Improvements to the Laser Polarization Measurement Inside a Laser Fabry-Perot Cavity

Dave Gaskell on behalf of
Amali Premathilake
Jefferson Lab

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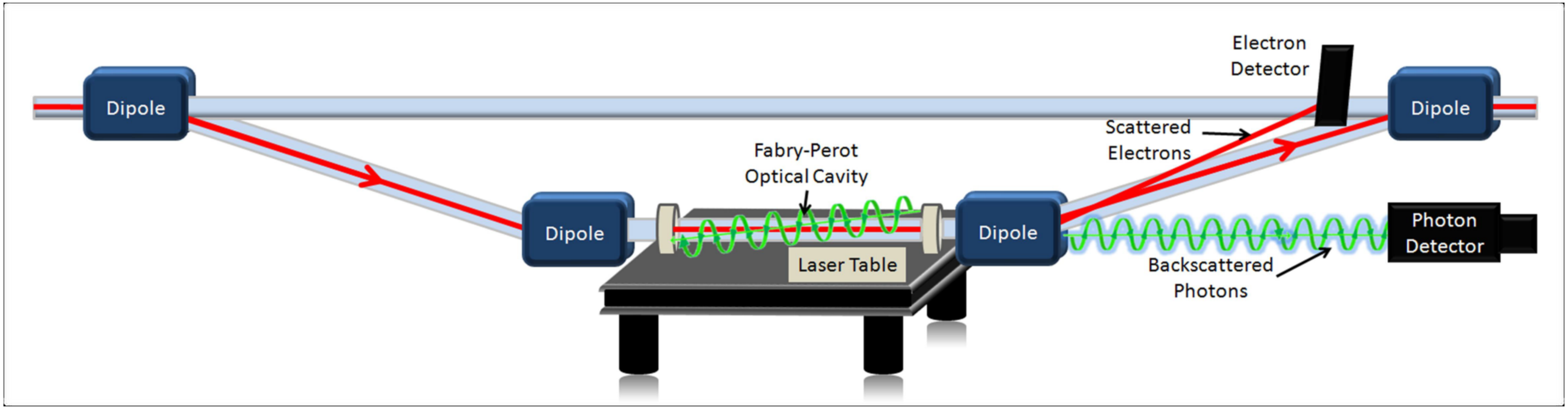
- → Hall A Compton Polarimeter Overview
- → Laser system
  - → Polarization before cavity
  - → Polarization inside cavity

Hall A Compton Overview

Components:

1. 4-dipole chicane: Deflect electron beam vertically
   - 6 GeV configuration: Hall A → 30 cm
   - 12 GeV configuration: Hall A → 21.5 cm
   - Laser system: Fabry-Pérot cavity pumped by CW laser resulting in few kW of stored laser power
2. Photon detector: PbWO4 or GSO – operated in integrating mode
   → see talk by Adam Zec
3. Electron detector: segmented strip detector



Systematic Uncertainties

Compton polarimetry becoming increasingly precise
→ Laser polarization must be well controlled in order to not become dominant source of uncertainty

Example from HAPPEX-III in Hall A

Systematic Errors	
Laser Polarization	0.80%
Signal Analyzing Power:	
Nonlinearity	0.30%
Energy Uncertainty	0.10%
Collimator Position	0.05%
Analyzing Power Total Uncertainty	0.33%
Gain Shift:	
Background Uncertainty	0.31%
Pedestal on Gain Shift	0.20%
Gain Shift Total Uncertainty	0.37%
Total Uncertainty	0.94%

M. Friend, et al, NIM A676 (2012) 96-105

Compton Laser System

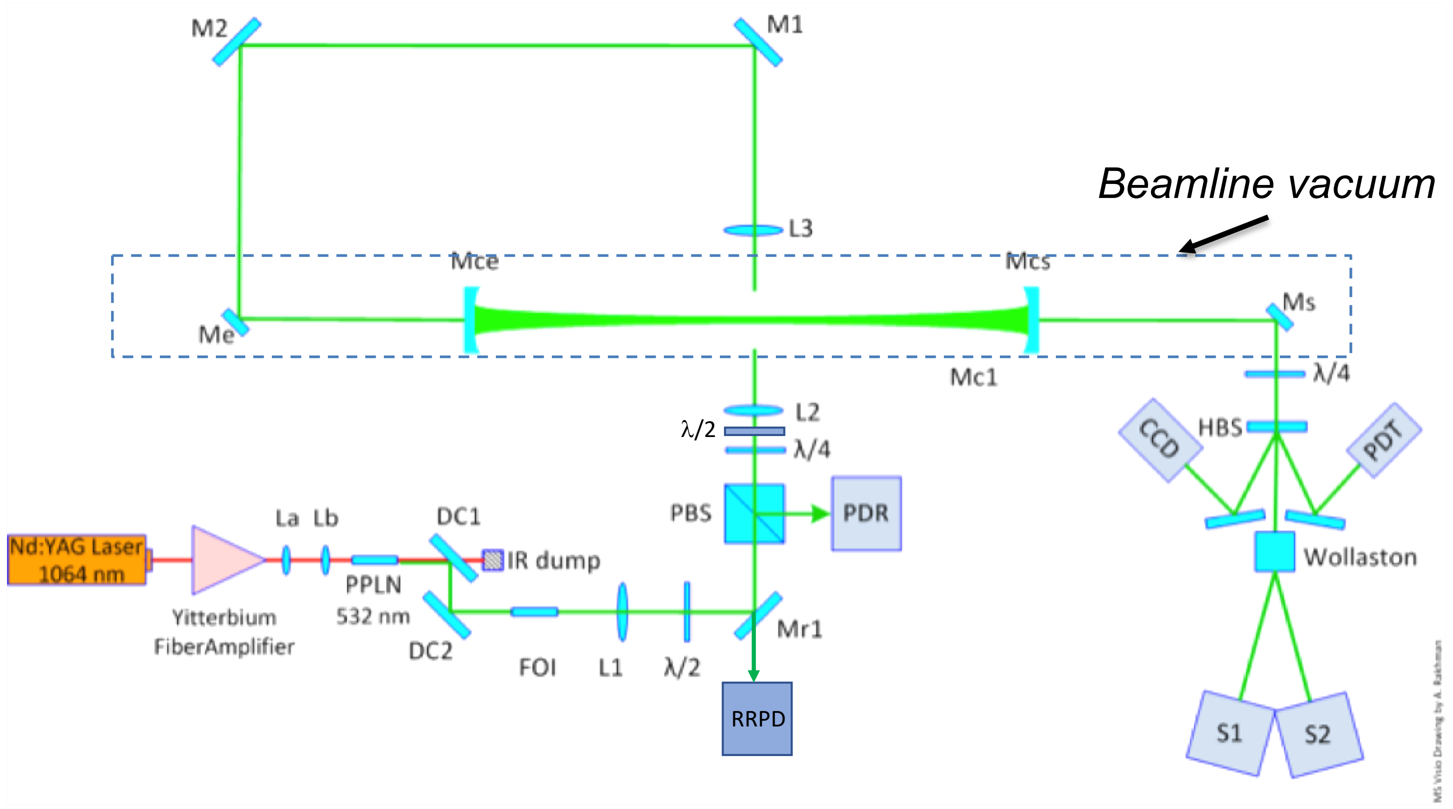
Laser system:

1. 2-10 kW CW green power
2. ~100% circular polarization

→ Known to high precision

Main components of Hall A Compton laser system:

1. Narrow linewidth 1064 nm seed laser
2. Fiber amplifier (>5 W)
3. PPLN doubling crystal
4. High gain Fabry-Pérot cavity
5. Polarization manipulation/monitoring optics



