Development of a Spin-Light Polarimeter for the EIC

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EIC Detector R&D Annual Meeting

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The Collaboration

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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
- Synchrotron Radiation

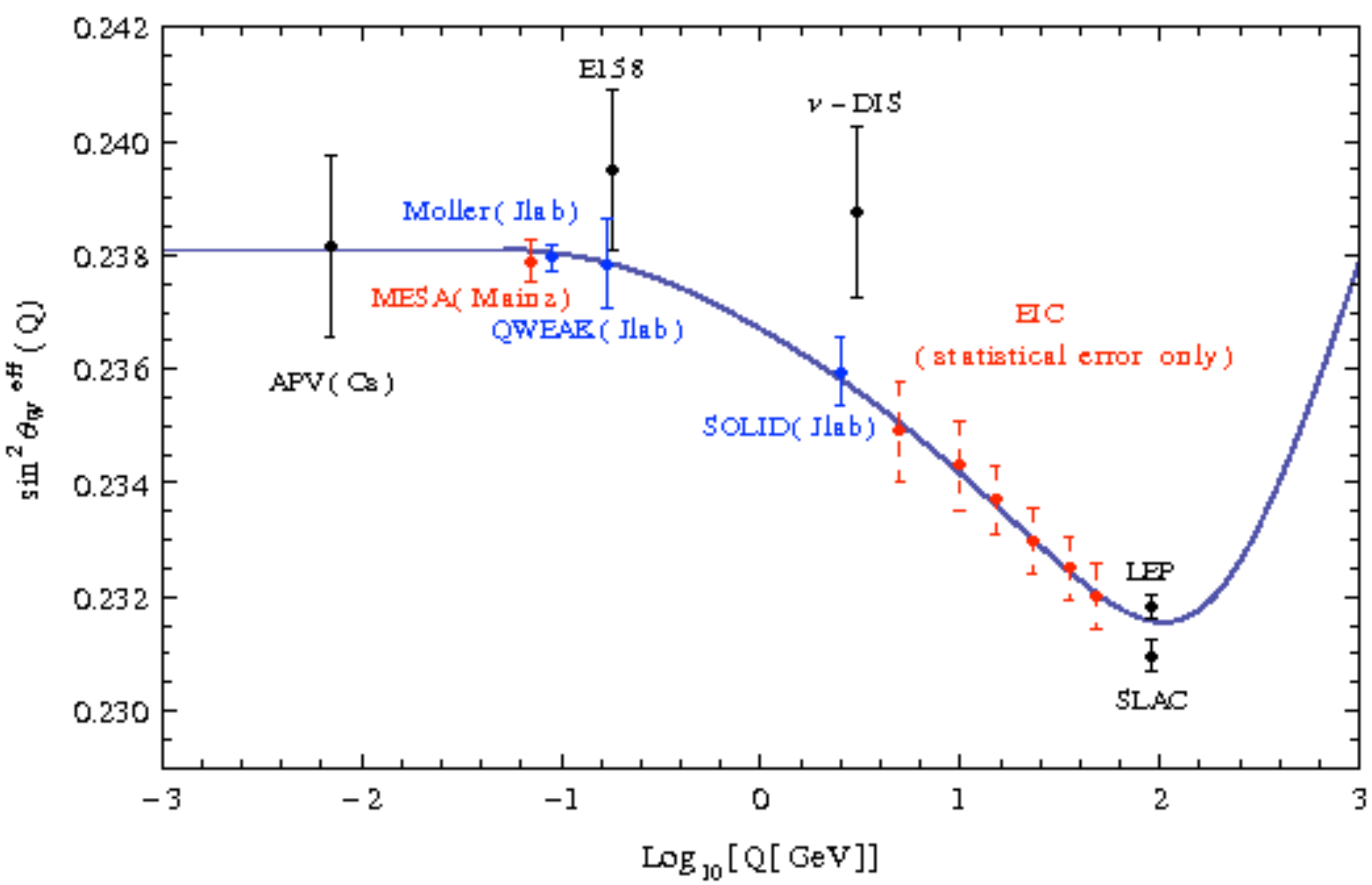
  Classical & Quantum description

- "Spin-Light"
- Conceptual Design of a "Spin-Light" polarimeter   Including Geant4 simulations
- 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 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

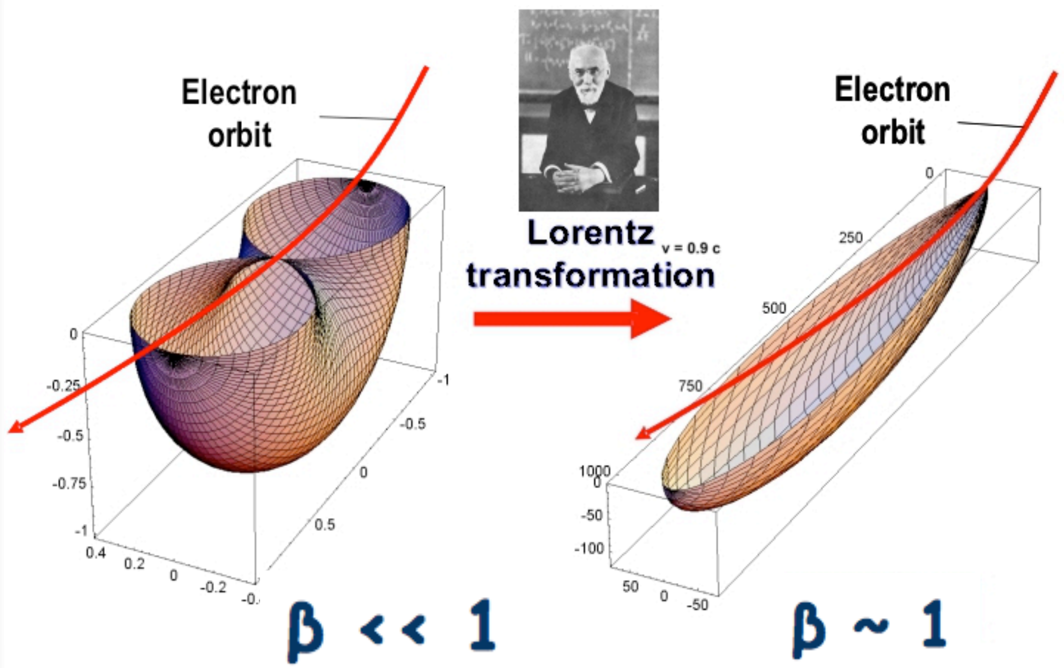
Sub-1% polarimetry requires multiple independent measurements of the beam polarization.

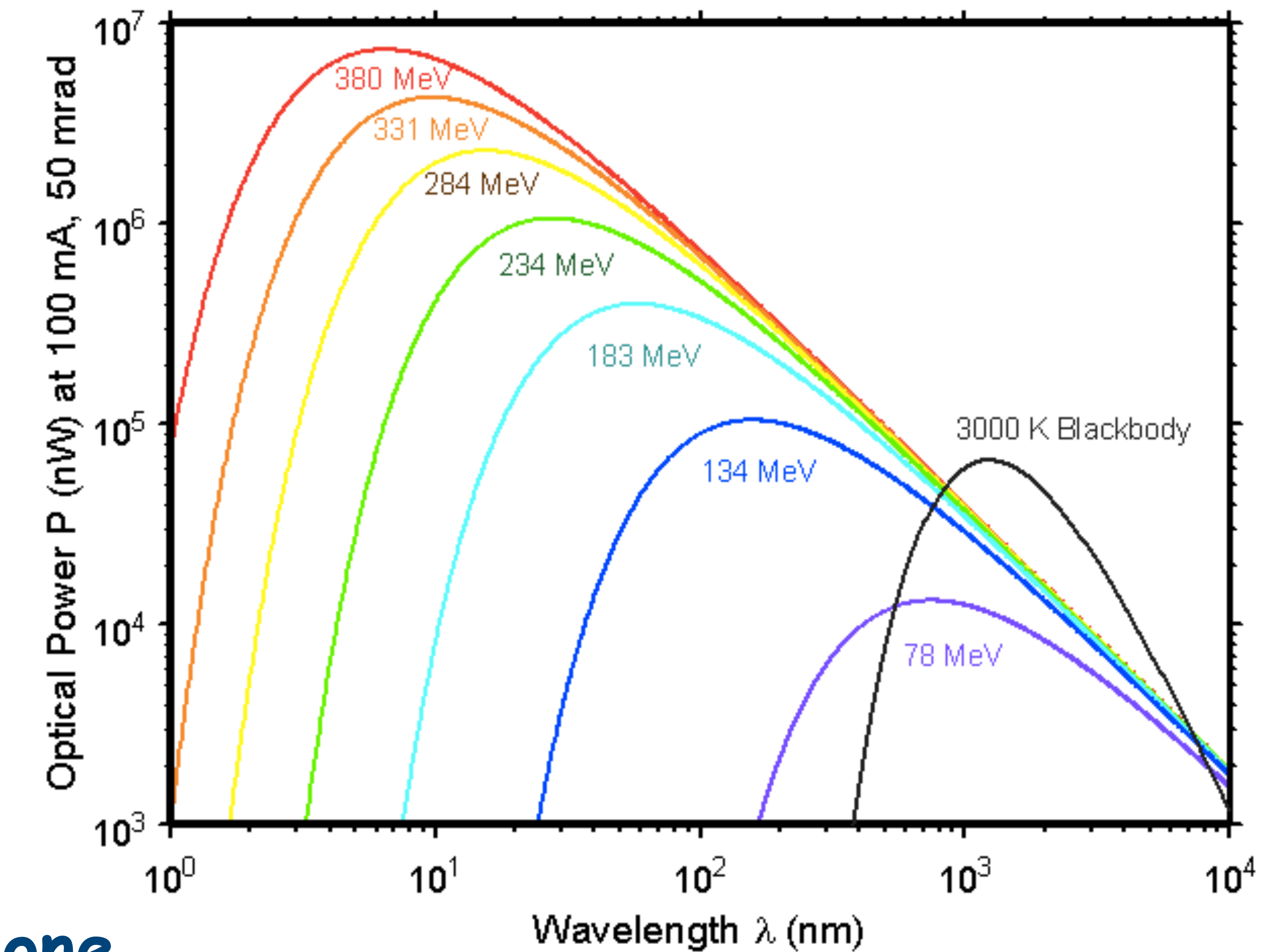
- **A Spin-light polarimeter is complimentary to the more popular Compton & Möller polarimeters.**
- **It will provide an independent measurement with completely different systematics**

Compton	Spin-Light	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	-	-

Synchrotron Radiation - "Electronic light"

The angular and spectral distribution is accurately described in classical E&M





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.

