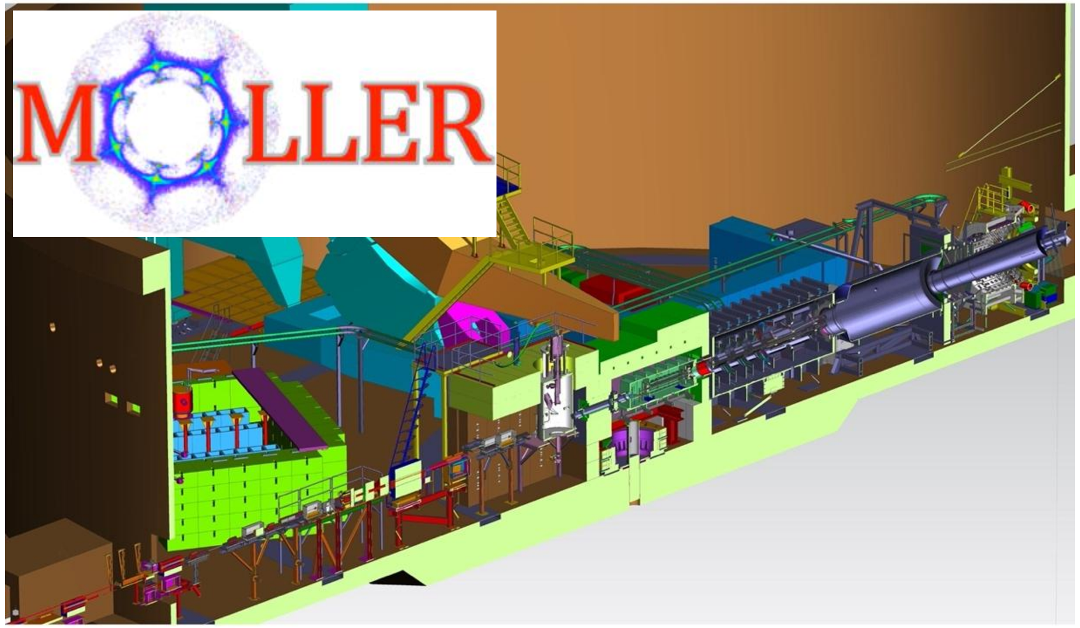
MOLLER 2025 ERR2

Main detector module status

Assembly

Testing

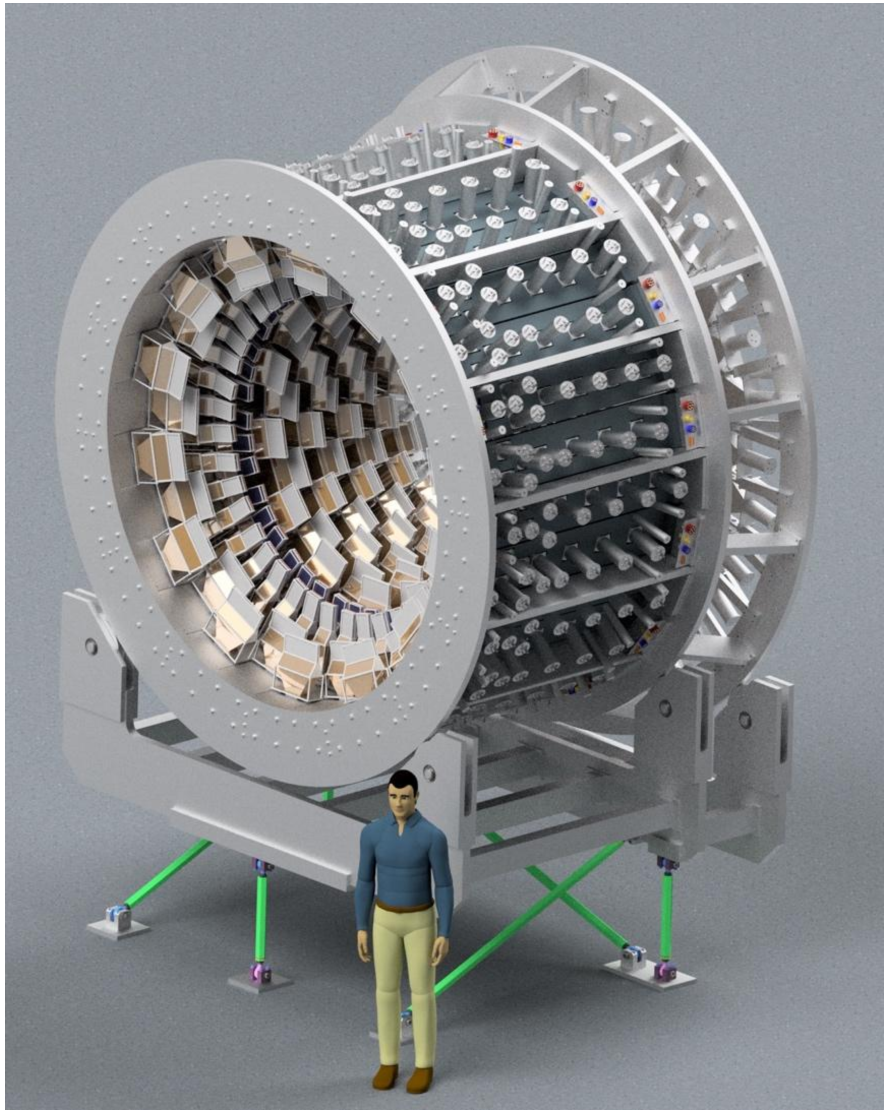
Shipping.



Michael Gericke

Outline

- System overview
- Main detector module design
- IRR Question 1 b
- IRR Question 2 a
- IRR Question 8 (partial)
- Detail slides in backup



Main Detector Subsystem Overview

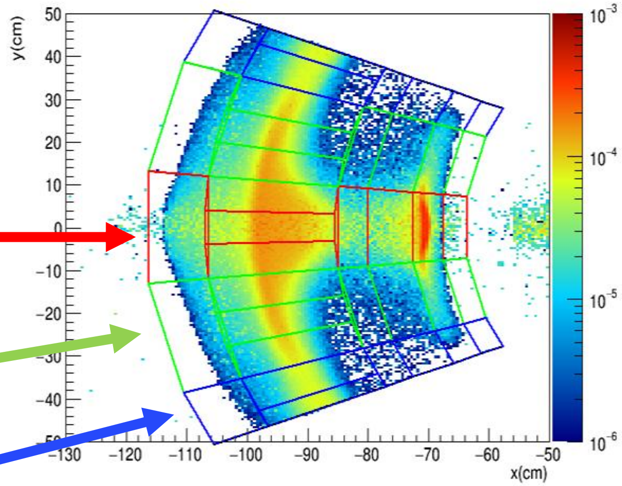
Final Main Detector Module Design :

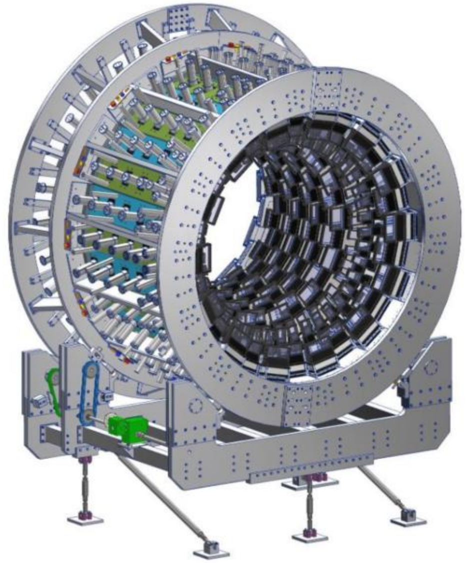
- **Septant**
- **Sector (open, transition, closed)**
- **Two Segment Section (one of 14)**
- **Module**
- **224 detector modules**

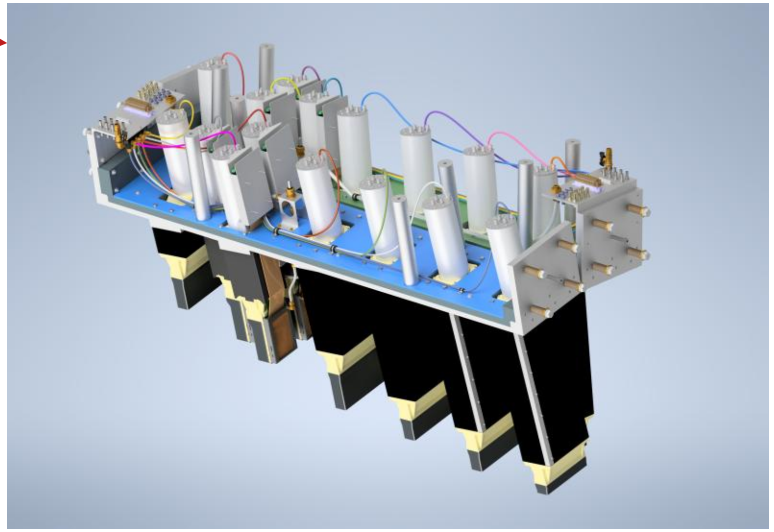
Open

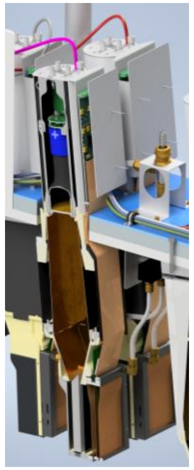
Transition

Closed







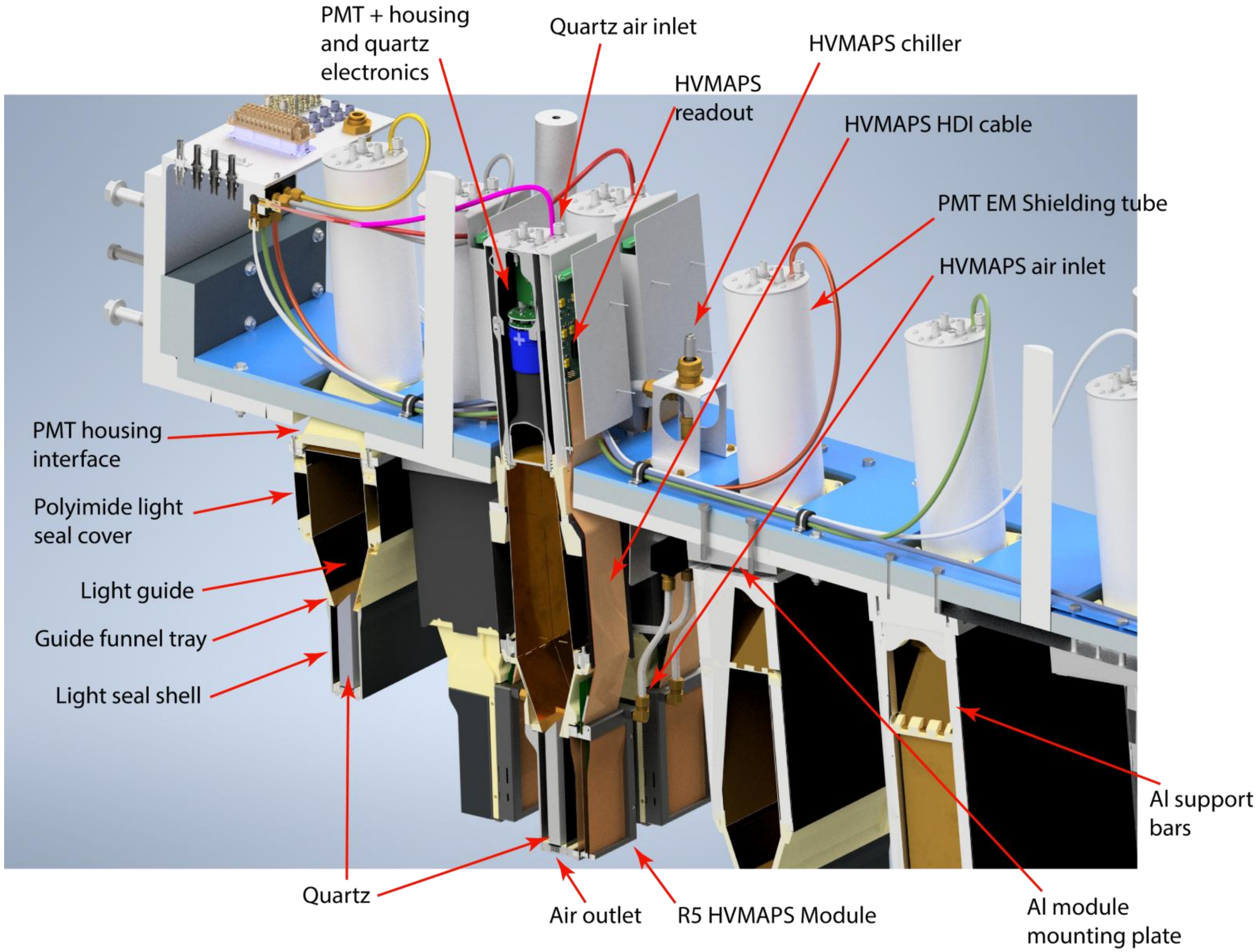


Main Detector Module Design

Final Main Detector Module Design :

Module parts:

- **Fused silica active volume (quartz)**
- **Air core light guide**
- **3D printed housing parts**
- **Aluminum module structure parts**
- **PMT**
- **Front-end electronics**
- **HVMAPS module (+ readout)**
- **Light seal cover**

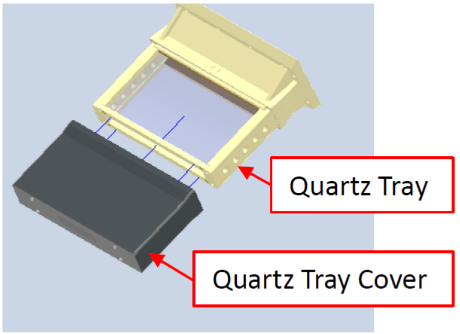


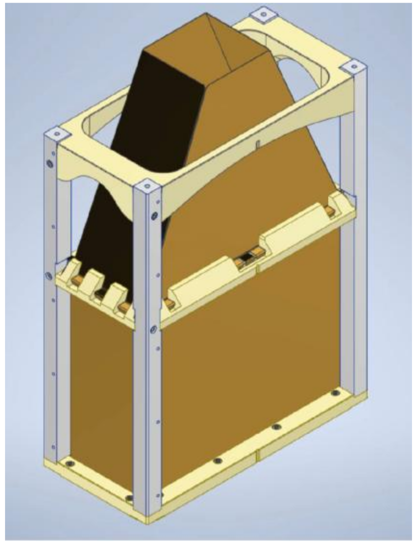
Main Detector Module Design

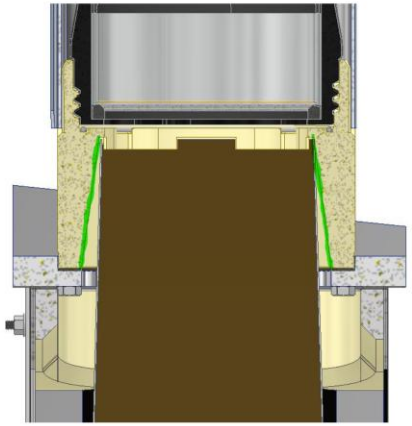
Final Main Detector Modules:

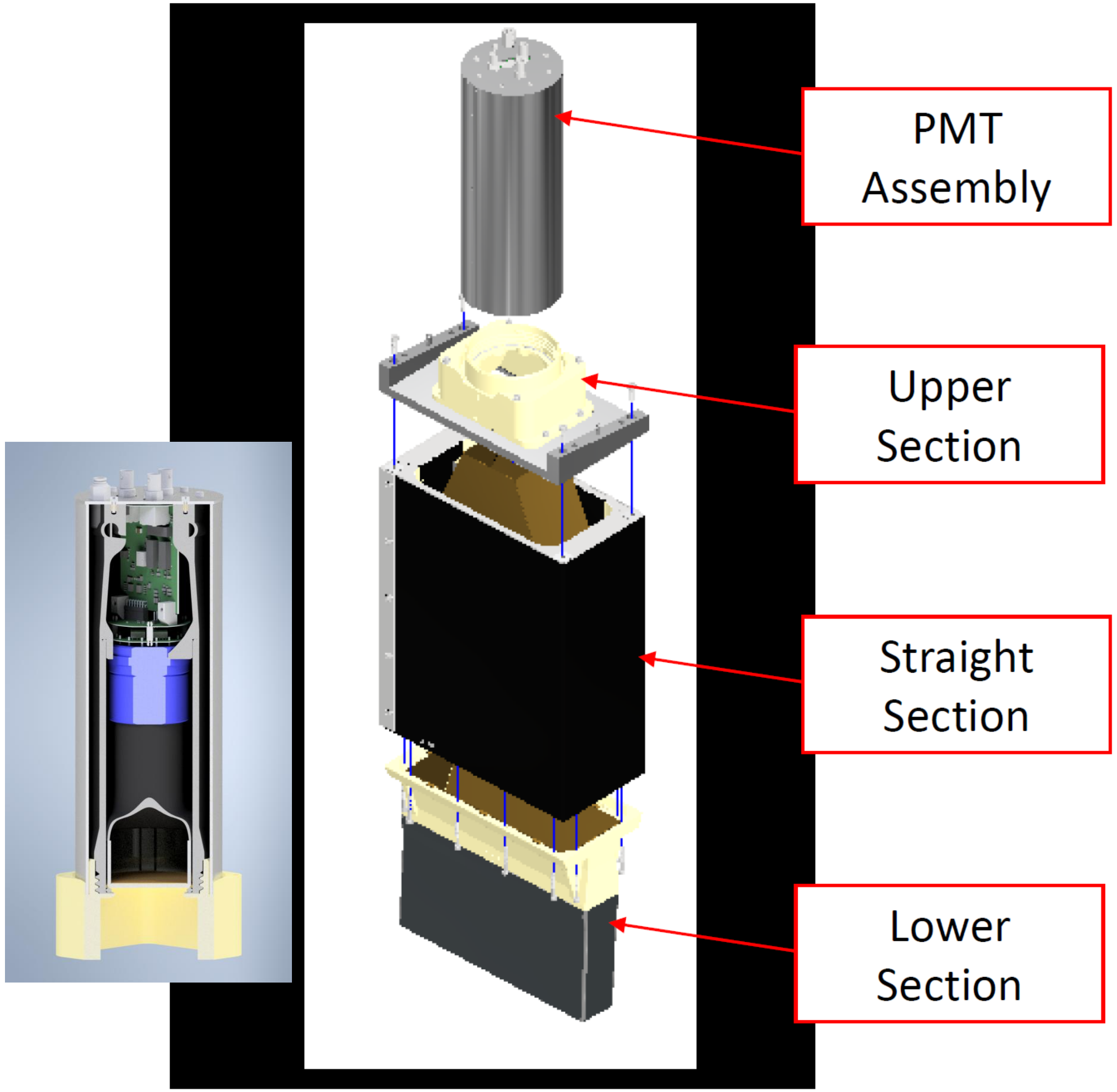
Modules split into four subassemblies:

- **Lower Section:** **Quartz tray and primary reflector**
- **Straight Section:** **Light guide and reducer funnel**
- **Upper Section:** **Interface between the light guide and PMT**
- **PMT Assembly**









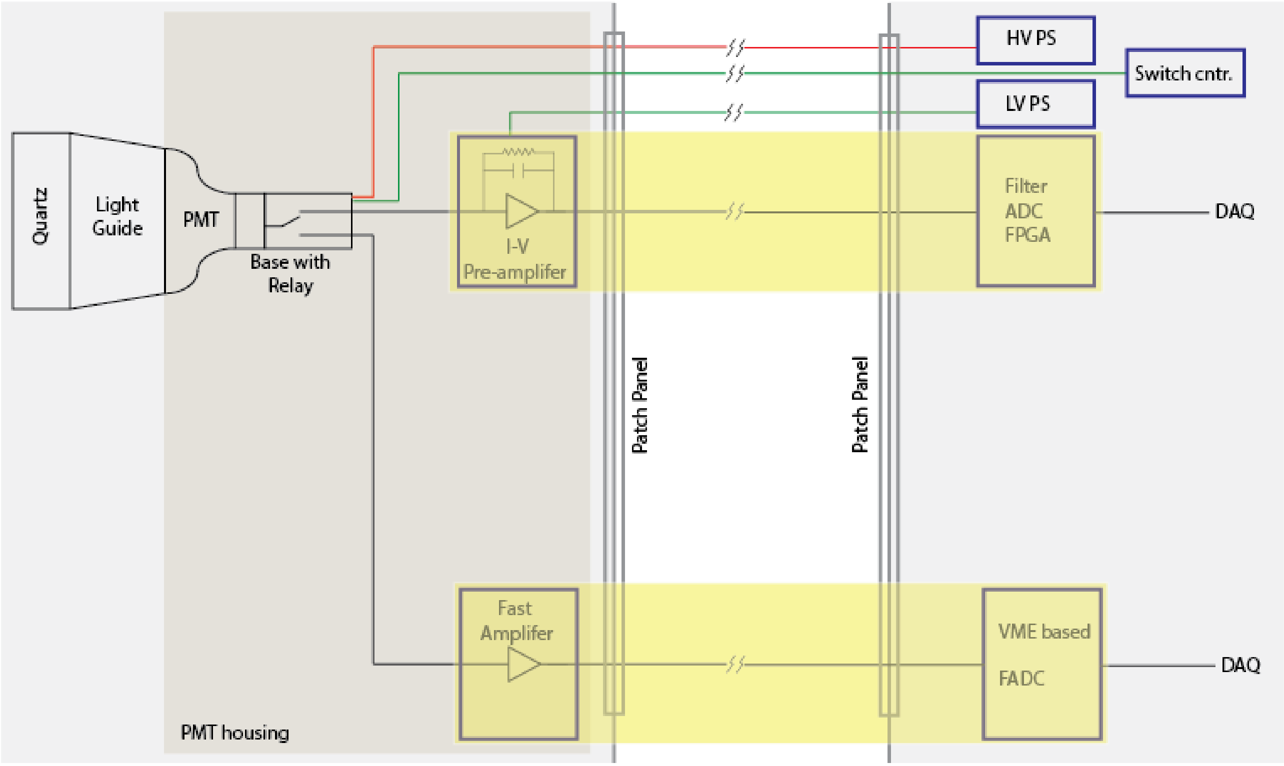
Main Detector Readout Chain

PMTs and Front-End Electronics:

- Separate readout chain for integration and counting mode
- Integration mode chain goes from PMT base to I-V preamp to ADC board (fully differential)
- Counting mode chain starts from base via separate cable
- Base is switched between the two modes via reed relay with a simple 10-12 V switching voltage

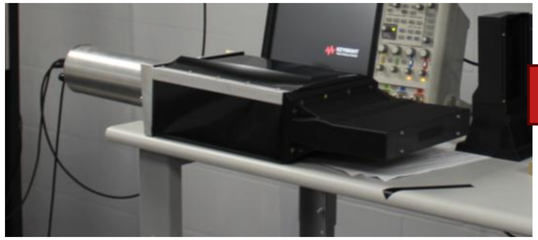
- 224 low voltage switching supply channels (Wiener)
- 224 high voltage channels (CAEN)
- 224 PMTs
- 224 PMT base / preamplifier assemblies

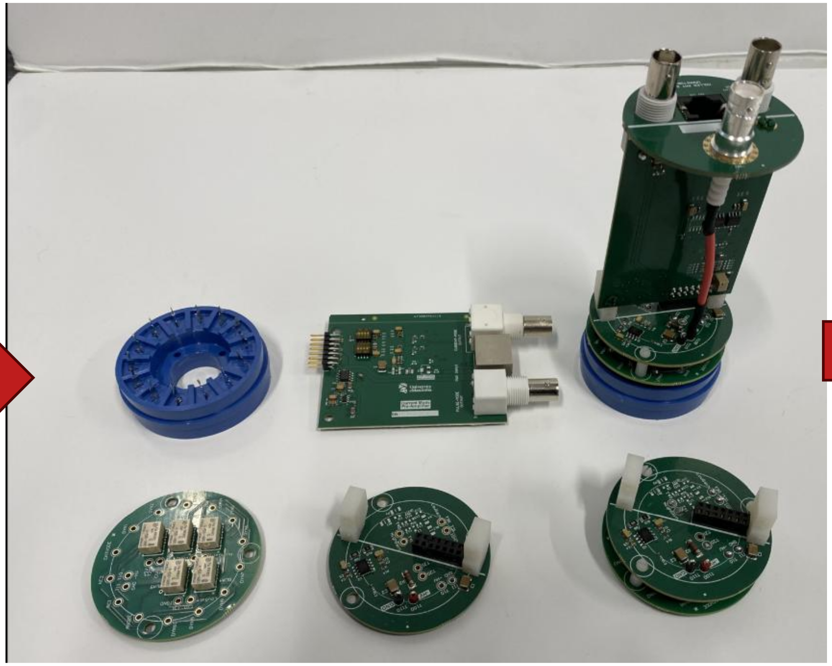
- 224 differential signal lines for integration mode
- 224 single-ended signal lines for counting mode



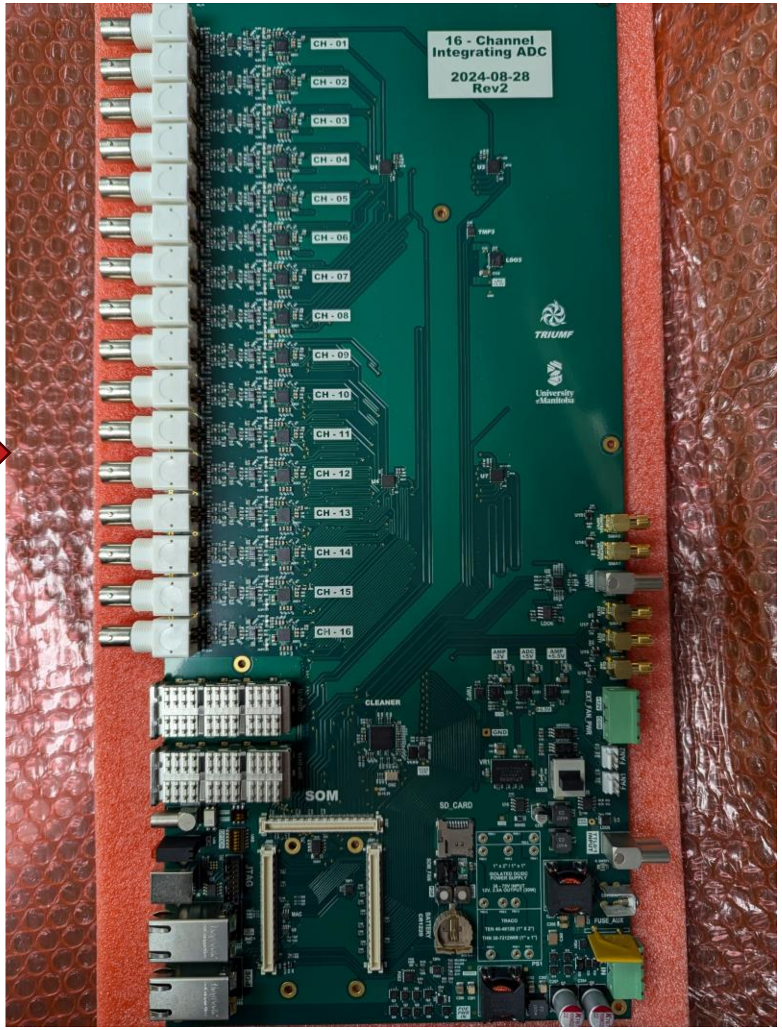
Main Detector Readout Chain

Integration mode readout chain:





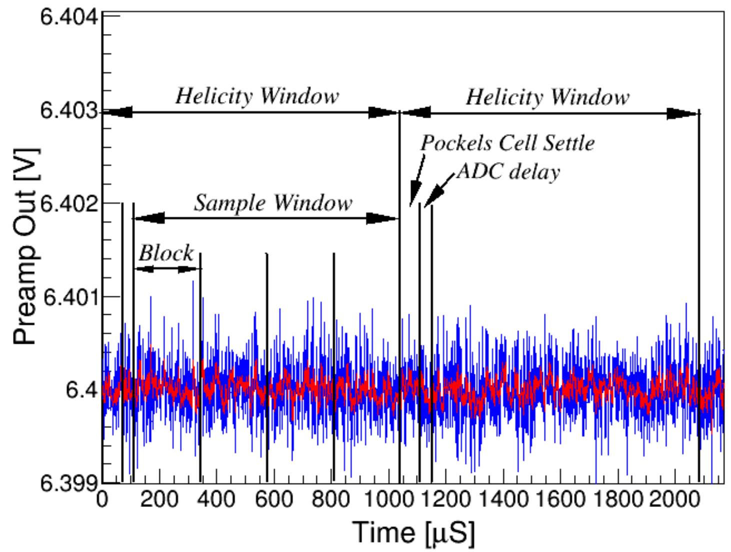
Work and photo by Jie Pan



Asymmetry Measurement Principle

Overview:

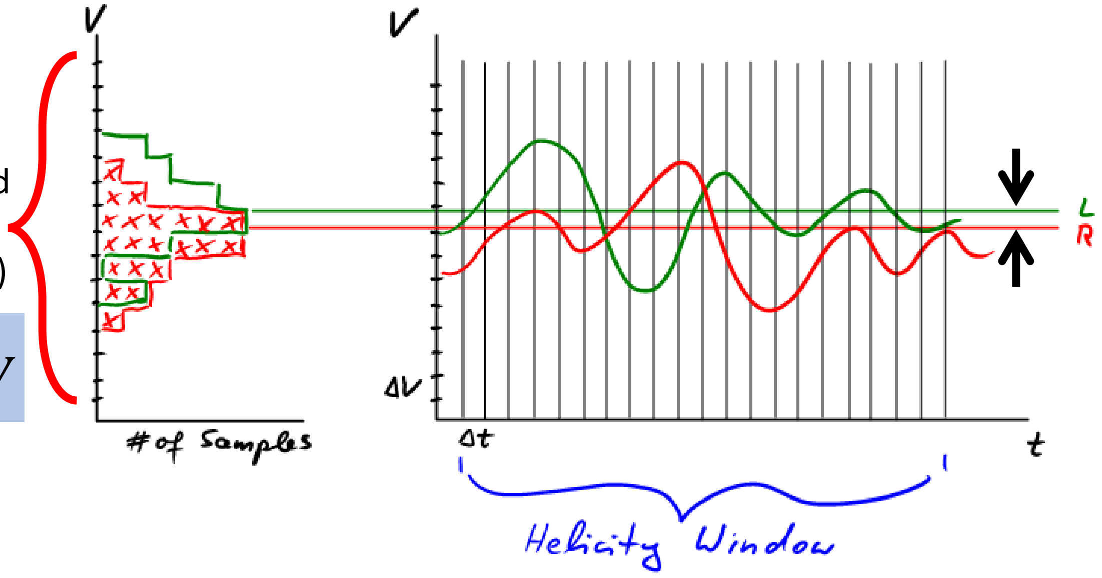
- Trying to measure a $30\ ppb$ asymmetry $\simeq 0.12\ \mu\text{V}\ @\ 2V$
- Optimize parameters: PMT signal, ADC range, resolution (timing and amplitude)
- Selected ADC: 18 bit, 15 Msps (~14 705 882 Hz actual)
- Dynamic range: $\pm 4.096\ V$
- Amplitude resolution: $\simeq 4V/2^{17} \simeq 32\ \mu V$
- Massively over-sample within each helicity window



Actually $\simeq 500\ \mu s$/Window

ADC range and resolution (0 suppressed)

$$\Delta V \simeq \frac{4\ V}{2^{17}} \simeq 30\ \mu V$$



$15\ Msps \rightarrow \Delta t = 68\ ns$

30 ppb asymmetry $\Delta\text{V} \simeq 0.12\ \mu\text{V}\ @\ 2V$

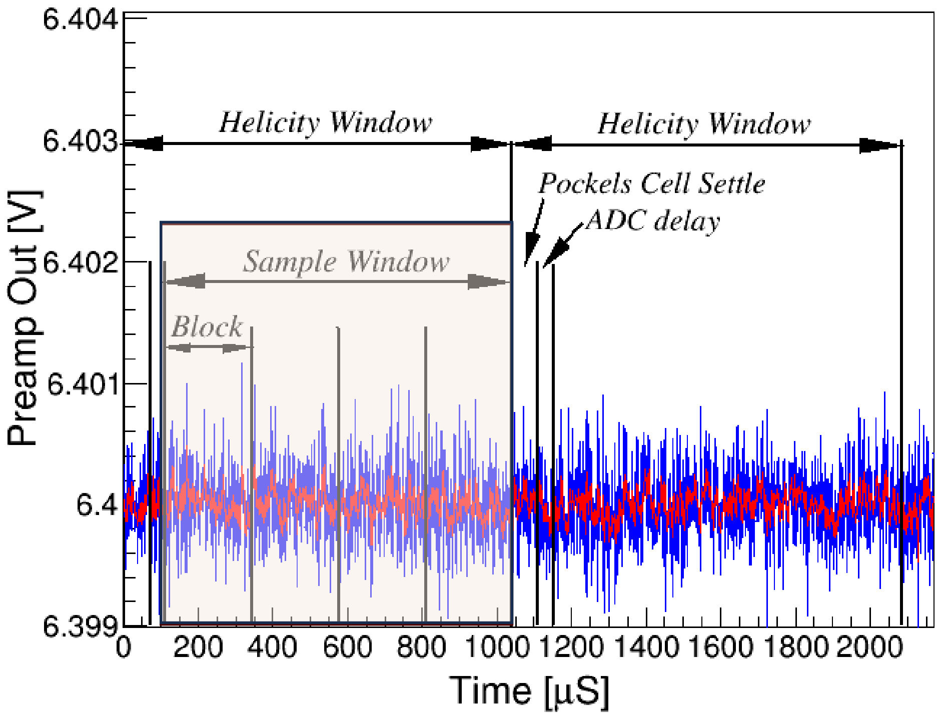
We need oversampling per helicity window to measure the asymmetry.

