Helicity Reversal and Systematics

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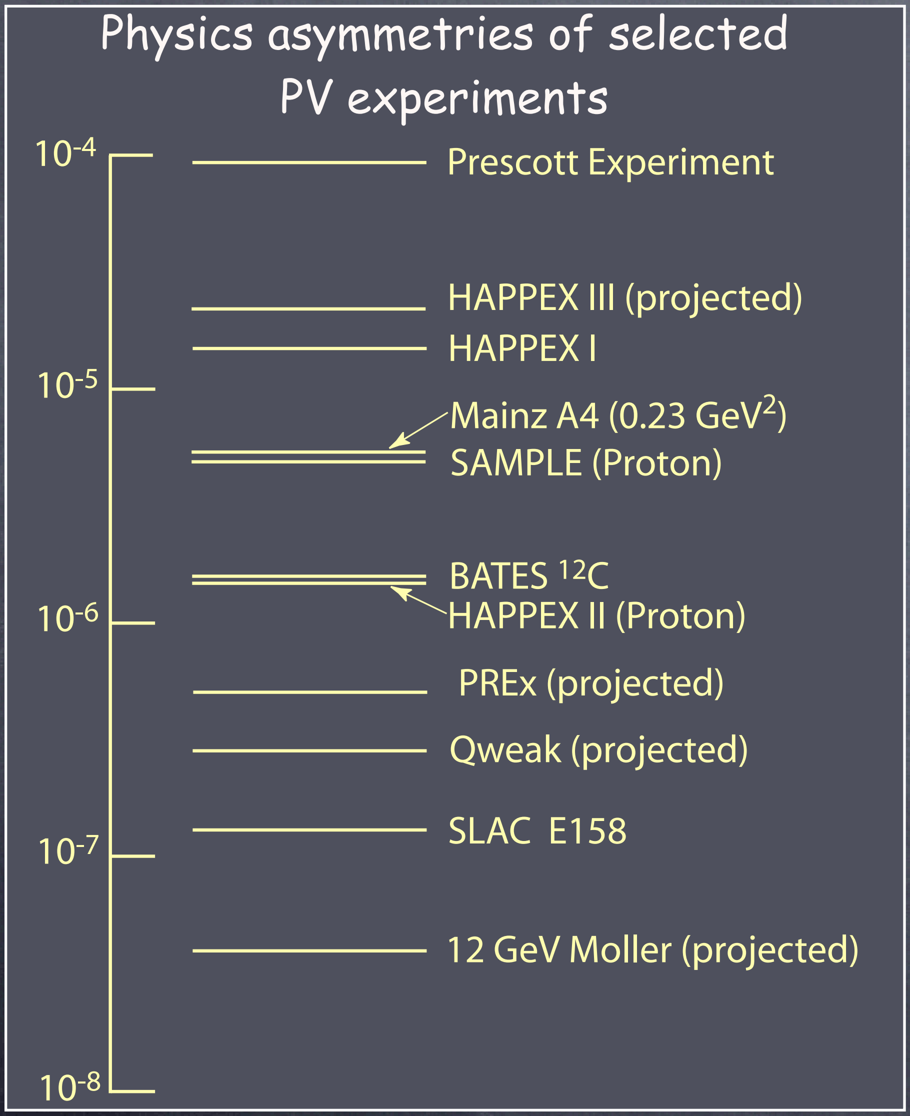
Special thanks to Kent Paschke and Rupesh Silwal

Experimental challenges have grown with increasingly small asymmetries



- Needed better and better statistics.
- Needed to reduce widths due to electronics to be well below statistics.
- Needed to regress out other noise and jitter.
- Needed better and better polarimetry.
- Needed to dramatically reduce the effects of helicity-correlated systematics associated with the polarized electron source.

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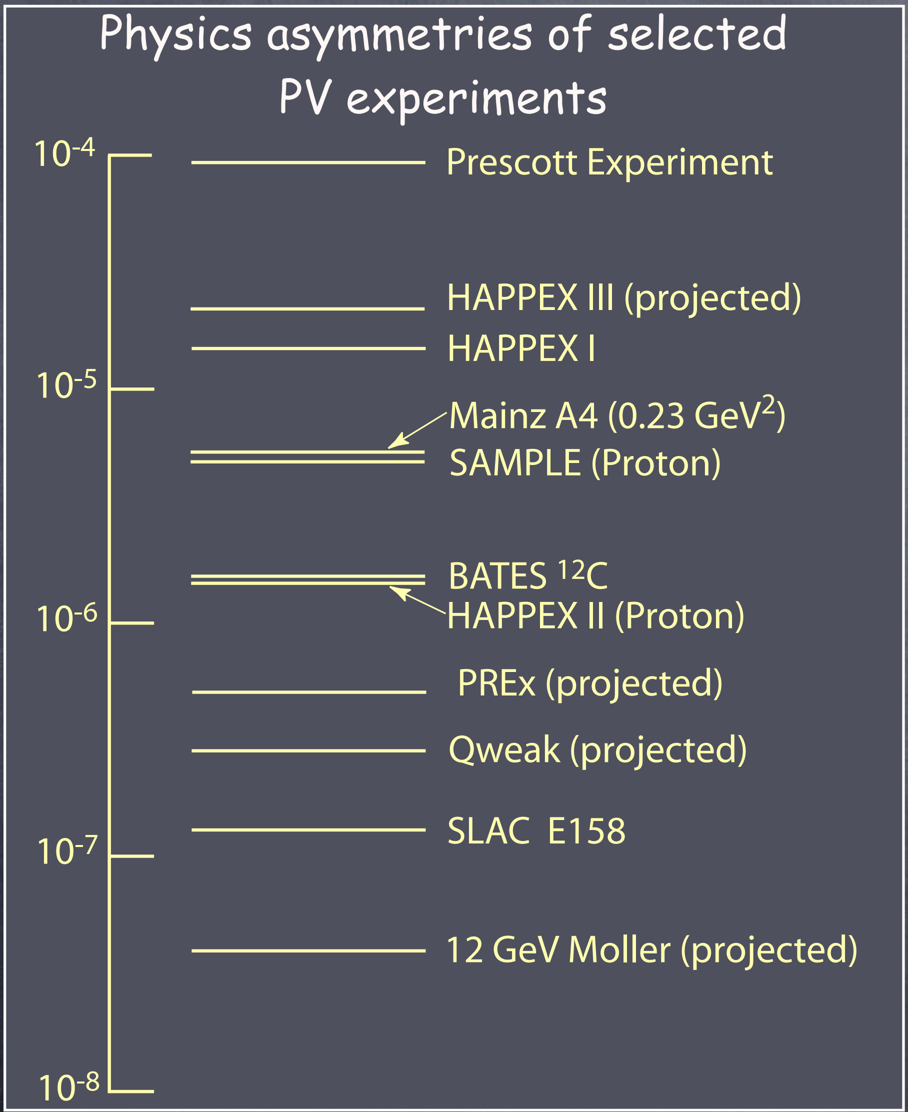

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The subject of my talk today.

