Green Fabry-Perot Cavity for Precision Compton Polarimetry

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3^{rd} Mini-Workshop on H^- Laser Stripping and Accelerator Applications

Fermilab, Batavia, IL

September 26 - 27, 2013

Outline

1 Introduction

- Polarized Electron Beam at JLab
- Compton Polarimetry

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2. **Building a Green Laser via SHG**
   - Quasi-phasematching
   - Frequency Doubling Setup
   - Results

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    - Cavity Transverse Modes
    - Pound-Drever-Hall Locking Scheme
    - Cavity Mechanics & Optics
    - Cavity Performance

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   - Cavity Mechanics & Optics
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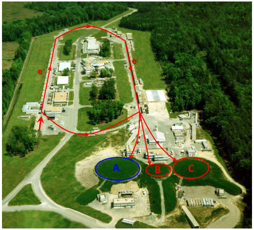
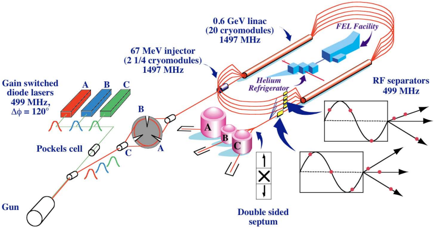
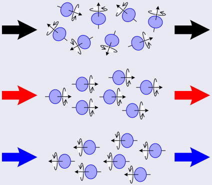
4. **Beam Polarization**
   - Cavity Polarization Transfer Function
   - Intra-Cavity Polarization Uncertainties
   - Electron Beam Polarization
5. **Summary**

Polarized Electron Beam at JLab





e-Beam Polarization:



Unpolarized
(N)

Right-handed
(N^+)

Left-handed
(N^-)

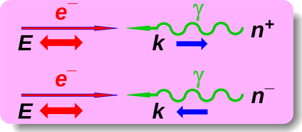
$$\mathcal{P}_e = \frac{N^+ - N^-}{N^+ + N^-}$$

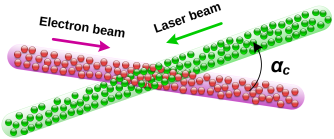
How to Measure Polarization of e-Beam ?

1. $e + Z \to e'$: **Mott Scattering**, spin-orbit coupling of electron spin with (large Z) target nucleus, (0.1 ∼ 10 MeV)
   Invasive, Different Beam
2. $e + e \to e' + e'$: **Møller Scattering**, atomic electrons in Fe (or Fe-alloy) polarized by external magnetic field and scatter off, (MeV ∼ GeV)
   Invasive, Different Beam
3. $e + \gamma \to e' + \gamma'$: **Compton Scattering**, laser photons scatter from electrons (**Nobel Prize !!**)
   Non-invasive, Same Beam (> GeV)

Compton Polarimetry

- The electron beam passes through laser light on its way to the target
- Detects both scattered electron and backscattered photons
- Can extract electron beam polarization by measuring asymmetries in scattering rates for circularly polarized laser light
- The electron beam is virtually **undisturbed**; **continuous** measurement
- Very good polarimetry at high energy or/and high currents



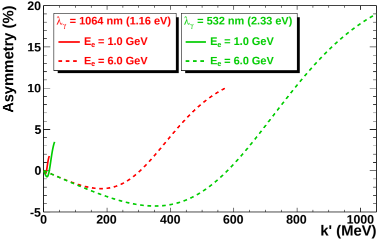


Asymmetry : $\mathcal{A}_{\mathbf{exp}} = \dfrac{n^+ - n^-}{n^+ + n^-} = \mathcal{P}_\gamma \cdot \mathcal{P}_{\mathbf{e}} \cdot \mathcal{A}_{\mathbf{L}}$

Cross Section : $\dfrac{d\sigma}{dk'} = \dfrac{d\sigma_0}{dk'} + \mathcal{P}_\gamma \cdot \mathcal{P}_e \cdot \dfrac{d\sigma_1}{dk'}$

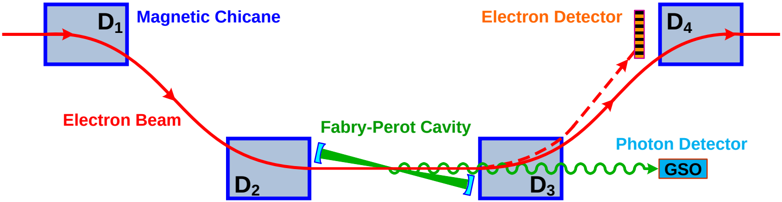
Luminosity : $\mathcal{L} \propto \dfrac{I_e P_L}{k\alpha_c} \dfrac{1}{\sqrt{\sigma_{ey}^2 + \sigma_{\gamma y}^2}}$

