Polarized Electron Beams at EIC

Polarized Ion Sources and Beams at EIC
Community Wide Meeting

Dave Gaskell
Jefferson Lab

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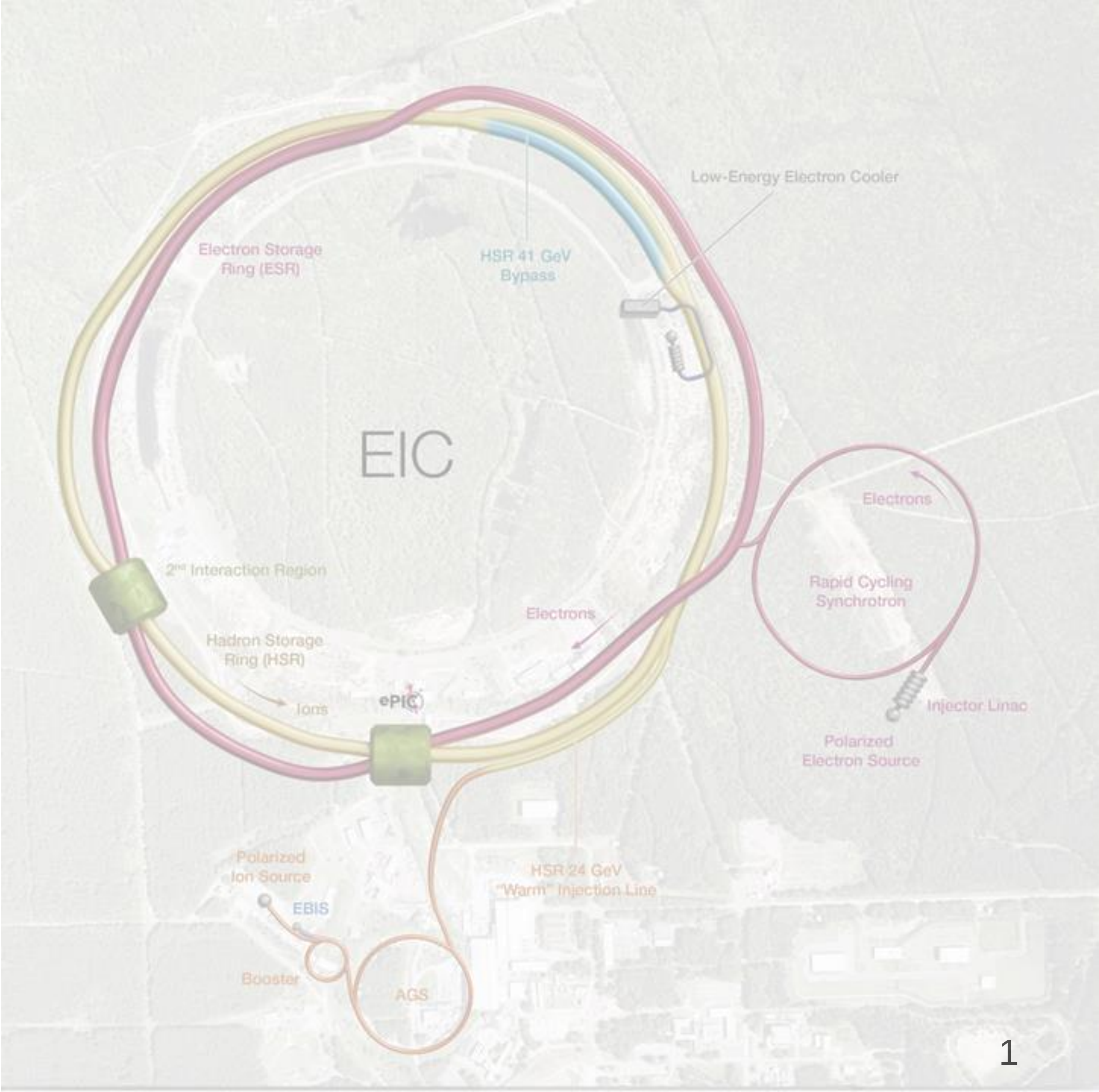


EIC Electron Beam Properties

EIC has challenging requirements to meet needs of physics program

→ Variable CM energies: electron beam @ 5, 10, 18 GeV

→ High polarization: P_{avg}>70%

→ High luminosity

  → Intense beams (up to 2.5 A)

  → significant amount of synchrotron radiation

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

Electron energies = 5, 10, 18 GeV

Table 1.1: Maximum luminosity parameters.

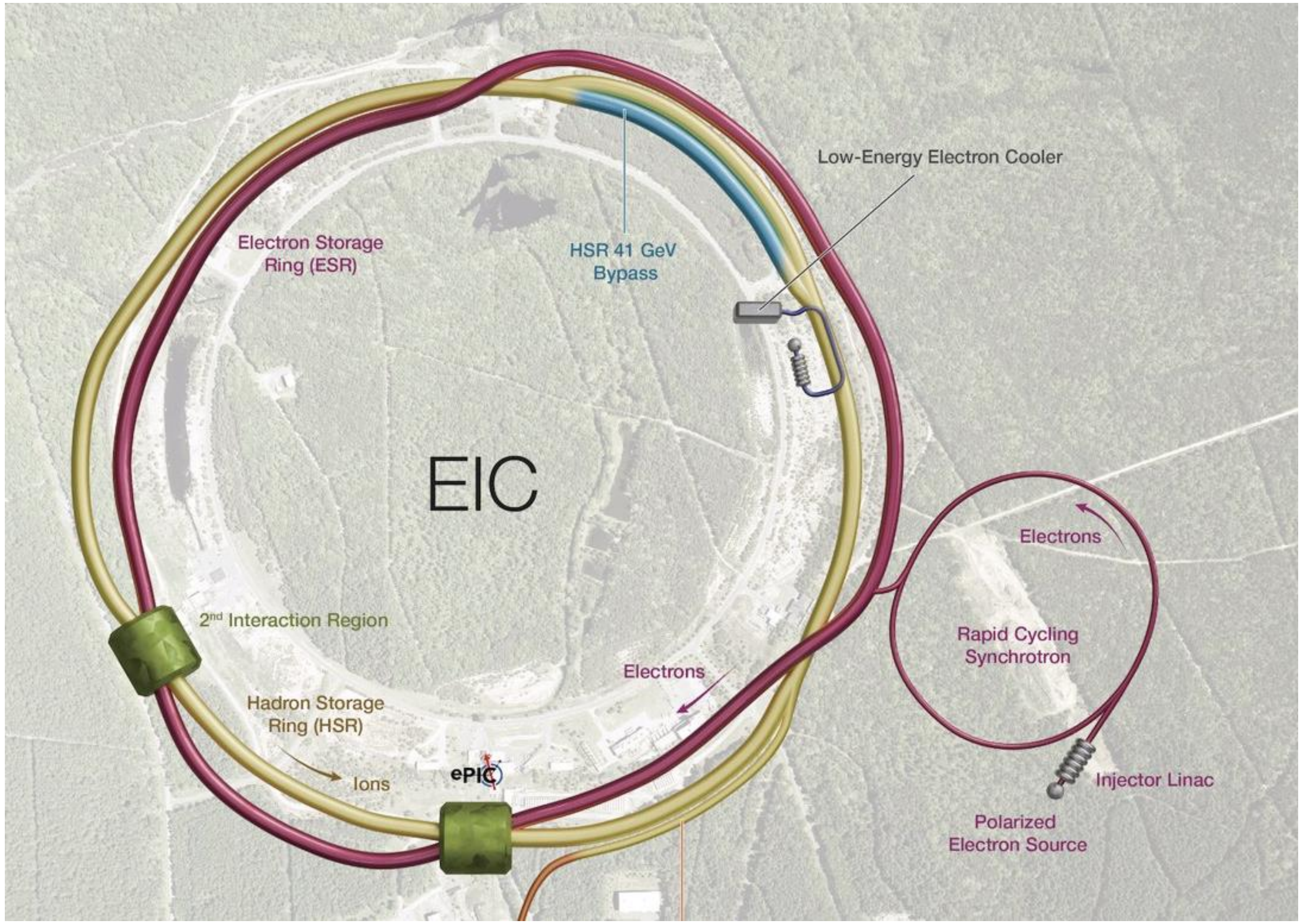
Parameter	hadron	electron
Center-of-mass energy [GeV]	104.9	
Energy [GeV]	275	10
Number of bunches	1160	
Particles per bunch [10^{10}]	6.9	17.2
Beam current [A]	1.0	2.5
Horizontal emittance [nm]	11.3	20.0
Vertical emittance [nm]	1.0	1.3
Horizontal β-function at IP β_x^* [cm]	80	45
Vertical β-function 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	

