Demands on polarized electron sources by future parity violating experiments

Mark Dalton

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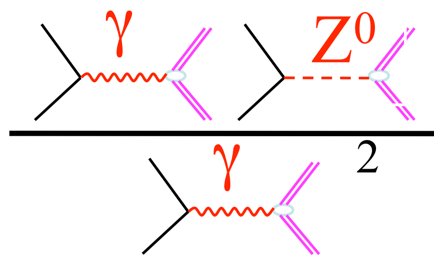
UVa: Kent Paschke, Manolis Kargiantoulakis, Gordon Cates
JLab EGG: Matt Poelker, Joe Grames, John Hansknecht

Parity Violating Asymmetry

Measurement: asymmetry in electron scattering rate (dependent on longitudinal polarization of the beam)

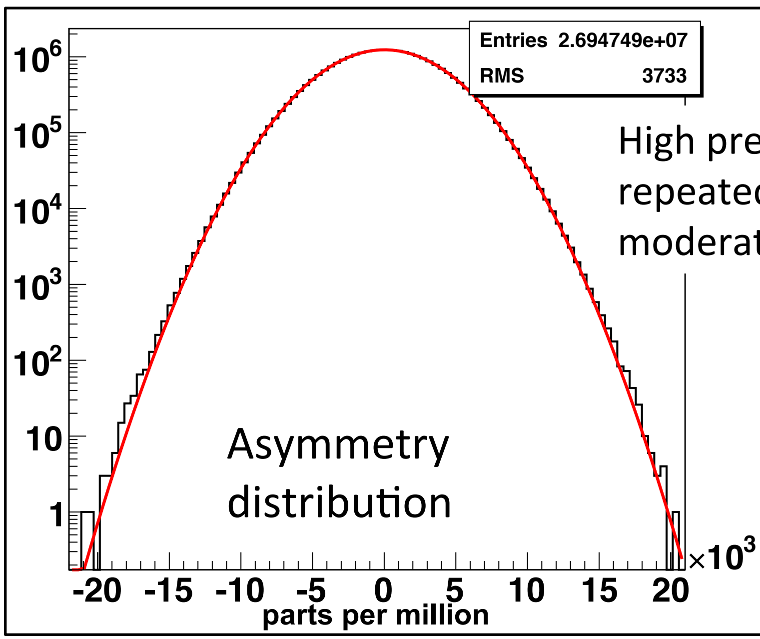
sensitive to weak neutral current

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$



$$\sim \frac{10^{-4} Q^2}{\mathrm{GeV}^2}$$

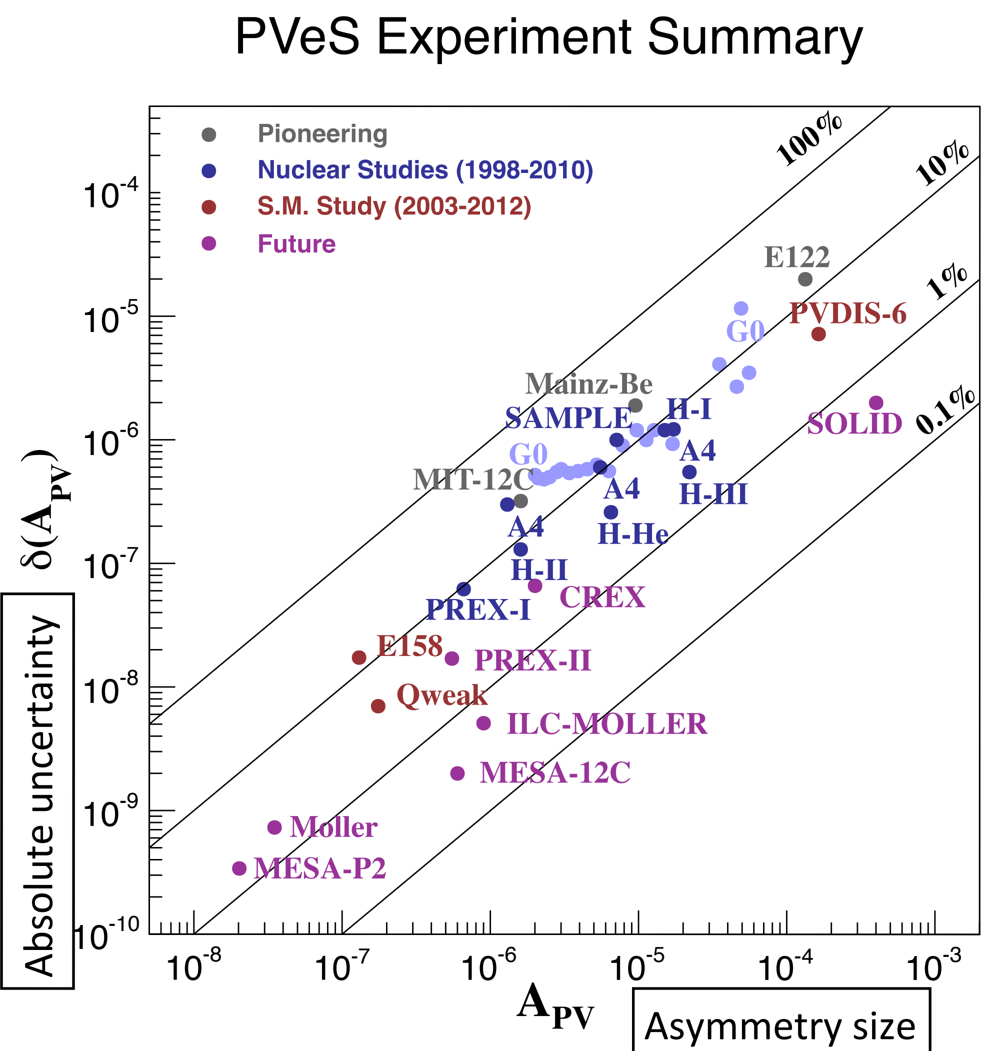
Very small effect!
part-per-million (ppm) to part-per-billion (ppb)



High precision obtained by repeated measurements at moderate precision.

- Precision tests of the Standard Model of particle physics
- Flavor separation of nucleon form-factors
- Neutron distribution in neutron rich nuclei

PVES Experiments



Experiment	Uncertainty	Reversal
HAPPEX:	δA ~ 1000 ppb	30 Hz
A4:	δA ~ 300 ppb	30 Hz
G0:	δA ~ 300 ppb	30 Hz
HAPPEX-II He:	δA ~ 250 ppb	30 Hz
HAPPEX-II H:	δA ~ 100 ppb	30 Hz
SLAC E158:	δA ~ 15 ppb	30 Hz
PREx II:	δA ~ 15 ppb	240 Hz
Qweak :	δA ~ 5 ppb	960 Hz
MOLLER :	δA ~ 0.5 ppb	1920 Hz
P2:	δA ~ 0.3 ppb	?

Beam False Asymmetries

The beam must look the **same** (intensity, position, shape, background) between the two polarization states. Any differences can lead to a false asymmetry.

$$A_{\rm false} = \sum_i \frac{\partial A}{\partial x_i} \Delta x_i$$

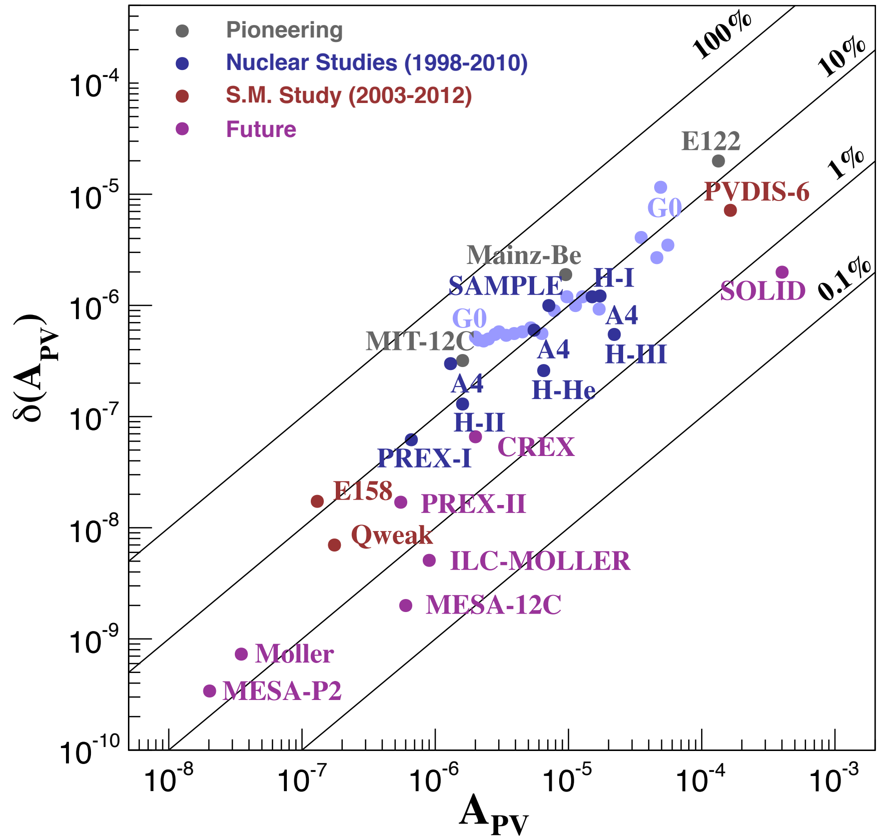
compare to size of physics asymmetry

$$x_i = x, y, x', y', E$$

Δx_i Polarization dependent beam differences:
Originate in the procedure used to change the polarization.

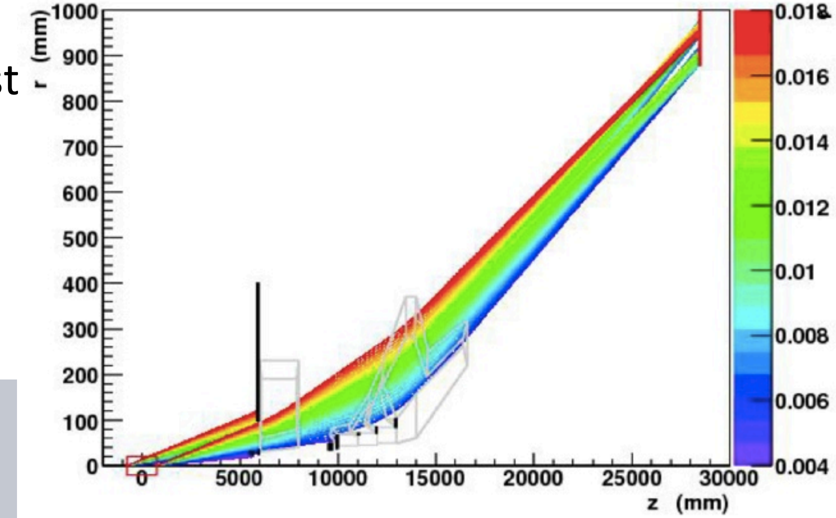
$\frac{\partial A}{\partial x_i}$ Sensitivity:
Depends on scattering angle, target nucleus and detector geometry.

PVeS Experiment Summary



MOLLER Experiment

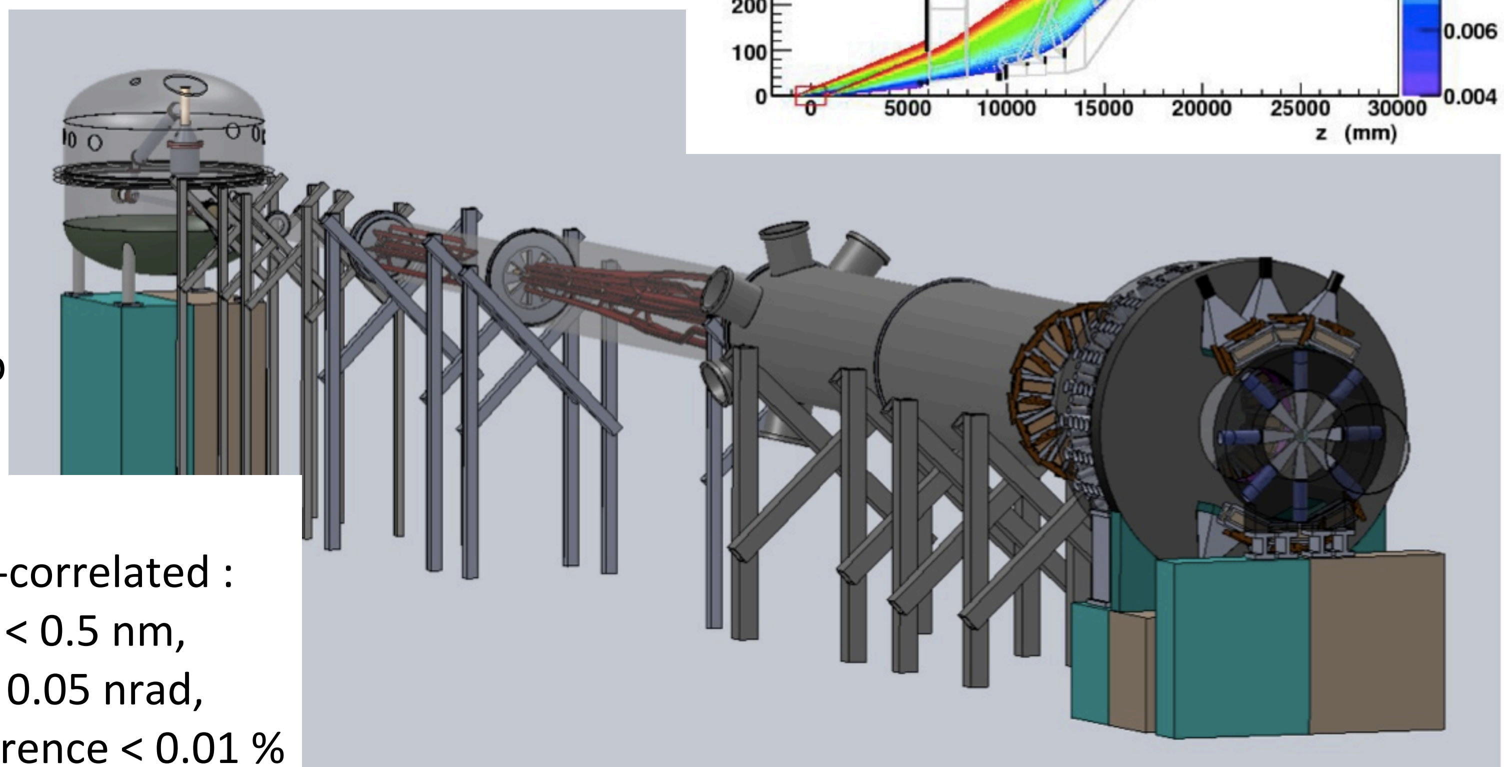
Flagship JLab experiment
important and powerful precision standard model test
tiny asymmetry, precision
open geometry, faster flip