MS Visio Drawing by A. Rakhman

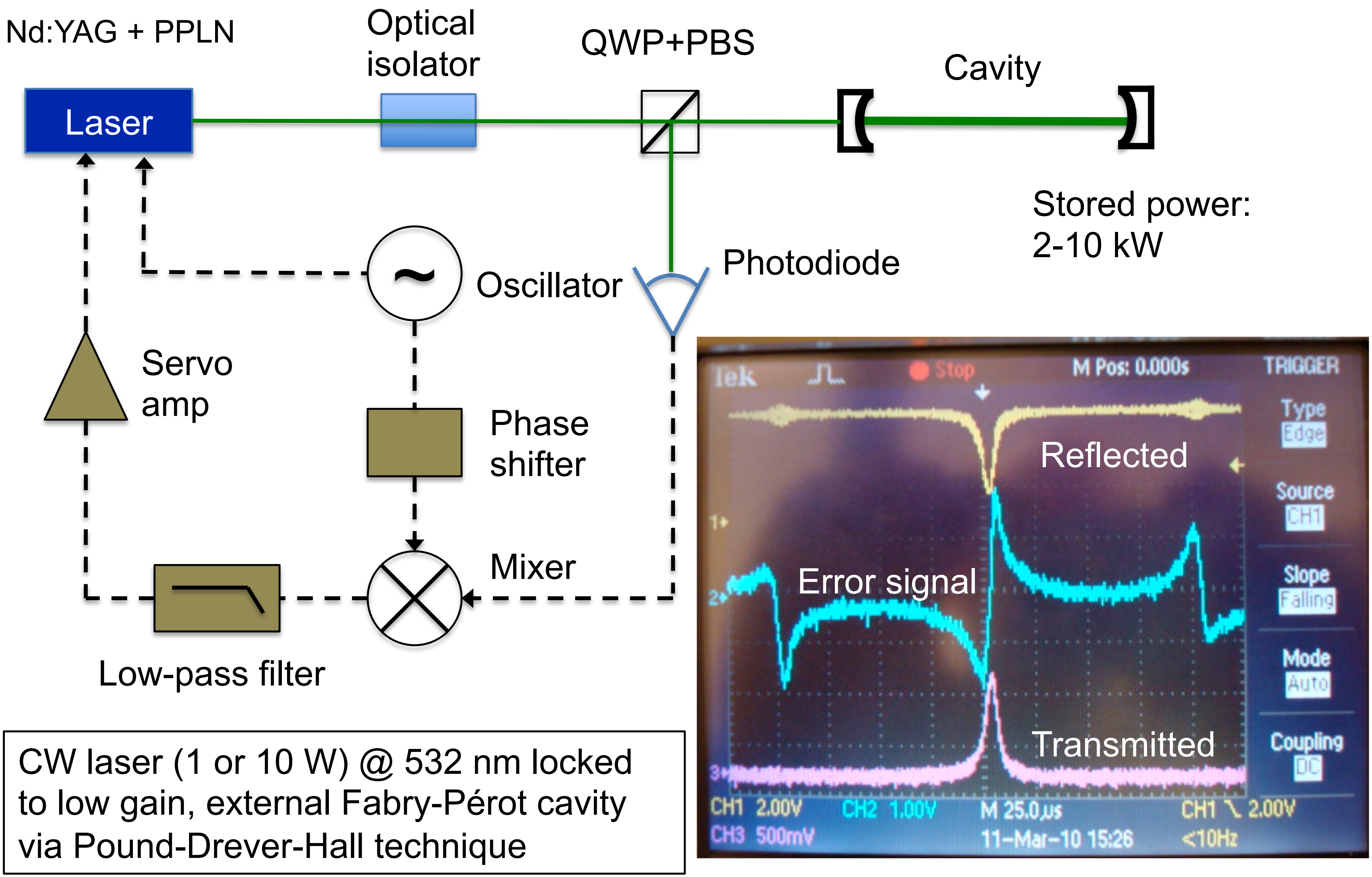
Fabry-Pérot Cavity

- Compton polarimeter measurement time a challenge at JLab
  - Example: At 1 GeV and 180 μA, a 1% (statistics) measurement with 10 W CW laser would take on the order of 1 day!
  - Not much to be gained with pulsed lasers given JLab beam structure (nearly CW)

- A high-finesse (high-gain) Fabry-Pérot cavity locked to narrow linewidth laser is capable of storing several kW of CW laser power
  - First proposed for use at JLab in mid-90's, implemented in Hall A in late 90's (Hall C in 2010, HERA..)

- Fabry-Pérot cavity poses significant challenge in determining laser polarization
  - Degree of circular polarization in cavity can be different than input laser DOCP
  - Vacuum system can introduce additional birefringence

Fabry-Pérot Cavity



Nd:YAG + PPLN

Laser

Optical isolator

QWP+PBS

Cavity

Stored power: 2-10 kW

Photodiode

Oscillator

Servo amp

Phase shifter

Mixer

Low-pass filter

Reflected

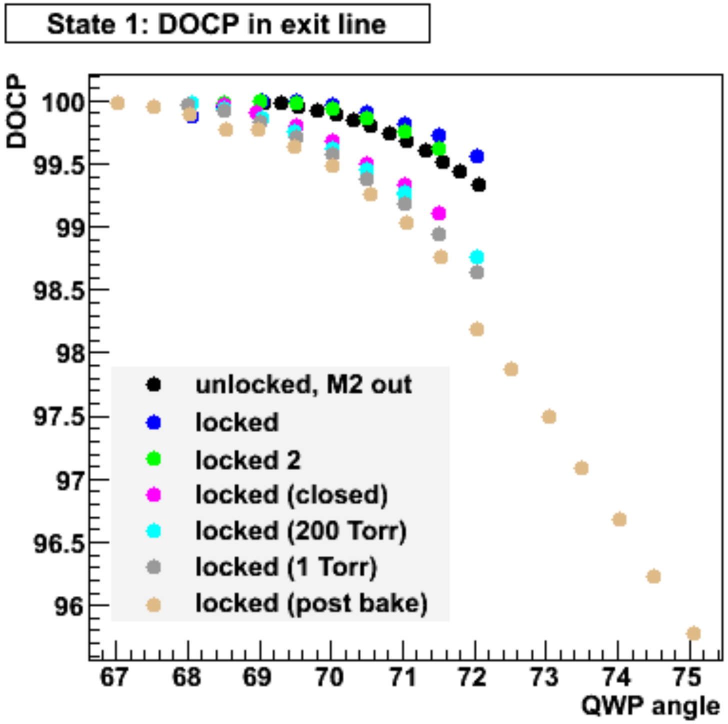
Error signal

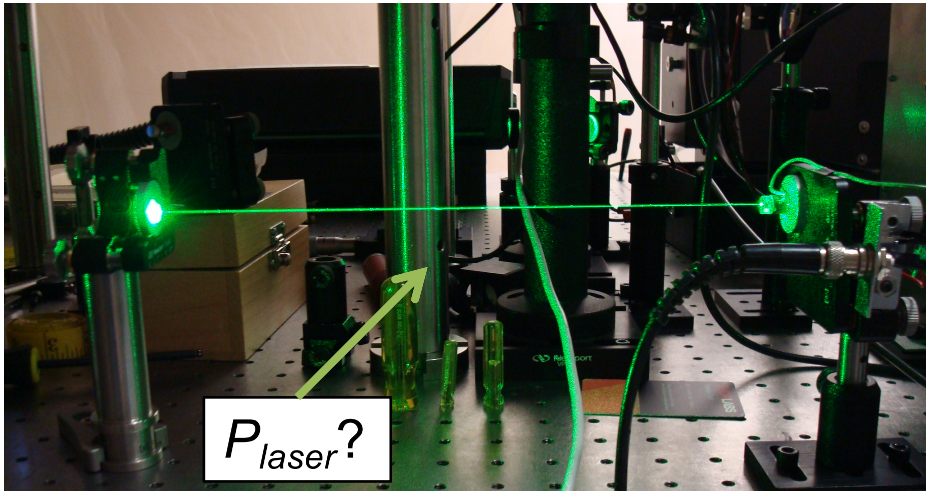
Transmitted

CW laser (1 or 10 W) @ 532 nm locked to low gain, external Fabry-Pérot cavity via Pound-Drever-Hall technique