Polarized Electron Complex

Previous storage rings/colliders relied on self-polarization of electrons due to Sokolov-Ternov effect

EIC: Polarized electrons injected into ring at full energy

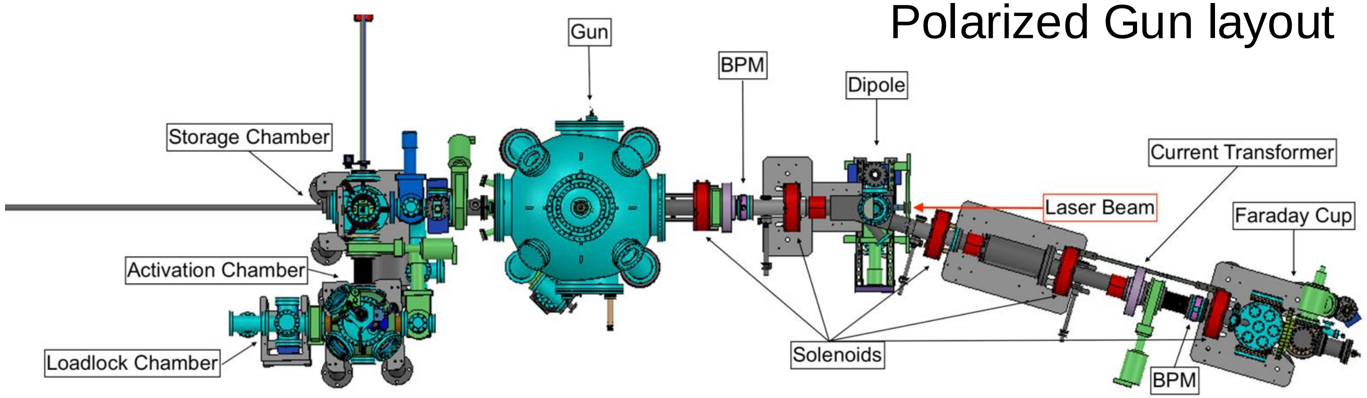
Key Components
1. Polarized source → photocathode
2. Injector system → linac + BAR + RCS
3. Electron storage ring



Polarized Electron Source

- Polarized source must generate 7* nC bunches (later, 3-bunch-train of 7 nC bunches)
- High polarization from the source ~85%

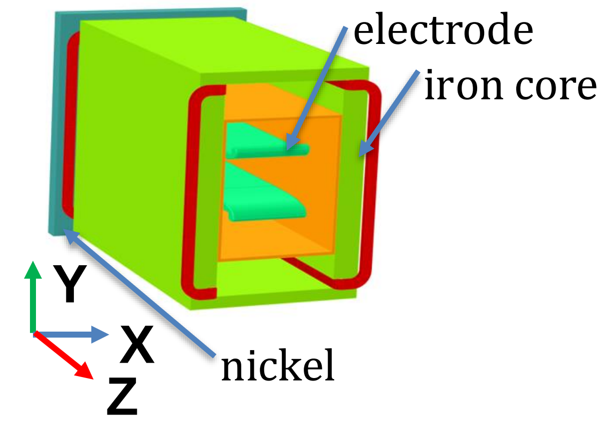
Polarized Gun layout



Wang et al., Appl. Phys. Lett. 124, 254101 (2024)

EIC will use HV (320 kV) DC gun
→ R&D under way to develop new sources of suitable photocathode material (GaAs-based)

Electrons longitudinally polarized from photocathode → must be rotated to vertical polarization before entering RCS
→ CDR assumed dipole-solenoid spin rotator at end of linac
→ Wein filter under consideration, but challenging due to 320 keV beam

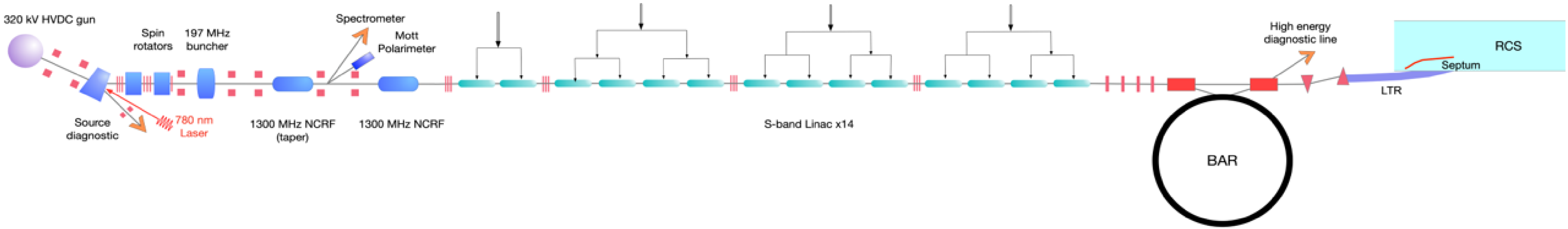


*updated design reduces this to 1 nC

RCS Pre-Injector

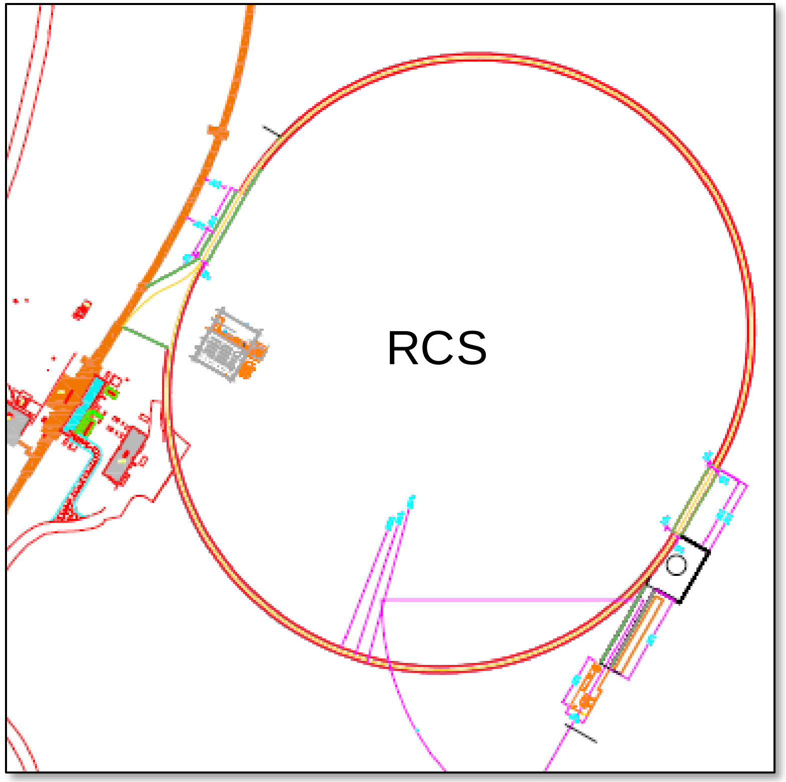
Between source and RCS, S-band (2856 MHz) linac accelerates beam to 750 MeV
→Beam accumulator ring between linac exit and RCS entrance
→Allows reduction of charge from photocathode to 1 nC per bunch
→Simplifies spin rotator design

RCS requires 7 nC/bunch at 1 Hz for lower electron beam energies, 28 nC/bunch for 18 GeV



Rapid Cycling Synchrotron (RCS)

