Compton polarimetry at PV experiments

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A4 Collaboration
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Outline

Why polarimetry?

PV experimental method:

- scattering experiments with polarized beams
- measure count-rate asymmetry to access cross-section asymmetry ($\Leftarrow$ contains the physics)

However:

$$A_{rate} = P_e A_{c.s.}$$

$\Rightarrow$ absolute polarimetry needed

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However:

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- beam polarimetry still (the) major error contribution:

Experiment	stat. err.	total syst.	polarimetry
A4 (2008)	4.8%	5.2%	4.0%
HAPPEx III	2.5%	1.5%	1.0%
G0 (H_2, high Q^2)	5.2%	1.7%	1.0%

Methods of beam polarimetry

three established methods: Mott, Møller, Compton

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Low energy only!

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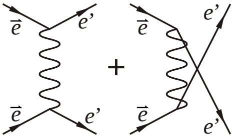


- spin-1/2 on spin-1/2
- target: magnetized foil
- long. or trans. polarized target
- c.s. asymmetry upon helicity reversal

Advantages

- high luminosity (fast)
- absolute polarimetry
- transv. and long. polarimetry
- relatively compact

Disadvantages

- low current only *
- destructive measurement *
- target polarization meas. challenging

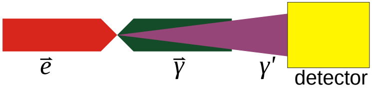
* improvement in progress, see talk by E. Chudakov

⇒ see talk by S. Glamazdin for this subject

Methods of beam polarimetry

three established methods: Mott, Møller, **Compton**

- photons on spin-1/2
- target: circ.-polarized photons
- c.s. asymmetry upon helicity reversal



Advantages

- absolute polarimetry
- transv. and long. polarimetry
- high current
- non-destructive

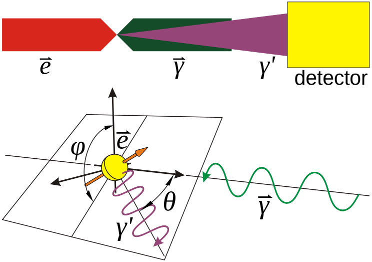
Disadvantages

- complex to build and operate
- low luminosity (slow)

$\Rightarrow$ continuous monitoring at nominal beam conditions possible!

Compton backscattering polarimetry

- based on Compton scattering
- detect final state photon
- relativistic electrons
  $\Rightarrow$ f.s. photons: high-energy γ's
  $\Rightarrow$ accessible with standard radiation detection methods



Compton cross-section

$$\frac{d\sigma(\theta,\phi)}{d\Omega} = \frac{d\sigma_0(\theta)}{d\Omega} + Q\frac{d\sigma_1(\theta)}{d\Omega} - V P_e^{long}\frac{d\sigma_2^{long}(\theta)}{d\Omega} - V P_e^{trans}\cos\phi\frac{d\sigma_2^{trans}(\theta)}{d\Omega}$$

with Q, V : "Stokes parameters" (light polarization)

- $Q = \pm 1$, $V = 0$: linearly polarized light
- $Q = 0$, $V = \pm 1$: circularly polarized light

Compton cross-section

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- use purely circular light

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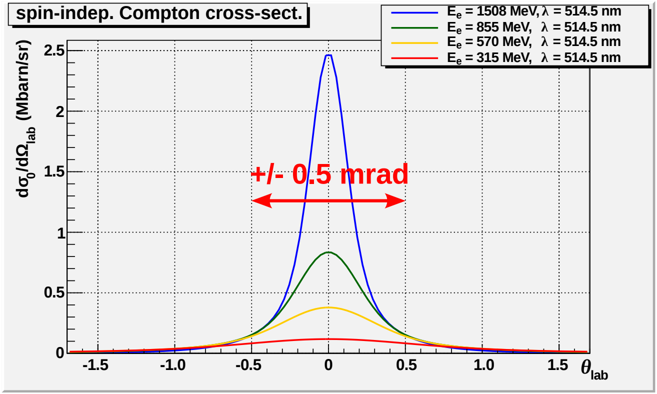
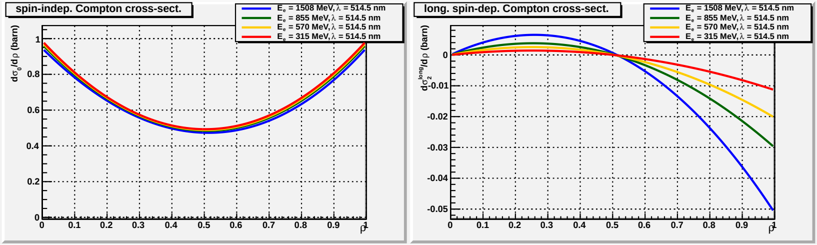
- use purely circular light
- consider directional characteristics:



