Beam Instrumentation Issues for Parity-Violating Electron Scattering Experiments

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What are the most critical aspects of beam instrumentation and control for parity-violating electron scattering experiments, and what are the requirements for the next (4th) generation of experiments?

Thanks to Gordon Cates, Krishna Kumar, Dave Mack, John Musson, Kent Paschke, Katherine Myers, Mark Dalton for slide materials and/or discussions

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What is Beam Property Instrumentation and Control used for in Parity-Violation Experiments?

$$Y = \frac{S}{I}$$

S = integrated detector signal

I = integrated beam current

Normalized yield: Requires precise (relative) beam charge measurement

$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-} = A_{phys} + \sum_{i=1}^{N} \frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

$\Delta P = P_+ - P_-$

P = beam parameter

$\rightarrow$ energy, position, angle

Correction for helicity-correlated beam parameters: Requires

- Good polarized source setup (Pockels cell, etc.) for small value of ΔP (Matt Poelker talk)
- Precise (relative) measurement of beam position (for energy, position, angle) for small error on measurement of ΔP
- Small beam noise or "jitter" (random fluctuations in ΔP) to keep systematic error on the correction small
- Ability to manipulate beam ("coil pulsing") to measure detector sensitivities $\frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)$ precisely

Outline

- Review of sizes and error on helicity-correlated beam parameter corrections from past and future experiments
- Techniques for measuring the sensitivities: forced beam motion and natural beam motion
- Criteria for needed beam monitor (intensity and position) resolution and beam "jitter"
- How to measure beam monitor resolution/jitter
- Review of existing standard beam instrumentation at the labs
- Projection of observed performance (resolution and jitter) for Qweak to the planned MOLLER experiment and discussion of needed R&D

SLAC E122: PVDIS on deuteron – Pioneering PV e-N Experiment

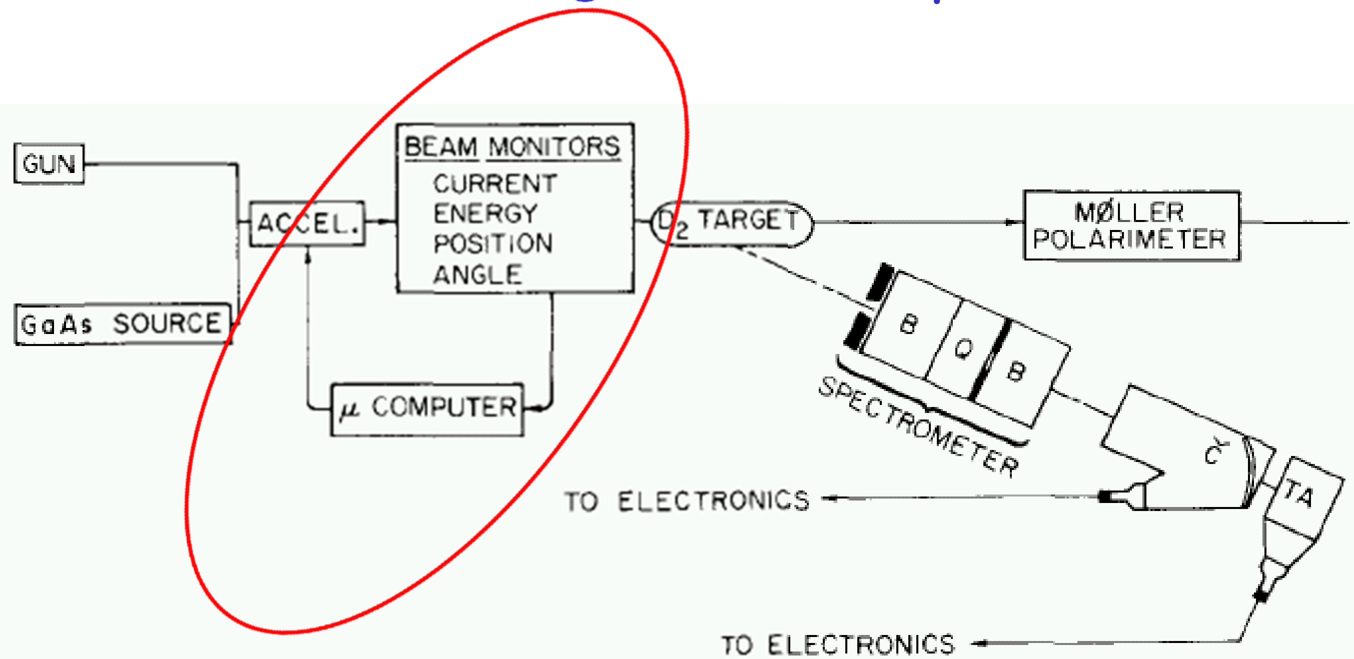


Fig. 1. Schematic layout of the experiment. Electrons from the GaAs source or the regular gun are accelerated by the linac. After momentum analysis in the beam transport system the beam passes through a liquid deuterium target. Particles scattered at 4° are analyzed in the spectrometer (bend-quad-bend) and detected in two separate counters (a gas Cerenkov counter, and a lead-glass shower counter). A beam monitoring system and a polarization analyzer are only indicated, but they provide important information in the experiment.

Prescott *et al.*, PLB 77, 347 (1978)
Prescott *et al.*, PLB 84, 524 (1978)

Precise beam monitoring and control have always been necessary to achieve the desired systematic errors in these experiments.

History of Helicity-Correlated Beam Correction Sizes

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%

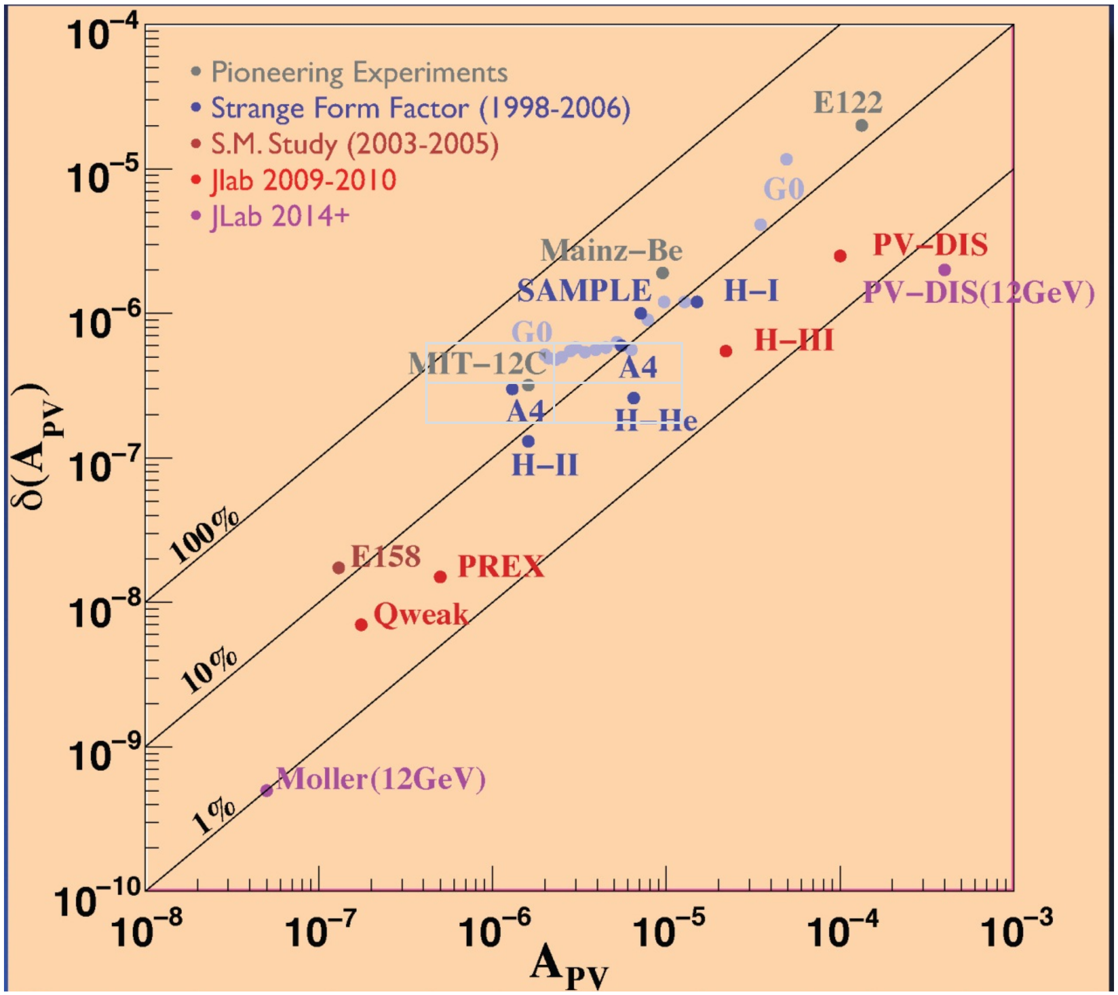
Typical goal:
- |total correction| < statistical error
- error for each correction term < (10%) statistical error

$$A_{corr} \equiv \sum_{i=1}^{N} \frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

Precision of Parity-Violating $\vec{e}$-N and $\vec{e}$-e Experiments: Past, Present, and Future

Technical progress over three decades since E122 has led to smaller measured asymmetries and smaller absolute and fractional errors on the asymmetries.

