“Development of a Spin-Light” Polarimeter for the EIC

Dipangkar Dutta

Mississippi State University

EIC Detector R&D Annual Meeting: December 12-13, 2011

The Collaboration

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University of Virginia, Charlottesville, VA

Paul Reimer (Co-PI)

Argonne National Lab, Argonne, IL

The collaboration has extensive polarimetry and detector development experience at DESY, JLab, Mainz, and RHIC.

Outline

- Introduction
- Synchrotron Radiation

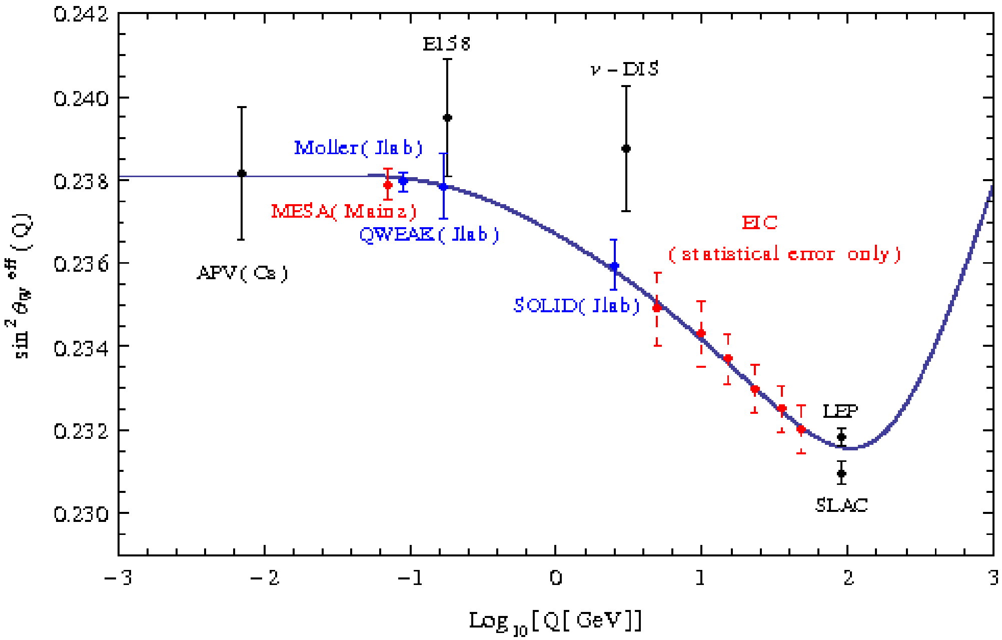
  Classical & Quantum description

- "Spin-Light"
- Conceptual Design of a "Spin-Light" polarimeter
- Detector and Prototype Development
- Summary

Introduction

The high energy and high luminosity polarized electrons, protons and ions at the EIC promises:

- a precise 3-D mapping of the proton's internal structure
- fundamental tests of QCD (such as Bjorken sum rule)
- tests of the SM at the quantum loop level that probe "new physics"



Projected uncertainties of future EIC measurements of $\sin^2\theta_W$.

This entire program at the EIC requires precision electron polarimetry.

We propose to develop a novel continuous non-invasive polarimeter based on the spin dependence of synchrotron radiation (SR)

Synchrotron Radiation- "Electronic Light"

After its discovery, the angular and spectral distribution were worked out in classical E&M

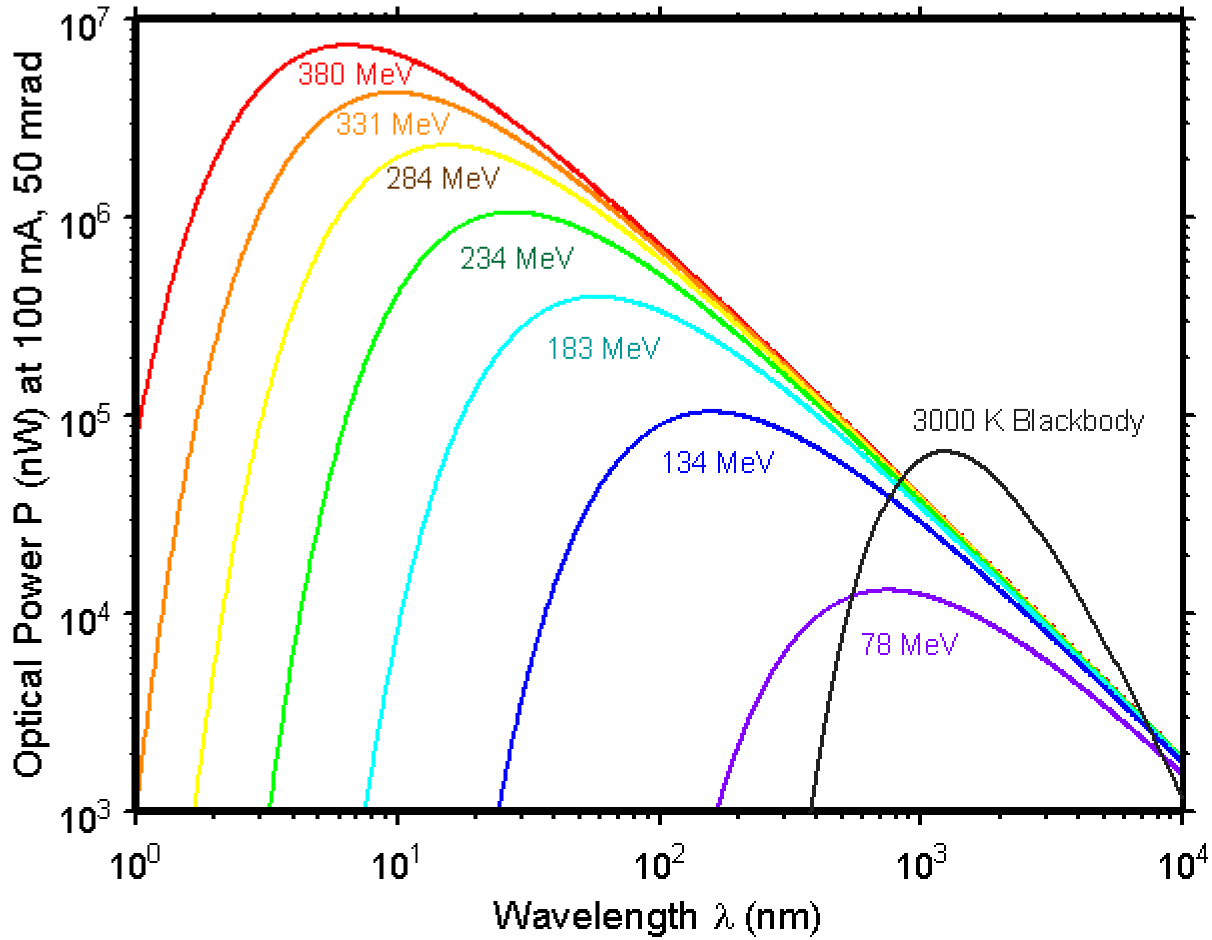
Total Rate

$$P = \frac{dU}{dt} = \frac{2}{3}\frac{e^2\gamma^4 c}{R^2}$$

$\gamma = \frac{E}{m_o c^2}$ **: Lorentz boost**

Strong linear polarization

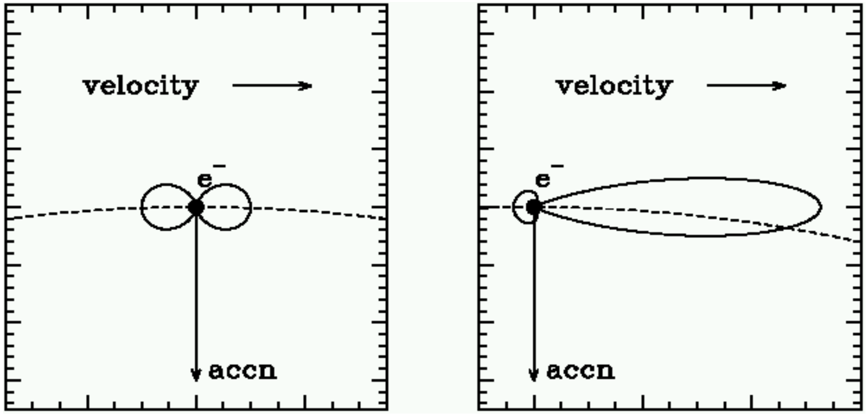
$$P_\sigma = \frac{7}{8}P \; ; \; P_\pi = \frac{1}{8}P$$



Synchrotron Radiation- “Electronic Light”

