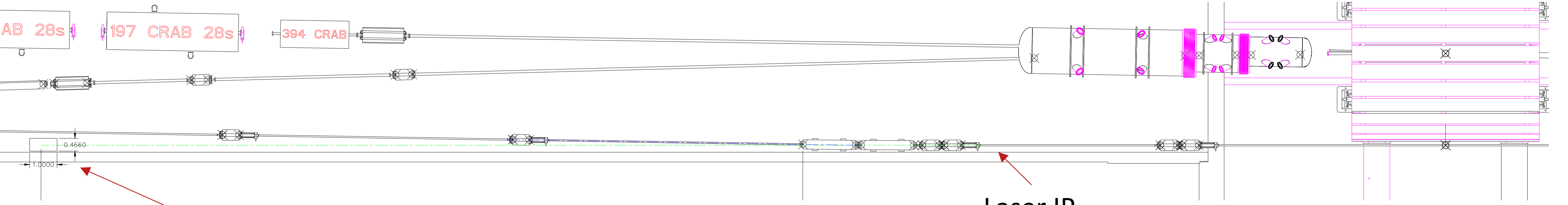
Polarimetry challenges

- 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

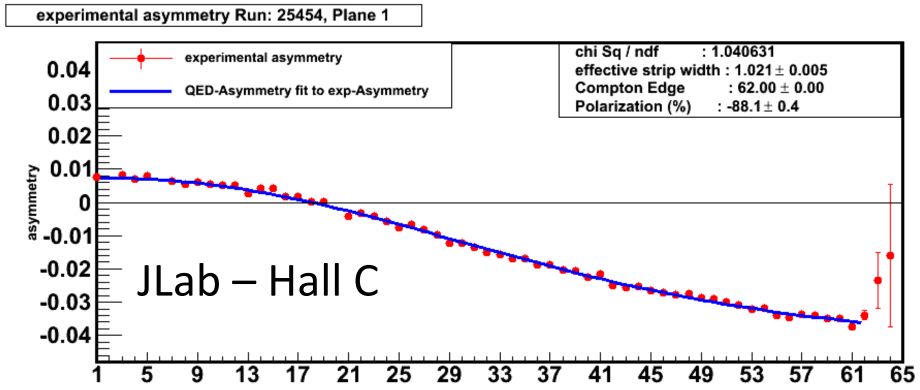
→ Measurements will be averaged over several bunches – can tag accelerating bunches to get information on bunches at fixed energy

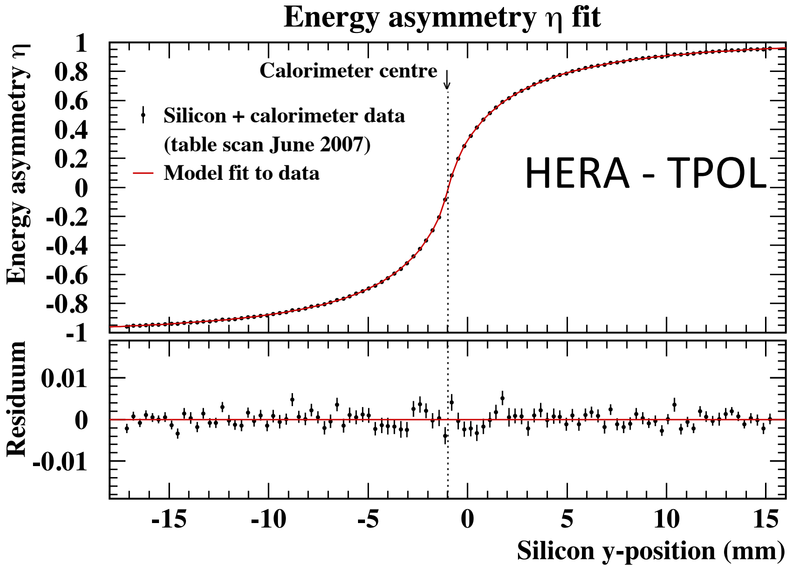
→ Requires measurement in multiphoton mode (many backscattered photons/electron bunch)



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)





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