$\Rightarrow$ calorimetric detectors are ϕ-averaging

Effective Compton cross-section

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{d\sigma_0(\theta)}{d\Omega} - VP_e^{long}\frac{d\sigma_2^{long}(\theta)}{d\Omega}$$



(as a function of backscattered photon energy)

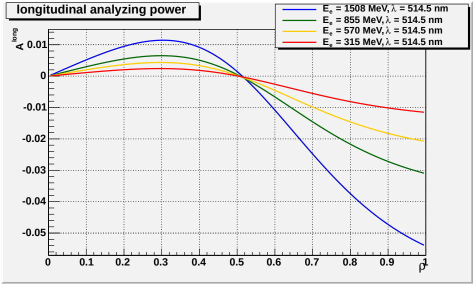
Effective Compton cross-section

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{d\sigma_0(\theta)}{d\Omega} - VP_e^{long}\frac{d\sigma_2^{long}(\theta)}{d\Omega}$$

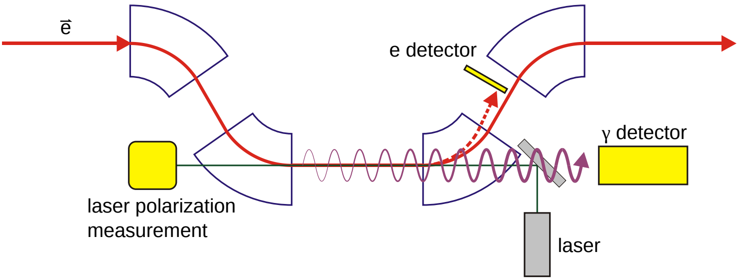
- switch between left- and right-circular light ($V = \pm P_\gamma$):

$$A_{Compton}^{long} = -P_\gamma P_e^{long} \frac{\left(\frac{d\sigma_2^{long}}{d\Omega}\right)}{\left(\frac{d\sigma_0}{d\Omega}\right)}$$

$\Rightarrow$ access to P_e



Building blocks of a polarimeter

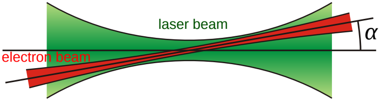


- chicane
- photon source (=laser system)
- detector for backscattered photons
- electron detector
- laser polarization measurement

The laser system (or: **pushing luminosity to the feasability threshold**)

Luminosity (“interaction density”)

$$\mathcal{L} = c(1 + \cos\alpha) \int d^3r\, \varrho_1(\vec{r})\varrho_2(\vec{r})$$



- measurement time $\propto 1/\mathcal{L} \Rightarrow$ increase $\mathcal{L}$
- $\mathcal{L}$ depends on: intensities, crossing angle, focusing

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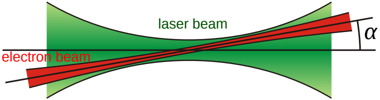

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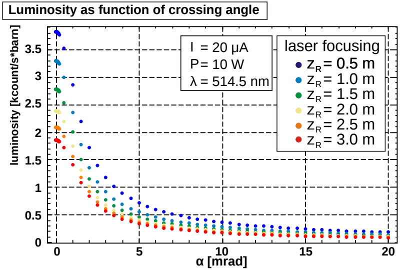

