e2ePV Toroidal Conceptual Design

+ miscellaneous experimental considerations

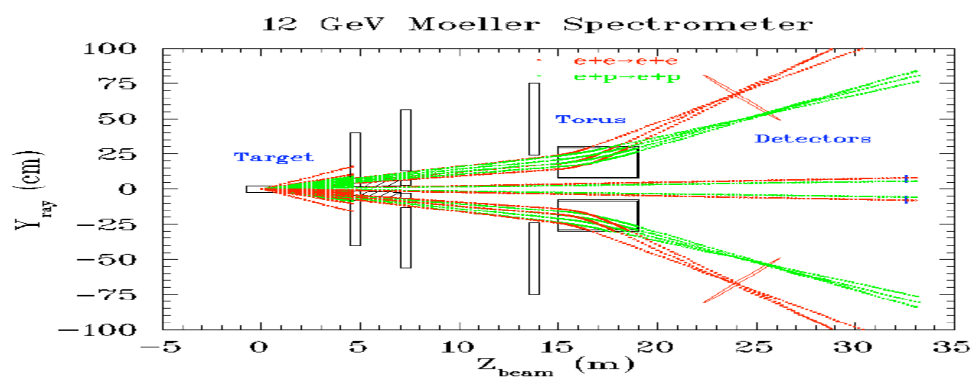
Dave Mack (TJNAF)
Moeller Workshop
December 12, 2006

When is Apv too small?

The nominal acceptance

oroidal Concept

isc. subsystems



Motivation

- $\sin^2\theta_W$ measurement

  Or
- New physics search

- It's impossible to predict the context an improved Moeller experiment would occupy in the year 2012+. We'll certainly know more about $\sin^2\theta_W$, but we should expect at least one revolution in particle physics before then.

- In most scenarios, an improved Moeller measurement will be **extremely** interesting.

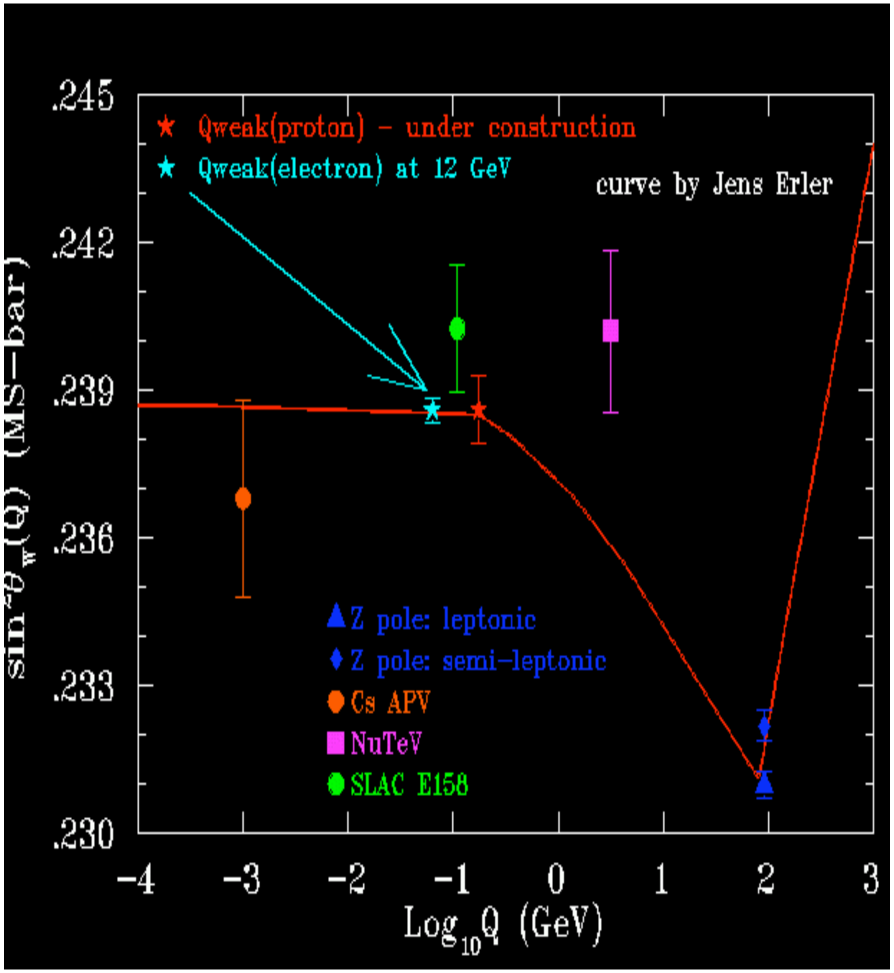


Figure of Merit for Comparing Experiments

The FOM for an e+e→e+e experiment is somewhat unique:

- The PV asymmetry is proportional to E
- The CM cross section is proportional to 1/E
- For fixed target length and CM acceptance, the statistical error is proportional to 1/sqrt(FOM) where

$$\mathbf{FOM = A^2 \times \sigma \times I_{beam} \times time,}$$

which is proportional to E x I_{beam} x time or **integrated beam power**.

Maximum extracted CW beam power is limited at SLAC and JLab to 1-2 MW by accelerator hardware limitations and electrical costs.

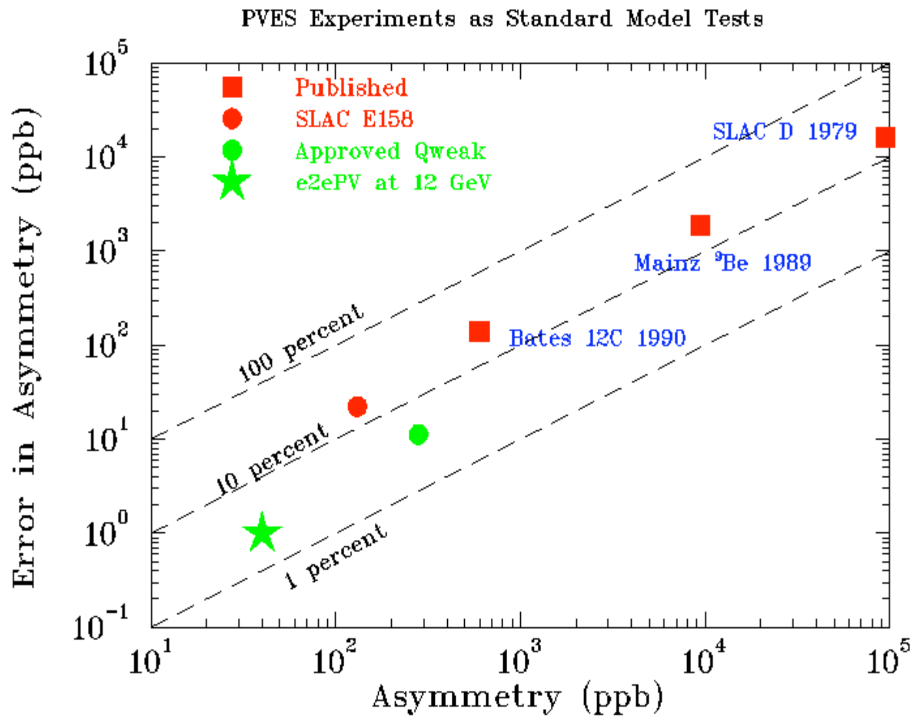
SLAC investment in E158 was 0.07 MWatt Years.
JLab e2ePV investment would be about 0.5 MWatt Years.

If statistical errors were the only consideration, JLab's SRF cavities make it the natural place to run a Moeller experiment.

How Small is Too Small?

The PV asymmetry decreases by x4 from 48 GeV to 12 GeV.

How small an asymmetry is TOO SMALL???



Assuming the required statistics, and that backgrounds are proportionate, then we need to look at

- false asymmetries due to beam properties
- electronic and target noise sources
- nonlinearities

Sensitivities

Jim Birchall preliminary:
Target+collimator, no magnet

Cause of error	Condition for $\varepsilon < 10^{-9}$	Example
Position modulation $x^{\pm} = x_0 \pm \delta x$	$x_0 \delta x < 3.1\times10^{-9}$ cm^2	$\delta x = 20$ nm $x_0 = 16\ \mu$m
Beam breathing $r^{\pm} = r_0 \pm \delta r$	$r_0 \delta r < 6.3\times10^{-9}$ cm^2	$r_0 = 75\ \mu$m $\delta r = 8$ nm
Angle modulation $\theta^{\pm} = \theta_0 \pm \delta\theta$	$\theta_0 \delta\theta < 5\times10^{-11}$ deg^2	$\theta_0 = 60\ \mu$rad $\delta\theta = 0.3$ nrad
Energy modulation $E^{\pm} = E_0 \pm \delta E$	$\delta E < 22$ eV	$\delta E < 22$ eV

Requires	Difficulty	Caveats
δx=2 nm X_0= 160 μm	**ok**	**alignment**
δr=8 nm	**difficult**	
δx=3 nm over 10m	**ok**	**alignment**
Δx=10?nm at 1C12	**easy**	**?**

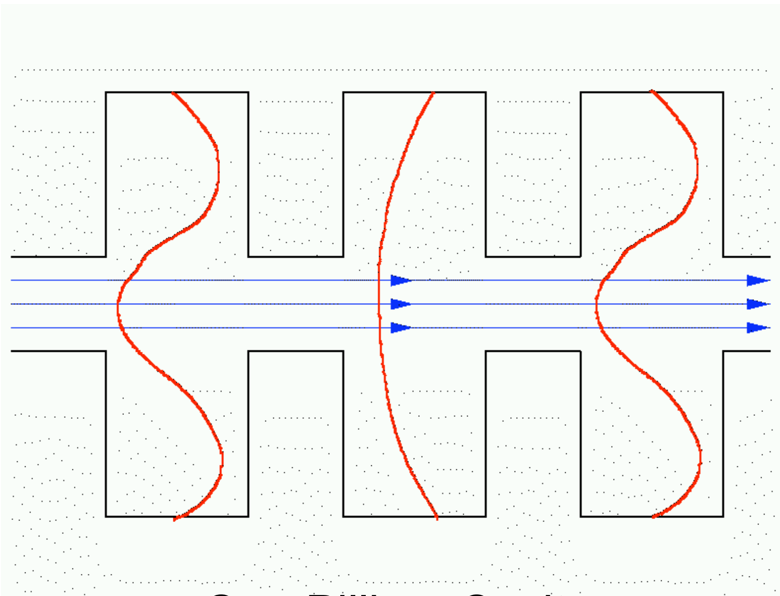
Beam spot size modulation appears to be the weakest link.

