# Measurement Of a Lepton Lepton Electroweak Reaction (MOLLER)

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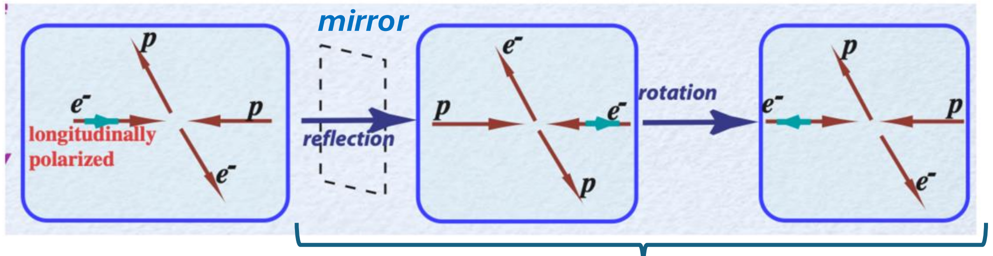
# Outline

- Experiment Overview
- Installation Progress and Current Status
- Upcoming Activities and Future Plans

# MOLLER Experiment

- Use the parity violation to measure the electron weak charge $Q_W^e$
- Process: longitudinally polarized electron beam scatters off an unpolarized electron target
- The parity transformation is achieved by flipping the beam helicity

Right-handed helicity




Left-handed helicity

Parity transformation

- Measure the parity-violating asymmetry between the two beam helicity states to determine the electron weak charge and the weak mixing angle.

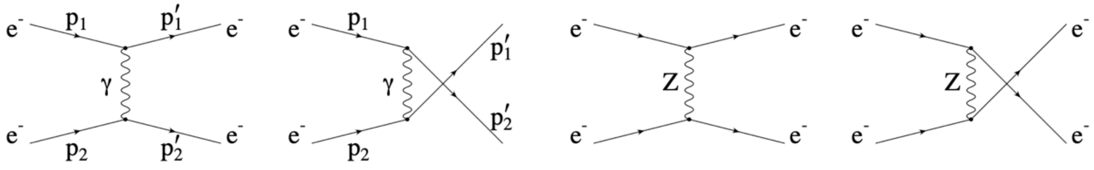
$$\sigma_{\{L,R\}} \propto \left|M_\gamma + M_Z\right|^2 \longrightarrow \quad A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{2Re(M\gamma M_Z^*)}{M_\gamma^2}$$

At tree level

$$A_{PV} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{2y(1-y)}{1+y^4+(1-y)^4}Q_W^e$$

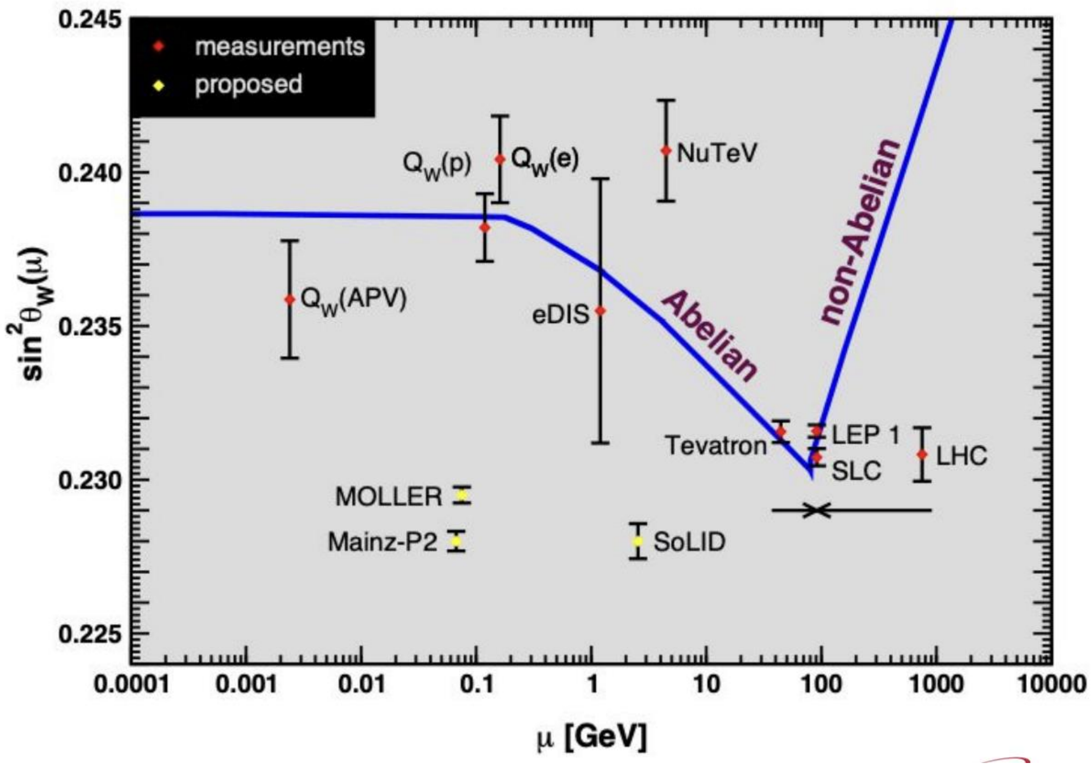
$$Q_W^e = 1 - 4\sin^2\theta_W$$

At tree level



# MOLLER Experiment

- **Ultra-high** precision measurement of the weak mixing angle at **low energy**
- Sensitive to BSM physics with minimal hadronic effect $Q_W^e = 1 - 4\sin^2\theta_W$
  - Sensitive to new neutral-current interactions from MeV to multi-TeV scales
  - Provides a powerful complement to the searches at high-energy colliders (e.g. the LHC)




- Predicated $A_{PV}$ for MOLLER: 33 ppb
- Overall uncertainty: 0.8 ppb
  - 2.4% uncertainty: 2.1% stat + 1.1% sys
- **DOE MIE project**
  - $50 Million from DOE NP
  - ~ $6 Million from NSF
  - ~ $6 Million from Canada CFI

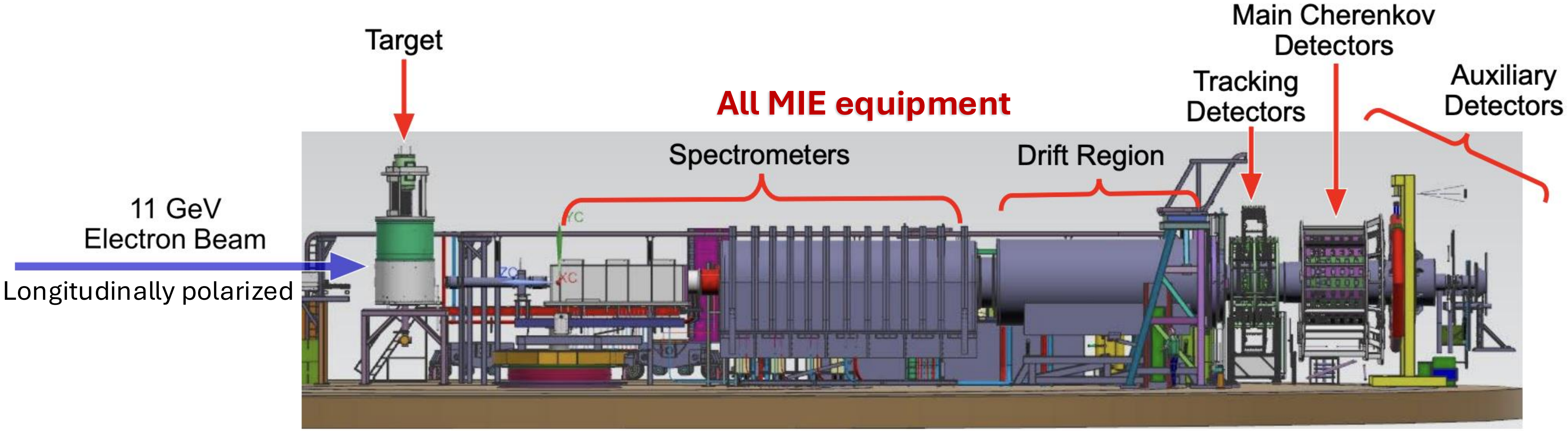
# Experiment Overview

- High luminosity: $3 \times 10^{39}\ cm^{-2}s^{-1}$
- 125 cm LH2 target
- Beam line:
  - Beam energy > 10.6 GeV
  - Beam current: 65 uA (Moller rate ≈ 134 GHz)
  - 90% longitudinal polarization
  - Helicity flip rate: 1.92 kHz
- 344 PAC days

