Beam Instrumentation Challenges for Parity-Violation Experiments

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Intense Electron Beams Workshop 2015
Cornell University

Many thanks to Mark Pitt, Kent Paschke, Mark Dalton, for slide materials and/or discussion

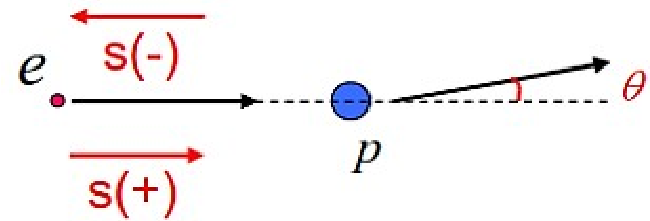
Parity-Violating Electron Scattering

Electromagnetic (PC) + Neutral-weak (PV)

EM amplitude dominates the interaction:

$$\sigma \propto \left|M_{EM} + M_{weak}\right|^2 \approx \left|M_{EM}\right|^2 + 2\, M^*_{EM} M_{weak}$$

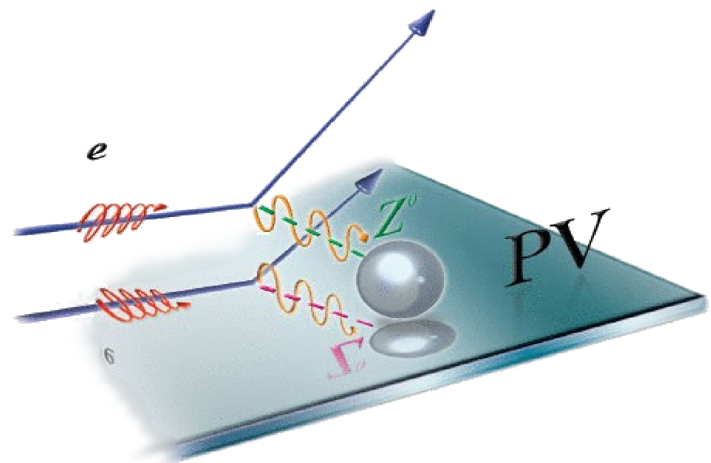
Experimental method:
Electrons prepared in two “mirror” states of opposite helicity.

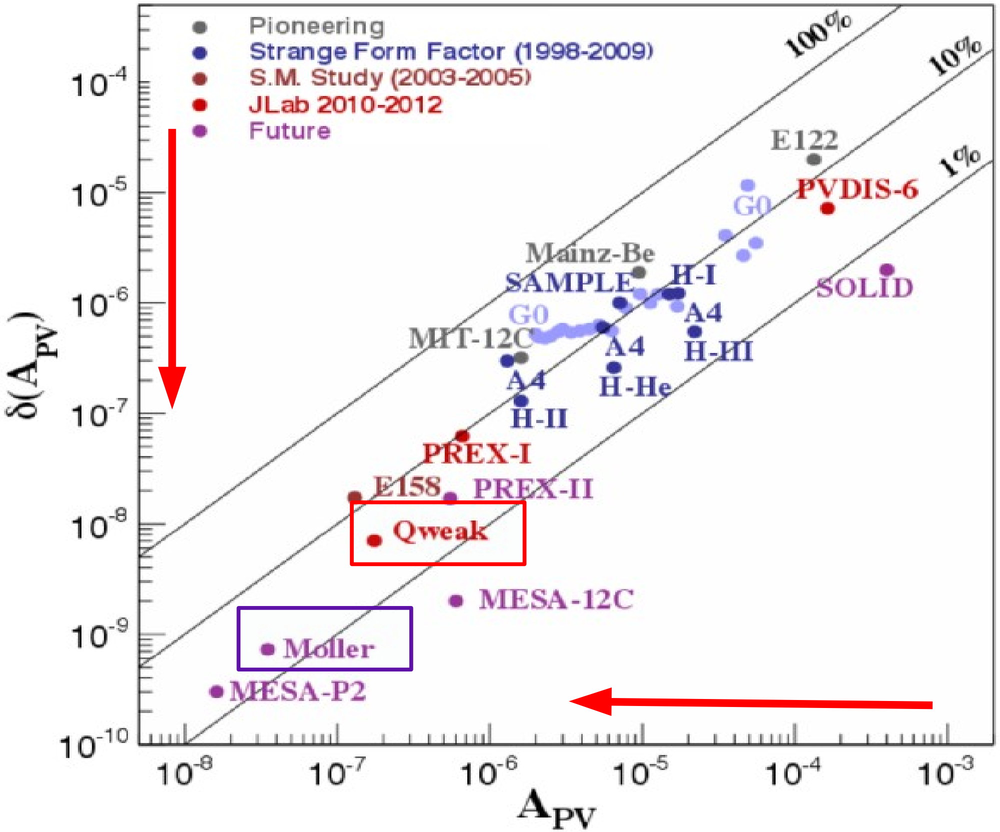


Parity-Violating asymmetry arises from γ and Z interference, allowing access to the weak amplitude:

$$A^{PV}_{ep} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{2\, M^*_{EM}\, \mathbf{M^{PV}_{weak}}}{\left|M_{EM}\right|^2} \propto \frac{G_F}{\alpha} Q^2$$

→ Small asymmetries at low Q^2,
tight control of systematics necessary





Q-weak: Performed in JLab Hall C, 2010-2012

Most recently completed PVES experiment (currently in analysis), expected to be most precise. This talk will draw heavily from Q-weak experience.

MOLLER (planned) : Next in JLab PVES program

Experimental specifications will be useful benchmark for low energy experiments (low E → low A_{PV})

In this talk, instrumentation challenges for high-precision PVES experiments:

- Methods to control false asymmetries from helicity-correlated beam parameters and backgrounds
- Precision monitoring: High monitor resolution, low beam jitter width

Charge-normalized yield : $Y = \frac{S}{I}$

S: Integrated detector signal
I: Integrated charge measurement

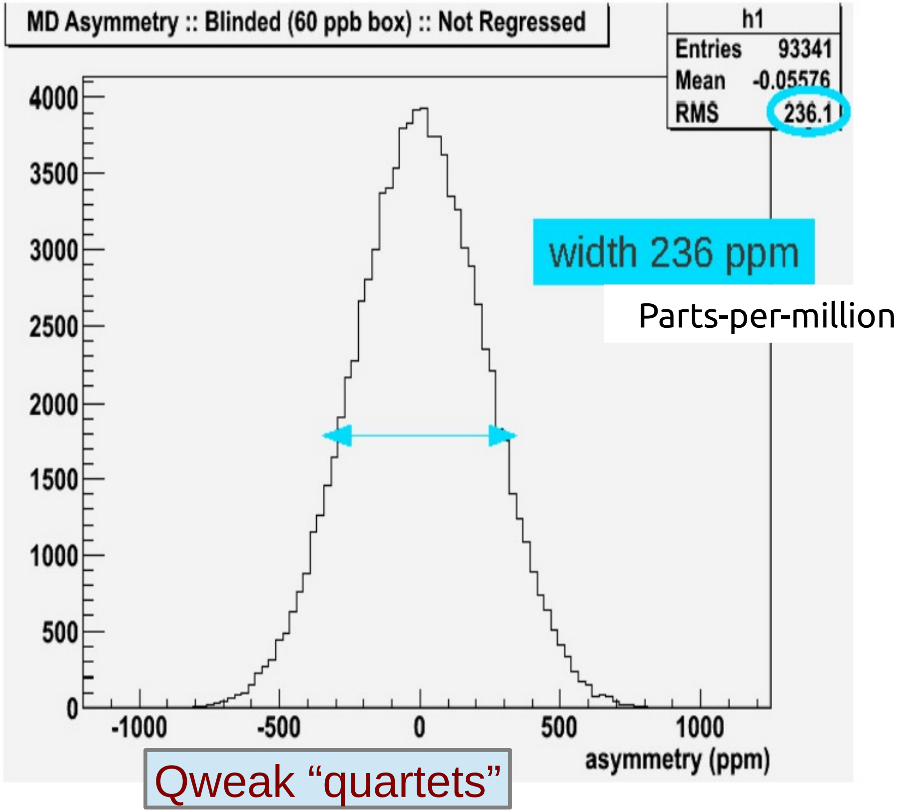
Requires precise (relative) charge measurement

Raw measured asymmetry :

$$A_{raw} = \frac{Y_{+} - Y_{-}}{Y_{+} + Y_{-}}$$

High precision (part-per-billion level) achieved through repeated measurements.

RMS of distribution important figure-of-merit.
Correct false asymmetries but also noise contributions must be suppressed, precision monitoring required.