Types of helicity-correlated electron beam effects

- Helicity-correlated charge asymmetries

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- Helicity-correlated beam-position differences

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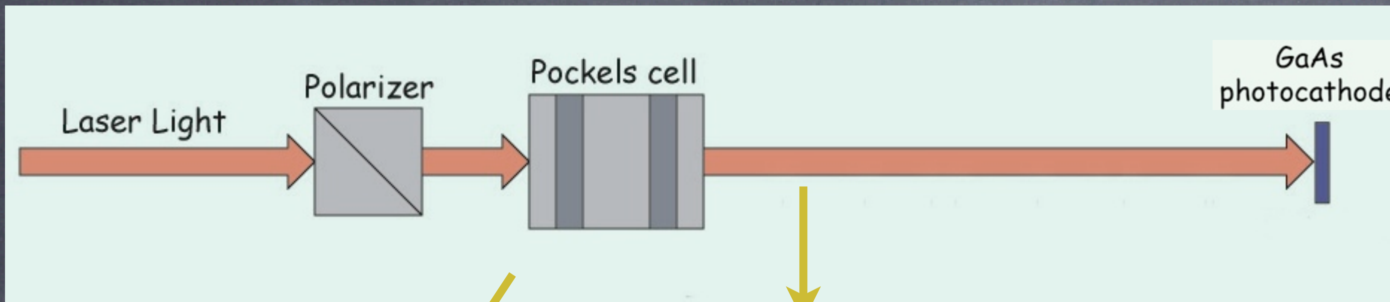
- Helicity-correlated beam-size differences

  Taking on new importance in experiments looking at very small asymmetries that already take advantage of high azimuthal symmetry.

Strategy to deal with helicity-correlated beam systematics

- Understand their origins and make them as small as possible.
- Measure them and make appropriate corrections.
- Judiciously apply feedback.
  - Sometimes this is essential, particularly if you cannot measure them with small enough errors to correct for them.
- Use lots of flips!

The polarized electrons are produced by irradiating GaAs with circularly polarized light

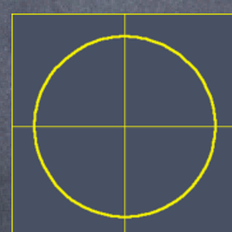


- Phase introduced by Pockels cell

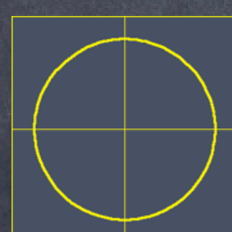
$$\delta_+ = +\frac{\pi}{2}$$

$$\delta_- = -\frac{\pi}{2}$$

Polarization ellipse emerging from Pockels cell



Left-handed light



Right-handed light

Ideally, the only difference in the light arriving at the GaAs crystal is its handedness.

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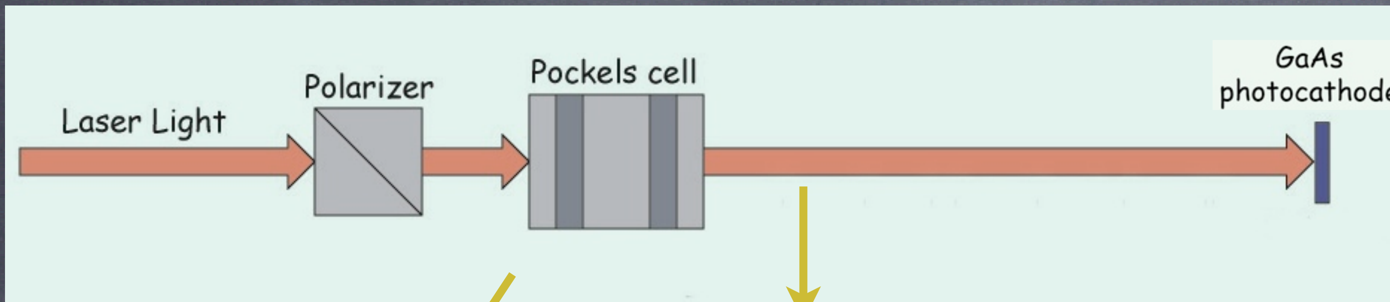

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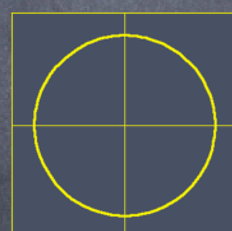

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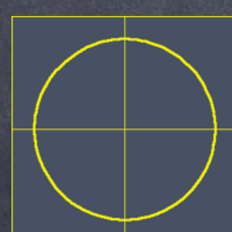
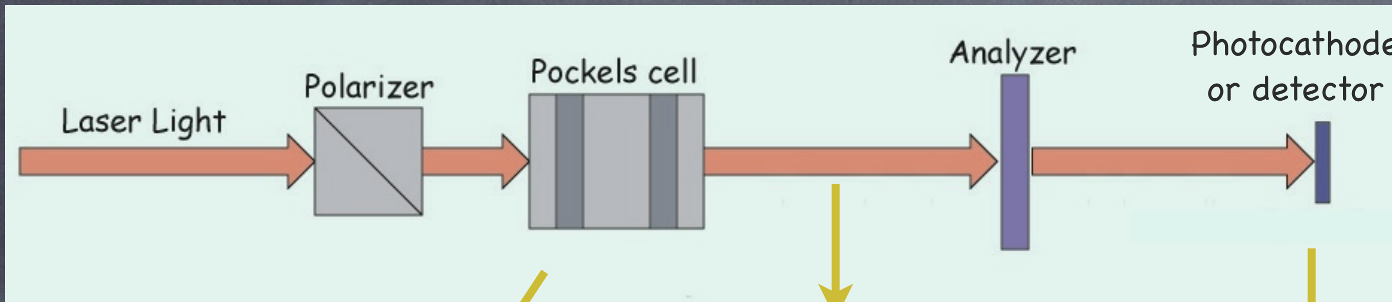
$$\delta_- = -\frac{\pi}{2}$$



Right-handed light

A spurious constant phase "Δ" causes an intensity asymmetry if the light is "analyzed"



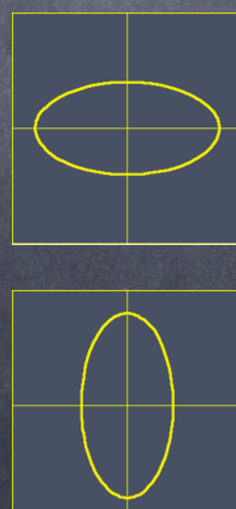
Phase introduced by Pockels cell

Polarization ellipse emerging from Pockels cell

Intensity at detector after passing through vertical analyzer.

$$\delta_+ = +\frac{\pi}{2} + \Delta$$

$$\delta_- = -\frac{\pi}{2} + \Delta$$



The phase Δ can be introduced by any optical element

The "Δ phase" and its effects

The Δ phase can be introduced by birefringence ANYWHERE, by any optical element (since it doesn't change sign when the helicity flips, the element can be passive).