Laser Polarization - the Transfer Function

How do know the laser polarization inside a FP cavity inside the beamline vacuum?
→ In the past, polarization was inferred from measurements of beam transmitted through cavity, after 2nd mirror





Typically a “transfer function” was measured with cavity open to air

<u>Possible complications due to:</u>
→ Change in birefringence due to mechanical stresses (tightening bolts)
→ Change in birefringence when pulling vacuum

Polarization of Light Stored in Fabry-Perot Cavity

Two key issues in determination of laser polarization in cavity:

1. Transport of laser from polarization-determining optics (QWP/HWP) through possible birefringent elements into vacuum system where it cannot be directly measured
2. Birefringent effects due to cavity itself

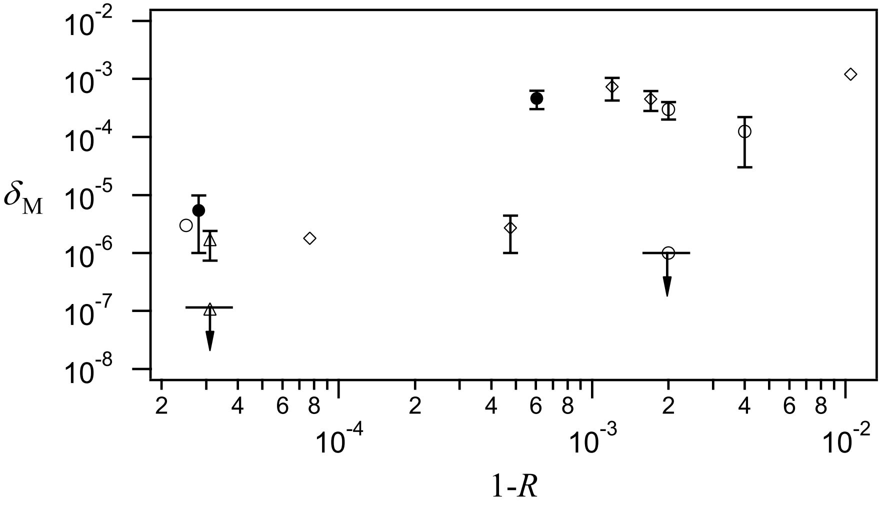
Measurements suggest that intrinsic phase retardation is low for very high R mirrors

No measurements in region near *1-R* ~ 2 x 10^{-4}
→Hall A mirrors nominal T=170 ppm

$\delta_{Total} = 2*(\text{\# round trips}) * \delta_M$
$\quad = 2*(\text{Finesse}/2\pi) * \delta_M$

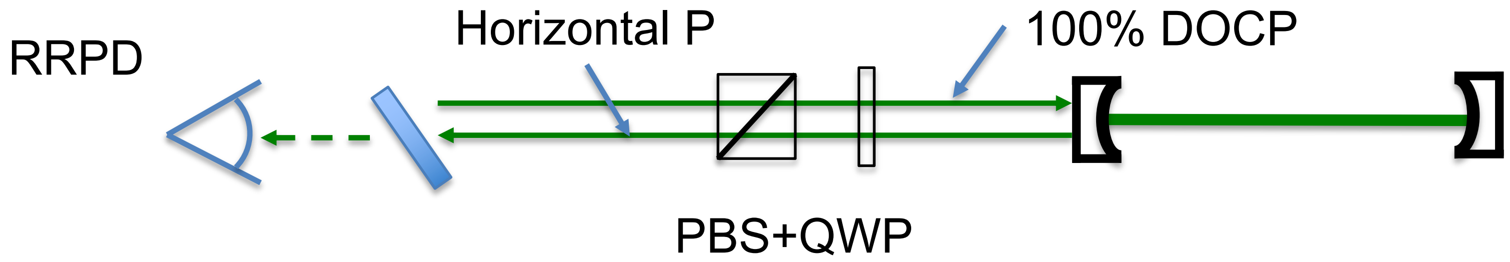
For δ_M 10^{-6}, impact negligible, but could be significantly larger

F. Bielsa et al. Appl. Phys. B (2009) 97: 457



Total impact on DOCP ~ $(\delta_{Total})^2/2$

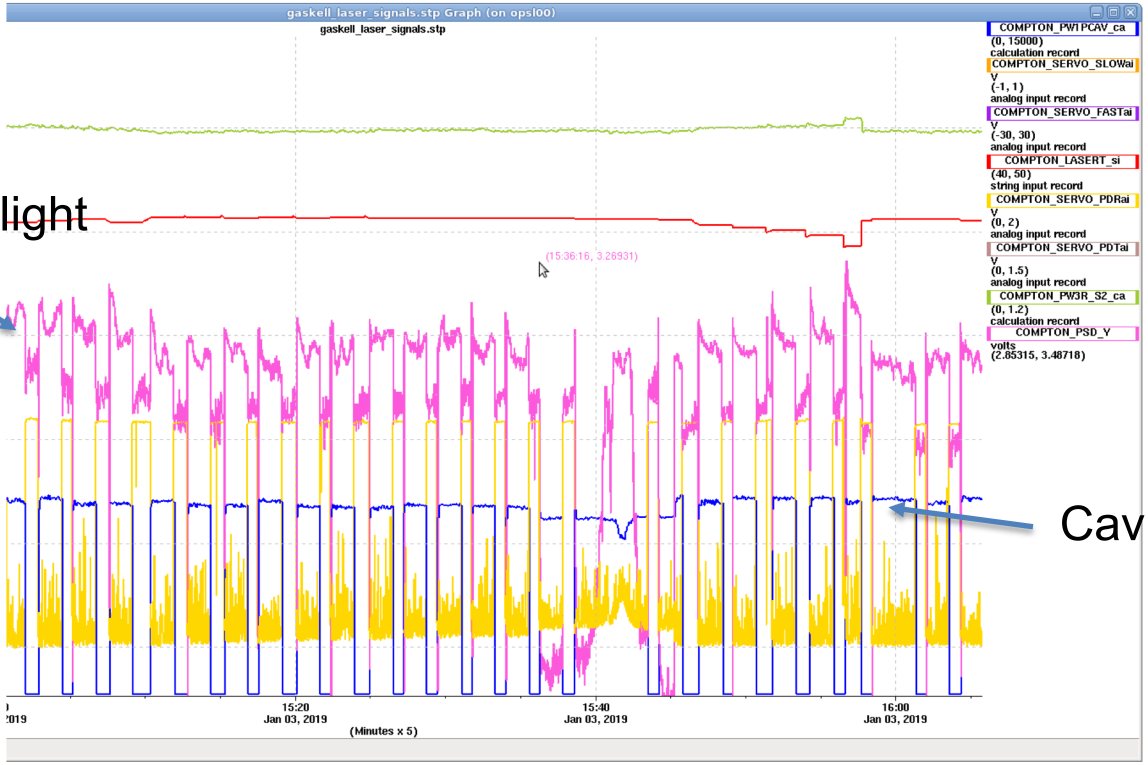
Evidence for Cavity Birefringence in Hall A Fabry-Pérot Cavity