Statistical errors:
- higher beam currents
- higher polarization
- denser targets



Normalization systematic errors:
- polarimetry
- Q^2 measurements

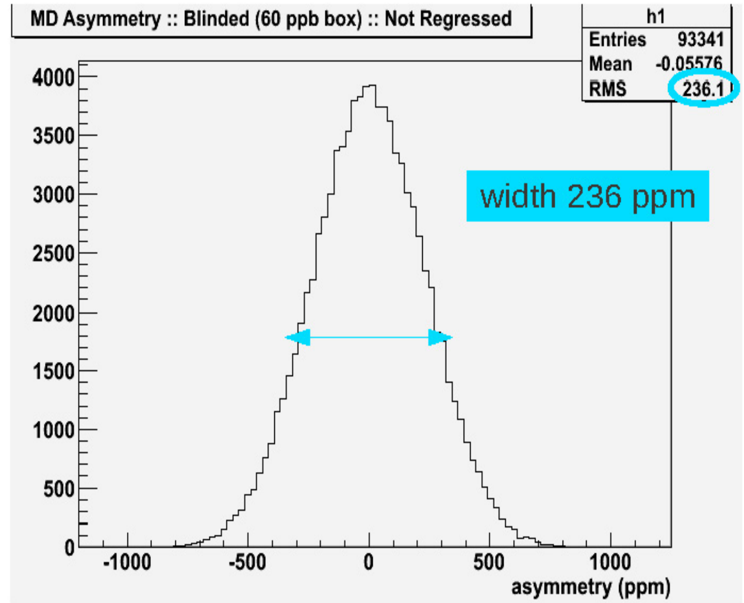
Figure from K. Paschke

"Additive" systematic errors: improved control of helicity correlated beam properties

Qweak and 12 GeV MOLLER

Qweak (ongoing):

- PV elastic scattering on proton: $\vec{e}^- + p \rightarrow e^- + p$
- Total rate ~ 5.3 GHz @ 150 μA
- expected A = -234 ± 5 ± 3 ppb
- Data taken at 960 Hz rate
- Typical asymmetry width (for quartets at 240 Hz) ~ 236 ppm



12 GeV MOLLER (proposed):

- PV elastic scattering on electron: $\vec{e}^- + e^- \rightarrow e^- + e^-$
- Total rate ~ 135 GHz @ 85 μA
- expected A = 35 ± 0.74 ± 0.39 ppb
- Data to be taken at 1.92 kHz rate
- Expected asymmetry width (for pairs at 960 Hz) ~ 83 ppm

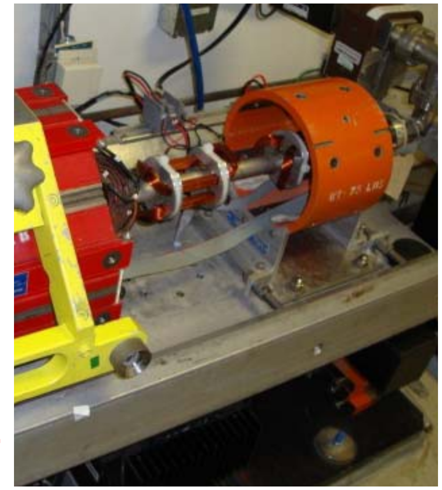
Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute value of Q^2	0.5
beam (second order)	0.4
beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
beam (position, angle, energy)	0.4
beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \rightarrow \pi + X$	0.3
Transverse polarization	0.2
neutrals (soft photons, neutrons)	0.1
Total systematic	**1.1**

Table 4: *Summary of projected fractional statistical and systematic errors.*

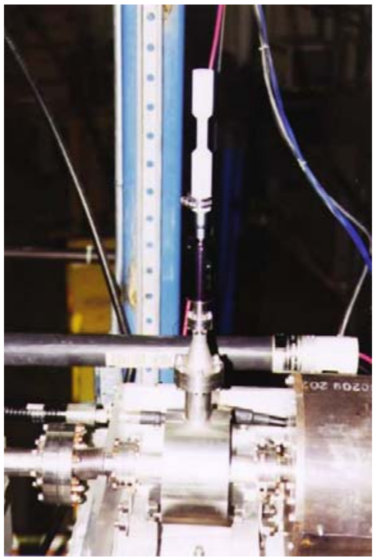
Note: Qweak and MOLLER are taking data at a high rate to suppress potential random noise contributions from target density fluctuations and electronic noise. Most other JLAB parity experiments have been run at 30 Hz.

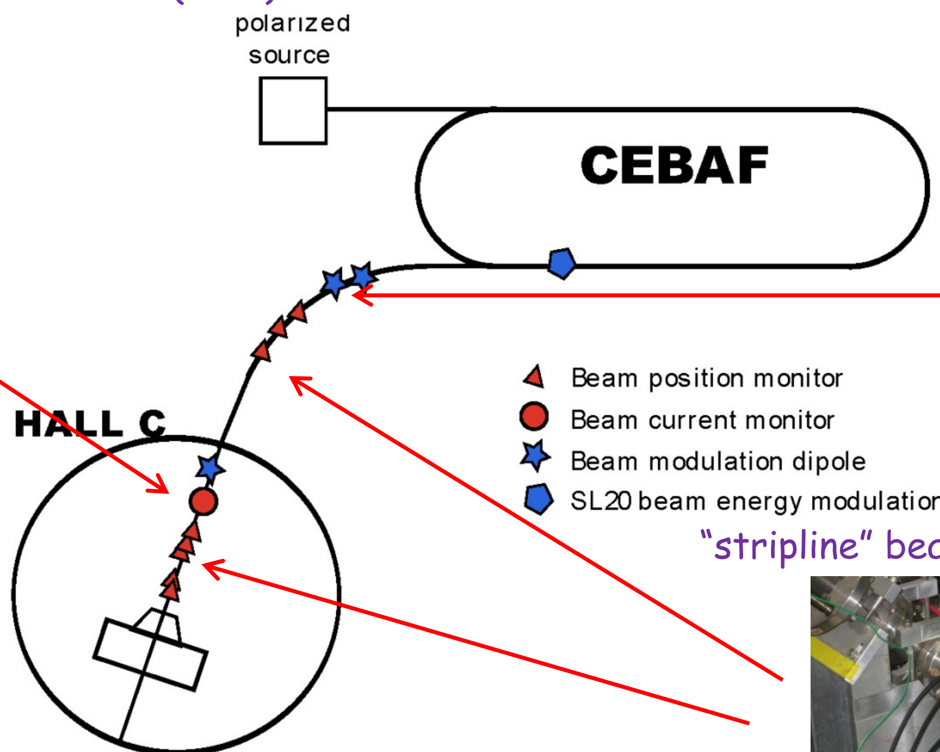
Beam Modulation System to Measure Sensitivities

Aircore beam modulation coils

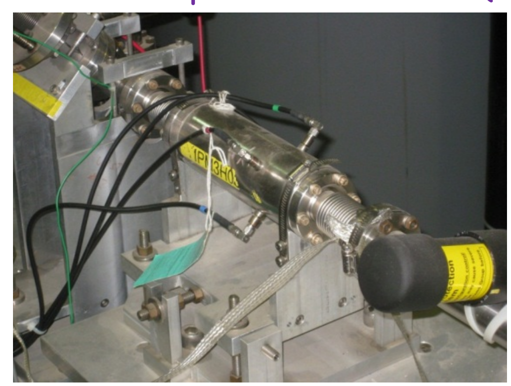


Microwave cavity beam charge monitor (BCM)





"stripline" beam position monitor (BPM)



Generic example of beam modulation and measurement system that has been used for many of these experiments – capability to measure helicity correlated beam properties continuously and deliberately vary beam position, angle and energy.

Measurement of Detector Sensitivities

Two methods used to get sensitivity slopes:

$$A_{corr} = \sum_{i=1}^{N} \frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

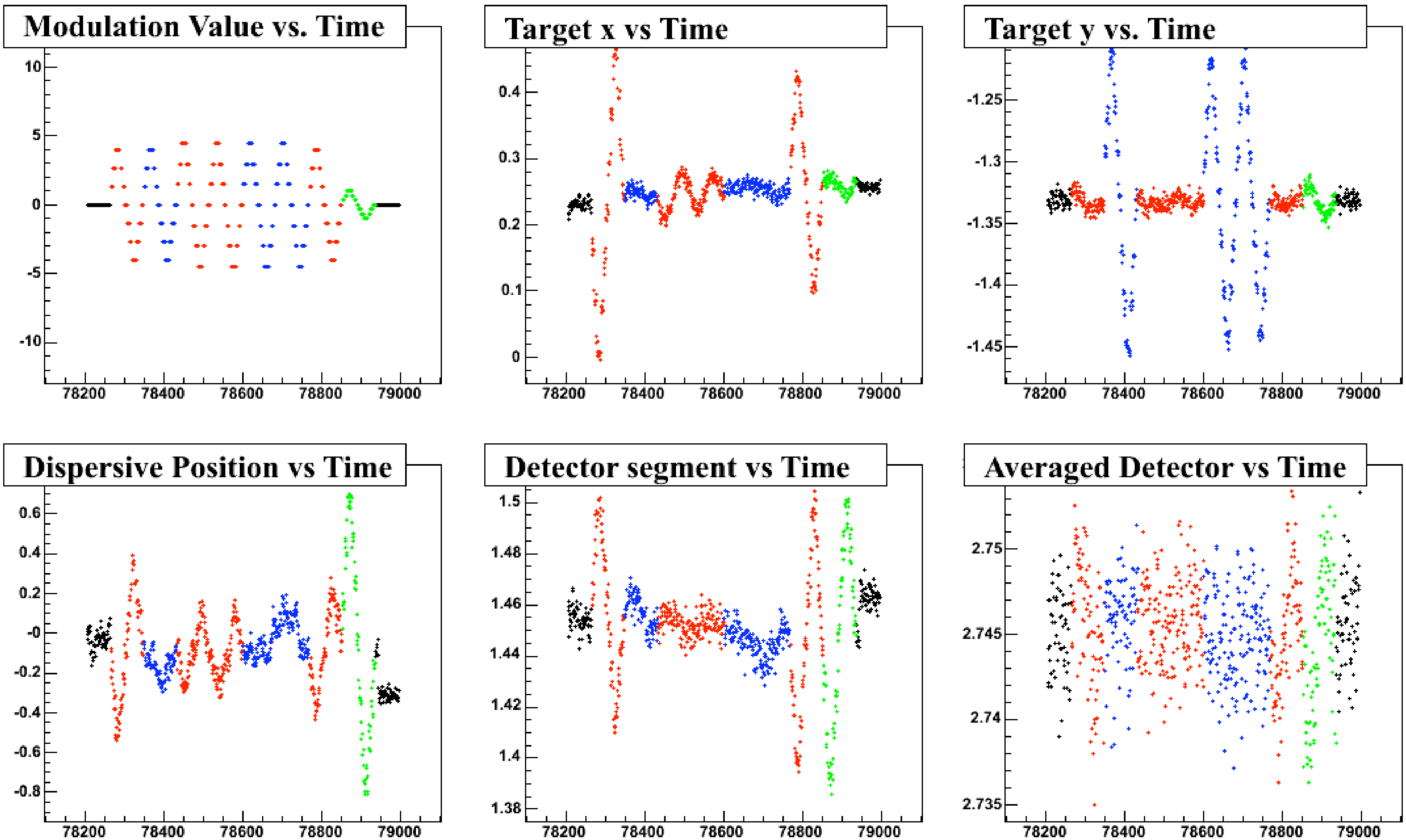
1. Linear regression using "natural beam motion":
   - done simultaneously during production running
   - no ability to control the correlations between the beam parameters