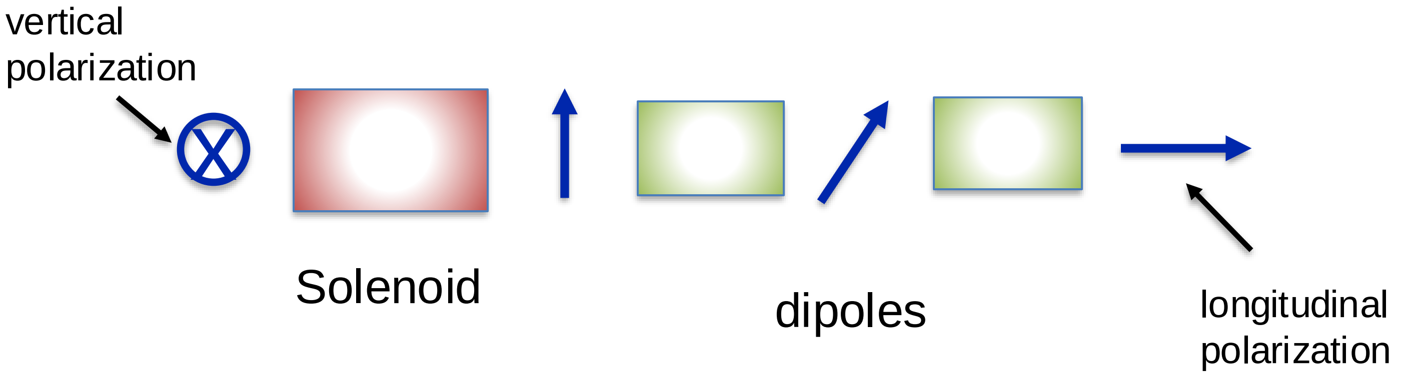
- RCS must accelerate electrons from 0.75 to nominal ESR beam energy → 5, 10 , 18 GeV
- Racetrack design: 2 accelerating linacs with recirculating arcs
- Designed to maintain (vertical) polarization through acceleration
- Ramp time < 500 ms at 10 GeV
- ESR fill time @10 GeV 19.33 minutes
  - 1160 buckets at 1 Hz

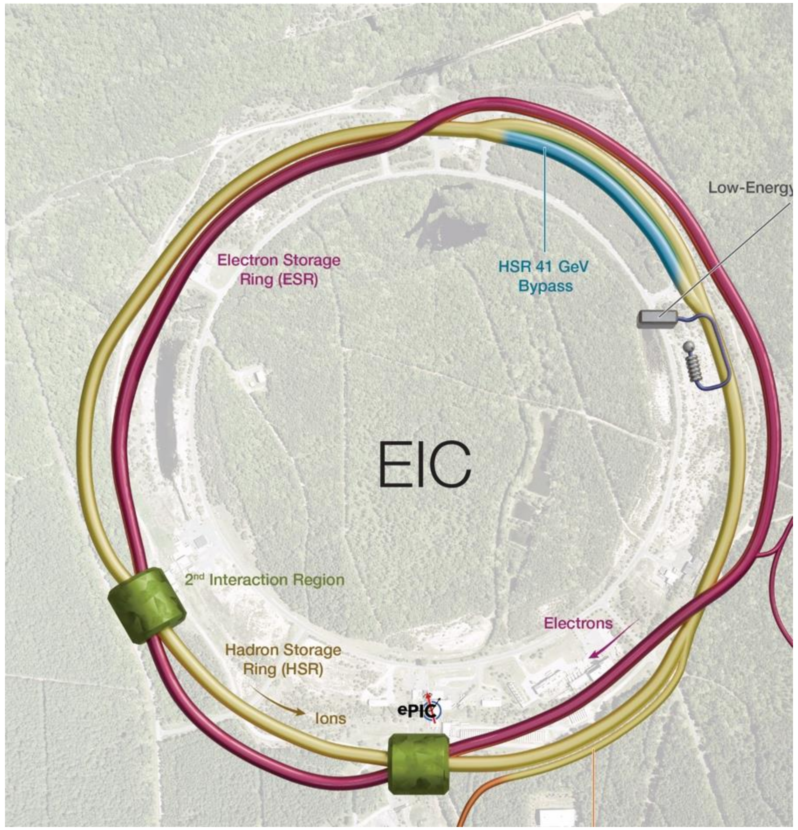


Property	Value
Injection energy	0.75 GeV
Bunch train repetition rate	1 Hz
Charge per bunch	Up to 28 nC
Max. current	5.9 mA
Circumference	1421.26 m

Electron Storage Ring

- Storage ring energies 5-18 GeV
- 1160 bunches, up to 2.5 A
- P_{avg} >= 70%
- Both beam polarization states – arbitrary structure?
- Design accommodates interactions at IP6 (ePIC) and a possible 2nd detector at IR8
- Polarization vertical in most of ring
- Experiments desire longitudinal polarization
    - Spin rotator required





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

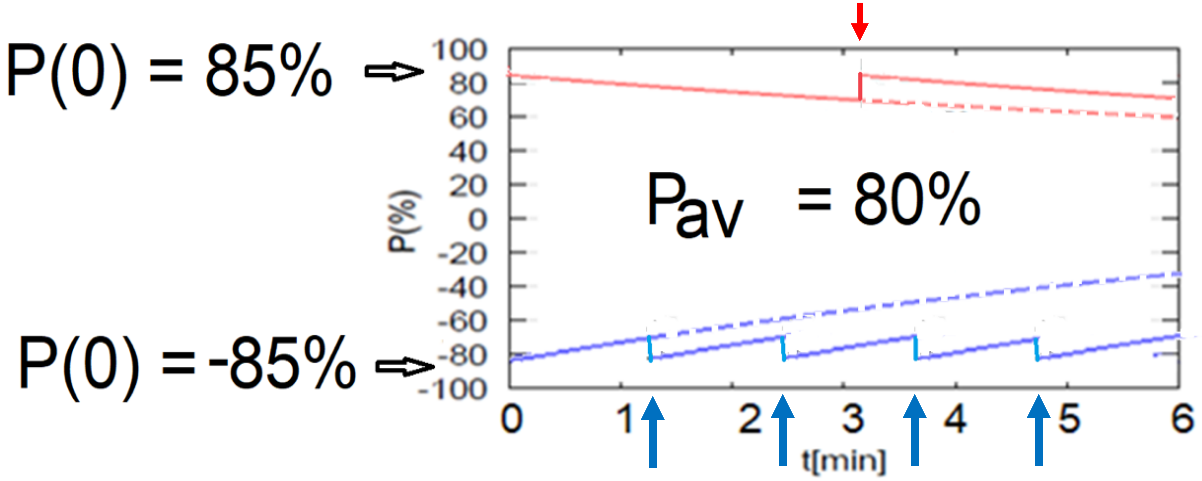
B P

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**

Electron Polarimetry Requirements

ESR	RCS
Highly polarized electrons, $P \approx 70\%$	
Fast feedback for machine setup	
Excellent measurement of absolute polarization, $\Delta P/P \approx 1\%$	Modest precision, $\Delta P/P \approx 3-5\%$
Non-destructive polarimetry	
Bunch-by-bunch polarization measurement (fill pattern: $P^{\uparrow}$,$P^{\downarrow}$, $\Delta t \approx 10\ \mathrm{ns\ for\ ESR}$)	Polarization averaged over several bunches, bunch repetition rate 1 Hz (at a given energy)
Sokolov-Ternov, $\Delta P^{\uparrow} \neq \Delta P^{\downarrow}$	Measurement at multiple energies
Polarization vector at experiment (transverse, longitudinal)	Transverse polarization only