The Spin Dependence

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

QED corrections → spin dependence of the radiated power $B_{crit} \sim 4\times10^{9}$ T

$$\xi = \frac{3}{2}\frac{B}{B_{crit}}\gamma$$

For $\xi \ll 1$ and electron spin j, j' = ± 1

$$P = P^{Clas}\left[\left(1 - \frac{55\sqrt{3}}{24}\xi + \frac{64}{3}\xi^2\right) - \underbrace{\left(\frac{1+jj'}{2}\right)\left(j\xi + \frac{5}{9}\xi^2 + \frac{245\sqrt{3}}{48}j\xi^2\right)}_{\text{spin dependent term}} + \underbrace{\left(\frac{1-jj'}{2}\right)\left(\frac{4}{3}\xi^2 + \frac{315\sqrt{3}}{432}j\xi^2\right)}_{\text{spin-flip dependent term}} + \ldots\right]$$

spin dependent term

spin-flip dependent term

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)

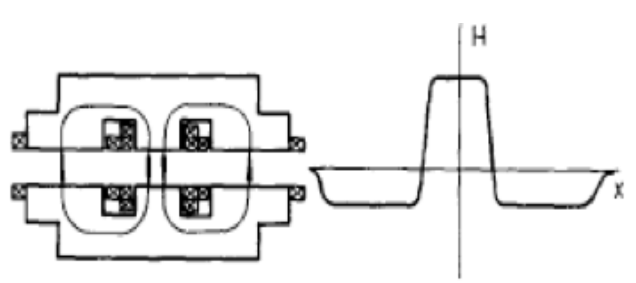


Fig. 1. The field vs the current in the 'snake'. A schematic of the 'snake' and the field distribution along its axis are shown below.

3 pole magnetic snake/wriggler

An RF field used to depolarize the electron

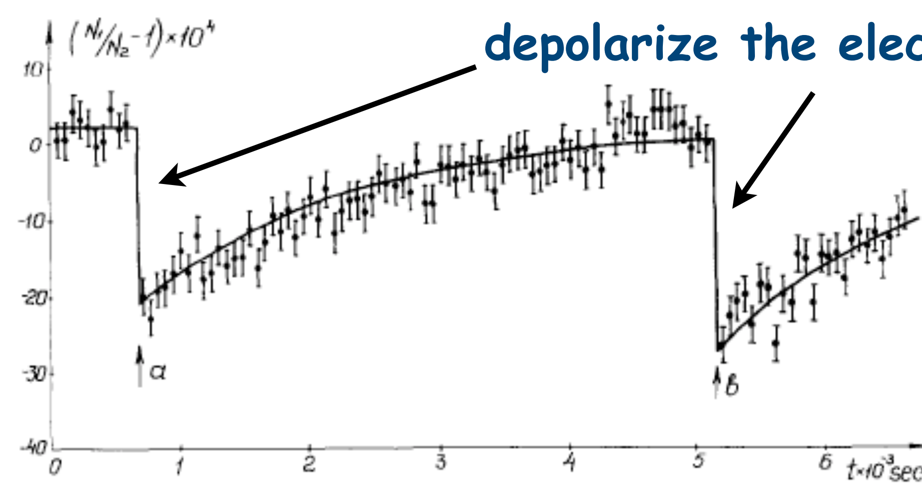


Fig. 12. The measurement results of the SR-intensity as a function of the degree of polarization of the beam. The field in the 'snake' coincides, in direction, with the storage ring guiding field. At points a and b one of the bunches (N_1), was quickly depolarized. The measurement time at a point is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

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

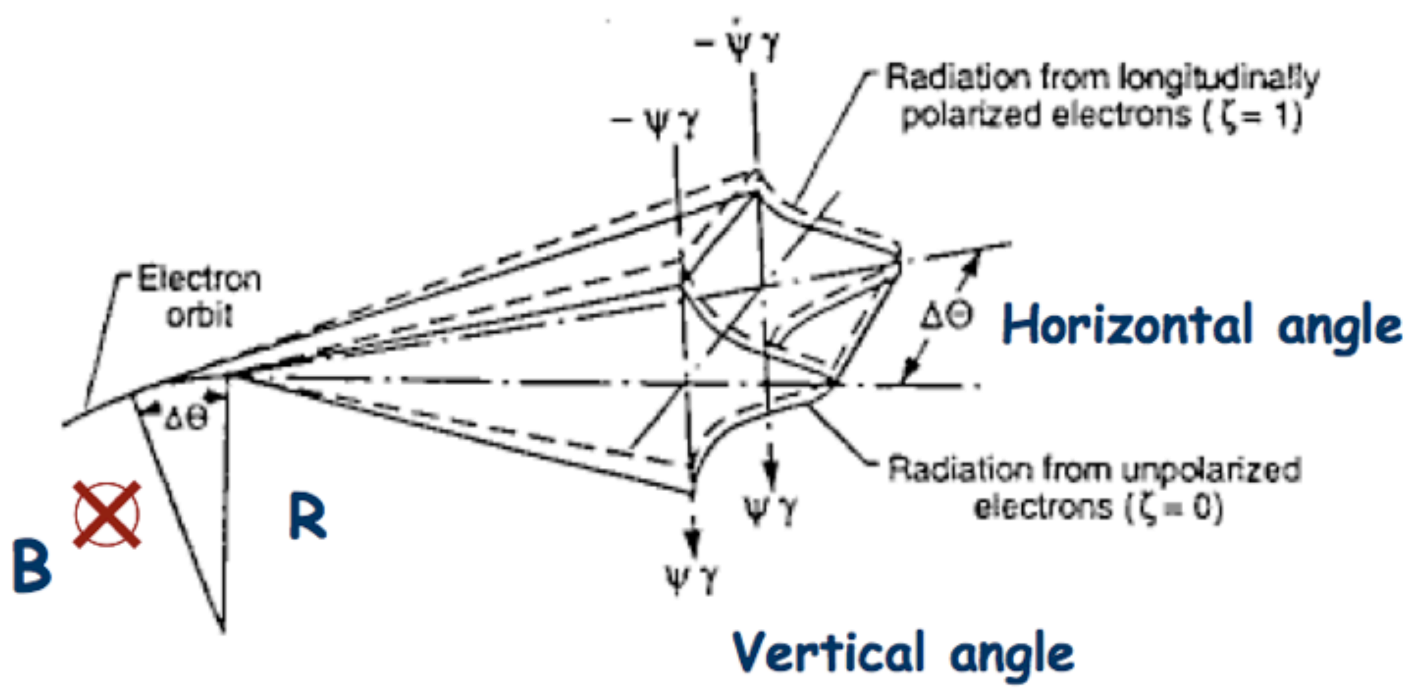


Figure 1: Geometrical definitions.

