EIC Polarimetry

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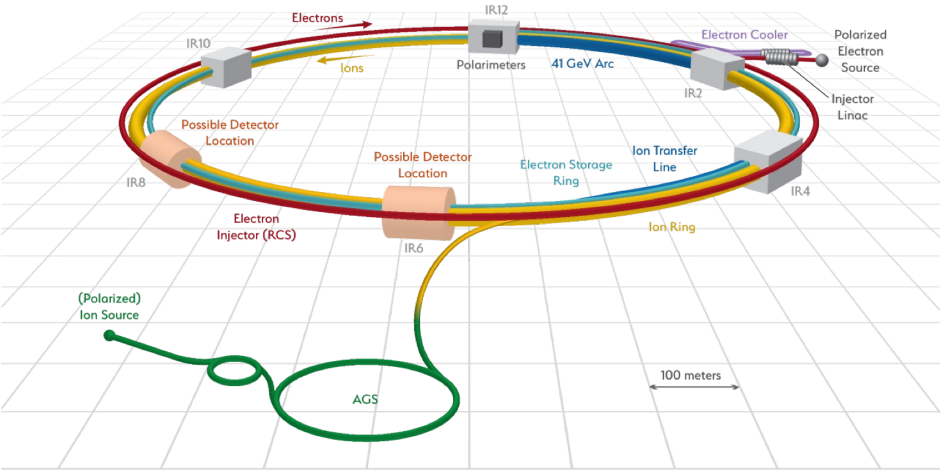
- Polarimetry at EIC
- Electron Polarimetry
  - ESR Compton
  - Mott Polarimeters
  - RCS Compton
- Hadron Polarimetry
  - p-Carbon Polarimeter
  - H-Jet Polarimeter



CFNS Workshop: High Luminosity-EIC (EIC-Phase II)

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Jefferson Lab

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EIC Beam Properties and Polarimetry Challenges

EIC will provide unique challenges for both electron and hadron polarimetry

Common challenge to both: small spacing between bunches

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

→ Intense beams (0.26 to 2.5 A)

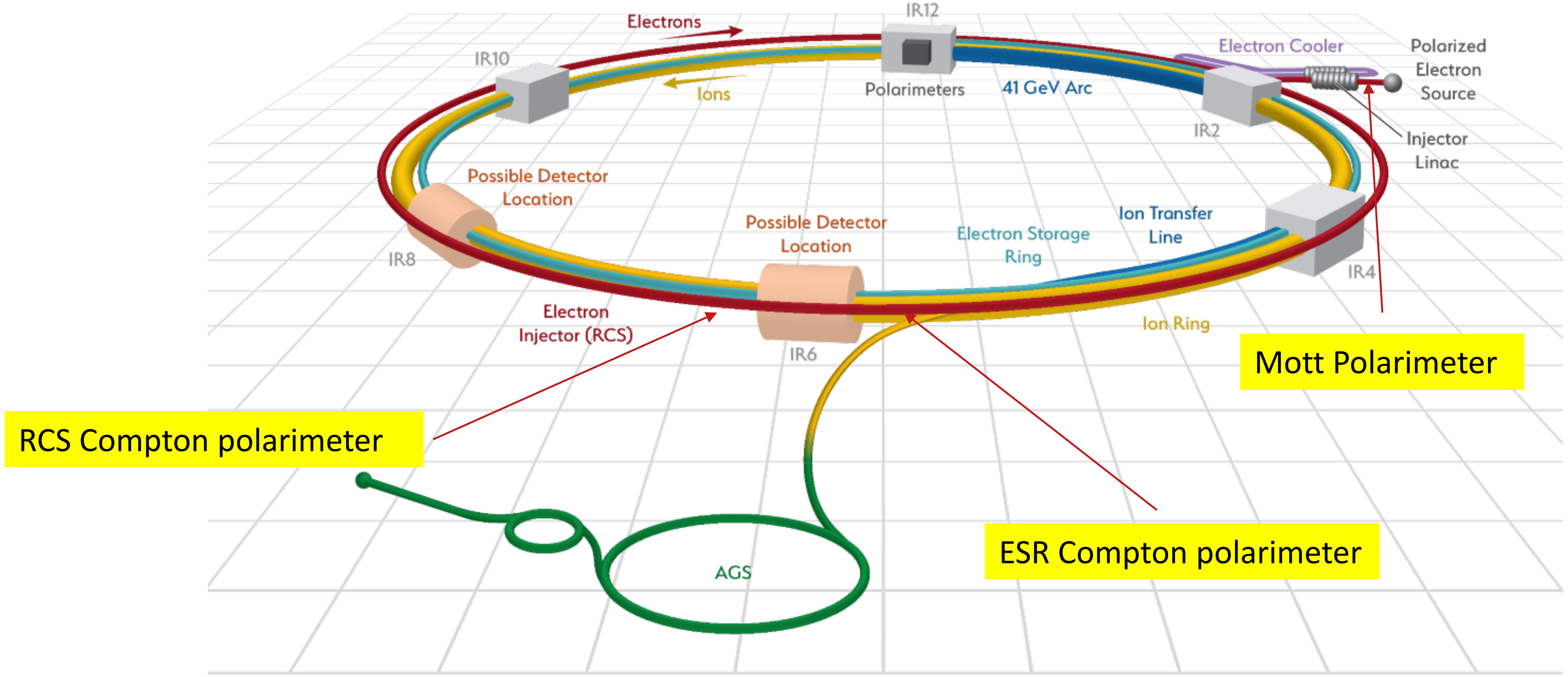
- → Large synchrotron radiation for electron beams result in large effects at detectors
- → Hadron beam intensity results in challenges for polarimeter targets

Polarimetry systematics:
Goal is ***dP/P = 1%*** or better for both electrons and hadrons

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	

EIC Electron Polarimeter Map



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

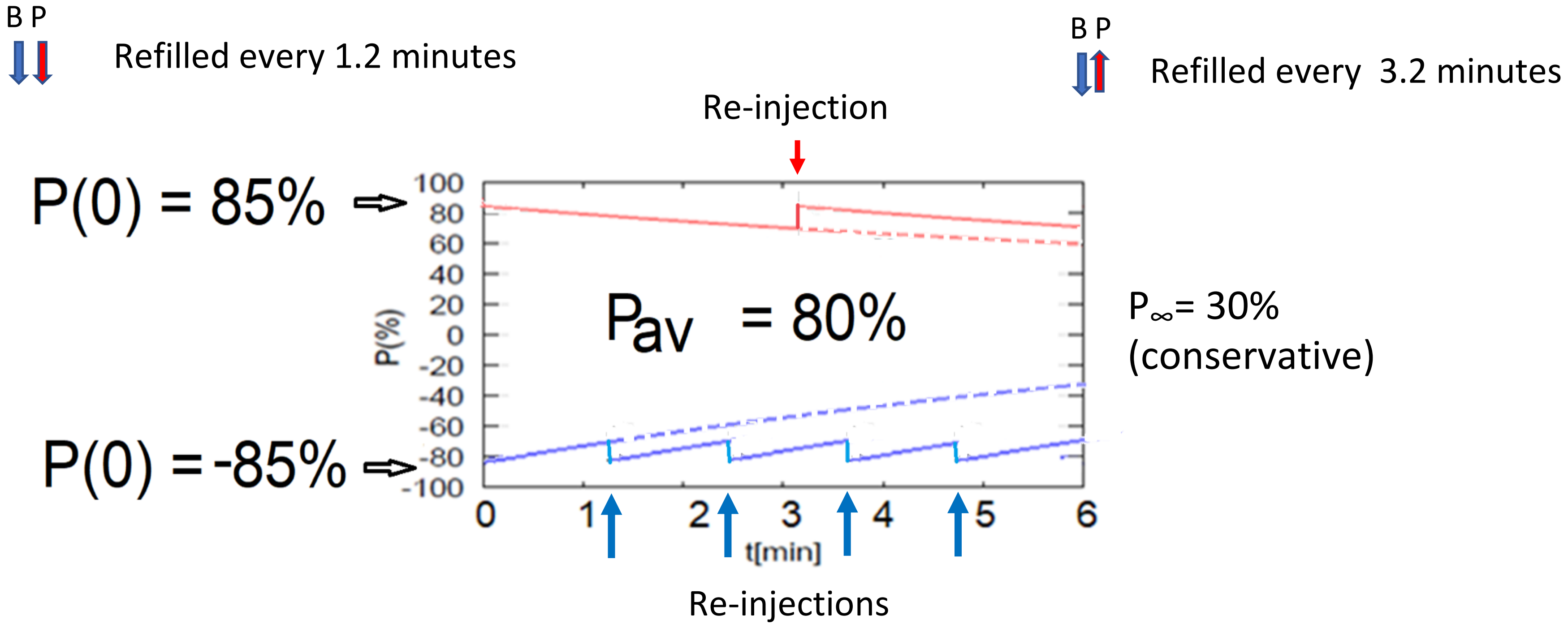


Figure from C. Montag (BNL)

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

ESR Compton Polarimeter

Planned Compton polarimeter location 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