Polarimeter Locations

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

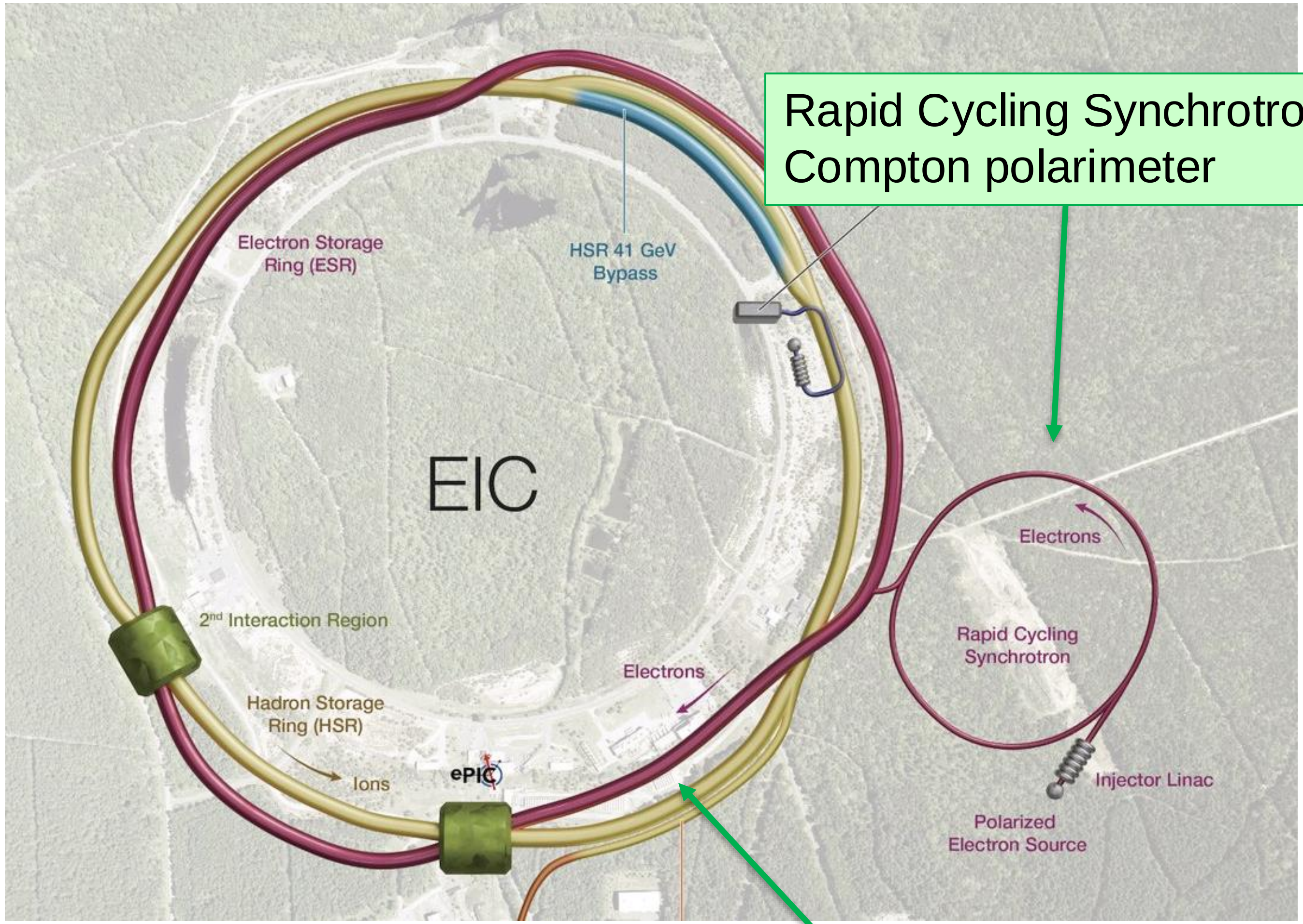
Rapid Cycling Synchrotron Compton (RCS)

→ Primarily for machine setup – less stringent precision requirements

→ Beam should be 100% transversely polarized

→ Detect backscattered photons, multi-photon mode

→ Average over several bunches



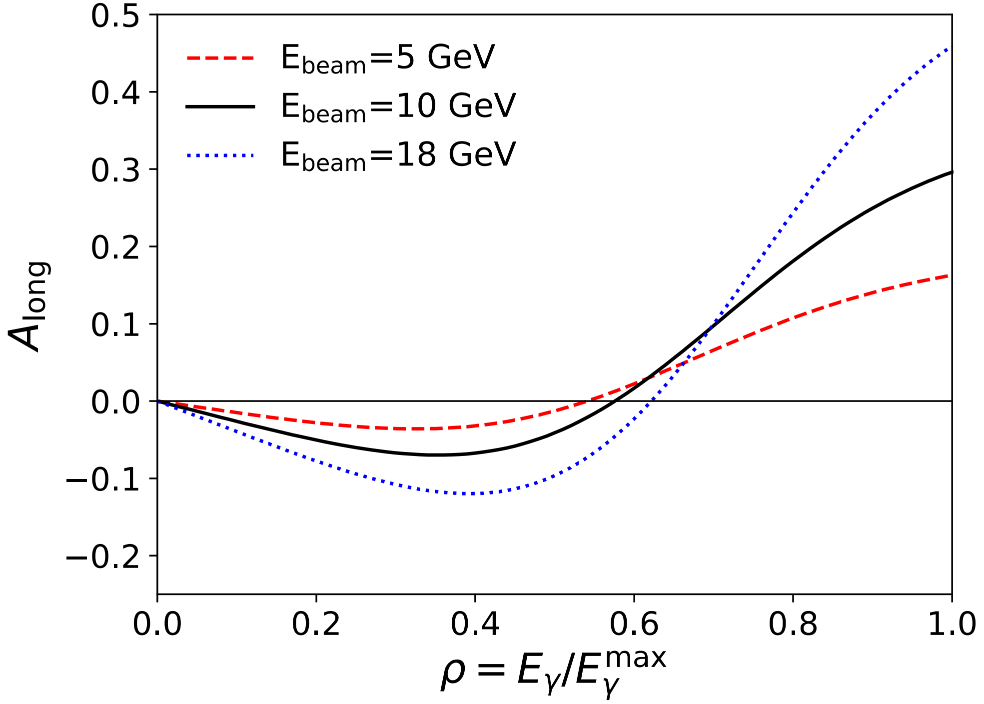
Rapid Cycling Synchrotron Compton polarimeter

Electron Storage Ring Compton polarimeter

Compton Analyzing Power

Longitudinal

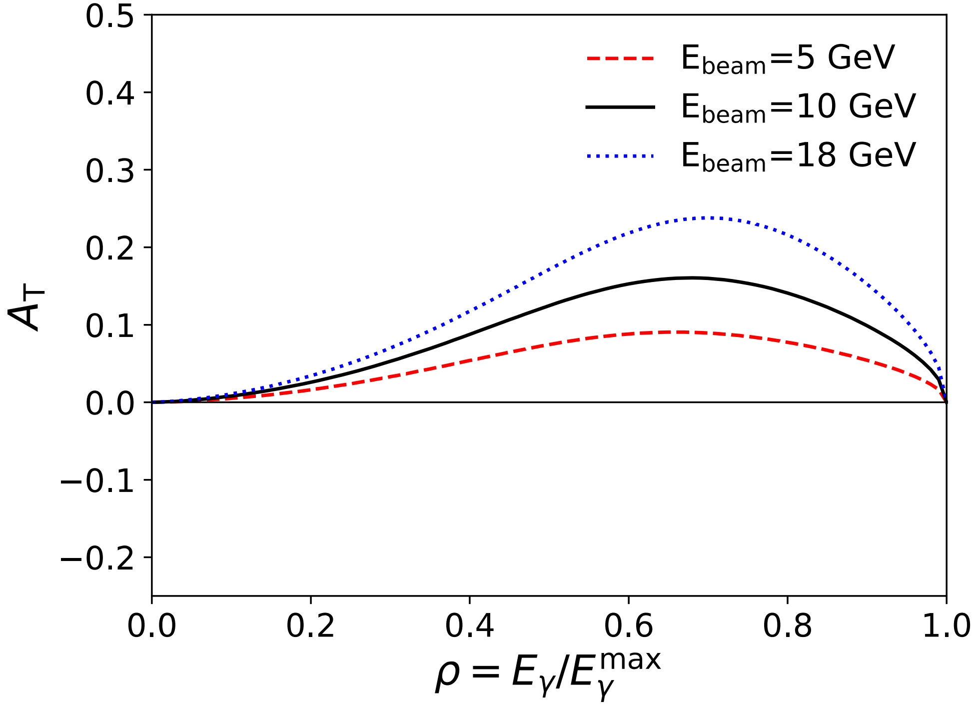
$$A_{\mathrm{long}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}(1-\rho(1+a))\left[1-\frac{1}{(1-\rho(1-a))^2}\right]$$



