Development of a Spin-Light Polarimeter for the EIC

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We have assembled an international collaboration with extensive polarimetry expertise to perform R&D towards a new type of electron polarimeter

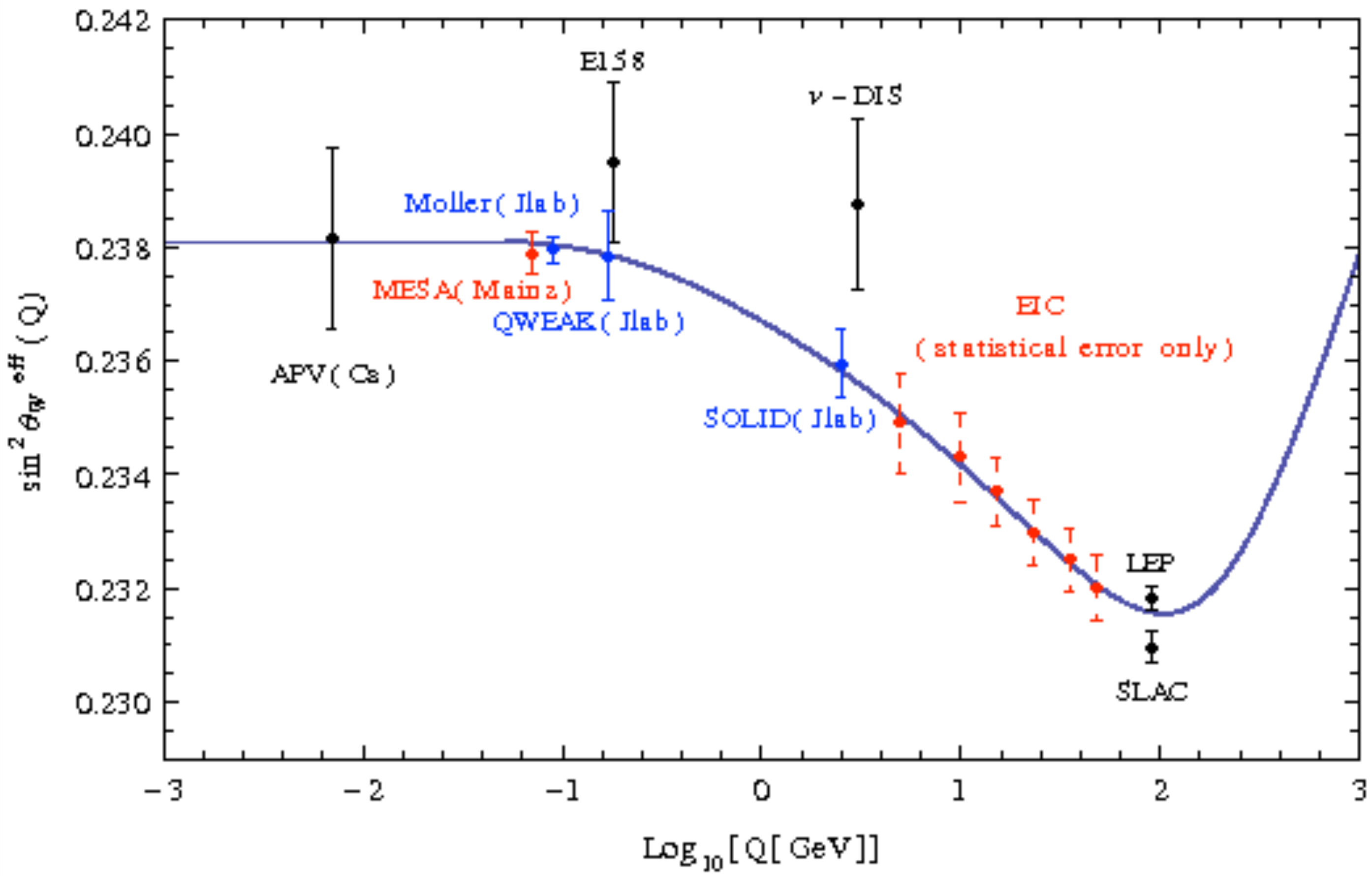
Outline

- Introduction and update
- Overview of “spin-light”
- The conceptual design of polarimeter
- 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 uncertainty for $\sin^2\theta_W$ measurement

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)

Introduction

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	Møller
non-invasive, continuous	non-invasive, continuous	invasive
analyzing power, energy dependent	analyzing power, energy dependent	analyzing power, energy independent
high currents	moderately high currents	low currents
target is 100% polarized (needs stable laser)	no target	target < 10% polarized
e and gamma detectors independent measurements	beam left/right detectors independent measurements	no independent measurements possible
high precision absolute pol.	high precision relative pol.	high precision absolute pol.
best inst. uncertainty = 0.4% best abs. uncertainty = 0.5%	expected inst. uncert. = 0.6% expected abs. uncert. = ~2.5%	best inst. uncertainty = 0.5% best abs. uncertainty = 0.9%

Update

A Spin-Light Polarimeter for Multi-GeV Longitudinally Polarized Electron Beams

Prajwal Mohanmurthy and Dipangkar Dutta

***Abstract*—The physics program at the upgraded Jefferson Lab (JLab) and the physics program envisioned for the proposed electron-ion collider (EIC) include large efforts to search for interactions beyond the Standard Model (SM) using parity violation in electroweak interactions. These experiments require precision electron polarimetry with an uncertainty of $< 0.5\%$. The spin dependent Synchrotron radiation (SR), called "spin-light," can be used to monitor the electron beam polarization. In this article we develop a conceptual design for a "spin-light" polarimeter that can be used at a high intensity, multi-GeV electron accelerator. We have also built a Geant4 based simulation for a prototype device and report some of the results from these simulations.**

***Index Terms*—Differential ionization chambers, polarized electrons, spin light, synchrotron radiation.**

I. Introduction

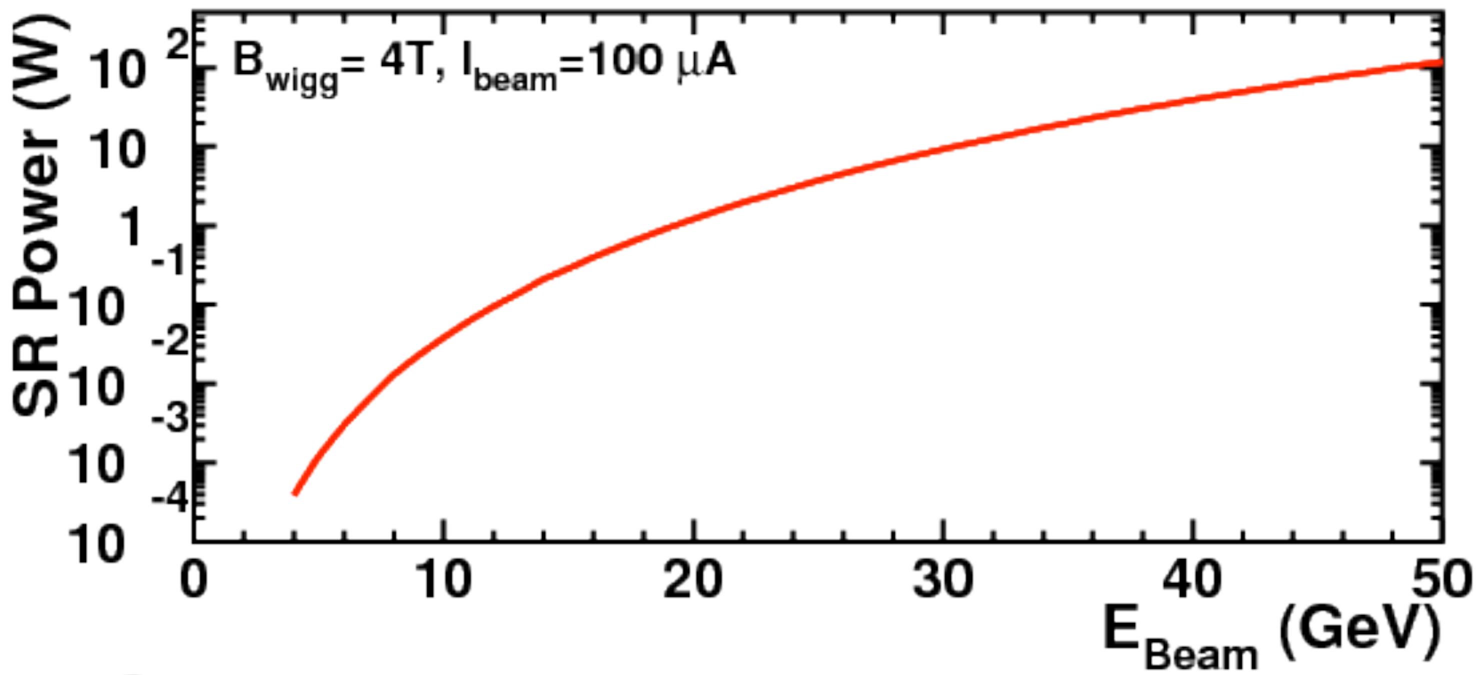
THE determination of the longitudinal polarization of the electron beam is one of the dominant systematic uncertainties in any parity violating electron scattering (PVES) experiment. In order to achieve the desired high precision, the polarization of the electron beam must be monitored continuously with an uncertainty of $< 0.5\%$. These ambitious goals can be achieved if multiple independent and high precision polarimeters are used simultaneously. In addition to being precise, the polarimeters must be non-invasive and must achieve the desired statistical precision in the shortest time possible. Compton and Møller polarimeters are typically the polarimeters of choice for these experiments and are essential to achieve the desired precision. However, a complimentary polarimetry technique based on the spin dependence of synchrotron radiation, referred to as "spin-light," can be used as a relative polarimeter. A spin-light polarimeter could provide additional means for improving the systematic uncertainties and when calibrated against a Compton/Møller polarimeter it could provide a stable continuous monitoring of the beam polarization. We develop the conceptual design for a continuous polarimeter based on "spin-light". The proposed spin-light polarimeter can achieve statistical precision of $< 1\%$ in measurement cycles of less than 10 minutes for 4 - 20 GeV electron beams with beam currents of $\sim 100\ \mu$A.

