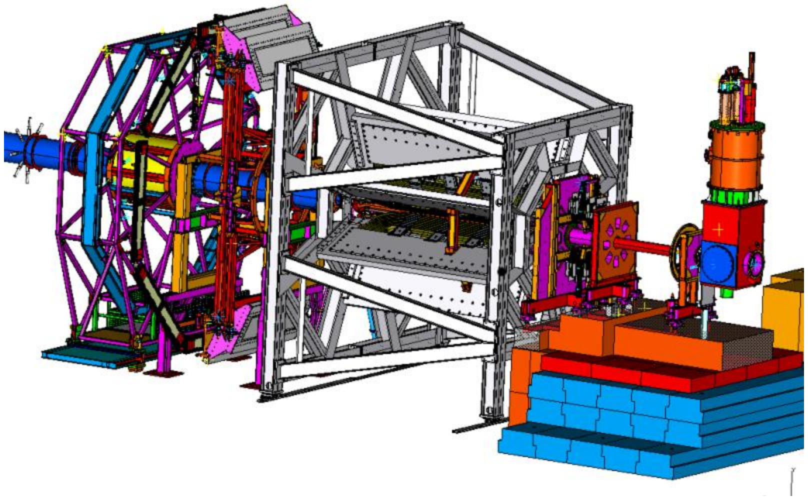
Precision Compton Polarimetry in Hall C at Jefferson Lab

PSTP 2013

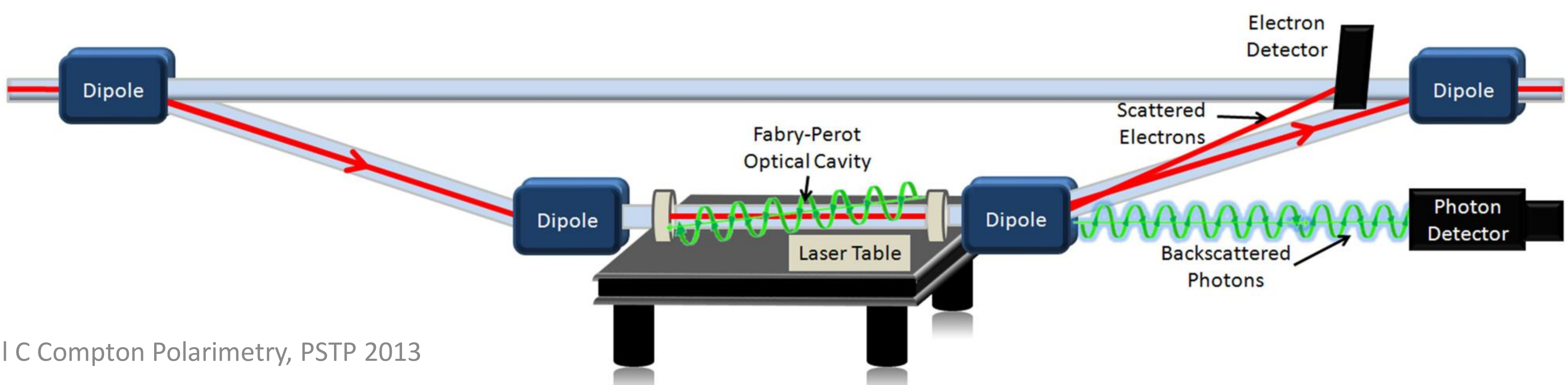
Don Jones -*for the Hall C Compton Collaboration*

New Compton Polarimeter for Hall C



Recent Qweak experiment in Hall C at Jlab with stringent error budget (dP/P~1%) required development of a Compton polarimeter for continuous, non-invasive measurement of polarization.

- 4 dipole magnets bend electron beam through chicane – vertical dispersion ~57cm
- Electron beam collides with 10W laser (532nm) locked to Fabry-Perot optical cavity (gain >200)
- >1500W of light focused to 180 micron waist
- Detect scattered electrons and backscattered photons separately
- Provides two somewhat independent measurements



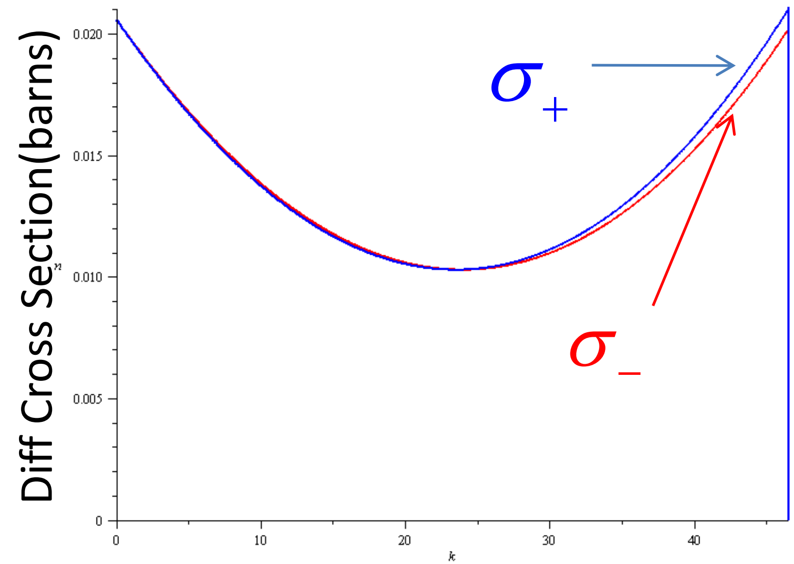
Compton Polarimetry

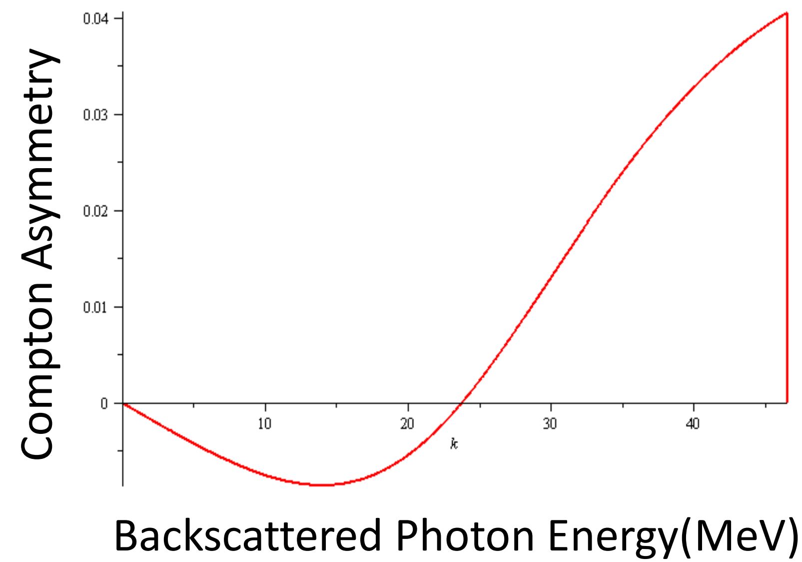
- The cross section of Compton scattering is different for right and left circularly polarized photons on polarized electrons.

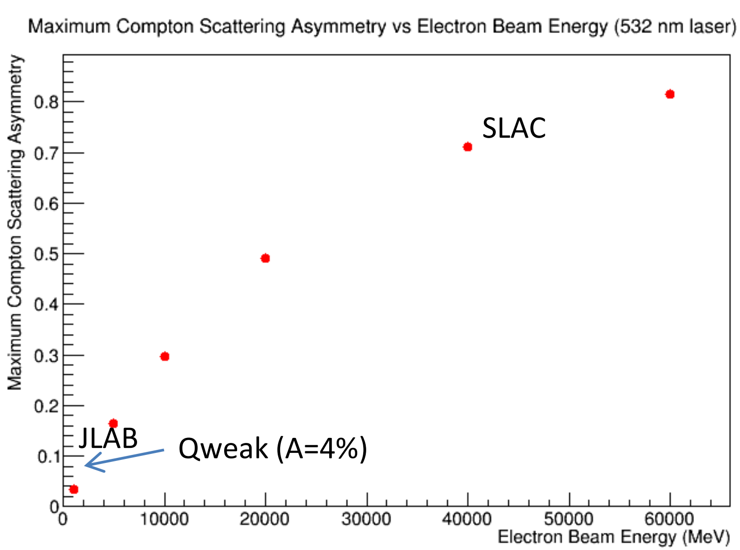
$$\sigma_{R_eR_\gamma} = \sigma_{L_eL_\gamma} > \sigma_{L_eR_\gamma} = \sigma_{R_eL_\gamma}$$

$$A_{Comp} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$\boxed{A_{meas} = P_\gamma P_e A_{Compton}}$$