Angular distribution

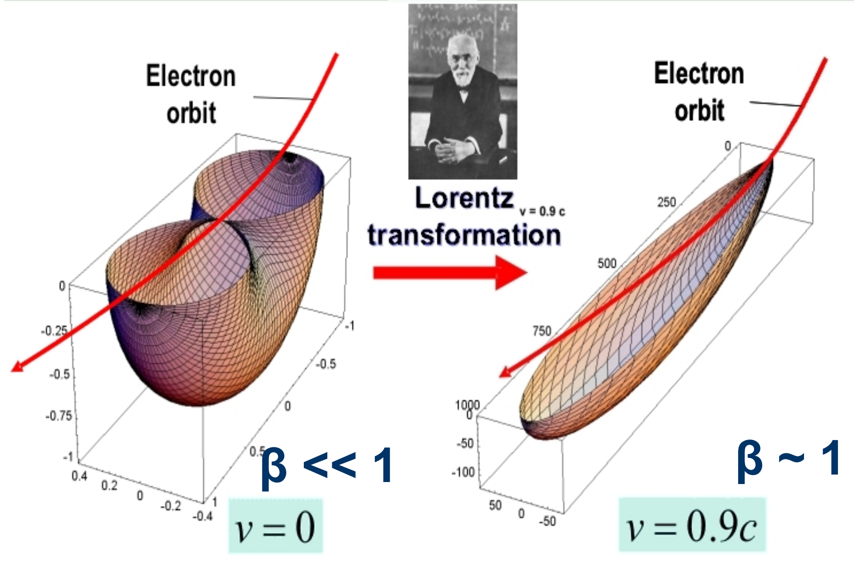
$$\frac{dU}{dt\,d\Omega} = \frac{e^2 \gamma^4 c}{4\pi R^2} \frac{(1-\beta\cos\theta)^2 - (1-\beta^2)\sin^2\theta\cos^2\phi}{(1-\beta\cos\theta)^5}$$



For γ >> 1 θ ~ 1/γ

SR emitted in a very small cone

For E_e = 11 GeV,
vert. size = 90 μrad
i.e. 10m from the source ~ 1 mm height.



Synchrotron Radiation- "Electronic Light"

Quantum Corrections

Exact QED calculations by A.A. Sokolov and I. M.Ternov (1960s)

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Classical theory (continuous SR spectrum) valid for

$E \ll E_{crit} \sim 10^6$ GeV and $B \ll B_{crit} \sim 4 \times 10^9$ T

E_{crit} : single SR photon carries away all of the electron's energy

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But even at lower energies

QED corrections ➔ spin dependence of the radiated power

$$P = P^{clas}\frac{9\sqrt{3}}{16\pi}\sum_{s'}\int\frac{y\,dy}{(1+\xi y)^4}I^2_{ss'}F(y)\,; \qquad y=\frac{\omega}{\omega_c}\,;\ \xi=\frac{3}{2}\frac{B}{B_{crit}}\gamma\ ;$$

s = radial quantum #
I = Laguerre func.

For ξ << 1 and electron spin j, j' = ± 1

$$P = P^{Clas}[(1-\frac{55\sqrt{3}}{24}\xi+\frac{64}{3}\xi^2)-(\frac{1+jj'}{2})(j\xi+\frac{5}{9}\xi^2+\frac{245\sqrt{3}}{48}j\xi^2)+(\frac{1-jj'}{2})(\frac{4}{3}\xi^2+\frac{315\sqrt{3}}{432}j\xi^2)+\ldots]$$

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spin dependent term **spin-flip dependent term**

The Spin Dependence

To the first order in ξ the difference in SR intensity between polarized and unpolarized electrons is $\delta = \xi j \sim 10^{-4}$ for 100 μA, 5.0 GeV electrons

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Verified experimentally at the VEPP-4 storage ring in Novosibirsk

Belomesthnykh et al., NIM 227, 173 (1984)

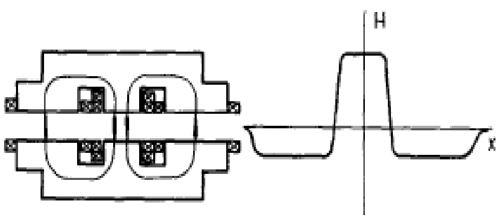

Fig. 1. The field vs the current in the 'snake'. A schematic of the 'snake' and the field distribution along its axis are shown below.

3 pole magnetic snake/wriggler

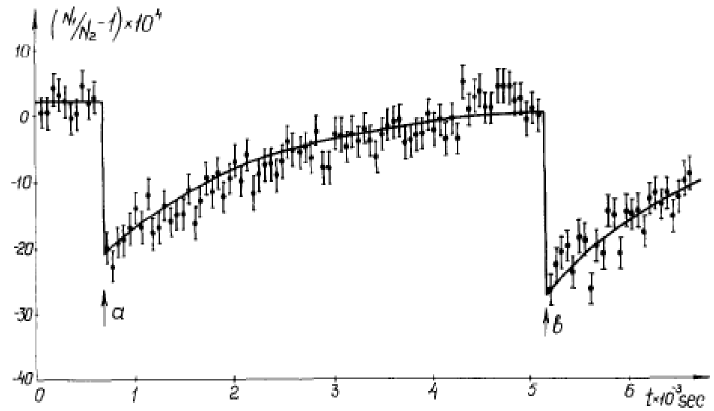

Fig. 12. The measurement results of the SR-intensity as a function of the degree of polarization of the beam. The field in the 'snake' coincides, in direction, with the storage ring guiding field. At points a and b one of the bunches (N_1), was quickly depolarized. The measurement time at a point is 60 s. The bunch polarization time is $\tau_p = 1740 \pm 20$ s ($\zeta = 0.726$).

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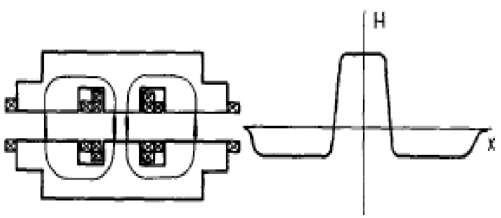

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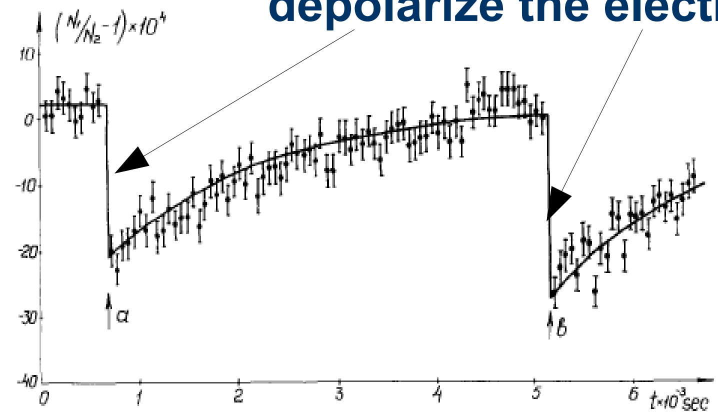
An RF field used to depolarize the electrons



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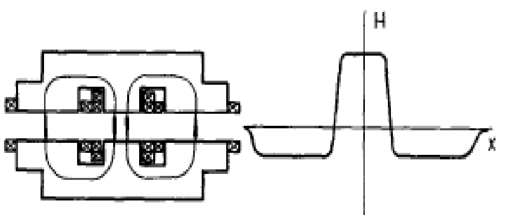

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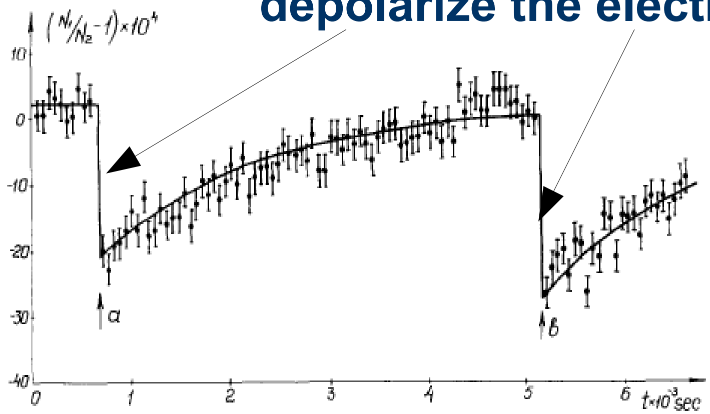

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The spin-flip term contributes only as ~ ξ^2

This is responsible for the transverse self polarization of electron beams in storage rings: called the Sokolov-Ternov effect

Used to produce polarized electrons at various accelerator such as DESY

Longitudinal “Spin Light”

For longitudinally polarized electrons

Power from n_e electrons (ignoring spin flip and all terms $O(\xi^2)$)

$$P_\gamma(long) = \frac{9\,n_e}{16\pi^3}\frac{c\,e^2}{R^2}\gamma^5\int_0^\infty \frac{y^2\,dy}{(1+\xi y)^4}\oint d\Omega\,(1+\alpha^2)^2\left[K_{2/3}^2(z) + \frac{\alpha^2}{1+\alpha^2}K_{1/3}^2(z) + j\,\xi\,y\,\frac{\alpha}{\sqrt{1+\alpha^2}}K_{1/3}(z)K_{2/3}(z)\right]$$