The 8 nm here is **much** smaller than Qweak's requirement of 400 nm.

Proposed Beam Spot Size Monitor

Mack and Wissman,
Qweak 541-v1

Two rectangular Cavities
TM310 and TM130



One Pillbox Cavity

TM010

After normalizing the $\langle x^2 \rangle$ and $\langle y^2 \rangle$ cavity outputs with the I cavity, an asymmetry is formed to subtract the offset:

$$A_{310} \equiv \frac{\mathbf{V}^{+}_{\mathbf{310}} - \mathbf{V}^{-}_{\mathbf{310}}}{\mathbf{V}^{+}_{\mathbf{310}} + \mathbf{V}^{-}_{\mathbf{310}}}$$

The result measures beam width differences, but position regressions can be relatively large if cavity is not centered.

$$A_{310} = -\frac{3}{8}\left(\frac{\pi}{a}\right)^2 w_0 \Delta w - \frac{9}{8}\left(\frac{\pi}{a}\right)^2 x_0 \Delta x$$

X_0 <1 mm for Qweak, <100 microns for e2ePV?

Nonlinearities

Nonlinearities – Unknown

The sensitivity to beam spot size is already an example of a nonlinearity since it depends on $\Delta\langle x^2\rangle$ rather than $\Delta\langle x\rangle$. In this case the nonlinearity is due to cross-section and $\Delta\Omega$ effects.

(It would probably be worse including target response.)

Most of these effects probably cancel with the $\lambda/2$ plate in principle, but present experiments wait far longer than the time scale for significant changes in the beam spectrum.

(Is it practical to make the slow reversal faster?)

Needs more study. Eg, there are no JLab bounds on $\Delta\langle I^2\rangle$, but it may be easy to measure with a power meter.

Target Noise

Target Noise – Unknown

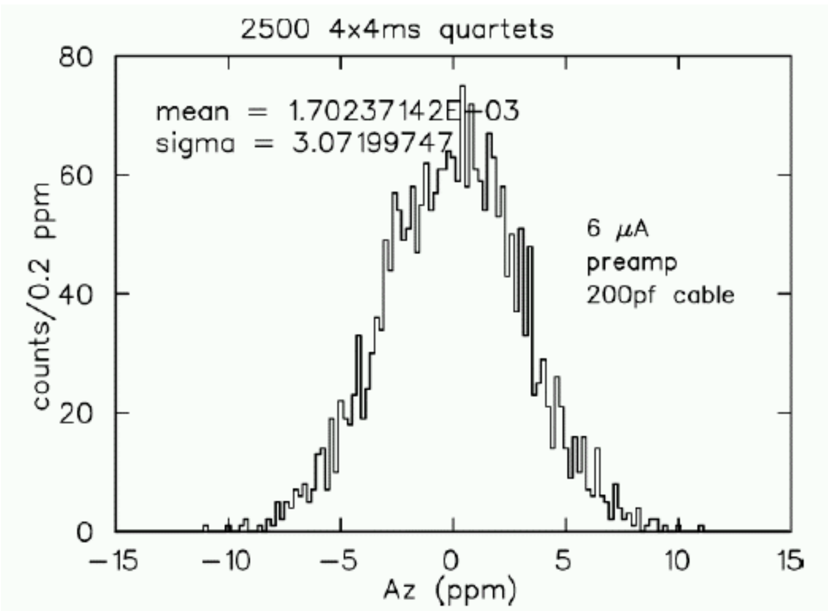
Need results from Qweak target.

Excess noise potentially addressable by

- Normalizing to a small angle luminosity monitor. (Don't want to go there. Regressions could bite.)
- Increasing the reversal frequency

Electronic Noise

Des Ramsay



At 300 Hz reversal, Moeller electron shot noise is only 23 ppm/pair.

TRIUMF low-noise (I-to-V) preamplifiers and digital integrators have measured noise at few ppm level.

A battery test is expected to yield about 5 ppm.

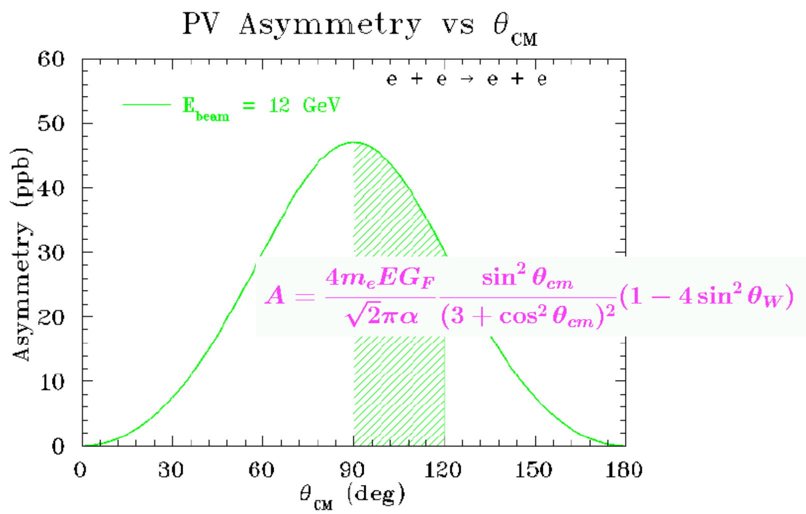
Good enough?

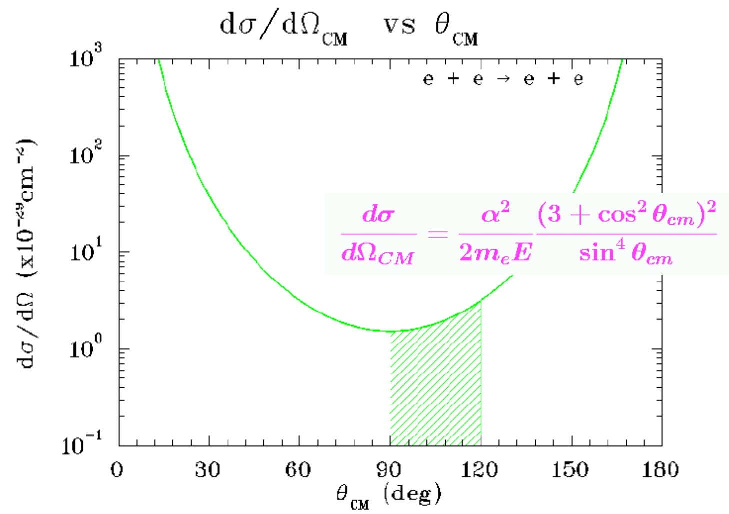
Helicity pickup of direct helicity reversal signal can be tested with battery sources at a level far below the e2e statistical error bar.

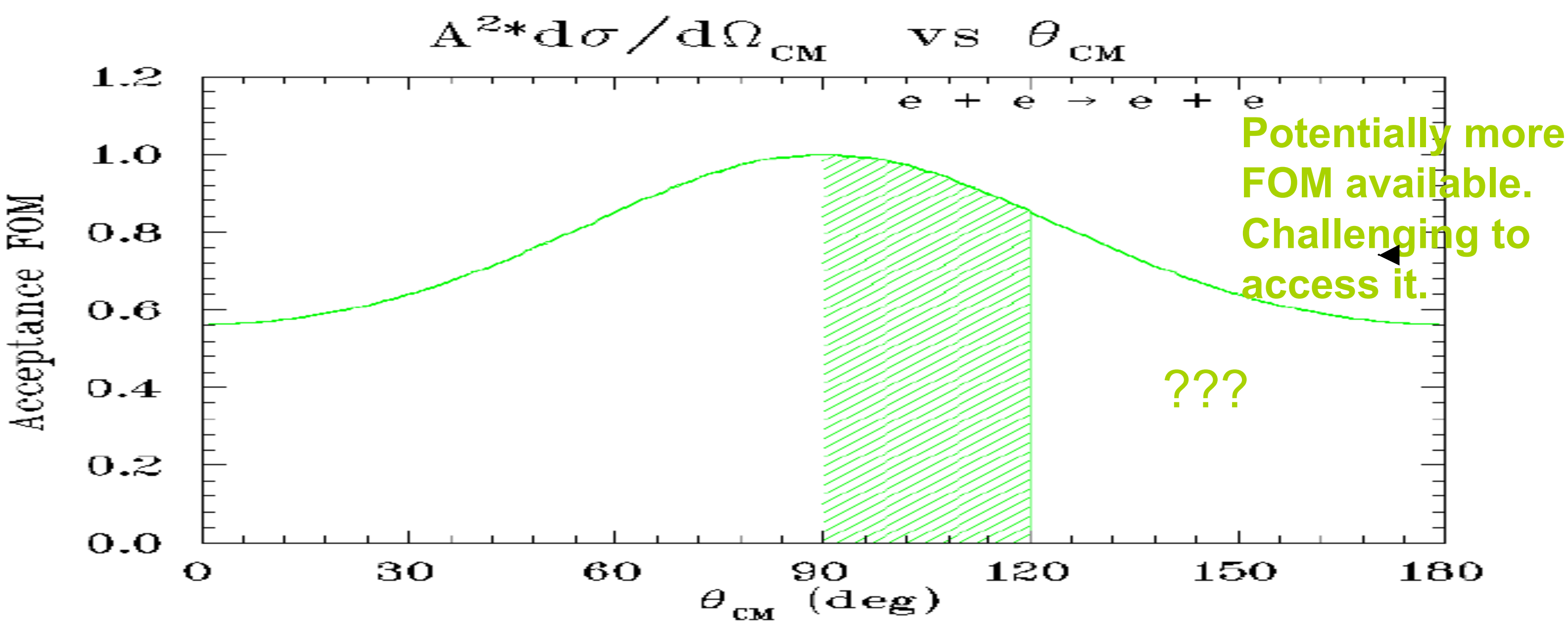
(Still need to look at differential linearity.)