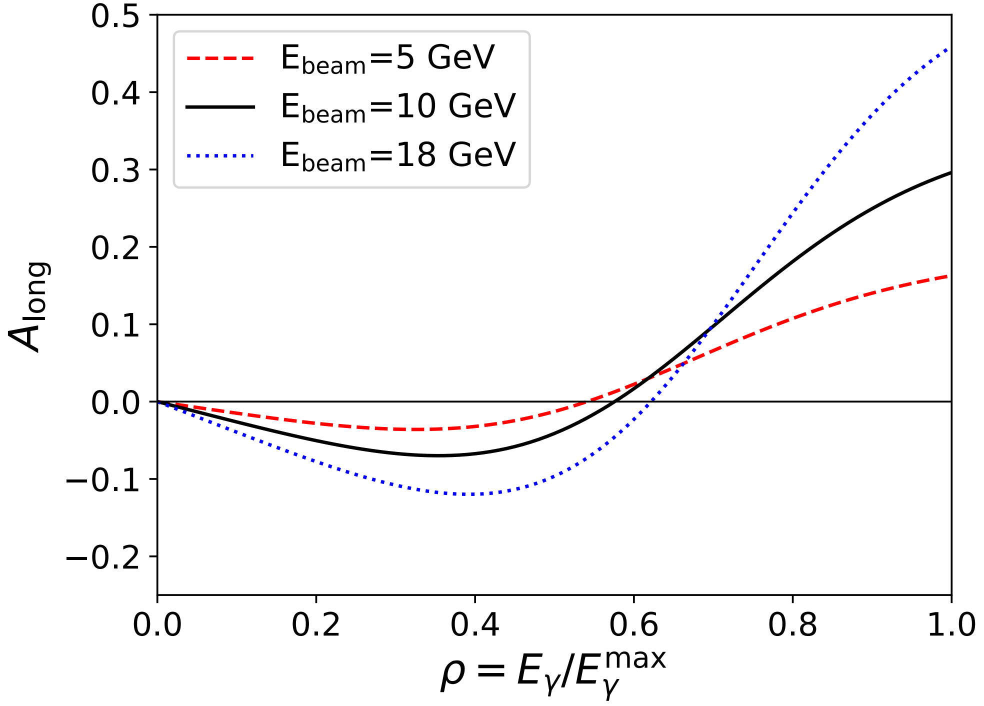
EIC Compton will provide first high precision measurement of P_L and P_T at the same time

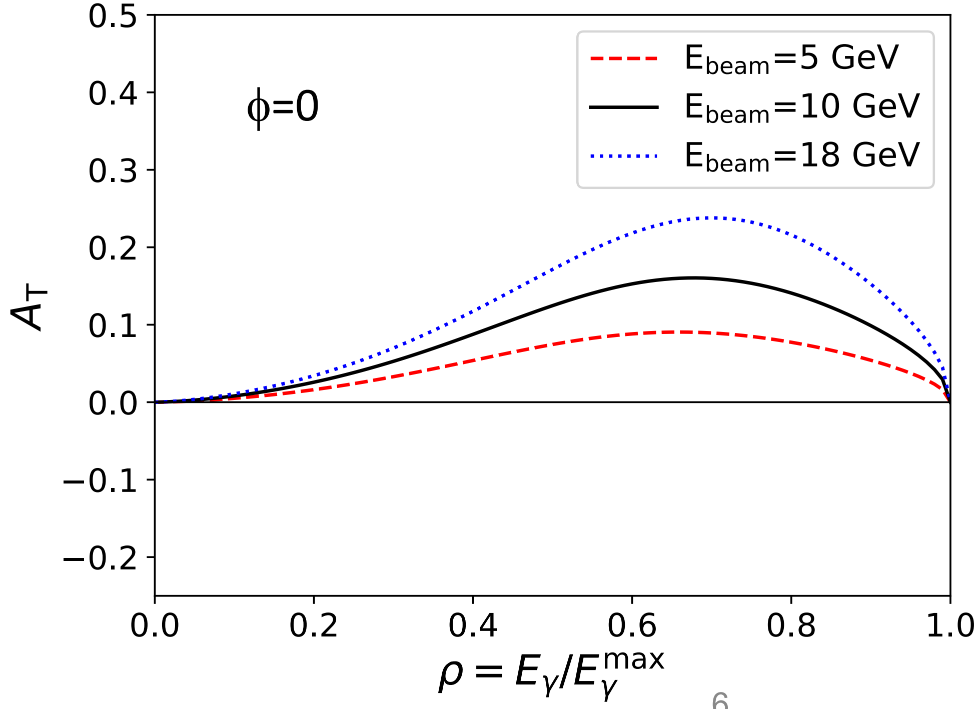
Polarization Measurement via Compton Polarimetry

Compton longitudinal and transverse analyzing powers

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

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





Compton Placement

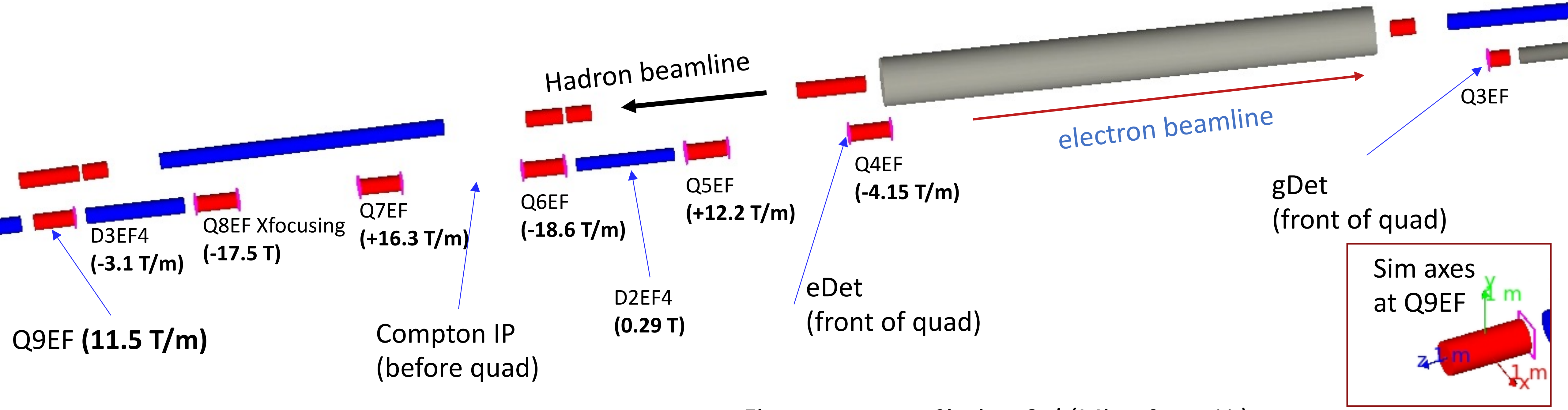
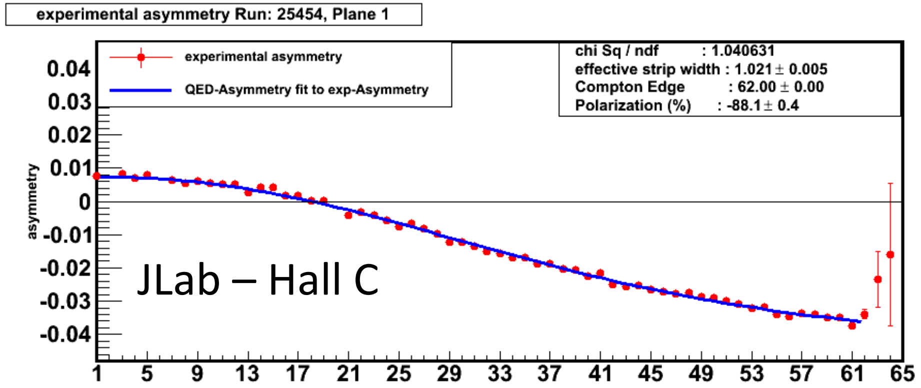


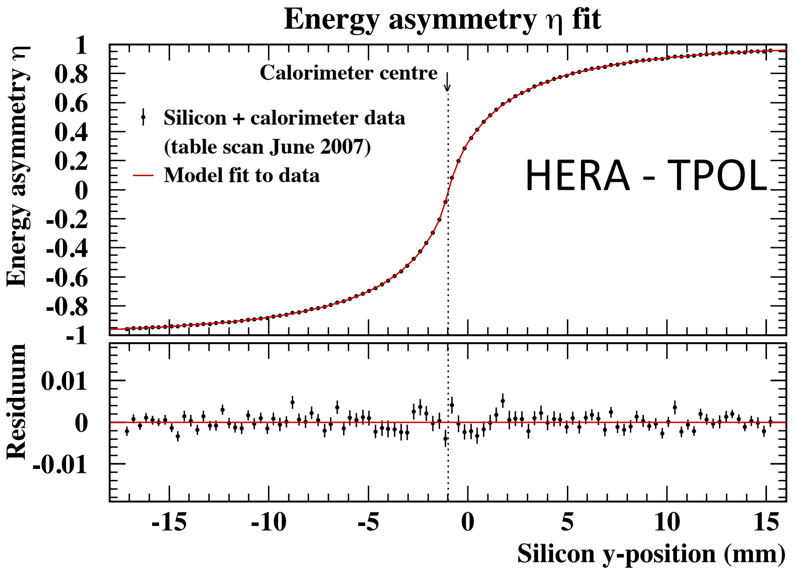
Figure courtesy Ciprian Gal (Miss. State U.)