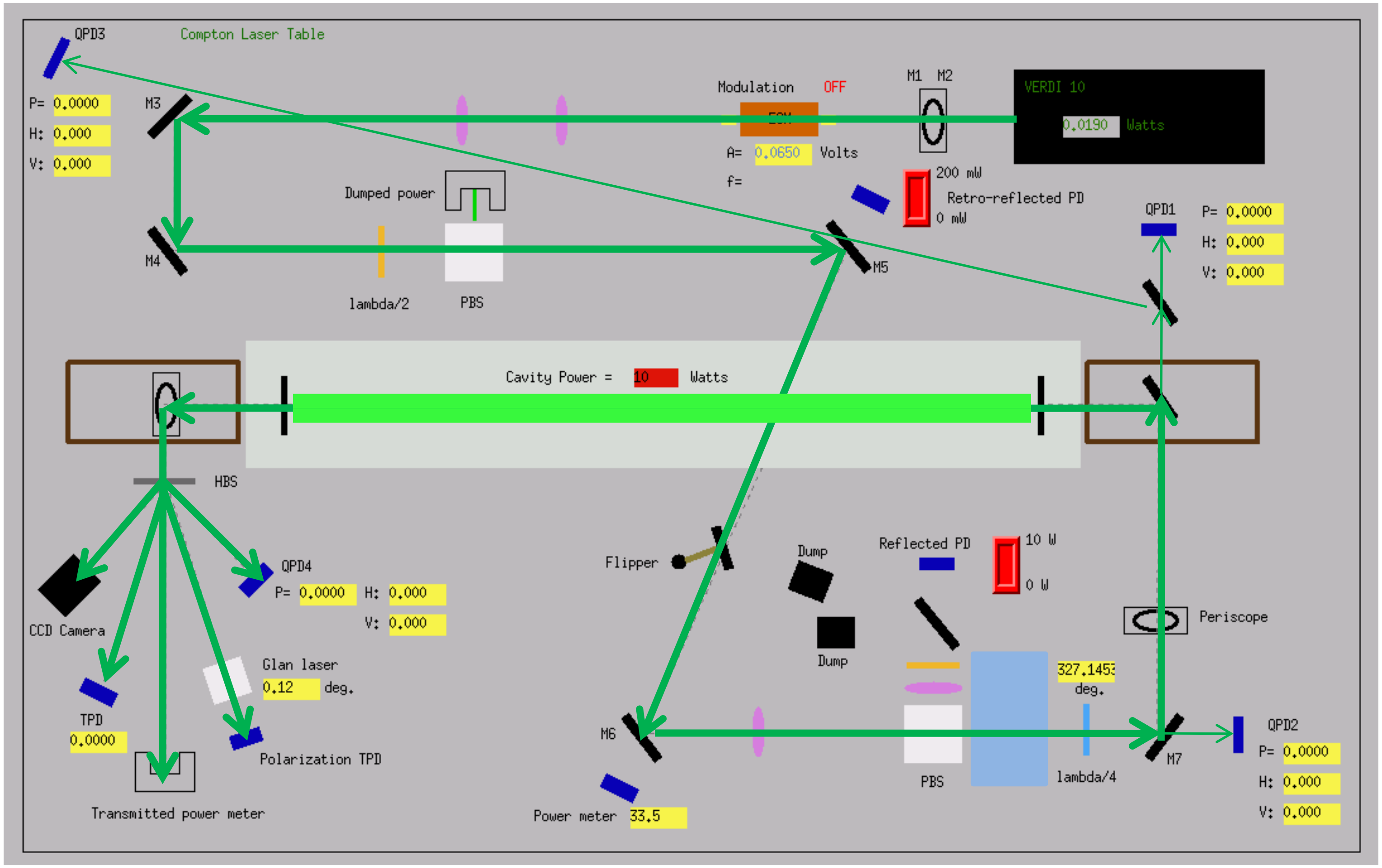
Photon Target Considerations

- 10 W Coherent Verdi laser locked to Fabry-Perot optical cavity with feedback on wavelength.
- Manufacturer stated line width <5MHz rms over 50ms. Not obvious that it was possible to lock to an optical cavity with a linewidth ~100-300kHz.
- Measurements on a similar laser (different feedback hardware) showed intrinsic linewidth ~150kHz.
- Stable lock with cavity of gain>200 and linewidth ~250kHz.
- Lock hard to maintain on higher finesse cavity with linewidth ~95 kHz. Unclear whether it was electronics or linewidth that was limiting factor.

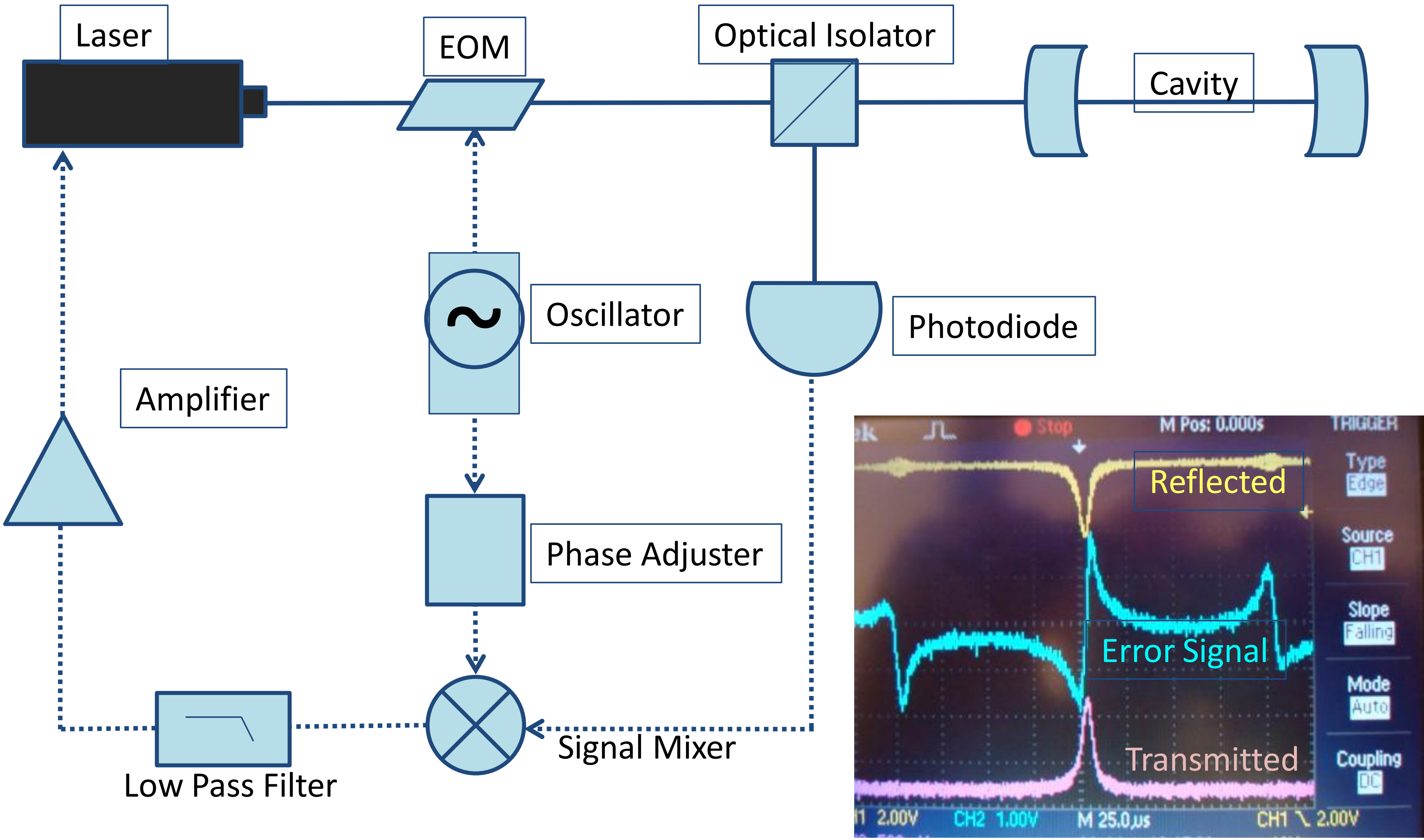
Cavity Specs:

Length	85cm
Mirror Ref	0.995
Mirror Tran	0.005
Mirror Loss	>50ppm

Laser Table Schematic

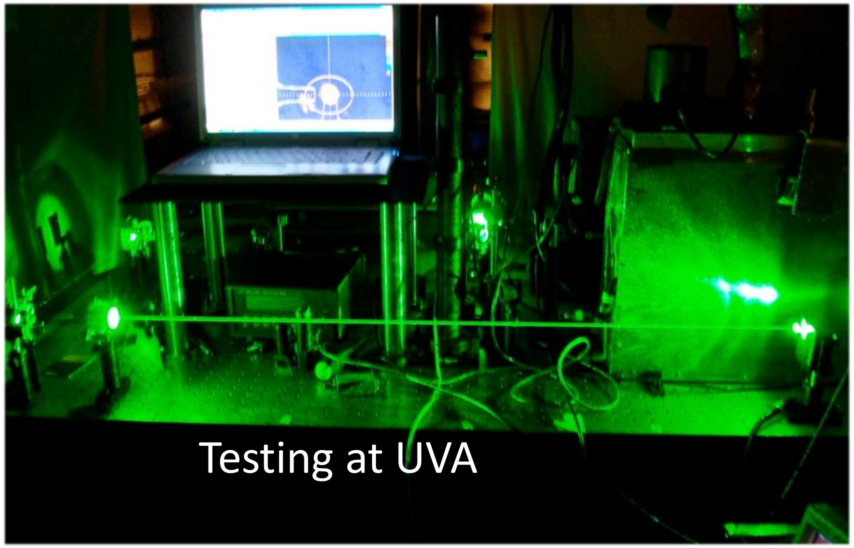


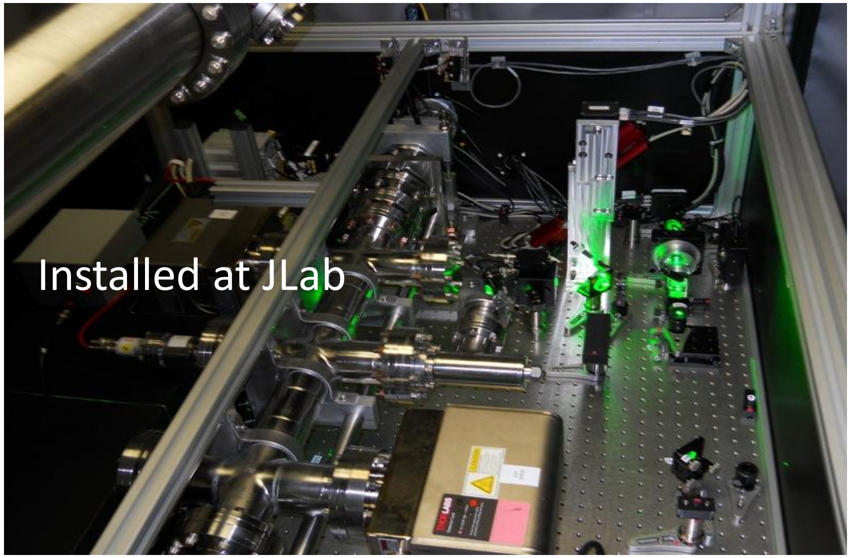
Locking the Optical Cavity with PDH Method



Photon Target for Compton Polarimeter

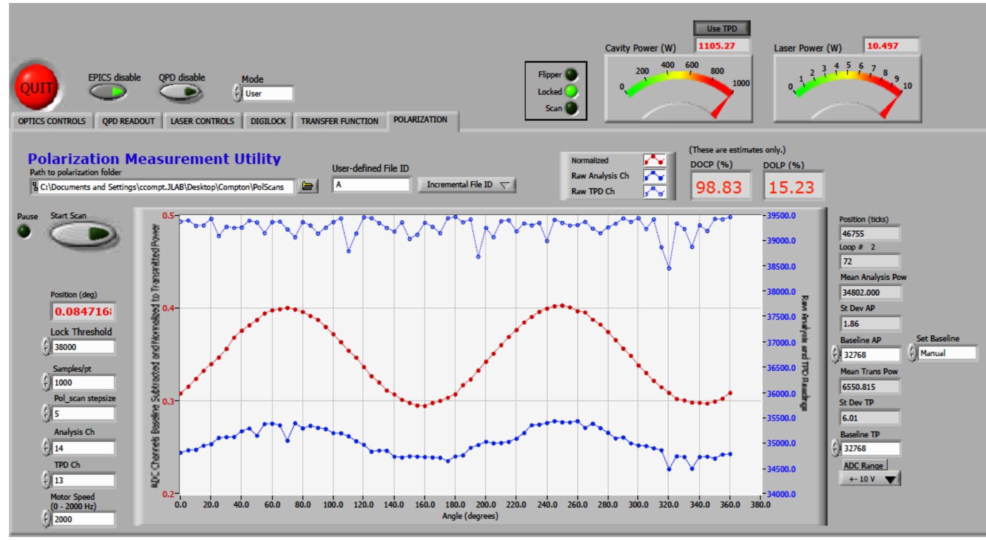
- Toptica Digital Electronics for cavity lock
- LabVIEW based monitoring and remote control of laser position.alignment and power
- Remote monitoring and control of laser polarization and helicity
- Communication with Jlab's EPICS program for continuous data logging of key parameters

