# Electron Beam Polarimetry at Jefferson Lab

**Dave Gaskell**
***EIC Collaboration Meeting***
**January 12, 2010**

1. Mott Polarimeter
2. Møller Polarimeters
2. Compton Polarimeters
3. Summary

# JLab Polarimetry Techniques

- Three different processes used to measure electron beam polarization at JLab
  - Møller scattering: $\vec{e}+\vec{e}\rightarrow e+e$ , atomic electrons in Fe (or Fe-alloy) polarized by external magnetic field
  - Compton scattering: $\vec{e}+\vec{\gamma}\rightarrow e+\gamma$ , laser photons scatter from electron beam
  - Mott scattering: $\vec{e}+Z\rightarrow e$ , spin-orbit coupling of electron spin with (large Z) target nucleus
- Each has advantages and disadvantages in JLab environment

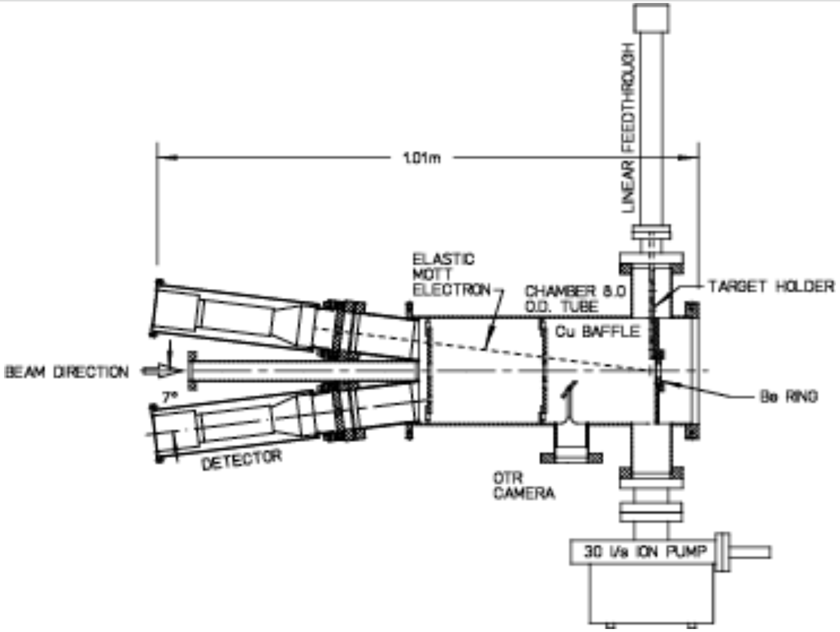
| Method | Advantage | Disadvantage |
|---|---|---|
| Compton | Non-destructive | Can be time consuming, systematics energy dependent |
| Møller | Rapid, precise measurements | Destructive, low current only |
| Mott | Rapid, precise measurements | Measures at 5 MeV in the injector only – not the experimental hall |

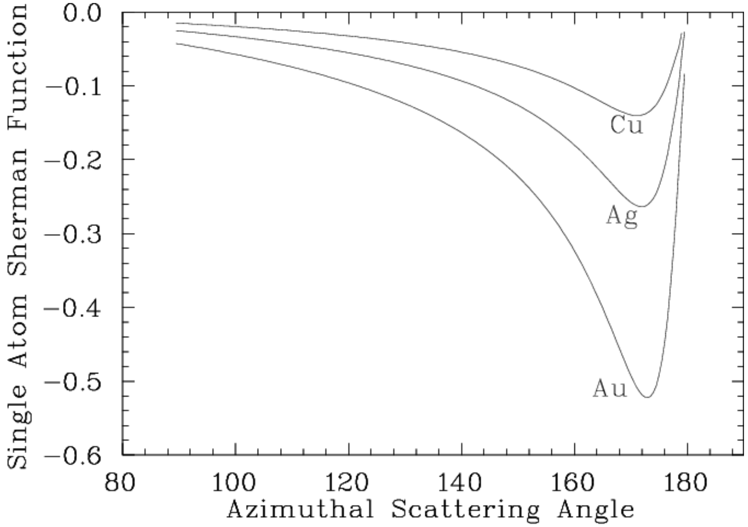
# 5 MeV Mott Polarimeter

- Mott polarimeter located in the 5 MeV region of the CEBAF injector
- Target must be thin, large Z material → 1 $\mu$m Au foil
- Asymmetry maximized near 172°, given by

$$A = \frac{N_r - N_l}{N_r + N_l} = P_{beam} S(\theta)$$

- *S(θ)* is the Sherman function → must be calculated from e-nucleus cross section
- Knowledge of Sherman function dominant systematic uncertainty ~ ***1.0%***





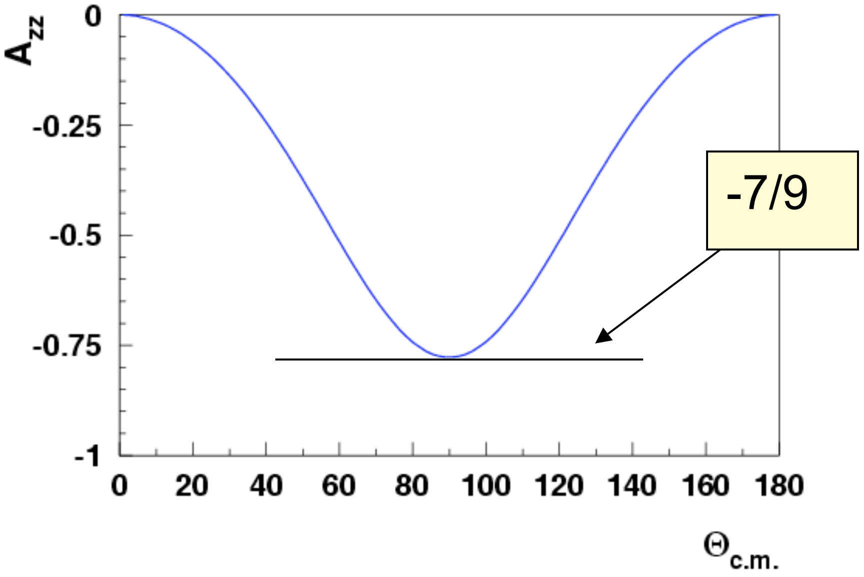
# JLab Mott Polarimeter

- Mott polarimeter has proved extremely useful at JLab
  - allows polarized source group to quantify photocathode performance without beam in main machine → not dependent on experiments (halls) for feedback
  - allows quick cross-check when polarimeters in experimental halls yield odd results → also helps diagnose problems with transport (Wien filter not set correctly, etc.)
- Mott drawbacks and limitations
  - Low current measurements only
  - Source group is too busy to make this a "1%" device all the time – it works well, but ideally should not be counted on for your physics results
  - Making a Mott measurement interrupts beam to everyone

# Møller Polarimetry at JLab

- Møller polarimetry benefits from large long. asymmetry → -7/9
  - Asymmetry independent of energy
  - Relatively slowly varying near $\theta_{cm}=90^o$
  - Large asymmetry diluted by need to use iron foils to create polarized electrons

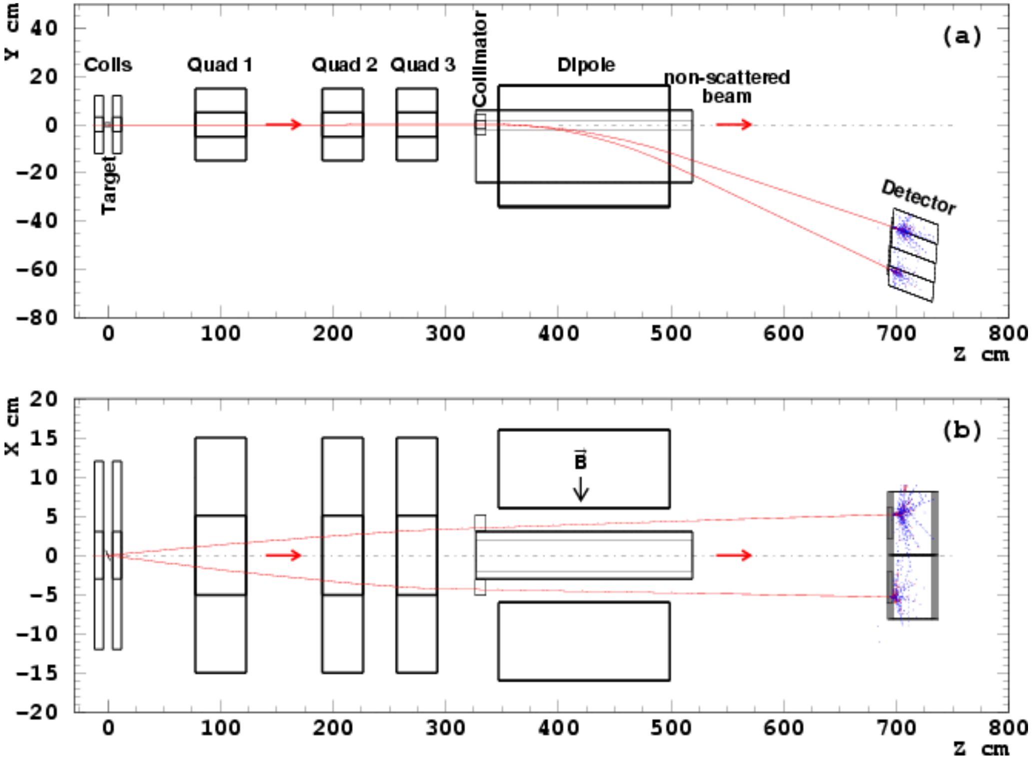
    → $P_e$ ~ 8%
- Rates are large, so rapid measurements are easy
- Need to use Fe or Fe-alloy foils means measurement must be destructive



- Making measurements at high beam currents challenging

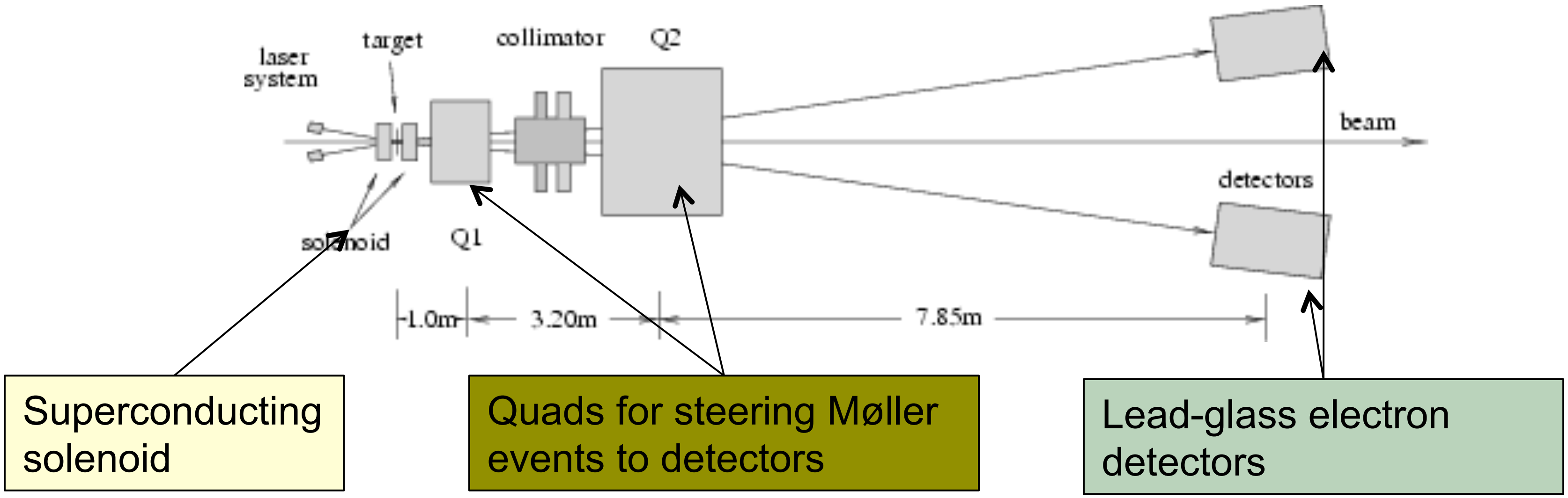
# Hall A Møller Polarimeter

- Target =supermendeur foil, polarized in-plane
  - Low field applied (240 G)
  - Tilted 20° relative to beam direction
  - Target polarization known to ~ *2%* → *this will improve*
- Large acceptance of detectors mitigates potentially large systematic unc. from Levchuk effect (atomic Fermi motion of bound electrons)
- Large acceptance also leads to large rates dead time corrections cannot be ignored, but are tractable