The Δ phase can (and usually does) vary spatially across the laser beam spot.

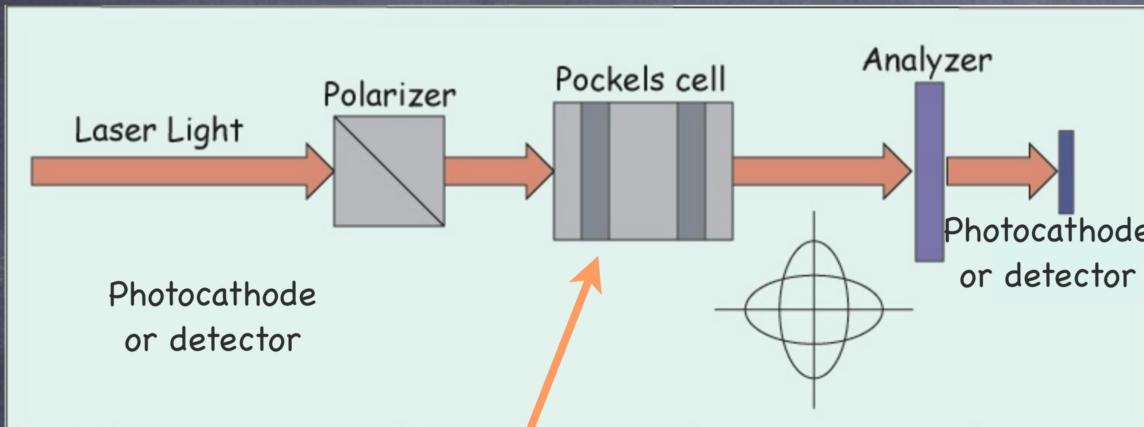
- If Δ is constant across the laser beam, a charge asymmetry results.
- If Δ varies linearly across the laser beam, position differences result.
- For higher-order variations of Δ across the laser beam, beam-size or beam-shape differences result.

Sources of a "Δ phase"

- Residual birefringence in the Pockels cell.
- Birefringence in any optical element, such as the vacuum window to the polarized electron source.
- Unwanted birefringence due to TINY MISALIGNMENT of the Pockels cell that cannot be detected using traditional alignment schemes.
- Incorrect voltage settings on the Pockels cell.

Zeroing out the first moment of the Δ phase

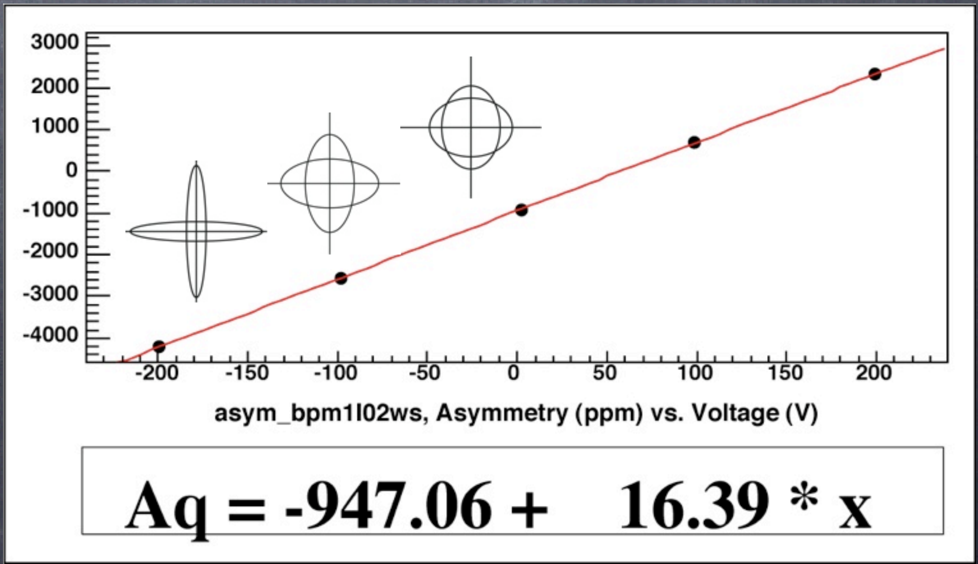
(and hence zeroing out charge asymmetries)



The Pockels cell can be adjusted to zero out the average phase Δ seen by the laser beam. Doing so zeros the charge asymmetry.

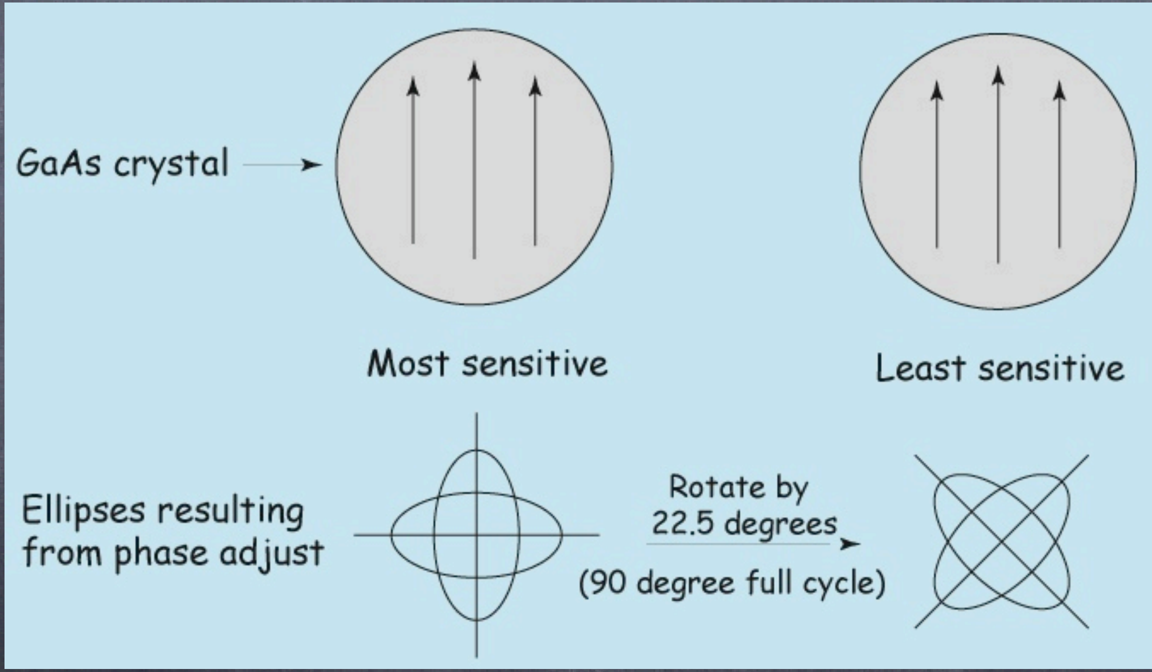
$$A(\Delta) \equiv \frac{I_+ - I_-}{I_+ + I_-} = \frac{\epsilon}{T}\Delta\, sin(2\theta)$$

Translate both "+" and "-" voltages over a few hundred volts.