P_L **from energy dependence of asymmetry**

Transverse

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



P_T **requires measuring spatial dependence**

Electron Storage Ring 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

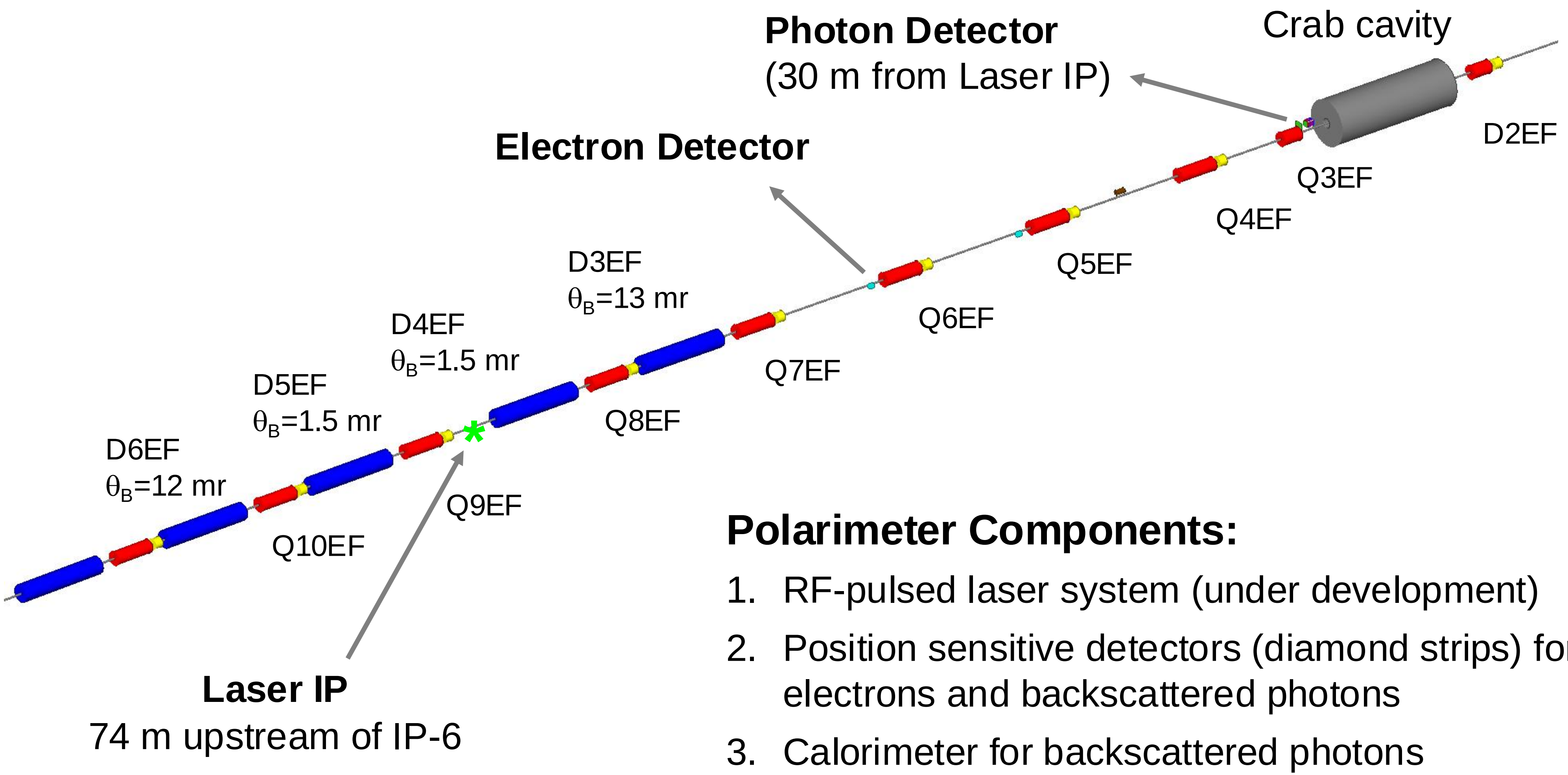
Beam energy	**P_L**	**P_T**
5 GeV	99.1%	13.2%
10 GeV	96.5%	26.2%
18 GeV	89.0%	45.6%

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

ESR Compton Polarimeter Layout

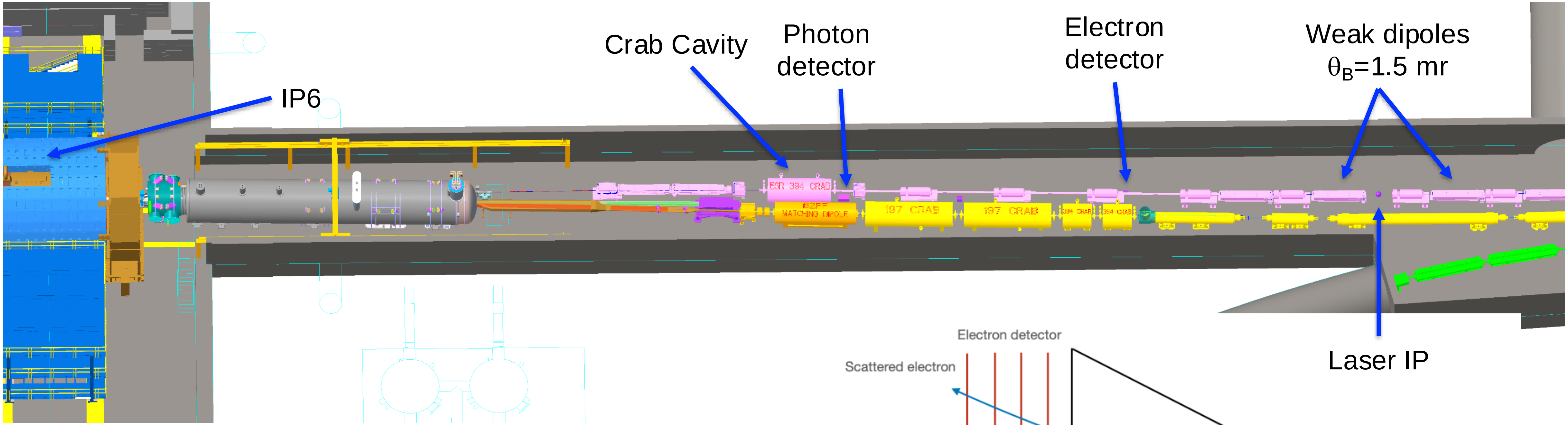


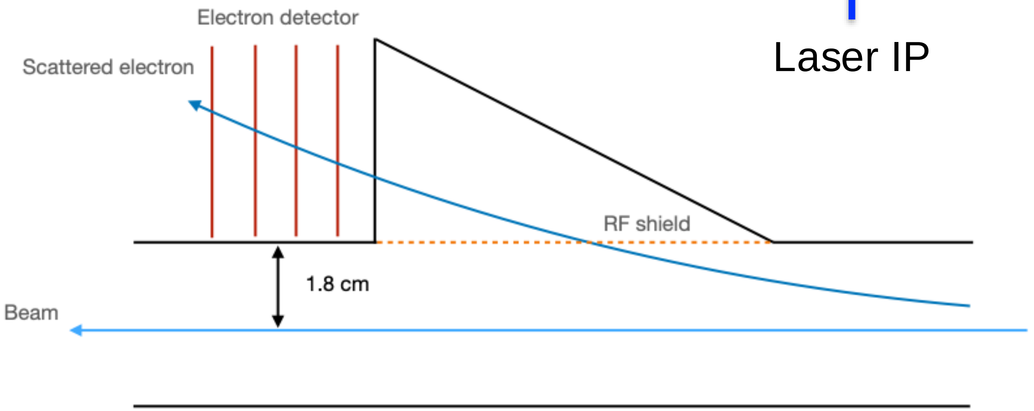
Polarimeter Components:

1. RF-pulsed laser system (under development)
2. Position sensitive detectors (diamond strips) for scattered electrons and backscattered photons
3. Calorimeter for backscattered photons

Will operate in single-photon mode

ESR Compton Beamline Design

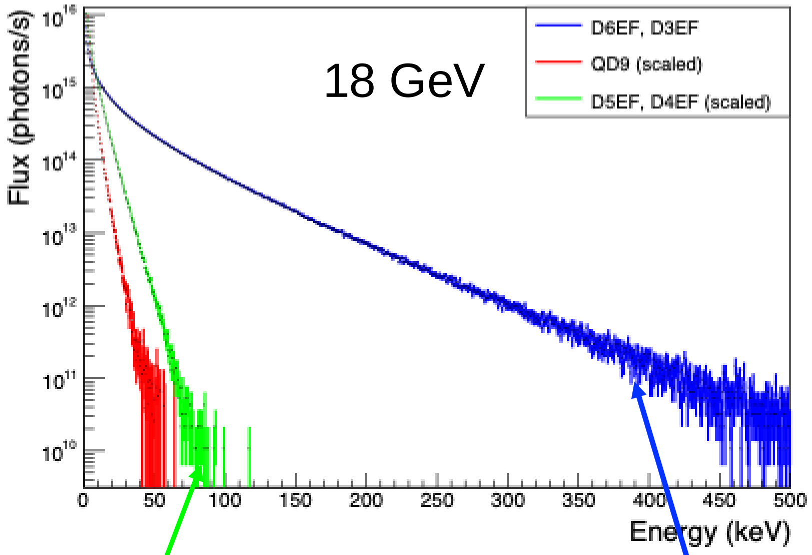


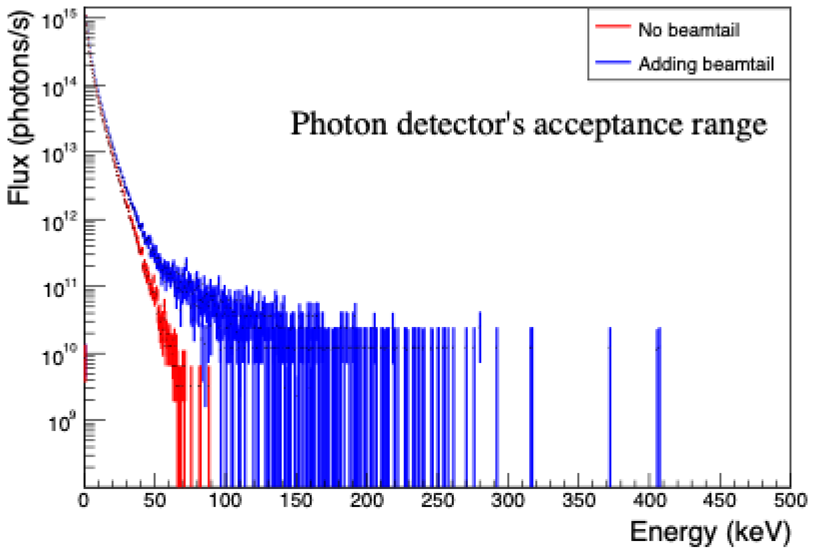


- **New beamline design with 2 weak and 2 strong dipoles mitigates synchrotron radiation**
  → only need collimator plus ~1 mm W shield

- Electron detector outside vacuum pipe → RF shield used to mitigate beam impedance issues

Synchrotron Backgrounds in ESR Compton





Simulations by Zhengqiao Zhang (Synrad+ and Geant4)

Weak dipoles

Strong dipoles

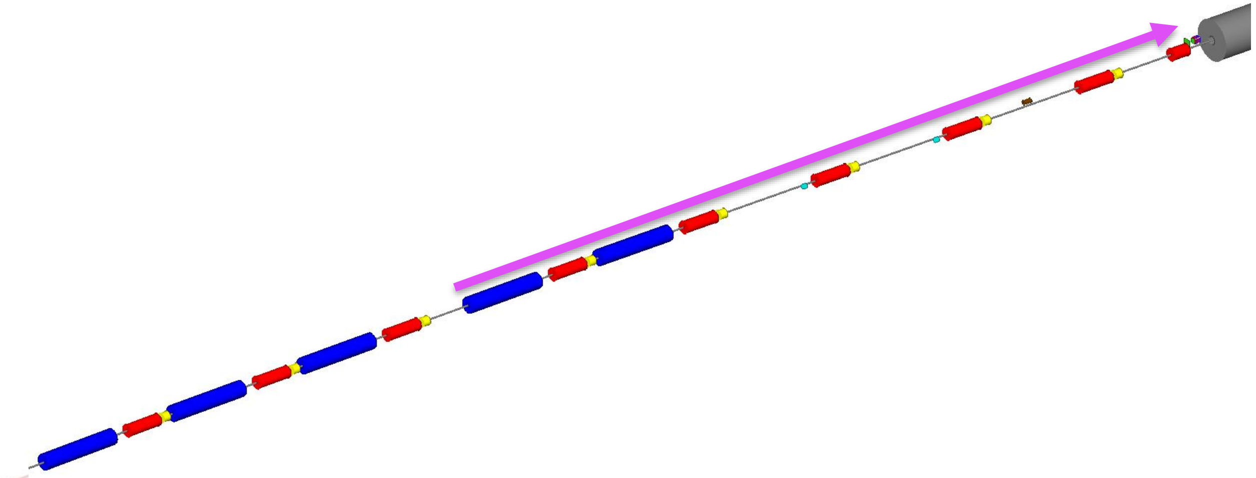
Synchrotron radiation from strong dipoles (D6EF, D3EF) too large – thick shield needed for photon detector

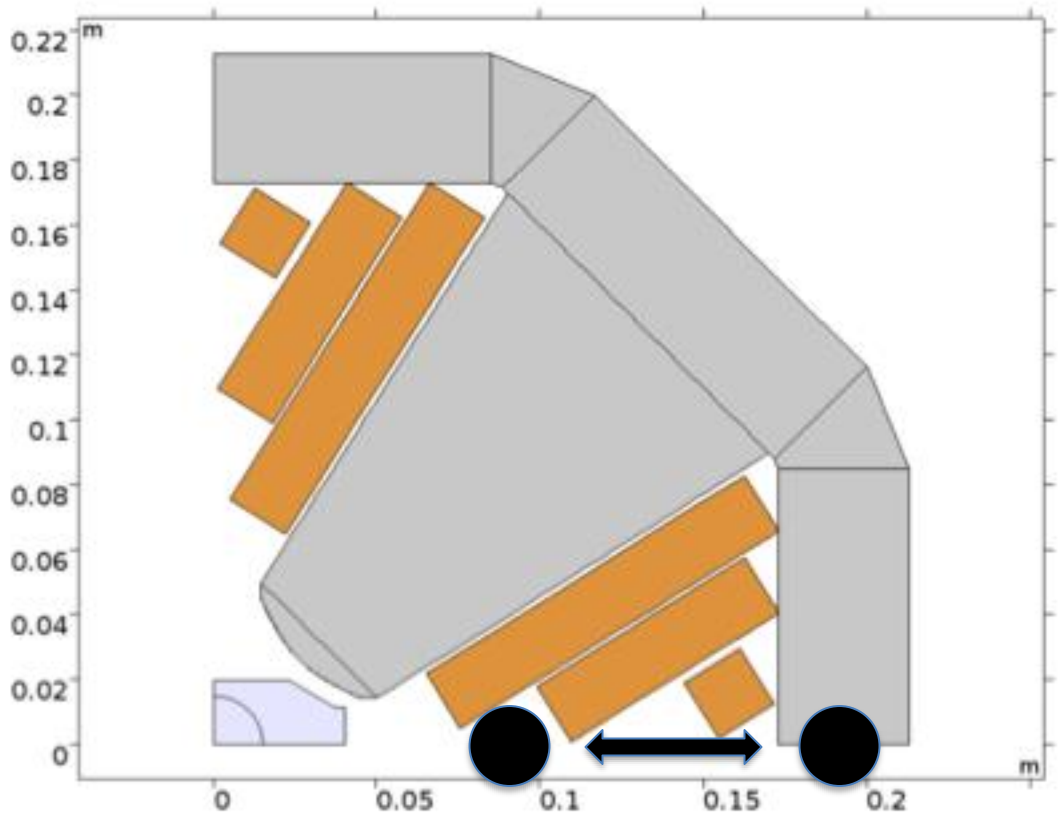
→ Weak dipoles with small bend will re-direct synchrotron flux from strong dipoles to be outside photon detector acceptance