Measurement Time : $T \propto \dfrac{1}{\sigma \cdot \mathcal{A}_L^2} \propto \dfrac{1}{k^2 \cdot E^2}$



Green Compton Polarimeter in Hall A at JLab

1. Magnatic Chicane: Four dipoles; $L_{total} = 15.35$ m
2. **Laser System:** Nd:YAG IR (1064 nm) seed laser (CW); Yb doped fiber amplifier; Single-pass PPLN doubler (532 nm)
3. **Fabry-Perot Cavity:** $L = 85$ cm; $G \sim 4{,}000$; $P_{cav} \sim 3.5$ kW; $\alpha_c = 1.4^\circ$(24 mrad)
4. **Electronics:** Pound-Drever-Hall (PDH) feedback scheme for lock acquisition
5. **Laser Polarization:** Circularly polarized ($\sim$100%) light at the center of the cavity
6. Photons: Single crystal Gd_2SiO_5 (GSO) calorimeter; $\varnothing = 6$ cm; $L = 15$ cm
7. Electrons: Silicon micro-strips; 240 μm pitch; 4 planes; 192 strips/plane
8. **Goal:** Cover operating range for $5 \sim 180$ μA @ 499 MHz; $1.0 \sim 12.0$ GeV; **1.0% precision** in e-beam polarization measurement

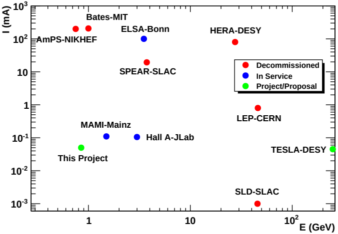


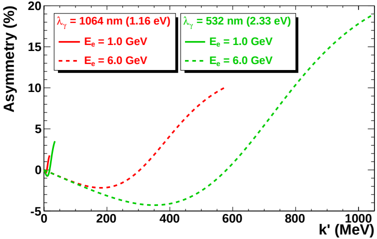
Outline

Building a Frequency Doubled Green Laser

Motivation:

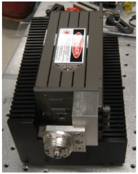
- Photons with higher energy (shorter wavelength) give us higher asymmetry and therefore a smaller systematic error in Compton polarimetry
- Going for green (532 nm) laser was an ultimate decision
- Commercially available green lasers sacrifice fast feedback and tunability for power
- Advancement in Yb doped fiber laser technology made the power amplification of IR (1064 nm) lasers feasible
- We use Second Harmonic Generation (SHG) to make our own 532 nm laser with the desired characteristics from our narrow linewidth (5 kHz) IR laser

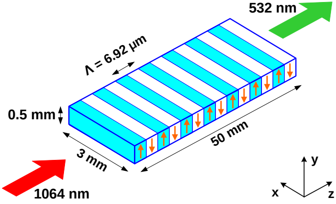


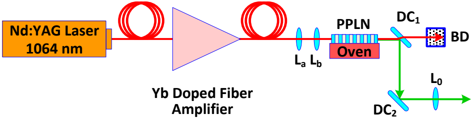


Frequency Doubling Setup

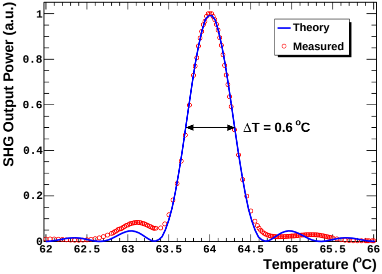
- Seed Laser: NPRO Nd:YAG single-frequency ($\Delta\nu = 5$ kHz) @ 1064 nm (JDSU Lightwave-126)
- Fiber: single-mode polarization maintaining (PM) fiber
- Fiber Amplifier: Yb doped; linearly polarized; max ouput 10 W @ 1064 nm (IPG Photonics YAR-10K-1064-LP-SF)
- Crystal: Periodically Poled Lithium Niobate (PPLN); doped with 5% MgO (HC Photonics)
- Geometry: 0.5 mm × 3 mm × 50 mm
- Domain Structure: $\Lambda = 6.92\ \mu$m with 50% duty cycle
- Oven: Homemade TEC based unit with commercial temperature controller; 0.01^{o}C resolution (Arroyo Instruments)
- Dichroic Mirrors: Refl. @ 532 nm; Trans. @ 1064 nm
- Mode matching lenses and beam dump