$$\overbrace{\begin{pmatrix} \langle \delta P_1 \delta Y \rangle \\ \langle \delta P_2 \delta Y \rangle \\ \cdot \\ \cdot \\ \cdot \\ \langle \delta P_N \delta Y \rangle \end{pmatrix}}^{\text{measure}} = \underbrace{\overbrace{\begin{pmatrix} \langle \delta P_1 \delta P_1 \rangle & \langle \delta P_1 \delta P_2 \rangle & \cdot & \cdot & \cdot & \langle \delta P_1 \delta P_N \rangle \\ \langle \delta P_2 \delta P_1 \rangle & \langle \delta P_2 \delta P_2 \rangle & & & & \cdot \\ \cdot & & \cdot & & & \cdot \\ \cdot & & & \cdot & & \cdot \\ \cdot & & & & \cdot & \cdot \\ \langle \delta P_N \delta P_1 \rangle & \cdot & \cdot & \cdot & \cdot & \langle \delta P_N \delta P_N \rangle \end{pmatrix}}^{\text{measure}}}_{\text{invert this matrix}} \overbrace{\begin{pmatrix} \partial Y / \partial P_1 \\ \partial Y / \partial P_2 \\ \cdot \\ \cdot \\ \cdot \\ \partial Y / \partial P_N \end{pmatrix}}^{\text{extract}}$$

2. Beam modulation (also referred to as "coil pulsing" or "dithering")
   - typically only done for some small fraction of the production running
   - allows one more control to insure the matrix is not singular

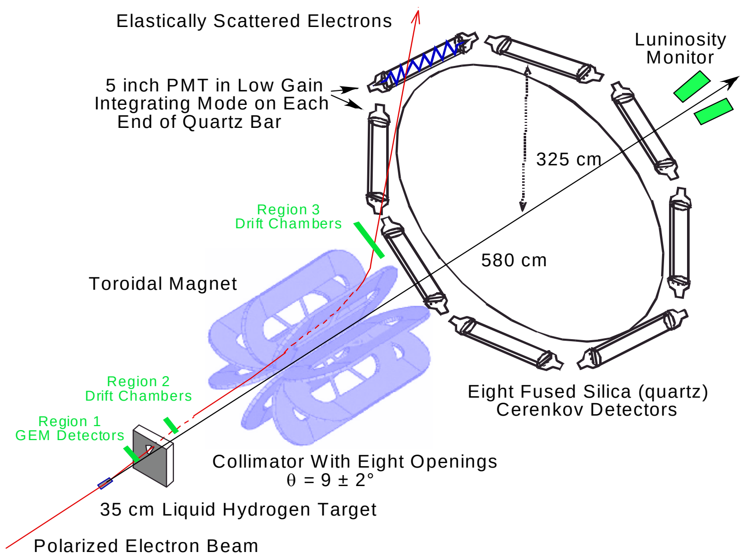
$$\overbrace{\begin{pmatrix} \partial Y / \partial C_1 \\ \partial Y / \partial C_2 \\ \cdot \\ \cdot \\ \cdot \\ \partial Y / \partial C_N \end{pmatrix}}^{\text{measure}} = \underbrace{\overbrace{\begin{pmatrix} \partial P_1 / \partial C_1 & \partial P_1 / \partial C_2 & \cdot & \cdot & \cdot & \partial P_1 / \partial C_N \\ \partial P_2 / \partial C_1 & \partial P_2 / \partial C_2 & & & & \cdot \\ \cdot & & \cdot & & & \cdot \\ \cdot & & & \cdot & & \cdot \\ \cdot & & & & \cdot & \cdot \\ \partial P_N / \partial C_1 & \cdot & \cdot & \cdot & \cdot & \partial P_N / \partial C_N \end{pmatrix}}^{\text{measure}}}_{\text{invert this matrix}} \overbrace{\begin{pmatrix} \partial Y / \partial P_1 \\ \partial Y / \partial P_2 \\ \cdot \\ \cdot \\ \cdot \\ \partial Y / \partial P_N \end{pmatrix}}^{\text{extract}}$$

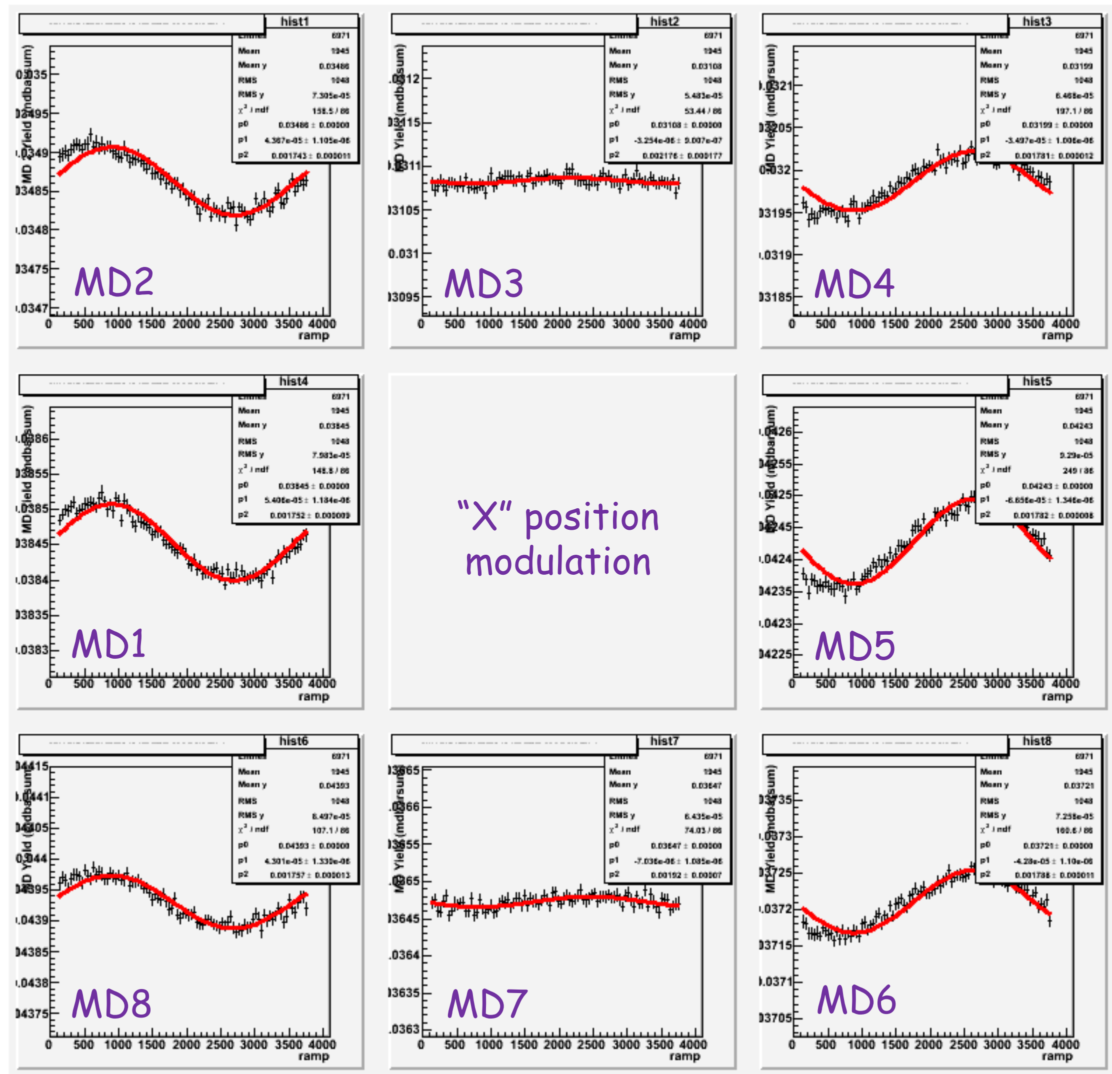
HAPPEx Coil Dithering System in JLAB Hall A



HAPPEx coil dithering system previously used in Hall A; uses 7 air-core coils and energy vernier with a single modulation cycle (represented above) lasting 23 seconds.