# Basel-Hall C Møller Polarimeter

- 2 quadrupole optics maintains constant tune at detector plane
- “Moderate” (compared to Hall A) acceptance mitigates Levchuk effect → still a non-trivial source of uncertainty
- Target = pure Fe foil, brute-force polarized out of plane with 3-4 T superconducting magnet
- Total systematic uncertainty = ***0.47%*** *[NIM A 462 (2001) 382]*



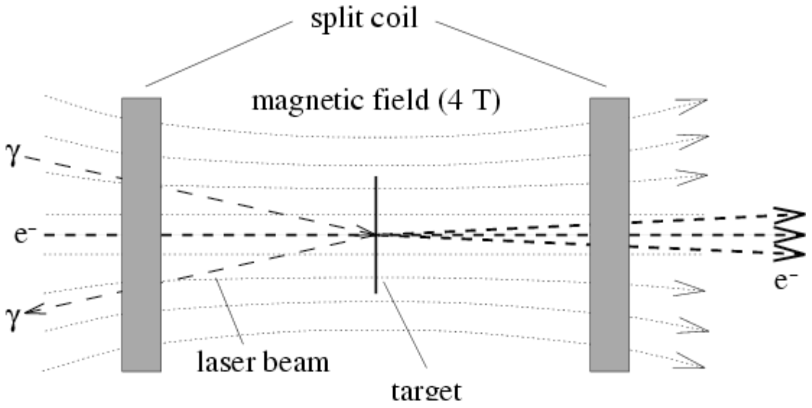
Superconducting solenoid

Quads for steering Møller events to detectors

Lead-glass electron detectors

# Hall C Møller Target

- Fe-alloy, in-plane polarized targets typically result in systematic errors of 2-3%
  - Requires careful measurement of magnetization of foil
- **Hall C uses a pure Fe saturated in 4 T field**
  - Spin polarization well known → 0.25%
  - Temperature dependence well known
  - No need to directly measure foil polarization



| Effect | $M_s[\mu_B]$ | error |
|---|---|---|
| Saturation magnetization (T→0 K,B→0 T) | 2.2160 | ±0.0008 |
| Saturation magnetization (T=294 K, B=1 T) | 2.177 | ±0.002 |
| Corrections for B=1→4 T | 0.0059 | ±0.0002 |
| Total magnetization | 2.183 | ±0.002 |
| Magnetization from orbital motion | 0.0918 | ±0.0033 |
| Magnetization from spin | 2.0911 | ±0.004 |
| Target electron polarization (T=294 K, B= 4 T) | 0.08043 | ±0.00015 |

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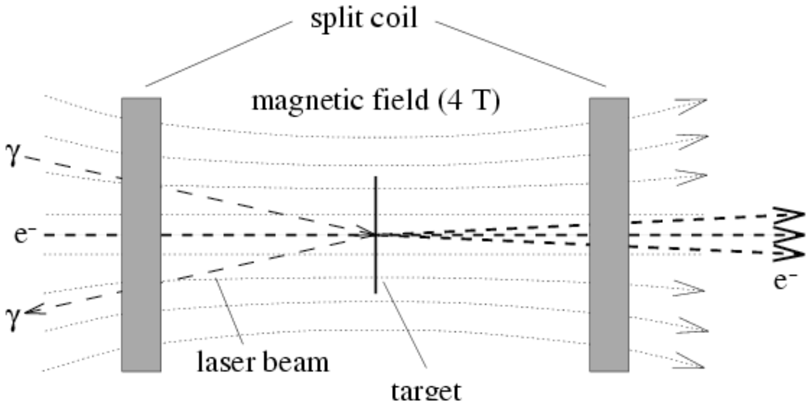

| Effect | M [[illegible] | [illegible] |
|---|---|---|
| Saturation magnetization (T→0 K,B→0 T) | [illegible] | [illegible] |
| Saturation magnetization (T=[illegible] | [illegible] | [illegible]0.002 |
| Corrections f[illegible] | [illegible]0.0059 | ±0.0002 |
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Hall A will move to similar target system this year (installation January-March 2010)

# Møller Polarimetry at High Beam Currents

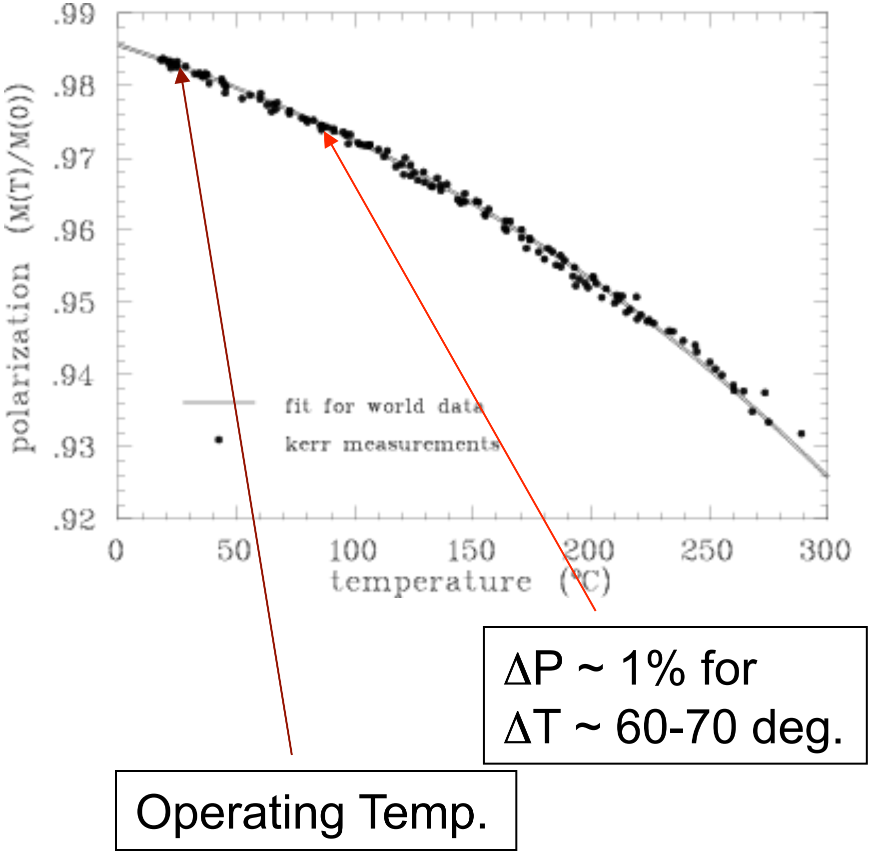
In general Møller polarimeter limited to low beam currents to avoid foil depolarization

This can be mitigated in 2 ways:

→ Use raster to increase effective beam size; upper limit still only 10-20 μA for reasonable raster sizes

→ Use fast kicker at low duty cycle to maintain low “average” beam current on target, dwell time short enough to keep effects of instantaneous heating small; in principle allow measurements up to 100 μA

Fe Foil Depolarization

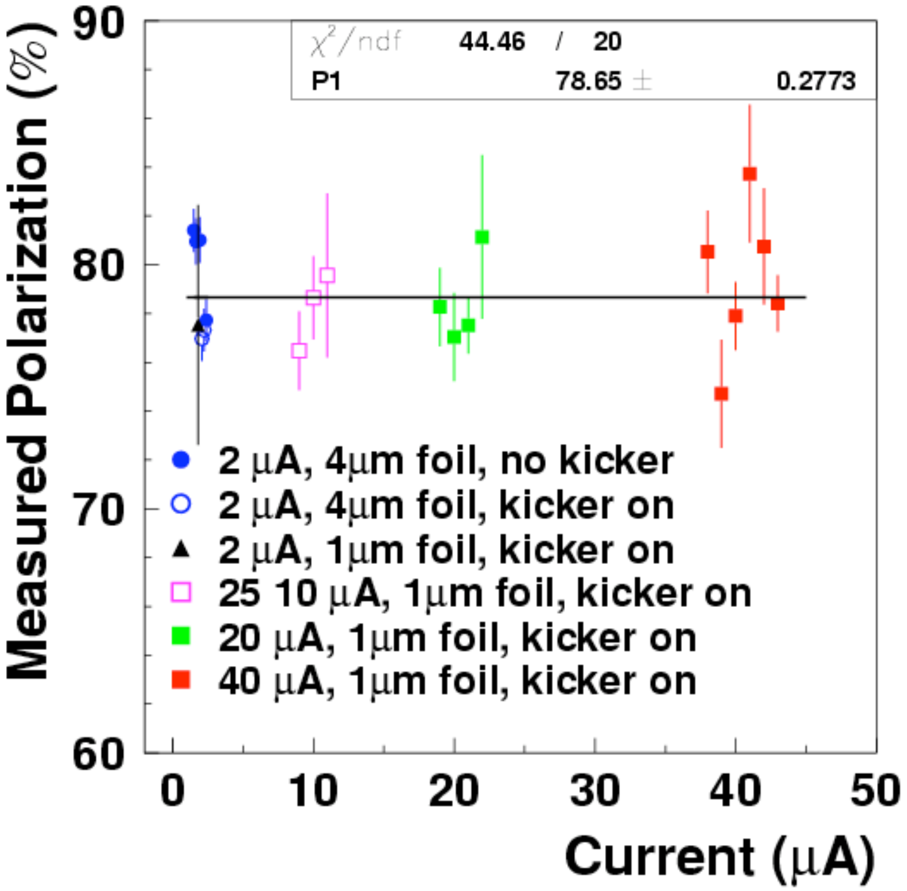


ΔP ~ 1% for
ΔT ~ 60-70 deg.

Operating Temp.