Møller and Compton polarimeters have a proven track record of very high precision, the JLab Hall-C Møller polarimeter has an instrumental uncertainty of 0.47% [1] and absolute uncertainty of 0.85% [2], while the Compton polarimeter used in the SLD experiment achieved an instrumental uncertainty of 0.4% [3] and an absolute uncertainty of 0.5% [3], hence they are essential for any PVES program. However, a spin-light polarimeter would have a few operational and instrumental advantages over conventional polarimeters, such that when used in parallel with Compton/Møller polarimeters they might help reduce the systematic uncertainties and achieve the very high precision essential for the future PVES program. For example, Møller polarimeters use a polarized Fe target, and the polarization of the target is difficult to determine and may depend on the beam intensity. Moreover, Møller polarimeters operate at low current, and are invasive to the primary experiment. Compton polarimeters require a stable laser (the photon target) and are very sensitive to backgrounds. The proposed spin-light polarimeter is a target free device, hence it should be easier to operate over long periods, with its stability governed just by the stability of the electron beam. Moreover, this novel polarimeter would facilitate cross-checks and systematic studies when used with other conventional polarimeters. On the other hand, one of the disadvantages is that the proposed device can achieve comparable instrumental uncertainties only as a relative polarimeter, whereas the absolute polarization is what is required in the PVES experiments. Nevertheless a precise and stable relative polarimeter can be a very useful device. The spin-light polarimeter could be used in conjunction with a Compton polarimeter, such that the difficult to operate Compton polarimeter is used for calibration and the easier to operate and stable spin-light polarimeter is used to continuous monitor the beam polarization. Moreover, only the Møller and the spin-light polarimeters allow measurement of the transverse component of a longitudinally polarized electron beam. The key features of conventional polarimeters and a spin-light polarimeter are summarized in Table I.

Manuscript received July 11, 2013; revised September 20, 2013; accepted

An article on the conceptual design is to appear in the IEEE trans. in Nucl. Science, in their next issue.

Update



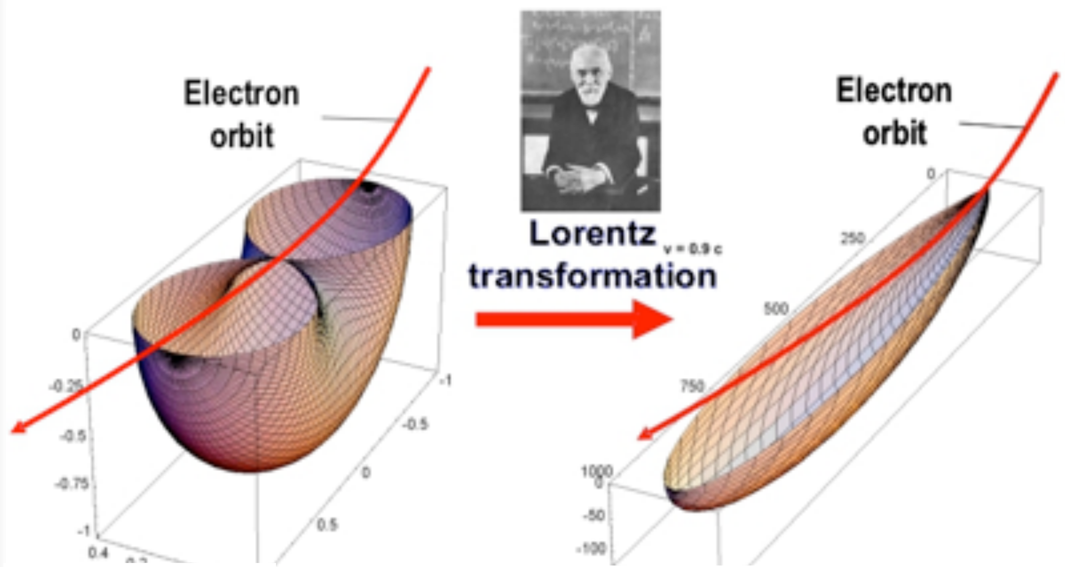
SR power will be distributed over an area of 100 mm x 1 mm.

Materials such as GlidCop (Al and $Al_2 0_3$ dispersion strengthened copper) and configurations such as crotch absorbers have been demonstrated to withstand power densities of 100 W/mm^2
We estimate that it is best suited for the 4 - 20 GeV energy range for currents less than 10 mA

For the eRHIC Gatling electron gun design each cathode will have an electronic tagging signal which can be used to accumulate counts from a particular cathode. Thus, it will be possible to measure the relative beam polarization of individual cathodes and monitor the inter-cathode variation in polarization.

Overview of ”Spin light”

The angular and spectral distribution of Synchrotron radiation -”electronic light” is accurately described in E&M



$\beta << 1$ $v = 0$ $\beta \sim 1$ $v = 0.9c$

For $\gamma >> 1$ $\theta \sim 1/\gamma$

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

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

QED corrections → spin dependence of the radiated power

$B_{crit} \sim 4x10^9$ T $\xi = \frac{3}{2}\frac{B}{B_{crit}}\gamma$

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

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

spin dependent term — spin-flip dependent term

Overview of "Spin light"

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

Verified experimentally at the VEPP-4 storage ring in Novosibirsk

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

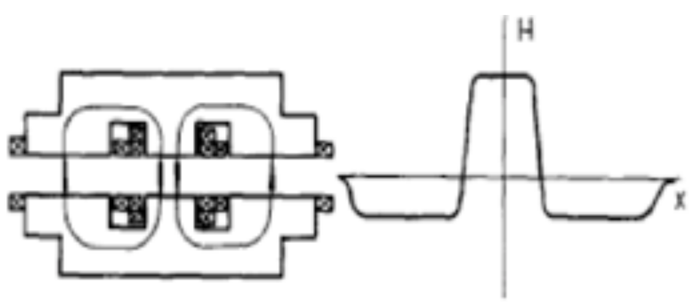


Fig. 1. The field vs the current in the 'snake'. A schematic of the 'snake' and the field distribution along its axis are shown below.

3 pole magnetic snake/wriggler

An RF field used to depolarize the electron

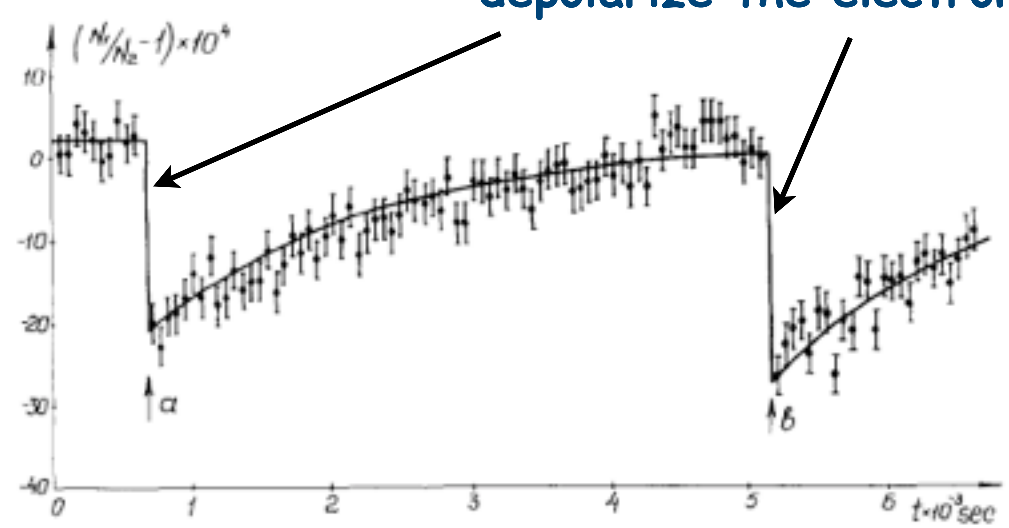


Fig. 12. The measurement results of the SR-intensity as a function of the degree of polarization of the beam. The field in the 'snake' coincides, in direction, with the storage ring guiding field. At points a and b one of the bunches (N_1), was quickly depolarized. The measurement time at a point is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

Longitudinal Spin Light

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

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

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

An odd function of the vertical angle

⇩

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

⇩

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

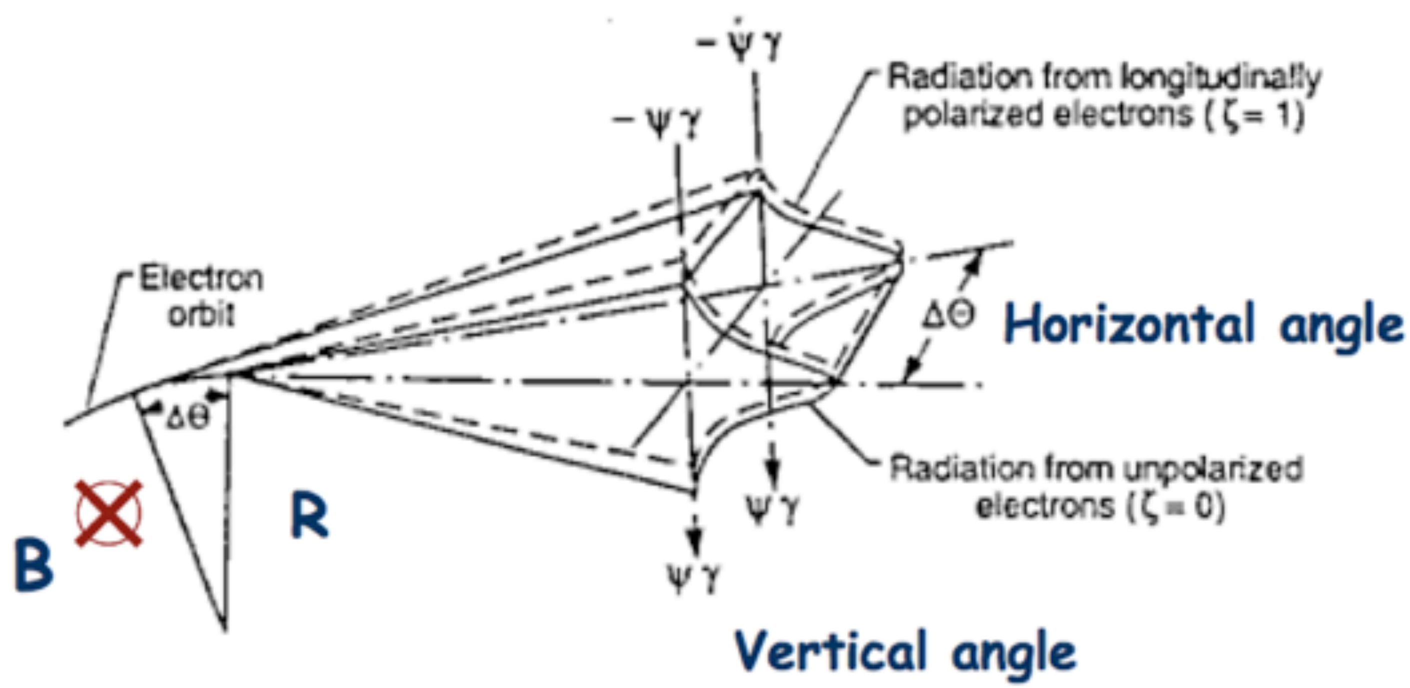


Figure 1: Geometrical definitions.