"Spin Light" - Some Characteristics

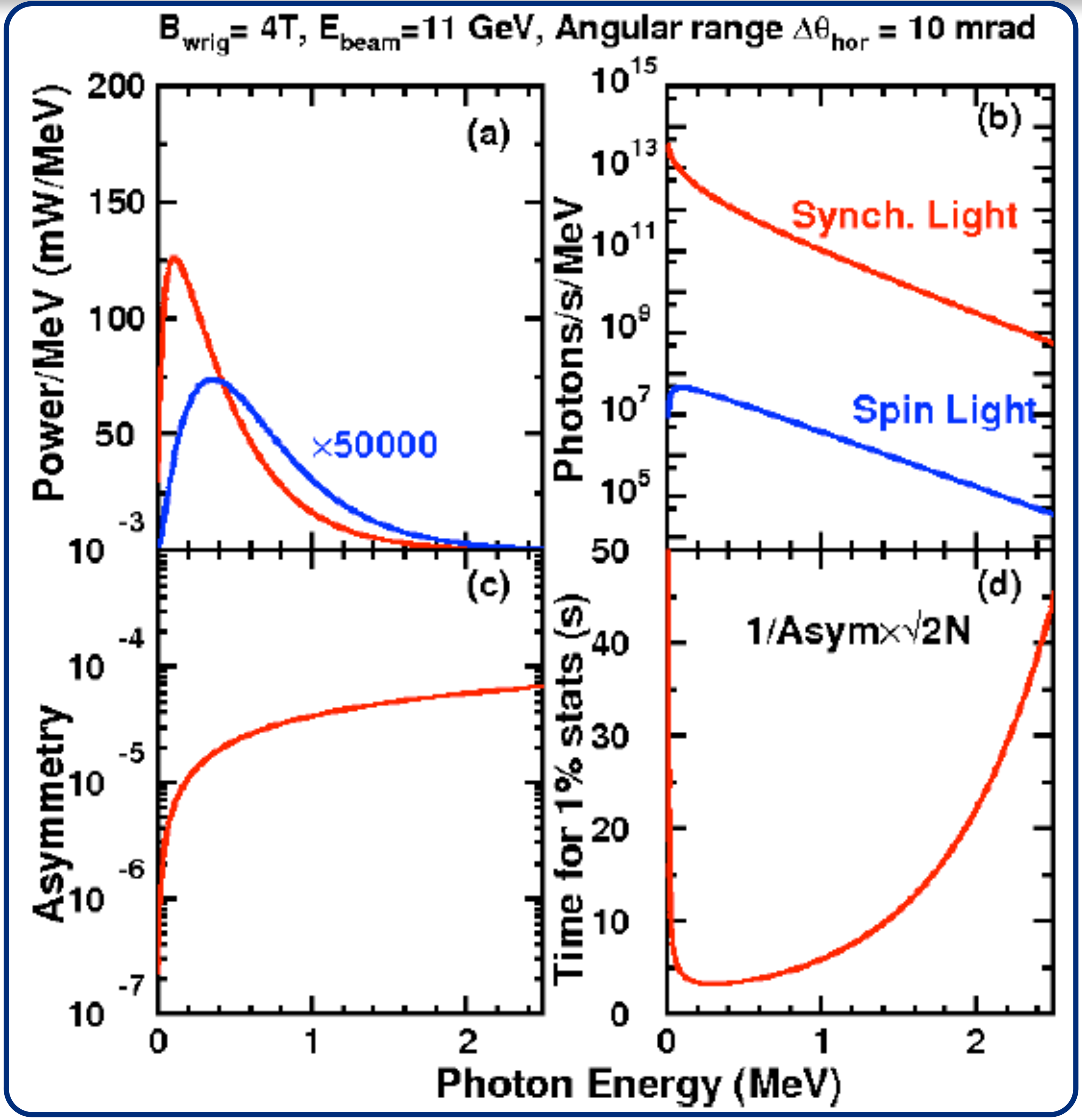
Sync and Spin light peak at different energies

Number of photons/s ~ 10^5 different

small asymmetry

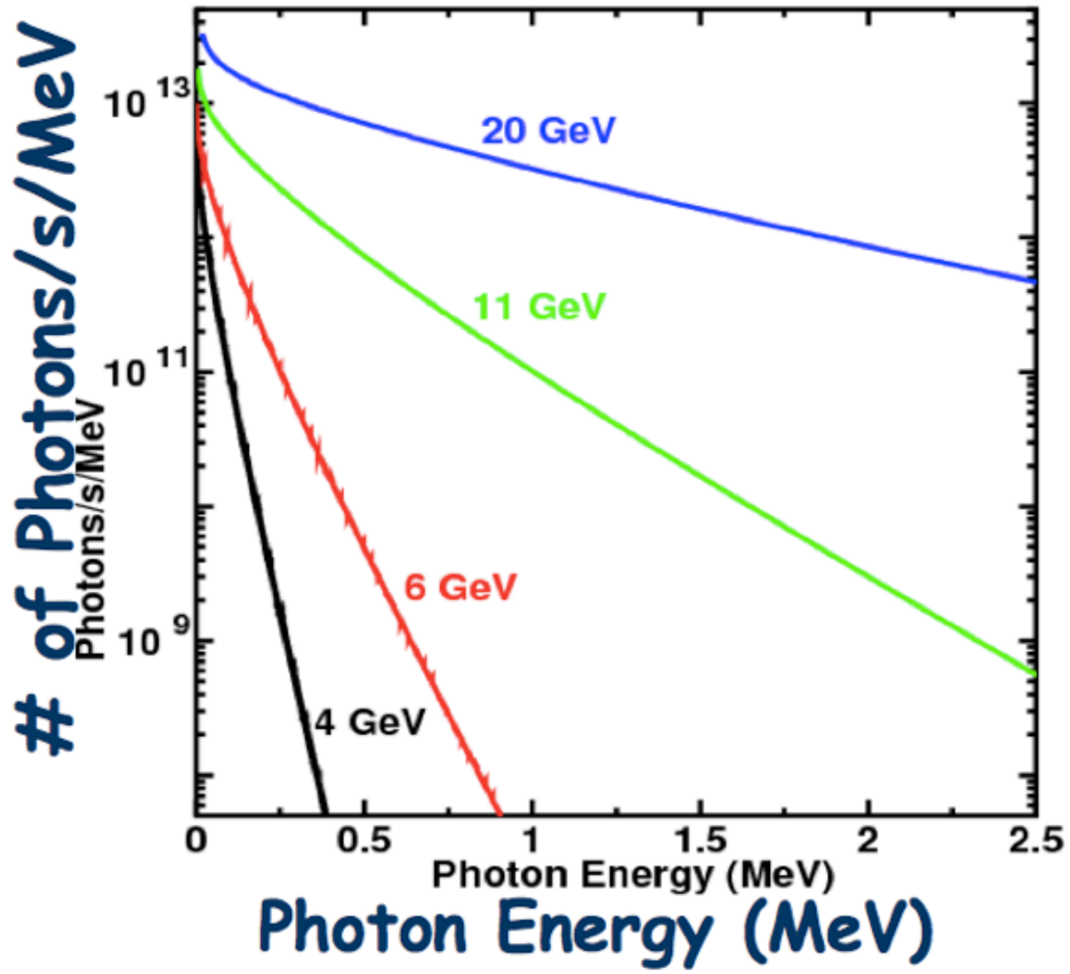
But high rates imply 1% stats in ~ 10 sec