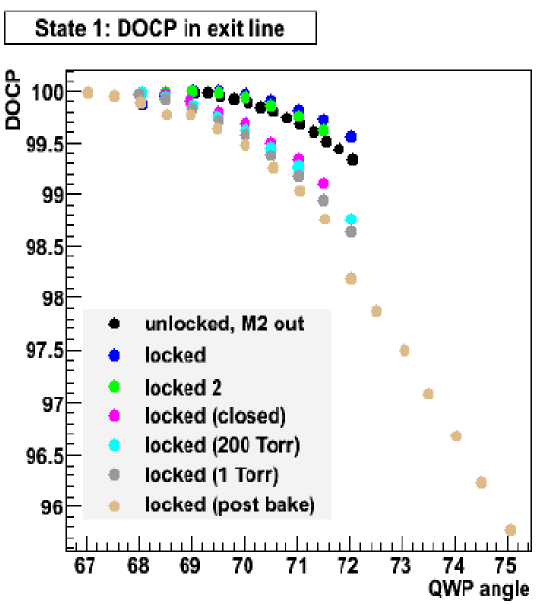


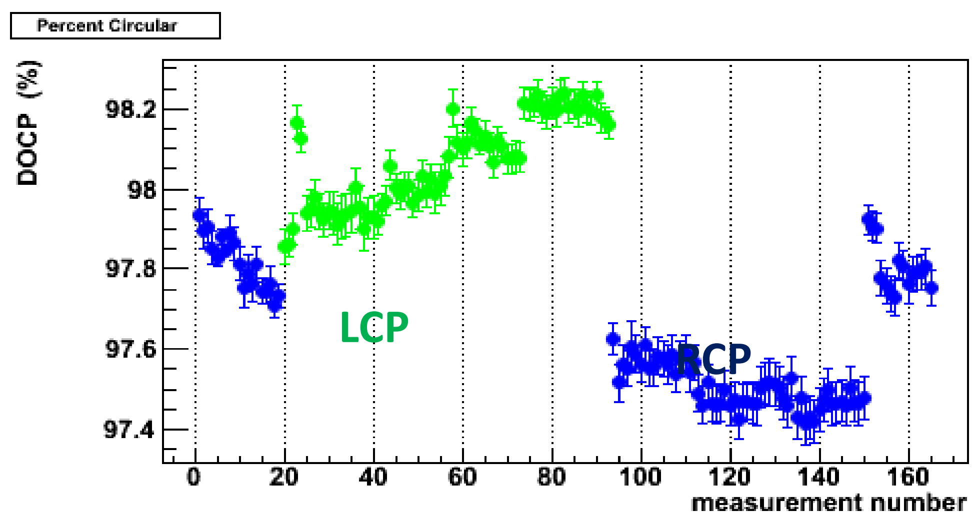


Determining Intracavity Laser Polarization

- Developed a set of tools for measuring polarization of the laser in the exit line
- Need to measure a Transfer Function to determine intracavity polarization from exit line measurement
- Transfer Function is simply an optical matrix used to model the change in light as it goes from the cavity to the exit station.
- Set up and accurately measure laser polarization states in the cavity and exit line regions and fit the data to determine the transfer matrix.
- Problem! The TF changed when we tightened flanges near the windows and when we pulled vacuum.
- DOCP = degree of circular polarization

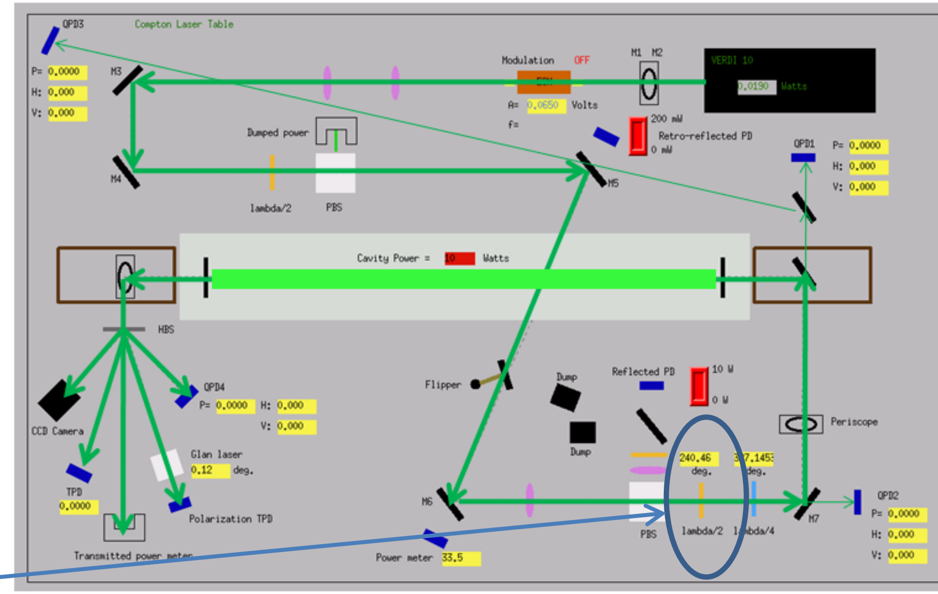


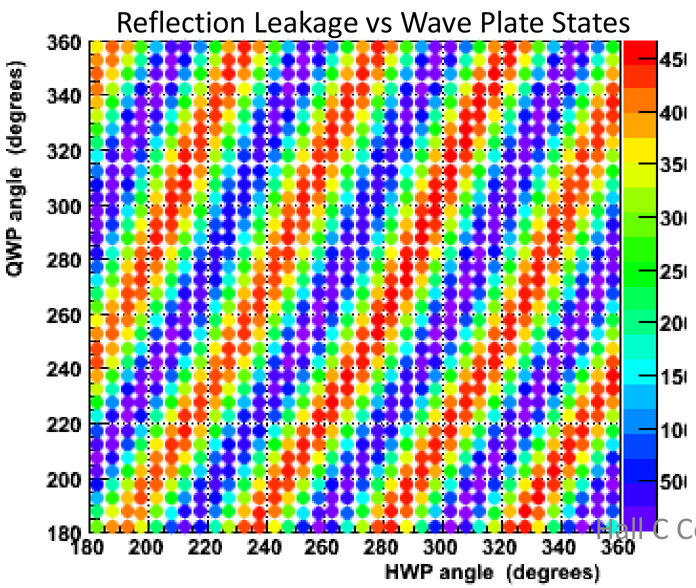




Relationship between DOCP and Reflected Light

- "Reflection leakage" anti-correlated to DOCP
- Convinced ourselves this was a fundamental relationship and decided to minimize the reflection leakage to maximize DOCP
- Later found a publication detailing the use of this technique for remote control of laser polarization.
- Added an extra HWP to the hardware to allow the setup of any arbitrary polarization state





Optical reversibility theorems for polarization: application to remote control of polarization

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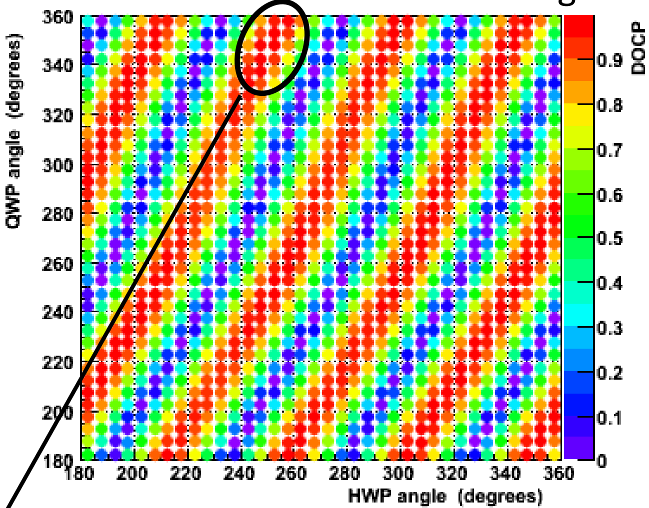
Using Jones's formalism, we prove three optical reversibility theorems that relate the polarization ellipticity at the output of an optical system to the polarization of the retroreflected light at the input. We describe how these theorems can be used to measure the ellipticity of a polarization remotely and thus to control it remotely. As an example, we use this method to create a linear or a circular polarization after a total internal reflection inside a prism, and the impurity of polarization is found to be better than 10^{-3}. Finally we describe the use of this remote control to create polarization configurations that are useful for laser cooling of atoms.

Scans of RRPD Power

- Took scans of power in RRPD vs. angle of QWP and HWP over full phase space
- Model includes imperfect HWP and QWP and an arbitrary birefringent element at undetermined angle
- Fit of data to model yields HWP 3.3% thin and QWP 1.1% thick and the arbitrary element with bifrefringence $\pi/30$
- Beautiful correlation allows fine tuning of DOCP with monitoring only reflection leakage
- Under assumption that there is no depolarization the error on the polarization appears to be <0.2%

DOCP from Model Fit to Leakage

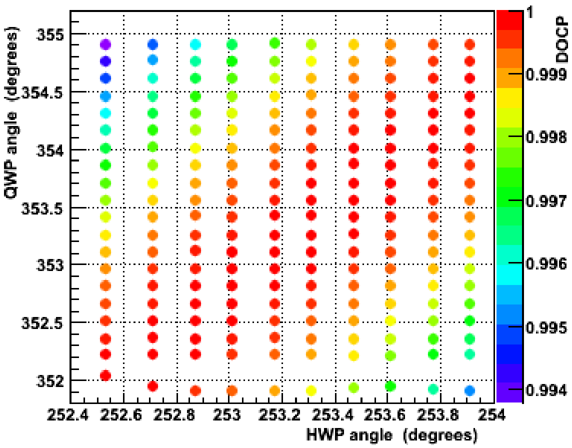


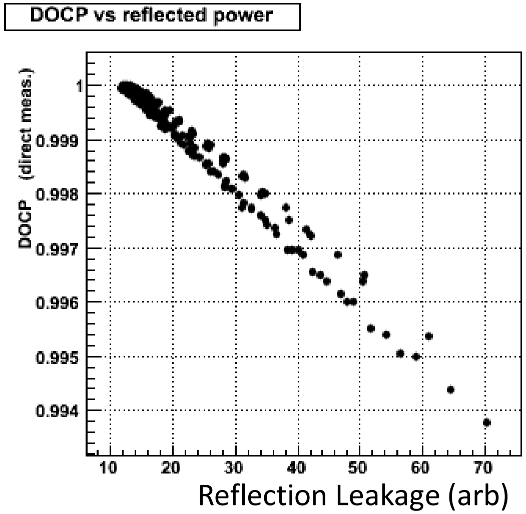
Results of direct test:

->Minimized reflection leakage

->Directly measured DOCP in cavity region

DOCP Measured in Cavity Region





What assumptions have been made?