“Spin Light” - Some Characteristics

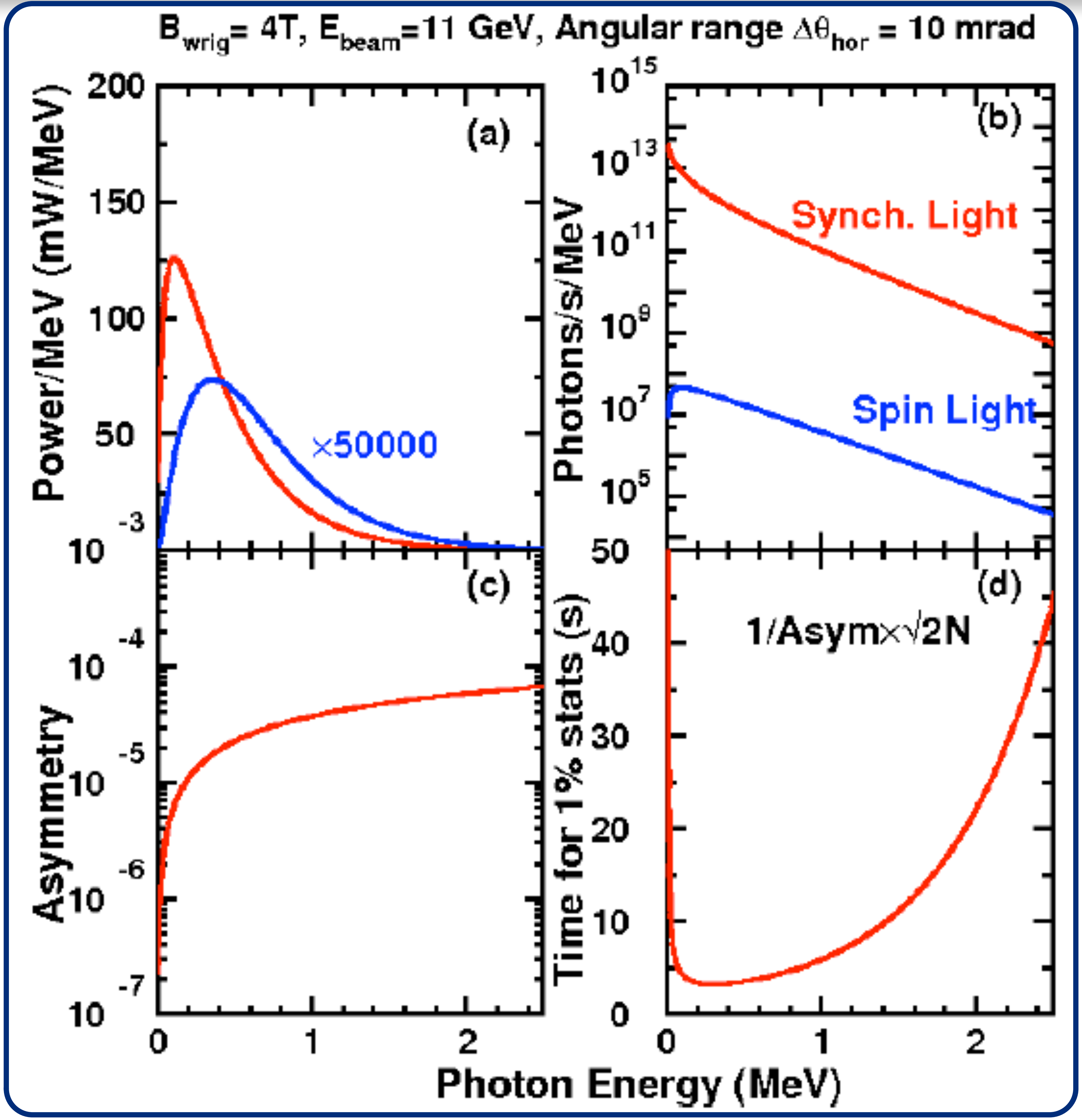
Sync and Spin light peak at different energies

Number of photons/s ~ 10^5 different

small asymmetry

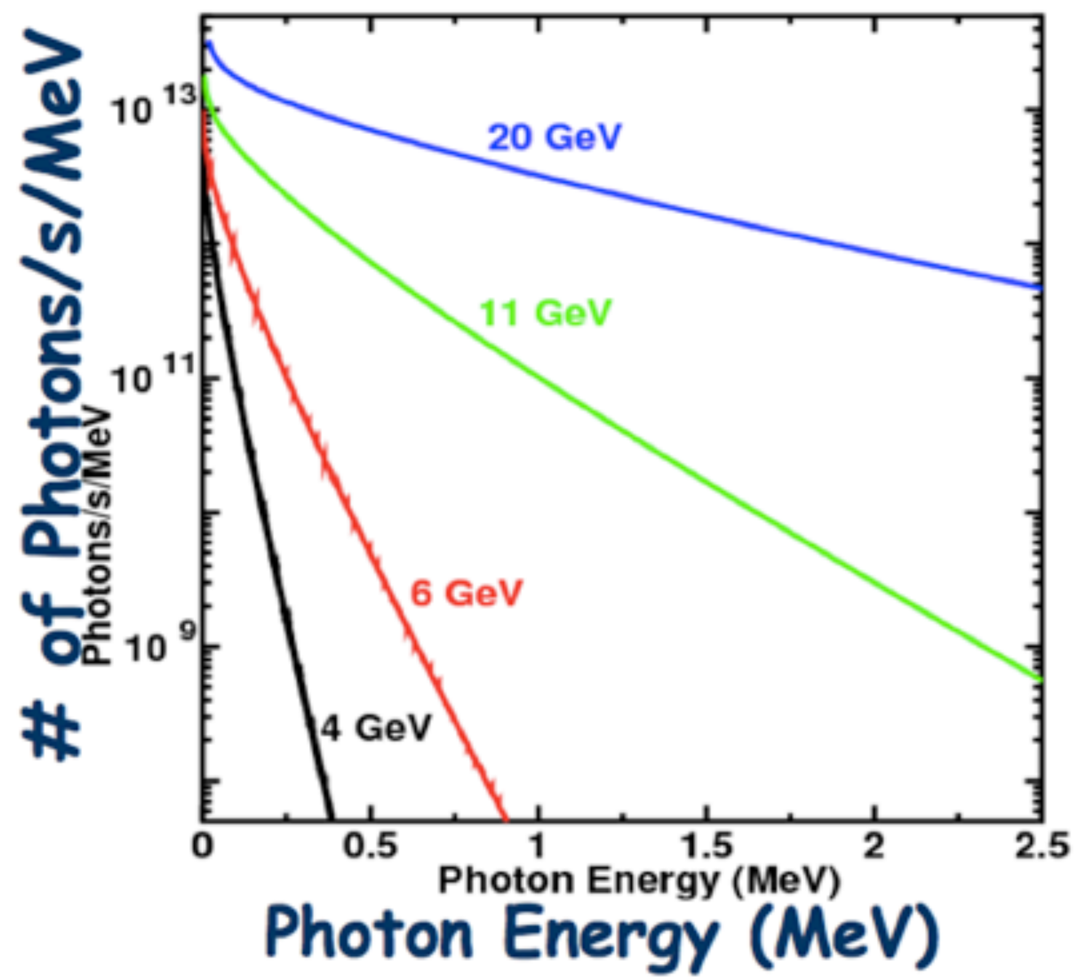
But high rates imply 1% stats in ~ 10 sec

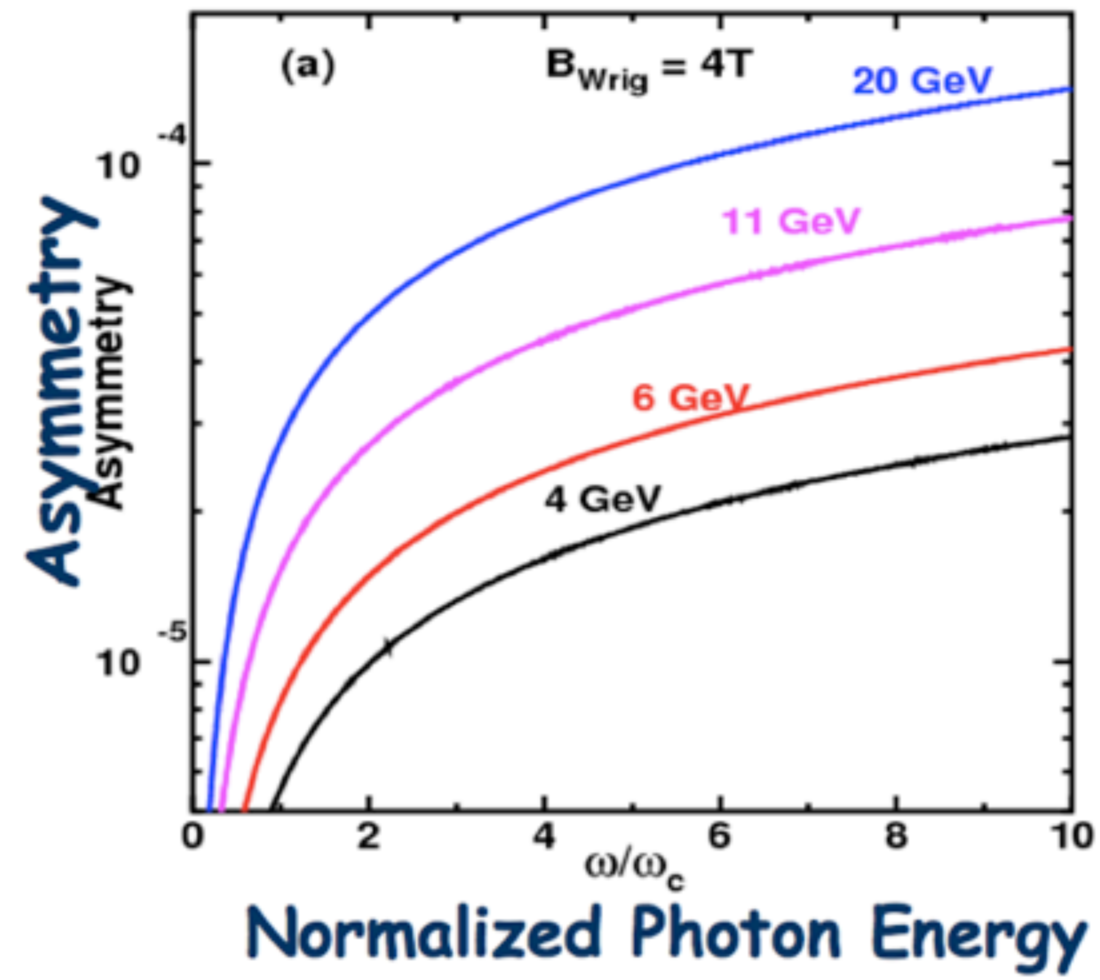
Assuming Ion chambers efficiency ~ 10%



"Spin Light" - Energy dependence

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





# of photons increases sharply with energy but asymmetry increases slowly

Spin light polarimeter would be a relative polarimeter, it will be an integrating device and an averaging device.

