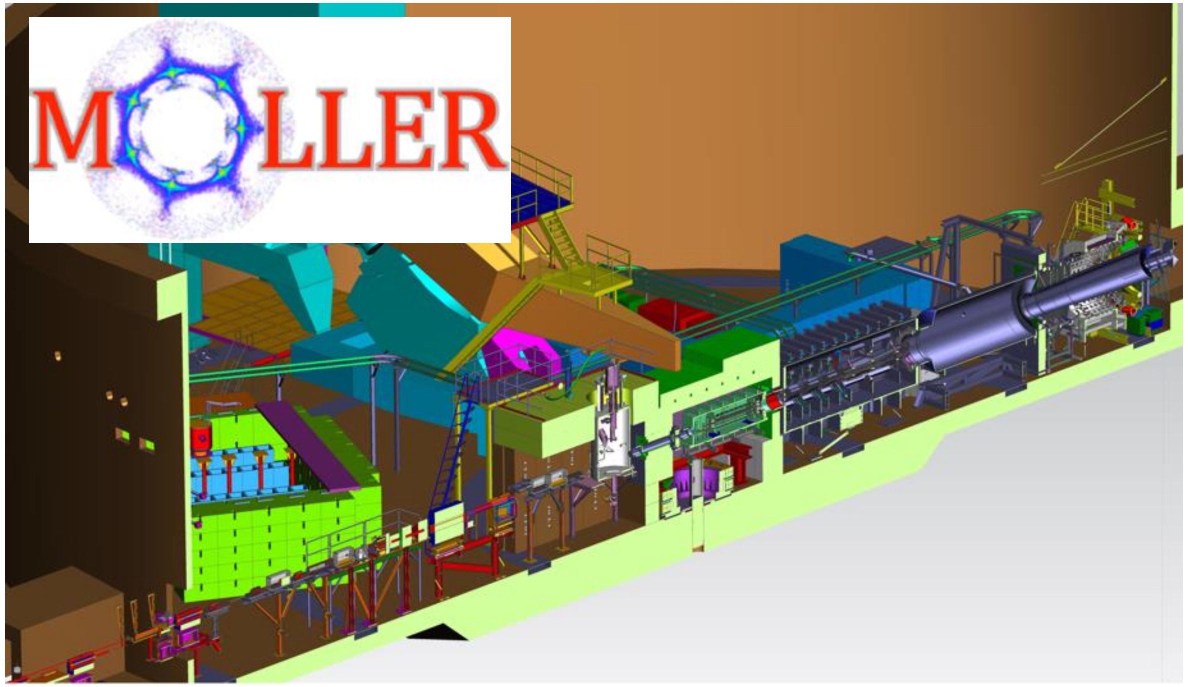
MOLLER Experimental Readiness Review 2

July 29, 2025



Mark Pitt – Virginia Tech

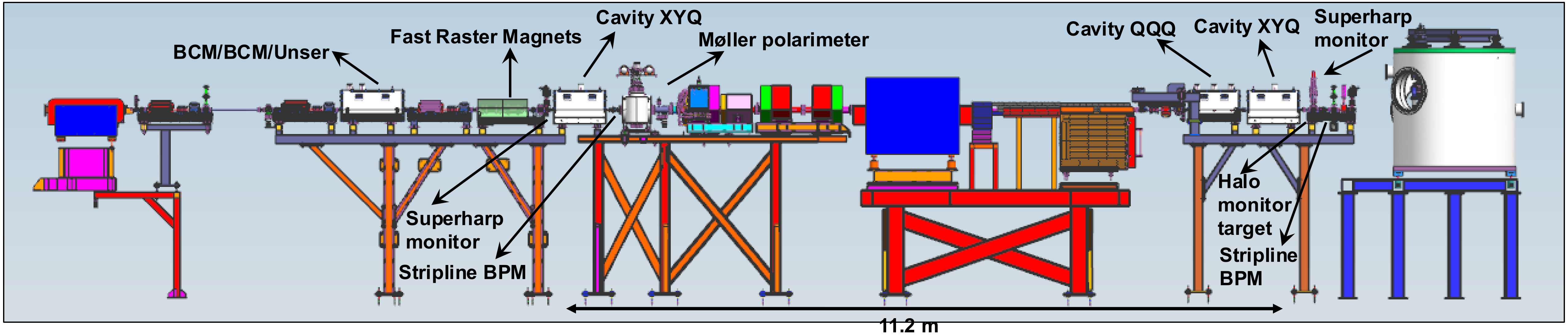
MOLLER-NSF Project Coordinator/Point of Contact

MOLLER Collaboration Executive Board Chair/Deputy Spokesperson

Outline

- MOLLER Beamline Overview
- MOLLER Position and Intensity Monitoring Requirements
- MOLLER BPM Status
- MOLLER BCM Status
- Low beam current monitoring
- Halo monitor

MOLLER Incoming Beamline: Final MOLLER Incoming Beamline Design

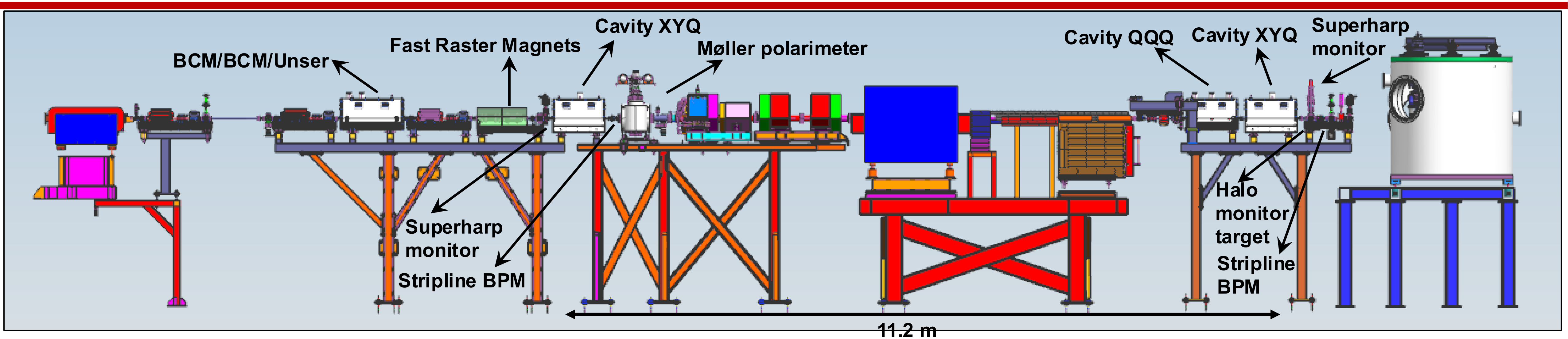


The final MOLLER incoming beamline design was designed by Jay Benesch and verified with beam optics calculations by Yves Roblin (*J. Benesch and Y. Roblin JINST 16 T12007 (2021)*)

It allows for:

- Movement of MOLLER hydrogen target 4.5 meters upstream of nominal Hall C target position
- Necessary beam instrumentation and controls to achieve physics requirements

MOLLER Incoming Beamline: System Requirements

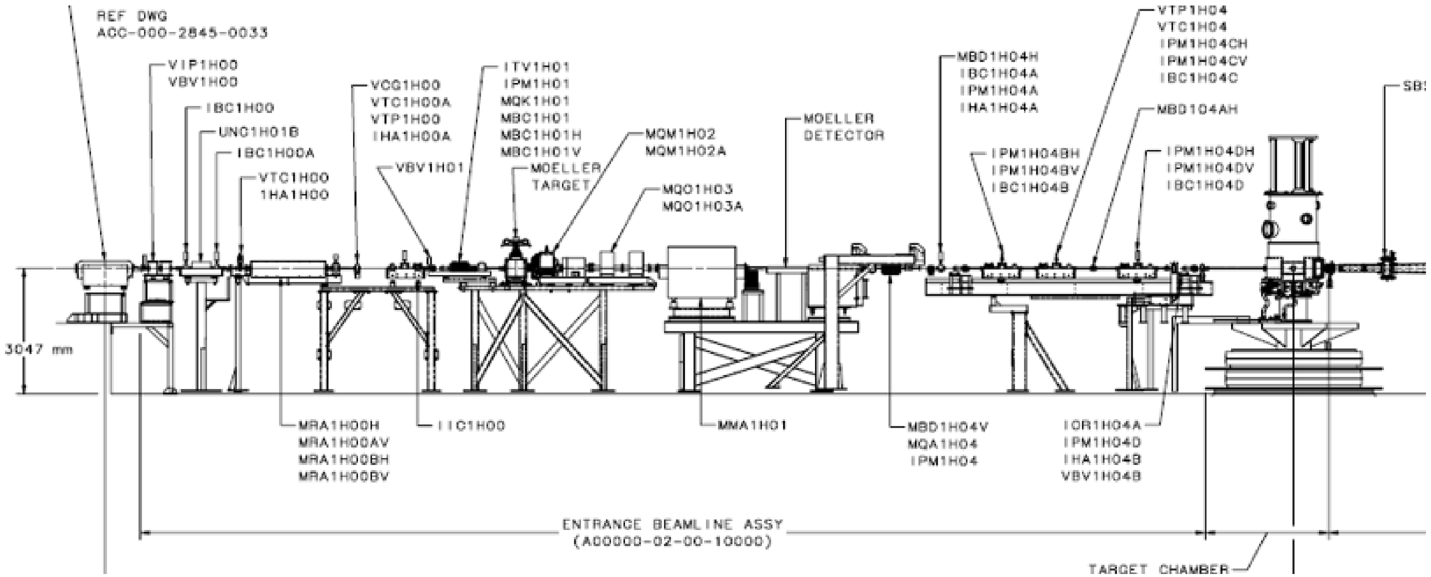


Design documented in MOLLER Incoming Beamline System Requirements document (Rev0-Final)

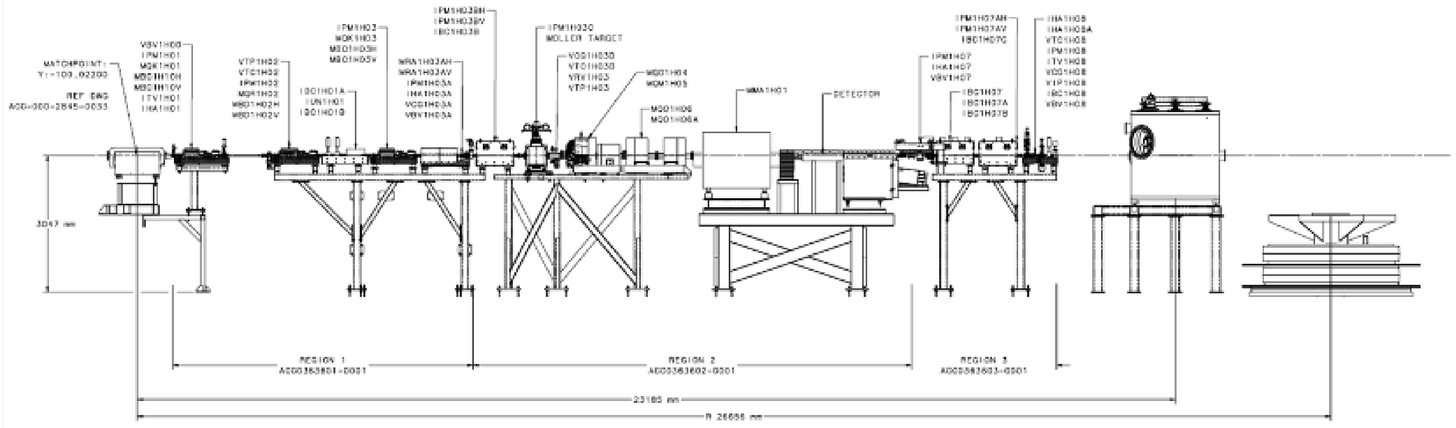
- Moller polarimeter magnets unmoved from current location, but with fully degaussed quads/dipoles during production running
- Redundant position/angle measurements with thin-wire “stripline” and microwave cavity position monitors separated by > 10 m
- Fast feedback will work independent of anything downstream of the Hall A arc
- Adequate quad count for envelope matching at Compton and Moller polarimeters and physics targets
- Independent slow orbit locks available before and after Compton polarimeter
- Phase advance from beam modulation correctors to BPMs is > $\pi/6$
- Moller polarimeter target is moved 30 cm upstream from its current location
- Faster raster system capable of 5.0 mm x 5.0 mm spot at MOLLER target (assuming square pattern)
- Microwave cavity (QQQ and XYQ) monitors will be electrically isolated from beamline

MOLLER Incoming Beamline

- Existing beam line



- MOLLER beam line



Parts for the redesigned upstream beamline will be ready for installation at the needed times in the installation schedule.