R = bending radius, $y = \frac{\omega}{\omega_c}$; $\xi = \frac{3}{2}\frac{B}{B_{crit}}\gamma$; $\alpha = \gamma\,\psi$; $z = \frac{\omega}{2\,\omega_c}(1+\alpha^2)^{3/2}$; **$K_{1/3}$, $K_{2/3}$ modified Bessel function**

vertical angle

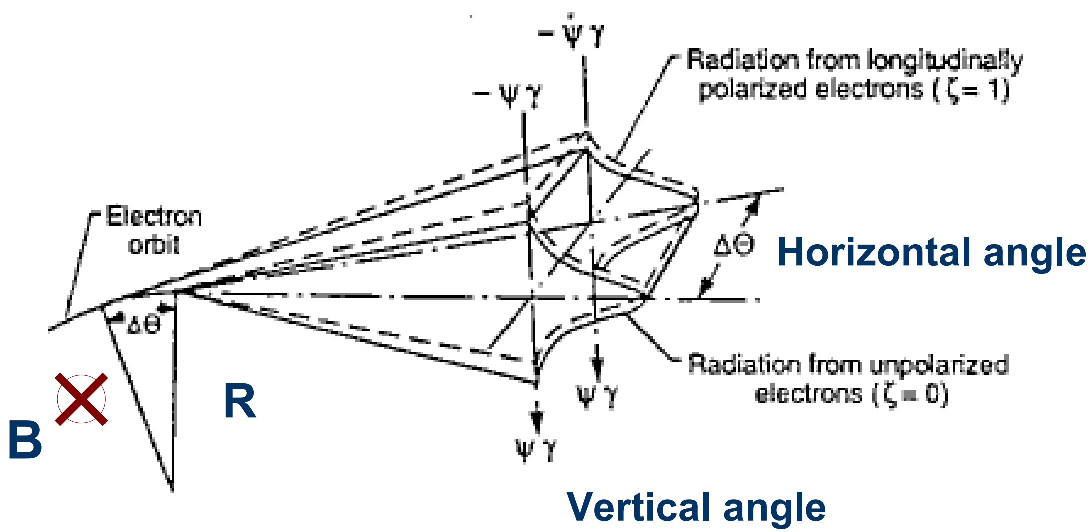

Figure 1: Geometrical definitions.

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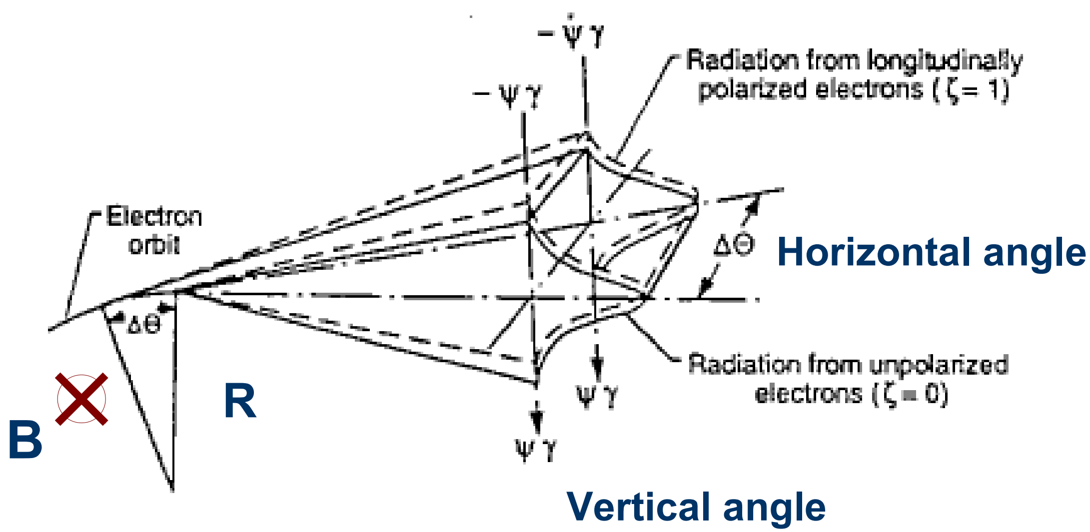
An odd function of the vertical angle



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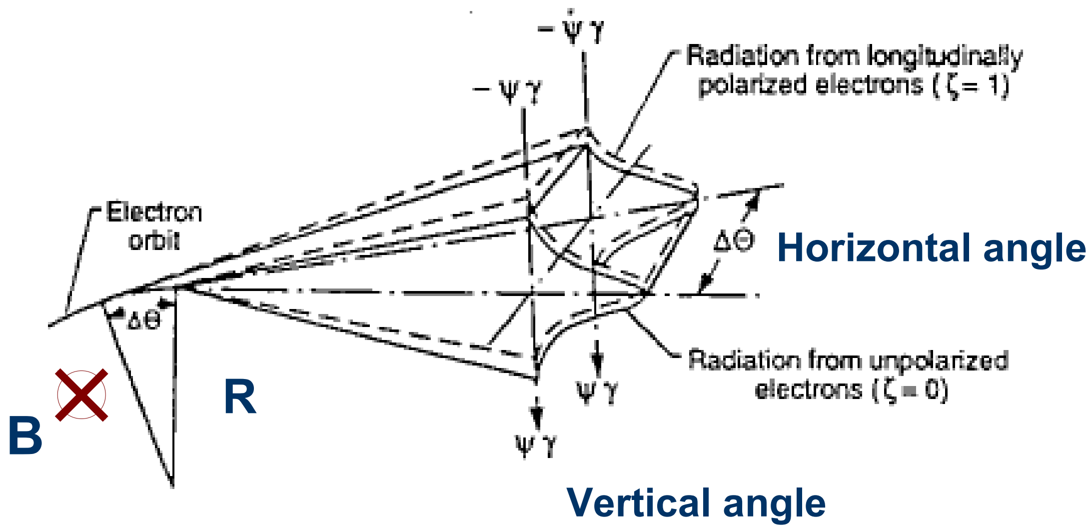

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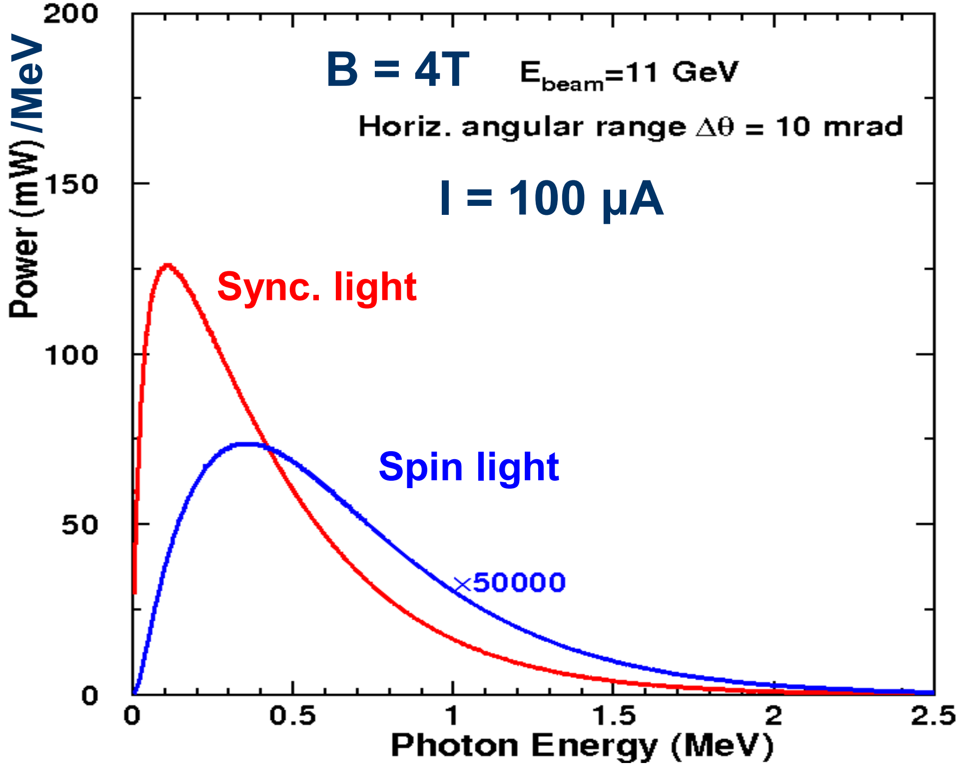
Integrated over all vertical angles the total SR power is spin independent

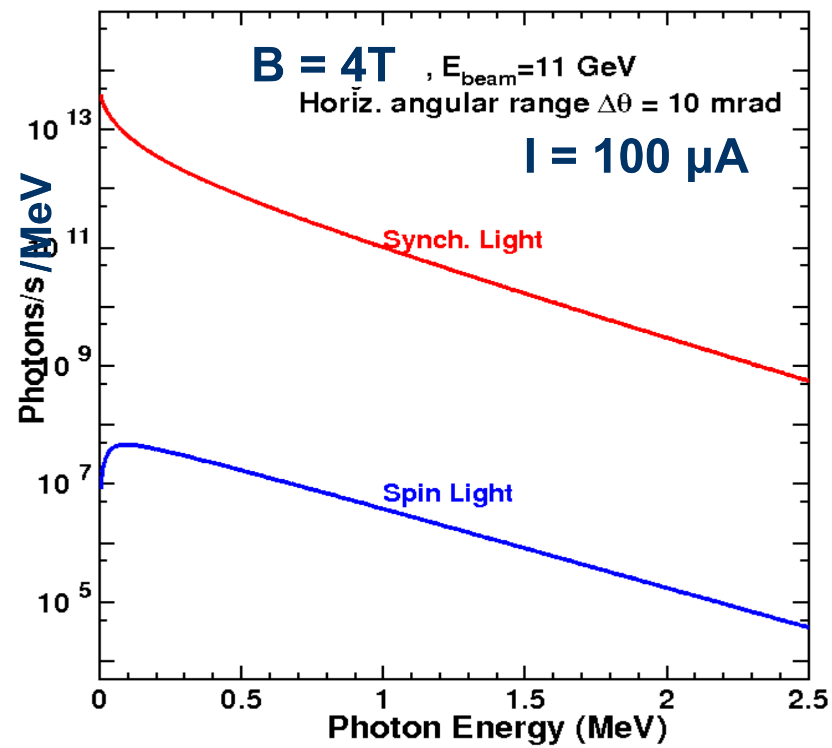
# of photons radiated above and below the orbital plane are not equal