Qweak Beam Modulation in JLAB Hall C





- Uses four air-core coils and energy vernier; coils driven with 250 Hz sine wave; differential measurement more immune to slow drifts
- Single modulation cycle for pair of coils to drive pure X "position" is shown

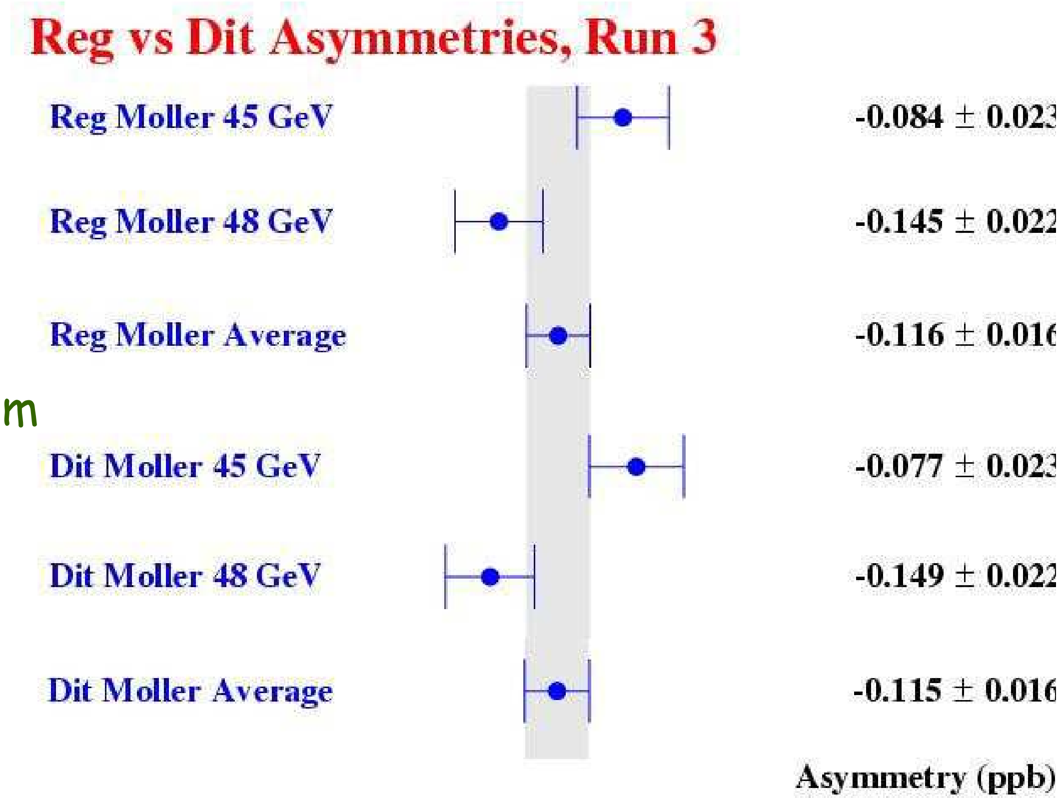
Comparison of Linear Regression to Beam Modulation - Examples

HAPPEx Helium
- from Bryan Moffitt Ph.D.
- quoted error on correction: .059 ppm

Spectrometer Arm	Raw (ppm)	Beam Modulation Corrected (ppm)	Regression Corrected (ppm)
Left	6.37 ± 1.18	5.84 ± 1.16	5.77 ± 1.16
Right	5.18 ± 0.91	5.50 ± 0.89	5.47 ± 0.89

TABLE 3.3: Comparison of the raw, beam modulation corrected, and regression corrected asymmetry for each spectrometer arm. Errors shown are statistical.

SLAC E158
- from Zachary Marshall thesis
- quoted error on correction: .016 ppm



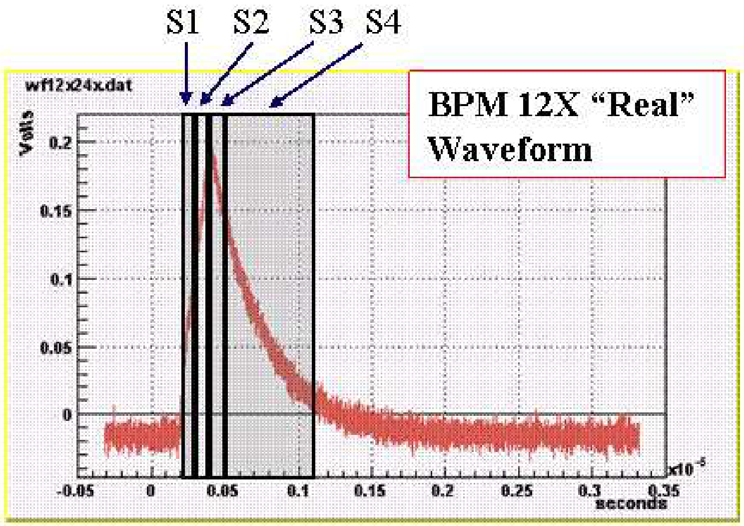
Agreement between the two techniques is within the quoted correction error in both cases.

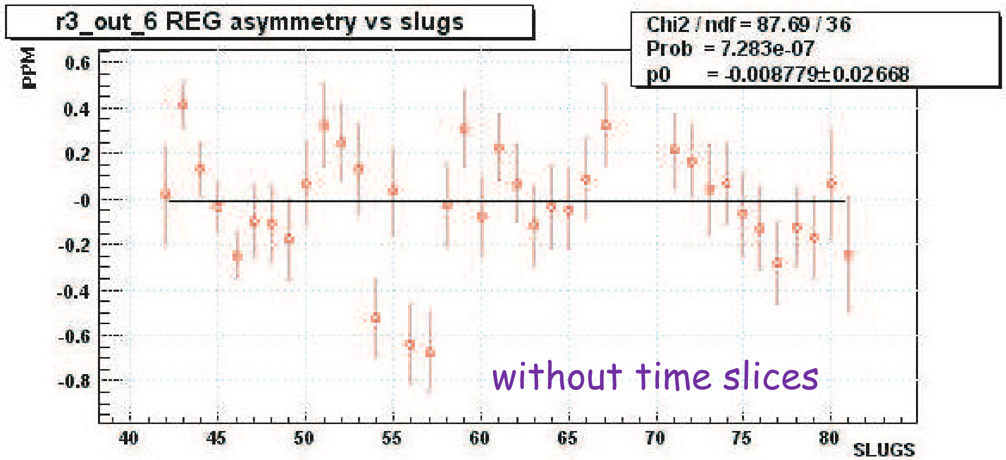
Pulsed Machines are Even More Interesting!

E158 (running at SLAC's pulsed 120 Hz, 270 nsec pulse width linac) found in Runs 1 and 2 that their outer Moller detector run did not behave well statistically after linear regression

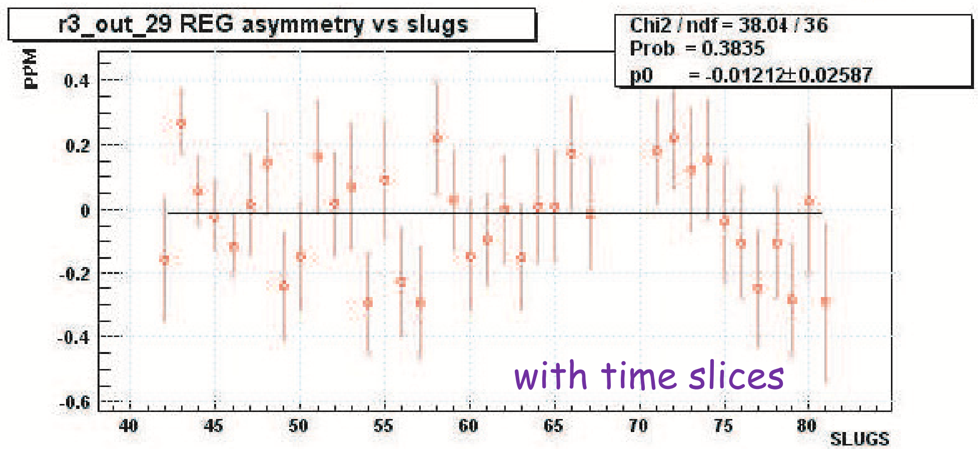
→ problem: time dependence of beam properties within the pulse

→ solution: Digitize the beam monitors in four independent time slices within each pulse





χ^2 of the Ring 3 asymmetry data was improved considerably with inclusion of the time slices



Setting Specification on BPM Resolution and Beam Jitter

BPM Monitor Resolution:

Beam position/angle/energy fluctuations are removed from the normalized yields Y by regression

→ this introduces an additional (beyond counting statistics) source of random error from the finite measurement precision of the beam monitor

→ Example of goal from MOLLER experiment:

Keep this additional error to < 10% of the counting statistics error for a single one of the seven detector sectors (200 ppm/sector)

$$\left(\frac{1}{2Y}\right)\frac{dY}{dP}\sigma_P = \sigma_{random}$$

$$\text{position}: \left(\frac{1}{2}\right)(8.5\,\text{ppb/nm})\sigma_{pos} = 20\,\text{ppm} \quad \rightarrow \quad \sigma_{monitor} = 5\,\mu\text{m}$$

Beam random fluctuations ("jitter"):

The sensitivities (dY/dP) are typically only determined with ~ 10% relative precision

→ this introduces an error that gets larger as the beam jitter gets larger

→ Example of goal from MOLLER experiment:

Keep this additional error to < 10% of the counting statistics error for a single one of the seven detector sectors (200 ppm/sector)