## Accelerator MOLLER Tasks

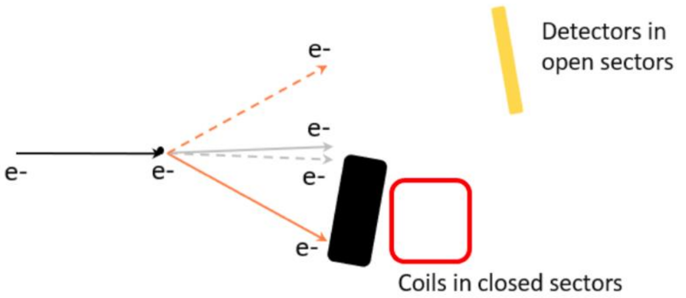
| Task ID | Topic | Scope | Status | Comment | Completion |
|---|---|---|---|---|---|
| 1 | Helicity Generator | Helicity board with new settings | Settings are available and tested at 2 kHz and 1 kHz | **Perform CEBAF-wide beam test to check readiness** | 100% |
| 2 | Helicity Decoder | New Boards for delayed helicity reporting | Built and distributed to few users | **All DAQs must use – distribute boards to halls** | 100% |
| 3 | RTP Pockels Cell HV | Build, install a new 8-channel driver, with 10 µs risetime, electrically isolated | Final optimization | Install in SAM25 | 90% |
| 4 | IA HV Driver | Build, install a new 4-channel driver, with 10 µs risetime, electrically isolated | Prototype design is ready | Build, test, and install in 2026 | 60% |
| 5 | Helicity Magnets Controller | Build, install new control system, with 10 µs rise-time, electrically isolated | Requirement document is ready. Bench testing. | Build, test, and install in 2026 | 30% |
| 6 | Polarization Feedback | Provide Wien feedback to keep longitudinal polarization within 0.03° | Beam tests showed viability of using keV Wiens | Possible Phase II SBIR to build MeV Wiens | 90% |
| 7 | Wien Filter Slow Reversal | Study Wiens Flip-Right and Flip-Left setups | Initial beam studies showed a reasonable reversal | Implemented water cooling | 75% |
| 8 | Injector Transmission and PQB | Optimize injector transmission for > 95% | Initial beam studies showed acceptable transmission | Evaluate apertures (A1, A2, A3, and A4) | 50% |
| 9 | Matching and Adiabatic Damping | Deliver matched beam and adequate damping | Measured across Booster, Accelerator will use raytrace | Finish raytrace analysis | 80% |
| 10 | Fast Feedback | Test and maintain existing system | FFB works as designed | Measure current noise affecting vertical position | 90% |
| 11 | Compton Polarimeter Background | Setup beam thru polarimeter with low halo > 100 Hz/µA | Added harp. No beam to Hall A till 2027 | Working on Compton AI/ML | 50% |
| 12 | Beam Modulation | Hot checkout and maintain system | Beam study showed a working system | Need final results | 100% |
| 13 | Phase Advance | Design Hall A beam optics with sufficient phase advance | Was done before and designed optics with phase advance | Test in 2027 | 100% |
| 14 | Low Beam Current | Deliver low beam current for detectors calibration | **New Task, ERR Recommendation** | **Have requirements – planning beam studies** | 10% |
| 15 | Control of Charge Asymmetry | Measure and control charge asymmetry of Halls B, C, D | New IA system was added in Hall D laser | Perform feedback tests for Hall B and D beams | 25% |
| 16 | PQB in Injector and Hall A | Setup PQB in injector and Hall A and perform beam studies | Performed initial beam studies | More beam studies and reduce vertical position noise | 60% |
| 17 | Hallo Monitors in Hall A | Install halo target and detectors and provide FSD and EPICS controls | New halo monitor is being built | Install halo monitor in Hall A beamline | 50% |
| 18 | MOLLER Apparatus Protection | Protect apparatus from beam mis-steering | Comprehensive scheme has been outlined | Implement with Ops and RadCon Group (**ERR Comment**) | 10% |
| 19 | BPM Receivers | New receivers in Hall A line instead of old SEE electronics | Digital receivers are ready | Implement during MOLLER installation | 60% |
| 20 | BCM Receivers | New BCM receivers in Hall A line to meet linearity and noise requirements | Receivers meet linearity requirement but not resolution | Identify source of noise and rebuild digital receivers | 30% |
| 21 | Laser Table Configuration | Configure laser table and injector for MOLLER | A laser will be reference | Common practice. Coordinating with MOLLER Coll | 10% |
| 22 | Intensity Modulation | Build, install new control system to modulate beam current by <1% | Waiting on approval and requirements document | **New task** | 0% |

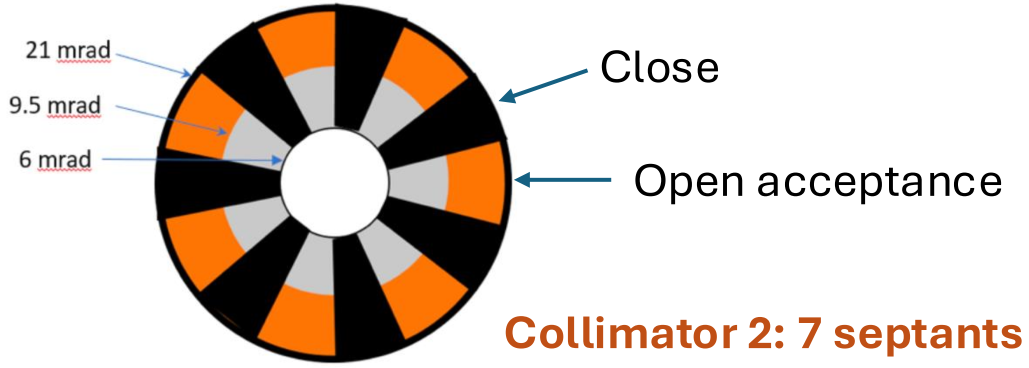
High requirements on both Accelerator and the Hall equipment



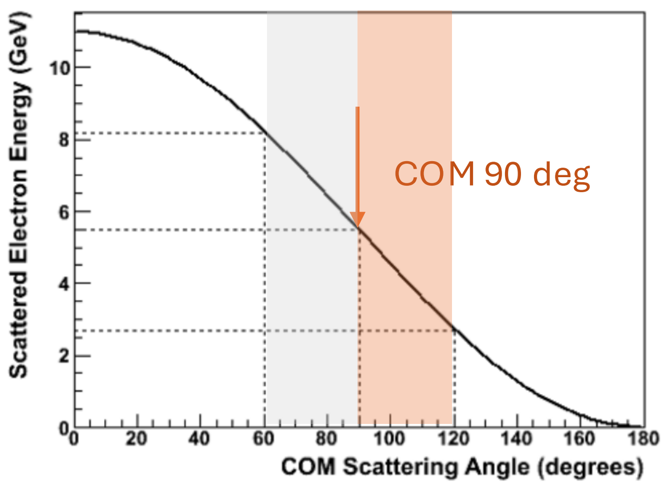
# Spectrometer Overview

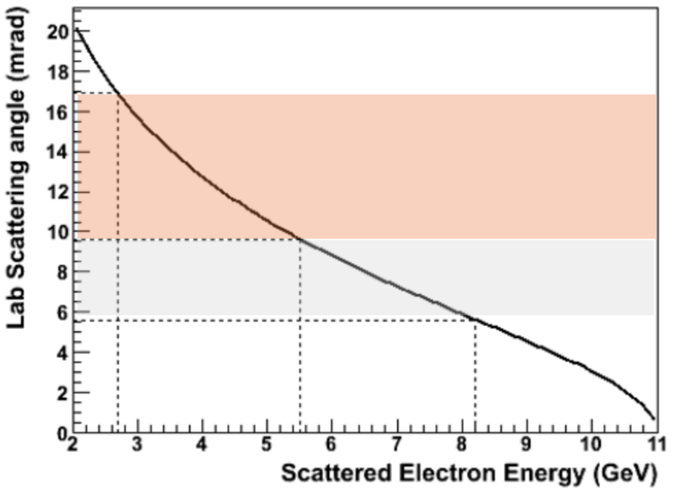
- The two scattered electrons are identical particles; detect one is sufficient for the integrated flux measurement.
- The scattered electrons are back-to-back in azimuth; only one passes through the collimator while the other is blocked.




- The maximum figure of merit for the Moller asymmetry occurs at a COM scattering angel equals to 90 deg

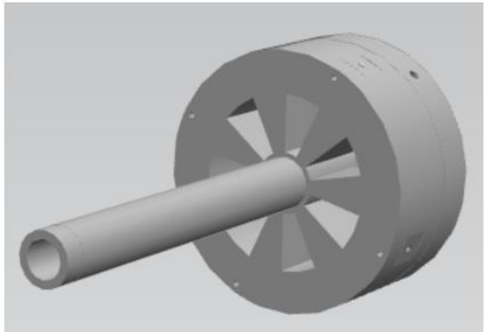



- COM acceptance [60°, 120°]

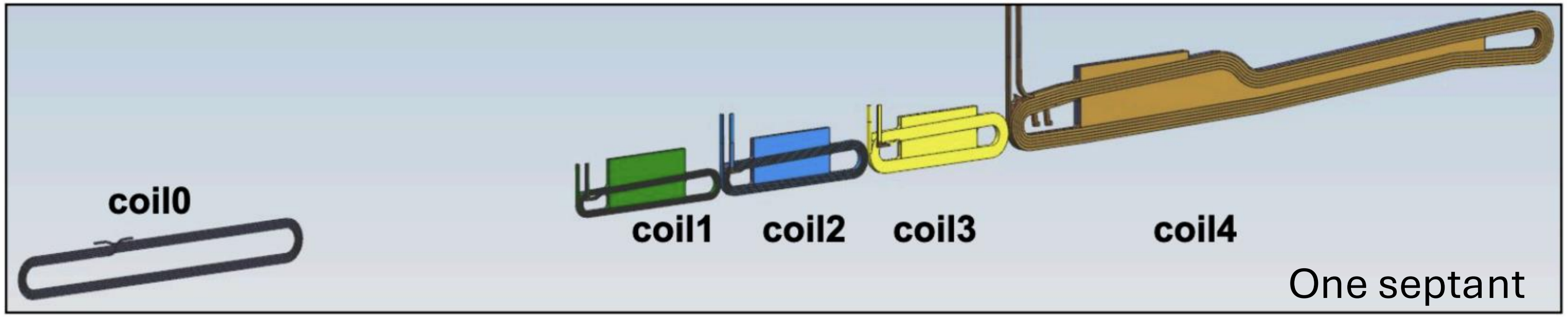
- Lab acceptance (0.3°, 1.1°)
- Momentum acceptance (2.5 GeV, 8.5 GeV)