The measured asymmetry must be corrected for false asymmetries arising from helicity-correlated differences in beam parameters

$$A_{raw} = A_{Phys} + \sum_i \frac{\partial A}{\partial x_i} \Delta x_i$$

x_i : Beam parameters (position, angle, energy)
$\Delta x = x_+ - x_-$: Helicity-correlated difference
$\partial A / \partial x$: "Sensitivity"

Strategy to minimize and correct for these false asymmetries:

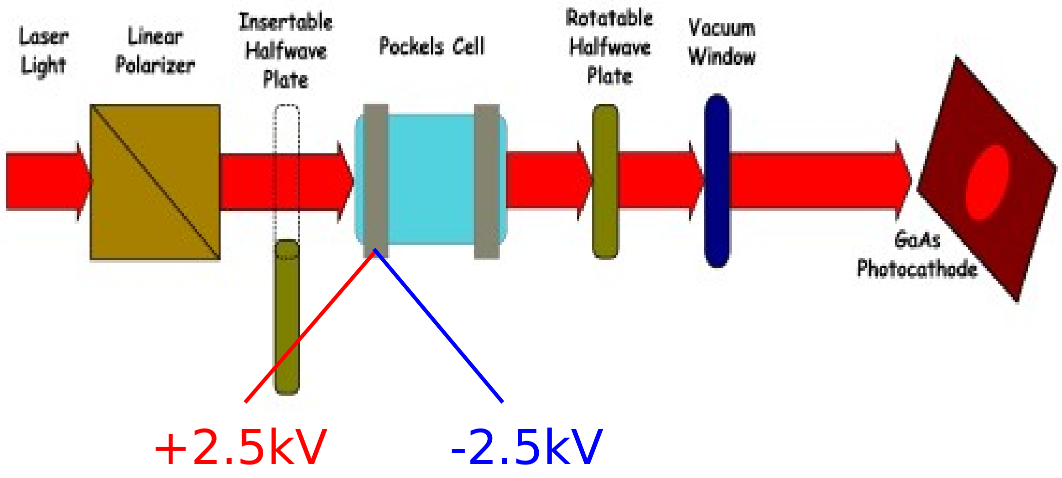
- Optimized polarized source setup and beam transport to minimize value of Δx
- Precise (relative) measurement of beam parameters for small error on Δx
- Low beam noise ("jitter" - random fluctuations in Δx)
- Methods to measure the sensitivities $\partial A/\partial x$ to correct false asymmetries
- Implement reversals of the Physics asymmetry to cancel residual false asymmetries

Typical goal:
- |Total correction| < Statistical error
- Error for each correction term < 10% Statistical error

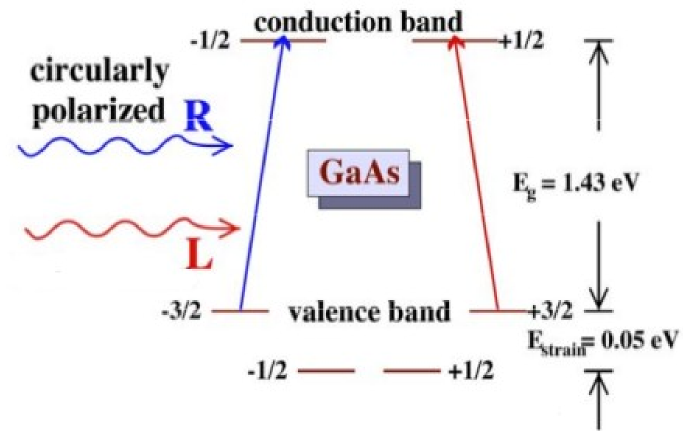
History of Helicity-Correlated Beam Corrections

Experiment	Phys. Asym (ppm)	|Correction|(ppb)	Corr/ Stat err.	Corr. err/Stat err
SLAC E122	-152 ± 15 ± 15	4000 ± 4000 ⬅	27%	27%
Bates C^{12}	1.62 ± .38 ± .05	110 ± 16	29%	4%
Mainz Be^{9}	-9.4 ± 1.8 ± 0.5	50 ± 370	3%	21%
SAMPLE proton	-4.92 ± 0.61 ± 0.73	200 ± 200	33%	33%
SAMPLE deuteron	-6.79 ± 0.64 ± 0.55	300 ± 300	47%	47%
A4 p @ .23 GeV^2 F	-5.44 ± 0.54 ± 0.26	590 ± 60	109%	11%
A4 p @ .11 GeV^2 F	-1.36 ± 0.29 ± 0.13	280 ± 110	97%	38%
A4 p @ .22 GeV^2 B	-17.23 ± 0.82 ± 0.89	140 ± 390	17%	48%
HAPPEx – I	-15.05 ± 0.98 ± 0.56	30 ± 30	3%	3%
HAPPEx – II H	-1.58 ± 0.12 ± 0.04	10 ± 17	8%	14%
HAPPEx – II He	6.40 ± 0.23 ± 0.12	183 ± 59	80%	26%
HAPPEx – III	-23.80 ± 0.78 ± 0.36	18 ± 40	2%	5%
G0 forward	-1.51 ± 0.44 ± 0.28	20 ± 10	5%	2%
G0 backward	-11.25 ± 0.86 ± 0.51	200 ± 70	23%	8%
E158	-0.131 ± 0.014 ± 0.010	11 ± 1.6 ⬅	79%	11%
PREX – I	0.6571 ± .0604± .0130	? ± 7.2		12%
QWEAK – projected	-0.234 ± .005 ± .003	? ± 1.2 ⬅		24%
MOLLER – projected	35 ± 0.74 ± 0.39 ppb	? ± 0.2 ⬅		27%

The Jefferson Lab Polarized Source



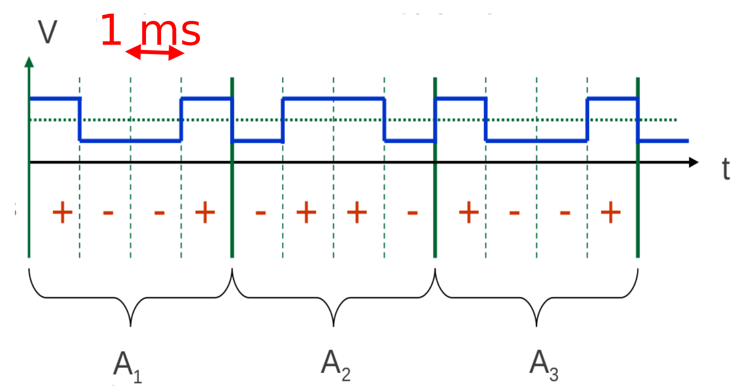
Polarized e^- produced from strained superlattice GaAs photocathode



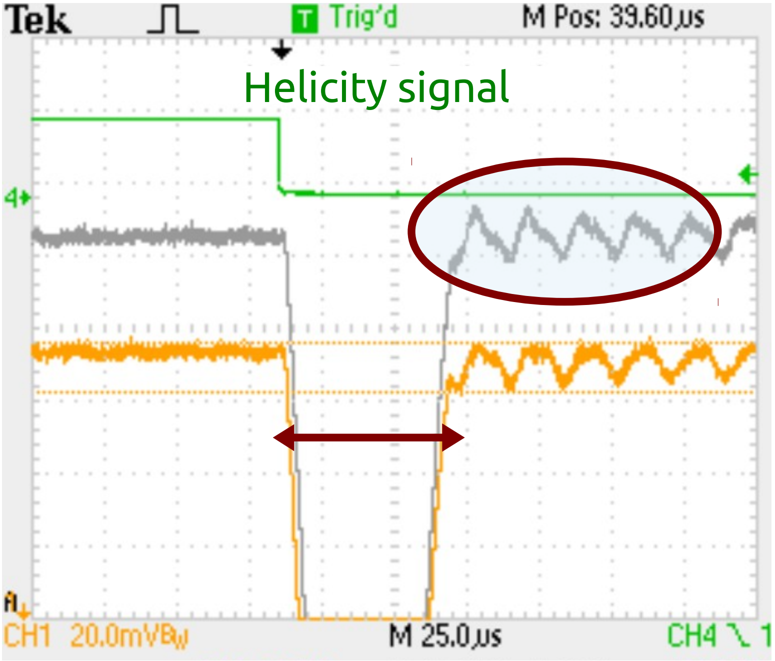
Electron helicity controlled by Pockels Cell acting as a λ/4 plate (electro-optic effect) creates circularly polarized light.

Qweak: 960 Hz helicity flip, pseudorandom quartet pattern
Fast helicity reversal → measurement insensitive to slow drifts

Insertable Half-Wave Plate (IHWP): reversal for cancellations
Rotatable HWP : Manipulation of residual linear light



Instrumentation Challenges with Fast Helicity Control



Transmitted light after PC and analyzer on helicity reversal

Minimize Pockels Cell "ringing"
Inverse piezoelectric effect, crystal vibrations.
Potentially troublesome if coupled to other effects.
Tests on different cells and high-voltage drivers.