$\Rightarrow$ antiparallel geometry

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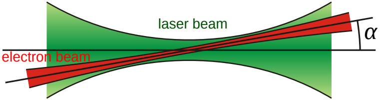

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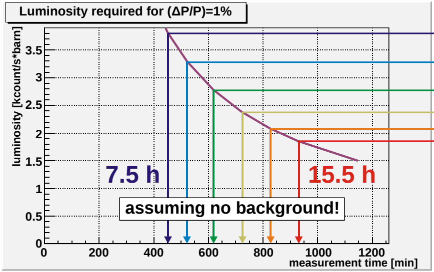
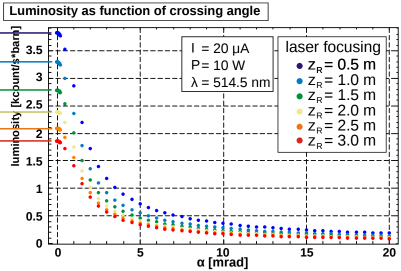




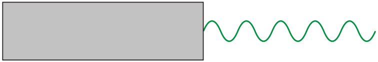
$\Rightarrow$ more laser power!

$\Rightarrow$ antiparallel geometry

Ways to increase the laser intensity

1. External Fabry-Pérot cavity

- feed laser output into resonator with $l = n \cdot \lambda/2$



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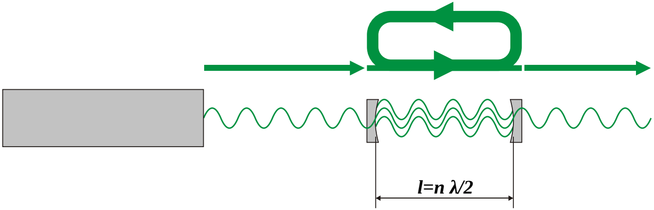

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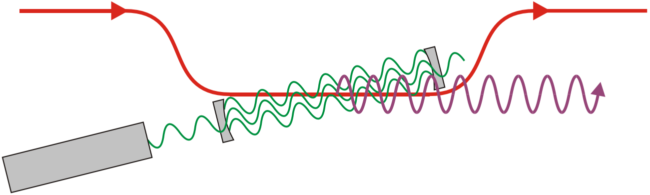

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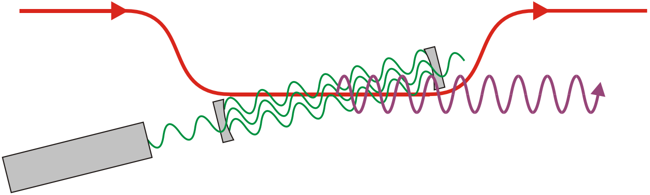

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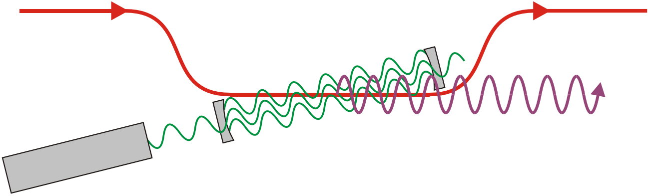


$G \cdot \Delta\omega$= const. $\Rightarrow$ longitudinal stabilization necessary

JLab Hall A: high-gain cavity

- ultra-low-absorption mirrors
- old: IR laser, G=7500, 1.7 kW
- new: green, G=5000, 5 kW*

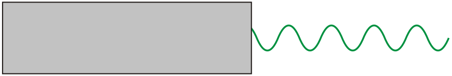
JLab Hall C: low-gain cavity

- (stronger) green laser
- G=100, P=1000 W*

* preliminary

Ways to increase the laser intensity

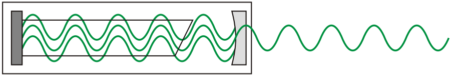
2. Internal cavity



Ways to increase the laser intensity

2. Internal cavity

- lasers already comprise Fabry-Pérot cavity
- output only small fraction of internal recirculating power



