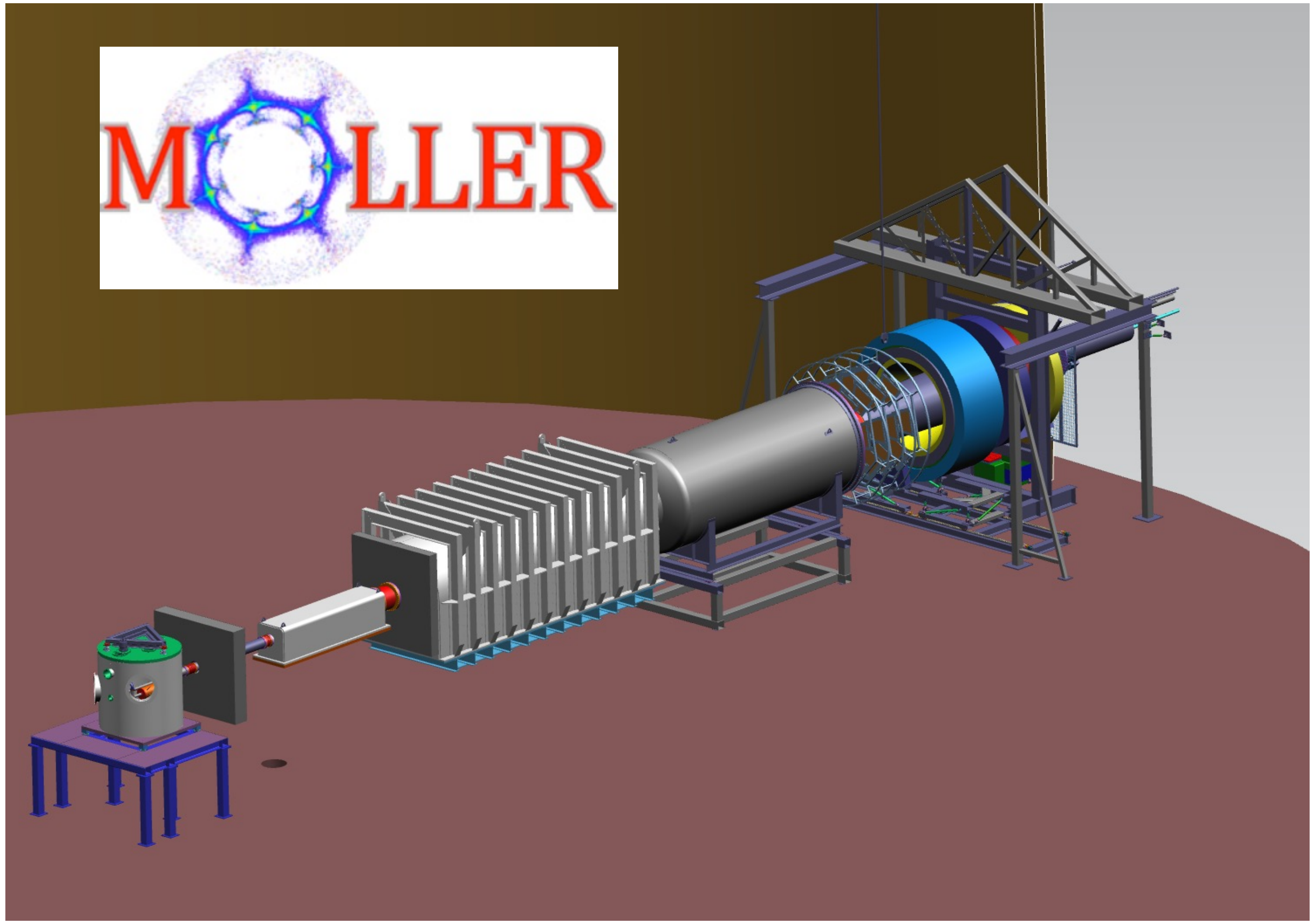
The MOLLER Experiment

Conceptual Design Primer



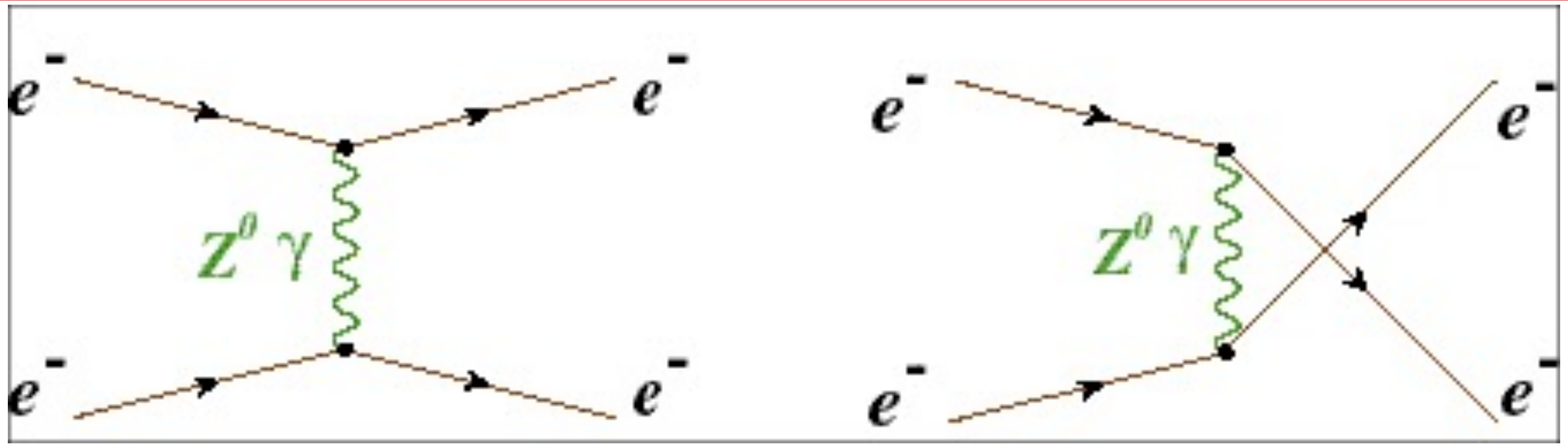
Krishna Kumar,
MOLLER Collaboration Spokesperson
UMass, Amherst

Tuesday, November 2, 2021

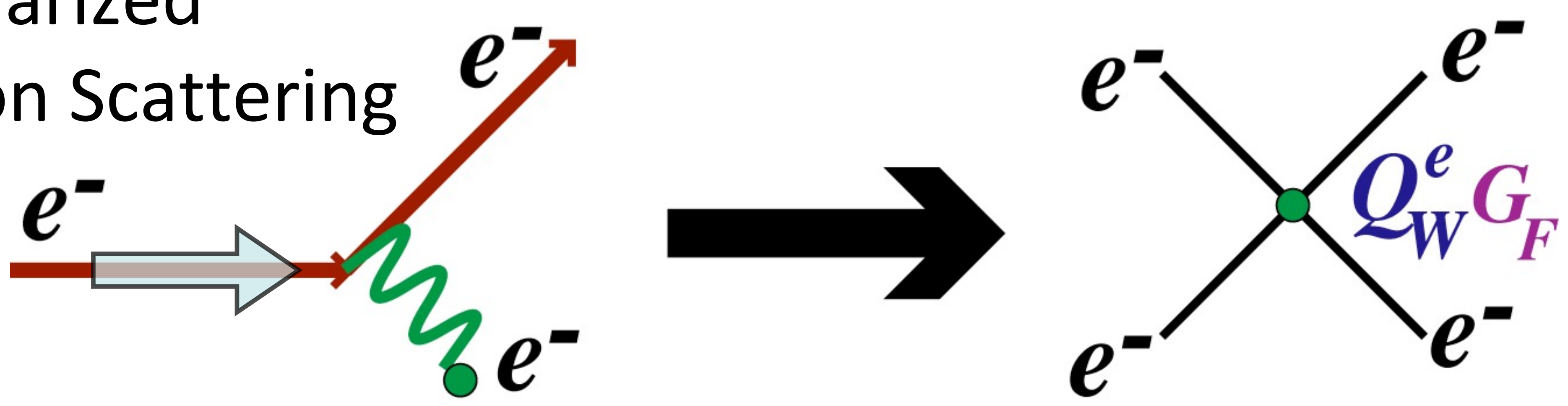
Outline

- **The MOLLER Measurement**
  - The observable and the experimental goal
- **Experimental Technique**
  - Overview of a parity violating electron scattering asymmetry measurement
  - Unique Capabilities of 11 GeV Beam Delivery at Jefferson Laboratory
  - Overview of the MOLLER Apparatus
  - Relevant Experience from Previous Experiments
- **The MOLLER Collaboration**

The Observable: PV Asymmetry in Møller Scattering



Fixed Target Polarized
Electron-Electron Scattering



$$\mathbf{A_{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

COM Scattering Angle

$$= -mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{16 \sin^2 \Theta}{(3 + \cos^2 \Theta)^2} Q^e_W$$

$$Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075$$

The Weak Charge of the Electron

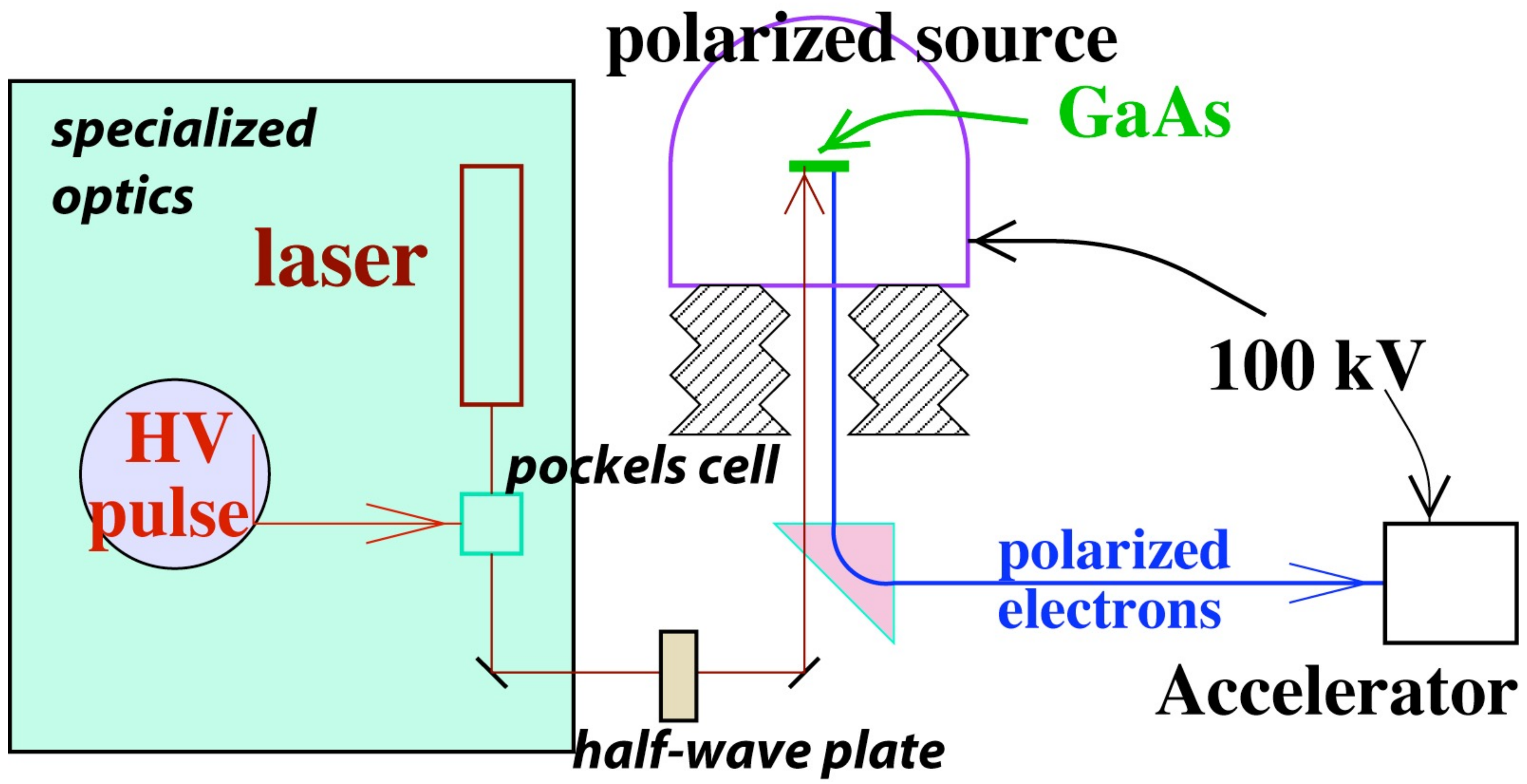
$\delta(Q^e{}_W) = \pm\, 2.1\ \%\ (stat.) \pm 1.1\ \%\ (syst.)$

Jefferson Lab polarized electron beam
11 GeV, 65 μA *90% beam polarization*

A_{PV} ~ 32 ppb ***$\delta(A_{PV})$ ~ 0.8 ppb***

- **Unique sensitivity to TeV scale physics coupling more to leptons than to quarks**
- **Purely leptonic low Q^2 reaction: theory prediction accurately calculable with negligible hadronic physics uncertainty**

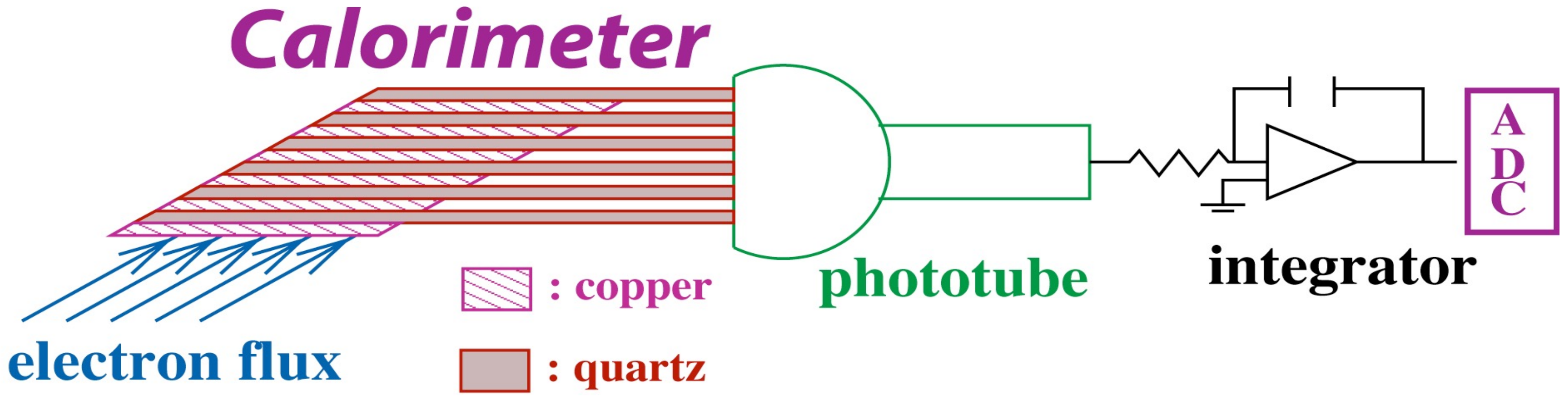
Conceptual Overview of the Experimental Measurement Technique



·**Optical pumping of a GaAs wafer:** "black magic" chemical treatment to boost quantum efficiency

·**Rapid helicity reversal:** polarization sign flips > 100 Hz to minimize the impact of drifts

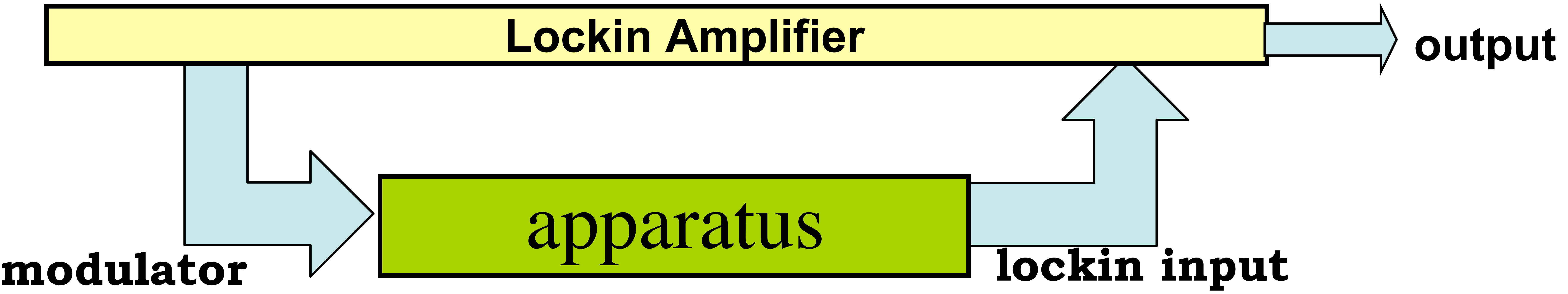
·**Helicity-correlated beam motion:** under sign flip, beam stability at the sub-micron level