MOLLER Position and Intensity Monitoring Requirements

$$\left(A_{cxpt}\right)_i = \left(\frac{\Delta F}{2F} - \frac{\Delta I}{2I}\right)_i - \sum_j \left(\alpha_j \left(\Delta X_j\right)_i\right)$$

The intensity asymmetry and position differences are:

$$A_I = \frac{\Delta I}{2I} = \frac{I_R - I_L}{I_R + I_L} \qquad \Delta X = X_R - X_L$$

Contributions to σ_{pair} - "Pair width"

Parameter	Random Noise (65 μA)
Statistical width (0.5 ms)	**$\sim$ 82 ppm**
Target Density Fluctuation	30 ppm
Beam Intensity Resolution	10 ppm
Beam Position Noise	7 ppm
Detector Resolution (25%)	21 ppm (3.1%)
Electronics noise	10 ppm
Measured Width (σ_{pair})	**91 ppm**

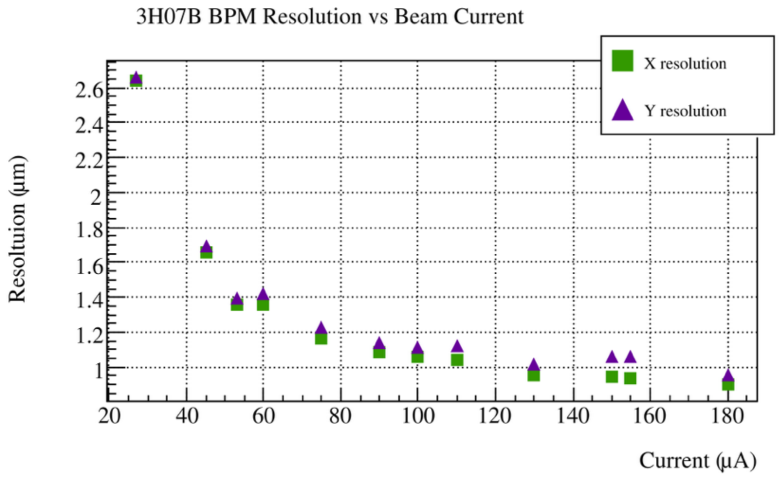
Requirements:

- Position: Relative beam position changes measured with resolution < 3 um for 960 Hz window-pairs
- Intensity: Relative beam intensity changes measured with resolution < 10 ppm for 960 Hz window-pairs
  - Ideally, we want to strive for the 10 ppm resolution goal for each of the BCM monitors; this allows us to do systematic comparisons between the monitors to show that this 10 ppm is truly uncorrelated, random noise.
  - Since we have 7 BCMs in the MOLLER beamline, we could brute force average all seven, which relaxes the resolution requirement to $\sim \sqrt{7}\,(10\text{ ppm}) \sim 26\text{ ppm}$

(Further information available in BCM and BPM Requirements Document provided to Nate Rider.)

MOLLER Beam Position Monitors

- Intrinsic BPM resolution can be extracted by using two (or more) upstream monitors to project to downstream monitor
- Results shown are for Q_{weak} with standard JLab thin-wire “stripline” BPM for 240 Hz quartets



B. Waidyawansa,

Ph.D. thesis 2013

- MOLLER @65 μA for 960 Hz pairs, estimate (assuming “white” noise and correction for quartets vs. pairs): $1.3\,\mu\text{m} \times \sqrt{2} \times \sqrt{2} \sim 2.6\,\mu\text{m}$

MOLLER goal for position monitor resolution of ~ 3 μm for 960 Hz pairs is met

- Also will have redundancy of microwave cavity monitors at similar resolution

MOLLER Beam Position Monitors - Phaseout of SEE Electronics

- The SEE (Switched Electrode Electronics) that have been used with “thin-wire” stripline BPMs for all prior JLab PVES experiments are being phased out (parts obsolete). They are being replaced with JLab digital receivers that work with stripline BPMs.
  - Concern: Lots of experience with the existing electronics; replacing with new can introduce new issues
  - Opportunity: Existing SEE system always had concerns with multiplexed readout; new system may allow removal of the multiplexing and increase of sample frequency
- We have requested that we need to be able to test the new receivers in parallel with the existing SEE systems on some critical devices such as the last two BPMs in Hall A.

MOLLER BCM (Beam Current Monitors) – measuring the resolution

In practice, to obtain the random measurement precision (resolution) of a monitor, we need to compare two monitors to remove the correlated noise from their common signal (either the electron beam or the split signal from an RF source in bench tests). So, we measure the "double difference" between monitor 1 and 2

$$DD \equiv A_1 - A_2$$

The resolution – the random measurement precision of a single monitor - is determined from the RMS of the double difference as: (note: this assumes the resolution is the same for each monitor)

$$resolution \equiv \frac{DD\ RMS}{\sqrt{2}}$$

Both resolution and double difference need to be quoted with the parameters of the measurement:

- Multiplet type: pair, quartet, octet, etc.
- Time-window frequency (i.e. data-taking rate) and resulting multiplet rate; Examples:
  - 1920 Hz data-taking rate for pairs -> 960 Hz pair rate (MOLLER quotes its random error goals in these terms)
  - 960 Hz data-taking rate for quartets -> 240 Hz quartet rate (This was the standard Q_{weak} condition.)
  - 1920 Hz data-taking rate for 64 window multiplet -> 30 Hz "64 window multiplet" rate (This is the intended actual way that MOLLER will likely combine its data.)

History of work on BCM monitors

We have experience with two types of monitors:

- Q_{weak} BCM Receivers – receivers designed (~2010) specifically for BCMs
- Digital Receivers – digitial receivers designed (~2013 with improvements over time) to be general purpose for stripline monitor and cavity receivers

- 2010 – 2016: During Q_{weak} lots of experience developed with Qweak receivers with beam; after run (in 2016) bench tests (with rf source) confirmed the beam experience and further explored parameters and did bench tests with the digital receivers. Reason for optimism with modest improvements.

- Fall 2023 - present: Started work again with Devi Adhikari and John Musson check how digital receivers performed with beam in Hall A and in bench tests – used the Hall A parity DAQ
  - Initial studies were focused on “spikes” and “jumps” observed in the output; confirmed by Musson with lab instrumentation – after time-consuming studies these issues were resolved.
  - More recent studies have been focusing back on the resolution issue. Musson can now effectively do a 960 Hz window rate DAQ in his lab, speeding up the evaluation of changes.

BCM Resolution – History and Current Status

Recall: resolution goal is 10 ppm for 960 Hz window-pairs, but 26 ppm (and averaging 7 BCMs) for 960 Hz window-pairs is possible fall-back position

Mark Pitt Summary of Past Testing:

Receiver	Measured Results	Extrapolated to MOLLER pairs
Q_{weak} receiver (2016 Bench test)	42 ppm DD RMS 30 ppm resolution for 480 Hz quartets	59 ppm DD RMS 42 ppm resolution for 960 Hz pairs
Digital receiver (2016 Bench test)	32 ppm DD RMS 23 ppm resolution for 240 Hz quartets	64 ppm DD RMS 46 ppm resolution for 960 Hz pairs
Digital receiver (best Devi 2025 bench results	100 ppm DD RMS 71 ppm resolution for 960 Hz pairs	Same: the measured results were for 960 Hz pairs

I & C Testing 2025: I & C testing summary from Nate Rider

Receiver	Firmware	480Hz Pairs Double Difference Single Chassis	480Hz Pairs Double Difference Two Chassis	960Hz Pairs Resolution PPM
B0820D01 (DR)	FW 3	NA	59.6	59.6
	FW 7	NA	61.9	61.9
	FW 26	70.5	89.2	89.2
	Moller Mod 1	NA	56	56
B0792D01 (Qweak)	Moller Mod 1	13.4	41.2	41.2

Conclusions:

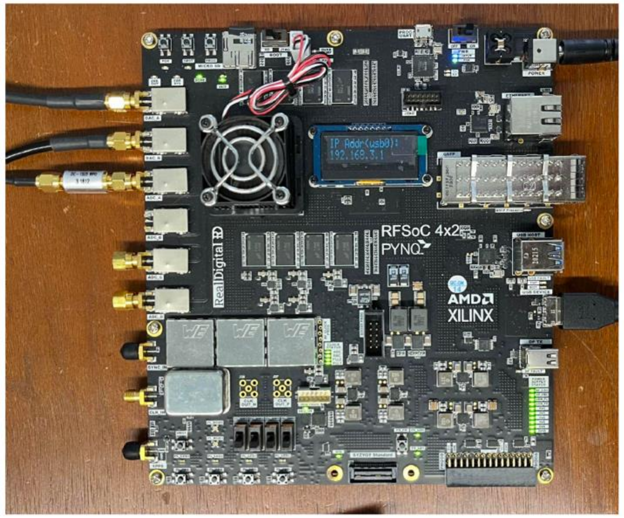
- Qweak results are reproducible
- DR results are not reproducible
- Single chassis (i.e. shared local oscillator) results are promising that improvements might be found
- Both best DR result (56 ppm) and Qweak result (41 ppm), when averaged over 7 BCMs (21 ppm for DR, 15 ppm for Qweak) would be adequate for Run 1 with its relaxed ”1 kHz width” goal of 101 ppm

Jefferson Lab

BCM Resolution – Current plans

- Qweak receivers are still in use in Hall C. One output has always been shipped over to Hall A for charge asymmetry monitoring purposes. A second cable was run, so we can make current day measurements on the Qweak receivers with beam
- John Musson currently can study firmware changes, etc. quickly with his DAQ that gives the same results as our DAQ. Two things being pursued, with goal to have something ready by Spring 2026:
  - Modify digital receivers
  - Build new receiver based on Qweak receiver architecture
- UC Berkeley/LBNL has developed an all-digital, direct-sampling BCM receiver that was initially tested during CREX. That work is being picked back up, so this could be an alternate way to measure the beam charge.