We only measure LP so method assumes totally polarized beam i.e.

$$DOCP^2 + DOLP^2 = 1$$

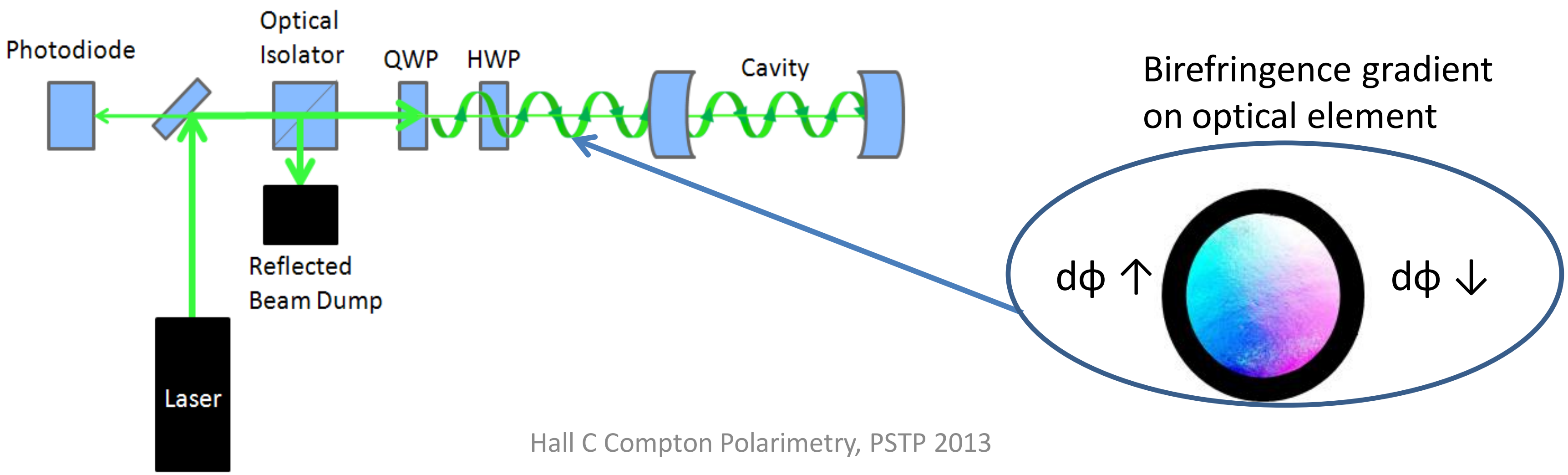
Optics with a birefringence gradient will introduce polarization gradient. Cancelation between regions of + and – linear polarization would look like circularly polarized light in the intra-cavity measurement; however, linear reflected light is being measured in the reflection leakage monitor

→already bounded at sqrt(2)*0.2%.

Worst case …randomly depolarized light

→still sampling ½ of this in leakage monitor

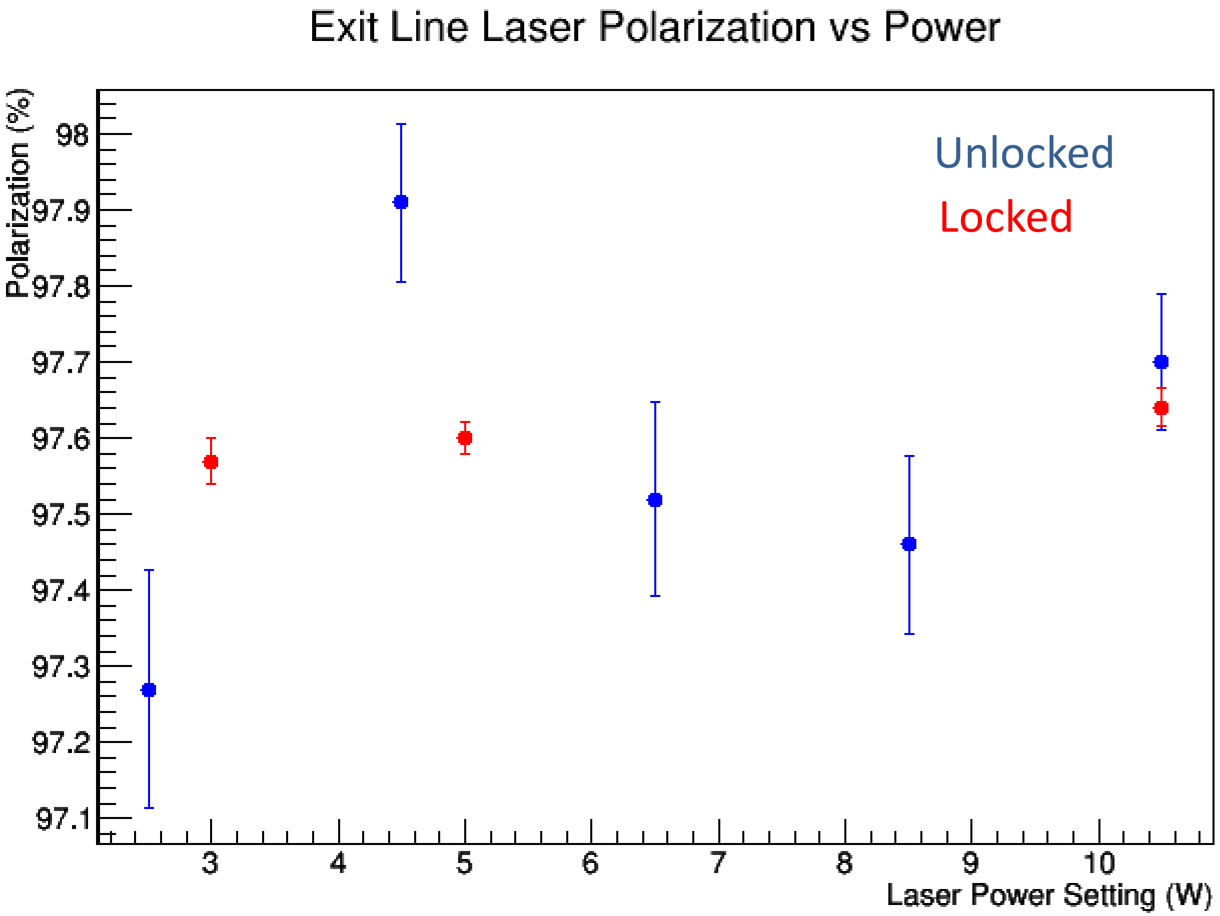
→Depolarization bounded at >2x0.2% =0.4%



What has been overlooked?

We measure laser polarization with cavity unlocked. What about locked?

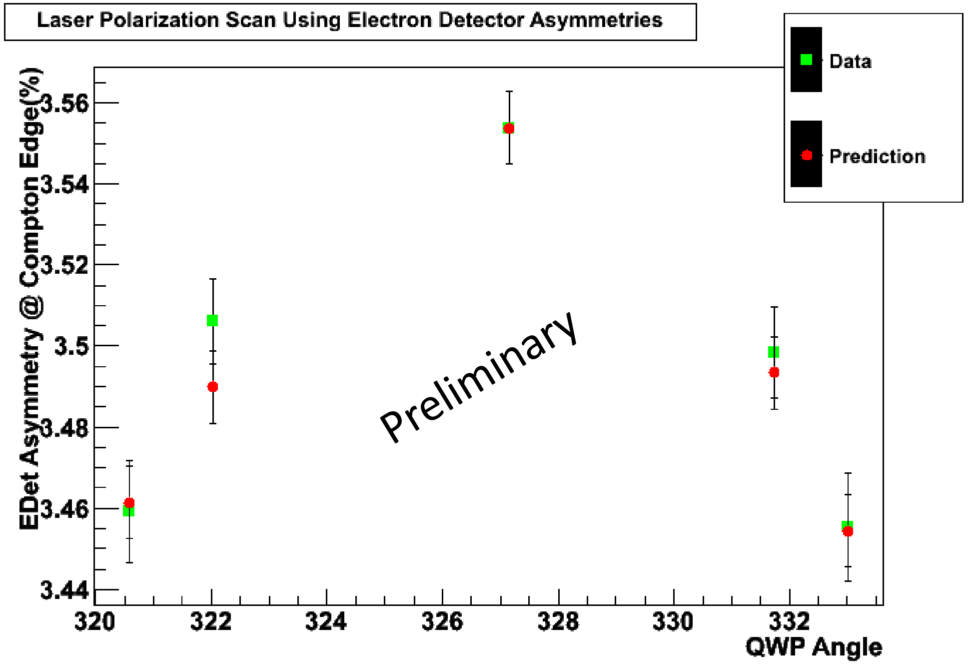
We took measurements in the exit line after the cavity in both locked and unlocked* states and found no measureable difference in polarization.