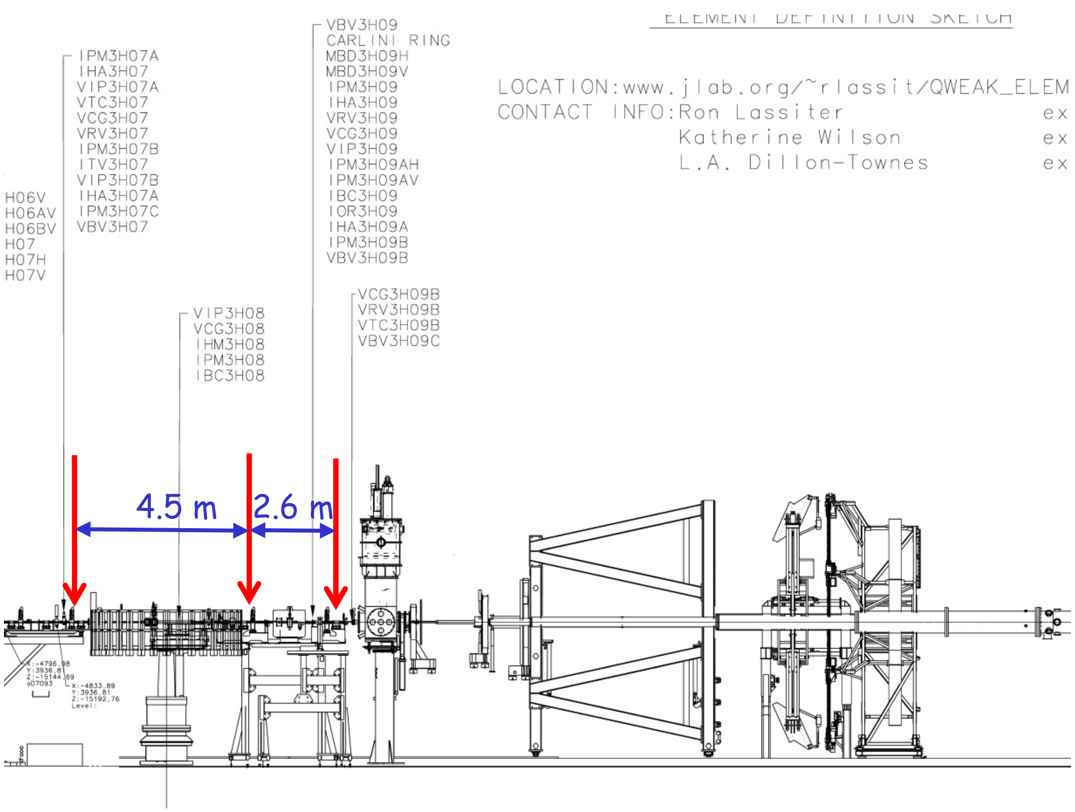
$$\left(\frac{1}{2Y}\right)\frac{dY}{dP}\sigma_P = \sigma_{random}$$

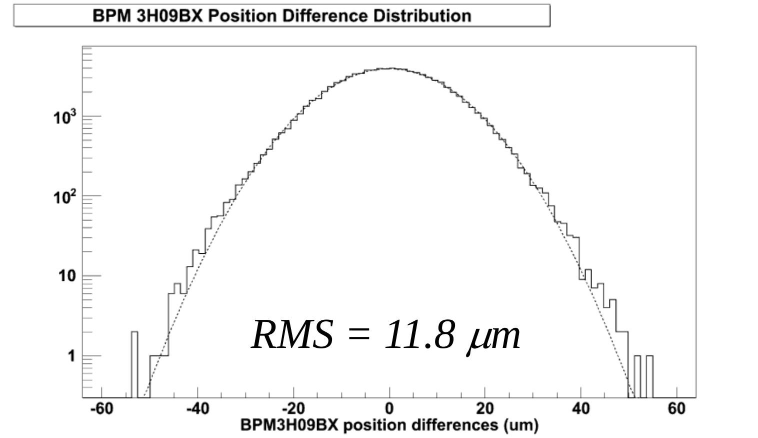
$$\text{position}: \left(\frac{1}{2}\right)(8.5\,\text{ppb/nm})\sigma_{jitter} = 200\,\text{ppm} \quad \rightarrow \quad \sigma_{jitter} = 50\,\mu\text{m}$$

Qweak: BPM Resolution and Beam Jitter Results

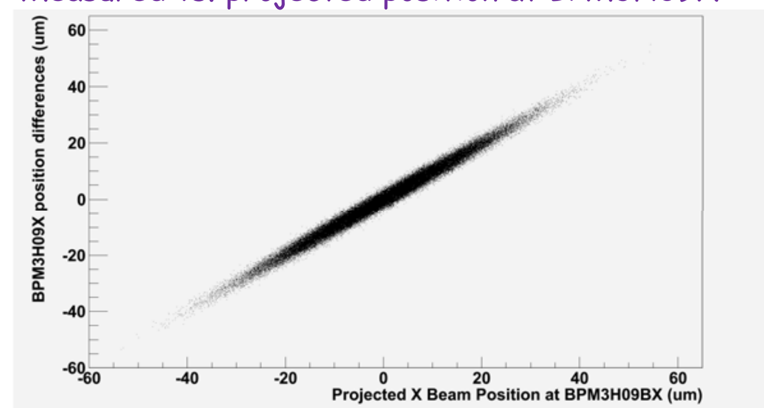
Beam "jitter" dominates the typical noise for a "position difference distribution"; X+ - X-

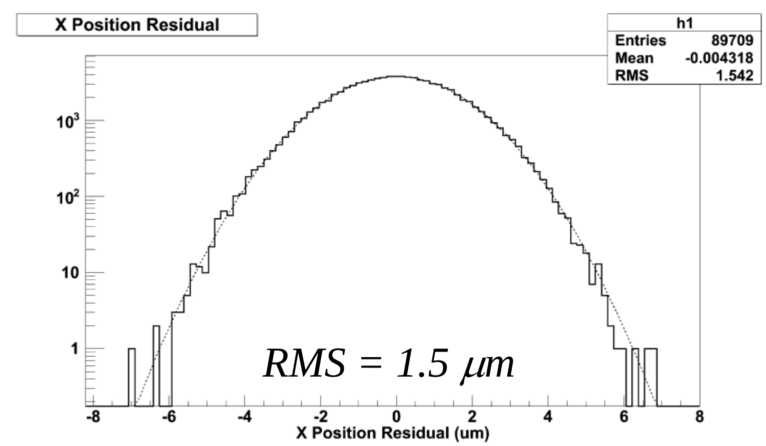
Intrinsic BPM resolution can be extracted by using two (or more) upstream monitors to project to a downstream monitor





Measured vs. projected position at BPM3H09X





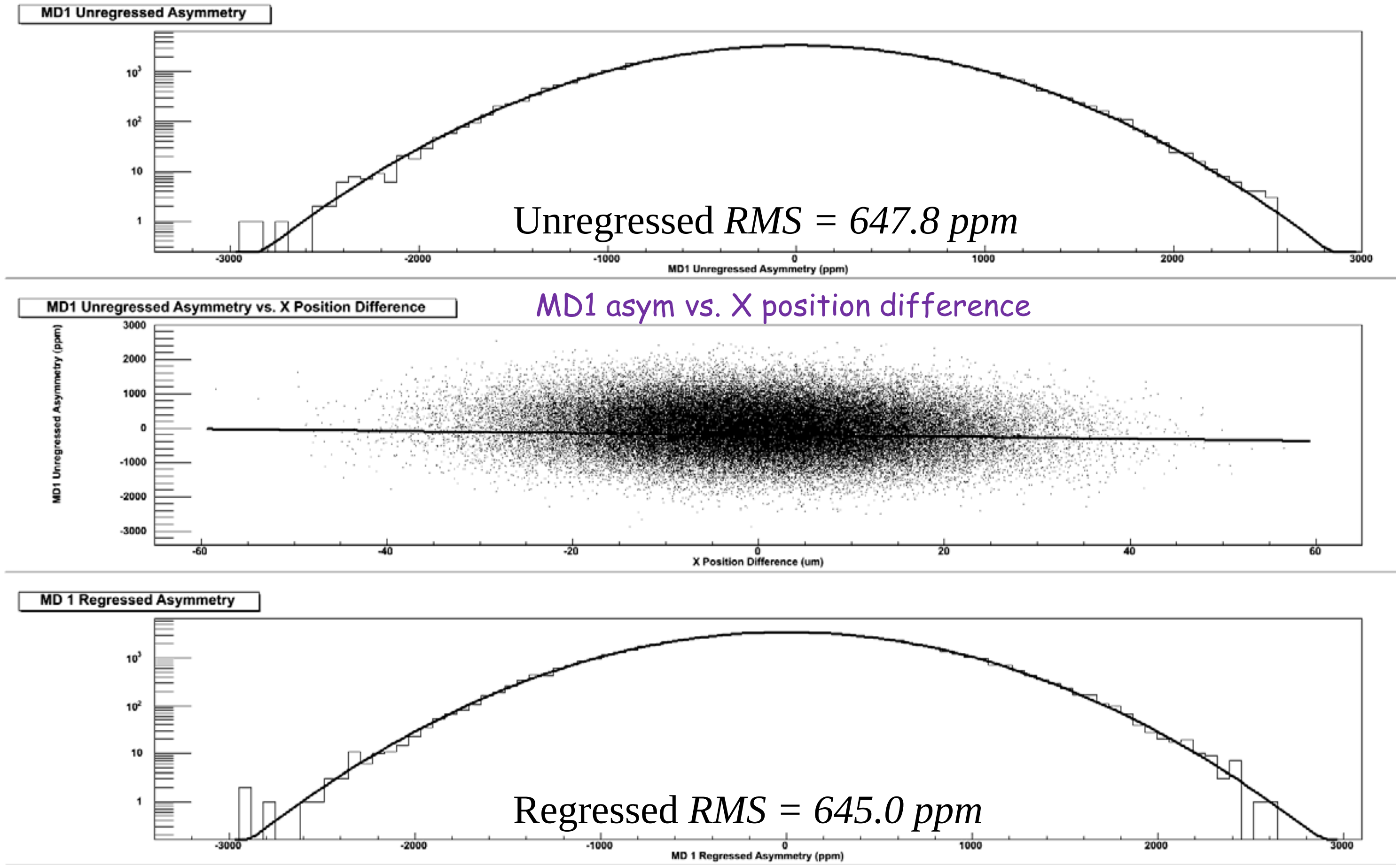
Qweak: Contribution of Beam Jitter to Random Width

Consider a detector in a single octant (MD1 – dominantly sensitive to X motion)