"Flux Integration": very high rates

direct scattered flux to background-free region

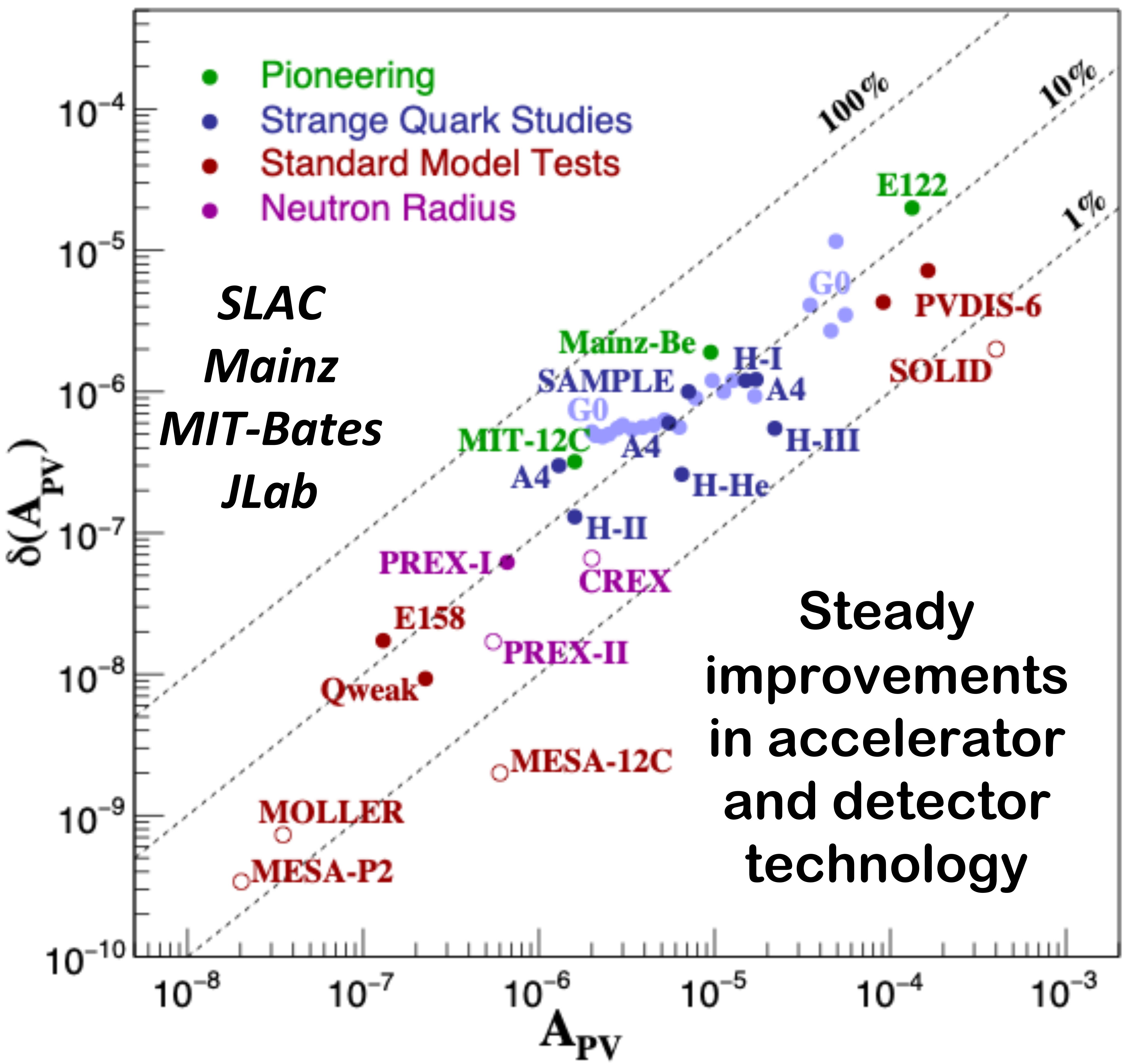
Tiny signal buried in known background



Apparatus:

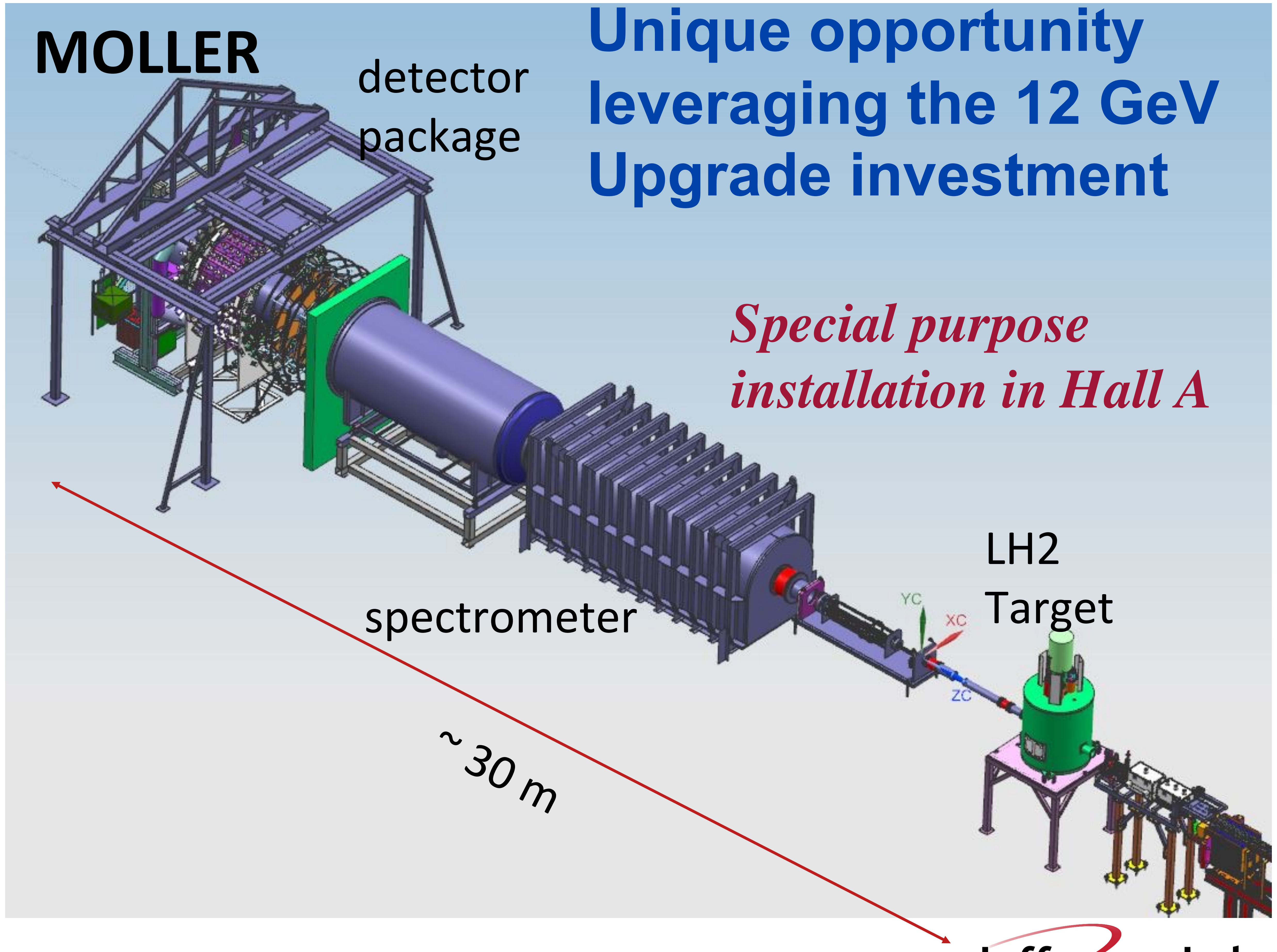
beam, target, spectrometer, detectors and accelerator all interconnected!

4th Generation PVES Experiment at JLab



State of the Art

- sub-part per billion statistical reach and systematic control
- sub-1% normalization control



Variety of Physics Topics:

continuous interplay between hadron physics and electroweak physics

Asymmetry Measurement Overview

Suppose instantaneous signal rate ~ 100 GHz and the beam helicity is reversed at 2 kHz

1 kHz Pulse Pair Width: ~100 ppm → 10 Billion Pairs: 1 ppb (average 10^7 s)

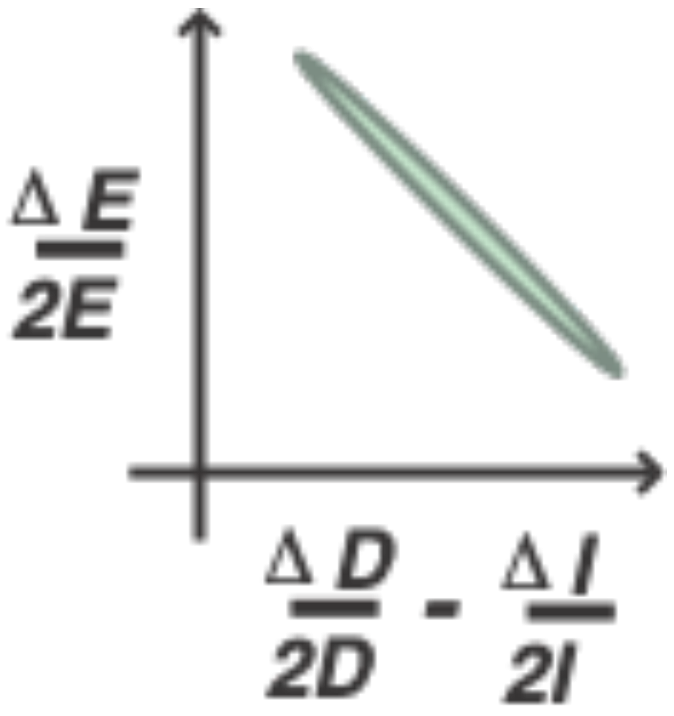
Detector D, Current I: F = D/I

$$A_{pair} = \frac{F_R - F_L}{F_R + F_L}$$

$$A_{pair} = \frac{\Delta F}{2F} + \Delta A$$

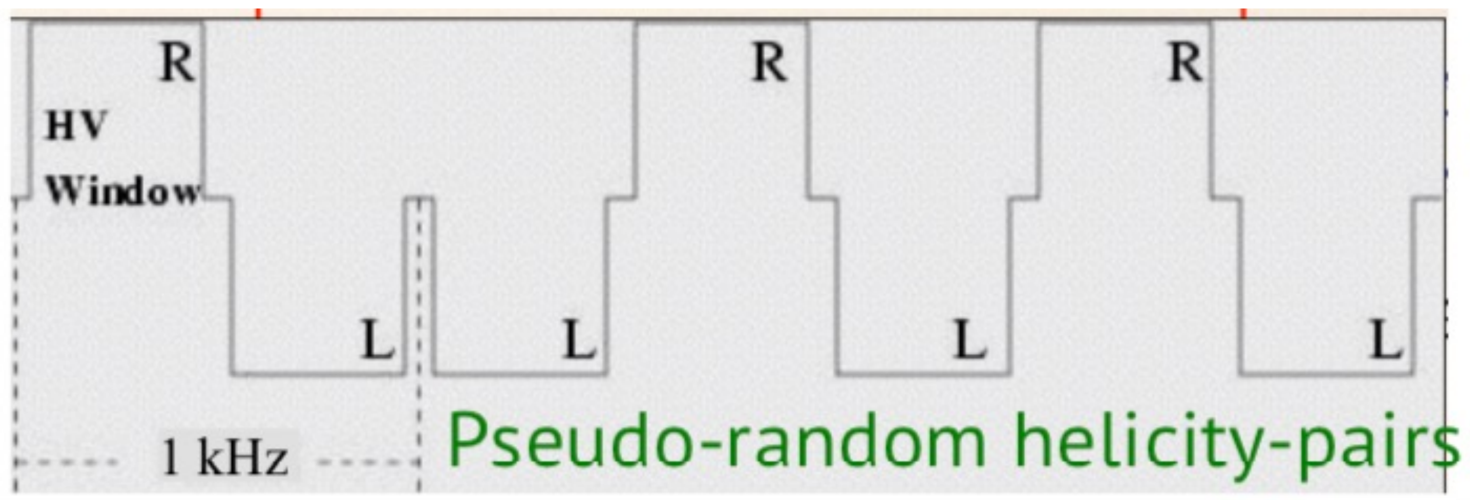
$$\left(A_{expt}\right)_i = \left(\frac{\Delta F}{2F} - \frac{\Delta I}{2I}\right)_i - \sum_j \left(\alpha_j \left(\Delta X_j\right)_i\right)$$

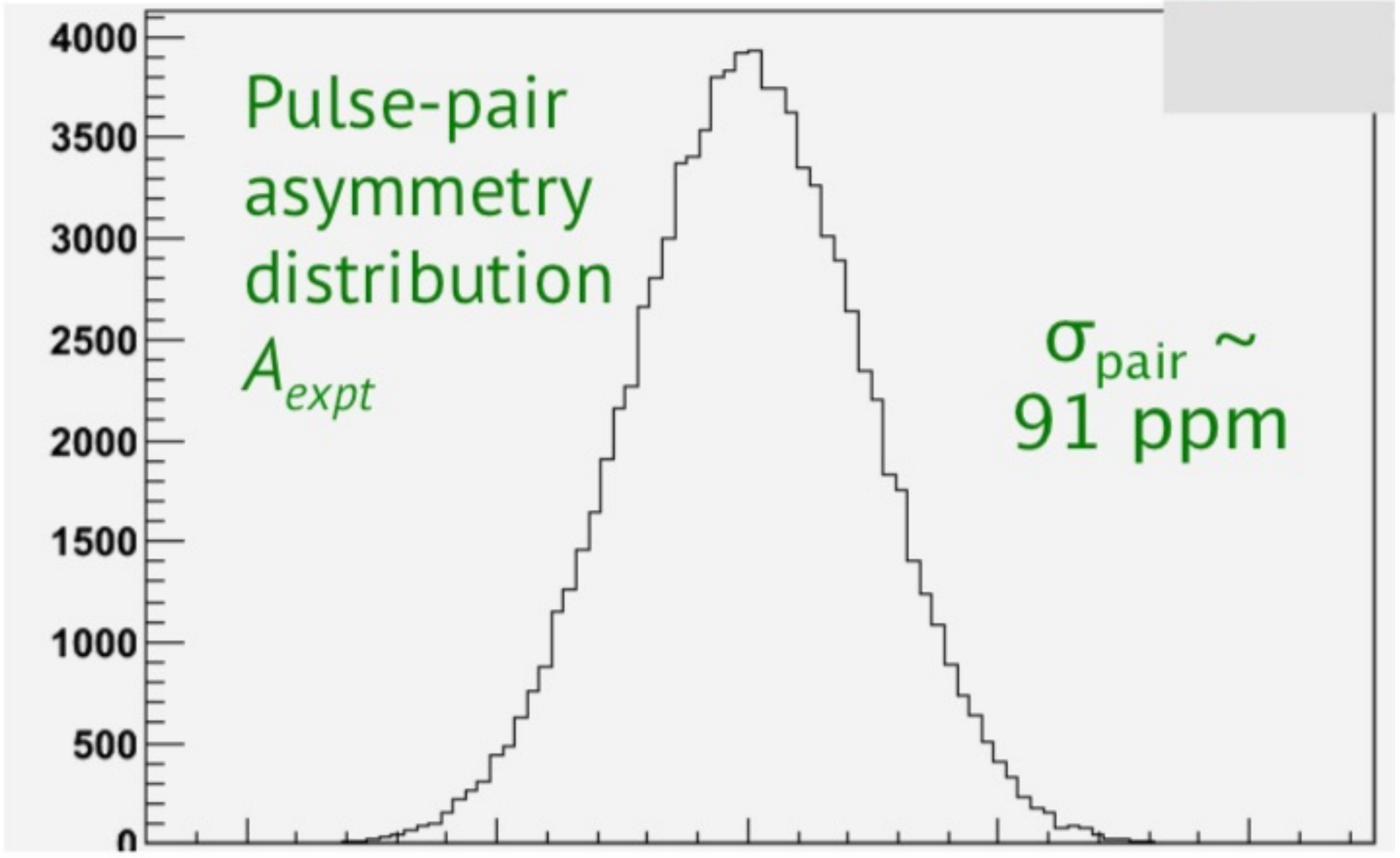
I order: x, y, θ_x, θ_y, E
II order: e.g. spot-size



Must minimize both random and helicity correlated fluctuations due to electron beam trajectory, energy and spot-size

After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 100 ppm (1kHz pairs); central value then reflects A_{phys}





$$\sigma_{A_{expt}} = \frac{\sigma_{pair}}{\sqrt{N_{pair}}} = \frac{91\,\text{ppm}}{\sqrt{30\times 10^9}} = 0.5\,\text{ppb}$$

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

Essential Characteristics of the CEBAF Polarized Electron Beam

Highly intense, stable, high energy electron beam with longitudinal beam polarization