*This is possible with low gain cavity -- mirror transmission ~0.5%

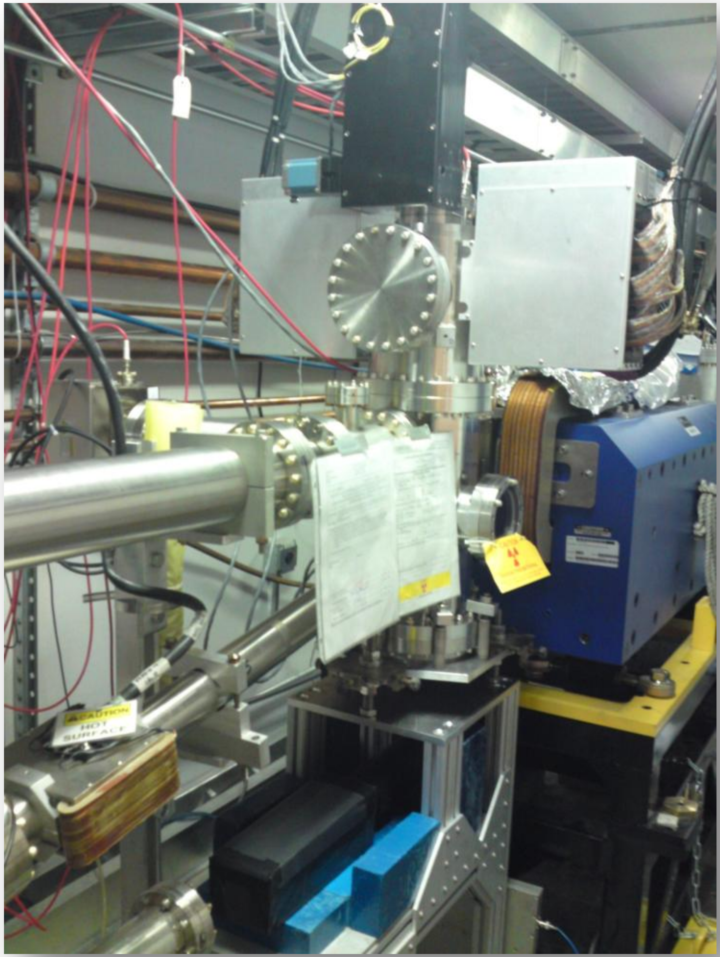
Sanity Check Using Electron Detector

- Varied laser polarization according to the model around the peak 100% DOCP position under stable electron beam conditions
- Results from preliminary electron detector asymmetries verify that we were indeed running on a peak DOCP
- We can at least say that the model correctly determines position of a maximum of DOCP

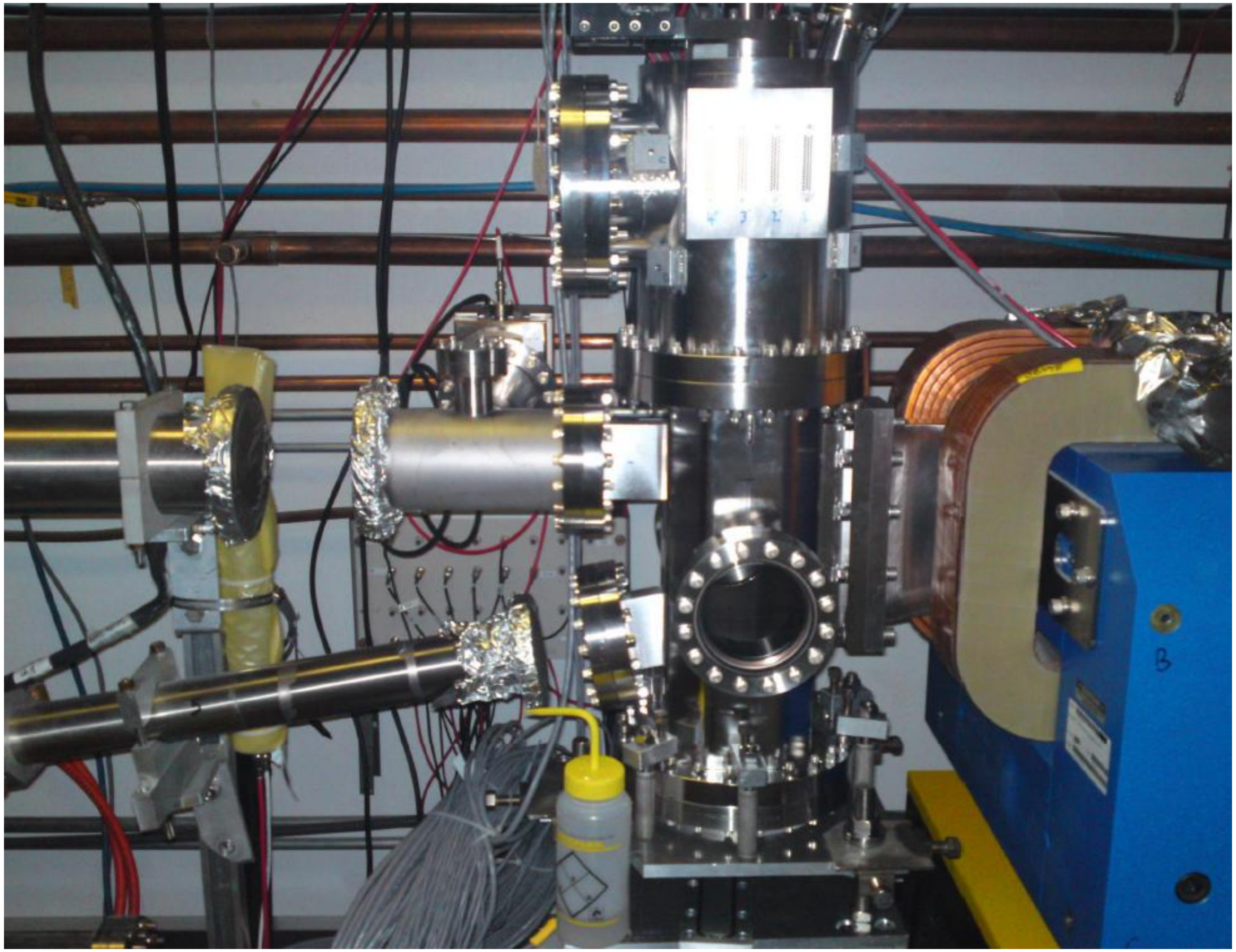


Electron Detector

- Sits about 5mm from the electron beam.
- 3rd dipole acts as a spectrometer to separate scattered electrons by energy
- Uses diamond plates with metal microstrips adhered to the surface
- First diamond strip detector to be used in a Compton polarimeter

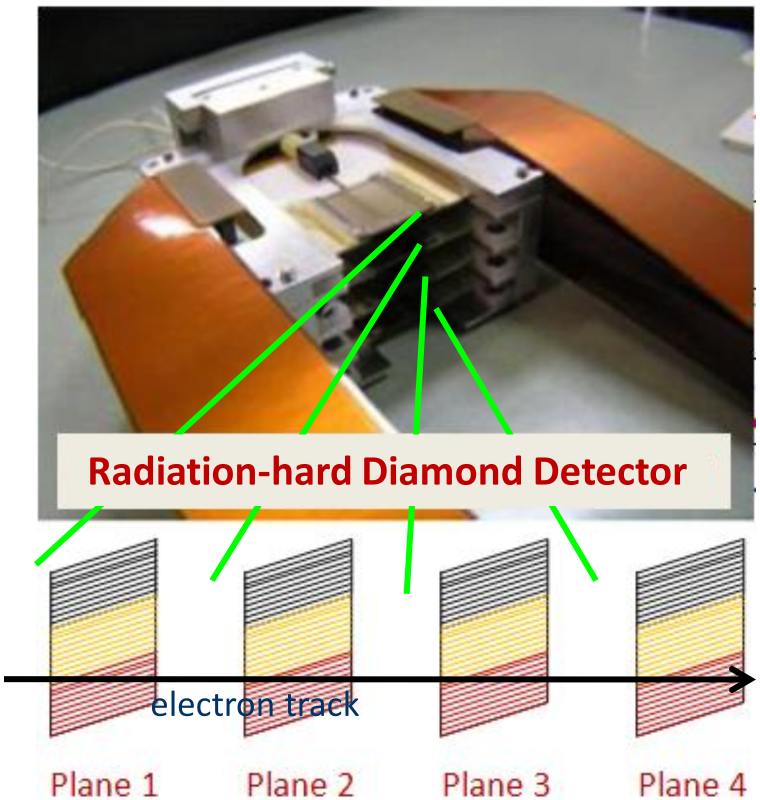


Electron Detector

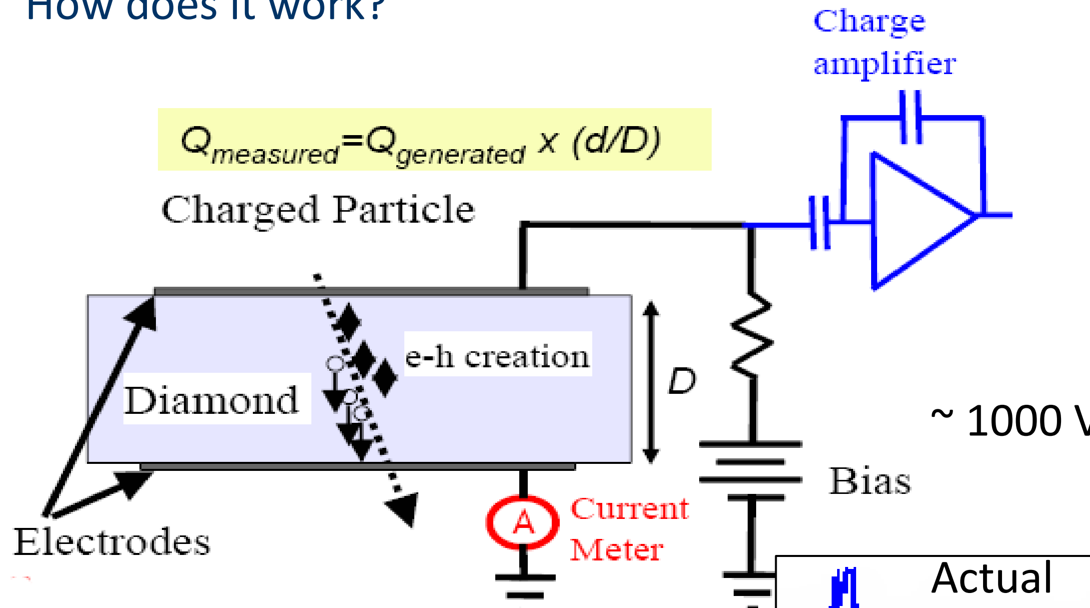


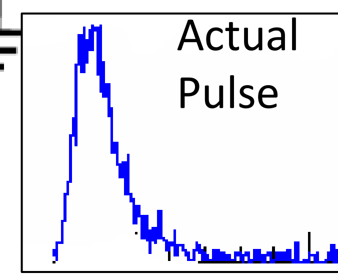
The Diamond Detector

- Diamond is known for its radiation hardness
- We chose artificially grown Diamond (grown by Chemical Vapor Deposition)
- Four 21mm x 21mm planes each with 96 horizontal 200um wide micro-strips.



How does it work?