Experiment Parameters

Figure of Merit for Acceptance



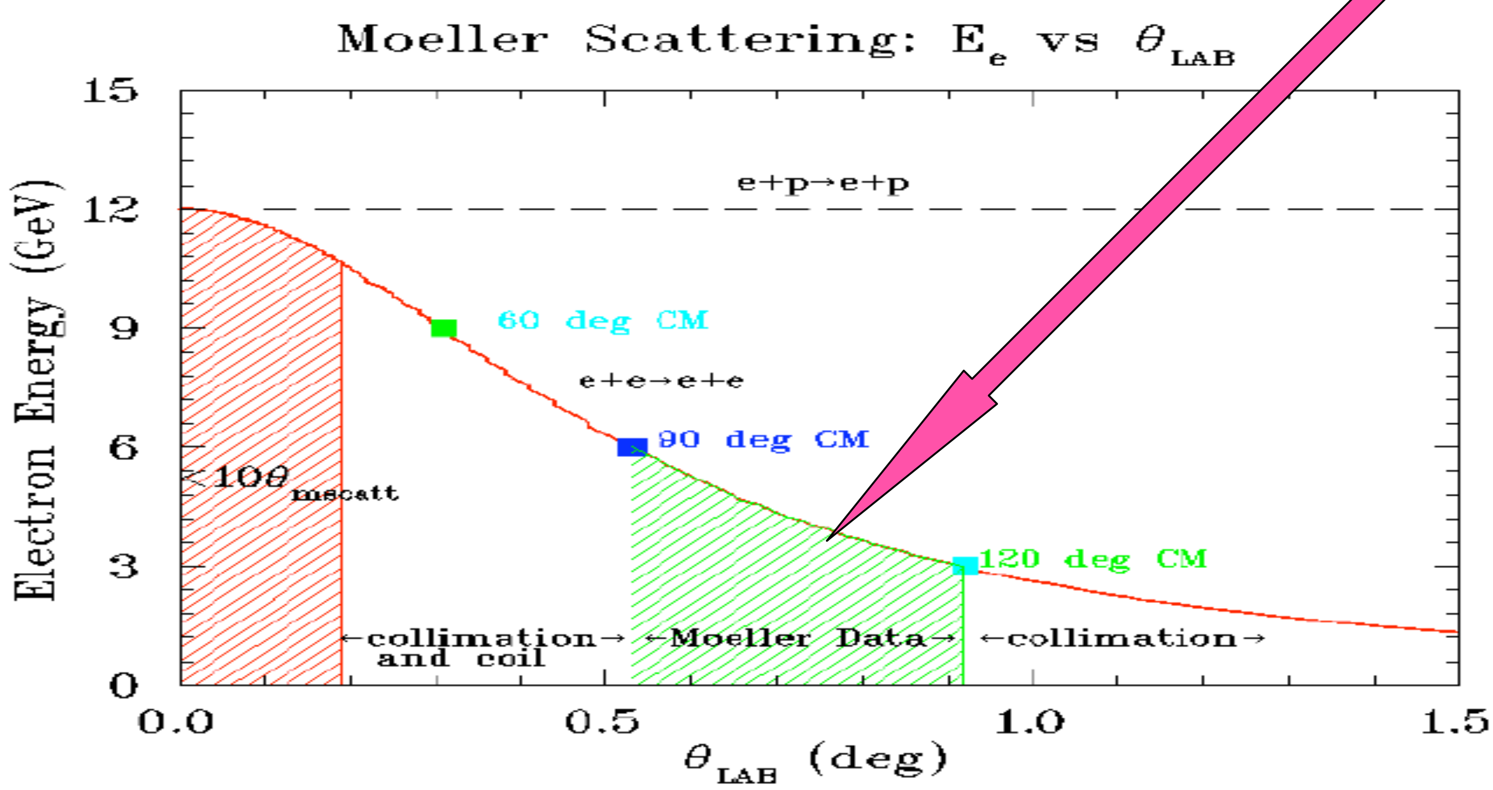




Semi-generic Acceptance

Considerations of double-counting, magnet strength, and momentum bites lead to the same conclusion as E158:

E' = 3-6 GeV
θ_{CM}= 90^0-120^0



Generic Experiment Parameters

Parameter	12 GeV JLab
E	12 GeV
E'	3-6 GeV
Polarization	85%
$< Q^2 >$	$.008\ (GeV/c)^2$
θ_{cm}	90°-120°
θ_{lab}	0.53°-0.92°
$< A_{pv} >$	40 ppb
$< A_{expt} >$	34 ppb
σ	$6.4 \cdot 10^{-29}\ cm^2$
Current	100 μA
Target Length	150 cm
Luminosity $cm^{-2} sec^{-1}$	$4.4 \cdot 10^{39}$
Time	4000 hours [1]
Luminosity*Time	$6.4 \cdot 10^{46}\ cm^{-2}$
Rate	282 GHz (35 GHz/octant)
Counting Statistics	23 ppm/pair at 300 Hz reversal
$\Delta A(stat) = \frac{1}{P}\frac{1}{\sqrt{N}}$	0.58 ppb
$\frac{\Delta A}{A}(stat)$	1.7%

[1] 32 weeks at 75% efficiency

- E = 12 GeV
- E' = 3-6 GeV
- Θ = .5°-.9°
- A_{PV} = -40 ppb

For reference, the $Q_w(p)$ experiment asymmetry is currently projected to be about 260 ppb.

Fine print:

Born xsect,

ΔΦ = 2π,

Typo fixed

(thanks JB and KK)

Errors

Errors	12 GeV JLab Anticipated $\Delta A/A$
Statistical:	
statistics	1.7%
+10% excess noise	
total statistical	1.9%
Systematic:	
P_{beam}	1%
Q^2	0.5%
background	0.5%
corrections	1%
total systematic	1.6%
Total:	2.5%

Statistical errors from previous page plus allowance for excess noise.

These systematic error estimates are similar to those for Q_w(p).

Which would allow a $\sin^2$thetaW error of about +-0.00025, on par with the best Z pole measurements.

Anemia by a Thousand Cuts

- Phi acceptance?
- Radiative losses?
- Dilutions from bkgs?
- E < 12 GeV?
- I < 100 microA?
- T < 4000 hours*75%?
- Target heating?

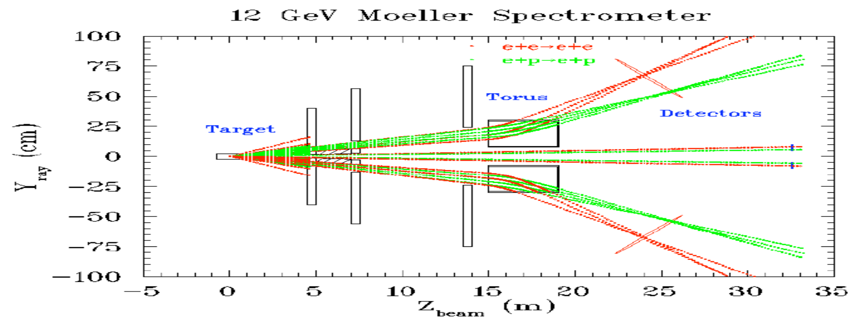
At this level of precision, any little bump in the road increases the error from 2.5% error to 3% or more.

We probably need more statistical reserve.

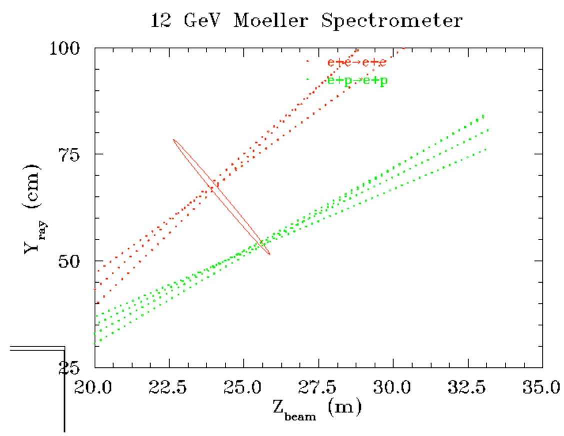
Toroid Spectrometer Concept

Requirements and Concept

For θ_{CM}= 90^0-120^0
(6 to 3 GeV/c),



- Drift scattered electrons to acceptance-defining collimator
- Bend angle + collimation must block 1-bounce backgrounds
- Drift electrons to the detector
- Hardware focus electrons with the momentum vs angle correlation of Moeller electrons