RRPD

Horizontal P

100% DOCP

PBS+QWP



Backreflected light

Cavity power

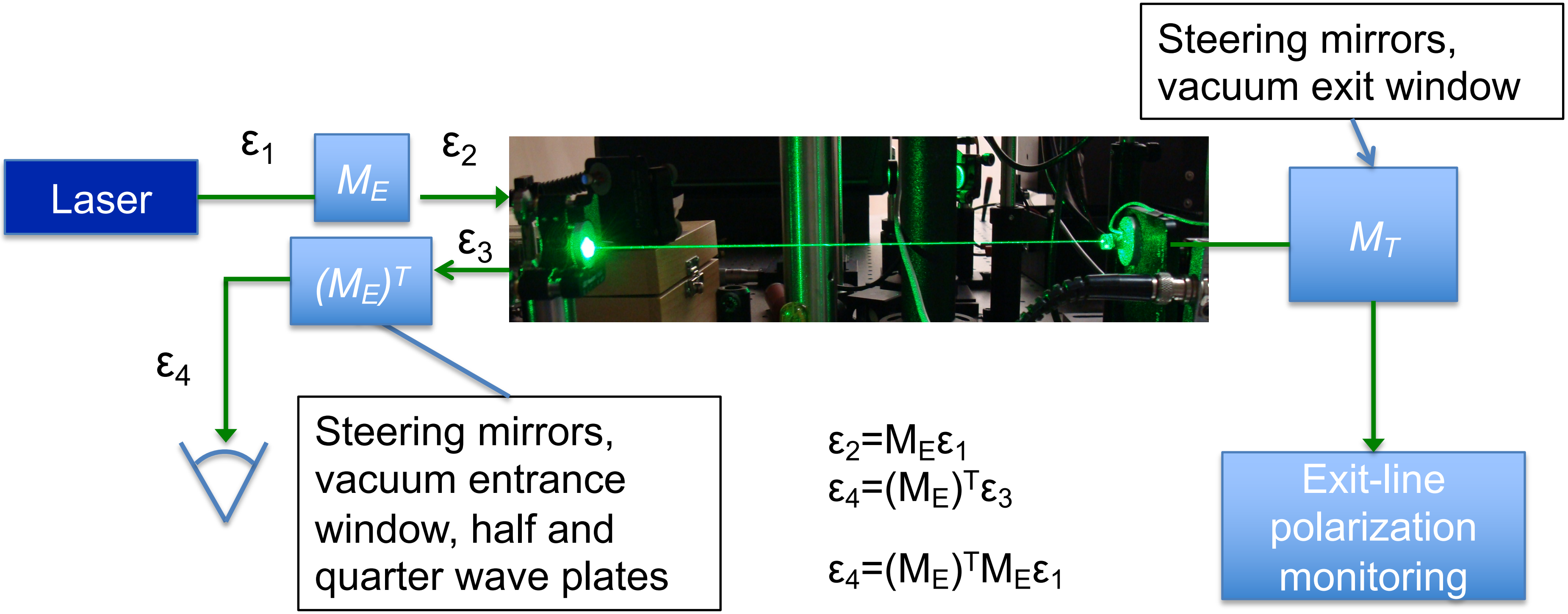
Amount of light reflected back from cavity increases when it is locked!

Laser Polarization – the "Entrance" Function

Propagation of light into the Fabry-Pérot cavity can be described by matrix, ***M_E***

→ Light propagating in opposite direction described by transpose matrix, ***$(M_E)^T$***

→ If input polarization (ε_1) linear, polarization at cavity (ε_2) circular only if polarization of reflected light (ε_4) linear and orthogonal to input*



Steering mirrors, vacuum exit window

Laser

ε_1

M_E

ε_2

ε_3

$(M_E)^T$

M_T

ε_4

Steering mirrors, vacuum entrance window, half and quarter wave plates

$\varepsilon_2 = M_E \varepsilon_1$

$\varepsilon_4 = (M_E)^T \varepsilon_3$

$\varepsilon_4 = (M_E)^T M_E \varepsilon_1$

Exit-line polarization monitoring

JINST 5 (2010) P06006

*J. Opt. Soc. Am. A/Vol. 10, No. 10/October 1993

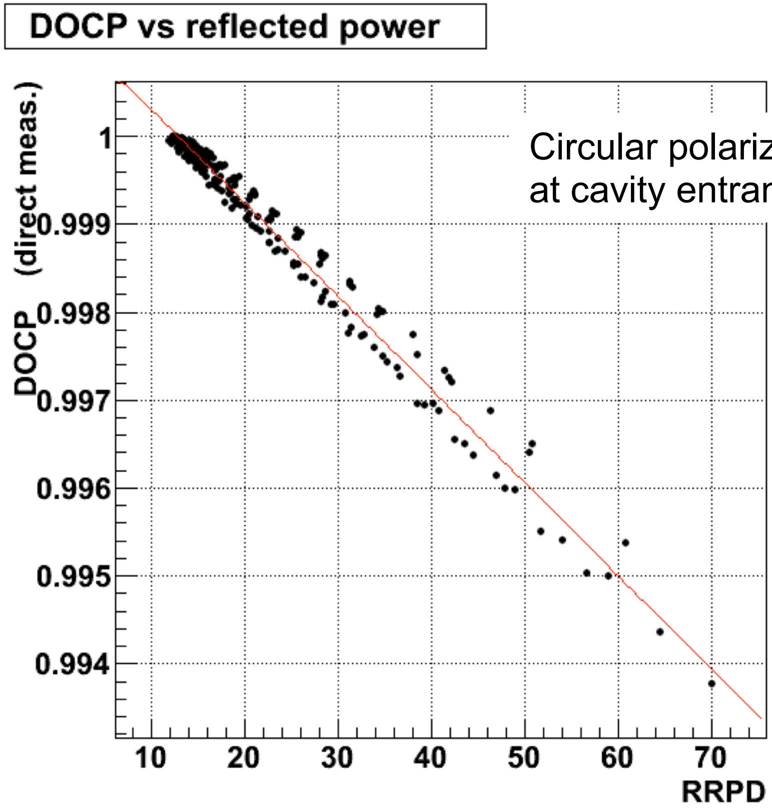
Polarization at Cavity Entrance via Reflected Power

“If input polarization (ε_1) linear, polarization at cavity (ε_2) circular only if polarization of reflected light (ε_4) linear and orthogonal to input”

→ In the context of the Hall A Compton, this means that the circular polarization at cavity is maximized when retro-reflected light is minimized

→ Optical reversibility allows configuring system to give 100% DOCP at cavity entrance, even when the system is under vacuum, just by minimizing signal in one detector

→ In addition, response of whole system can be modeled by sampling all possible initial state polarizations