The Berkeley all-digital receiver

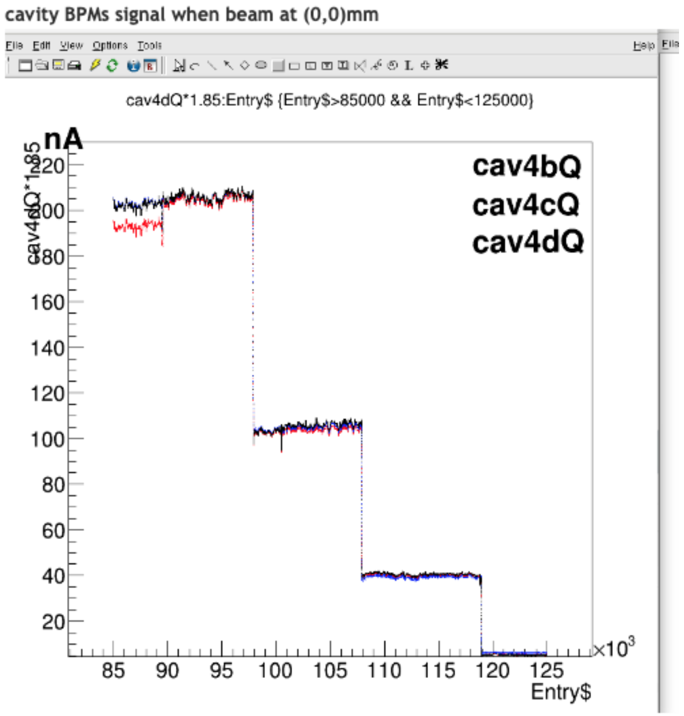


The Berkeley RFSoC 4x2 board

Low Current Beam Monitoring

- The "pulse counting" (or tracking mode) phase of the MOLLER experiment will involve lower beam currents; perhaps as low as 0.1 nA that was successfully used during Q_{weak}.

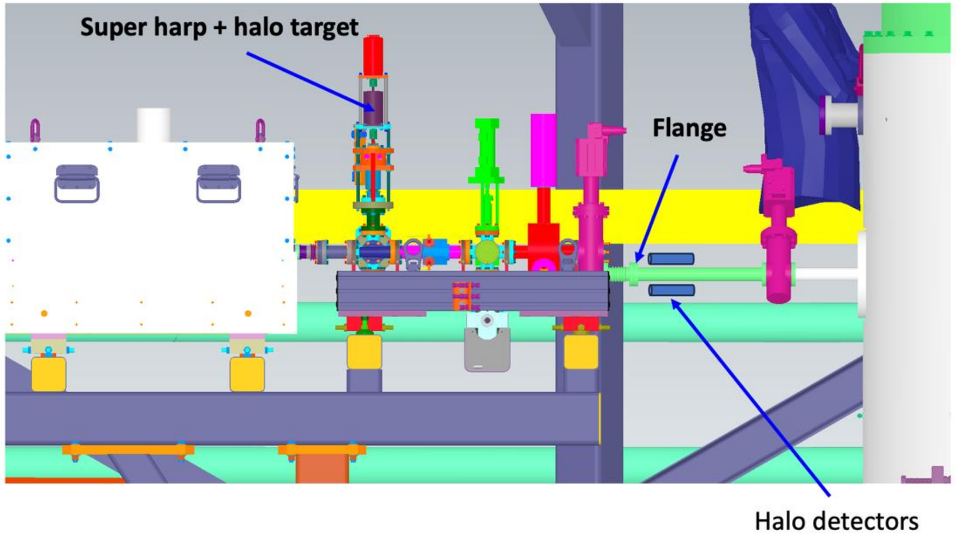
- The microwave cavity beam position/intensity monitors successfully operated down to 15 nA during PREXII/CREX.



- For lower beam currents, the Q_{weak} experiment successfully used their "downstream lumi monitors" (equivalent of MOLLER small angle monitors) to monitor the relative beam intensity and position. MOLLER should be able to do the same.

Halo Monitor

- We plan to install diagnostic equipment to invasively measure the beam halo and monitor the relative beam halo continuously – similar to what was done during Q_{weak}.
- Downstream halo monitor
  - Thin aluminum hole target will be mounted on a superharp drive; can be inserted periodically (with LH_2 target out) to measure any beam halo interacting with the aluminum - “halo fraction.”
  - Detectors: 2 inch PMTs attached to lucite mounted around the beampipe ~ 75 cm downstream of the halo target
- Upstream halo monitor
  - 2 inch PMTs attached to lucite mounted upstream of Møller polarimeter diploe magnet
  - Non-invasive
  - Continuous monitor of halo interacting in upstream apertures



Summary

- The MOLLER experiment will have a redesigned beamline installed that meets its requirements. The beamline equipment schedule is compatible with the planned installation schedule.

- The achieved beam position monitor resolution and low current monitoring capability from previous parity experiments (Q, PREXII/CREX) meet the MOLLER requirements.

- The achieved beam intensity monitor resolution from previous parity experiments (Q_{weak}, PREXII/CREX) and recent studies meets the MOLLER requirements for Run 1, but not yet the ultimate goals of Run III. Work in progress in the JLab I&C group and at UC Berkeley/LBNL to improve this.

Appendix Slides

Parity-Violating Electron Scattering Method

How do we take the bulk of our data? Pretty simple actually…

• **Flux integration:** Integrate the light signal in the Cerenkov detectors and record response *F* every 0.5 msec (planned data-taking rate is 1.92 kHz)

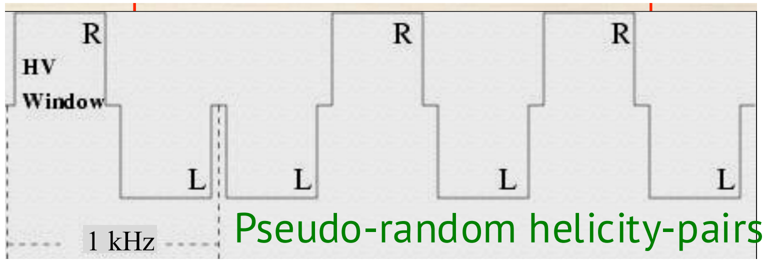
• **Flip the electron beam helicity** and form the asymmetry from adjacent data samples for i^{th} pair:

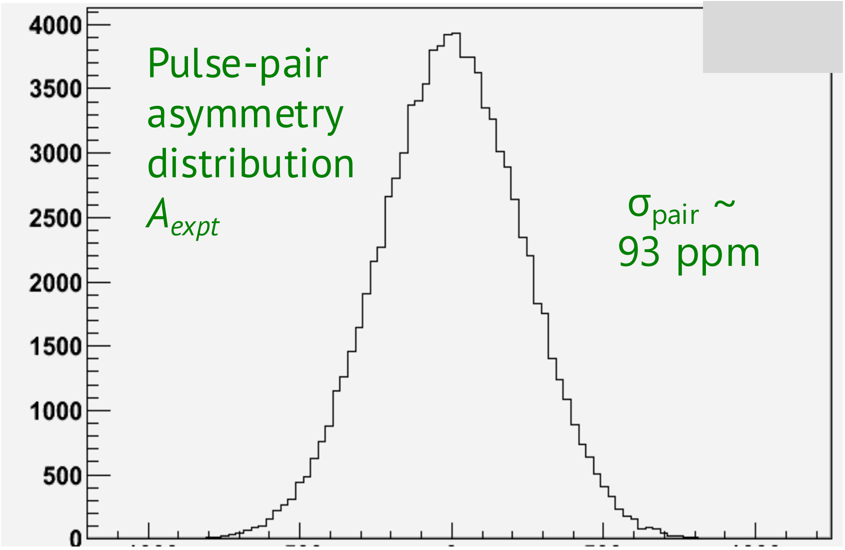
$$A_i = \left(\frac{F_R - F_L}{F_R + F_L}\right)_i \cong \left(\frac{\Delta F}{2F}\right)_i$$

• **Remove correlations** to beam intensity, position, angle, and energy fluctuations:

$$\left(A_{cxpt}\right)_i = \left(\frac{\Delta F}{2F} - \frac{\Delta I}{2I}\right)_i - \sum_j \left(\alpha_j \left(\Delta X_j\right)_i\right)$$

• Repeat 30 billion times! (8256 hours of data-taking) to get desired statistical error





$$\sigma_{A_{cxpt}} = \frac{\sigma_{pair}}{\sqrt{N_{pair}}} = \frac{93\,\text{ppm}}{\sqrt{30\times 10^9}} = 0.5\,\text{ppb}$$

Pulse-pair "width" σ_{pair} is the parameter that determines the statistical error

Required Beam Charge Monitor Resolution

$$\left(A_{cxpt}\right)_i = \left(\frac{\Delta F}{2F} - \frac{\Delta I}{2I}\right)_i - \sum_j \left(\alpha_j \left(\Delta X_j\right)_i\right)$$

The intensity (or charge) asymmetry is the second term in the above expression:

$$A_I = \frac{\Delta I}{2I} = \frac{I_R - I_L}{I_R + I_L}$$

Contributions to σ_{pair} - "Pair width"

Parameter	Random Noise (65 μA)
Statistical width (0.5 ms)	**$\sim$ 82 ppm**
Target Density Fluctuation	30 ppm
Beam Intensity Resolution	10 ppm
Beam Position Noise	7 ppm
Detector Resolution (25%)	21 ppm (3.1%)
Electronics noise	10 ppm
Measured Width (σ_{pair})	**91 ppm**

From the TDR: "The MOLLER requirement is 10 ppm resolution for relative beam intensity measurements for 960 Hz window-pairs, in order to keep this contribution small compared to the counting statistics contribution."

- Ideally, we want to strive for the 10 ppm resolution goal for each of the BCM monitors; this allows us to do systematic comparisons between the monitors to show that this 10 ppm is truly uncorrelated, random noise.
- Since we have 7 BCMs in the MOLLER beamline, we could brute force average all seven, which relaxes the resolution requirement to $\sim \sqrt{7}\,(10\text{ ppm}) \sim 26\text{ ppm}$

Verbatim text from Technical Design Report, slide 1

3.4.3 Beam Charge Monitor Resolution

The MOLLER requirement is 10 ppm resolution for relative beam intensity measurements for 960 Hz window-pairs, in order to keep this contribution to the random noise small compared to the counting statistics contribution. As described below, the existing beam current monitor (BCM) instrumentation is close but not fully sufficient to meet this goal. The best values achieved to date are reported, and progress toward improving the instrumentation is described.

The best BCM resolution achieved during an experiment was for the Q_{weak}measurement, which used BCMs consisting of the standard JLab hardware of resonant microwave cavities operating in the TM_{010} mode. The best results were obtained with all-digital receiver electronics designed at JLab [47]. The random noise in the beam charge measurement was determined by forming the "double-difference", which is the difference between the helicity-correlated charge asymmetry for two BCMs. The RMS of this distribution determines the uncorrelated random noise of the charge measurement, referred to as the resolution. A typical value of this RMS during regular Q_{weak} running at a beam current of 180 μA was $\sim$ 62 ppm.

To facilitate improvements, dedicated bench tests with these digital receivers were done with a Q_{weak} data acquisition test stand, with the beam signal replaced with a radio-frequency source signal. A more detailed description of these studies is in [48], but here we discuss the main conclusions. A study versus

Verbatim text from Technical Design Report, slide 2

data-taking frequency is shown in Fig. 10. The observed value at the Q_{weak} 240 Hz quartet frequency of 62 ppm agrees with what Q_{weak} observed with beam. At double that frequency, corresponding to the MOLLER data-taking frequency of 1.92 kHz, a lower value of 42 ppm was observed. That implies a resolution of 42 ppm for 960 Hz window-pairs[7]. As shown below, the MOLLER beamline will be equipped with seven BCMs, so brute force averaging of those seven, making the assumption of uncorrelated noise, would lead to 42 ppm/$\sqrt{7} \sim$ 16 ppm, close to the MOLLER goal[8]. However, this limits flexibility in doing systematic studies among the monitors, so ideally the resolution of an individual monitor would be improved further.