How does the 11.8 μm of beam jitter in X contribute to the detector width

$$\text{measured}\left(\frac{1}{2Y}\right)\frac{dY}{dP}$$

$$\sim -4.89\ \text{ppm}/\mu\text{m}$$



Excess noise $\sqrt{(647.8)^2-(645.0)^2} \sim 60\,\text{ppm}$ agrees with simple estimate:

$$\left(\frac{1}{2Y}\right)\frac{dY}{dP}\sigma_P = (4.89\ \text{ppm}/\mu\text{m})(11.8) = 58\ \text{ppm}$$

Setting Specification on BCM Resolution and Intensity Jitter

BCM Monitor Resolution:

Yields are normalized to the charge monitors, but there will be remaining random fluctuations due to the finite precision of the charge monitors – this needs to be small enough so it does not significantly increase the counting statistics width:

$$\sigma_{random} = \sqrt{\sigma_{counting}^2 + \sigma_{BCM}^2}$$

Example of goal from MOLLER experiment: BCM resolution of 10 ppm (for 1 kHz pairs) limits contribution to counting statistics width of ~ 80 ppm to < 1%

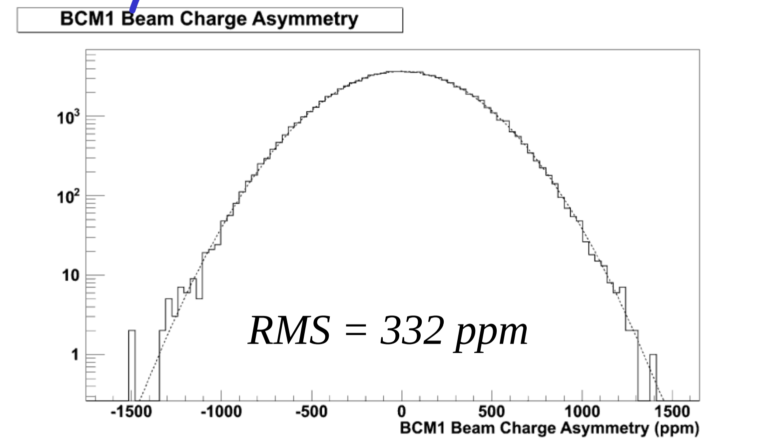
Beam intensity fluctuations ("jitter"):

The combined detector/BCM system has non-linearity which typically can be reduced to ~ 1% or less. This imposes a requirement on the tolerable beam noise.

→ MOLLER: To keep the random noise from this at the 10 ppm level requires <1000 ppm (for 1 kHz pairs) of intensity noise – ie. (.01) (1000 ppm) = 10 ppm

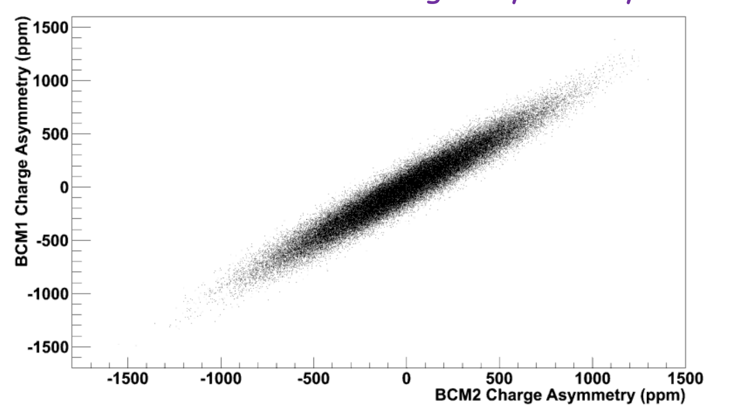
Qweak: BCM Resolution and Intensity Jitter Results

Beam "jitter" dominates the typical noise for a charge asymmetry $A_Q = (Q_+ - Q_-)/(Q_+ + Q_-)$



Monitor resolution is determined by comparing the charge asymmetry from nearby monitors with a "double difference" ($A_{Q1} - A_{Q2}$) plot – gives the uncorrelated noise.

BCM1 vs. BCM2 Charge Asymmetry



For a single BCM:

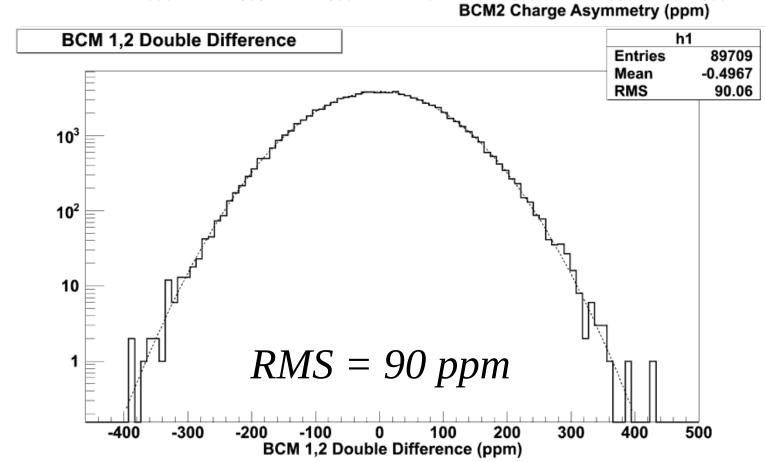
$\sigma(A_{Q1})$ *or* $\sigma(A_{Q2})$

$= \sigma(A_{Q1} - A_{Q2})/\sqrt{2} =$ 64 ppm

For the average of two BCMs:

$\sigma((A_{Q1} - A_{Q2})/2)$

$= \sigma(A_{Q1} - A_{Q2})/2 =$ 45 ppm



so this additional random noise contribution increases Qweak statistical width by only ~ 2%

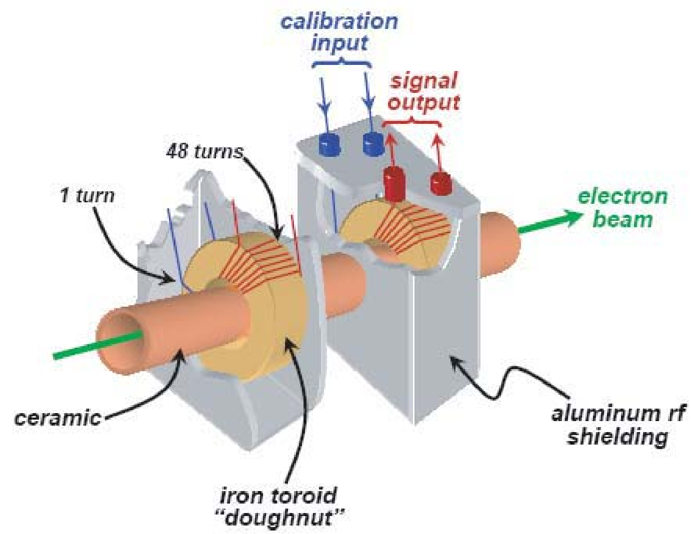
ie. $$\sqrt{(240\ \text{ppm})^2 + (45\ \text{ppm})^2} = 244\ \text{ppm}$$

BPM and BCM Instrumentation - SLAC and Mainz

BPMs at SLAC:
Copper microwave rectangular cavity monitors operating in TM_{210} and TM_{120} modes at the 2856 MHz resonant frequency.

Farinholt *et al.*, PAC 1967
Whittum, Kolomensky, Rev. Sci. Inst. 70, 2300 (1999)

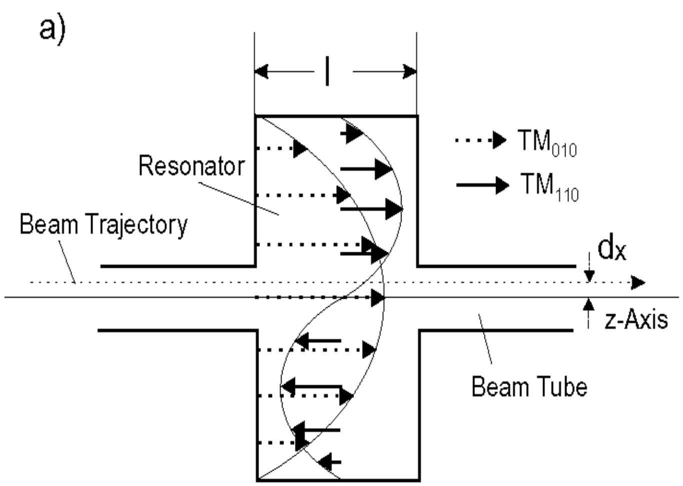
Current monitors at SLAC:
Toroids are used to inductively detect the beam current with copper wire wound around an iron ring

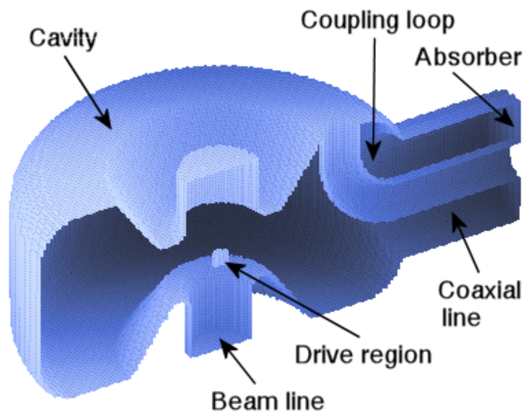


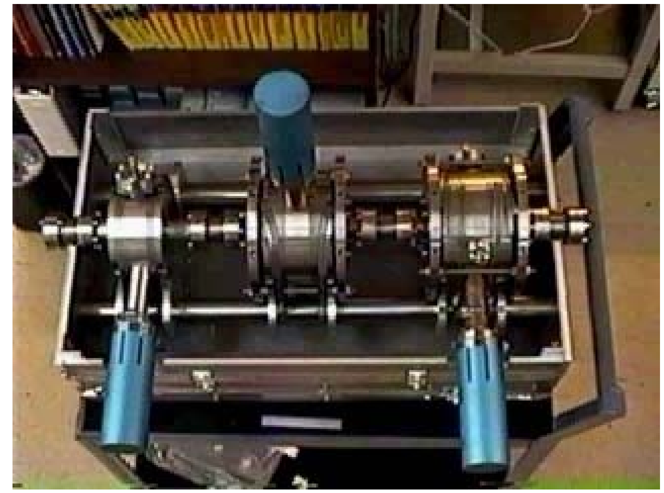
Mainz: Microwave cavity monitors are used for
- intensity: TM_{010} mode ("PIMO")
- position: TM_{110} mode ("XYMO")

