High Precision Polarimetry for Jefferson Lab at 11 GeV

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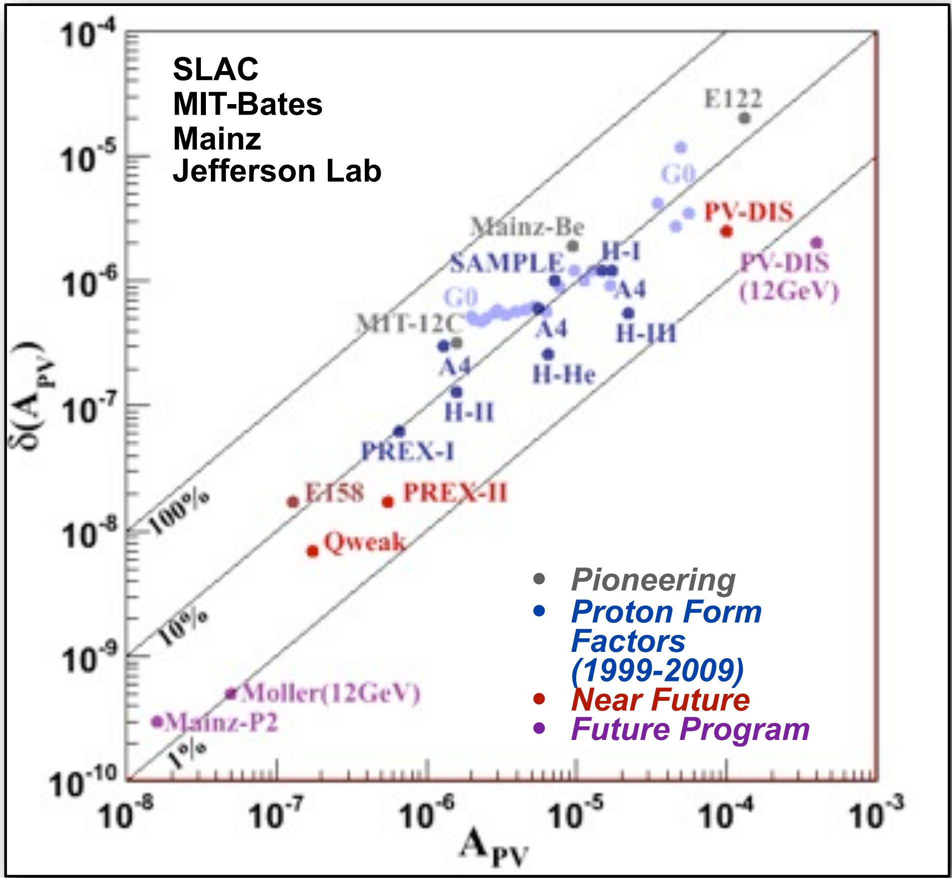
3 Decades of Technical Progress

Parity-violating electron scattering has become a precision tool



Interplay between probing hadron structure and electroweak physics

- ***Beyond Standard Model Searches***
- ***Strange quark form factors***
- ***Neutron skin of a heavy nucleus***
- ***valance parton nucleon structure***

photocathodes, polarimetry, nanometer beam stability, precision beam diagnostics, high power cryotargets, low noise electronics, radiation hard detectors

For future program: sub-1% normalization requires improved electron beam polarimetry

- *MOLLER: 0.4% at 11 GeV*
- *SOLID PV-DIS: 0.4% at 11, 6.6 GeV*

Strategy to meet required 0.4% accuracy

- **Unimpeachable credibility for 0.4% polarimetry**
- **Two independent measurements which can be cross-checked**
- Continuous monitoring **during production (protects against drifts, precession…)**
- **Statistical power to facilitate** cross-normalization **(get to systematics limit in about 1 hour)**
- **High precision operation at 6.6 GeV - 11 GeV**

Compton

Plan: Upgrade beyond 11 GeV baseline will meet goals

- significant independence in photon vs electron measurements
- continuous monitor with high precision

Møller

Default: Upgraded "high field" polarimeter

Plan: Atomic hydrogen gas target polarimeter

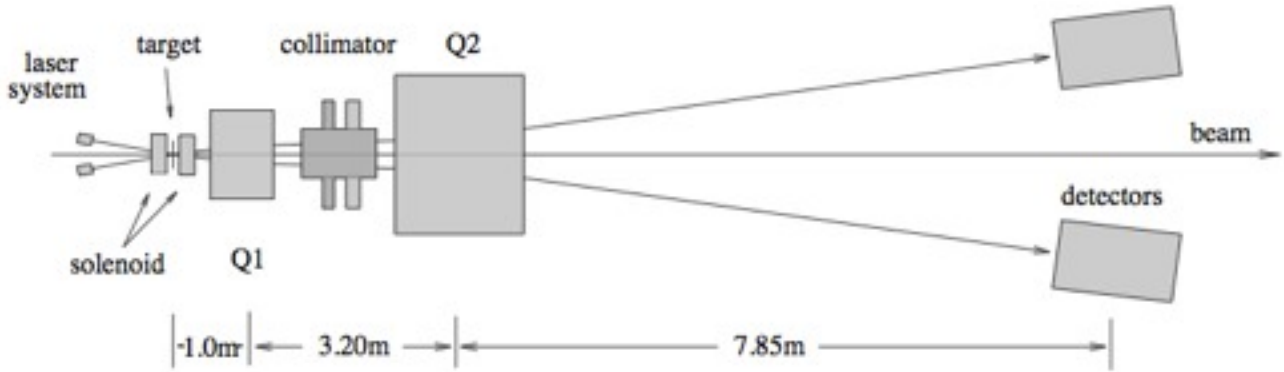
- expected accuracy to better than 0.4%
- non-invasive, continuous monitor
- Requires significant R&D

Moller Polarimetry

Hall C Moller Polarimeter

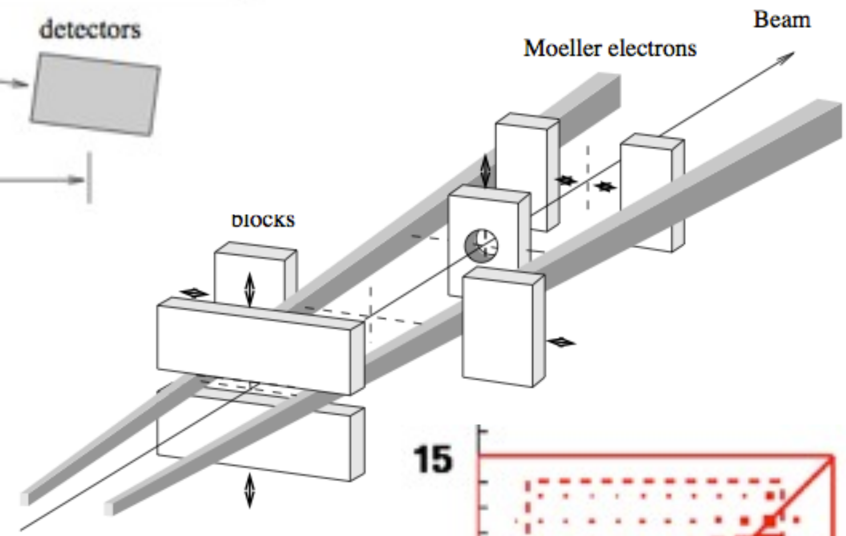
$$A_{zz} = -\frac{\sin^2\theta_{CM} \cdot (7+\cos^2\theta_{CM})}{(3+\cos^2\theta_{CM})^2}$$

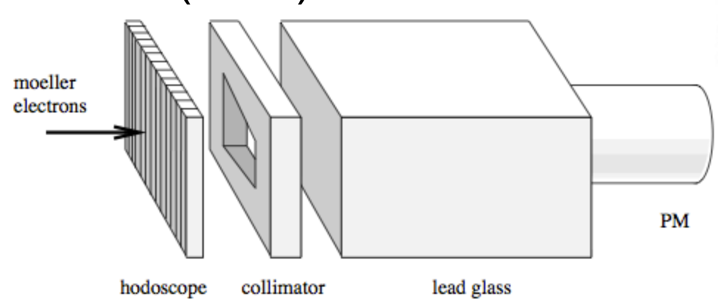
Peak analyzing power at 90º CM - coincidence rate of identical particles

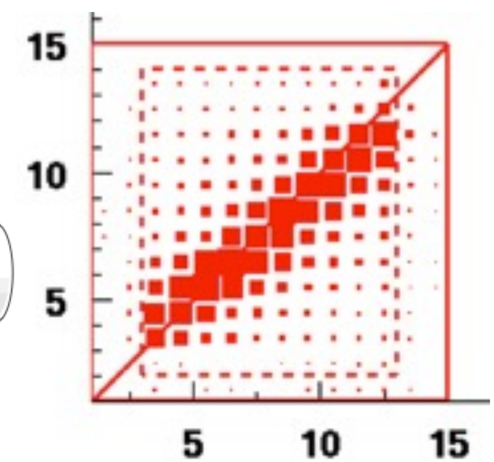


Precision Adjustable Collimators

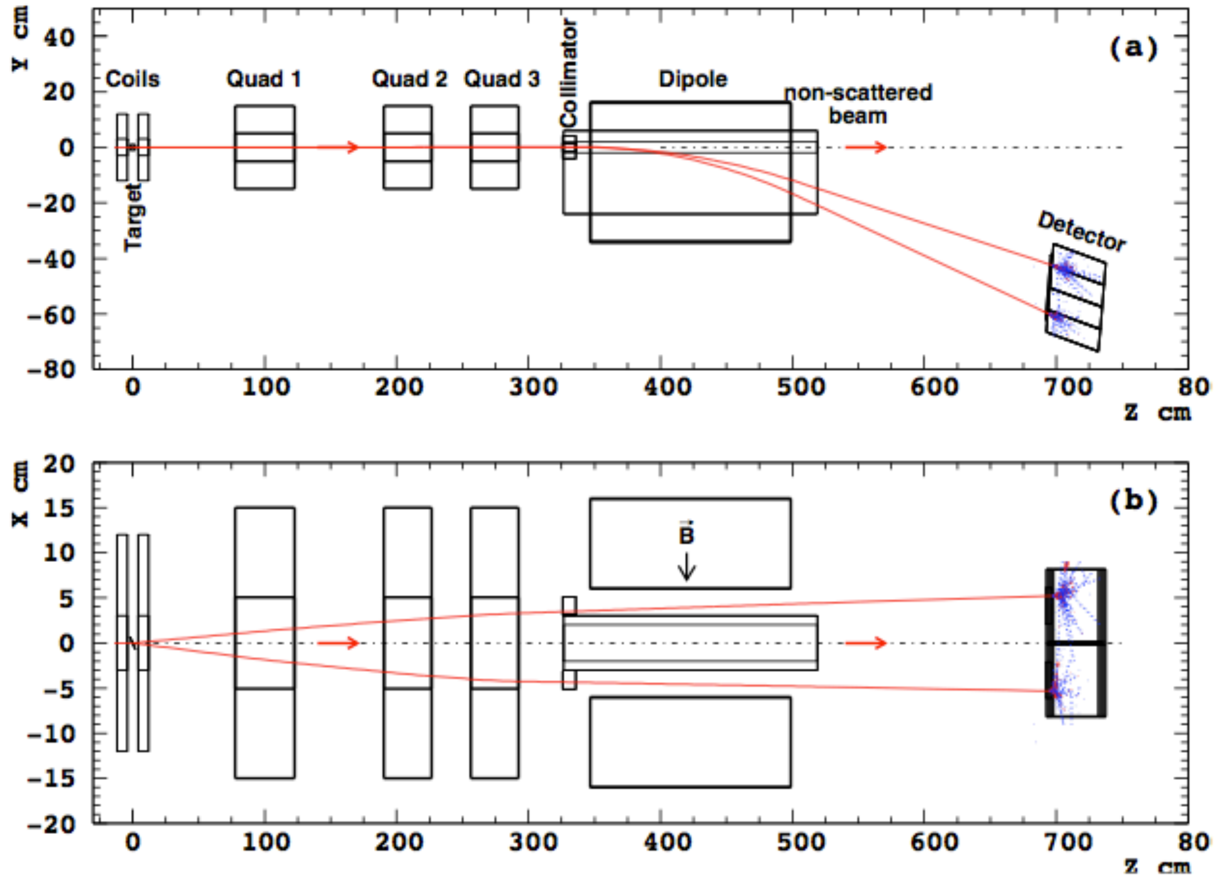
- Singles and coincidence rates under control
- Must be simulated to calibrate effective analyzing power, Levchuk correction (~3%)





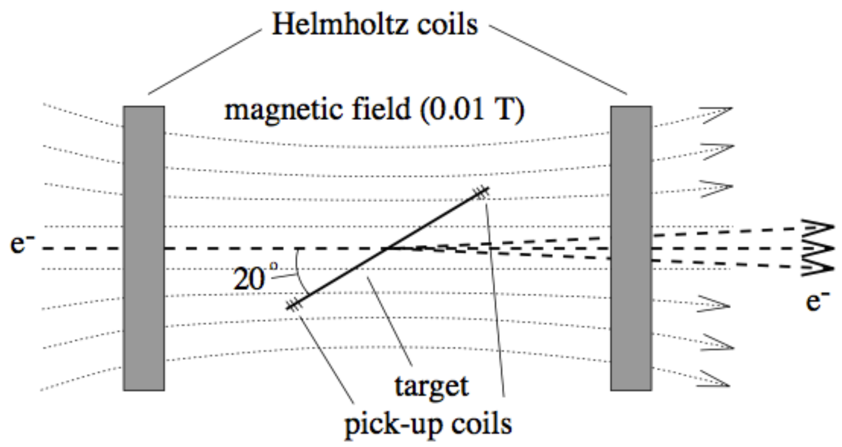


Hall A Moller Polarimeter



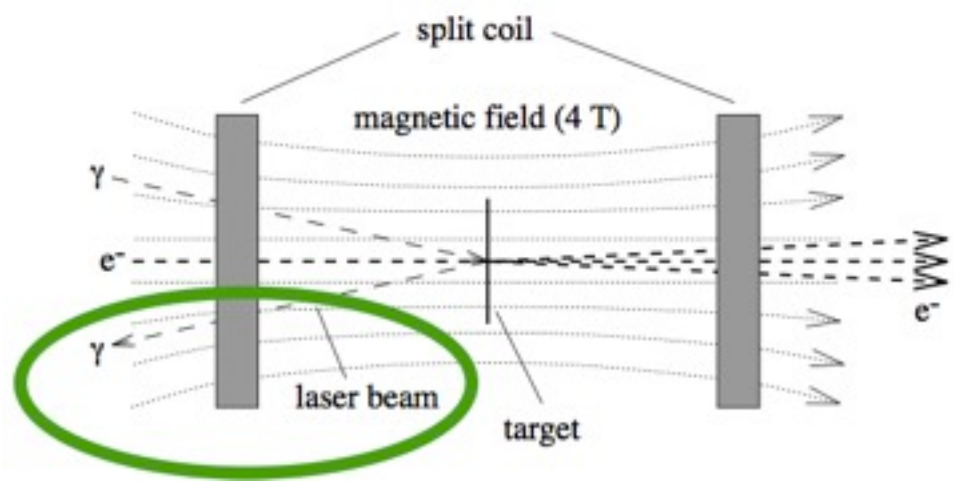
Open acceptance - Levchuck correction minimized (~1%)
FADC for "pipeline" acquisition on hodoscope detectors