"Spin Light" - Some Characteristics



Radiated power peak at different frequencies for Sync vs Spin light

Number of photons/s
~ 10^5 different



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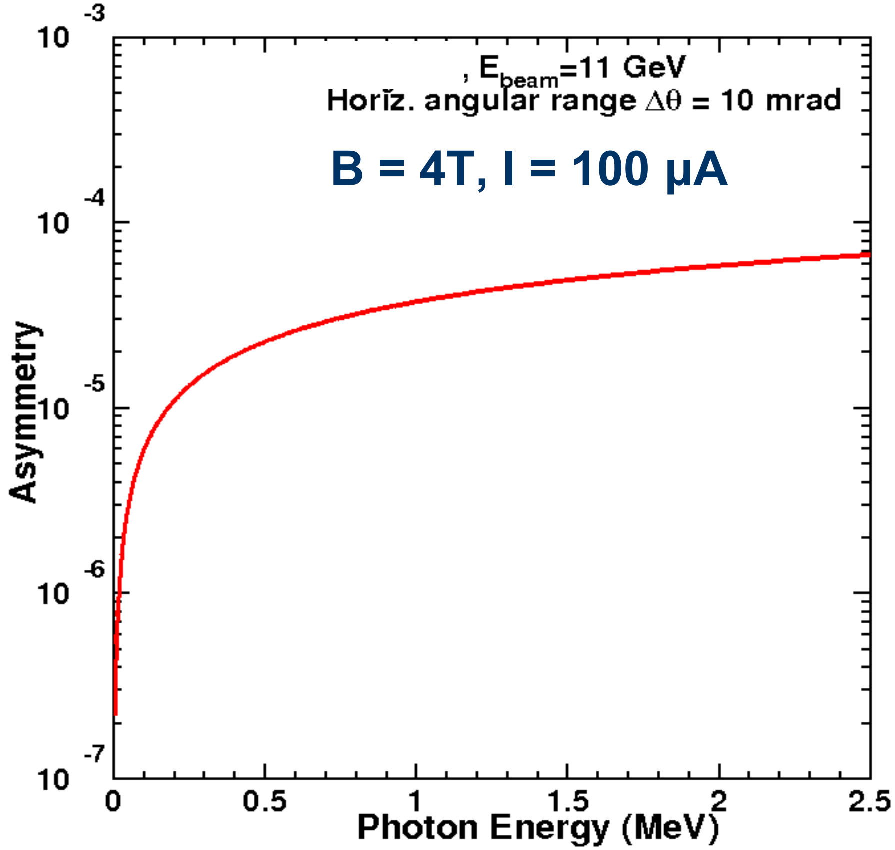
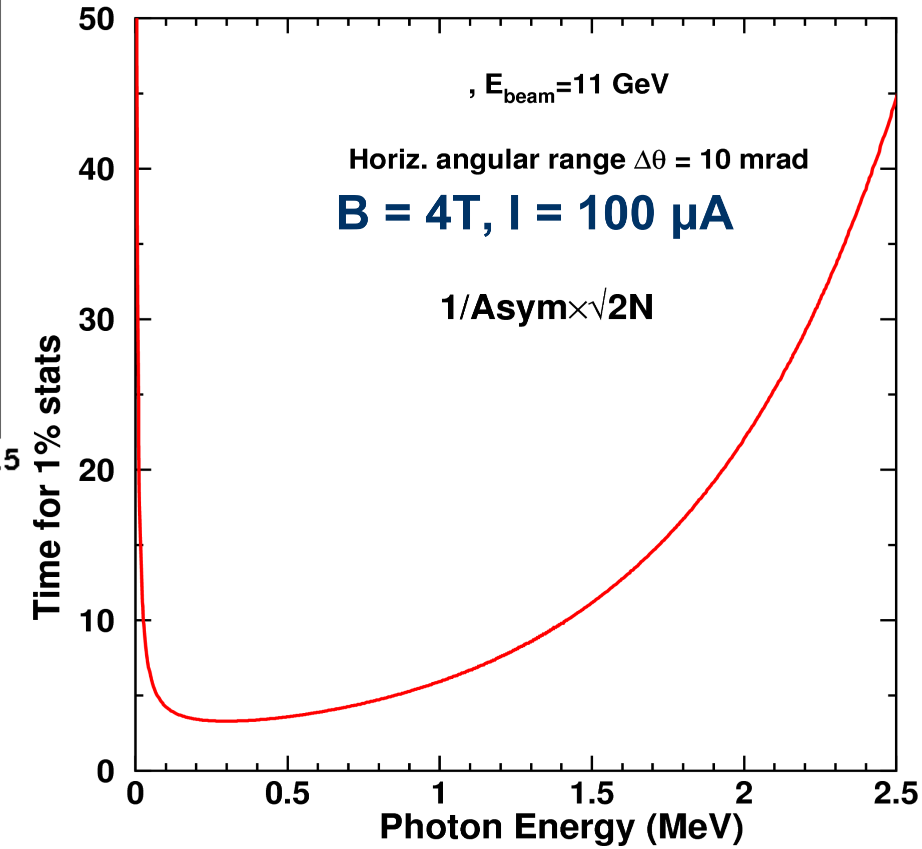


small asymmetry

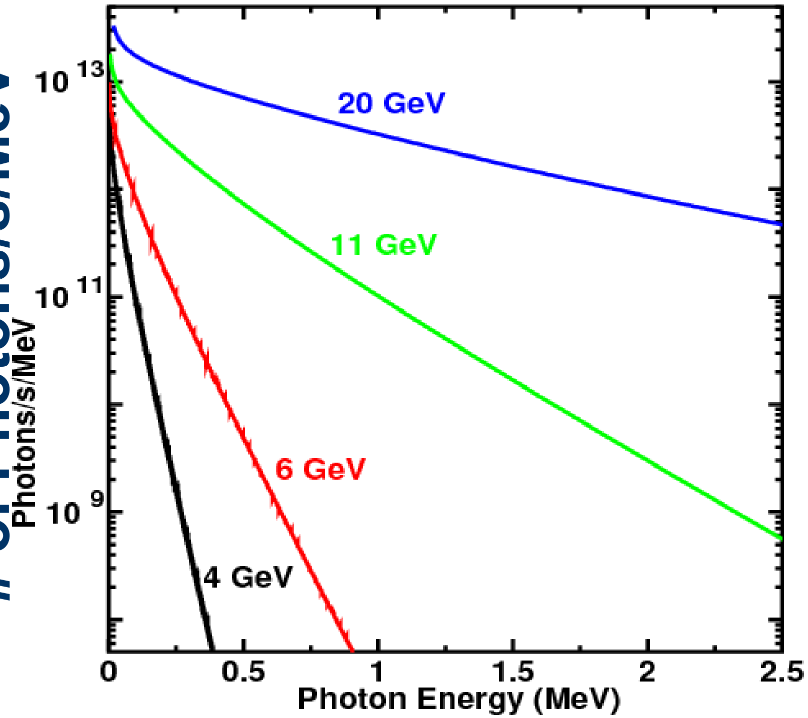
But high rates imply
1% statistics in ~ 10 sec
Assuming Ion chambers efficiency ~ 10%



“Spin Light” - Energy Dependence

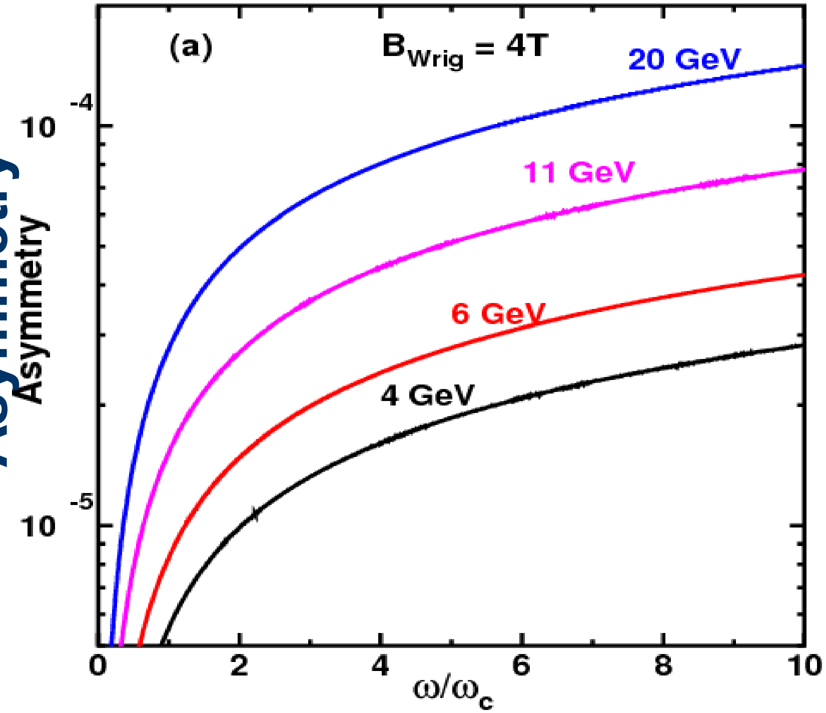
At fixed B = 4T, I = 100 μA and Δθ = 10 mrad