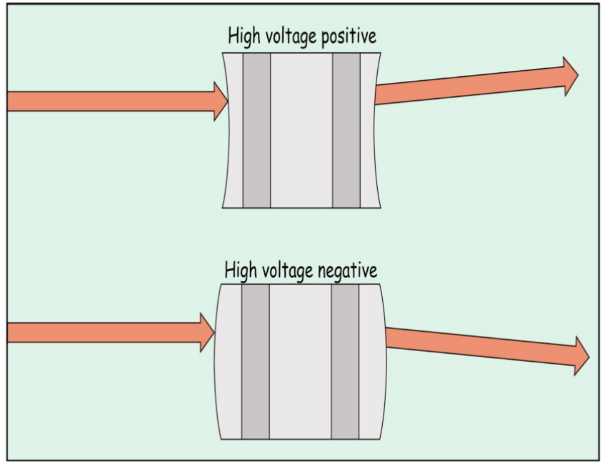
Minimize transition time
Qweak: Transition time of 60-70 µs
→ ~7% dead time at 960Hz reversal.
MOLLER needs even faster flip at 1920 Hz.

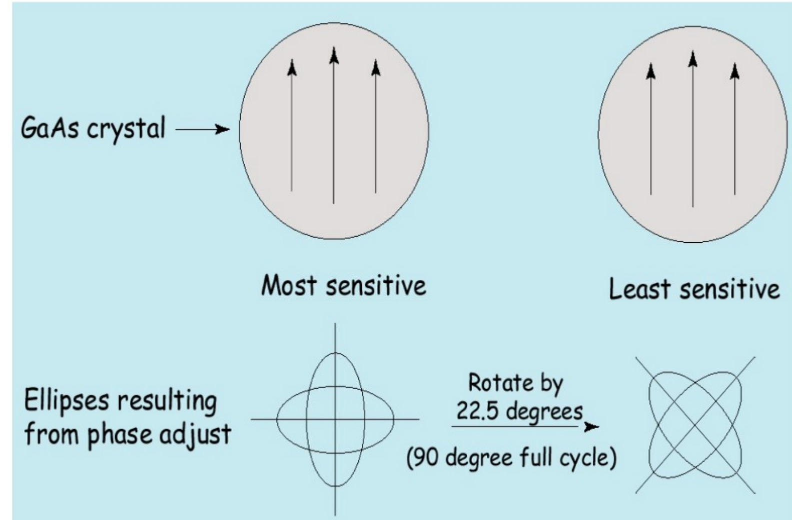
Some progress needed on the electro-optic system for fast helicity control
KD*P Pockels Cell: Too slow transition
RTP Pockels Cell: Too much ringing
Kerr Cell? – quadratic electro-optic effect

Generation of Helicity-Correlated differences in the source

Mechanical PC steering

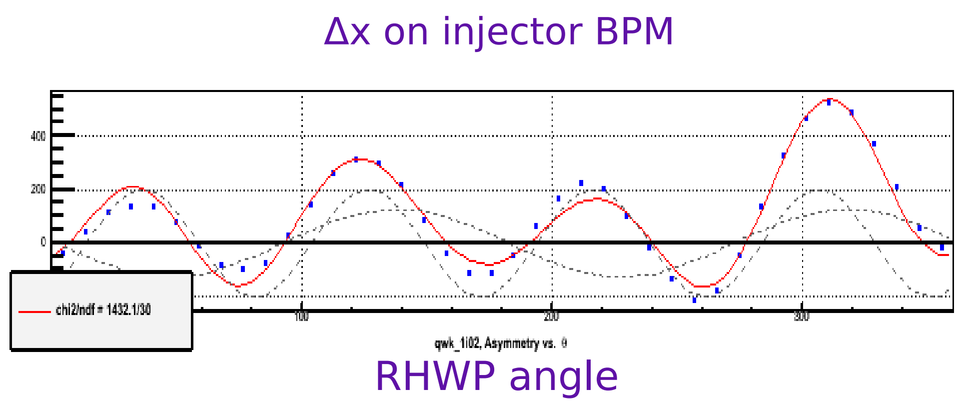
Polarization effects:
PC birefringence gradients coupled with cathode analyzing power





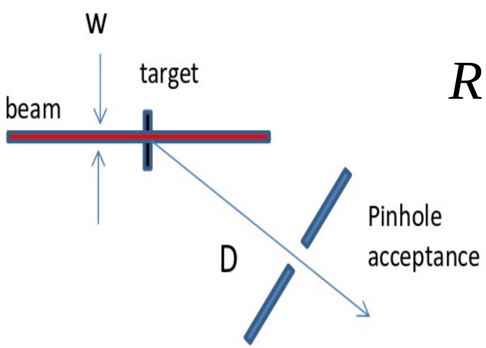
Optimization strategies:

- Careful alignment on laser table
- Balance residual linear polarization from PC with vacuum window birefringence and cathode analyzing power



Helicity-correlated difference in beam spot size, a 2nd order effect.

May result in helicity-correlated difference in scattering rate R:



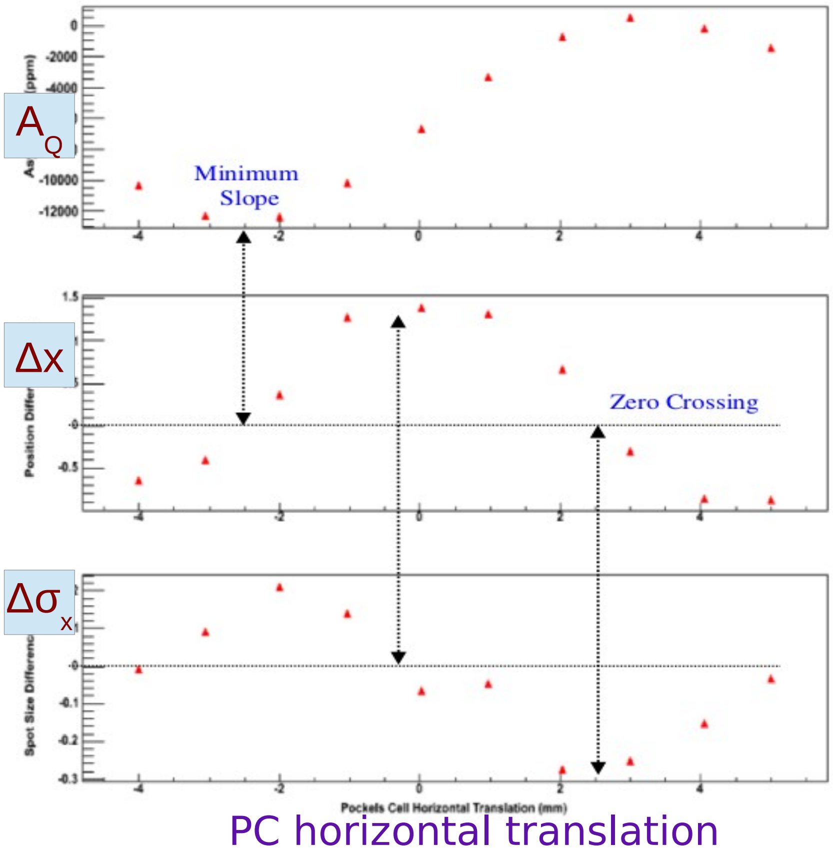
~0

$$R = R_0 + \frac{\partial R}{\partial \theta}\delta\theta + \frac{\partial^2 R}{\partial \theta^2}(\delta\theta)^2$$

$$\Rightarrow \Delta R \approx \frac{\partial^2 R}{\partial \theta^2}\frac{w \Delta w}{D^2}$$

Effect more important for heavier nuclei (scattering rate dependence on θ)

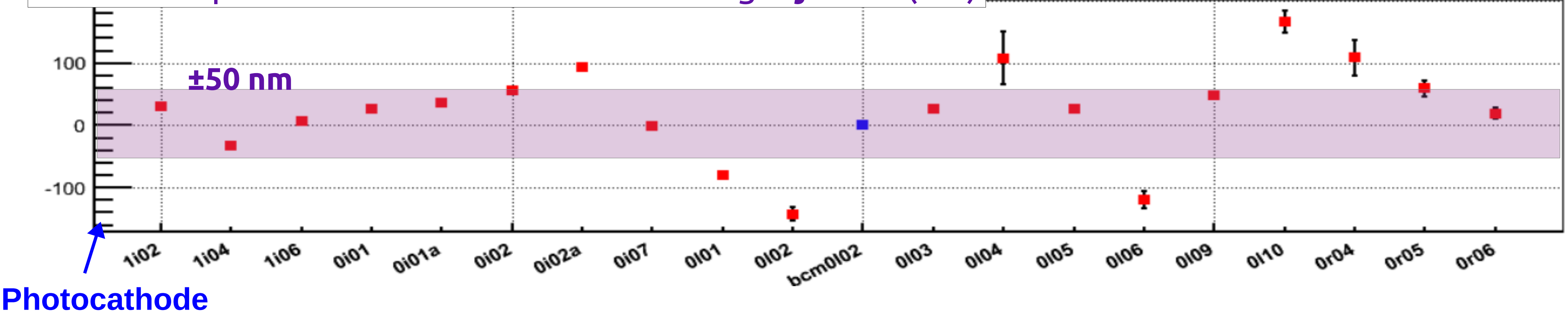
Experimental requirement: $\Delta\sigma_x/\sigma_x < 10^{-4}$



Bounded on the laser table for Qweak and relied on cancellations.
Next generation experiments should bound this effect better (possibly on e- beam)