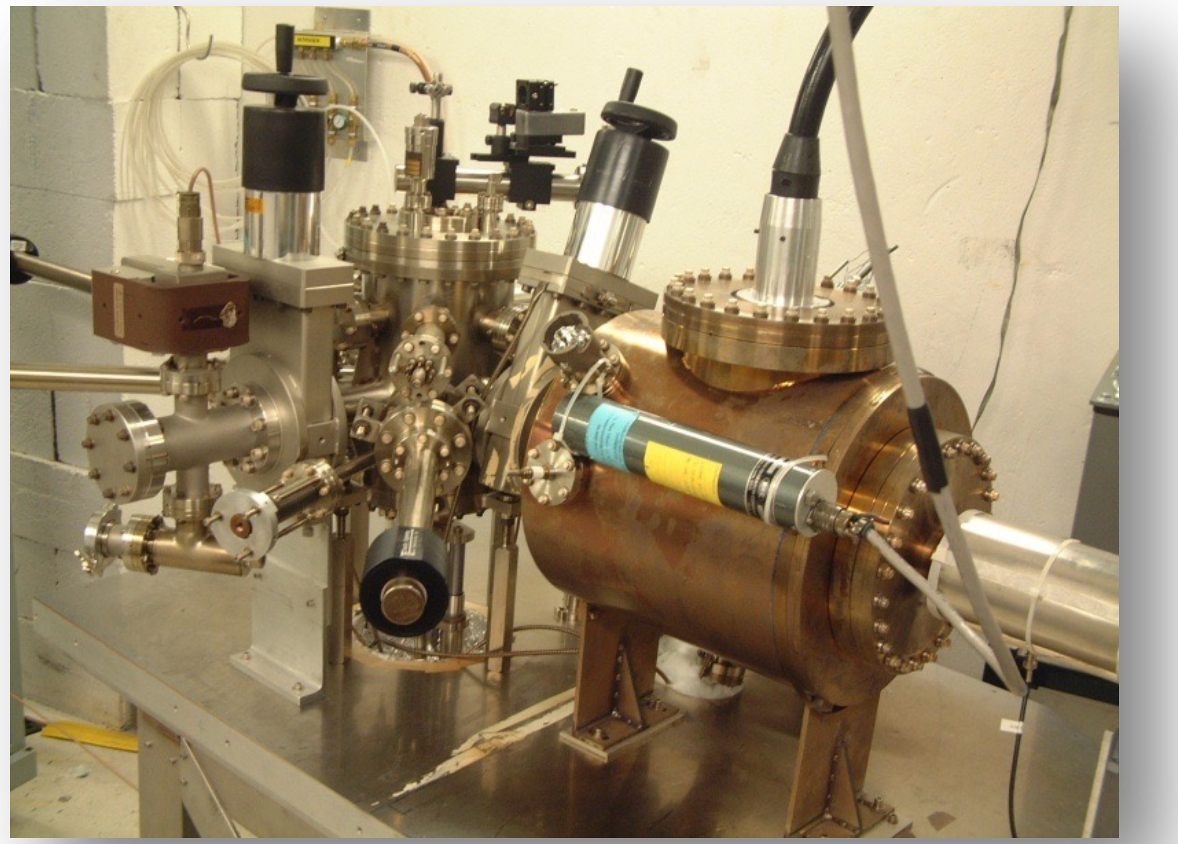
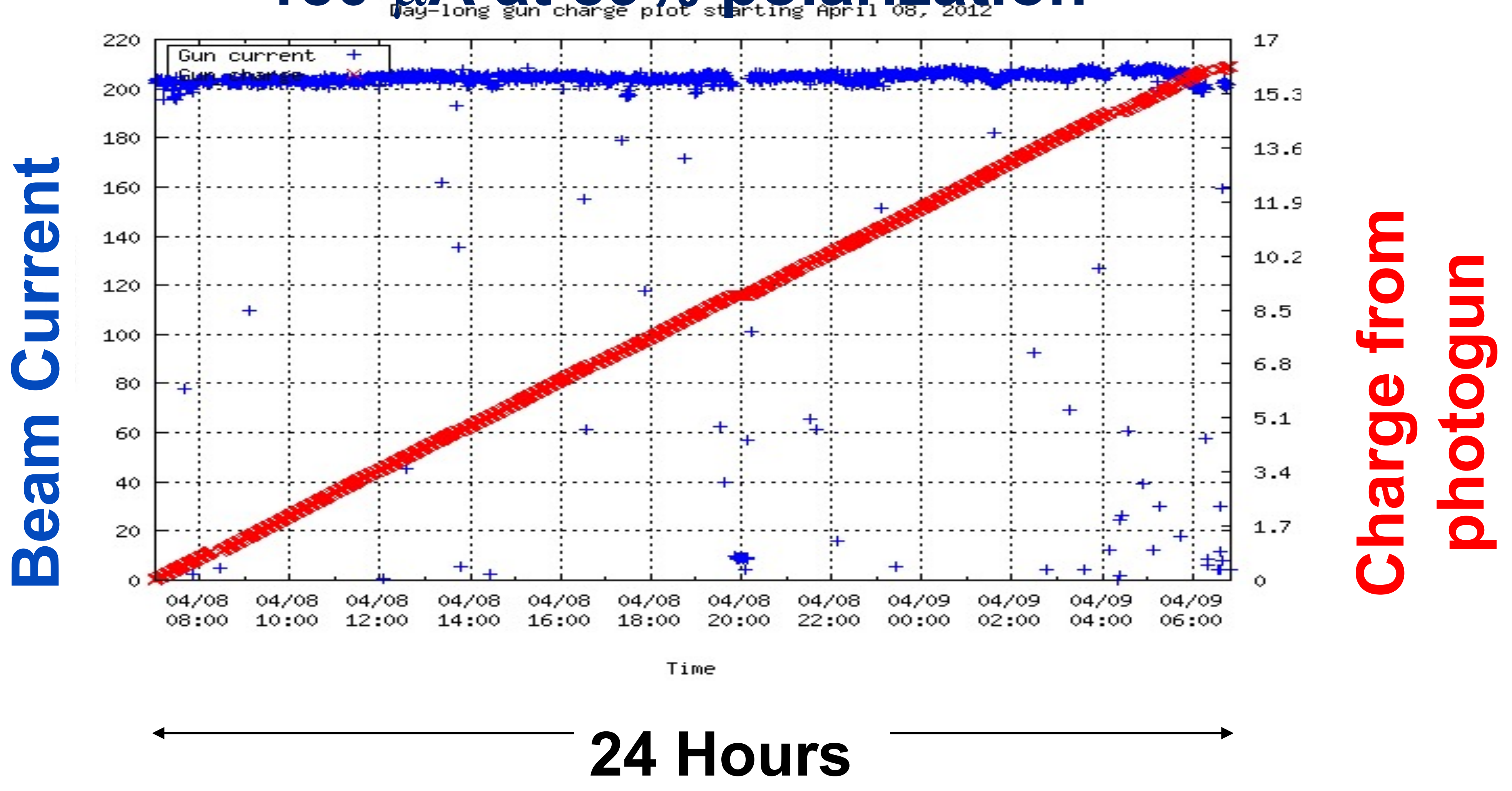


Figure of merit rises linearly with beam energy: experiment not viable below a few GeV with current state-of-the-art

Record Performance (2012):
180 μA at 89% polarization



MOLLER will plan to use 1.96 kHz reversal to reverse the electron beam helicity

CEBAF beam properties: 2 kHz time scale (~ppm, microns) AND days (~ppb, nm) must be carefully tuned, actively monitored and maintained with proper diagnostics

Systematic control likely impossible without a "cold" "CW" machine

Extensive operation experience in manipulating injector characteristics to control systematics

10's of ppb beam charge asymmetry and ~ 1 nm control of position asymmetry

MOLLER measurement cannot be done elsewhere; JLab's beam characteristics are unique

Projected Uncertainty Tables

$$\sigma_{A_{cxpt}} = \frac{\sigma_{pair}}{\sqrt{N_{pair}}}$$

Contributions to σ_{pair} - "Pair width"

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

$$\sigma_{A_{cxpt}} = 0.54\,\text{ppb} \quad A_{cxpt} \sim 26\,\text{ppb} \quad \frac{\sigma_{A_{cxpt}}}{A_{cxpt}} = 2.1\%$$

$$A_{PV} = \frac{\frac{A_{cxpt}}{P_b} - f_{bkgd}A_{bkgd}}{1 - f_{bkgd}}$$

Uncertainty budget for A_{PV}

Error Source	Fractional Error (%)
Statistical	2.1
Absolute Norm. of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Linearity	0.1
Total systematic	1.1

All systematics required at sub-1% level

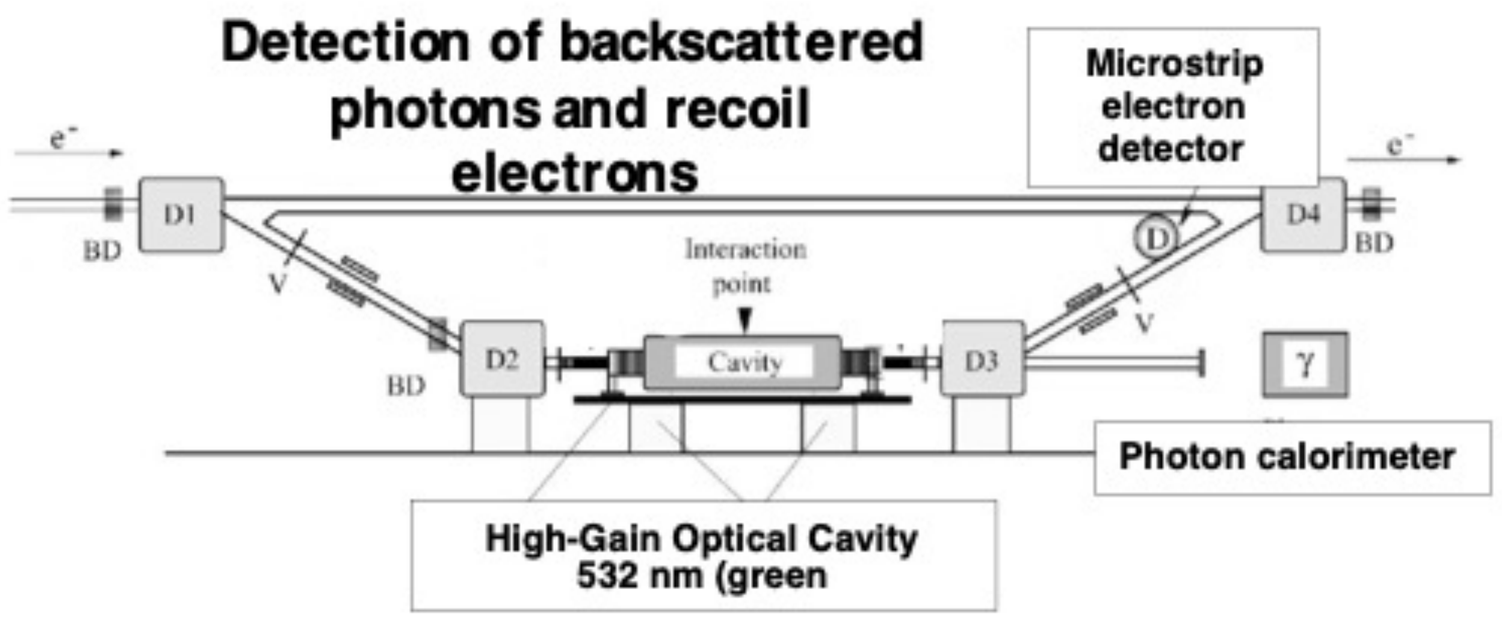
$$\text{Combined} \ \frac{\delta A_{PV}}{A_{PV}} = 2.4\%$$

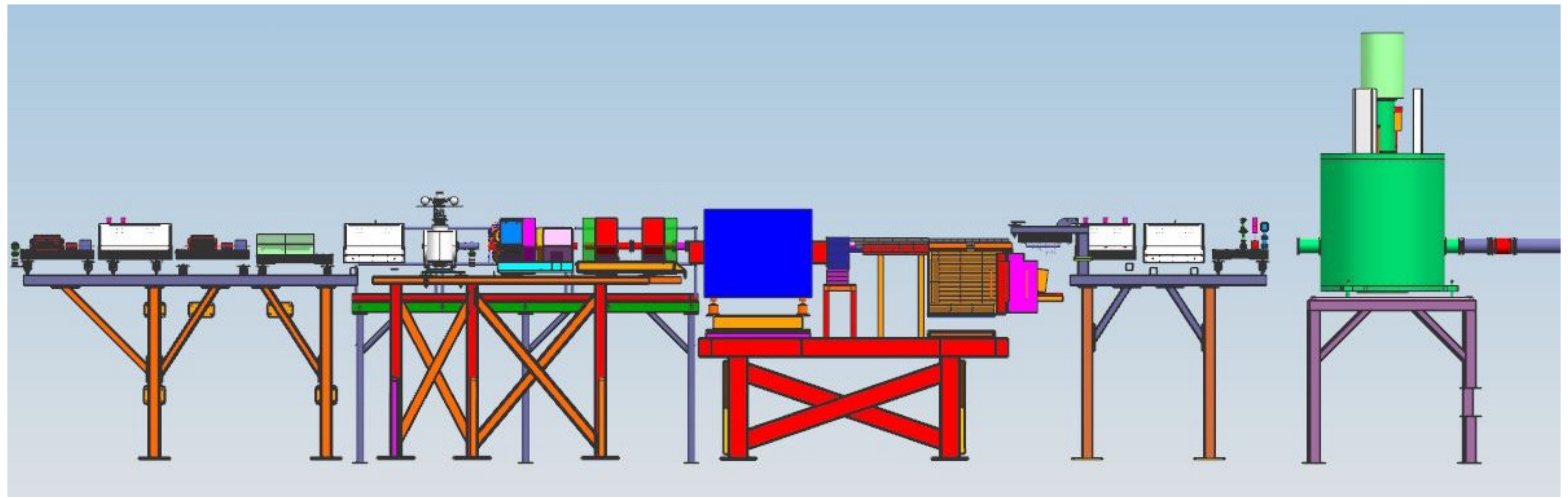
Experimental design driven by these goals:

Statistical error: Measure A_{expt} with precision ~ 2%

Systematic error: Measure and/or minimize all systematic error sources so their individual contributions are < 1%, resulting in statistics limited experiment

Beamline, Target and Polarimetry



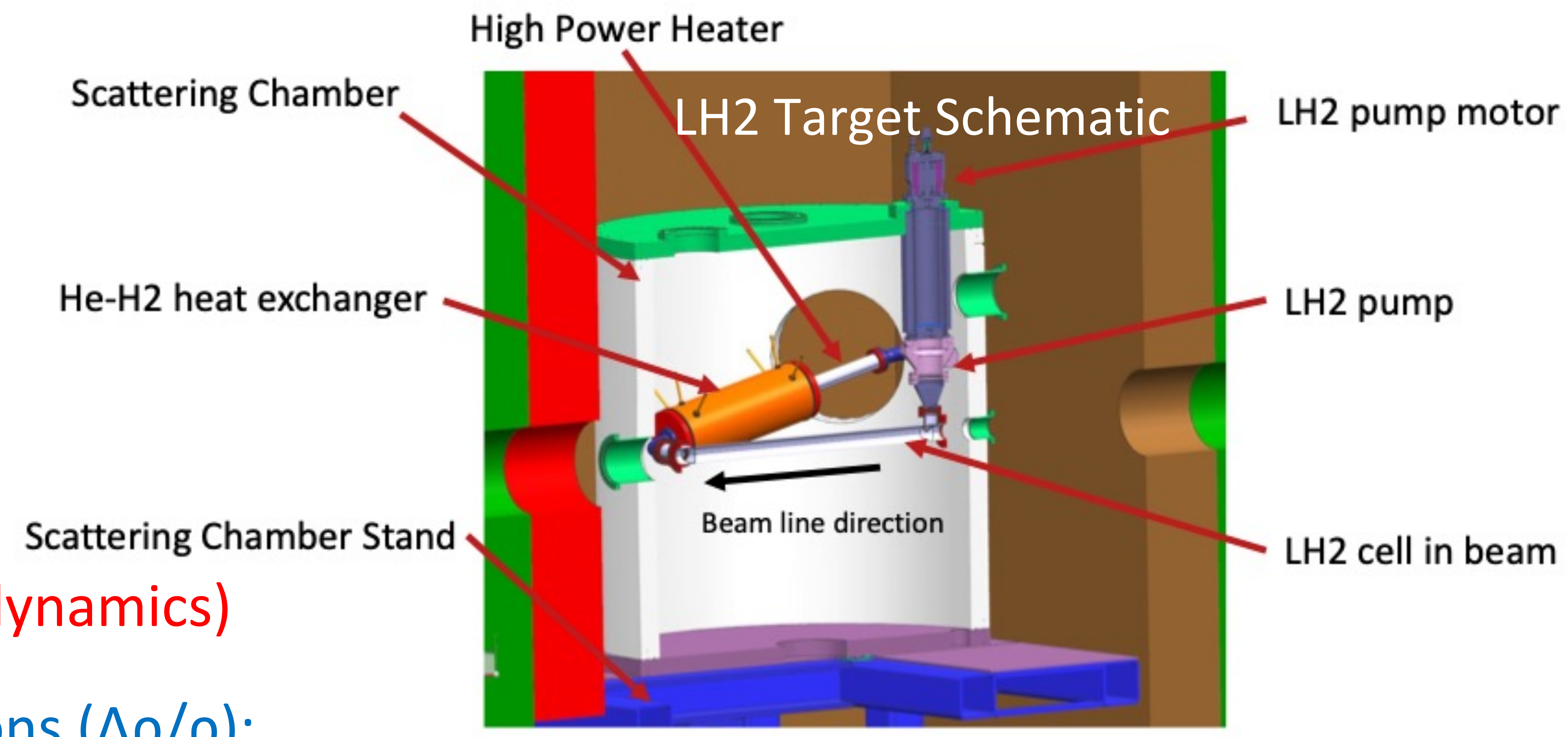


Beamline and Beam Monitoring

- Redundant position, angle, intensity monitoring
- Intensity, position monitor resolution requirements

Electron Beam Polarimetry

- Two independent measurements
- Compton: continuous monitor
- Møller: invasive at low beam current