# of Photons/s/MeV



Photon Energy (MeV)

Asymmetry



Normalized Photon Energy

# of photons increases sharply with energy but asymmetry increases slowly

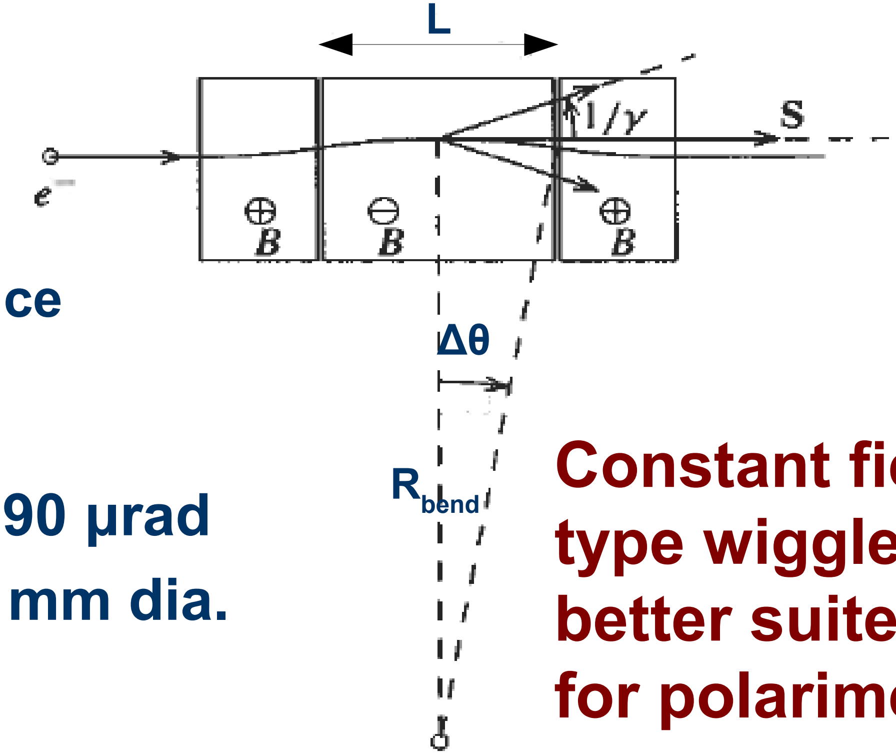
Conceptual Design

A Source of Spin Light: a 3 pole wiggler

$$R_{bend} = \frac{\gamma m_e c}{e B}$$

$$L = R_{bend} \Delta \theta$$

$$\oint B\, dl = 0$$



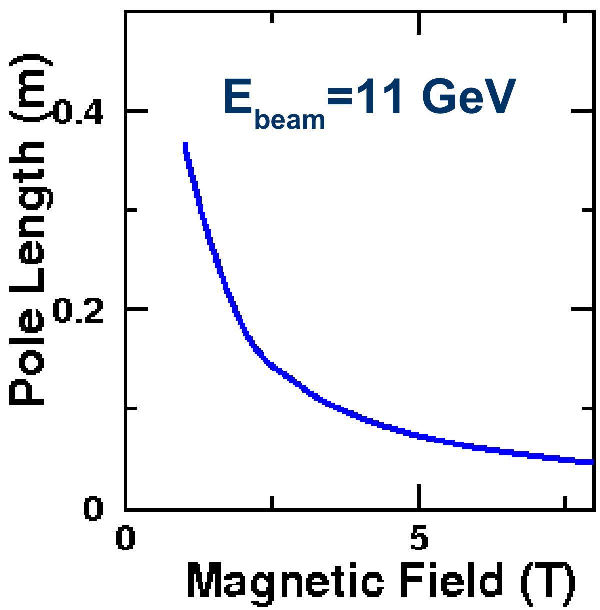
Horizontal angular acceptance
Δθ fixed to 10 mrad

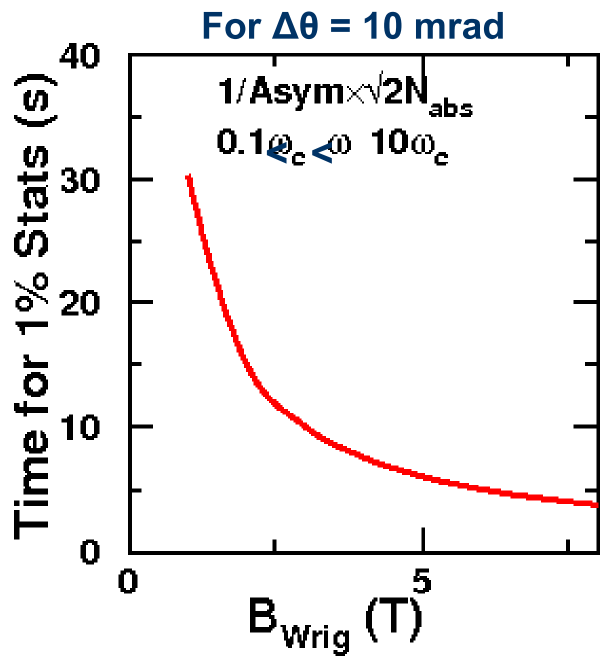
For E_e = 11 GeV, spot size = 90 μrad
i.e. 10m from the source ~ 1 mm dia.

Constant field type wiggler better suited for polarimeter

Conceptual Design

Choosing the $B_{wriggler}$





Pole length and figure of merit have similar dependence on the B- field.

Choose B = 4T

Is the Wiggler Non-invasive?

Effects of fluctuations related to the quantum nature of SR

(carefully studied for the Jlab recirculating arcs for up to E_e = 24 GeV)

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Mean # of γ emitted per e^- per radian $= n = 20.62\ E_e$

$\Delta E = \sqrt{n}\ E_c$

Mean energy of photon = $E_c = 3\hbar c\gamma^3/2R$

For E_e = 11 GeV, 10 mrad bend and R=10m: $n \sim 2$, E_c =199 keV and

$\Delta E/E = 2.5\mathrm{x}10^{-5}$

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Similarly $\Delta\theta_e = E_\gamma \sin\Theta_\gamma / E_e = 1.5\text{ x}10^{-8}$ **rad**

Depolarization due to wriggle

$$\Delta p = \frac{\tau_{(transit\,thru\,wriggler)}}{\tau_{(depol.)}} = \frac{L_{Wrig}/\beta c}{98.66(1900R^2/E^5)} \sim 1.1\text{x}10^{-9}\ \%$$

“Spin Light” Detector

A Detector of Synchrotron + Spin light (X-rays)

A transparent differential ionization chamber

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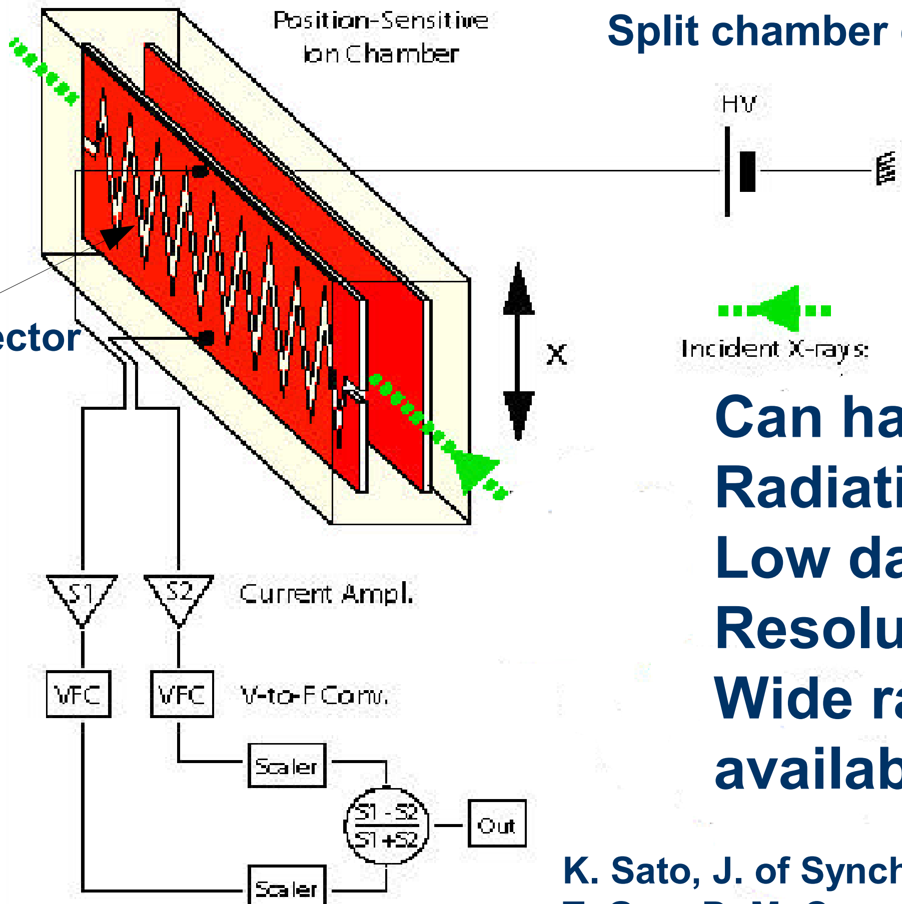
A transparent differential ionization chamber