# Spectrometer Overview

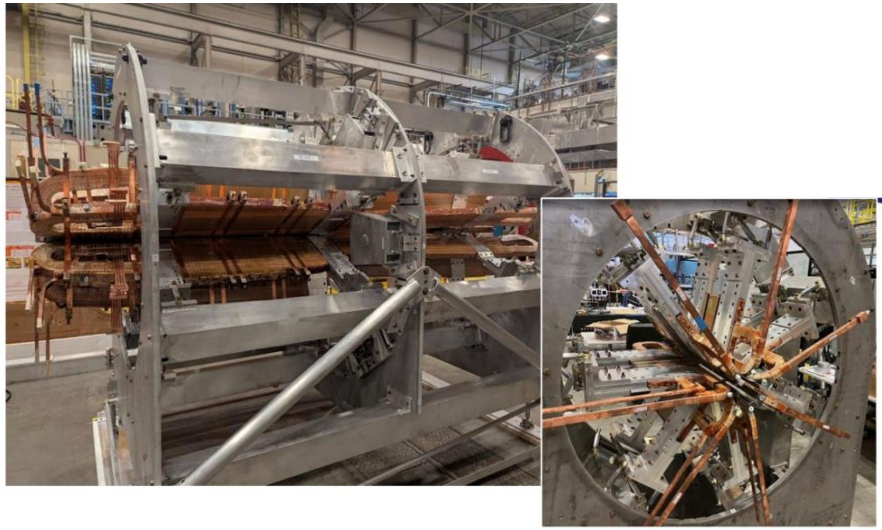


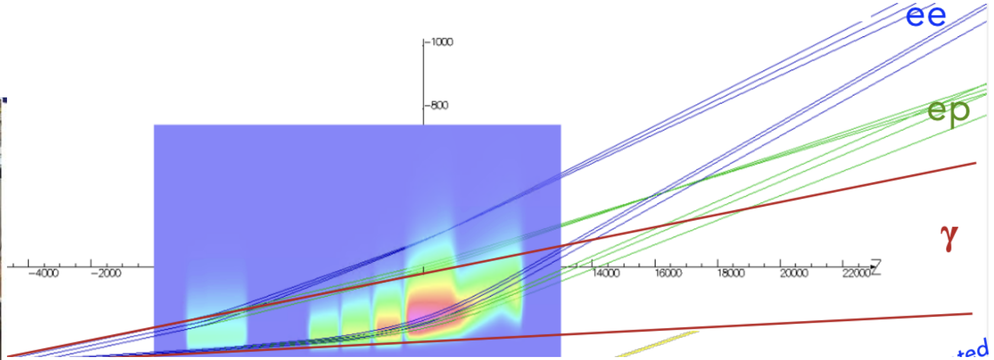
Collimator 1&2
Acceptance defining

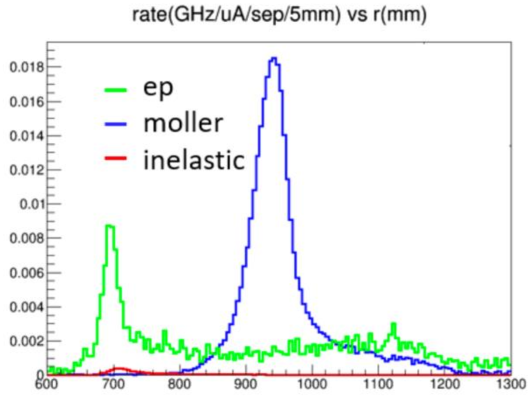
5 toroidal coils of varying strength and shape




Separate the Moller scattering
from e-p scattering



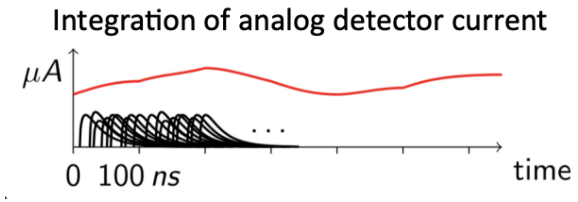


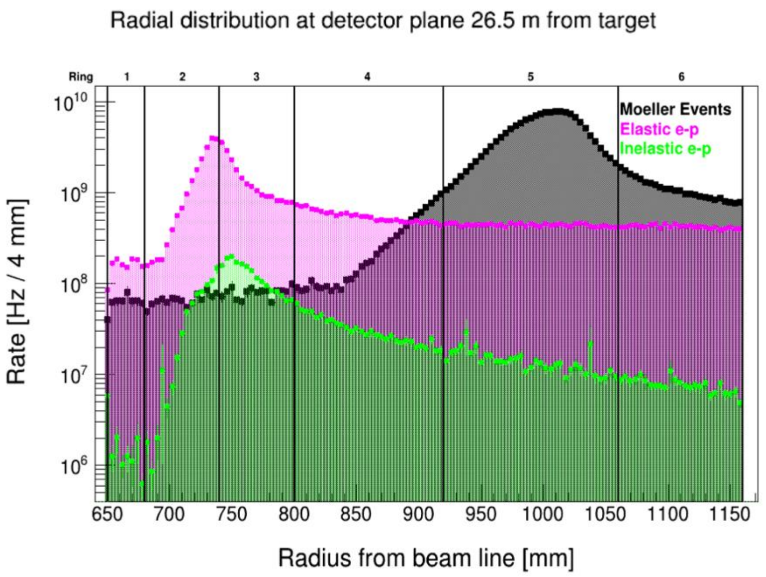

Main detector radial direction

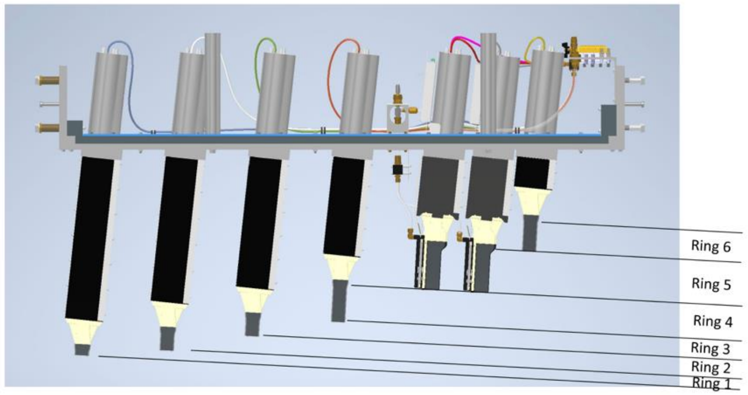
# Main Detector

- The peak electron rate can reach 1 MHz/mm$^2$ in certain regions → very challenge to count pulses
- Radiation hard, highly linear with relatively large active area fused silica (quartz) Cherenkov detectors
- The highest total rate for a tile is GHz → produce continuous current at the PMT
- The PMT base is designed to switch between pulse mode and current mode



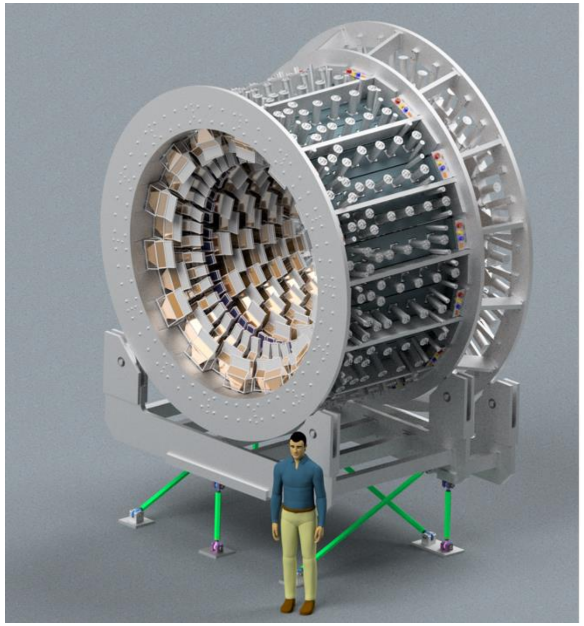

- The active region is separated into 6 radial regions, called rings, for different physics channels;



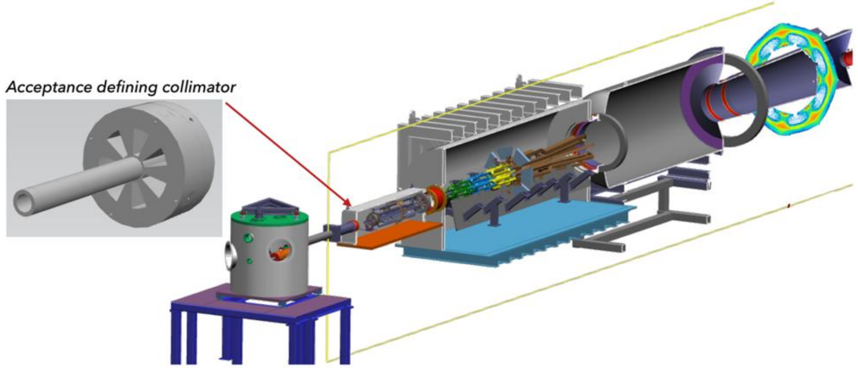

**The detector array is separated into six rings:**

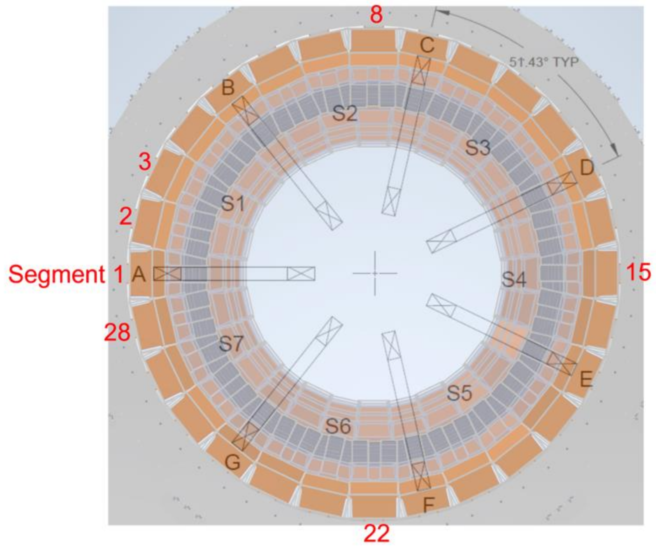
- **Ring 1- 4:** $e + p \rightarrow e + p$ **and** $e + p \rightarrow e + X$
- **Ring 5:** $e + e \rightarrow e + e$
- **Ring 6:** **Radiative tail**



# Main Detector

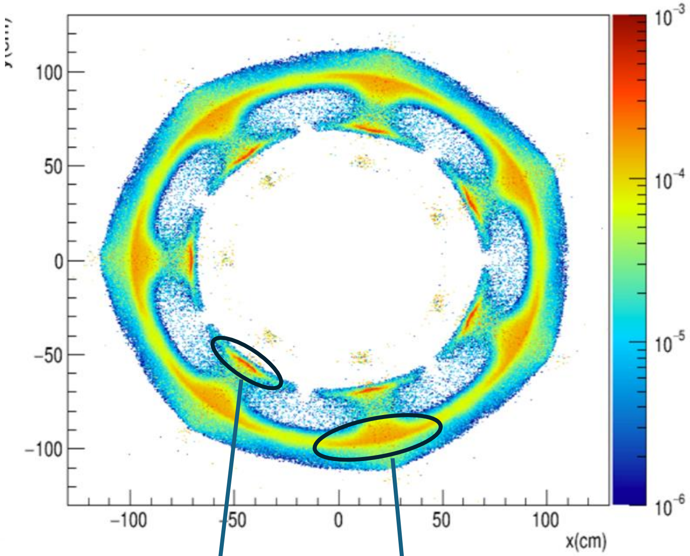
- The 6 rings are divided into 28 segments in the azimuthal angle;
- Ring 5 (Moller ring), each segment is further divided into 3 modules
- Each module is one quartz detector with one PMT → 224 modules