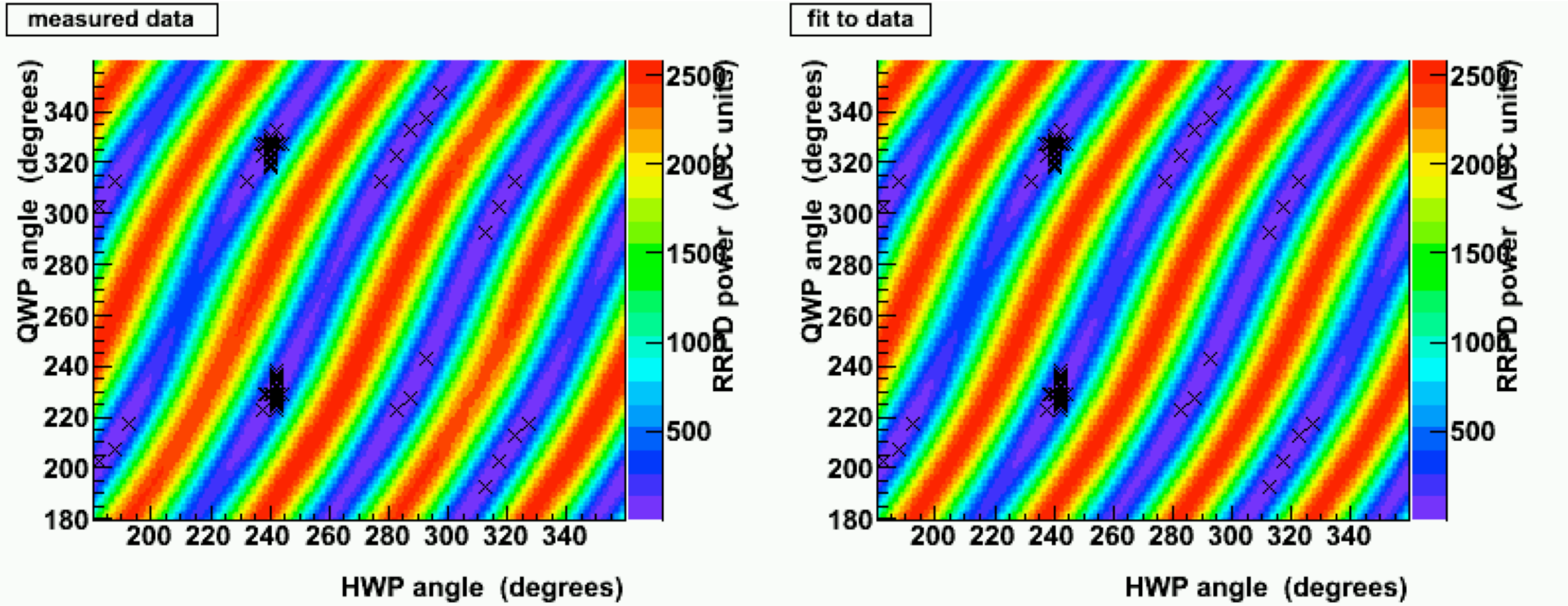
Circular polarization at cavity entrance

Reflected Power Scans

Using a combination of half and quarter wave plates, we can build an arbitrary polarization state

→ Scanning this polarization phase space and monitoring the retro-reflected power, we can build a model for the entrance function, M_E

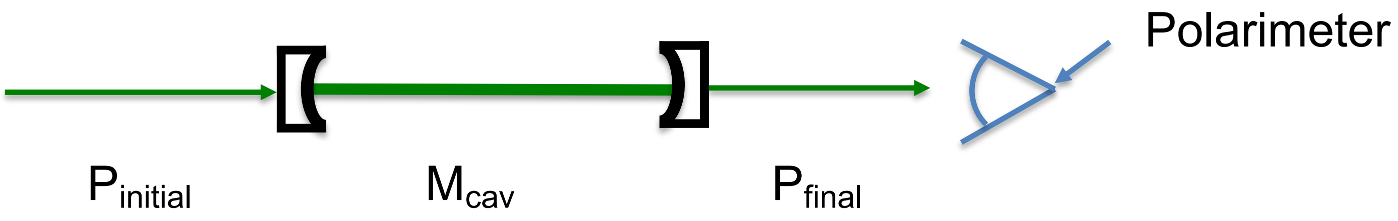
→ Free parameters include variations to HWP and QWP thicknesses, arbitrary element with non-zero birefringence



Using this entrance function, we can determine the laser at cavity entrance for an arbitrary input state

Determination of Cavity Birefringence

Cavity birefringence can be measured by:
1. Prepare known input polarization state
2. Measure polarization after second cavity mirror → assumes negligible additional birefringence as light is transmitted through last mirror



Mathematically, system can be described using Jones matrix formalism

$\boldsymbol{P_{final} = M_{cav}\, P_{initial}}$

→ $\boldsymbol{M_{cav}}$ encodes total effect of birefringence due to cavity system

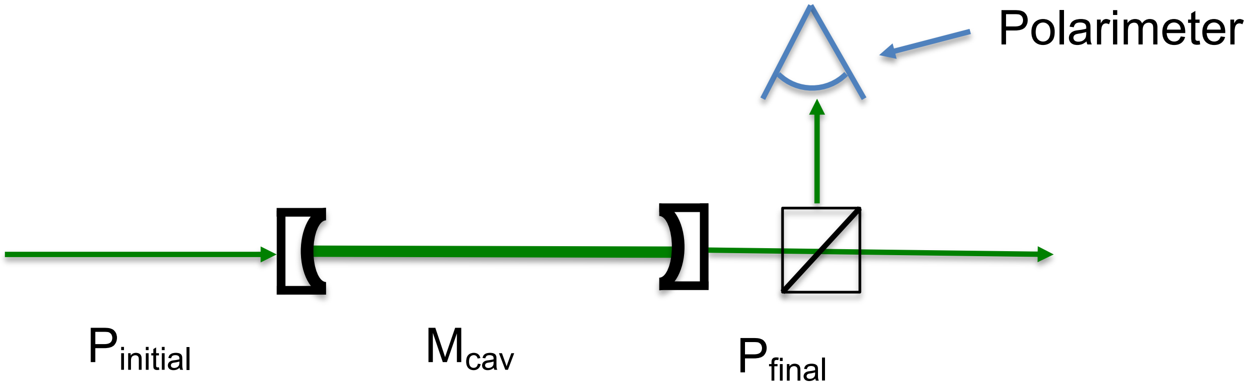
Parameterized: $\boldsymbol{M_{cav} = R(\eta)\, PH(\delta)\, R(\theta)}$

Rotator

Phase retarder

Determination of Cavity Birefringence

Actual measurement of transmitted power requires additional component due to geometrical/locking-servo constraints



Can use non-polarizing beamsplitter cube (NPBS) to sample transmitted beam while allowing locking electronics to monitor state of cavity lock