$Q^2 = 0.0056\ (GeV/c)^2$
$E_{beam} = 11$ GeV
$0.29^o < \theta_{lab} < 0.97^o$

~85 μA,
1.5 m LH2 target

$A_{PV} \approx 35 \pm 0.73$ ppb

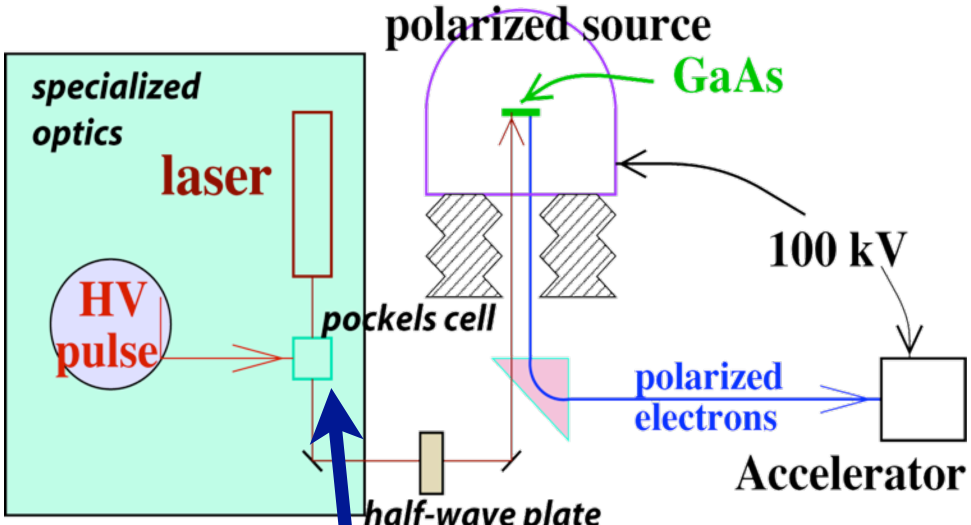


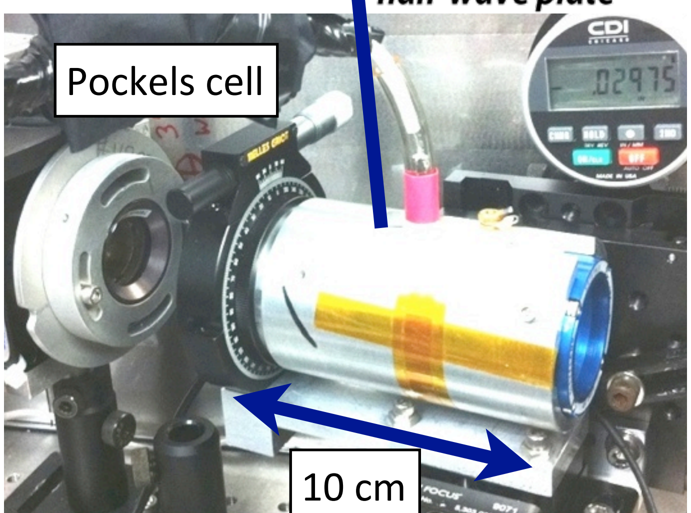
MOLLER limits
cumulative helicity-correlated :
position difference < 0.5 nm,
angle differences < 0.05 nrad,
laser spot size difference < 0.01 %

Changing Electron Polarization

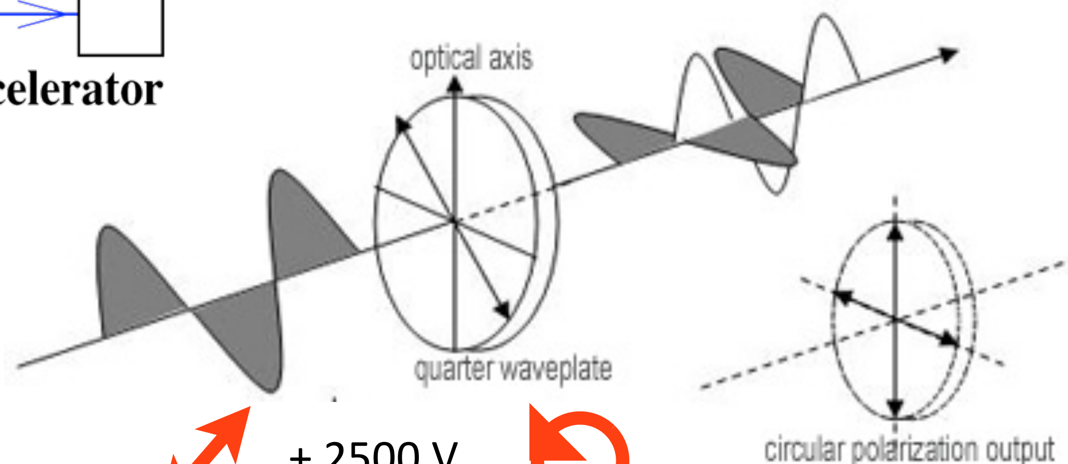
Electrons produced by photoemission from laser light.

Laser polarization determines electron polarization





Laser helicity changed using a Pockels Cell (electro-optic birefringent element) acting as a variable-wave plate.
Rotate initial linear light into right-circular or left-circular



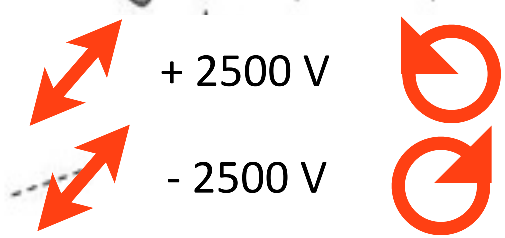
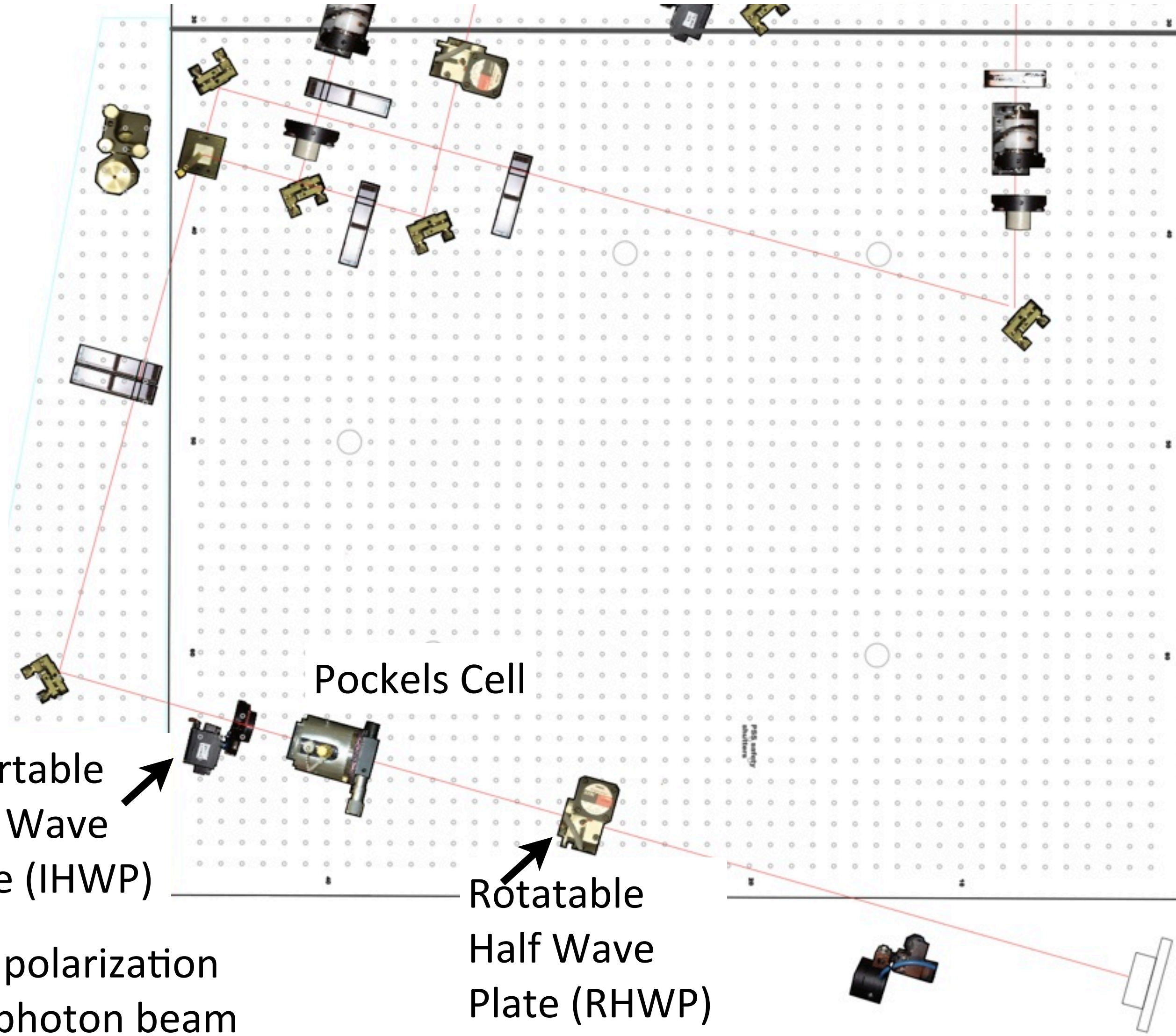