→ Laser IP in field-free area – space to insert laser in beamline
→ Photon detector 29 m from laser/beam IP
→ Quad after dipole (Q5EF) horizontally defocusing – facilitates use of electron detector
→ Synchrotron from D3EF4 may impact electron detector

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)





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

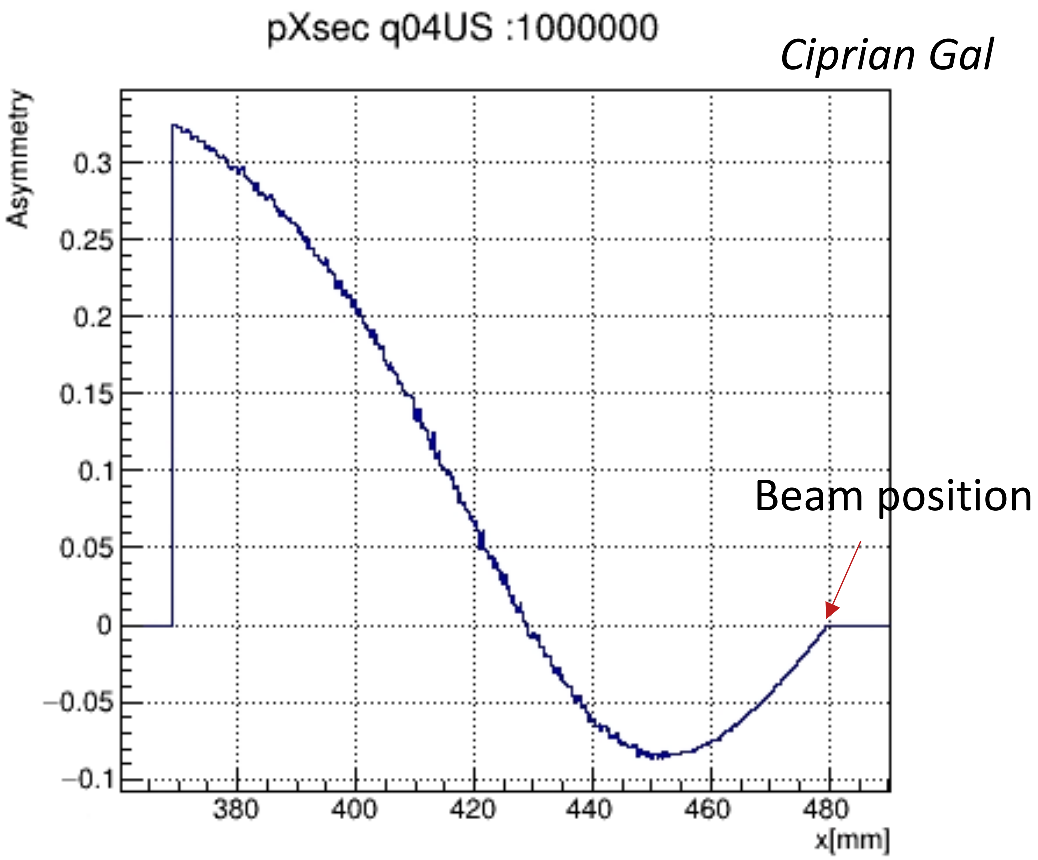
Laser power constraint: sufficient power to result in ~ 1 backscattered photon/bunch-laser crossing
→ Want to make “single photon” measurements – not integrating

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

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 EDET

At Compton location – significant transverse beam polarization
→ Unfortunately, this transverse polarization is in the horizontal direction
→ Same coordinate as momentum-analyzing dipole

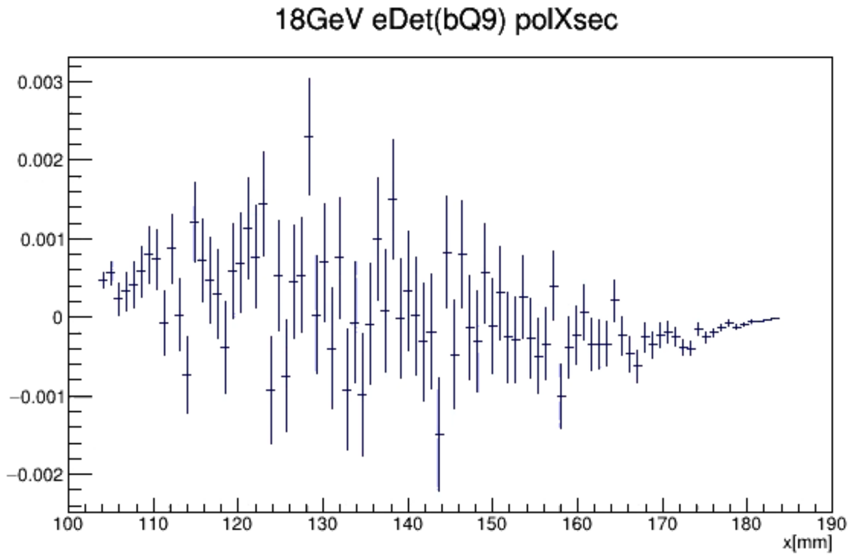
Beam energy	P_L	P_T
5 GeV	96.5%	26.1%
10 GeV	86.4%	50.4%
18 GeV	58.1%	81.4%

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 $\boldsymbol{P_L}$

100% transversely polarized beam



Ciprian Gal

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%
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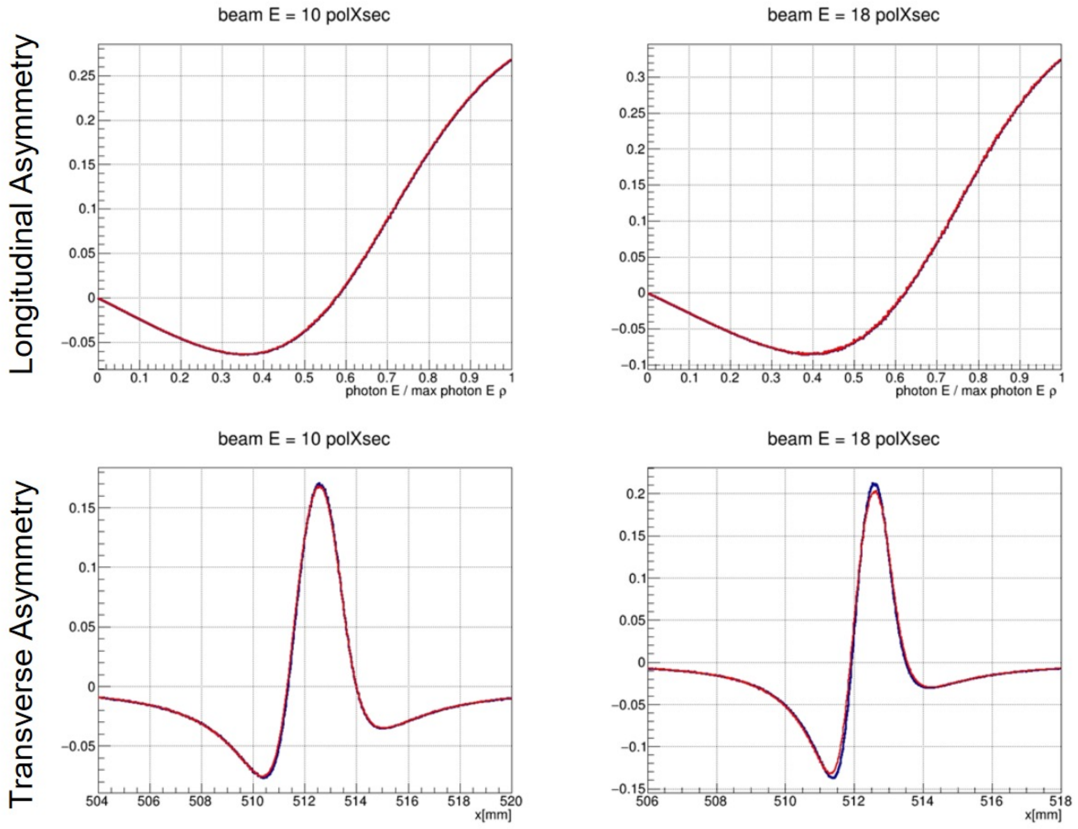


Ciprian Gal

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

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:

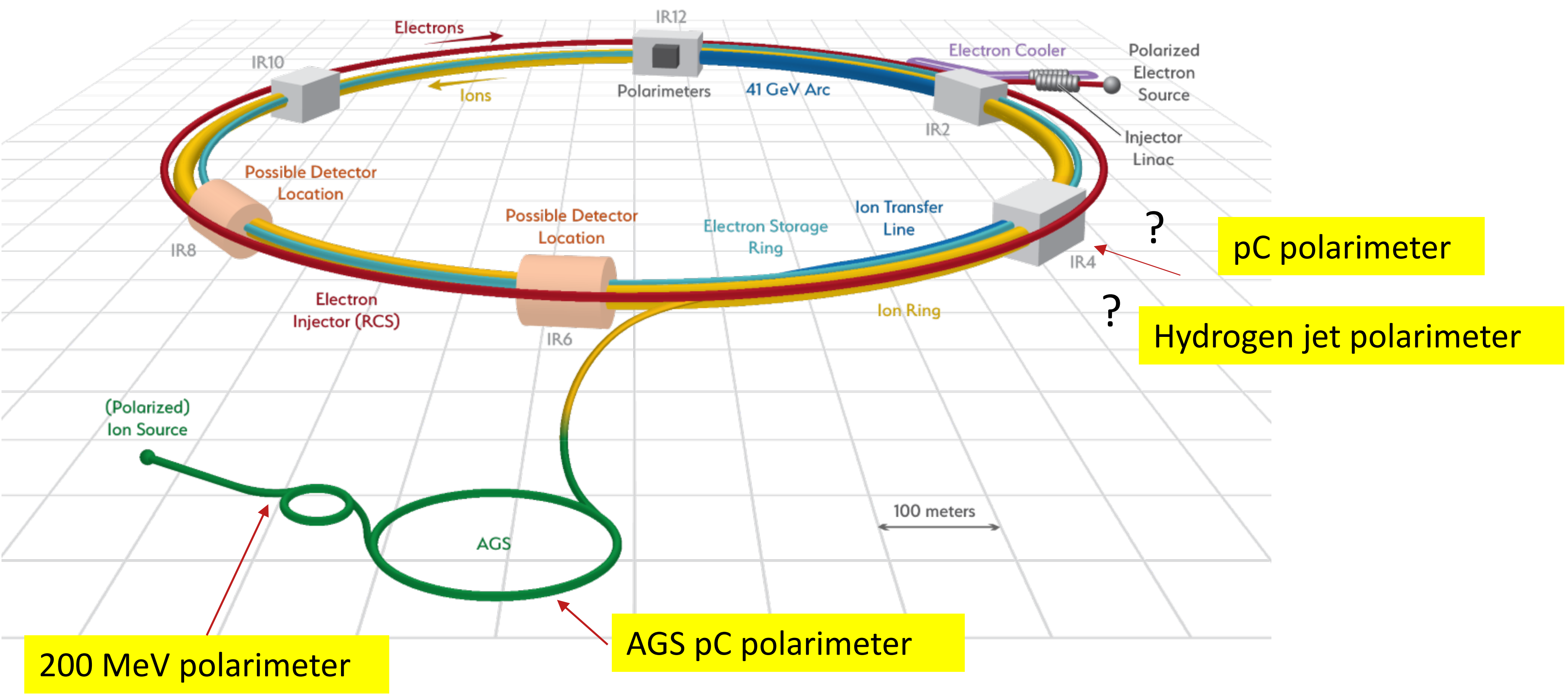
TPOL @ HERA: dP/P=1.87% → Photon detector in counting mode

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

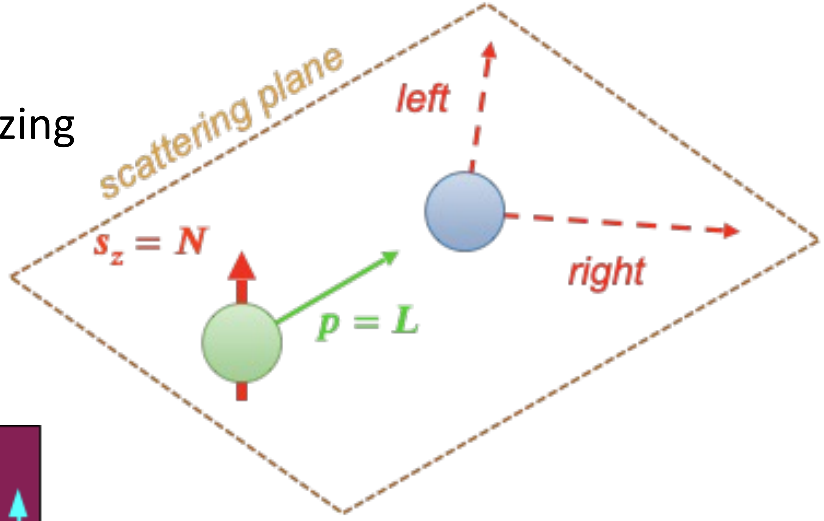
Hadron Polarimeter Map



Measurement of Absolute Polarization

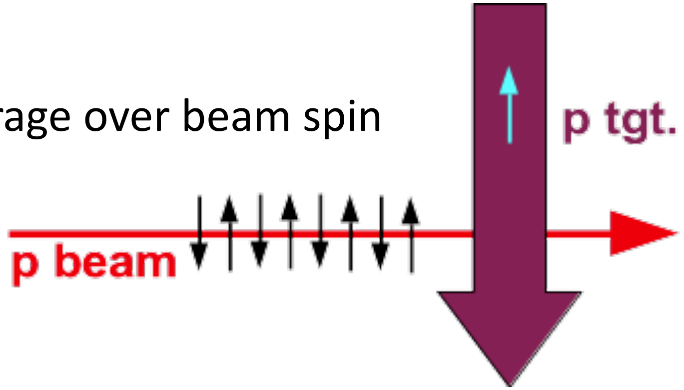
Electron polarimetry benefits from known QED processes (Compton, Møller scattering)
→ No equivalent processes for hadrons to measure absolute polarization → analyzing power a priori unknown

Use of polarized target with polarized beam bypasses need to determine analyzing power from first principles



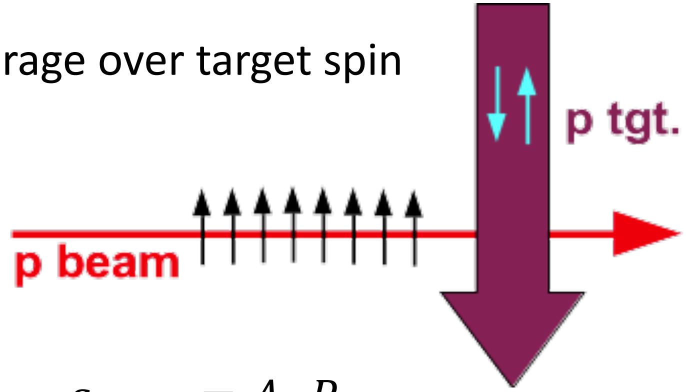
$$\epsilon = \frac{N_R - N_L}{N_R + N_L} = A_N P$$