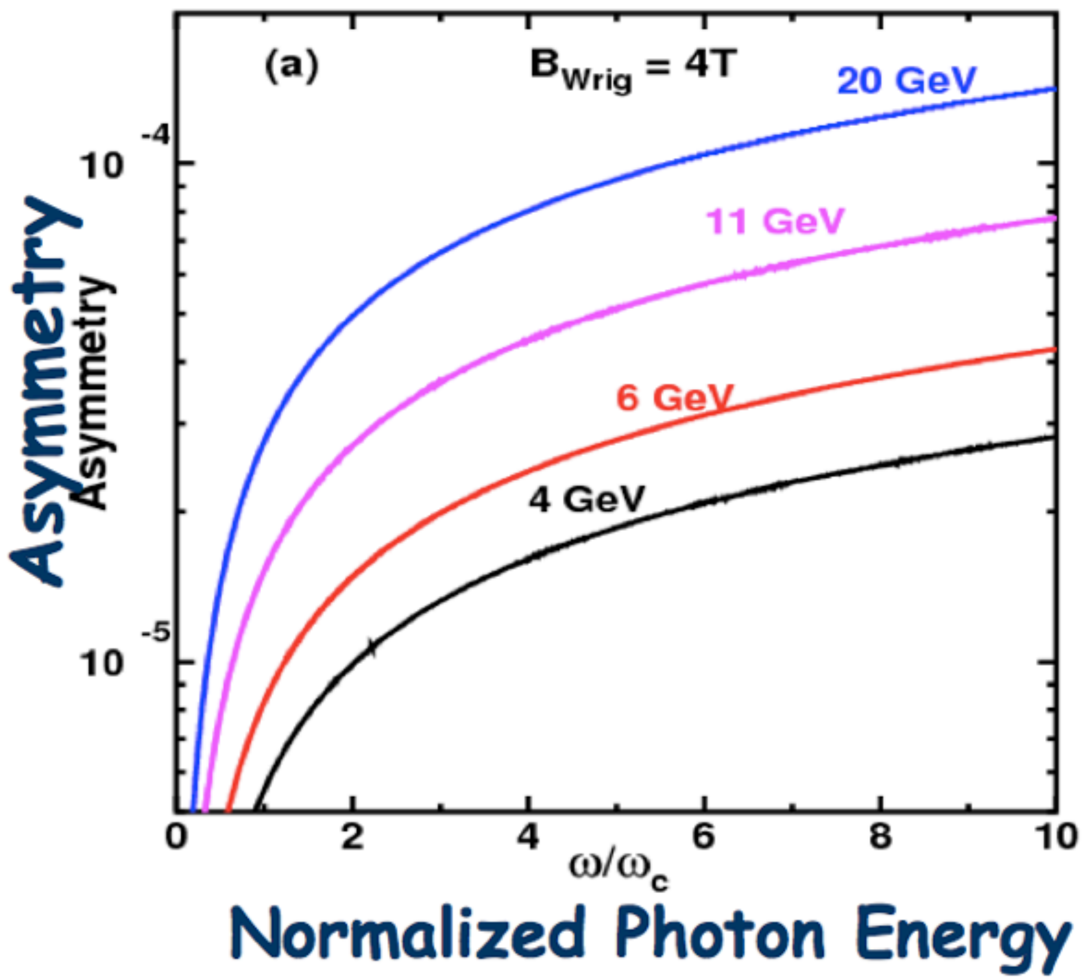
Assuming Ion chambers efficiency ~ 10%



"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

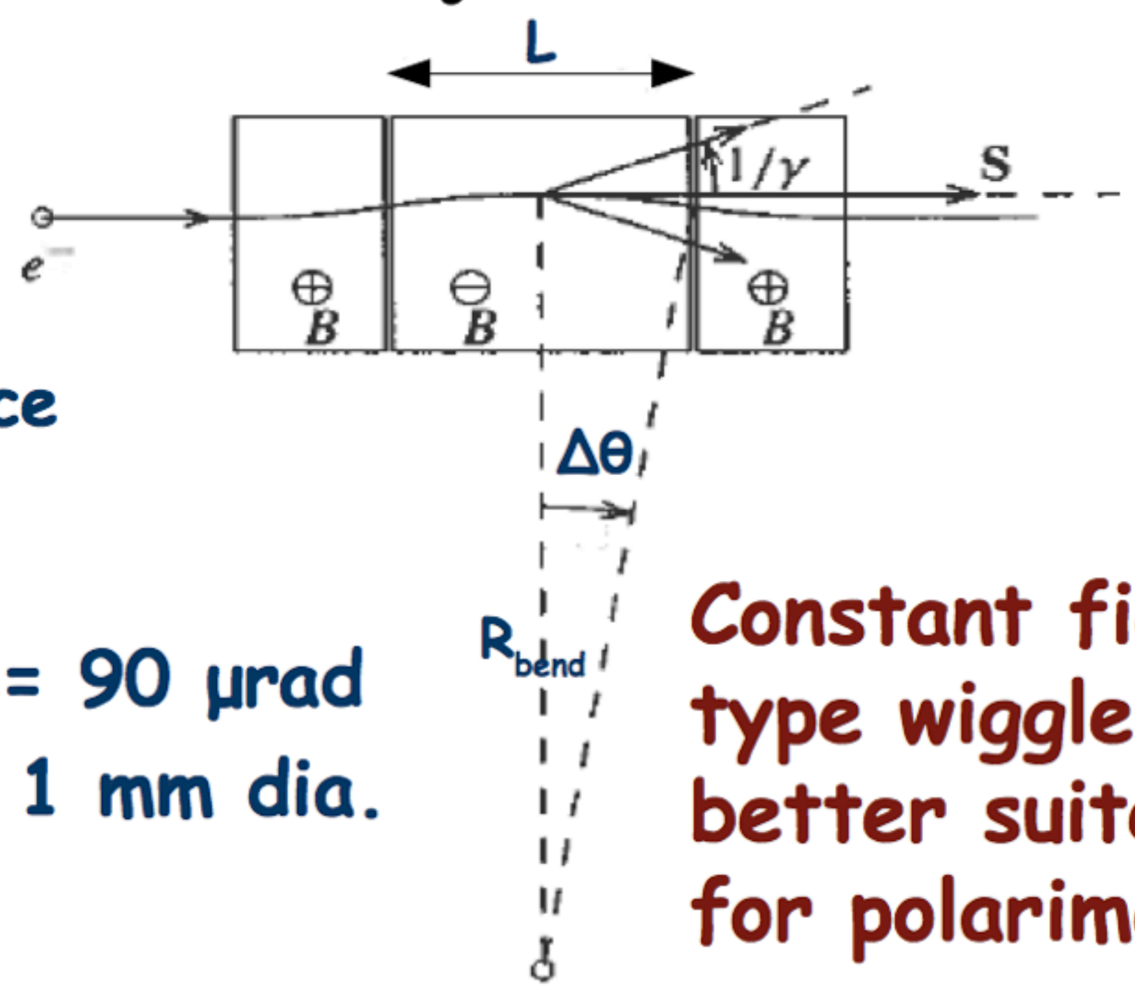
$$R_{bend} = \frac{\gamma m_e c}{e B}$$

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

Horizontal angular acceptance
$\Delta\theta$ 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

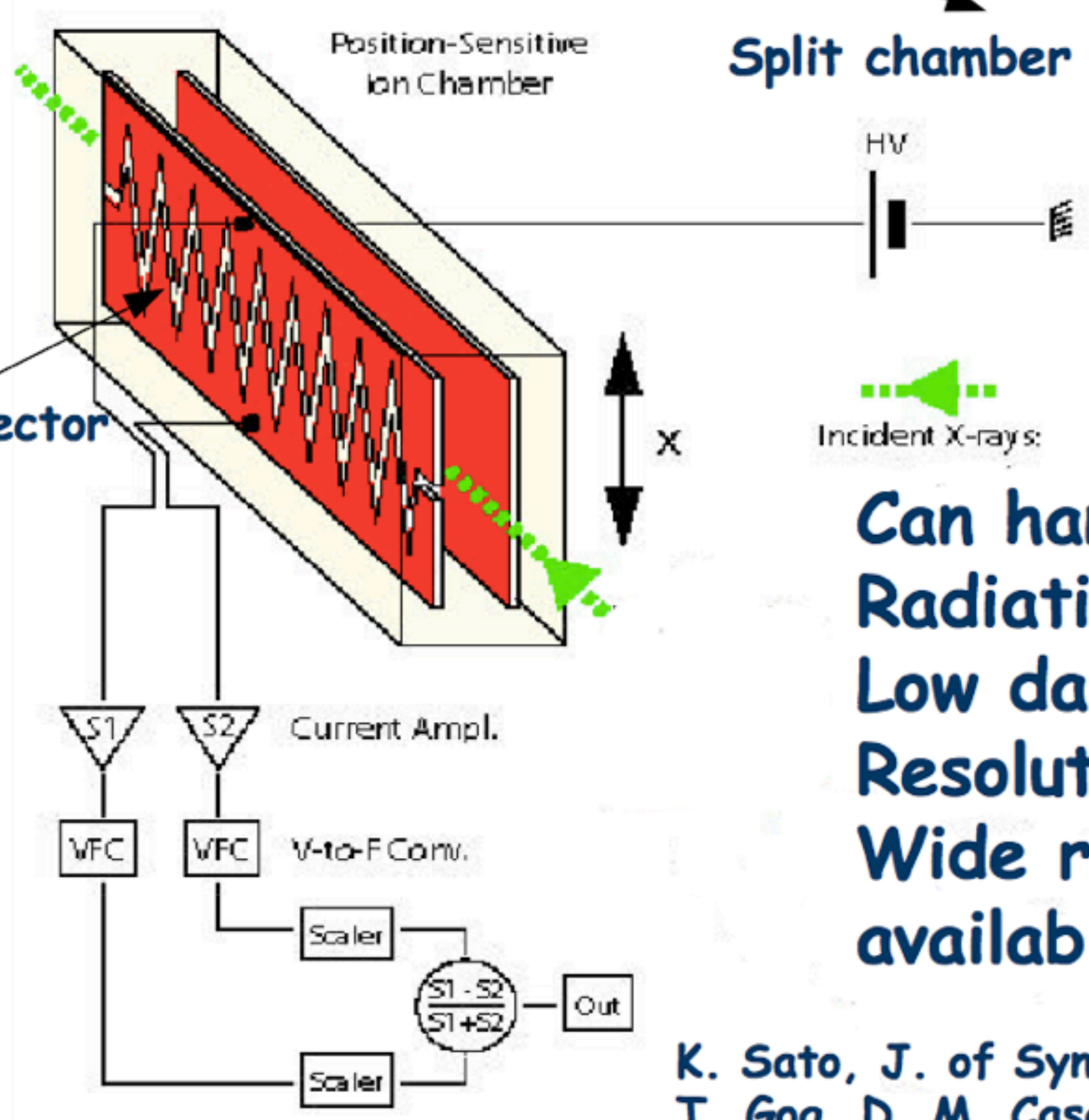
B = 4T is a reasonable choice for field strength