$\simeq$ **7000** samples/window

Higher effective resolution

Asymmetry Measurement Principle

- Production Mode Readout
  - ADC FPGA accumulates helicity window-based data items including:
    - sum of all samples,
    - sum-of-squares of all samples,
    - number of summed samples
    - minimum and maximum amplitude sample values
    - window time stamp
  - Allow splitting helicity window into blocks with separate accumulation of the above items in each



This is the data taking mode that provides the signal yield ***Y*** from which the asymmetry is calculated:

$$A_{msr} = \frac{Y^{+} - Y^{-}}{Y^{+} + Y^{-}}$$

The asymmetry can be separately calculated from the data blocks or the entire helicity window, allowing (for example) for data loss cross checks.

Construction Status and Work Planning

Answer to question: 1 b (Main detectors / Thin quartz)

Construction/purchase status overview:

- **Fused silica:**
  The fused silica (radiation hard H2 doped) raw material was manufactured by Heraeus (100% on hand)
  The polishing is done by S&S optical in Indiana (83% done 199/240 tiles)

- **Module structure parts:**
  The majority of the metal parts for the modules structure were made at outside machine shops a few parts were made in-house (100% done)
  All of the 3D printed parts are being produced in-house at UofM. Due to production time and storage, parts are made roughly in sync with module assembly (about 70% done)

- **Light guides:**
  The light guide material was purchased 2 years ago. Cutting the light guide parts was mostly done in-house and is complete (100%)

- **Module assembly:**
  We have a well-organized module assembly and testing process (see subsequent slides). The work is ongoing and at about 50% completion.

- **PMTs**
  250 PMTs were purchased in 2023/2024 and are on-hand (100%). PMT testing is in progress and is at about 70% completion.

- **FE Electronics**
  PCB production is complete (100%). Assembly and testing are at about 50% of total production volume and at 100% of minimum needed.

Construction Status and Work Planning

Answer to question: 1 b (Main detectors / Thin quartz)

Construction/purchase status overview:

- **ADC Boards**
  The production, assembly, and testing (operational) of the 40 ADC boards for MOLLER is complete (100%).

- **High voltage power supplies:**
  Ordered from CAEN, received, and tested (100%)

- **Low voltage power supplies and switching modules:**
  Ordered from Kontron, received and tested (100%)

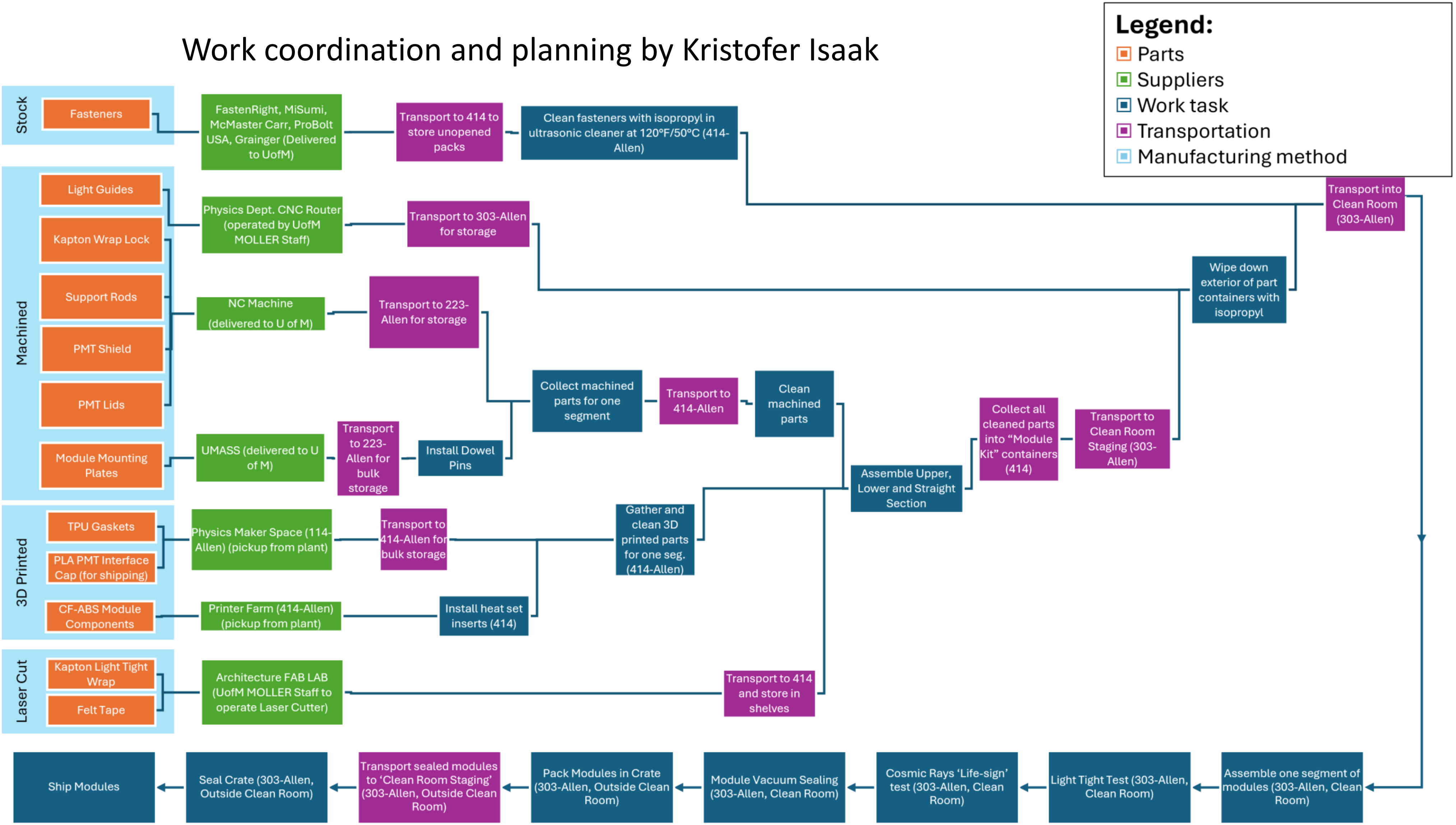
- **Detector cabling:**
  Long HV cables are on hand from previous experiments. Long signal cables have been delivered. Segment internal cables have been delivered. Long LV cables are being produced.

- **Detector cooling / tubing:**
  Cooling equipment purchased on the JLab side (in progress). Tubing and detector end parts (100%).

Construction Status and Work Planning

Production flow:

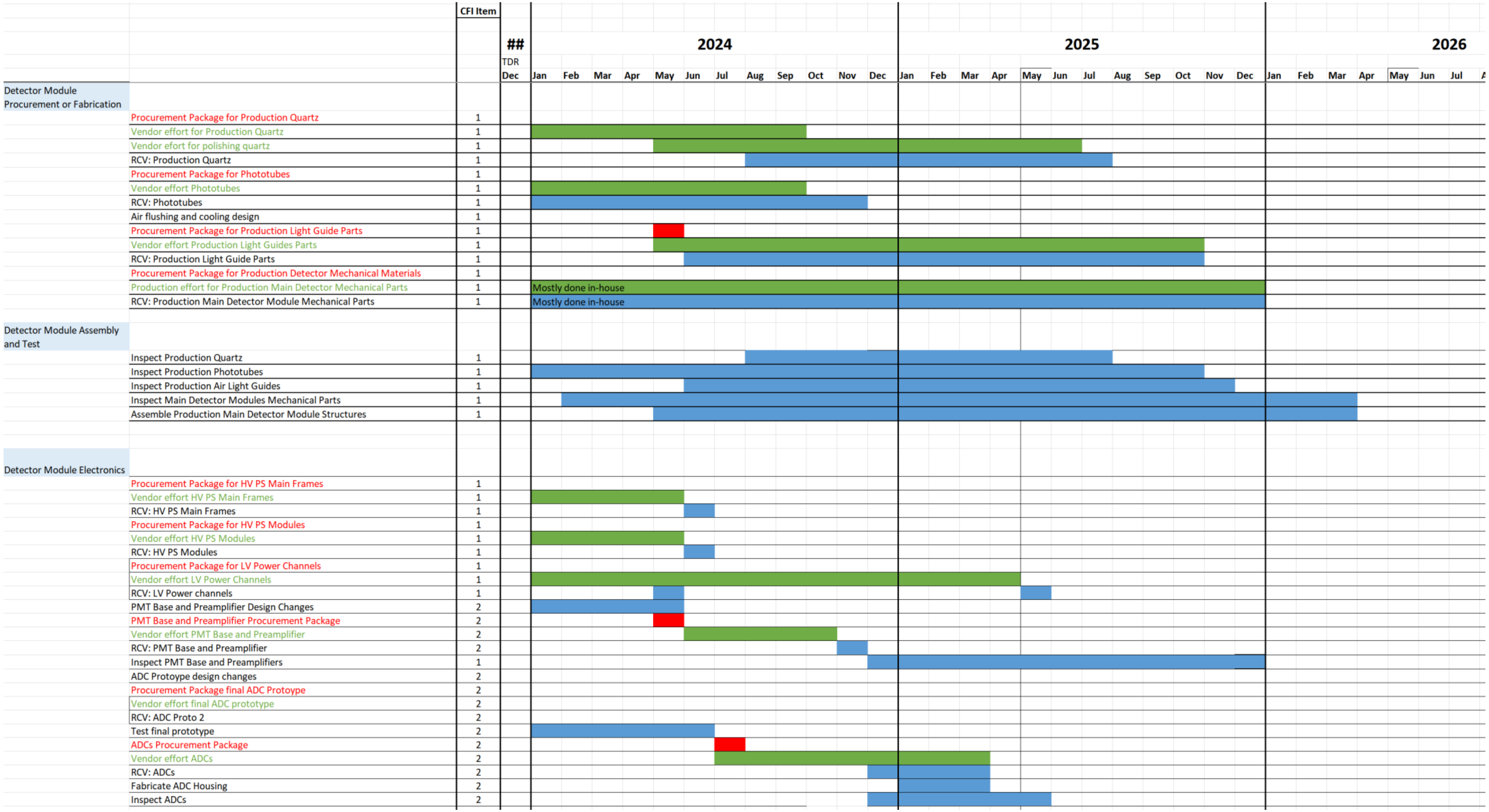
Work coordination and planning by Kristofer Isaak



Construction Status and Work Planning (Schedule)

- **Detector modules, PMTs, and electronics will all be shipped in badges as we finish modules segment by segment.**

- **Module assembly, light guide production, 3D printing, electronics assembly, and testing all happen in parallel over the entire production schedule.**



Workforce and Resources

Answer to question: 1 b (Main detectors / Thin quartz)

Workforce:

The majority of the detector work is done at the University of Manitoba. There are presently 20 UofM students (9 graduate and 11 undergraduate) working on the various tasks associated with the detector module production.

There are several other groups working on the main detector, who have and continue to be involved in various aspects of assembly and testing.

People and activities are listed on the next slide.

Overview (not including faculty and people do switch between jobs as needed – so this is an estimate):

- **Module assembly – 16 people**
- **Module testing (overall, including beam tests and radiation testing at other facilities) – 22 people – almost everyone participates in some aspect**
- **Electronics assembly and testing – 10 people (including people at JLab and TRIUMF not listed on the next slide)**
- **PMT testing – 6 people**
- **Final detector segment assembly and final testing – 5 people (now the bottleneck)**

Workforce (there are also several JLab and one W&M staff not listed here who are supporting the work)

MOLLER

Team Members (students in red):

Bianca Alexis (U. Manitoba)	Module electronics assembly
Brecken Allegood (Idaho State U.)	Module Radiation testing
David Armstrong (W&M)	
Sebastian Baunack (JGU, Mainz)	Beam testing
Joelle Beck (U. Massachusetts)	Module prototyping
Sudip Bhattarai (Idaho State U.)	Module testing
Brynne Blakie (U. Manitoba)	Module design/testing/assembly/**final QA**
M. Tausif Tajwar Bhuiyan (U. Manitoba)	Module assembly
Katherine Burke (Idaho State U.)	Module testing
Sayak Chatterjee (U. Massachusetts)	Module testing/assembly/final QA
Ryan Conaway (Ohio U.)	Electronics/DAQ
Conner Coyle (Idaho State U.)	Module radiation testing
Noel Cruz Venegas (U. Manitoba)	Module assembly, PMT testing
Wouter Deconinck (U. Manitoba)	
Cyprian Gal (Jefferson Lab)	Infrastructure, cabling, electronics
Michael Gericke (U. Manitoba)	
Boris Gläser (JGU, Mainz)	Beam testing
Anuradha Gunawardhana (U. Manitoba)	PMT testing
Binh Huynh (U. Manitoba)	Module assembly
Kristofer Isaak (U. Manitoba)	Module design, testing, assembly **supervisory**
Karsten Jennings (Idaho State U.)	Module radiation testing
Seth Johnson (Idaho State U.)	Module radiation testing
Tavleen Kainth (U. Manitoba)	PMT testing
Paul King (Ohio U.)	
Rahima Krini (JGU, Mainz)	Beam testing
Krishna Kumar (U. Massachusetts)	
Michael Ladipo (Idaho State U.)	Module radiation testing
Savino Longo (U. Manitoba)	
Dustin McNulty (Idaho State U.)	
Justin Gahley (Idaho State U.)	Module radiation testing
Alex Gwinner (U. Manitoba)	Module assembly
Juliette Mammei (U. Manitoba)	
Karina Mendoza Ramirez (U. Manitoba)	PMT testing
Laheji Mohammad (U. Manitoba)	Module design, testing, assembly **supervisory**
Jonathan Mott (U. Massachusetts)	Module design/testing/assembly
Nafis Niloy (U. Manitoba)	Module design/assembly/testing **supervisory**
Jie Pan (U. Manitoba)	Electronics design/assembly/testing **superv.**
Dhruv Patel (U. Manitoba)	Module assembly
Amilia Petryk (U. Manitoba)	Module assembly
Wayantha Rathnakela (U. Manitoba)	Module assembly
Sagar Regmi (Idaho State U.)	Module testing
Juan Jacobo Quiceno Rengifo (U. Manitoba)	Module / electronics assembly and testing
Nazanin Roshanshah (U. Manitoba)	Module assembly and PMT testing
Sakib Sarkar (U. Massachusetts)	Module testing
Arindam Sen (Ohio U.)	DAQ
Kashish Singh (U. Massachusetts)	Module testing
Paul Souder (Syracuse)	
Edwin Sosa (Idaho State U.)	Module radiation testing
Arina Tseragotin (U. Manitoba)	Electronics assembly and testing
Buddhika Uduwaraarachchi (U. Manitoba)	Software
Malte Wilfert (JGU, Mainz)	Beam testing
K Yabe (U. Massachusetts)	Module testing
Ian Zapp (U. Manitoba)	Module assembly
Carl Zorn (Jefferson Lab)	
Larry Bartoszek (Bartoszek Engineering)	

Workforce and Resources

Answer to question: 1 b (Main detectors / Thin quartz)

Resources:

- At UofM: 4 lab spaces, including one preparatory ("dirty") lab, two assembly/testing areas and one clean-room assembly area
- At UofM: Several electronics test setups to test FE electronics and ADC boards
- At UofM: Three PMT testing areas (linearity, QE, and gain) – only 1 gain test setup is currently the bottleneck at UofM
- At UofM: Two 3D printing farms with more than 10 printers operating more or less 24/7 to print detector module parts
- At UofM: Enough storage space for completed parts and up to 10 segments worth of completed modules (packed in crates)
- At W&M: High bay area for final detector segment assembly and testing
- At W&M: Storage space for detector module and quartz shipments, as well as HV and LV modules and crates intermediate storage
- At W&M: Lab spaces for assembly work and testing
- At W&M: Front-end electronics (HV,LV,ADC) and DAQ setup for final detector testing (complete MOLLER chain setup)
- At W&M: Cosmic ray testing setup (final KPP verification – UMass group)
- At JLab: ADC test stand, PMT testing setup (Idaho group), electronics group support (cabling, FE electronics testing, DAQ interface, etc.)

Radiation hardness and contingency

Answer to question: 2 a (Main detectors / Thin quartz)

Quartz:

Effect:

Peak dose areas:

- **45 MRad per $5 \times 5\ mm^2$ for Ring 5**
- **120 MRad per $5 \times 5\ mm^2$ for Ring 2**

Irradiations conducted at the Idaho Accelerator Center.

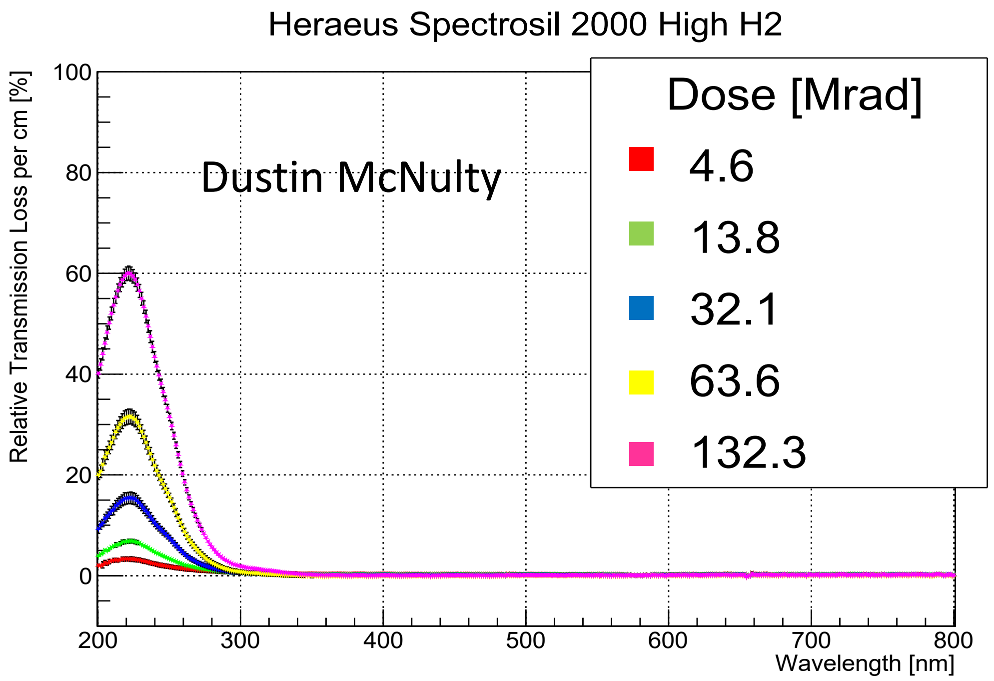
Evaluated several different quartz types and settled on Heraeus H2 doped for the main detector modules.

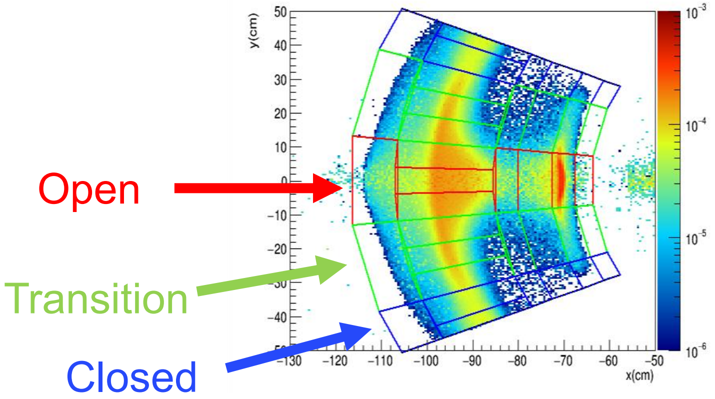
Contingency:

There should be very little effect from radiation damage in the signal yield since the light guide reflectivity essentially cuts off much of the yield below $300\ nm$.

We can rotate/switch detector modules between open and closed sectors part way through the experiment, if need be.

In addition, JLab may purchase additional tiles.





Radiation hardness and contingency

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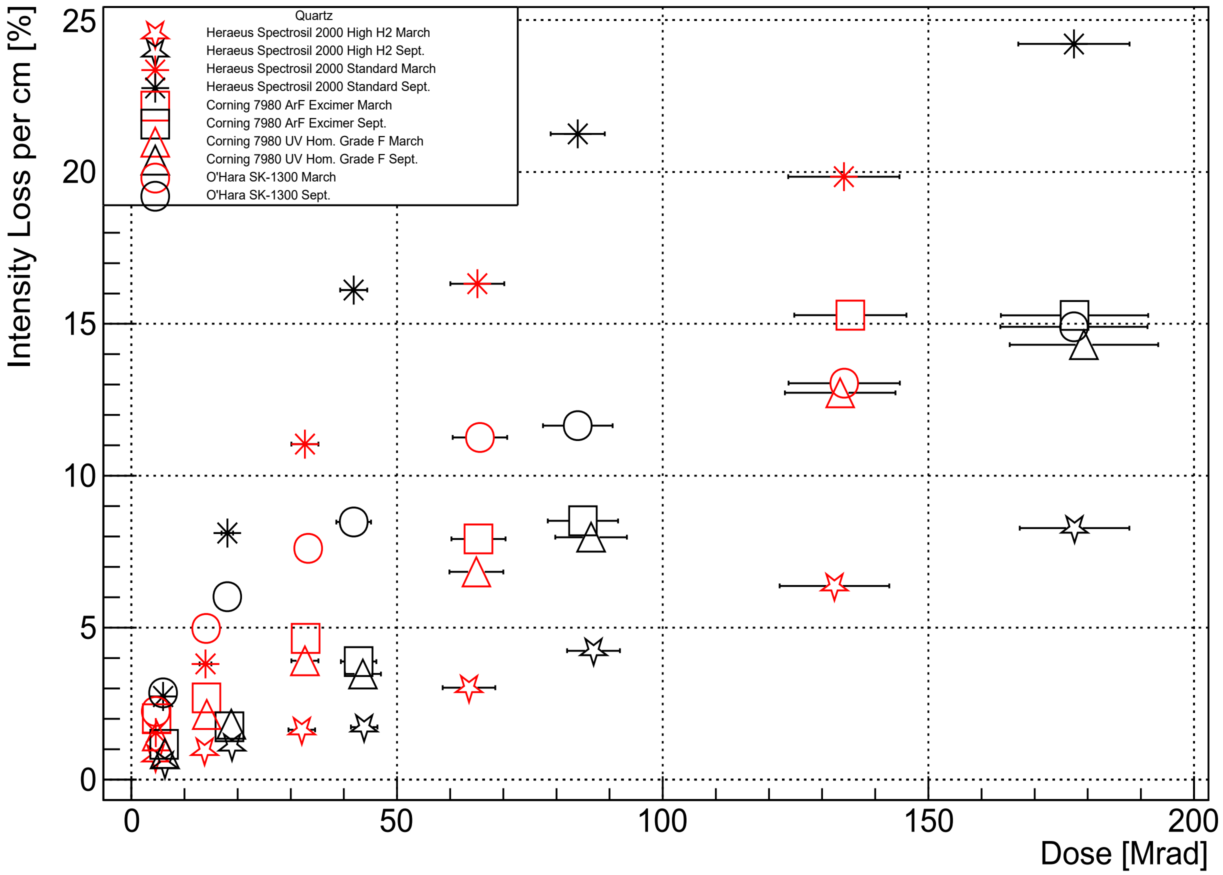
Total Intensity Loss Across Wavelengths 220-400 [nm]



Refer to Dustin McNulty's talk for details

Radiation hardness and contingency

Answer to question: 2 a (Main detectors / Thin quartz)

Module structure materials:

There are some commonly used materials that are known to be radiation hard, including:

- Polyimide film
- Aluminum
- Brass
- Other metals

These were not tested, but confirmed to be okay from literature.

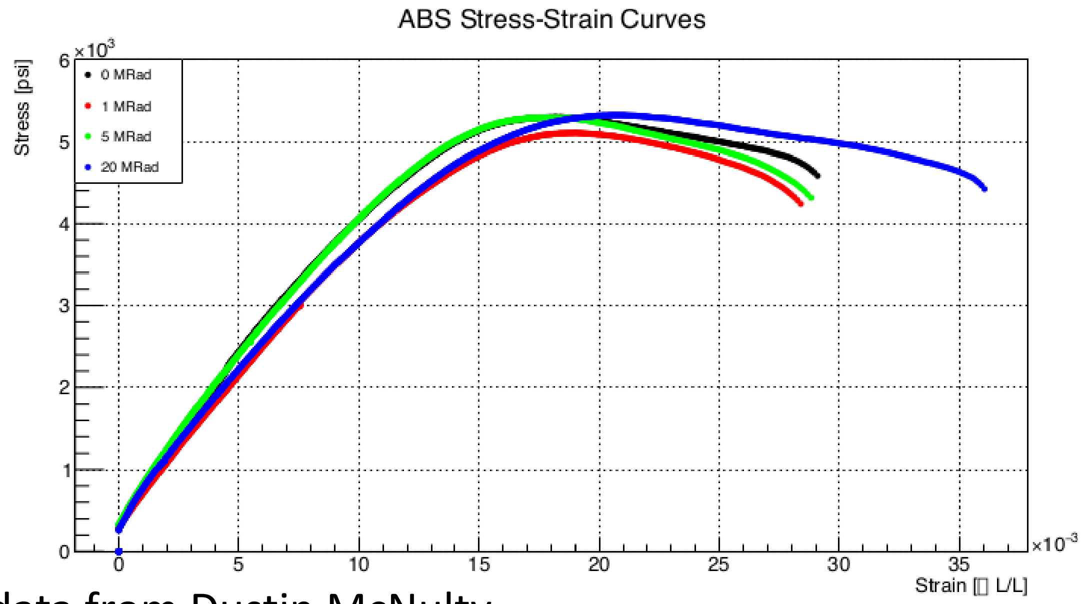
The primary concern was the 3D printing material.

Various materials were again tested at the Idaho Accelerator Center.

Strain tests were done on a few available materials after irradiation. CF-ABS was found to perform best.

Contingency:

We will be printing additional modules components after production concludes.