# Kicker Studies in Hall C

- Since 2003, have been pursuing studies with a fast kicker magnet and various iron wire/strip targets
- Most successful tests in 2004
  - Short test – no time to optimize polarized source
  - Tests cannot be used to prove 1% precision
- Took measurements up to 40 μA
  - Machine protection (ion chamber) trips prevented us from running at higher currents
  - Lesson learned: need a beam tune that includes focus at Møller target AND downstream
- Demonstrated ability to make measurements at high currents – good proof of principle



# Møller Polarimetry with Atomic H Target

Proposal to use atomic hydrogen as target; operates at full beam current, non-destructive measurement

→at 300 mK, 8 T, $P_e$ ~ 100%

→density ~ 3 $10^{15}$ $cm^{-3}$

→lifetime >1 hour

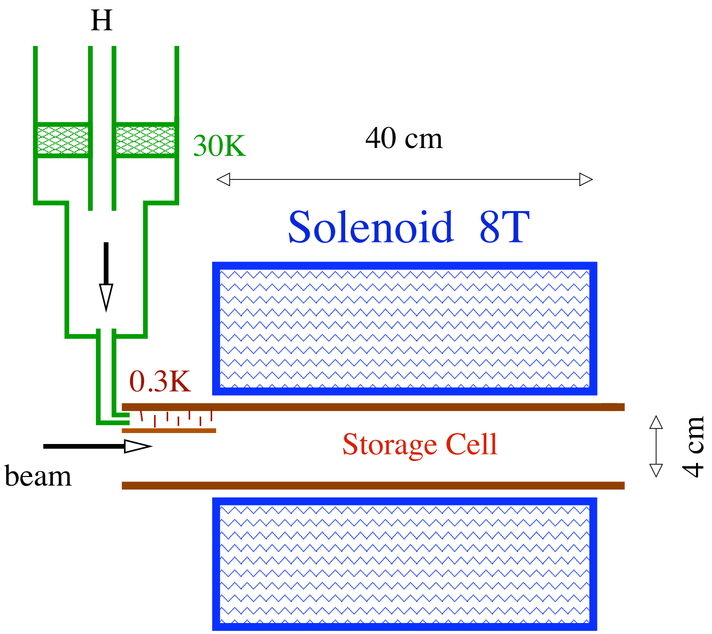
→Expected precision < 0.5%!

Contamination, depolarization expected to be small → < $10^{-4}$

Desired for Hall A 12 GeV *but*

→Target very complex – expertise disappearing

→Resources, manpower not identified



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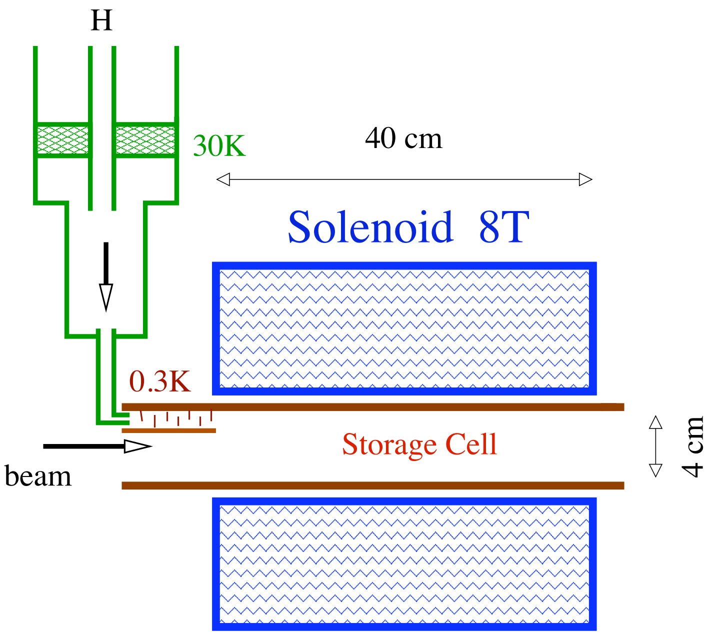

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Application at EIC? → unlikely

→ Gas heating by radiation drops density by factor ~ 100 to 1000

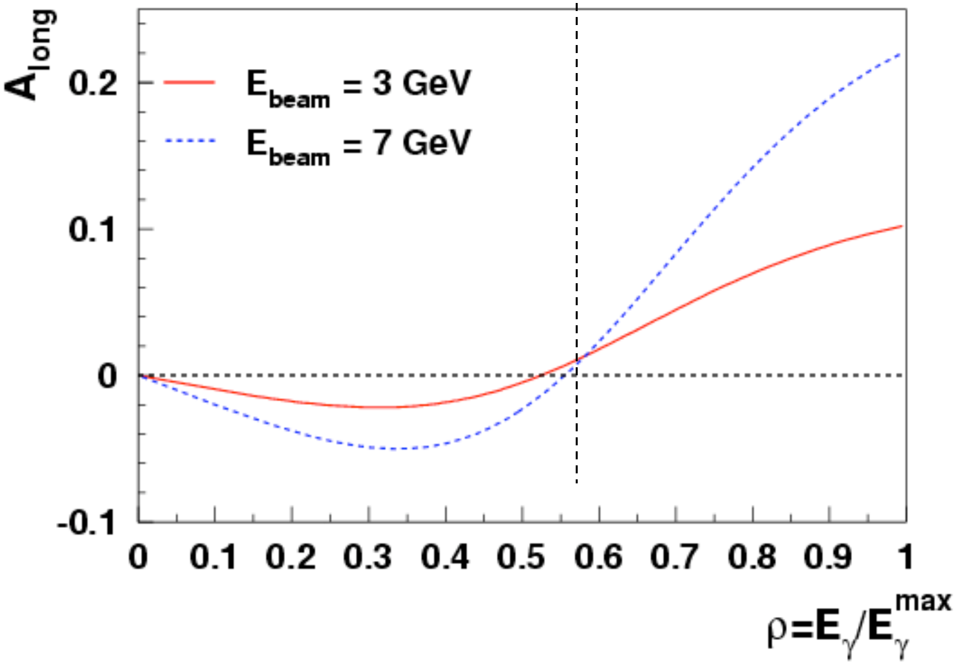
→Beam creates field 0.2-2 kV/cm – traps positive ions

*Maybe some kind of H jet target can be used instead?*

# Compton Polarimetry at JLab

Two main challenges for Compton polarimetry at JLab

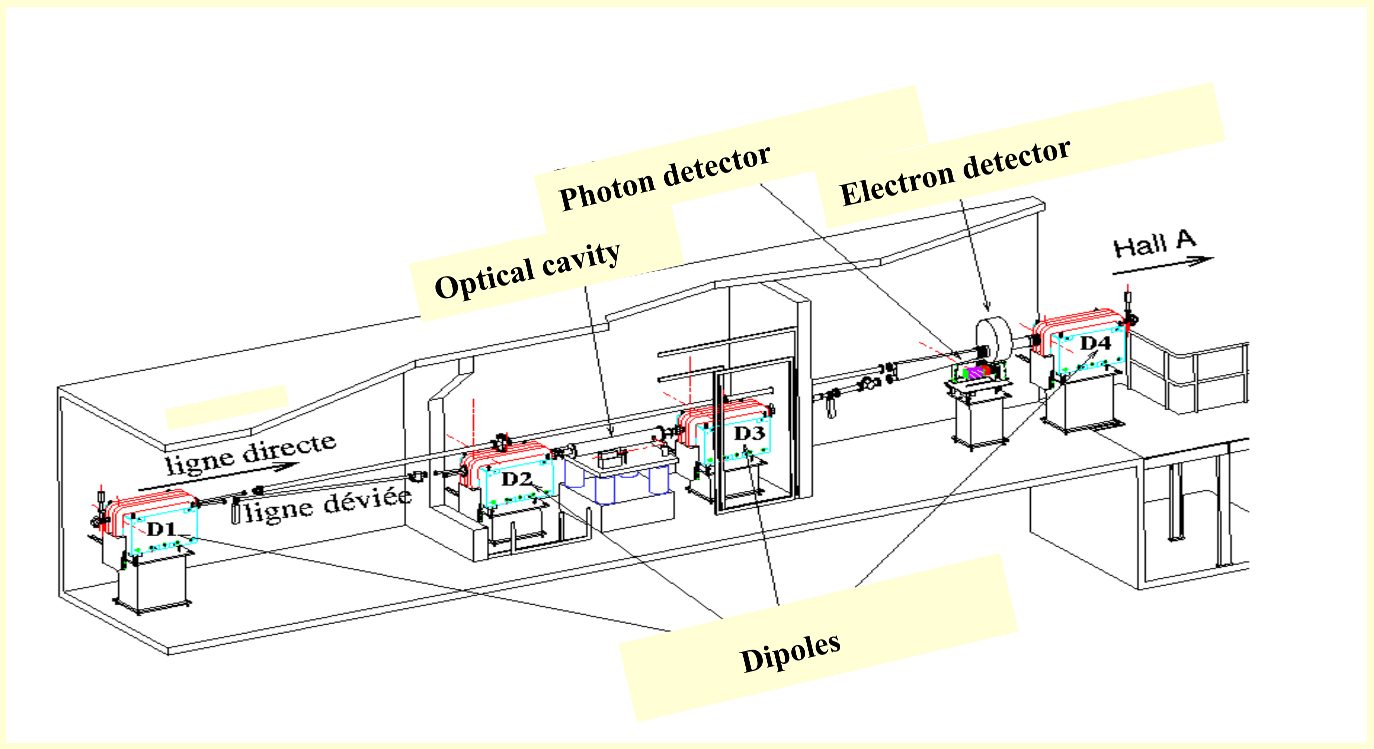
- Low beam currents (~100 $\mu$A)
  - Measurements can take or the order of hours
  - Makes systematic studies difficult
- Relatively small asymmetries
  - Smaller asymmetries lead to harder-to-control systematics



- Strong dependence of asymmetry on $E_\gamma$ is a challenge
  → Understanding the detector response is crucial

# Hall A Compton Polarimeter

- Hall A Compton polarimeter uses high gain Fabry-Perot cavity to create ~ 1 kW of laser power in IR (1064 nm)
- Detects *both* scattered electron and backscattered γ → 2 independent measurements, coincidences used to calibrate γ detector
- Systematic errors quoted at ***1%*** level for recent HAPPEx experiments @ 3 GeV *[PRL 98 (2007) 032301]*



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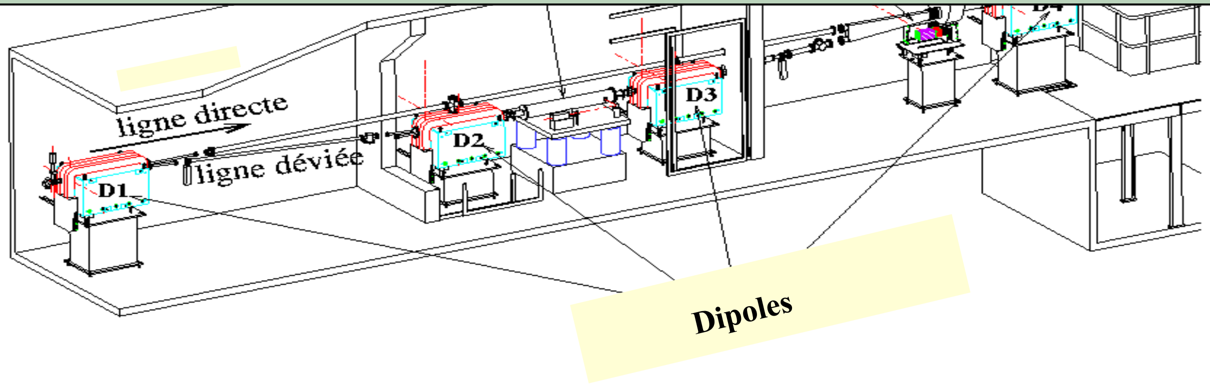
**Upgrade in progress to achieve same precision at ~ 1GeV**