The bench studies reported in [48] strongly suggest that the beam current independent noise floor observed for the digital receiver electronics is limited by phase and amplitude noise in the 1.5 GHz local oscillator that is mixed with the incoming signal in the receiver electronics.

An upgraded version of the aforementioned digital receivers has been developed. Among various changes, a different local oscillator was employed. Initial bench tests with these receivers for Q_{weak} running parameters gave a factor of two smaller double-difference, about 32 ppm. That would bring the brute-force averaged result quoted above down below the MOLLER goal of 10 ppm. The signal from the microwave cavity monitors in Hall A is typically split between two independent readout chains. This allows for testing digital receiver modifications with beam, parasitically during other experiments in Hall A or in dedicated beam tests during upcoming running periods.

[7]This conclusion assumes white noise spectrum, so that the $1/\sqrt{2}$ conversion from the double-difference width to resolution cancels with a factor of $\sqrt{2}$ to convert from quartets to pairs.

[8]This BCM noise above the goal would imply a pair width of 91.5 ppm, compared to the goal of 91 ppm discussed in Sect. 2. Additionally, there are ongoing efforts at LBNL to design a single BCM with higher resolution

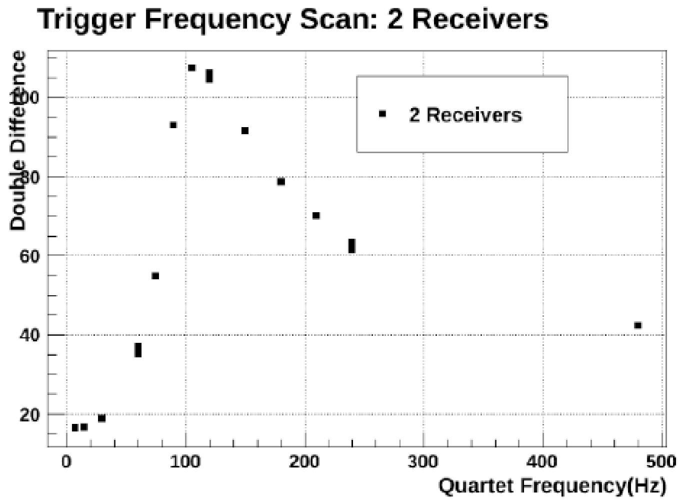


Figure 10: *Bench study of Q_{weak} digital receivers with two receivers and a common RF source to simulate the beam signal. The observed double difference versus quartet frequency is shown.*

Determining the Resolution from the "Double Difference"

In practice, to obtain the random measurement precision (resolution) of a monitor, we need to compare two monitors to remove the correlated noise from their common signal (either the electron beam or the split signal from an RF source in bench tests). So, we measure the "double difference" between monitor 1 and 2 (note: some previous talks in the past 2 years had this quantity divided by 2; we are adopting the DD below from now on)

$$DD \equiv A_1 - A_2$$

The resolution – the random measurement precision of a single monitor - is determined from the RMS of the double difference as: (note: this assumes the resolution is the same for each monitor)

$$resolution \equiv \frac{DD\ RMS}{\sqrt{2}}$$

Both resolution and double difference need to be quoted with the parameters of the measurement:

- Multiplet type: pair, quartet, octet, etc.
- Time-window frequency (i.e. data-taking rate) and resulting multiplet rate; Examples:
  - 1920 Hz data-taking rate for pairs -> 960 Hz pair rate (MOLLER quotes its random error goals in these terms)
  - 960 Hz data-taking rate for quartets -> 240 Hz quartet rate (This was the standard Q_{weak} condition.)
  - 120 Hz data-taking rate for quartets -> 30 Hz quartet rate (This was the standard CREX condition.)
  - 1920 Hz data-taking rate for 64 window multiplet -> 30 Hz "64 window multiplet" rate (This is the intended actual way that MOLLER will likely combine its data.)

Extrapolating from other measurement parameters to “MOLLER pairs”

To extrapolate from other measurements to the MOLLER pair condition of 960 Hz pair rate (for which our goal is 10 ppm resolution), we need to make an assumption.

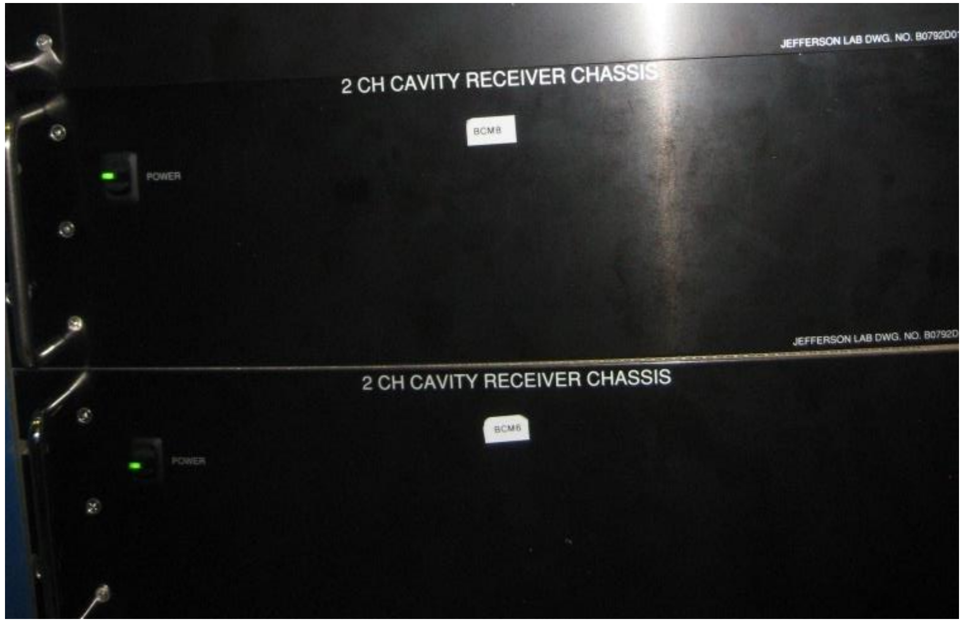
- We assume that the resolution (same as RMS of double difference up to the sqrt(2) factor) follows the “white noise assumption” or basically that it reduces (or increases) in size as the total integration time that contributes to the multiplet increases (or decreases).

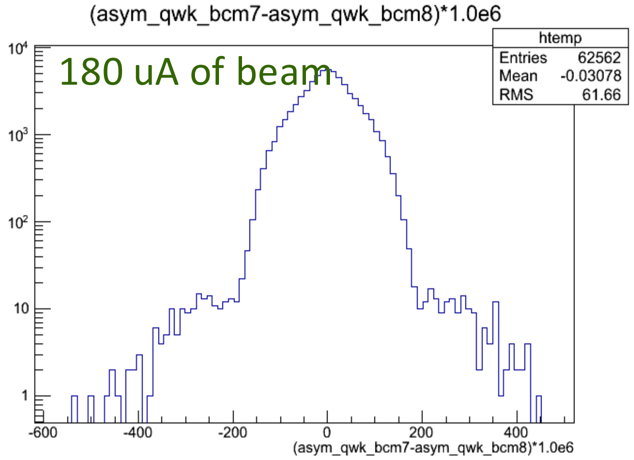
- Extrapolating from a measured multiplet N_{meas} (i.e. N_{meas} = 2 for pairs, 4 for quartets, etc.) to pairs requires multiplying the measured resolution (or RMS of DD) by a factor: $\sqrt{\frac{N_{meas}}{2}}$

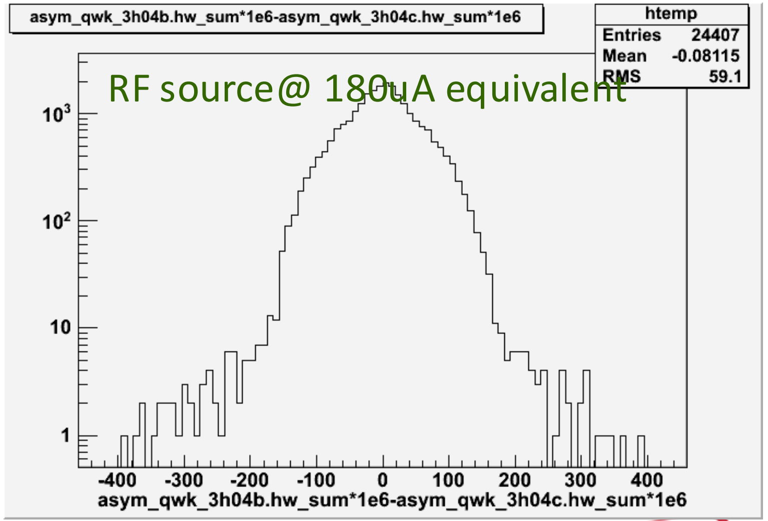
- Extrapolating from measurements with a time-window frequency (data-taking rate) of f_{meas} to 1920 Hz requires multiplying the measured resolution (or RMS of DD) by a factor: $\sqrt{\frac{(1920\ \mathrm{Hz})}{f_{meas}}}$

Q_{weak} Experience – Beam (2010 – 2012), Bench Tests (2015 – 2016)

Q_{weak} Receivers: Used during the experiment in 2010 – 2012 and extensively tested with bench tests in 2015 - 2016







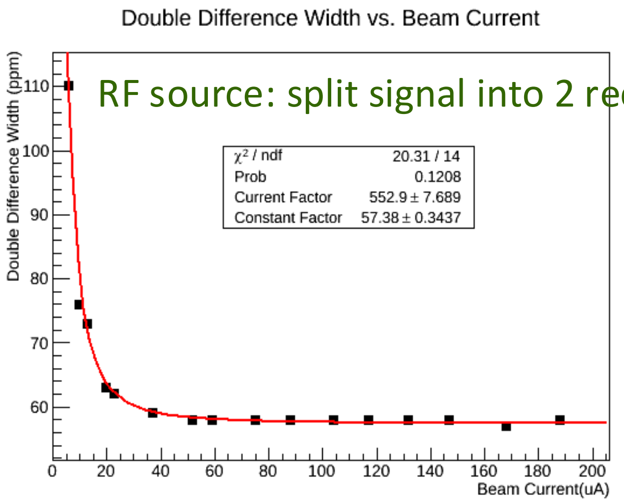
Q_{weak} Receiver Results (verified with beam and rf sources):

- Multiplet type: quartet
- Time-window frequency: 960 Hz
- Quartet rate: 240 Hz
- Observed double difference RMS ~ 62 ppm
- Implied resolution ~ 44 ppm for 240 Hz quartets

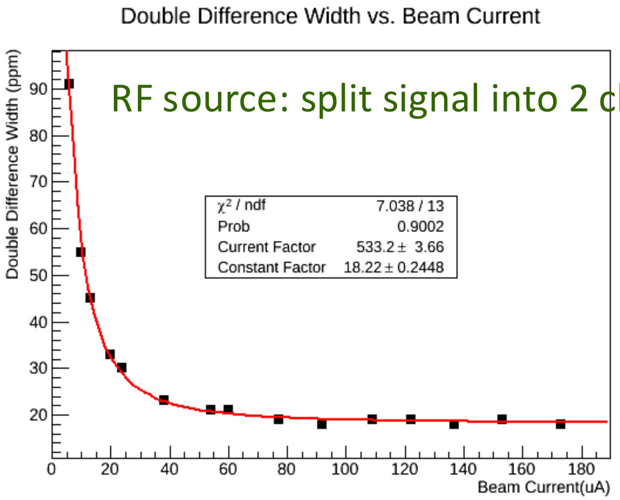
Q_{weak} Experience – Bench Tests (2015 – 2016)