Electron Detector

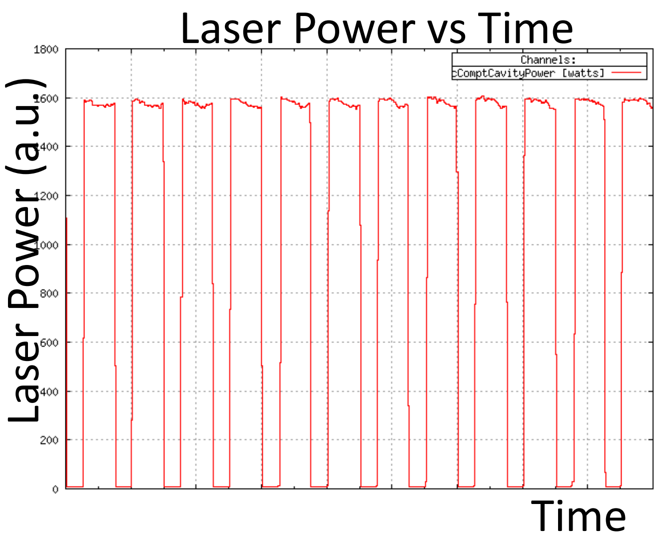
- We cycle the laser continuously on and off to measure backgrounds

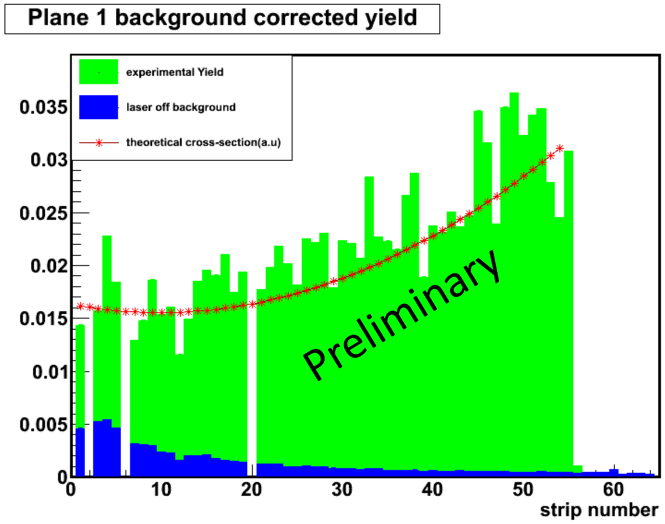
$$A_{meas}=\frac{\left(N_{On}^{+}-a^{+}N_{Off}^{+}\right)-\left(N_{On}^{-}-a^{-}N_{Off}^{-}\right)}{\left(N_{On}^{+}-a^{+}N_{Off}^{+}\right)+\left(N_{On}^{-}-a^{-}N_{Off}^{-}\right)},$$

$$a^{+}=\frac{Q_{On}^{+}}{Q_{Off}^{+}},\quad a^{-}=\frac{Q_{On}^{-}}{Q_{Off}^{-}}$$

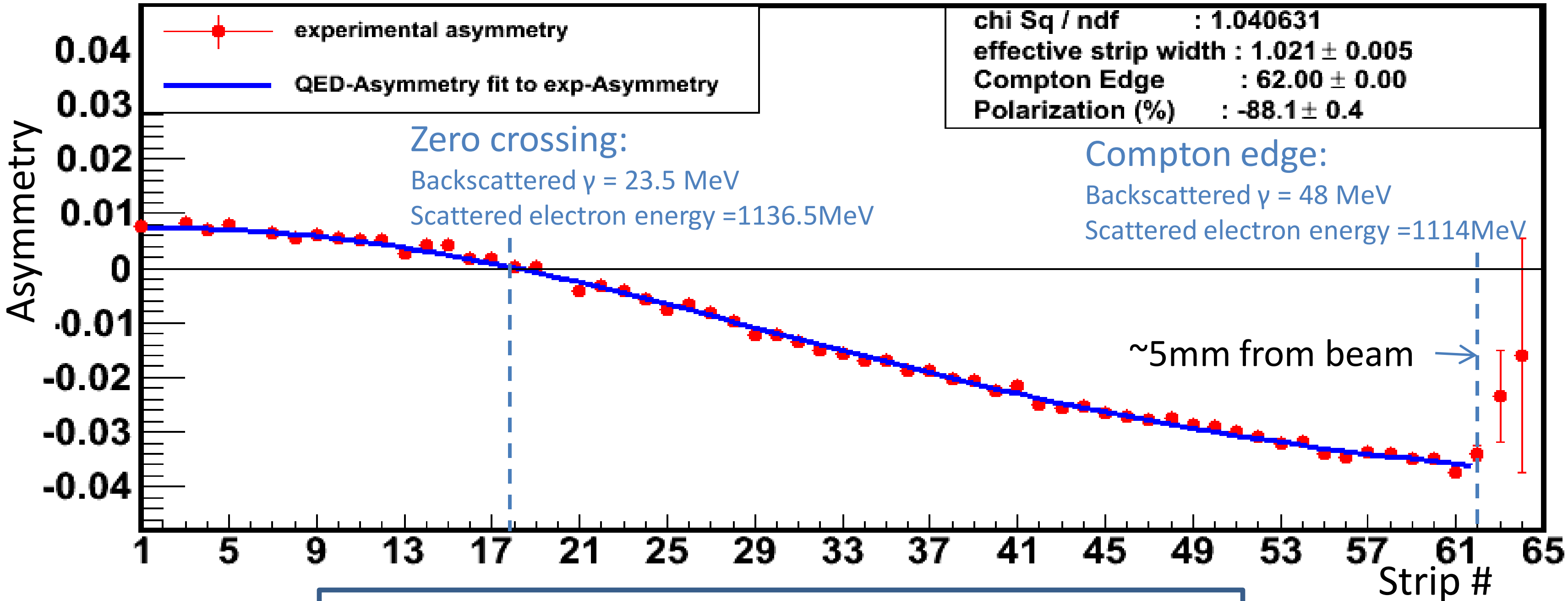
$$P_e = A_{meas}/P_\gamma$$

- Either a 2 out of 3 or a 3 out of 4 plane trigger
- Efficiencies vary from strip to strip but asymmetries formed for each strip so to first order strip to strip efficiencies not an issue.
- Simulations being done to determine effect of efficiency on trigger bias





Electron Detector Analysis

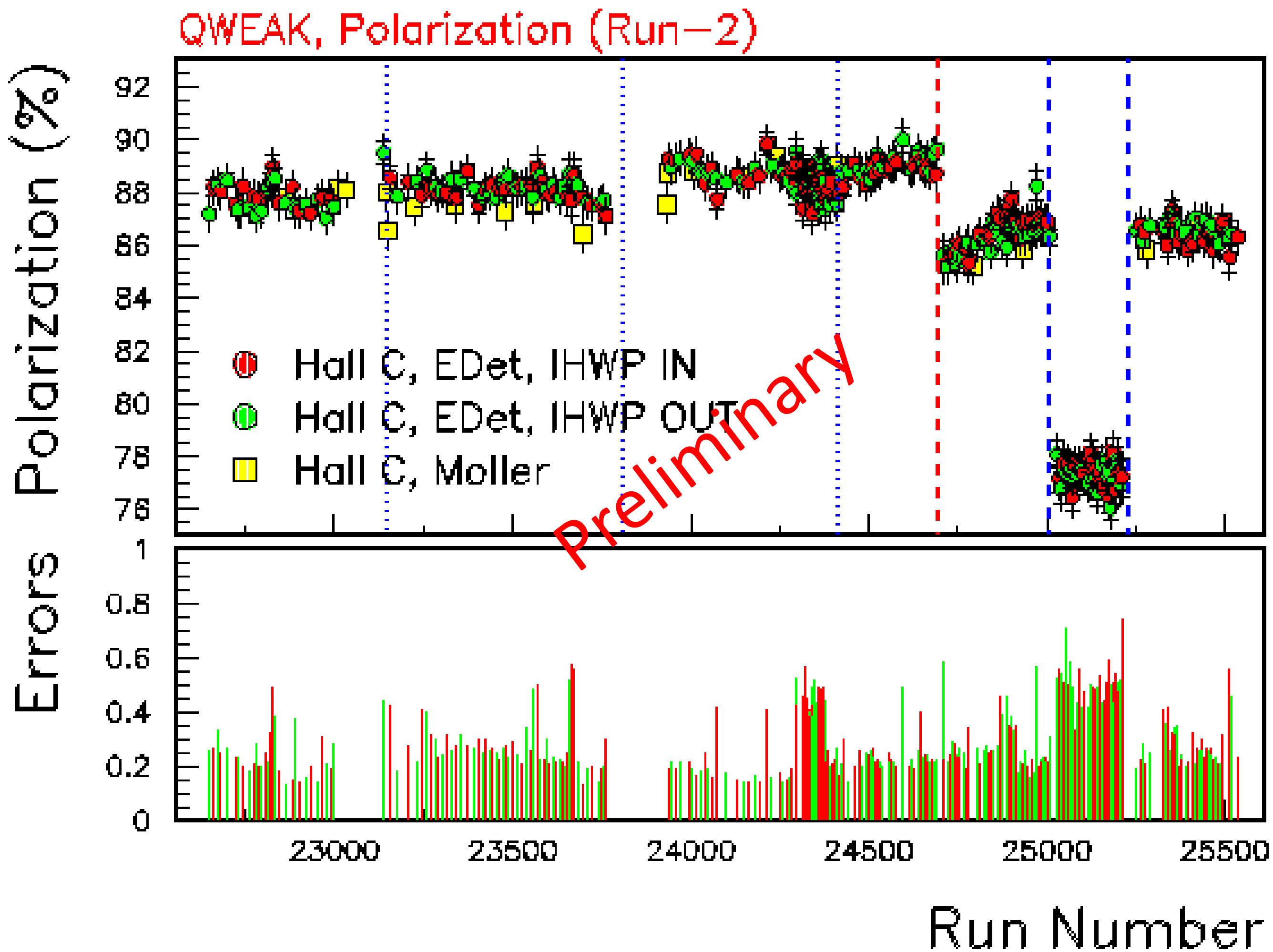


2 key steps in electron detector analysis:

1. Build the asymmetry in each strip:
   ->Requires measurement of laser-off and laser on yields as well as noise.

2. Convert strip number to scattered electron energy:
   ->Requires 2 reference points to position and scale the asymmetry curve. Asymmetry/Yield endpoint and asymmetry shape provide these key kinematic references.