Split chamber design helps pick out small signal



Gas – Xe or Ar

- Can handle high rates
- Radiation hard
- Low dark current/noise
- Resolution ~ 5 μm
- Wide range of ICs commercially available

K. Sato, J. of Synchrotron Rad., 8, 378 (2001)
T. Gog, D. M. Casa, I. Kuzmenko, CMC-CAT@ the APS

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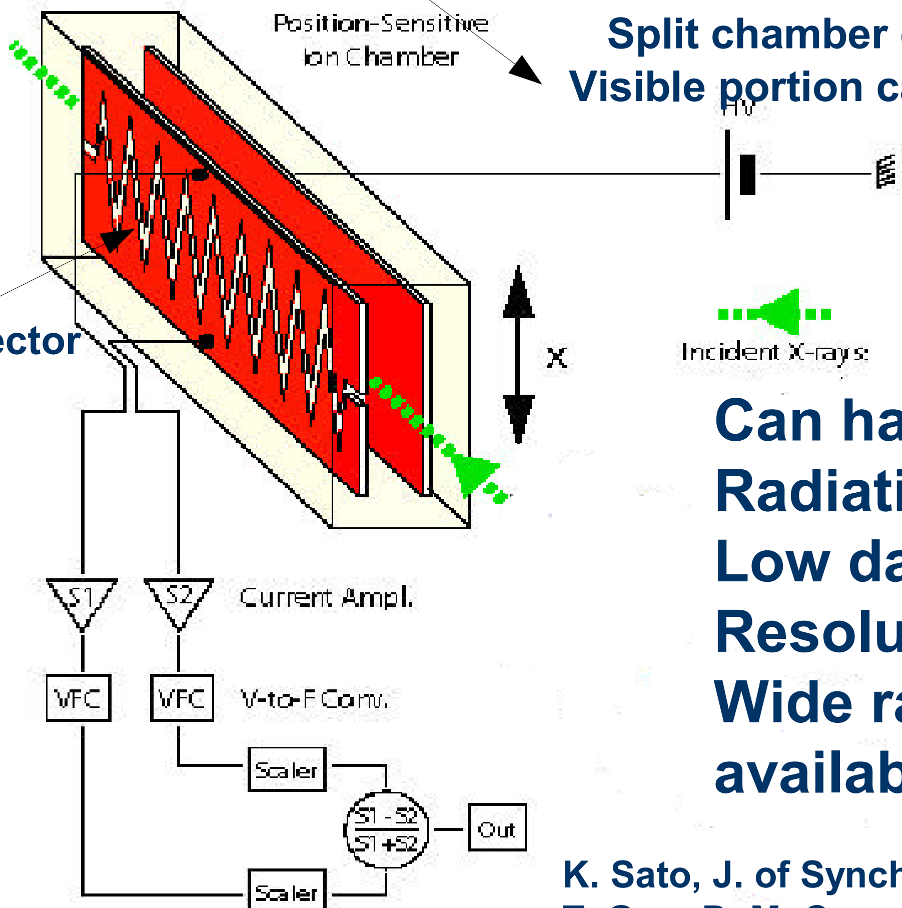
Split chamber design helps pick out small signal

Visible portion can be used to center chamber



Split collector Plate

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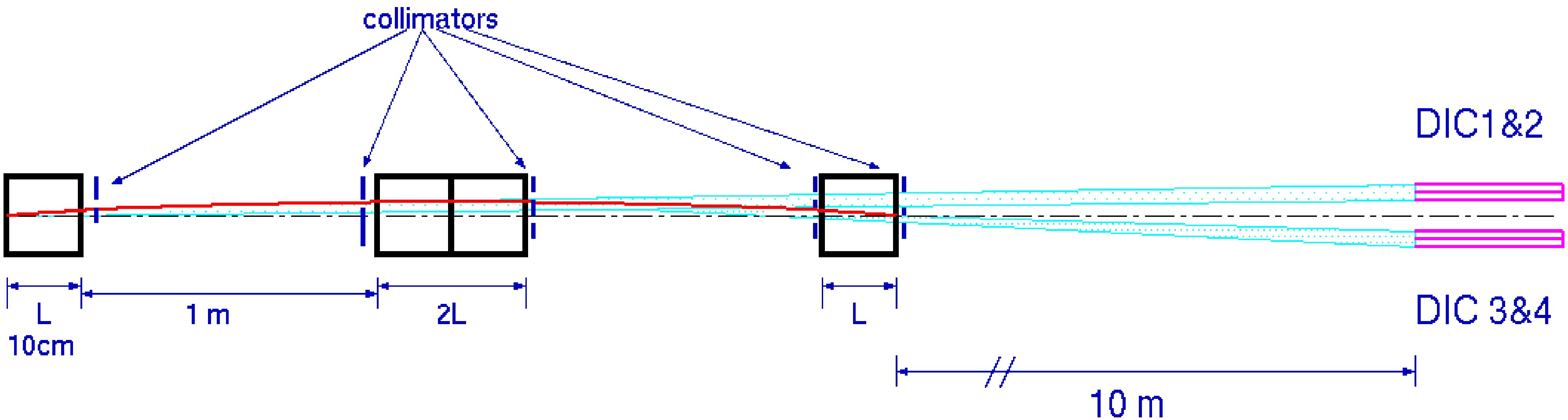
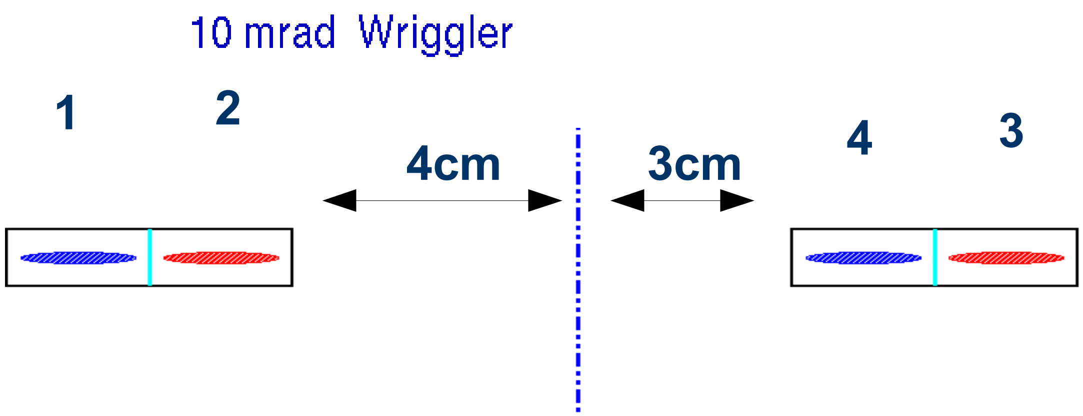
A “Spin Light” Polarimeter

Putting it all together





SR spot size 10 m from the wigglers

With appropriate slits/collimators after each pole of the wriggler

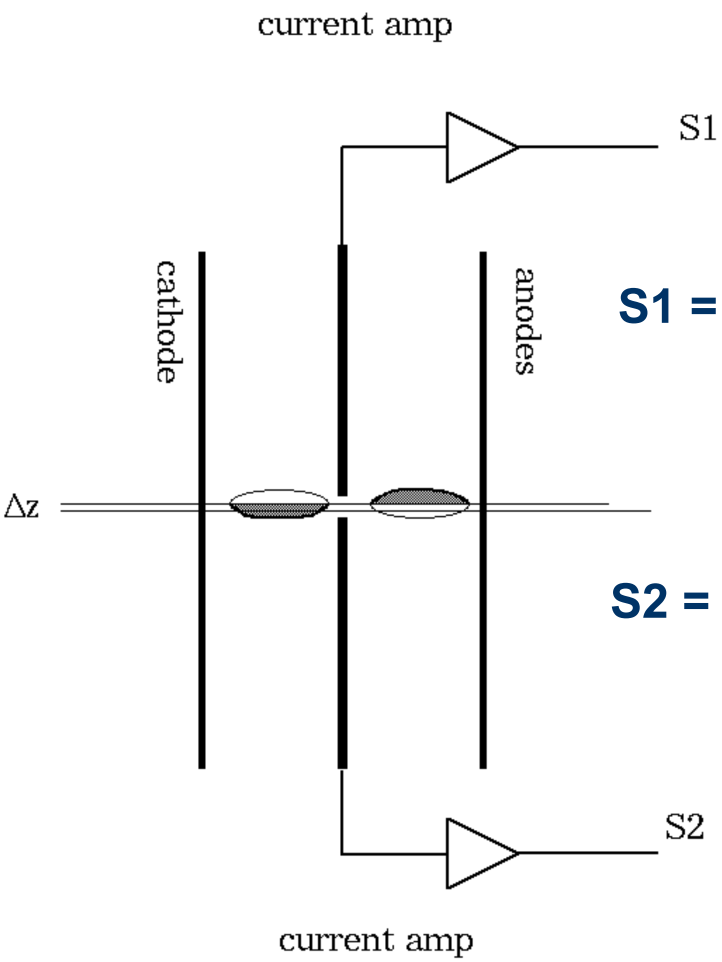
Comparing Polarimetry Techniques

Sub-1% polarimetry requires multiple independent measurements of the beam polarization.