Graph and data from Dustin McNulty

	1 Mrad		5 Mrad		20 Mrad	
Material	Modulus [ksi]	Yield [ksi]	Modulus [ksi]	Yield [ksi]	Modulus [ksi]	Yield [ksi]
ABS	390 ± 30	4.7 ± 0.2	380 ± 20	4.7 ± 0.2	370 ± 30	4.7 ± 0.2
toughPLA	480 ± 20	5.1 ± 0.2	460 ± 30	4.3 ± 0.1	480 ± 30	1.2 ± 0.1
Nylon	380 ± 30	5.0 ± 0.2	230 ± 70	6.2 ± 0.3	220 ± 60	6.1 ± 0.1

	0 Mrad (baseline)	
Material	Modulus [ksi]	Yield [ksi]
ABS	390 ± 20	4.7 ± 0.2
tough PLA	430 ± 20	4.8 ± 0.2
Nylon	250 ± 30	6.1 ± 0.2
C-fiber Nylon	520 ± 50	5.6 ± 0.3

Radiation hardness and contingency

Answer to question: 2 a (Main detectors / Thin quartz)

Electronics:

The primary concern is for the front-end amplifier and power regulation:

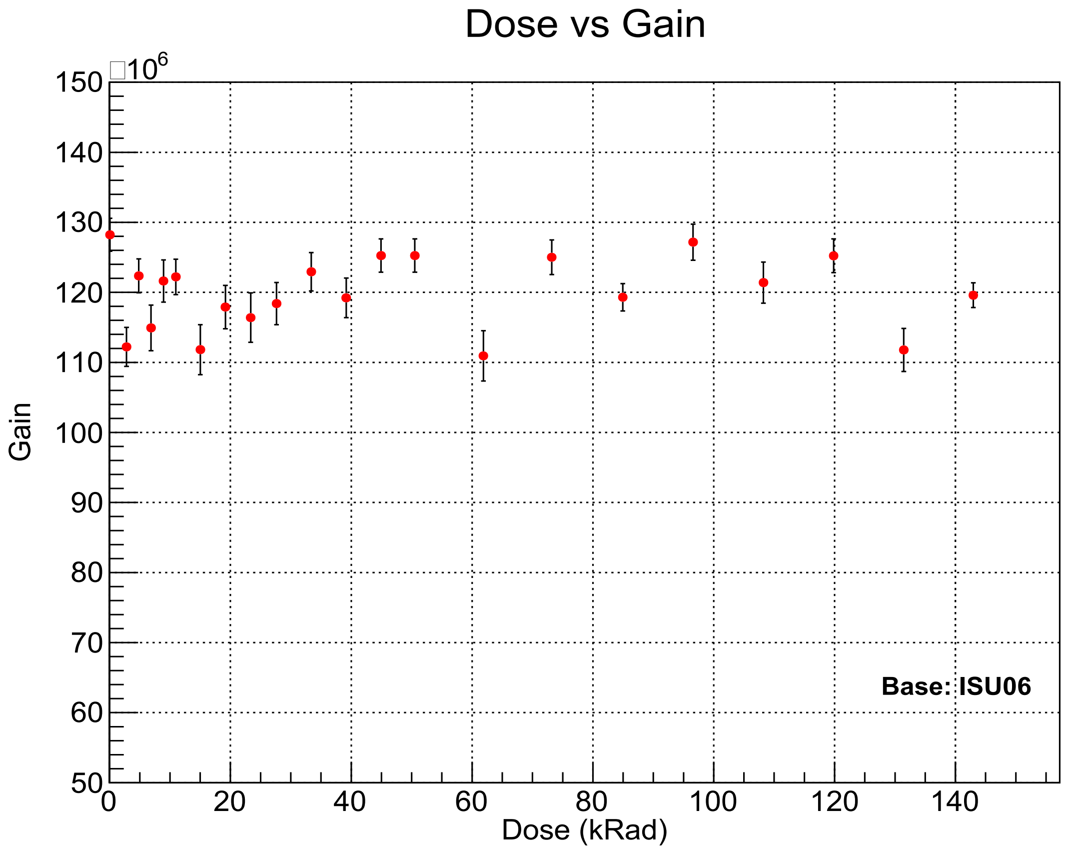
The radiation environment in the aera is relatively low, at 60 kRad .

Several vulnerable components were tested:

- All operational amplifiers
- DC/DC converts / power regulators
- Switching relays (?)

The electronics performance was evaluated for:

- Event mode gain
- Integration mode gain
- Current/power stability



Refer to Dustin McNulty's talk for detailes

Radiation hardness and contingency

Answer to question: 2 a (Main detectors / Thin quartz)

Electronics:

Results:

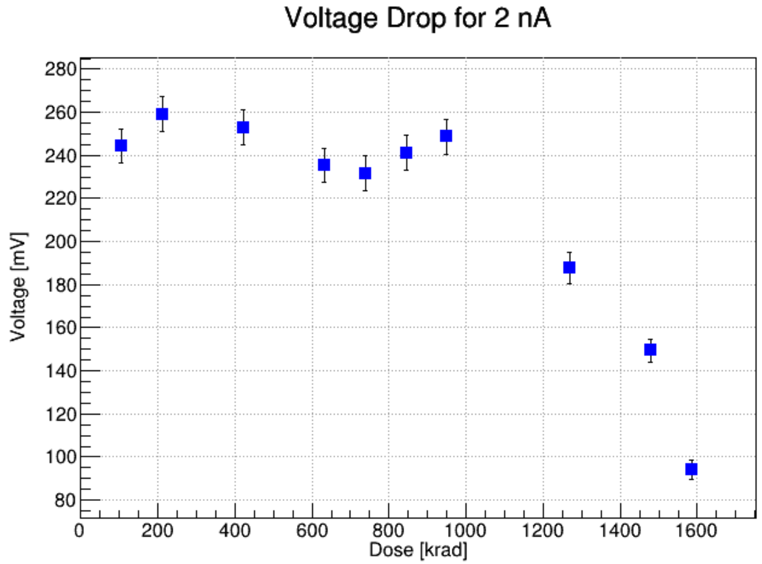
- **Integration mode amplifiers were seen to survive past 1 MRad**
- **Event mode amplifiers survived past 140 kRads**
- **Most DC/DC converters / power regulators failed before the 60 kRad dose**
- **Relays appeared to be unaffected (parasitic dose)**

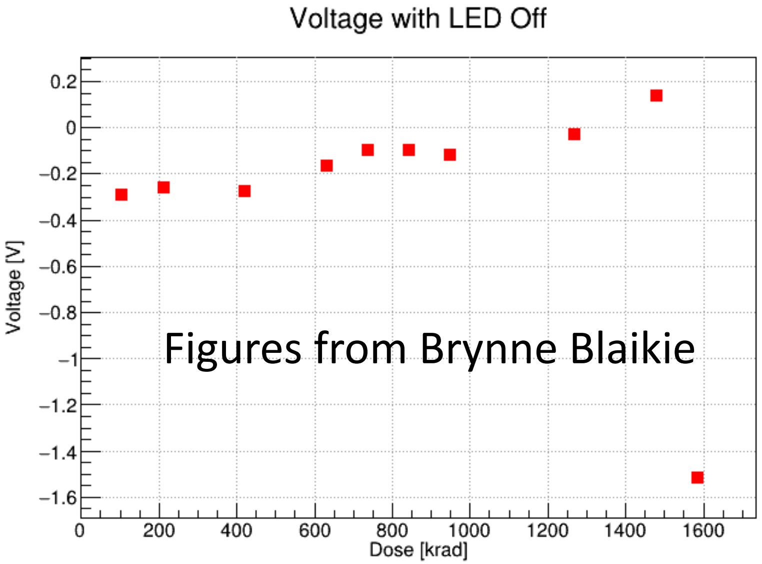
Contingency/mitigation:

We have designed the electronics and the detector module/segment such that replacement of the DC/DC converters is possible without disassembly of the detector modules or the array as a whole.

We have ordered 3 times the number of needed converters.

We are making 2 times the number of needed FE electronics modules.





Jefferson Lab

Long term stability / operation / durability

Answer to question: 2 a (Main detectors / Thin quartz)

Materials (quartz, light guides, etc.):

Quartz is extremely durable and the purchased Heraeus H2 Spectrosil 2000 quartz is very radiation hard. No other degradation is expected or likely.

The modules are completely wrapped (light tight) and flushed with dry air, removing moisture and preventing accumulation of deposits such as radicals from the PCBs or remnants from electron beam induced hydrocarbon breakup (e.g. white deposit on light guides).

The same dry air flushing also reduces the effect of hygroscopy on the 3D printed components.

PMTs:

The purchased PMTs have a maximum cathode current of $500\ nA$ and a maximum anode current of $100\ \mu A$.
The signal levels in the main detector modules (at production current) are such the cathode currents are well below the maximum ($\leq 30\ nA$) minimizing cathode degradation over time.

Likewise, the PMT voltage dividers are designed for gains that keep the anode current around $10\ \mu A$ to ensure that the PMTs last for the experiment before reaching their end-of-life (defined to be a gain drop larger than a factor of 2 – see subsequent slides).

Electronics:

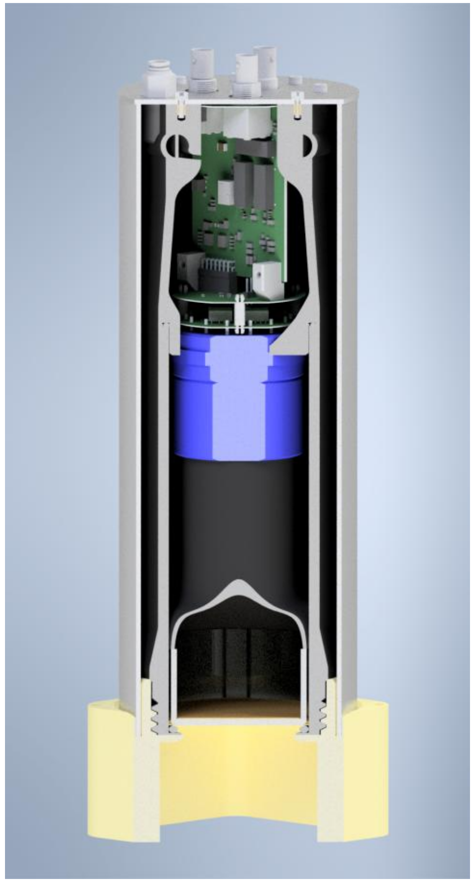
Long term stability of the front-end electronics can be somewhat controlled through temperature regulation, which is done via air flushing.

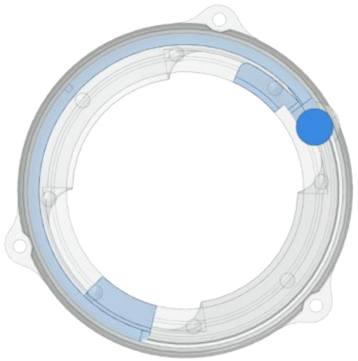
The electronics are designed to operate well withing manufacturer specified limits under any of the MOLLER running conditions and small stability variations are effectively filtered out through the integration mode acquisition method (see subsequent slides).

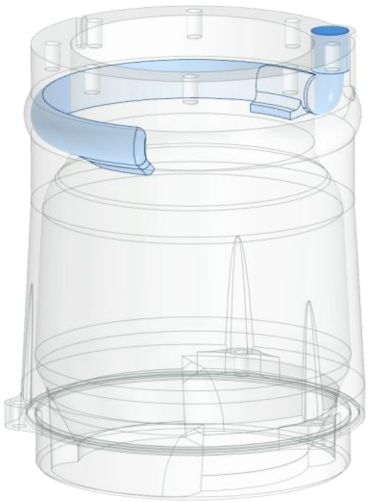
Long term stability / operation / durability

- **Physical design and simulation of the PMT housing**

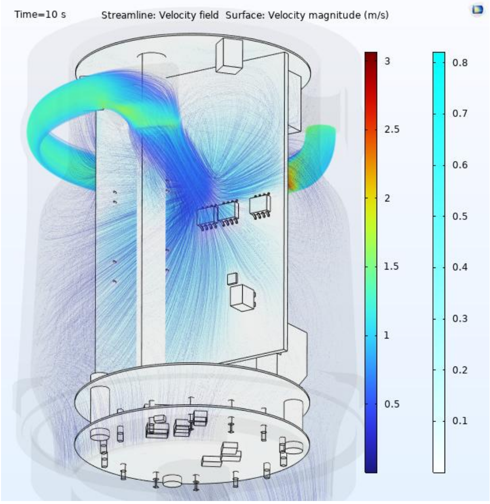
  Cooling the electronics (actual cooling test have been done):

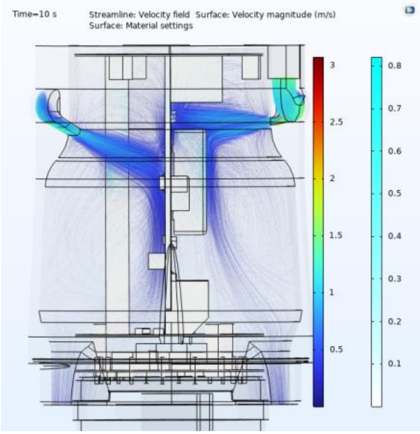


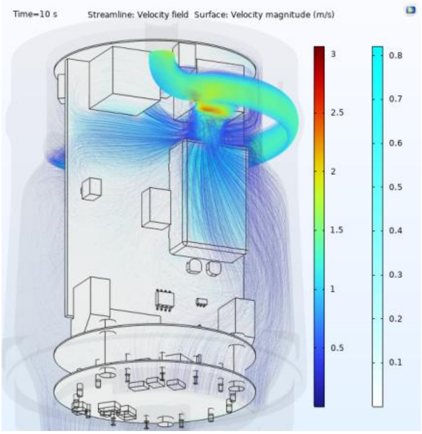




Figures from Laheji Mohammad





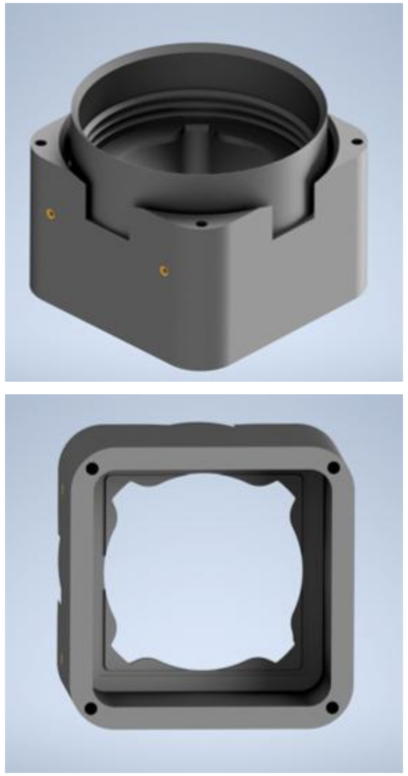


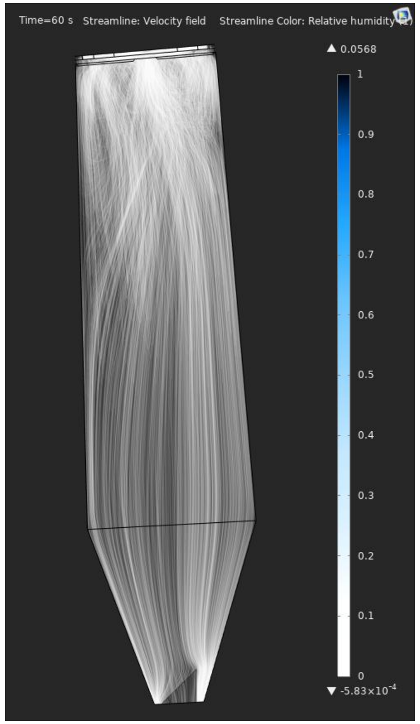
Long term stability / operation / durability

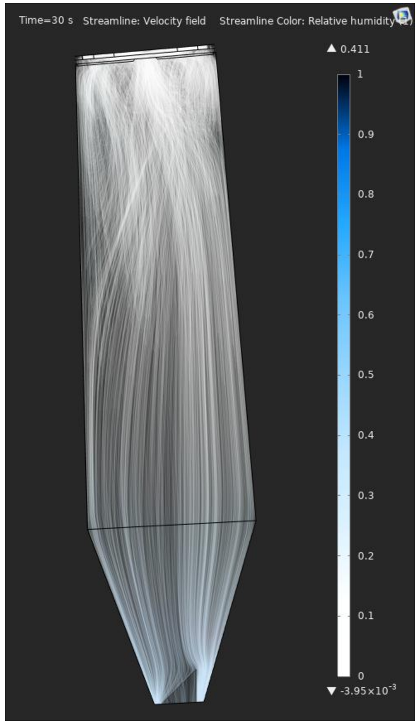
- **Physical design of light guide air inlet and outlet**

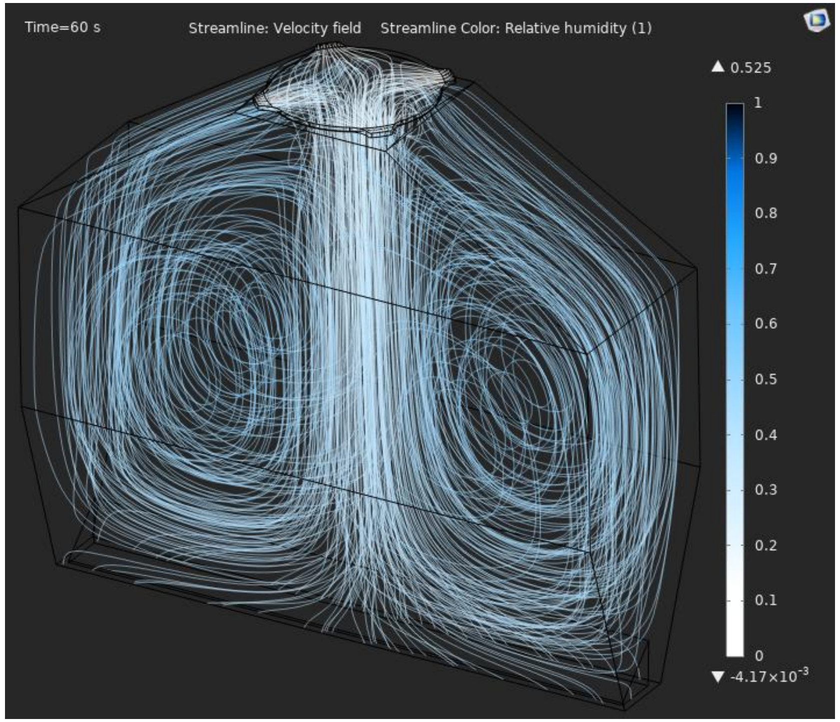
  Light guide should be flushed with dry air to cut down on background

Figures from Laheji Mohammad









Systematic Effects

Answer to question: 2 a (Main detectors / Thin quartz)

Light yield uniformity:

In combination with helicity correlated beam changes, light yield variations associated with detector tile electron hit position can lead to false asymmetries. These effects can be studied in detail and removed using the beam monitoring and detector data. Any yield variation across the detector is a secondary effect and is also removed in the same way.

Without event profile motion the light yield variation does not matter, since the events are integrated over the detector tile.

Nonetheless, a large light yield variation would make the removal of systematic effects and the asymmetry analysis much more cumbersome.

Light yield variations across the detector quartz tiles have been verified to be small, both from simulations and beam tests.

PMTs:

The only PMT related systematic effect is that of a non-linearity. The overall goal is to have non-linearities at the $\leq 0.5 \pm 0.1\ \%$ level. If this cannot be realized (and it cannot for every PMT), it is important know the actual non-linearity of each PMT at that level precision, so that the effect can be removed in the analysis. Measuring the non-linearity for all PMTs is in progress with roughly 70% done.

Electronics:

Systematic effects that could lead to false asymmetries include: Helicity correlated EM pickup in the transmission lines or possible ground loops and the mixing into the data signal of any voltage/current changes associated with the helicity change.

The first effect is mitigated using differential signal lines for all detector signals from the preamplifers to the ADC boards. The second effect is removed by ensuring that no electrical signal is shared between the source and the rest of the front-end/DAQ system (see DAQ talk).

Systematic Effects

Answer to question: 2 a (Main detectors / Thin quartz)

Optical transmission:

Not sure what this refers to.

It could mean the (fiber) optical transmission from the ADC board to the DAQ system or the light collection within the detector.

The answer to the former is no. High speed data transmission via optical fiber with our ADC has been tested and verified on the bench. The beam condition doesn't add anything to that test.

The answer to the latter is yes, many times, using beam tests at the MAMI test facility in Mainz, starting in 2013 (see subsequent slides).

Detector Calibration

Answer to question: 2 a (Main detectors / Thin quartz)

Optical calibration:

The calibration of the light yield or event by event response of the detector modules is calibrated through a combination of beam test data and, as the final instance, through a serious of precise photo-electron yield validations (comparison with test beam data) using cosmic ray events after the modules have been installed into the segments. This final test before installation happens at W&M.

Optical performance tests / PE yield calibrations will also be done again during commissioning and from time-to-time during the experiment, in low current event mode data taking. These calibration runs will utilize the GEMs in combination with the main detectors to measure the single event detector response and compare that data to the design level expected / simulated response and data from prototyping beam tests.

Note that an absolute calibration of the detector is not needed, since the asymmetry measurements are relative by nature.

Electronic and PMT calibration:

Baseline performance of the front-end electronics and the ADC board has been established through bench tests. Here the most important criteria is the reduction of excess noise and the pedestal level adjustments.

All ADC boards have been evaluated for noise levels and pedestal values and are within the design criteria and component level expected performance.

Each of the front-end (voltage divider and preamplifers) are tested on the bench. Pedestal levels are adjusted and noise levels established.
The entire chain performance is calibrated using exact input sources (current sources at the preamp input and voltage sources at the ADC input).

Detector Calibration

Final Main Detector Modules:

- **Overall detector geometry (arrangement of tiles, light guides, and PMT) was fixed in 2023 and beam-test validated (many times).**
- **All design aspects and prototype testing were completed by April 2024**
- **Test verify that the basic operation/performance criteria are all satisfied**

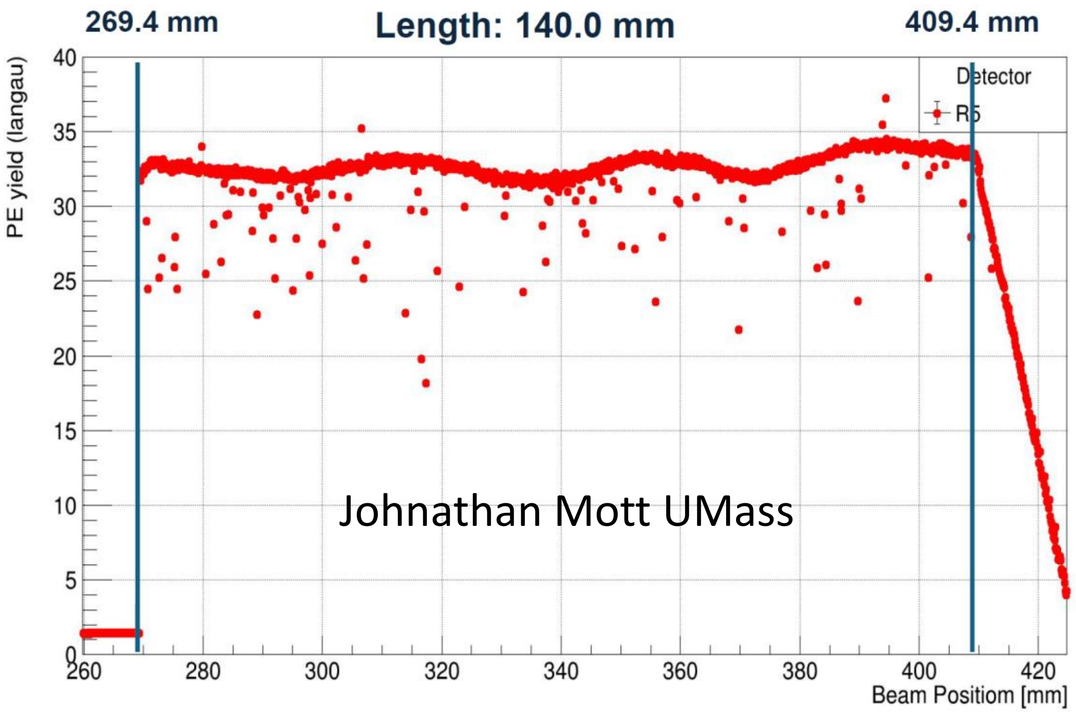
Rings	PE yield	Resolution (Gsigma/Mean)	RMS/MEAN
1	26.6 ± 0.1	~ 20 %	~ 30 %
2	25.0 ± 0.1	~ 22 %	~ 28 %
3	22.5 ± 0.8	~ 21 %	~ 28 %
4	23.6 ± 0.2	~ 23 %	~ 30 %
5 BF	32.0 ± 0.2	~ 18 %	~ 25 %
6	20.7 ± 0.2	~ 22 %	~ 32 %

October 2023 Beam Test Results

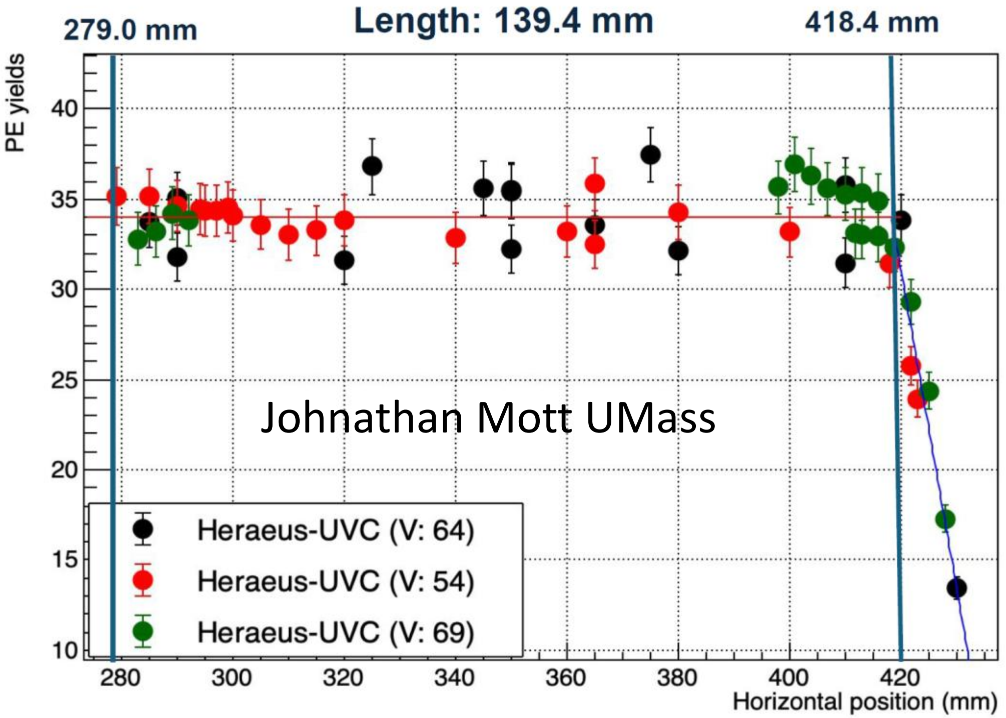
Detector Calibration

Answer to question: 2 a (Main detectors / Thin quartz)

Simulations



Data

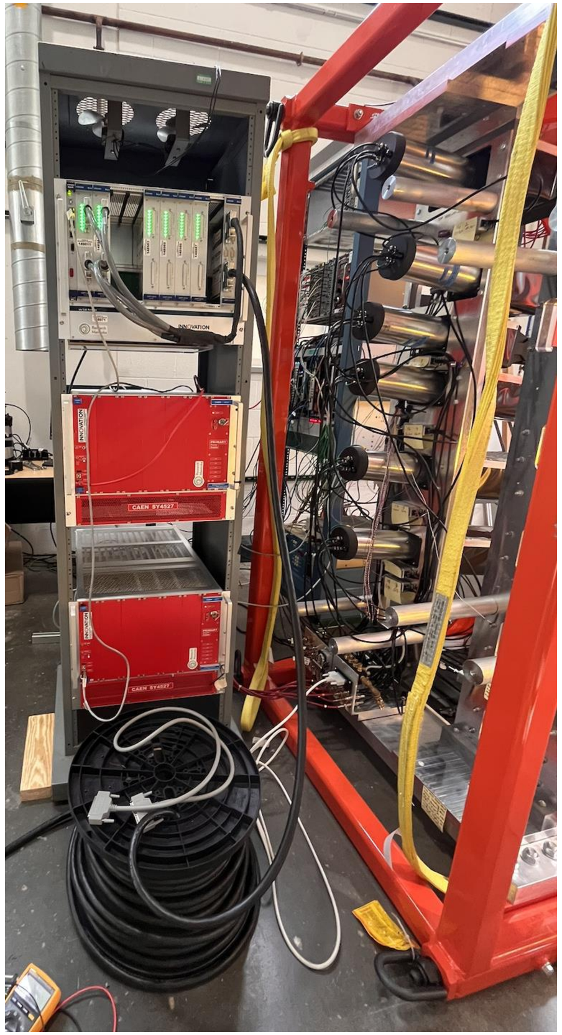


- Langau fitted PE yield vs. radial beam position
- Length is measured from where data begins to where the 'notch' begins
  - Data begins when enough scattered particles are hitting the tile to generate a healthy signal. Due to a spread in the beam as it travels downstream, this does not necessarily align with the actual tile start (< 1 mm for R5)

Detector Assembly

Final main detector module production:

- Alongside with the cosmic testing of the production modules, the testing of the LV, HV crates are also being carried out at W&M
- Testing of routing of the cables (signal, HV, LV) and gas tubes
- Main detector related mechanical assembly (e.g. loading and unloading of the fully instrumented segment plates on to the storage rack)



Failure Modes / Mitigation

Answer to question: 2 a (Main detectors / Thin quartz)

Quartz:

There are no obvious failure modes under normal conditions.

Mitigation: A few replacement tiles have been purchased (particularly for R5). More may be purchased through DOE. Also tile rotation (see earlier slides on radiation damage)

Light Guides:

Loss of reflectivity due to electron impact associated surface deposits.

Mitigation: Dry air flushing

PMTs:

Loss of radiant sensitivity or loss of gain (generally PMT dies).

Mitigation: Additional / replacement PMTs have been purchased (10%). More may be purchased trough DOE.

Electronics:

General electronic component failure (radiation induced or otherwise).

Mitigation: 25% additional ADC boards have been produced and we have 800 DC/DC converters (power regulators) and 600 voltage dividers and 35% additional preamplifiers. The DC/DC converters and the voltage dividers are most likely to fail at some point.

Main Detector FE and DAQ

Answer to question: 8 (Main detectors / Thin quartz)

Integration Mode / Production Mode:

Bandwidth:

1. **There is the bandwidth we set at the electronics level, which should be large enough to resolve the temporal features of the signal we care about (i.e. limited by the helicity reversal Pockels cell settle time $\simeq 10\ \mu s$). The main detector electronics bandwidth is $1\ Mhz$, which is more than enough to resolve the settle ringing in streaming mode (every ADC sample is recorded and transmitted).**

2. **There is the integration mode (non streaming) bandwidth, which is set by the helicity reversal frequency and the integration window. This is set at whatever we decide minimizes systematic effects and maximizes the measurement precision.**

3. **There is the data transmission bandwidth, which needs to be large enough to allow for loss-less data transfer. The ADC boards currently have 1 Gbps fiber links (SFP) working, but they are built for up to 40 Gbps (QSFP ports). The current bandwidth is enough to run the board as intended for MOLLER production and to read out two channels per board at a time in full streaming mode (15 Msps). All channels per board can be read out in streaming mode simultaneously, but with a larger sample decimation.**

   The implementation of the higher bandwidth transfer speed via QSFP is just a matter of purchasing and implementing the corresponding firmware IP. No hardware changes are needed for that. This is currently being explored and would only be necessary to improve diagnostic mode running.

4. **Additional things that can lead to bandwidth limitations are cable lengths and impedances. The entire integrating mode DAQ chain up to and including the ADCs has been tested with the full cable lengths (70 m between preamplifier and ADC).**

Thank You

See backup slides for additional details

Main detector production/purchase status

Final main detector module production:

- All design aspects and prototype testing were completed by April 2024
- Module production started in May 2024:
  - 3D printing of radiation hard module parts is ongoing as we assemble modules

U. Manitoba print farm

Main detector production/purchase status

Final main detector module production :

- All design aspects and prototype testing were completed by April 2024
- Module production started in May 2024:
    - 3D printing of radiation hard module parts is ongoing as we assemble modules
    - All machined parts are on hand
        - support struts
        - PMT shielding
        - mounting plates
        - etc.