Ways to increase the laser intensity

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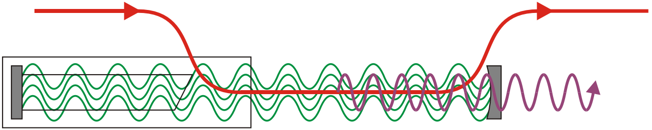
- lasers already comprise Fabry-Pérot cavity
- output only small fraction of internal recirculating power
- extend and “close” cavity, use internal power



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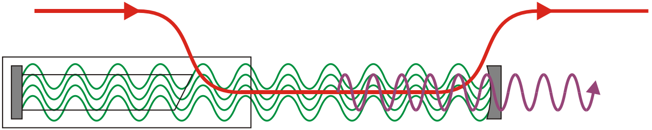

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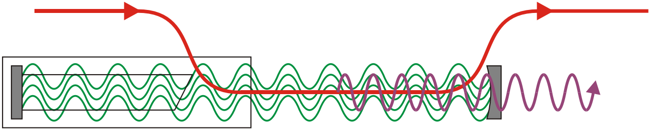
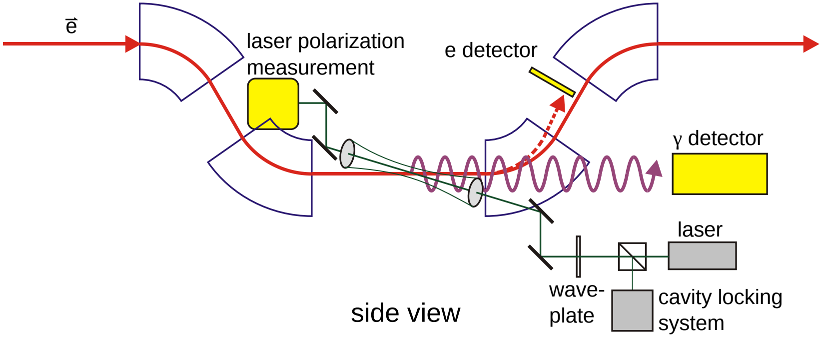


⇒ no longitudinal stabilization necessary

A4 @ MAMI

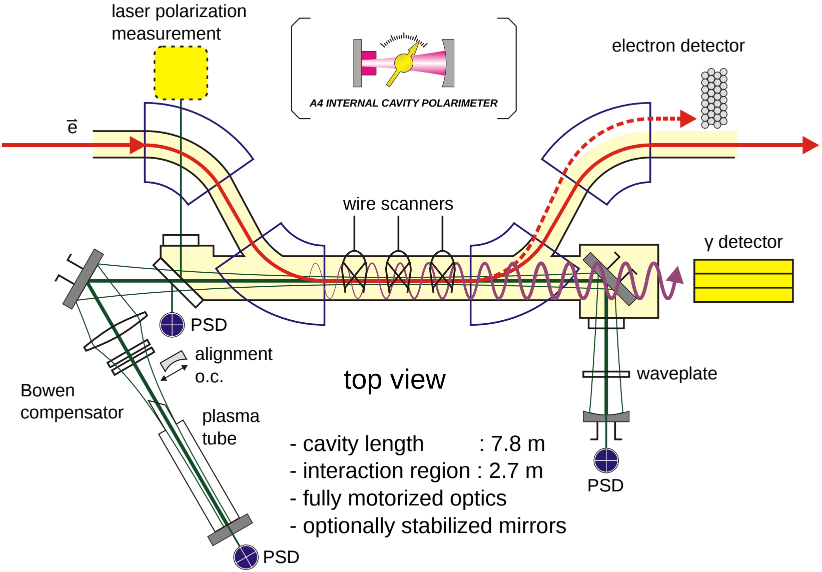
- green laser
- std. research-grade optics
- power: 120 W

Polarimeter design: JLab Hall A,C



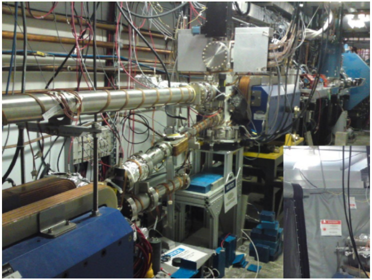
- both polarimeters use the same layout
- vertical chicane, beams crossing in horizontal plane (20 mrad)
- cavity length : 0.85 m