IR → Green laser

Increase segmentation of electron detector

New γ detector, better suited for low energies



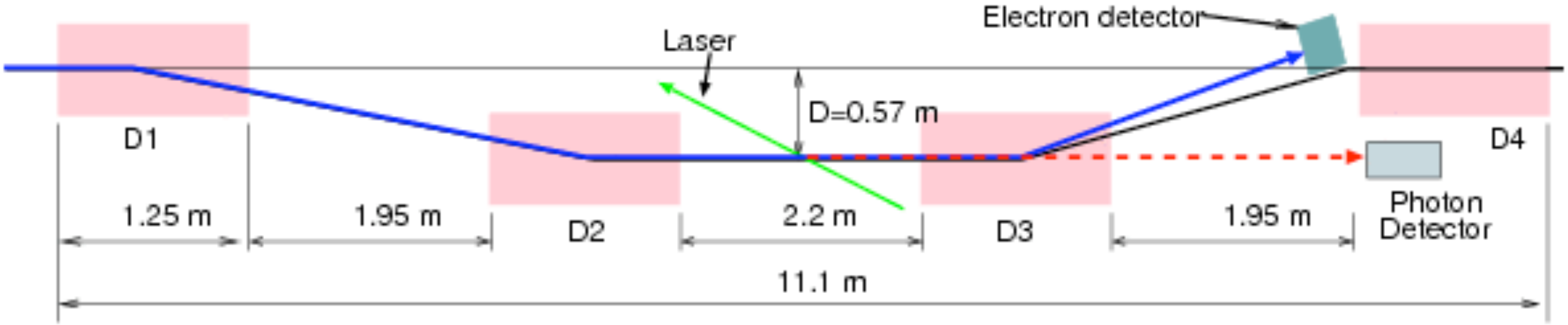
# Hall C Compton Polarimeter

Hall C Compton Polarimeter under construction – completion by beginning of Q-Weak experiment in May 2010

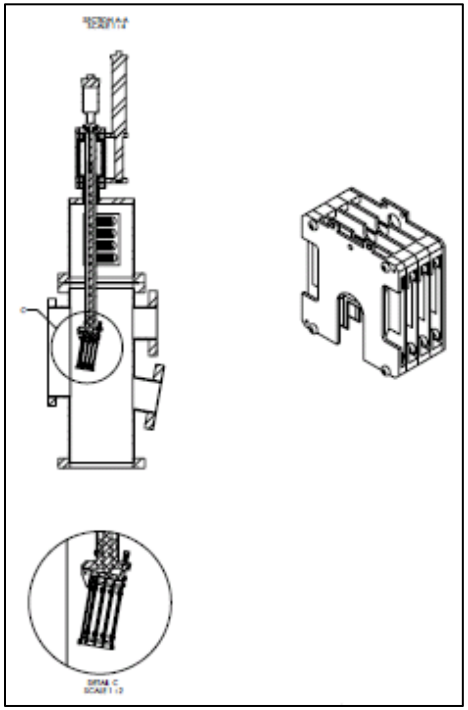
→ Design very similar to Hall A concept with some small differences

Components

1. Laser: Low gain (~100-200) cavity pumped with 10 W green laser
2. Photon Detector: CsI from MIT-Bates Compton polarimeter
3. Electron Detector: Diamond strip detector
4. Dipole chicane (MIT-Bates) and beamline modifications



# Electron Detector



Diamond strip detector built by Miss. State, U. Winnipeg

→4 planes of 96 strips

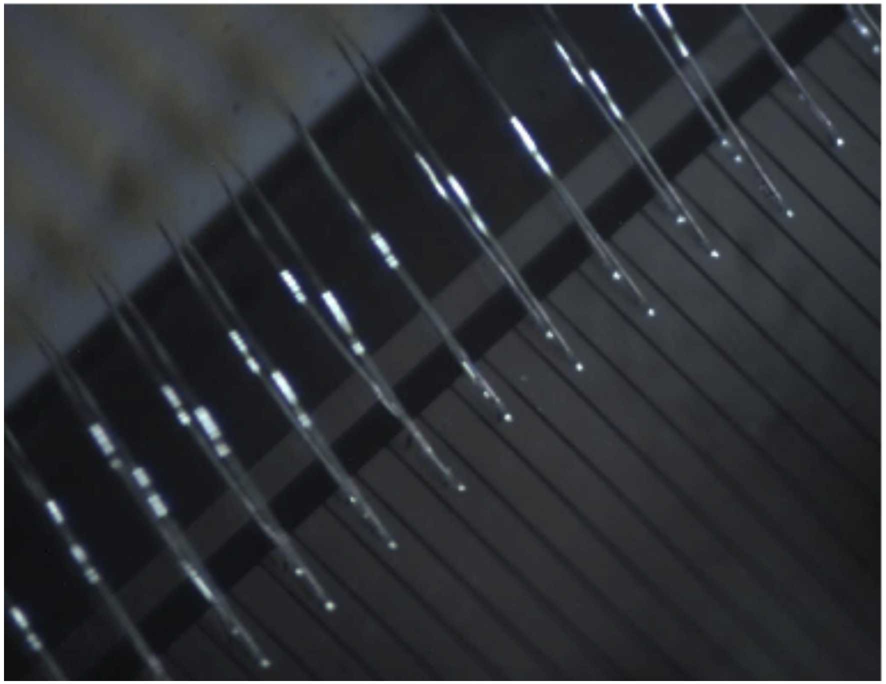
→200 μm pitch

Key component (not shown): amplifier-discriminator electronics

Readout using CAEN v1495 boards

→Should be able to read out either in event mode or in "scaler" mode

→ Capable of high rate readout – we are shooting for 100 kHz in event mode: higher rates likely possible



# CsI Photon Detector

## Pure CsI crystal

- 10 x 10 x 30 cm$^3$, slightly tapered → from MIT-Bates polarimeter
- Decay time: 16 ns (1000 ns), yield 2000 γ/MeV (5% of NaI)

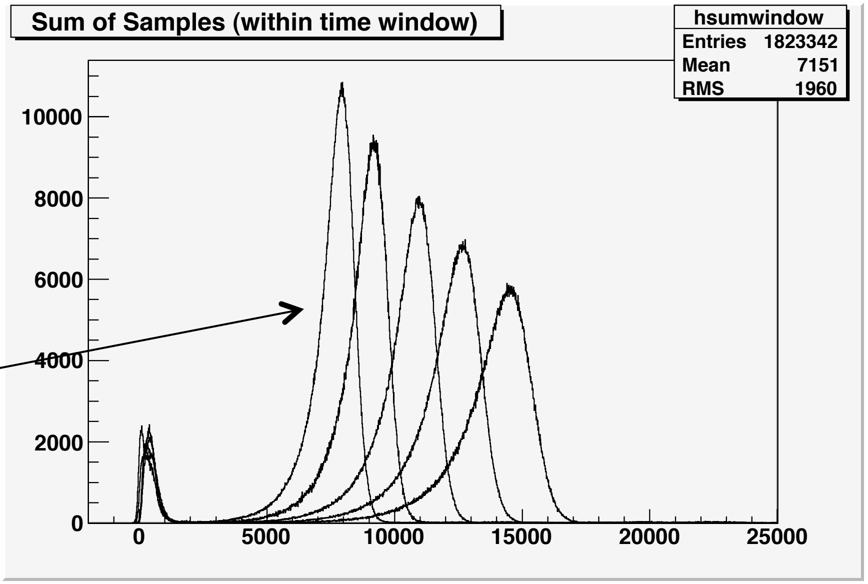
## Read out

- 250 MHz sampling ADC with integrated accumulators (developed for Hall A Compton by Hall A/Carnegie Mellon University)

## HIγS tests

- Photon beam tests performed at HIγS facility at Duke

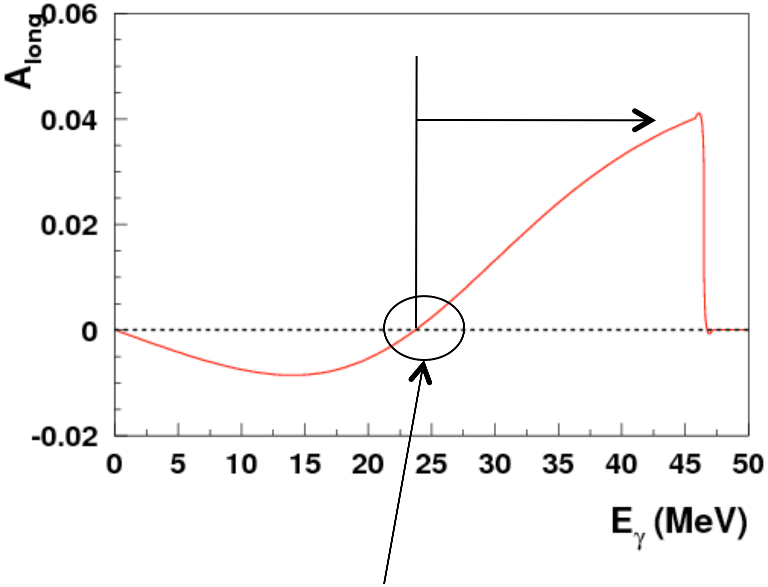
*Photon beam energy from 22 to 40 MeV ($Q_{Weak}$ endpoint = 46 MeV)*
*→ variable intensity*



# Compton Polarimeter Systematics

Systematic errors based on HAPPEX-II in Hall A using “zero-crossing” technique

| ***Source*** | ***dA/A (%)*** |
|---|---|
| Dipole Bdl, detector pos. | 0.03 |
| $E_{beam}$ ($10^{-3}$) | 0.10 |
| Detector efficiency | 0.1-0.2 |
| $A_{background}$ | 0.02 |
| Radiative corrections | 0.25 |
| $P_{laser}$ | 0.35 |
| Cuts, beam spot size | 0.5 |
| ***Total*** | ***0.70*** |

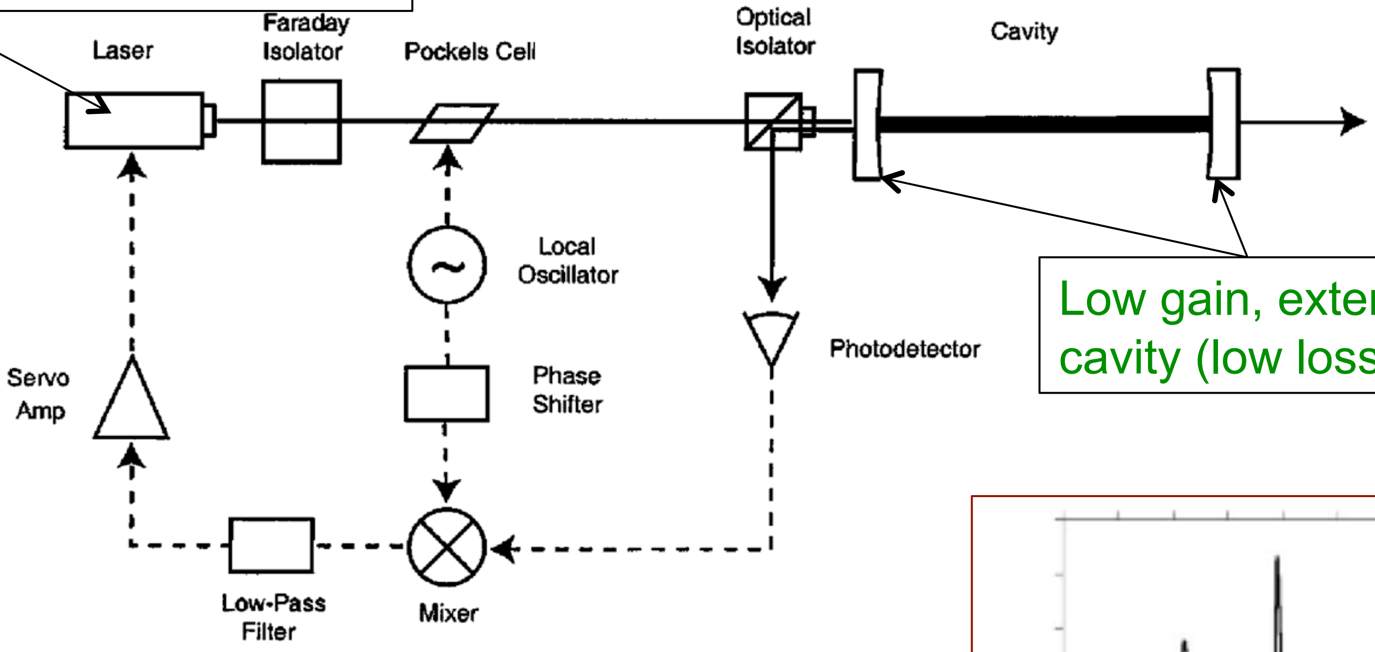


Integrate response from asymmetry zero crossing

Crucial that zero-crossing in electron detector acceptance
→ Hall C Compton designed with this in mind; zero crossing ~ 1 cm from beam