Moller Polarimetry Target



supermendur iron alloy

- Magnetization along foil
- near saturation at H = 20mT
- sensitive to annealing, history
- 1.5-3% accuracy



Pure Iron at High Field

- Magnetized perp. to foil
- Magnetization saturated
- Magnetization from world data
- Precision claimed at 0.25%

Hall C Moller Systematics

M. Hauger *et al.*, NIM A 462, 382 (2001)

Effective Analyzing Power

source	uncertainty	effect A
beam position x	0.5mm	0.15%
beam position y	0.5mm	0.03%
beam direction x	0.15mr	0.04%
beam direction y	0.15mr	0.04%
current Q1	2%	0.10%
current Q2	1%	0.07%
position Q2	1mm	0.02%
multiple scattering	10%	0.12%
Levchuk effect	10%	0.30%
position collimator	0.5mm	0.06%
target temperature	50%	0.05%
direction B-field	2°	0.06%
value B-field	5%	0.03%
spin polarization in Fe		0.25%
total		0.47%

Acceptance calibration
~0.4%

Levchuk

Target Polarization
~0.26%

<u>Asymmetry Measurement</u>
Deadtime, background

Uncertainty in iron foil polarization

Magnetization/polarization values for the iron target polarized out-of-plane. M_s: saturation magnetization, μ_B: Bohr magneton

Effect	M_s [μ_B]	Error	Ref.
Saturation magnetization ($T \to 0$ K, $B \to 0$ T)	2.2160	±0.0008	[22]
Saturation magnetization ($T = 294$ K, $B = 1$ T)	2.177	±0.002	[18]
Corrections for $B = 1$–4 T	0.0059	±0.0002	[21]
Total magnetization	2.183	±0.002	
Magnetization from orbital motion	0.0918	±0.0033	[23]
Remaining magnetization from spin	2.0911	±0.004	
Target electron polarization ($T = 294$ K, $B = 4$ T)	0.08043	±0.00015	

L.V. de Bever *et al.*, NIM A 400, 379 (1997)

Magnetization measured measured by force due to magnetic gradients, at low temperature and applied fields. (~1.8% correction)

Magnetization measured by magneto-torque techniques treat orbital and spin contributions differently: separate spin from orbital polarization (~4.5%)

Note:

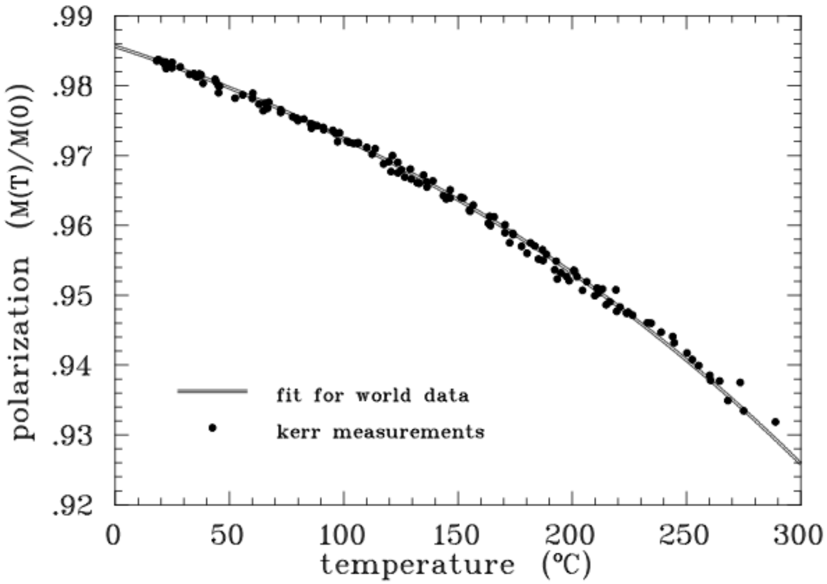
$$g_e = 2.00231930436146(56)$$

I believe this enters twice (once in spin vs orbital, once in M->P_e): 0.23% correction

Historically a topic of great intellectual interest, but no model calculations or other measurements match this precision.

Target Polarization vs. Temperature

Trend of surface polarization vs. sample temperature.
Relative effect measured via Kerr effect on reflected light.

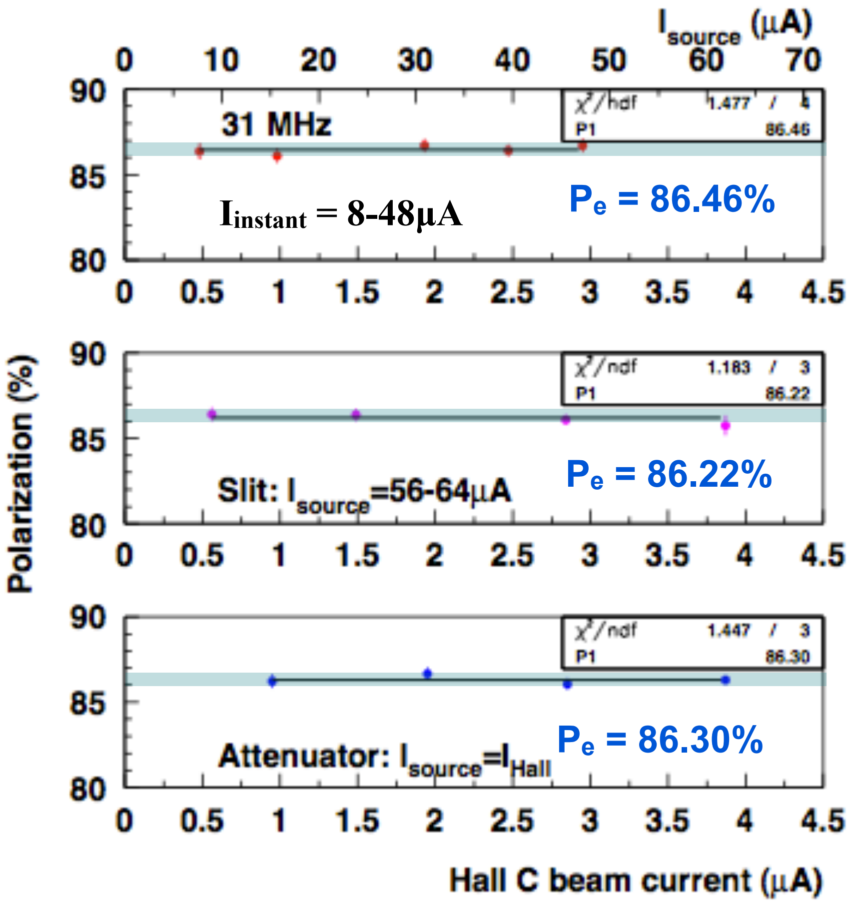


in situ Kerr relative monitoring is proposed, but challenging

The effect potentially complicates the question of whether Moller measurements at low currents provide a good measure of the polarization at high current

Beam Current vs Polarization

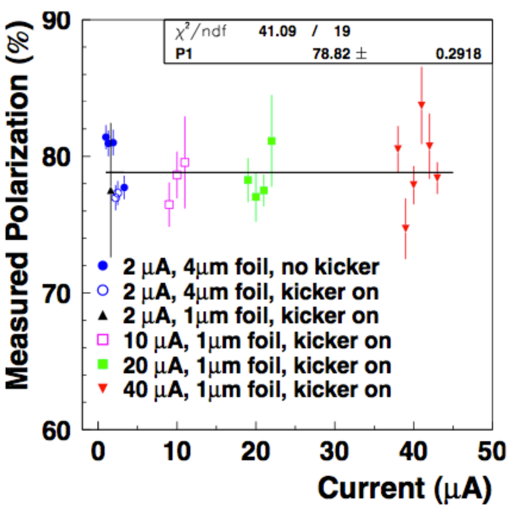
There is no convincing empirical evidence for a possible systematic variation of polarization with beam current, but existing evidence against is also limited



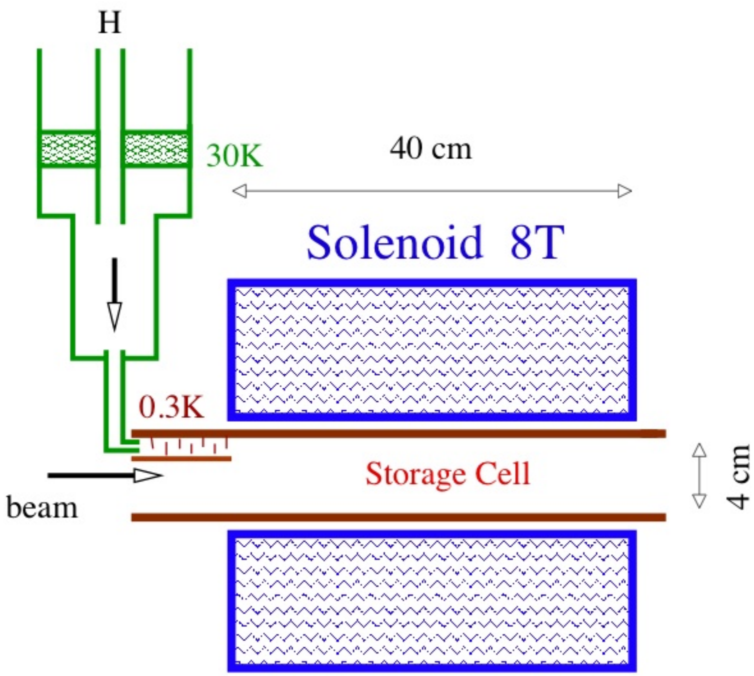
(bands show +/- 0.5%)

Beat frequency technique allows high instantaneous current

"Kicker" to move beam on Moller foil with low duty factor.



Atomic Hydrogen For Moller Target



10 cm, $\rho = 3 \times 10^{15}/cm^3$
in B = 7 T at T=300 mK

$$\frac{n_+}{n_-} = e^{-2\mu B/kT} \approx 10^{-14}$$

Brute force polarization

Moller polarimetry from polarized atomic hydrogen gas, stored in an ultra-cold magnetic trap

- 100% electron polarization- opposite polarization quickly ejected
- tiny error on polarization
- thin target (sufficient rates but low dead time)
- Non-invasive, high beam currents - continuous measurement over experiment
- no Levchuk effect

E. Chudakov and V. Luppov, IEEE Transactions on Nuclear Science, v 51, n 4, Aug. 2004, 1533-40

Significant technical challenges

Strategy for Moller polarimetry

High Field Moller: 4T to saturate iron foil magnetization

- Based on Hall C system
- Levchuck effect and integration of analyzing power can be well controlled
- Is foil polarization so well understood?

Direct cross-check with Compton polarimeter might offer best hope of verifying iron target polarization

Potential systematic errors	Hall C	Atomic H
Target Polarization	0.25%	0.01%
Analyzing Power	0.24%	0.30%
Levchuk	0.30%	-
Target Temp	0.05%	-
Dead Time	-	0.10%
Background	-	0.10%
Total	0.47%	0.35%

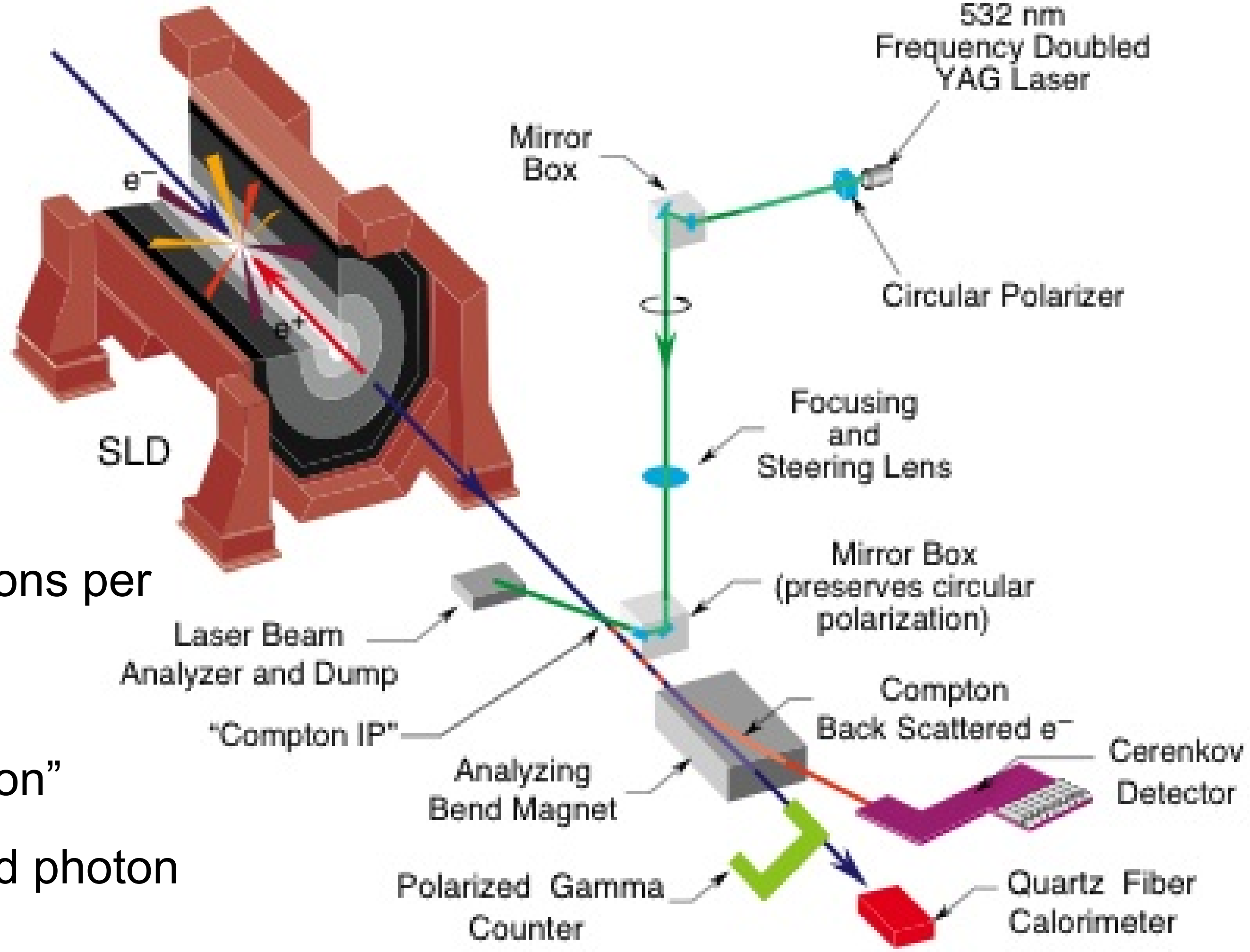
Atomic Hydrogen Polarimeter:

- Precise electron polarization (100%)
- No Levchuk effect
- Reduced radiation / kinematic uncertainty
- non-invasive, continuous monitor
- **R&D required - underway at Mainz**

Compton Polarimetry

SLD Compton Polarimeter

"The scanning Compton polarimeter for the SLD experiment" (SLAC-PUB-7319)



- Pulsed laser
- ~1000 scattered electrons per pulse
- 2/3 operating time was calibration, not "production"
- Integrating electron and photon detectors
- Published results $\delta P/P \sim 0.5\%$

Collider Compton Polarimetery

Uncertainty (%)	$\delta\mathcal{P}_e/\mathcal{P}_e$
Laser polarization	0.10
Detector linearity	0.20
Analyzing power calibration	0.40
Electronic noise	0.20
Total polarimeter uncertainty	0.50
Chromaticity and interaction point corrections	0.15