Table Layout

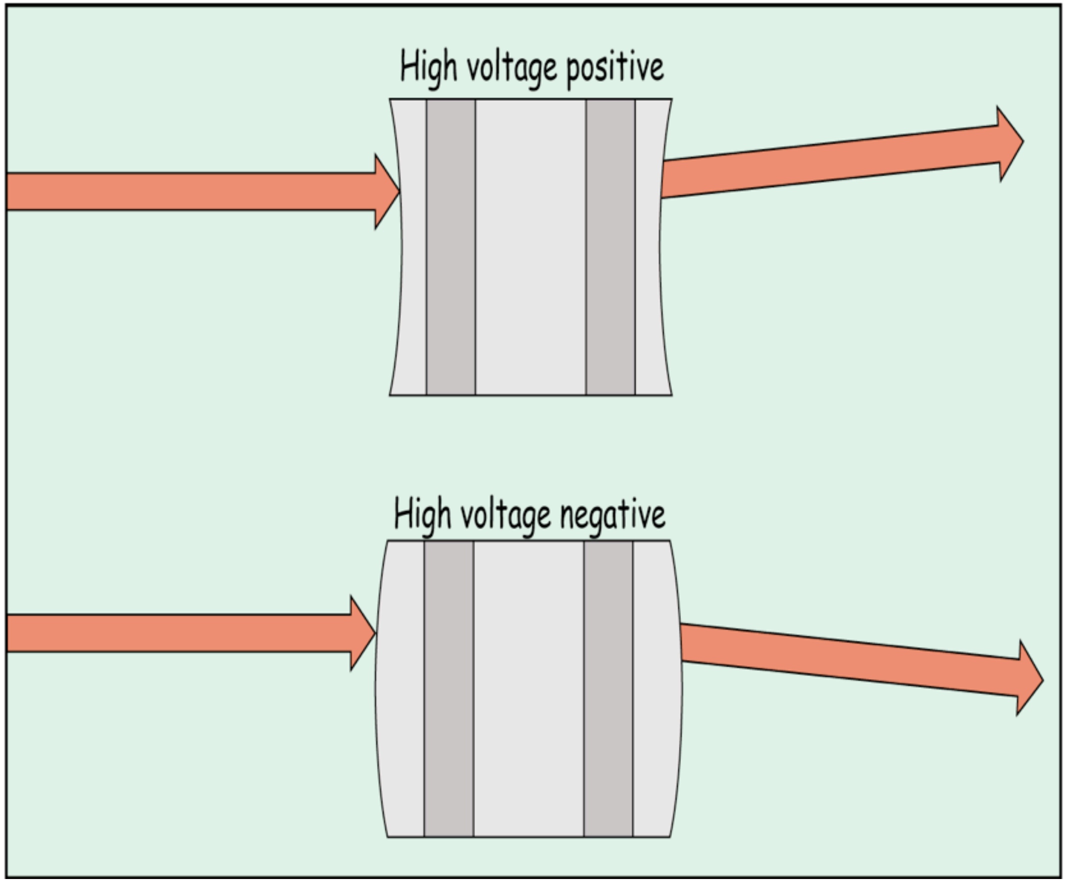


Reverses the polarization of the linear photon beam

Rotates the polarization ellipse

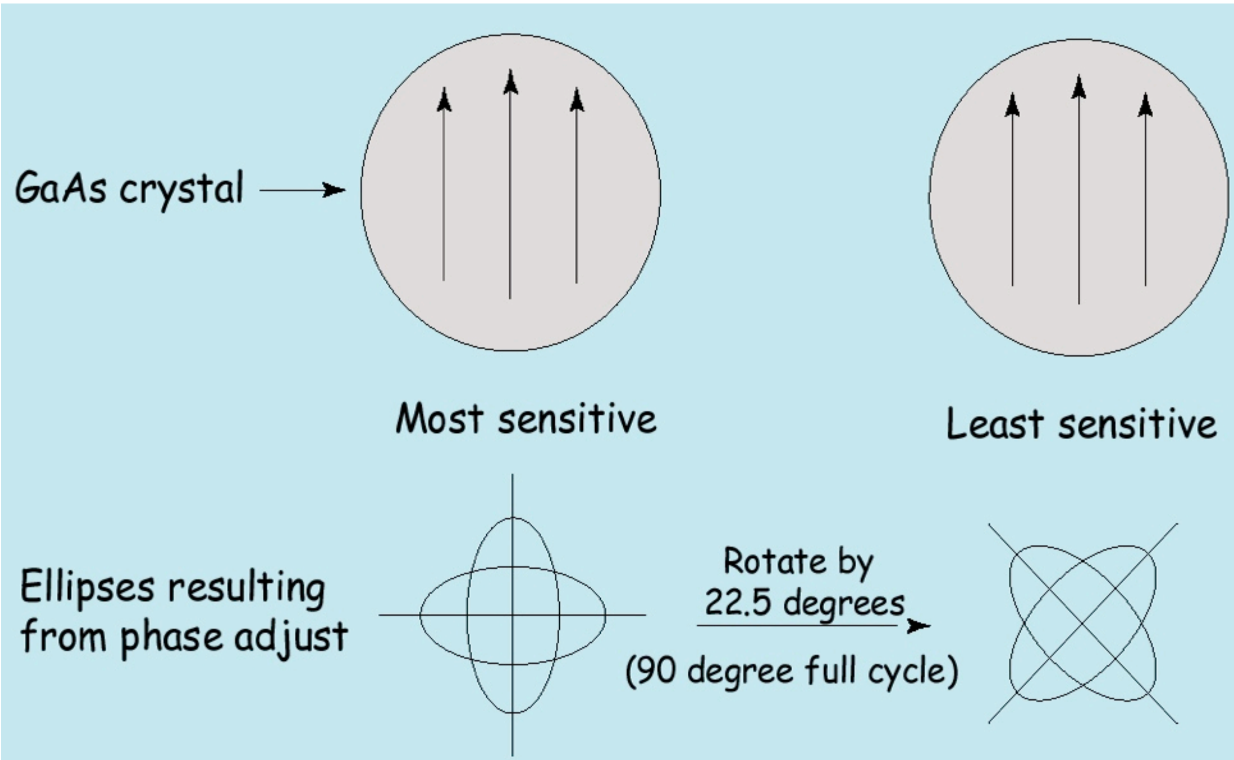
Pockels Cell Steering

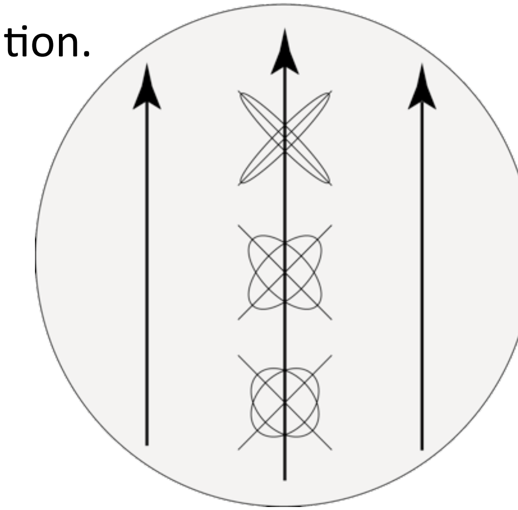
Crystal nature of Pockels medium leads to steering effects and vibrations after high voltage shocks which damp slowly.



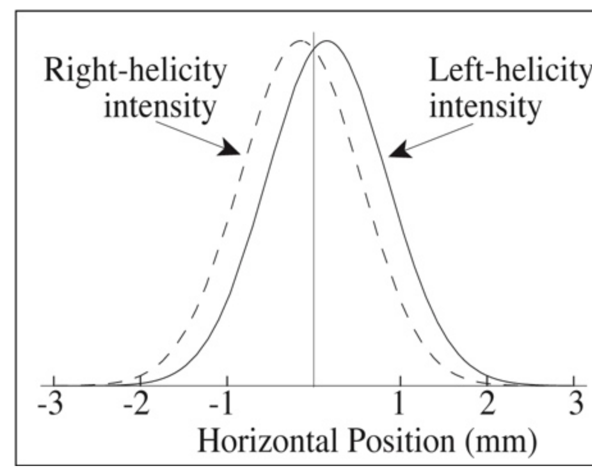
Cathode Analyzing Power

Cathode has ~4% analyzing power acting on residual linear polarization.

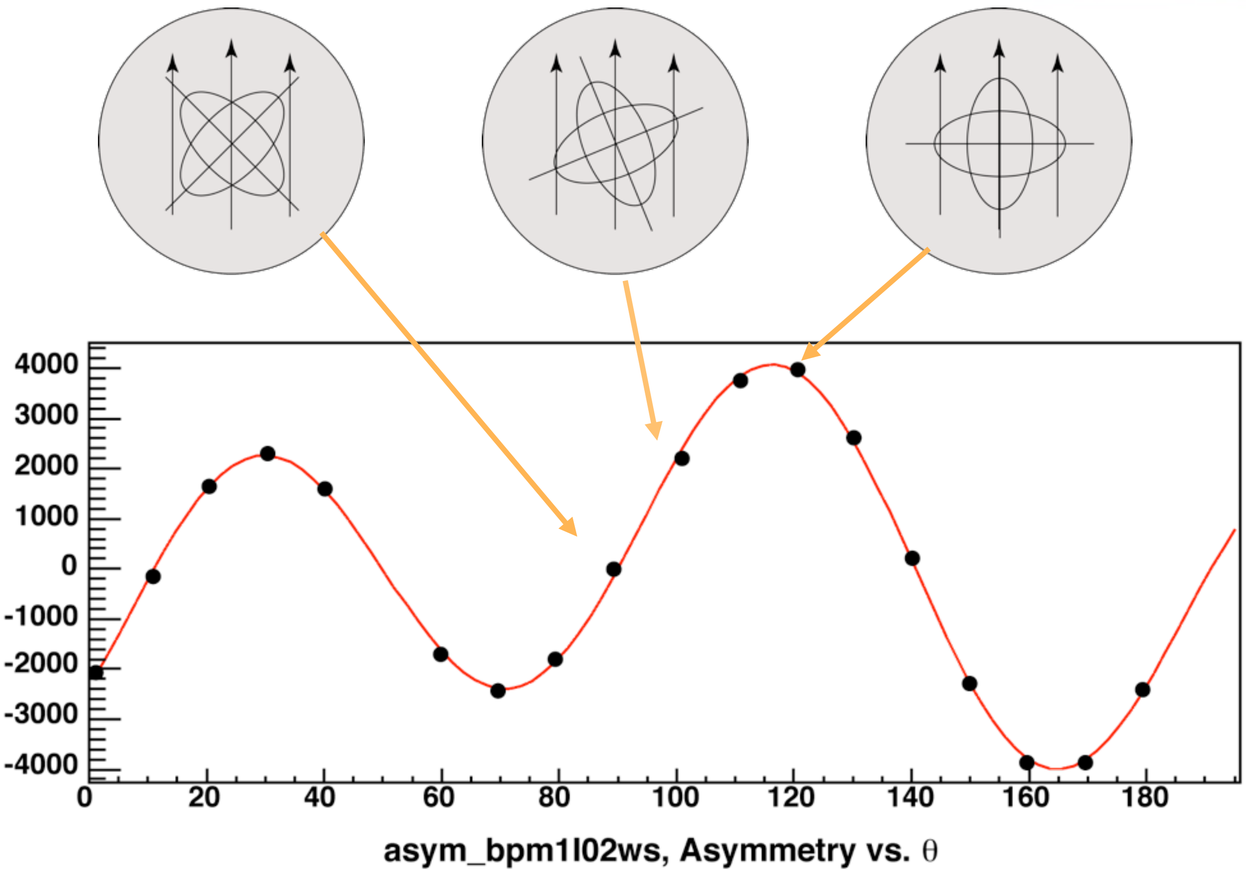




Birefringence gradients cause beam differences



General RHWP scan



Separate out mechanical and polarization effects and help to determine sources.

Careful alignment on the table to minimize as much as possible

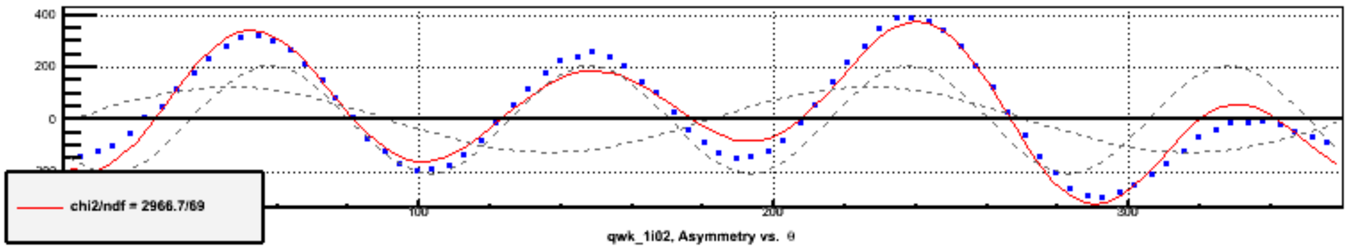
$$Aq = -7.98 + -1211.75 \sin(2x + 75.52) + -3151.04 \sin(4x + 158.47)$$

2θ term measures RHWP phase error and axis

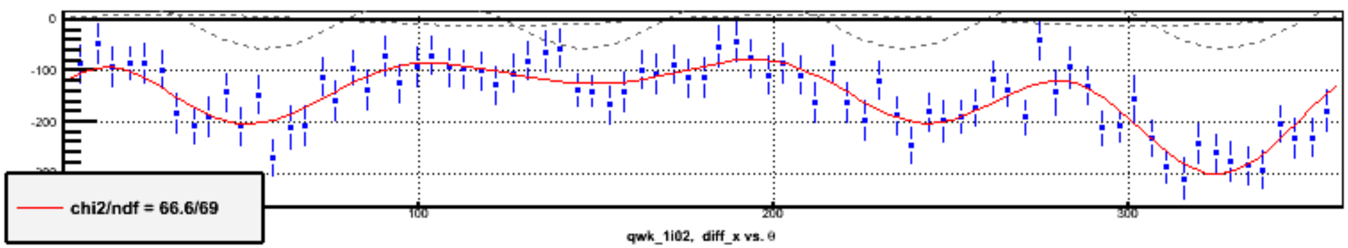
4θ term measures analyzing power*DoLP (from Pockels cell)

General RHWP scan

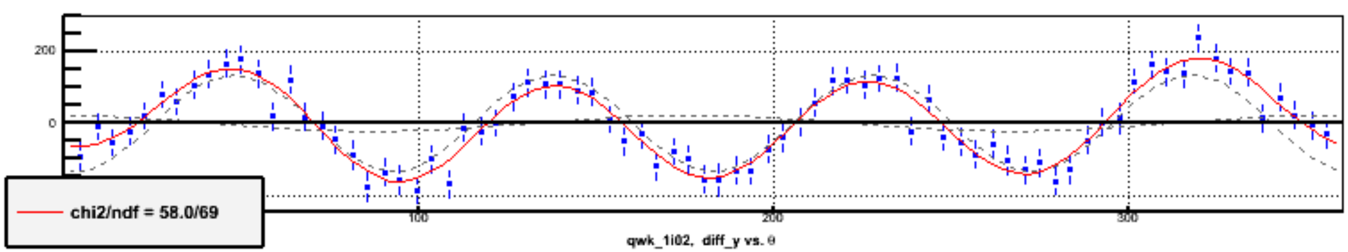
RHWP scan, Run 15630, IHWP (1,2) = (IN,OUT), PITA=0



$$Aq = +31.0 + 124.6 \sin(2\theta + 2.8) \;\; -205.6 \sin(4\theta - 38.2) \;\; +71.2 \sin(\theta + 61.0) \;\; +85.5 \sin(\theta - 17.0) \sin(4\theta + 38.2)$$



$$Dx = -149.3 + 53.1 \sin(\theta + 53.8) \;\; -11.0 \sin(2\theta + 151.4) \;\; -55.6 \sin(4\theta + 135.9) \;\; +53.1 \sin(\theta + 53.8) \;\; -36.9 \sin(\theta + 64.1) \sin(4\theta + 302.1)$$