- **A Spin-light polarimeter is complimentary to the more popular Compton & Möller polarimeters.**
- **It will provide an independent measurement with completely different systematics**

Compton	Spin-Light	Möller
Non-invasive/continuous	Non-invasive/continuous	invasive
Analyzing power is energy dependent	Analyzing power is energy dependent	Analyzing power is energy independent
Ideal for high currents	Ideal for high currents	Used at low currents only
Target is 100% polarized	No target needed	Target is <10% polarized
e & γ detection provide 2 independent polarimeters	-	-

The Signal



Current mode operation

$$S1 = (N^l_{SR} + \Delta N^l_{spin} + \Delta N^l_z) - (N^r_{SR} - \Delta N^r_{spin} + \Delta N^r_z)$$

Vertical beam motion cancels out

$$S2 = (N^l_{SR} - \Delta N^l_{spin} - \Delta N^l_z) - (N^r_{SR} + \Delta N^r_{spin} - \Delta N^r_z)$$

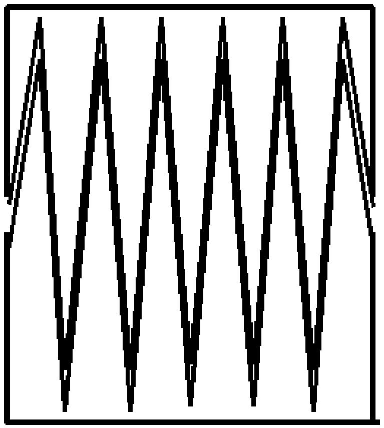
$$(S1 - S2) = 4\Delta N_{spin}$$

$$(S1 + S2) = 0$$

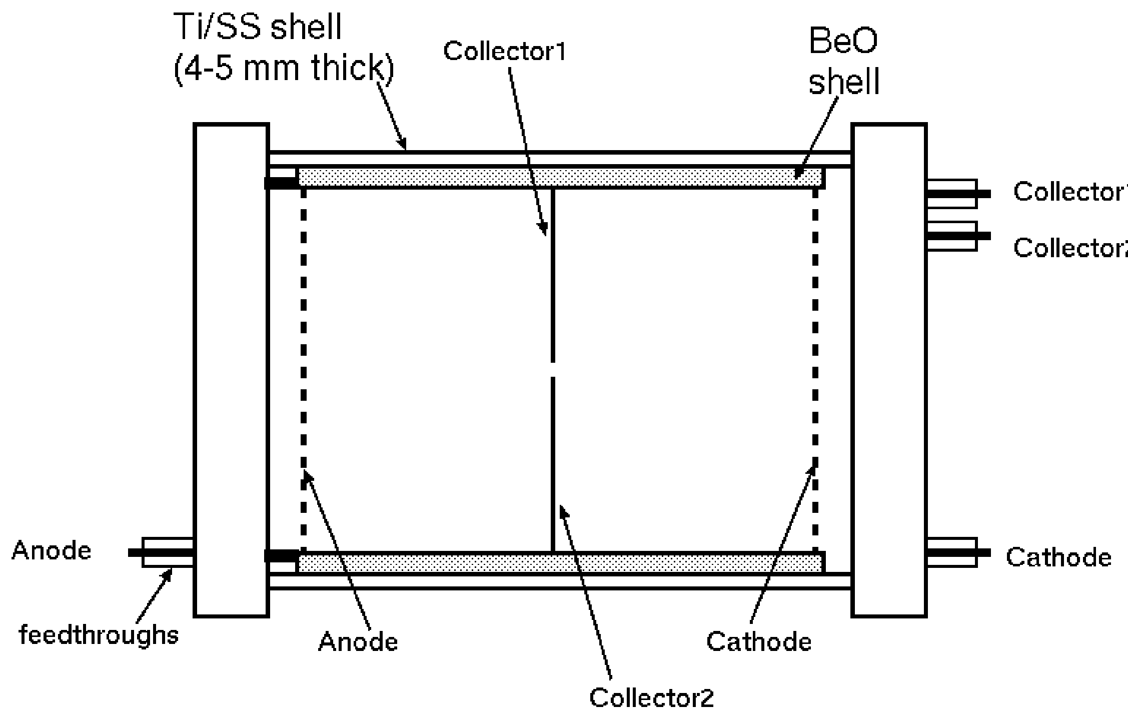
This sum for the two helicities can be used to separate out the efficiency and B-field related dilutions.