Module mounting plate from U. Syracuse @ U. Manitoba

PMT shield @ U. Manitoba

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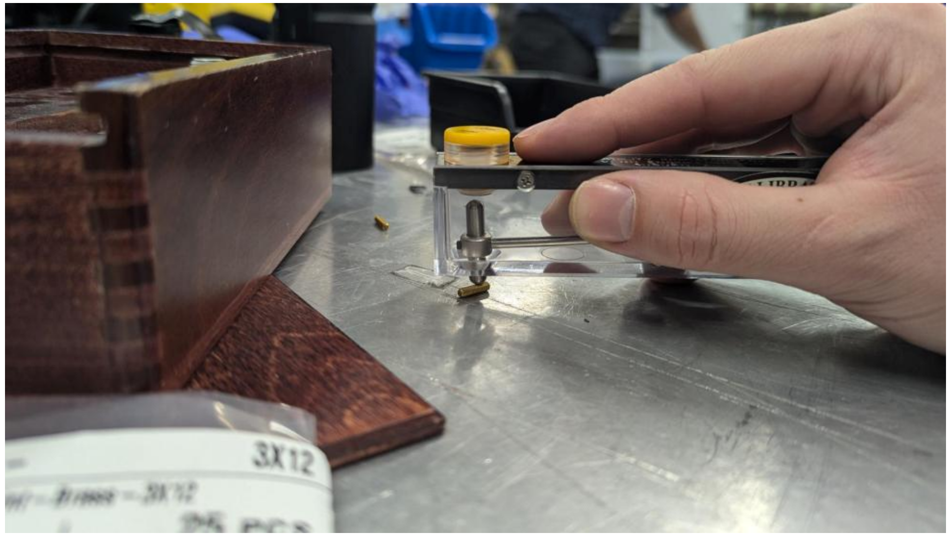
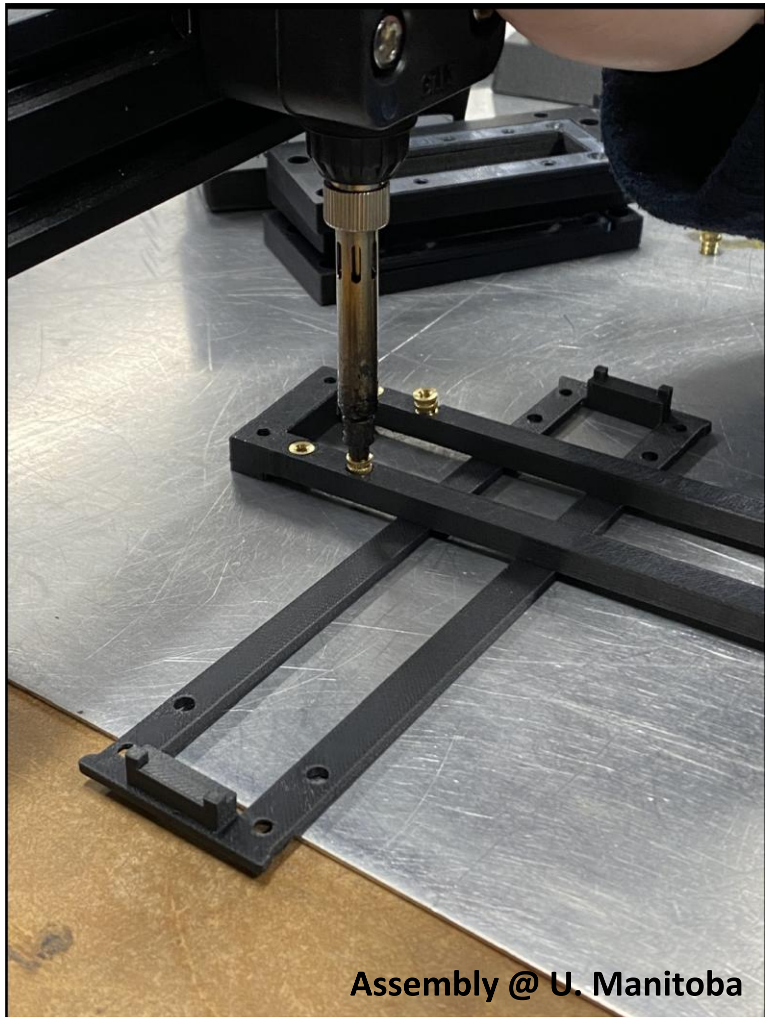
  - All fasteners are on-hand




Assembly @ U. Manitoba

Main detector production/purchase status

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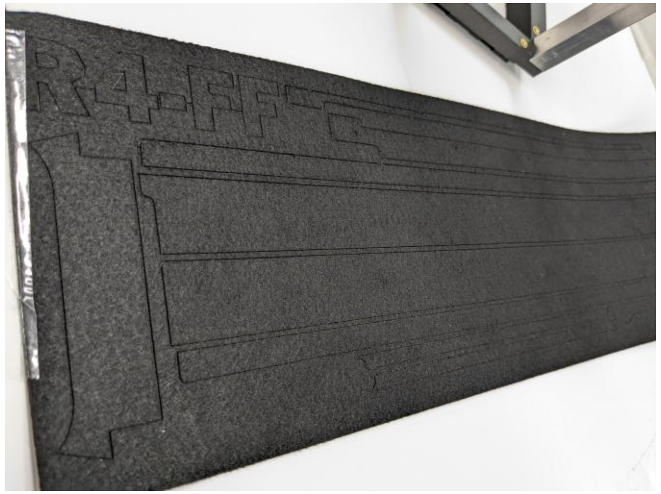
  - All machined parts are on hand (support struts, PMT shielding, mounting plates)
  - All fasteners are on-hand
  - Assembly and testing of modules is under way (currently assembling segment 5)
    - “Dirty lab” assembly:



Assembly @ U. Manitoba

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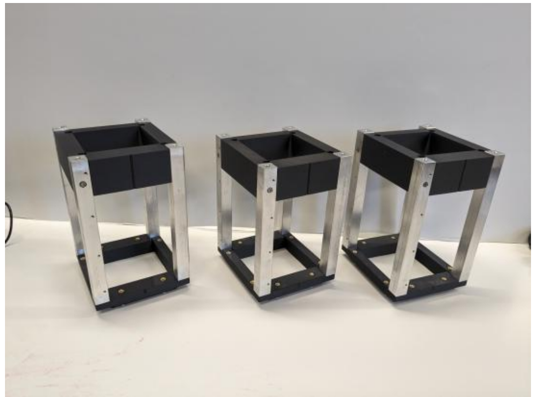

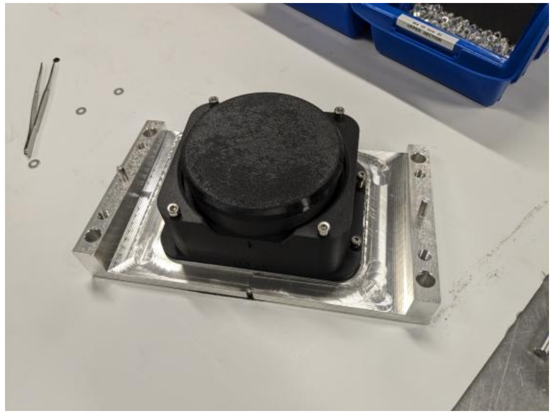

Assembly @ U. Manitoba

Main detector production/purchase status

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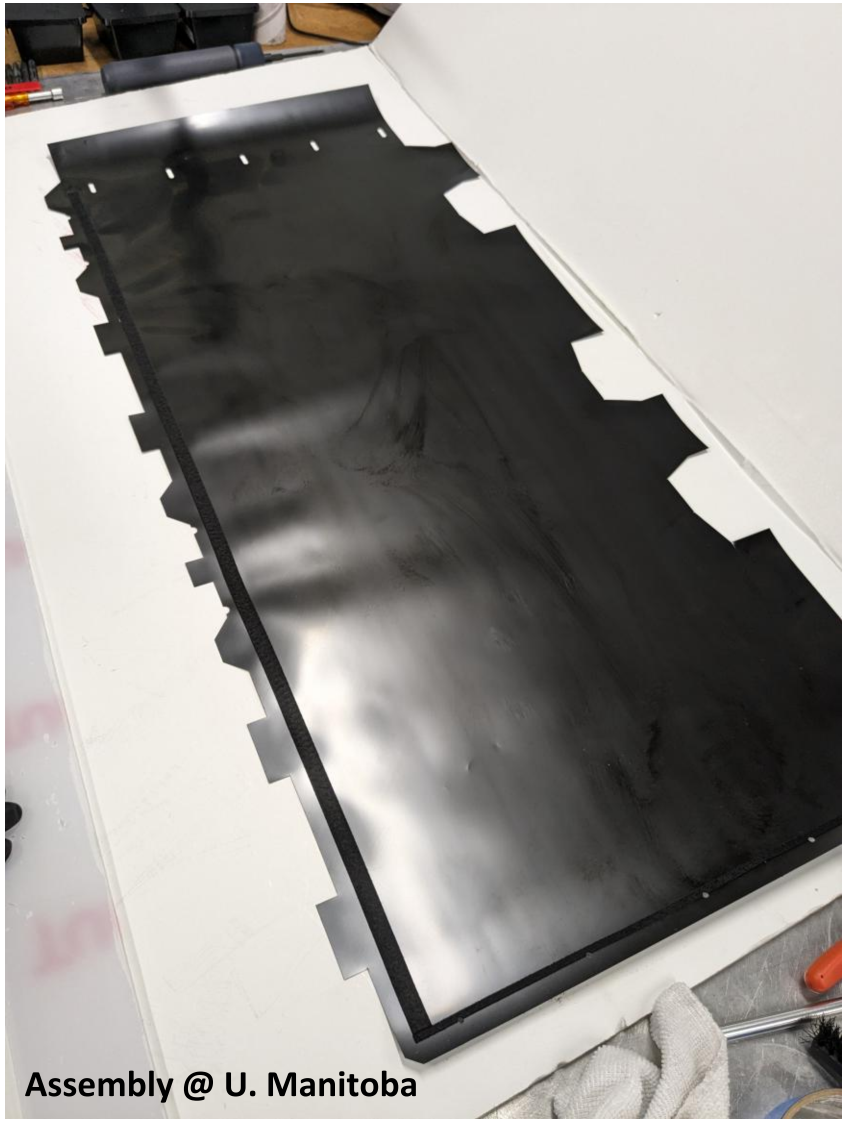

Assembly @ U. Manitoba

Main detector production/purchase status

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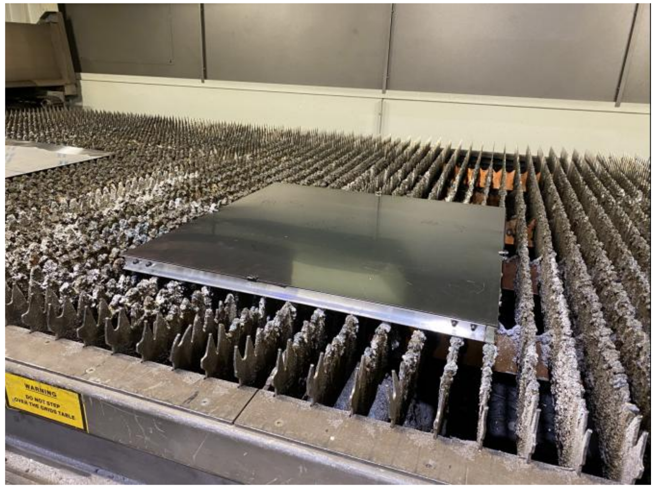
    - All fasteners are on-hand
    - Assembly and testing of modules is under way (currently assembling segment 5)
        - "Dirty lab" assembly
        - Light guide cutting



Laser cutting @ SCT (local company)

Main detector production/purchase status

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  - All machined parts are on hand (support struts, PMT shielding, mounting plates)
  - All fasteners are on-hand
  - Assembly and testing of modules is under way (currently assembling segment 5)
    - “Dirty lab” assembly
    - Clean room assembly

Final assembly in clean room @ U. Manitoba

Main detector production/purchase status

Final main detector module production:

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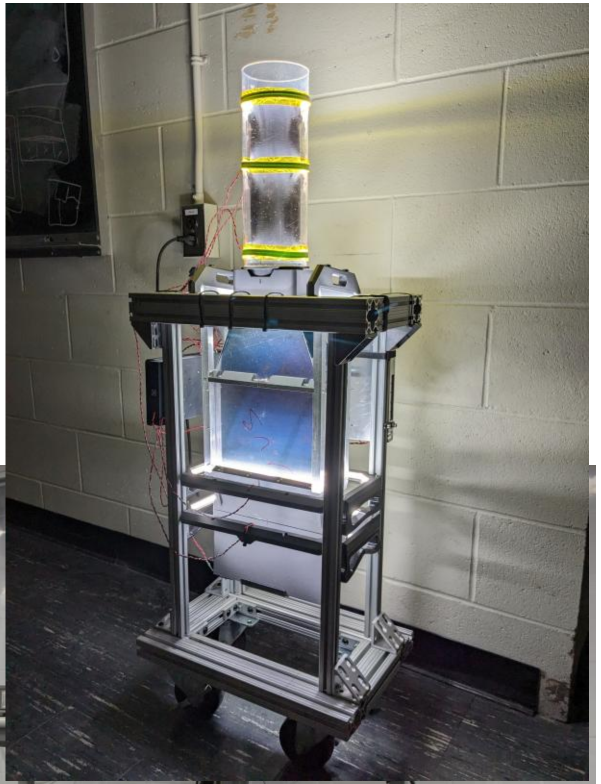
    - All fasteners are on-hand
    - Assembly and testing of modules is under way (currently assembling segment 5)
        - “Dirty lab” assembly
        - Clean room assembly
        - Testing completed modules (cosmics and light seal)

Assembled module testing in clean room @ U. Manitoba



Main detector production/purchase status

MOLLER

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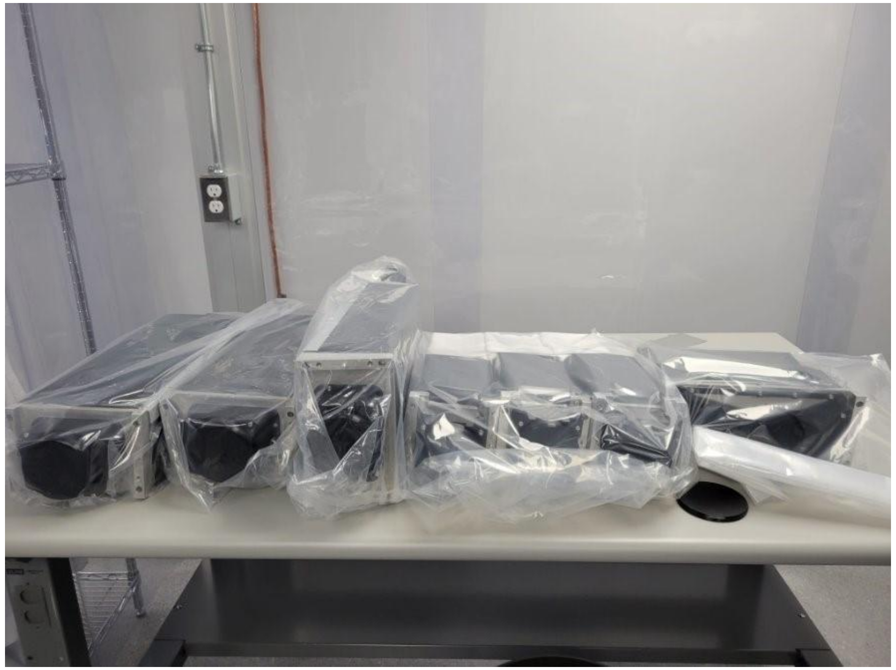
    - All fasteners are on-hand
    - Assembly and testing of modules is under way (currently assembling segment 5)
        - “Dirty lab” assembly
        - Clean room assembly
        - Testing completed modules (cosmics and light seal)
        - Vacuum sealing (preparation for shipment)



Main detector production/purchase status

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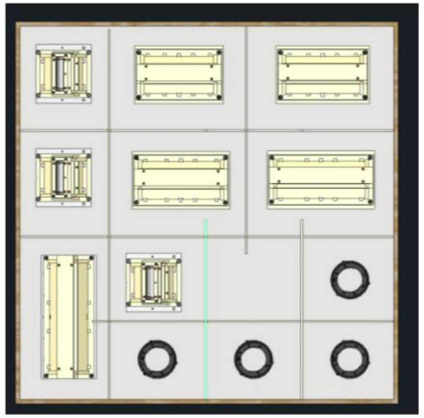
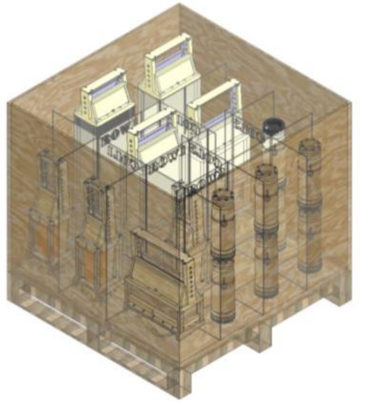
  - All fasteners are on-hand
  - Assembly and testing of modules is under way (currently assembling segment 5)
    - “Dirty lab” assembly
    - Clean room assembly
    - Testing completed modules (cosmics and light seal)
    - Vacuum sealing (preparation for shipment)
  - Modules for segments 1-4 have shipped
  - Next shipment of 48 modules (segments 5 - 10) scheduled for April 2025
  - Following shipments of 48 modules each at roughly 3 months intervals





Main detector production/purchase status

Final main detector module production:

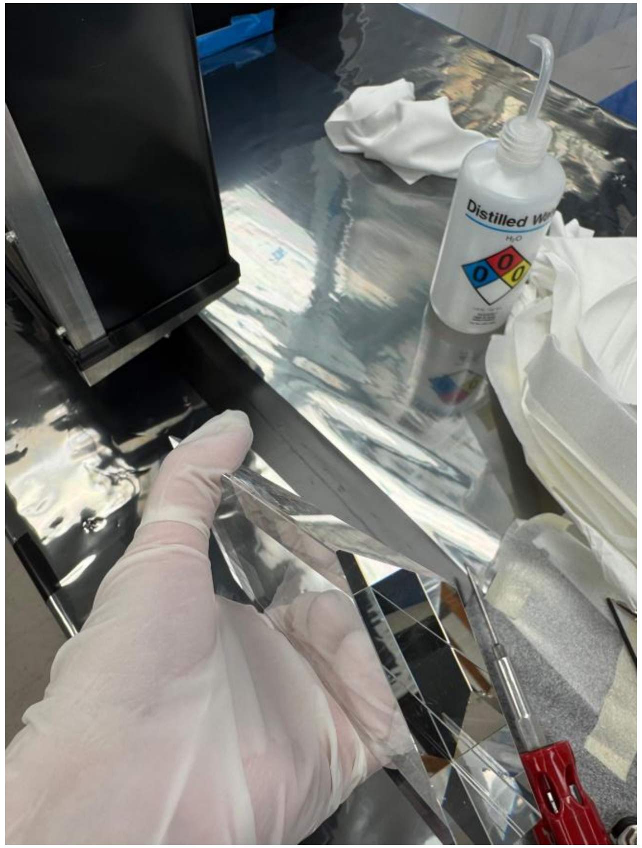
- All design aspects and prototype testing were completed by April 2024
- Module production started in May 2024:
- Modules and quartz and other equipment at W&M:

  - Receiving modules at W&M

Main detector production/purchase status

Final main detector module production:

- All design aspects and prototype testing were completed by April 2024
- Module production started in May 2024:
- Modules and quartz and other equipment at W&M:
    - Receiving modules at W&M
    - All raw quartz material has been received from Heraeus
    - First batch of cut and polished quartz plates has been received (45 R5 tiles and 6 each of rings R1-R4, R6)
    - Remaining quartz tiles to ship in Summer 2025



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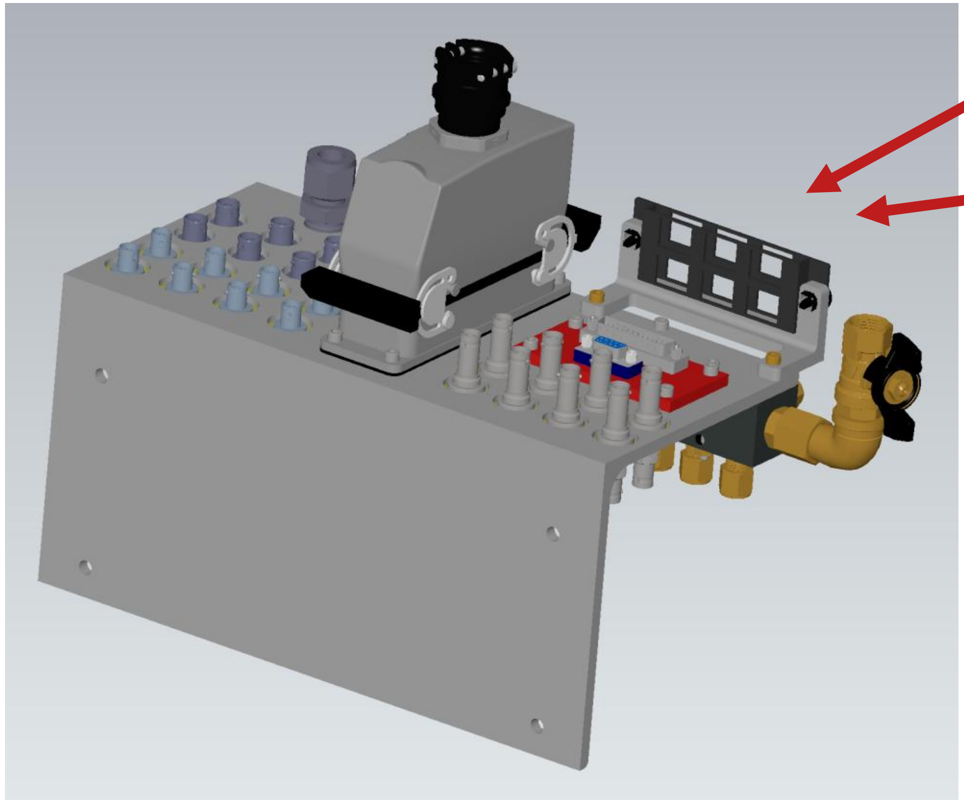
    - Remaining quartz tiles to ship in Summer 2025
    - Setup and testing of detector modules in their segment assemblies has started.

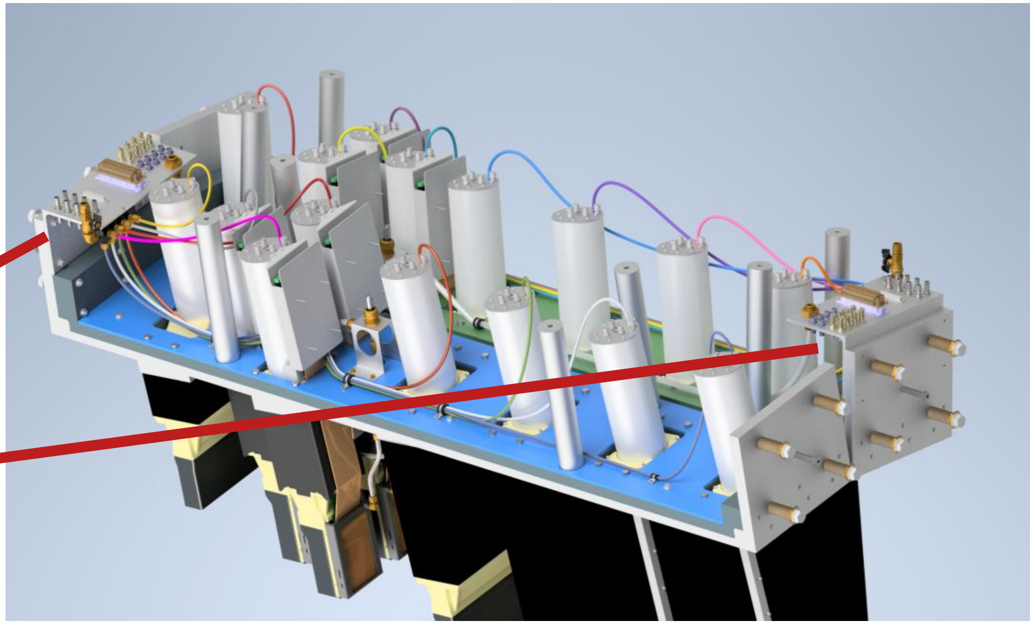
Jefferson Lab

Detector Segment Patch Panel Design (Dustin McNulty, Ciprian Gal)

The design of the detector segment patch panel is final.

Production is in progress.





Main detector production/purchase status

Final main detector module production:

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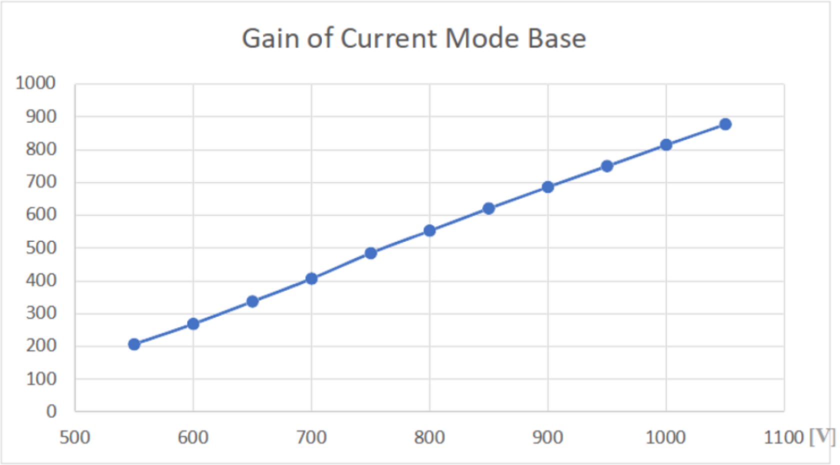
- Modules and quartz and other equipment at W&M:
    - Receiving modules at W&M
    - All raw quartz material has been received from Heraeus
    - First two batches of cut and polished quartz plates has been received (45 R5 tiles and 6 each of rings R1-R4, R6)
    - Remaining quartz tiles to ship by end of Summer 2025
    - Setup and testing of detector modules in their segment assemblies has started.
    - All HV and low voltage power supplies have been received
    - Low voltage switching modules have been received

Main detector production/purchase status

PMTs:

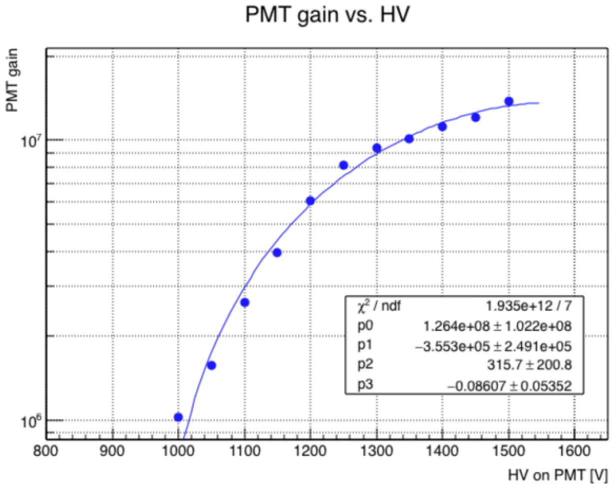
- All 250 ordered PMTs have been received
- Nearly 200 of them have been tested for linearity (and therefore their operating condition)
- Gain tests and cathode sensitivity tests are all underway
- Shipment of completely tested PMTs has begun

Current-Mode – 3 stages



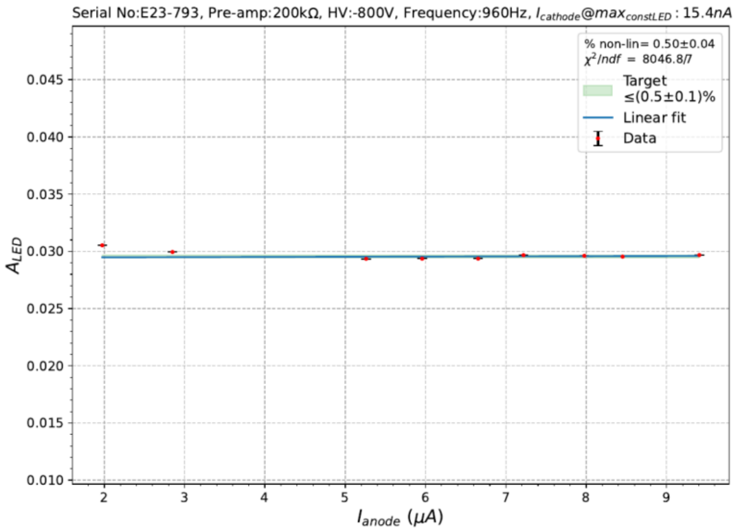
PMT gain ≈ 550, when HV = -800 V

Event-Mode – 10 stages



PMT gain curve in event-mode: 10^6 - 10^7

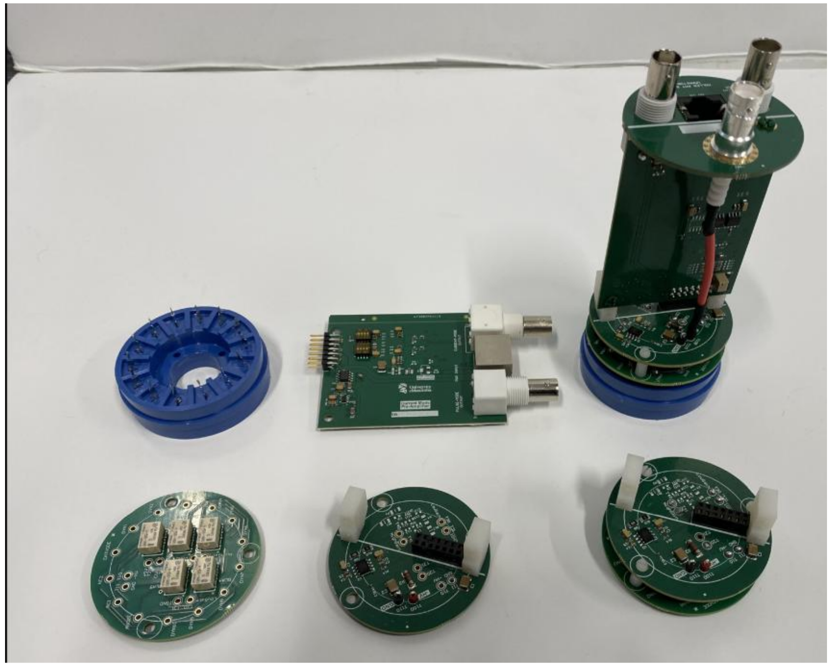
LED Asymmetry vs. Anode Current

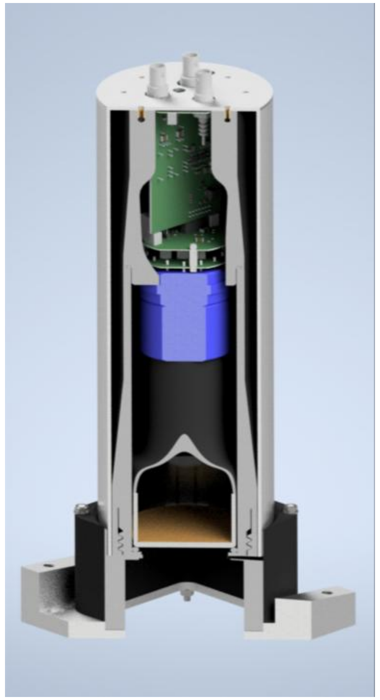


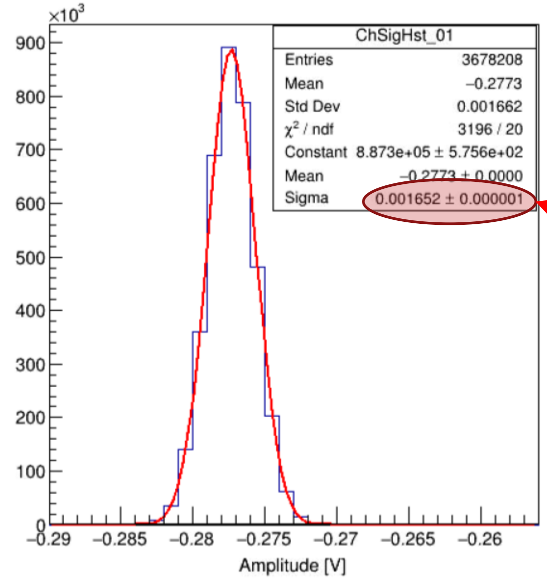
Main detector production/purchase status