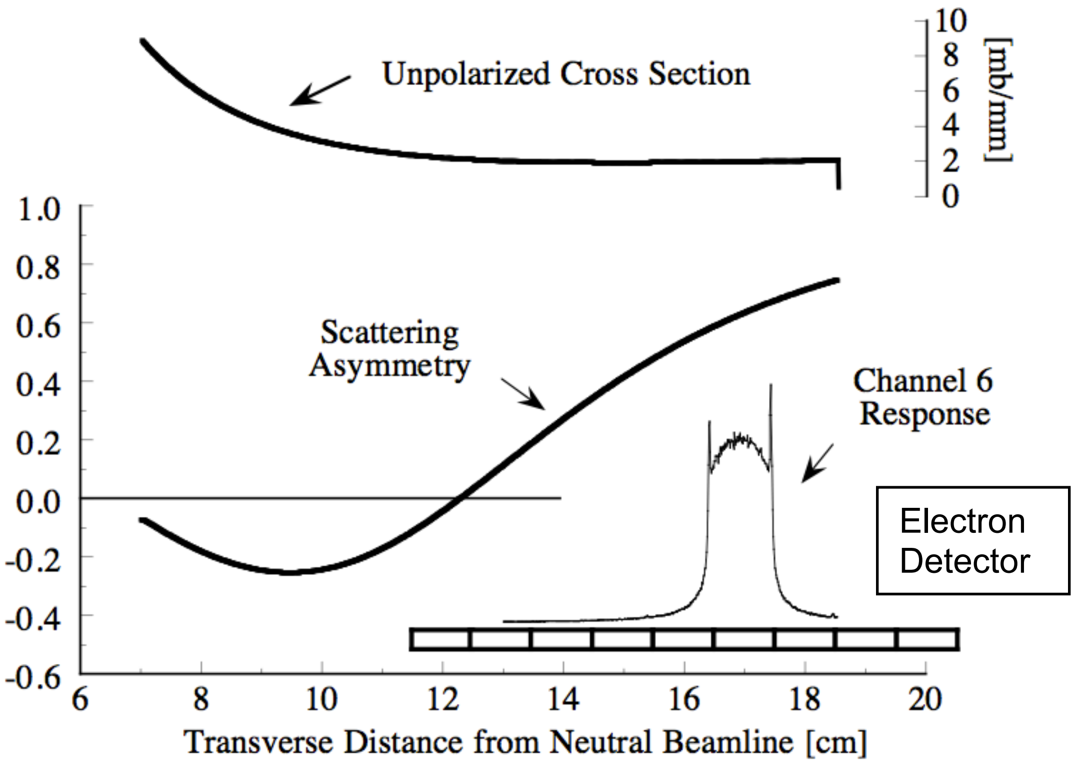
collider specific

Table from:
Annu. Rev. Nucl. Part. Sci. 2001. 51:345–412

Electron detector was corrected for energy calibration, response function

Detector element at the Compton edge was least sensitive to corrections, and so most precise

$\sin^2\theta_W$ rested on a single electron detector channel !



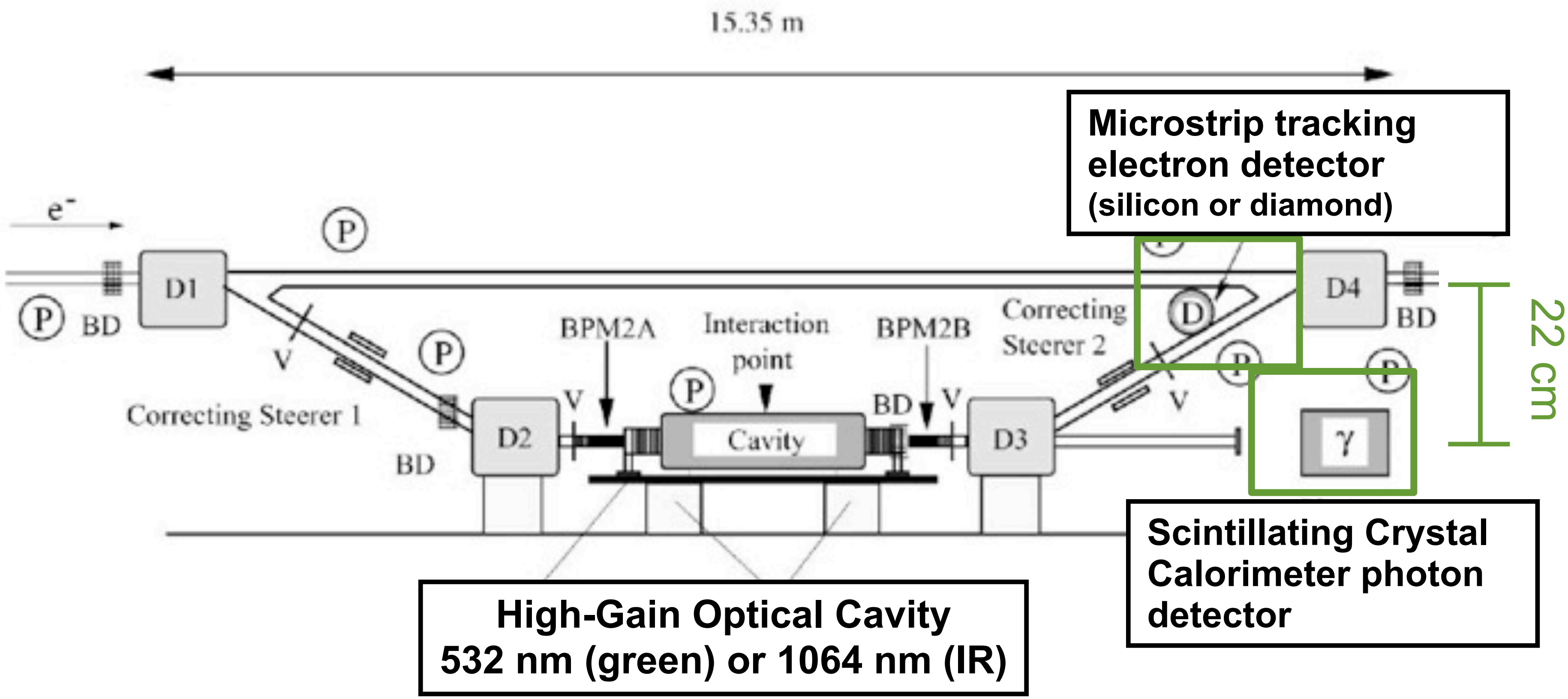
High Precision Compton

At higher energies, SLD achieved 0.5%.

Why do we think we can do better?

- SLD polarimeter near interaction region
  - No photon calorimeter for production
- Hall A has single-photon / single-electron mode (CW)
  - Efficiency/resolution studies
  - Tagged photon beam
  - Measured spectrum vs. simulation
- Greater electron detector resolution
  - less resolution correction, more precise calibration
- Greater coverage of Compton-scattered spectrum

Hall A Compton Polarimeter



Operated at 1-6 GeV, now upgraded for 11 GeV operation and improved precision

- Green (532 nm) or IR (1064 nm) laser cavity at 10kW+
- Detection of backscattered photons and recoil electrons

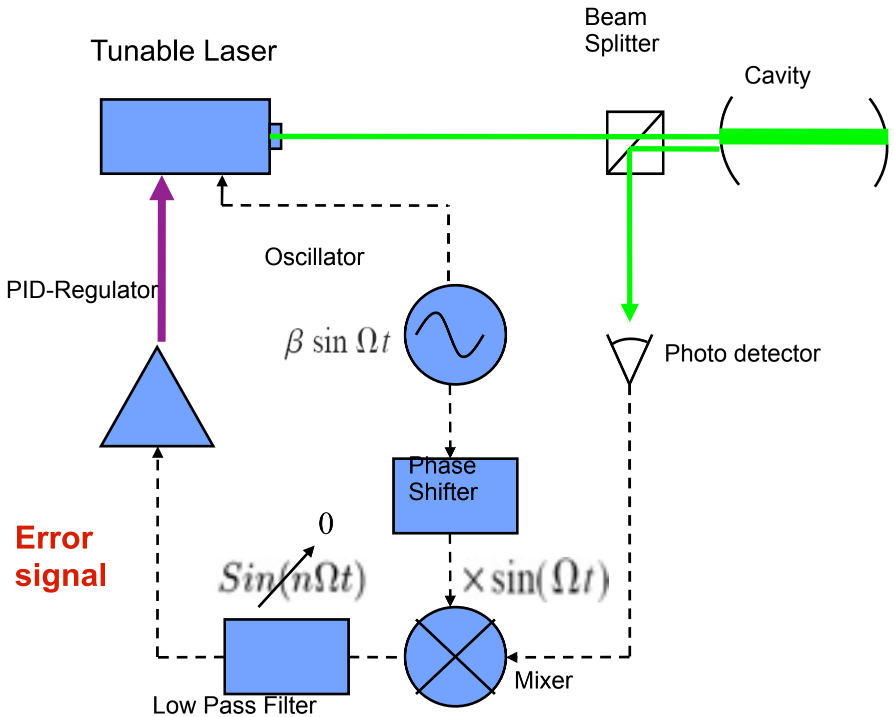
Fabry-Perot Resonant Cavity

532 nm (green) upgrade

- Continuous wave
- 1064nm (IR) tunable laser
- amplified (>5W), SHG doubled to 532nm (1-2W)
- Gain ~ 10000
- up to 10kW(!) stored

Challenges

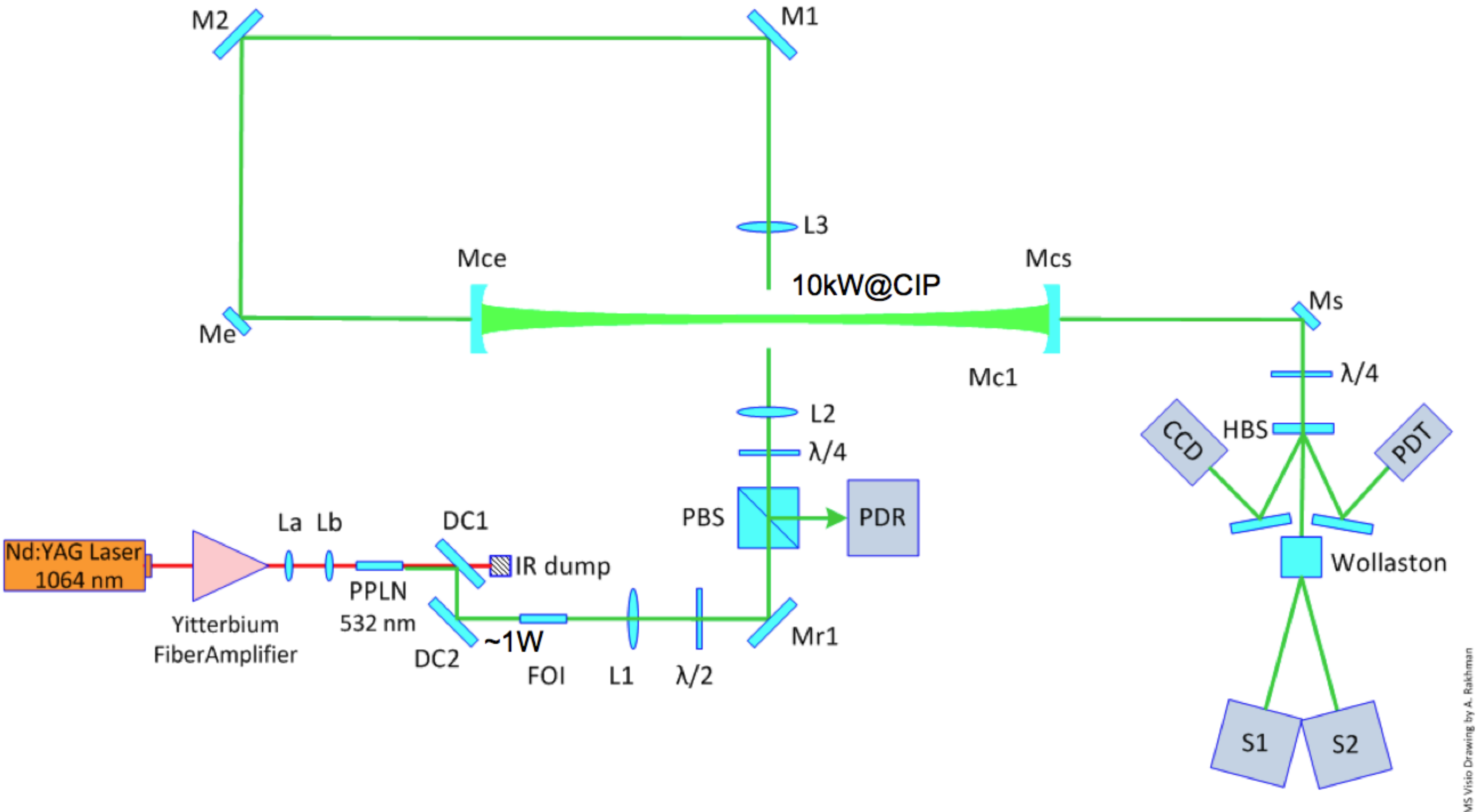
- Laser polarization
- Mirror lifetime (radiation damage)
- Operational stability at 10kW
- background due to beam apertures



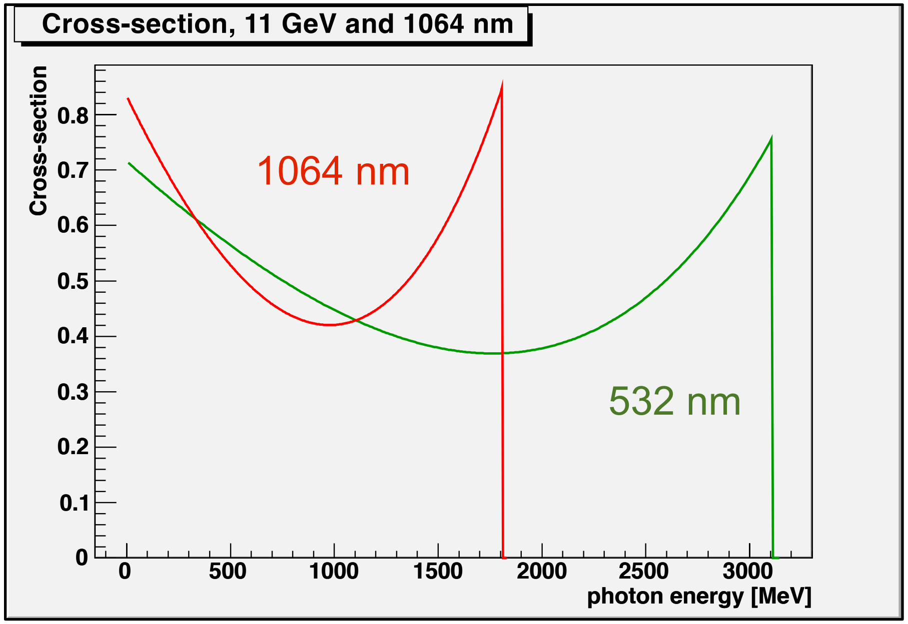
R&D efforts

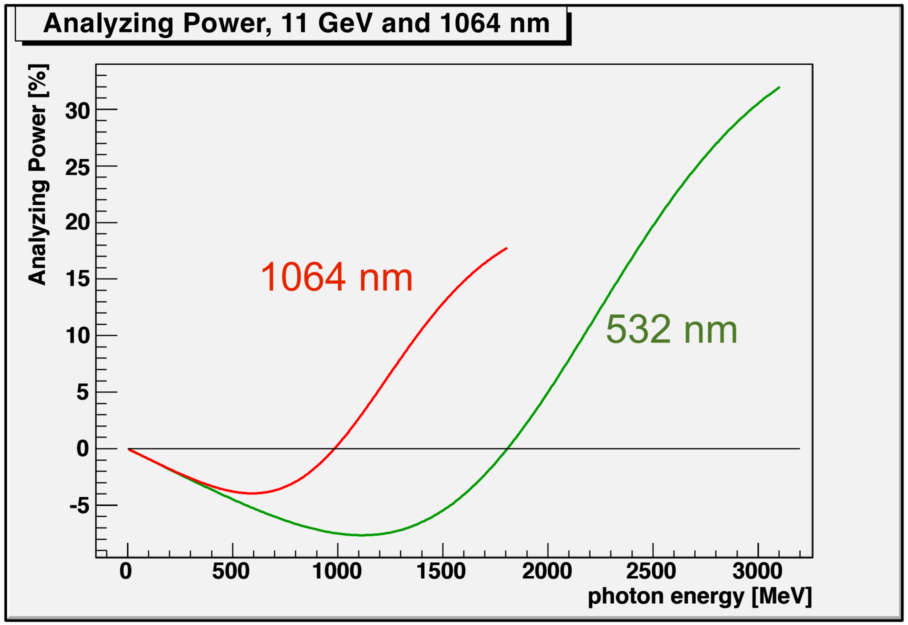
- Maintainable locking electronics
- Intra-cavity Stokes polarimeter
- Improved mechanical design for improved vacuum load stability
- mirror tests (rad damage?)
- design option for larger apertures

Optical Layout



High Power Laser in IR or Green





Laser Power

- Green, 1-2W Injected, 10kW stored
- IR, 5W injection power available...
- for same power, IR has twice γ's as Green

Statistical precision won't be a problem, and backgrounds should be manageable as long as total rate is manageable.