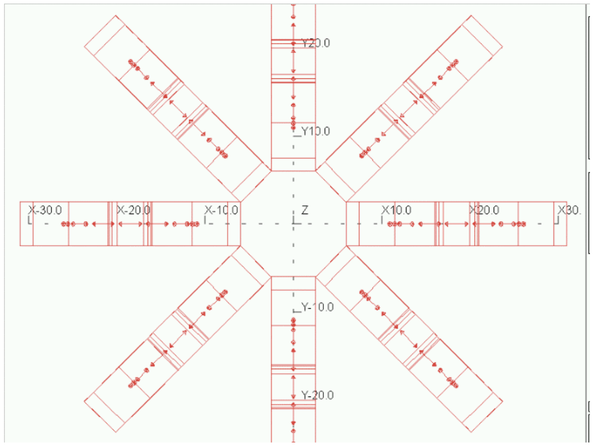


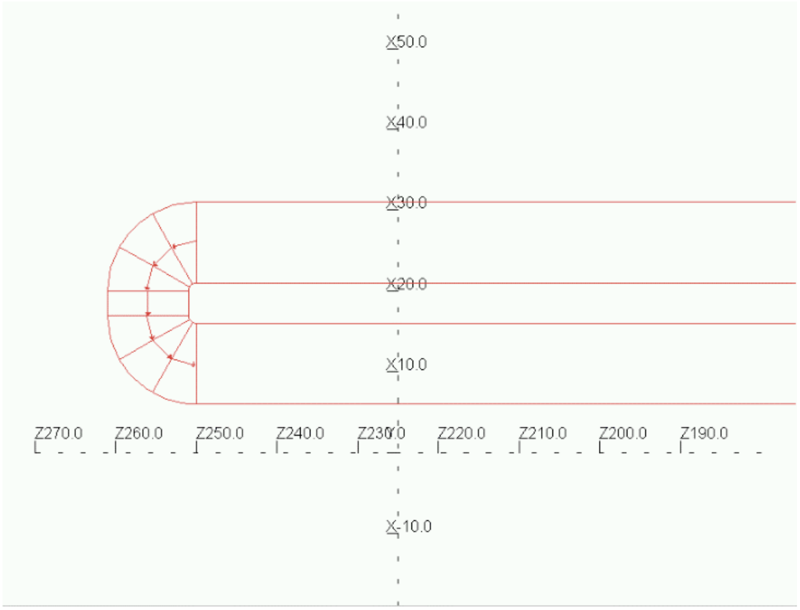
This conceptual design is based on an iron-free, resistive torus.
Toroids provide a high field integral with resistive magnets.

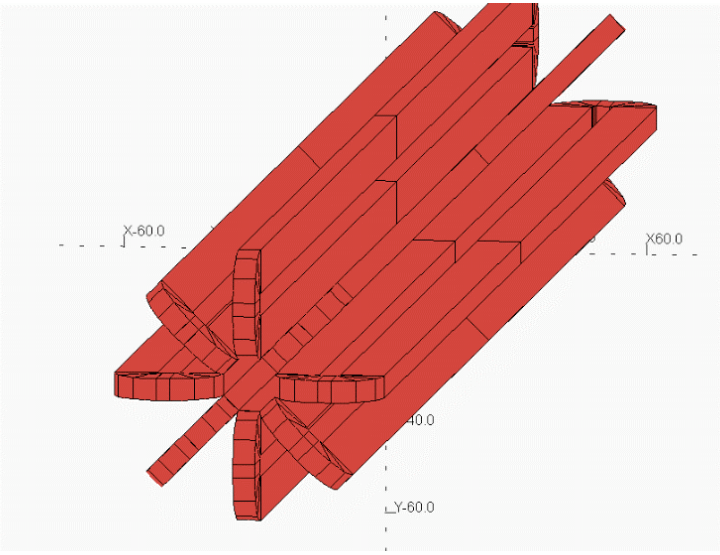
A 1/R field was assumed to get a 0th order design. Good hardware foci for small angle e+e and e+p reactions were obtained.

Resistive Torus
TOSCA by Paul Brindza

- Length = 5 m long
- Radius = 32 cm



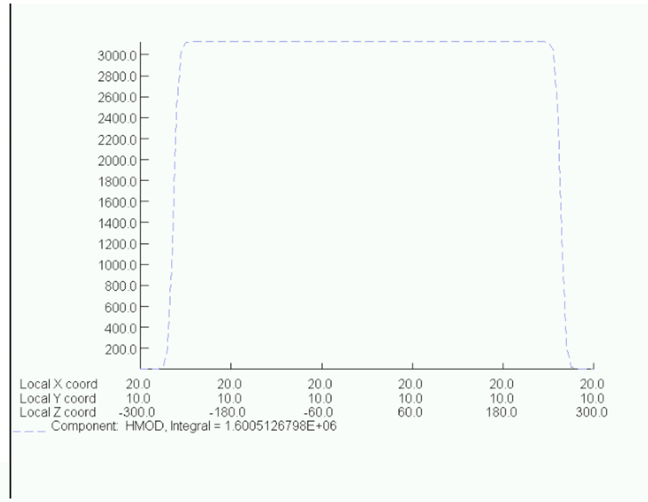




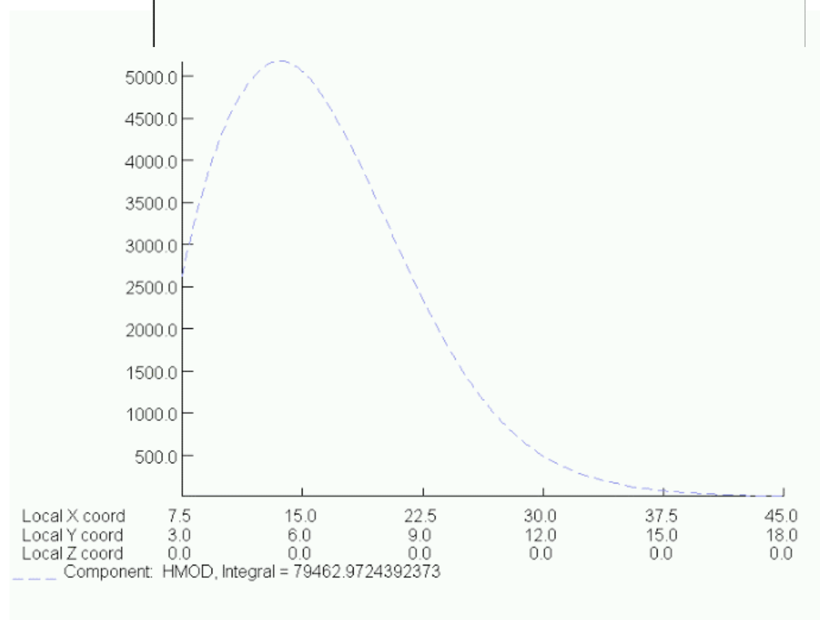
Resistive Torus Fields

- 3 kGauss at small radius.
- Field integral along inner coil is 1.5 Tesla-m

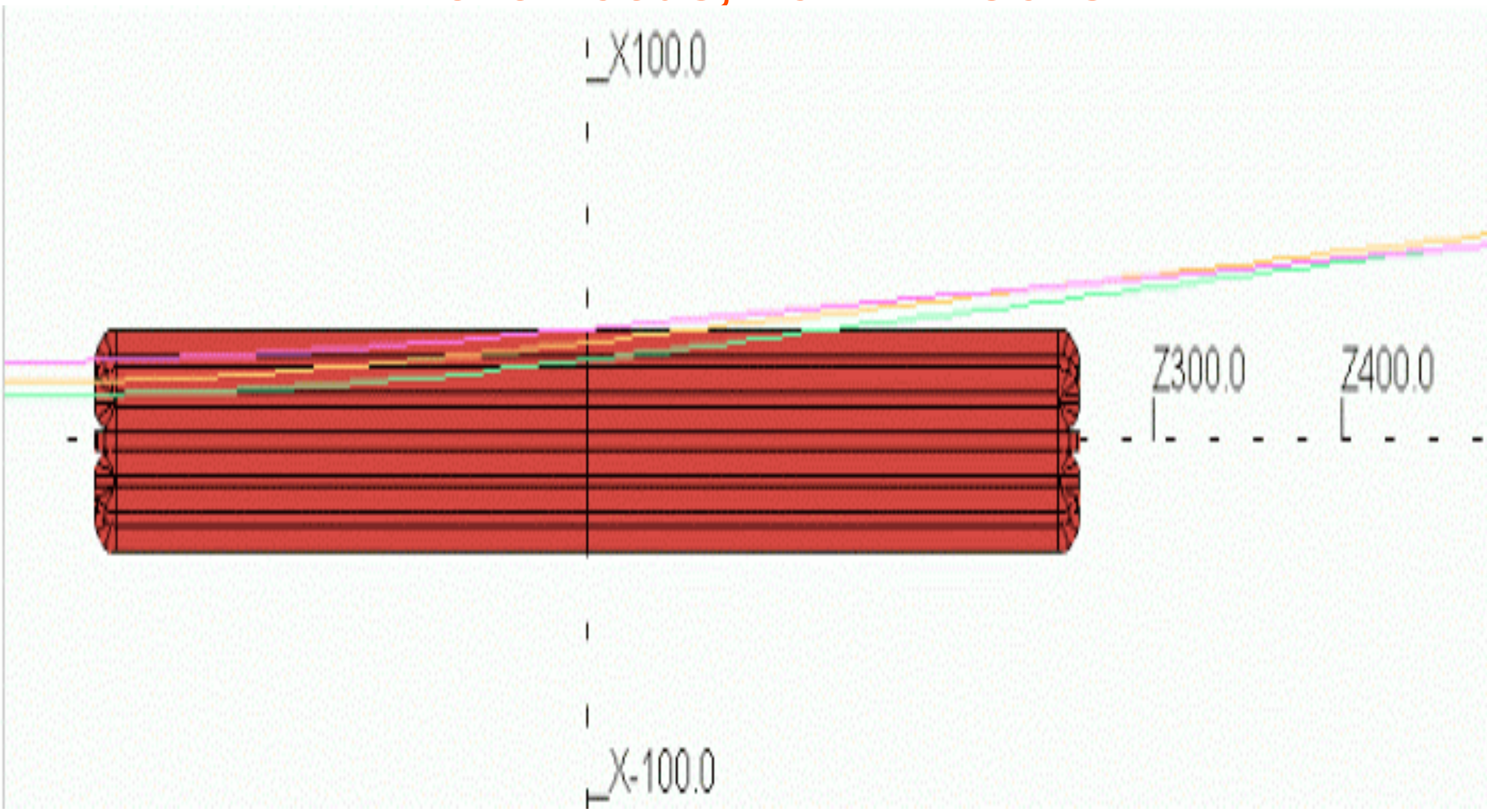
(but effective length is slippery)



- Despite freshman physics class, the radial field drops faster than 1/R.
- → bend angle won't be as large as in the toy model.