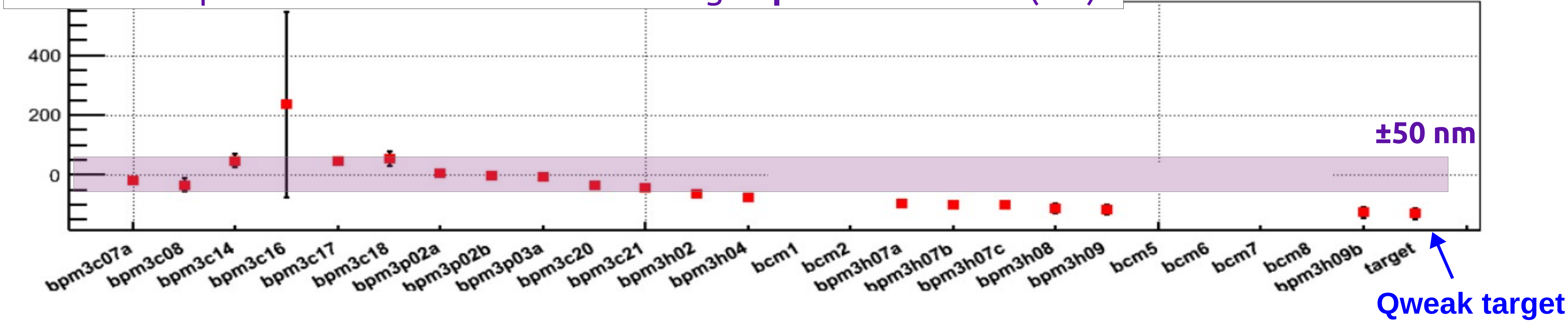
Upon optimization, achieved smallest-ever position differences in early injector, <50 nm

Horizontal position differences vs BPM along **injector** (nm)



However suppression not achieved through acceleration and transport to experimental hall, position differences would actually increase, ~100 nm

Horizontal position differences vs BPM along **experimental hall** (nm)



In spite improvements in polarized source, previous experiments had much smaller differences in hall due to better injector/accelerator optics matching.

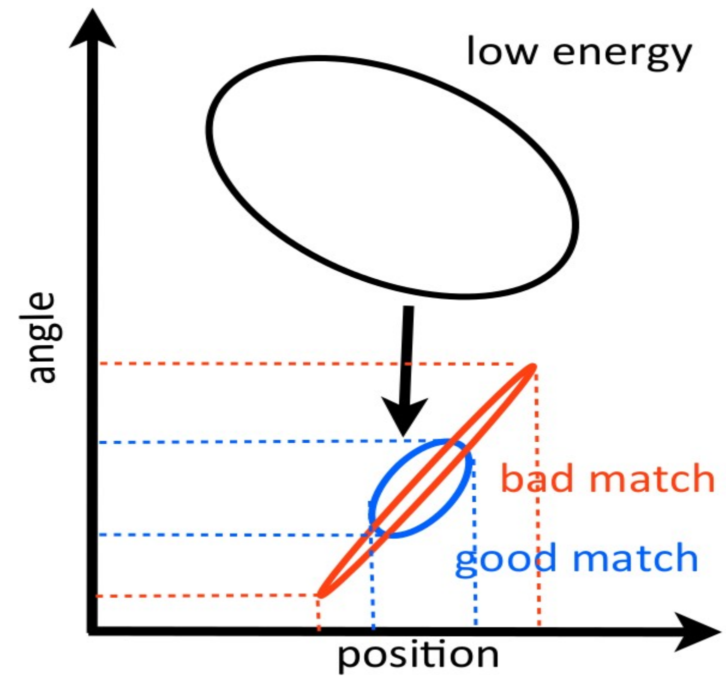
Beam Transport, Adiabatic Damping

As longitudinal beam momentum increases the transverse phase space should be suppressed under linear beam optics in a perfectly tuned machine

'Adiabatic' Damping: $$x, x' \propto \sqrt{\frac{p_0}{p}}$$

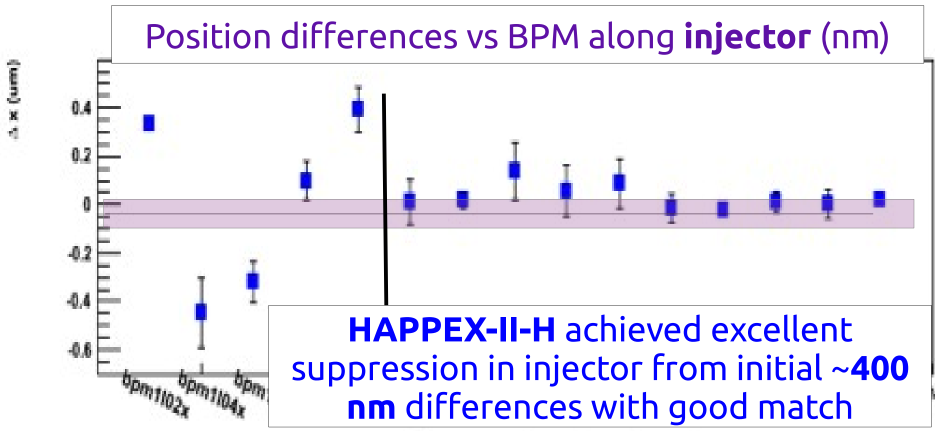
Eg, for Q-weak E_{beam}~1.15 GeV, expect reduction:

$$\sqrt{\frac{1.155 \text{ GeV}}{335 \text{ keV}}} \approx 60$$



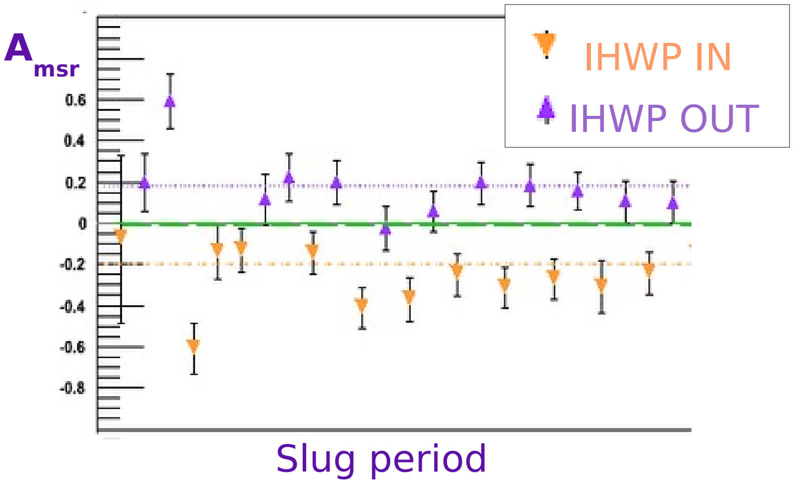
Ability to achieve this reduction limited by imperfections of beam tune – a bad match of beam emittance to accelerator acceptance.

Achieving “matching” may require periodic time investment from the experiment, synergy with accelerator division and other experimental halls.

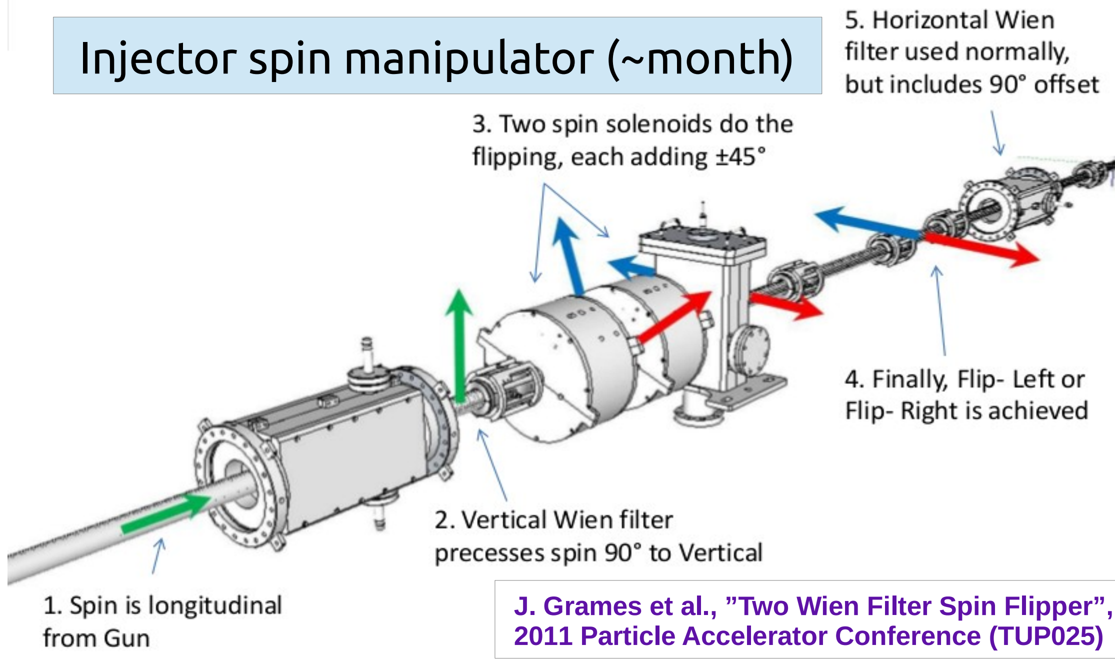


Slow Reversals, Cancellations

Laser table IHWP (~8 hrs)