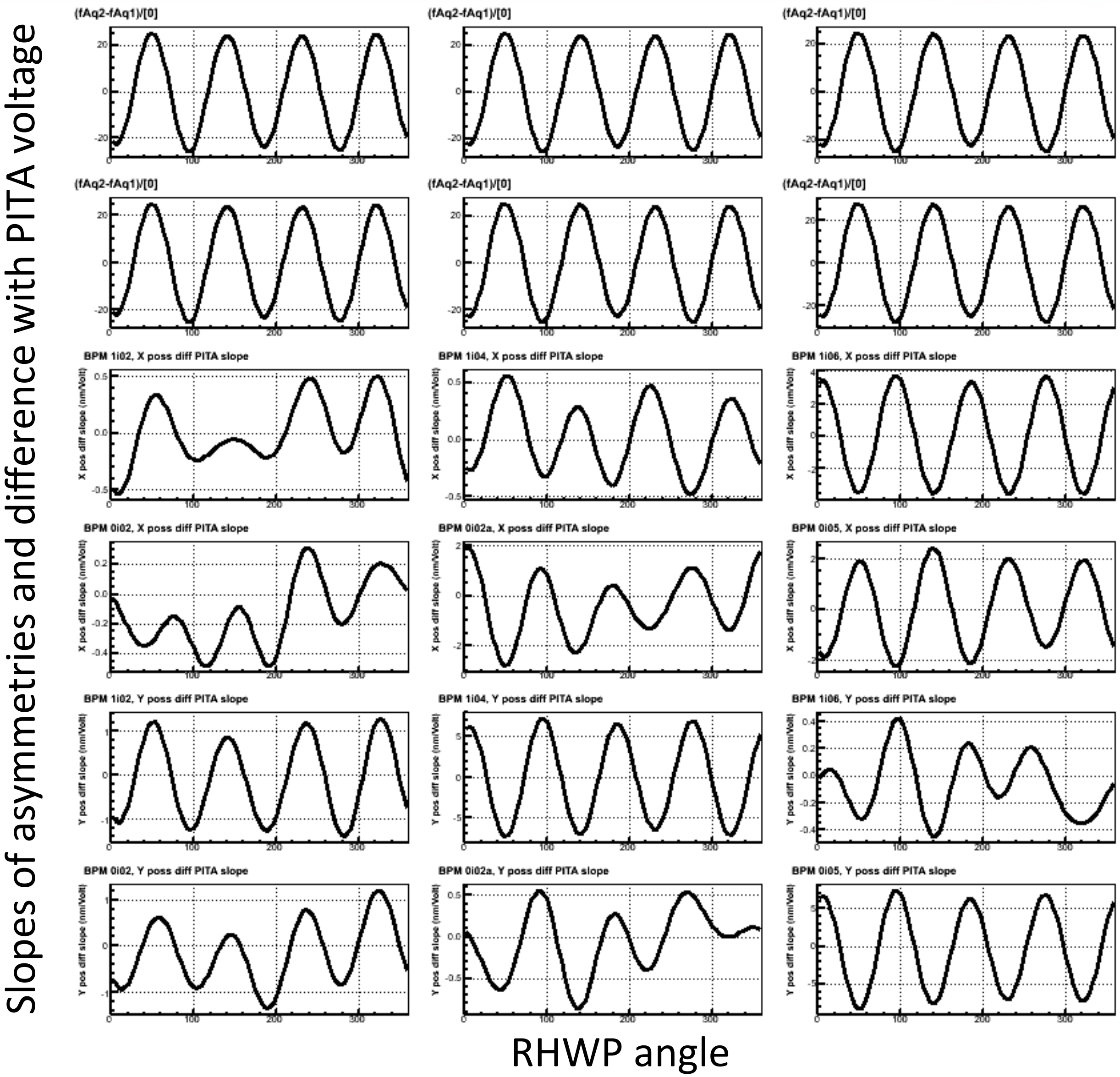
RHWP angle

Careful alignment on the table to minimize as much as possible

Separate out mechanical and polarization effects

Balance birefringence of vacuum window and cathode analyzing power

Measure Position Differences



As a function of monitor in the injector

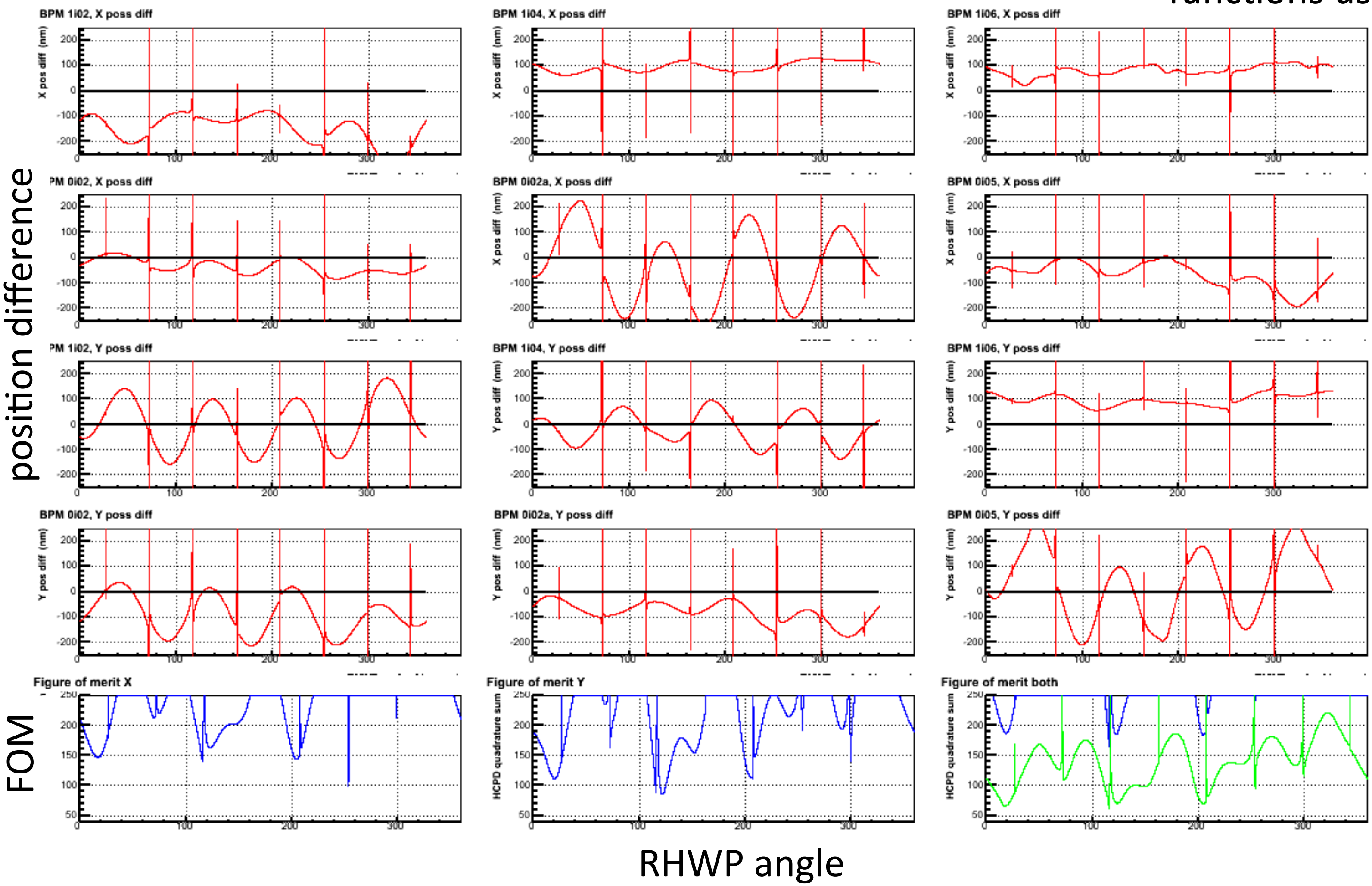
Charge asymmetry slope depends on RHWP

PITA effect depends on RHWP

Optimization

Optimize some figure of merit using a lot of data

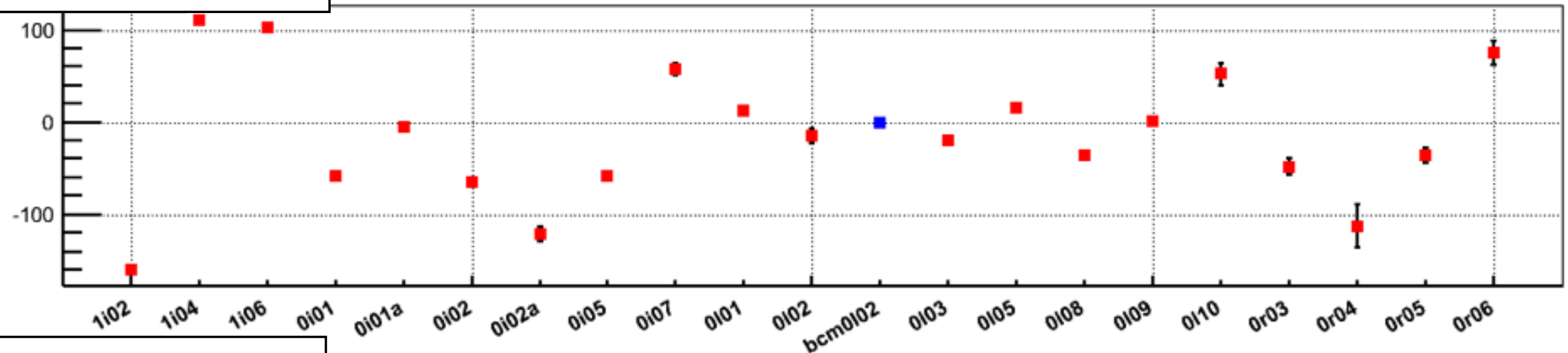
Physically motivated functions used to project



Position Differences

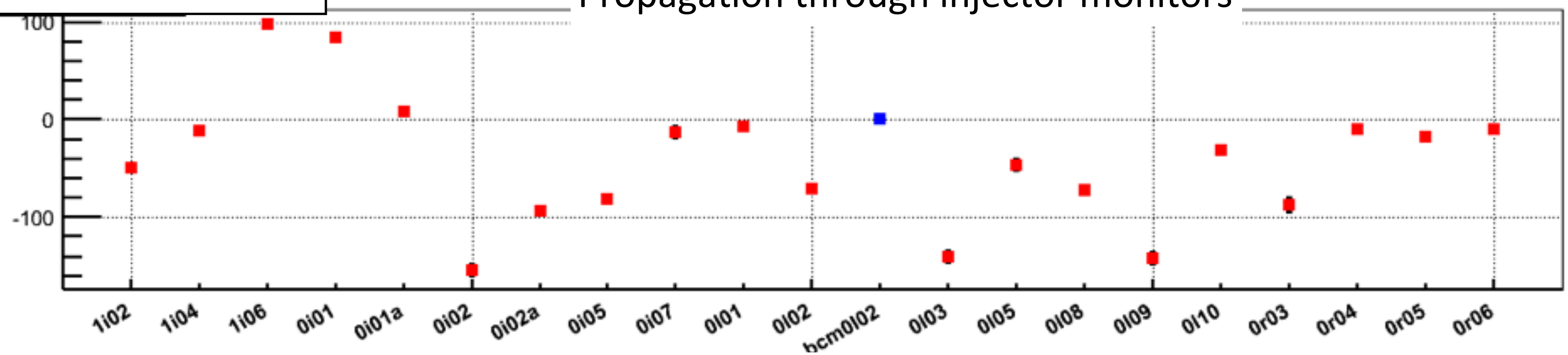
Qweak Experiment: Position differences start out at ~ 100 nm off the cathode.
As-good or better than previously achieved.

X position differences



Y position differences

Propagation through injector monitors

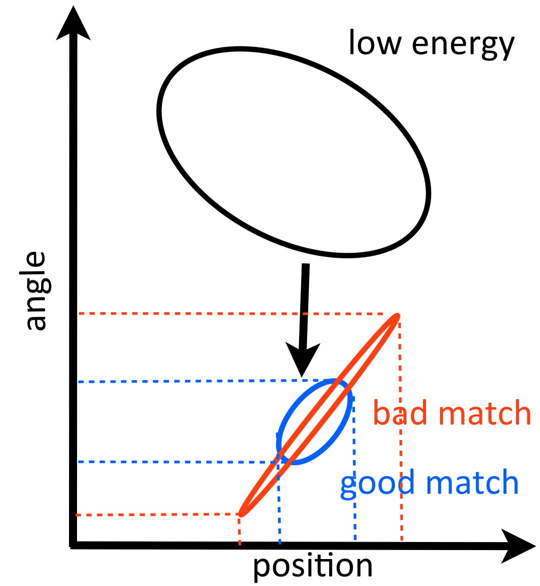


Kinematic Damping

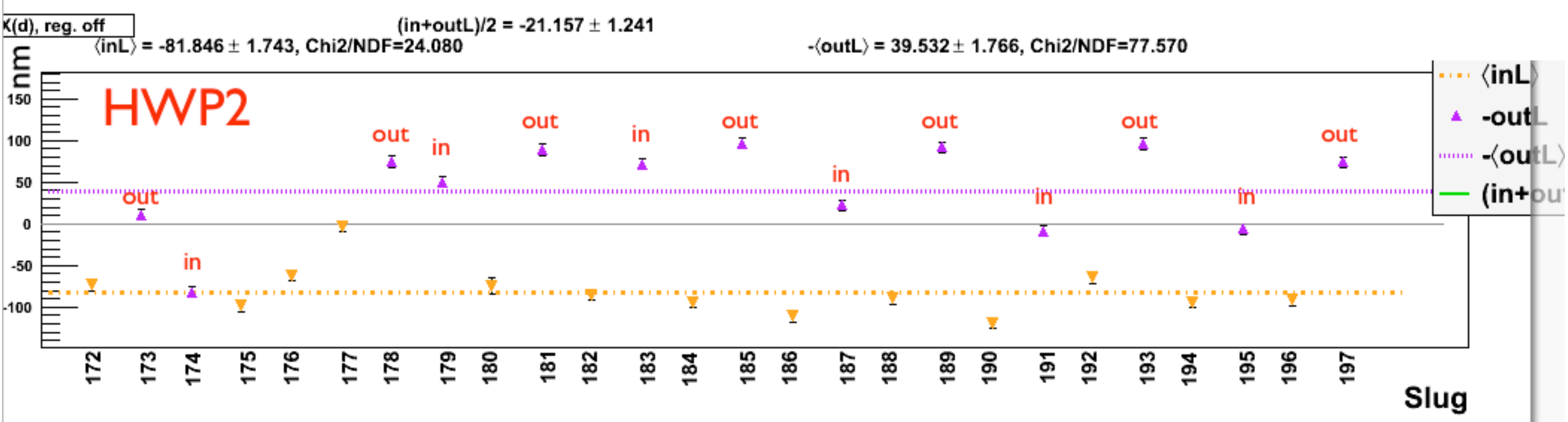
Try to obtain additional suppression due to Lorentz boost (so call 'kinematic' or 'adiabatic' damping.) Area of beam distribution in phase space (emittence) is inversely proportional to momentum. Requires commitment from the collaboration to allow careful (time consuming) setup of accelerator optics.