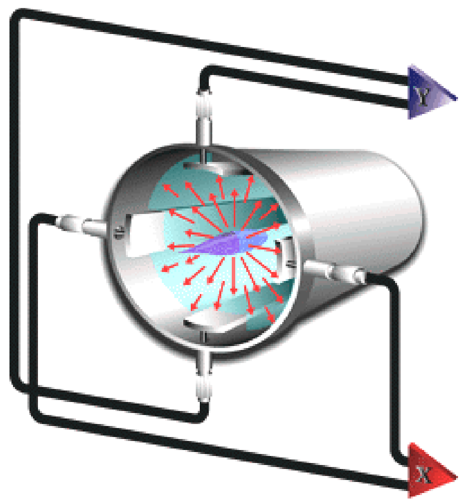
BPM Instrumentation – Jefferson Lab

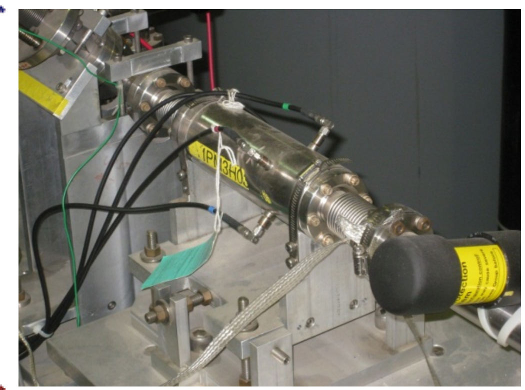
Microwave cavity monitors: Electromagnetic cavity resonant at accelerator RF (1497 MHz)
TM_{010} → measure beam intensity
TM_{110} → measure beam position









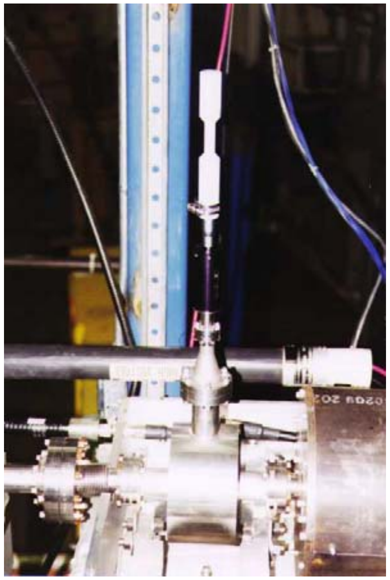


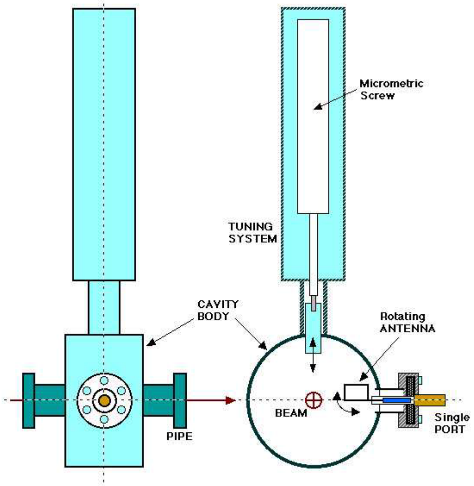
"Stripline" beam position monitors
- standard JLAB beam position monitor
- 4 quarter-wave antennae
- uses "switched electrode electronics" (SEE)

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

BCM Instrumentation – Jefferson Lab

Cylindrical stainless steel microwave cavities operating in TM_{010} mode at 1497 MHz

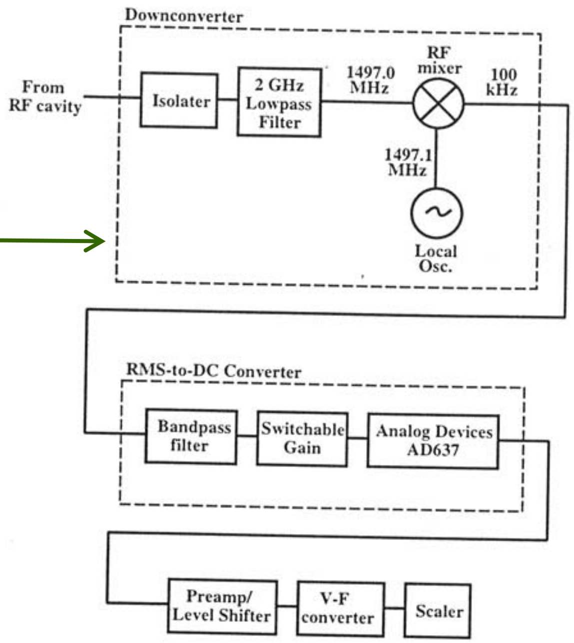




Two styles of electronics exist:

- Analog: conventional analog heterodyne processing chain
- Digital: digital receiver chain

H. Dong *et al.*, PAC 2005



..4: A simplified schematic of the electronics used with BCM1 and

MOLLER Specifications for Resolution/Jitter compared to Qweak Observations

Monitor resolutions at 1 kHz pair rate

Monitor type	MOLLER spec.	Qweak observed
BCM	10 ppm	120 ppm
BPM	3 μm	6 μm

Random beam fluctuations at 1 kHz pair rate

Beam property	MOLLER spec.	Qweak observed
Intensity	< 1000 ppm	500 ppm
Energy	< 286 ppm	6.5 ppm
Position	< 47 μm	48 μm
Angle	< 4.7 μrad	1.4 μrad

Note: the Qweak observed numbers are extrapolated to higher frequency (2 kHz vs. 1 kHz) by assuming "white noise" scaling, and they are corrected for quartets vs. pairs.

Beam fluctuations ("jitter"): Look to be easily satisfied for MOLLER asssuming 12 GeV machine is not too different from 6 GeV machine.

Monitor resolution:
BPM: quoted number is for striplines; cavities are at least a factor of 2 better
BCM: further R&D is likely needed to achieve the goals

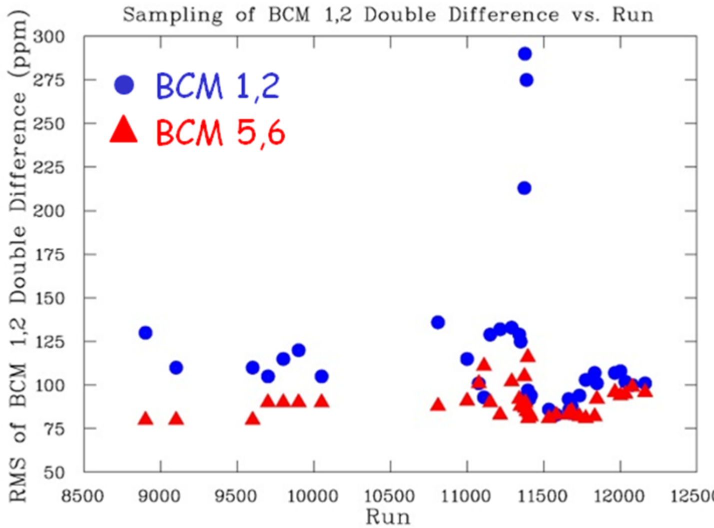
Qweak BCM Resolution Experience – Part 1

BCM resolution has been adequate for Qweak's needs, but not adequate for MOLLER. The Qweak observations and experience can serve as initial R&D for MOLLER.

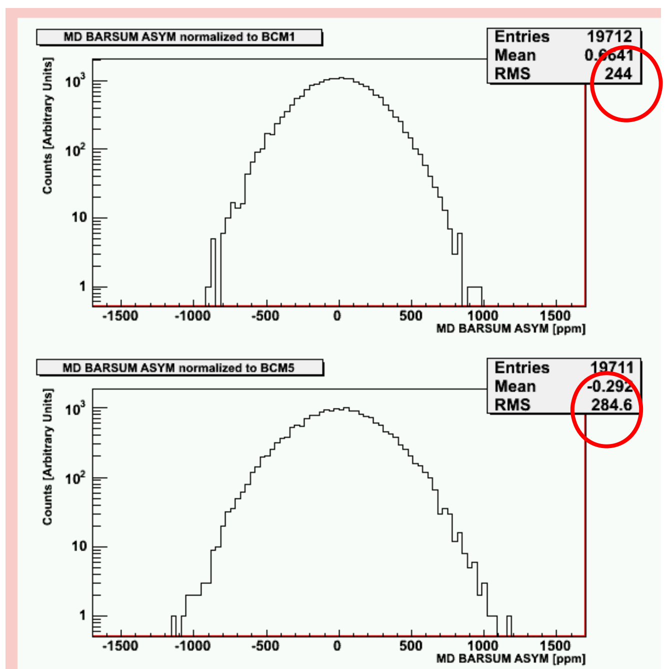
BCM1/2: "analog" electronics readout
BCM5/6: "digital" electronics readout

Double difference (uncorrelated noise) observations over ~ 4 months:

- Varied from ~ 90 ppm – 125 ppm for 150 – 180 μA
- BCM5/6 DD typically more stable and smaller
- "Bad period" when beam had high frequency ~ 20 – 30 kHz noise on it