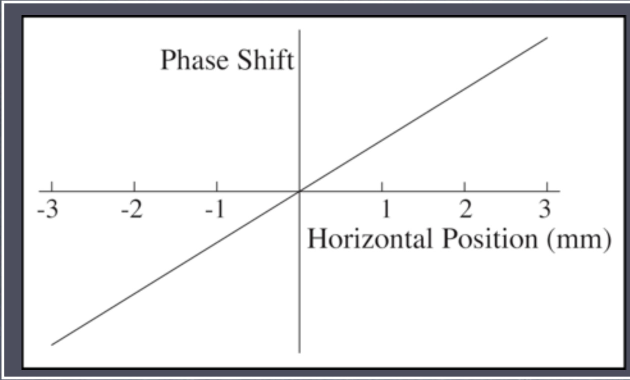
The dominant "analyzer" is typically the strained GaAs photocathode

- Other examples include mirrors, vacuum windows and other components.



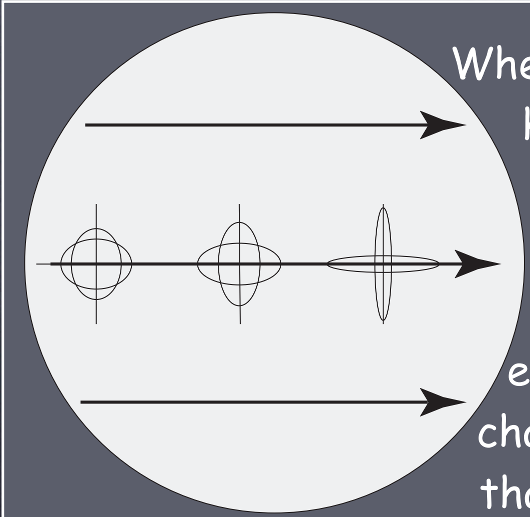
The ability to rotate the polarization ellipses makes it possible to reduce sensitivity to the analyzer, whatever it is.

Gradients in the Δ phase cause beam position (and size) differences



A gradient in the Δ phase across the laser beam causes different polarization ellipses for different parts of the beam.

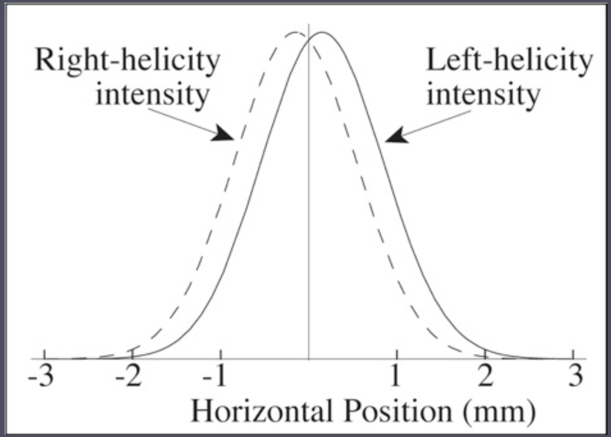
⇓



When the laser beam hits the GaAs crystal, the different polarization ellipses cause a charge asymmetry that varies across the crystal.

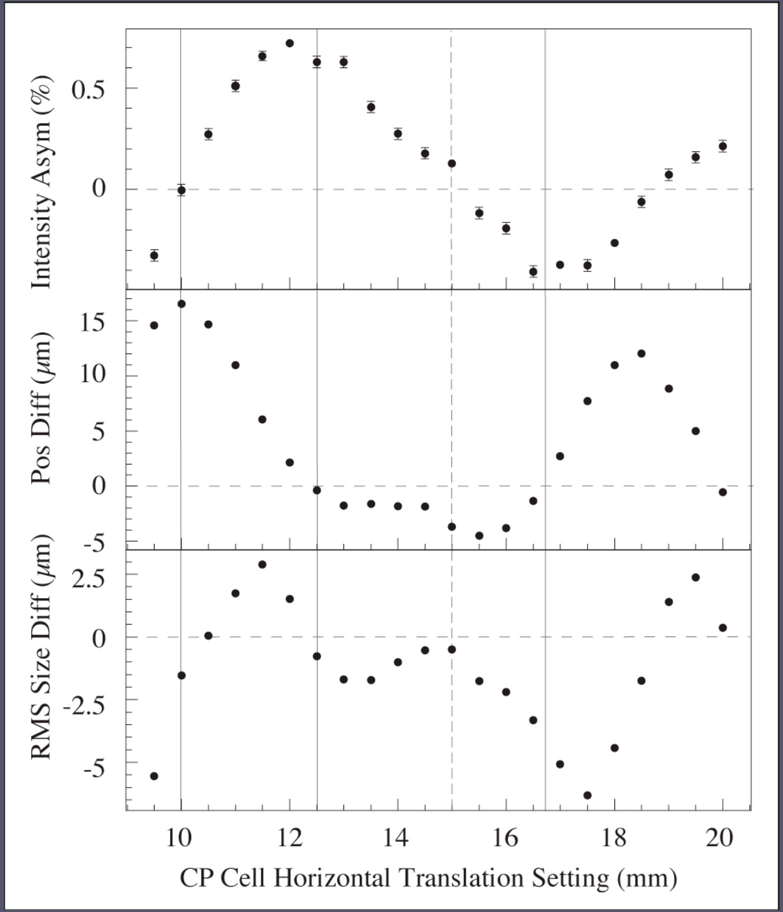
⇒

The variation in the charge asymmetry reverse sign upon helicity reversal, causing helicity-dependent shift in position centroid



Recognizing the importance of gradients in Δ was key to the success of E158

Here, helicity-correlated charge, position and size differences are measured while the Pockels cell is translated across the laser beam.