For Qweak this was not done and position differences do not decrease from the injector values.

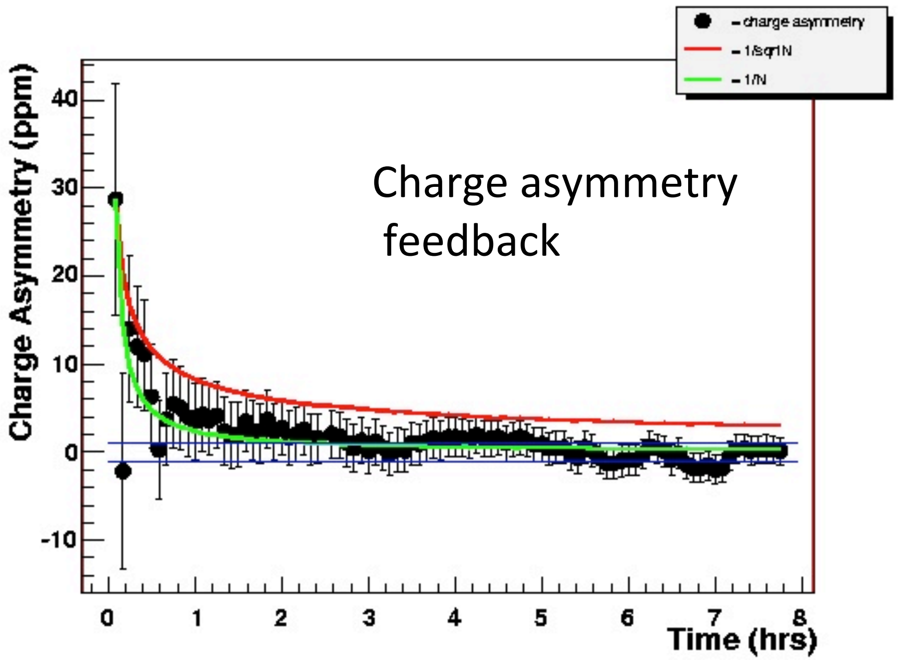
Position differences do not change sign with passive polarization

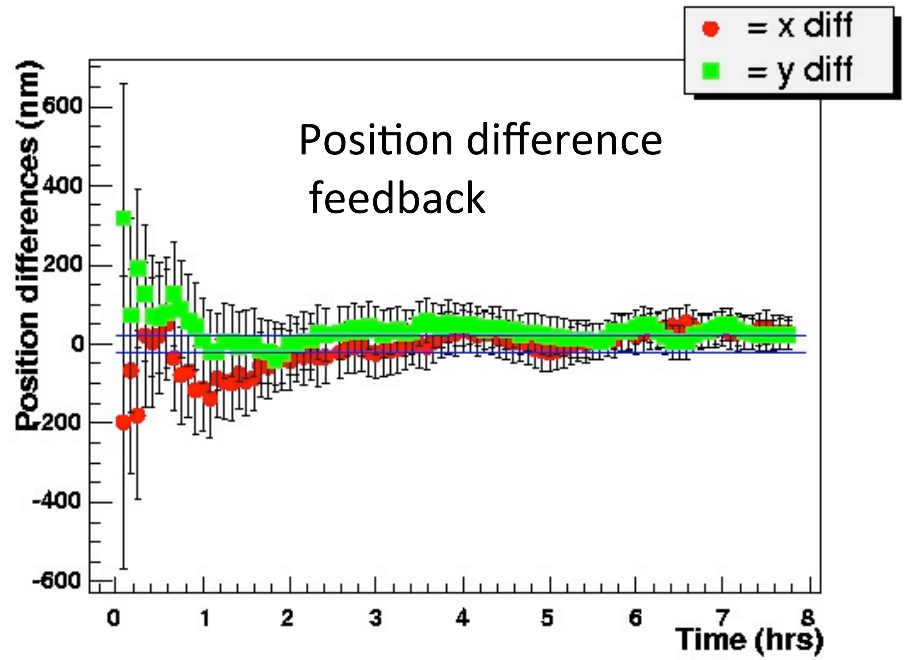


Target X



Feedback





This works, but these are heavy hammers for a subtle problem.
Does nothing to fix higher-moment problems, may even create them.
Preferred strategy: configure system with care to minimize effects.
If you do it right, all problems get small together*!
If you do your best there, you can use feedback to go the last mile (or nanometer).

Higher Moment Effects

Beam spot size asymmetries

Simple breathing .

Same <x>, <I>,

Different <x^2>

Interaction between scraping and intensity feedback.

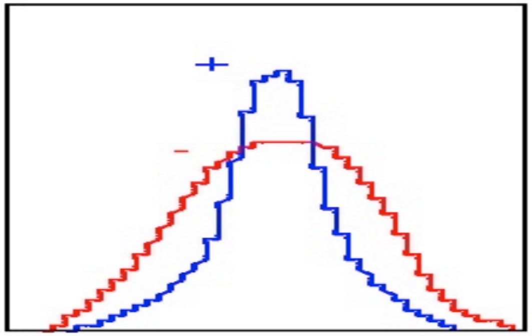
Same <x>, <I>,

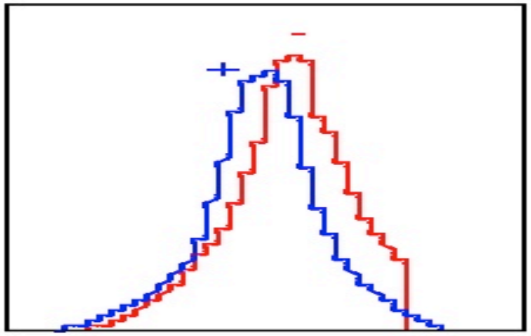
Different <x^2>

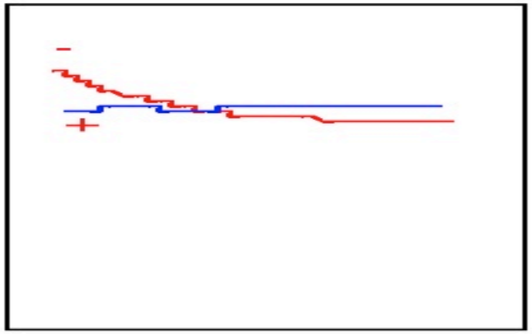
Differential intensity bounce.

Same <x>, <I>,

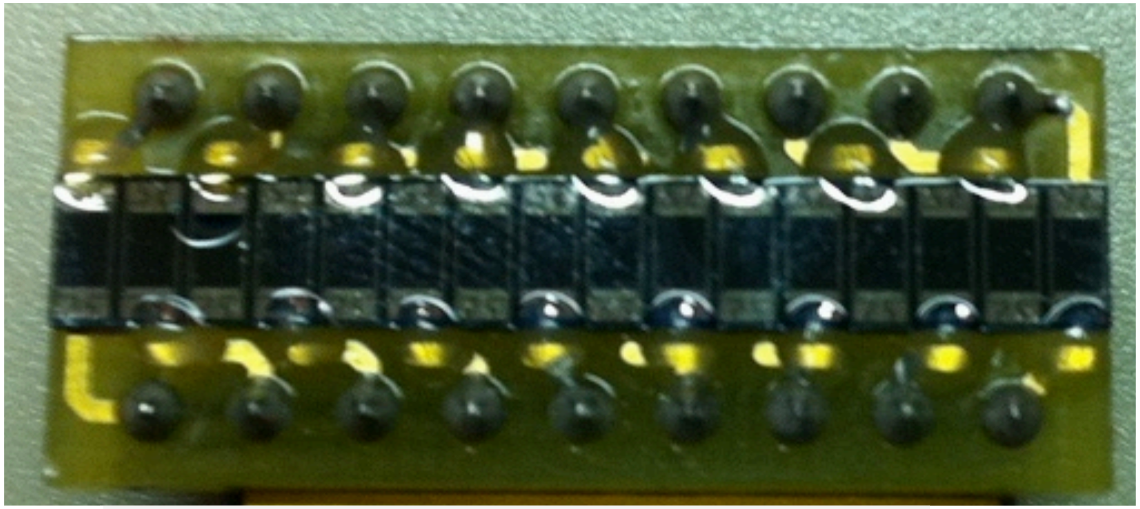
Different <I ^{2}>





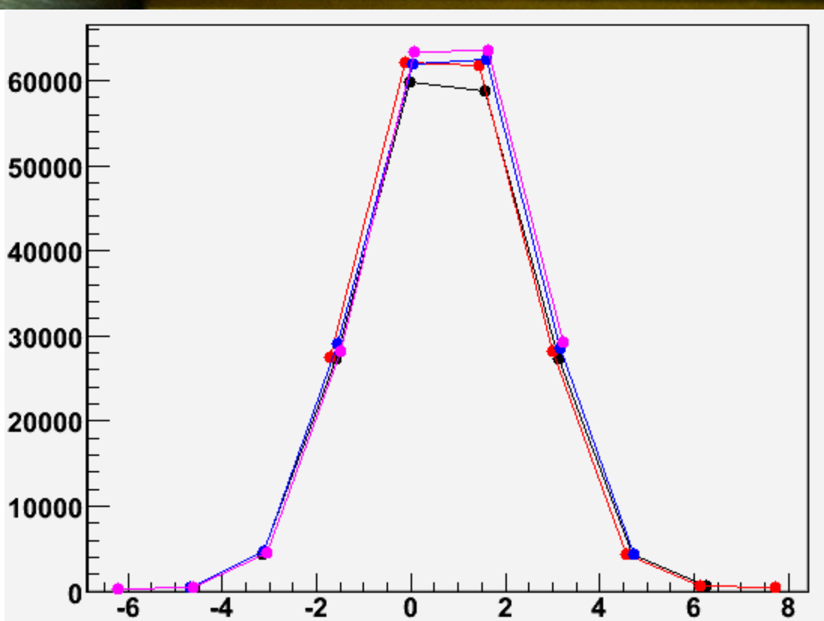


Spot Size Asymmetry



Linear Photodiode Array

Profile laser beam in 1 dimension at high differential rate



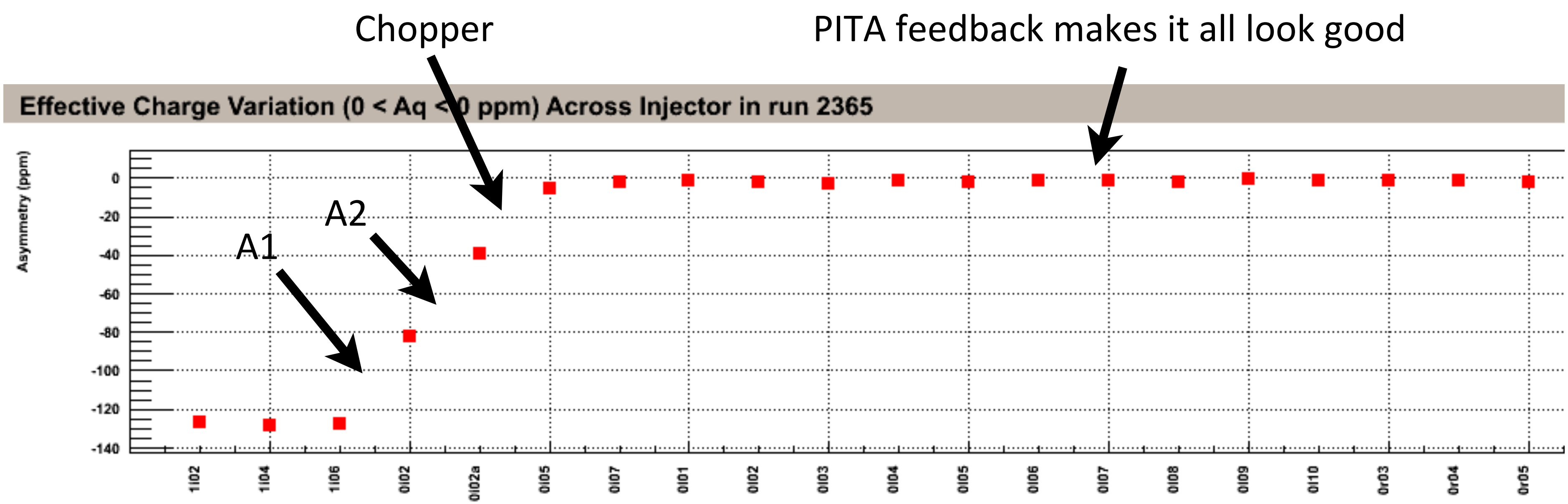
Measure helicity correlated
spot size asymmetry
higher moment spot "shape" asymmetry

Using this technique, bounded spot size asymmetry for
PREx to < 10^{-4}
and QWeak to < 10^{-3}

Clipping on Apertures

Qweak was clipping or close to clipping on the injector apertures most of the time.