Front-end electronics:

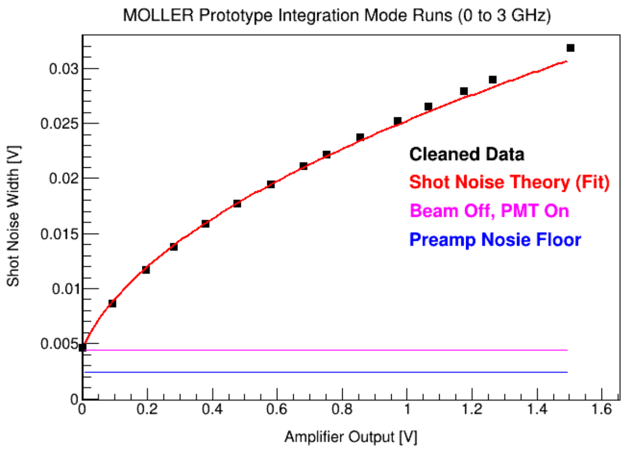
- **300 preamplifier PCBs and 300 3-stage and 4-stage integration mode voltage dividers have been received**
- **Assembly of PCBs into complete module FE electronics has started.**
- **We so far have 150 assembled electronics modules**
- **Testing of the electronics modules has started**
- **Shipment of completely tested electronics modules is combined with the PMT shipment**







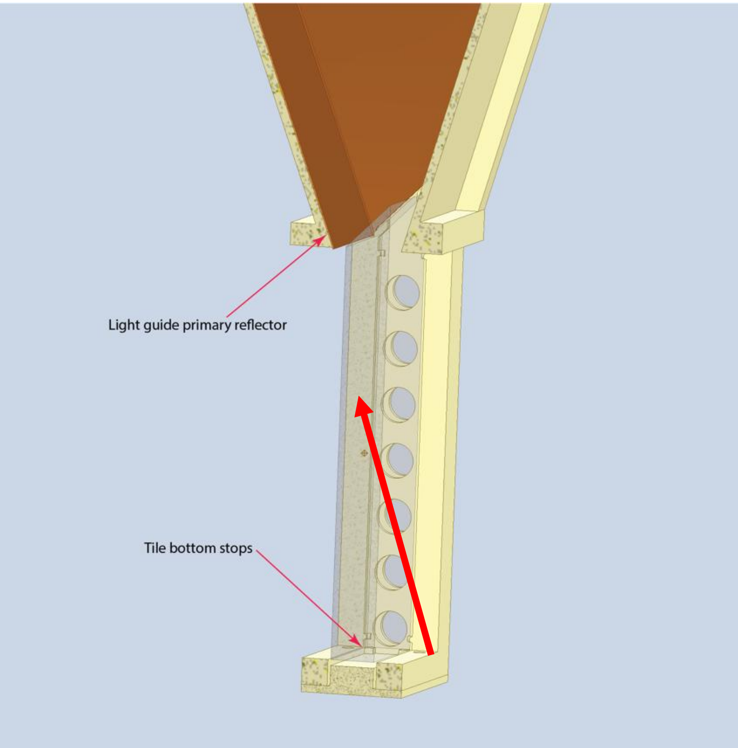
Achieving design noise width $\sigma_{amp} \simeq 1.7\ mV$

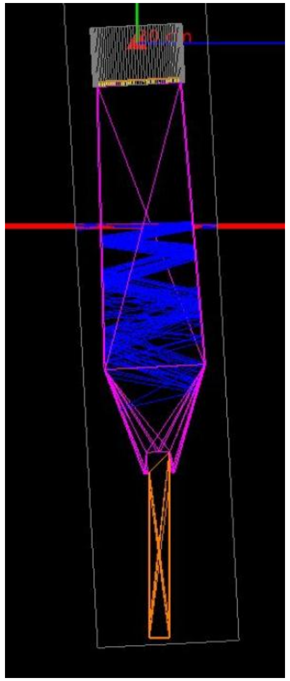


Thin Detector Module Design Process and Simulations

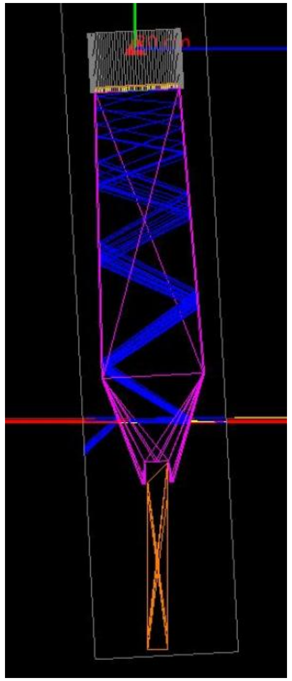
Maximizing the light yield from the active volume events, relative to background events:

Light guide geometry can be tweaked to optimize quartz light readout and suppress light guide background

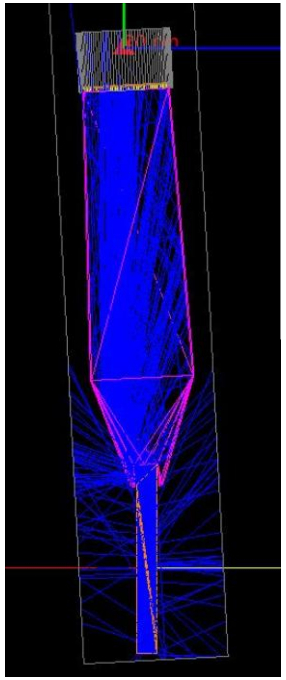




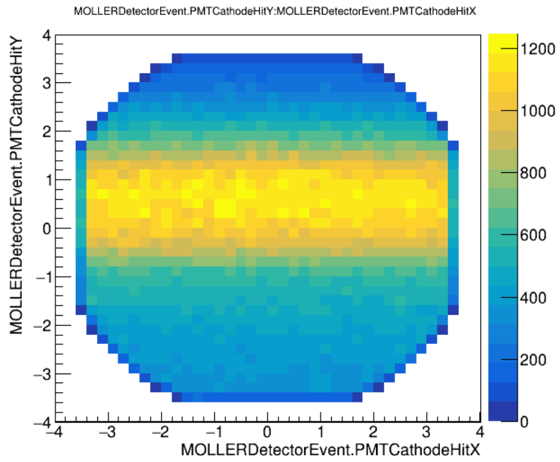
Upper guide events

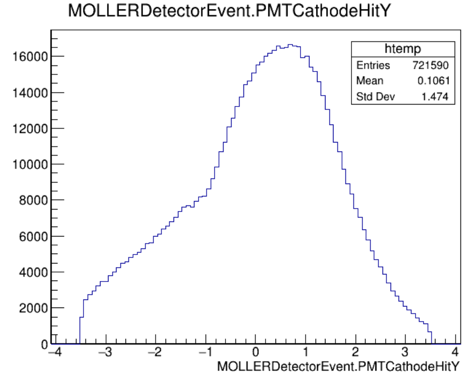


Lower guide events



Quartz events





Monolithic tray for quartz and light guide that fixes the angle relationship.

Impossible to machine, but relatively easy to 3D print.

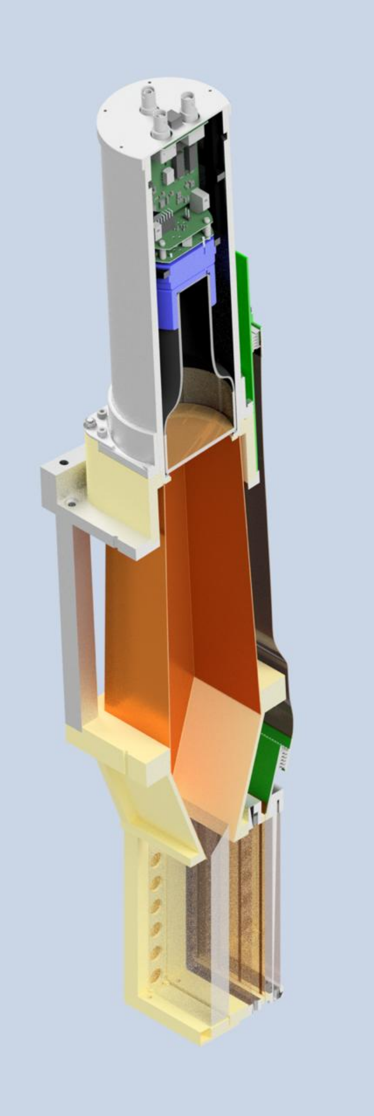
Thin Detector Module Design Criteria

- **Module mounting structure**
  - **Allow secure, precise ($\pm 1\ mm$) position of quartz tiles, providing for fiducialization of each module**
  - **Allow light tight sealing**
  - **Allow proper mounting of the PMT, base, and pre-amplifier**
  - **Allow air flushing of guide, PMT base, and pre-amplifier**
  - **Allow cooling of pre-amplifier and dry air flushing of light guide**
  - **Minimize material budget**

- **Light guides**
  - **Optimize light readout through reflective properties and geometry optimization**
  - **Minimize background through geometry optimization**
  - **Minimize material budget**

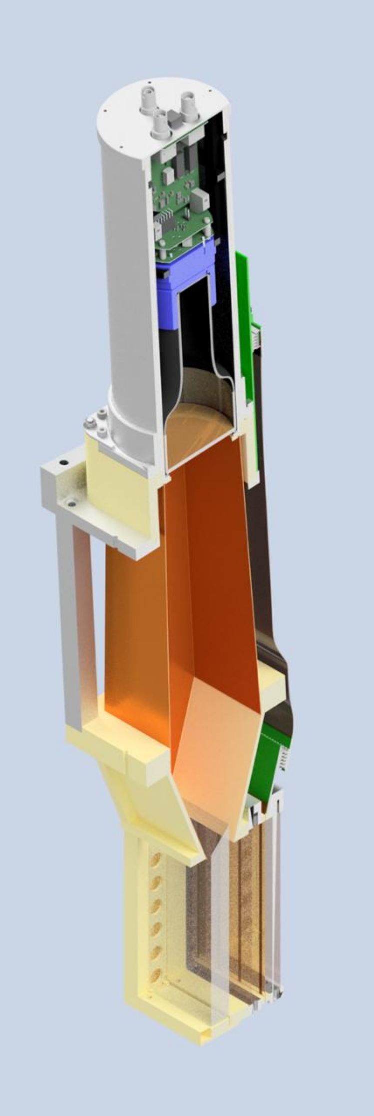
- **Quartz tiles**
  - **Maximize light yield (increase quartz thickness and precision)**
  - **Minimize background sensitivity**
  - **Minimize excess noise (reduce quartz thickness – overall want $\leq 4\%$ excess noise)**

Total excess noise: $\frac{1}{\sqrt{N}}\sqrt{1+\alpha_{exc}^2} = \frac{1}{\sqrt{N}}\sqrt{\mathbf{1}+\boldsymbol{\delta}_{Det}^2+\boldsymbol{\delta}_{PMT}^2+\boldsymbol{\delta}_{Elect}^2}$



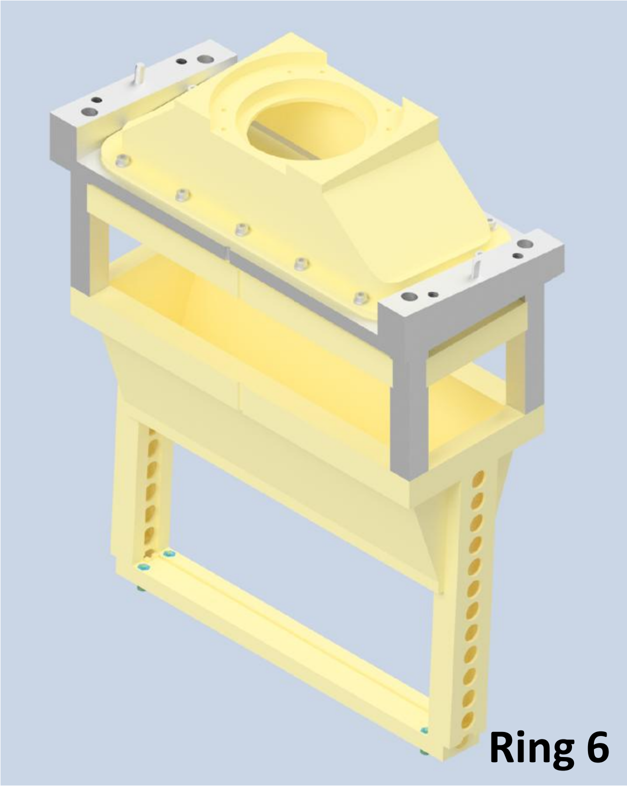
Thin Detector Module Design Criteria

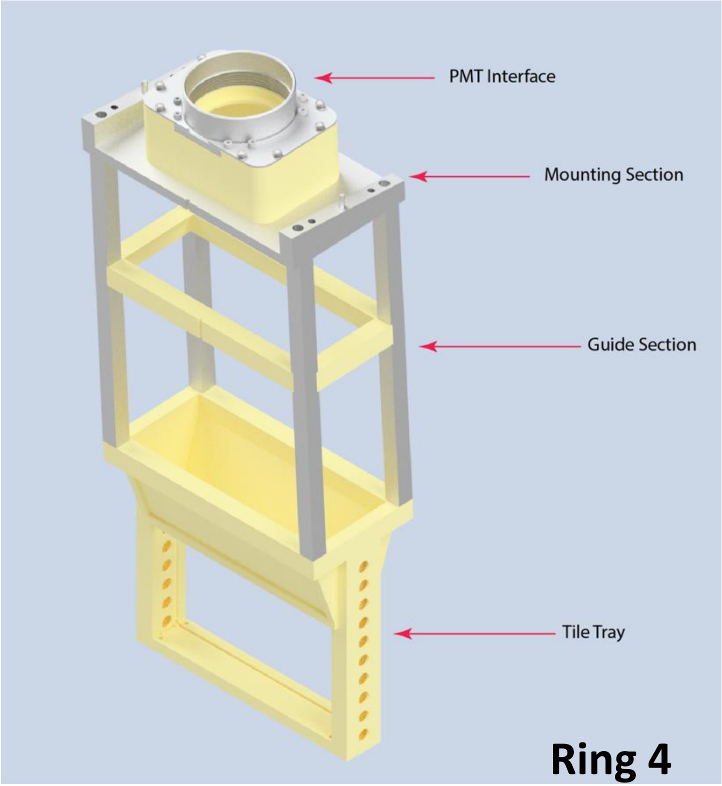
- **PMT**
  - Quantum efficiency + light yield: $\sim 12 - 30$ pe / electron event (~30 pe for ring 5 $\rightarrow \delta^2_{Det} \sim 3\%$ excess noise)
  - Non-Linearity: $\leq 0.5 \pm 0.1\,\%$
- **PMT voltage divider**
  - Integrating gain: $g_{PMT} \simeq 500$ (cathode and anode currents around $\lesssim 20\,nA$ and $\lesssim 10\,\mu A$)
  - Low noise: $\delta^2_{PMT} < 1\%$
  - Switchable to event mode gain: $g_{PMT} \simeq 10^7$
- **Integration mode pre-amplifier**
  - High gain: $g_{amp} = 100\,k\Omega - 1\,M\Omega$
  - High bandwidth: $B \approx 1\,MHz$
  - Low noise: $\delta^2_{Elect} < 1\%$
- **ADC board (DAQ Talk)**
  - High resolution: $\Delta = \frac{V_{ref}}{2^{18}} \approx 16\,\mu V \Rightarrow \sigma_{dig} = \frac{\Delta}{\sqrt{12}} \approx 4.5\,\mu V$
  - Reasonably fast: $15\,Msps$
  - Linear: $INL = 3\,LSB \approx 48\,\mu V$, $DNL = 1\,LSB \approx 16\,\mu V$



Module Mounting Structure Design

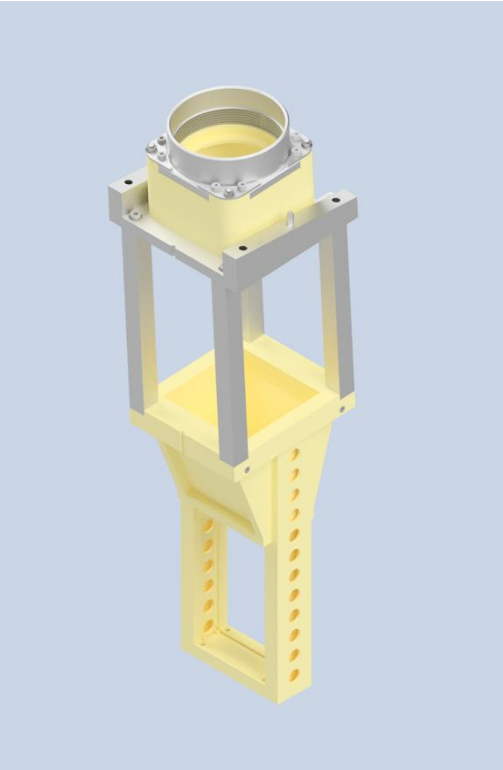
- For ring 5 several versions of the module mounting structure have been implemented in CAD and were constructed
- CAD design of the other rings is completed; rings 1-3 have same construction as ring 4 shown here
- Ring 6, 1, and 2 structures have been built

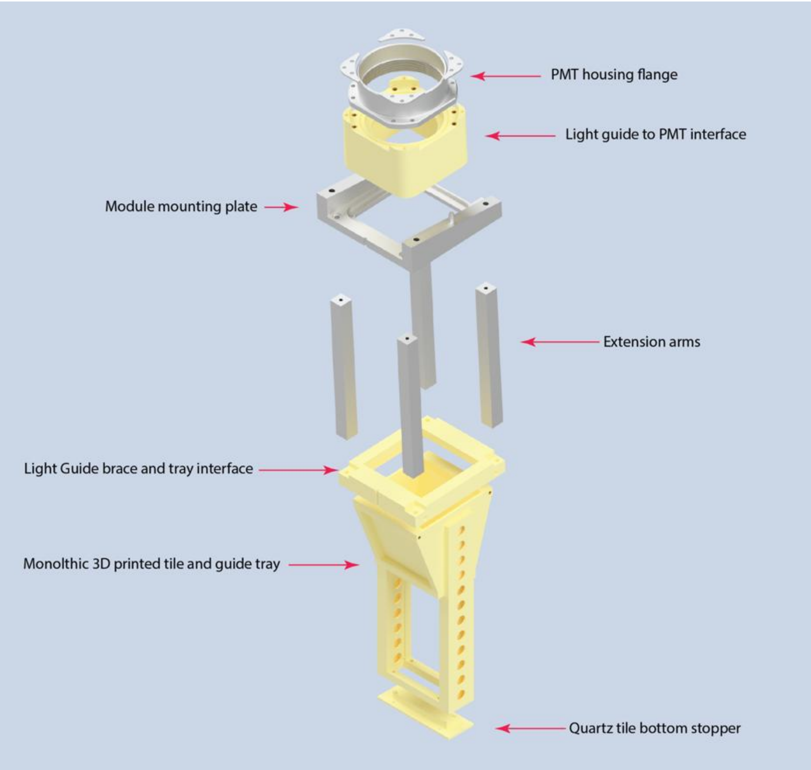


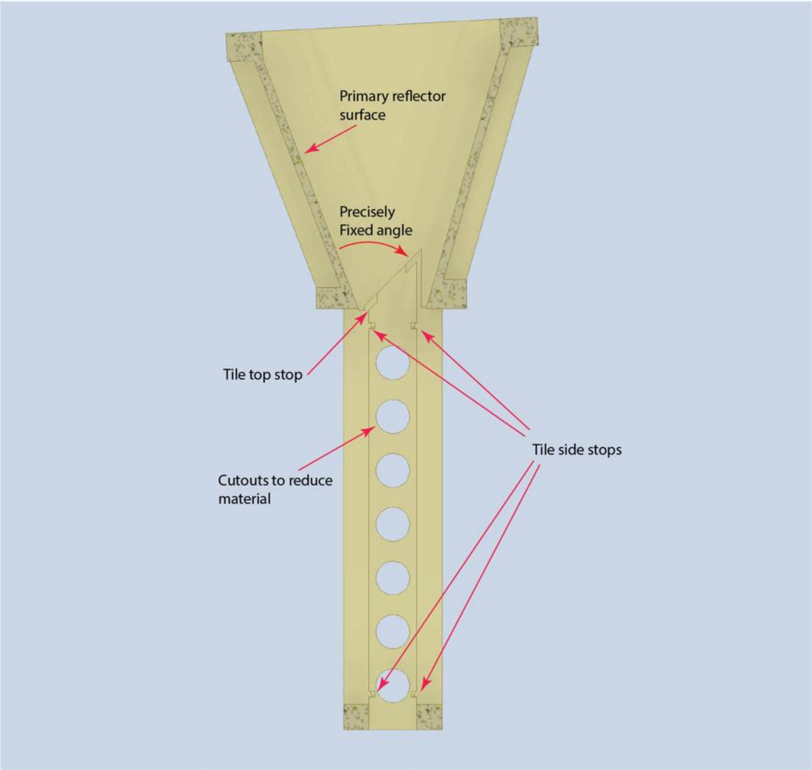


Module Mounting Structure Design

- The quartz tray (right) fixes the most important relationship in the design - the angle between the quartz tile and primary reflector.
- The middle section holds the light guide geometry defined and in place.
- The top section provides a secure and accurate interface with the PMT – easy attachment and removal





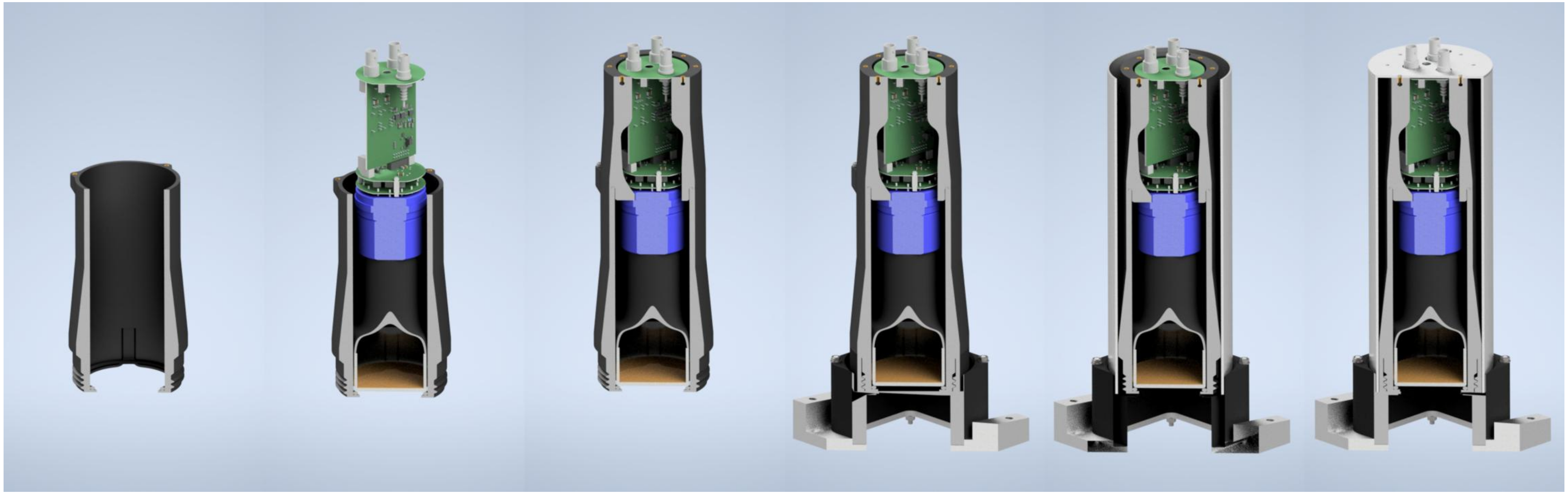


Electronics Cooling and Light Guide Flushing

- **Physical design of the PMT housing**

  Preamp will be housed inside PMT housing – needs moderate cooling (such as would be provided by a computer fan)

  Provide an air inlet at the top of the PMT housing and design the housing at the bottom such that air can flow around the PMT into the light guide.



Front-end Electronics Design Criteria

Excess noise (leads to longer run times):

Need to keep noise contributions above counting statistics to: $\frac{1}{\sqrt{N}}\sqrt{1+\alpha_{exc}^2}-1=\frac{1}{\sqrt{N}}\sqrt{1+\delta_{Det}^2+\delta_{PMT}^2+\delta_{Elect}^2}-1\ \leq 4\%$

Detector resolution: $\frac{{\sigma_{n_{pe}}}^2}{\langle n_{pe}\rangle^2} \leq 4\%$ (for $n_{pe}>25$)

PMT noise (base design): $\delta_{PMT}^2 < 1\%$ (Goal)

Electronic noise: $\delta_{Elect}^2 = 4k_BTR+\delta_{Amp}^2+\delta_{ADC}^2 < 1\%$ (Goal)

$\delta \equiv \frac{\sigma}{V}$

For $n_{pe}=30$, $G_{PMT}=500$, and $R=4\ GHz$ we'd have $\sigma_V \simeq 48\ mV$ so we should have $\sigma_{PMT}=\sigma_{Elect}<4.8\ mV$.