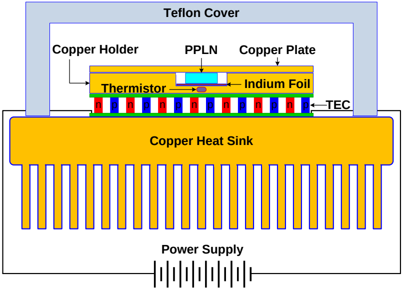


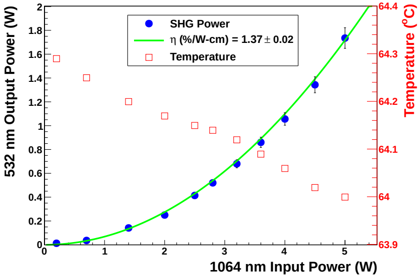


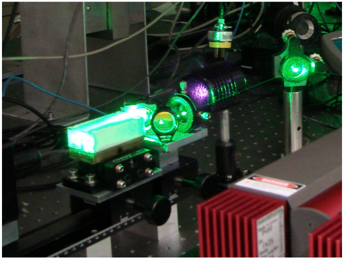


SHG Efficiency

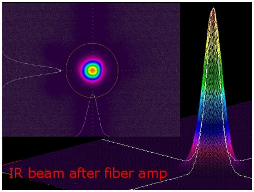


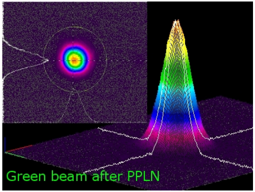


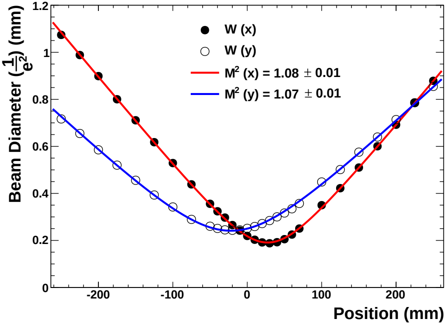




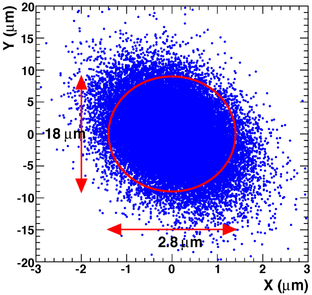
Green Beam Quality

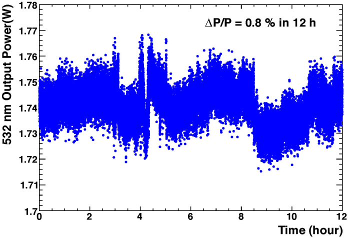






Pointing Stability < 6 μrad





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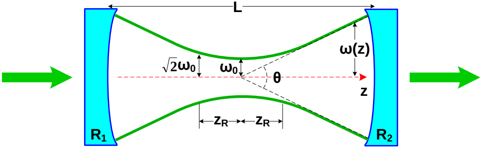
Cavity Transverse Modes

$$E(r,z) = E_0 \frac{\omega_0}{\omega(z)} exp\left[-\frac{r^2}{\omega^2(z)}\right]$$

$$\omega(z) = \omega_0 \sqrt{1 + \left[\frac{z}{z_R}\right]^2}, \qquad z_R = \frac{\pi \omega_0^2}{\lambda}$$

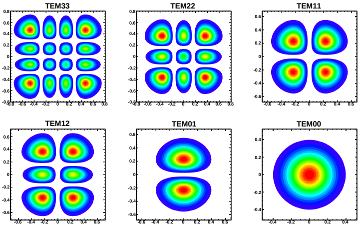
$$\omega_0^2 = \frac{L\lambda}{2\pi}\sqrt{\frac{1+g}{1-g}}, \qquad g = 1 - \frac{L}{R}$$



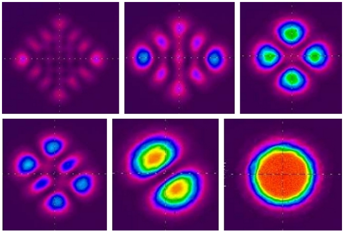
Hermite-Gaussian Modes:

$$I_{mn}(x,y) = I_0 \left[H_m\left(\frac{\sqrt{2}x}{\omega(z)}\right) H_n\left(\frac{\sqrt{2}y}{\omega(z)}\right) e^{\frac{-(x^2+y^2)}{\omega(z)^2}}\right]^2$$

Theory

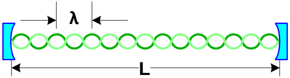


Experiment

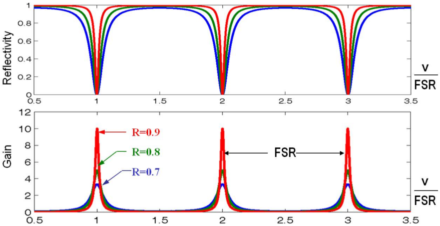


Cavity Resonance

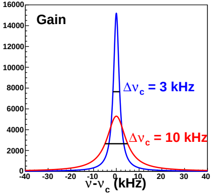
- Two highly reflective mirrors are spaced in an integer number of half-wavelengths apart