- Occurs after the table (can't measure)
- Blows up charge asymmetry width
- Potentially causes higher moment beam moments
- Potentially couple various otherwise-independent effects (charge asymmetry, position differences, higher moments)

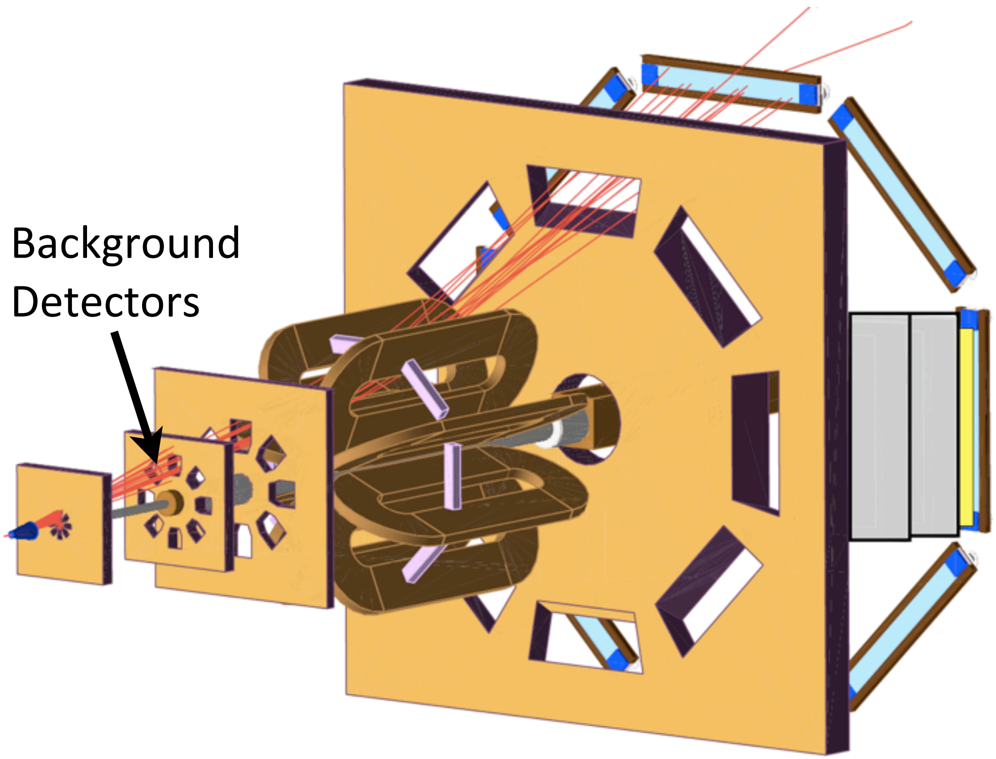


Qweak Background Asymmetry

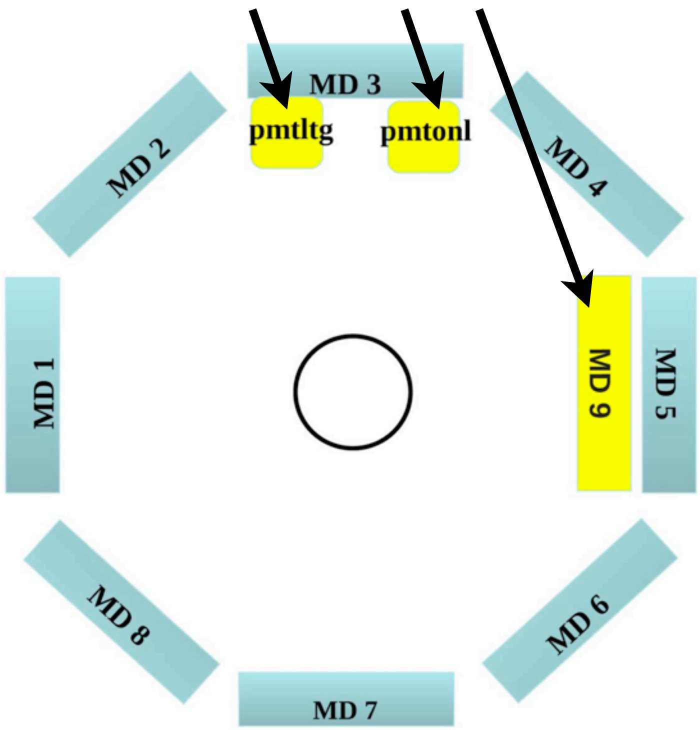
Qweak is an open geometry experiment. Background detectors measure asymmetries at positions away from the main scattered flux.

Hypothesis is that background signal is halo scattering from the beamline, particularly a small tungsten collimator. Asymmetry is presumed to be from a charge asymmetry on the halo. Needs to be studied with simulation.

Background Detectors

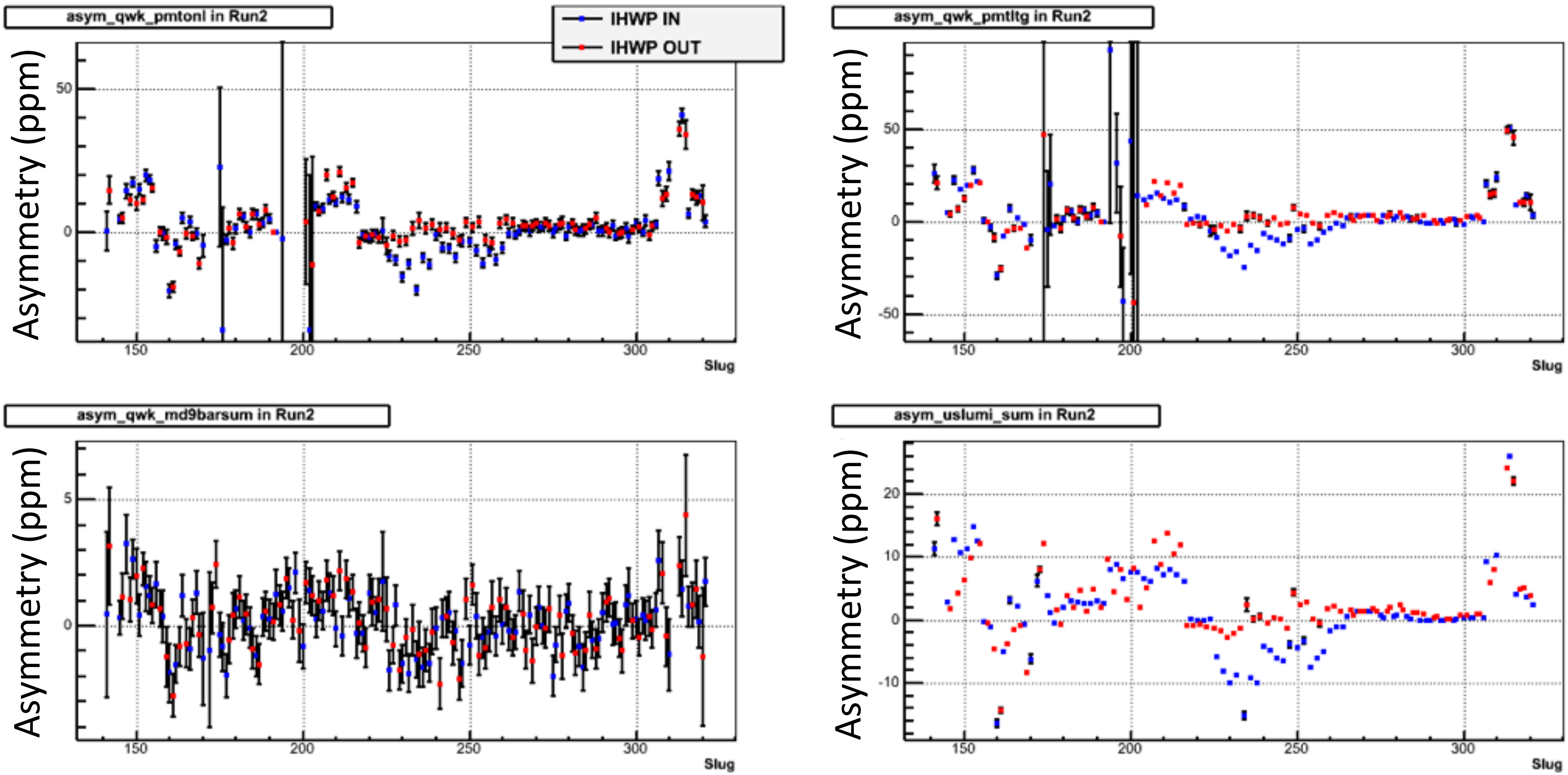


Background Detectors



Qweak Background asymmetry

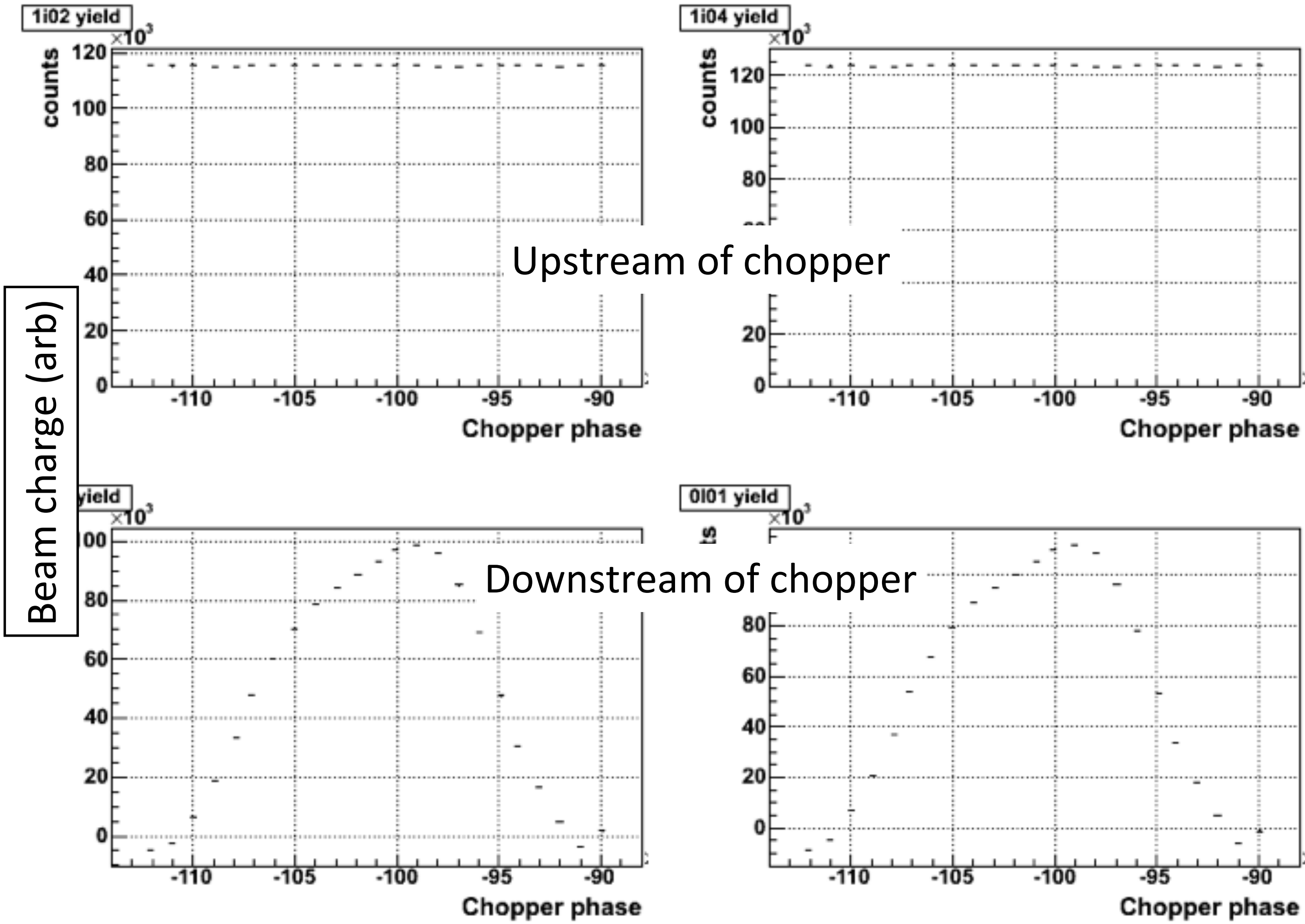
Asymmetry is large (50 ppm) in background detectors, normal running.
Asymmetry show qualitative agreement between all background detectors.



Chopper Phase Study

The chopper is an RF device which allows the beam pulses to be chopped in the longitudinal direction at front or back to set the pulse length.