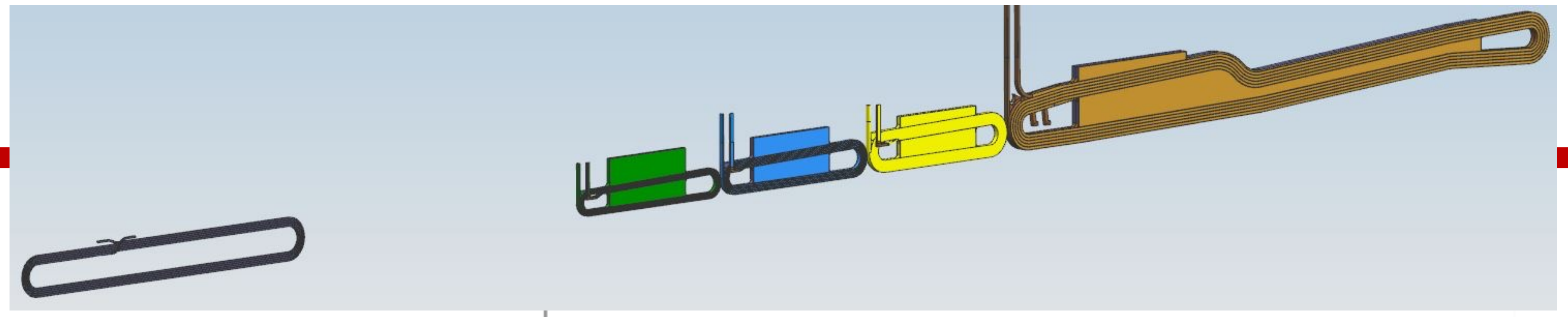
Liquid Hydrogen Target

- up to 70 μA on 125 cm LH_2 target - 3.7 kW
- Q_{weak} experience: use of CFD (computational fluid dynamics)

Main requirement: minimize target density fluctuations ($\Delta\rho/\rho$):

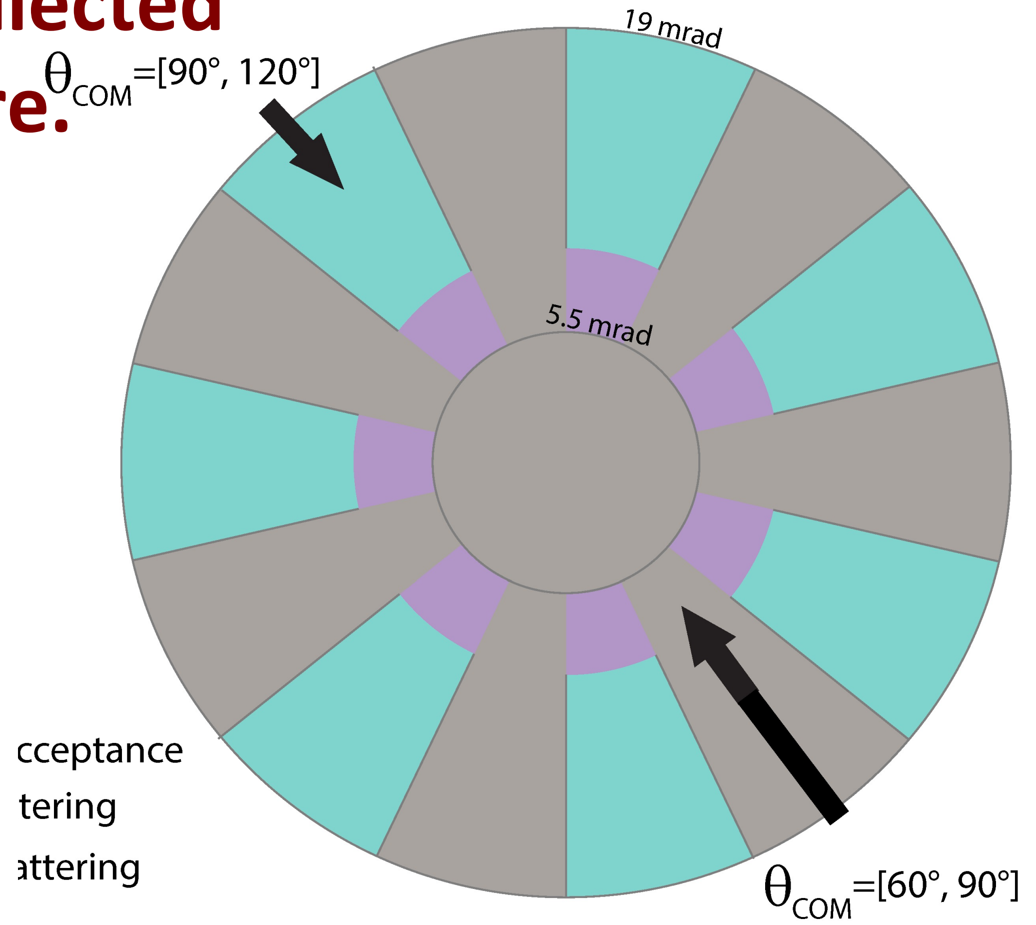
Γ_{target} < 30 ppm for 70 μA, 5x5 mm^2 raster, 1.92 kHz flip

Spectrometer and Collimation

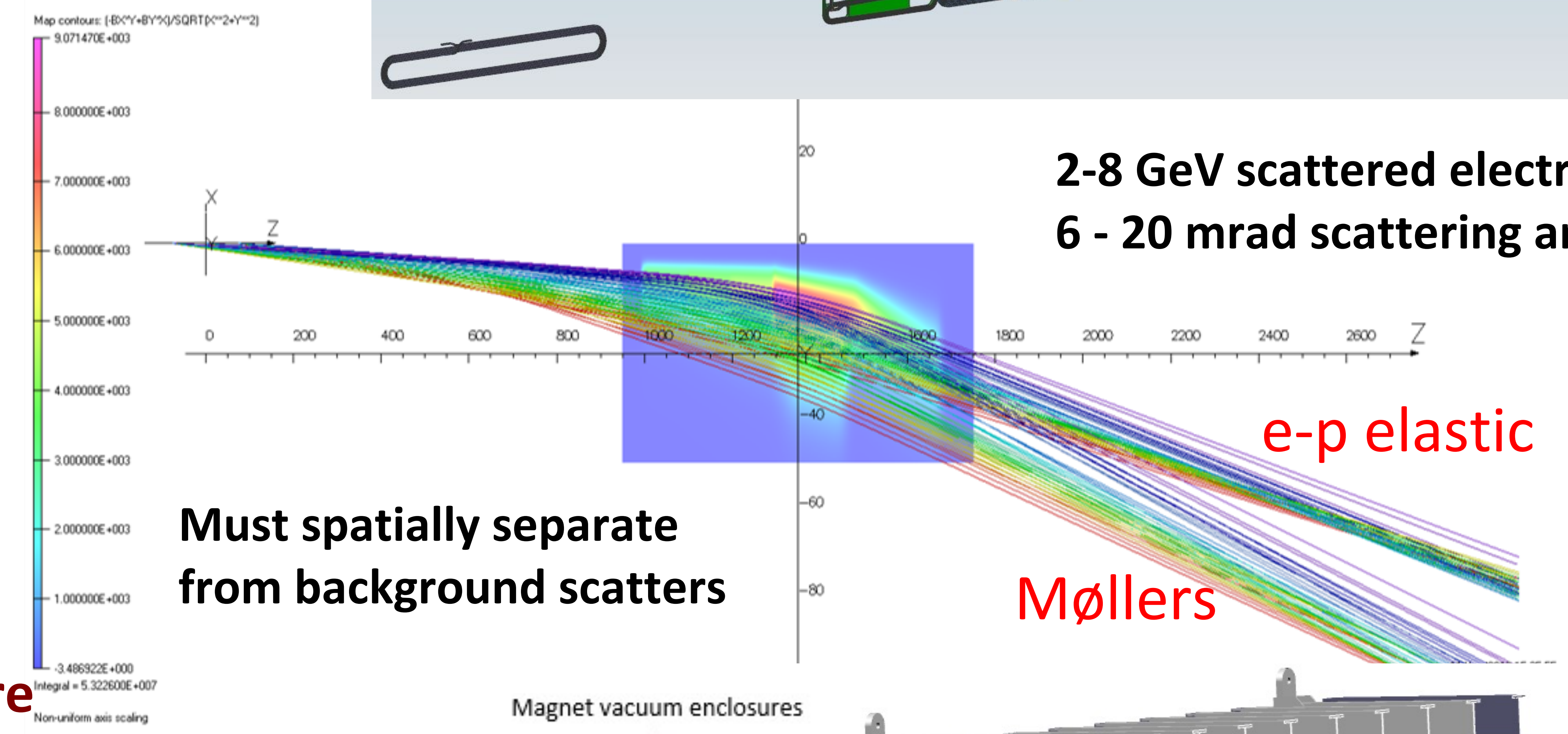


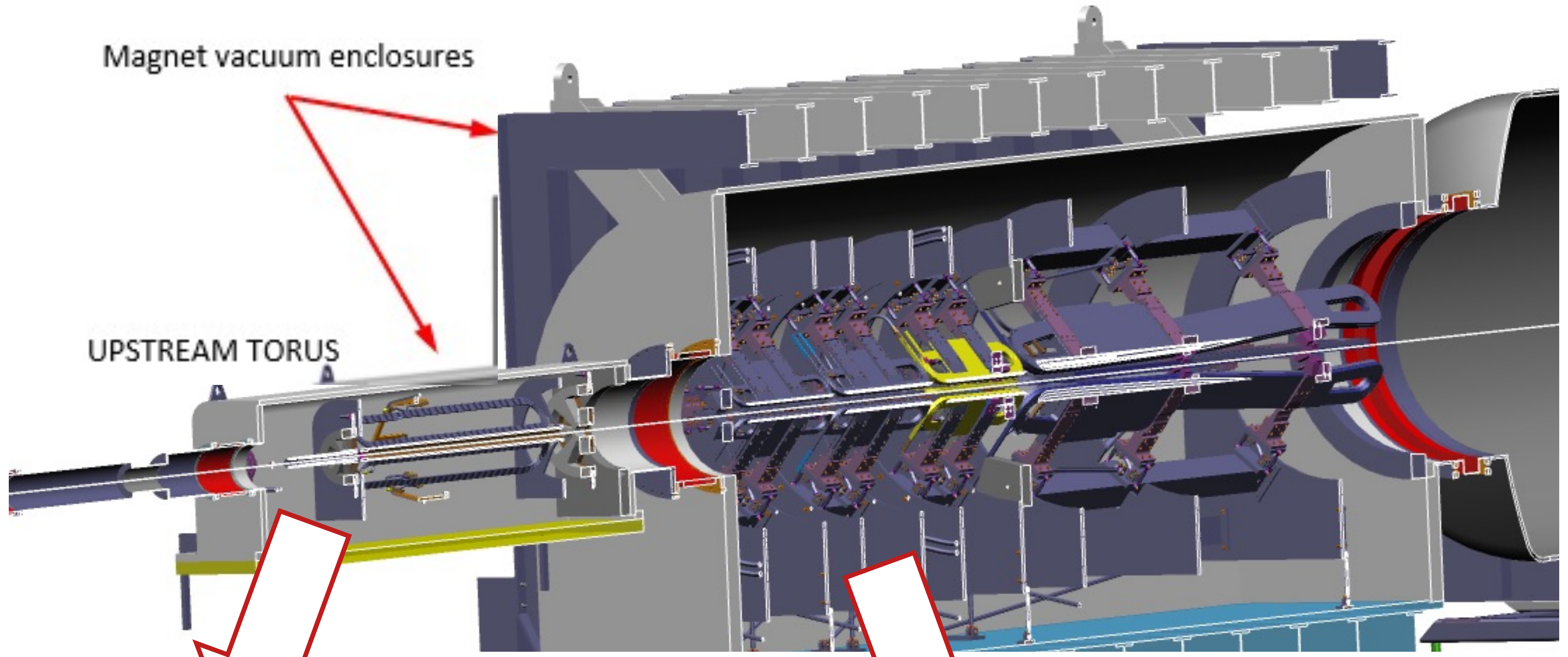
- Accept all Møller scattered electrons in range Θ_{CM} = 50° – 130°
- **Exploit identical particle nature for 100% azimuthal acceptance**; needs odd number of coils

…are collected over here.



The rays that are blocked here…





Collimation system requirements:

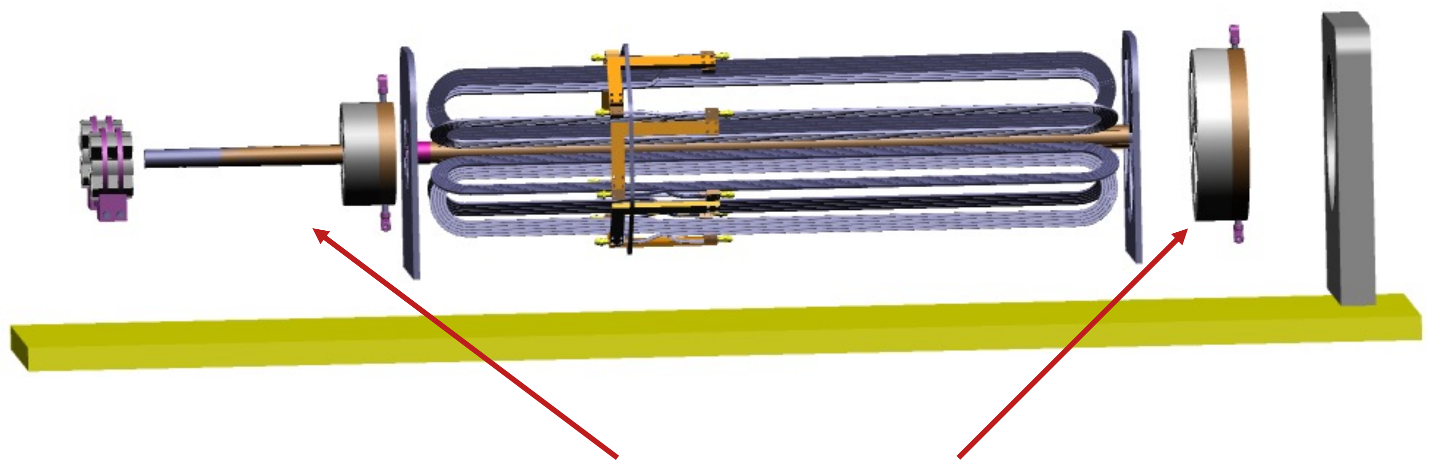
- define Møller electron acceptance
- block detector line-of-sight to target and localize backgrounds
- shield the toroid coils

Designed to achieve “two-bounce” criteria for low energy neutral backgrounds

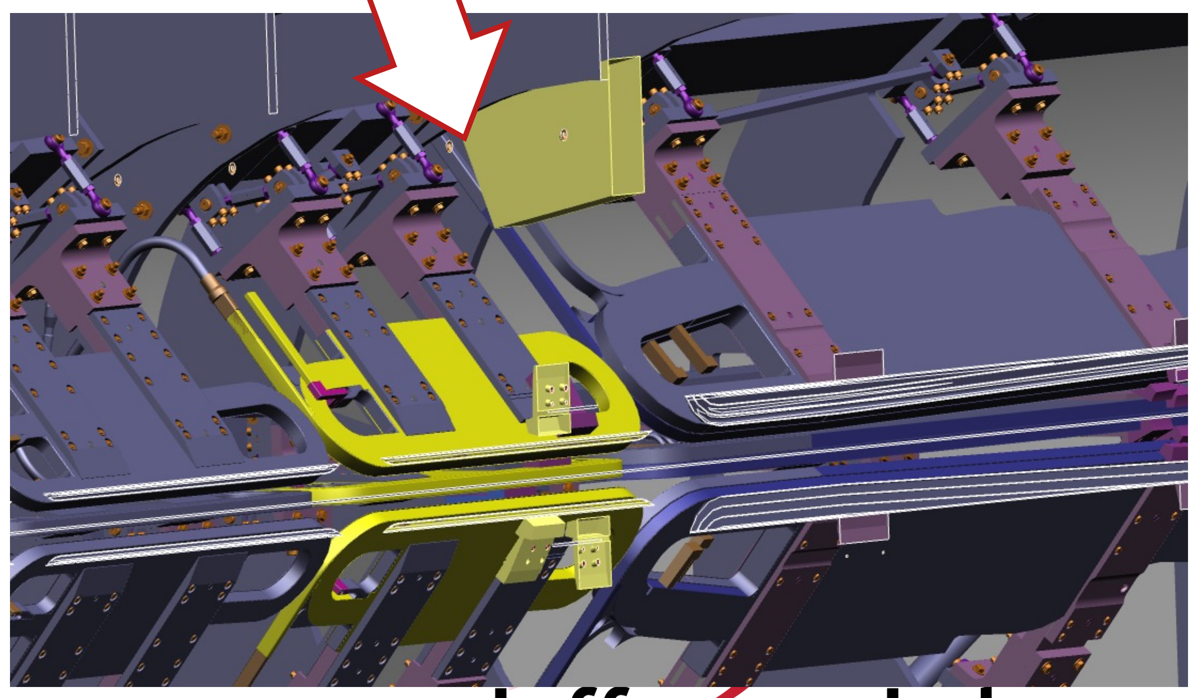
Most critical required tolerances:

±200 μm machining tolerance on defining inner edge

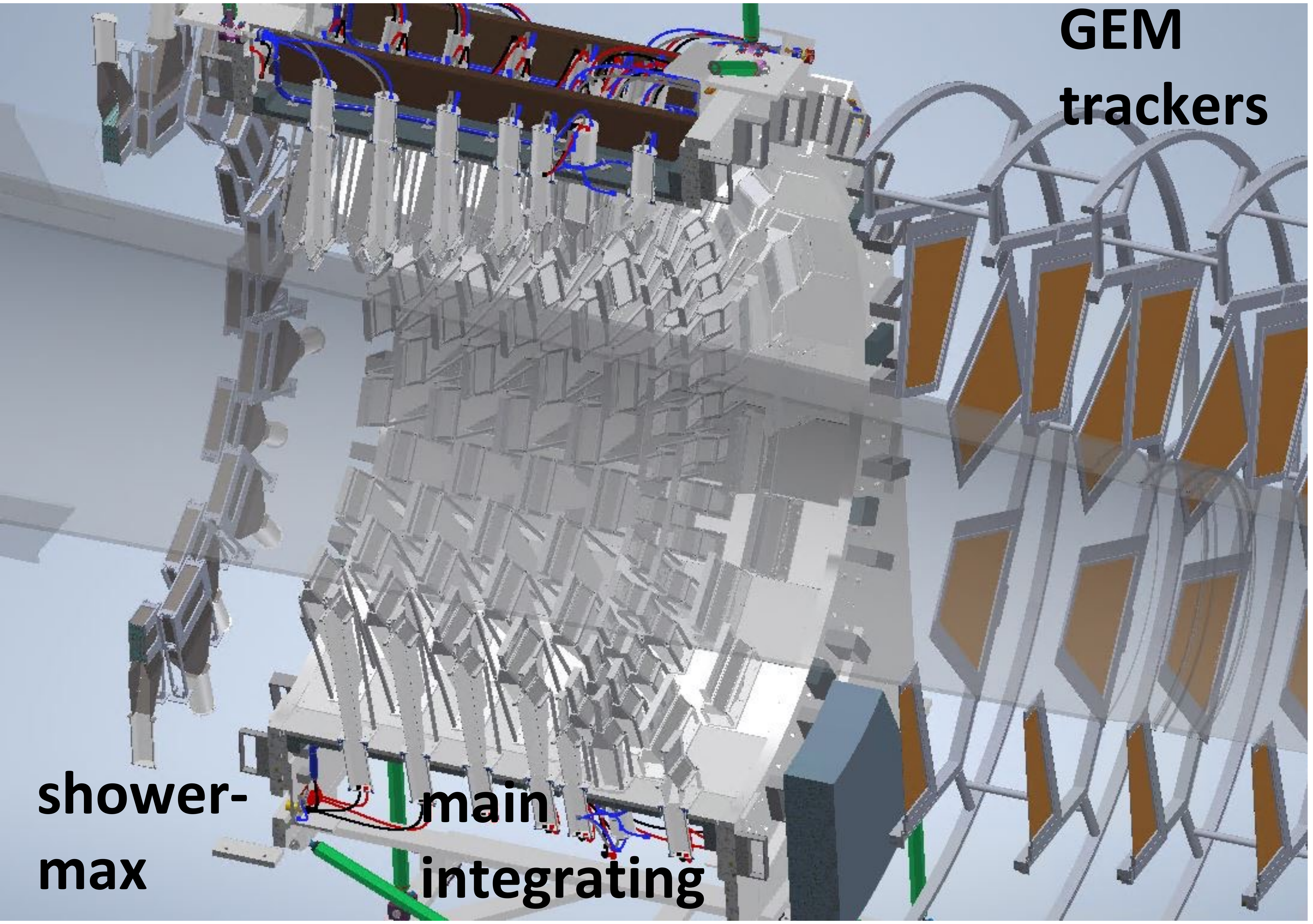
±1 mm positioning tolerance for most critical collimat



Primary collimators



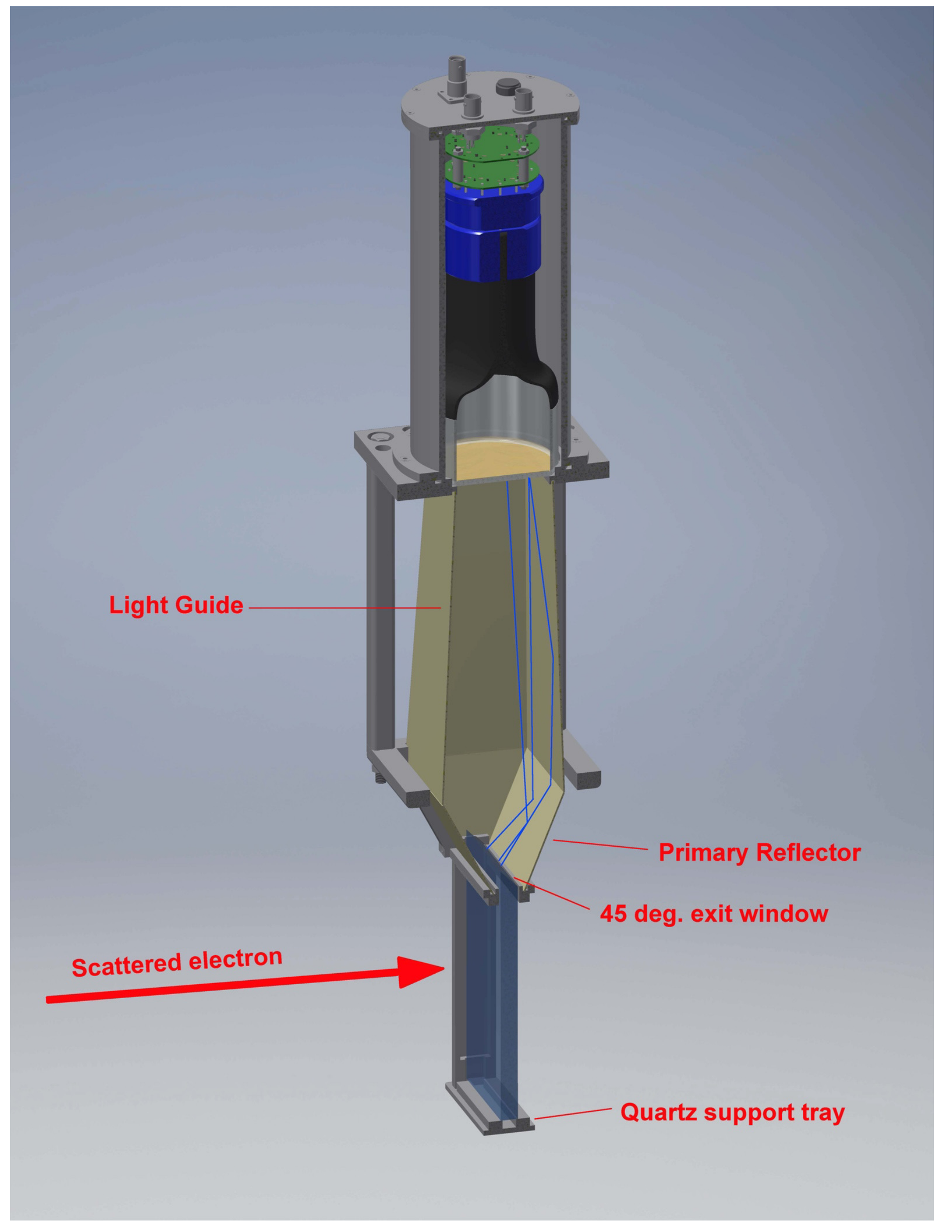
Primary and Auxiliary Integrating and Tracking Detectors

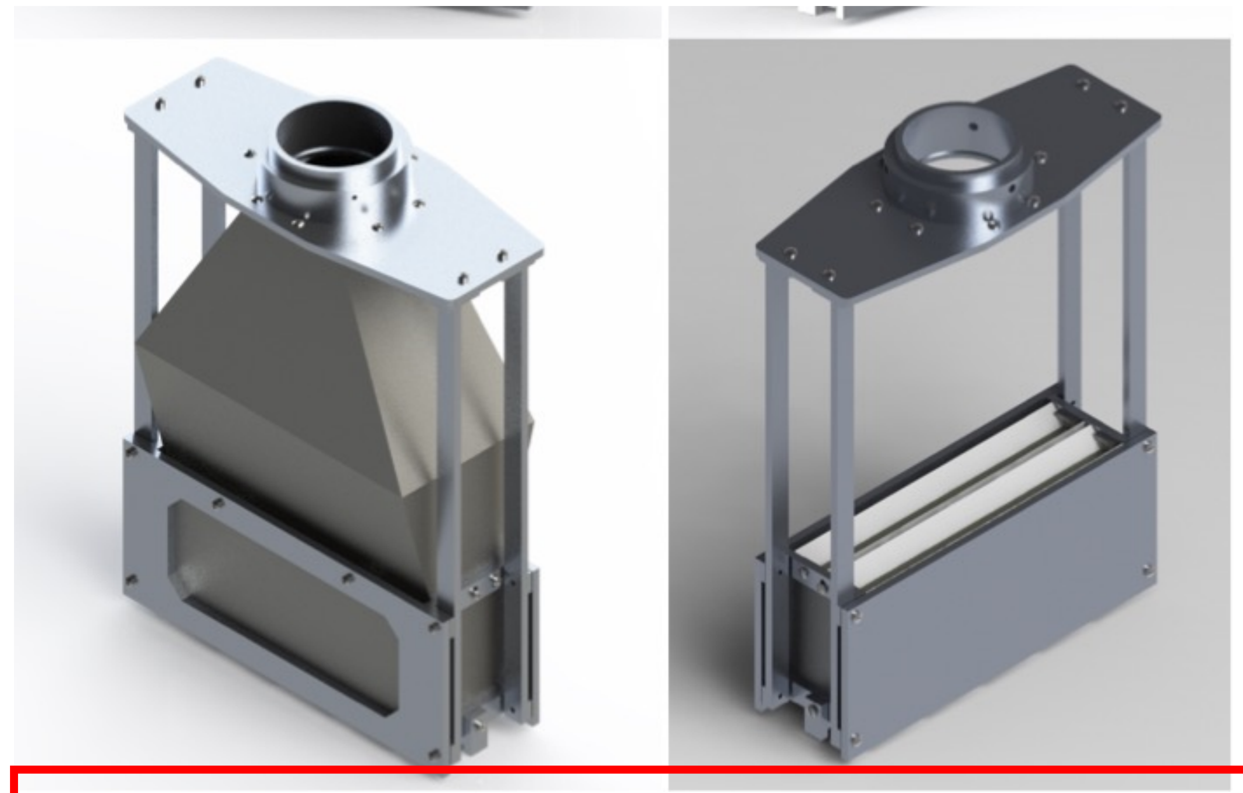


Tracking (counting mode) detectors:

spectrometer calibration, electron scattering angle distribution, and background measurements

- Gas electron multipliers (GEM) detectors
- "Pion" acrylic Cherenkov detectors





Key requirement:
Detector resolution < 25%
for detector excess noise < 4%

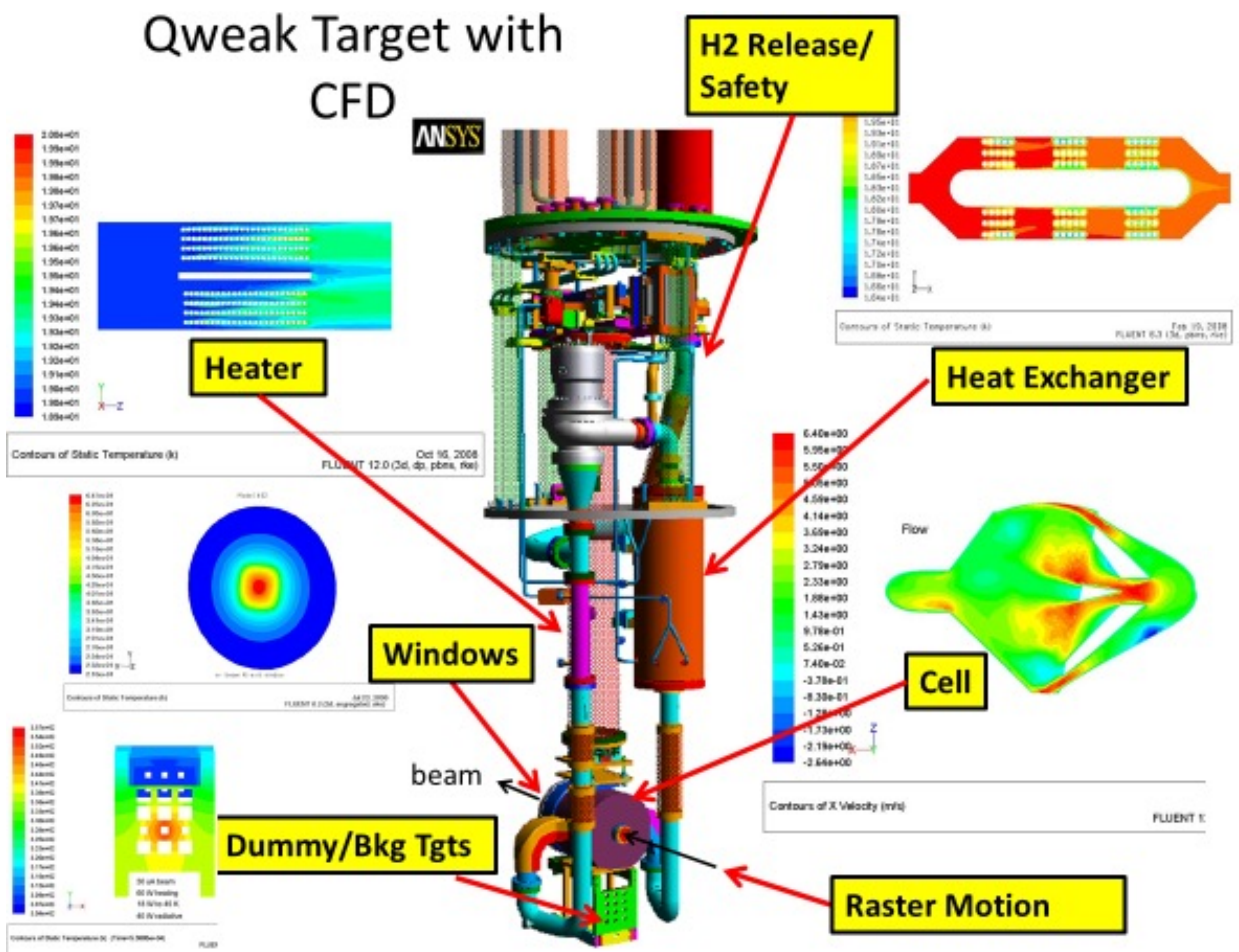
Integrating (current mode) detectors:

asymmetry measurements of both signal and background, and beam and target monitoring

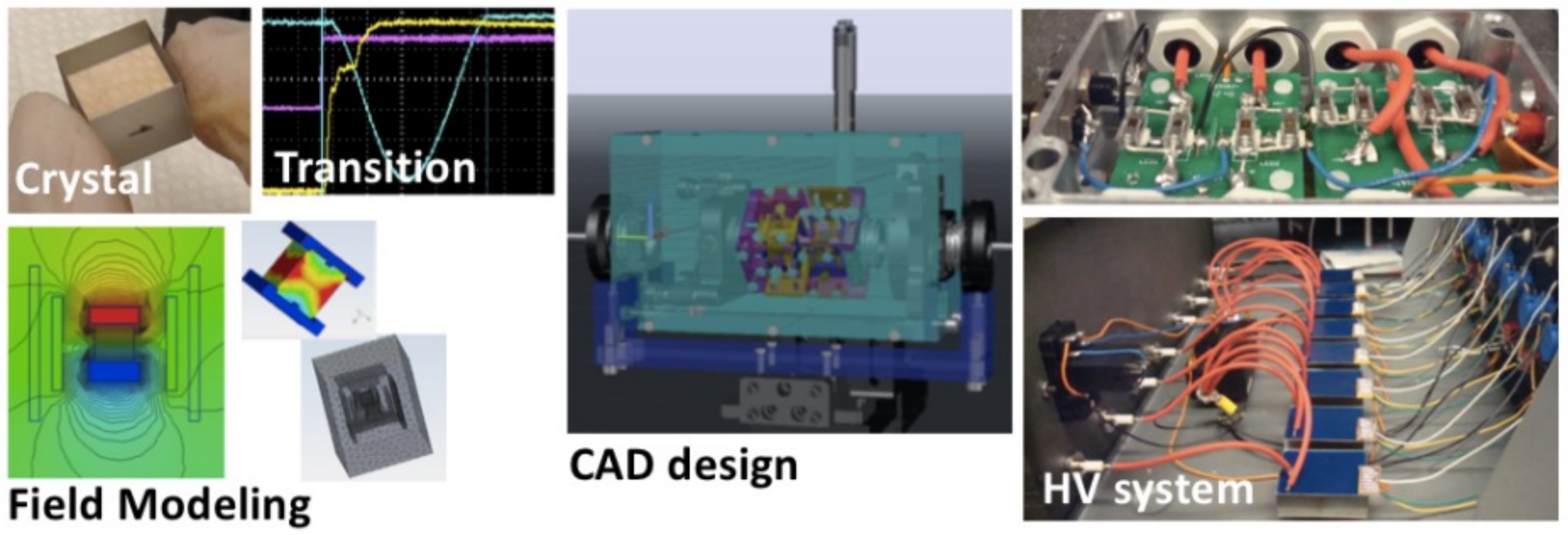
Readout Electronics:

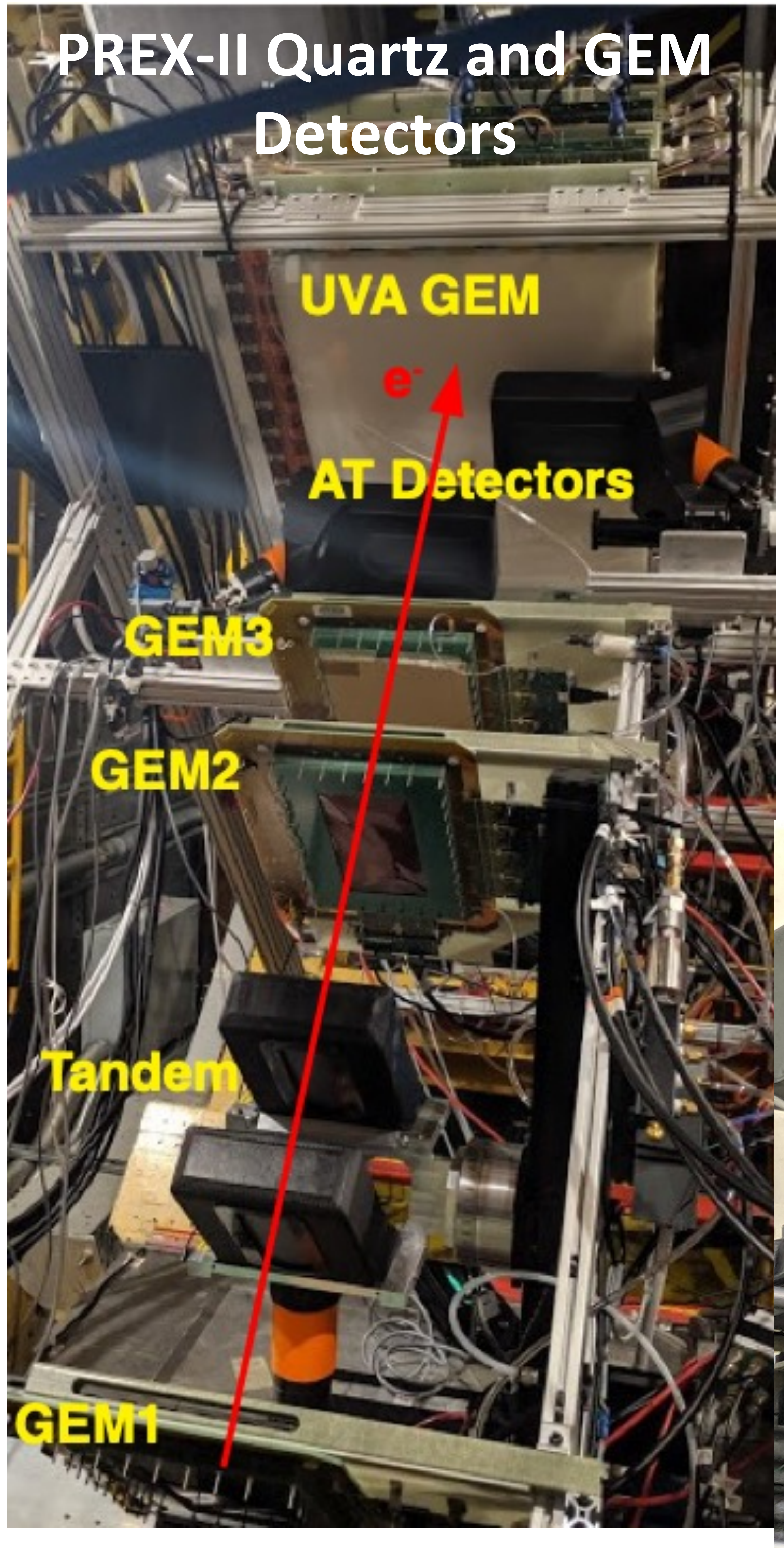
- Integration mode DAQ & trigger
  – *Collect & analyaize100% of the helicity windows*
- Counting mode DAQ & trigger
  – *input rates between 10~kHz and 300~kHz*

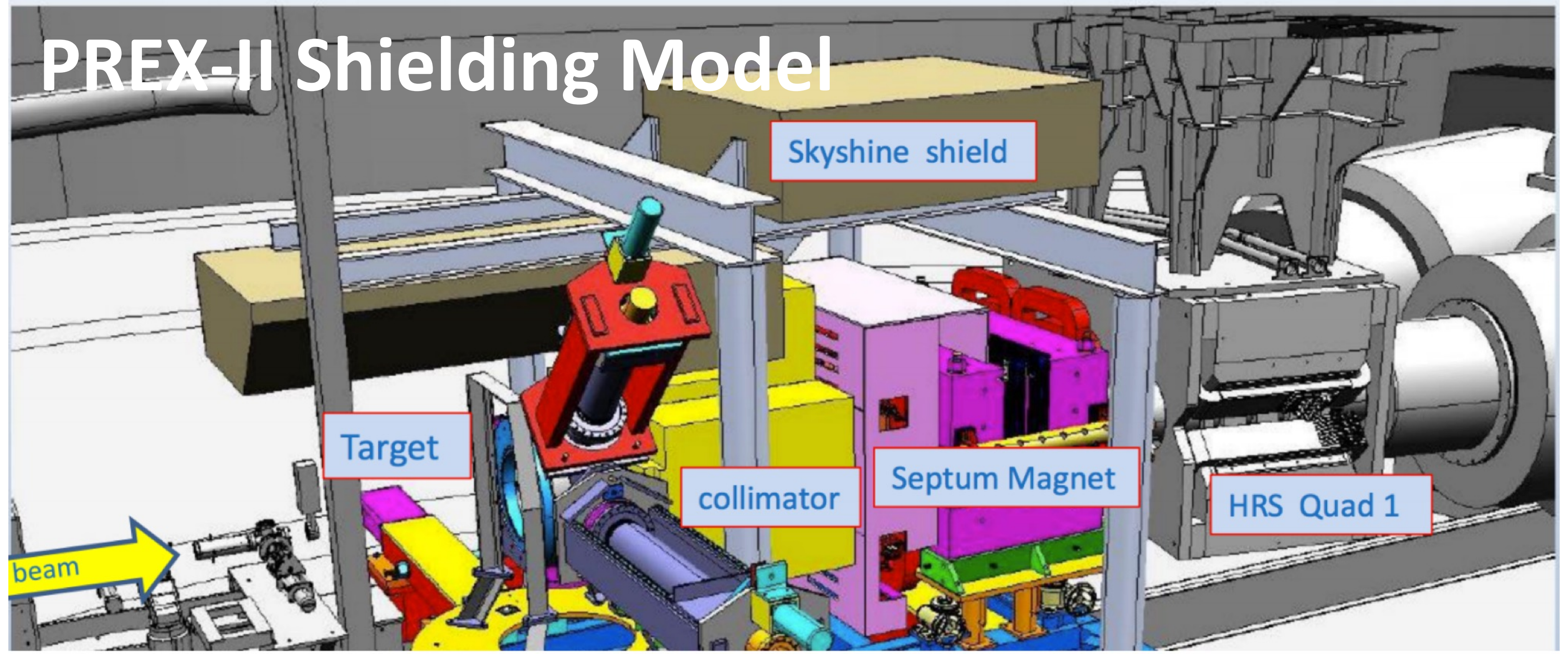
Relevant Technical and Operational Experience from 3rd Generation Experiments



RTP Pockels Cell: Improved control of beam fluctuations







Radiation Shielding: Close collaboration between collaboration physicists, engineers and Radiation Safety

Outstanding Beam Performance During PREX-2 and CREX

Careful configuration of the polarized source kept beam difference averages very small during PREX-2

Δx_i	Mean (nm)	Convergence
Angle x	-0.28 nrad	0.32 nrad
Target x	-1.1 nm	2.0 nm
Angle y	0.14 nrad	0.09 nrad
Target y	1.1 nm	0.5 nm
Energy	2.3 nm	1.1 nm

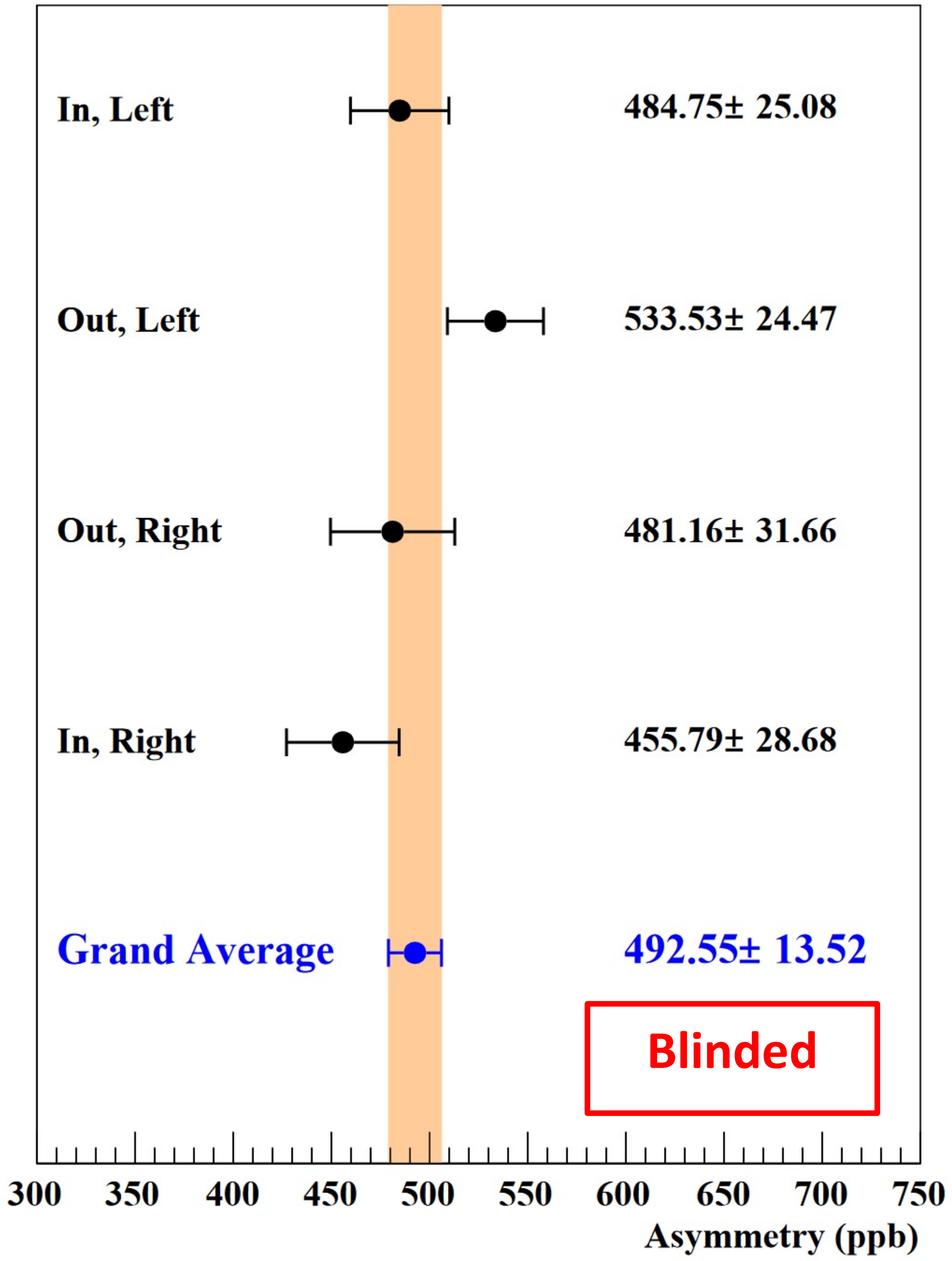
(Helicity Correlated Beam Asymmetries)

	MOLLER (344 PAC days)	MOLLER Run 1 (25 PAC days)	PREX II achieved (~19 PAC days)
Intensity	<10ppb	<30ppb	20ppb
Energy Asymmetry	<0.7ppb	<3.5ppb	1.6ppb
Position Difference	<0.6nm	<3nm	2.5nm
Angle Difference	<0.13nrad	<0.6nrad	0.6nrad
Size Differences	<10ppb	<50ppb	5-30ppb

- Left/right symmetric detectors, so correction dominated by energy

type	Mean(ppb)
X1	-22.33
Y1	22.5
E	-70.44
Y2	-2.84
X2	9.7
	1.27
	-0.01
	1.06
	0.26
	0.24
	0.18
	0.06
	-60.38

Total beam corrections:
(60.4 ± 2.5) ppb



MOLLER Collaboration: ~ 160 authors, 37 institutions, 6 countries

Spokesperson: K. Kumar, UMass, Amherst

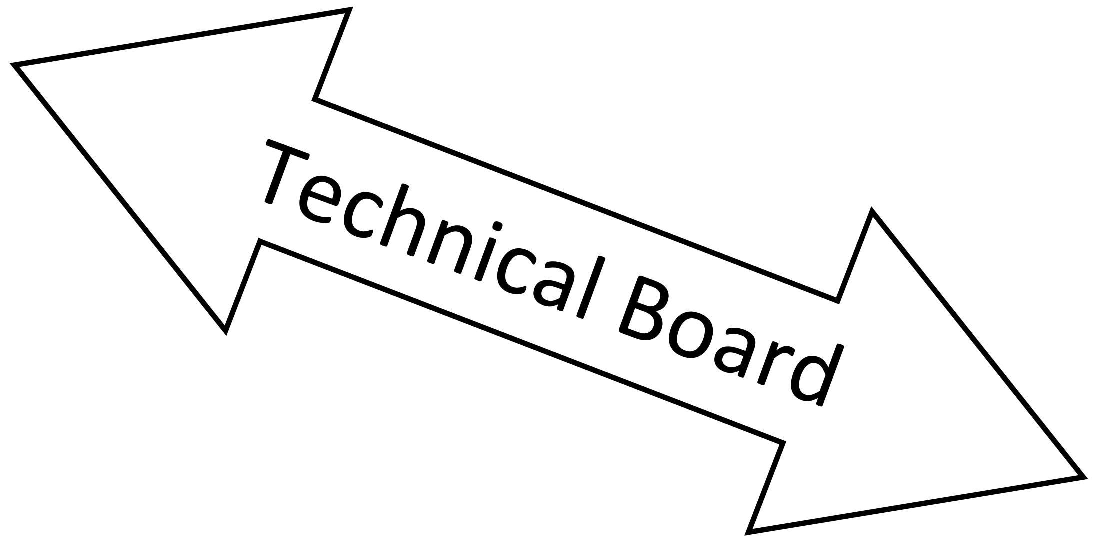
Executive Board Chair and Deputy Spokesperson: M. Pitt, Virginia Tech

Other Executive Board Members

D. Armstrong (William & Mary), J. Fast (JLab), C. Keppel (JLab), F. Maas (Mainz), J. Mammei (Manitoba), K. Paschke (UVa), P. Souder (Syracuse U.)

MOLLER Working Groups

Polarized Source
Beam Instrumentation
Hydrogen Target
Spectrometer
Integrating Detectors
Tracking Detectors
Hall Integration
Polarimetry
Electronics/DAQ/Offline
Simulations
Physics Extraction