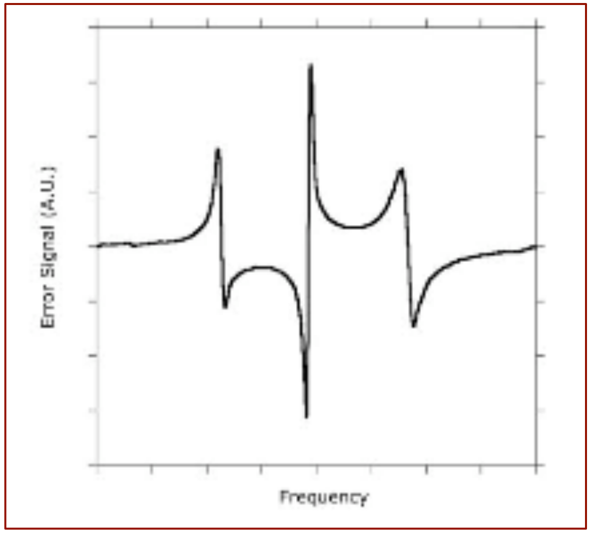
# External Fabry-Perot Cavity

Hall C: Coherent VERDI-10



Low gain, external cavity (low loss mirrors)

Laser locked to cavity using Pound-Drever-Hall (PDH) technique



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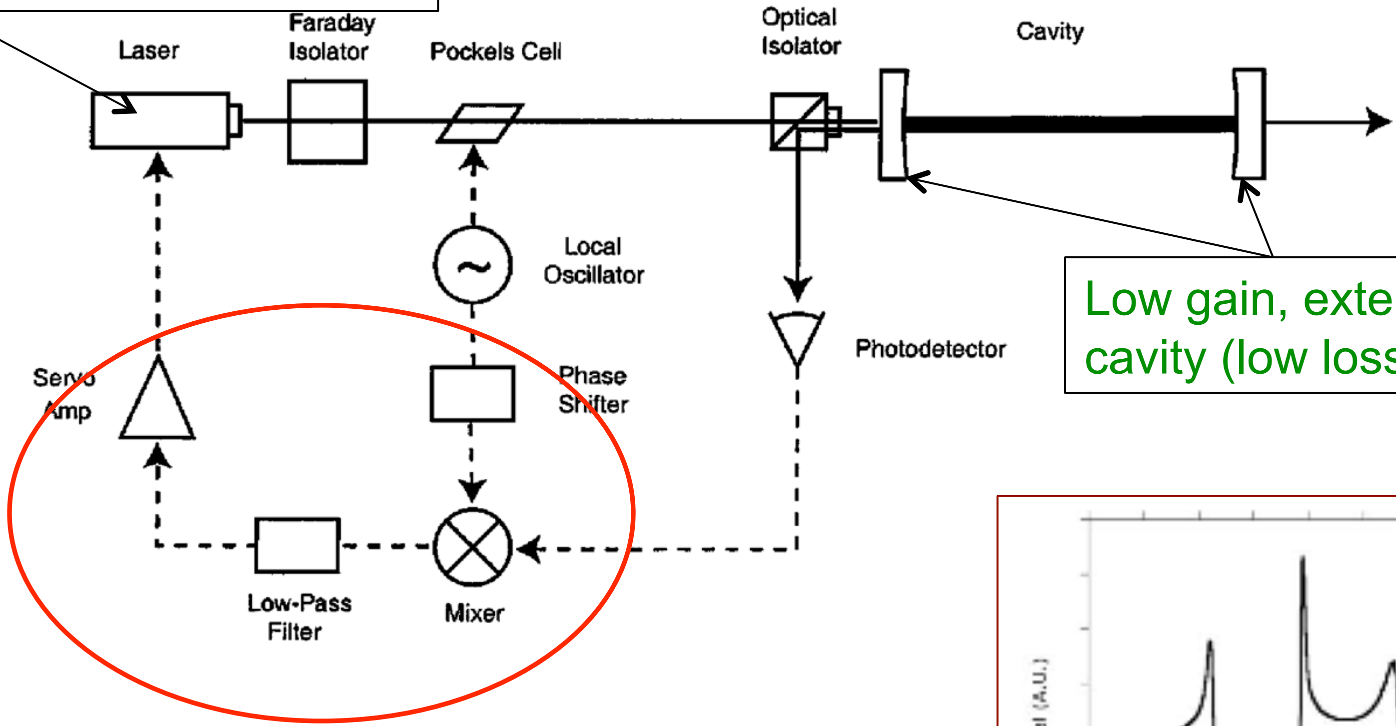

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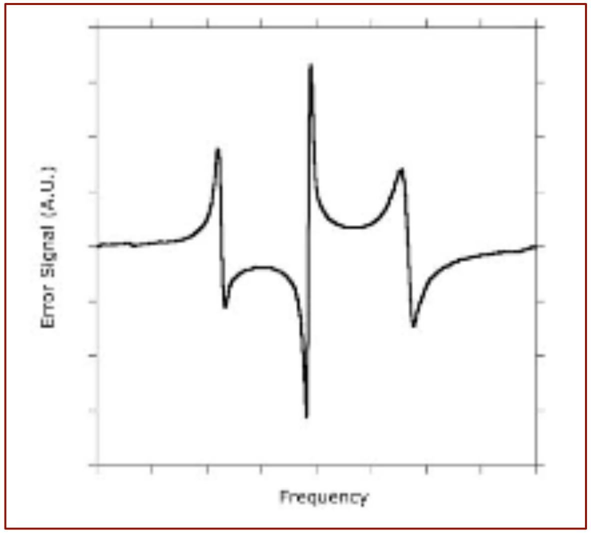
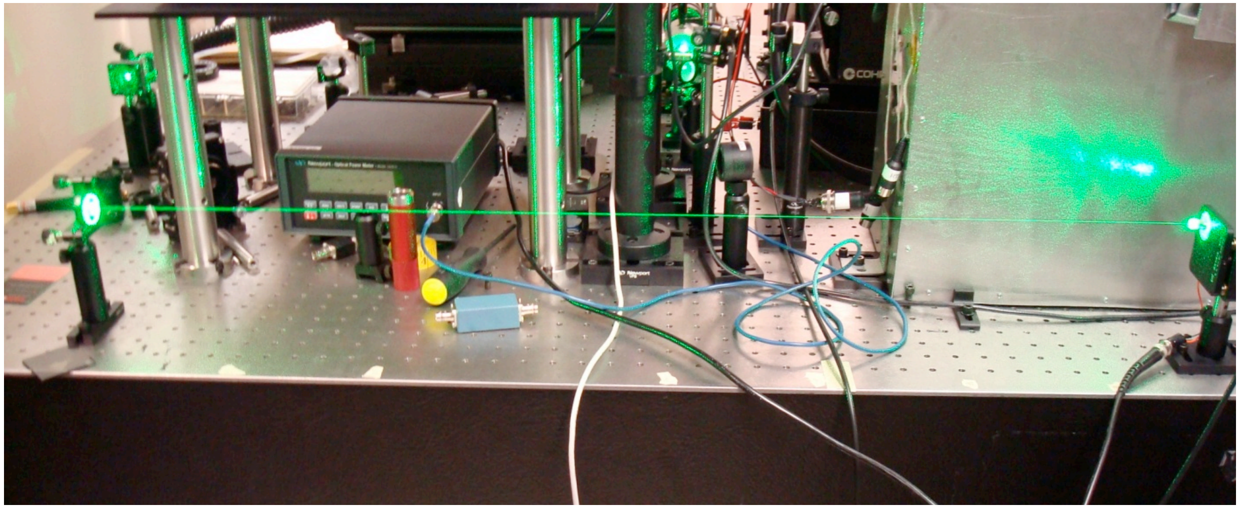
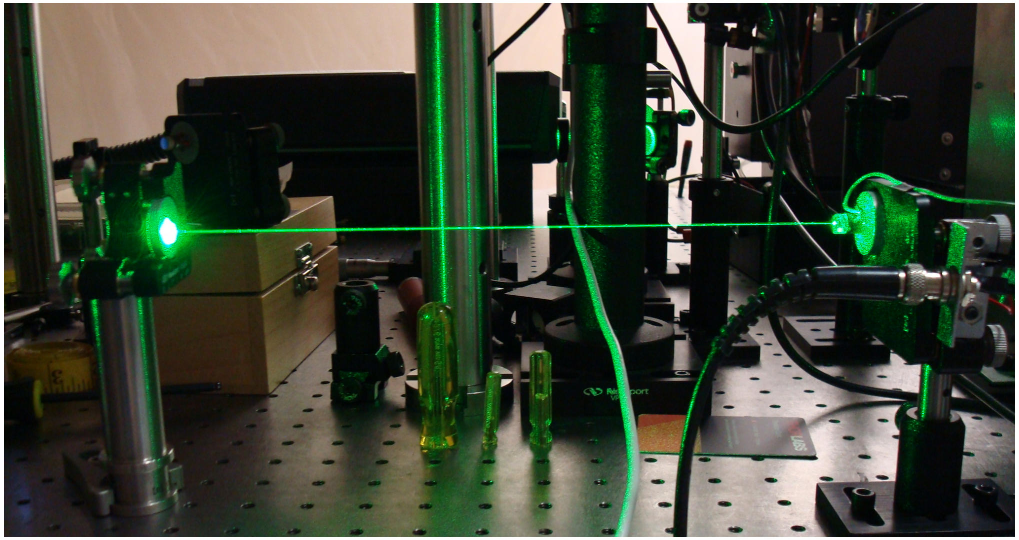