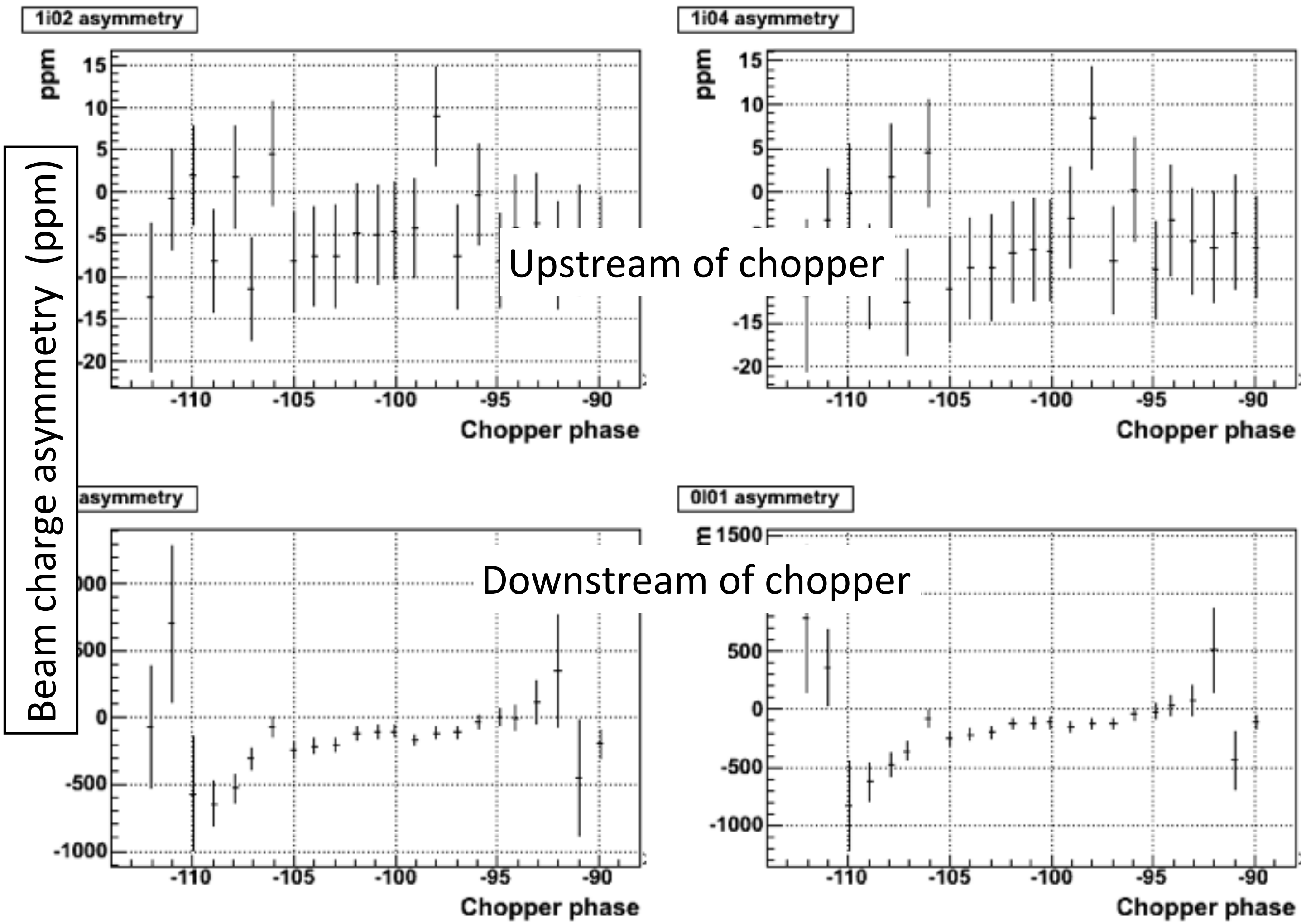
Sharply narrowing the aperture (master slit) and varying the chopper phase allows the longitudinal profile of the beam to be measured.



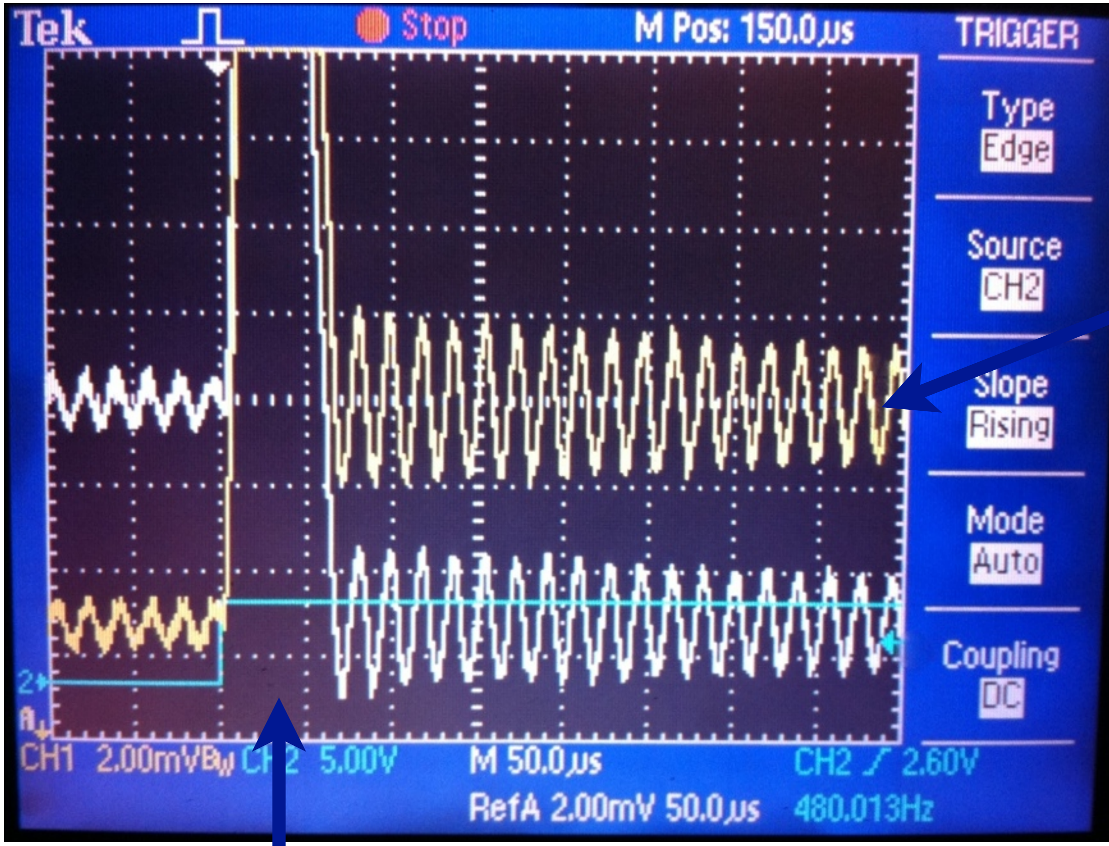
Chopper Phase Study

There exists a non-zero beam charge asymmetry for some portions of the beam in the longitudinal profile.

This is at least a proof of principle that small portions of the beam phase space can carry large charge asymmetries.



Fast Flip Pockels Cell 'Ringing'



QWeak experience

Potentially troublesome 'ringing' if coupled to other effects

Better Pockels Cells and high voltage switches exist but the setup is notoriously tricky.

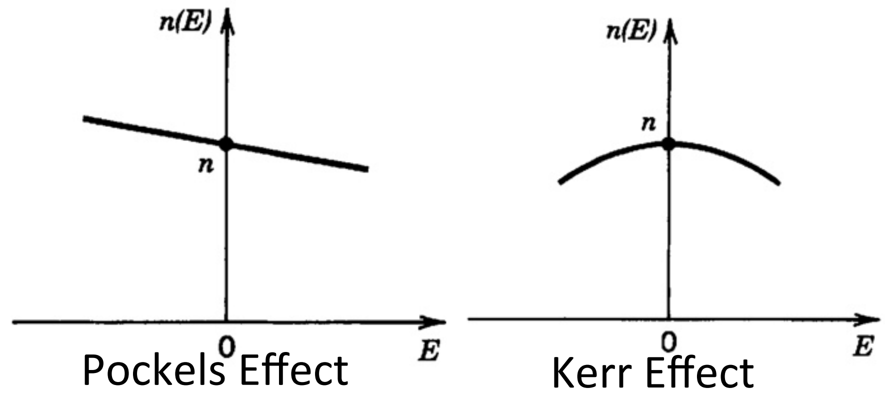
70 µs switching time

For 960 Hz flip frequency ⇒ ~ 7 % dead time

Kerr Effect and Kerr Cell

$$n(E) \approx n + a_1 E + \tfrac{1}{2} a_2 E^2$$

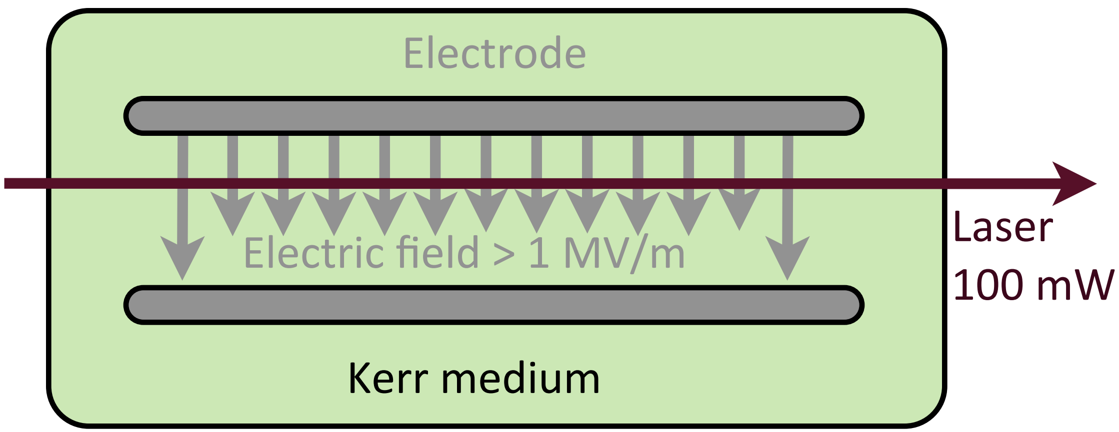
very small



Kerr Material: centrosymmetric materials (gases, liquids, and certain crystals)

$$n(E) \approx n + \tfrac{1}{2} a_2 E^2$$

$$\Delta n = \lambda K E^2$$



A Kerr Cell is cell containing a Kerr Material with an applied electric field through which a laser beam propagates.

Problems with Kerr Cells

Weakness of effect

Difficulty designing cell

- High voltages
- Close electrode spacing

Non-linearity of effect

Field uniformity very important

- Symmetry provided by field not by a crystal

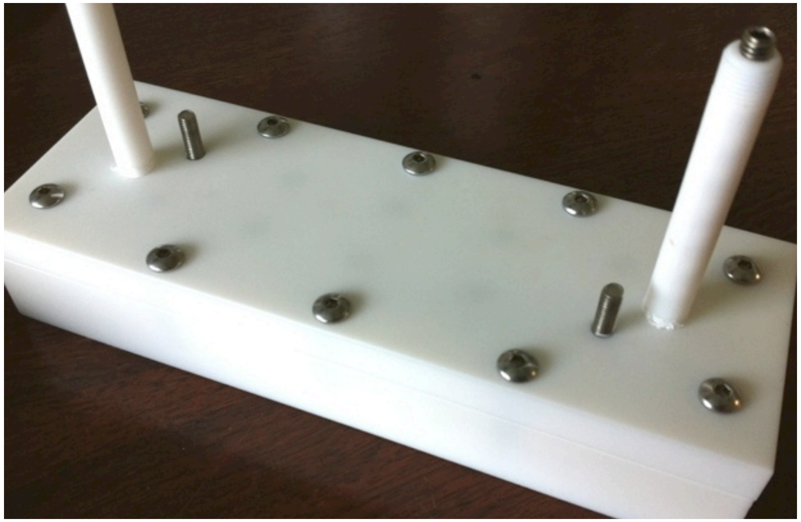
Transverse E

Self interaction

- Optic Kerr (AC) Effect
- Laser field causes self focussing
- Spot size depends on beam power.
- Mitigate by shortening the cell and increasing the high voltage.

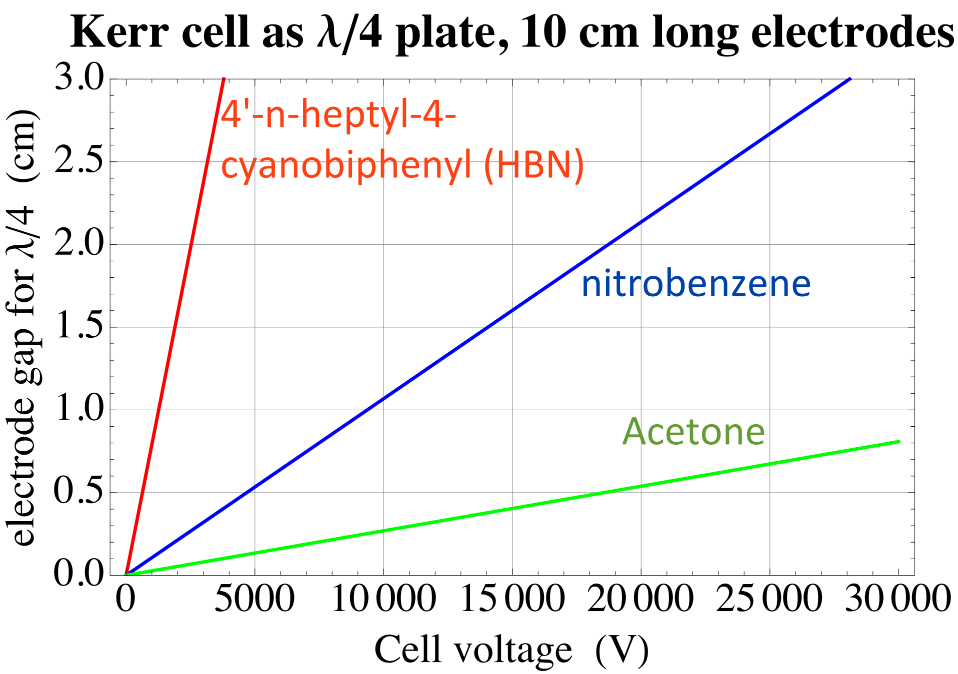
Sign Independent

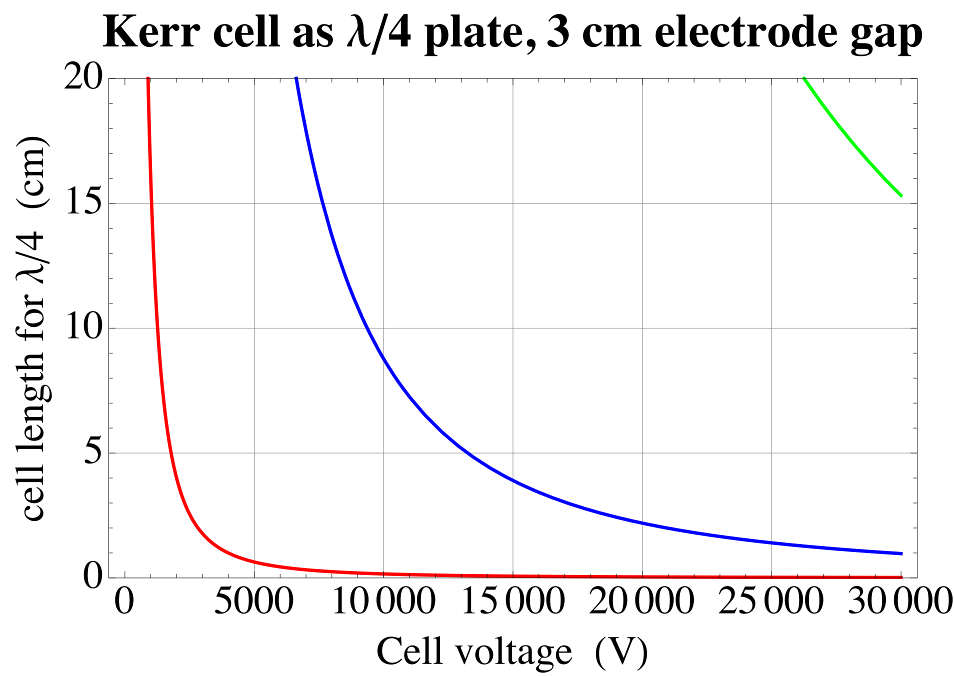
reversing the laser circular-polarization more difficult