Average over beam spin



$$\varepsilon_{target} = A_N P_{target}$$

Average over target spin



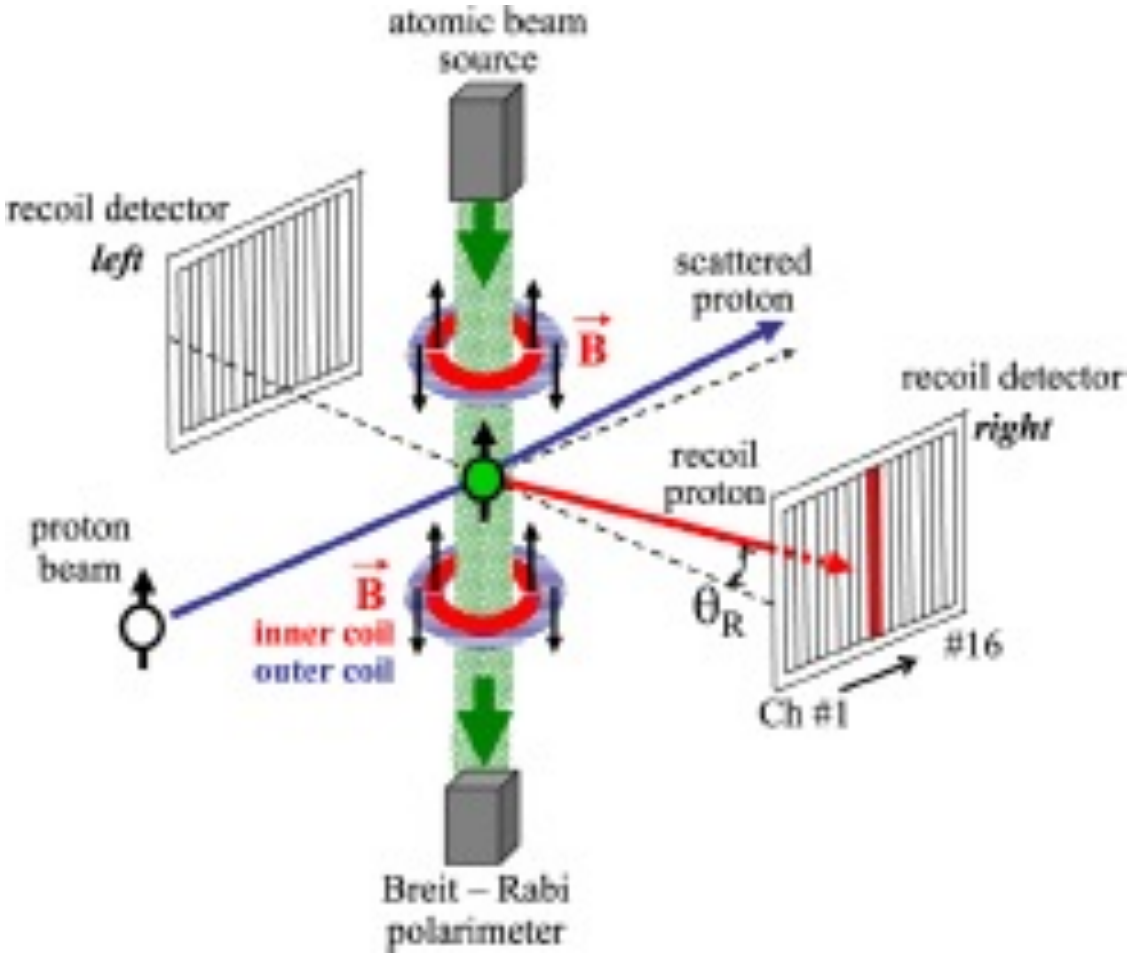
$$\varepsilon_{beam} = A_N P_{beam}$$

$$\Rightarrow \quad P_{beam} = \frac{\varepsilon_{beam}}{\varepsilon_{target}} P_{target}$$

Hydrogen-Jet Polarimeter

H-Jet Polarimeter (presently) installed at IP12

→ Uses elastic p-p scattering in the Coulomb-nuclear interference (CNI) region
→ Polarized atomic H source, $1.2 \cdot 10^{12}$ atoms/cm2
→ Target polarization measured w/ Breit-Rabi polarimeter, $P_{target} \approx 96\%$
→ Silicon strip detectors, 12 strips 3.75 mm pitch
→ H-Jet has achieved high precision at RHIC: $(dP/P)_{syst}=0.6\%$
→ Measurements time consuming: $(dP/P)_{stat} \sim 2\%$ for 8 hour period



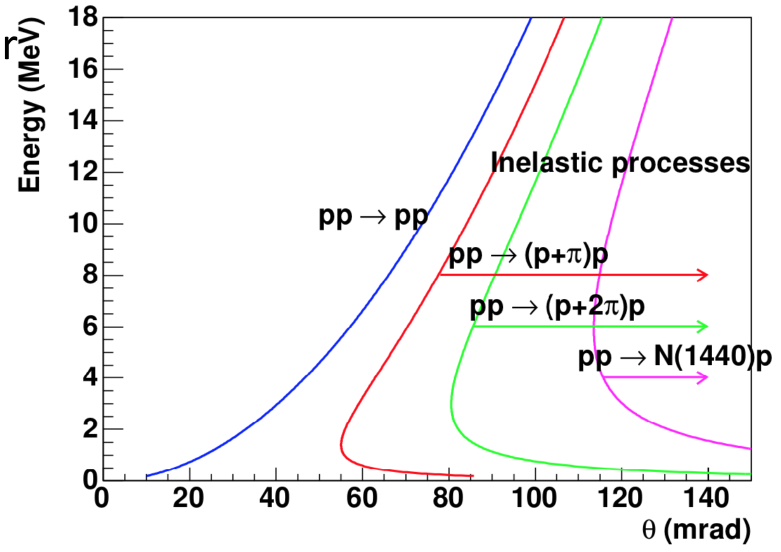
Hydrogen-Jet Polarimeter

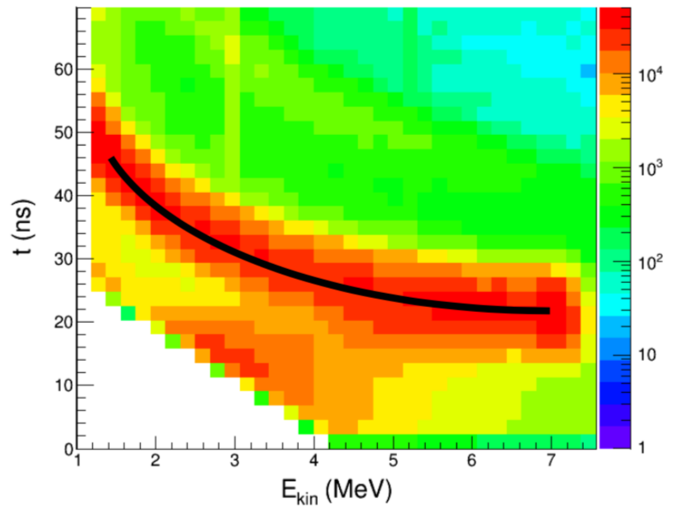
Elastic events identified via TOF-Kinetic energy correlation
→ "Banana" plot
Silicon strip detectors read out with wave-form digitizers that simultaneously provide energy and TOF information

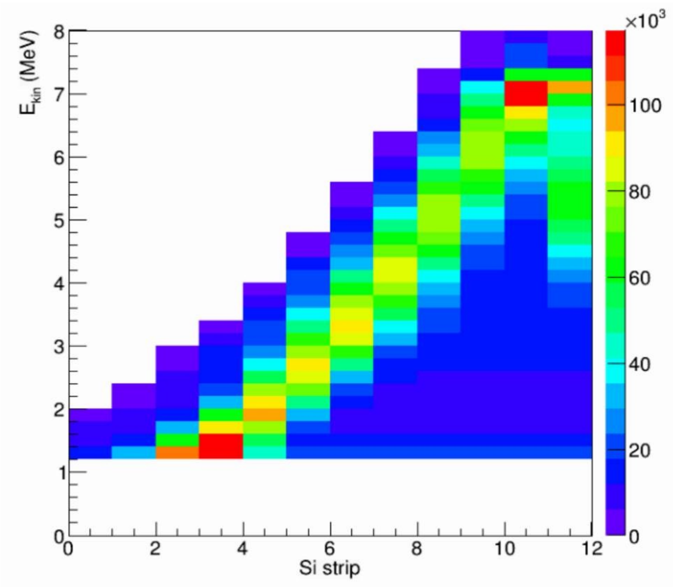
Asymmetry extracted from "cross-ratio" → reduces sensitivity to left-right acceptance differences

$$\epsilon = \frac{\sqrt{N_{R+}N_{L-}} - \sqrt{N_{L+}N_{R-}}}{\sqrt{N_{R+}N_{L-}} + \sqrt{N_{L+}N_{R-}}}$$

E-θ correlation different for elastic and inelastic processes



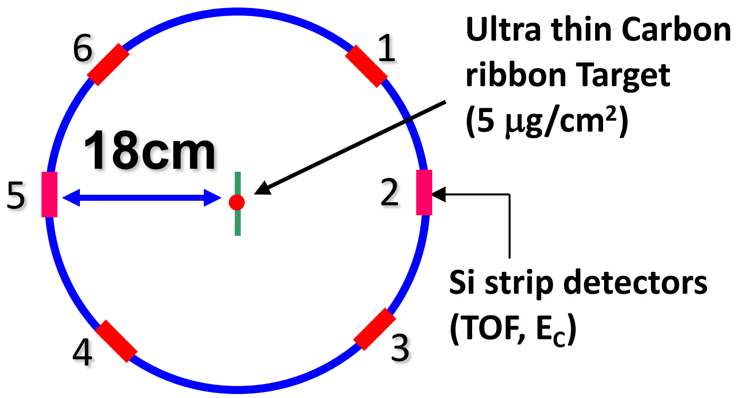




Strip number → θ

p-Carbon Polarimeter

p-Carbon polarimeter also uses elastic scattering in CNI region
→ Located about 70 m from IP12
→ Uses thin carbon ribbon
→ Very low energy, recoiling carbon detected in silicon strip detectors
→ Polarization extracted via L-R asymmetry
→ Analyzing power requires cross-calibration with H-jet polarimeter
2 p-Carbon polarimeters → vertical and horizontal target to characterize beam profile