The charge asymmetry measures the average of Δ across the laser beam

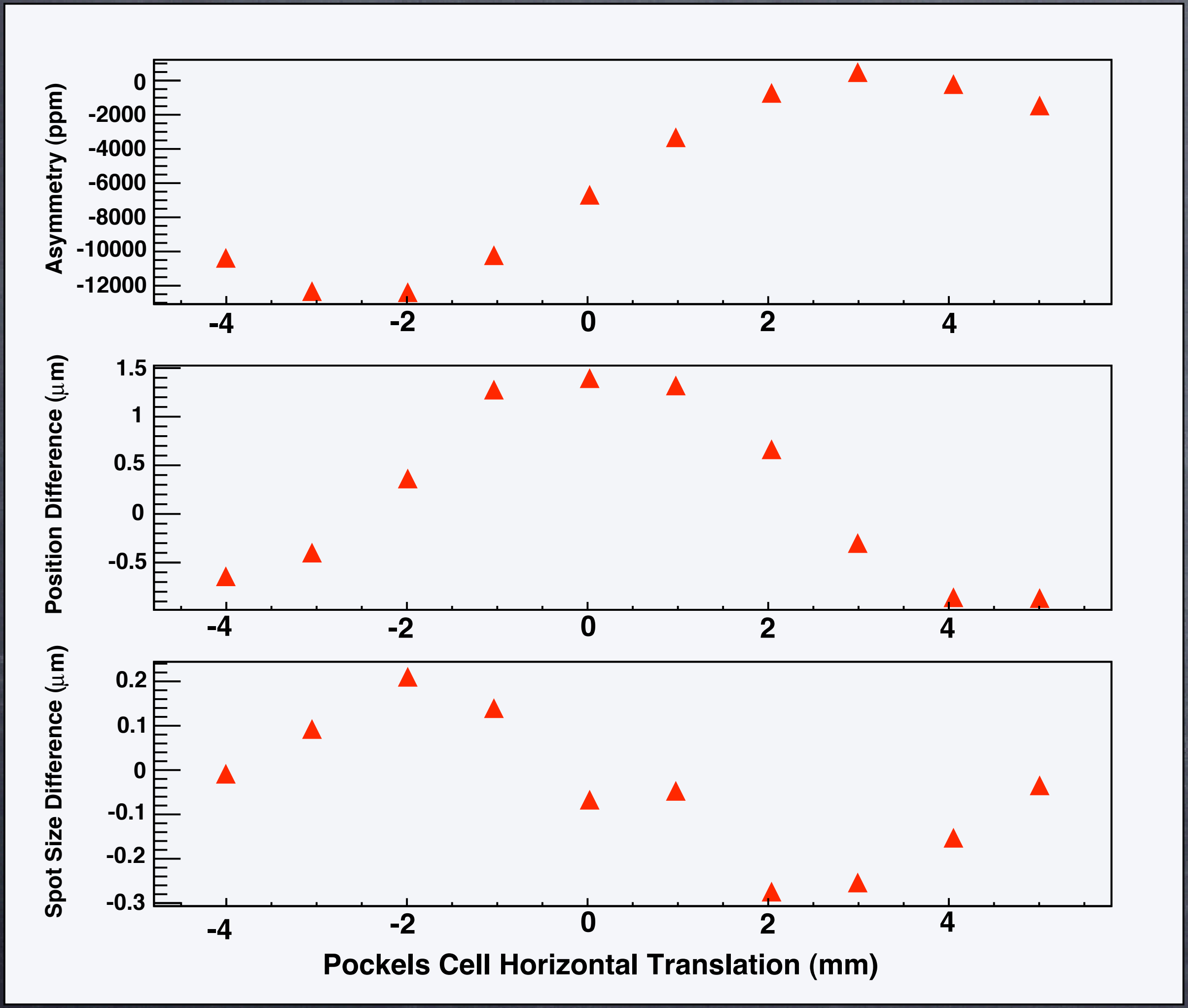
The position difference measures the gradient of Δ across the laser beam.

The spot-size difference measures the 2nd derivative of Δ across the laser beam.

Humensky et al., NIM A521, 261 (2004)

One of the Pockels cells used in E158 is characterized.

More recent translation scans



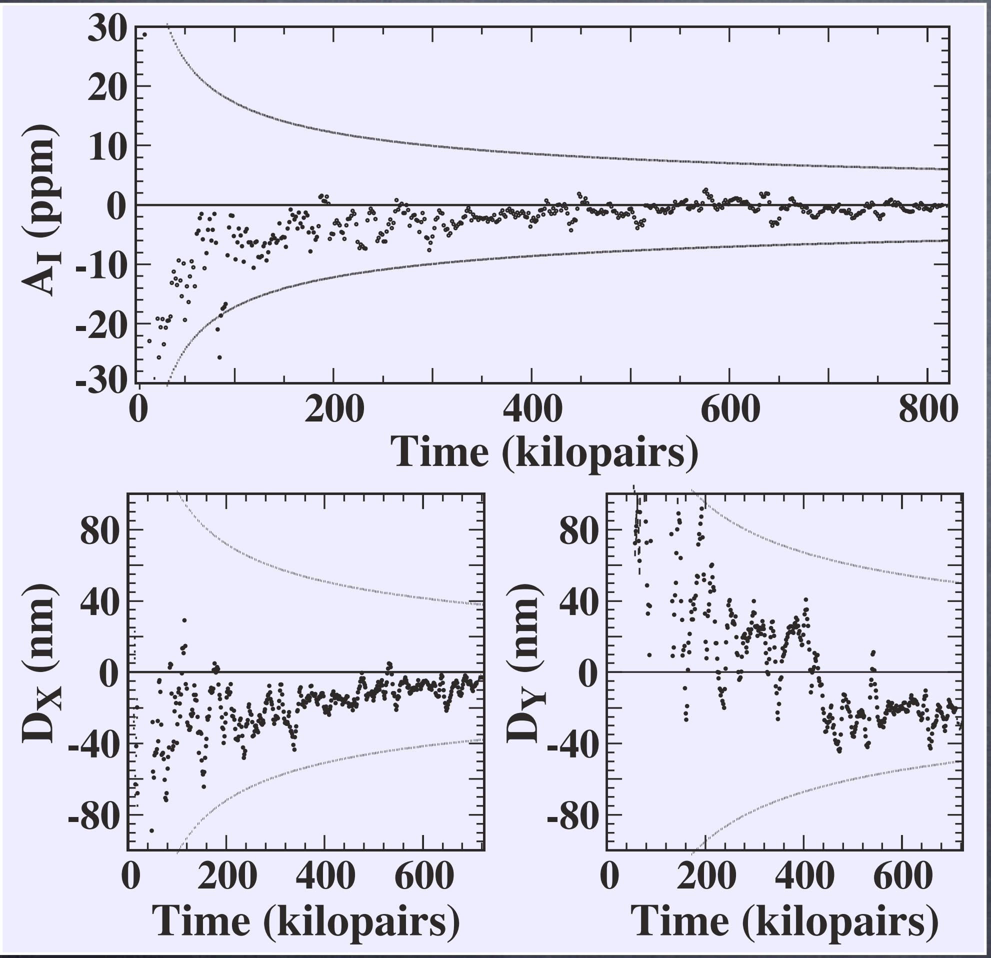
Translation Scan

The charge asymmetry measures the average of Δ across the laser beam

The position difference measures the gradient of Δ across the laser beam.

The spot-size difference measures the 2nd derivative of Δ across the laser beam.

With passive measures optimized, feedback zeroes helicity-correlated effects even further.