Injector spin manipulator (~month)



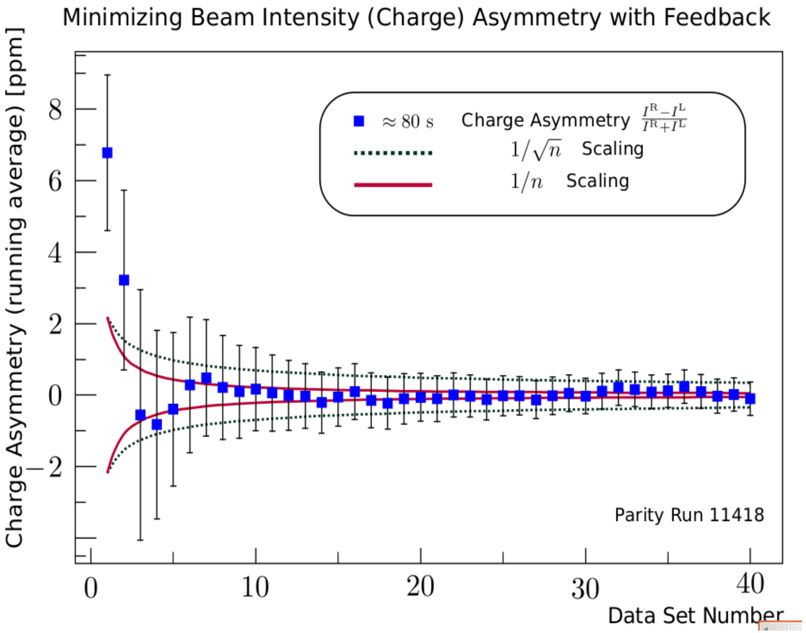
J. Grames et al., "Two Wien Filter Spin Flipper", 2011 Particle Accelerator Conference (TUP025)

Systematic effects that are uncoupled to a helicity reversal should cancel.

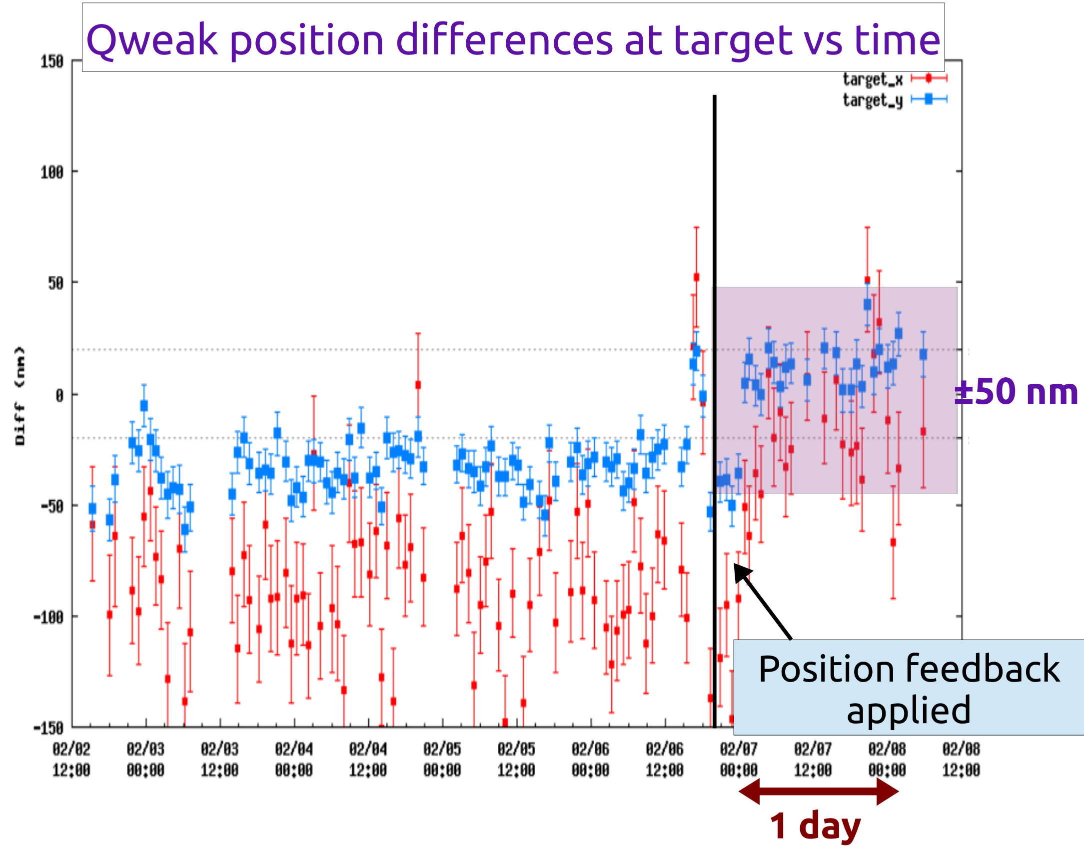
Reversing helicity on electron beam through Wien flip or g-2 precession should cancel most of helicity-correlated differences from source, including beam spot size, if reversal can be achieved with minimal effect on beam trajectory and envelope.

Multiple reversals desirable.

Feedback



Charge feedback through adjusting Pockels Cell voltages.



Position feedback: 'Helicity magnets' recommissioned for Qweak:
4 air-core dipoles in 6 MeV injector, differentially kick the two helicity states.
No signs of residual effects, electrically isolated, same setting applied on both IHWP states.
Ideally feedback should be used only for small corrections.

Monitoring and Beam Specifications: MOLLER

BPM and BCM resolution

Beam Position and Charge Monitors used to remove beam parameter fluctuations from detectors
→ finite precision injects noise

Beam jitter

Correction factors (“sensitivities”) known only with finite precision
→ introduces error that increases with the size of beam jitter

Specifications defined from requirement that additional error remains smaller than ~10% of statistical error.

Monitor type	MOLLER spec.
BCM	10 ppm
BPM	3 μm

Beam property	MOLLER spec.
Intensity	<1000 ppm
Energy	<286 ppm
Position	<47 μm
Angle	< 4.7 μrad

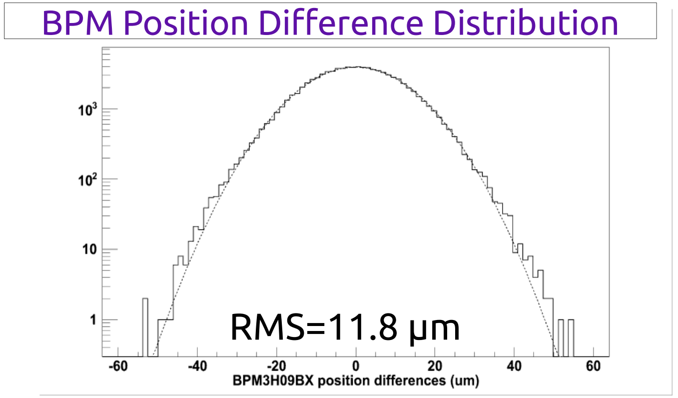
MOLLER specifications for 1kHz pairs

Qweak: BPM Resolution and Beam Jitter Results

Position difference distribution: $\Delta x = x_+ - x_-$

Dominated by beam jitter ~11.8 μm

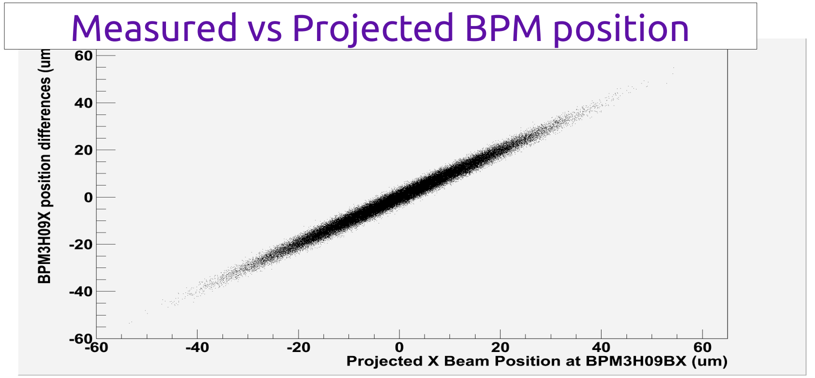
→ already better than MOLLER specification