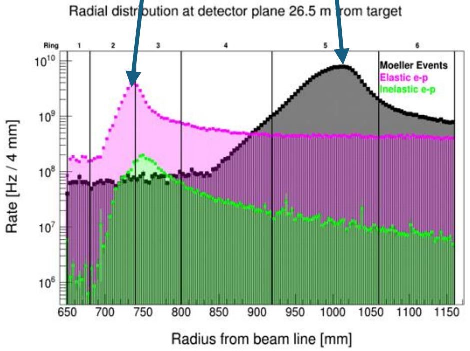


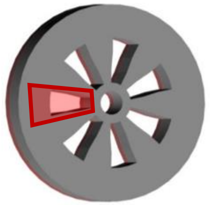




Main detector front view

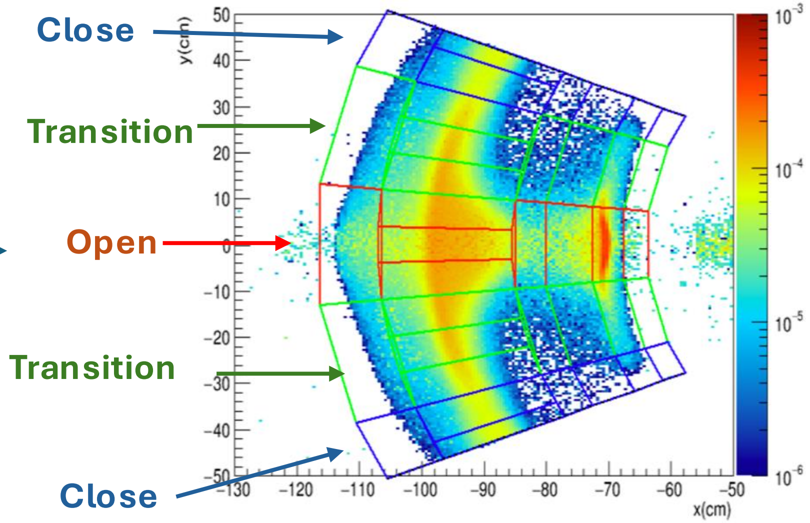
Main detector hit map



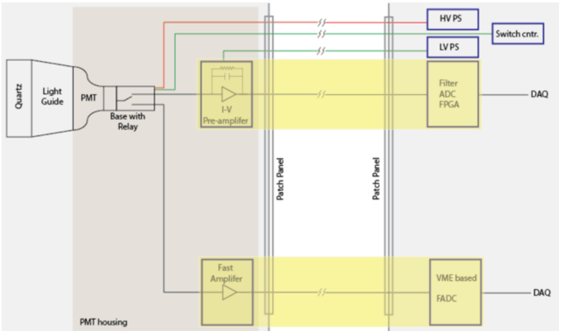
One Septant




One septant hit map

Open: center of the acceptance
Close: blocked acceptance
Transition: region between open and close

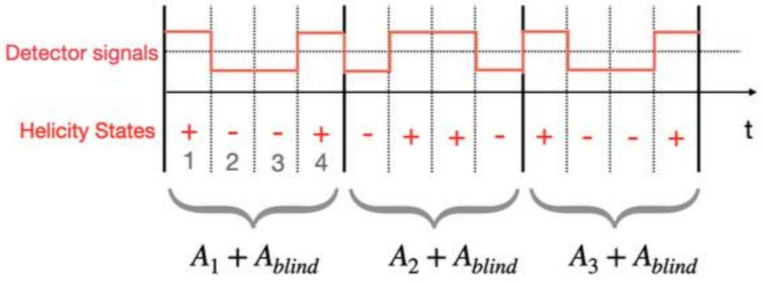
# Integrating DAQ and Asymmetry analysis



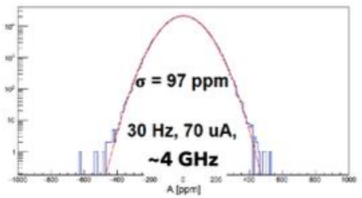


- The PMT base is set to current mode; read out by MOLLERADC → Production runs
- MOLLERADC:
  - 68 ns sampling period; input range of ± 4.096 V
  - Streaming mode: two channels at the full sampling rate for readout (diagnosis purpose)
  - Integrating mode: report sample sum for a sub-block of a helicity window (production)
- Using the reported integrating sum, the asymmetry is calculated per pattern
  - The 64 windows per pattern
  - The asymmetry resolution is achieved by over-sampling within each helicity window

  (1.92 kHz flip rate → 7659 samples per window)




$$A_i = \frac{N_1^+ - N_2^- - N_3^- + N_4^+}{N_1^+ + N_2^- + N_3^- + N_4^+}$$



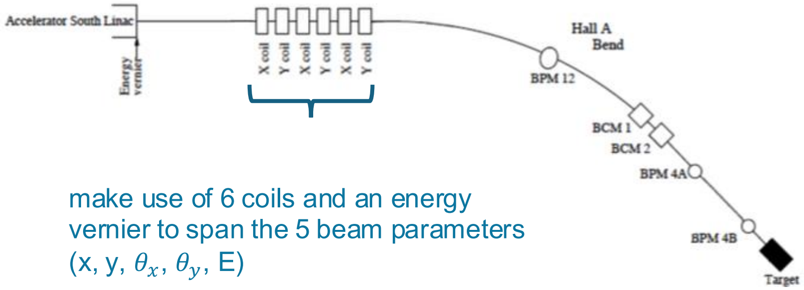

Example of asymmetry measurement in PREX

- The width of the asymmetry distribution is driven by the statistics per helicity pattern
- It’s sensitive to beam fluctuations

# Parity Violating Asymmetry Extraction

- Raw asymmetry with beam intensity correction: $\mathrm{A_i^{raw}} = \frac{N_R/I_R - N_L/I_L}{N_R/I_R + N_L/I_L}$
- Remove beam trajectories induced asymmetries:
  - Beam modulation system
  - Correlation studies

$$A_i = A_i^{raw} - \sum_j \alpha_j \left(\Delta X_j\right)_i$$




Beam modulation system during PREXII/CREX

- Beam Background corrected asymmetry:

$$\langle A \rangle = \frac{1}{N}\sum_i^N A_i; \quad \sigma_{\langle A \rangle} = \sigma_{A_i}/\sqrt{N},$$

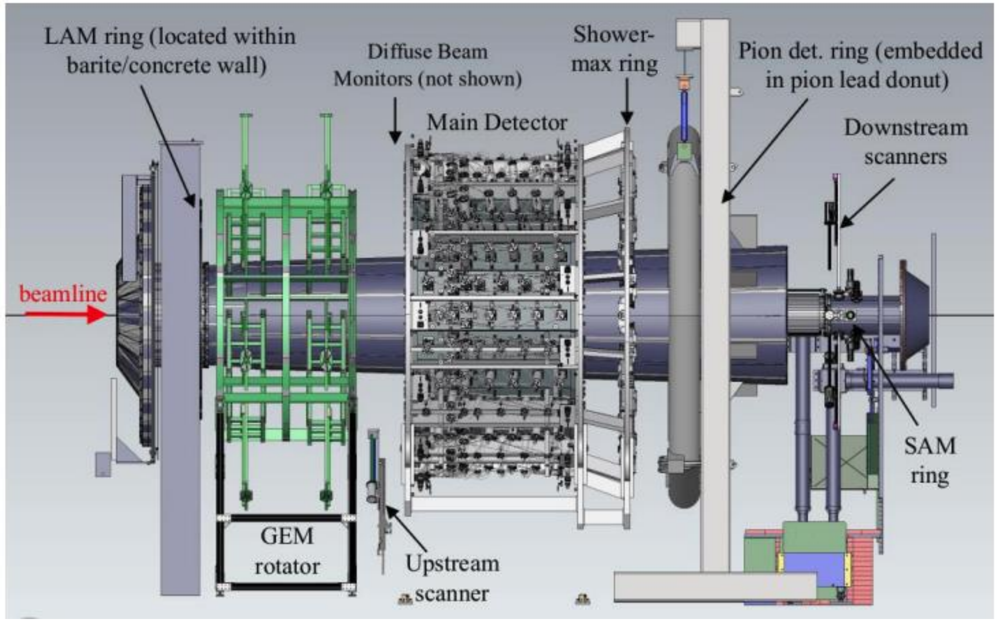
- Other corrections:
  - Beam polarization $P_B$,
  - Kinematic factor $\epsilon$
  - Background asymmetries $A_i$: e-p elastic, e-p inelastic etc.
  - PMT non-linearity $A_{lin}$
  - Other false asymmetry $A_F$

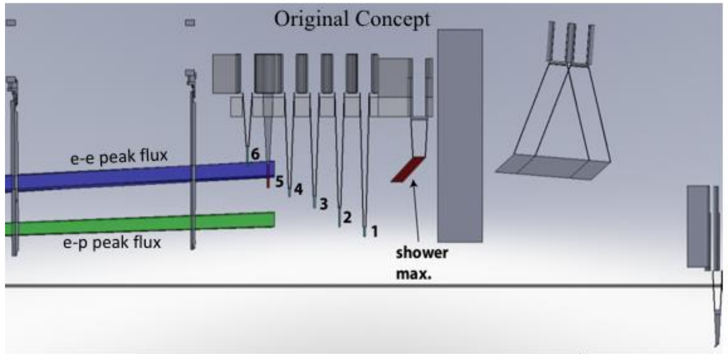
$$\mathrm{A_{phys}} = \frac{1}{P_B \epsilon} \frac{A_{meas} - A_F - A_{lin} - \sum_i \Delta A_i}{1 - \sum_i \mathrm{f_i}}$$