Polarimeter design: A4 @ MAMI

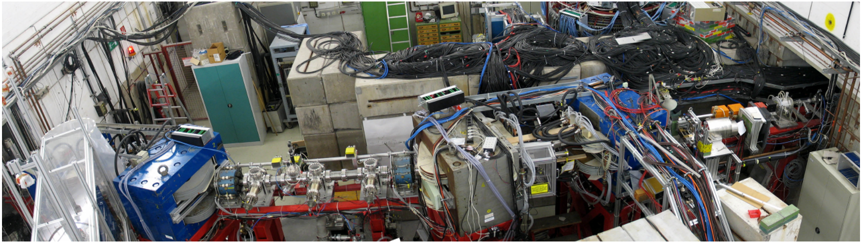


- cavity length : 7.8 m
- interaction region : 2.7 m
- fully motorized optics
- optionally stabilized mirrors

Impressions



(picture courtesy A. Narayan)

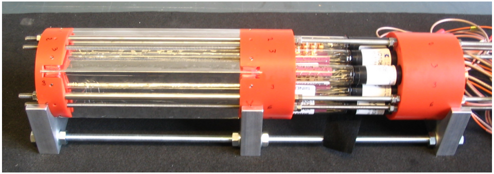


The photon detector

- usually a calorimeter

	JLab Hall A*	JLab Hall C	A4 @ MAMI
segmentation	1x1 (11 X_0)	2x2 (25 X_0)	3x3 (16 X_0)
material	GSO(Ce)	$PbWO_4$	LYSO(Ce)
density (g/cm^3)	6.7	8.3	7.1
radiation length (cm)	1.38	0.89	1.22
pulse decay time (ns)	30 - 60	10 / 30	41
light yield (% NaI(Tl))	20	0.3 / 0.08	75

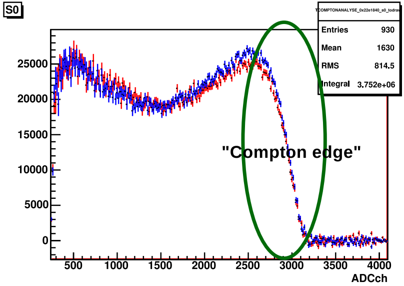
* see talk by M. Friend



- A4: two types of PMTs, different gain for different beam energies

Asymmetry extraction

- simple photon counting
- weighted photon counting (e. g. energy-weighting*)
- binwise asymmetry from spectra



- not too different from statistics p.o.v.
- influence of systematics changes dramatically

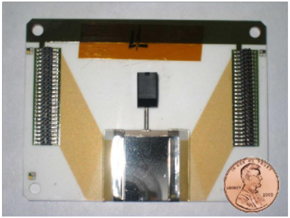
* see talk by M. Friend

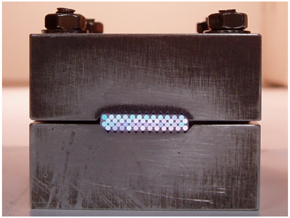
The electron detector

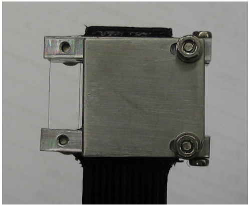
- a segmented position-sensitive device
- turn chicane into spectrometer

	JLab Hall A	JLab Hall C*	A4 @ MAMI
type	Si microstrip	diamond microstrip	SciFi array
channels	4 x 192	4 x 96	2 x 24
pitch	240 μm	200 μm	600 μm

* see talk by A. Narayan







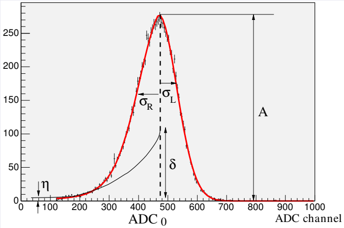
picture courtesy A. Narayan

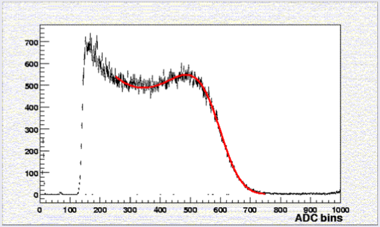
The electron detector

- calibration of the photon detector (segmented calorimeters!)
- suppression of uncorrelated background (halo, ...)
- control of photon detector systematics