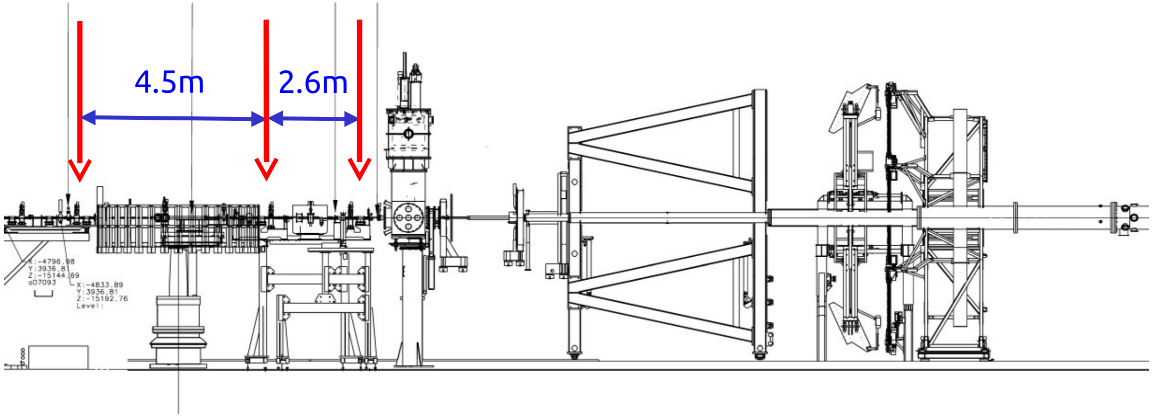


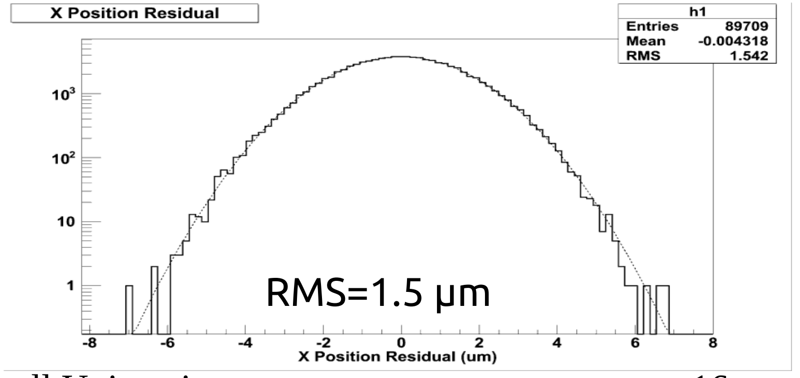
Access intrinsic resolution by projecting from upstream monitors, compare to measured position.

Existing BPM resolution ~1.5 μm

→ already at level of MOLLER specification





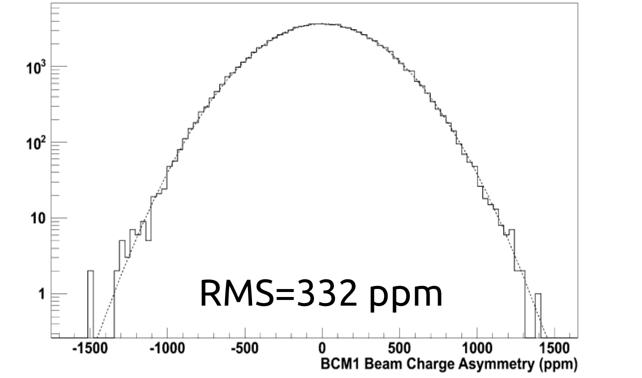


Qweak: BCM Resolution and Beam Jitter Results

BCM measures charge asymmetry: $A_Q = (Q_+ - Q_-)/(Q_+ + Q_-)$

Dominated by beam jitter ~11.8 μm
→ also better than MOLLER specification

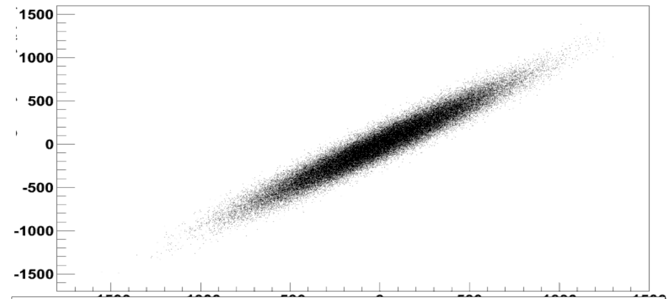
BCM Charge asymmetry distribution



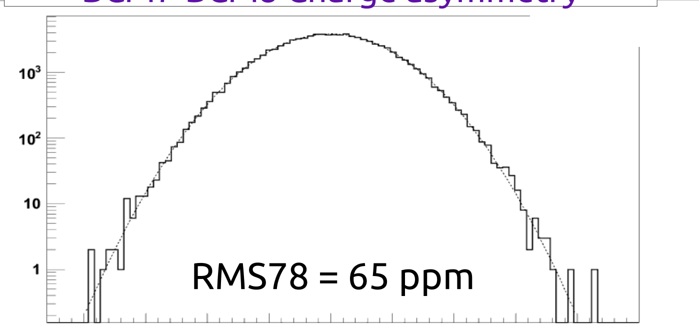
Monitor resolution accessed by difference in A_Q between BCMs.

For a single BCM,
$\sigma(A_{Q1})$ or $\sigma(A_{Q2}) = \sigma(A_{Q1} - A_{Q2})/\sqrt{2}$
Scaled to 1 kHz Pairs (MOLLER freq) as white noise,
BCM resolution ~65 μm → negligible for Qweak,
but higher than MOLLER spec (10 μm)

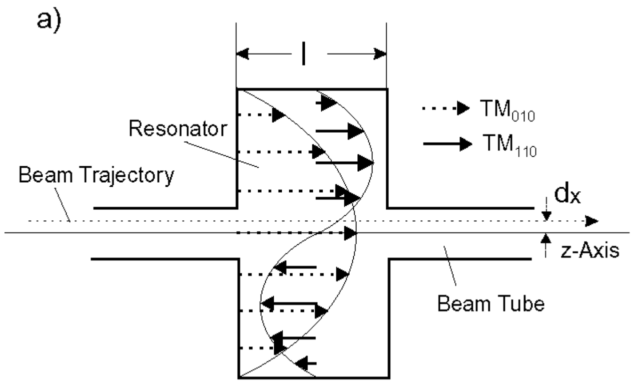
BCM7 vs BCM8 Charge asymmetry

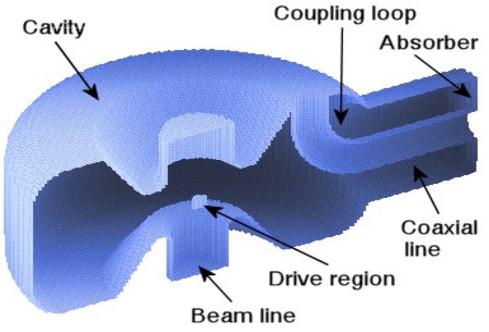


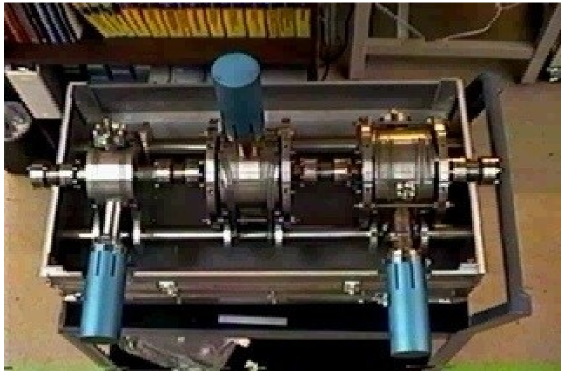
BCM7-BCM8 Charge asymmetry

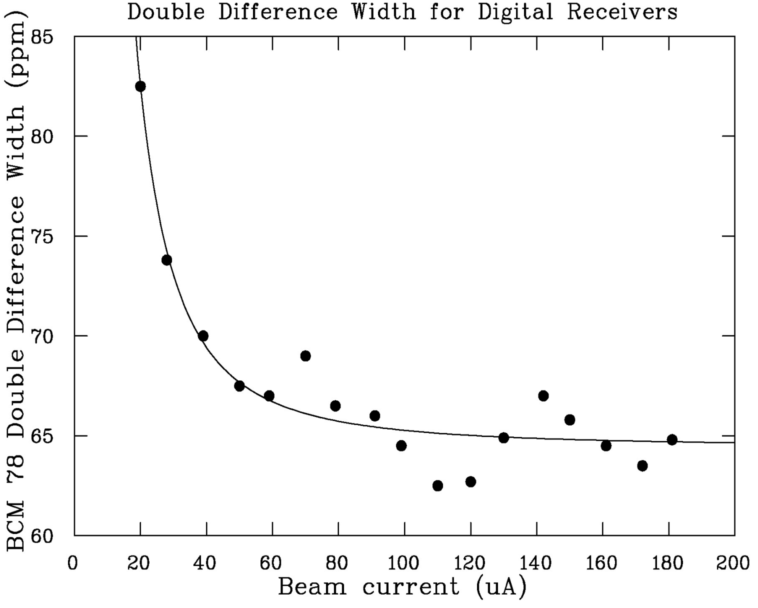


JLab BCM instrumentation: TM_{010} Microwave cavity monitors with digital electronic chains









Dependence with current:

$$\Gamma = \sqrt{\left(\frac{1032\,\mathrm{ppm}\,\mu\mathrm{A}}{I}\right)^2 + (64.5\,\mathrm{ppm})^2}$$

→ Apparent noise floor at ~65 ppm

Bench studies attempt to understand and improve on this noise.