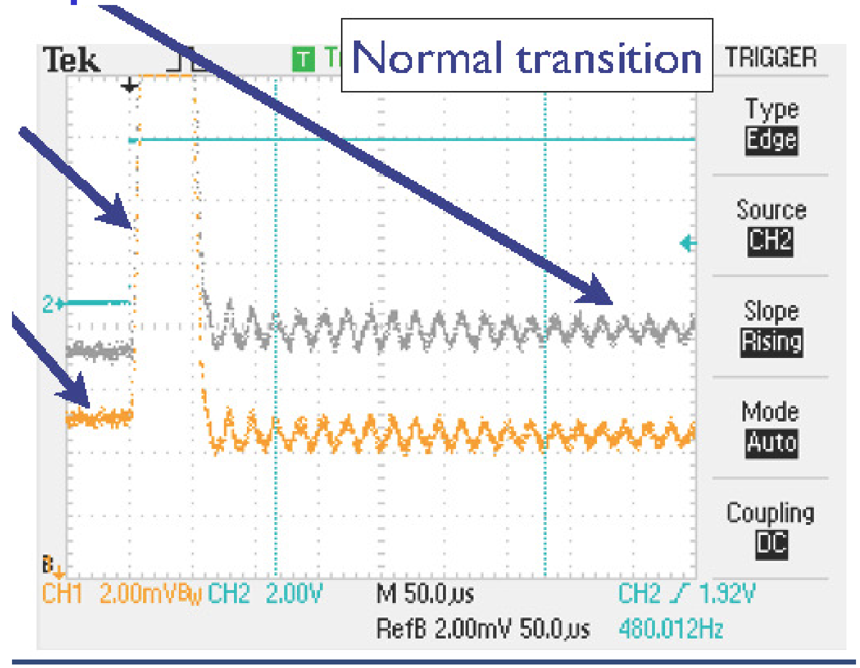
Evidence for common mode noise in BCM5/6 chain – despite smaller DD, gives larger width than BCM1/2 when used as normalizer; should be improved for Run II



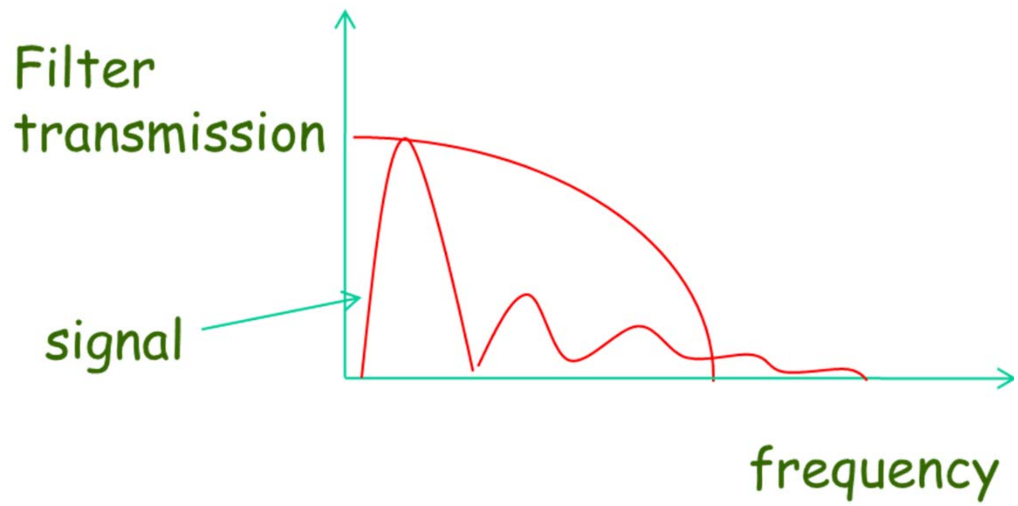
Qweak BCM Resolution Experience – Part 2

The beam intensity can have high frequency components to it due to Pockels cell ringing, etc.

This makes it important to match the frequency response (bandwidth) between detector and BCMs
- this was observed to be important both in PREX and Qweak



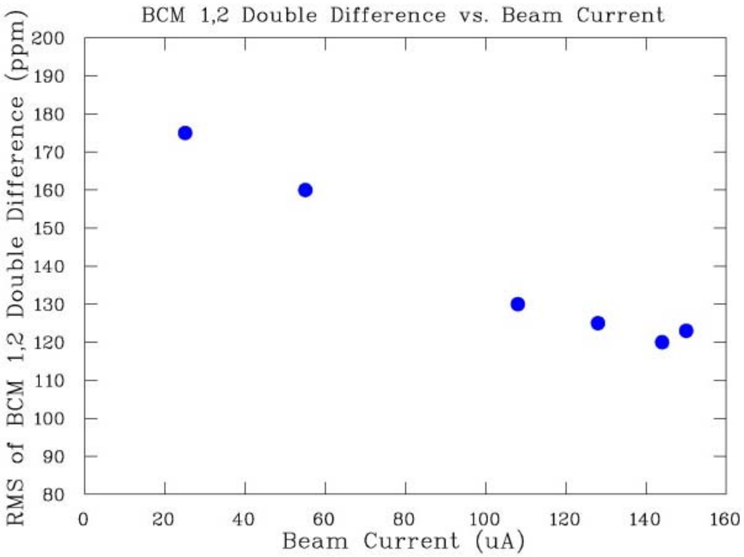
Example from Dave Mack: If injector intensity spectrum is near filter cutoff then we are very sensitive to the exact cutoff between detectors and BCMs



Qweak BCM Resolution experience – Part 3

The observed Qweak BCM resolutions imply ~ 120 ppm BCM resolution under MOLLER conditions (compare to MOLLER counting statistics width of ~ 80 ppm).

Data will be taken during Qweak Run II to try to understand the resolution behavior better and determine the optimum R&D upgrade path



Dependence on beam current: Can we improve things simply by boosting the signal (ie. copper cavities instead of stainless steel)?

Needs more study; first look indicates that DD doesn't fall as 1/I as one would naively expect.

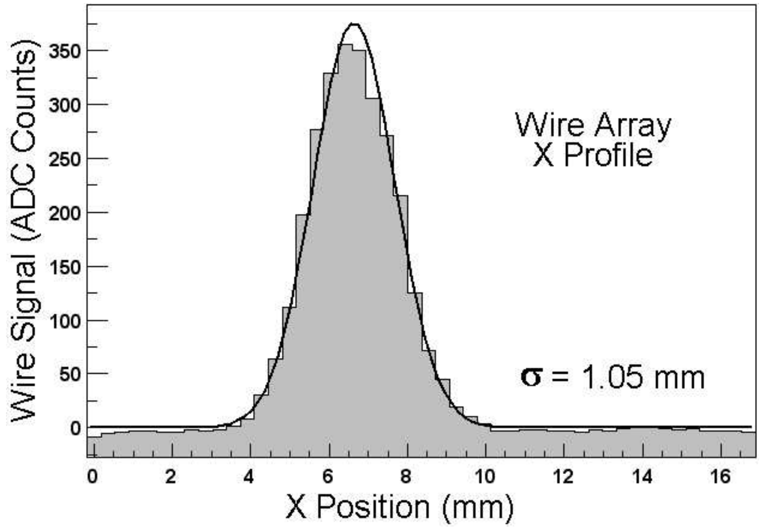
Dependence on data-taking frequency: This should tell us about the frequency spectrum of the relevant noise. Need to do this at a variety of frequencies in the 30 Hz – 2 kHz range of interest.

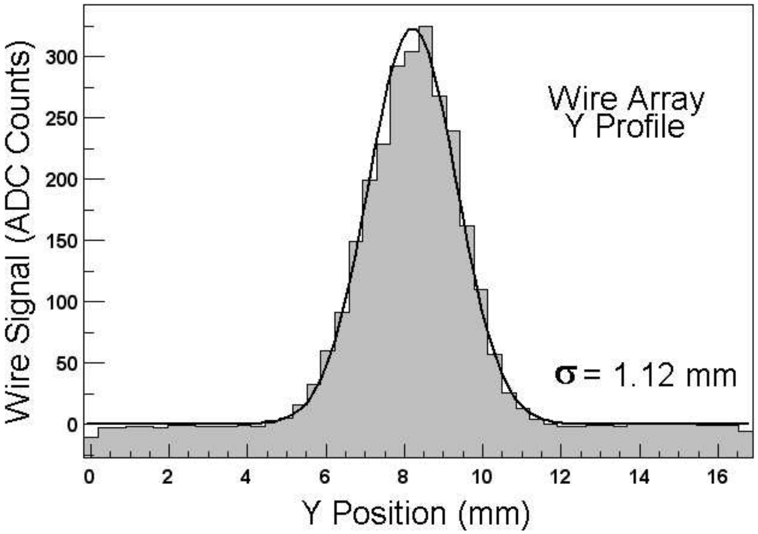
Example: At 30 Hz, typical BCM resolutions of ~ 14 ppm @ 80 uA were observed

Second Order Effects – Helicity Correlated Spot Size

Second order effects, like helicity correlated spot size, have been dealt with indirectly.
Example: MOLLER will bound the helicity-correlated laser spot size at the polarized source then obtain further suppression with multiple slow reversals ("Double-Wien" and g-2)

E158 at SLAC had a wire array that could be invasively inserted into the electron beam (2 grids of 48 wires each)





Observed values for average spot size asymmetry:
- Run I: $(5.5 \pm 6.9) \times 10^{-6}$ mm^2
- Run II: $(-3.7 \pm 25.2) \times 10^{-6}$ mm^2

Conclusions

- The beam instrumentation and control techniques employed over the last 30 years have insured small (compared to statistical error) errors stemming from corrections for helicity-correlated beam properties.

- Future experiments like MOLLER will put greater demands on beam instrumentation (and fluctuations).
  - will exploit the full potential of BPM's
  - will likely require upgrades to BCM's

- Initial experience from the Qweak experiment indicates that the most important beam instrumentation upgrade that will be needed for the MOLLER experiment is in beam current monitoring.