Conceptual Design

A Source of Spin Light: a 3 pole wiggler

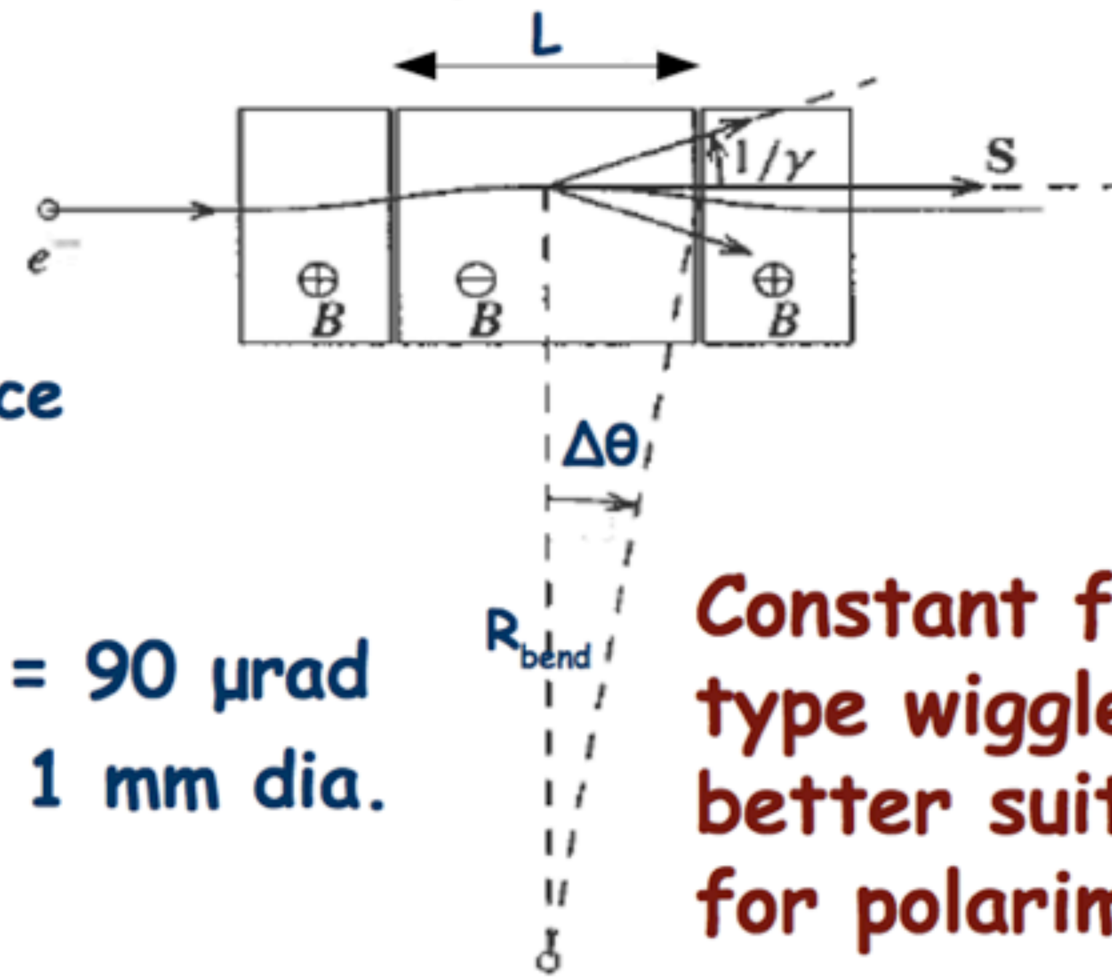
$$R_{bend} = \frac{\gamma m_e c}{e B}$$

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

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.

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



Constant field type wiggler better suited for polarimeter

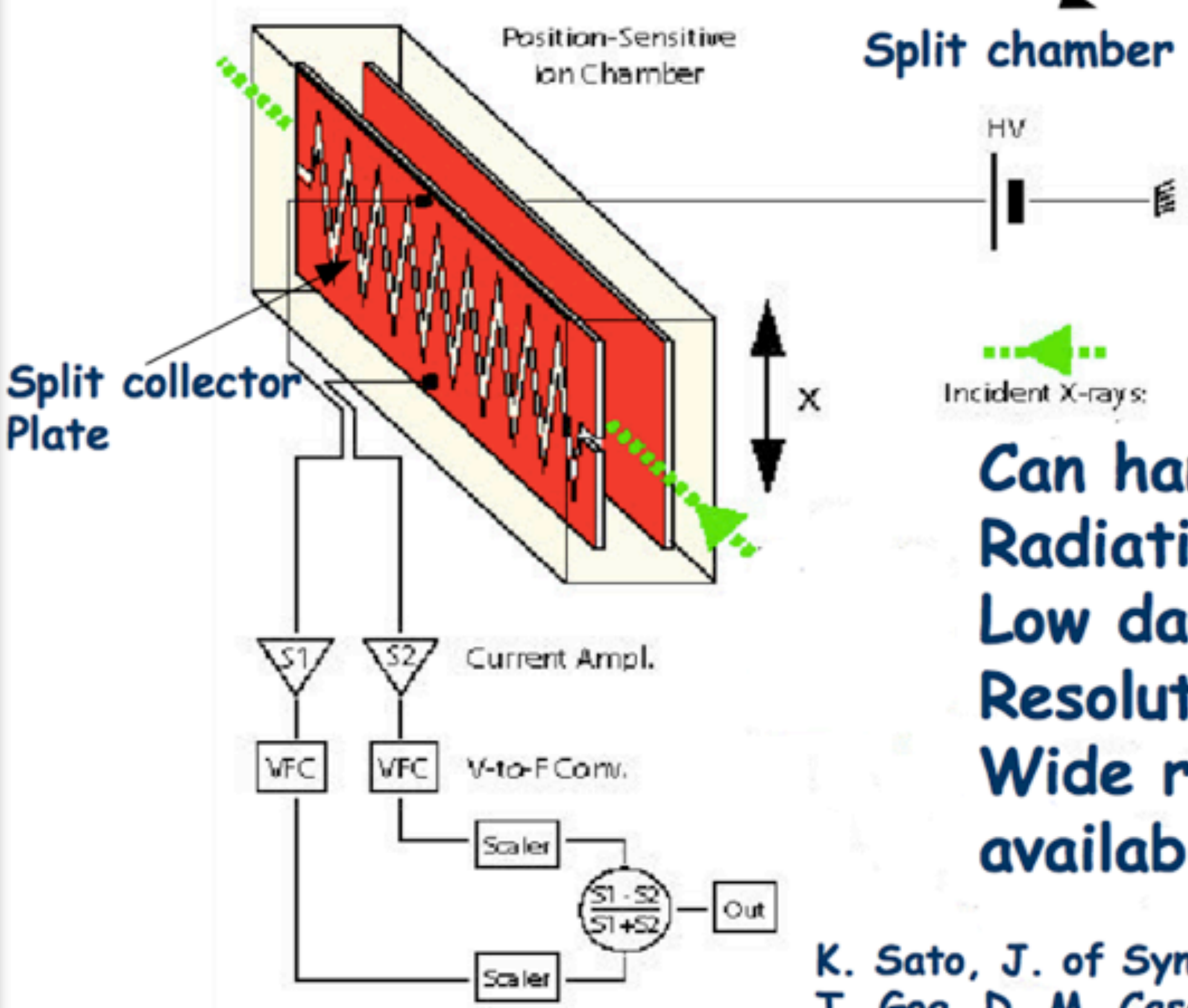
B = 4T is a reasonable choice for field strength