MOLLER Project Personnel

J. Fast, MOLLER Project Manager

Project Leads

Control Account Managers

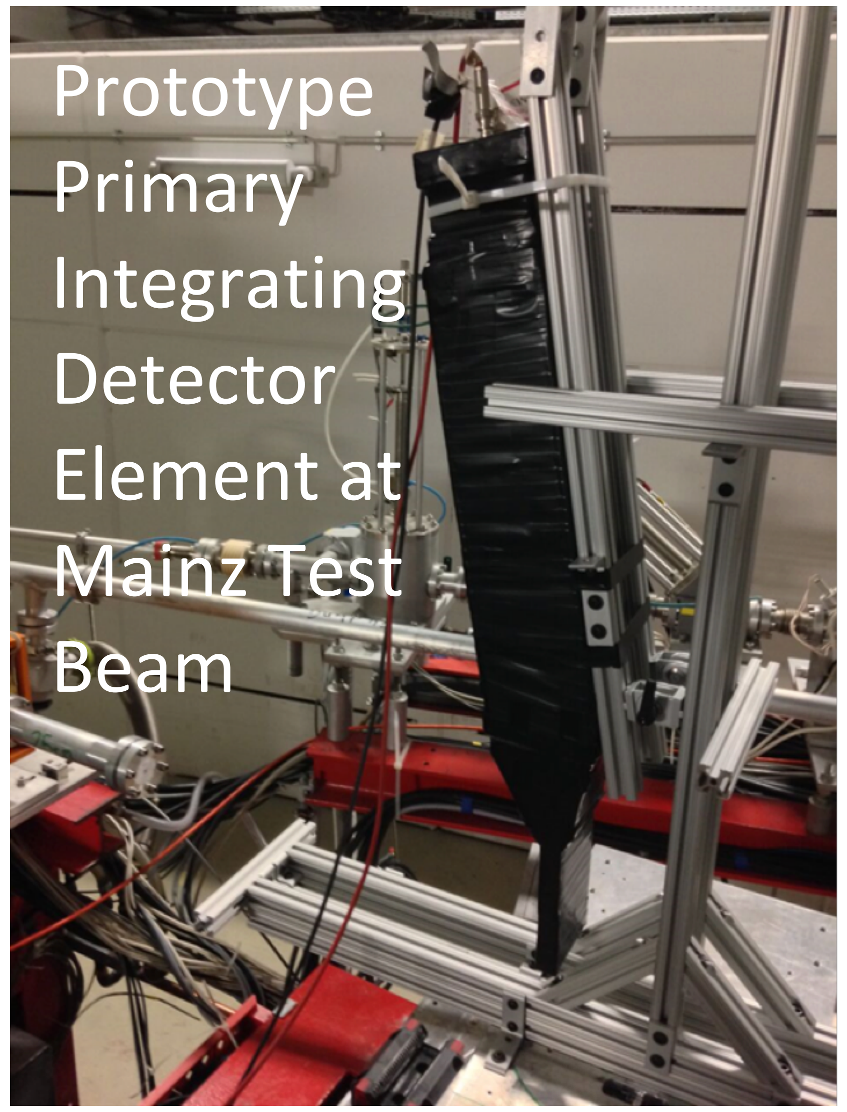
Technical Leads

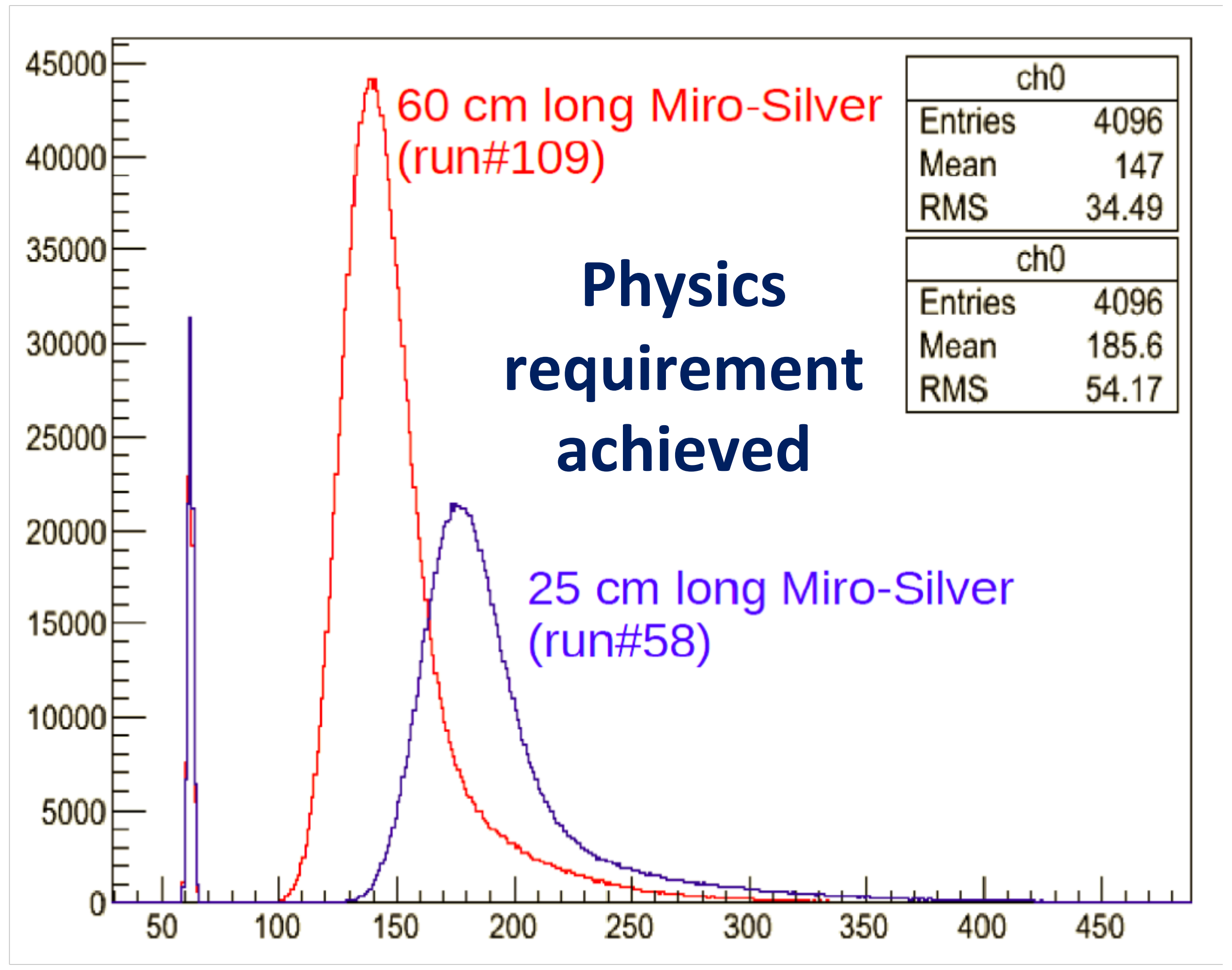
Summary

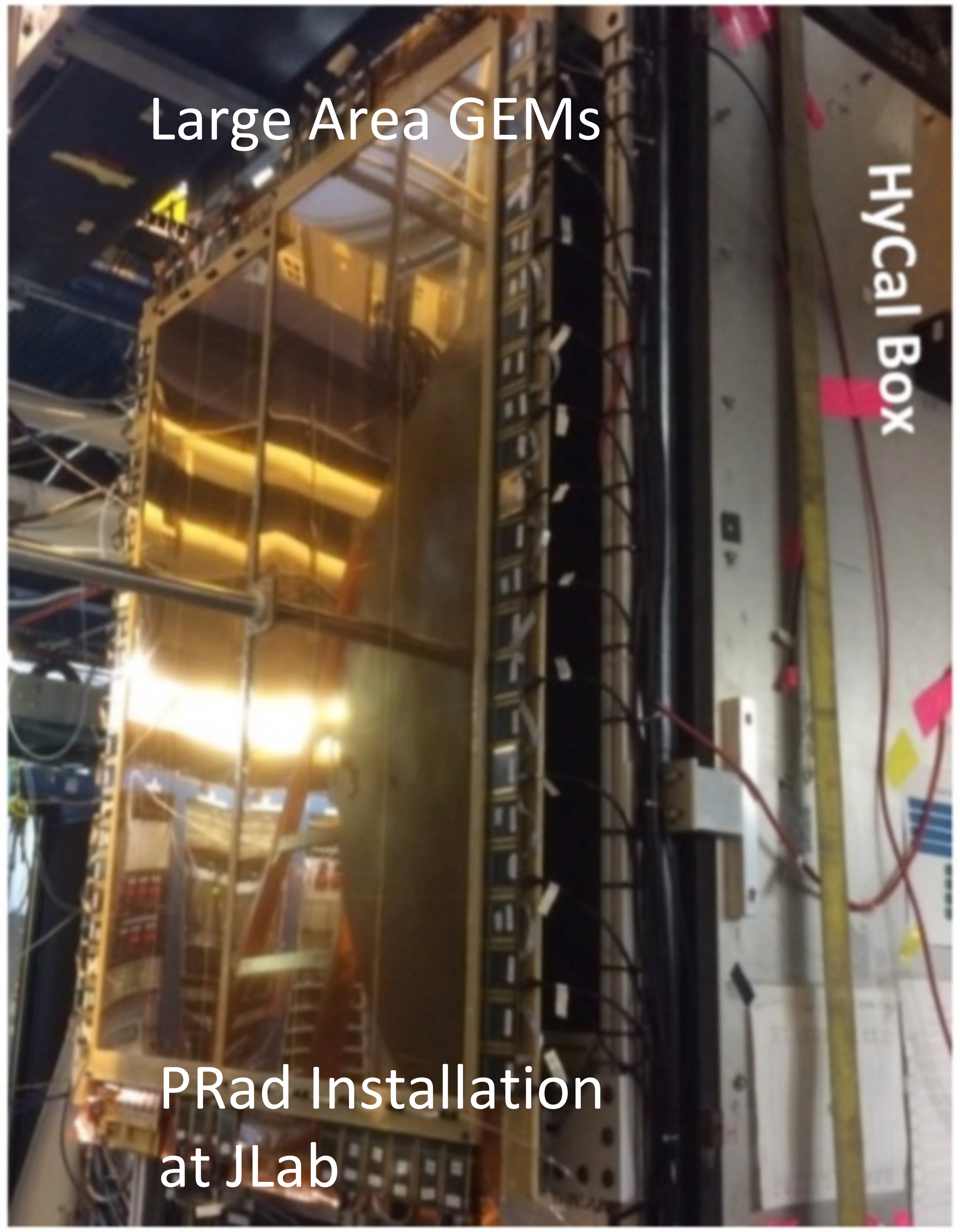
- MOLLER represents an outstanding opportunity to take advantage of the unique instrument (11 GeV CEBAF beam) enabled by the 12 GeV upgrade
- The science case remains compelling and the plan is to run physics at about the time that precision results from high luminosity phases of 14 TeV LHC are becoming available
- The science goals cannot be accomplished in existing or planned facilities elsewhere worldwide
- Mature conceptual design and advanced preliminary engineering design leveraging 3rd generation parity violation experiments and prototyping efforts during pre-R&D phase
- An enthusiastic and well-experienced international collaboration with an integrated project team is eager to complete the engineering design and launch into construction and deployment of the apparatus, followed by commissioning, data collection and physics analysis

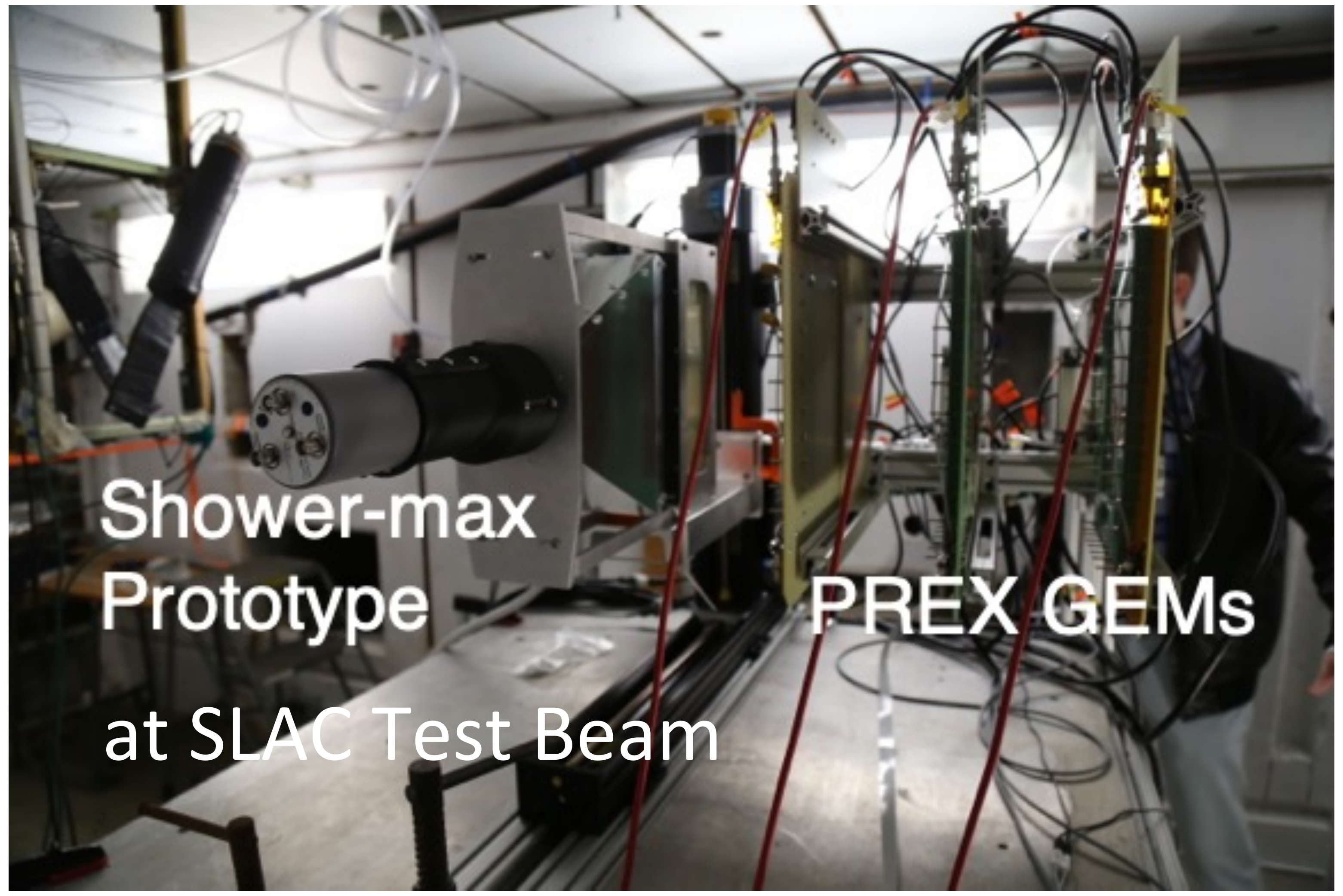
Appendix

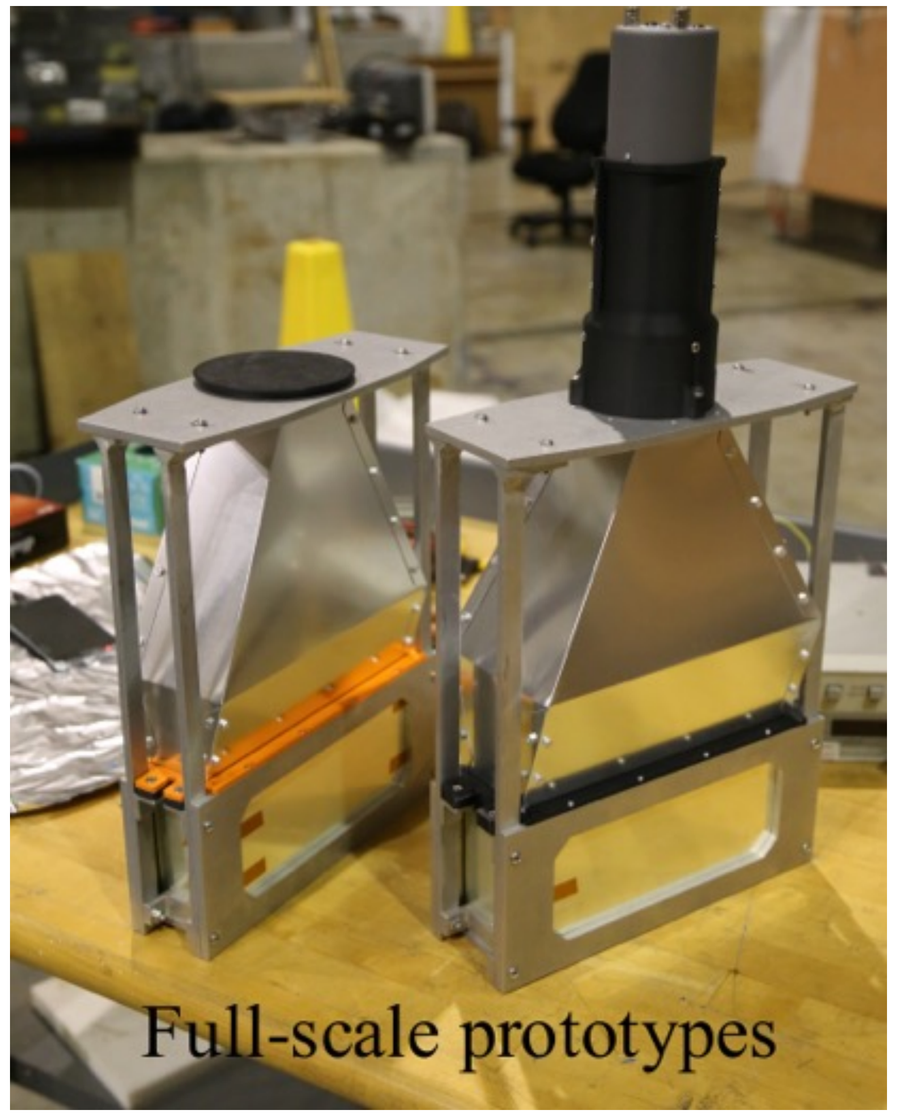
Significant Prototyping and Validation from R&D Efforts











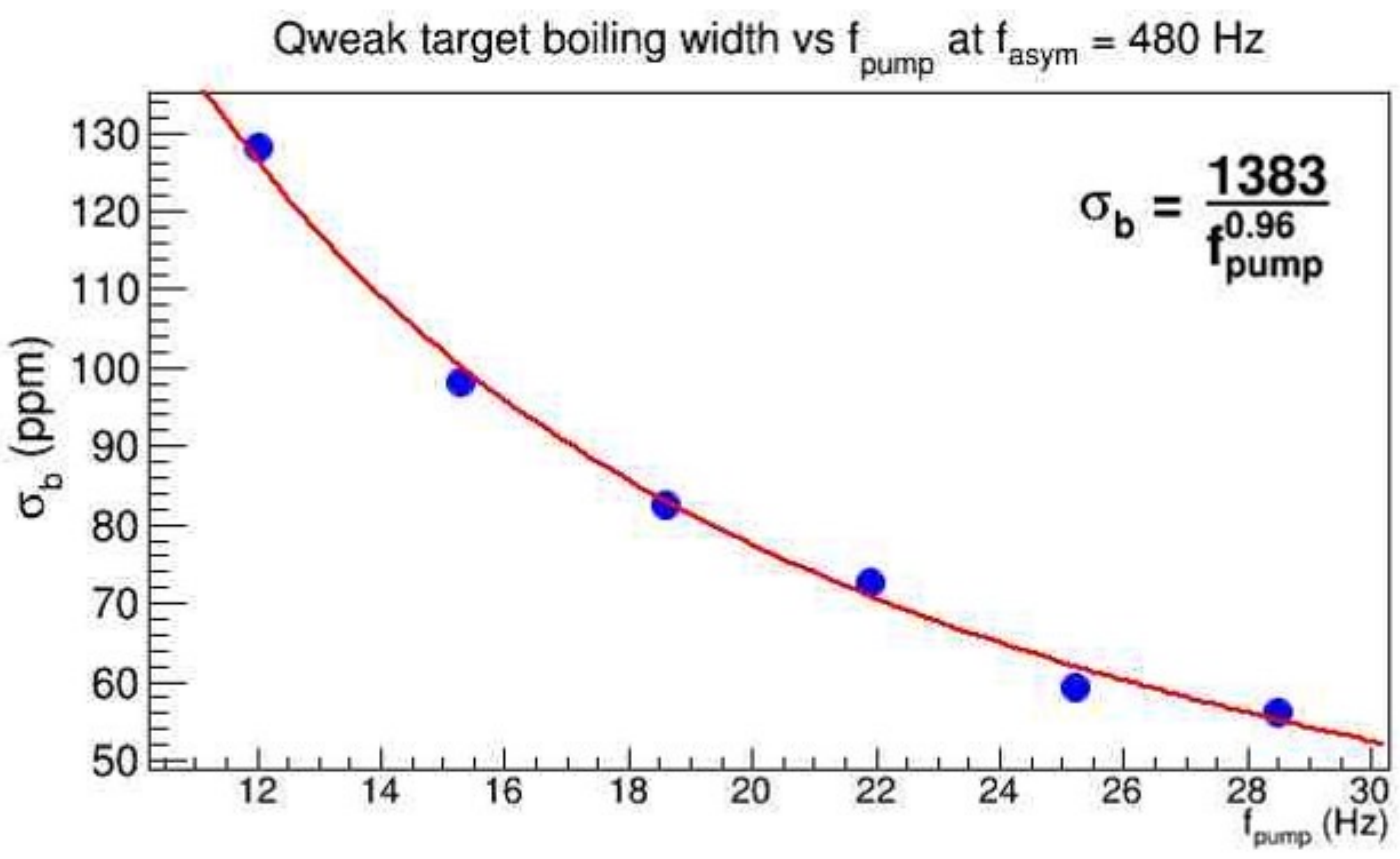
Ultimate Performance Parameters for Full Scientific Discovery Potential