Nominal target size:
2.5 cm · 10 μ · 50 nm

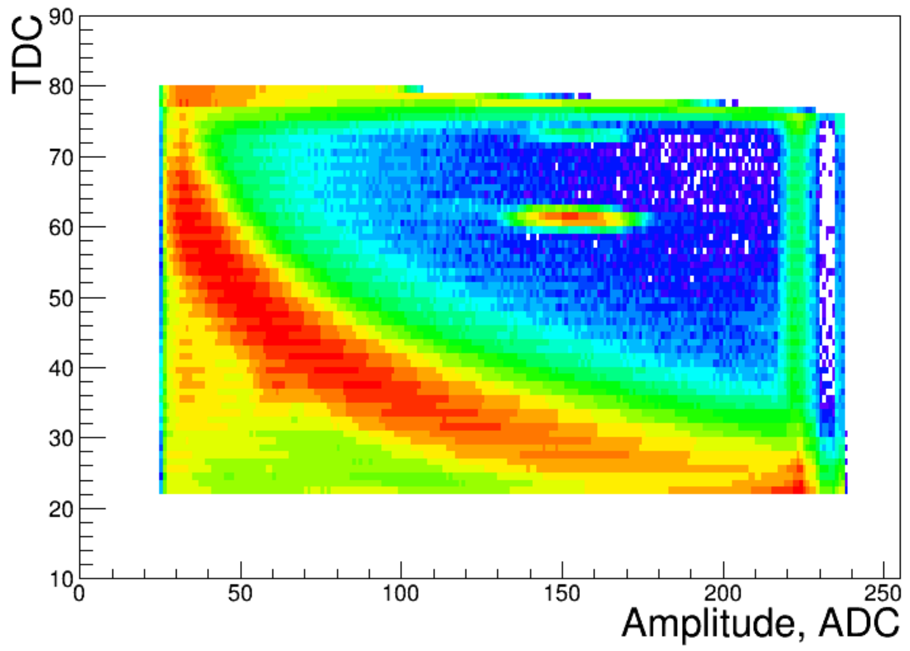
Passed across beam & back
~2-5 sec. in beam each pass
lifetime: few - few hundred passes

Hadron Polarimetry Challenges at EIC

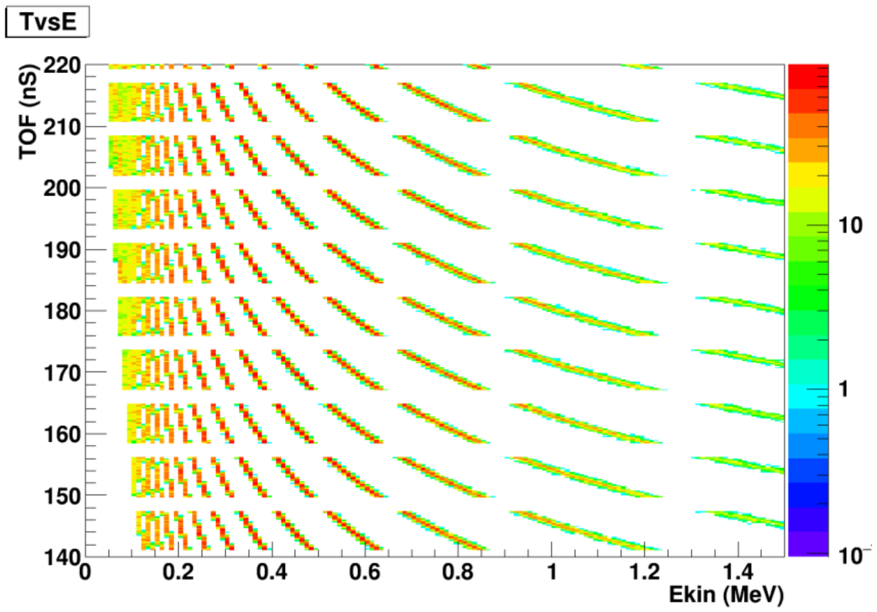
- EIC Hadron Polarimetry will make use of existing H-Jet and p-Carbon systems moved to new location → not enough room at IP12
- EIC will have shorter bunch spacing than RHIC → challenges for identifying good events
- EIC will have higher beam current → p-Carbon target will likely not survive in beam
- Light-ion polarimetry
  - RHIC polarimeters designed for protons
  - Similar processes can be used for light-ions (^3He), but there may be additional backgrounds from breakup
  - Deuteron beams not part of baseline, but are also of interest → analyzing power for deuteron predicted to be much smaller than for p and ^3He

Bunch Spacing

RHIC – pC data (107 ns bunch spacing)



EIC – (~10 ns bunch spacing)

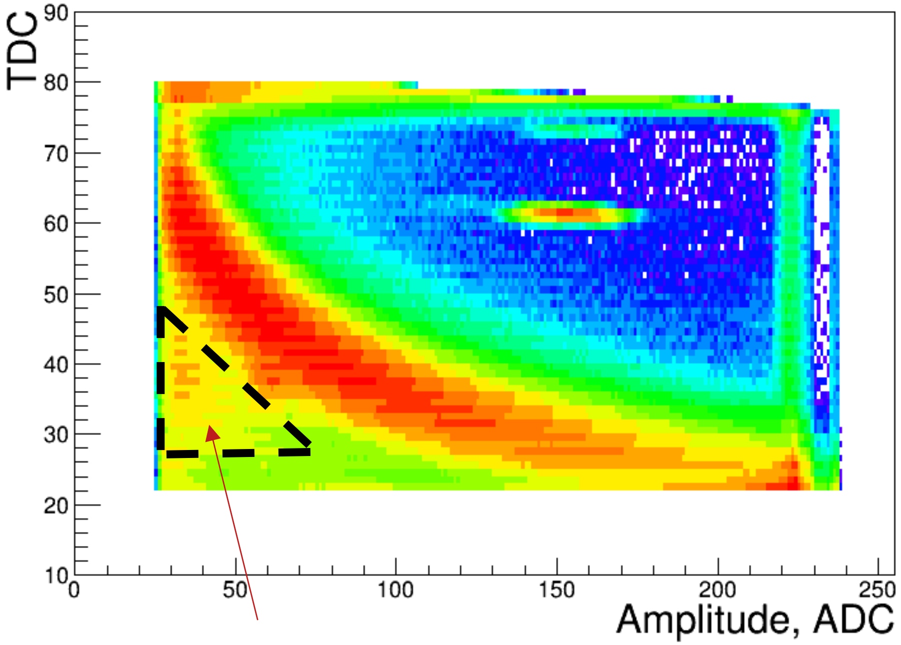


Smaller bunch spacing makes selection of good events via TOF-E correlation impossible

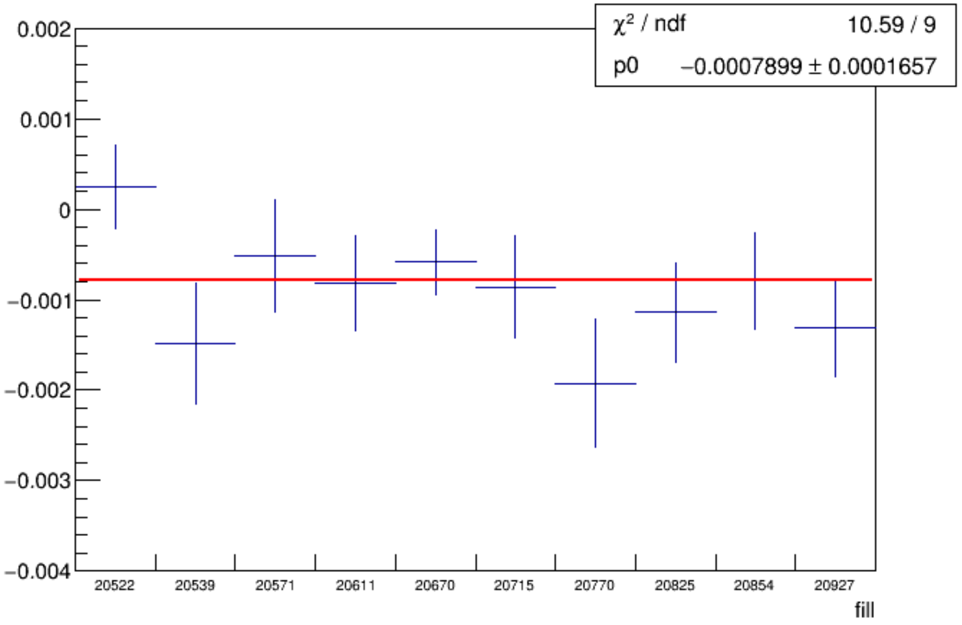
→ Several bunches will overlap

→ Impossible to cleanly identify elastic signal, remove background

Backgrounds



background



Background asymmetry

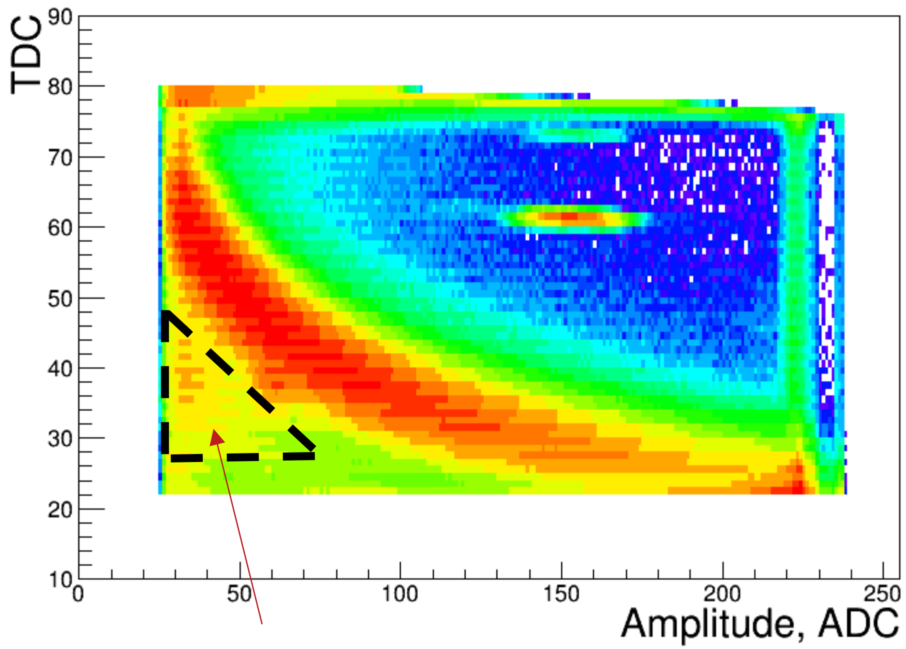
Bunch-spacing issues prevent clean removal of backgrounds