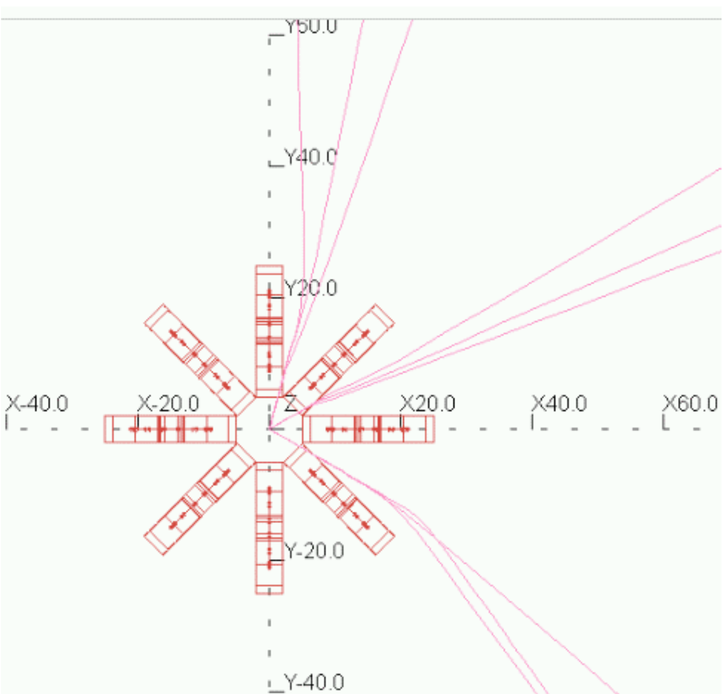
Resistive Torus
e2e Focus, no Trim Coils

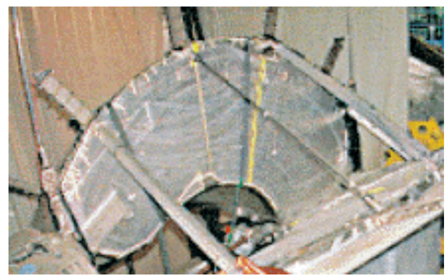


This coil gives a (e,2e) focus at about 4m downstream of the coil center, and 50cm from the beamline (vs 65cm in toy model)

Resistive Torus
Azimuthal Defocusing, No Coil Contouring

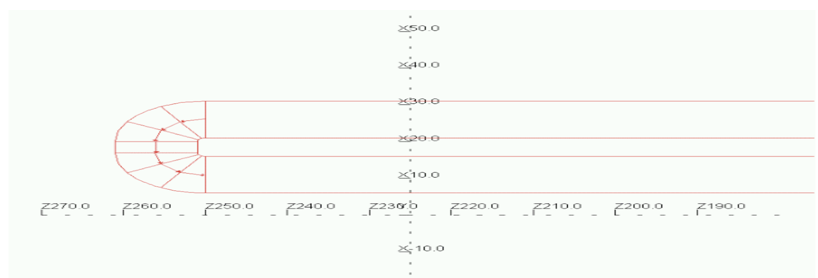
- Radial magnetic fields near inner coil surfaces provide a transverse kick. For the outbending particle, this defocuses in the azimuthal direction, increasing the spot size. Octant beams are close to overlapping at the Qweak focal plane.





The effect that brought you the CLAS torus lima-bean!

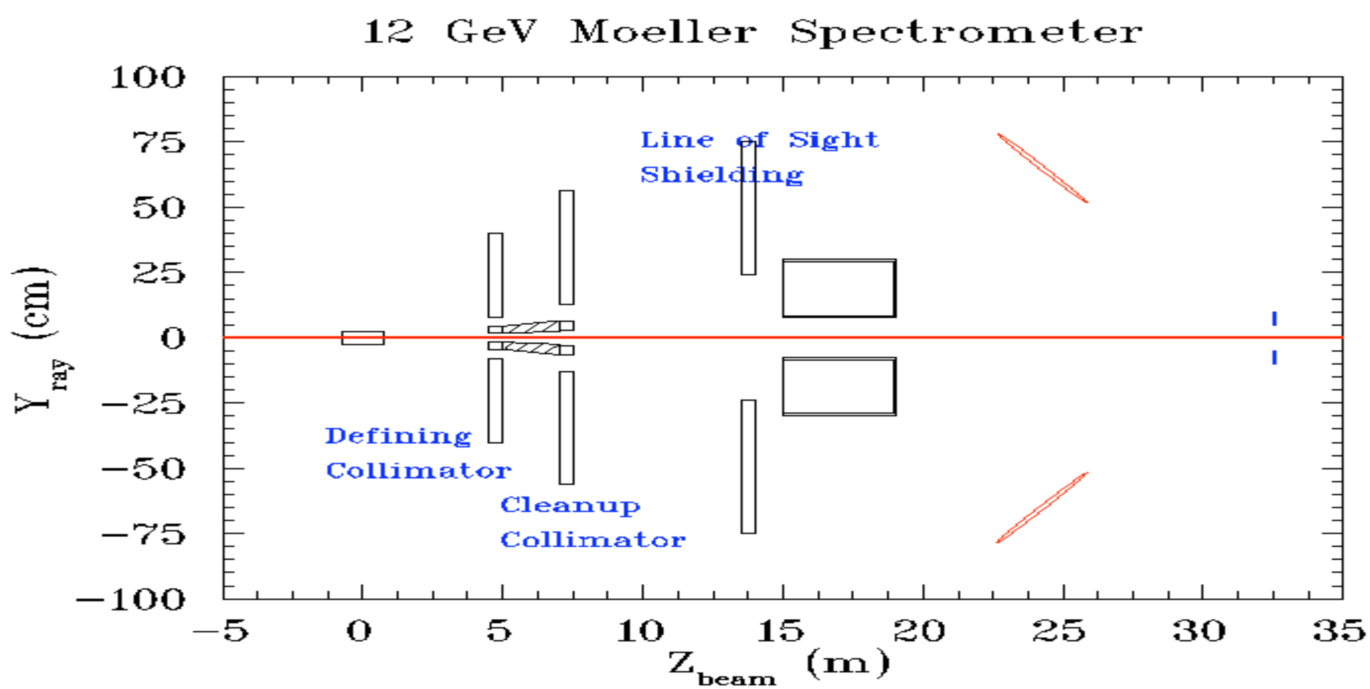
Effect is minimized if coil boundary is normal to particle trajectories.



Toroid Backgrounds - Beam

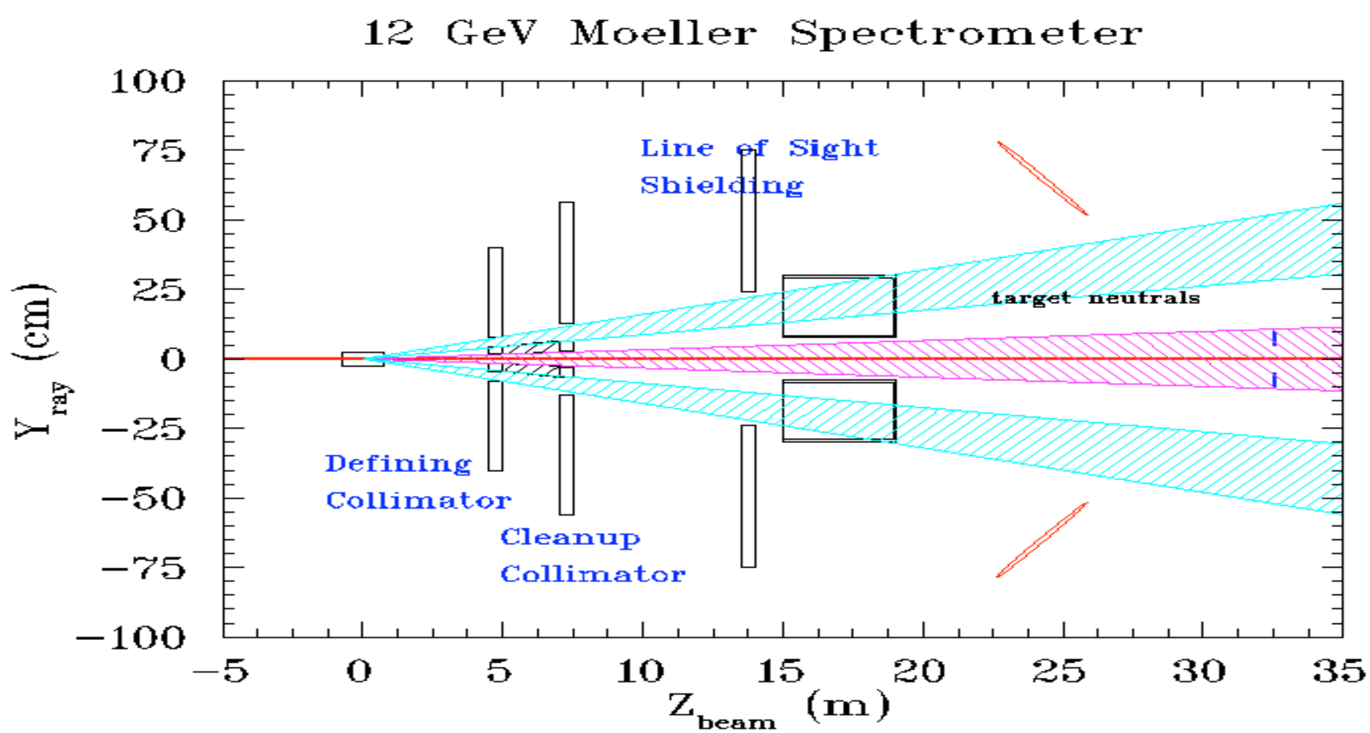
No bending of the primary beam means low energy, zero degree electrons mostly end up in the dump.