Beam Aperture

Collimators protect optics at small crossing angles... but at the cost of larger backgrounds?

Typical “good” brem rate: ~ 100 Hz/uA
Residual gas should be about 10x less

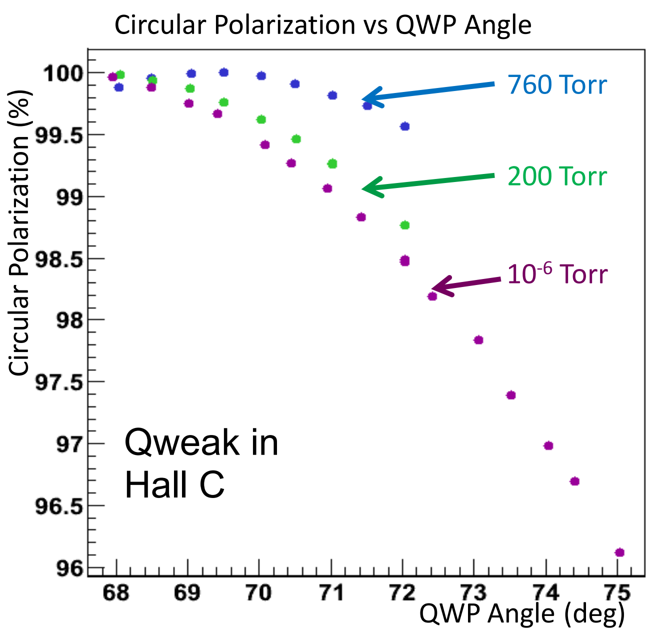
How much larger will the halo and tail be, due to synchrotron blowup?

UPTIME and PRECISION will go up if we use larger apertures (and therefore larger crossing angles), hit in luminosity worth it if backgrounds are an issue.

Determining Laser Polarization

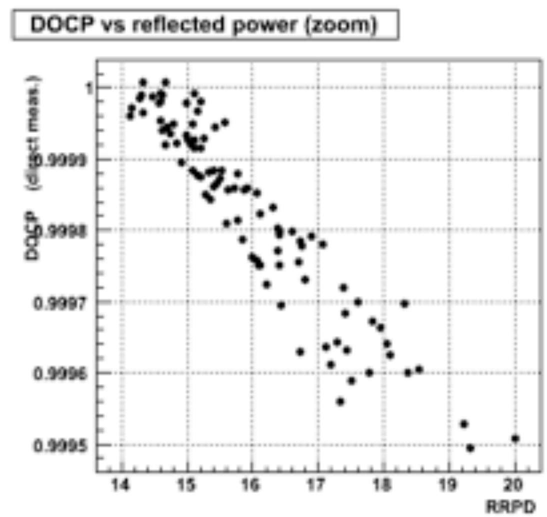
Polarization inside the **cavity** can be monitored using transmitted light or reflected light.

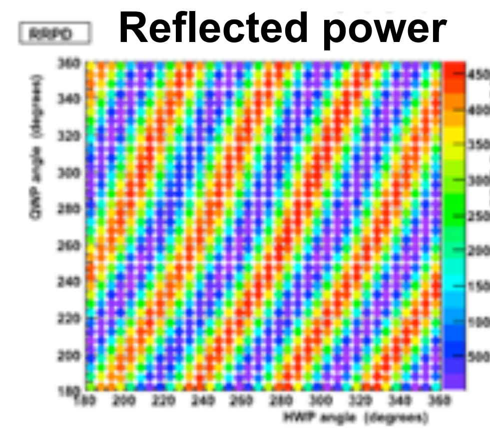
Transfer function translates measured polarization of transmitted light to polarization in the cavity

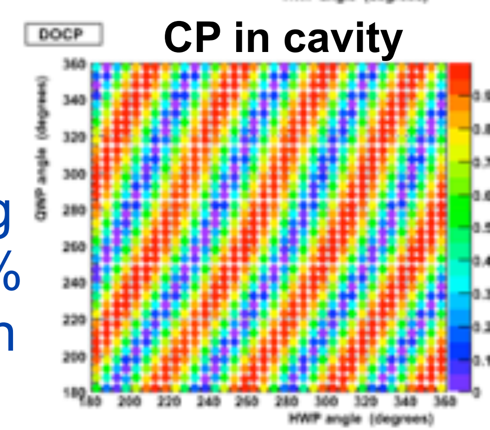


- vacuum stress
- power level (heating)
- alignment variations?

Reversibility Theorem for optical transport, and the phase shift on reflection by the cavity mirror, provides 0.1% level control of DOCP into the cavity





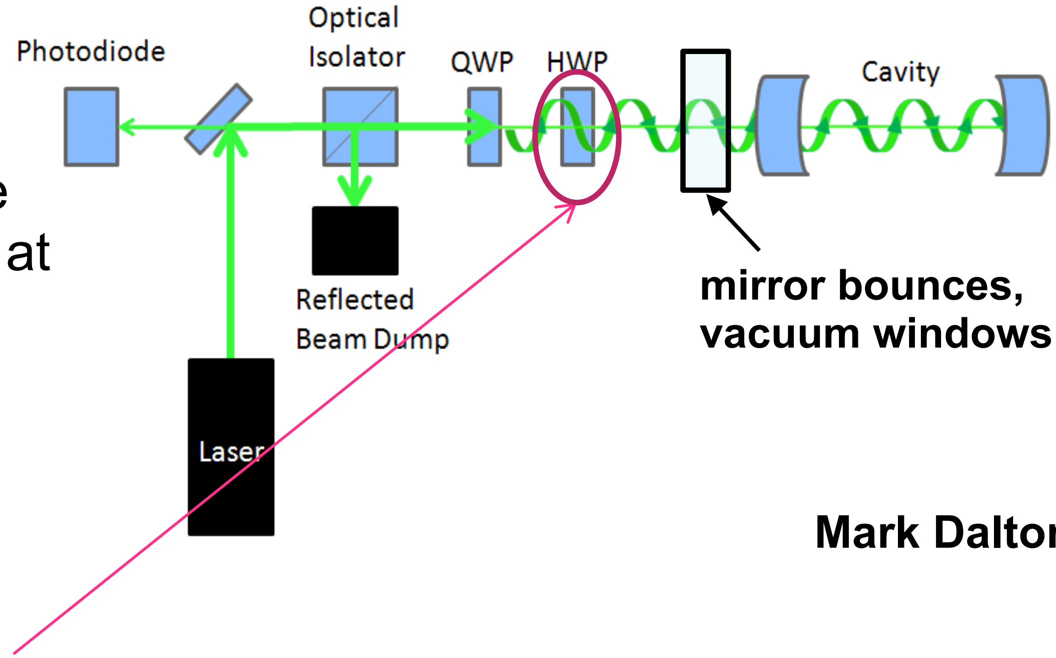


Verified and used during Qweak: will provide 0.2% level knowledge of CP in the cavity

Optical Reversibility Theorem

Beam polarization is used for optical isolation: back-reflected circular light is opposite handedness, and is opposite to initial linear polarization after the QWP

This isolation fails, to the degree that light is not perfectly circular at the reflecting surface.

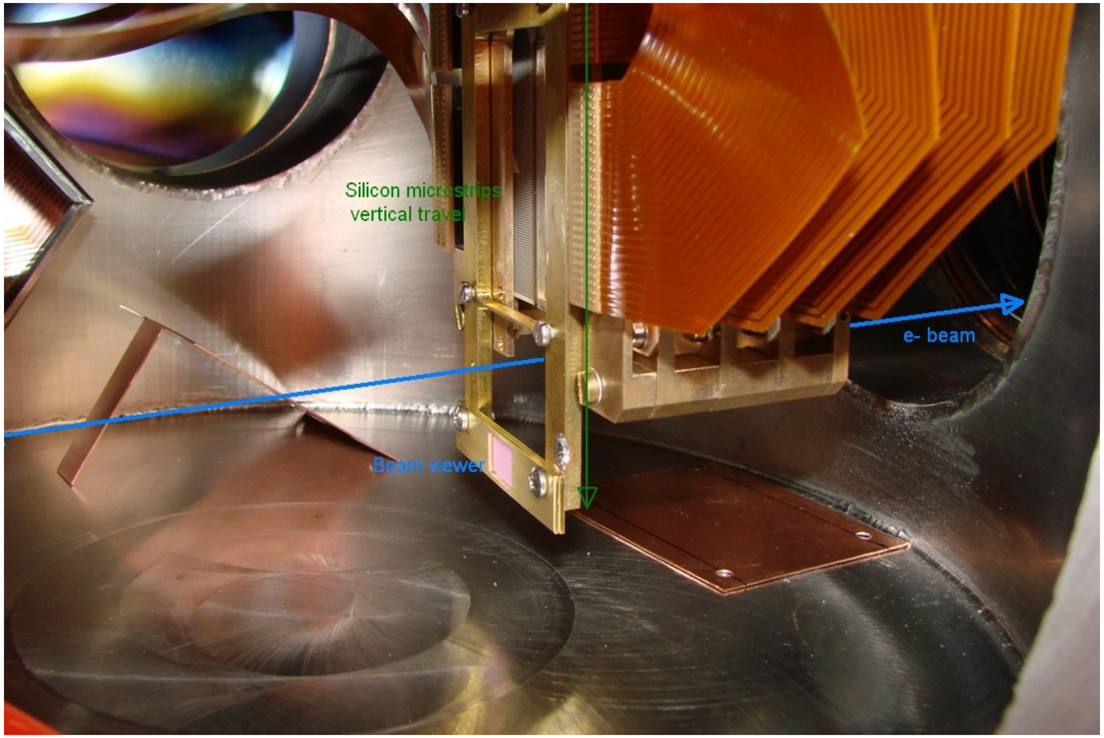


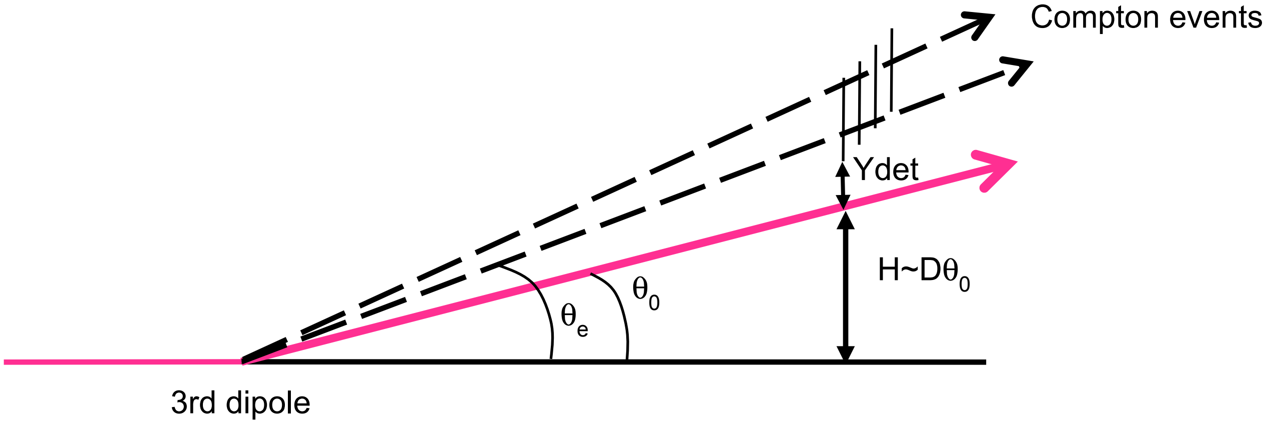
Mark Dalton

This provides a technique to repeatably maximize circular polarization, even in the case of changing intermediary birefringent elements (vacuum or thermal stress, etc.)