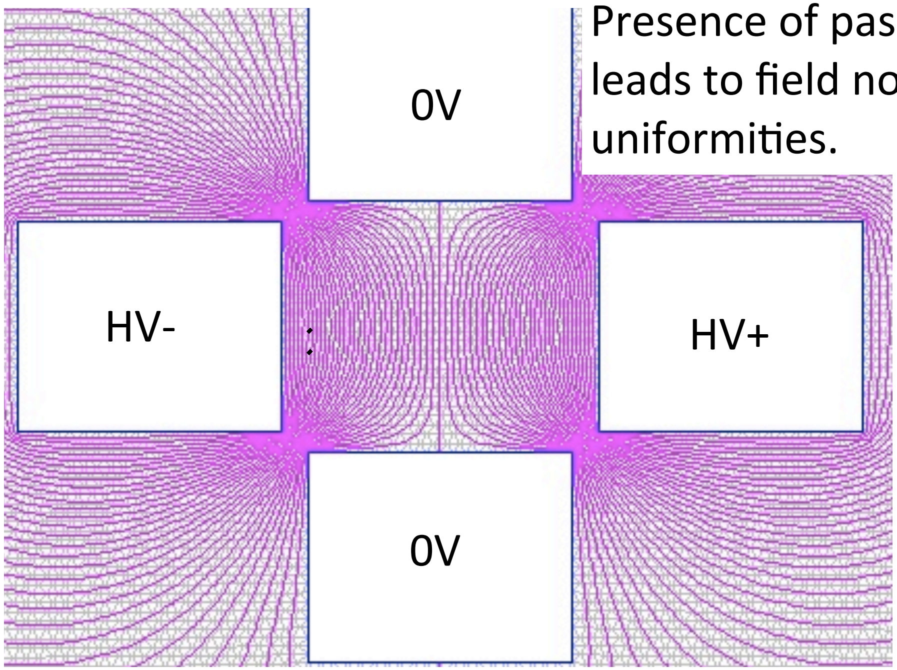
Weakness of Kerr effect

Requires some combination of:
1) long cell
2) close electrodes
3) high voltages
4) difficult materials

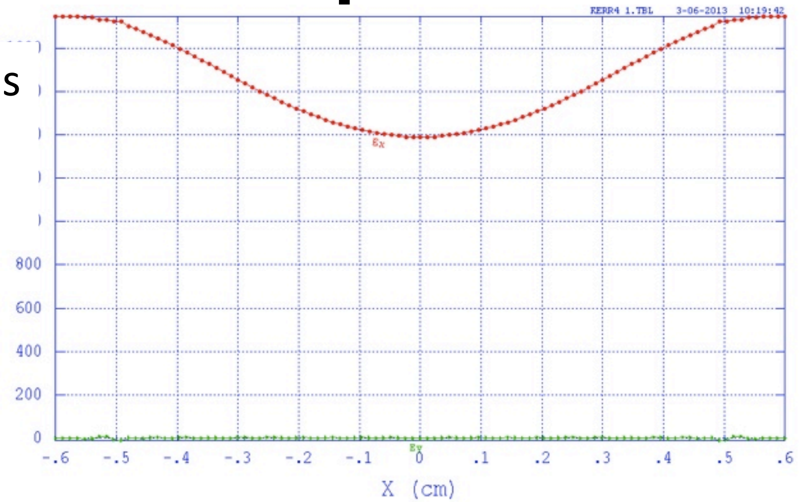


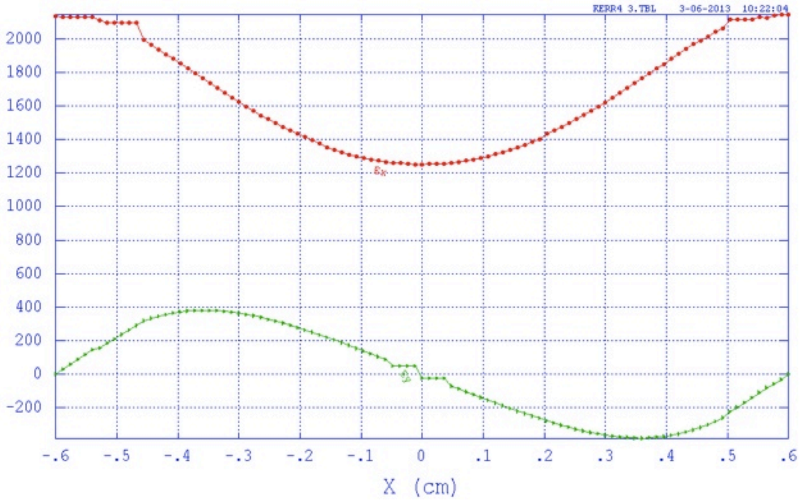


Kerr Cell: no “crossed” plates



Presence of passive plates leads to field non-uniformities.





Thus two Kerr Cells would be required, in series, one for each state. However, this introduces a natural source of asymmetry between the states.

Sign Independent

Changing sign of electric field does not reverse birefringence

$$\Delta n = \lambda B E^2$$

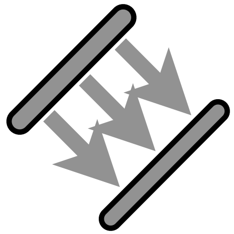
"plate number"

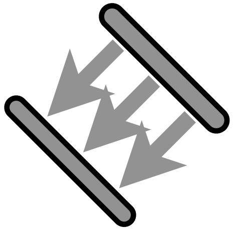
$$N = L\Delta n/\lambda$$

Two ways to reverse the birefringence

need to either:

"rotate" the electric field





use the 3/4 wave voltage

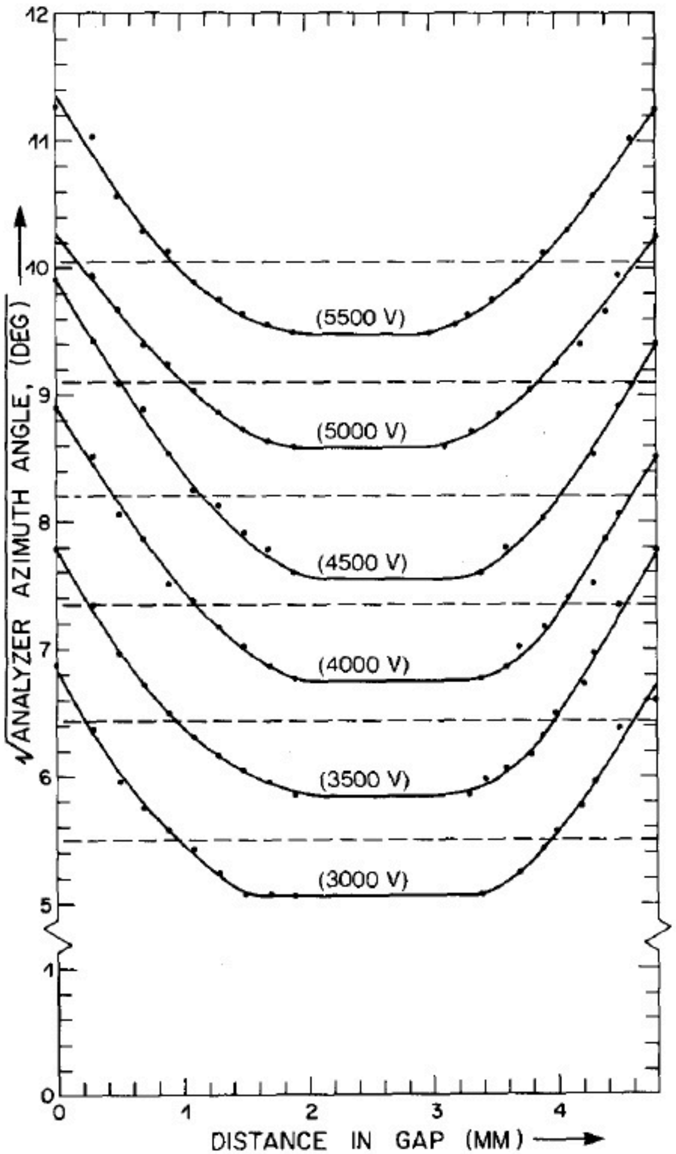
$$N = 1/4$$

$$E_{\frac{1}{4}}$$

$$N = 3/4$$

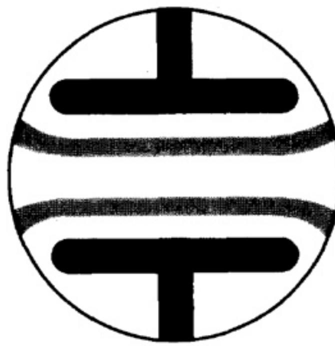
$$E_{\frac{3}{4}} = \sqrt{3}\ E_{\frac{1}{4}}$$

Non–linearity and field uniformity

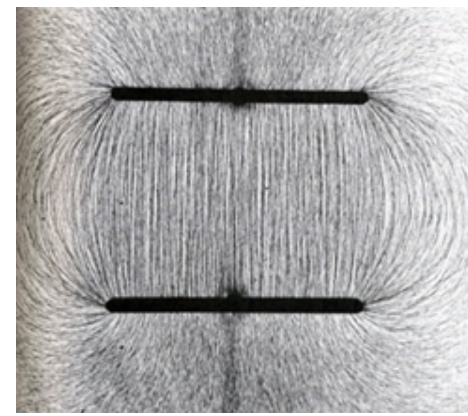


Previous Kerr cells may have seen a non-uniform electric field between the plates (apparently due to charge screening effects.)

American Journal of Physics -- October 1975 -- Volume 43, Issue 10, pp. 888
The Kerr effect in nitrobenzene—a student experiment
Arthur W. Knudsen, University of Calgary

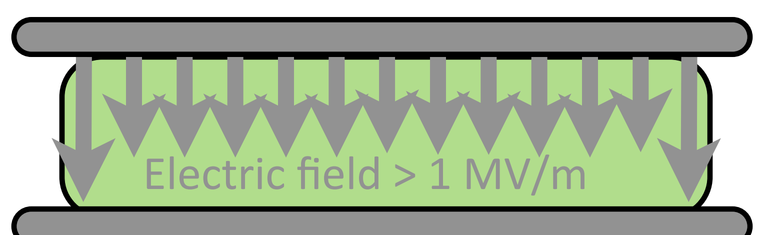


line of equal linear polarization



Parallel plates have non-uniform edges.

Confine Kerr material to uniform region.



Kerr vs Pockels Effects

$$\Delta n = \lambda K E^2$$

birefringence that depends on the square of a transverse electric field

Pockels Cell	Kerr Cell
Crystal	Liquid or gas
Longitudinal Field	Transverse Field
Commercially available	Development required
Strong Effect ~3 kV (KD*P) Deuterated Potassium Dihydrogen Phosphate	Weak Effect ~ 30 kV (nitrobenzene, acetone)

mitigate steering effects, or physical oscillations following large potential changes.

Self focussing, since laser is transverse E.

Even higher voltage

Kerr Cell Summary

Kerr cells could offer advantages over Pockels cells for future measurements in Parity Violating Electron Scattering

1) No ringing
2) Birefringence gradients should only come from electric field gradients
3) helicity reversed quicker, less dead time
4) reduced helicity correlated effects?

Potential Issues

1) More than a simple sign change is required to reverse the polarization
2) A charge asymmetry on the incoming beam would become a spot size asymmetry on the exiting beam.
3) Obtaining uniform high electric fields is both difficult and important for these purposes.

Summary

Future Parity Violating Electron Scattering experiment will still have to worry about the classic false asymmetries.

In addition, higher moment effects, which generally cannot be measured will be serious issues for future experiments.

Open geometry experiments will need to worry about asymmetric background scattering.

Kerr Cells could be useful but there are significant potential issues and development is required.