Recent Q_{weak} Electron Detector Data Using Fixed CE

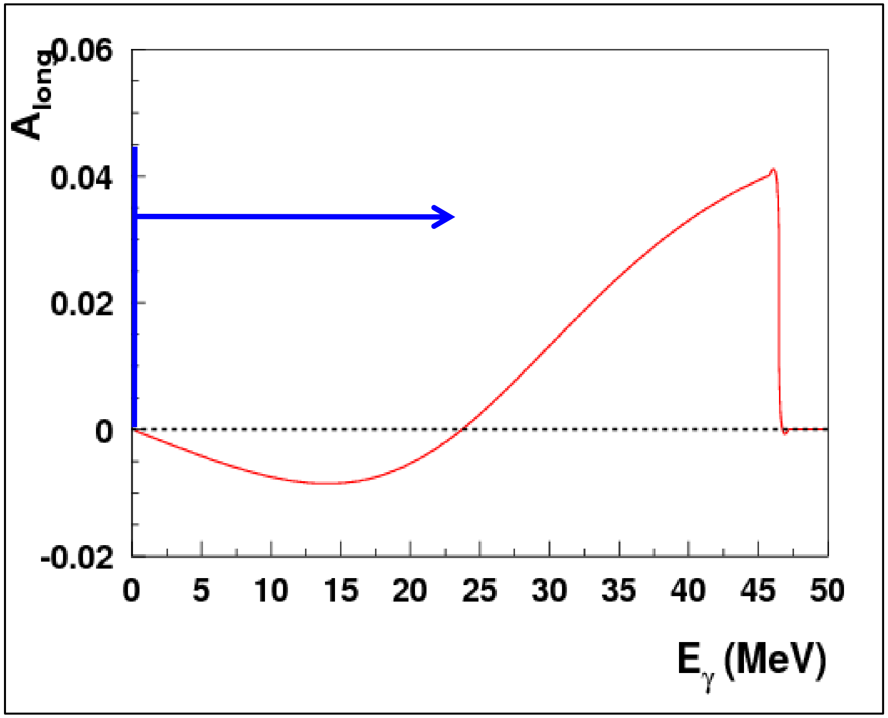


Routinely delivered dA/A<0.6% statistical error per hour.

Photon Detector

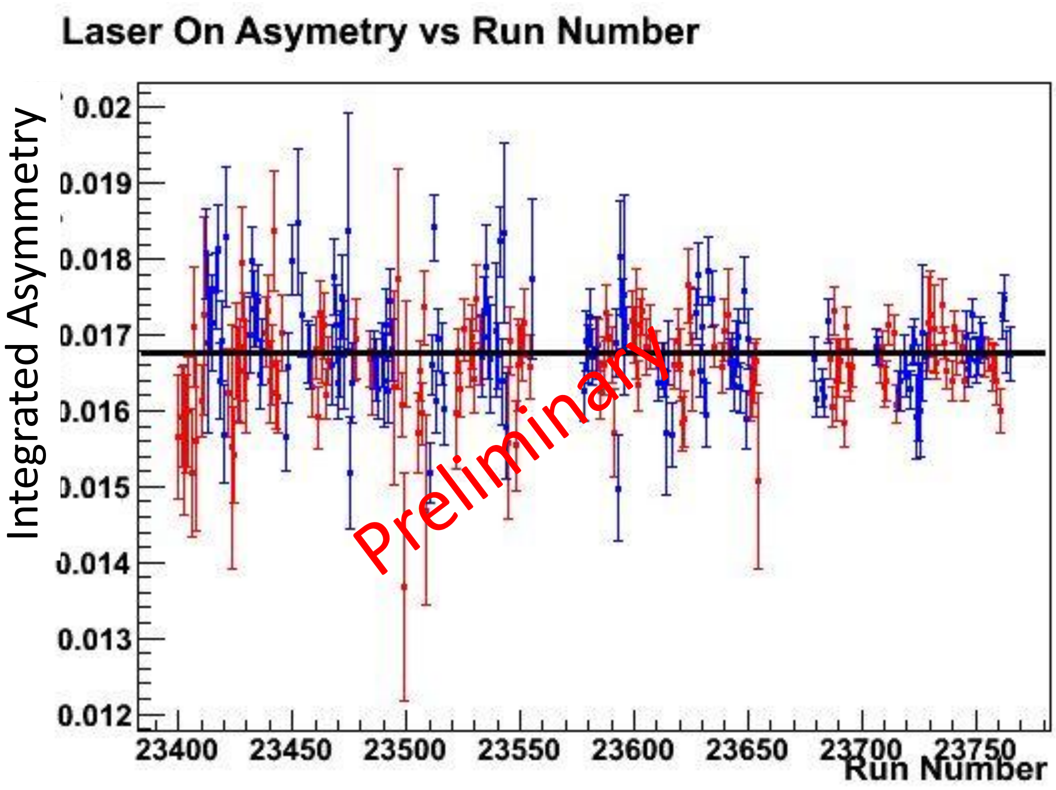
Photon detector operates in energy-weighted integrating mode with no threshold

$$A_{meas} = \frac{\int_0^{E_\gamma^{max}} A_{Compton} E_\gamma dE_\gamma}{\int_0^{E_\gamma^{max}} E_\gamma dE_\gamma}$$



→Independent of detector gain shifts (PMT or temperature dependent crystal resolution) since we are not fitting the shape of the spectrum.
→Need to subtract pedestal very accurately – a small miscalculation of pedestal can drastically change the measured asymmetry.

Photon Detector Asymmetries



Photon detector asymmetries shown for a period during the Qweak experiment.
→No corrections for non-linearity
→Photon detector delivered dA/A~1% every 8 hrs. Systematic error not yet determined
→Need detector resolution and non-linearity to convert asymmetries to polarizations.

Conclusions

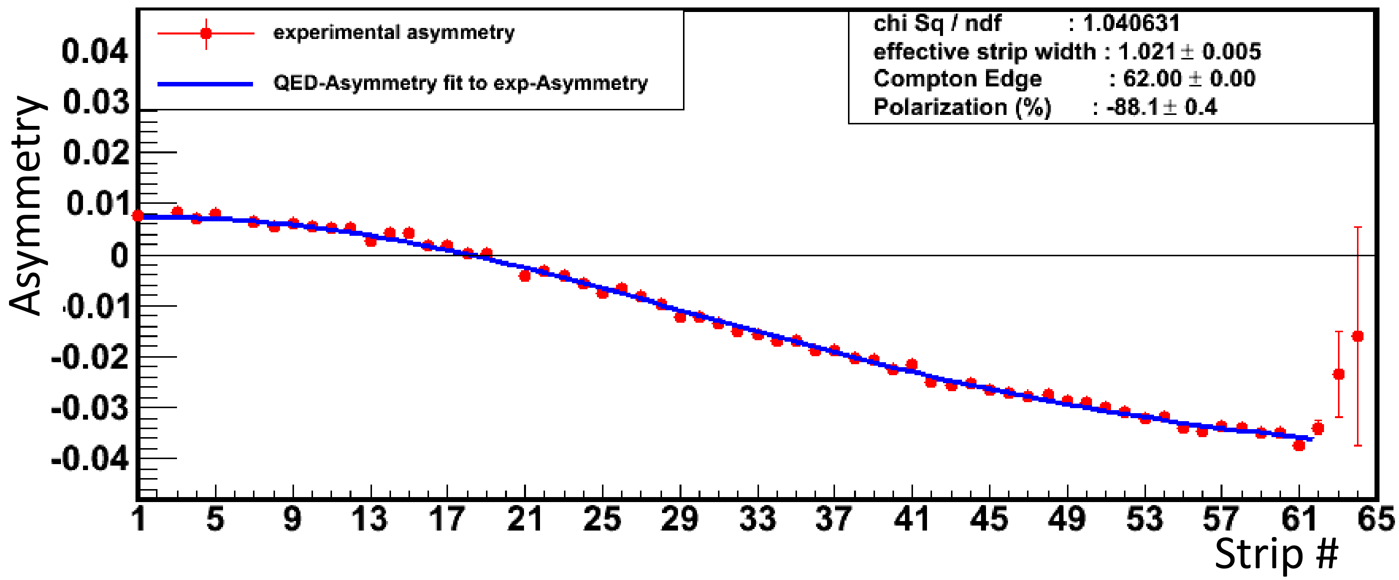
- New Compton polarimeter in Hall C at Jefferson Lab appears to be on track to meet or beat it's design goal dP/P<1%.
- Electron detector routinely delivered (dP/P)/hr <0.5 %(statistical) and systematic error still being studied but appears to be small.
- Photon detector would be a nice cross check but so far detector linearity not determined.
- Laser polarization accurately determined by new technique. This key systematic common to both detectors appears to be under control.

Contributors

Jefferson Lab, *D. Gaskell and the Hall C staff,* Mississippi State University, *D. Dutta , A. Narayan,* University of Virginia, *K. Paschke , M. Dalton, D. Jones,* University of Winnipeg/TRIUMF, *J. Martin , V. Tvaskis, L. Lee, D. Ramsay, L. Kurchaninov,* College of William and Mary, *W. Deconinck, J. C. Cornejo,* MIT-Bates, *S. Kowalski, E.Ihloff, and technical staff.*

Backups

Electron Detector Analysis



Developed 2 methods for strip to scattered electron energy conversion.

1. Set Compton edge (CE) strip from yields and fit polarization and scale parameters.

$$Dist = MaxDistance - 0.2*(CE-i_{Strip})*scale$$

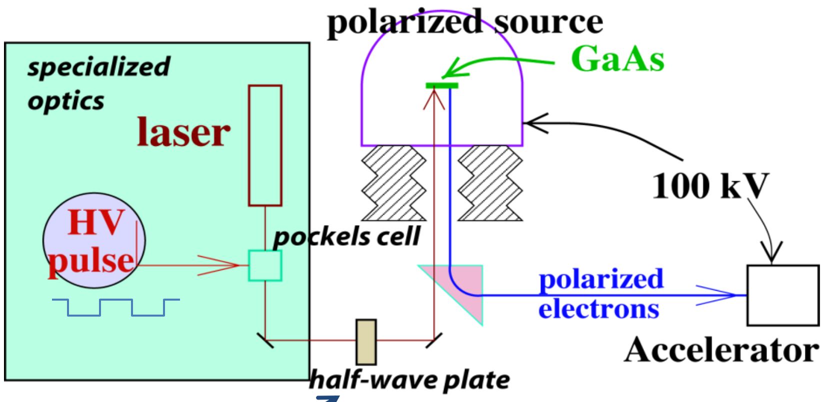
- Pros: uncertainty in dispersion, position and angle of detector folded into scale fit parameter.
- Cons: uncertainty in Compton edge ±90µm due to finite size of strip ->dP/P ~ 0.6%

2. Precisely determine the dispersion, position and angle of the detector and fit with CE and polarization as fit parameters. $Dist = MaxDistance - 0.2*(CE-i_{Strip})$