# Auxiliary Detectors

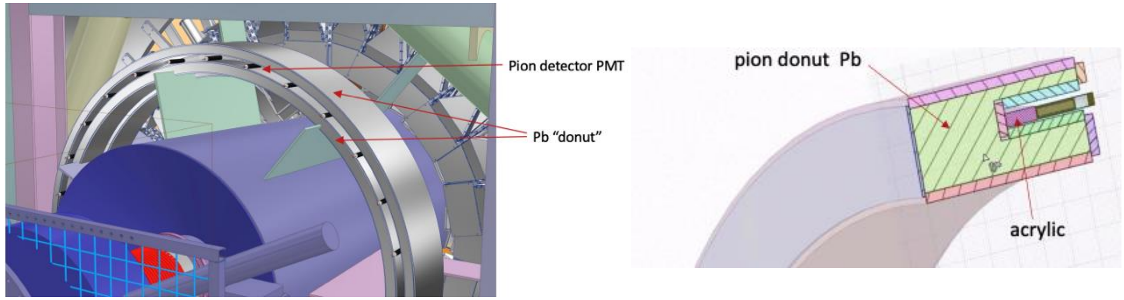
- Shower Max Detector
  - 28 segments at the same radius as Ring 5 (Moller ring)
  - Electromagnetic sampling calorimeter (less sensitive to soft and hadronic background);
  - Provide additional Ring 5 flux measurement
- Pion donut and Pion detector
  - Pion donut absorbs majority of electrons, so $\pi/e \approx 1$ at the pion detector
  - Pion detector covers the Ring 5 acceptance with 28 segments
  - Measures pion background and its asymmetry

MOLLER Detector Package
("physicist's CAD model")




Show Max location

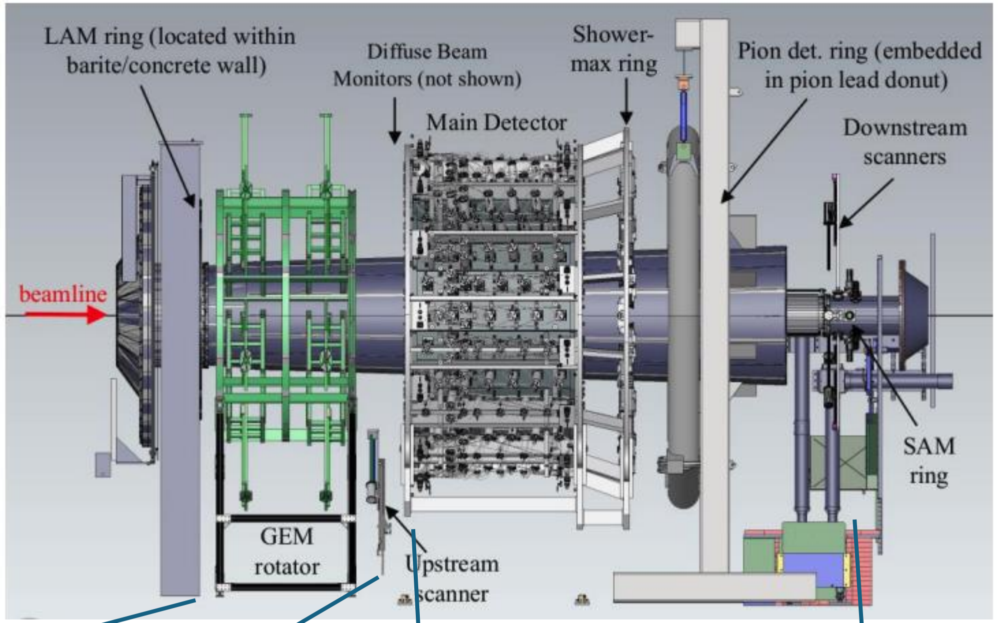


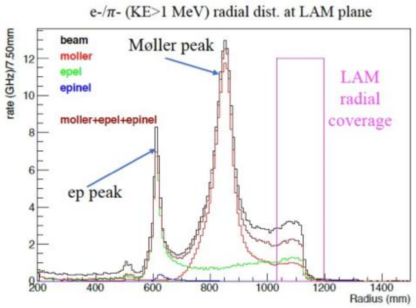

Pb detector is embedded in the Pion donut

# Auxiliary Detectors

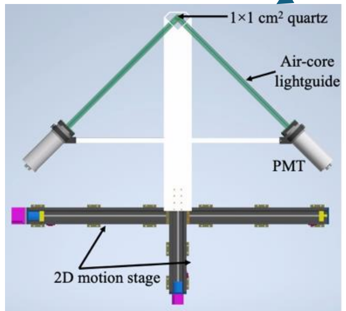
- Scattered Beam Monitors:
  - Large Angle Monitors (LAM): radiative tail monitor
  - Small Angle Monitors (SAM): null asymmetry monitor
  - Diffuse Beam Monitors (DBM): secondary interaction monitor
- Scanner Detectors (movable)
  - Upstream Scanner: flux distribution monitoring
  - Downstream Scanner: verify collimators alignment

MOLLER Detector Package
("physicist's CAD model")

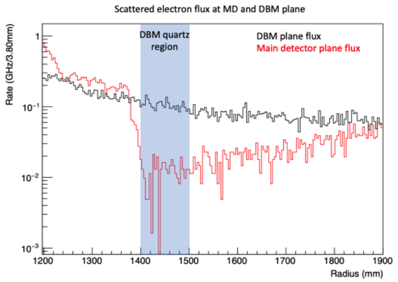


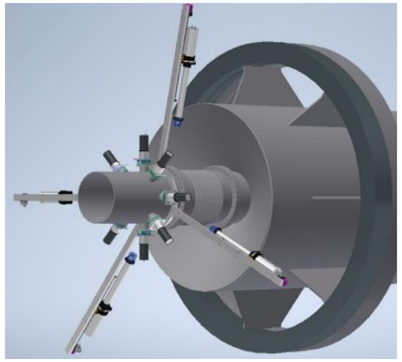

LAM radial coveragex




Upstream Scanner




DBM radial coverage



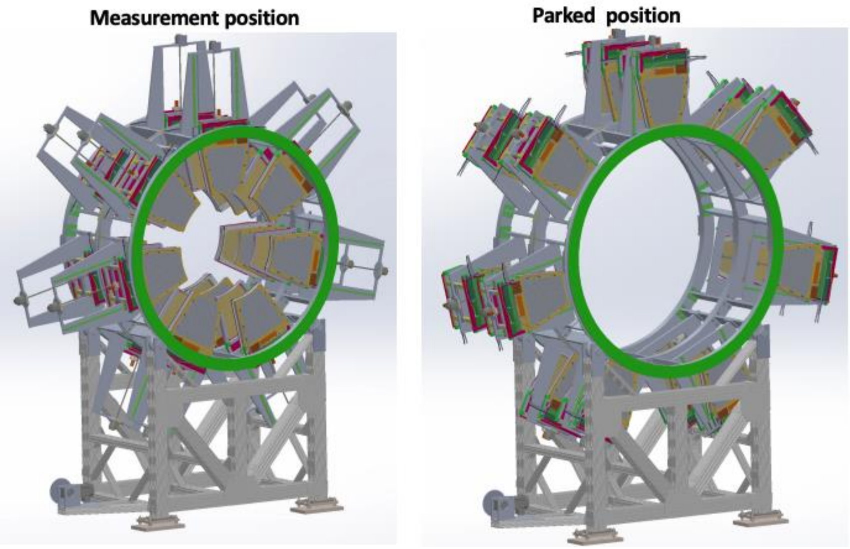
Downstream Scanner and SAM

# Tracking system

- Only run at low current (few nA); all detectors are switched to the pulse mode;
- The primary purpose is to determine the kinematics:

$$A_{PV} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\underbrace{\frac{2y(1-y)}{1+y^4+(1-y)^4}}_{\text{Kinematic factor}}Q_W^e$$

- Additional detectors: 28 GEMs (7 sectors, 4 layers); 14 Trigger Scintillators (7 sectors, 2 layers)
- The GEMs and scintillators are mounted on a rotator
  - Move into the acceptance during the low current measurement
  - 103° rotation to cover the full azimuthal angle

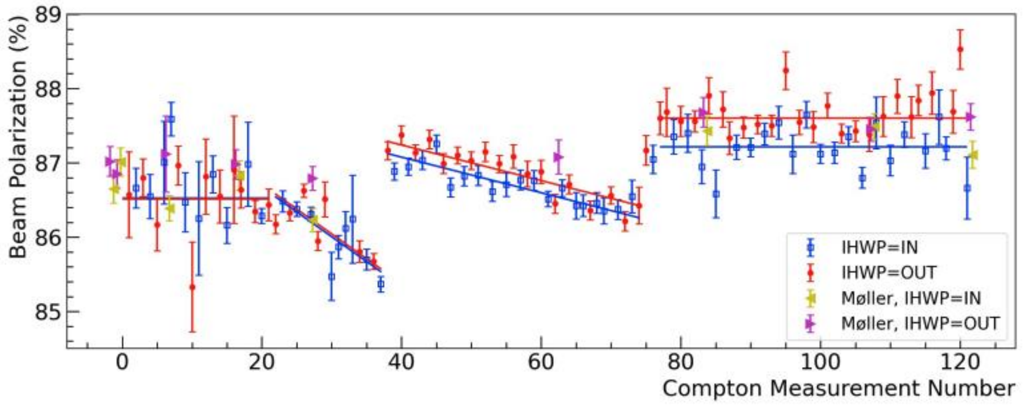



**Measurement position:**
Counting mode
(tracking) data-taking

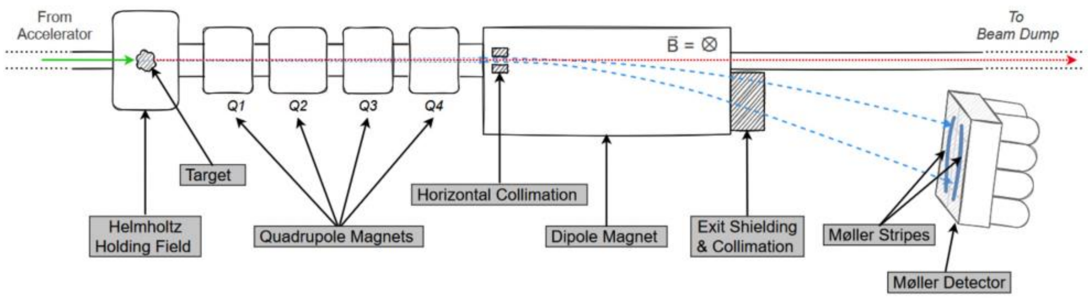
**Parked position:**
Integrating mode
(asymmetry) data-taking