# Low gain cavity at UVa

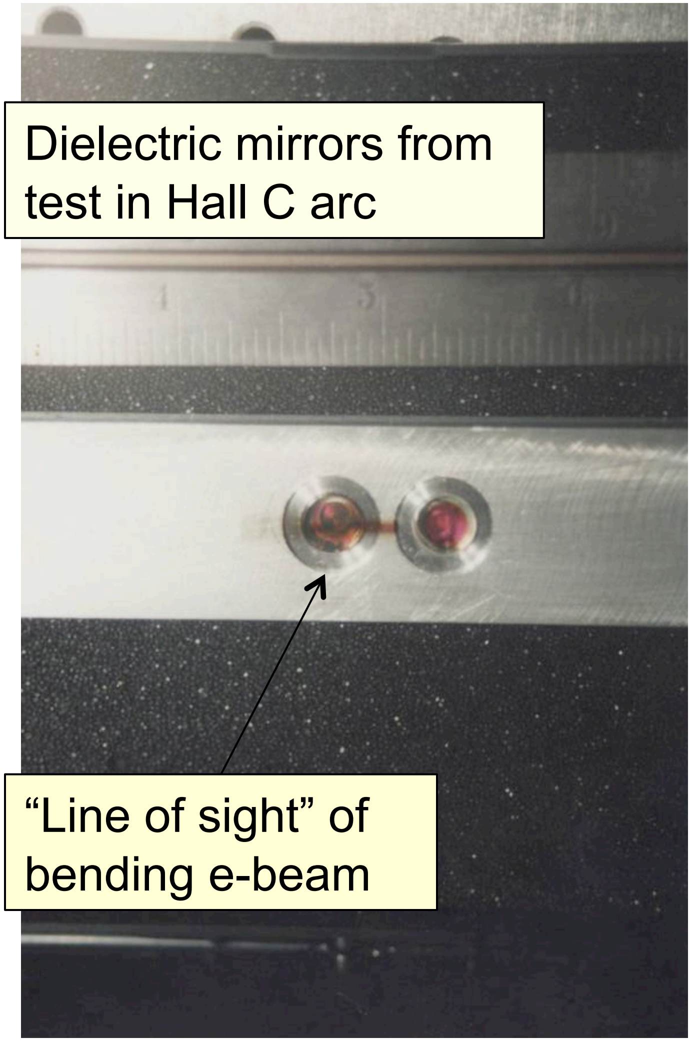
Gain 100 cavity
linewidth=400 kHz





Gain 300 cavity
linewidth = 175 kHz

# Dielectric Mirrors in the Beamline



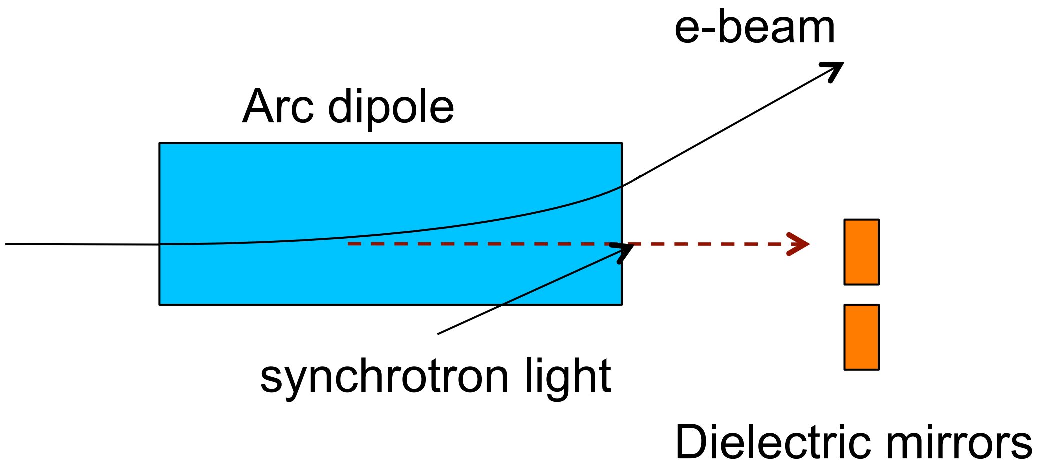
Dielectric mirrors from test in Hall C arc

“Line of sight” of bending e-beam

High power FP cavities require very low-loss (<50 ppm) dielectric mirrors

→Experience in Hall A has taught us these mirrors CAN survive in “high” current electron beamline for years at a time

→ BUT, you must take care ….



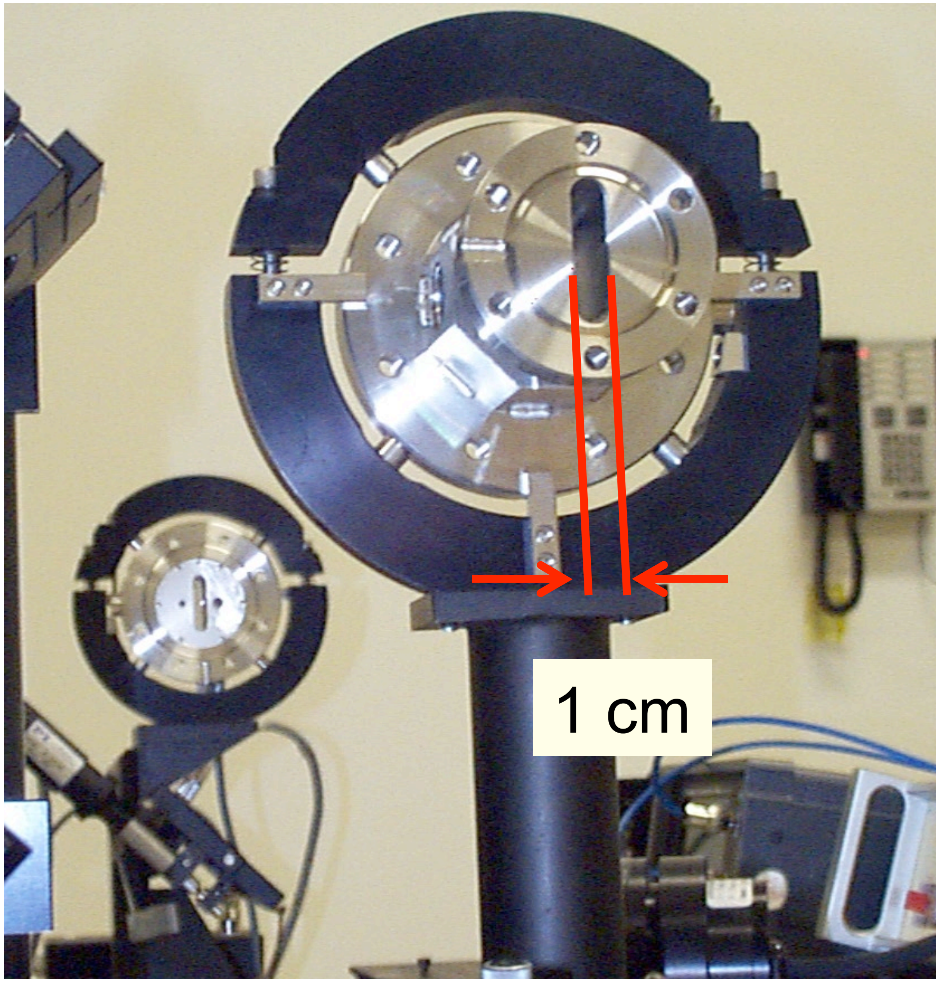
# Halo, small apertures and backgrounds

Hall A system uses narrow apertures to help protect cavity mirrors from
→Large beam related backgrounds
→Direct beam strikes

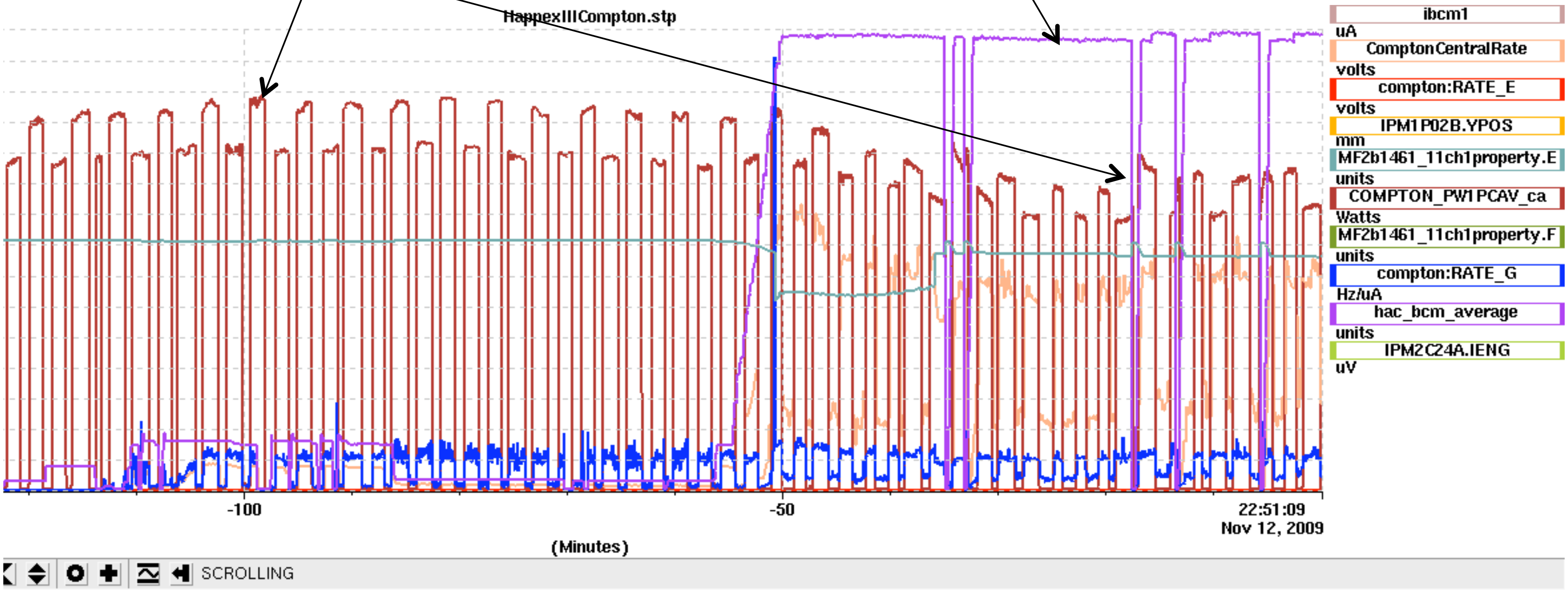
Large beam size, halo will result huge backgrounds from scraping on narrow apertures → ion chambers, machine protection system shuts off beam

This system has drawbacks → very small halos can still result in significant backgrounds

→ Halo may be small enough to run, but there still may be a lot of junk in your detectors



# Beam vs. Cavity

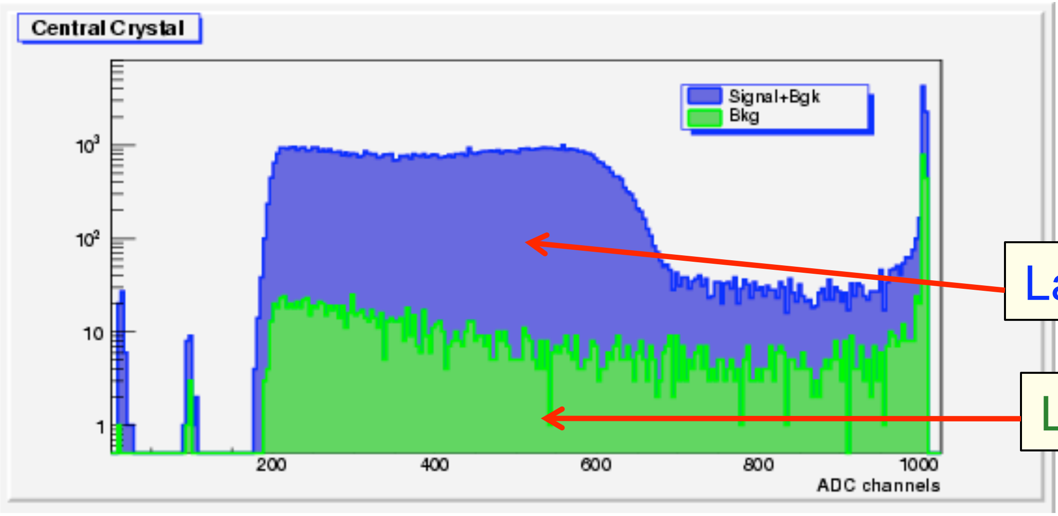


Stored cavity power

Beam current – 90 μA

Example: stored cavity power droops at high e-beam currents
→ Source unknown: synch light or beam scraping heating and distorting mirrors?