Unfortunately NPBS also has some birefringence so must be characterized

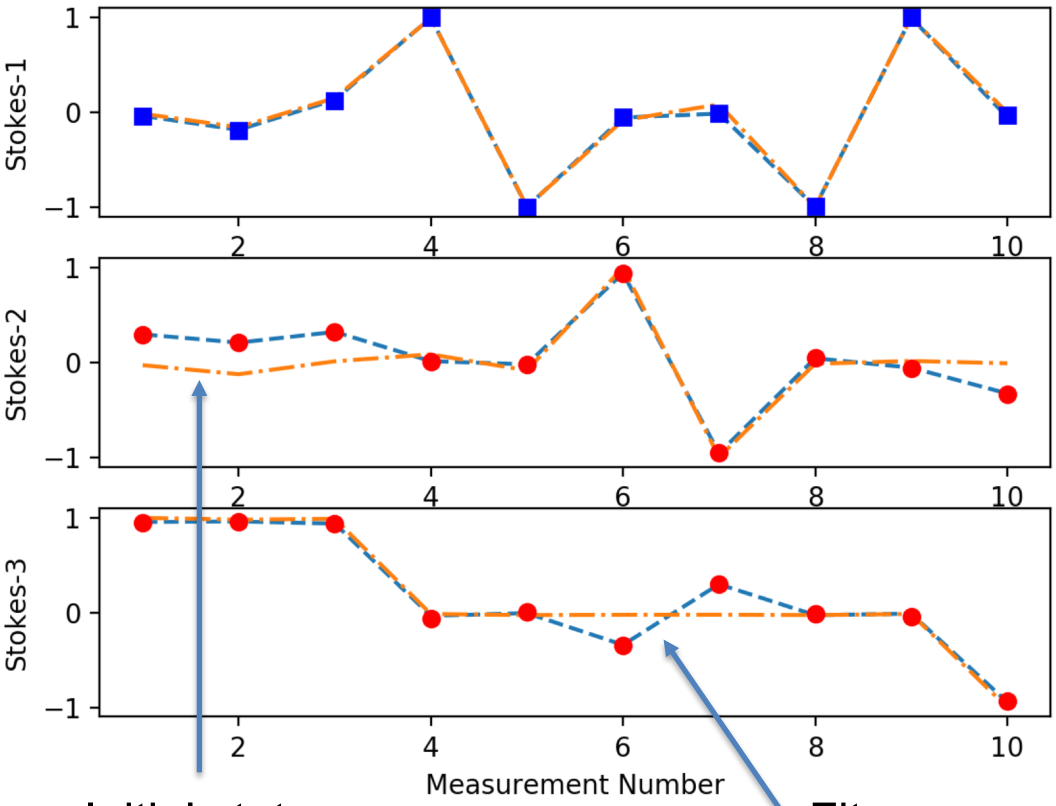
NPBS Characterization

Measured Stokes parameters of light transmitted through NPNS for a variety of initial states

S1 = 1, linear horizontal
S1 = -1, linear vertical

S2=1, linear +45 degrees
S2=-1, linear -45 degrees

S3=1, circular right
S3=-1, circular left



Initial state

Fit

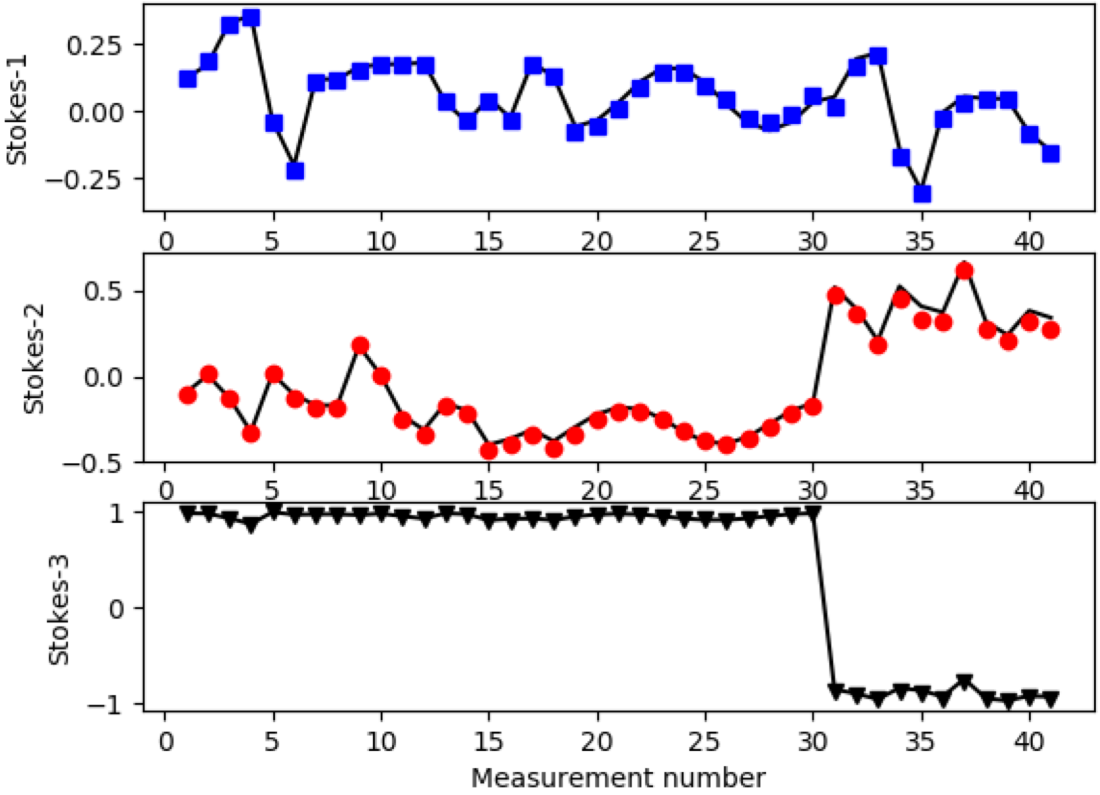
NPBS response fit using matrix similar to that used for cavity birefringence

Cavity Birefringence

$$P_{final} = M_{NPBS} M_{cav} P_{initial}$$

Phase space of initial polarization states somewhat limited → need to limit backreflection to avoid damaging laser system

→ Able to sample values close to 100% DOCP while introducing significant linear component



$M_{cav} = R(\eta)\, PH(\delta)\, R(\theta)$ → $\delta = -5.16 \pm 0.06$ degrees

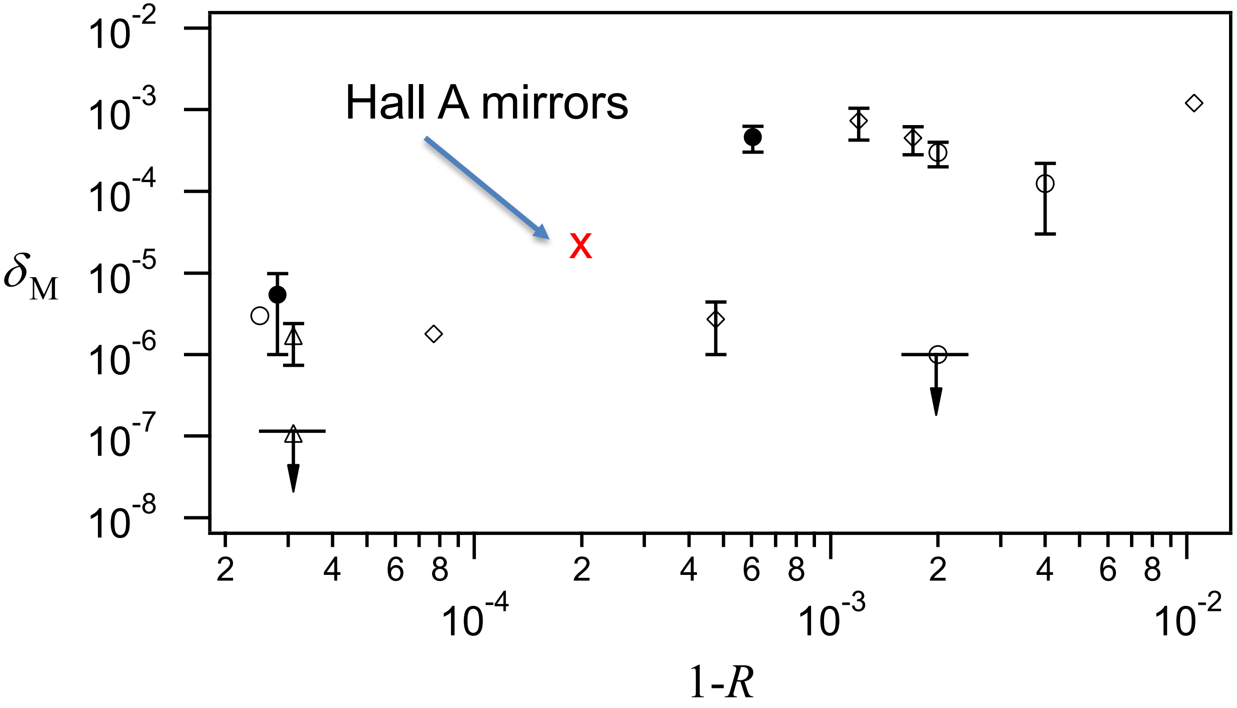
$$\delta_{Total} = 2*(\text{Finesse}/2\pi) * \delta_M$$