"Spin Light" - Detector

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

A transparent differential ionization chamber

Split chamber design helps pick out small signal

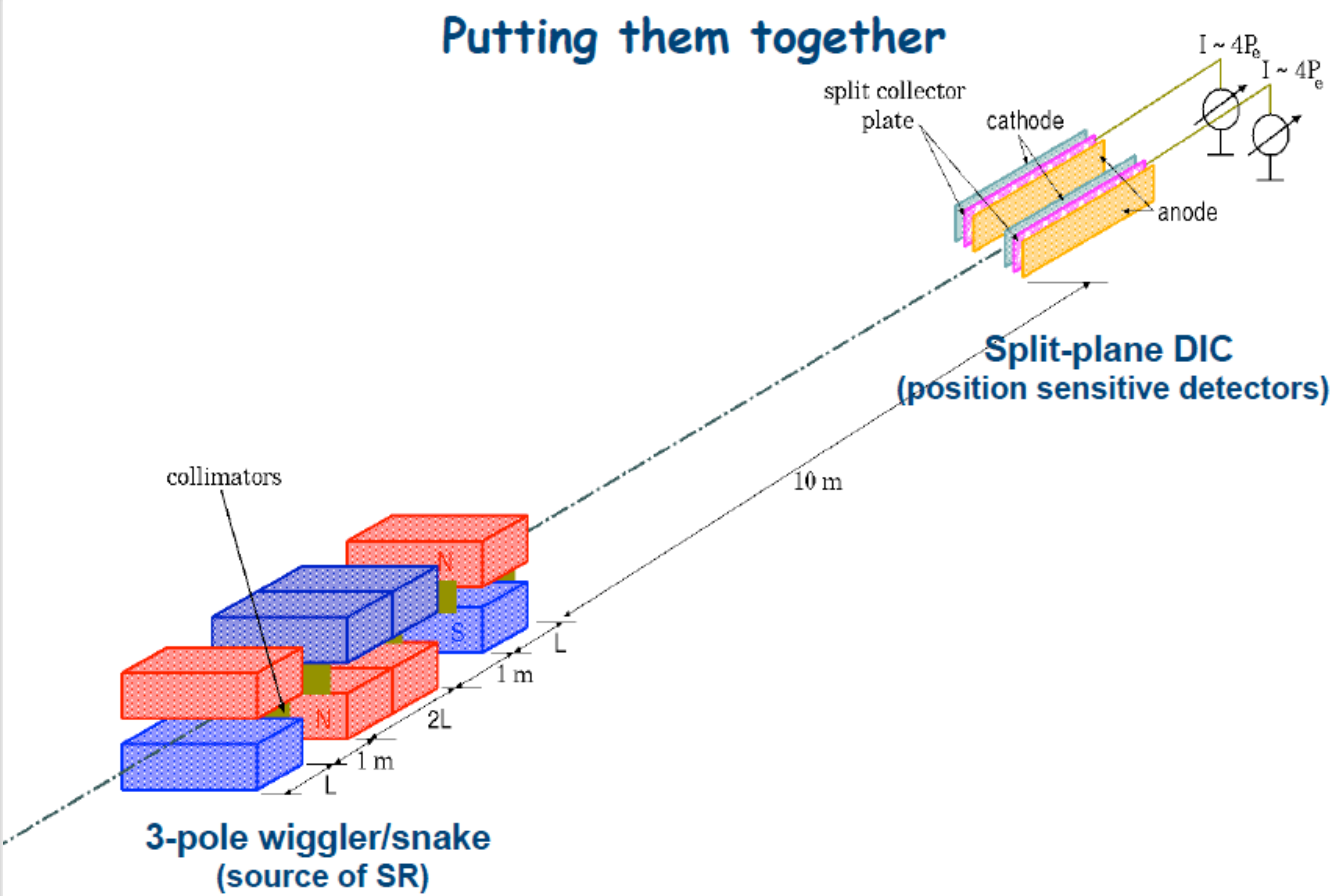


Gas – Xe or Ar

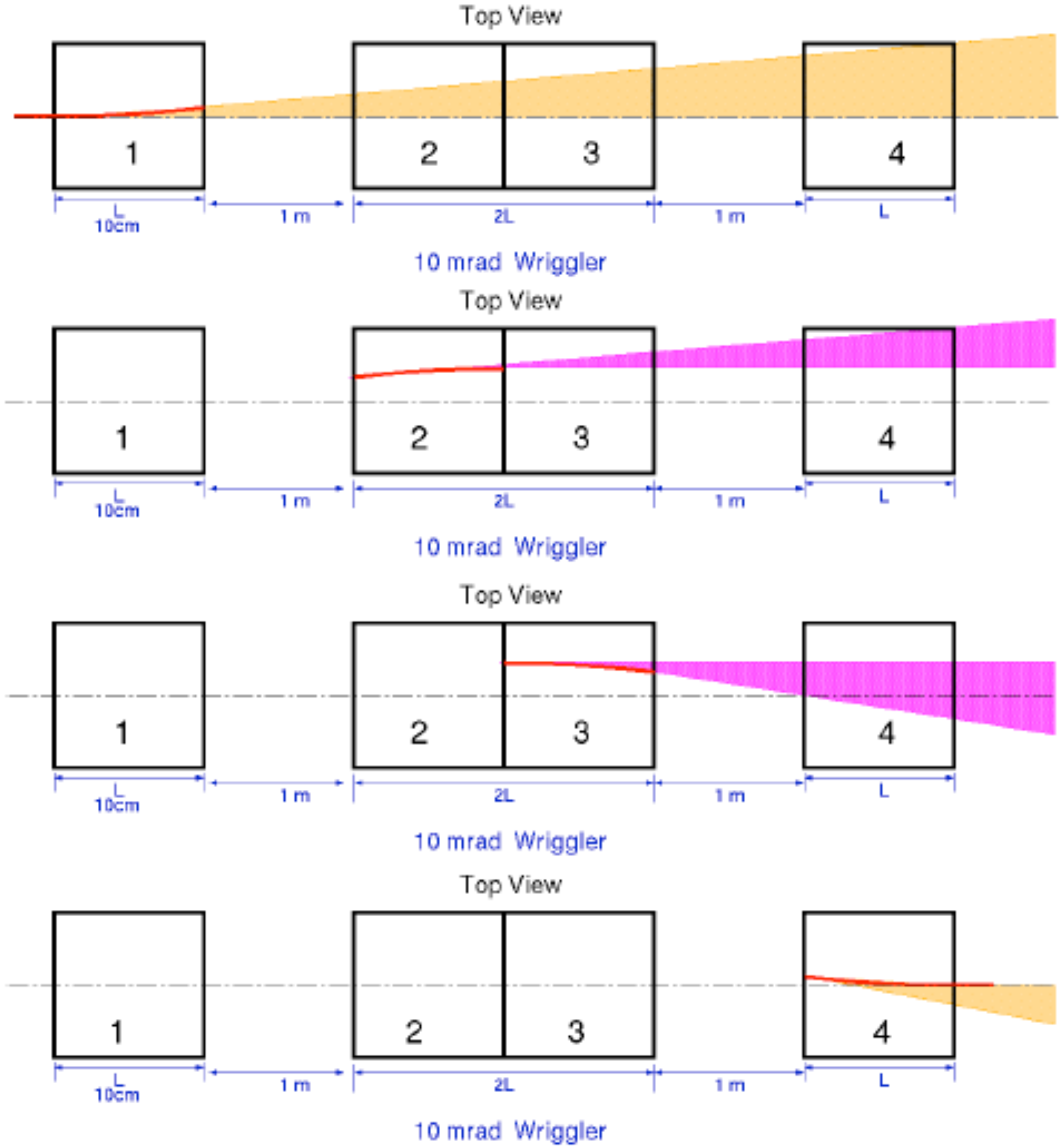
- Can handle high rates
- Radiation hard
- Low dark current/noise
- Resolution ~ 5 μm
- Wide range of ICs commercially available