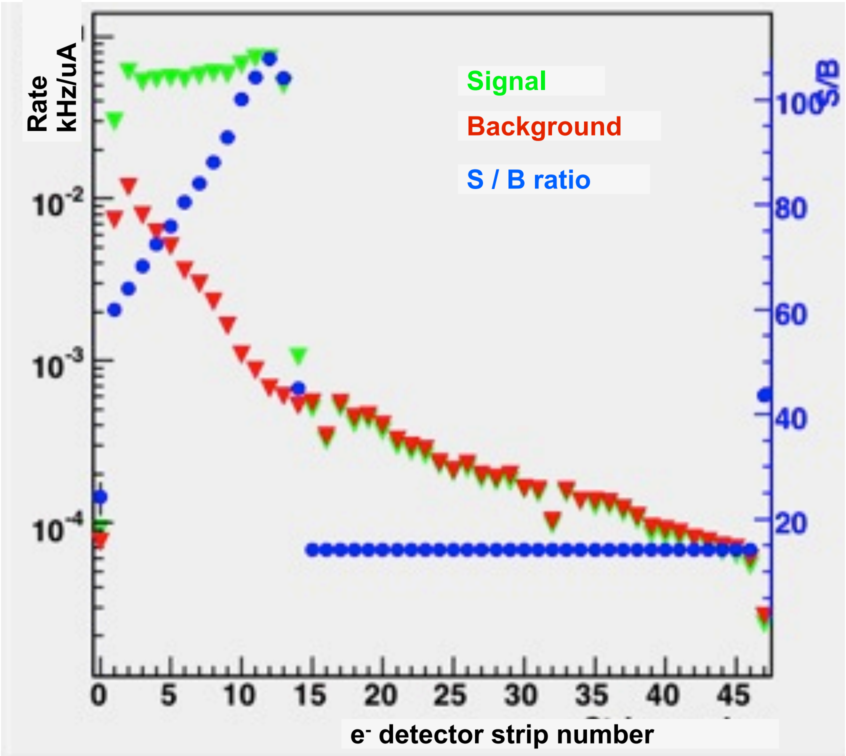
This technique appears in the literature as well, for similar configurations ("Remote control of polarization")

Electron Detector



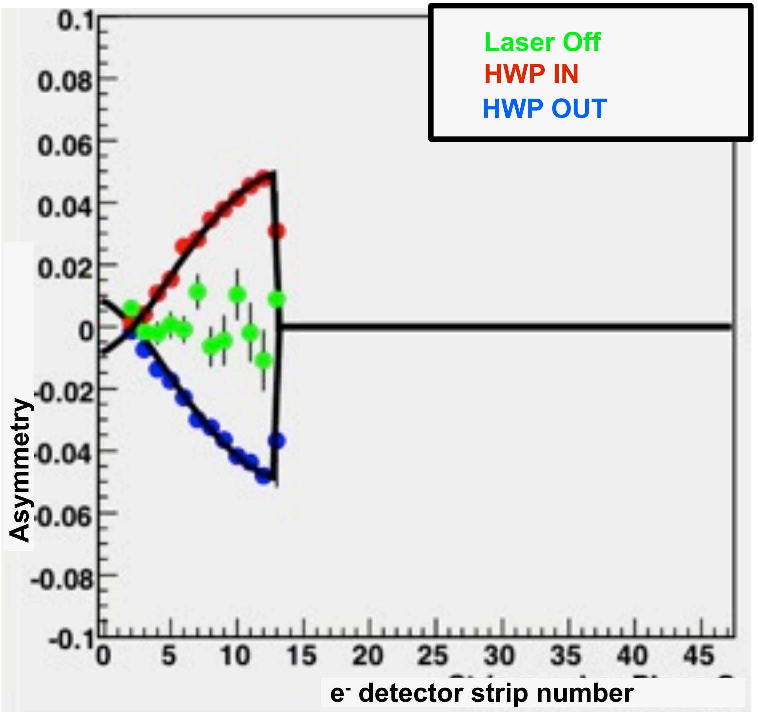


Electron Detector Data

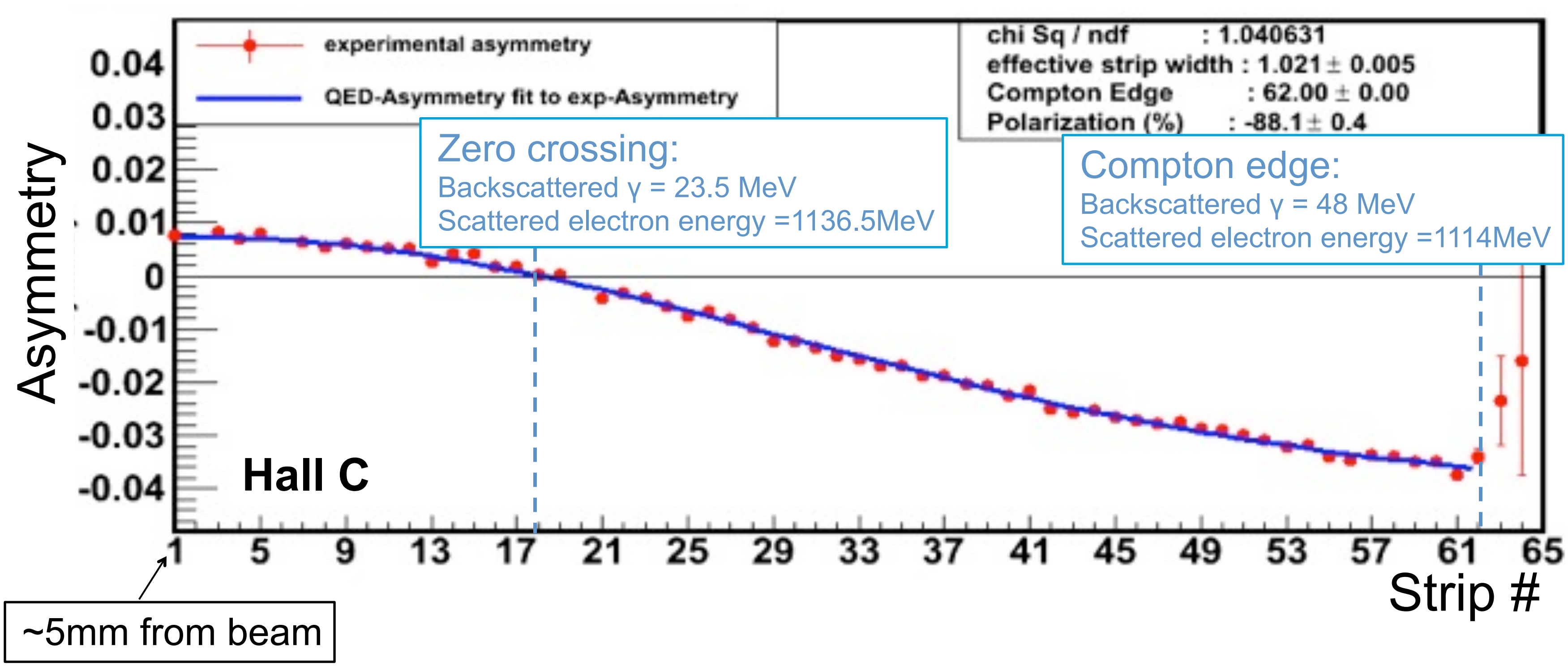


data from HAPPEX-II (2005)
E_{beam}~3 GeV, 45 uA,
P_{cavity} < 1000 W

Background ~ 100 Hz / uA at Y_{det} ~ 5mm



Electron Detector Calibration



Converting strip number to scattered electron energy requires 2 parameters: YDet and Bdl

The Compton edge in the rate spectrum, and the zero crossing in the asymmetry, give two reference points.

Bdl is known independently.
Asymmetry spectrum shape is another important cross-check

Electron analysis at 11 GeV

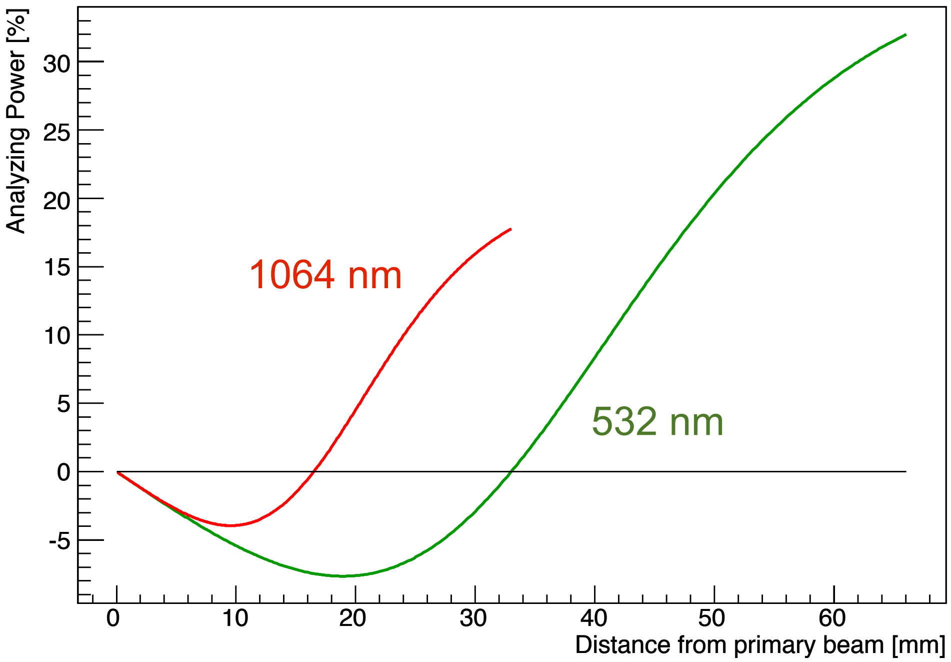
Calibration of energy is typically the leading source systematic error

Analyzing power should be very well known,

- **Asymmetry Fit:** using Compton edge and 0xing to calibrate
- **Edge "single strip"**- a single microstrip, 250 micron pitch, right at the compton edge. (~40 minutes to 0.4%)
- **Minimum single strip**- a single microstrip, at the asymmetry minimum (~1 day to 0.4%)

Other possible complications

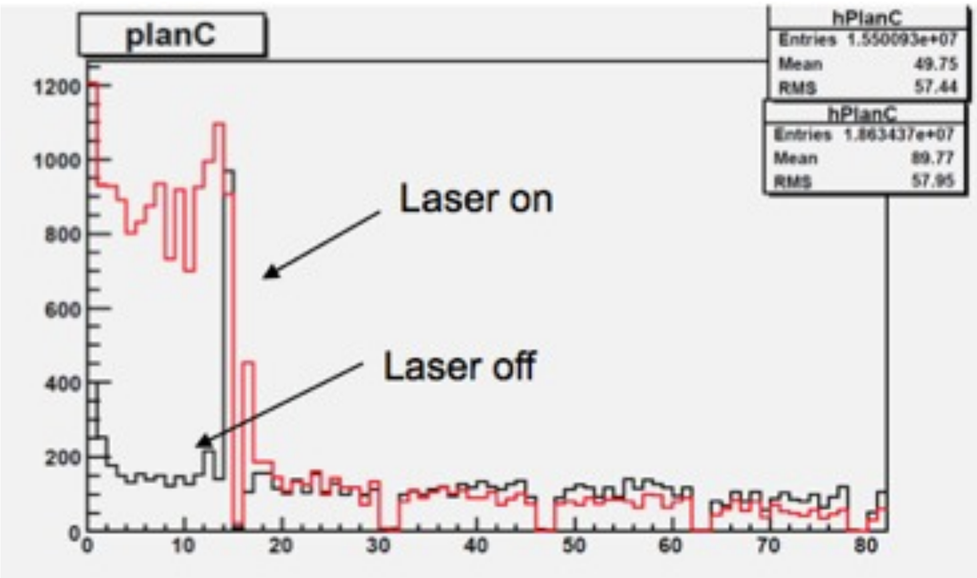
- Compton Edge location
- δ-ray (rescattered Compton e^-)
- Deadtime
- Efficiency,noise vs. trigger



Electron Detector Development

Noise vs. signal, especially in Hall, makes high efficiency hard

Existing Hall A Si strip system



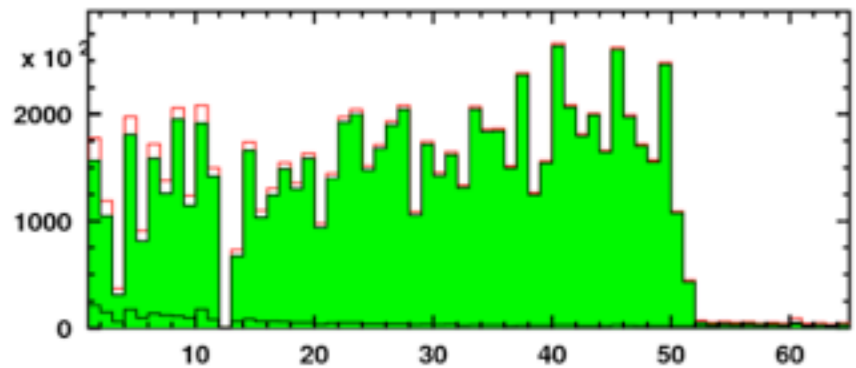
Thicker Si strips with existing electronics? (rescattering from Si substrate is important systematic correction)

New electronics for Si ustrips?

Radiation hardness, synch light sensitivity

Hall C Diamond strips

Rough guess: 65% efficient?



Hall C style diamond strips?

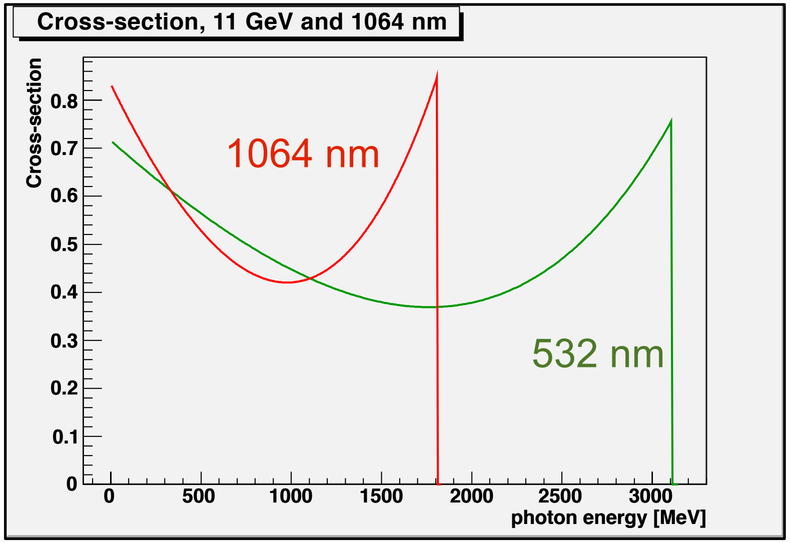
Improved electronics? (compton edge from hit pattern is an important calibration point: high efficiency needed!)