JLab Hall A (IR)

- parametrize detector response using tagged spectra
- use parametrization to extract Compton asymmetry from full spectra





S. Escoffier *et al.*, arXiv:physics/0504195v1 (courtesy D. Lhuillier)

The electron detector

- calibration of the photon detector (segmented calorimeters!)
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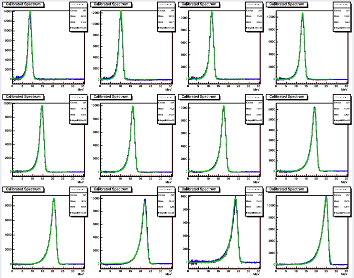
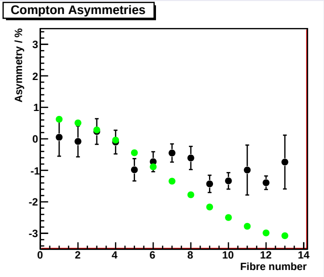
A4 @ MAMI

- exclusively use tagged spectra





courtesy J. Diefenbach

The electron detector

- calibration of the photon detector (segmented calorimeters!)
- suppression of uncorrelated background (halo, ...)
- control of photon detector systematics

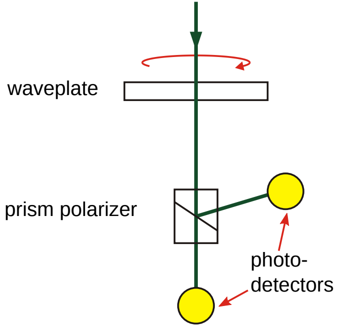
JLab Hall C

- independently measure Compton spectrum using electron detector

see talk by A. Narayan

Laser polarization measurement

- rotating QWP before linear polarizer
- transmitted light: intensity-modulated



$$I(\theta) = \frac{1}{4}\{(2I + Q) - 2V\sin 2\theta + U\sin 4\theta + Q\cos 4\theta\}$$

(I : tot. intensity; Q,U : linear components; V : circular component)

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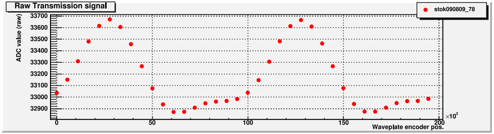
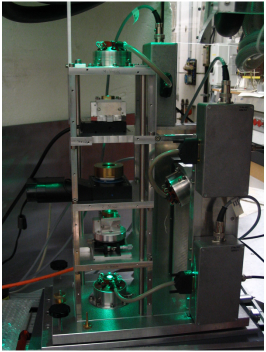




- well-established, accurate method
- statistics easily 0.1% rel.
- main challenge: systematics

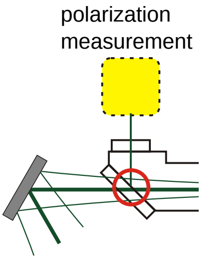
$$I(\theta) = \frac{1}{4}\left\{(2I + Q) - 2V\sin 2\theta + U\sin 4\theta + Q\cos 4\theta\right\}$$

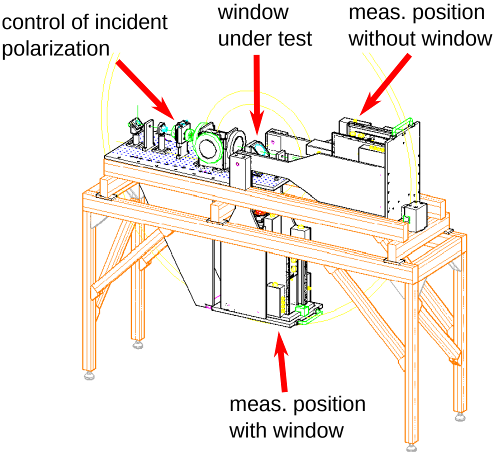
(I : tot. intensity; Q,U : linear components; V : circular component)