→ Fast particles – pions, photons up to a few GeV

→ Background more than just a dilution – appears to carry non-zero asymmetry

H-Jet will have similar issues

Multi-layer Detector Tests



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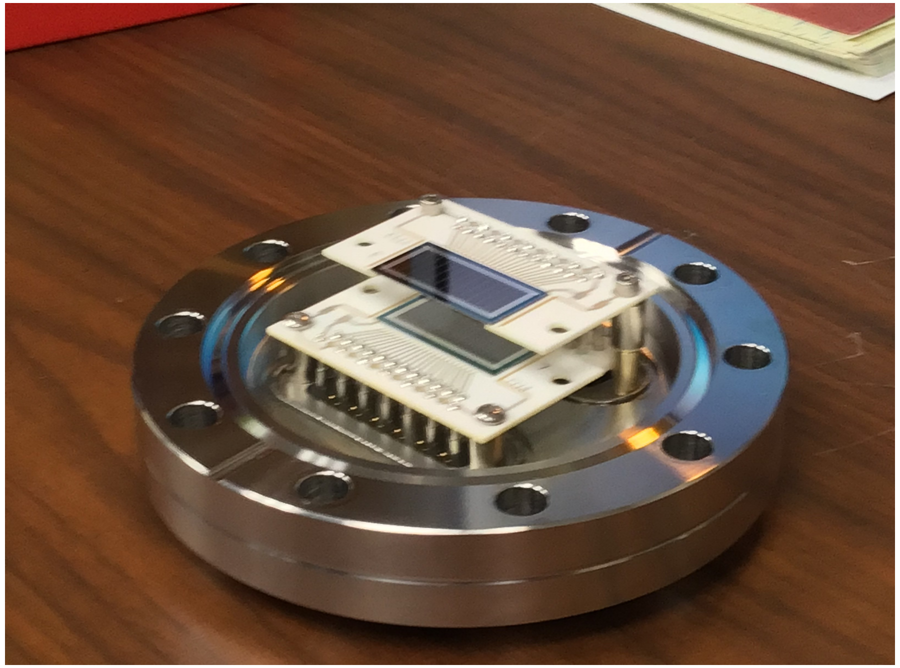


Si detectors

→ 12 x 2mm strips

→ 1 cm long

→ 200-250 μm thick

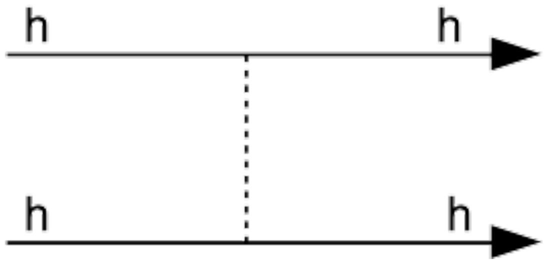
→ Since particles in background are expected to be fast perhaps they could punch through silicon detector, can they be vetoed using and extra layer?

→ Tests with 2 layer detectors – able to select beam induced prompts. Detectors too thick for "below-banana" backgrounds – thinner detectors?

^{3}He Breakup

Absolute polarimetry with polarized jet target requires elastic scattering

→ Helion can breakup into d+p or n+p+p

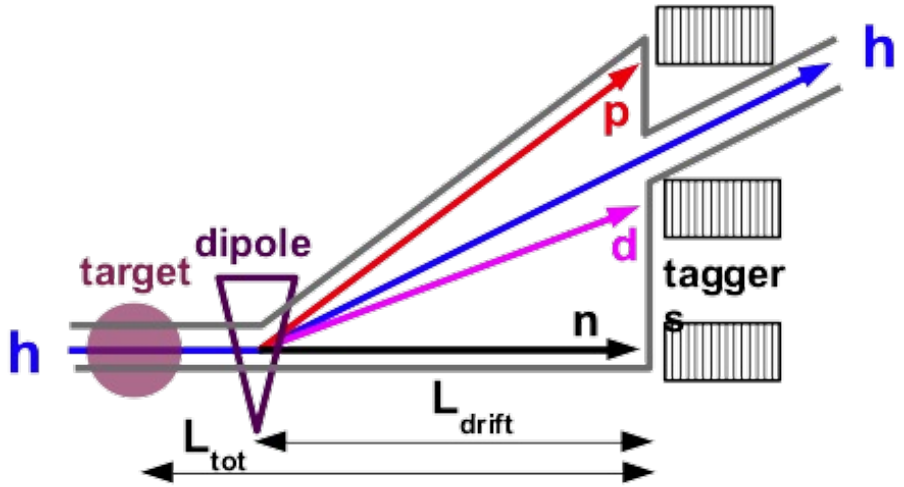


h = helion, ^{3}He
d = deuteron
p = proton
n = neutron

Mass difference between h and (d+p) only 5 MeV → too small to resolve with target recoil detectors
→ For elastic pp, nearest inelastic channel is single pion production, 140 MeV

Need to tag helion breakup fragments and reject from polarimetry analysis

Near threshold, breakup fragments travel colinearly with beam
→ Tagging requires dipole to separate n/p/d
→ Detectors placed at appropriate separation for each



Initial tests performed in 2022 – saw correlated signals in test detectors
Future:
→ Improve tagging
→ Test light ion breakup in future runs

Summary

- Nominal EIC goal is to measure both electron and hadron beam polarization to 1%
- Compton polarimeter for electrons
  - Must measure both P_L and P_T simultaneously since Compton not at IP
  - High current, short bunch separation pose challenges
  - <1% polarimetry may be possible, but P_T measurement may be biggest challenge
- Hadron polarimetry will use combination of:
  - H-Jet (absolute)
    - Has achieved dP/P=0.6%
  - p-Carbon (relative)
    - Can measure polarization profile (transverse and longitudinal)
  - Both polarimeters must overcome issues with background rejection
    - Must find new target for p-Carbon polarimeter

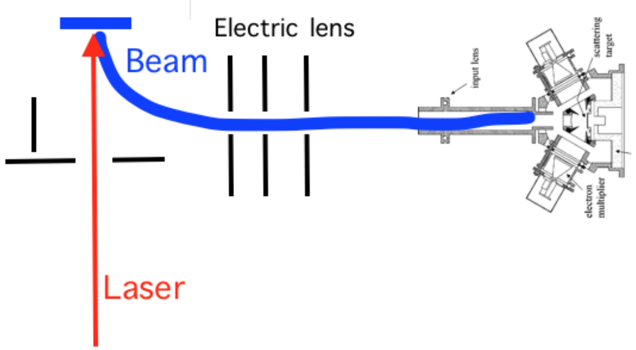
EXTRA

Mott Polarimetry at EIC

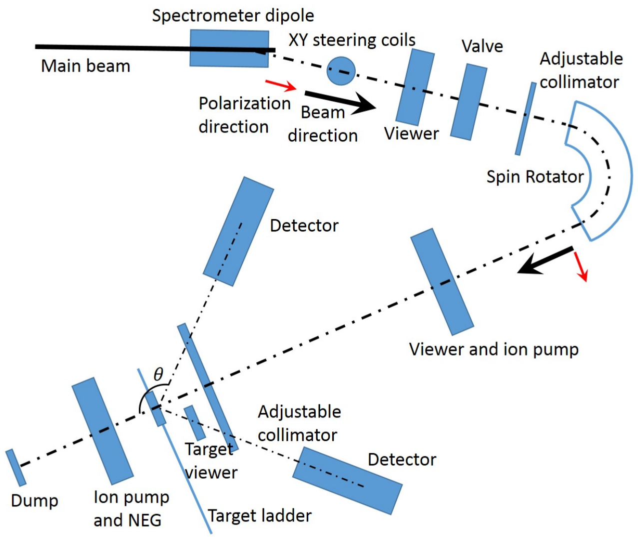
EIC will make use of two Mott polarimeters to measure the electron polarization from the source