# Beam Polarimetry

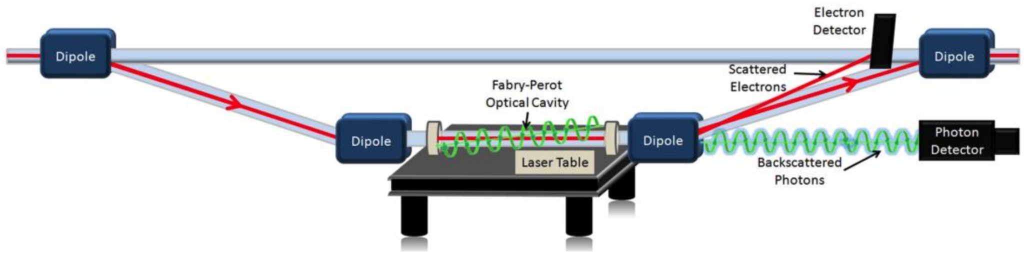
- Two independent beam polarimeters: Moller polarimeter, Compton polarimeter
- MOLLER requires the beam polarization to be 0.4% accurate
- Compton polarimeter monitors the beam polarization continuously
    - Achieved 0.36% accuracy during CREX
- Moller polarimeter:
    - Invasive measurement; run at low current (~ 1 uA)
    - Achieved 0.85% accuracy during CREX




Beam Polarization Measurement during CREX




Moller polarimeter




Compton polarimeter

# Installation

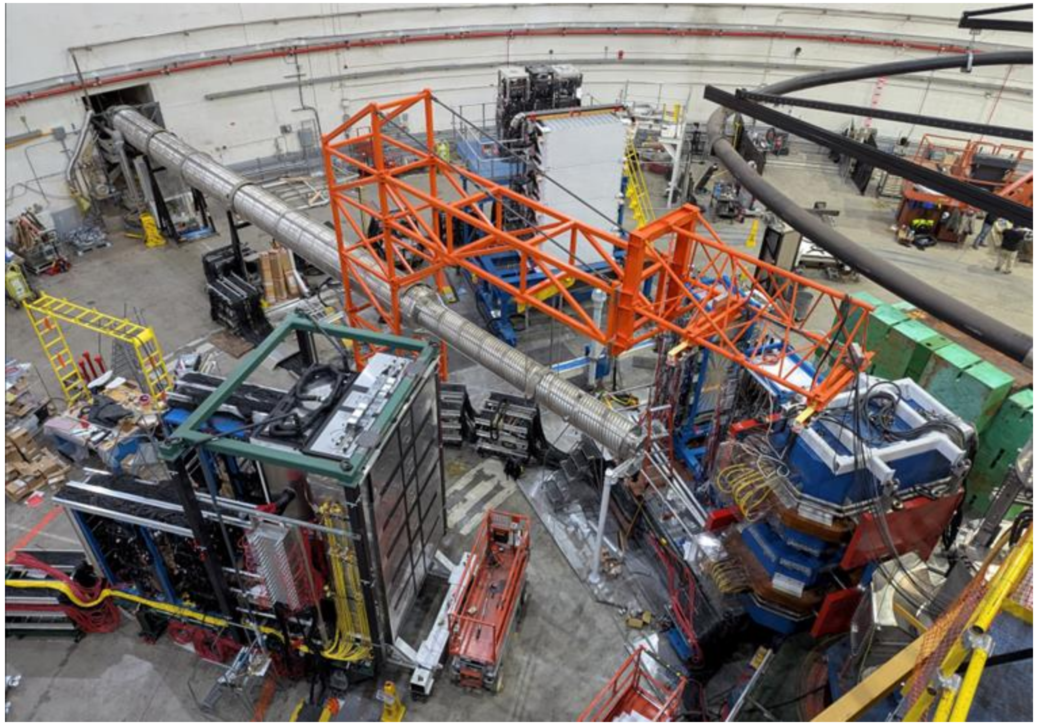
More details can be found at Vladimir Berdnikov's talk  at Hall A/C Summer Collaboration Meeting (https:// indico.jlab.org/event/1068/)

# Safety

- **Integrated Safety Management (ISM)** – The Jefferson Lab Integrated Safety Management system is applied to ensure all work is conducted safely using established work planning processes (ePAS).
- **Radiation Control (RadCon)** – RadCon is engaged for all material removal from Hall A, as well as for drilling into concrete or cutting materials that were exposed during beam operations.
- **Pressure Systems** – Compressed air systems are isolated as required, including Hall A air compressor LOTO and Accelerator Air LOTO.
- **Cryogenic system** is currently fully isolated from Hall A.
- **Material Handling** – A 40 lb lifting limit is enforced. Specialized components (e.g., bellows and other high-value or long-lead items) are designated as critical lifts, requiring detailed lift plans and review by the Material Handling Manager. Heavy lifts are supported by the 20-ton crane, with three technicians trained to Master Rigger level.
- **Fire Protection** – Flammable materials in the hall are minimized. VESDA system is operational. Hot work permits are required for welding, grinding, and other ignition sources.
- **Elevated Work** – Most elevated work will be performed using aerial work platforms, scissor lifts, and boom lifts in accordance with JLab guidance and required safety equipment. Elevated work permits will be obtained when required.
- **Electrical & High Voltage Work** – Electrical and high-voltage work is addressed in detail through ePAS, with isolation certificates required as applicable. Work will be performed by licensed electricians and/or led by experienced Qualified Electrical Workers (QEWs).
- **ES&H Oversight** – ES&H personnel conduct near-daily walk-throughs, with additional communication and guidance provided as needed.