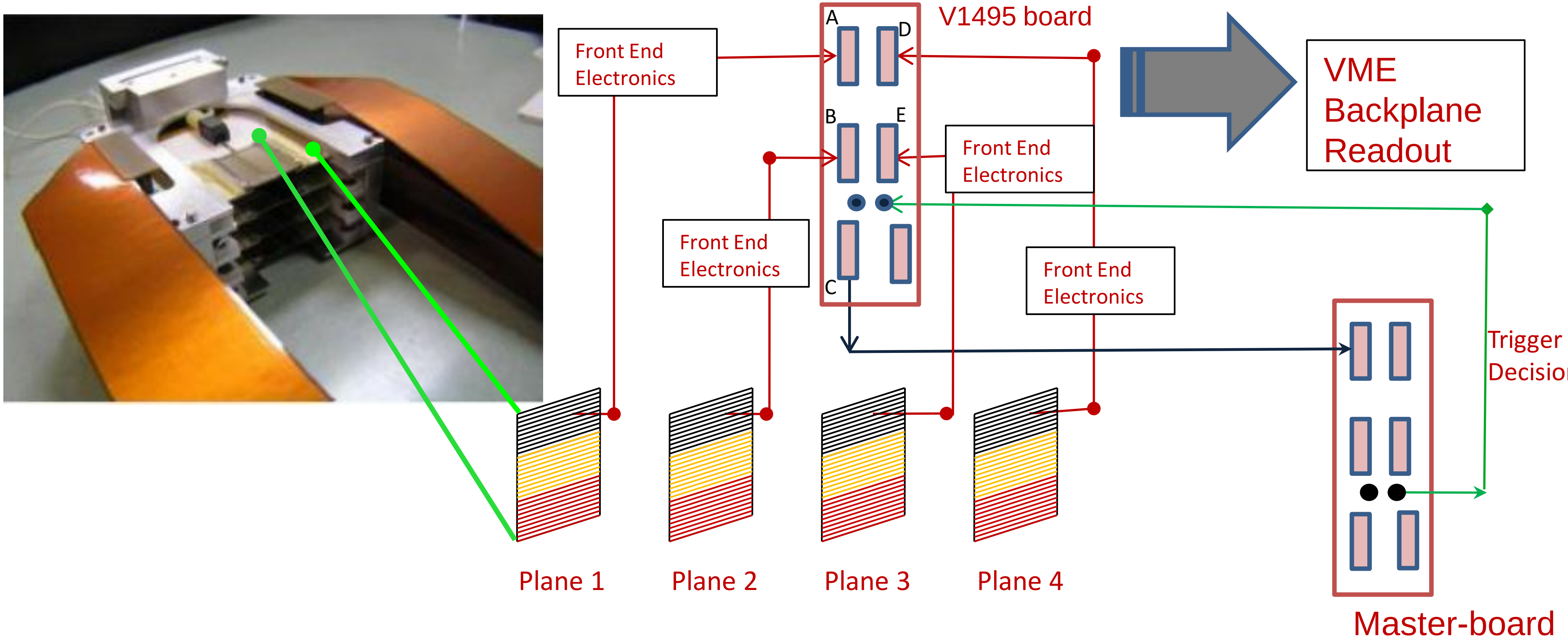
- Pros: CE position determination not limited by strip width
- Cons: must accurately measure dispersion, dipole fringe fields, detector position and beam energy. So far it appears that systematic error is smaller using this method, but statistical error is larger.

Polarized Electron Beam at Jefferson Lab

- Electron beam is produced by shining a high intensity laser on a “superstrained” GaAs cathode which then emits electrons due to the photoelectric effect. Routinely achieve P>85%.
- Hard to measure absolute polarization of one static spin state. Easier to determine polarization from asymmetry of measurements from a rapid beam helicity reversal.
- Circular polarization of the laser is flipped @ 960Hz using a Pockels cell and flipping the polarity of the high voltage.
- A family of systematic errors (false asymmetries0 can arise from differences between the two helicity states
- Some of these are canceled by periodically inserting a half-wave plate in the source laser beam to flip the laser spin and thus the electron helicity relative to the Pockels cell voltage.



Compton Electron Detector Schematic



- 96 strips of each detector plane is read out by the front end electronics and sent to a V1495 board
- This board reconditions the input signal and sends it to the master board for final Trigger decision.
- The Master board sends back a signal to indicating whether to keep or reject the detector hit-pattern.

slide contributed by A.Narayan

Comparison of Diamond with Silicon

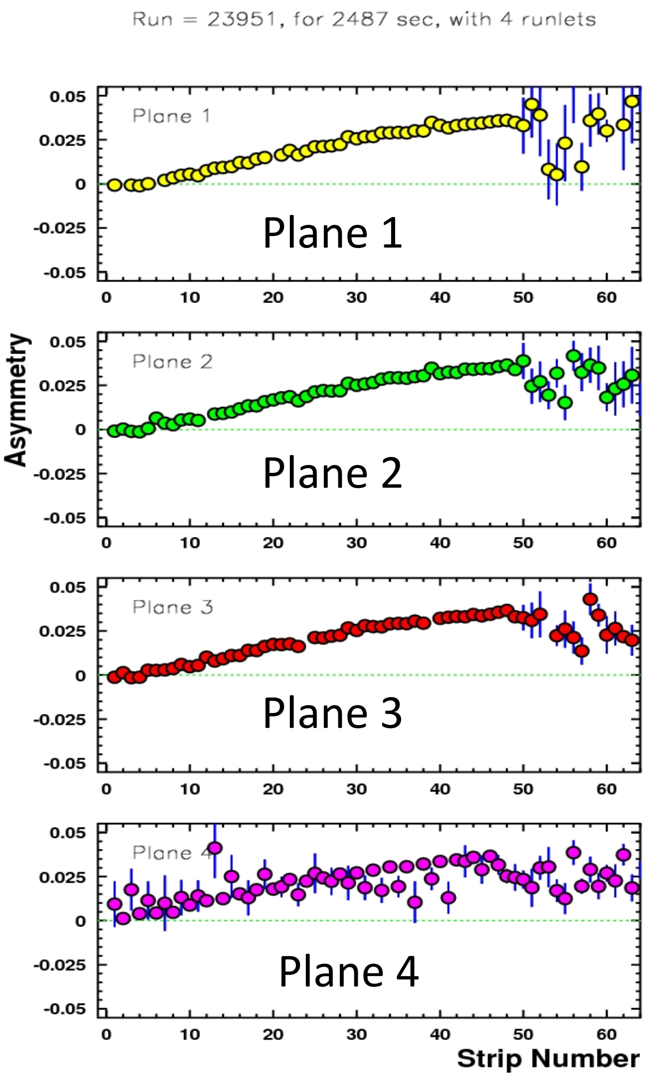
Property	Silicon		Diamond	
Band Gap (eV)	1.12	→	5.45	Low leakage current shot noise
Electron/Hole mobility (cm^2/Vs)	1450/500	→	2200/1600	Fast signal collection
Saturation velocity (cm/s)	0.8×10^7	→	2×10^7	
Breakdown field (V/m)	3×10^5	→	2.2×10^7	
Dielectric Constant	11.9	→	5.7	Low capacitance noise
Displacement energy (eV)	13-20	→	43	Radiation hardness
e-h creation energy (eV)	3.6	→	13	Smaller signal
Av. e-h pairs per MIP per micron	89	→	36	
Charge collection distance (micron)	full	→	~250	

Advantages: lower leakage current, faster, lower noise and Radiation Hard

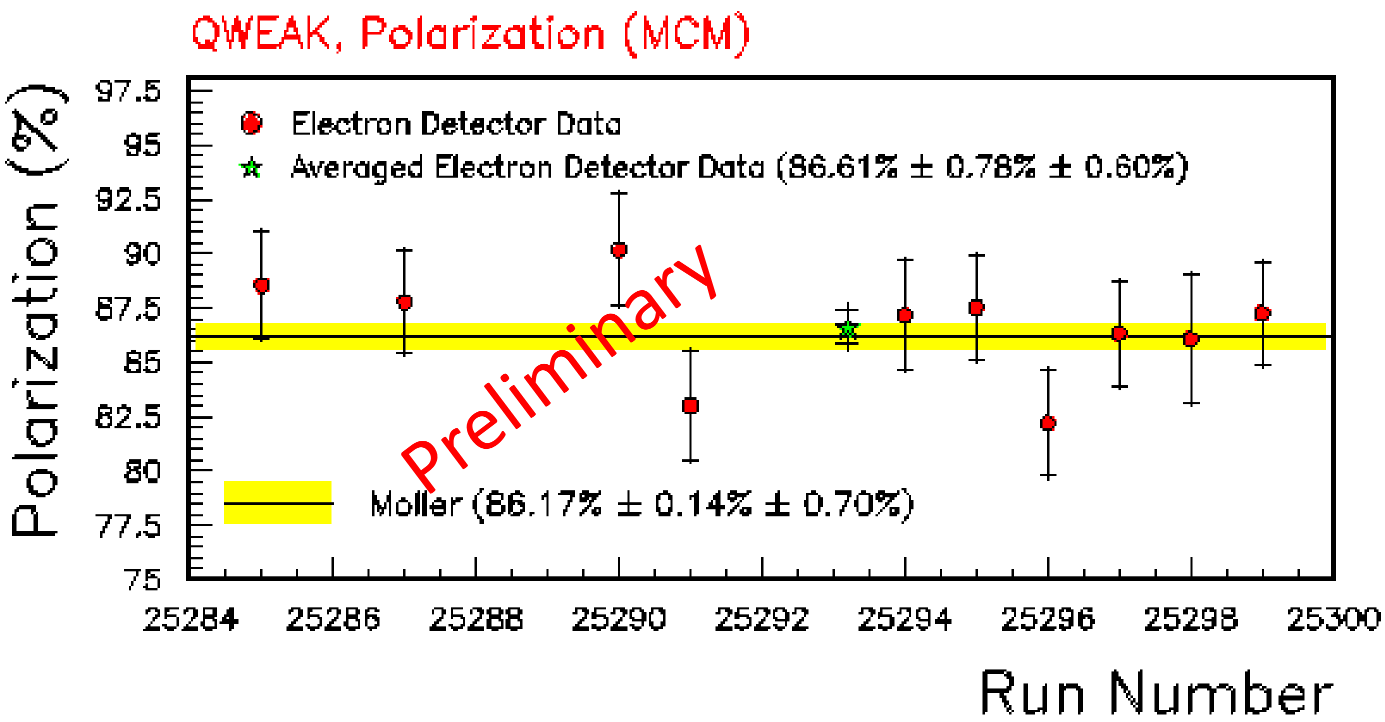
Disadvantages: signal ~ 40% smaller

Electron Detector Asymmetry

- Asymmetries formed strip by strip so efficiency differences not important
- Compton edge determined either manually or by using the size of the error in each strip
- Systematic studies are underway to determine the effect of dead time on the asymmetries



Møller-Compton-Møller Test



Systematic Uncertainty Comparison

Systematic Uncertainty	Uncertainty	ΔP/P (%)	
		Free CE	Free SFP
Compton edge location	90 μm	N/A	0.65
Dipole field strength	(0.0011 T)	0.02	0.01
Beam energy	1 MeV	0.09	0.08
Detector Longitudinal Position	1 mm	0.03	0.01
Detector Rotation (pitch)	1 degree	0.04	0.04

Floating Compton edge fit yields higher precision result at the expense of needing to keep track of beam energy, dipole field etc. run-by-run