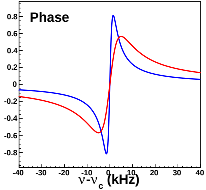


$$L = \frac{n\lambda}{2}, \qquad FSR = \frac{c}{2L}$$



- When the resonance conditions are met, light will build up
- There should be an active feedback either to the laser frequency or to the cavity length
- We provide frequency feedback signal to the laser in our system



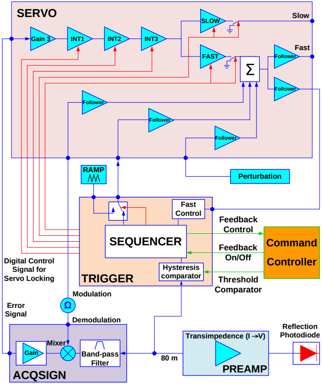


Finesse : $\mathcal{F} = \frac{\pi\sqrt{R}}{1-R}$, Bandwidth : $\Delta\nu_c = \frac{FSR}{\mathcal{F}}$, Q − factor : $Q = \frac{\nu}{\Delta\nu_c}$

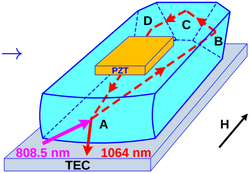
Decay Time : $\tau = \frac{1}{2\pi\Delta\nu_c}$, Gain : $G_{max} = \frac{T}{(L+T)^2}$

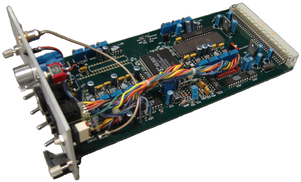
Laser Frequency Control

- NPRO (Non-Planar Ring Oscillator) Nd:YAG laser is a fine tunable laser
- The frequency control is done by:
  1. Temperature control of the NPRO crystal via TEC (bandwidth ∼1 Hz, dynamic range ∼60 GHz)
  2. Applying a voltage to piezoelectric transducer (PZT) (bandwidth ∼100 kHz, dynamic range ∼200 MHz) bonded to the laser crystal
- PZT also enables a direct phase modulation to the seed laser head
- Fiber amplifier has a relatively narrow linewidth (∼10 kHz) to follow
- Single-pass SH generated green beam keeps beam tunability of the seed laser

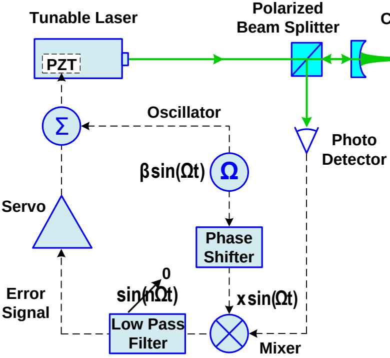


NPRO crystal →



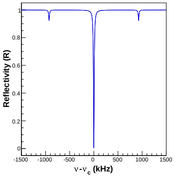


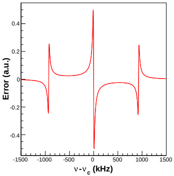
Pound-Drever-Hall Locking Scheme



Condition : $\Delta\nu_c \ll \frac{\Omega}{2\pi} \ll FSR$

$$\epsilon = -2\sqrt{I_c I_s}\,\mathrm{Im}\Big[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)\Big]$$

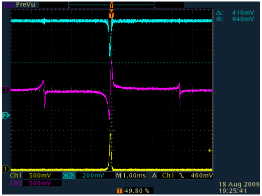




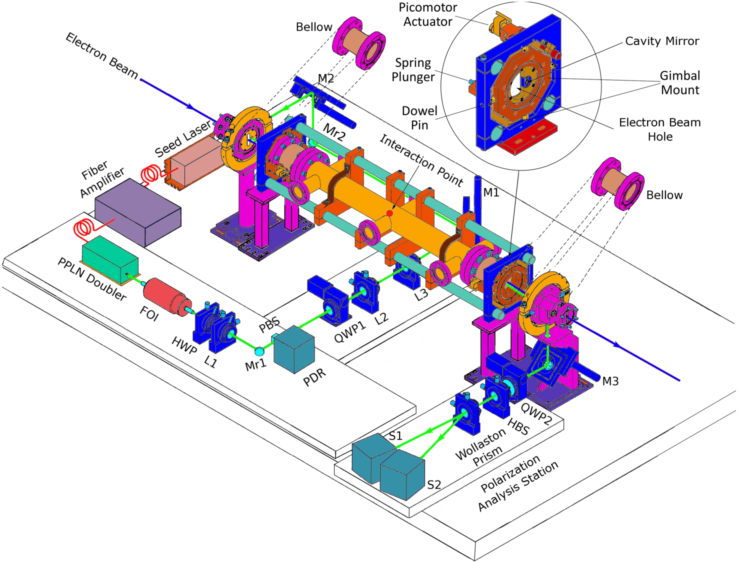
$$E_{inc} = E_0 e^{i\omega t}\Big[J_0(\beta) + J_1(\beta)e^{i\Omega t} - J_1(\beta)e^{-i\Omega t}\Big]$$

$$E_{ref} = E_0 e^{i\omega t}\Big[F(\omega)J_0(\beta) + F(\omega+\Omega)J_1(\beta)e^{i\Omega t} - F(\omega-\Omega)J_1(\beta)e^{-i\Omega t}\Big]$$