Intrinsic Phase Retardation of Mirrors

$$\delta_{Total} = 2*(\text{Finesse}/2\pi) * \delta_M$$

Hall A cavity: Finesse ~ 12000

For δ_{Total} =5.16 degrees (0.09 radians), $\delta_M = 2.4 \times 10^{-5}$



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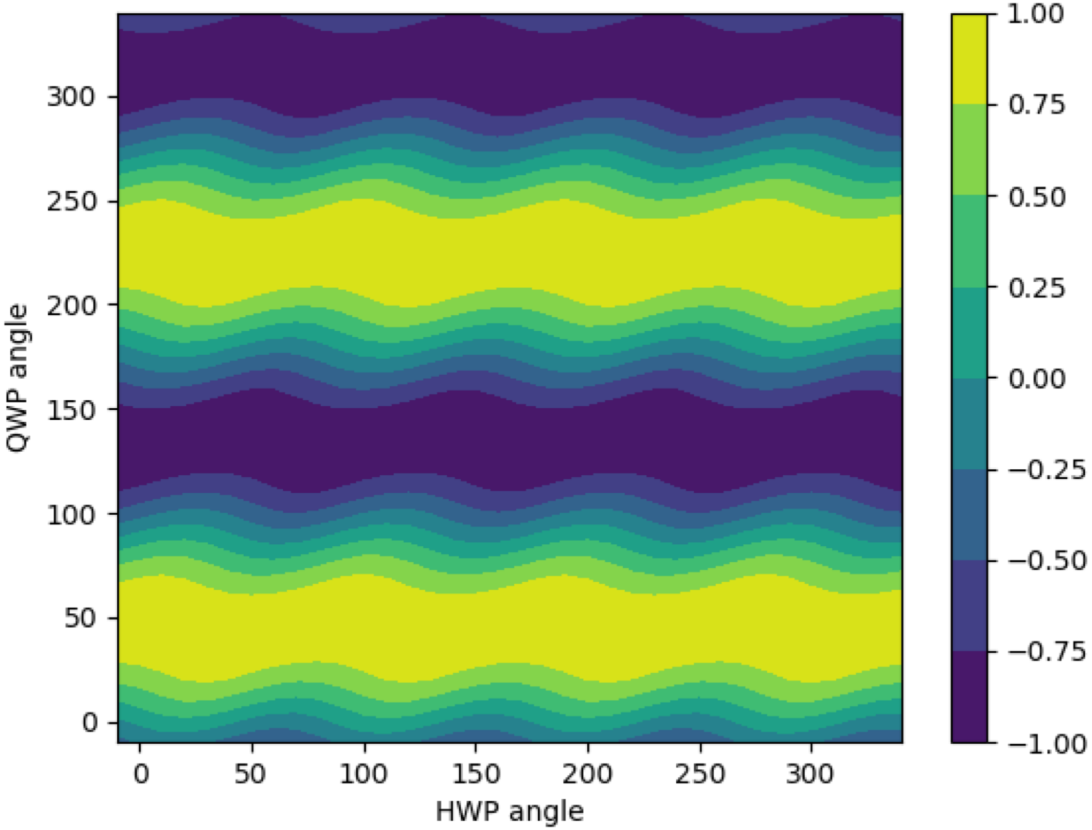
F. Bielsa et al. Appl. Phys. B (2009) 97: 457

DOCP in Cavity

With cavity birefringence and entrance function, can predict DOCP in cavity and determine optimum settings for left and right circular polarization:

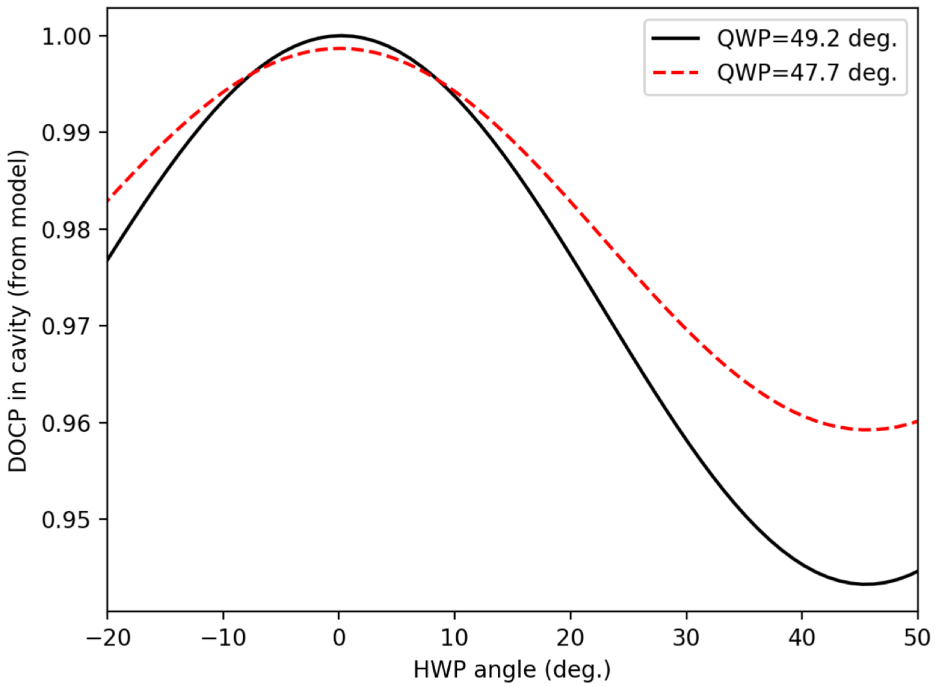
$P_{cavity} = M_{cav} M_E P_{initial}$



Testing Cavity DOCP Model

Model of polarization in cavity can be tested using asymmetry data from polarimeter

→ Mis-tune QWP/HWP to result in smaller DOCP, compare measured asymmetry



QWP angle (deg)	HWP angle (deg)	DOCP (predicted)
49.2	0.2	100%
49.2	15.2	98.7%
49.2	31.2	95.8%
47.7	19.1	98.2%