No synchrotron radiation loads.



Toroid Backgrounds - Neutrals

Neutrals from target would be conducted downstream in vacuum.

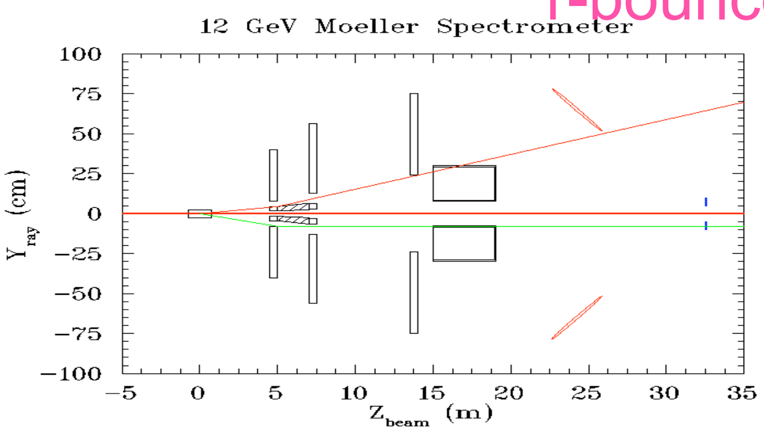


Toroid Backgrounds – 1 bounce

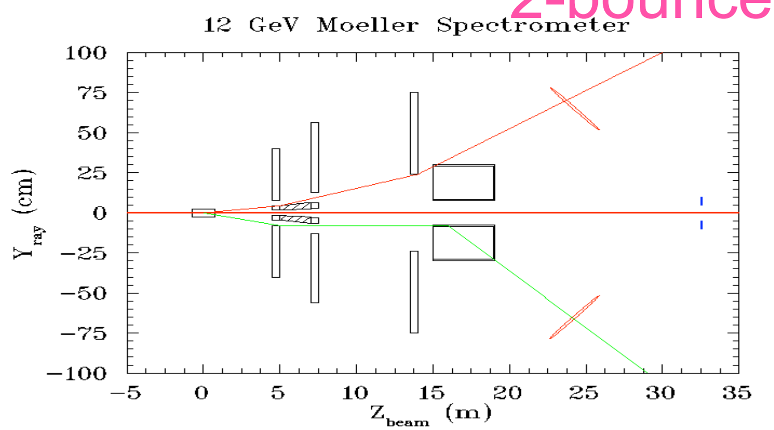
In addition to not having direct view of the target (0-bounce backgrounds), a reasonable goal is to have no 1-bounce backgrounds.

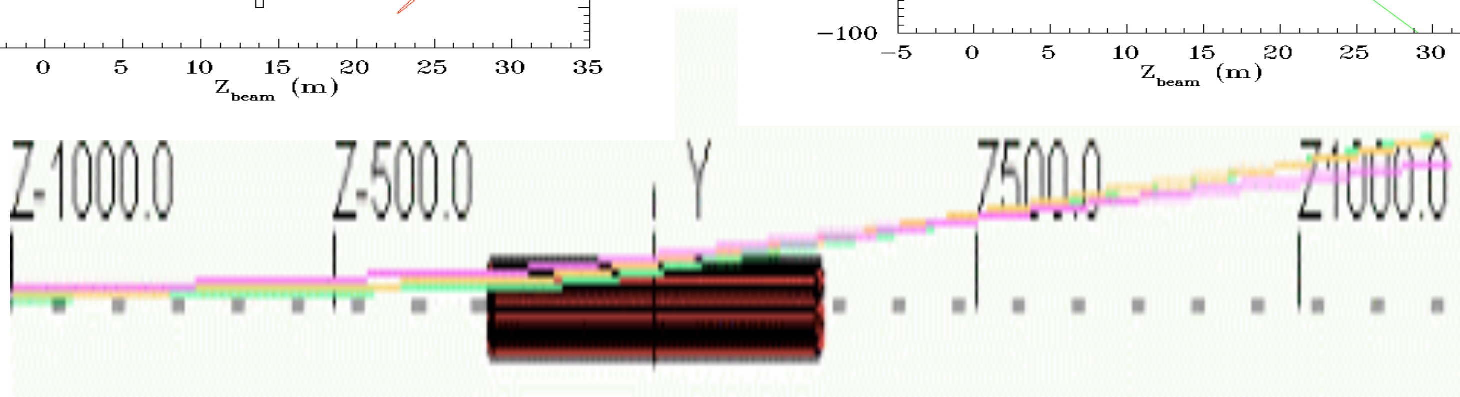
Hard to write down general rules, but in this case one needs a bend angle which is at least several times the lab scattering angles.

1-bounce



2-bounce





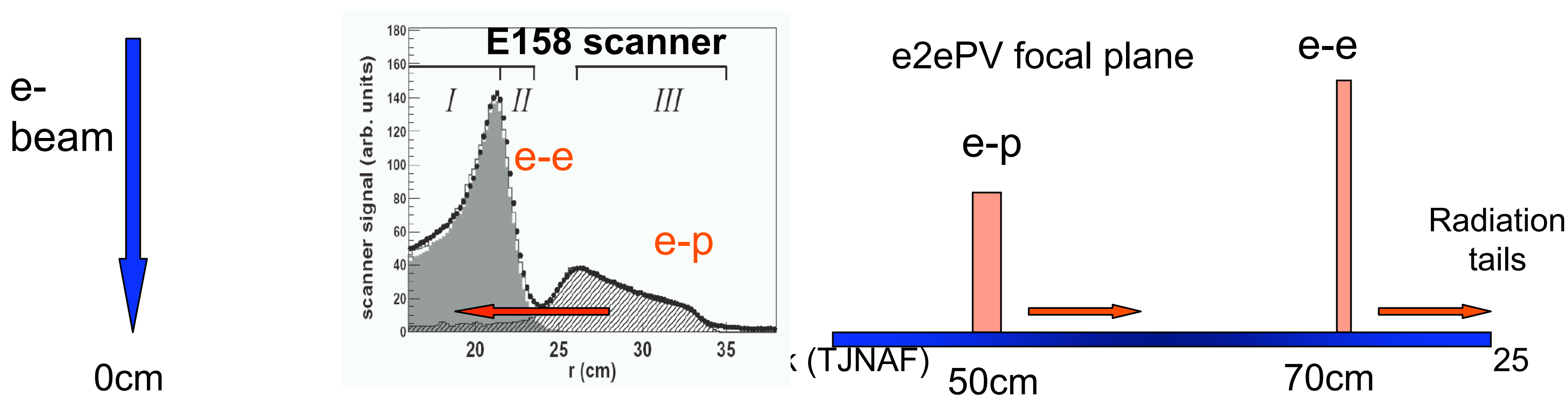
Toroid Backgrounds – High Asymmetry Tails

A good hardware focus for (e,2e) would minimize
tails from backgrounds with much larger asymmetries.

Focus e-e signal to O(1cm) radial

Detectors:

- possibility of < 1 cm resolution
- fully instrumented focal plane
- more electronics channels than usual



Resistive Toroid Stats

Power Dissipation	580 kW
Estimated Cost (conductor, winding, stand, DC bus, LCW)	$260k
Copper Weight	5,300 lbs

It's not that big, doesn't cost that much, and has a power consumption on par with the SOS.

Resistive Toroid Concept Summary

Good news:
Relatively cheap, easy to fabricate, "low" power consumption, easy to get some sort of focus, iron-free, bend angle large enough for 2-bounce system, no background production from bending of primary beam before or after target, faint possibility of useful e+p focus

•**Less good news:**

Phi acceptance for resistive coils is going to be 50% to 66%.

Makes lots of hot water.

Detailed work needed on focus.

Paul Brindza is happy to point out that the fields in question are low for SC coils. SC advantages for us would be greater Φ acceptance, greater bend angle, and greater dispersion which would make the e+p focus more interesting.

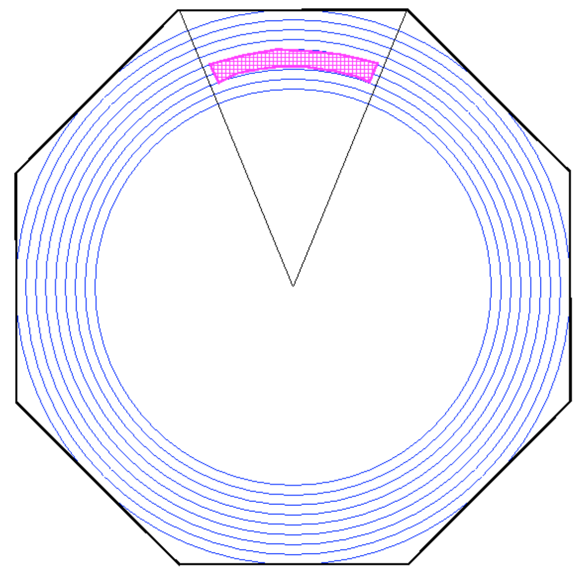
Detector Requirements

- Position sensitivity of order 1 cm (radial)
- Low excess noise for 3-6 GeV
- Insensitivity to soft backgrounds
- Good linearity
- Event mode operation at low luminosities a strong plus
- Inexpensive and ease of fabrication a plus

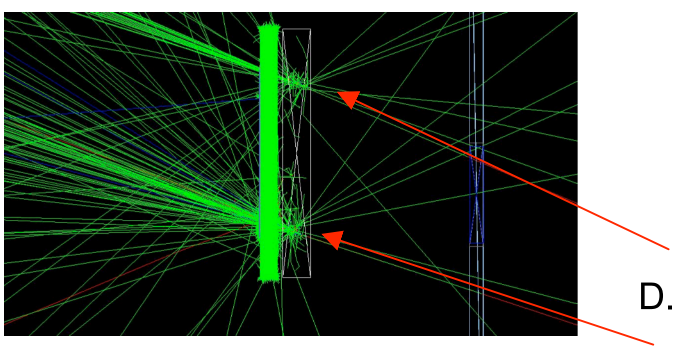
Fused Silica Cerenkovs

- Naked bars have little excess noise.
- Spectrosil 2000 has excellent properties, but material/polishing are expensive
- Difficult to sculpt to match crude hardware foci and collect light.
- From Qweak sims, easy to pick up O(1%) backgrounds from gamma's.