"Spin Light" - Detector

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

A transparent differential ionization chamber

Split chamber design helps pick out small signal



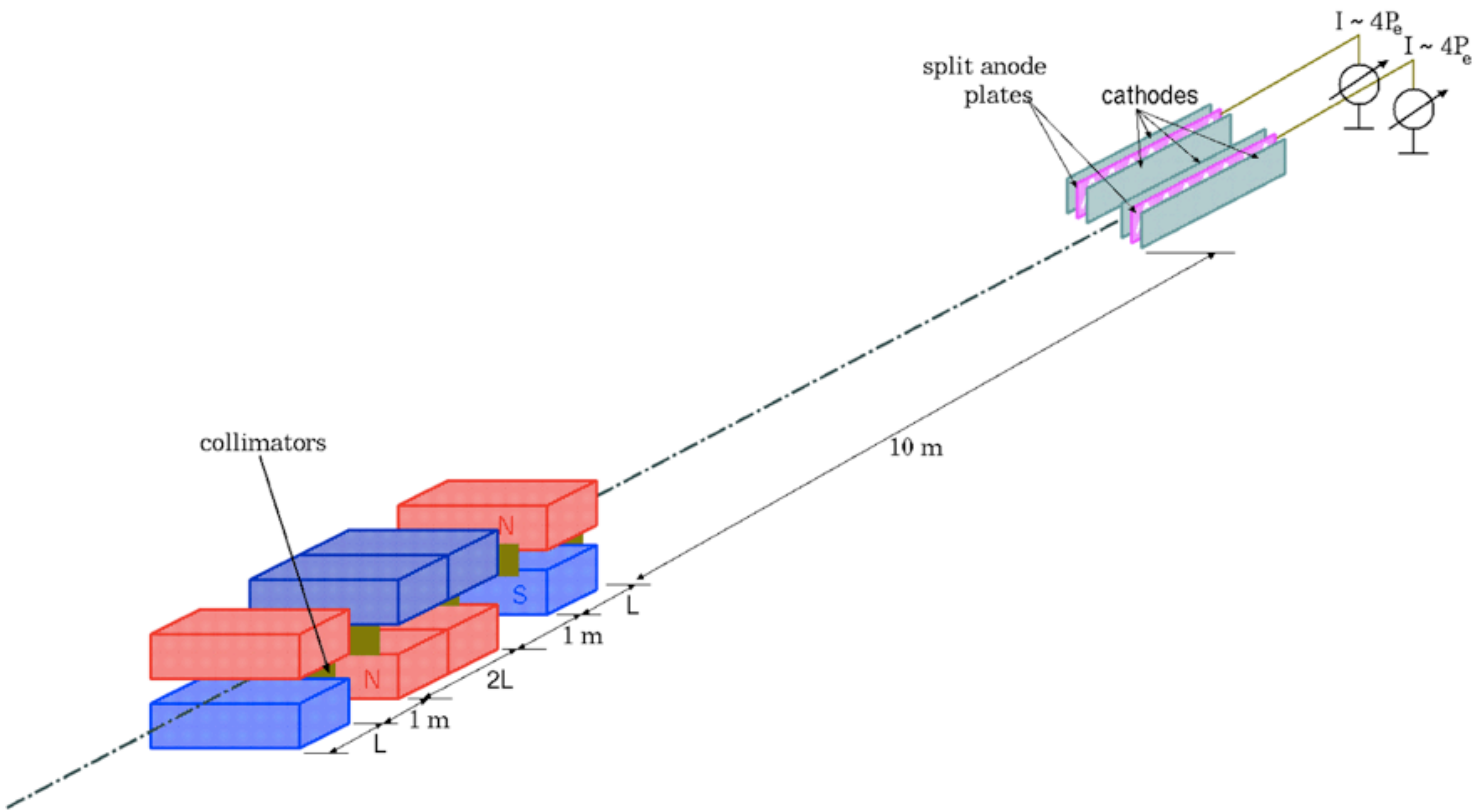
Gas - Xe or Ar

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

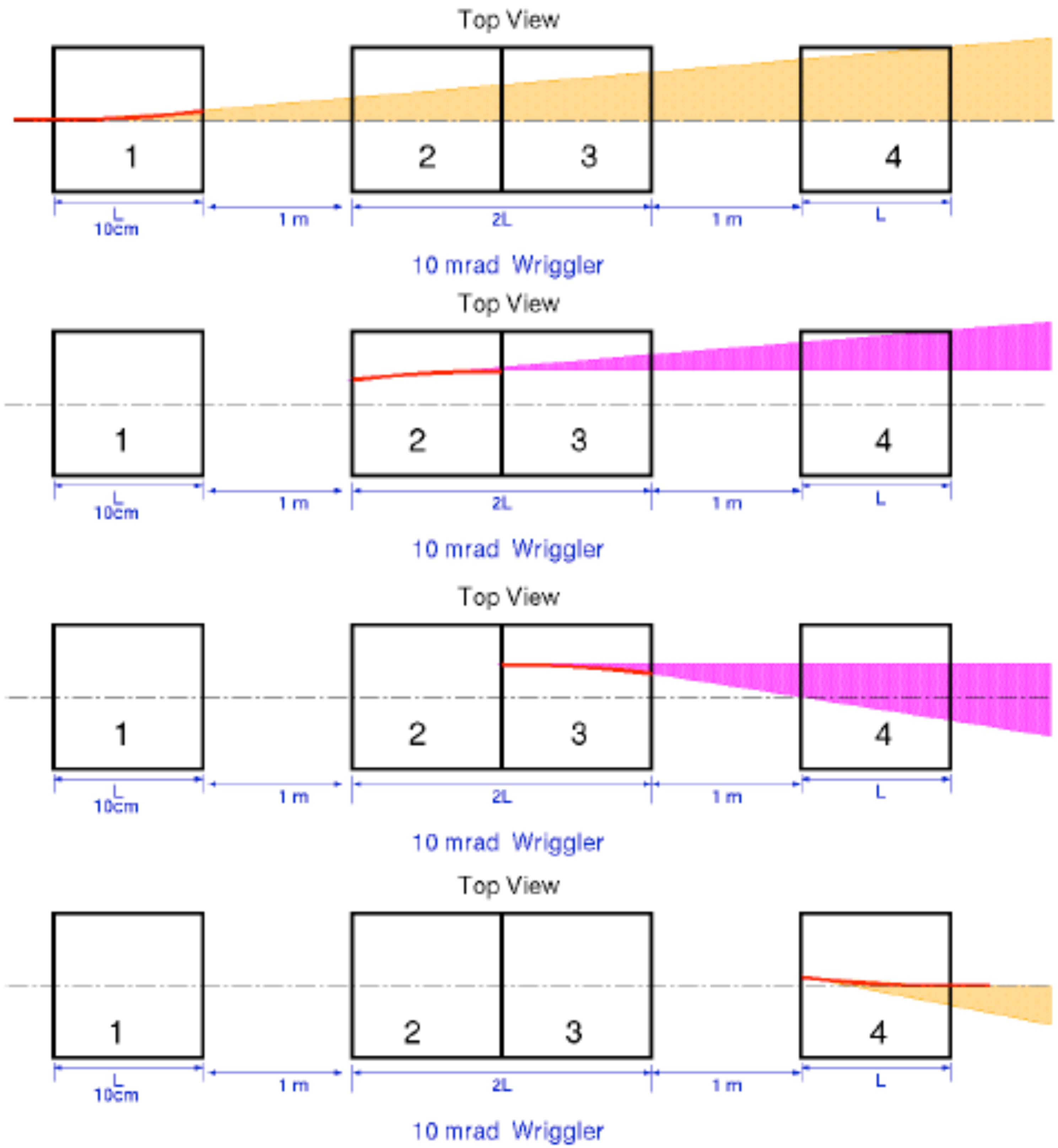
K. Sato, J. of Synchrotron Rad., 8, 378 (2001)
T. Gog, D. M. Casa, I. Kuzmenko, CMC-CAT@ the APS