Q_{weak} Receiver Results (DD vs. effective beam current bench studies)

- Multiplet type: quartet
- Time-window frequency: 960 Hz
- Quartet rate: 240 Hz
- Observed double difference RMS ~ 57 ppm for normal configuration and 240 Hz quartets
- Observed double difference ~ 18 ppm for special configuration (using 2 channels of 1 receiver) that cancels out the noise from elements in common between the two channels (like the local oscillator, etc.) and 240 Hz quartets



$$\Gamma = \sqrt{\left(\frac{553\,\mathrm{ppm}\,\mu\mathrm{A}}{\mathrm{I}}\right)^2 + (57.4\,\mathrm{ppm})^2}$$



$$\Gamma = \sqrt{\left(\frac{533\,\mathrm{ppm}\,\mu\mathrm{A}}{\mathrm{I}}\right)^2 + (18\,\mathrm{ppm})^2}$$

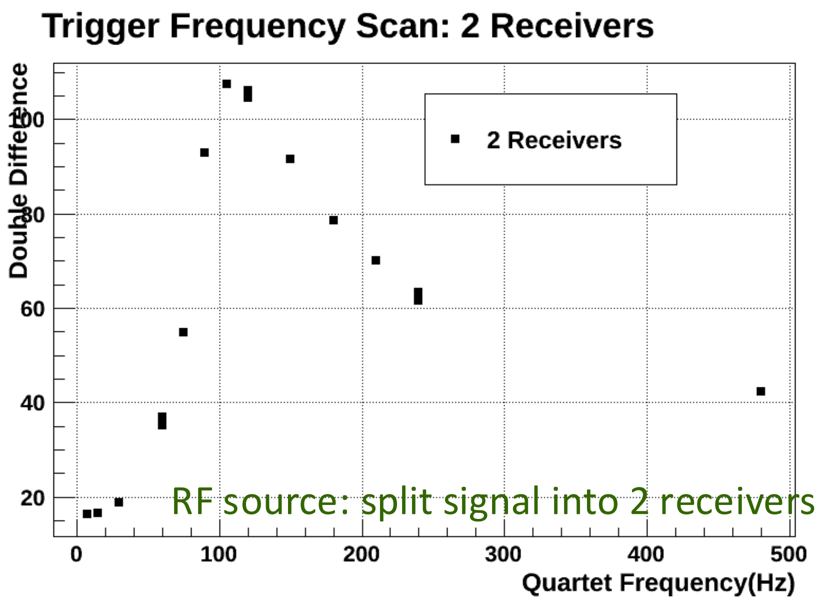
Q_{weak} Experience – Bench Tests (2015 – 2016) – Looking forward to MOLLER

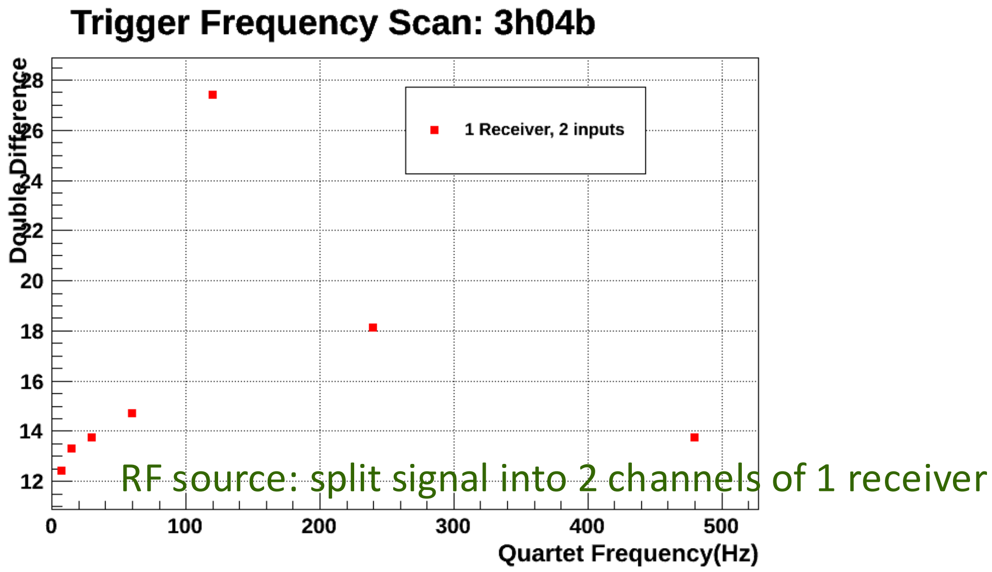
Q_{weak} Receiver Results – This is the result we have relied on to look forward for MOLLER:

- Multiplet type: quartet
- Time-window frequency: 1920 Hz (for the highest point in the plot to the right)
- Quartet rate: 480 Hz
- Observed double difference RMS ~ 42 ppm for normal configuration and 480 Hz quartets
- Observed double difference ~ 14 ppm for special configuration (using 2 channels of 1 receiver) that cancels out the noise from elements in common between the two channels (like the local oscillator, etc.) and 480 Hz quartets
- Translating to an implied 960 Hz pair rate resolution of the 42 ppm result gives:

$$(42\ \text{ppm})\left(\frac{1}{\sqrt{2}}\right)\left(\sqrt{2}\right) = 42\ \text{ppm}$$

Where the 1/sqrt(2) comes from converting from DD to resolution, while the sqrt(2) comes from converting form quartets to pairs.

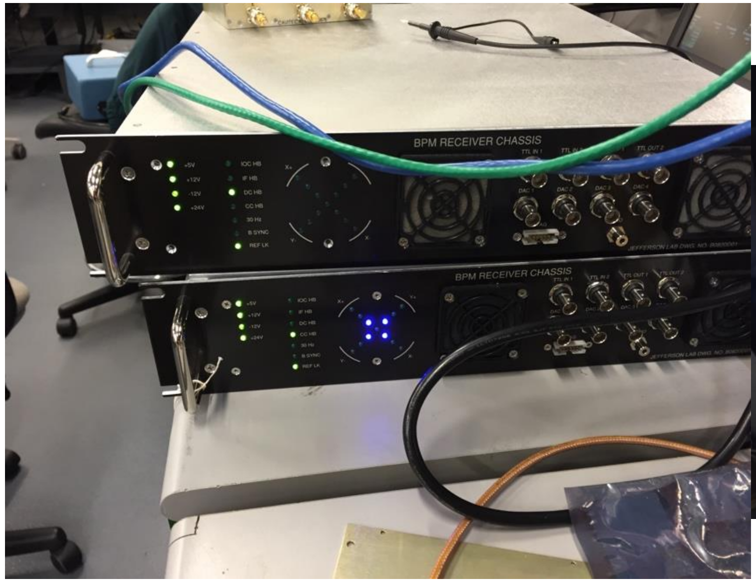


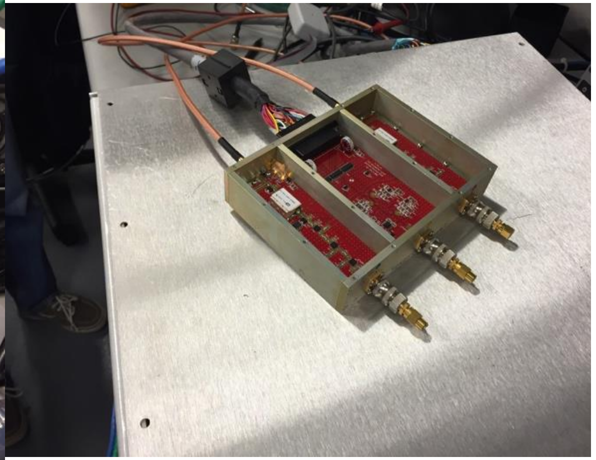


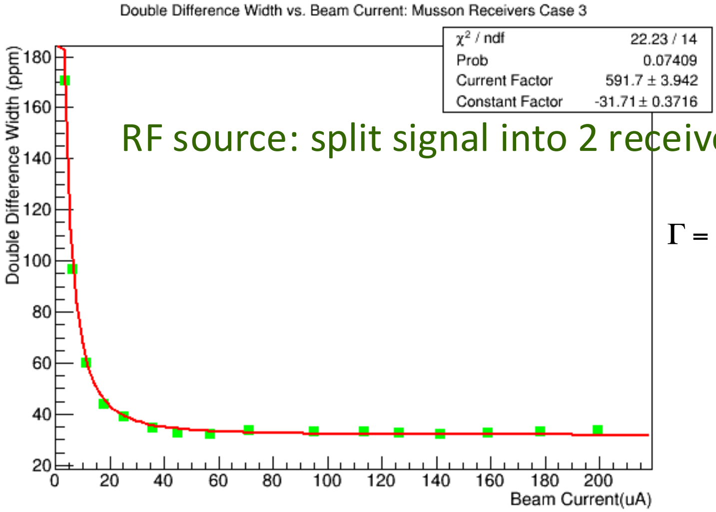
Jefferson Lab

Digital Receiver – Bench Tests (2015 – 2016)

During the 2015 – 2016 Bench Tests, we test the “Musson” digital receiver that was just being fielded.

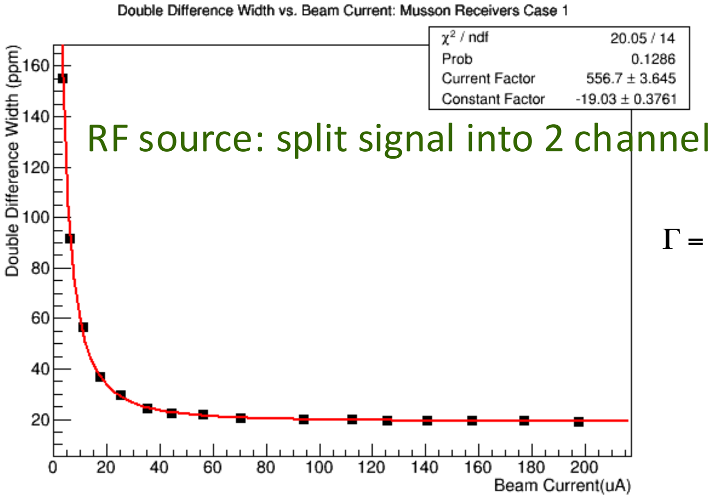






RF source: split signal into 2 receivers

$$\Gamma = \sqrt{\left(\frac{592\,\text{ppm}\,\mu\text{A}}{\text{I}}\right)^2 + (31.7\,\text{ppm})^2}$$



RF source: split signal into 2 channels of 1 receiver

$$\Gamma = \sqrt{\left(\frac{557\,\text{ppm}\,\mu\text{A}}{\text{I}}\right)^2 + (19.0\,\text{ppm})^2}$$