The present (3 stage) PMT design has a design noise of $\sigma_{PMT}\simeq 3\ mV$

The present preamplifier has a design noise of $\sigma_{Elect}\simeq 1.2\ mV$

Front-end Electronics Design Criteria

- **PMT:**

  The PMT is chosen to satisfy a high QE in the UV (with quartz window)
  Goal is to maximize the number of photoelectrons

- **PMT Voltage Divider:**

  Need to keep cathode and anode currents around $\lesssim\ 20\ nA$ and $\lesssim 10\ \mu A$ respectively

  Maximum PMT currents are $500\ nA$ and $100\ \mu A$ respectively (for the selected model)

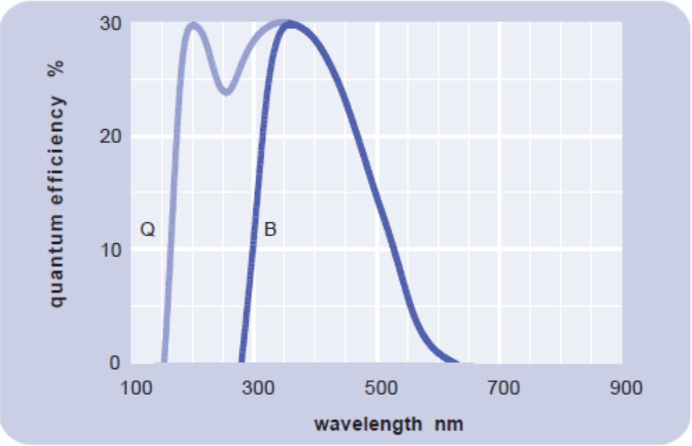
  Ring 5: The $30\ n_{pe}$ and $R = 4\ GHz$ gives $I_c^{\pm} \simeq 19\ nA$ so the gain should be about $g_{PMT} \simeq 500$

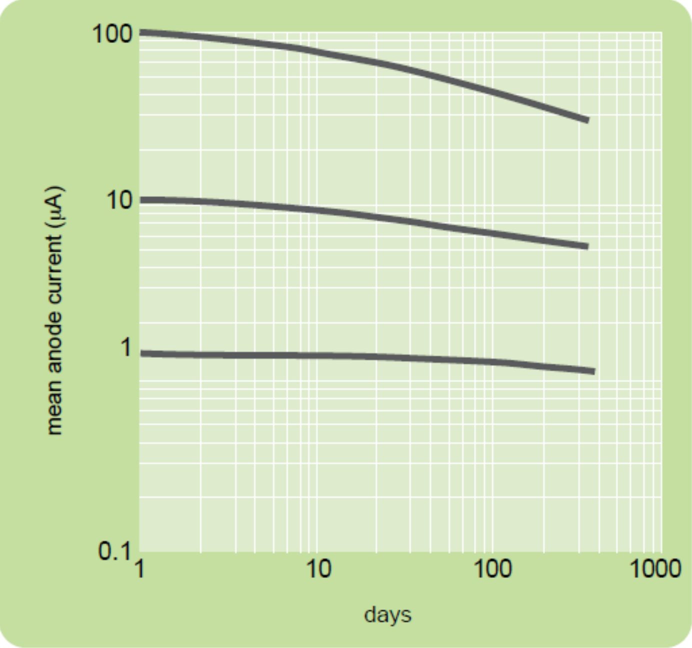
  Definition of PMT end-of-life: g_{PMT} dropped by factor of 2

  Reached at about $\simeq\ 300\ C$ for a $10\ \mu A$ anode current (about 1 year of continuous running)

  Have few dynodes with high gain on each to reduce excess noise non-linearity
  PMT Non-linearity produces a false asymmetry: $\varepsilon = \sum_n \alpha_n\ (I)^n$

  Want to suppress the non-linearity to $\frac{d\varepsilon}{dI}\ \leq 0.5 \pm 0.1\ \%$





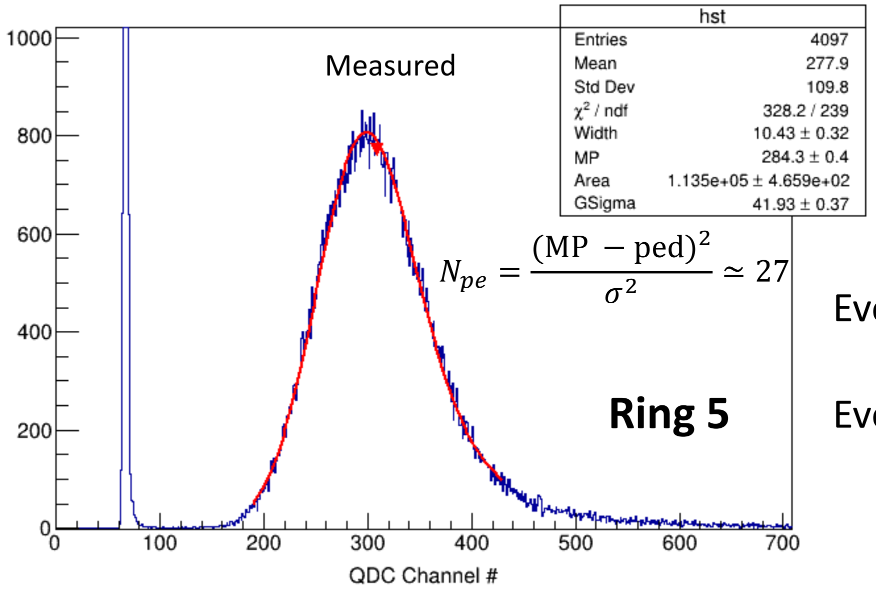
Jefferson Lab

Beam Tests

Event mode results:

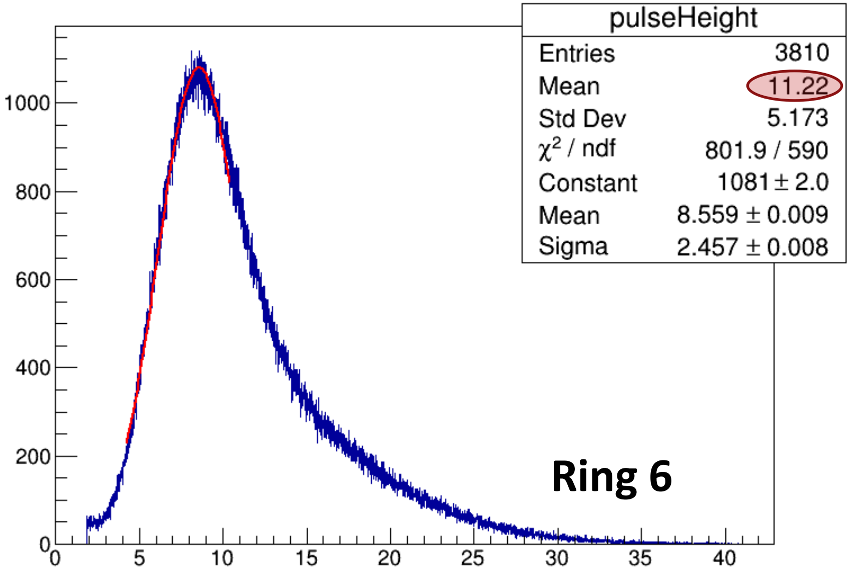
Event mode photo-electron yield tests, to test simulation results.

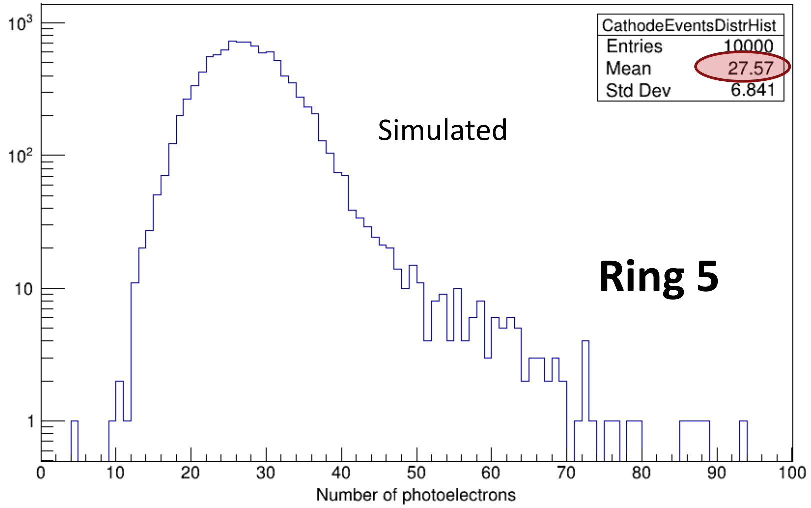
Ring 5 was done again in May 2023 with final polishing



Event mode with Myro Silver: $n_{pe} \simeq 25$

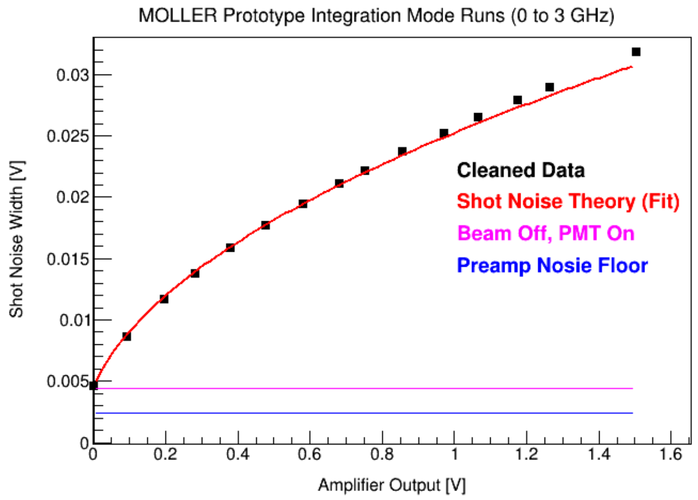
Event mode with UVS: $n_{pe} \simeq 36$

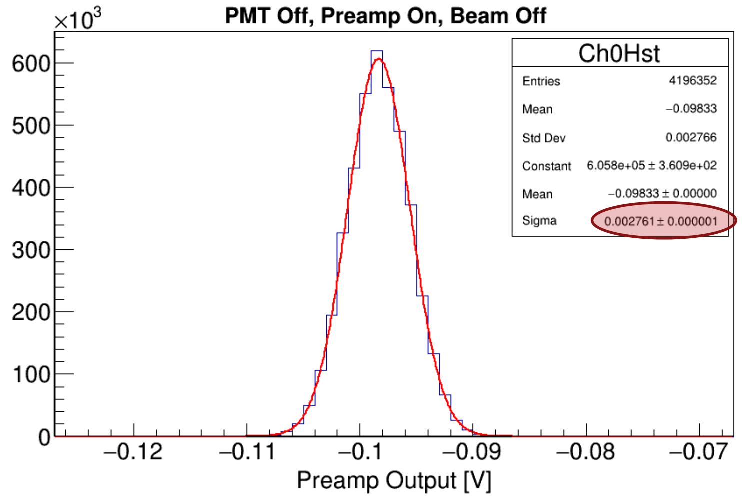


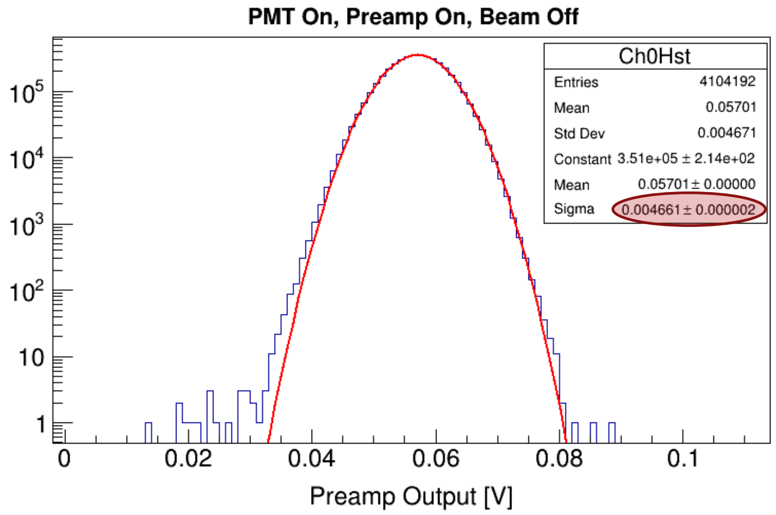


Integration mode results:

- The detector signal width is dominated by counting statistics, which means that we do not have significant additional noise sources from electronics
- Preamp noise signal: $\sigma_{amp} \simeq 2.8\ mV$ (Recall slide 23: The 1% limit for $n_{pe} = 30$ was $\sigma_{V_{Elect}} < 4.8\ mV$)
- Preamp + PMT noise signal: $\sigma_{total\ elec} \simeq 4.7\ mV$ (includes some beam noise) (Recall slide 23: The 1% limit for $n_{pe} = 30$ was $\sigma_{V_{Elect}} < 4.8\ mV$)







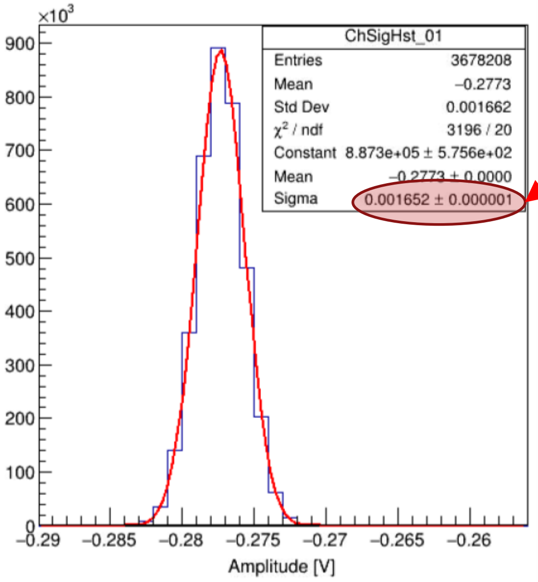
$$\sigma_S = \sqrt{2QI_a}\sqrt{B} = \sqrt{2\left(n_{pe}eG_{PMT}\right)\left(n_{pe}eG_{PMT}R\right)B} = Q\sqrt{2RB}$$

$$\delta_{A_{meas}} = \frac{\sigma_S}{I_a} = \frac{1}{\sqrt{N}}$$ (Ideal case)

Beam Tests

Some November/December 2022 Integration mode test results:

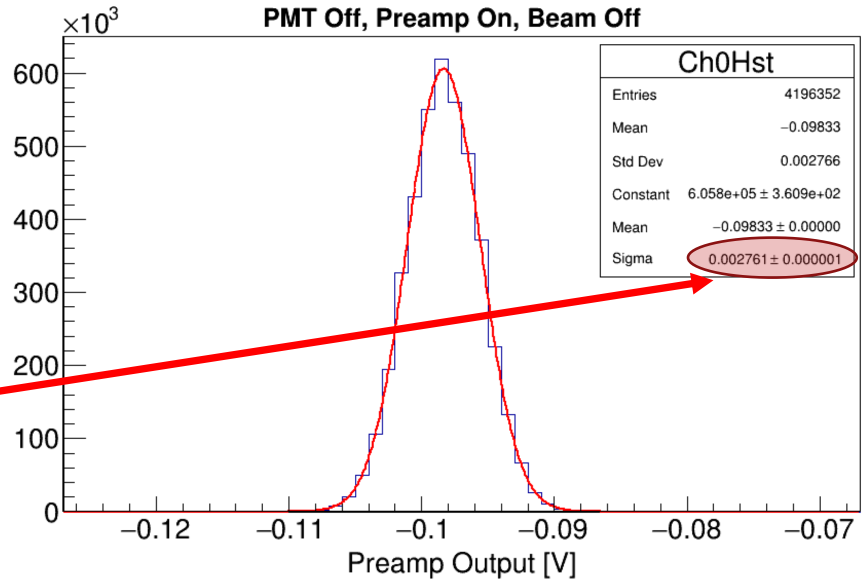
- The detector signal width is dominated by counting statistics, which means that we do not have significant additional noise sources from electronics. The most recent design produced a significant improvement in noise performance and stability.
- December 2022 Preamp noise signal: $\sigma_{amp} \simeq 1.7\ mV$ (Recall slide 23: The 1% limit for $n_{pe} = 30$ was $\sigma_{V_{Elect}} < 4.8\ mV$)
- Preamp + PMT noise signal: $\sigma_{total\ elec} \simeq 4.7\ mV$ (includes some beam noise) (Recall slide 18: The 1% limit for $n_{pe} = 30$ was $\sigma_{V_{Elect}} < 4.8\ mV$)



December 2022 electronic noise RMS

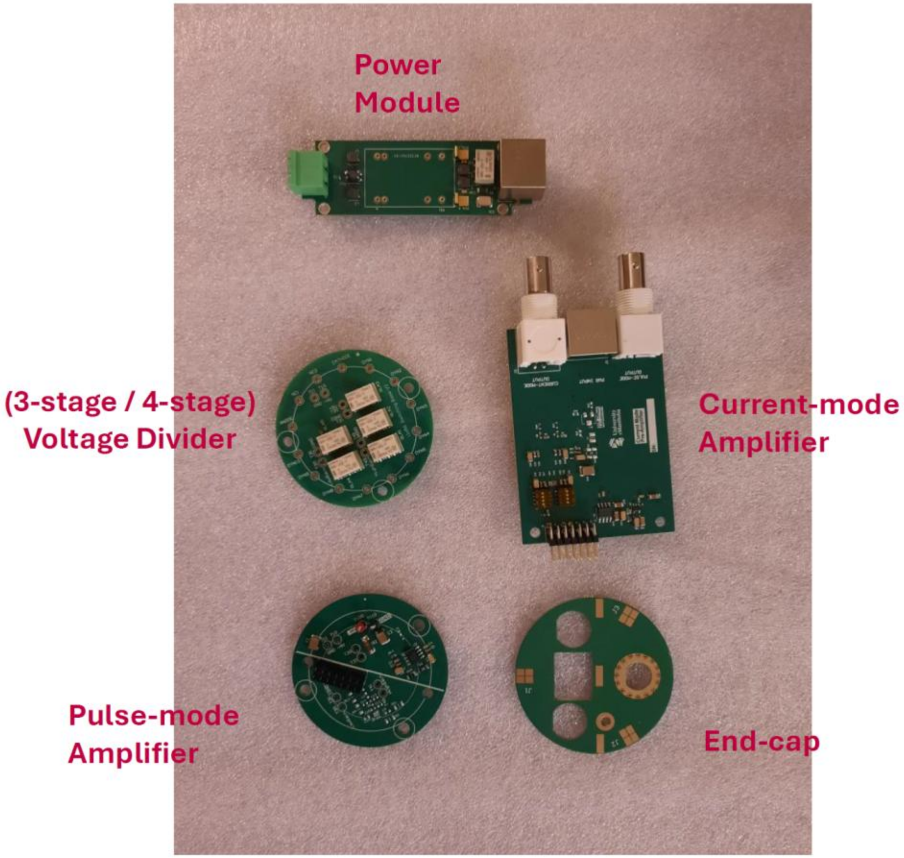
Next design iteration.

May 2022 electronic noise RMS



Front-End Electronics Assembly

Main Detector Front-end Electronics Production



Production of 300 sets integrated bases:

- 3-stages voltage dividers x300
- 4-stages voltage dividers x300
- Pulse-mode amplifier x300
- Current-mode amplifier x 300
- End-cap x 300
- Power modules x 300

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Main Detector Front-end Electronics Production

800 pcs of DC-DC converter were ordered in Mar. 2024

Production of PCB order was placed at the end of Oct 2024

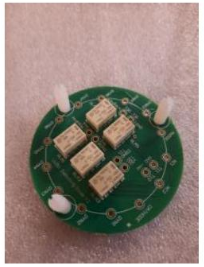
Received PCB boards at the end of Dec. 2024

Assembled 16 sets (half 3-stages & half 4-stages) and shipped to W&M in Jan. 2025

The rest were assembled (half 3-stages & half 4-stages);
10 sets were shipped in May 2025

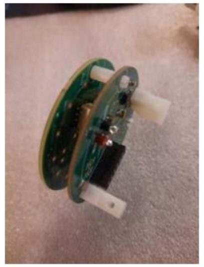
300 pcs more PMT sockets were ordered and just received

Main Detector Front-end Electronics Assembly

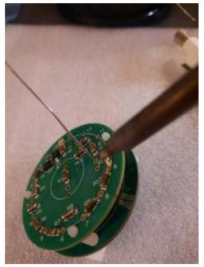


Insert support posts

Install mounting blocks using M3 screws



Connect the pulse mode amplifier with voltage divider using the posts

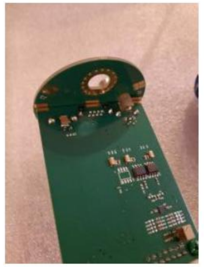


Connect the pulse mode amplifier with voltage divider using wires

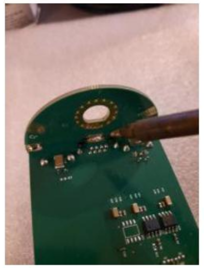
Insert the pins into the head connector

Fix the current mode amplifier with M3 screws

Fix the end cap onto the current mode amplifier with M3 screws



Align the copper and minimize the gap between the end cap and the current mode amplifier



Bridge the two boards with solder

Install SHV connector

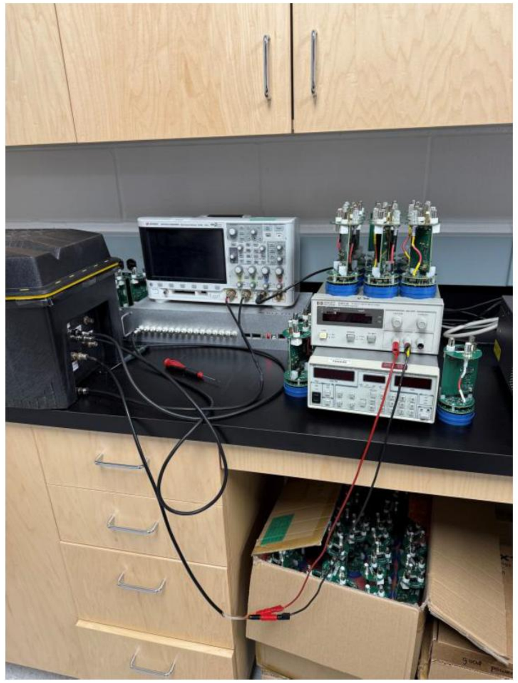
Solder HV wire

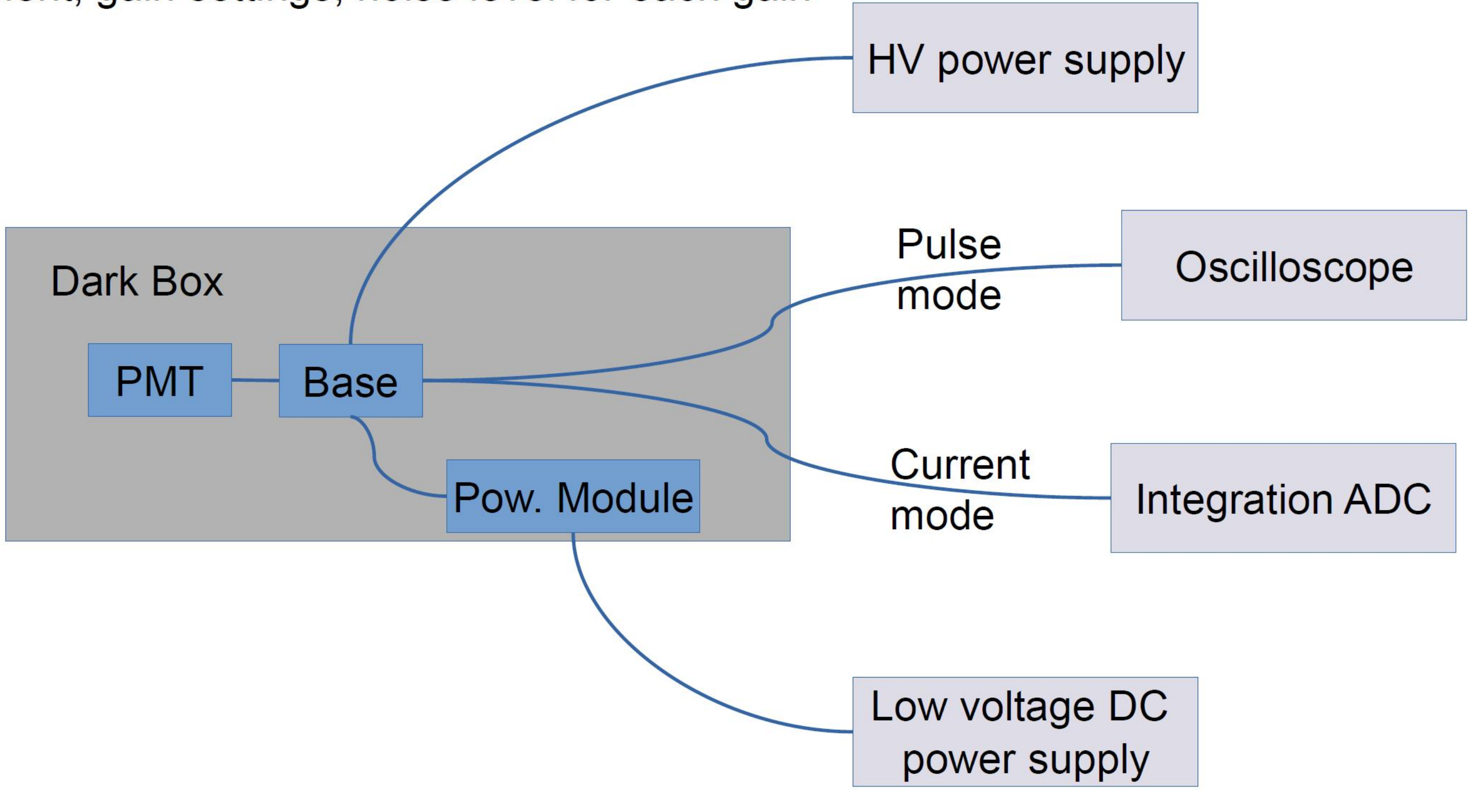
Solder PMT socket onto the voltage divider to complete the assembly

Front-End Electronics Testing

Main Detector Front-end Electronics – Functionality Tests

- Power module: current draw, mode switching
- Pulse mode: test HV and pulse shape
- Current mode: offset adjustment, gain settings, noise level for each gain

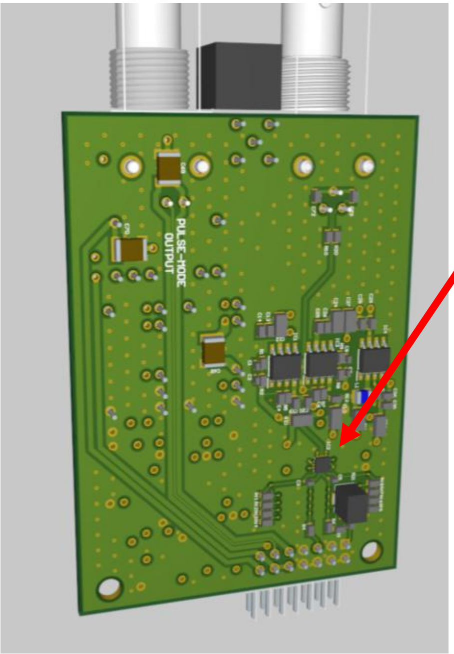




Beam Tests

December 2022 – July 2023 Electronics Radiation Tests

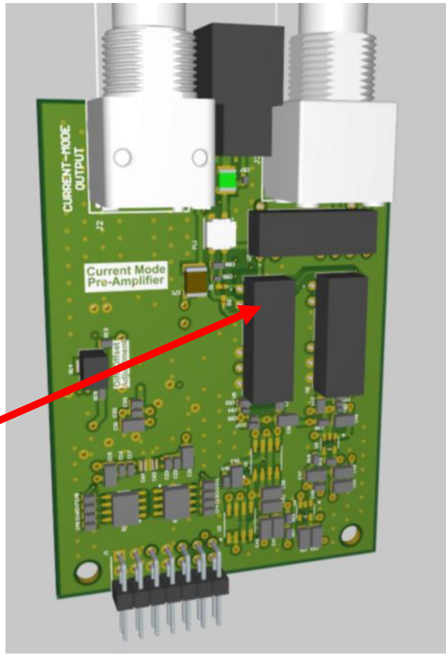
- Radiation hardness tests of the main detector front-end electronics were carried out at the Idaho accelerator center in mid Dec. 2022 and in July 2023
- Areas of focus were the ICs associated with amplification and power regulation
- The integration mode amplifier and DC/DC converters wer verified to be radiation hard.



I-V amplifier survived up to ~120 kRad acute dose without noticeable damage. Gradual gain drop after that.

DC/DC converters survived up to 500 kRad graduate dose.

Under large acute exposure they showed drastic increase in current drawn and temperature, but they recovered later.



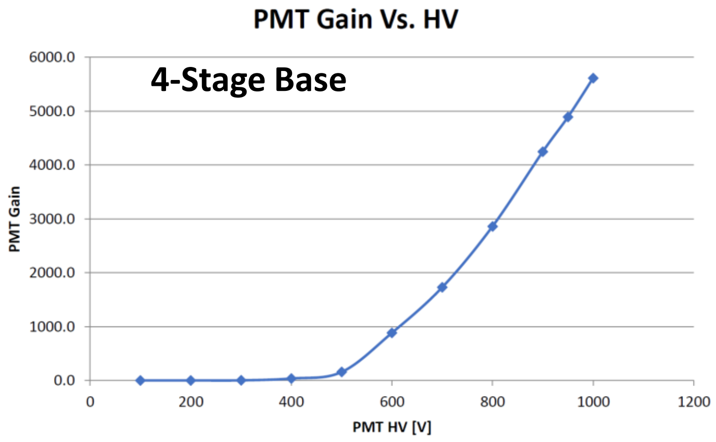
- Testing is to be completed this summer and we have a design that is radiation hard enough for MOLLER.