Feedback on charge asymmetries and position differences causes them to move toward zero with scaling that approaches:

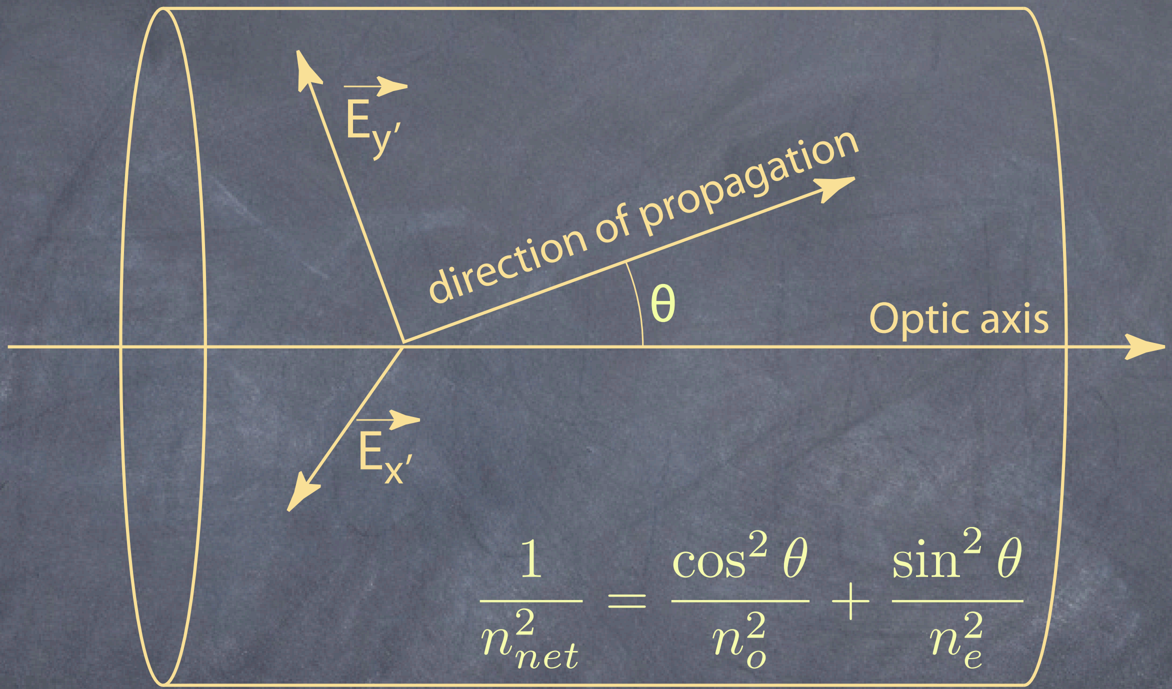
$$\text{Average} \longrightarrow \frac{\text{Error on individual measurement}}{N}$$

Not $\frac{1}{\sqrt{N}}$ scaling as you might expect.

During E158, in the absence of feedback, position differences of tens of nanometers remained.

What was the cause?

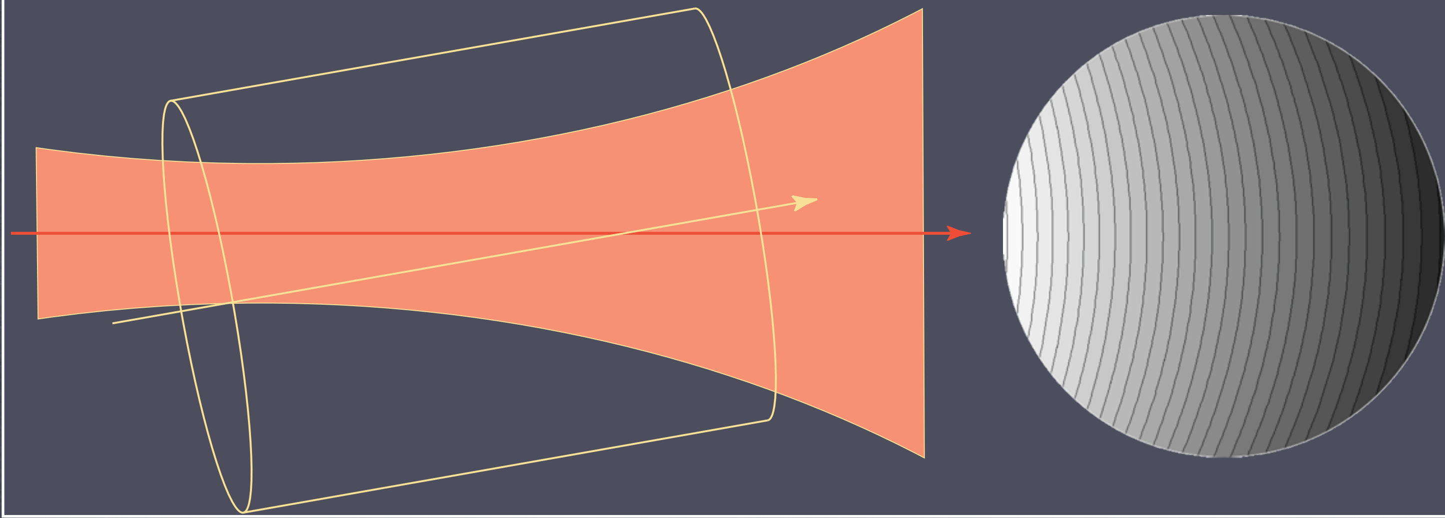
An unavoidable source of Δ phase from the Pockels Cell: the Skew/Paschke effect



$$\frac{1}{n_{net}^2} = \frac{\cos^2\theta}{n_o^2} + \frac{\sin^2\theta}{n_e^2}$$

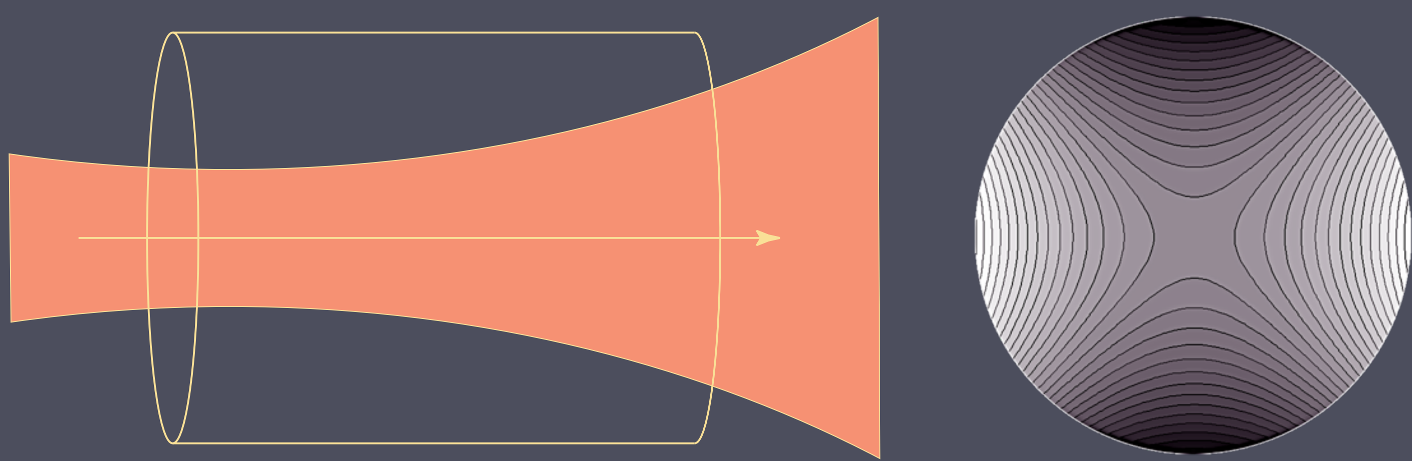
- Light parallel to the axis of an (unbiased) Pockels cell experiences no birefringence.
- Since all laser beams have non-zero divergence, however, most of the light will be at least slightly unparallel.
- There is thus an unavoidable "Δ phase" due to the interaction of the laser beams divergence and the optic axis of the cell.
- The effect is worse if the Pockels cell is tilted with respect to the laser beam.