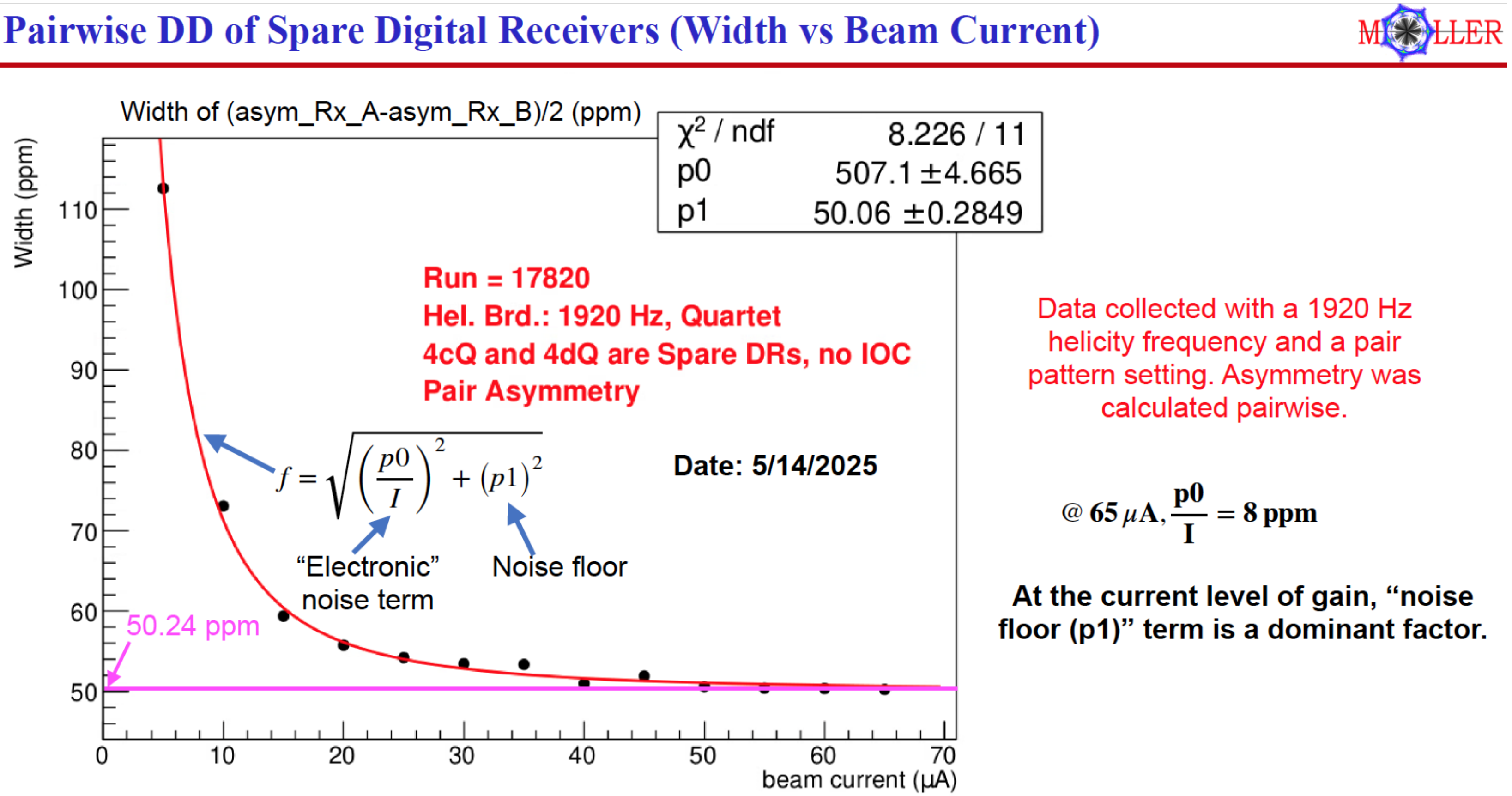
Digital Receiver Bench Results:

- Multiplet type: quartet
- Time-window frequency: 960 Hz
- Quartet rate: 240 Hz
- Observed double difference ~ 32 ppm
- Implied resolution ~ 23 ppm for 240 Hz quartets

Jefferson Lab

Best result with current configuration of Musson digital receiver from Devi

Below is a slide from Devi's June 2025 Collaboration meeting talk which showed the best result he had seen on bench tests with the digital receivers.



Translating:

- Multiply by factor of 2! (this used the old definition that we don't use from now on)
- Other than that, the plots shows the DD RMS for 960 Hz pairs
- So,

DD RMS = 100 ppm for 960 Hz pairs

Resolution = 71 ppm for 960 Hz pairs

Summary Table

Receiver	Measured Results	Extrapolated to MOLLER pairs
Q_{weak} receiver (2016 Bench test)	42 ppm DD RMS 30 ppm resolution for 480 Hz quartets	59 ppm DD RMS 42 ppm resolution for 960 Hz pairs
Digital receiver (2016 Bench test)	32 ppm DD RMS 23 ppm resolution for 240 Hz quartets	64 ppm DD RMS 46 ppm resolution for 960 Hz pairs
Digital receiver (best Devi 2025 bench results	100 ppm DD RMS 71 ppm resolution for 960 Hz pairs	Same: the measured results were for 960 Hz pairs
Digital receiver (best Musson 2025 bench results)		

Conclusion:

- The best recent ”Devi” digital receiver result is about 1.6 times worse than the 2016 extrapolated result. It is 7x higher than our 10 ppm resolution goal and 2.7x higher than our “brute force” 26 ppm upper limit.
- Summarize here the best Musson result:

MOLLER Project Dependencies

From January 23, 2019 MOLLER Project Dependencies document:

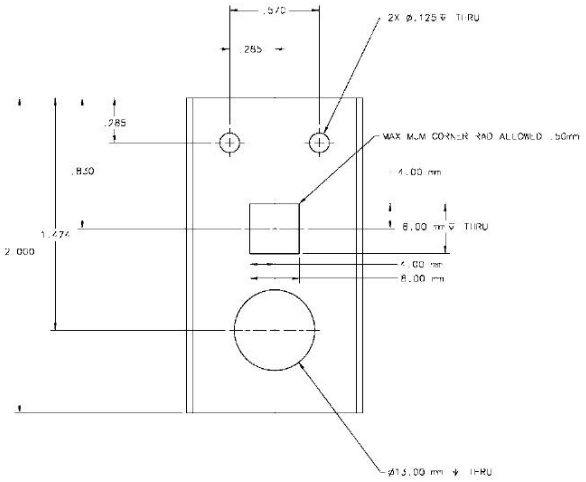
5. ***Hall A Beam Line.*** Hall A beam line diagnostic cavities and instrumentation, including an ultrafast (2 kHz) and compact beam raster system, will be installed and operational, capable of ensuring helicity-dependent beam position measurements of 3 μm or better, and helicity-dependent beam charge measurements of 10 ppm or better. This dependency is assumed to be funded through capital equipment as a general-purpose parity beam line data acquisition and associated beam line electronics system (FY21-FY23).

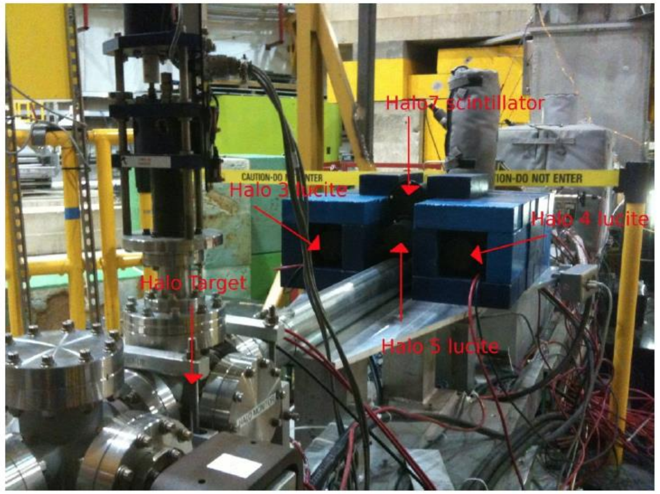
Qweak Beam Halo Monitoring System

Qweak Beam Halo Measurement System

Qweak had a diagnostic system for direct invasive measurement of beam halo and continuous monitoring

Qweak Beam Halo Measurement System





Halo target: thin aluminum with two holes, mounted near usual Hall C pivot on superharp linear drive mechanism

- 8 x 8 mm square hole (for invasive check on beam halo "specs")
- 13 mm diameter hole; to put in place during routine production running

  → size of the smallest aperture in the experiment – tungsten beam collimator

Monitored with lead shielded lucite+ 2 inch PMT "halo monitors"

Calibrated by putting 1 nA of beam directly into halo target frame

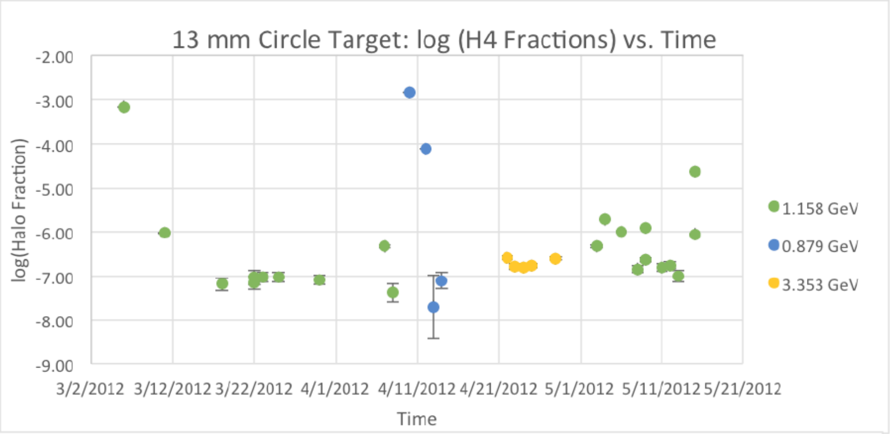
3.6. Beam halo monitors

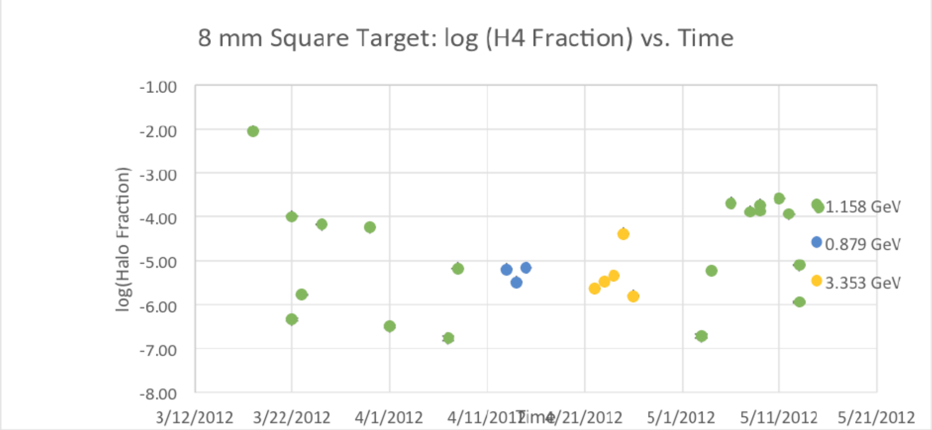
Several PMT monitors straddled the beamline between 1 m and 5 m upstream of the LH_2 target to monitor beam halo, providing crucial feedback used to tune the beam. Four monitors had lucite blocks coupled to their 5.1 cm diameter PMTs, and two used small scintillator blocks. All six monitors used 12-stage Photonis XP2262B PMTs read out in event (pulse-counting) mode. Each halo monitor pair was shielded with lead and pointed upstream at a retractable halo "target" 6 m upstream of the LH_2 target. The halo target consisted of a 2.8 cm $\times$ 5.1 cm aluminum frame 1 mm thick with a 13 mm diameter circular hole and an 8 mm $\times$ 8 mm square hole cut out of it. The target could be positioned with a linear actuator such that either hole (or the frame) could be positioned in the beam, or it could be retracted completely out of the beam pipe.