A "Spin Light" Polarimeter

Putting all the elements together



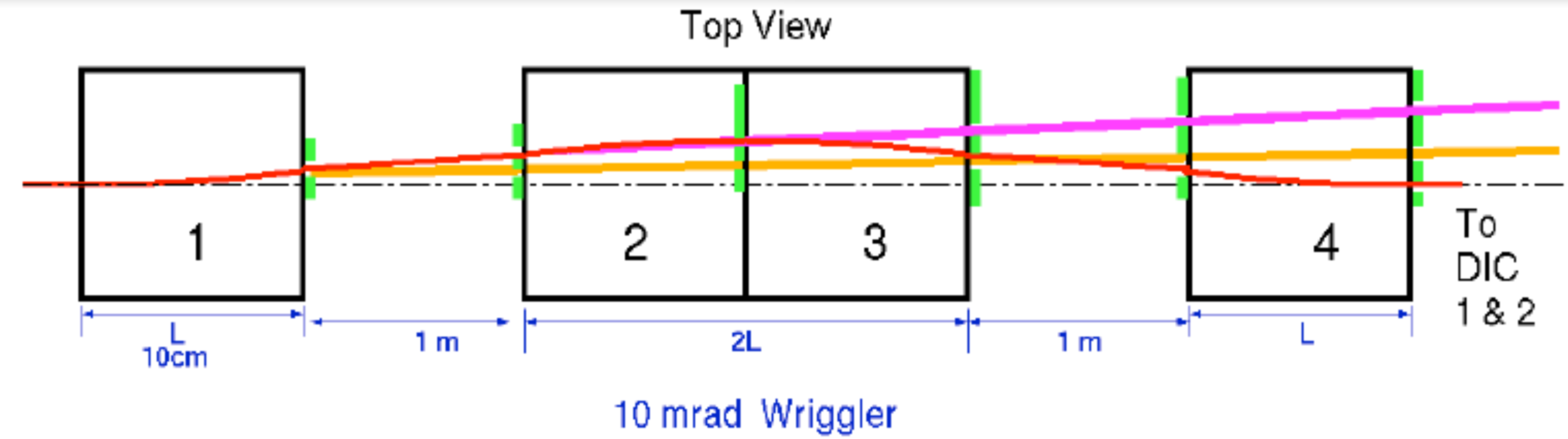
SR from the Wiggler

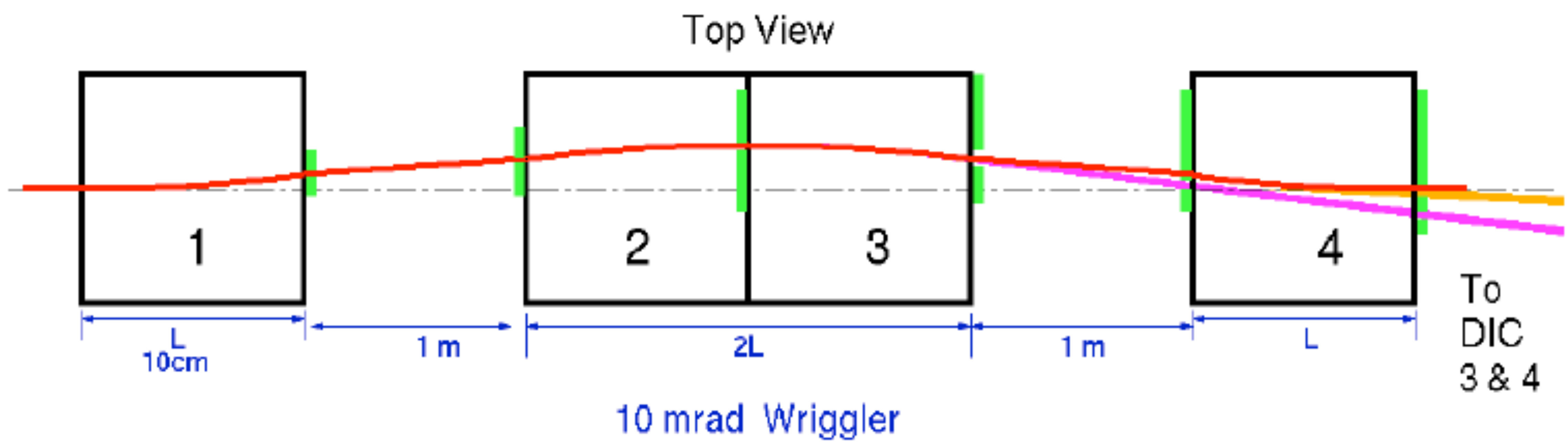


The SR fan for each pole of the wiggler

The sign of the asymmetry flips for pole 2 and 3

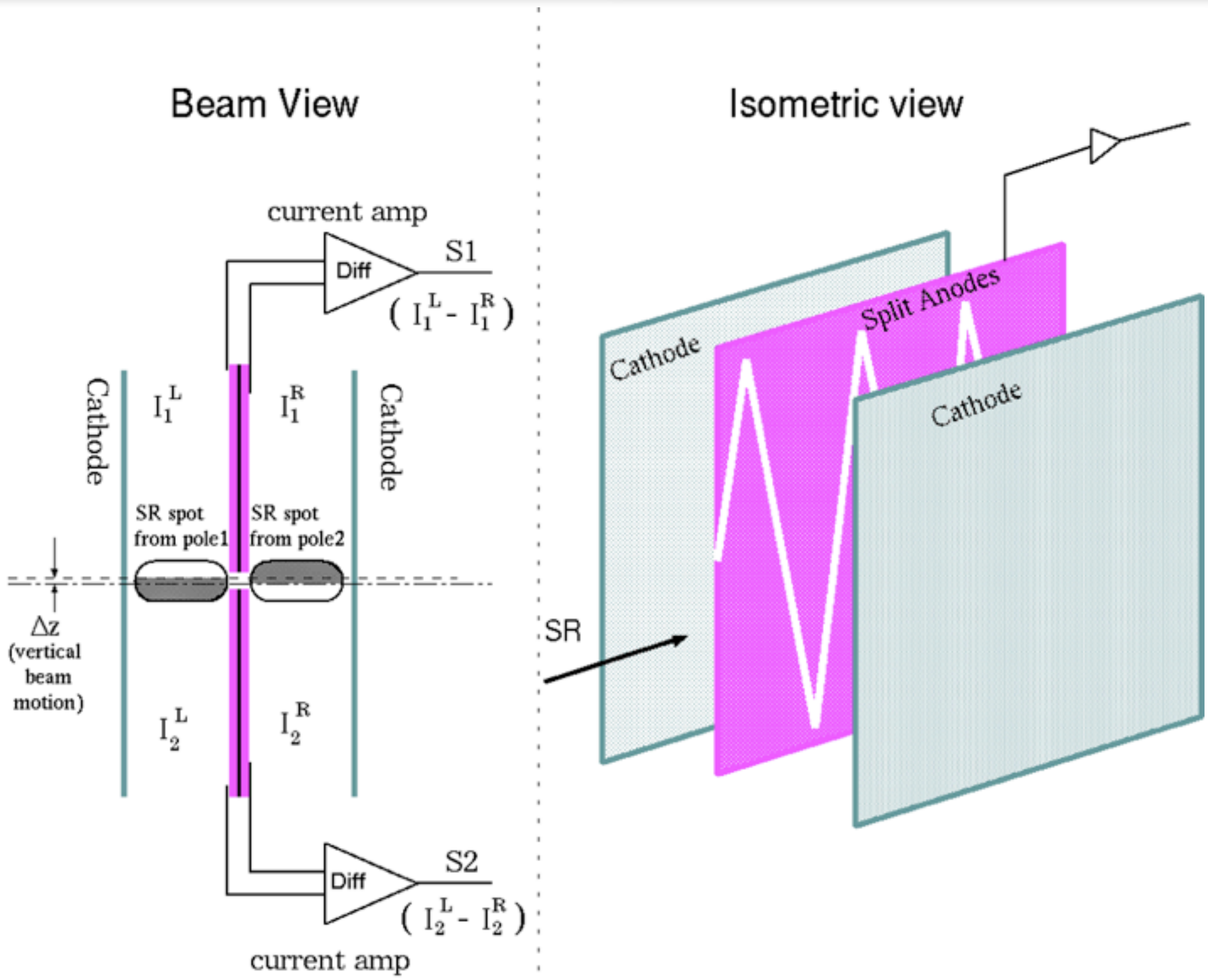
Collimating the SR





A set of slits select unique angular ranges for each pole

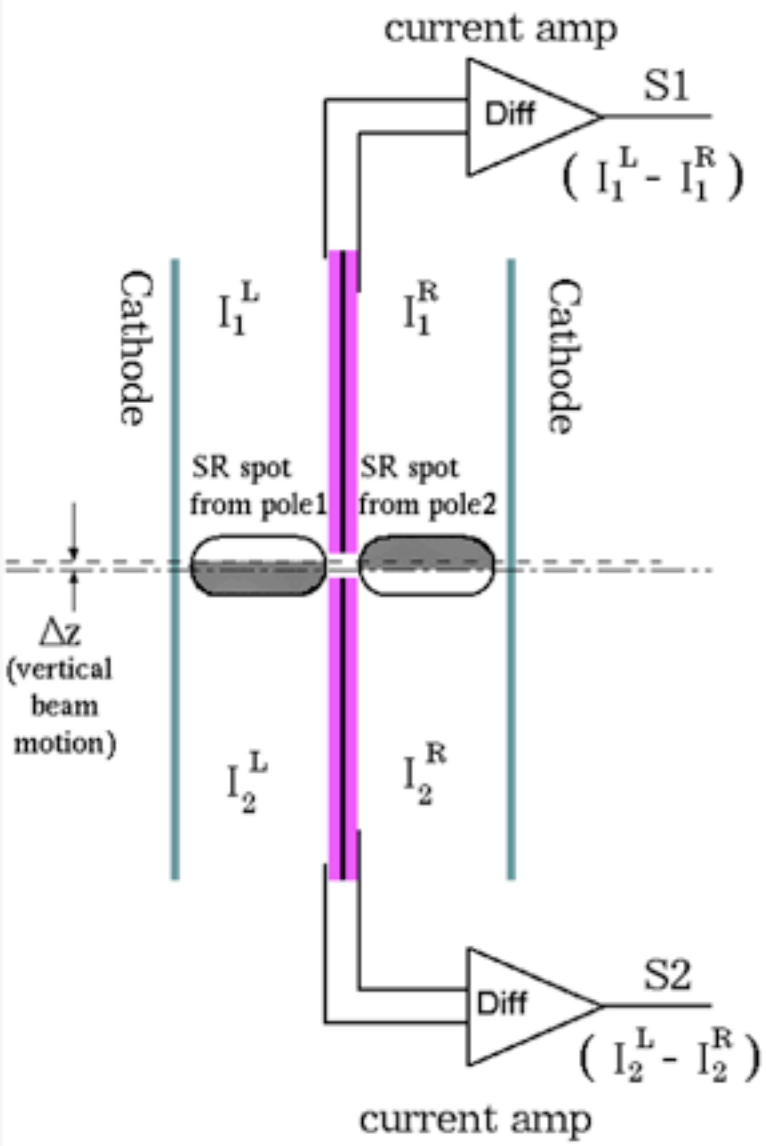
Detecting the Collimated SR



A schematic for detection of SR

The Signal

DIC operated in current mode
Currents ~ 10 nA



$$S1 = I_1^L + I_1^R$$
$$= (N^L_{SR} + \Delta N^L_{spin} + \Delta N^L_z) - (N^R_{SR} - \Delta N^R_{spin} + \Delta N^R_z)$$

Vertical beam motion cancels out

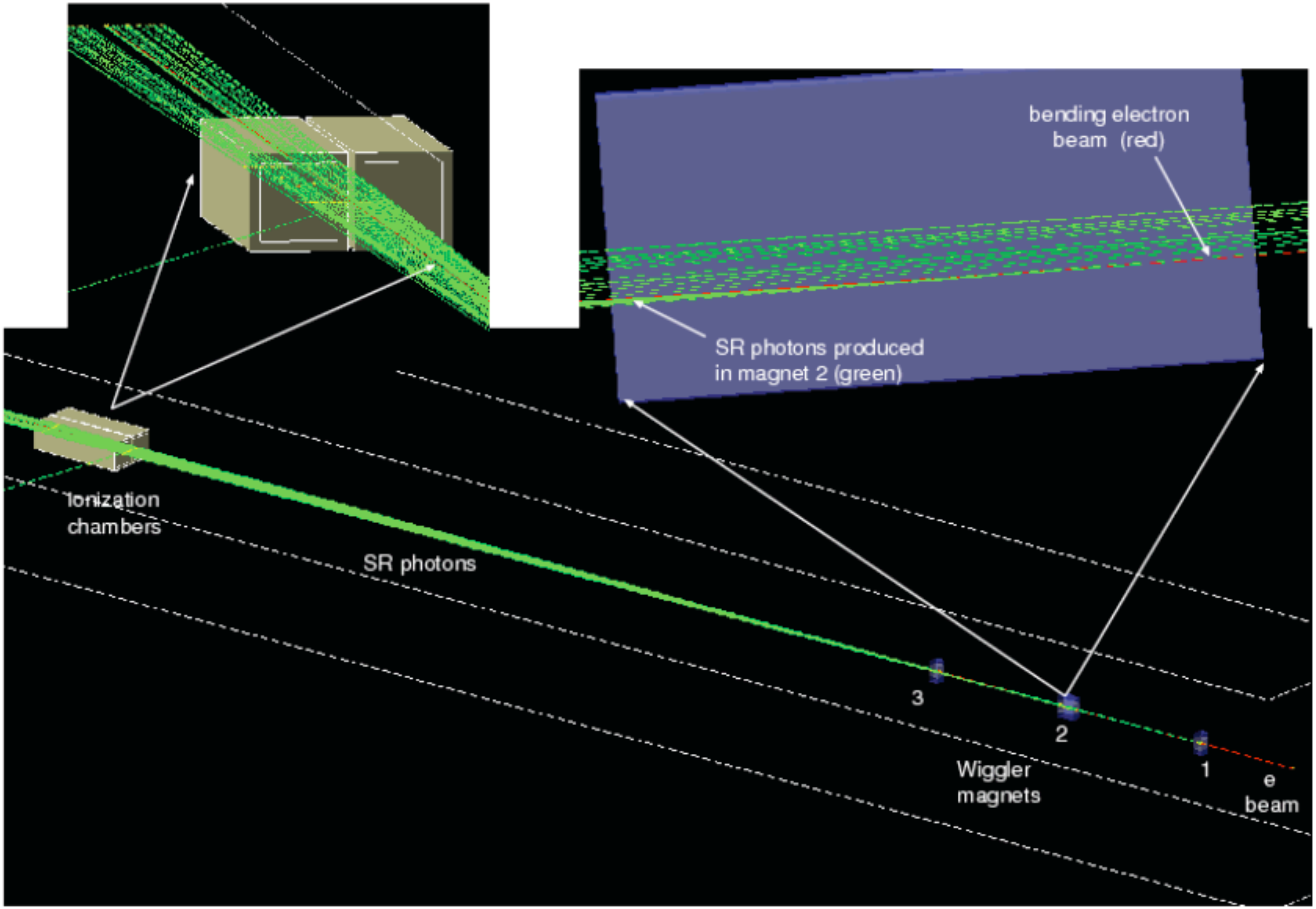
$$(S1 - S2) = 4\Delta N_{spin} \sim 4P_e$$

$$(S1 + S2) = 0$$

Vertical beam motion cancels out

$$S2 = I_2^L + I_2^R$$
$$= (N^L_{SR} - \Delta N^L_{spin} - \Delta N^L_z) - (N^R_{SR} + \Delta N^R_{spin} - \Delta N^R_z)$$