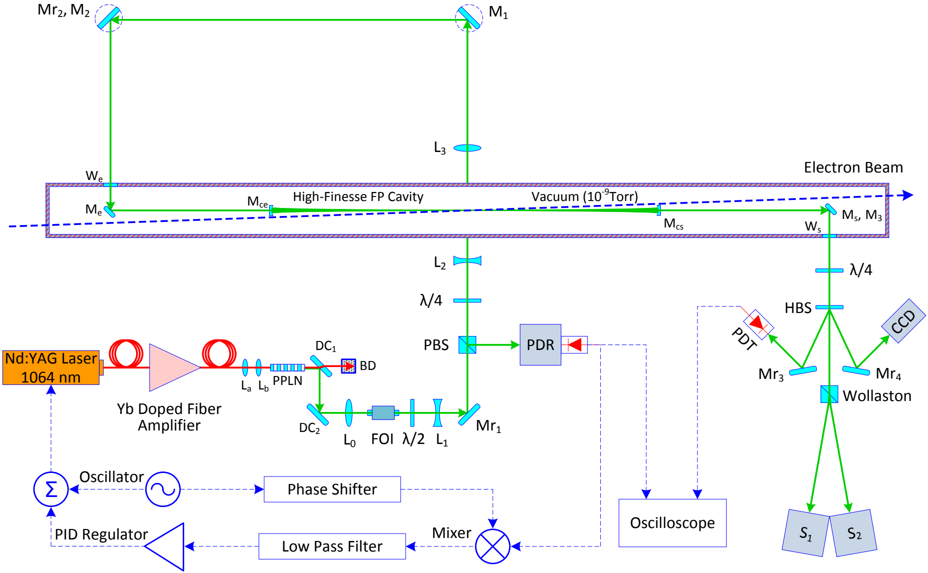
$$F(\omega) = E_{ref}/E_{inc}, \qquad I_s = J_1^2(\beta)I_0, \qquad I_c = J_0^2(\beta)I_0$$



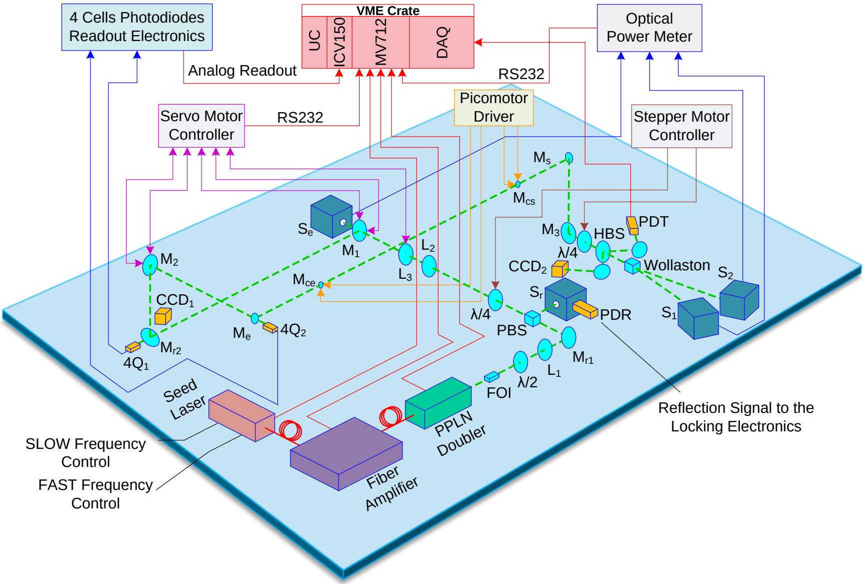
Cavity Mechanical Structure



Optical & Electronic Schematics

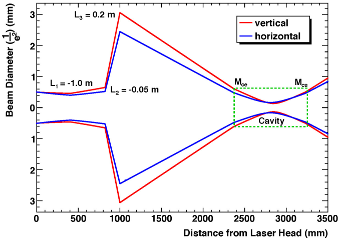


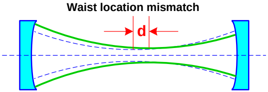
Cavity Functional View

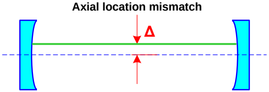


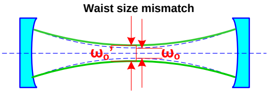
Cavity Mode Matching

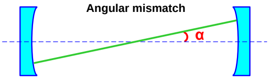
- Laser mode (beam) should match the cavity resonator mode
- Beam waist at the center should match the natural waist of the cavity
- Two cavity mirrors have to be highly parallel and the beam has to pass through their optical axis
- Mode matching determines the amount of primary power actually amplified in the fundamental mode
- The wavefront curvature of incoming beam must be equal to the ROC of one of the mirrors