- At 1 GeV, use of shower-max preradiator improves S/B by factor of 10, but Qweak would have to run 15% longer. Unacceptable at lower energies.



M. Gericke



At 4.5 GeV, excess noise with 2 cm Pb pre-shower is 1.04 (ie, would have to run 8% longer to compensate).

Position Sensitive Ion Chambers (PSIC's)

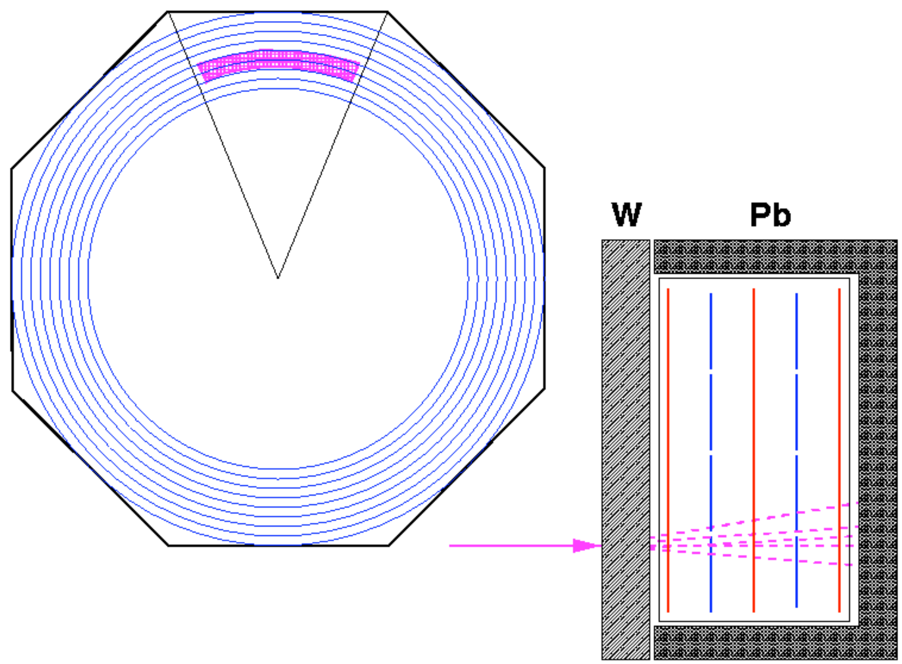
- Ion chambers are promising:
  good time response, good linearity, rad-hard, no fast gain changes, easy to match octants, cheap

- By partitioning the anode into strips, it is possible to make detectors with radial resolutions of < 1 cm.

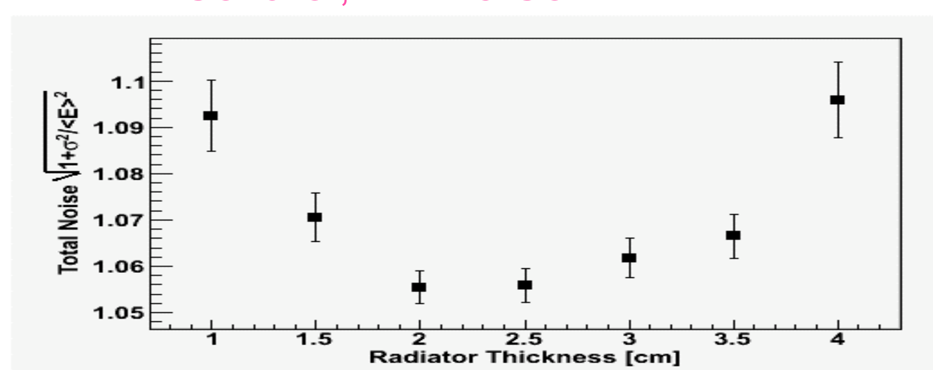
- M. Gericke modeled 10cm of 1atm He gas with 2 cm Pb preshower

- Excess noise is 1.055, or 11% additional running time.

- P Souder asked about soft backgrounds.
  still needs study



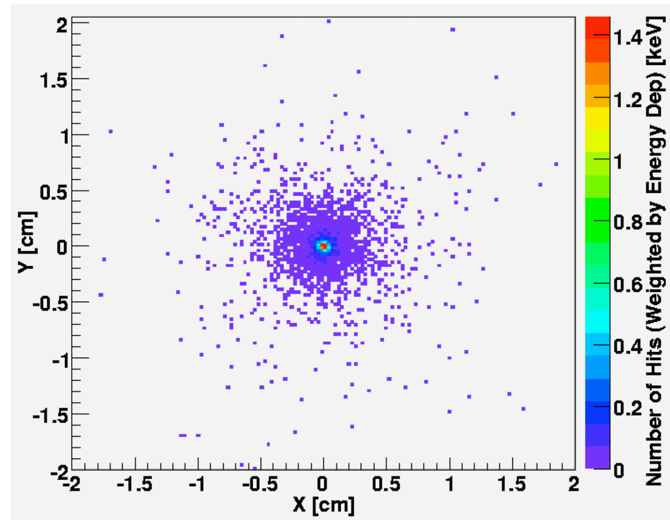
M. Gericke , E = 4.5 GeV

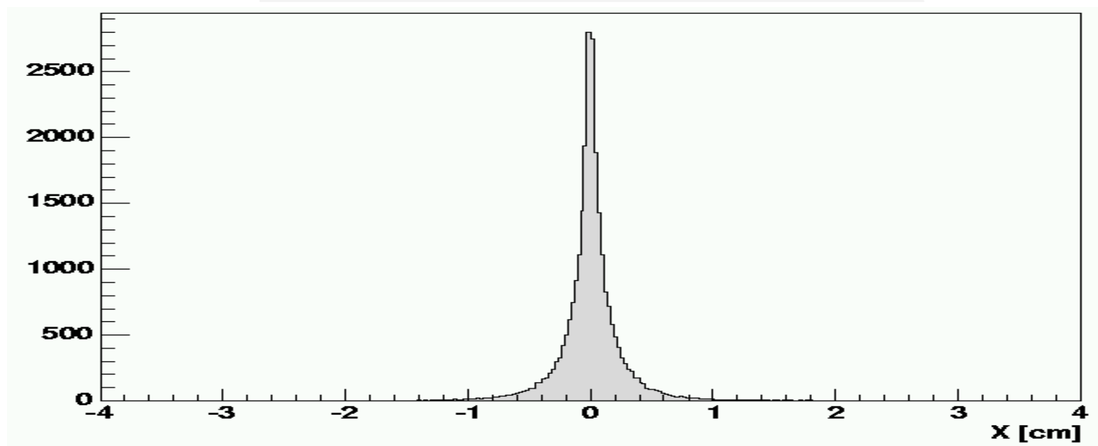


Minimum Position Resolution with Preshower

M. Gericke (U. Manitoba)

- Simulation:
  E_e = 4.5 GeV
  1.9 cm W (5.4 X_0)
  (shower max!)
  +10 cm, 1 atm He gas





- Minimum position resolution is a few mm but with a Lorentzian character
  (consistent with $r_{Moliere}$)

- Minimum resolution from fused silica should be similar.

Target Choice

- Any element can in principle provide the necessary electrons.
- LH_2 would minimize nucleon backgrounds, but that may not be a driver.
- Radiation length for a given electron areal density **is** a likely driver (due to radiative losses or multiple scattering).

Material	$N_e(?)/N_e(LH_2)$ for fixed X_0
LH_2	1.00
Be	0.47
C	0.35

LH_2 is probably best. **If** we're limited by radiation length, we can't lightly take a factor of 2-3 loss in electron target density unless someone shows the LH_2 target is impossible to build.

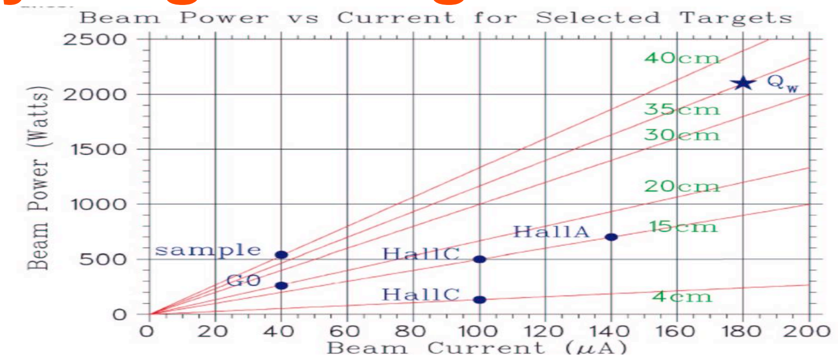
If someone in the collaboration wanted to look into this more carefully with a real spectrometer design, that would be great.