MOLLER Specifications, Qweak Observations

Need to improve understanding of BCM resolution.
Further R&D probably needed to achieve goal.

Otherwise MOLLER specifications already satisfied from Qweak.

Important specs to keep in mind for any planned PVES experiments.

Monitor type	MOLLER spec.	Qweak observed
BCM	10 ppm	65 ppm
BPM	3 μm	3 μm

Beam property	MOLLER spec.	Qweak observed
Intensity	<1000 ppm	500 ppm
Energy	<286 ppm	6.5 ppm
Position	<47 μm	24 μm
Angle	< 4.7 μrad	1.4 μrad

MOLLER specifications for 1kHz pairs, Qweak scaled to that frequency

Sensitivities, Preliminary Qweak Results

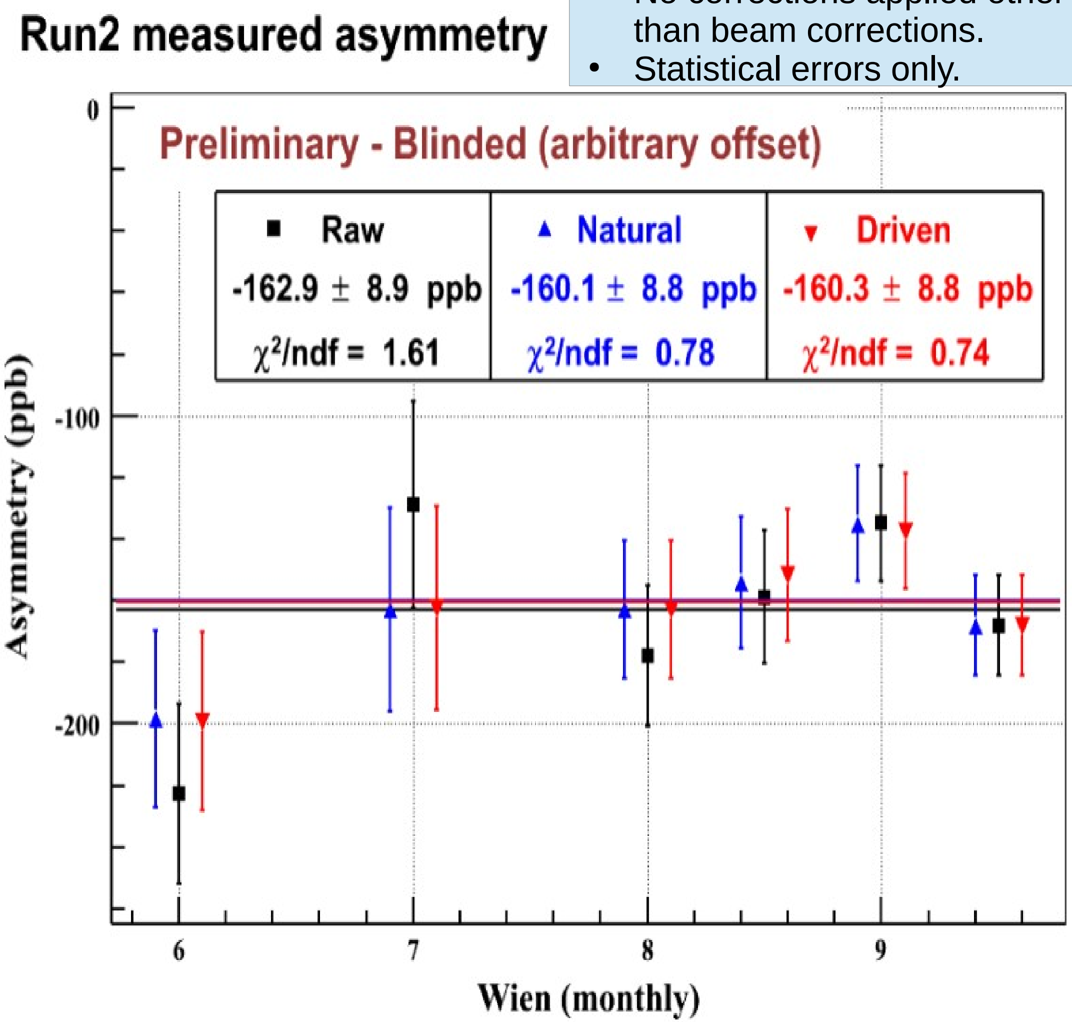
- About 77% of Run2 data-set.
- No corrections applied other than beam corrections.
- Statistical errors only.

$$A_{raw} = A_{Phys} + \sum_i \frac{\partial A}{\partial x_i} \Delta x_i$$

Sensitivities needed for correction, measured from natural or driven beam motion – the two methods are completely independent.

Preliminarily:
Excellent consistency and small correction on the Run2 subset where both available.
Run2: ~2/3 of full Qweak data.

Qweak analysis still in progress;
Many more lessons to be passed on.



Summary

Beam instrumentation challenges for next-generation PV experiments

Polarized source

- Some progress needed on fast reversal
- Procedure to optimally set up the source probably already adequate
- Higher order spot size asymmetry should be bounded

Helicity reversals and feedback

- Reversals can be invaluable if properly applied; preferably several
- Feedback applied judiciously

Beam transport

- Invest time to match the machine, achieve kinematic damping

Monitoring instrumentation and beam parameter requirements

- Mostly under control in JLab, some R&D needed for BCM resolution spec

A lot more lessons to be learned from Qweak experience

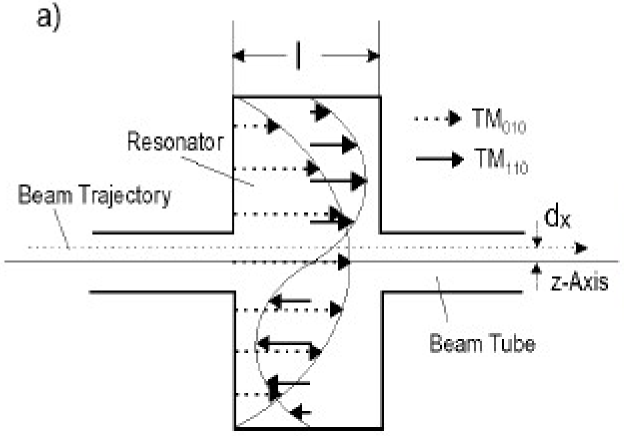
Back up slides

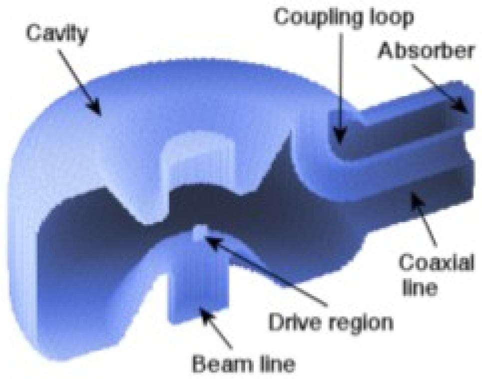
BPM Instrumentation - Jefferson Lab

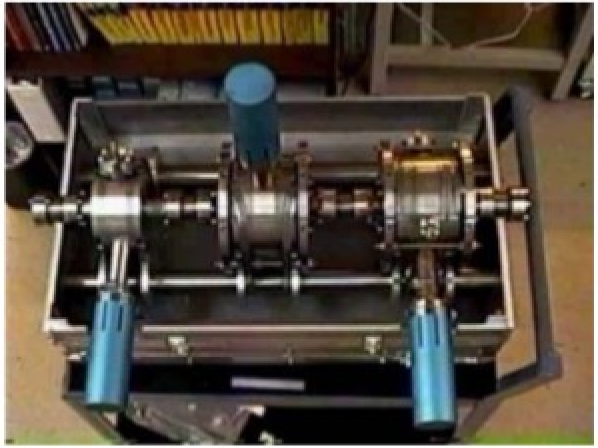
Microwave cavity monitors: Electromagnetic cavity resonant at accelerator RF (1497 MHz)

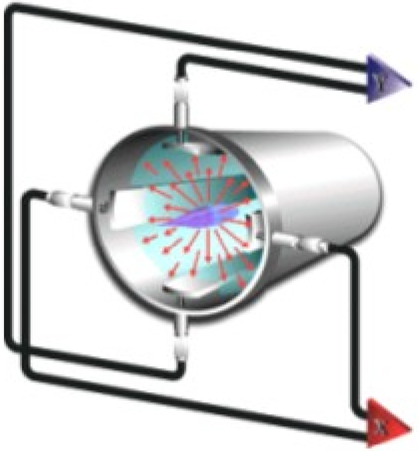
TM_{010} → measure beam intensity

TM_{110} → measure beam position









"Stripline" beam position monitors

- standard JLAB beam position monitor
- 4 quarter-wave antennae
- uses "switched electrode electronics" (SEE)