Laser polarization measurement

- need to know polarization *inside* cavity
- can only measure *outside* cavity

e.g. A4:





$\Rightarrow$ measure transport matrix for every window

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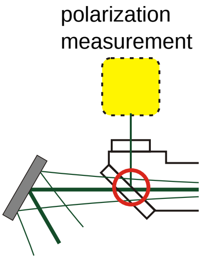

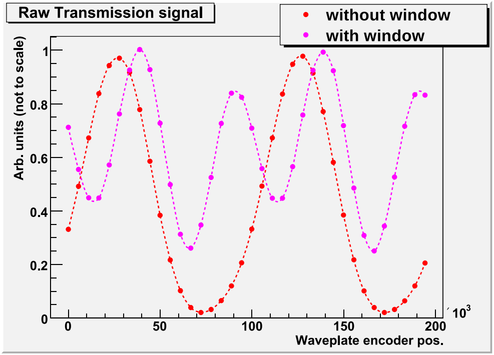

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(Approximate) design comparison

- difficult because all built for different conditions
- approach: compare statistical FOM of designs ($\propto 1/T$)

$$f = \langle A_l \rangle^2 \sigma_{tot} \mathcal{L}$$

- take Hall A IR as reference

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	Hall A IR	green	FOM?	Hall C	FOM?	A4	FOM?
λ (nm)	1064	532	x 4	532	x 4	514.5	x 4.3
P_{Laser} (W)	1700	5000	x 2.9	1000	x 0.6	100	x 0.06
α (mrad)	20	20	x 1	20	x1	0	x 20
design	:=1		x 11.6		x 2.4		x 5.2
E_e (GeV)	4.6	1	x 0.05	1.17	x 0.06	0.86	x 0.03
I_e (μA)	40	50	x 1.25	180	x 4.5	20	x 0.5
exp. cond.	:=1		x 0.06		x 0.27		x 0.02
total	:=1		x 0.7		x 0.6		x 0.1

(caveat: some simplifications used)

Performance

Hall A IR @ 4.6 GeV

- 0.6 % stat. in 1 h

source	contribution
background	0.05%
dead time	0.10%
events cut	0.10%
beam pos.	0.30%
det. response	0.45%
energy calib.	0.6%
pile-up	0.45%
radiative	0.26%
laser polarization	0.60%

S. Escoffier *et al.*, NIM **A 551** (2005) 563 – 574

A4 @ 855 MeV*

- 2 % stat. in 11 h (beam profile!)

source	contribution
lower thr.	0.20%
fibre det. geom.	0.26%
dead time	0.19%
random coinc.	0.20%
background	0.02%
energy calib.	0.12%

+ laser polarization

* preliminary numbers!

Performance

Hall A IR @ 4.6 GeV

- 0.6 % stat. in 1 h
- 1.4 % syst.

Hall A green @ 1 GeV*

- 1.0 % stat. in 1 h
- 0.9 % syst.

see talk by M. Friend

Hall C @ 1.17 GeV*

- 1% stat. in 1 h
- (0.55 + x)% syst.

see talk by A. Narayan

A4 @ 855 MeV*

- 2 % stat. in 11 h (beam profile!)
- (0.45 + x)% syst.

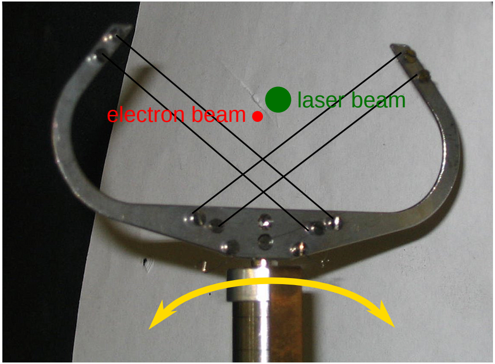
* preliminary numbers!