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

A "Spin Light" Polarimeter



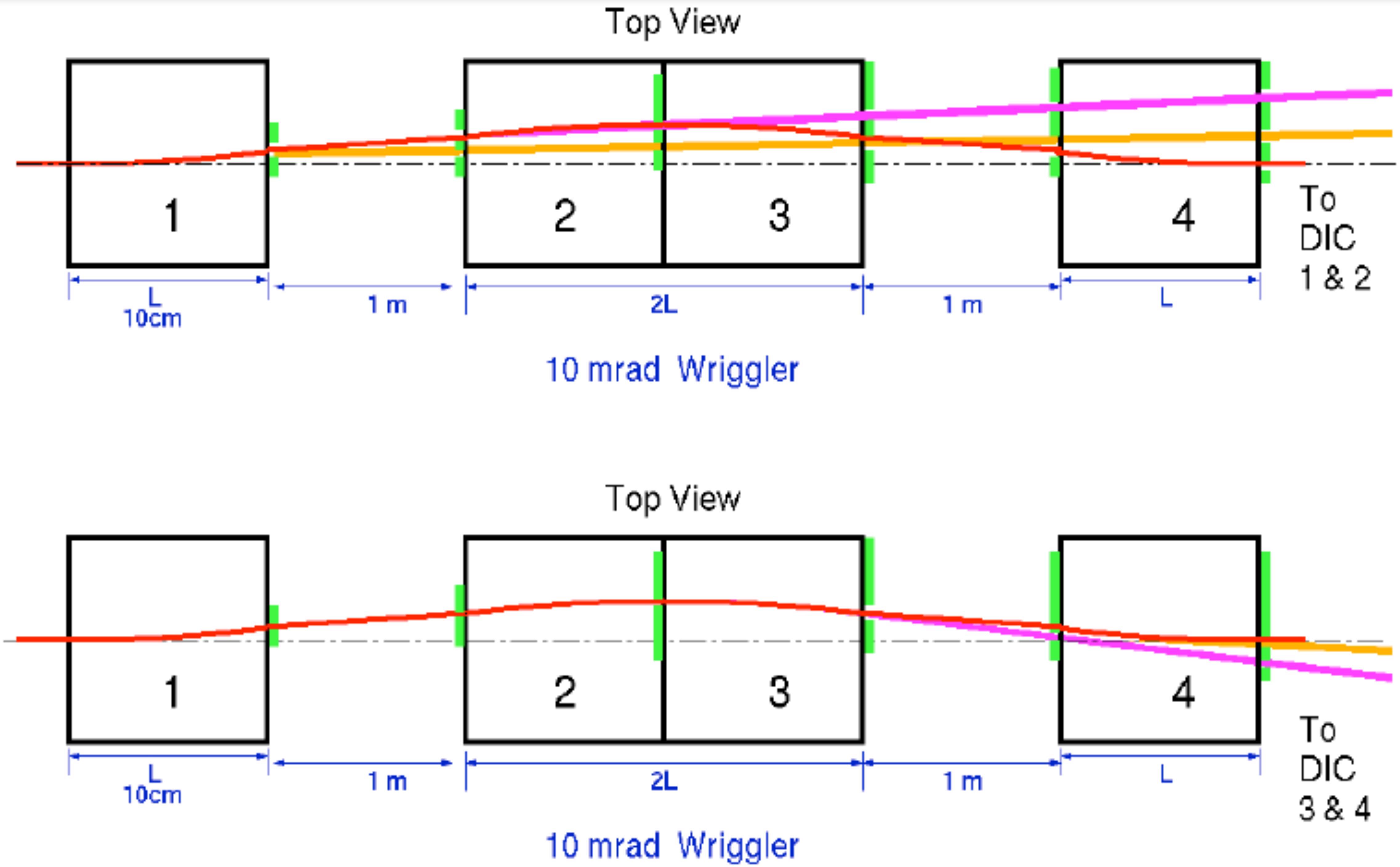
SR from the Wiggler



The SR fan for each pole of the wiggler

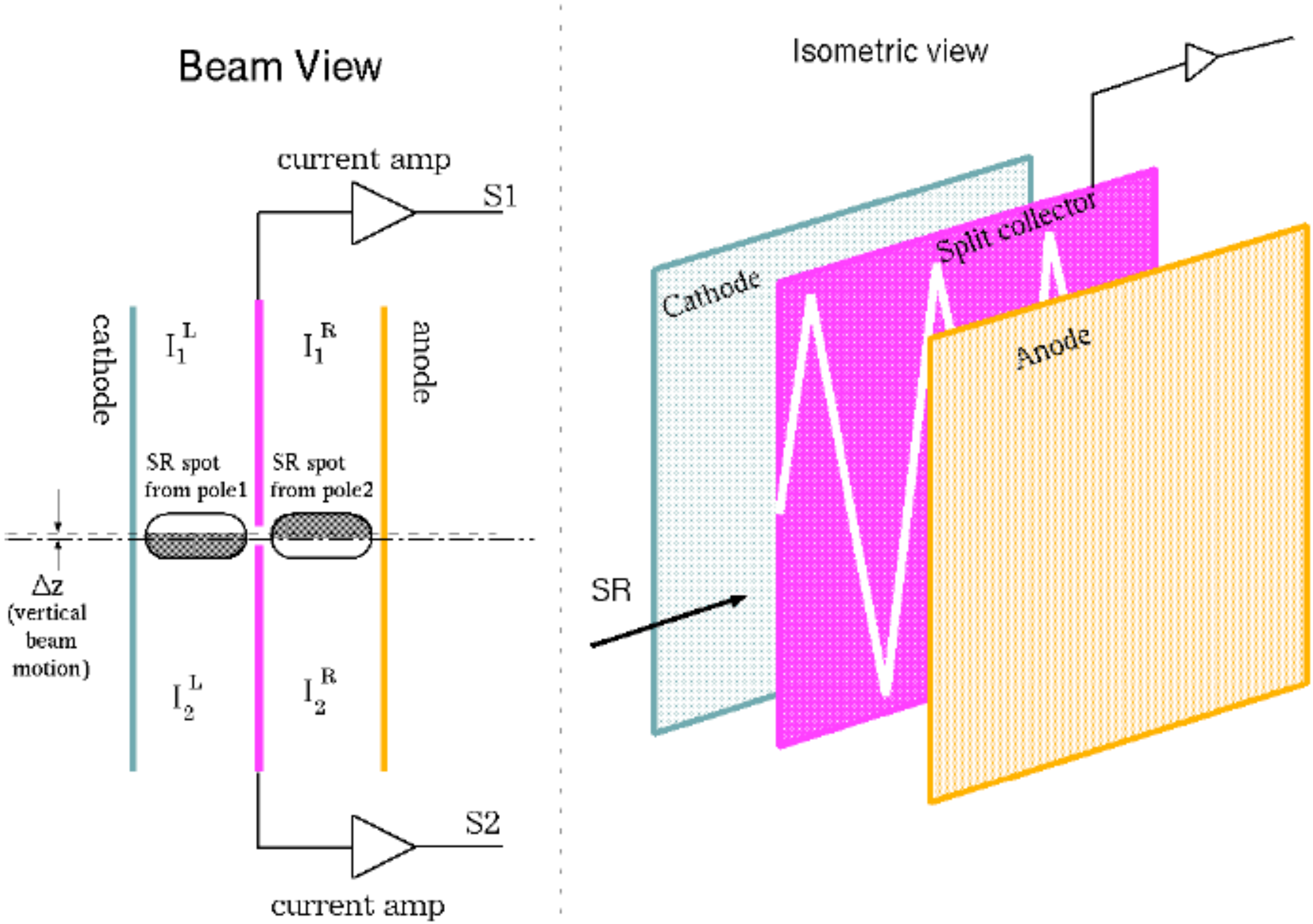
The sign of the asymmetry flips for pole 2 and 3

Collimating the SR



A set of slits select unique angular ranges for each pole

Detecting the Collimated SR



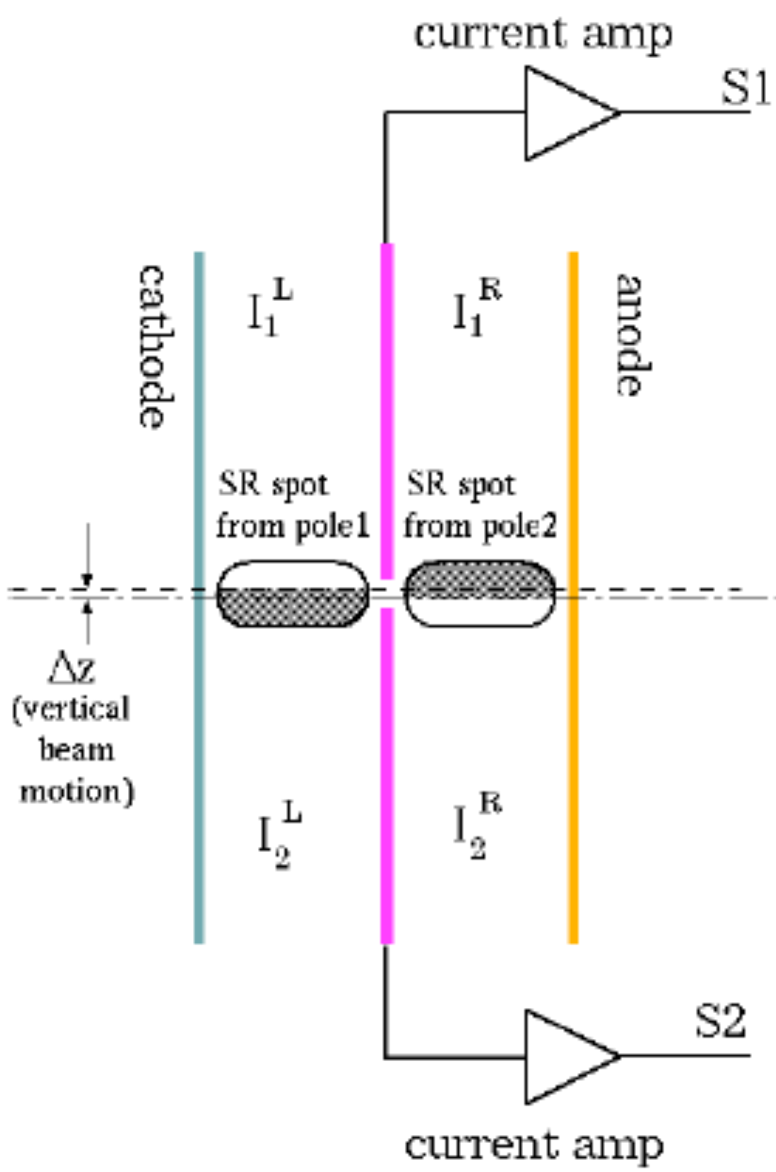
A schematic for detection of SR (alternative arrangements are a possible)