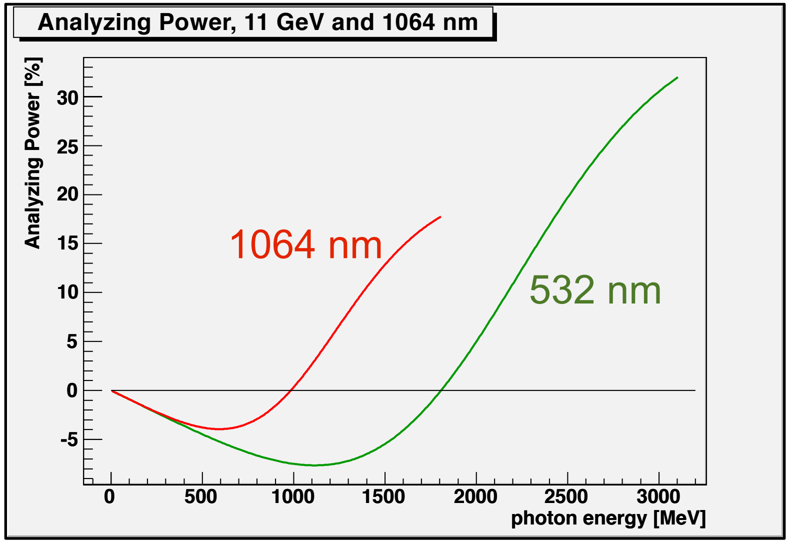
Improved: radiation hardness & synch light sensitivity

Photon analysis

Energy Weighted Integration
Optimal strategy for low energies.
Detector response function uniformity is important

Asymmetry Fit or Averaging, with Threshold.
calibration of response function with tagged photons



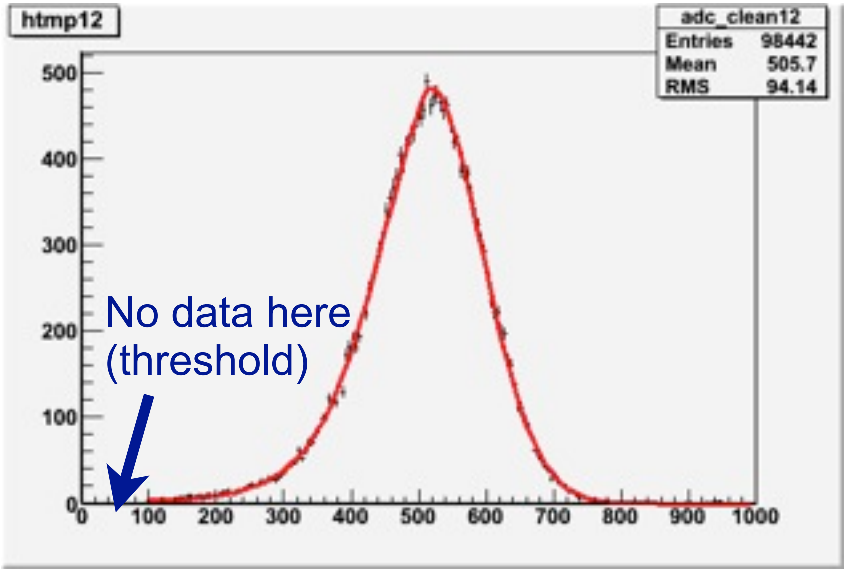


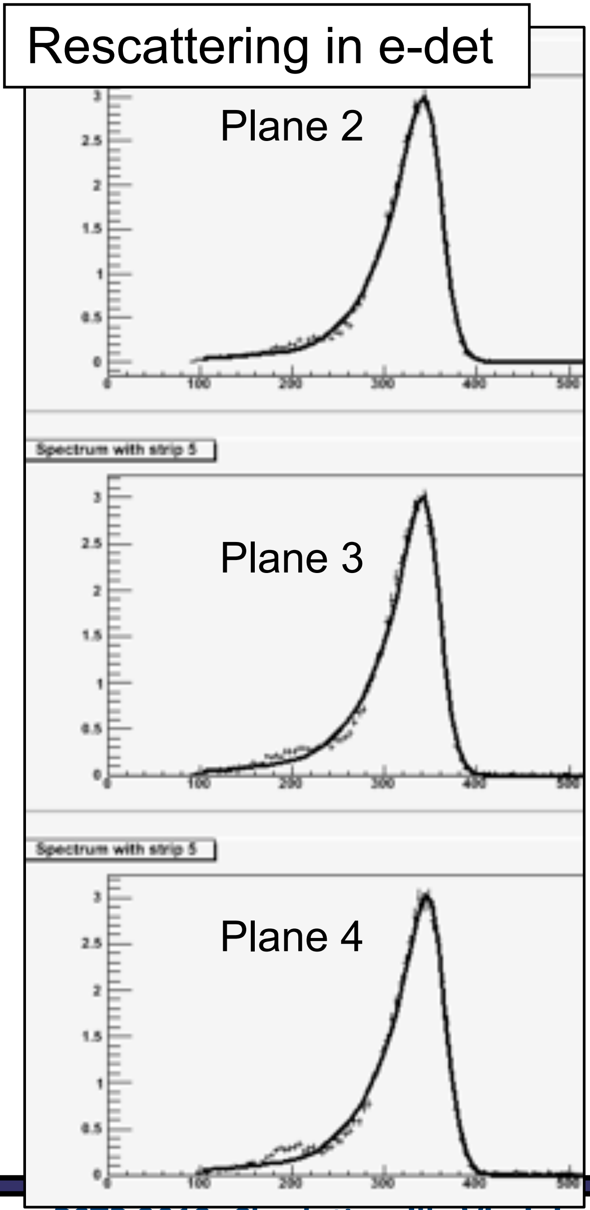
Detector Response Function -

- Resolution is less important for integrating technique.
  - Helps for e-det coincidence cross-calibration.
- Linearity is crucial in any case
  - large dynamic range in both average and peak current
- PMT and readout require care
- Effect of shielding on asymmetry spectrum

Photon Detector

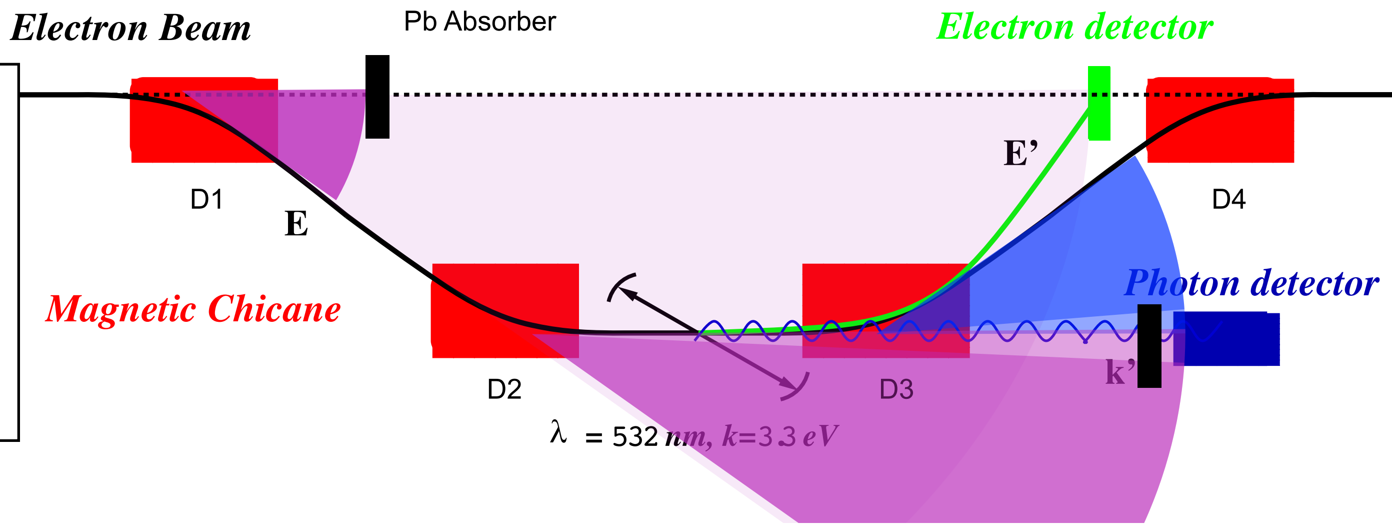
Response function of the γ detector using e^- det. as an energy tagger



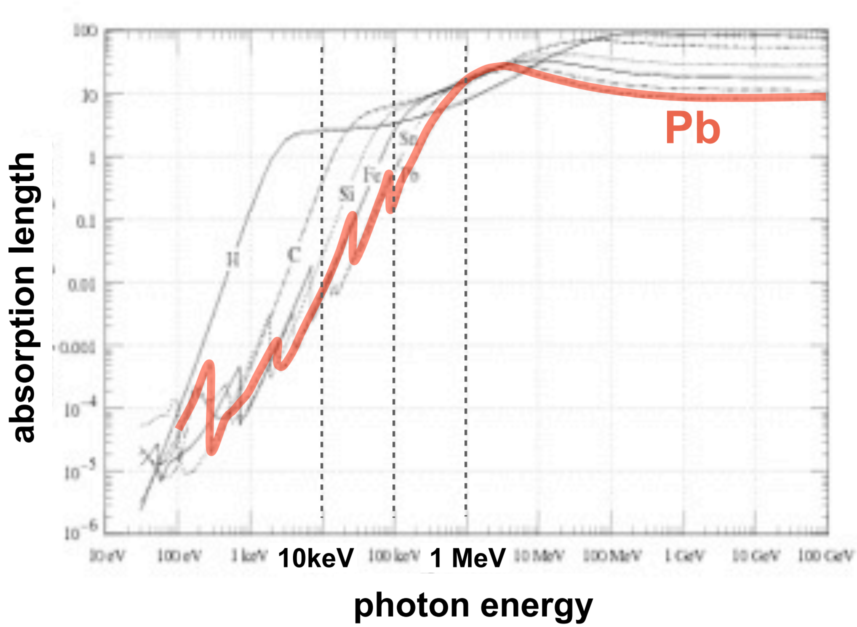


- Electron photon coincidence
- low-rate trigger (prescaled), high resolution
- Photon discriminator threshold and minimum e^- detector approach leaves some portion of this unmeasured.... ~1% uncertainty unless controlled via Monte Carlo

Synchrotron Radiation



Synchrotron radiation will carry an order of magnitude more power than present 6 GeV running



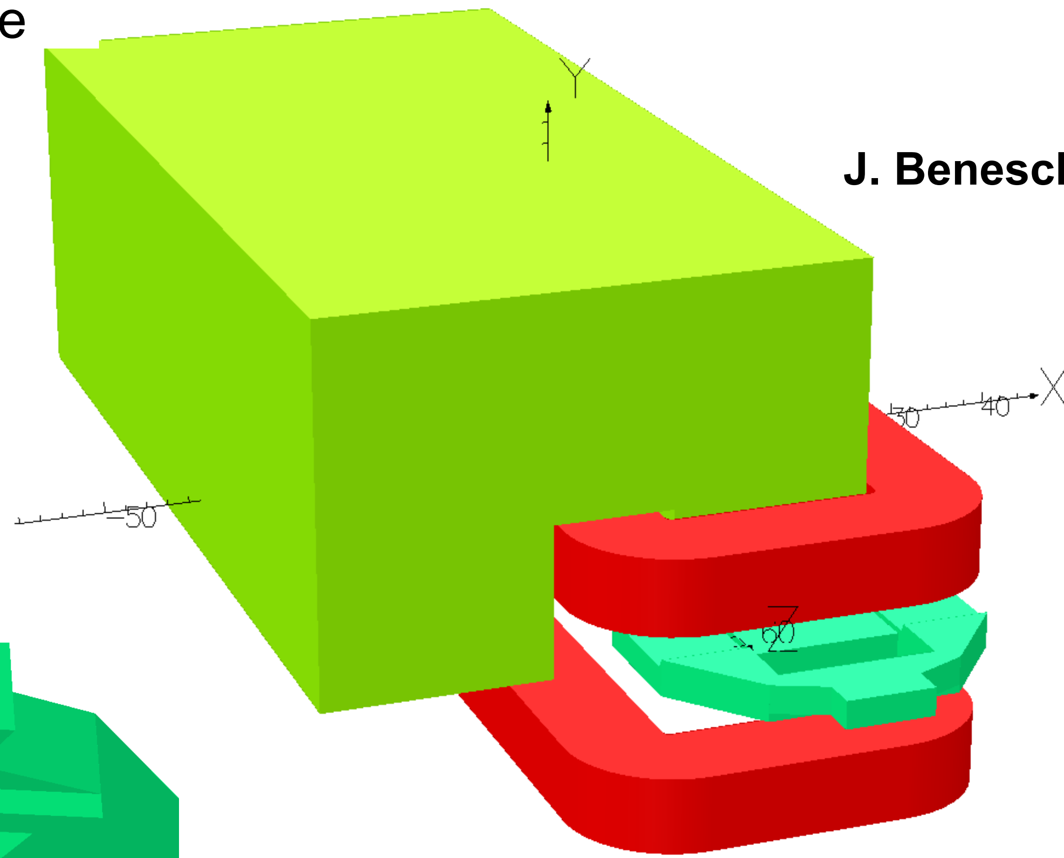
SR intensity and hardness can be reduced with D2, D3 fringe field extensions

- Excessive SR power overwhelms Compton signal and may increase noise
- SR is blocked by *collimator* (1mrad) to photon detector, except for portion most aligned to interaction region trajectory
- *Shielding* helps, but distorts Compton spectrum, forcing larger corrections to analyzing power

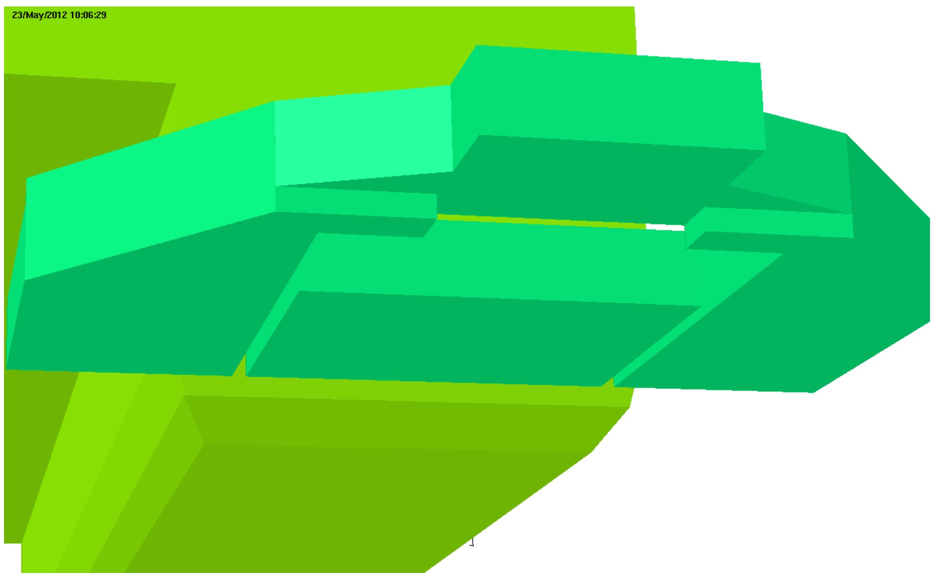
Modeling the Dipoles

Bolt-on shims, no cutting of iron yoke or modification of beamline

All 4 dipoles will be shimmed in this way, to improve operability



J. Benesch

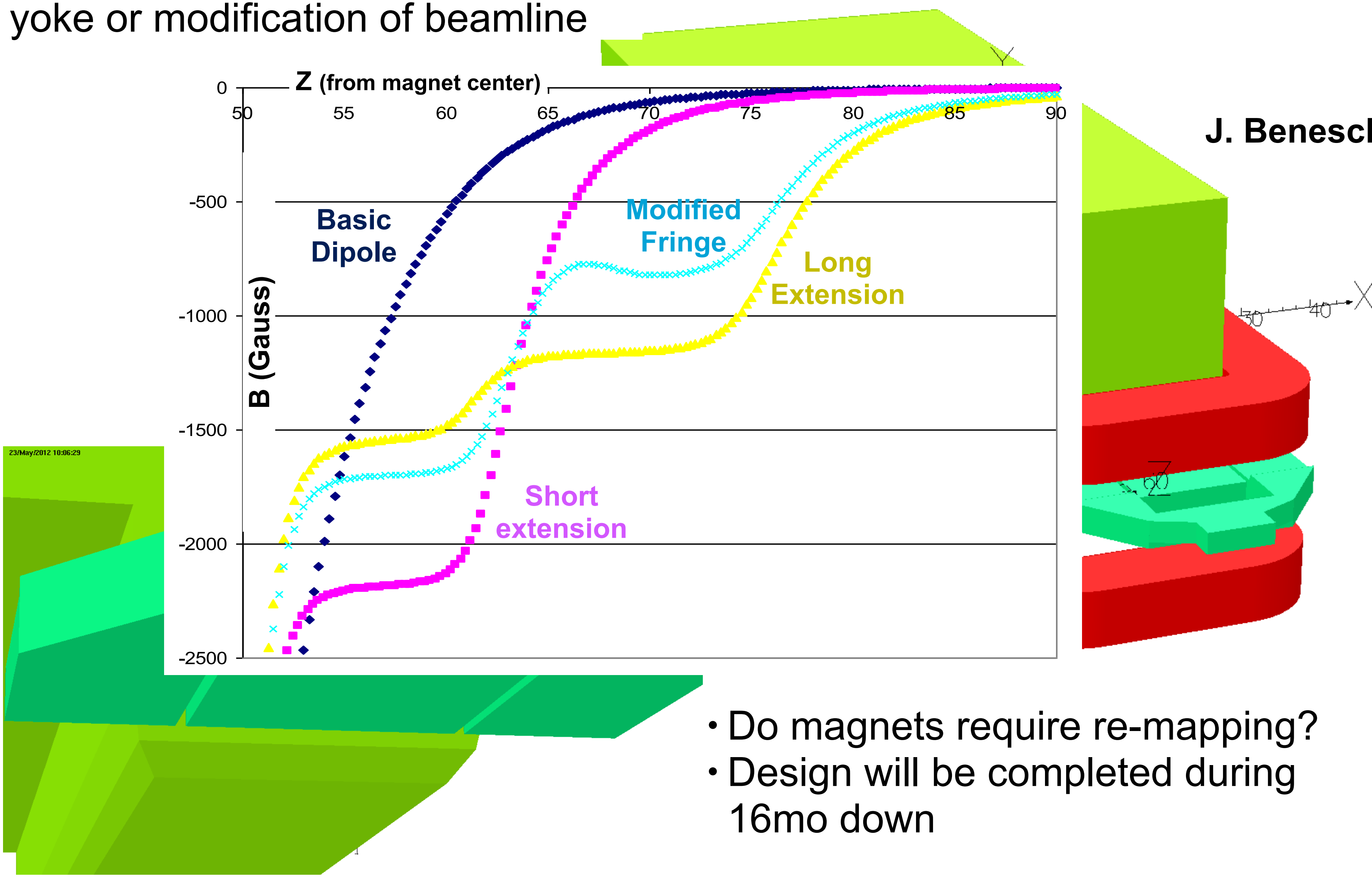


- Do magnets require re-mapping (planned during Fall 2012)
- Parts fabricated and will be installed