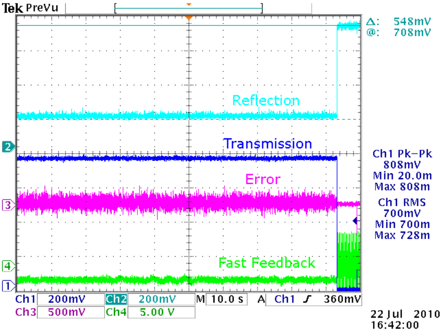




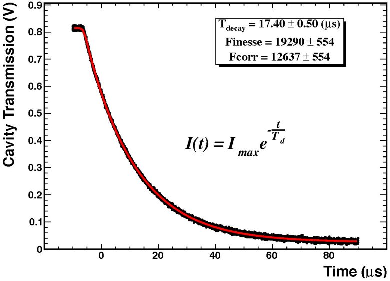
$$\frac{\Delta P}{P} = \left[\frac{\omega_0' - \omega_0}{\omega_0}\right]^2 + \left[\frac{\lambda d}{2\pi\omega_0^2}\right]^2$$

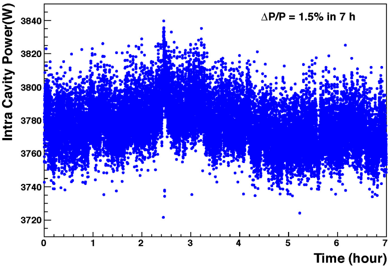
$$\frac{\Delta P}{P} = \left[\frac{\alpha\pi\omega_0}{\lambda}\right]^2 + \left[\frac{\Delta}{\omega_0}\right]^2$$

Cavity Performance



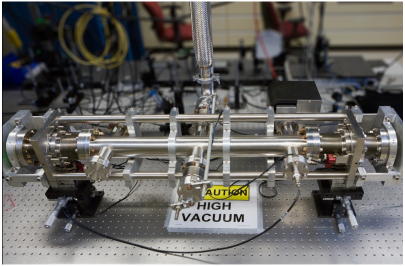
(Cavity Locking video)

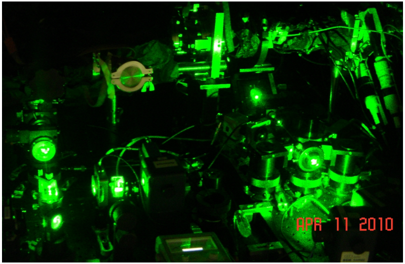




Characterization of Cavity Parameters

Length	85 cm
Mirror ROC	0.5 m
Mirror Diameter	7.75 mm
Wavelength	532 nm, CW, TEM_{00}
FSR	176.5 MHz
Intra-Cavity Power	**∼3.5 kW**
Optical Gain	**∼4,000**
Finesse	∼13,000
Decay Time	11.4 μs
Mode Match Coupling	0.80
Mirror Transmission	200 ppm
Mirror Loss	30 ppm
Bandwidth	14.0 kHz
CIP spot size (σ)	87 μm
Power Density @ CIP	**∼10 MW/cm^2**





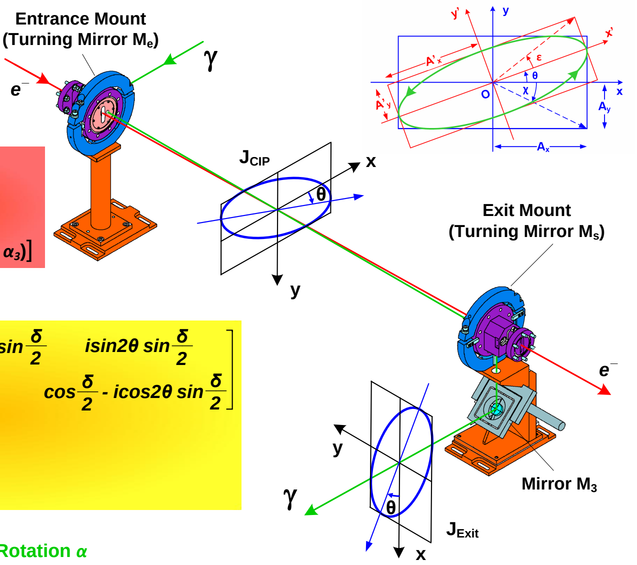
Mirror characterization method based on:

1. C. J. Hood, H. J. Kimble, J. Ye. Phys. Rev. A 64 (2001) 033804

2. N. Falletto *et al.* NIM A459 (2001) 412

Outline

Principle of Polarization Transfer Function



$$J_{Exit} = [TF] \bullet J_{CIP}$$

$$J_{CIP} = [TF]^{-1} \bullet J_{Exit}$$

$$TF = [M_s(\delta_s, \theta_s, \alpha_s) \bullet M_3(\delta_3, \theta_3, \alpha_3)]$$

$$M(\delta, \theta, \alpha) = \begin{bmatrix} \cos\frac{\delta}{2} + i\cos2\theta\sin\frac{\delta}{2} & i\sin2\theta\sin\frac{\delta}{2} \\ i\sin2\theta\sin\frac{\delta}{2} & \cos\frac{\delta}{2} - i\cos2\theta\sin\frac{\delta}{2} \end{bmatrix} \bullet \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}$$

Phase shift δ, Slow axis at θ, Rotation α

Polarization Measurement at the Interaction Point

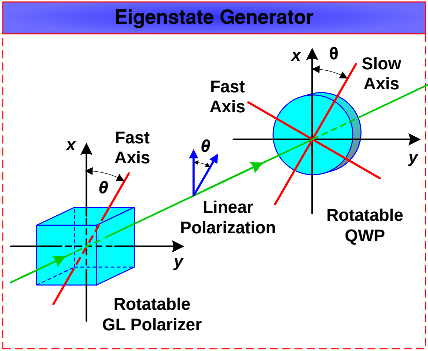
Constant DOCP (92%, 97%)

Scan ellipse angle

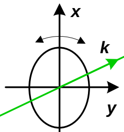
$$I(\theta) = I_{max}\cos^2(\theta - \varphi) + I_{min}\sin^2(\theta - \varphi)$$

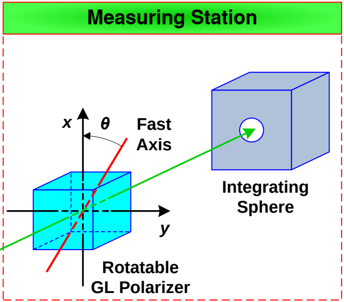
$$DOLP = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

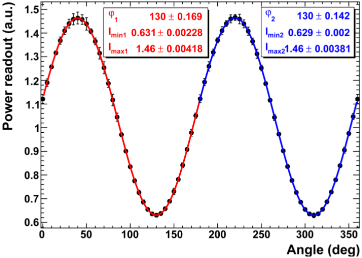
$$DOCP = \sqrt{1 - DOLP^2}$$



RIGHT/LEFT Circular Polarization







Polarization Measurement at the Cavity Exit

$$\hat{S}_1 = \frac{1}{2}(P_0 - P_1\cos^2 2\theta + P_2\cos 2\theta\sin 2\theta - P_3\sin 2\theta)\begin{bmatrix}1\\1\\0\\0\end{bmatrix}$$

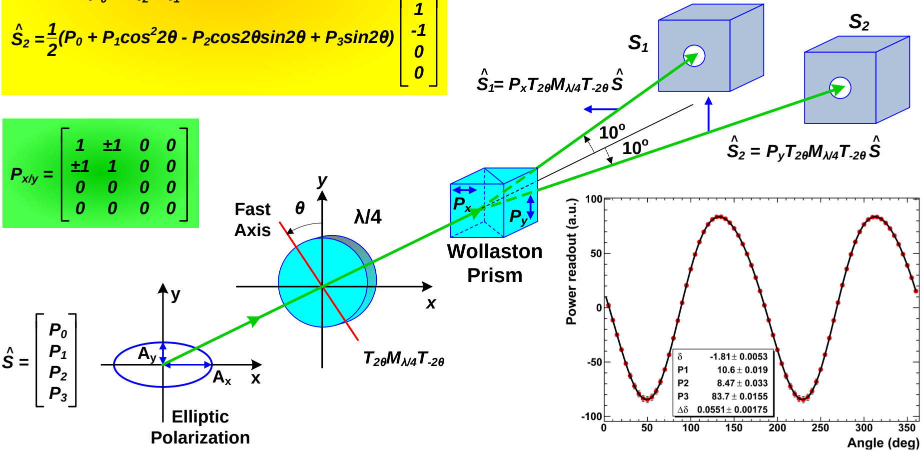
$$DOCP = \frac{P_3}{P_0} = \frac{I_2 - I_1}{I_2 + I_1}$$

$$\hat{S}_2 = \frac{1}{2}(P_0 + P_1\cos^2 2\theta - P_2\cos 2\theta\sin 2\theta + P_3\sin 2\theta)\begin{bmatrix}1\\-1\\0\\0\end{bmatrix}$$

$$T_{2\theta} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos 2\theta & -\sin 2\theta & 0\\ 0 & \sin 2\theta & \cos 2\theta & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$M_{\lambda/4} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & -1 & 0\end{bmatrix}$$

$$P_{x/y} = \begin{bmatrix}1 & \pm 1 & 0 & 0\\ \pm 1 & 1 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$$