The Signal

DIC operated in current mode

Beam View

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

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

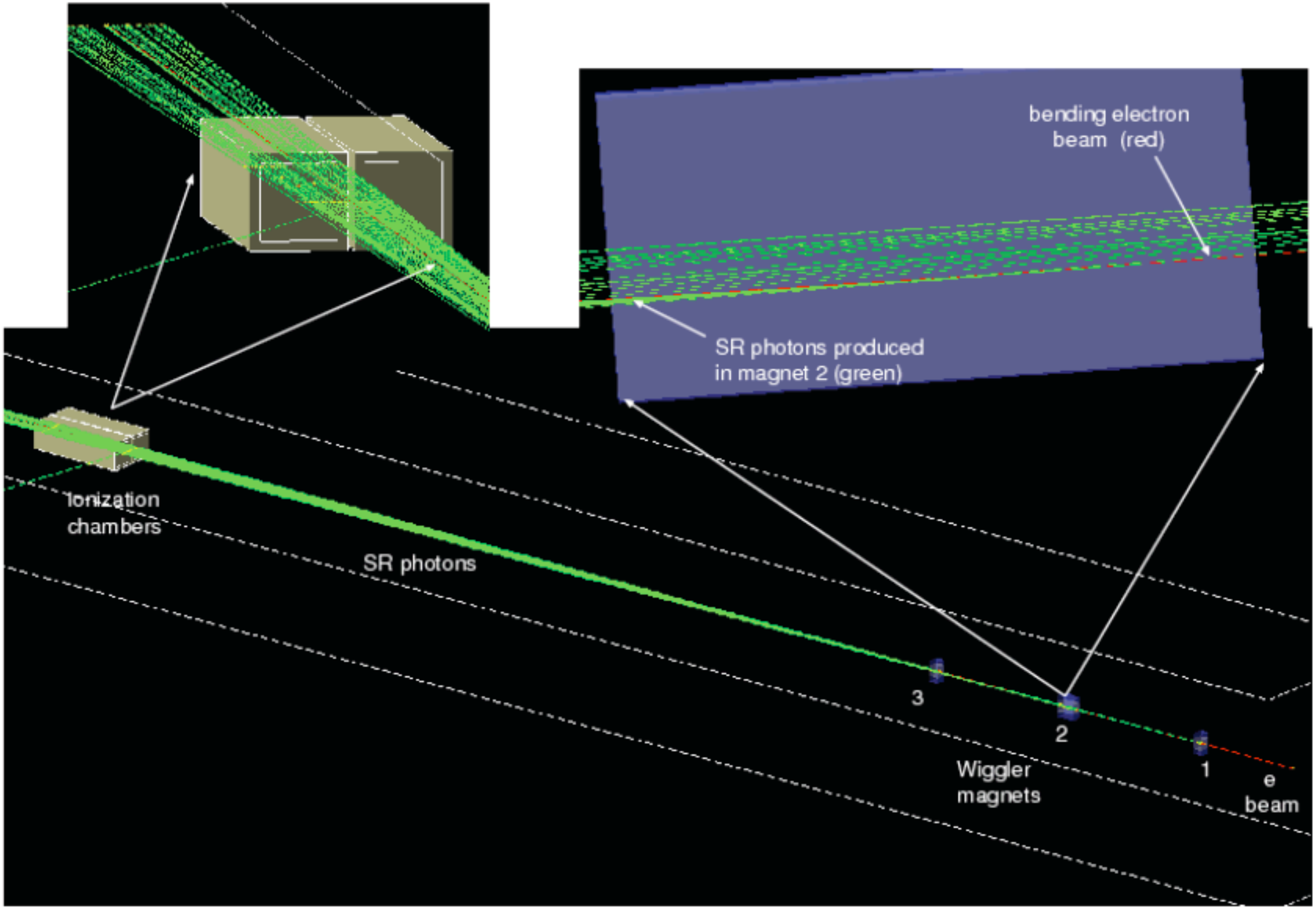
$$(S1 + S2) = 0$$

Vertical beam motion cancels out

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

The sum S1+S2 can be used for systematic studies

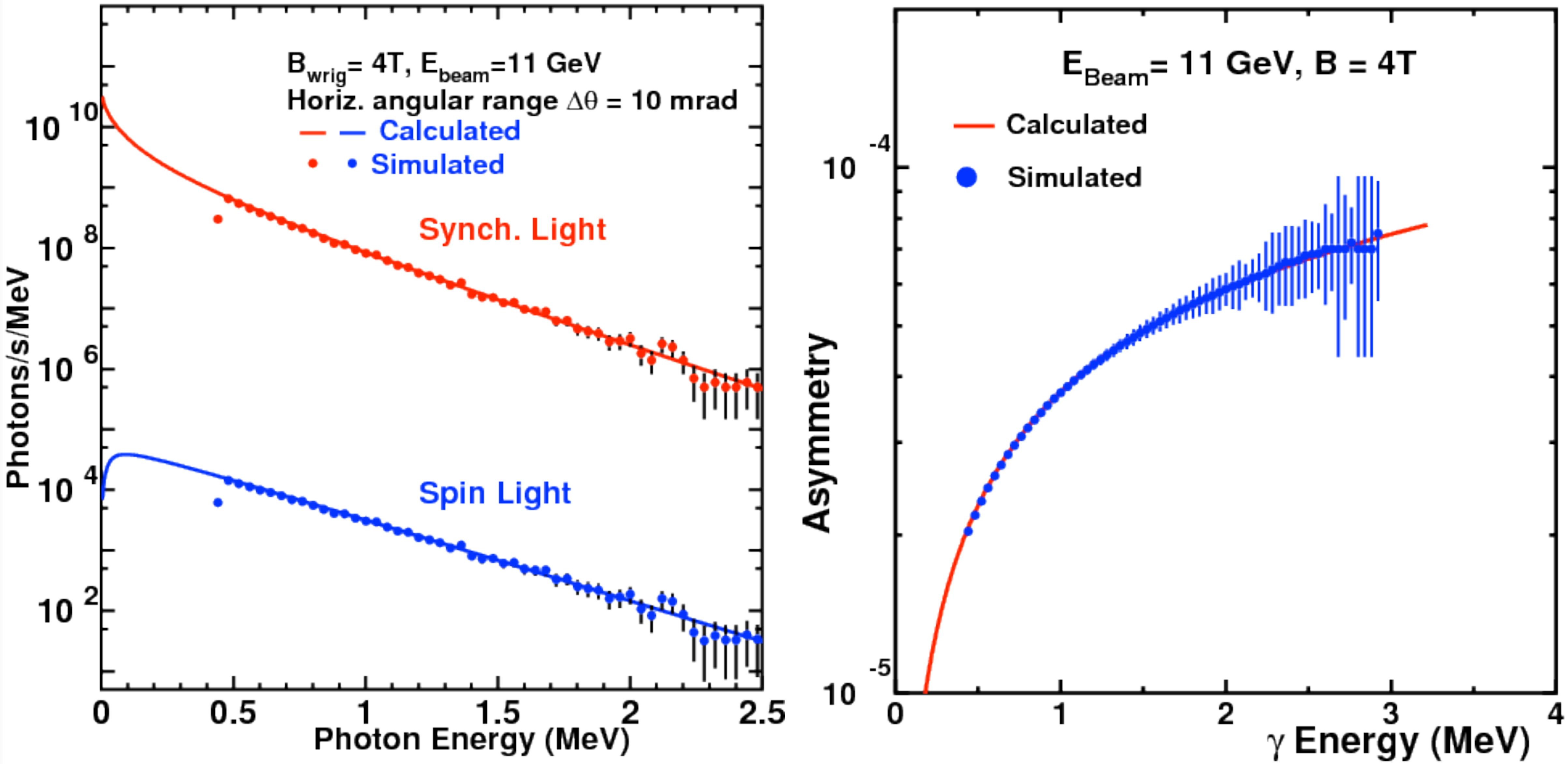
A Geant4 Simulation



by MSU student; Prajwal Mohanmurthy

A Geant4 Simulation

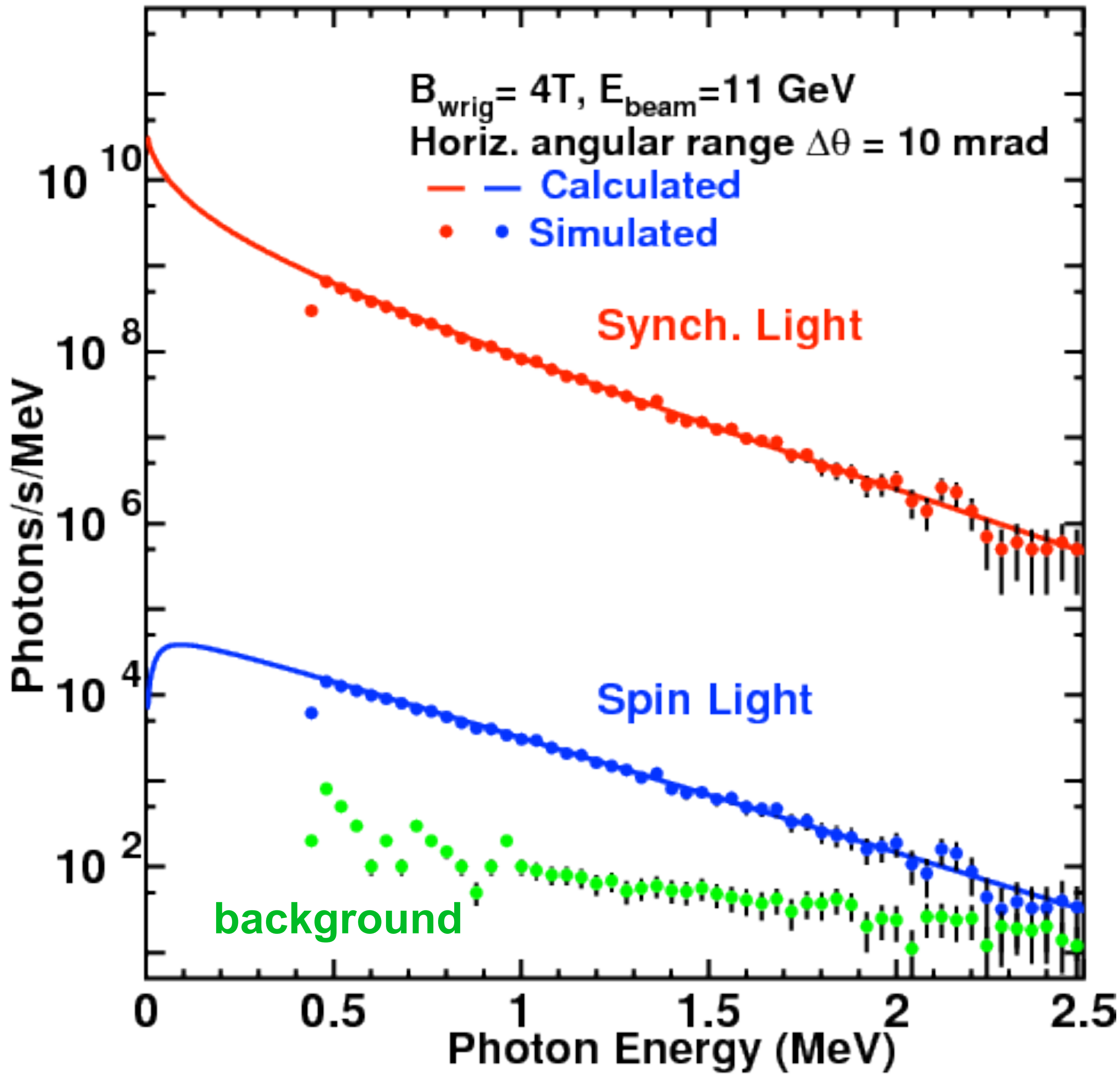
Simulation reproduces photon spectrum and asymmetry