Measurements taken during summer run – data under analysis

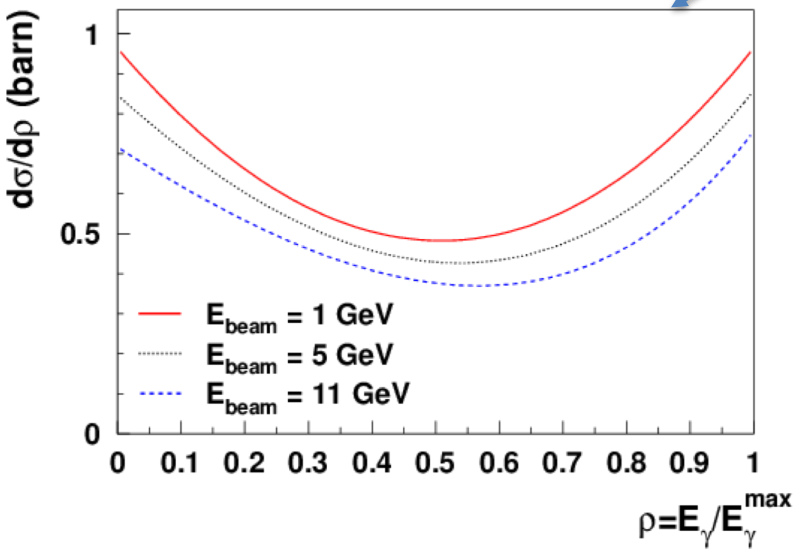
Summary

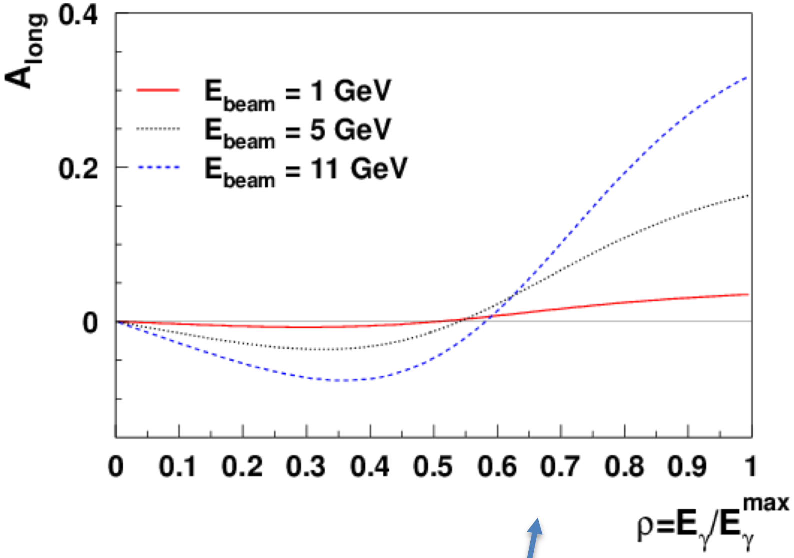
- Fabry-Pérot cavity required for Compton polarimetry measurements at Jefferson Lab
- Laser polarization in cavity a key source of systematic uncertainty that must be controlled
- Previous technique of measuring the exit-line transfer function suffers from birefringence changes in exit window (vacuum, mechanical stresses)
- New technique:
  - Use back-reflected light to determine "entrance function" → this can be done with system under vacuum
  - Measure cavity birefringence directly
- Model of cavity polarization will be tested with asymmetry data taken during the summer

EXTRA

Compton Scattering – Cross Section and Asymmetry

$$\rho = \frac{E_\gamma}{E_\gamma^{\mathrm{max}}} \quad \Rightarrow \quad \frac{d\sigma}{d\rho} = 2\pi r_o^2 a \left[\frac{\rho^2(1-a)^2}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)} \right)^2 \right]$$





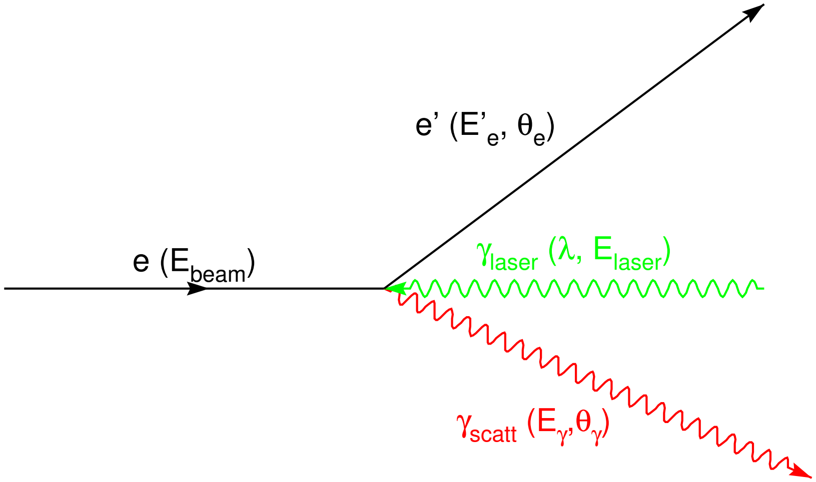
$$A_{\mathrm{long}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} (1-\rho(1+a)) \left[1 - \frac{1}{(1-\rho(1-a))^2} \right]$$

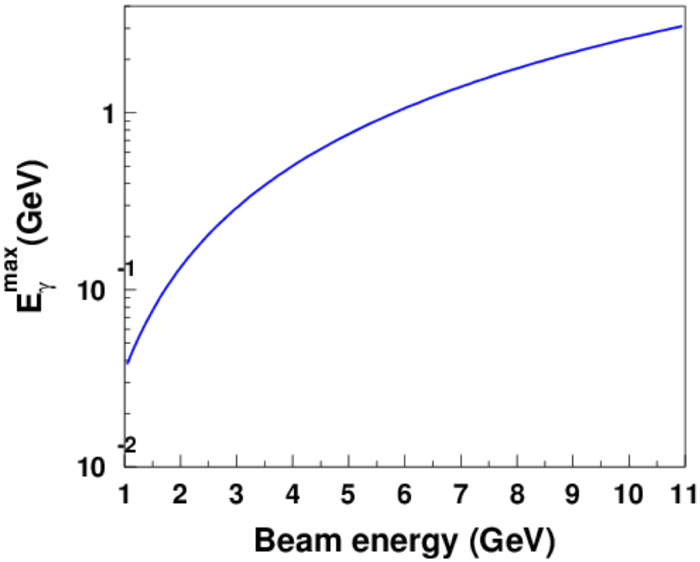
Compton Scattering - Kinematics

Laser beam colliding with electron beam nearly head-on

$$E_\gamma \approx E_{\mathrm{laser}} \frac{4a\gamma^2}{1 + a\theta_\gamma^2\gamma^2}$$

$$a = \frac{1}{1 + 4\gamma E_{\mathrm{laser}}/m_e}$$



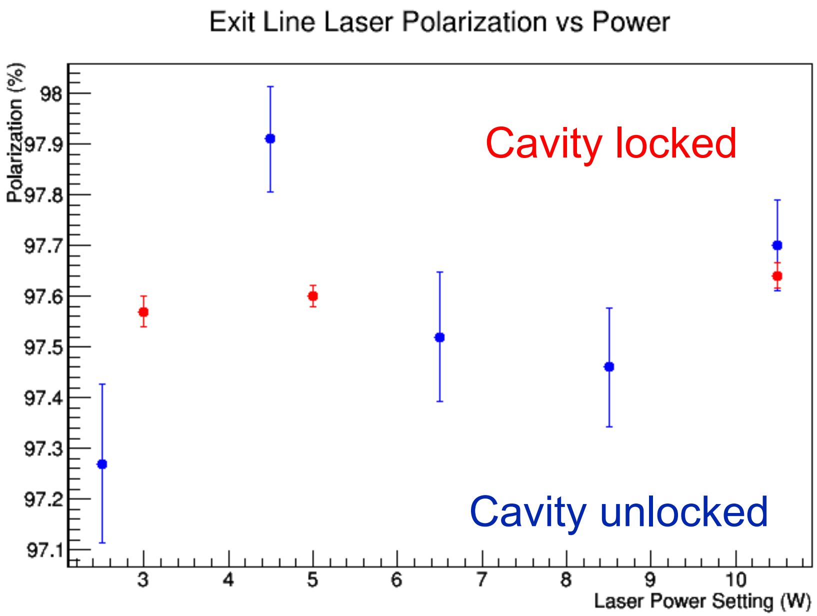


Maximum backscattered photon energy at θ=0 degrees (180 degree scattering)

For green laser (532 nm):

→ E_γ^{max} ~ 34.5 MeV at E_{beam}=1 GeV
→ E_γ^{max} = 3.1 GeV at E_{beam}=11 GeV

Laser Polarization in Low Gain Fabry-Perot Cavity



Cavity polarization optimization scans performed with cavity unlocked
→ In Hall C - no measureable difference in laser polarization when comparing to locked cavity