An absolute measure of the beam halo was obtained by calibrating the halo monitors with beam passing through the 1 mm thick halo frame. The most useful monitors for absolute determination of the beam halo fraction were two of the lucite monitors (one with a 2 cm thick lead block in front to suppress low-energy particles). These were well shielded on five sides with lead, and located 16.5 cm from the beam centerline on opposite sides of the beampipe 75 cm downstream of the halo target. The mean scattering angle of these monitors relative to the halo target was $\sim 12.4°$. Background from upstream of the halo target was accounted for with the halo target out. With this correction, the absolute halo fraction was determined to a precision of $\sim 2 \times 10^{-8}$ at a beam current of 180 μA. In addition to these dedicated measurements of the halo fraction, the 13 mm hole was in place about half the time during the experiment to provide a continuous monitor of the beam halo. Typical measured beam halo was between 0.1 and 1 ppm.

Typical Qweak Halo Results

Typical Qweak Halo Characterization Results





13 mm Halo “Circle” Target: Typical: 10^{-7} – 10^{-6} but as large as 10^{-3} observed

8 mm “Square” Target: Typical: 10^{-7} – 10^{-4} but as large as 10^{-2} observed 12

Beam Current Monitor (BCM) Requirements

- BCM signals are integrated over the interval dictated by the data-taking rate (1.92 kHz for MOLLER)
- The relative beam intensity changes need to be measured with a resolution of **≤10 ppm for 960 Hz window-pairs** (1.92 kHz data-taking rate)
  - Preferably, each individual BCM should independently meet this goal but could be challenging
  - As many as 7 BCMs may be averaged to achieve this sensitivity
  - Single BCM root mean squared resolution must be better than $\sqrt{7} \times 10 \text{ ppm} = 27 \text{ ppm}$
- Less than 0.1 % differential non-linearity (local non-linearity)
- Less than 0.1 % (requested) - 1 % (required) integral non-linearity

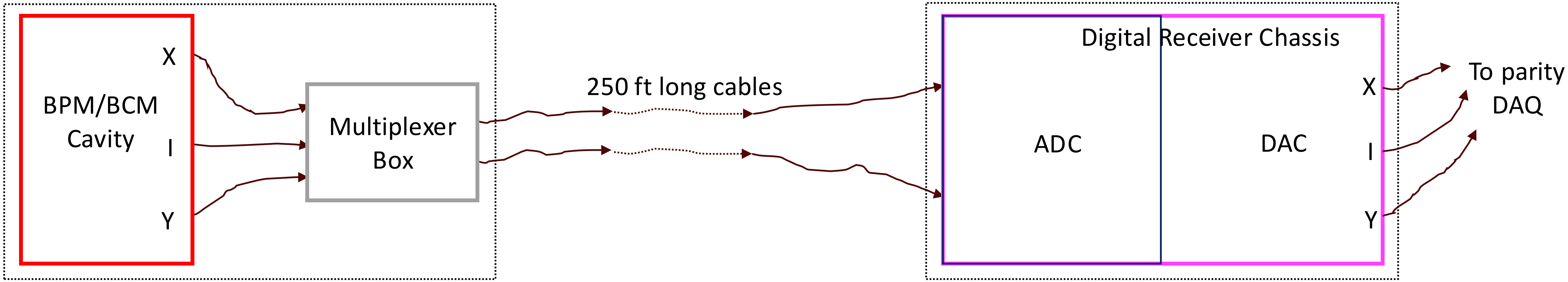
Naming convention in the following slides:

Cavity => BCM in the cavity triplet box. There are three of them 4bQ, 4cQ, and 4dQ.

Digital Receiver => Digital receiver chassis used for the cavity triplets.