Backscattered Photons

Backscattered photons require unimpeded transport from laser IP to photon detector
→ quadrupole aperture = 37 mm (radius)

At larger distances from laser, photon cone at larger radius than quad aperture
→ this can be accommodated by careful coil design, hole in return steel

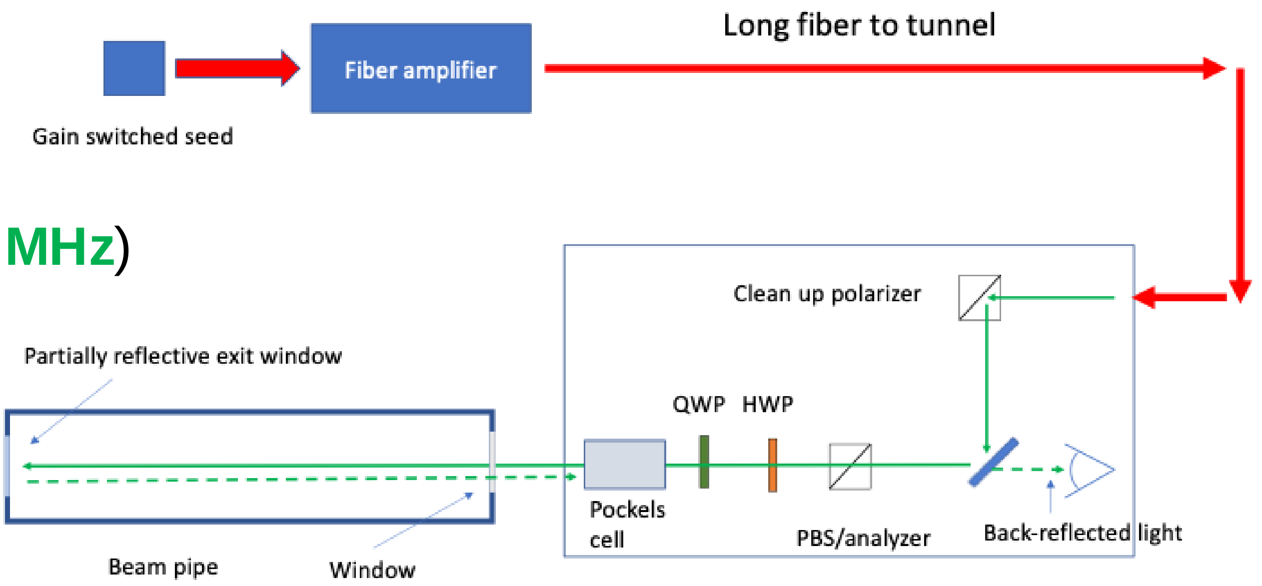




Arc quadrupole

ESR Compton: Laser System

- Laser system based on similar system used in JLab injector and LERF
- Gain-switched diode seed laser
  10 ps pulses @ 1064 nm
  - Variable frequency allows optimal use at different bunch frequencies (**100 MHz vs 25 MHz**)
- Fiber amplifier → average power 10-20 W
- Optional: Frequency doubling system (LBO or PPLN)

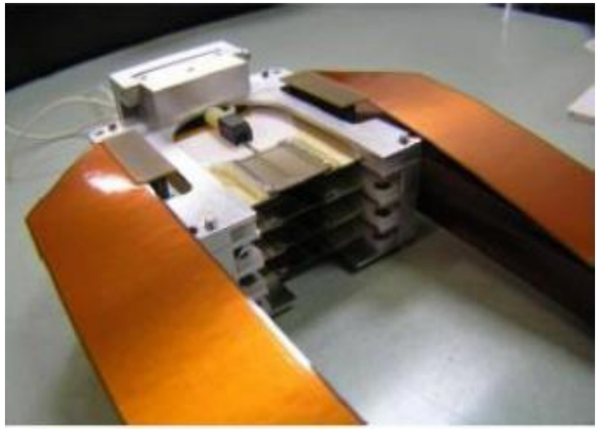


- Partially reflective exit window to monitor reflected laser polarization

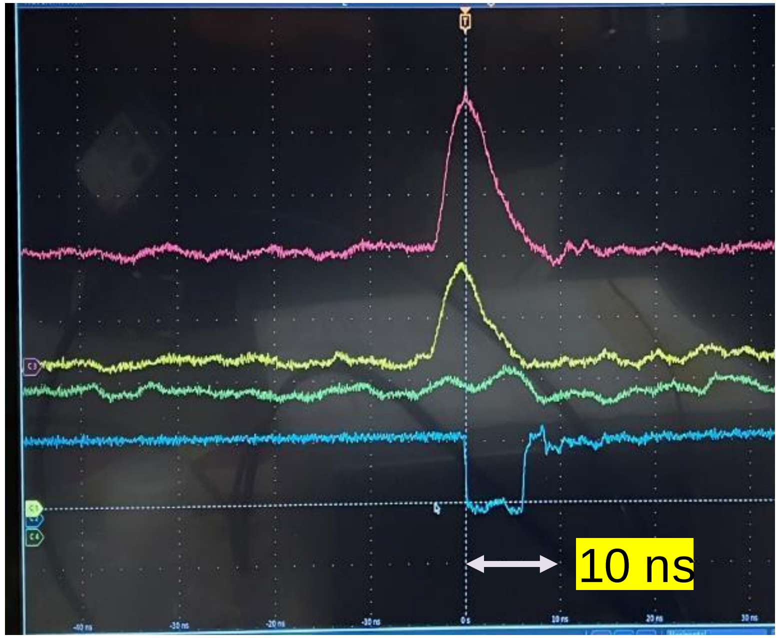
Development underway at Jefferson Lab

ESR Compton: Position Sensitive Detectors

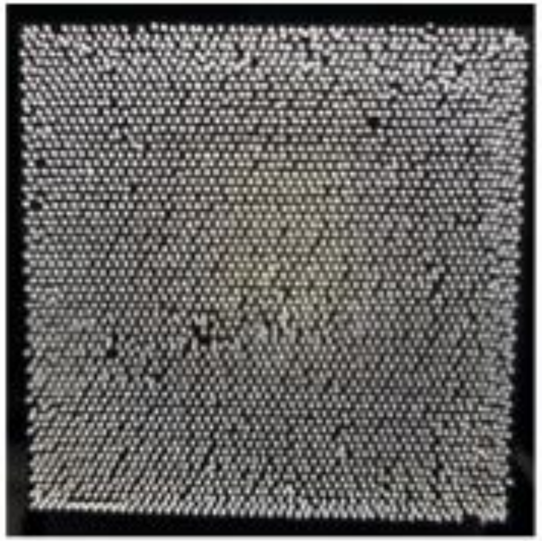
- Position sensitive detectors needed to measure:
  - Scattered electrons → P_L
  - Backscattered photons → P_T
- Technology choice – diamond strips → radiation hard, good time response
- Diamond used during Q-Weak expt at JLab → no performance degradation after 10 MRad of exposure
- Required detector segmentation = 500 μm (electrons)/100-200 μm (photons)
- Detector size = 6 cm (electrons), 5 cm (photons)
- Custom ASIC required → new "FLAT32" chip based on "CALYPSO" (used at LHC) developed for Jlab/MOLLER
  - Already meets timing requirements of EIC (10 ns)