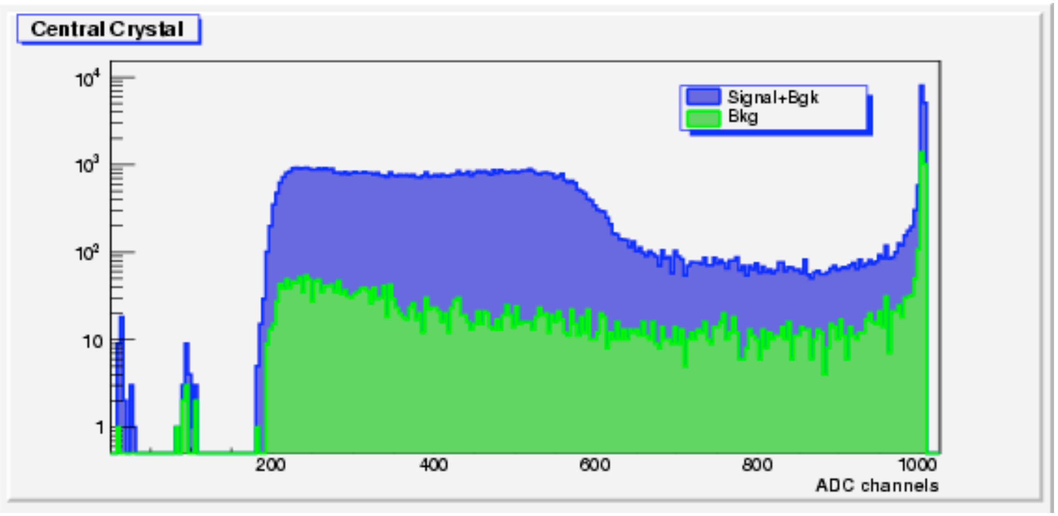
# Backgrounds and Beam Tune



Laser on

Laser off

“Good” beam tune
Signal/Background = 16



“Bad” beam tune
Signal/Background = 5

A lot of time and effort devoted to beam tuning to achieve good signal to noise – very sensitive to small changes in the machine!

# RF pulsed FP Cavity

JLab 12 GeV:

Control of beam halo, spot size likely worse

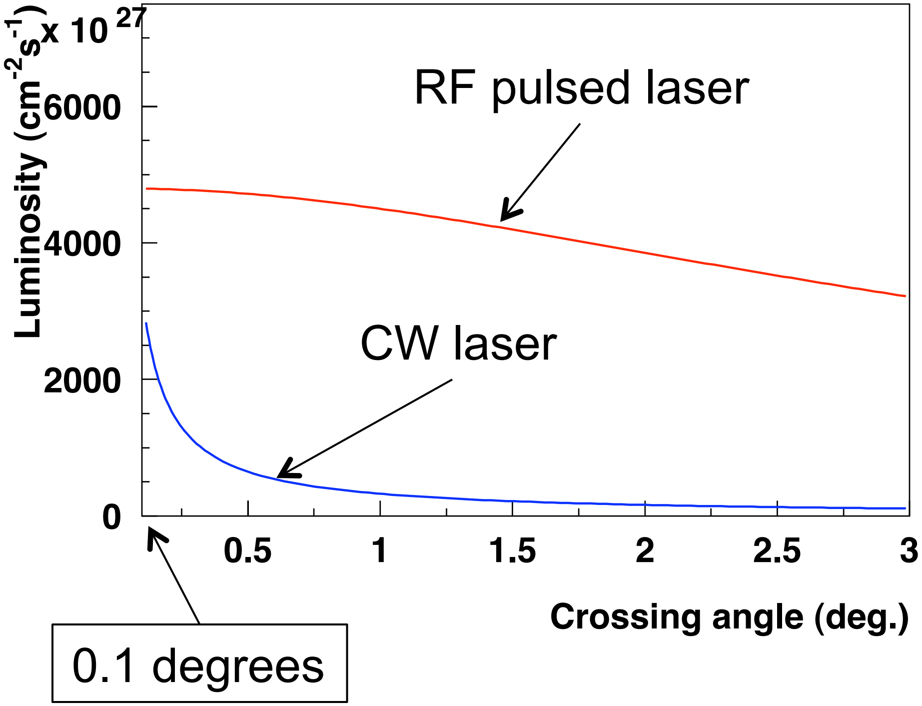
At 6 GeV, it already takes considerable effort to tune the beam for the Compton

Highly desirable to get mirrors further from beamline without reducing luminosity unduly

→This could be accomplished by switching from CW cavity, to RF pulsed cavity

→At non-zero crossing angle, luminosity larger, drops more slowly with crossing angle

*JLab beam → 499 MHz, $\Delta\tau$~0.5 ps*

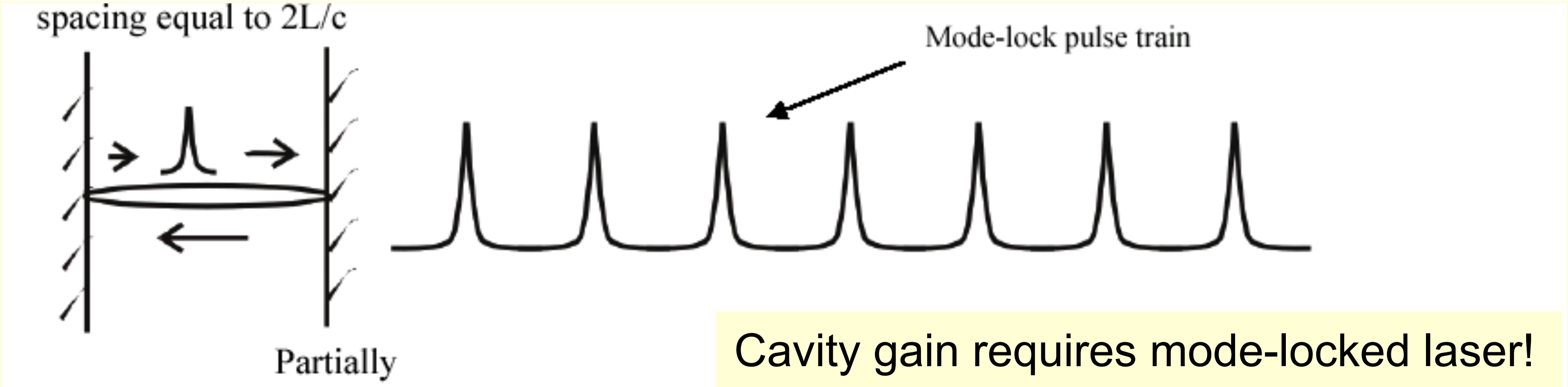


RF pulsed cavities have been built – this is a technology under development for ILC among other applications

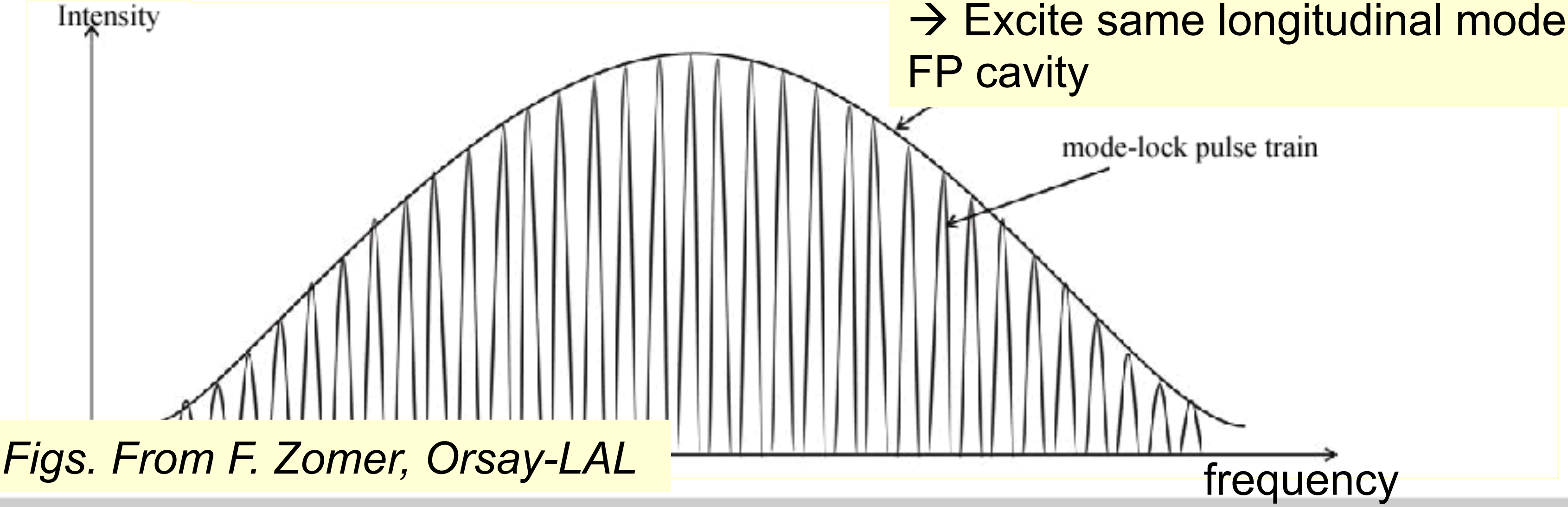
# Pulsed vs. CW FP Cavity

CW cavity resonance condition: $2L_{cavity} = n\,\lambda$

Additional condition for pulsed laser: $2L_{cavity} = n\,c/f_{RF}$



Cavity gain requires mode-locked laser!
→ Excite same longitudinal modes in FP cavity



*Figs. From F. Zomer, Orsay-LAL*

# Cavity Design Considerations

- In general – “low-finesse” (gain) cavities are easier than high-finesse
  - Better off if you can start with higher power laser (1 W better than 100 mW)
- Keep mirrors far from beamline
  - Naively, you can just make the cavity longer → same crossing angle, but mirrors further away
  - But, longer cavity results in smaller linewidth at fixed finesse → this may make locking more challenging
- RF pulsed system an intriguing solution
  - Extra degree of freedom in feedback, but has been demonstrated to work
  - Greater sensitivity to helicity correlated pathlength changes in the machine?