# MOLLER Assembly steps

- Step 0: Hall A legacy experiment and beamline removal -- **complete**



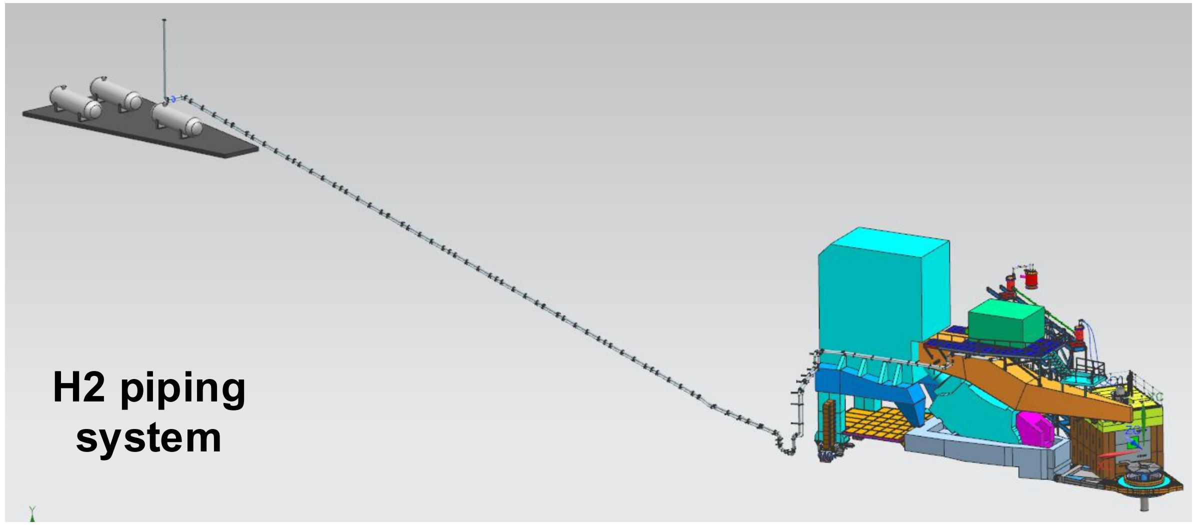
SBS Experiment Setup – August 2025

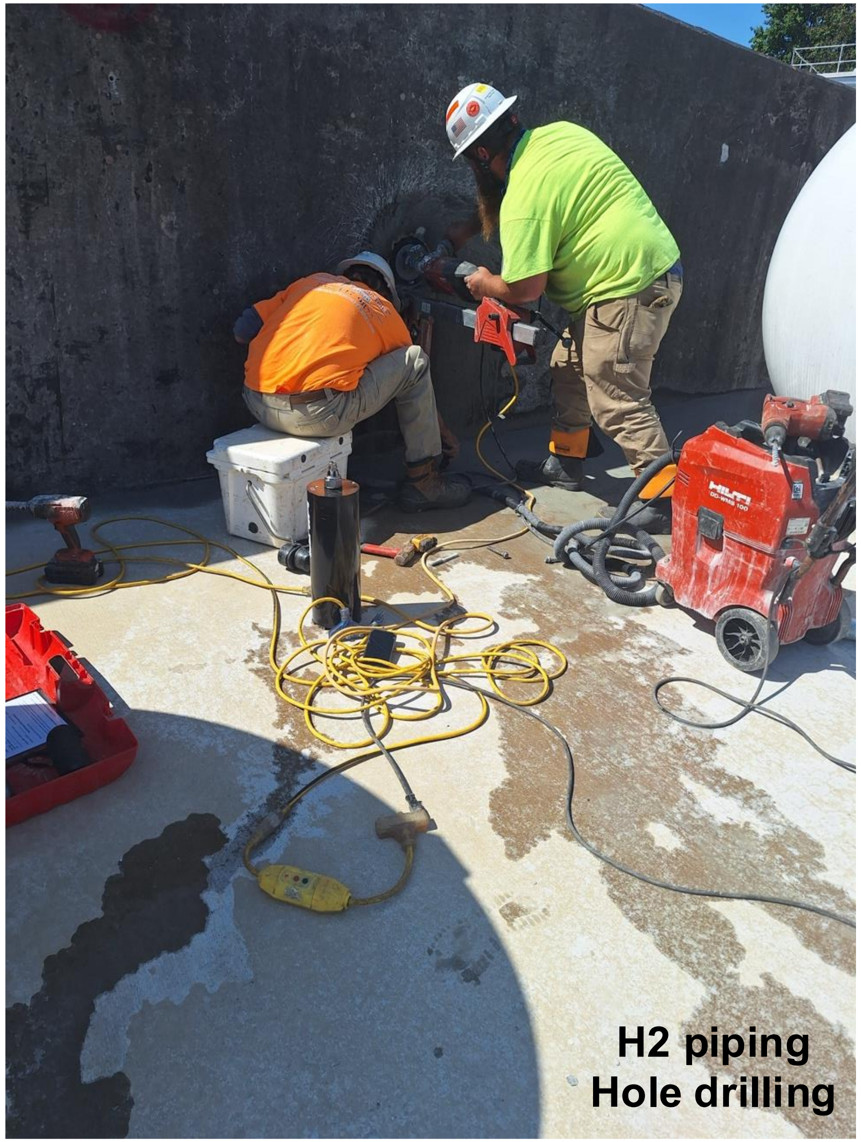
Hall A  Winter 2026

# MOLLER Assembly steps. Step 1/4

- Step 0: Hall A legacy experiment and beamline removal **Complete**
- Step 1: Hall A reconfiguration. Spectrometer, Infrastructure, and DAQ installation **Ongoing, 90% complete**
    - 10802040 Install H2 Tank - done
    - 10802050 Blue utility platform work target – 95% complete
    - 10803235 Downstream Beampipe and bellows assembly
        - Beam dump support assembly and SAM pipe installation - done
        - Detector pipe and Pion Donut support frame Assembly - done
        - Drift pipe and bellows Assembly - 75% complete
    - Magnet Power Supplies and infrastructure installation
        - 10803110 Assembly and install power supplies and control racks - 60% complete
        - 10803015 Connect Power and LCW to MPS - 50% complete
        - 10806081 MOLLER Electrical work - 30% complete
        - 10803050 Route cables to spectrometer - done
    - 10806420 Quad Magnet and Pivot Link Removal -Contractor Support - done
    - 10806020 Modify HRS Pivot platform - done
    - 10806059 Utilities Removal and Platform Modifications - 99% complete
    - 10806216 LCW Assembly- 90% complete
    - 10806035 Assemble Magnet Power Supply Bunker – done
    - 10806055 Assemble Detectors Infrastructure – done
    - 10807000 Assemble and Test DAQ and Trigger in Hall A - done

# Install H2 Tank

# New Power Supplies, LCW and control racks

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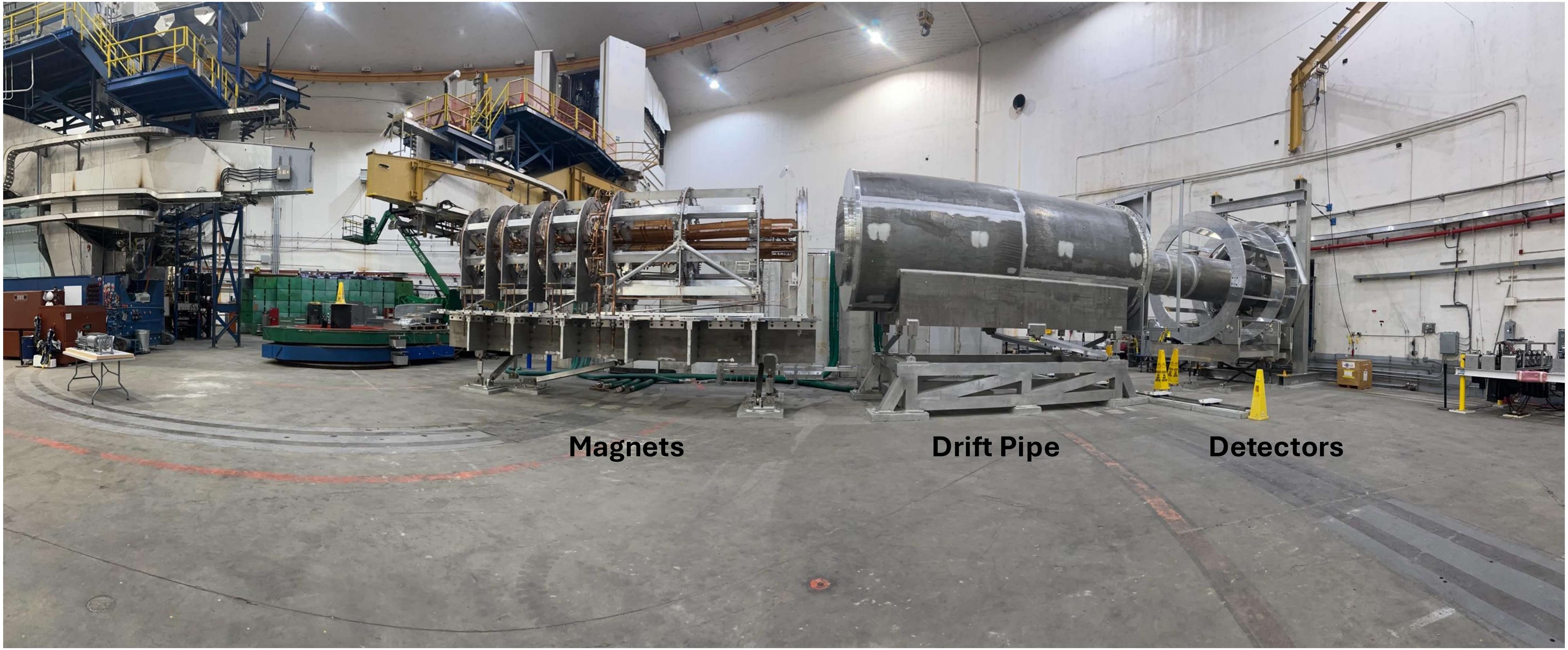
# Pivot Removal and Platform Modifications


# MOLLER Assemble in Hall A



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# MOLLER Assembly steps. Future steps

- Step 0: Hall A legacy experiment and beamline removal **Complete**
- Step 1: Hall A reconfiguration. Spectrometer, Infrastructure, and DAQ installation **Ongoing, 90% complete**
- Step 2: Downstream spectrometer and Main Detector installation. Target piping and assembly. **Next (5 – 6) months**
- Step 3: Target cell and Hall A Infrastructure are complete. Tracking Detector, and Upstream spectrometer installation
- Step 4: MOLLER Assembly in Hall A Complete and KPP demonstration

# Summary

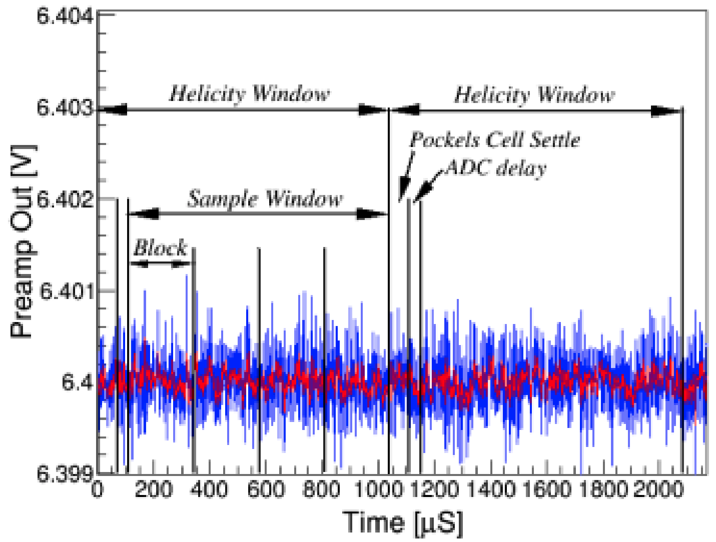
- MOLLER ERR3 is planned for winter 2027
- MOLLER assembly will be completed in March/April 2027
- Low-current parasitic commissioning will begin shortly afterward
- High-current running will start in early July of 2027 --- the goal is to achieve E158 statistics
- Production running will continue in 2028 and will last for two to three years

# Backup

# Asymmetry Measurement Principle

**Overview:**

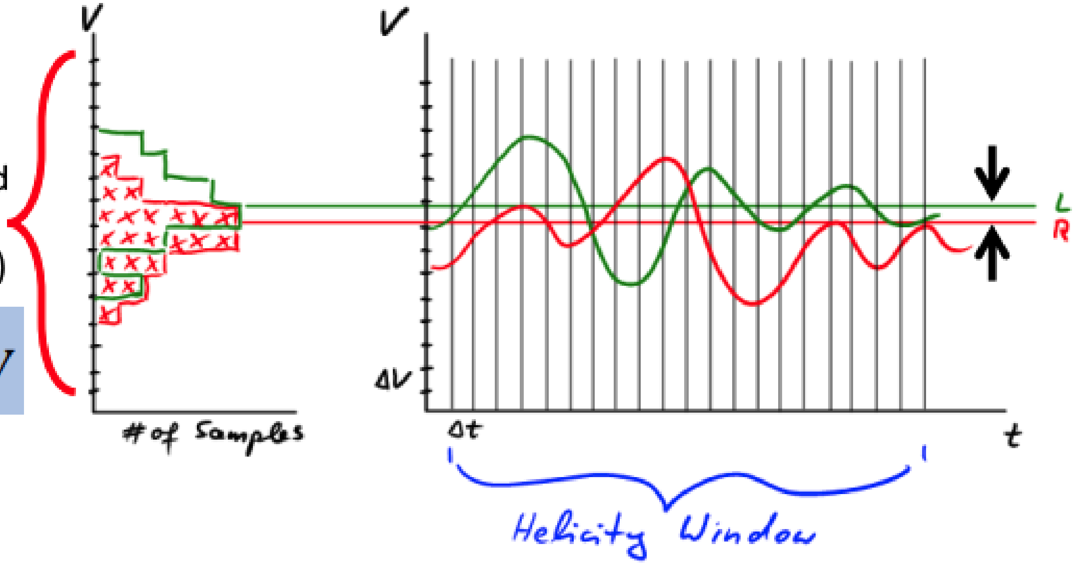
- Trying to measure a $30\ ppb$ asymmetry $\simeq 0.12\ \mu V\ @\ 2V$
- Optimize parameters: PMT signal, ADC range, resolution (timing and amplitude)
- Selected ADC: 18 bit, 15 Msps (~14 705 882 Hz actual)
- Dynamic range: $\pm 4.096\ V$
- Amplitude resolution: $\simeq 4V/2^{17} \simeq 32\ \mu V$
- Massively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

We need oversampling per helicity window to measure the asymmetry.