Barry, W., NIMA 301, 407 (1991)

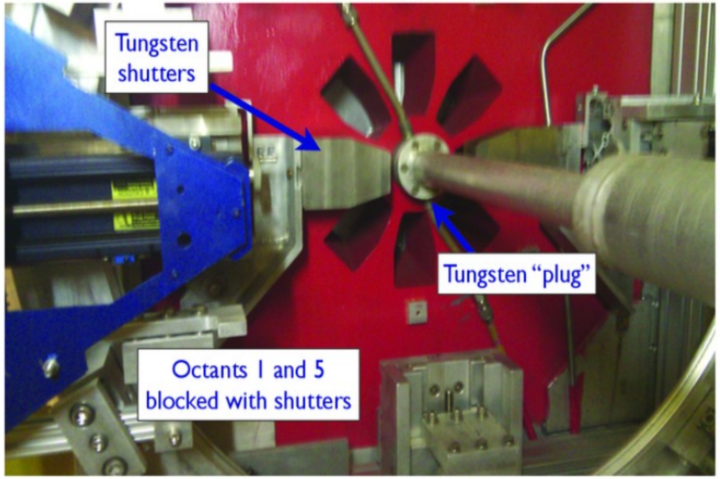
Current Analysis Status: *Backgrounds from Beamline Scattering (b_2)*

→ Highest contribution to systematic uncertainty for initial result.

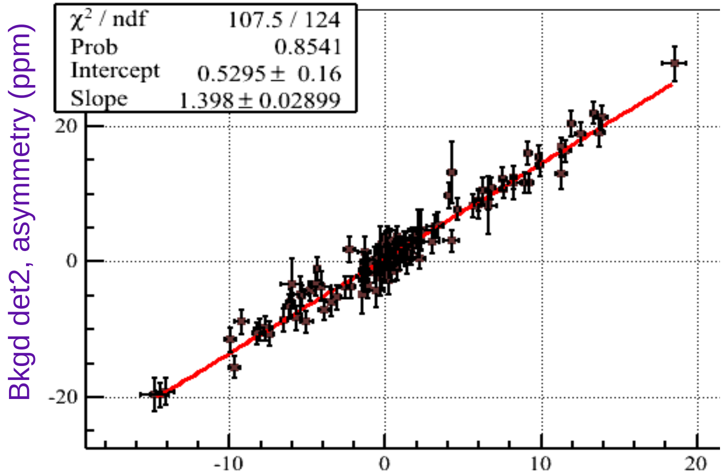
- Background from electrons scattering on beamline or tungsten "plug" collimator.
- Thought to be associated with large asymmetries on outer part of beam ("halo").
- Yield fraction on Main Detector measured directly by blocking primary e^- on two octants:

$$f_{b_2}^{MD} \approx 0.19\,\%$$

- Background detectors in various locations monitored this component and measured highly correlated asymmetries.
- Scaling of background asymmetries also consistent with expectation from dedicated measurement.



Correlation between bkgd asymmetries, Run2

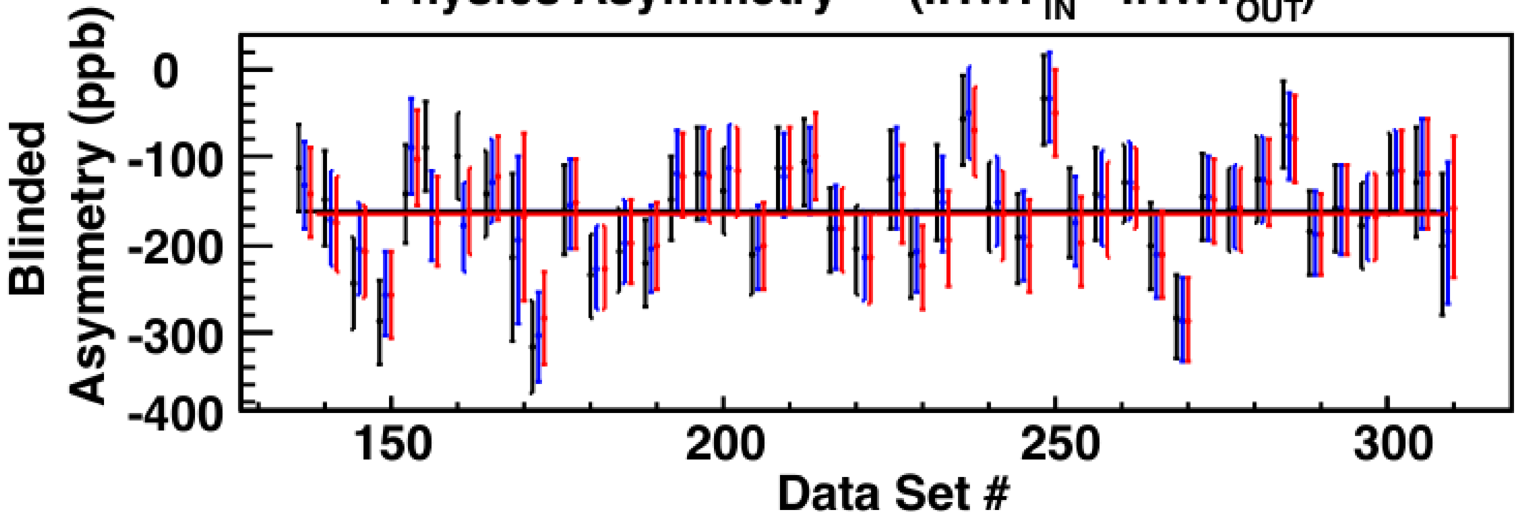


Bkgd asymmetries up to **20 ppm**

Qweak Run 2 - Blinded Asymmetries

(statistics only - not corrected for beam polarization, Al target windows, ΔQ^2, etc.)

Physics Asymmetry = $(IHWP_{IN} - IHWP_{OUT})$



Raw = -161.8 ± 7.6

(χ^2/ NDF = 1.40, Prob = 0.043)

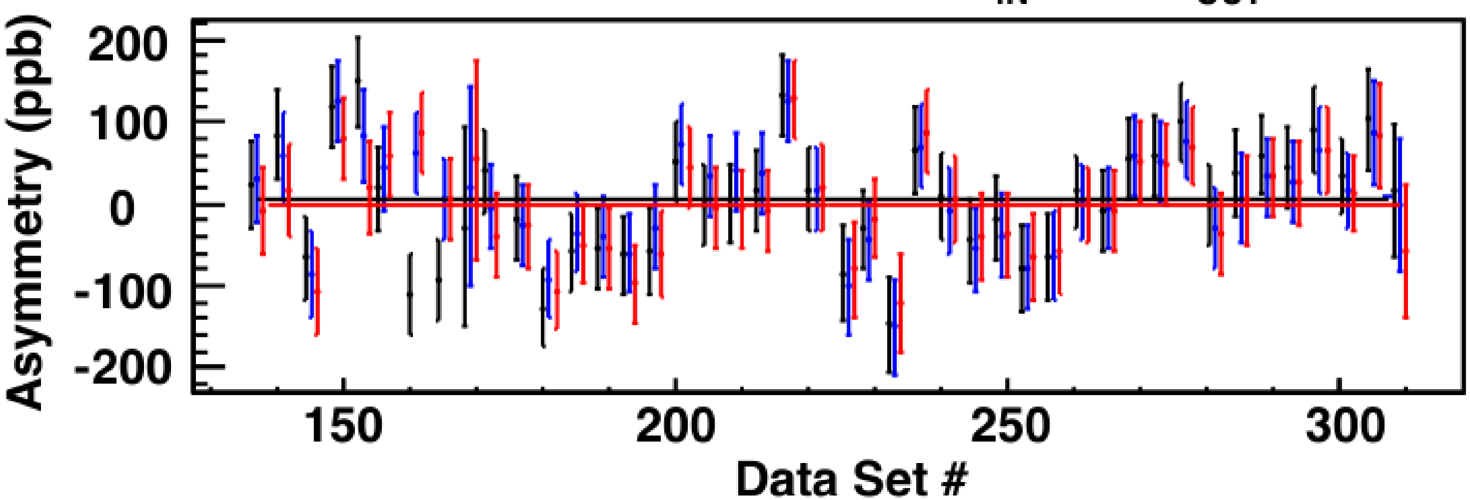
Regressed = -160.9 ± 7.6

(χ^2/ NDF = 1.19, Prob = 0.18)

Beamline
Bkgd Corrected = -164.5 ± 7.6

(χ^2/ NDF = 1.08, Prob = 0.33)

NULL Asymmetry = $(IHWP_{IN} + IHWP_{OUT}) / 2$



Raw = 4.7 ± 7.7

(χ^2/ NDF = 1.84, Prob = 0.001)

Regressed = 7.9 ± 7.7

(χ^2/ NDF = 1.38, Prob = 0.048)

Beamline
Bkgd Corrected = -1.4 ± 7.7

(χ^2/ NDF = 1.29, Prob = 0.097)