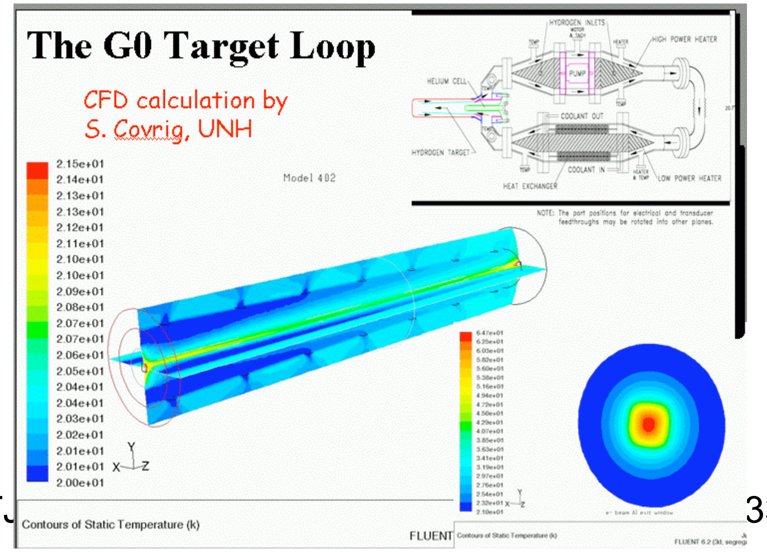
e2ePV Liquid Hydrogen Target

G. Smith et al.

- Target cooling power requirements are about 2.4 times more aggressive than $Q_w(p)$ (➔ 5 kWatt target)
- $Q_w(p)$ already plans to increase helicity reversal to nearly 300Hz in order to "freeze" density fluctuations.
- $Q_w(p)$ target groups are now using finite element analysis codes to upgrade existing G0 design.
- The plan is to make evolutionary modifications to a successful Qweak target design. First,

NEED A QWEAK TARGET!





Target Cooling Power

- Astonishingly, Greg Smith has determined that sufficient cooling power is already available on site.
- More refrigeration would allow more flexibility in scheduling the FEL and other halls.

Absolute Calibrations

1. Beam Polarization

This is the (systematic) achilles heel of sub-GeV electron scattering experiments. However, at 12 GeV, 1% absolute measurements with Compton polarimeters

laser γ + $\vec{e}$ → hard γ +e'

are quite feasible.

(Not meaning to belittle someone else's hard work. I'm not an expert on Compton polarimeters.)

2. Q^2 (= 4EE' $\sin^2(\theta/2)$)

E: arc energy measurement system will be recommissioned for 12 GeV

(Unfortunately, I am enough of an expert that I'm stuck with the job.)

θ: absolute angles come from survey

(P Souder notes that 90deg is self-calibrating, so dominant error comes from the low FOM large angle cutoff)

(The spectrometer itself does not require precise absolute calibration of its field integrals. The e-e and e-p elastic peaks will be dominant features of the spectrum.)

e2ePV LOI

- There will probably be a call for 12 GeV LOI’s/proposals for non-standard equipment for the summer ’06 PAC.

- Given our other commitments, we could presumably still submit a nice LOI with multiple conceptual designs for the spectrometer.

Summary

Critical experiment issues are becoming clearer:

- Keeping small statistical errors small
- LH_2 target and refrigeration
- Beam spot size monitor
- Redundancy in polarimetry
- Continue work on conceptual designs

The target and spot size monitor work are synergistic with the $Q_w(p)$ experiment effort.

extras

Misc. Model Sensitivities (non-SUSY)

scaled from R-Musolf, PRC 60 (1999), 015501 Collider limis from Erler and Langacker, hep-ph/0407097 v1 8 July 2004

Experiment	Z' $M(Z_X)$ (TeV)	$M(Z_{LR})$ (TeV)	Leptoquarks M_{LQ}(up) (TeV)	M_{LQ}(down) (TeV)	Compositeness (LL) e-q (TeV)	e-e (TeV)
Colliders (LEP2, CDF, Hera)	.67	.80	"1.5"	"1.5"		
0.5% Q_w(Cs) exists!	1.2	★ 1.3	★ 4.0	3.8	★ 28	---
13.1% Q_w(e) exists!	.66	.34	---	---	---	13
2.5% Q_w(e)	★ 1.5	.77	---	---	---	★ 29
4% Q_w(p) under construction	.95	.45	3.1	★ 4.3	★ 28	----
1% $Q_w(0^+ \rightarrow 0^+)$	.91	.92	3.0	3.0	22	----

One has to be careful taking model-dependent sensitivities too seriously. The listed E6 Z' models don't couple to up-quarks, so d-quark rich targets are favored.

However, for these particular models, a 2.5% Q_w(e) measurement looks appealing, in fact irreplaceable as an e-e compositeness test.

Systematic Checks

- Radial profile of yield and asymmetry of Signal+Bkg continuously measured with the main detector (PSIC) with <1 cm radial resolution.
- Offset-type errors (due to beam parameter false asymmetries) monitored with small(er) angle Moeller scattering in lumi monitors.
- Scale-type errors (mostly P_{beam}) monitored with larger PV asymmetries e+p and DIS.
- Isolation from the reversal signal continuously monitored with current sources in the experimental area.
- Event-mode operation would be useful, but the feasibility of doing this in PSIC-type detectors isn't yet clear.

Subsystems

Lot’s of responsibilities to parcel out:

- Spectrometer Magnet
- Target
- Detector
- Low noise pre-amps
- Low noise digitizers
- Polarimetry
- Beamline diagnostics (lumi monitors, spot size)
- Beam dithering
- DAQ: parity and pulsed mode
- Slow Controls
- Data analysis
- Simulations, simulations, simulations
- more software, more software, more software

12 GeV Experiment Overview

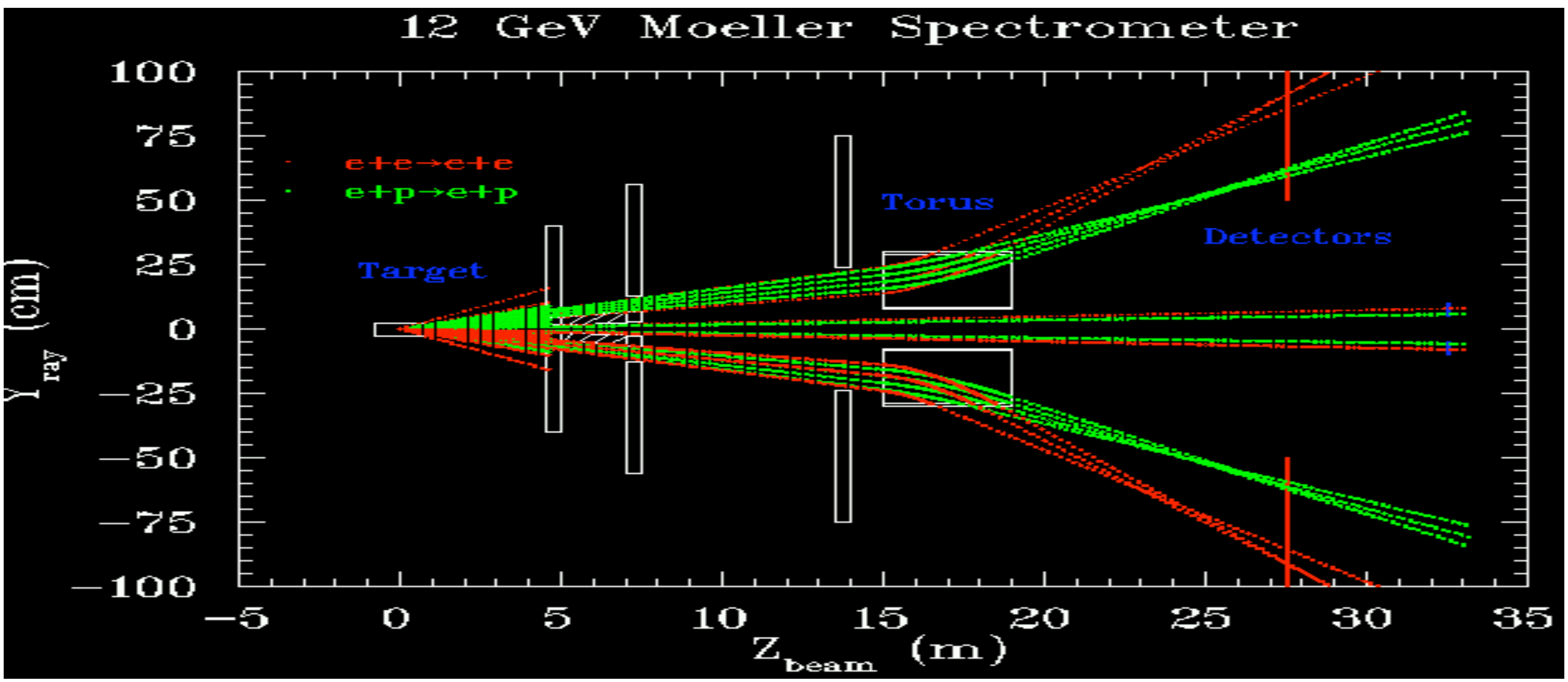
World's highest power LH_2 target

Scattered electrons drifted to Q^2-defining collimator

Moeller-focusing, resistive spectrometer

Position Sensitive Ion Chamber (PSIC) detectors

Fits in endstation A or C



New Contact Interactions

The sensitivity to new physics Mass/Coupling ratios can be estimated by adding a new contact term to the electron-quark Lagrangian:
(Erler et al. PRD 68, 016006 (2003))

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{\rm PV} + \mathcal{L}_{\rm NEW}^{\rm PV} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\ \bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q\ \bar{q}\gamma^\mu q$$

where g is the coupling constant, Λ is a Mass scale, and the h_V^q are quark-specific coefficients. If an absolute shift from the SM value of the protons weak charge $Q_W(p)$ is seen, it can be attributed to

$$\frac{\Lambda}{g} = \frac{1}{\sqrt{\sqrt{2}G_F}} \cdot \frac{1}{\sqrt{\Delta Q_W(p)}} \simeq 4.6\ TeV$$

This was derived for $Q_w(p)$, but the general lesson is that any few % measurement of a suppressed weak-scale quantity is sensitive to physics at the **multi-TeV scale**, well above present colliders and complementary to LHC.