$\simeq 7000$ samples/window

Higher effective resolution

# Error budget

| Error Source | Fractional Error (%) | |
|---|---|---|
| | Run 1 | Ultimate |
| Statistical | **11.4** | **2.1** |
| Absolute Norm. of the Kinematic Factor | 3 | 0.5 |
| Beam (second moment) | 2 | 0.4 |
| Beam polarization | 1 | 0.4 |
| $e + p(+\gamma) \rightarrow e + X(+\gamma)$ | 2 | 0.4 |
| Beam (position, angle, energy) | 2 | 0.4 |
| Beam (intensity) | 1 | 0.3 |
| $e + p(+\gamma) \rightarrow e + p(+\gamma)$ | 0.6 | 0.3 |
| $\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$ | 1.5 | 0.3 |
| $e + Al(+\gamma) \rightarrow e + Al(+\gamma)$ | 0.3 | 0.15 |
| Transverse polarization | 2 | 0.2 |
| Neutral background (soft photons, neutrons) | 0.5 | 0.1 |
| Linearity | 0.1 | 0.1 |
| Total systematic | **5.5** | **1.1** |

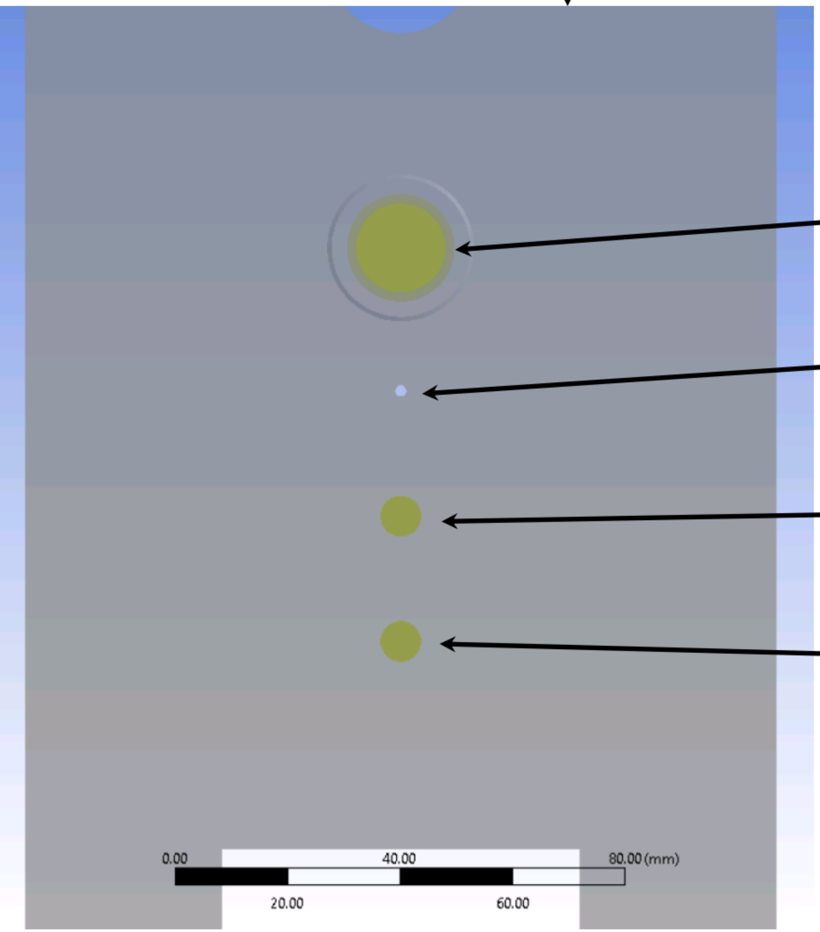
# Path to CD-4. Key Performance Parameters

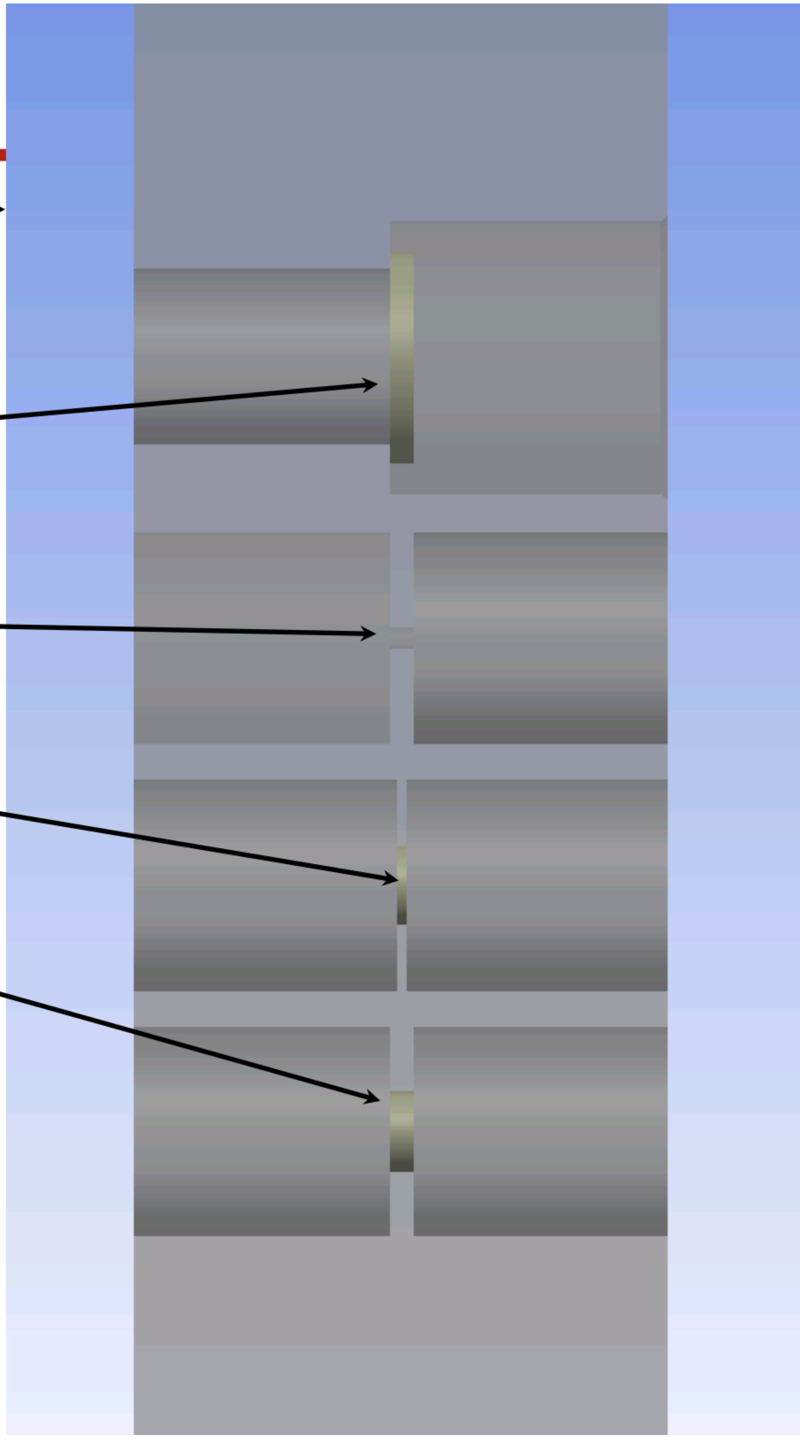
**Table 1: Key Performance Parameters**

| Key Performance Parameters | Threshold KPPs | Objective KPPs |
|---|---|---|
| Cryogenic liquid hydrogen and solid target systems assembled in Hall A and tested. | Demonstrate liquid hydrogen target operation with ≥1.4[1] kW load from heater at nominal operating density. | Demonstrate liquid hydrogen target operation with ≥3.1 kW load from heater at nominal operating density. |
| Upstream and downstream magnetic spectrometers assembled in Hall A and shown to be operable. | Demonstrate operation at ≥96% of nominal operating current[2] and magnetic field strength stability <500 ppm over 24 hours. | Demonstrate operation at design operating current, allowing for operation at ≥10% over-current above the nominal operating current and magnetic field strength stability <100 ppm over 24 hours. |
| Assembly in Hall A and successful operation of thin quartz detector modules with light guides, PMTs and front-end electronics. | Assembly in Hall A of 224 thin quartz detectors. For the detectors in Ring 5, ≥ 75% shall have measured response of ≥ 20 photoelectron (p.e.) for β=1 particles. For the remaining rings, ≥ 35% shall have measured response of ≥10 p.e. for β=1 particles. | Assembly in Hall A of 224 thin quartz detectors. For the detectors in Ring 5, 80% shall have measured response of ≥ 20 photoelectron (p.e.) for β=1 particles. For the remaining rings, ≥ 80% shall have measured response of ≥10 p.e. for β=1 particles. |
| Assembly in Hall A and successful operation of Shower Max detector modules with light guides, PMTs and front-end electronics. | Assembly in Hall A of 28 Shower Max detectors with measured response of ≥75% shall have measured response of ≥100 p.e. for electrons with E>2 GeV or ≥15 p.e. for cosmic ray muons. | Assembly in Hall A of 28 Shower Max detectors with measured response of ≥80% of the Shower Max detectors ≥100 p.e. for electrons with E>2 GeV or ≥15 p.e. for cosmic ray muons. |
| Assembly in Hall A and successful operation of gaseous electron multiplier (GEM) tracking detectors. | Sixteen modules assembled in Hall A and operating with single-plane hit efficiency > 90% for >75% of GEM modules. | Twenty-eight modules assembled in Hall A with single-plane hit efficiency >90%. Single-plane track position residual width σ <1mm. |
| DAQ and trigger systems for readout of detector systems in both counting (low rate) and integrating (high rate) modes assembled in Hall A and stress-tested successfully. | Demonstrate integrating mode readout rate of ≥0.96 kHz (pulser test). Stress-test data transfer rate to Mass-Storage System with ≥500 Mbit/sec pulser test. | Demonstrate integrating mode readout rate of 1.92 kHz (pulser test). Stress-test data transfer rate to Mass-Storage System with ≥1 Gbit/sec pulser test. |
| Assembly in Hall A and confirmation of alignment of spectrometer to beamline axis and collimators, beam pipes, detectors and shielding to beam line and spectrometer magnetic axis. | Alignment tolerances are within threshold tolerances in the WBS 1.08 Systems Requirement Document. | Same but to objective tolerances in documentation. |

# Target Ladder US

Upstream ladder – beam-view and side-view



C12-2 mm

2 mm diameter alignment hole

Al – 1 mm, built-in

Al – 2 mm, built-in

# Target Ladder DS