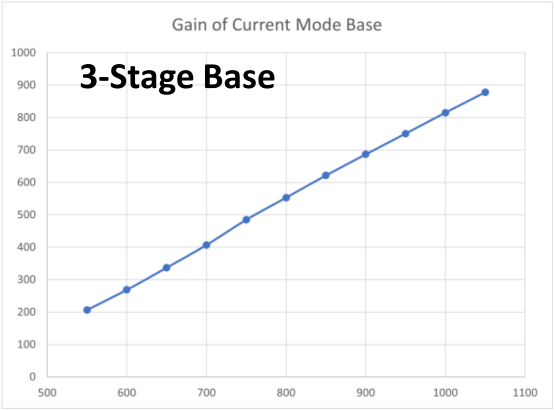
PMT / Electronics Verification

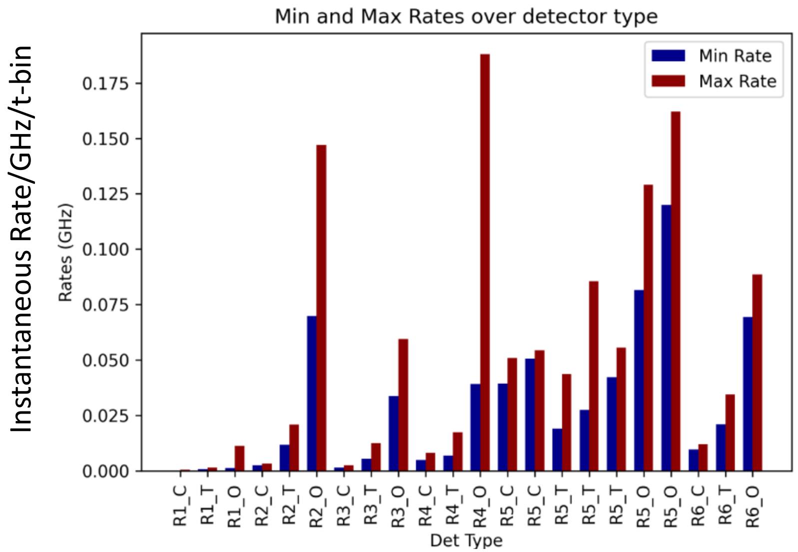
Electronics Status:

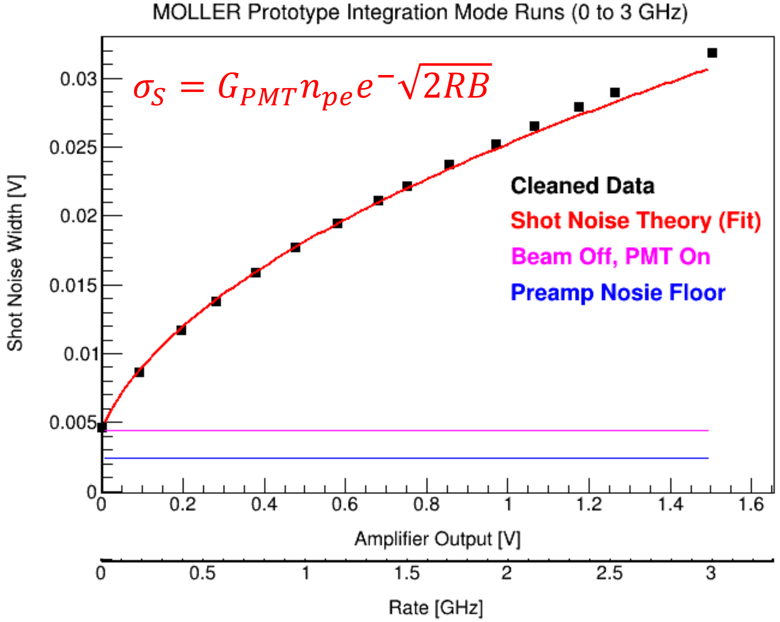
- Front-end electronics (see Jie's talk for details as well as Dustin's talk on radiation hardness)
  - The detector rate variation with raster pattern requires selecting carefully between 3 stage and 4-stage base design
  - Examples:

Ring 1 Closed:	$R_L \simeq 5\ MHz$	$R_H \simeq 12\ MHz$	$\rightarrow$	4-stage, $HV > 1000$
Ring 1 Open :	$R_L \simeq 33\ MHz$	$R_H \simeq 325\ MHz$	$\rightarrow$	4-stage, $HV \simeq 1000$
Ring 4 Open :	$R_L \simeq 1\ GHz$	$R_H \simeq 4.7\ GHz$	$\rightarrow$	3-stage, $HV \simeq 800$
Ring 5 Open :	$R_L \simeq 2\ GHz$	$R_H \simeq 4\ GHz$	$\rightarrow$	3-stage, $HV \simeq 800$





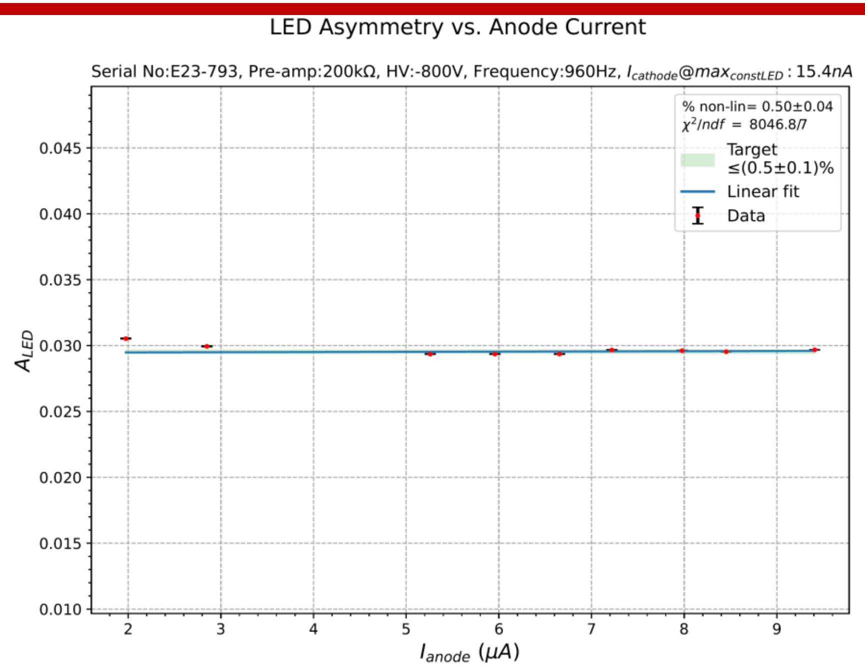


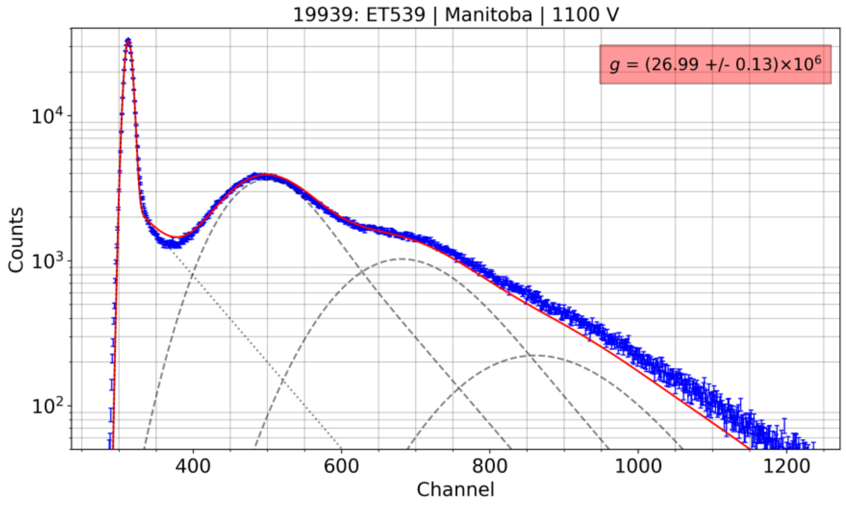


Overall Thin Detector Module Design

Quality Assurance:

- PMT + base
  - Fully operational linearity test setup (will be done for all PMTs and base types)
  - Gain tests (will be done for all PMTs)
- Preamplifers
  - Gain tests (measured with precise detector signal emulator)
  - Noise tests (detailed characterization of noise figure)
- ADCs
  - Full board tests (all channels) for all production modules (zero input width + xTalk)
- Detector Modules
  - Component size verification during assembly
  - All modules will be shipped fully assembled (minus the PMT or quartz)
  - Light leak tests will be performed for all modules
  - Air flow tests
  - Post assembly brief cosmic ray test for all modules to verify basic functionality

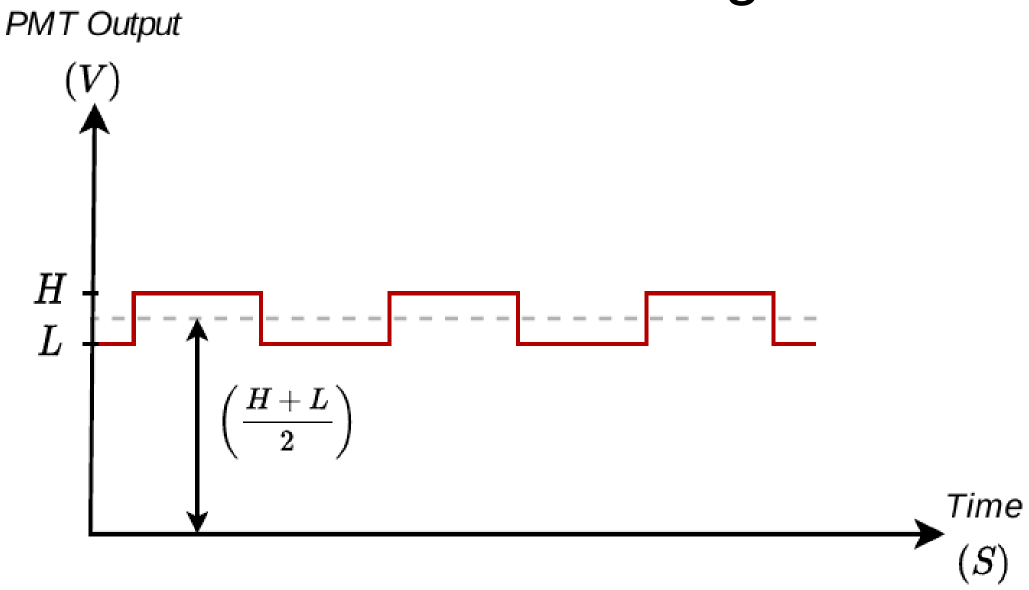




Jefferson Lab

Non-linearity calculation

- To measure the non-linear behavior of the PMT, asymmetry signal was simulated using two LEDs.
  - LED1: Bright constant LED to simulate the overall light intensity
  - LED2: A dim flashing LED to simulate the asymmetrical behavior



H: LED1=ON, LED2=ON

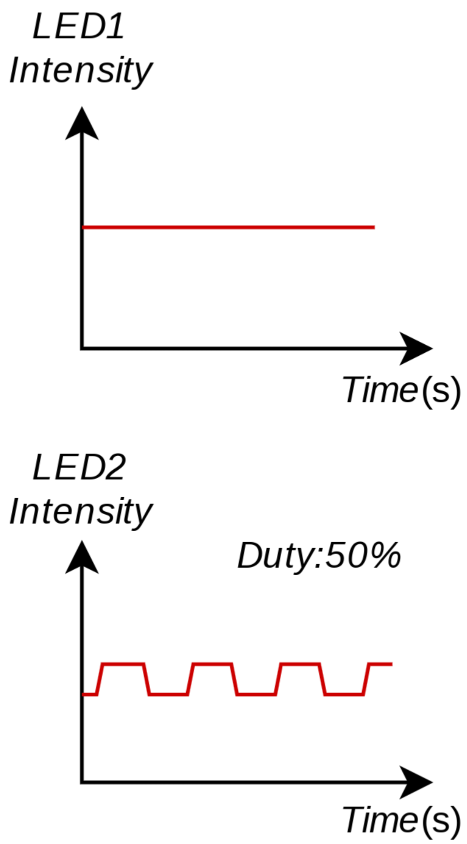
L: LED1=ON, LED2=OFF

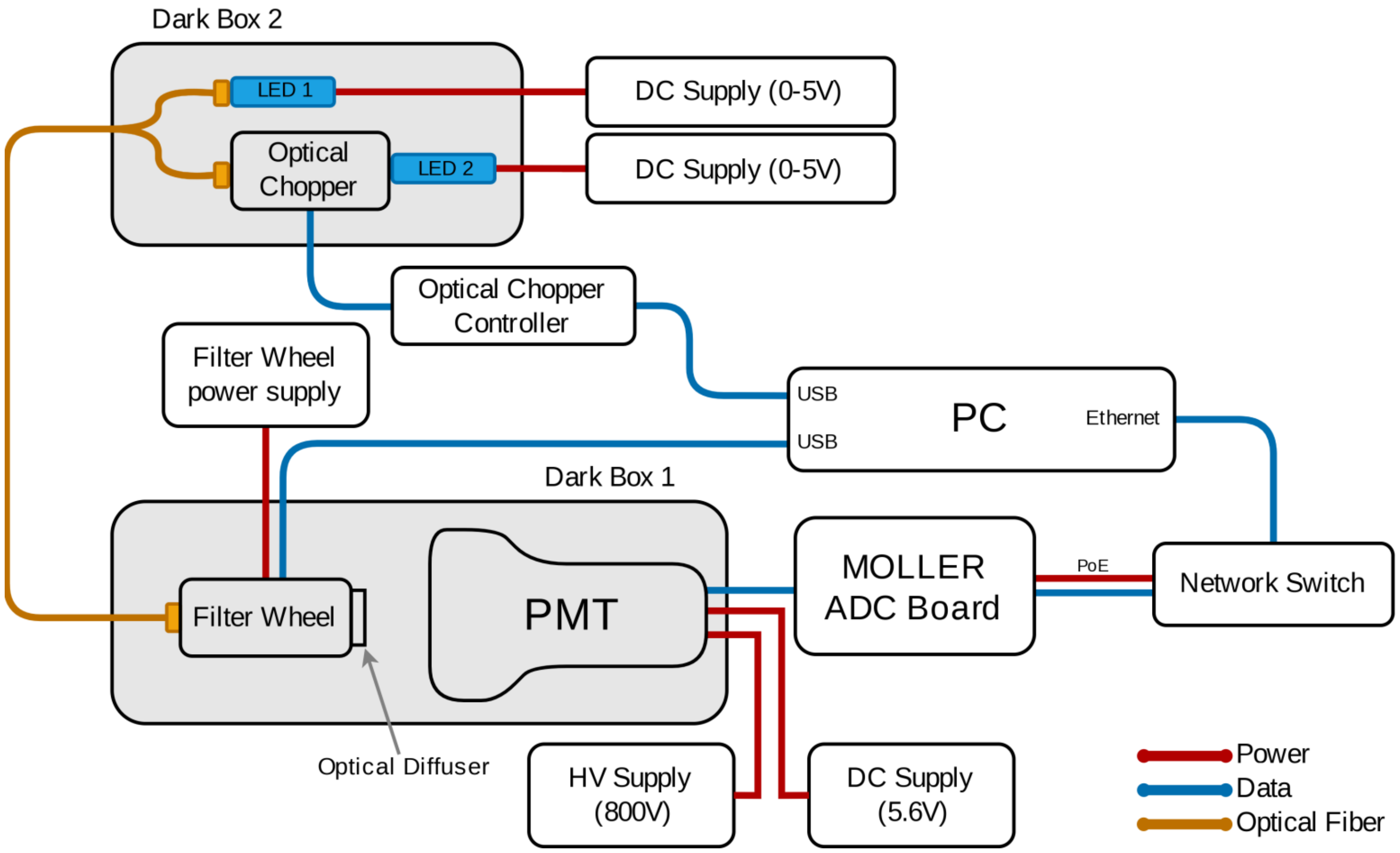
LED Asymmetry: $A_{LED} = \left(\frac{H-L}{H+L}\right)$

Mean Voltage $V_{mean} = \left(\frac{H+L}{2}\right)$

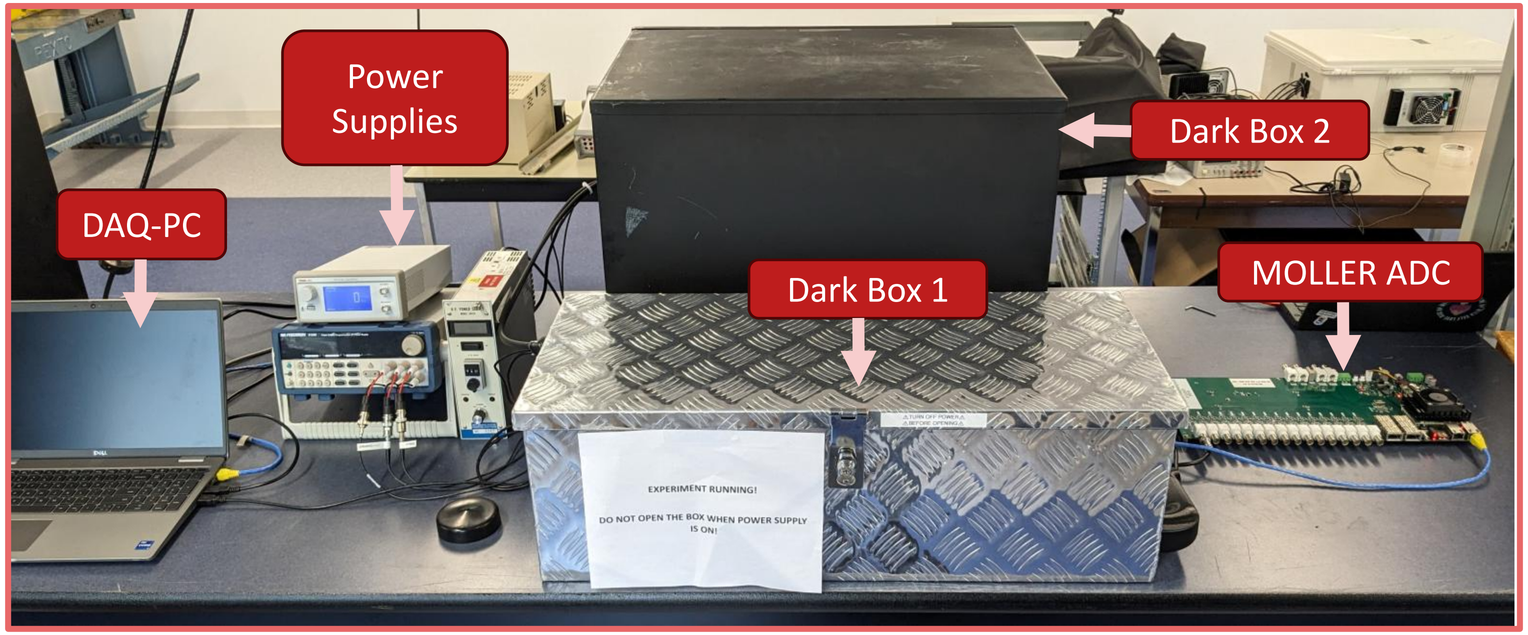
- *The response is considered linear if* A_{LED} *constant with respect to* V_{mean}

Experimental setup block-diagram

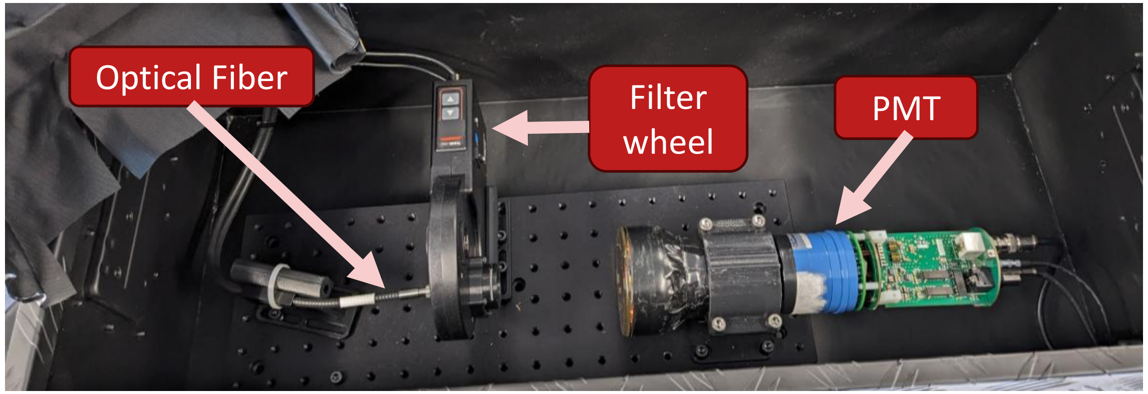




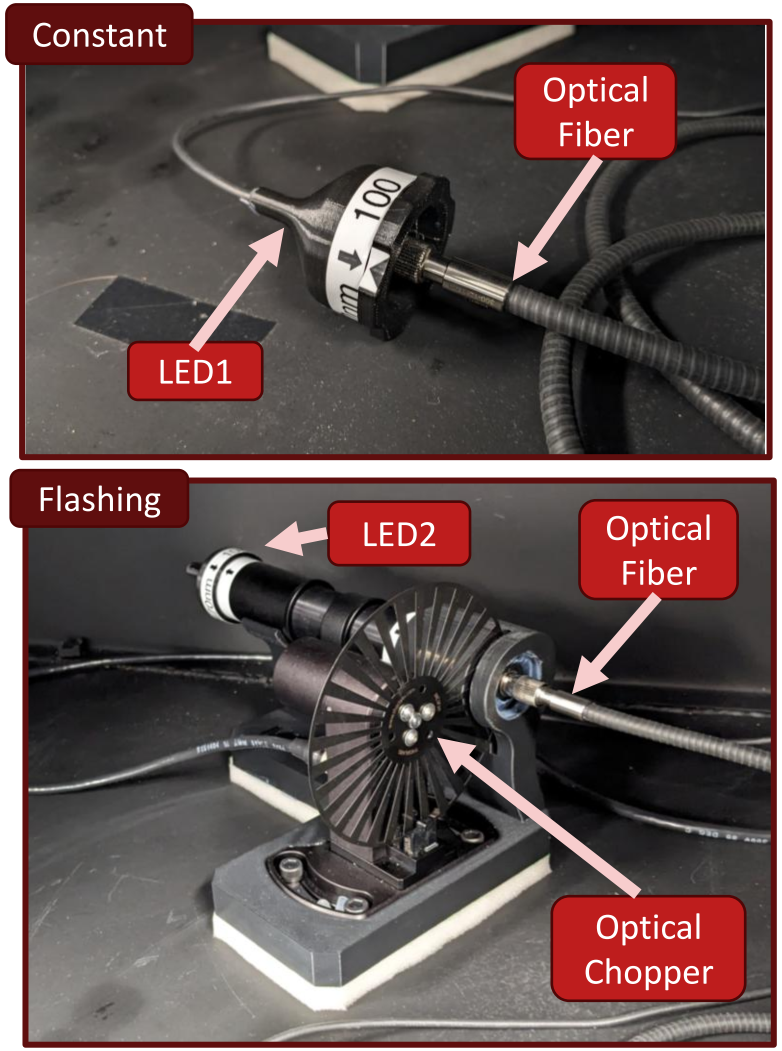
Experimental setup



Dark Box 1

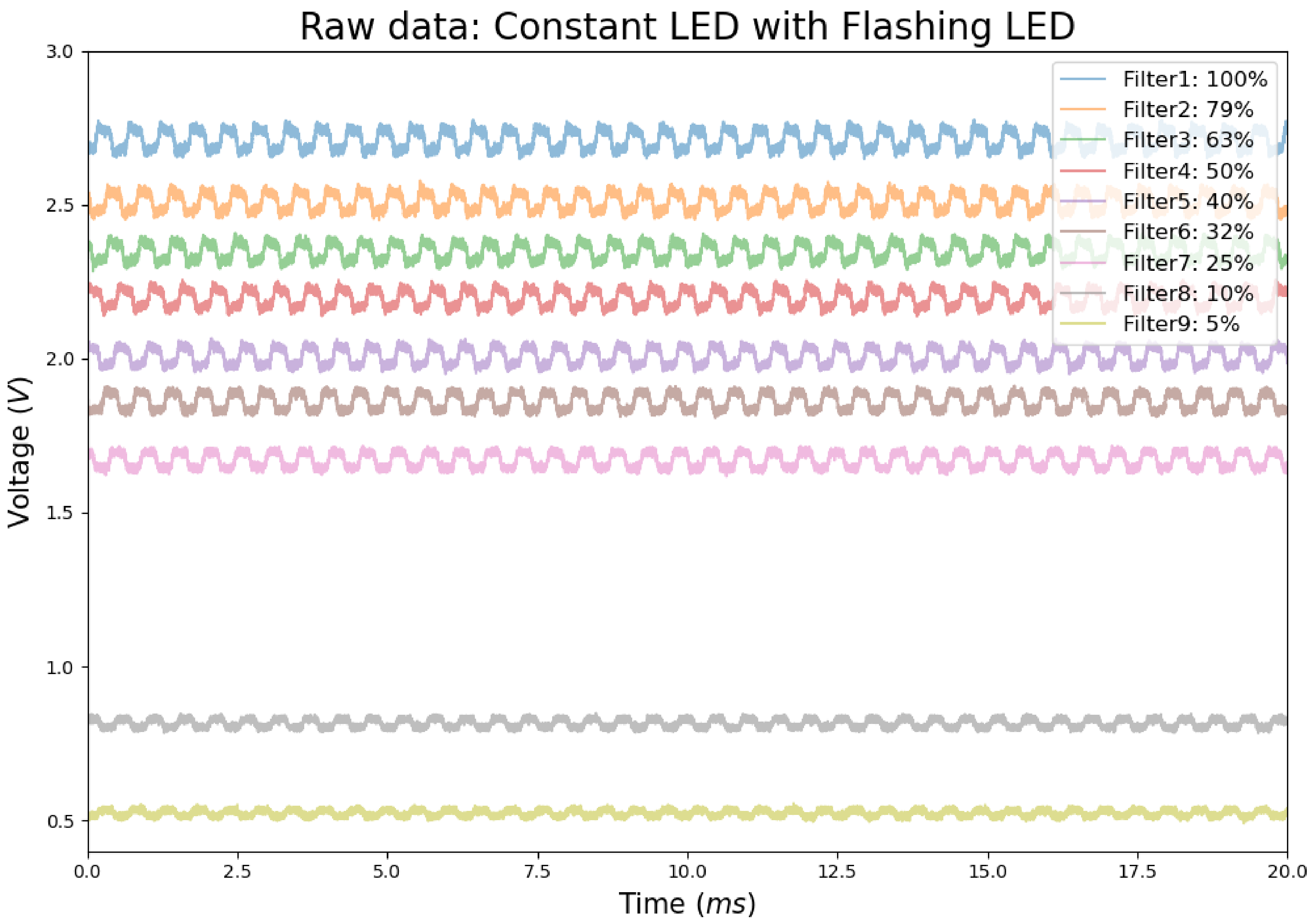


Dark Box 2



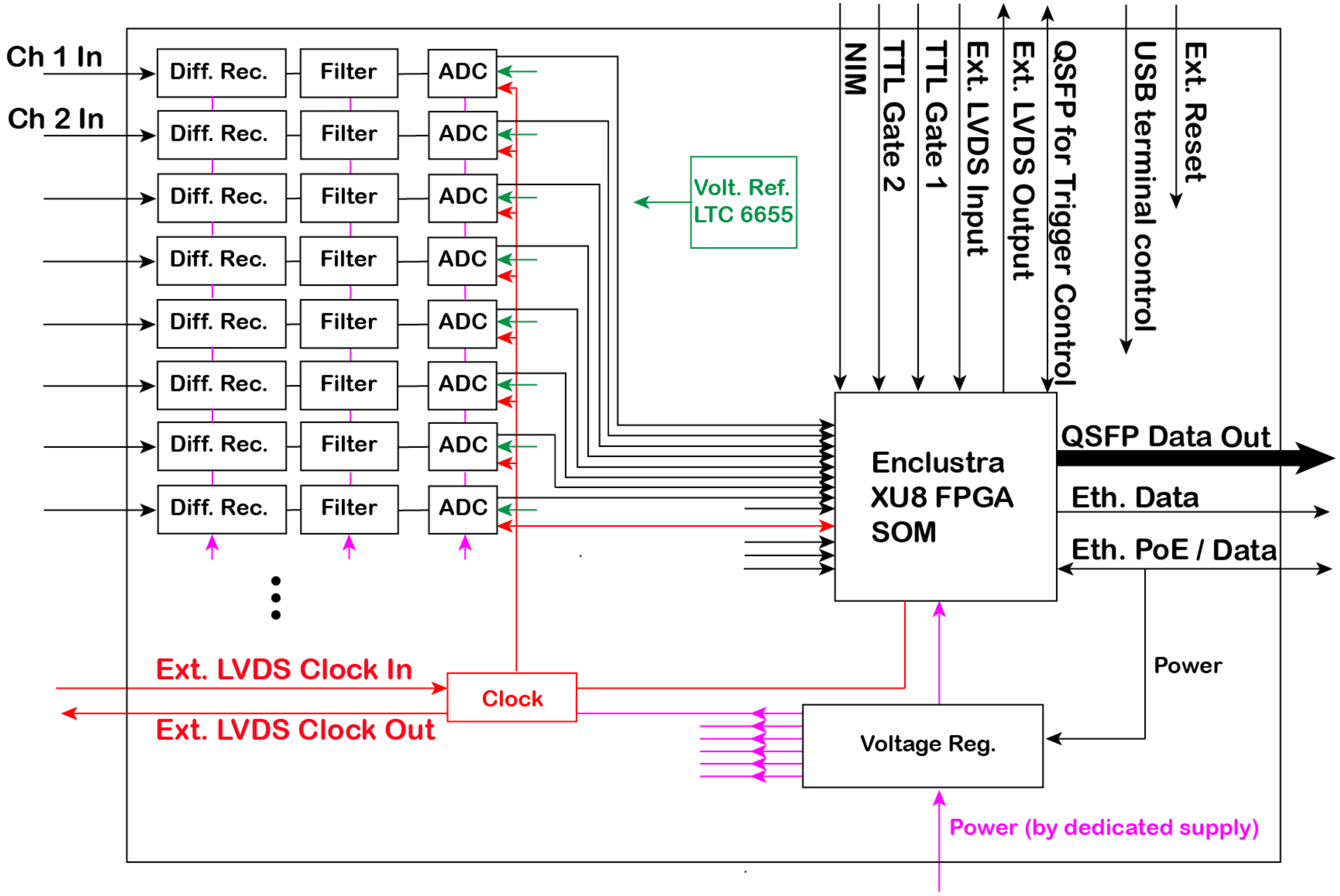
Raw data

- PMT HV: -800 V
- Record length per filter: 200 ms
- Chopper frequency: 1920 Hz
- LED supply voltages:
  - LED1: 3.0 V
  - LED2: 3.0 V
- Intensity ratio:
  - [LED1 : LED2] = [100 : 1]



ADC board design details

- 16 detector signal channels
- 1 MHz low pass input filter per channel
- 15 Msps 18 bit ADC
- Xilinx Ultrascale+ FPGA
- Fiber trigger control
- Fiber readout
- On board clock
- External clock
- External gates
- Diagnostic outputs



ADC board design details

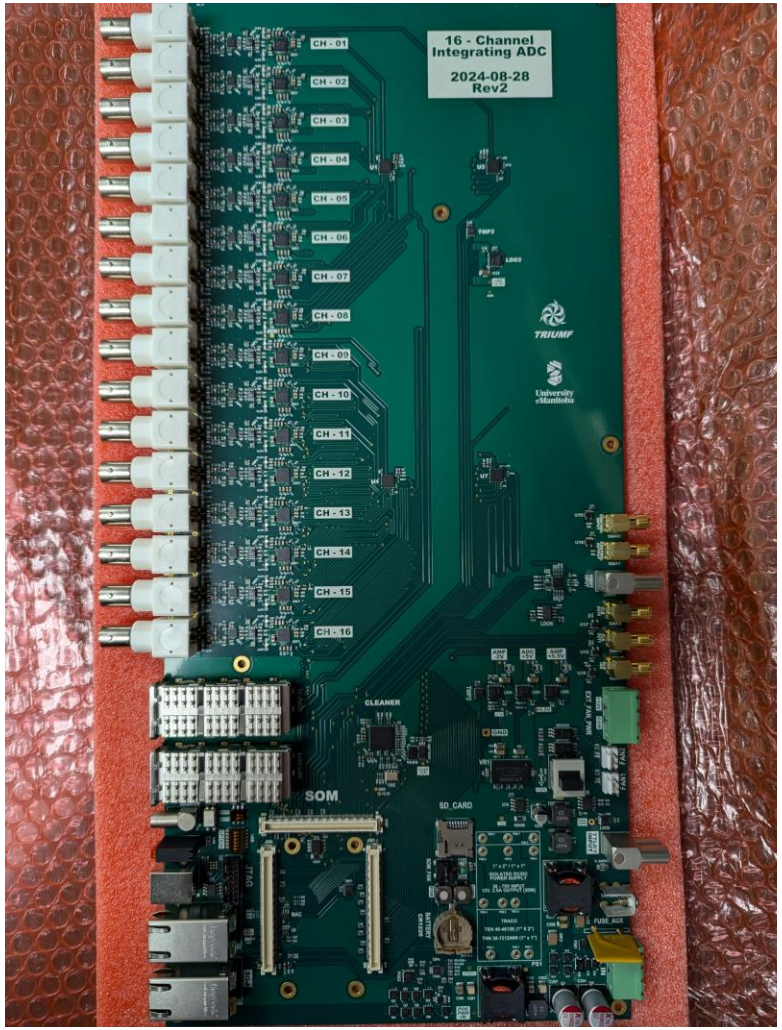
Hardware:

- ADC chip maximum manufacturer spec. sampling rate 15 Msps
- Board clock 250 MHz
- ADC board maximum selected sampling rate 250 MHz/17 $\Rightarrow$ 68 ns sample period