Cavity BCMs and Digital Receivers

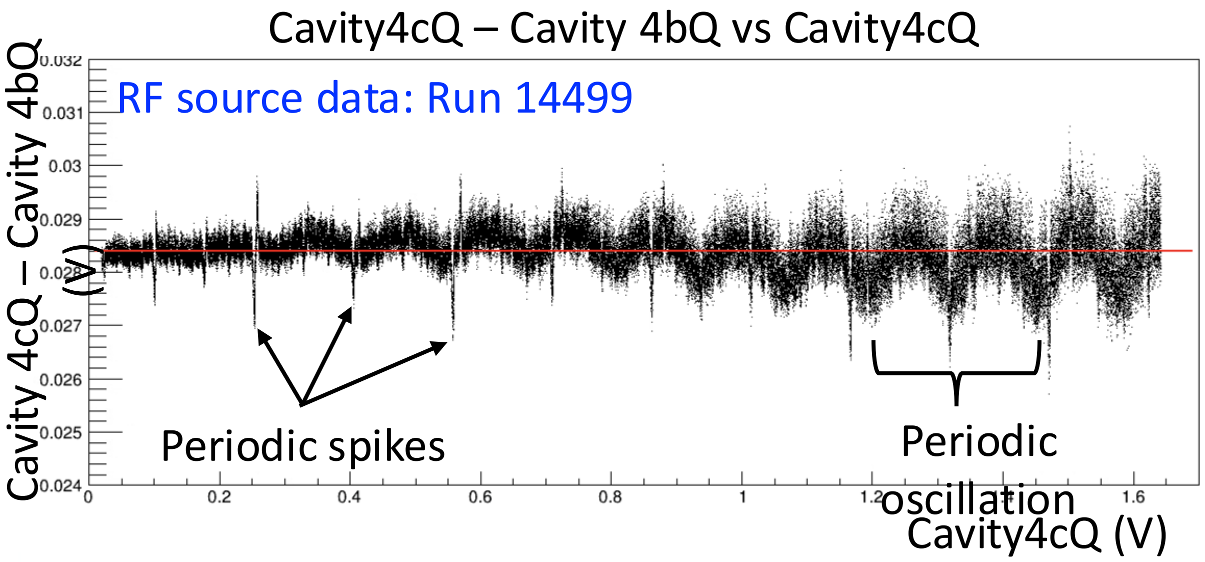
Digital receivers in the CH

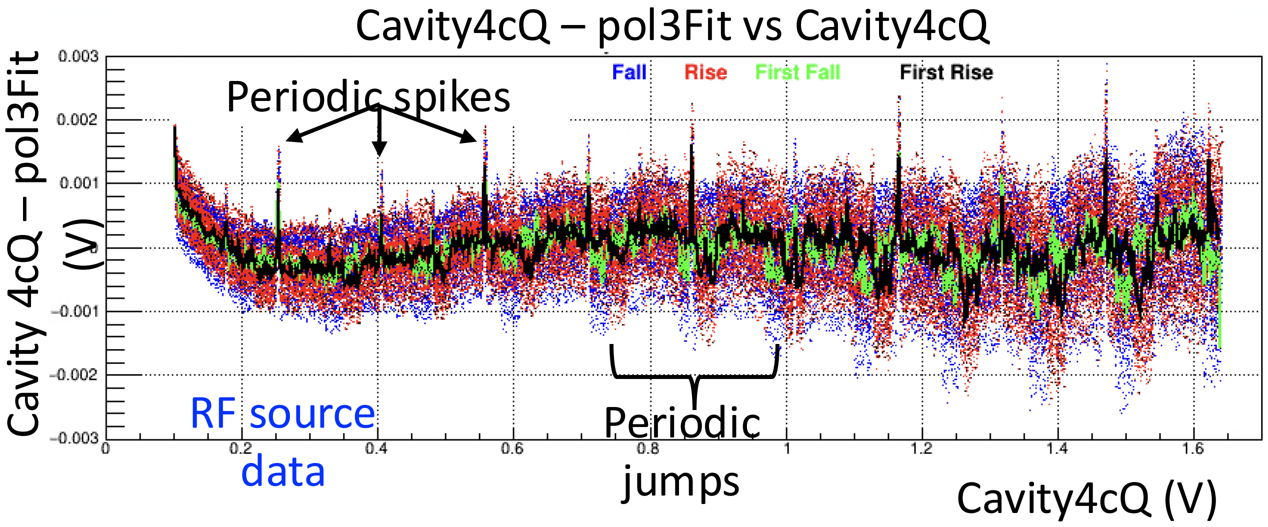


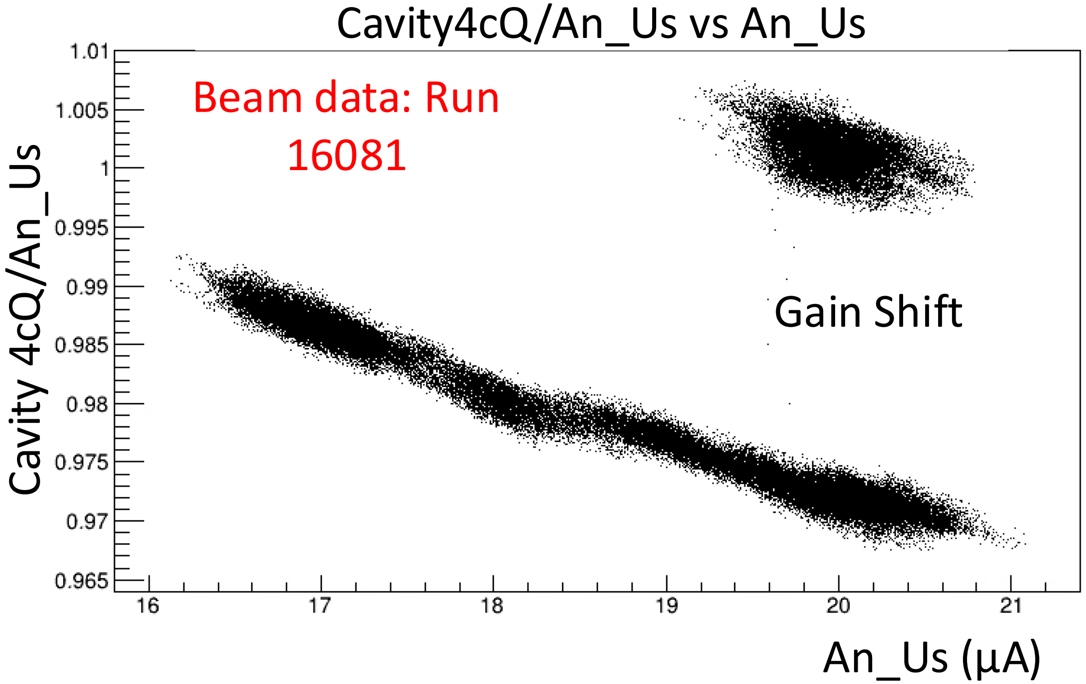
In Hall A

In Counting House

Concerns We are Investigating

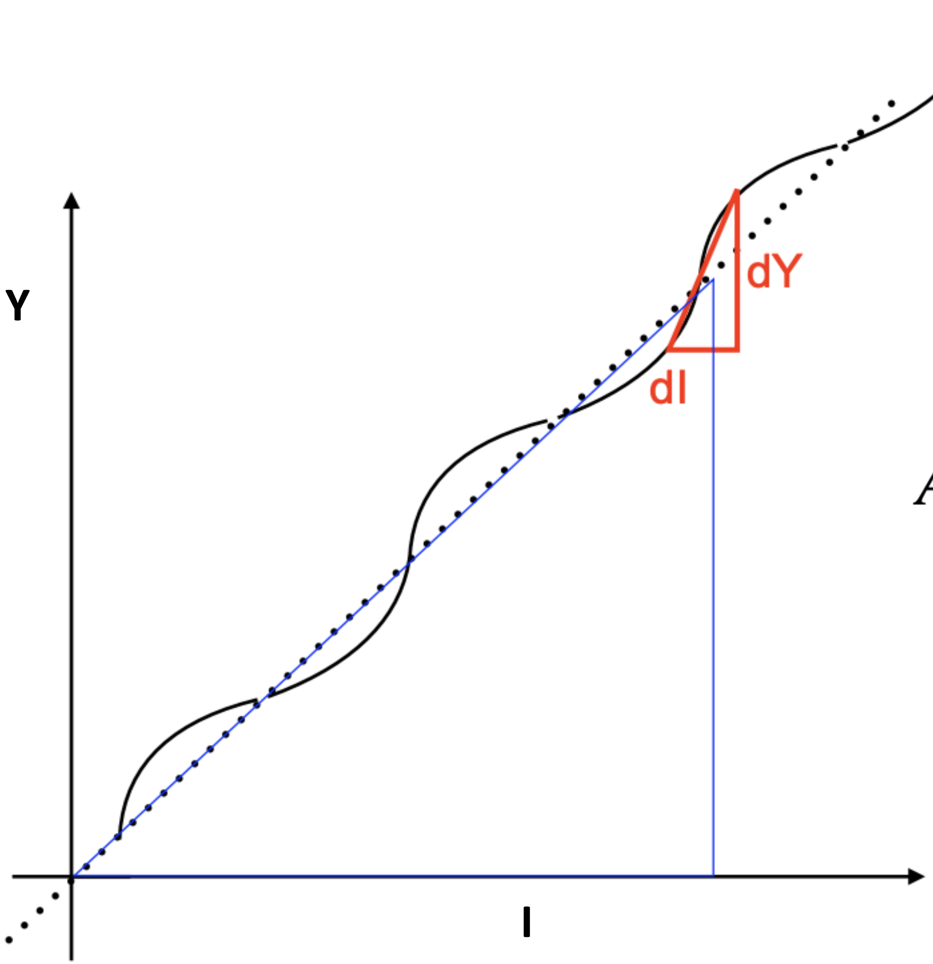






1. Periodic oscillation in double difference or periodic jumps in signal → **Function of time, appears to be in the ADC part of the receiver.**
2. Periodic spikes in signal → **Function of output signal, can be seen with beam and bench test**
3. Gain shift → **seen only with beam; could be associated with the multiplexer box in the hall**

Effect of Differential Non-Linearity (the Spikes)



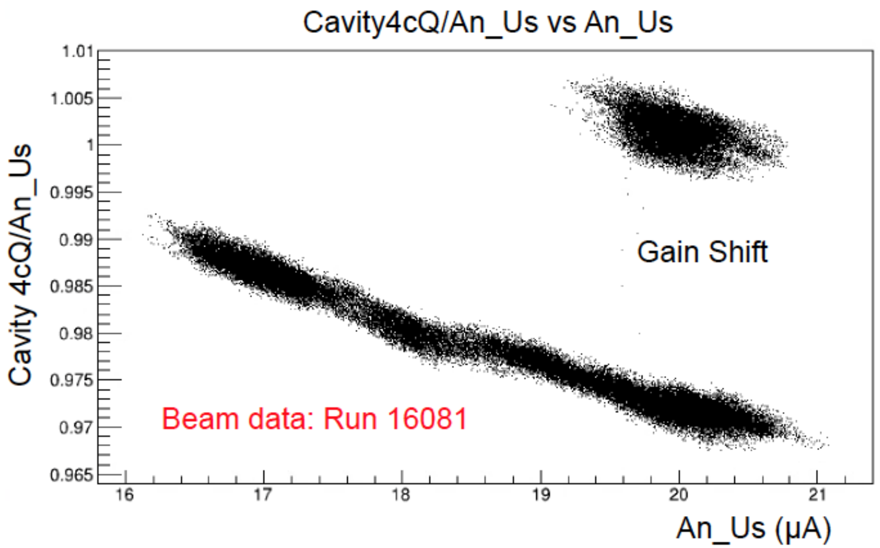
$$A_Q^{meas} = \frac{Y(I_R) - Y(I_L)}{Y(I_R) + Y(I_L)} \sim \frac{\frac{dY}{dI}(I_R - I_L)}{\frac{Y}{I}(I_R + I_L)} = A_Q^{real}\frac{\frac{dY}{dI}}{\frac{Y}{I}} = A_Q^{real}\frac{\frac{dY}{Y}}{\frac{dI}{I}}$$

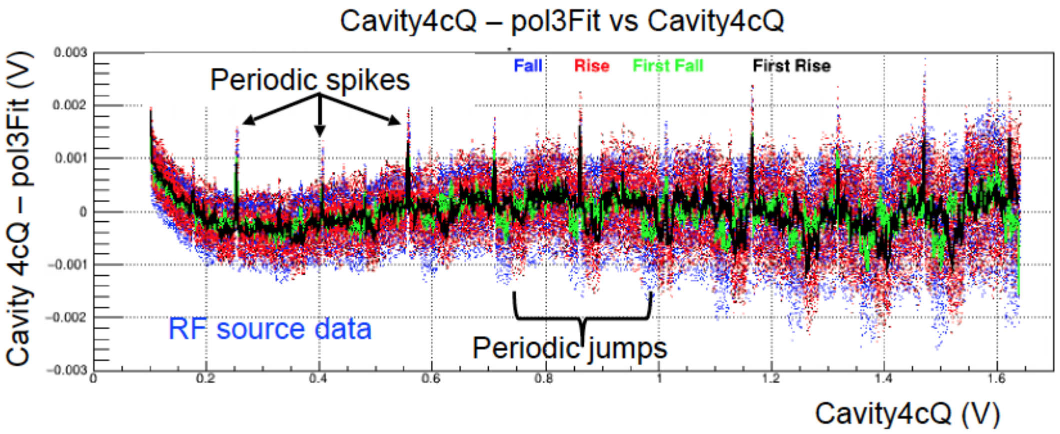
$\frac{dY}{Y}$ may be small, but when it happens over a short range of I, it represents a large effect i.e., $\frac{dY}{Y} = 0.1\ \%$ over 5 % of the signal range leads to 2 % error in A_Q.

Summary of Studies Performed To Date

- Evaluated BCM performance during PREX and CREX
  - ➡ Significantly higher noise floor and gain shift in cavity BCM digital receivers
- Bench test with modulating signal (saw-tooth) from an RF source upstairs
- Bench test with pseudo-PITA scan
- Beam studies (April 2024)
- **Investigation on three digital receivers in the counting house, Qweak receivers, the receivers used in standard Hall A BCMs (digital part), and a number of spare receivers**
  - ➡ **All of them showed the time-dependent jumps and signal-dependent spikes**
  - ➡ **Investigation on the DAC and ADC part of the receivers**

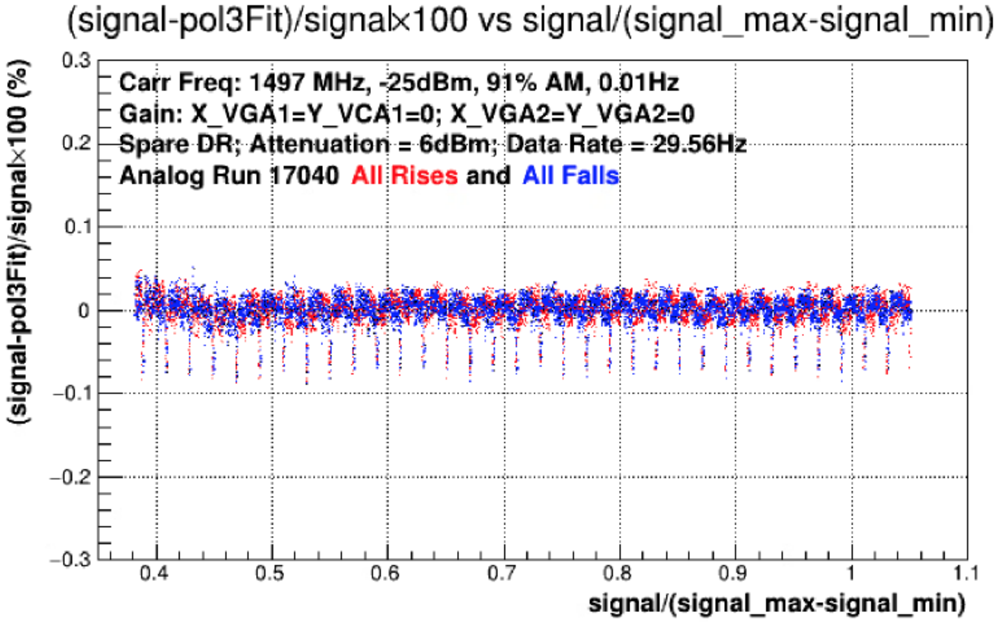
Concerns Investigated and Resolved

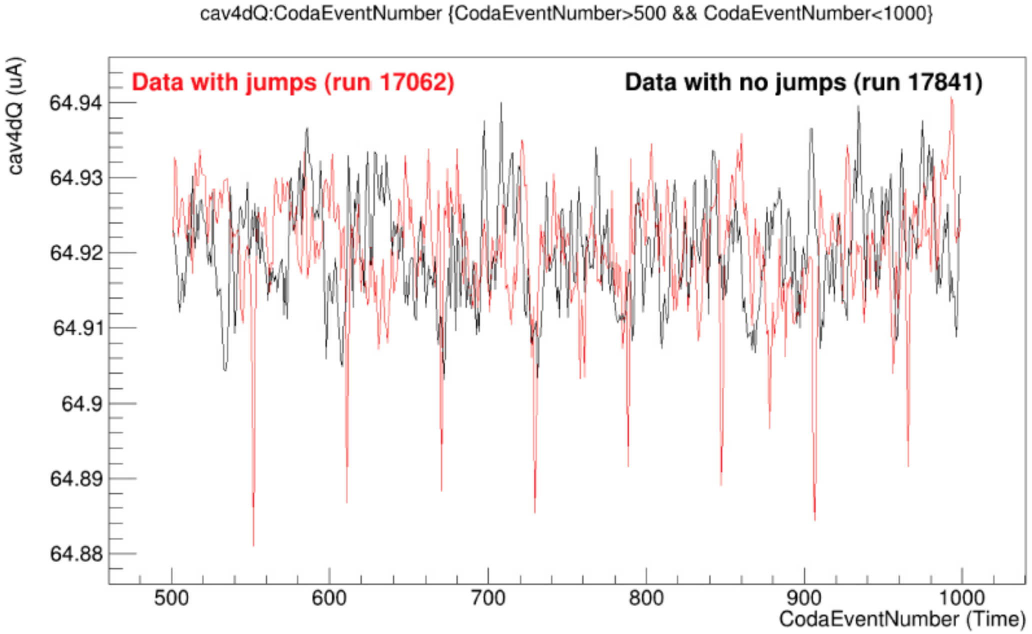




- Periodic jumps in signal: Function of time, appears to be resolved removing IOC
- Periodic spikes in signal: Function of output signal, appears to be resolved with firmware change
- Gain shift: Problem associated with multiplexer box in the hall. Bypassing the multiplexer box should resolve the issue.

Spikes and Jumps Resolved





This shows that the signal-dependent spikes are resolved!

This shows that the time-dependent jumps are resolved!