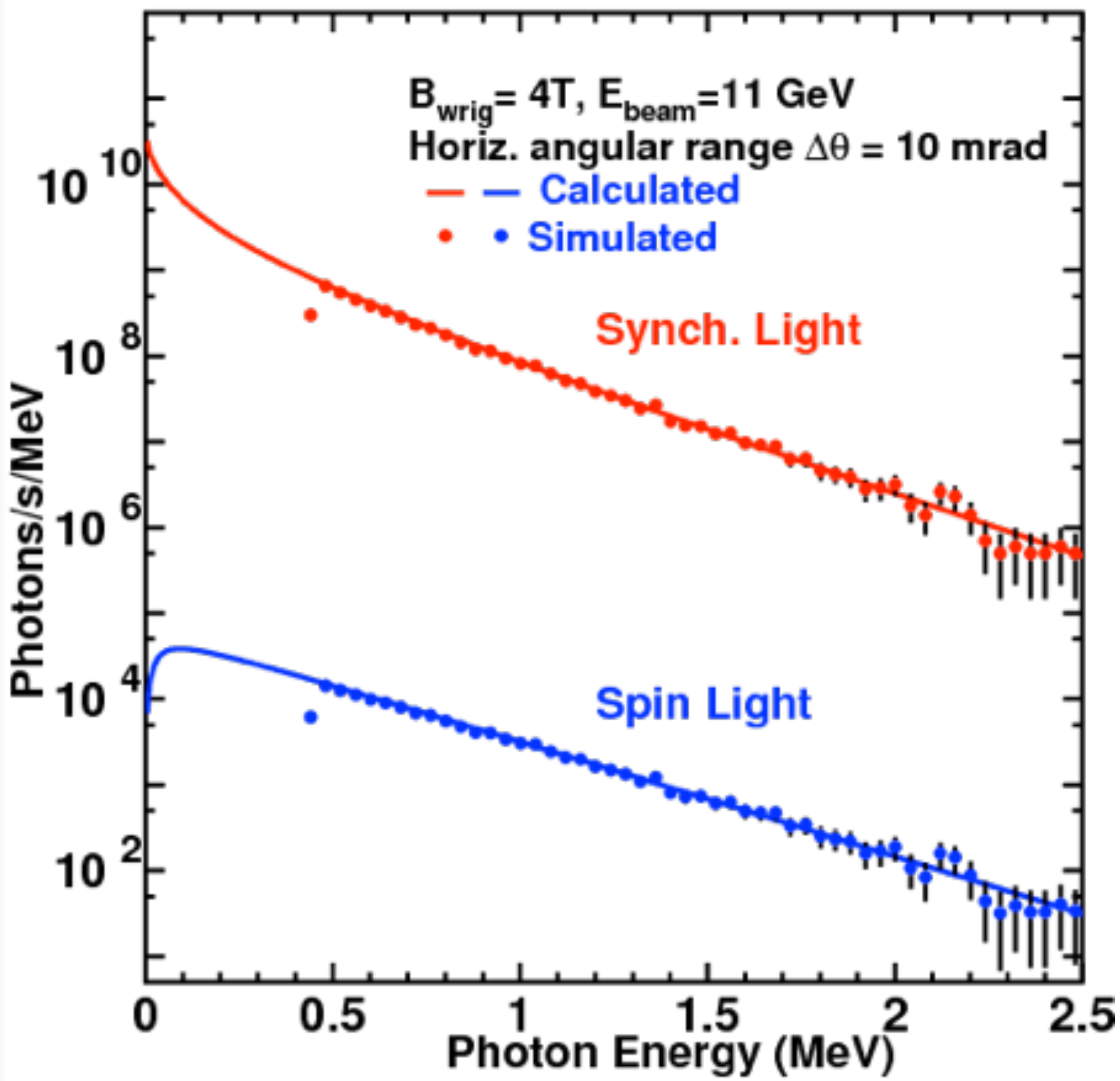
A Geant4 Simulation

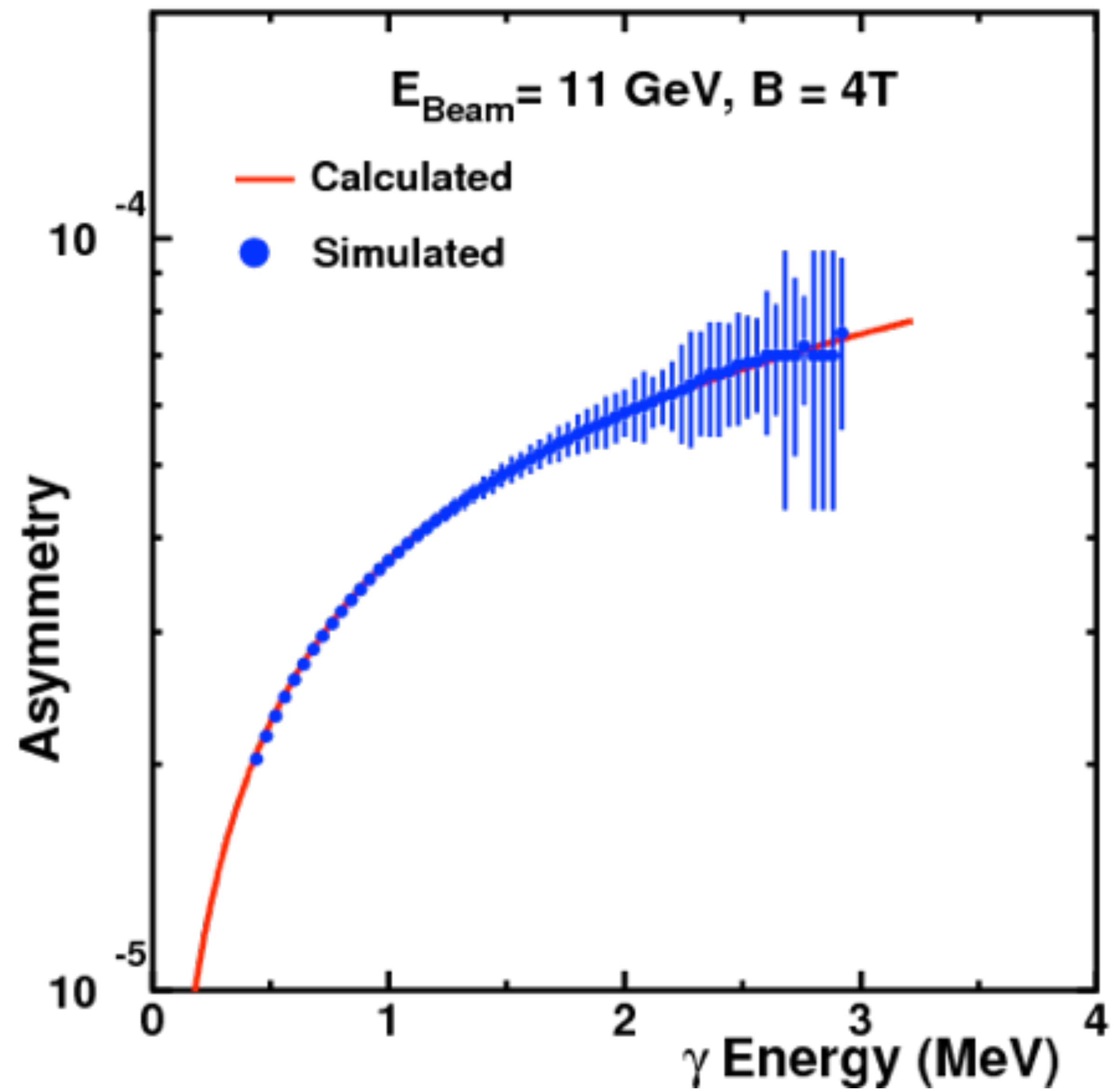


by MSU student; Prajwal Mohanmurthy

A Geant4 Simulation

Simulation reproduces photon spectrum and asymmetry

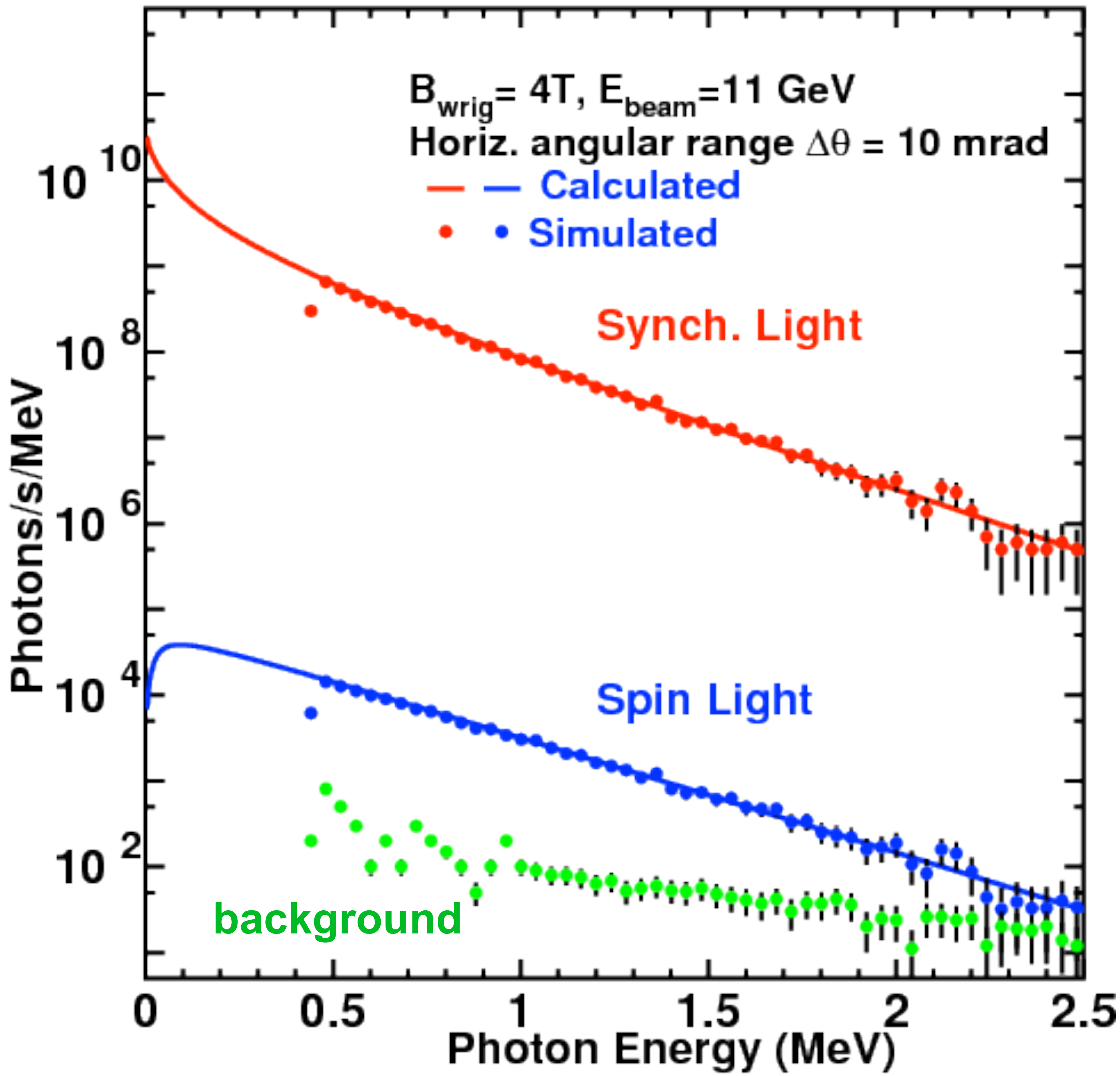




Only a single DIC is being simulated along with collimators

A Geant4 Simulation

Preliminary Background Simulation



Systematic Uncertainties

We have assumed that the electron beam is "parity quality" beam. i.e. helicity correlated beam motion is controlled at the *nm* level and the helicity correlated changes in beam energy are controlled to better than *1 ppb.*