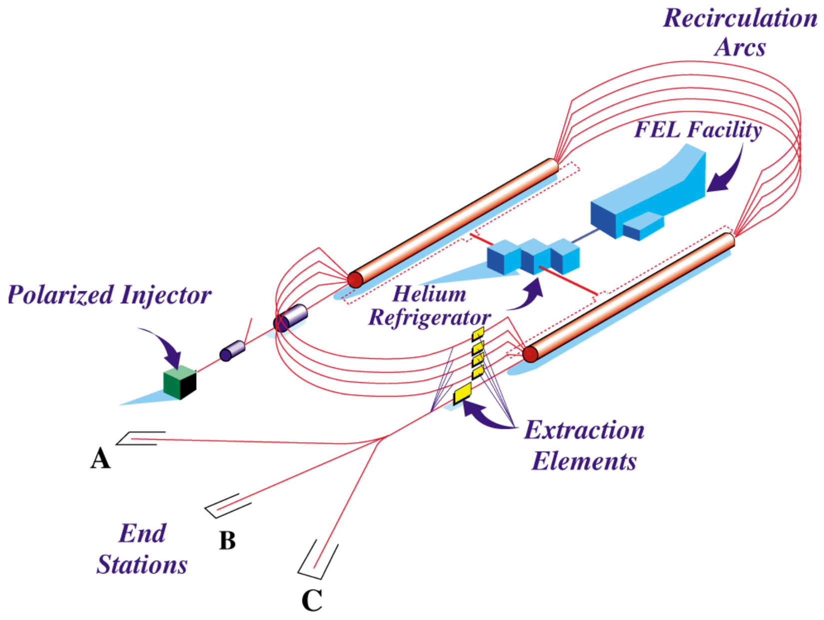
# Summary

- JLab benefits greatly from multiple techniques for electron beam polarimetry
  - Mott allows independent measurement at the injector – no reliance on experimenters
  - Different techniques provide different systematics – increased confidence in “high precision” measurements
- Møller polarimetry perhaps the “simplest” technique to implement and achieve high precision
  - Limited to low currents
  - Measurements destructive, cannot be done without interrupting beam to experiment
- Compton polarimetry ideal technique from perspective of experimenter *but*,
  - More difficult to implement → low beam currents at JLab require creative solutions to achieve timely measurements
  - FP cavity presents beam tuning complications – already difficult, may be impractical at 12 GeV

# Extra

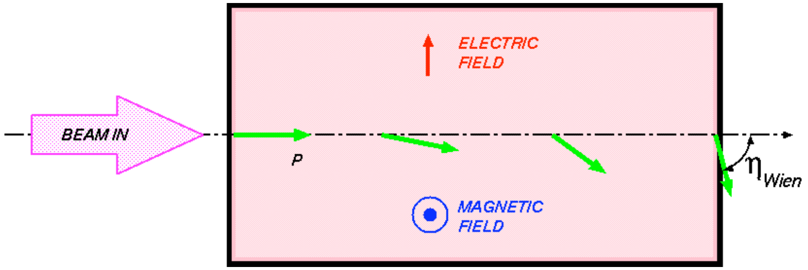
# Polarized Electrons at Jefferson Lab

- Polarized electrons generated “at the source” using Superlattice GaAs photocathode
- Electrons polarized in the plane of the accelerator
  - → spin direction precesses as beam circulates (up to 5 times) through machine



$$\phi_{spin} = \frac{g-2}{2}\frac{E_{beam}}{m_e}\theta_{bend}$$

- Spin direction manipulated at source using Wien filter to get long. Polarization in Halls
- JLab now routinely provides electron beam polarizations >80% to experimental halls

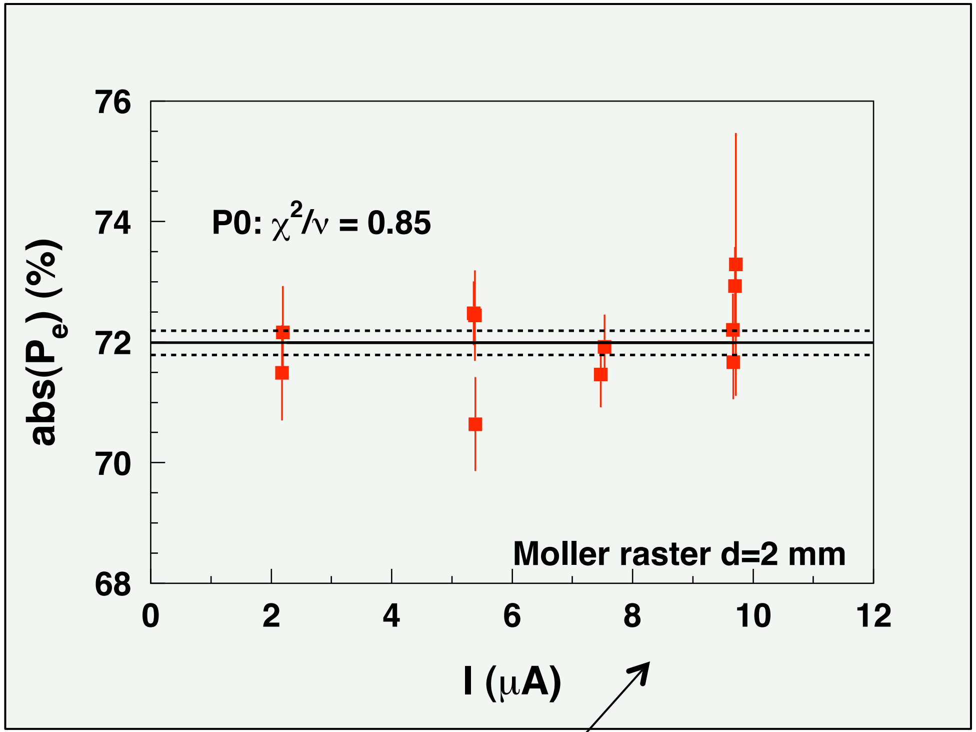


# Møller Raster

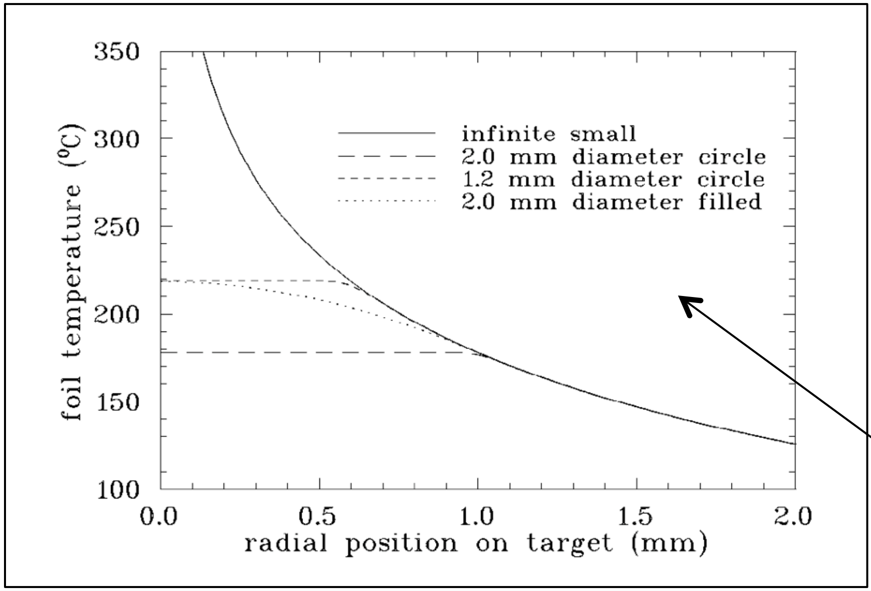
→Using a circular raster with radius of 2 mm, can run up to 10 to 20 μA without significant heating effects

→ Experiments (especially $Q_{Weak}$) run at significantly higher currents – 150 μA!

→ Møller running up to 100 μA (or higher) desirable



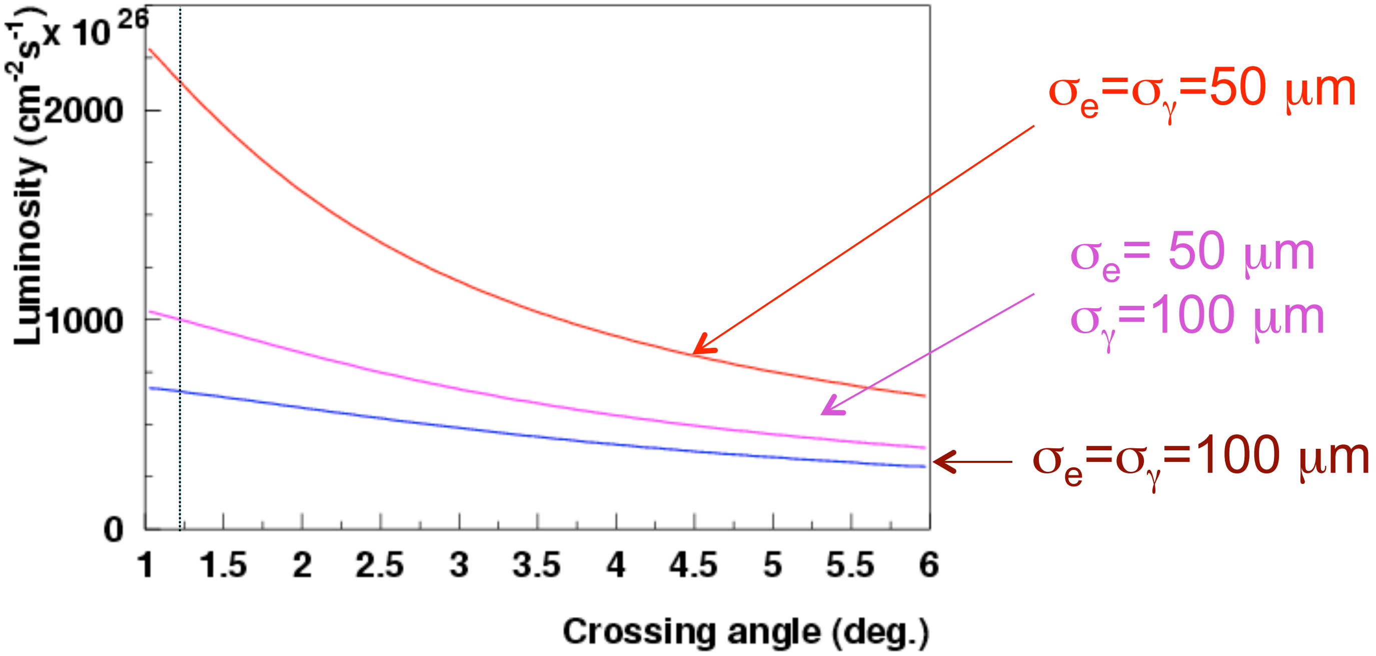
Møller current dependent tests during G0 forward angle (2003)



Calculated target heating vs. "raster size" at 20 μA

# Luminosity and Rate

$$L \approx \frac{2f(1+\cos\alpha_c)}{\sin\alpha_c}\frac{N_e N_\gamma}{4\pi}\frac{1}{\sqrt{\sigma_e^2+\sigma_\gamma^2}}\frac{1}{\sqrt{\sigma_{e,c\tau}^2+\sigma_{\gamma,c\tau}^2+\frac{\sigma_e^2+\sigma_\gamma^2}{\sin^2\frac{\alpha_c}{2}}}}$$



# Luminosity from RF (Fiber) Laser

Fiber laser pulse-width about 15 times larger than electron beam – no problem!

$$\frac{L_{pulsed}}{L_{CW}} \approx \frac{c}{f\sqrt{2\pi}}\left(\sqrt{\underbrace{\sigma^2_{c\tau,laser}}_{1\ \mathrm{cm}^2} + \sigma^2_{c\tau,e} + \underbrace{\frac{1}{\sin^2(\alpha/2)}\left(\sigma_e^2 + \sigma_{laser}^2\right)}_{2.0\ \mathrm{cm}^2}}\right)^{-1}$$

$\sigma_e = \sigma_{laser} = 100\ \mu\mathrm{m}$, $\alpha = 20$ mrad

Luminosity gain only weakly dependent on laser pulse width → for laser pulses ~ 10's of ps