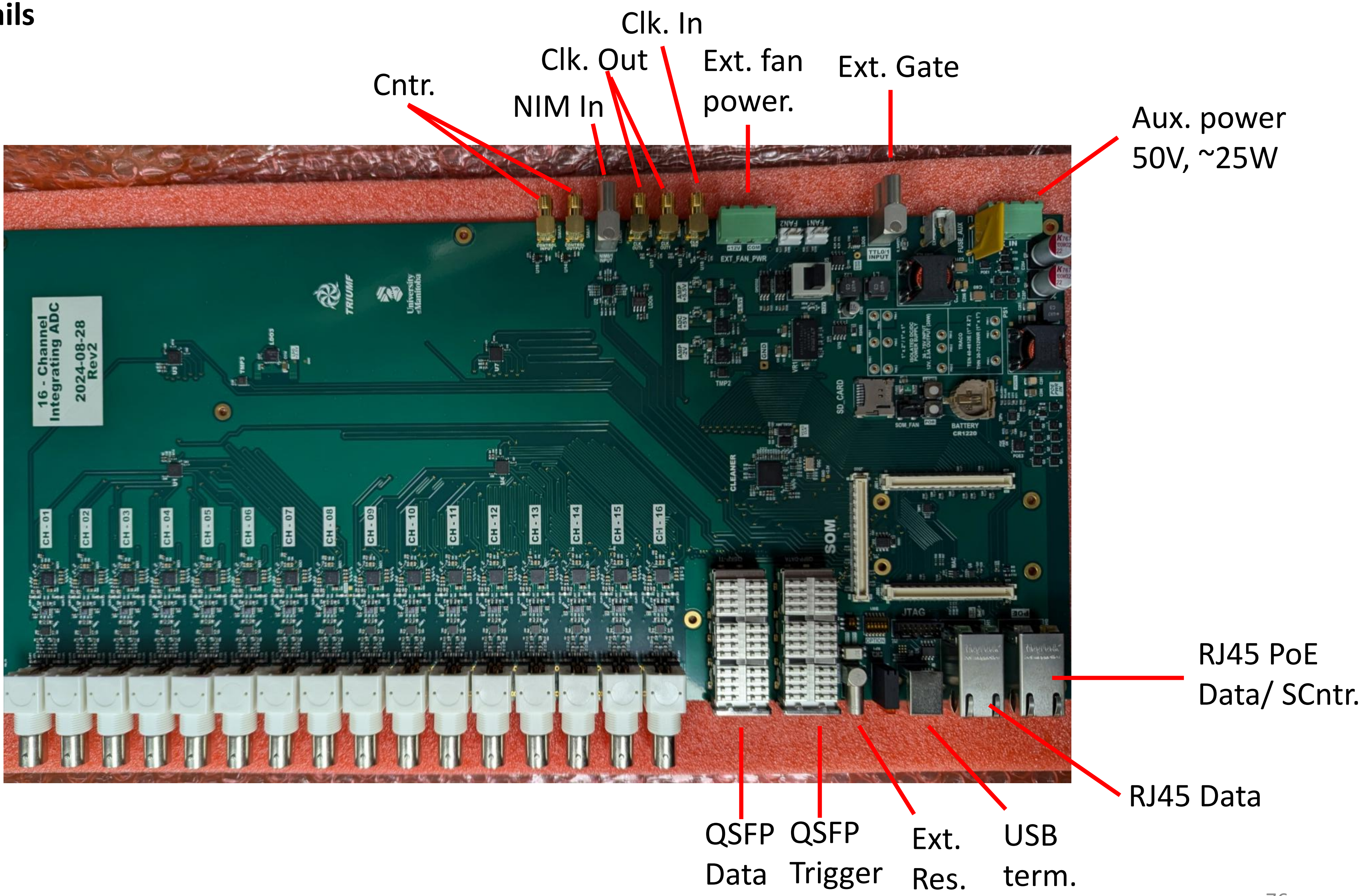
- Front connectors:
  - 16 Twinax differential input signals
  - Two QSFP (fiber sockets)
    - 1 designated for trigger interface
    - 1 designated for data out (up to 10 Gbps)
  - Two RJ45 network connections for slow control and firmware upgrades (SoM OS interface)
  - USB connector (SoM OS interface/boot)
  - Board external reset

- Back connectors:
  - Two TTL inputs at the back that can be used as benchtop gate/trigger (10 ns min width)
  - Two NIM inputs (1 ns min width) – not currently connected in the firmware – usage open
  - One LVDS external clock input (must be 125 MHz) – requires special jumper setting
  - One LVDS clock output (156.25 MHz synched to the board or input clock)
  - One LVDS pair output (not presently connected in firmware – usage open)
  - One LVDS pair output (not presently connected in firmware – usage open)

- Two possibilities for power (37 – 57 V , 25W)
  - either through PoE+ (power over ethernet) or
  - separate power supply



ADC board design details



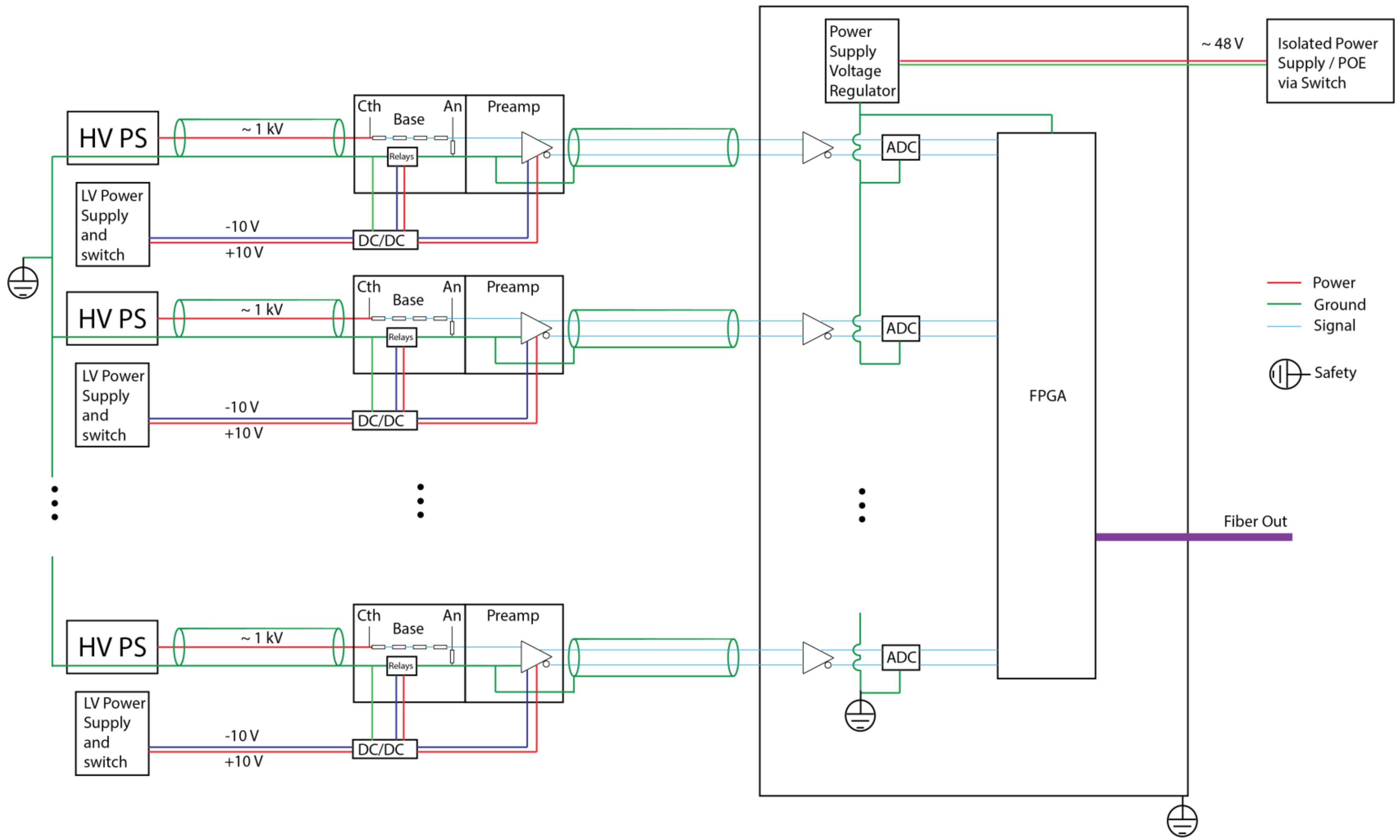
Asymmetry Measurement Principle

Firmware/Software:

- Streaming Mode Readout (i.e. waveform digitization):
  - Every sample for a given set of ADC input channels is read out to data (no data condensation is done on the FPGA SoM in this case).
  - Streaming data is sent in packets including a 16-byte header and a user defined set of two 4-byte sample data words that for each sample:
    - **the channel amplitude data**
    - **channel number**
    - **the chosen pre-scale factor**
    - **the state of the two TTL input gate bits**
    - **number of samples**
    - **time stamp, relative to which the sample time for all samples in**
  - Streaming data transfer at full sampling rate is presently possible for 2 channels at a time (with QSFP+ 40 Gbs we would be able to do this for all channels simultaneously – but we don't have the IP)
  - To be implemented: Settable time delay and acquisition period w.r.t. helicity trigger through TI interface (or other sync system)

Integrating Detector Grounding

- Detector ground to safety at the HV end
- Preamps and ADC boards are powered from LV isolated PS via separate DC/DC converter
- DC/DC converters and the low voltage end (preamps) use HV GND as reference.
- In the figure, ground lines (green) only connected to boxes they go into
- The ADC module and electronics has separate connection to safety.
- Power lines to components now shown



Integrating Detector Grounding

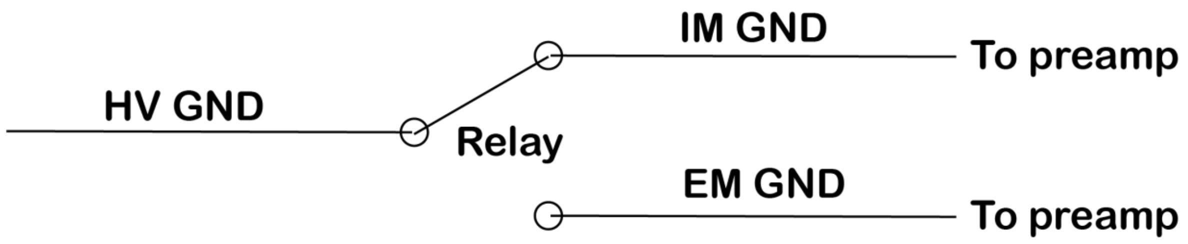
- In integration mode the integration mode preamp GND is connected to the HV GND and the pulse mode GND is floating

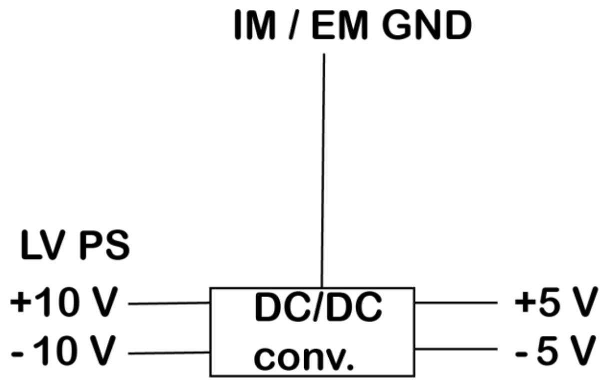
- In event counting mode the event mode preamp GND is connected to the HV GND and the integration mode GND is floating

- LV PS output reference (GND) is connected to HV GND in either mode

- LV PS inputs are floating. Both input lines are isolated

- All grounds in one mode are connected to HV GND and all grounds in the other mode are floating

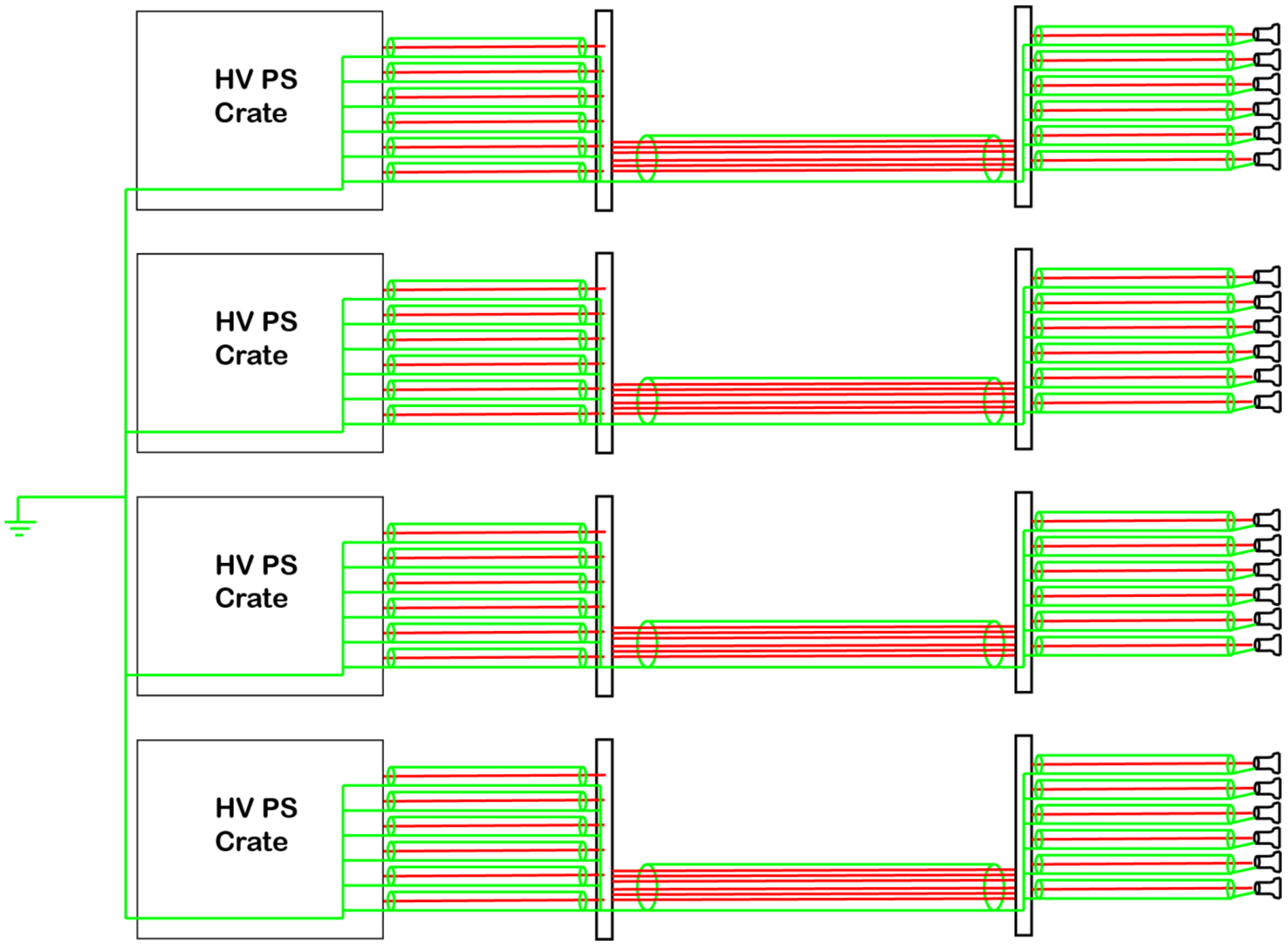




Integrating Detector Grounding

High voltage end:

- The HV channels all share a common ground.
- All HV crates should be connected to the same single ground.
- We would like to use a multi-conductor trunk cable with one GND line/shield between two patch panels (one at the PS side and one close to the detector side).
- Propose to tie together all channel based HV GND lines at the HV side patch panel.
- Choice has been reviewed by engineering.



Initial Testing

ADC board channel cross-talk (Brynne Blaikie)

Dual Function Generator

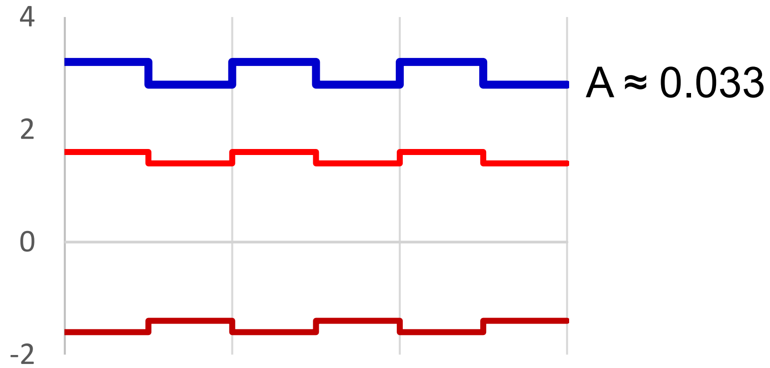
square wave

frequency: 2 kHz (synced to gate)

amplitude: 101 mVpp

offset: -1.5 V || +1.5 V

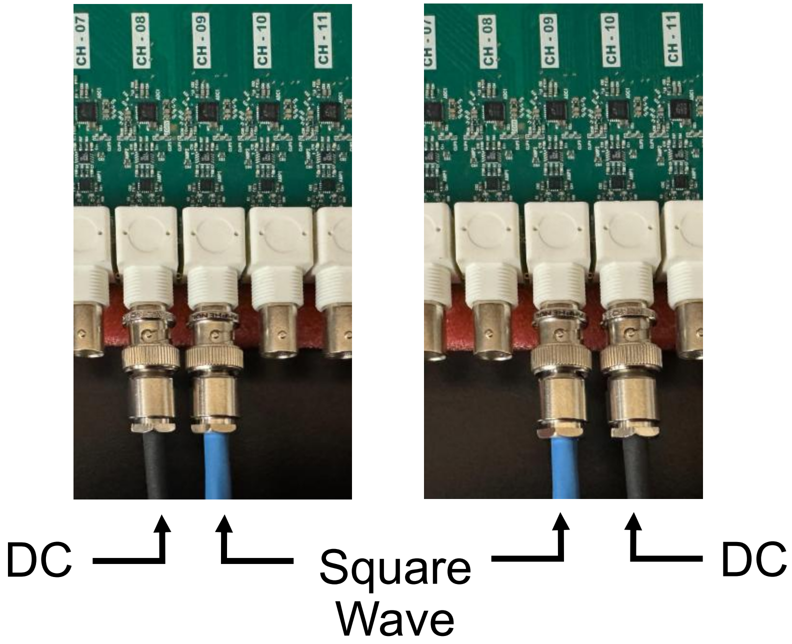
phase: 0° || 180°



LV Power Supply

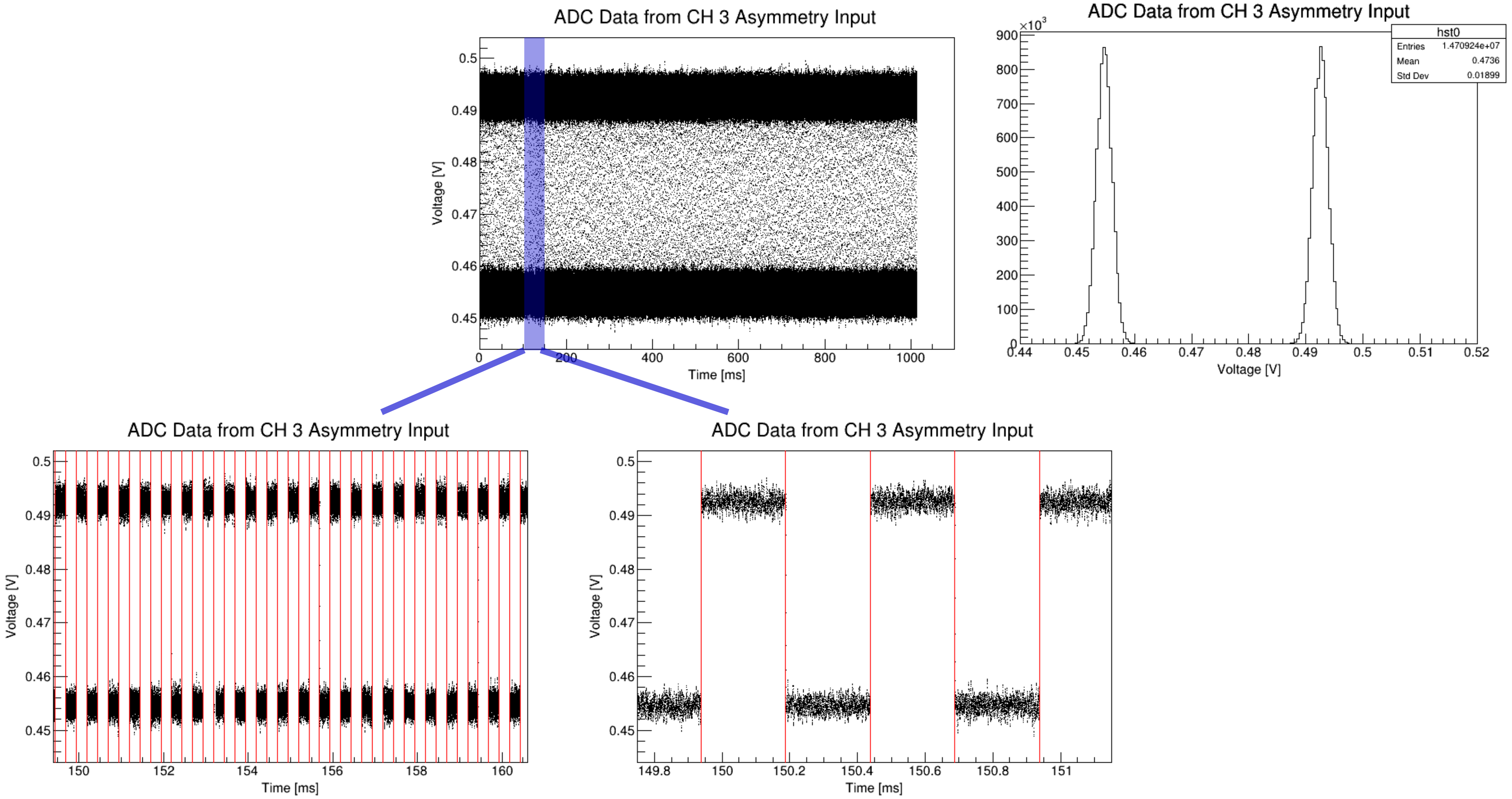
2.86 V – split into differential signal

set to match ADC readout average of square wave



Initial Testing

ADC board channel cross-talk (Brynne Blaikie)

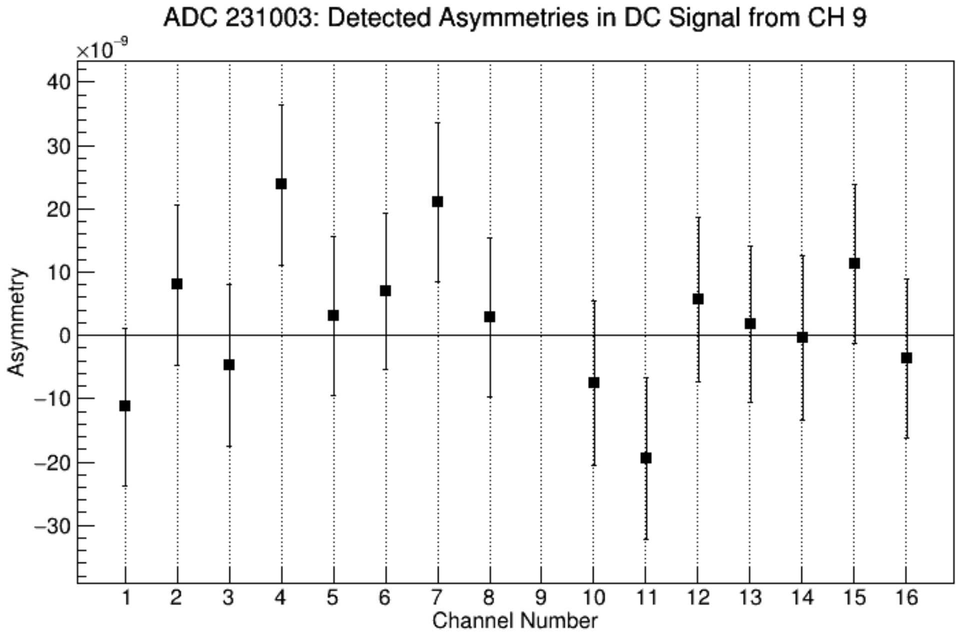


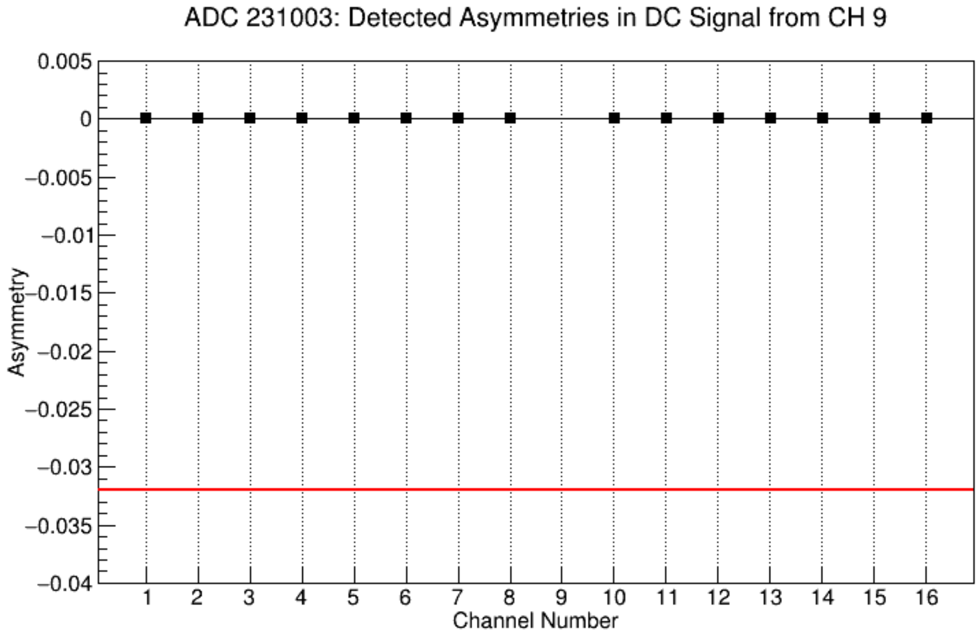
Initial Testing

ADC board channel cross-talk (Brynne Blaikie)

Example:

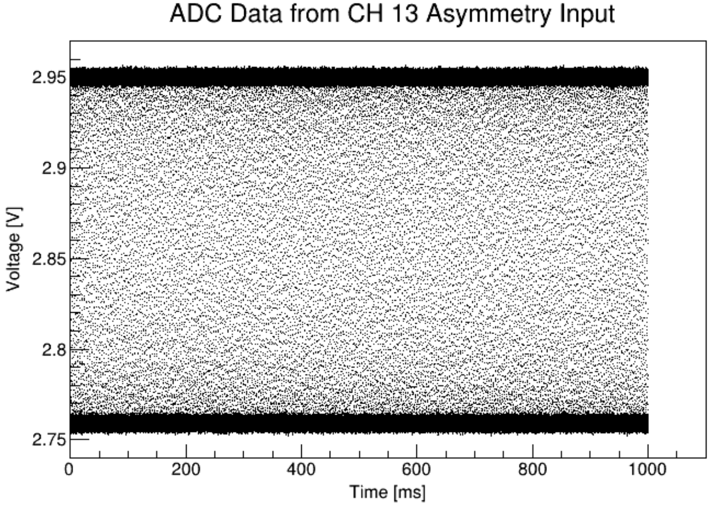
- 0.032 asymmetry from 10 kHz square wave input, 0.76 V average into Ch. 9
- 0.76 V DC signal for all remaining channels
- 10 x 1 second runs for each channel
- Also demonstrates small time to integrate electronic false asymmetries down to experimental goal precision.

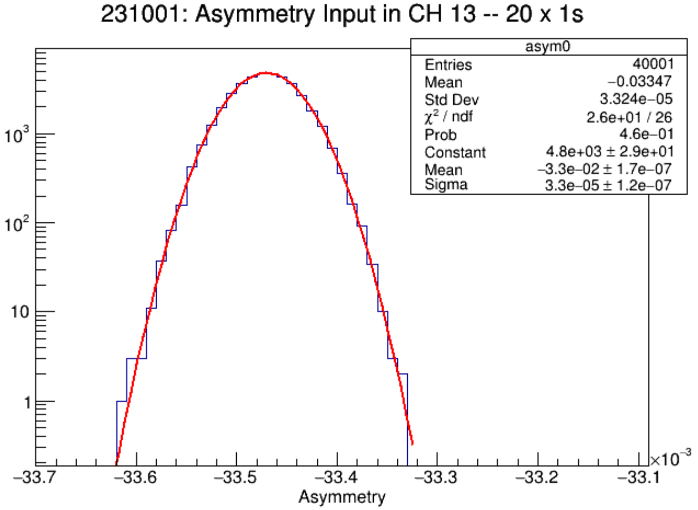




Initial Testing

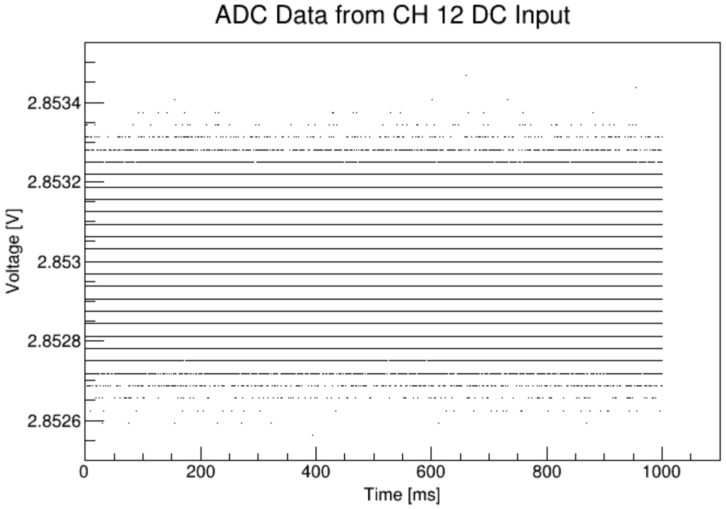
ADC board channel cross-talk (Brynne Blaikie)

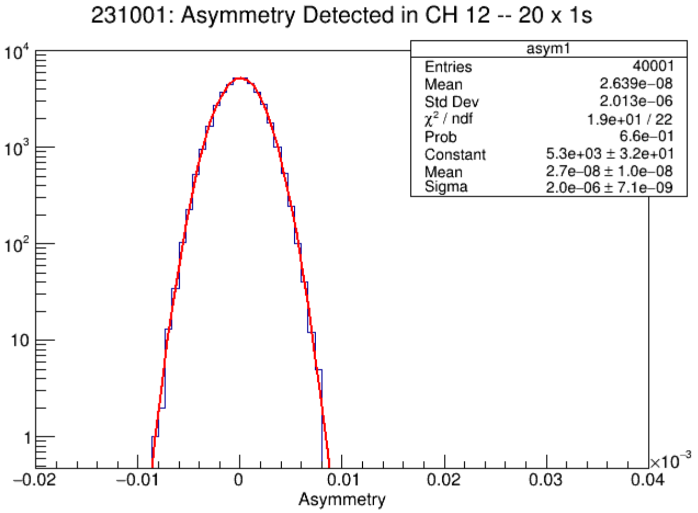




Square Wave Asymmetry Input:

-33 x 10^3 ppm ± 17 ppm





Asymmetry detected in DC Input:

0.027 ppm ± 0.010 ppm