Beam overlap

- mainly an issue for A4 polarimeter

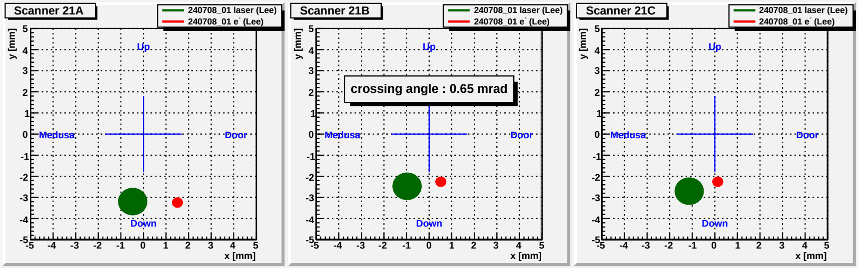
Beam overlap

- mainly an issue for A4 polarimeter
- 3 customized wire scanners



Beam overlap

- mainly an issue for A4 polarimeter
- 3 customized wire scanners
- iterative computer-assisted overlap optimization



Beam overlap

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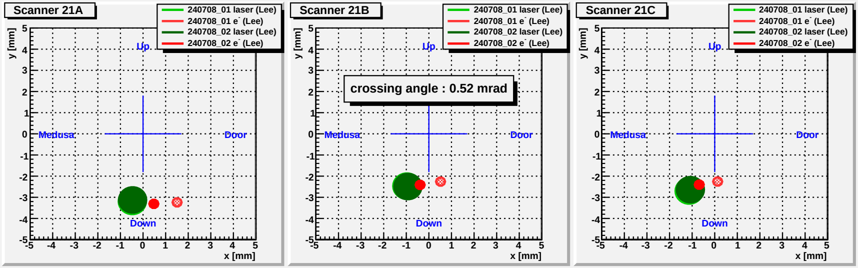
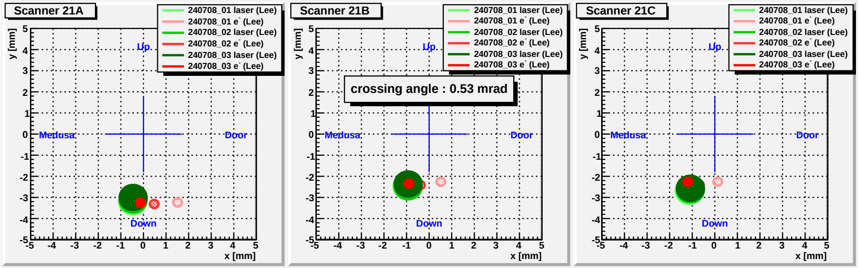


Beam overlap

- mainly an issue for A4 polarimeter
- 3 customized wire scanners
- iterative computer-assisted overlap optimization



⇒ finished in 20 min. even from scratch!

Conclusion

- Compton polarimetry is reliable, established method
- so far, only non-invasive method for modern PV experiments
- techniques for precision polarimetry at demanding conditions exist (Hall A IR, A4)
- improvements for next generation of PV experiments underway (Hall A green upgrade, Hall C)

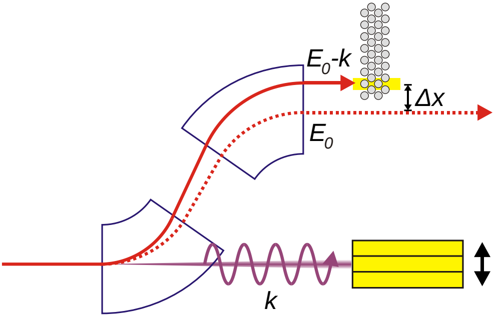
$\Rightarrow$ Compton polarimetry will keep its decisive role in PV for near future

- will be complemented by advanced Møller techniques soon

Thanks to: W. Deconinck, M. Friend, A. Narayan and K. Paschke for information on the JLab polarimeters!

Photon detector calibration

- in particular for segmented calorimeters
- low-energy: radioactive sources (^{60}Co, gammas from neutron capture, LYSO intrinsic activity ...)
- high-energy: on the beam, using electron detector as tagger



center every crystal on beam ⇒ same spectrum for all crystals