The Detector R&D Proposal

Stage1: Develop a split plane differential ionization chamber



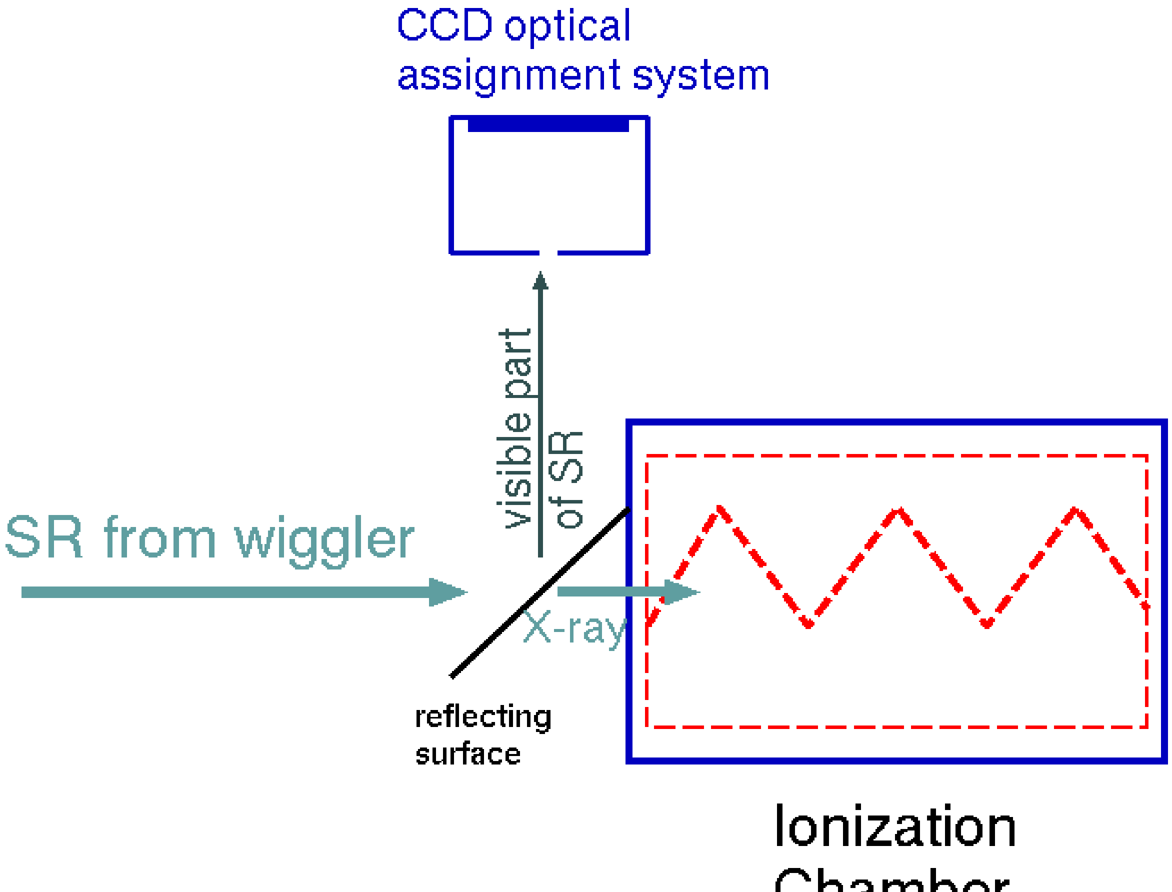
side view of
split collector plate



Front view of DIC

The Detector R&D Proposal

Stage1: Develop a CCD based ionization chamber alignment system



The Detector R&D Proposal

Stage1: Test the DIC in the JLab Hall-A Compton chicane

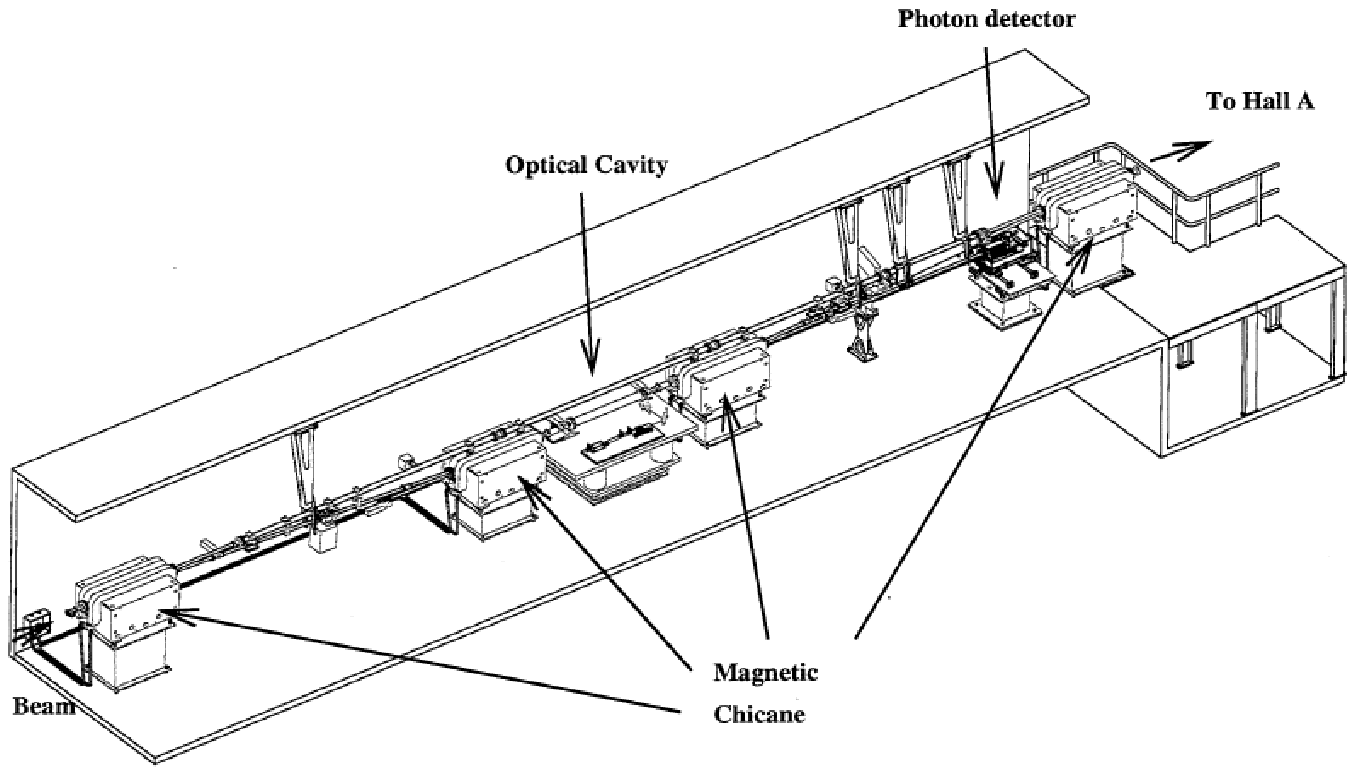


Fig. 14. The Compton Polarimeter Setup at TJNAF Hall A. Total length 15 m.

The Detector R&D Proposal

Stage 2: **Develop a full prototype spinlight polarimeter** (a set of dual ionization chambers and a suitable wiggler magnet.)

Activity	Year 1	Year 2	Year 3
Design and build prototype DIC	√	√	
Test DIC in Hall A Compton beamline			√
Design CCD based alignment system	√	√	
Design and build set of dual DIC			√
Build CCD system			√
Design wiggler magnet		√	
Design slits and collimators		√	
Identify suitable wiggler magnet at the APS			√
Select suitable site to test prototype polarimeter			√

The Detector R&D Proposal

The collaboration has extensive polarimetry and detector development experience at DESY, JLab, Mainz, and RHIC.

Students & Postdocs

Grad. Students:
Edward Leggett (MSU) and Valerie Gray (W&M) and MSI student(s) (Stony Brook U., during yrs. 2 and 3)
Post doc: M. Shabestari (MSU, 25% FTE only)
Additional post-doc during 2nd / 3rd yr. desirable

Funding Request

Item	Year 1	Year 2	Year 3	Total
0.5 Grad Student (MSU)	\$17k	\$17k	\$17k	\$51k
0.5 Grad student (W&M)	\$17k	\$17k	\$ 17k	\$51k
Equipment	\$46k	\$44k	\$48k	\$138k
Travel	\$10k	\$10k	\$10k	\$30k
Total	\$90k	\$88k	\$92k	\$270k

The Detector R&D Proposal

Equipment	Total cost
prototype DIC	10000
Split plane electrodes	5000
Electronics for DIC(2 channels)	
current amps	8000
High voltage power supplies	10000
V-to-Fs and scalers	15000
VME crate	10000
Single board computer	7000
Gas Handling system	10000
The Dual DICs	
Custom dual DICs	12000
with split collector	
additional amps	8000
CCD alignment system	25000
Custom beamline vacuum	10000
elements	
slits and collimators	8000
Total Equipment Cost	138000

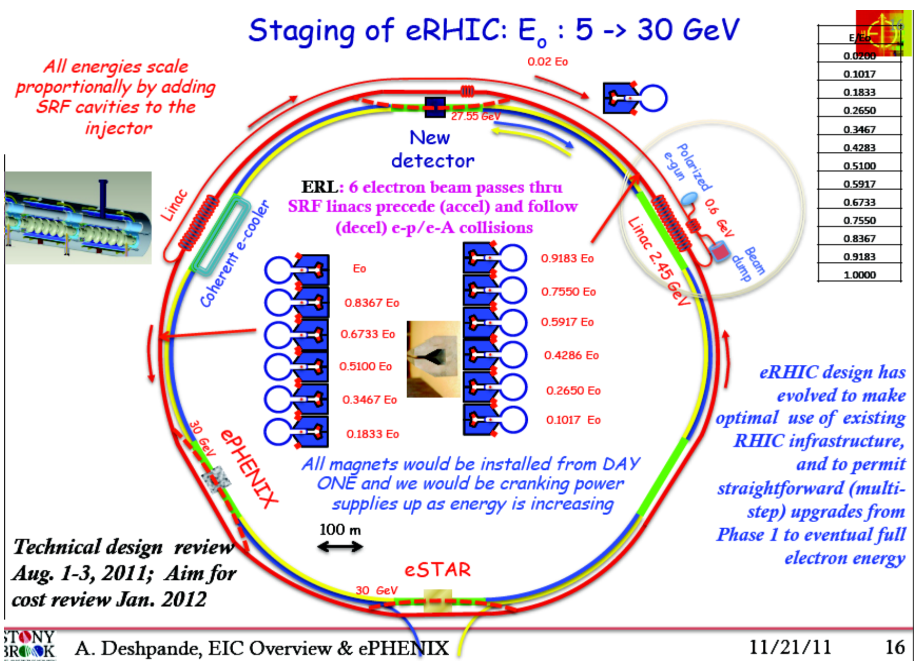
Table 1: Equipment cost breakup

Summary

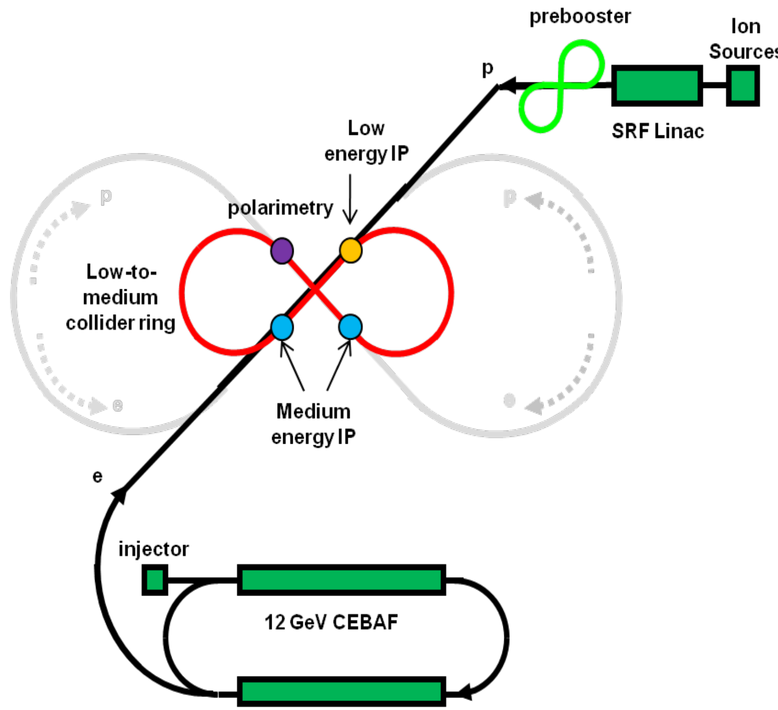
- Spin light based polarimeter is a viable option for precision non-invasive polarimetry
- It is based on a well demonstrated concept (for transversely polarized electrons), the necessary technology is readily available and widely used in light sources across the world.
- We propose to develop a split plane ionization chamber and demonstrate proof of principle for longitudinally polarized electrons using 12 GeV beam at JLab.
- Begin developing a full prototype spin light polarimeter

Possible Locations at an EIC

A 2.5 m long straight section of e-beamline and a 10 m long free flight path (along the beamline) for SR photons to a set of DICs



EIC@RHIC



EIC@JLab