Modeling the Dipoles

Bolt-on shims, no cutting of iron yoke or modification of beamline

J. Benesch



- Do magnets require re-mapping?
- Design will be completed during 16mo down

Modeling the Dipoles

Bolt-on shims, no cutting of iron yoke or modification of beamline

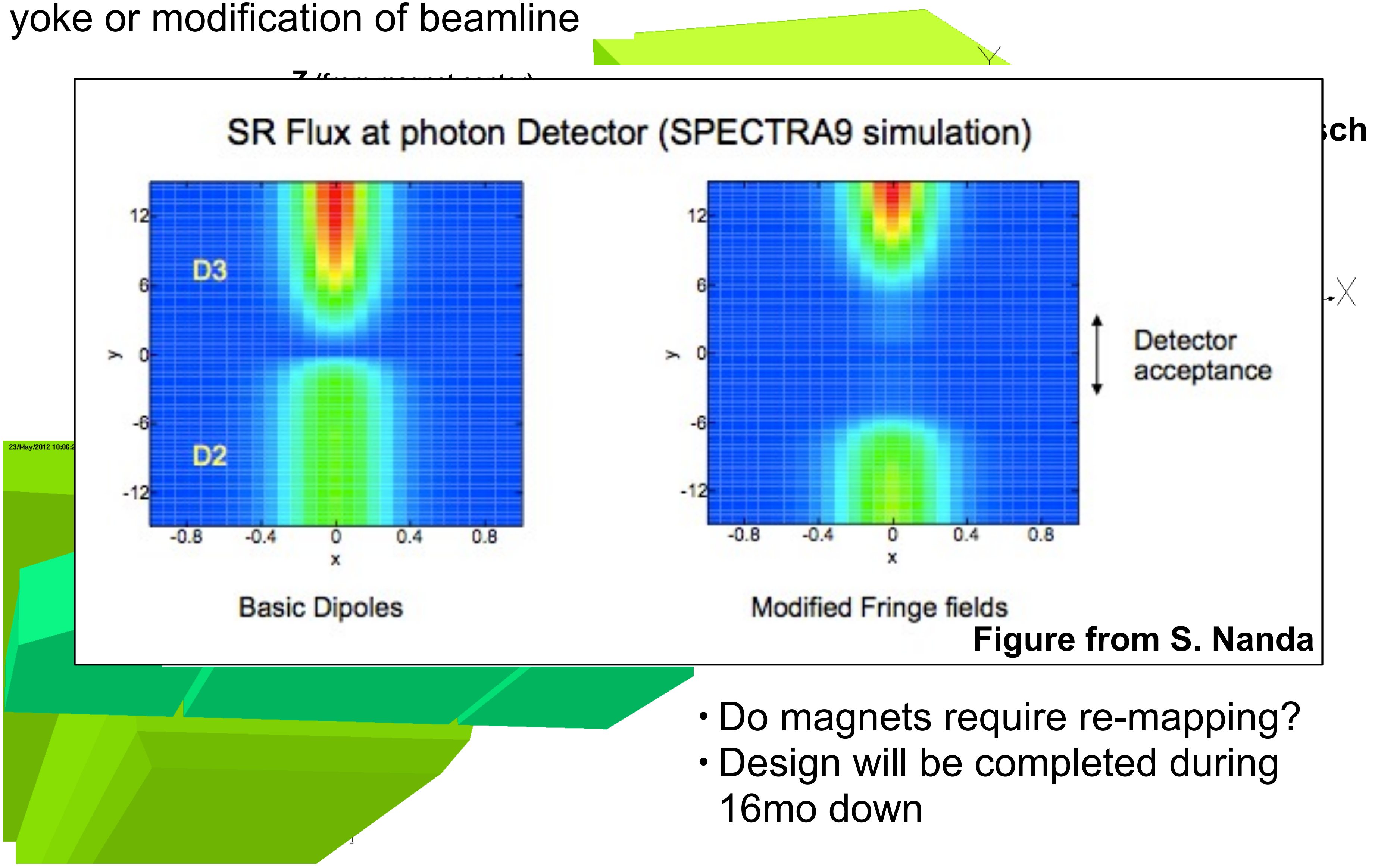
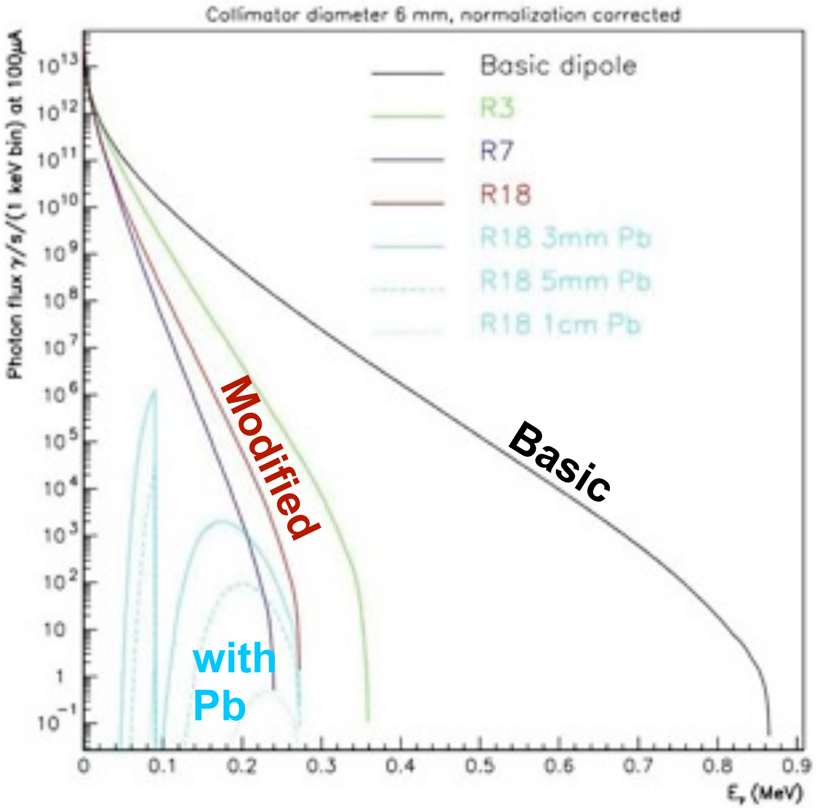
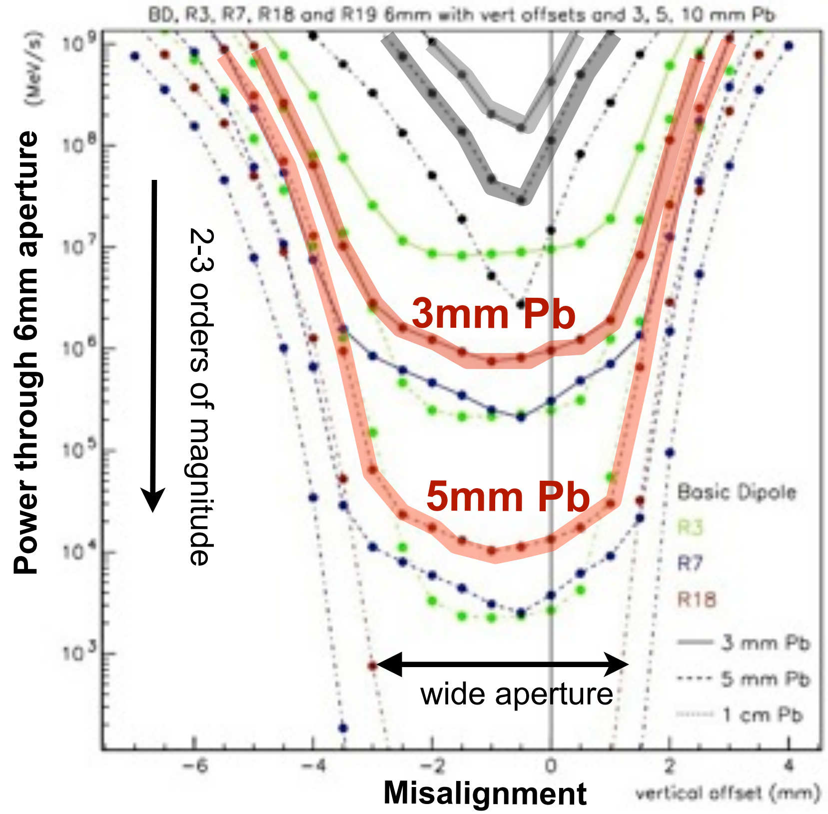


Figure from S. Nanda

- Do magnets require re-mapping?
- Design will be completed during 16mo down

Reduced SR power, robust operation





Benesch, Quinn (CMU)

All 4 dipoles will be shimmed in this way, to improve operability

	3mm Pb	5mm Pb
Basic Dipole	450 TeV/s	120 TeV/s
Modified Dipole	1 TeV/s	0.01 TeV/s
Compton Signal	860 TeV/s	860 TeV/s

High Precision Goals

Relative Error (%)	electron	photon
Position Asymmetries	-	-
E_{beam} and λ_{laser}	0.03	0.03
Radiative Corrections	0.05	0.05
Laser Polarization	0.20	0.20
Background/Deadtime/Pileup	0.20	0.20
Analyzing Power Calibration / Detector Linearity	0.25	0.35
Total	0.38	0.45

correlated

uncorrelated

Independent detection of photons and electrons provides **two (nearly) independent polarization measurements**; **each should be better than 0.5%**

What's been achieved: ~1% (HAPPEX-3, PREX, Qweak)

Challenges:
- Laser Polarization ✓
- Synchrotron Light ✓
- Calibration
- Signal / Background

more

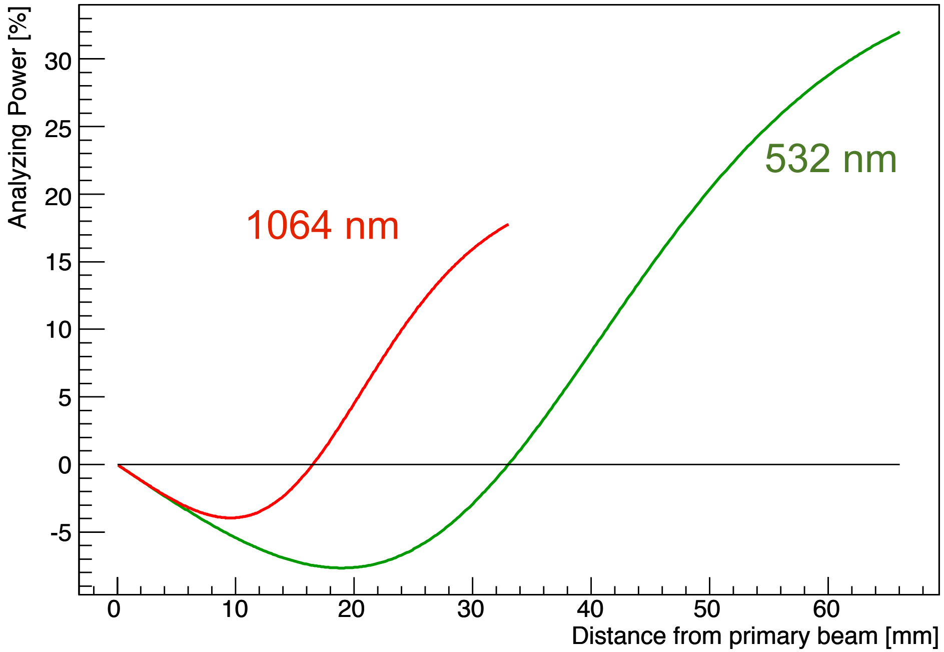
Electron analysis at 11 GeV

- **Edge "single strip"**- a single microstrip, 240 micron pitch, right at the compton edge.

  (~900Hz, A = 17.8%, ~40 minutes to 0.4% stat, with 0.35% calibration error from 125micron uncertainty in CEdge)

- **Minimum single strip**- a single microstrip, at the asymmetry minimum

  (~540Hz, A = -3.95%, ~1 day to 0.4% stat, with 0.35% calibration error from 0.5mm uncertainty in minimum point)

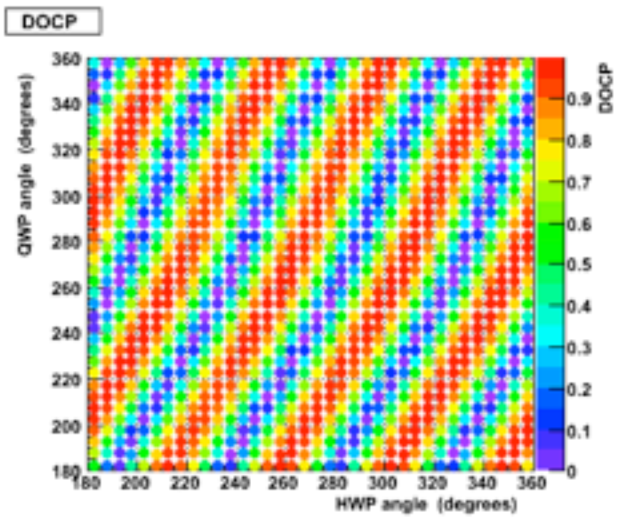


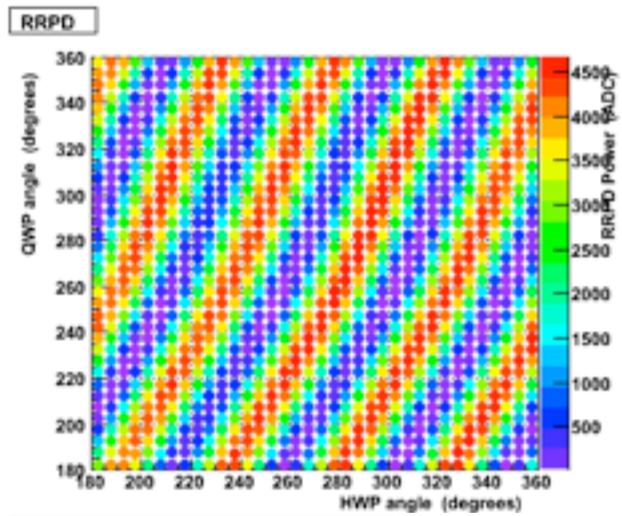
Direct Test of Optimizing Circular

Measurements while scanning over initial polarization set by QWP and HWP.