JLab Hall C diamond detector



ESR Compton Photon Calorimeter



- **Will use a Forward EMCAL module from EPIC detector for photon calorimeter**
  - Block of $5\ x\ 5\ x\ 17\ \mathrm{cm}^3$ W/SciFi, subdivided into 4 towers
  - 2 cm light guide from block to PMT
  - Expected resolution:

$$\frac{\sigma_E}{E} \approx \frac{10\%}{\sqrt{E}} \bigoplus 1-3\%$$

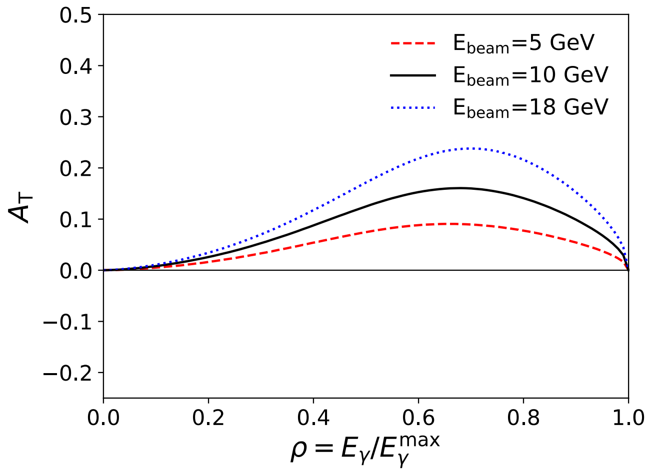
- Only modest resolution required since calorimeter will be used in threshold-less integrating mode for longitudinal polarization measurements

RCS Compton Polarimeter

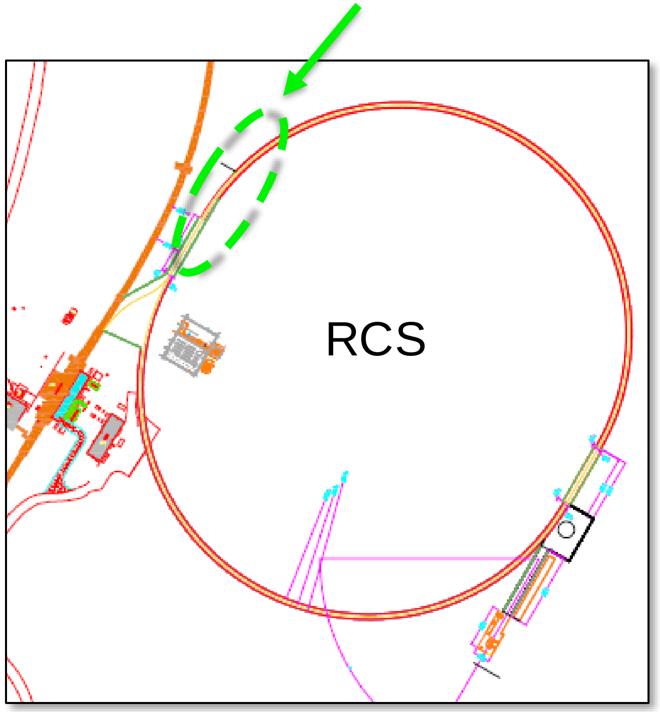
RCS relocated outside ESR/HSR tunnel → new location for polarimeter needs to be found
→ Possibly near straight section, with laser just before last dipole in arc?

Polarimeter laser and detector requirements driven by beam structure
→ Bunch frequency ~ 1 Hz
→ Bunch charge: 7 nC
→ RCS ramps from 0.75 GeV to full injection energy (5, 10, 18) GeV

Bunch will have different energy each time it passes Compton
→ Energy dependence of analyzing power makes bunch-by-bunch measurement impossible
→ Average over several bunches



Possible Compton location?



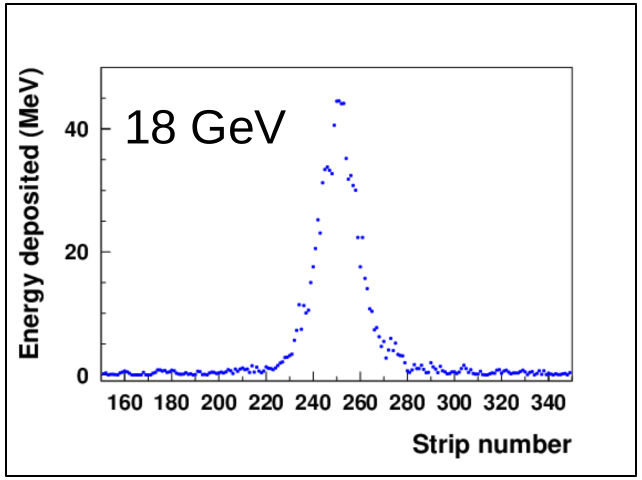
Requires measurement in ***multiphoton*** mode – several thousand collisions per crossing

RCS Compton Detector Simulations

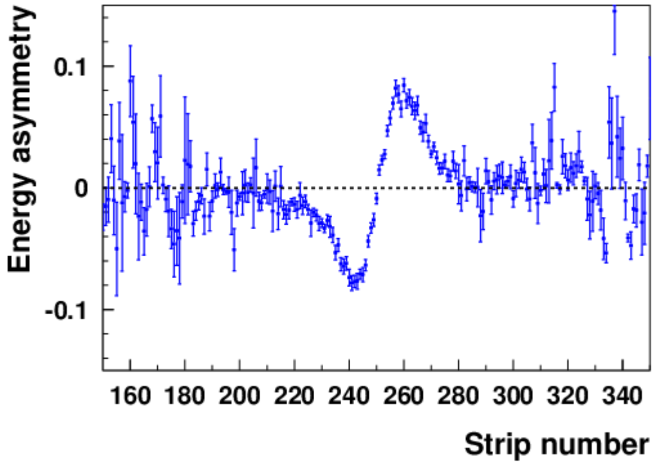
Multi-photon mode Compton polarimeter

→ Polarization will be extracted by measuring the energy-asymmetry vs. position

→ Total energy deposited in the detector for each laser helicity state

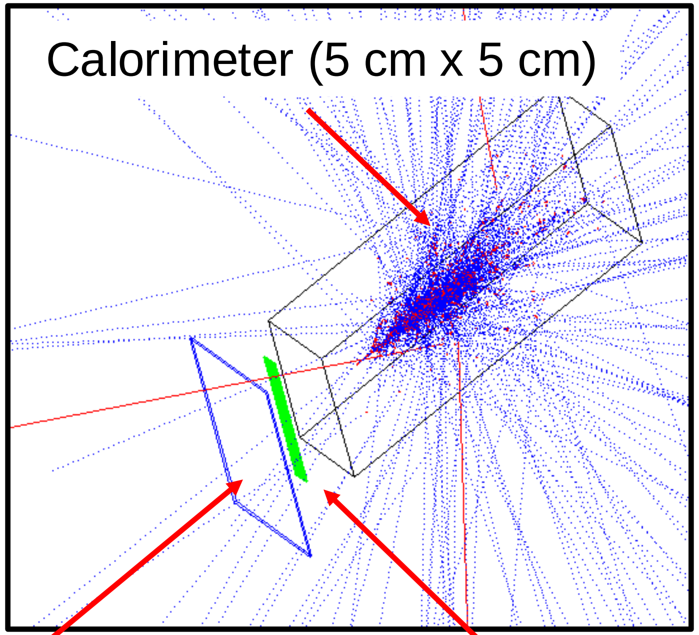


Energy deposited in each strip of diamond detector



Energy asymmetry

$$A_{strip} = \frac{E^{+}_{strip} - E^{-}_{strip}}{E^{+}_{strip} + E^{-}_{strip}}$$



Tungsten converter

Diamond strips (0.1 mm pitch)

Simulated 10 laser pulses → 10,000 backscattered photons per pules

Summary

- EIC requirements proposes several challenges for the needed polarized electron beam
  - High intensity and polarization
- Electron beam components:
  - Polarized electron gun, linac+BAR+RCS, electron storage ring
- Integration of beam polarimeter(s) requires careful planning
- ESR Compton has challenging requirements
  - Bunch-by-bunch operation with small bunch spacing
  - First polarimeter to measure PL and PT with high precision simultaneously
- Location for polarimeter in “new” RCS to-be-determined
  - Detector and laser requirements unchanged