Spatial distribution of Δ phase associated with Pockels cell



Pockels Cell Tilted.

non-zero position differences.

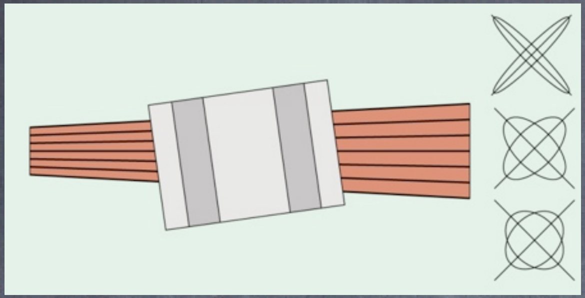


Pockels Cell Untilted.

non-zero size differences

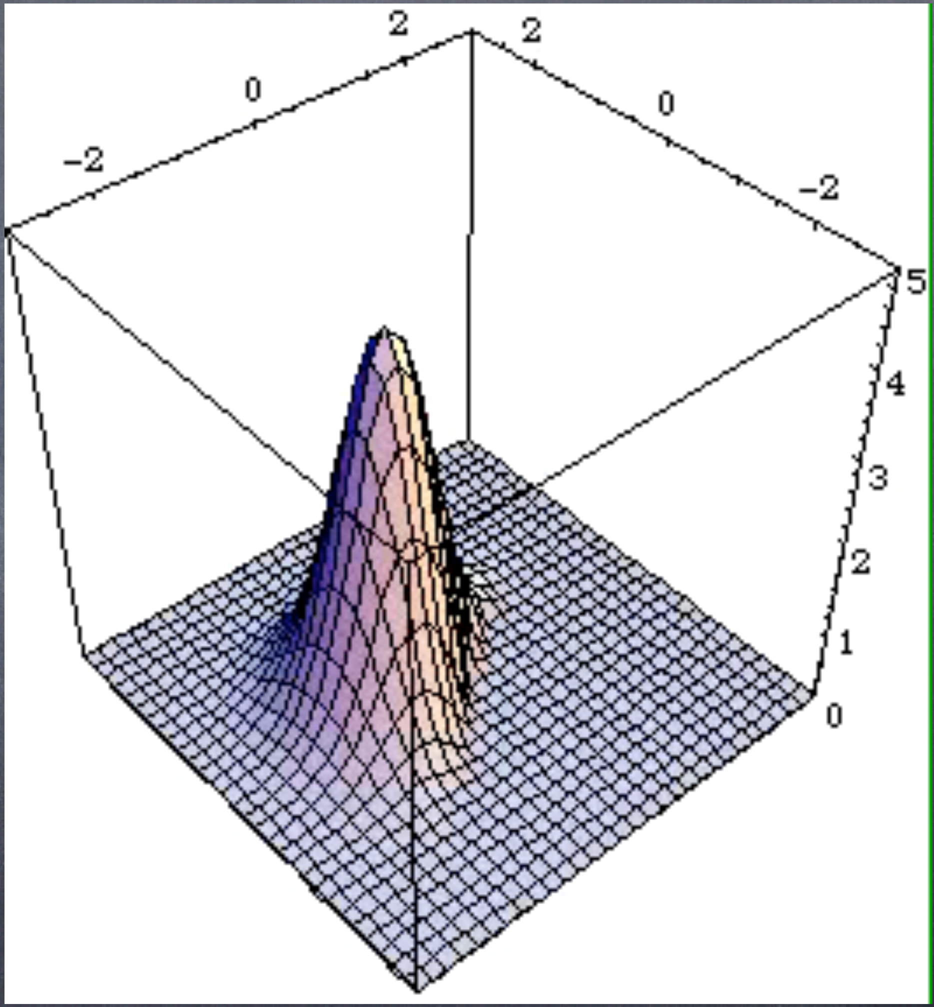
Induced phase gradients: the Skew/Paschke effect

(phase gradient due to coupling between laser-beam divergence and Pockels cell tilt)