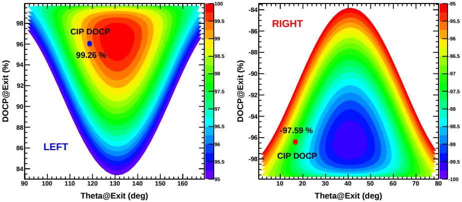
$$\hat{S}_1 = P_x T_{2\theta} M_{\lambda/4} T_{-2\theta}\hat{S}$$

$$\hat{S}_2 = P_y T_{2\theta} M_{\lambda/4} T_{-2\theta}\hat{S}$$

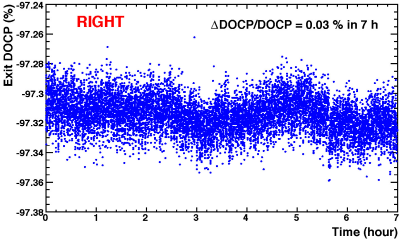
$$T_{2\theta} M_{\lambda/4} T_{-2\theta}$$

$$\hat{S} = \begin{bmatrix}P_0\\P_1\\P_2\\P_3\end{bmatrix}$$

Cavity Polarization & Systematics



Cavity Polarization Transfer Function



Measurement	
DOCP (%)	**Angle (°)**
99.57	58.60
-98.07	19.35

Calculation	
DOCP (%)	**Angle (°)**
99.26	83.52
-97.59	17.50

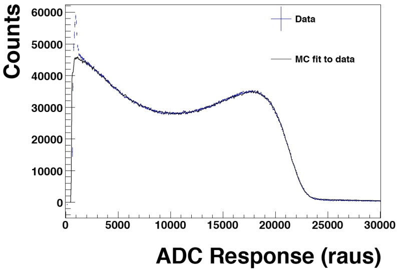
The measured and calculated values of DOCP and ellipse angle at the CIP

Source of Error	Uncertainty (%)
DOCP at Exit Line	0.02
Theta at Exit Line	0.13
Variation in Time	0.04
Validation of Trans. Func.	0.48
Trans. Through M_e	0.10
Trans. Through M_s	0.10
Coupling	0.10

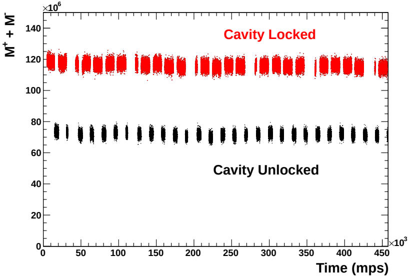
Total systematic error bounded to 0.7% by cavity vs. without cavity, assumed to be from other sources (birefringence of mirrors, etc.)

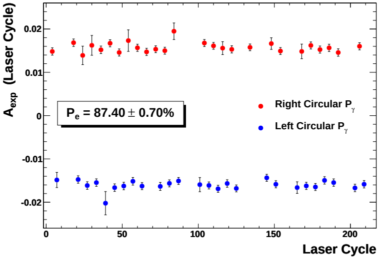
Electron Beam Polarization

1. The scattered photon signal is integrated over each electron helicity state
2. The laser ON/OFF periods and photon polarization reversal is used to cancel the systematic errors from e-beam
3. Measure energy-weighted average $\langle A \rangle_E$
4. e-beam polarization found by comparison with theoretical asymmetry $\langle A \rangle_{th}$



photon energy spectrum for calibration





$$\langle \mathcal{P}_e \rangle = 88.20\% \pm 0.12\% (\text{stat}) \pm 1.04 (\text{sys})\%$$

Outline

Summary & Conclusions

1. Frequency locking of a frequency doubled green laser generated by seeding an Nd:YAG laser to the fiber amplifier makes the intra-cavity power scalable
2. Provided Hall A at JLab with a unique laser source to carry out precision Compton polarimetry
3. Tested the low energy ($\sim$1.0 GeV) e-beam polarimetry for the first time in JLab history
4. Cavity birefringence should be studied very carefully. It is important for studying the systematic errors in polarization
5. New laser source (RF pulsed mode-locked) for future Compton polarimeter is being proposed to make the system even more precise, robust and efficient