Only a single DIC is being simulated along with collimators

A Geant4 Simulation

Preliminary Background Simulation



Systematic Uncertainties

$$A_{expt} = A_{raw}(1 + B/S) - A_B(B/S) + A_E + A_F + A_W$$

- background/signal (differential background) → B/S
- background asym → A_B
- efficiency related asym. → A_E
- vertical beam motion asym. → A_F
- wriggler field related asym. → A_W
- $A_E + A_F + A_W$: Cancels to first order

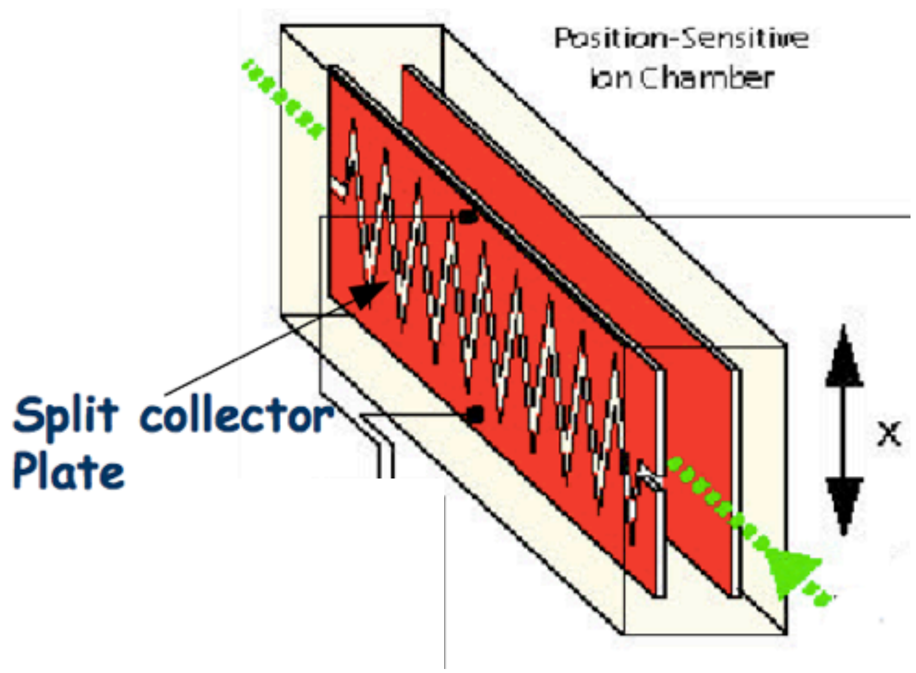
Background and background asymmetry has to be measured with the wiggler on/off

Simulation was used to estimate background

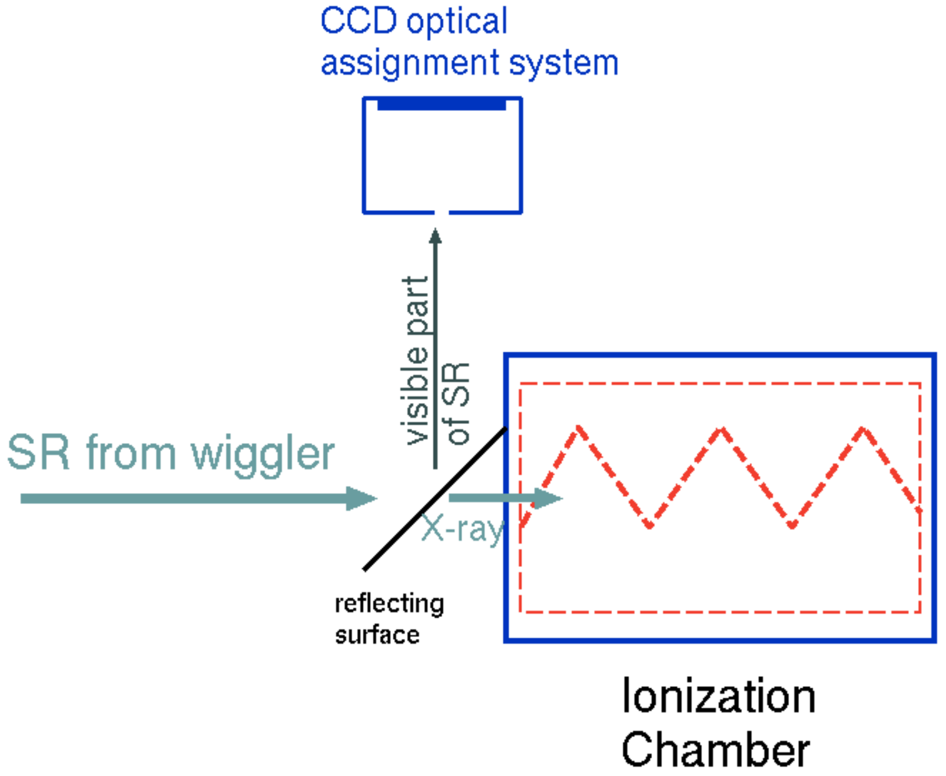
source	uncertainty	$\frac{\delta A}{A}$
Dark current	$\sim$ pA	$< 0.01\%$
Intensity fluctuations	$\Delta N \times 10^{-3}$	$<0.1\ \%$
Beam energy	1.0×10^{-3}	$< 0.05\ \%$
Density of chamber gas,	relative difference	$<0.01\%$
slit width	100 μm	$<0.2\ \%$
Background related Dilutions	known to 0.5% with B/S $\sim$ 0.02	0.5 %
other dilutions	cancel to first order	$< 0.1\%$
Band-width of X-rays (only for absolute measurement)	2% uncertainty on the lower bound	1.2 %

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 (JLab/ Novosibirsk) and SLAC test beam (unpol. tests)

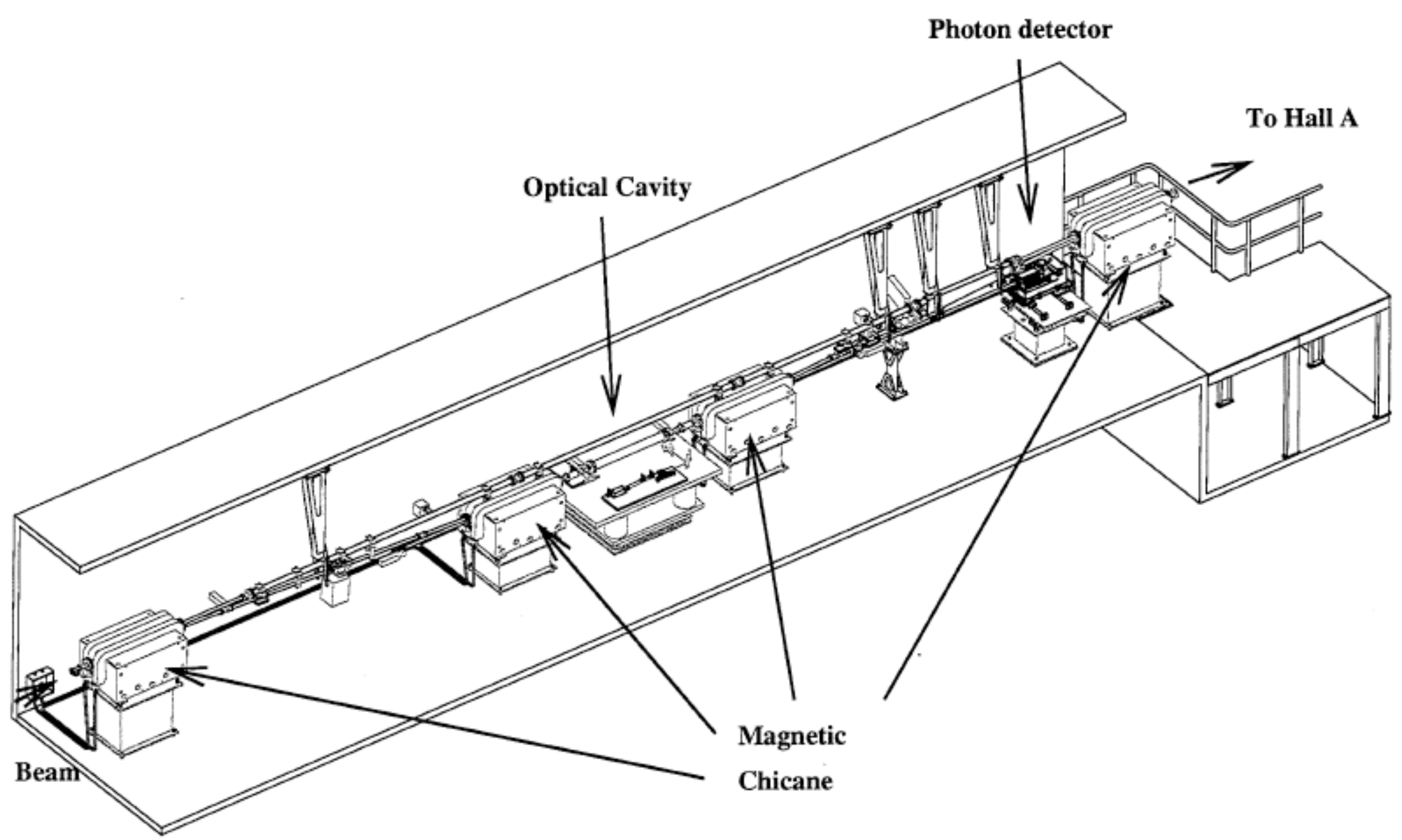


Fig. 14. The Compton Polarimeter Setup at TJNAF Hall A. Total length 15 m.

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