Background and background asymmetry has to be measured with the wiggler on/off

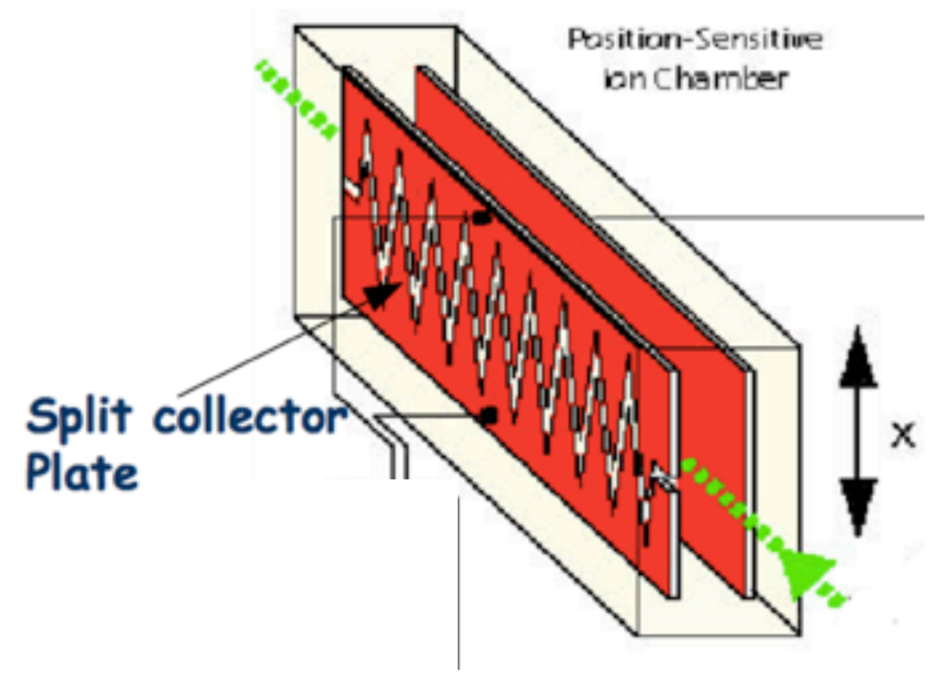
Simulation was used to estimate background

Source	Uncertainty	$\frac{\delta A}{A}$
Dark current	$\sim$ pA	$< 0.01\%$
Intensity fluctuations	$\Delta N \times 10^{-3}$	$<0.1\ \%$
Beam energy	1.0×10^{-3}	$< 0.05\ \%$
Density of chamber gas,	relative difference	$<0.01\%$
Slit width	100 μm	$<0.2\ \%$
Background related dilutions	known to 0.5% for B/S $\sim$ 0.02	0.5 %
Other dilutions	cancel to first order	$< 0.1\%$
Halo contributions	10^{-8}	$< 0.1\ \%$
Total		0.6 %

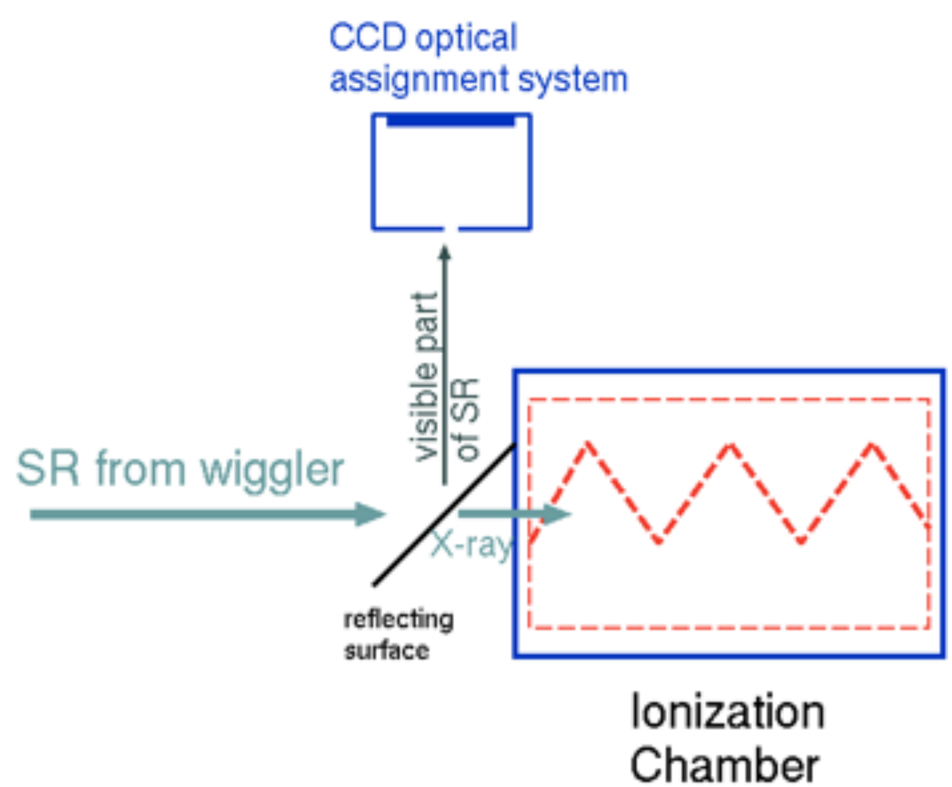
We estimate that a spin-light polarimeter would only be capable of ~ 2.5% absolute polarization measurement.

The Detector R&D Proposal

Stage1: Develop a split plane differential ionization chamber



Stage2: Develop a CCD based alignment system



The Detector R&D Proposal

Stage 3: test the diff. IC and measure position resolution at a light source (APS/ Spring 8)

Stage 4: test the detector with longitudinally polarized electrons at a multi-GeV electron accelerator

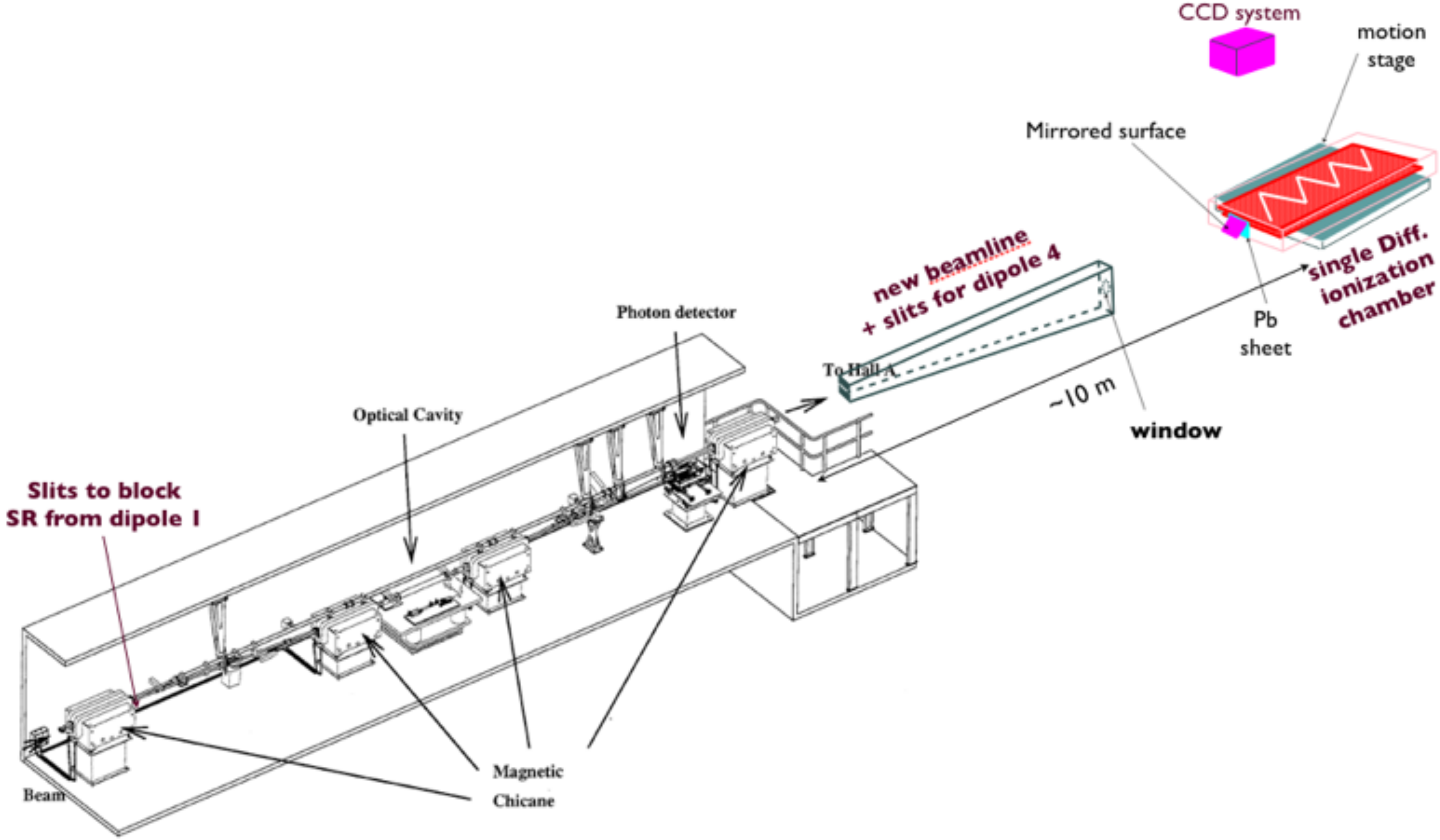


Fig. 14. The Compton Polarimeter Setup at TJNAF Hall A. Total length 15 m.

Students and Postdocs

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

Grad Students: Yipeng Jiang (MSU) and Valerie Gray (W&M) and MSI student(s) (Stony Brook U.)

Under Grad Students: Prajwal Mohanmurthy (MSU) (worked on Geant4 simulation)

Postdoc: Mitra Shabestari (MSU, 50% FTE)

Funding Request

Item	Year 1	Year 2	Year 3	Total
0.5 Post-doc (MSU)	\$40k	\$40k	\$40k	\$120k
0.5 Grad student (W&M)	\$17k	\$17k	\$ 17k	\$51k
Equipment	\$30k	\$43k	\$18k	\$97k
Travel	\$10k	\$10k	\$10k	\$30k
Total	\$97k	\$110k	\$85k	\$292k

Summary

- Spin light based polarimetry 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 at light sources across the world.
- We propose to develop a split plane ionization chamber and demonstrate proof of principle for longitudinally polarized electrons.

Project Timeline

Activity	Year 1	Year 2	Year 3
Design and build prototype DIC	√	√	
Test prototype DIC at the APS		√	
Design and build slits and collimators			√
Test DIC in Hall A Compton beamline (or equivalent)			√
Design CCD based alignment system	√	√	
Build CCD system		√	
Design wiggler magnet			√
Identify suitable wiggler magnet at the APS			√

Equipment Budget

Equipment	Yr 1	Yr 2	Yr3	Total cost
prototype DIC	10000			10000
Split plane electrodes	5000			5000
Electronics for DIC(2 channels)				
current amps		8000		8000
High voltage power supplies		5000		5000
V-to-Fs and scalers		9000		9000
VME crate		10000		10000
Single board computer		7000		7000
Gas Handling system		5000		5000
Custom beamline vacuum elements			10000	10000
slits and collimators			8000	8000
CCD alignment system				
motion stage, controller and driver (1)	8000			8000
high resolution CCD imager and fast readout (2)	4500			4500
light transport optics (2)	2500			2500
Total Equipment Cost	30000	43000	18000	91000

Photon Absorption