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

Polarimetry for RCS

<u>RCS properties</u>

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

<u>Polarimetry challenges</u>

- 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

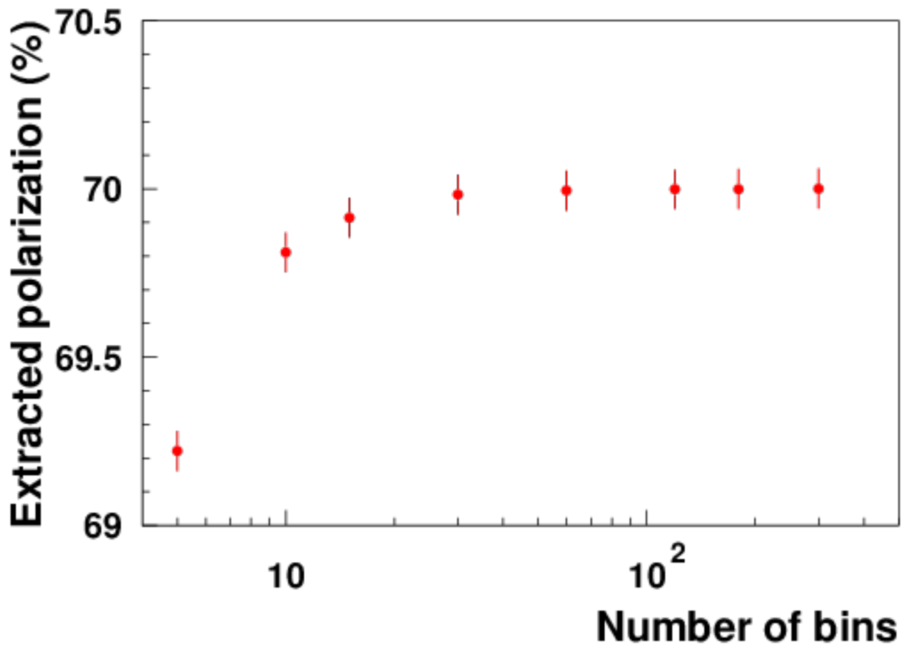
→ Measurements will be averaged over several bunches – can tag accelerating bunches to get information on bunches at fixed energy

→ Requires measurement in multiphoton mode (~1000 backscattered photons/crossing)

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%



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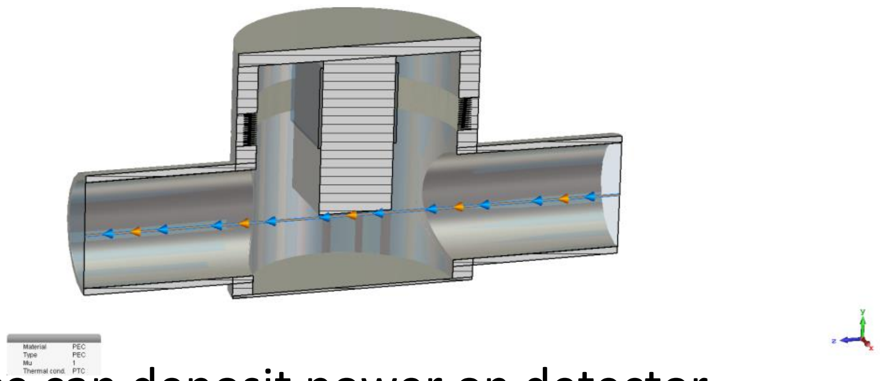
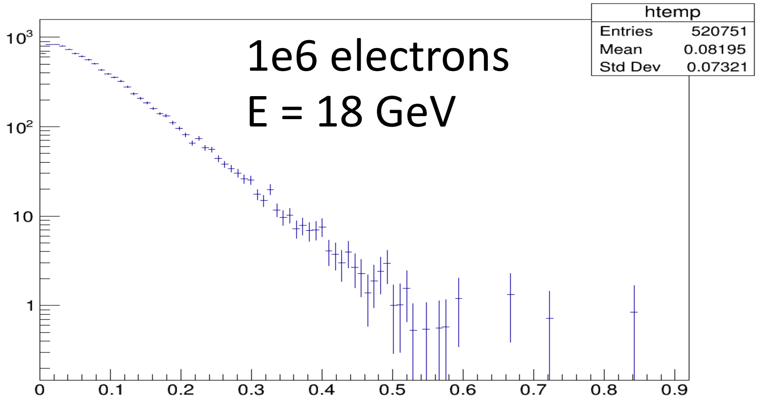
Electron detector considerations

Electron detector likely cannot live in vacuum directly – needs to be housed in a structure similar to Roman Pot

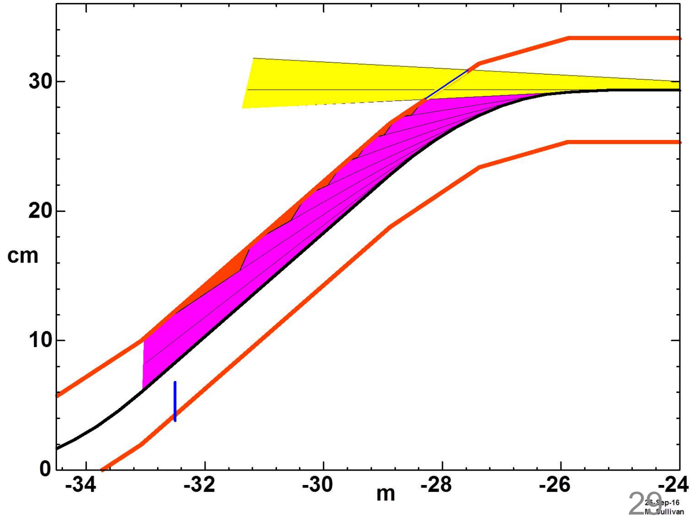
→ Preliminary wakefield calculations (alternate configuration) suggest power deposited manageable
→ This needs to be updated for latest EIC layout



Electron detector out of direct synchrotron fan, but single-bounce can deposit power on detector
→ Studies by Mike Sullivan (for different configuration) suggested large power deposition
→ Updated studies with GEANT4 for latest layout suggests that synchrotron backgrounds may not be a problem – work in progress



Sync photon energy [MeV]



Mike Sullivan

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)

Jefferson Lab

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

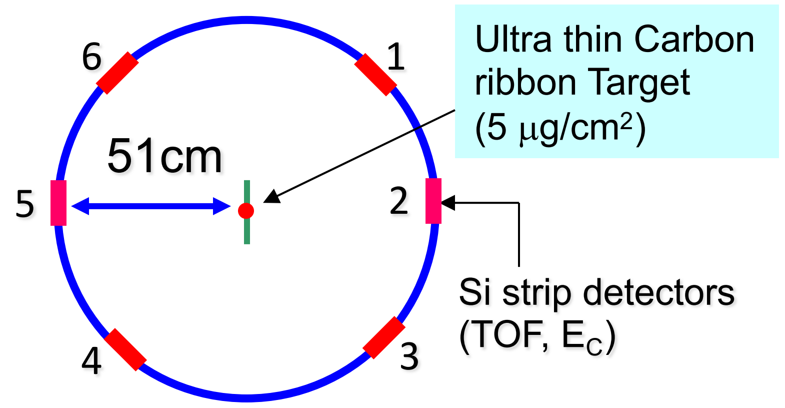
Differential: $A^2_{method} = \langle A^2 \rangle$ → Measurement of asymmetry bin-by-bin vs. energy, etc.

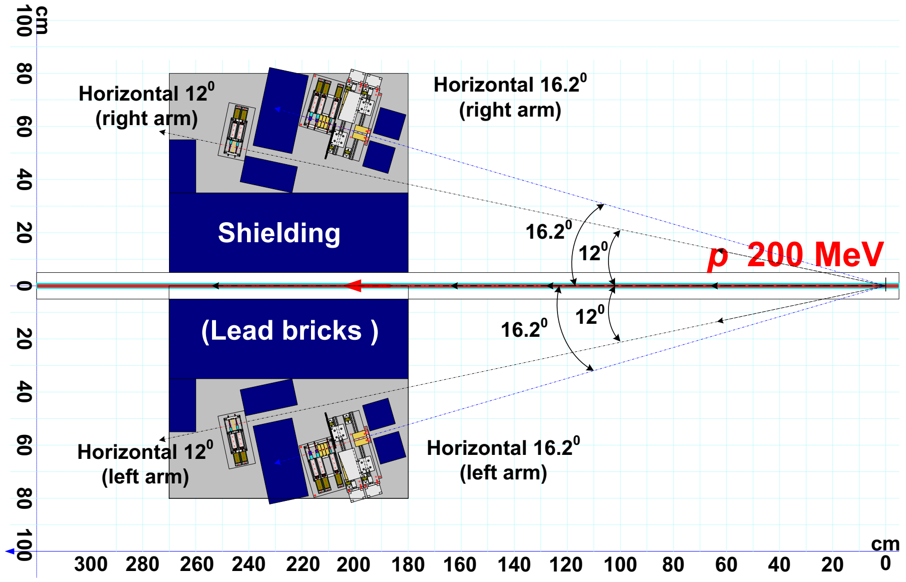
$$\langle A \rangle^2 < \left(\frac{\langle EA \rangle}{\langle E \rangle}\right)^2 < \langle A^2 \rangle$$

AGS and 200 MeV Polarimeters

AGS p-Carbon polarimeter similar to RHIC p-Carbon polarimeter with slightly different layout

→ Fast, relative measurements
→ Verify beam polarization before injection into EIC ring at ~ 25 GeV





200 MeV Polarimeter located after linac following polarized source
→ Analyzing power well known from measurements at IUCF
A_N= 0.993+/- 0.003
→ Total systematic error dP/P ~ 0.6%