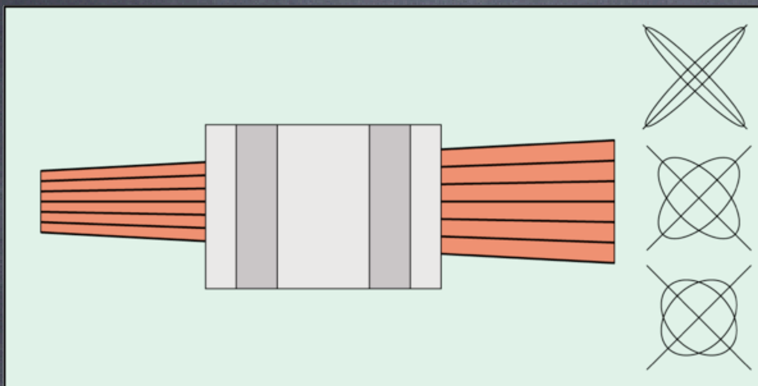


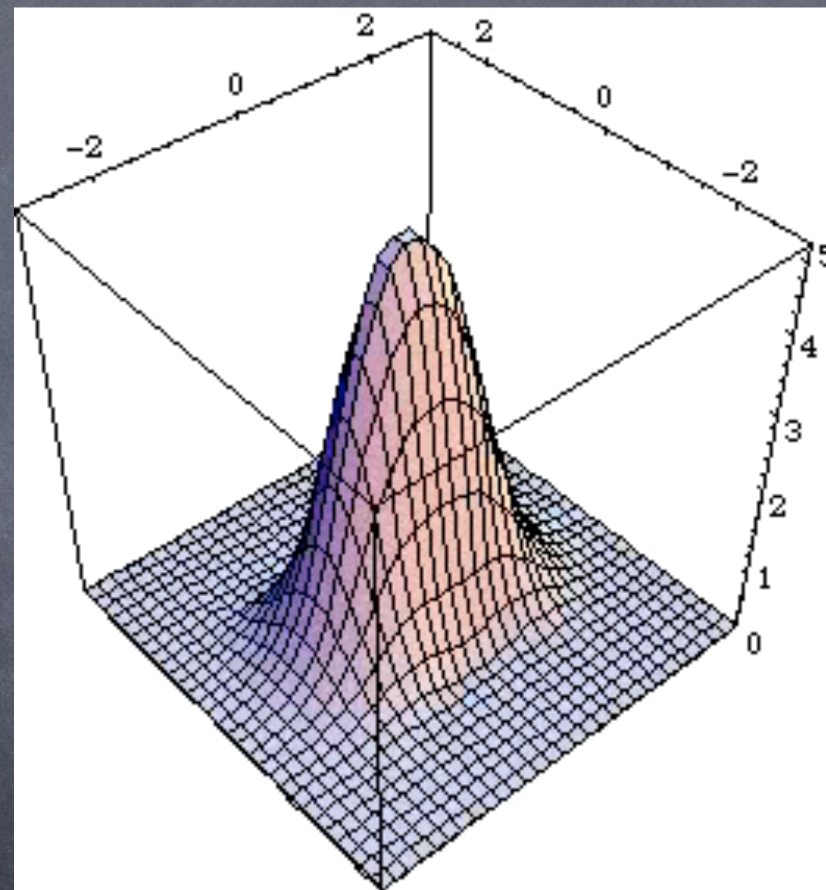
At right parameters are chosen to exagerate the effect. Also, the flipping between helicities is made continuous rather than a step function.

Can be minimized by aligning cell while acquiring parity-style position-difference data.



The Skew/Paschke effect, with an untilted Pockels cell causes a (tiny) breathing mode in the laser beam

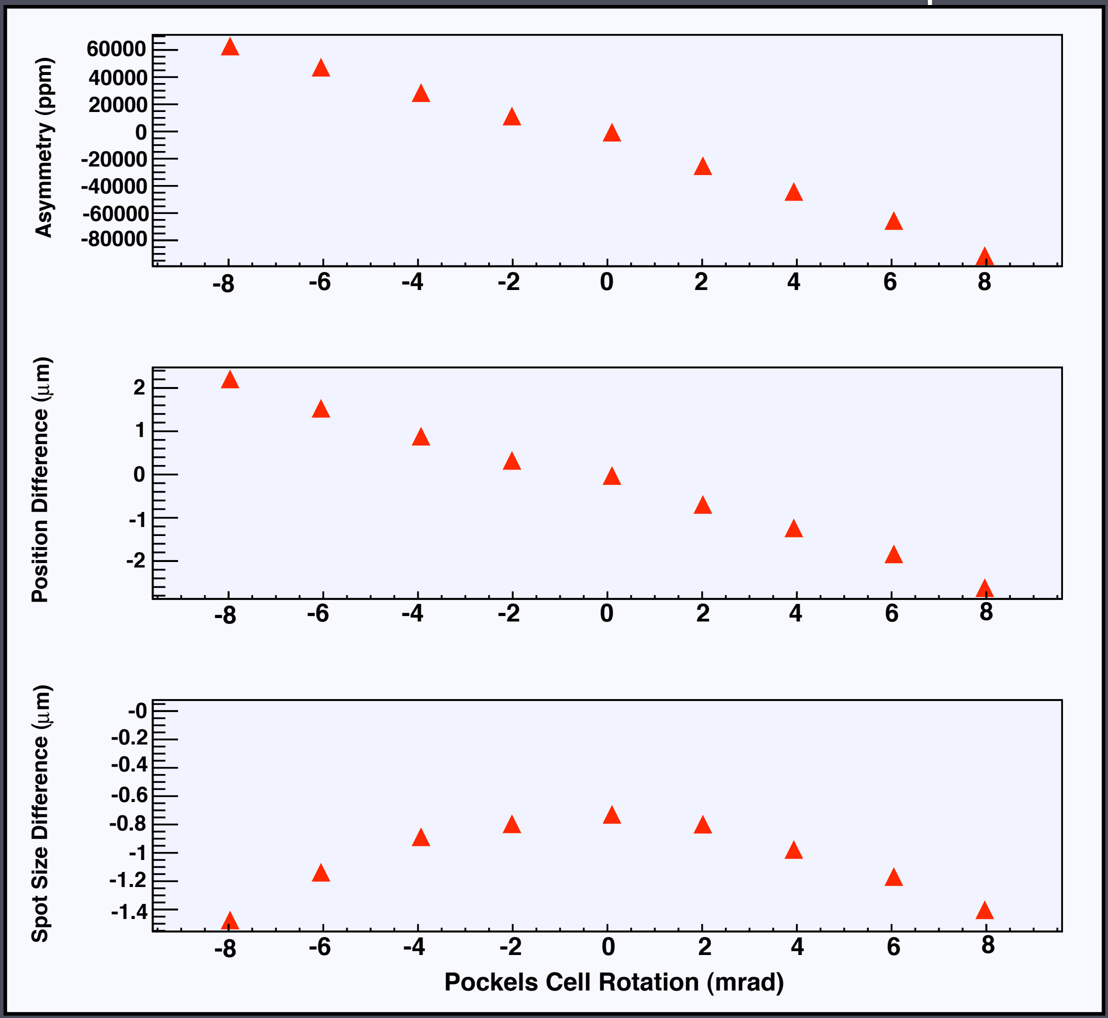




We currently trying to understand the size of the expected effect.

Tilt scans quantify skew effects

A "tilt scan" is ESSENTIAL to zero out position difference effects



Charge asymmetries

Position differences

Spot-size differences

The effects are so small that a parity-style DAQ must be used to see effects.

Averaged helicity-correlated beam parameters for HAPPEX II

		Helium	Hydrogen
Charge asymmetry →	A_Q	-0.377 ppm	0.406 ppm
Energy difference →	A_{Energy}	3 ppb	0.2 ppb
x-position difference →	Δx	-0.2 nm	0.5 nm
x-angle difference →	$\Delta x'$	4.4 nrad	-0.2 nrad
y-position difference →	Δy	-26 nm	1.7 nm
y-angle difference →	$\Delta y'$	-4.4 nrad	0.2 nrad

The control achieved during the hydrogen run was unprecedented.

Beam diameter differences

Tilt scan data limits (δ diameter)/diameter < 10^{-4}

What is needed?

Qweak < 7×10^{-3} (2007 proposal)

PREx < 1×10^{-4}

12 GeV Moller < 5×10^{-6} $\Rightarrow$ 0.06 ppb along single azimuthal φ

(10% of statistical error)

- Some suppression from azimuthal averaging (at least for breathing mode).
- Definitely want more flips !!! Wien filter very important (see Riad Suleiman's talk on Friday).
- More work desirable.

SUMMARY

- Enormous improvement has occurred in the control of helicity-related systematics.
- Demonstrated levels of control, while challenging, are definitely sufficient for the current generation of parity experiments.
- Demonstrated levels of control, with additional flips, are sufficient for 12 GeV Moller, but some “breathing” room would be nice!