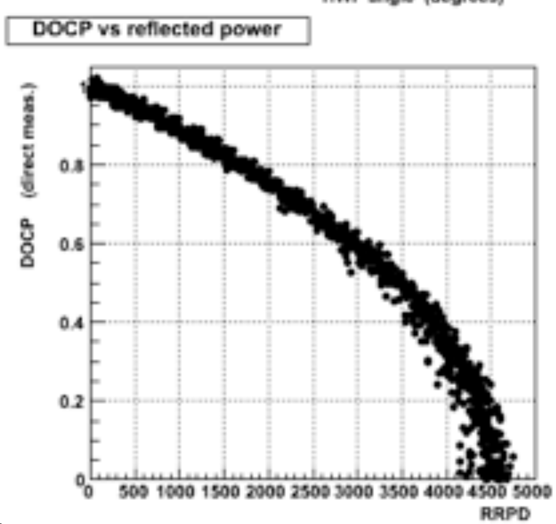
DoCP in (open) cavity

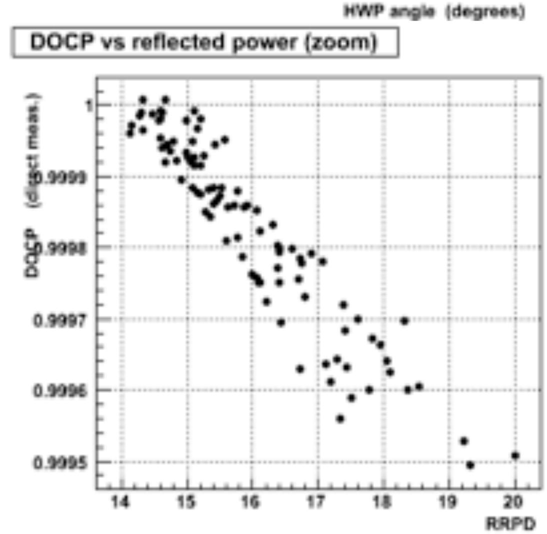
Return power (through isolator)





Excellent agreement

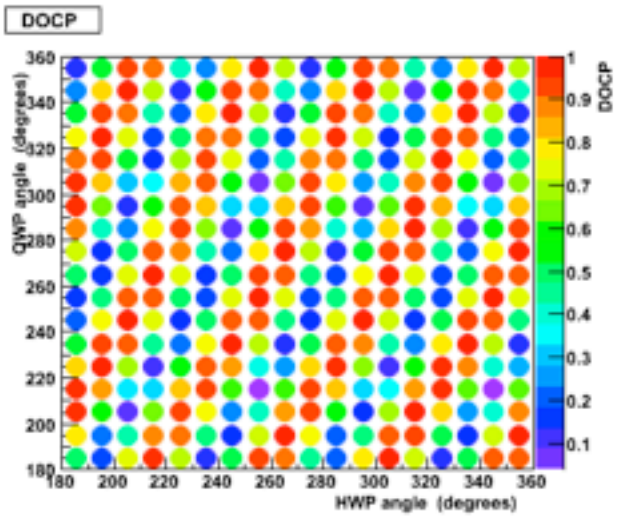


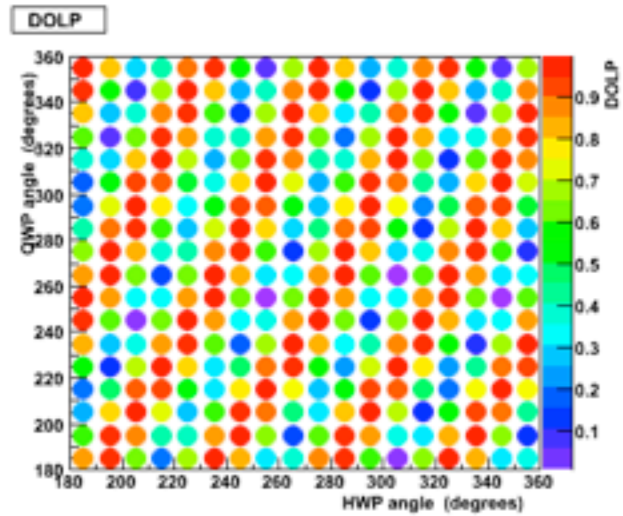


If minimizing return power, maximizing DoCP at 99.9%+*

Fitting Entrance Function

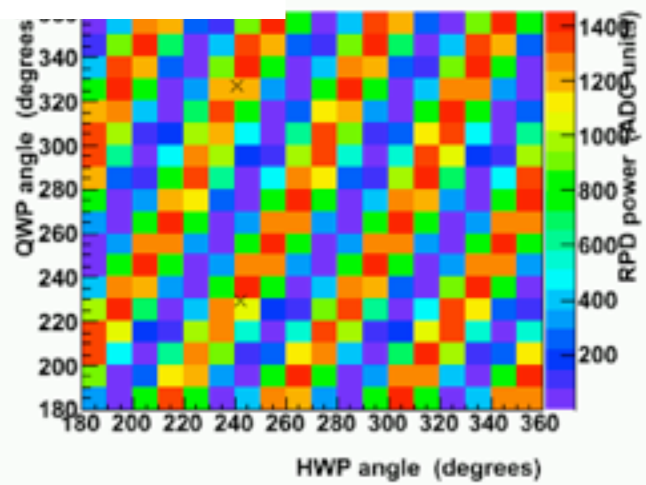
Measurements while scanning over initial polarization set by QWP and HWP.



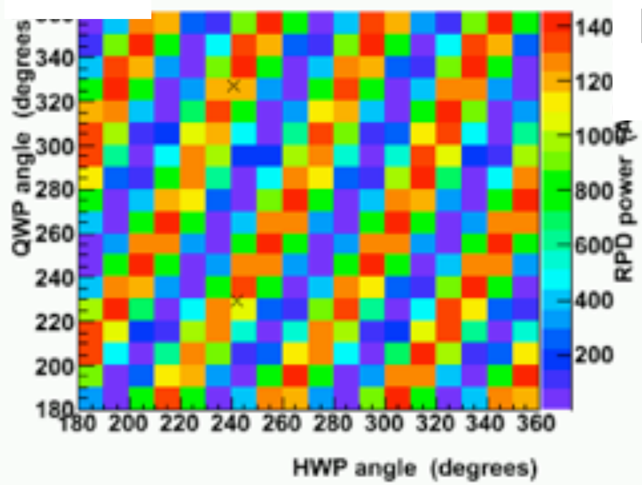


DoCP in (open) cavity

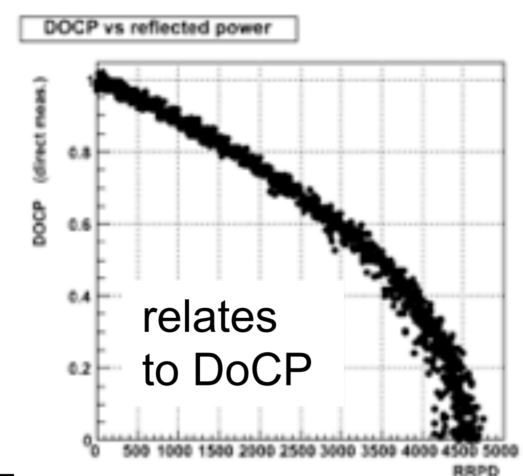
Measured



Fit



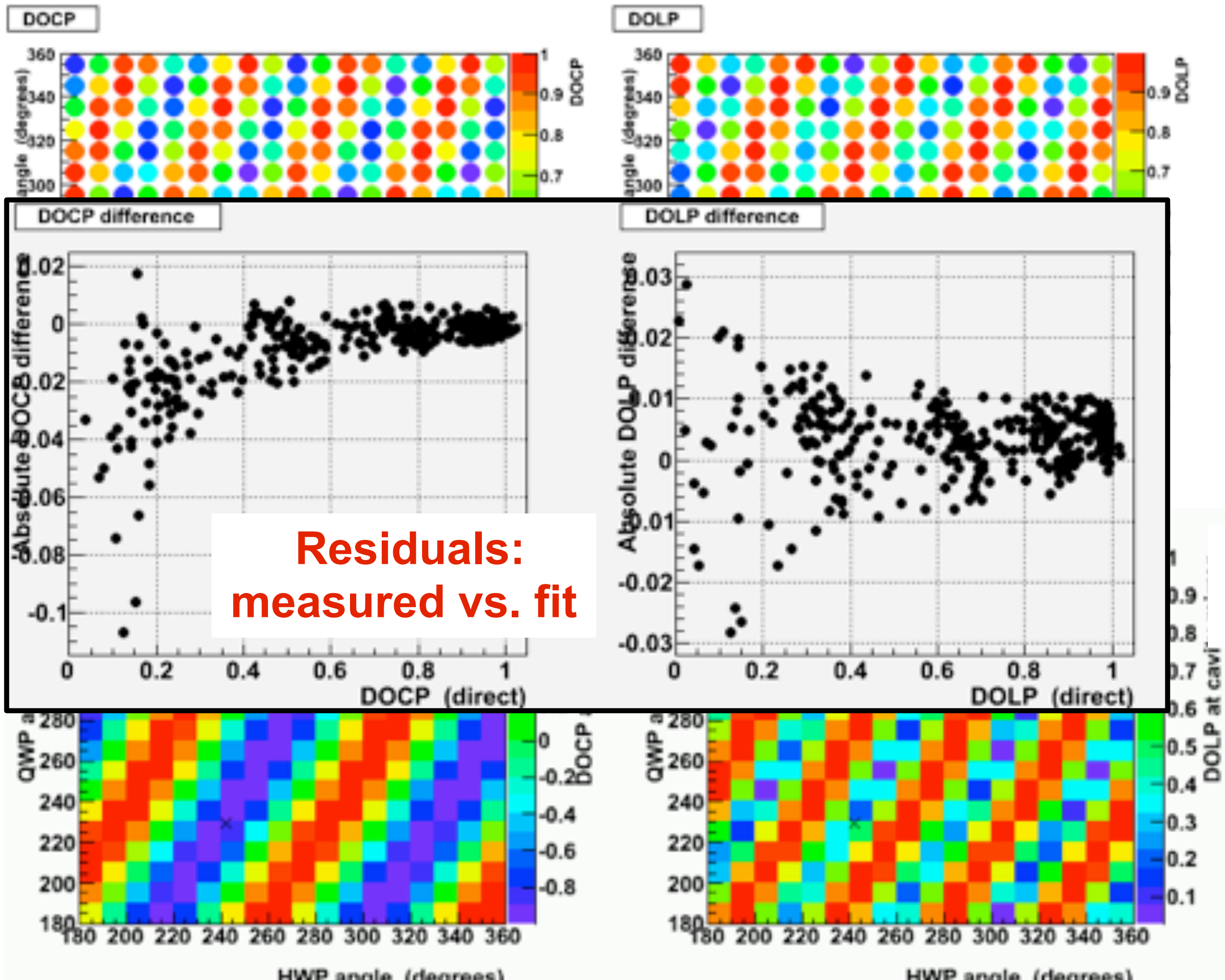
Return power, then **fit to (simple) optical model**



relates to DoCP

Fitting Entrance Function

Measurements while scanning over initial polarization set by QWP and HWP.



DoCP in (open) cavity

DoCP from fit to (simple) optical model

Measurement at 0.1% level in DoCP from external measurements

Alternative: RF Pulsed Laser

RF pulsed laser, at 499 MHz (or close subharmonic)

High duty factor: still single-photon/electron mode

Such a laser is feasible:

- commercial IR 100MHz, 10ps at 45 W

RF IR Pulsed "1-pass":

- 350 Hz/μA
- Fast on/off improves background subtraction

No cavity mirrors: does the "single-shot" laser path reduce uncertainty in the laser polarization measurement?

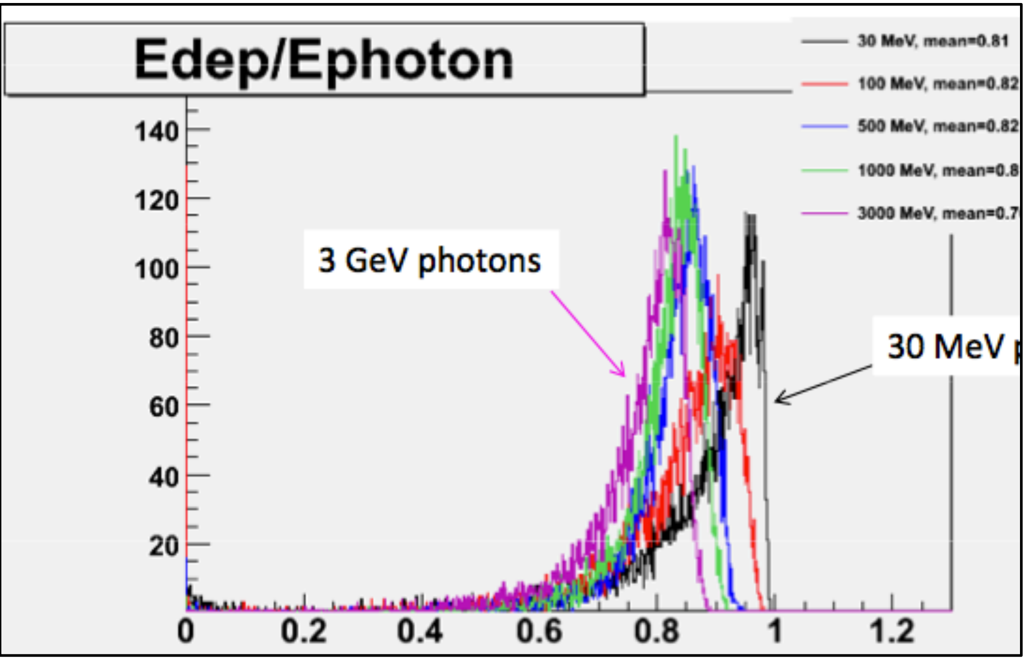
RF IR Pulsed cavity:

- proof of concept exists
- low gain = fairly robust
- statistical power matches CW cavity

New Problem: time-dependent polarization shift in 10ps pulse?

Given the progress on controlling laser polarization and the high power of the existing system, we do not expect (at this time) to pursue a pulsed laser option.

GSO Photon Detector



Existing detector:

GSO scintillating crystal,
15cm long, 6cm diameter
~60ns, ~150 photoelectron/MeV

Large GSO detector would be $$$

Something larger needed to contain showers at high energy, (maybe 6”x6”x15”)

Lead tungstate? Other scintillating or Cerenkov detector? Options exist: simulation and tests needed.