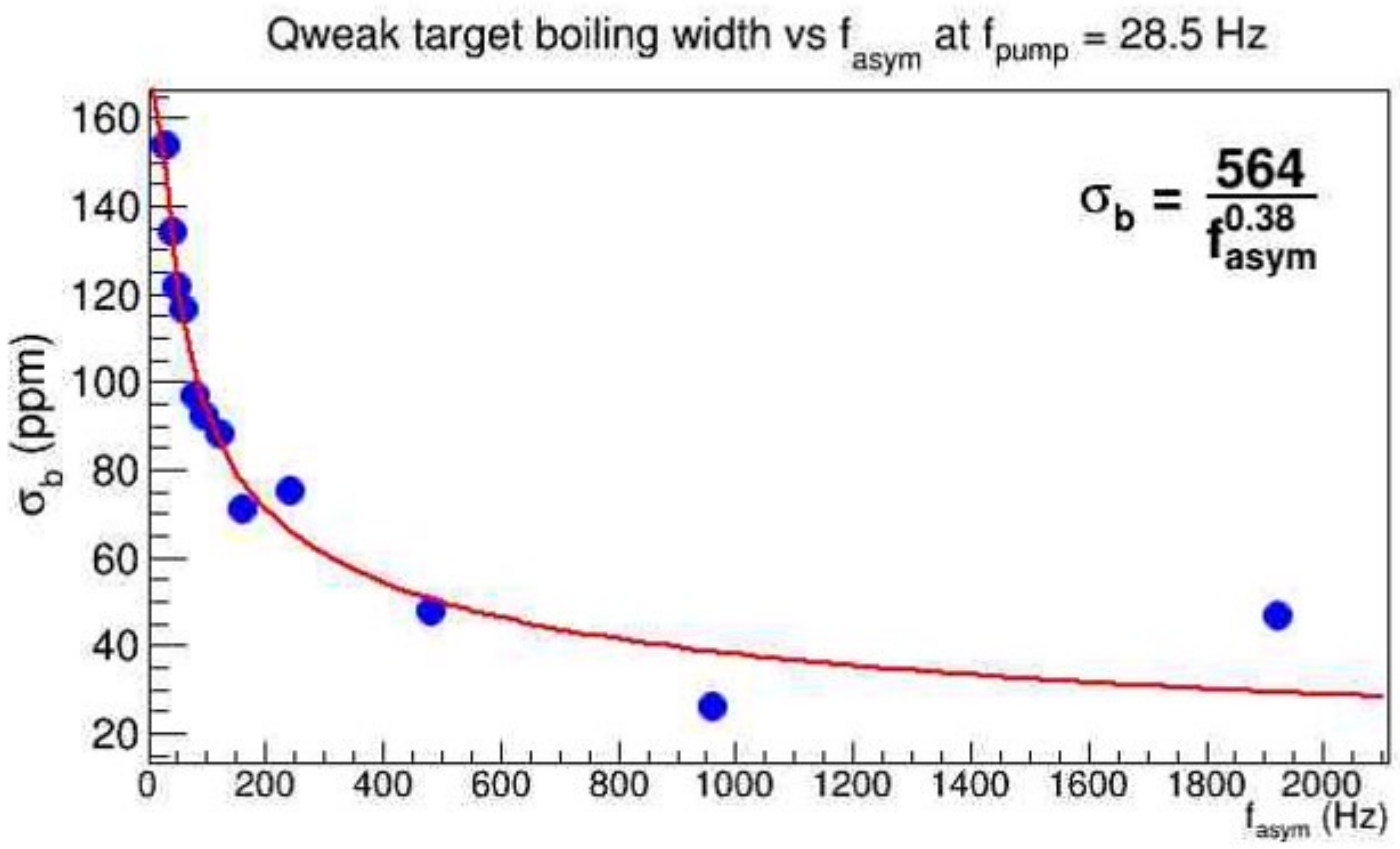
Primary UPP that captures overall integrated system performance and proves that final experiment precision is achievable with additional data

- Produce a full acceptance profile at the thin quartz detectors with the tracking detectors with ≥ 90% tracking efficiency and <1 mm single hit position resolution;
- Verify end-to-end beam transport by confirming predicted rates in each ring of the thin quartz detectors are as expected to better than 25%;
- Measure the e-p leakage correction to the Moller ring 5 rate to better than 10% accuracy;
- Measure the 0.96 kHz equivalent pulse-pair asymmetry width to be smaller than 120 ppm at 65 microamps and measure the main Moller asymmetry to better than 14% statistical and 17% combined uncertainty, comparable to SLAC E158.
- LH2 target stable with ≥ 4kW beam heating. Density fluctuation < 60 ppm.

Beam Property	Required 960 Hz pair random fluctuations	Cumulative helicity correlation Run 1	Cumulative helicity correlation full data set
Intensity	< 1000 ppm	< 40 ppb	< 10 ppb
Energy	< 108 ppm	< 6 ppb	< 0.7 ppb
Position	< 47 10^{-6} m	< 4 10^{-9} m	< 0.6 10^{-9} m
Angle	< 4.7 10^{-6} radian	< 0.5 10^{-9} radian	< 0.12 10^{-9} radian

Qweak Target Noise



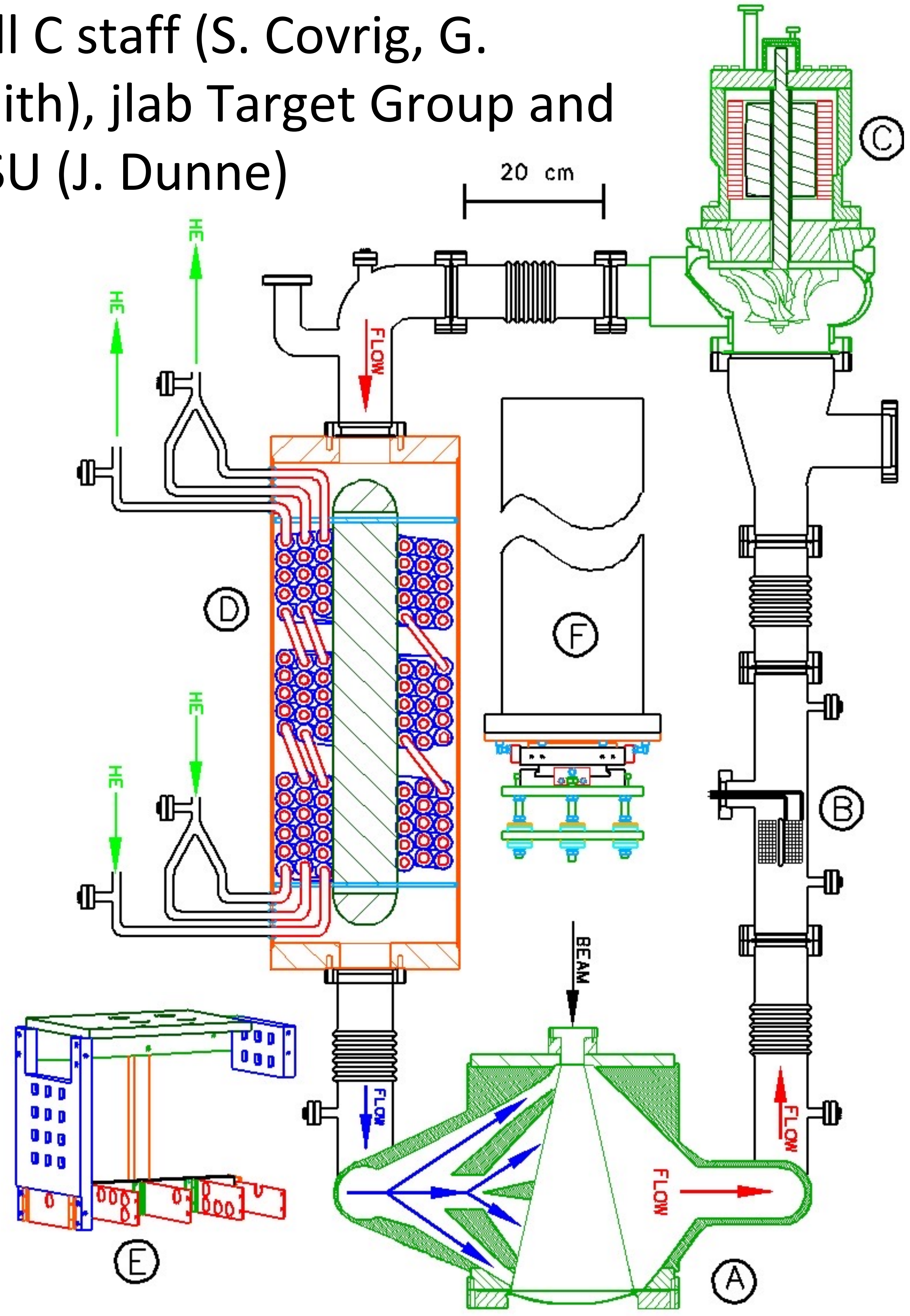


Target density fluctuations vs. LH2 pump speed, flowing the LH2 faster reduces the target noise ~ inversely proportional with the pump speed

Measured asymmetry width (σ_m) is an uncorrelated sum between counting statistics (σ_0) and target noise (σ_b)

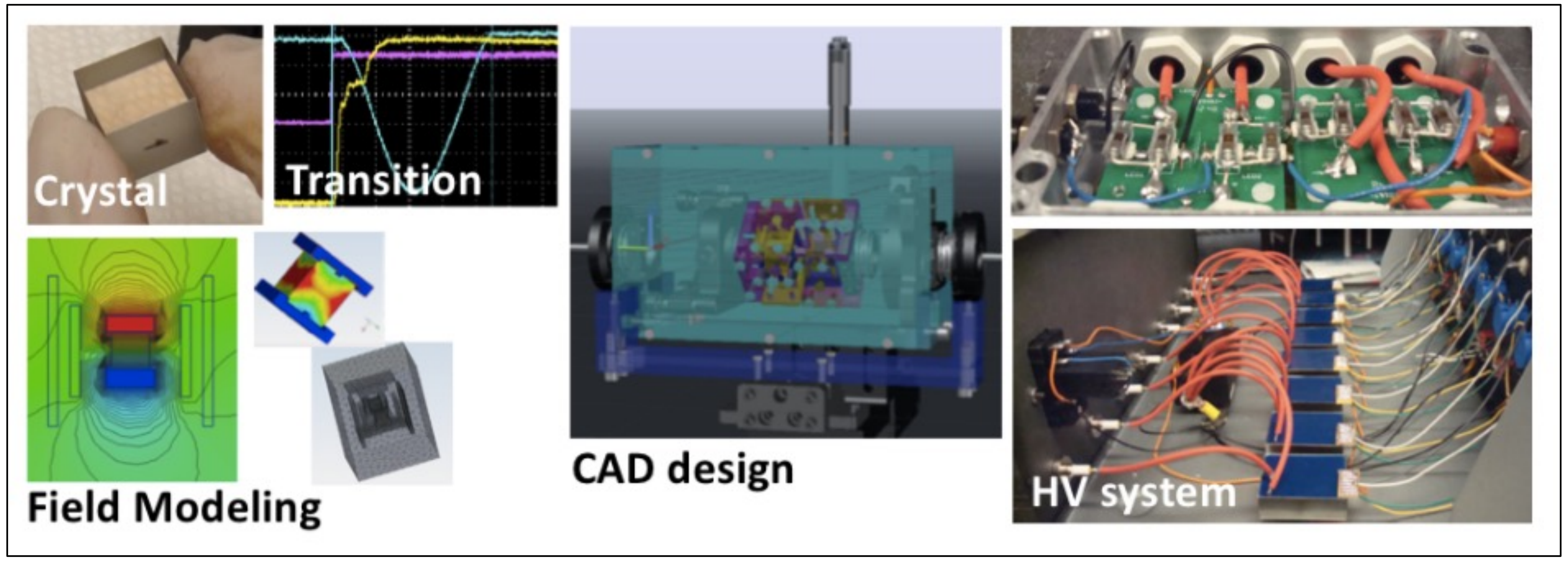
Target density fluctuations vs. quartet helicity frequency, the Qweak yield data has been regrouped to form asymmetry quartets in the range 7.5 – 1920 Hz, flipping the helicity faster reduces the target noise ~ $f^{-0.38}$

Collaborative effort among Hall C staff (S. Covrig, G. Smith), jlab Target Group and MSU (J. Dunne)



New RTP Pockels Cell and Beam Performance During PREX-II

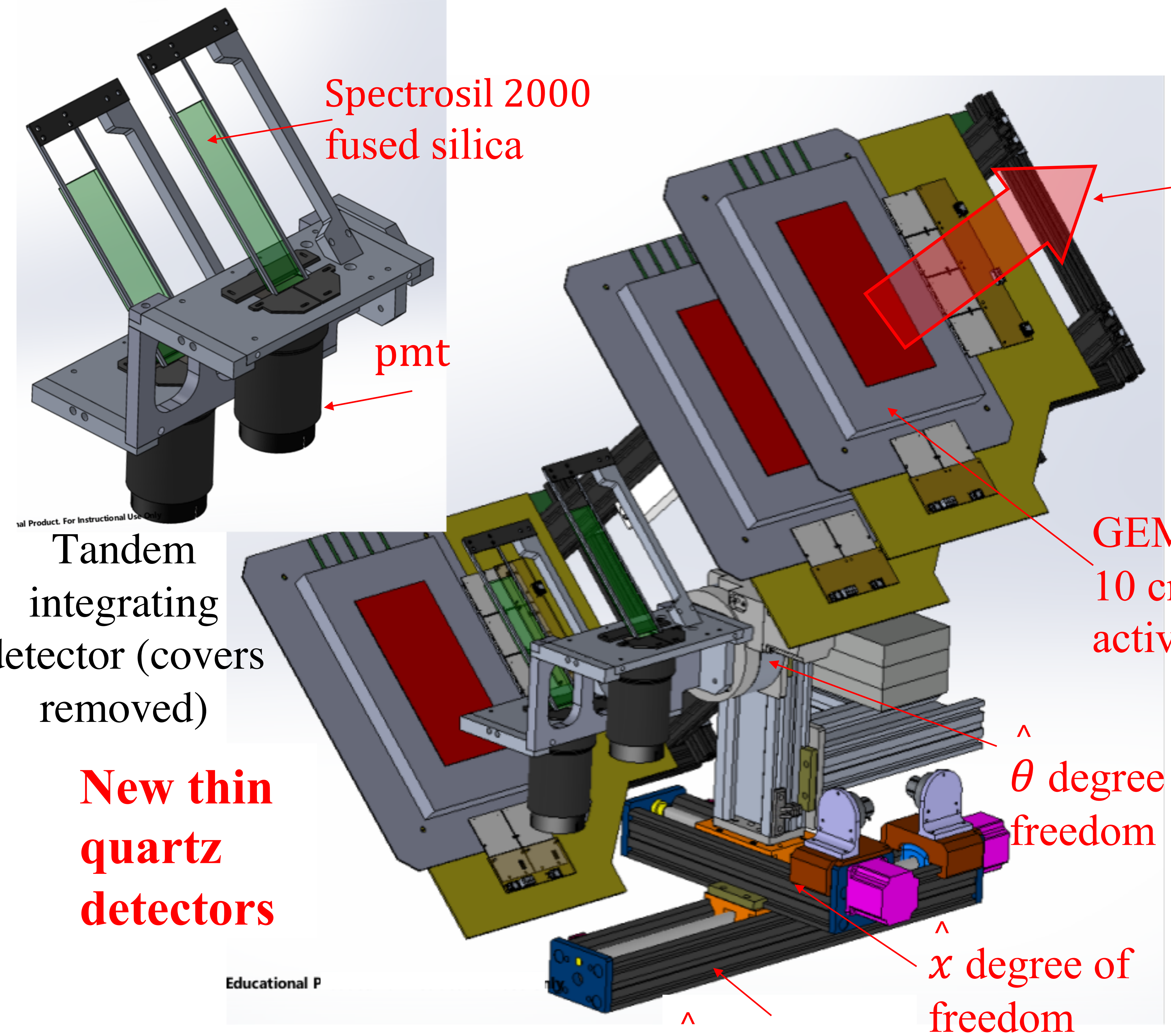
- R&D on the Pockels Cell:
  - MOLLER requires 2kHz helicity flip rate, but the Pockels cell which controls the helicity needed to be very fast (<10us transitions) to take data at this rate; previous technology would result in up to 20% dead time loss
  - This requirement motivated innovation in the PC design using RTP (Rubidium Titanyl Phosphate) material.
  - **R&D on the Pockels Cell was crucially necessary for MOLLER primarily to reduce dead time (as well as enhanced tools to control beam position asymmetries)**



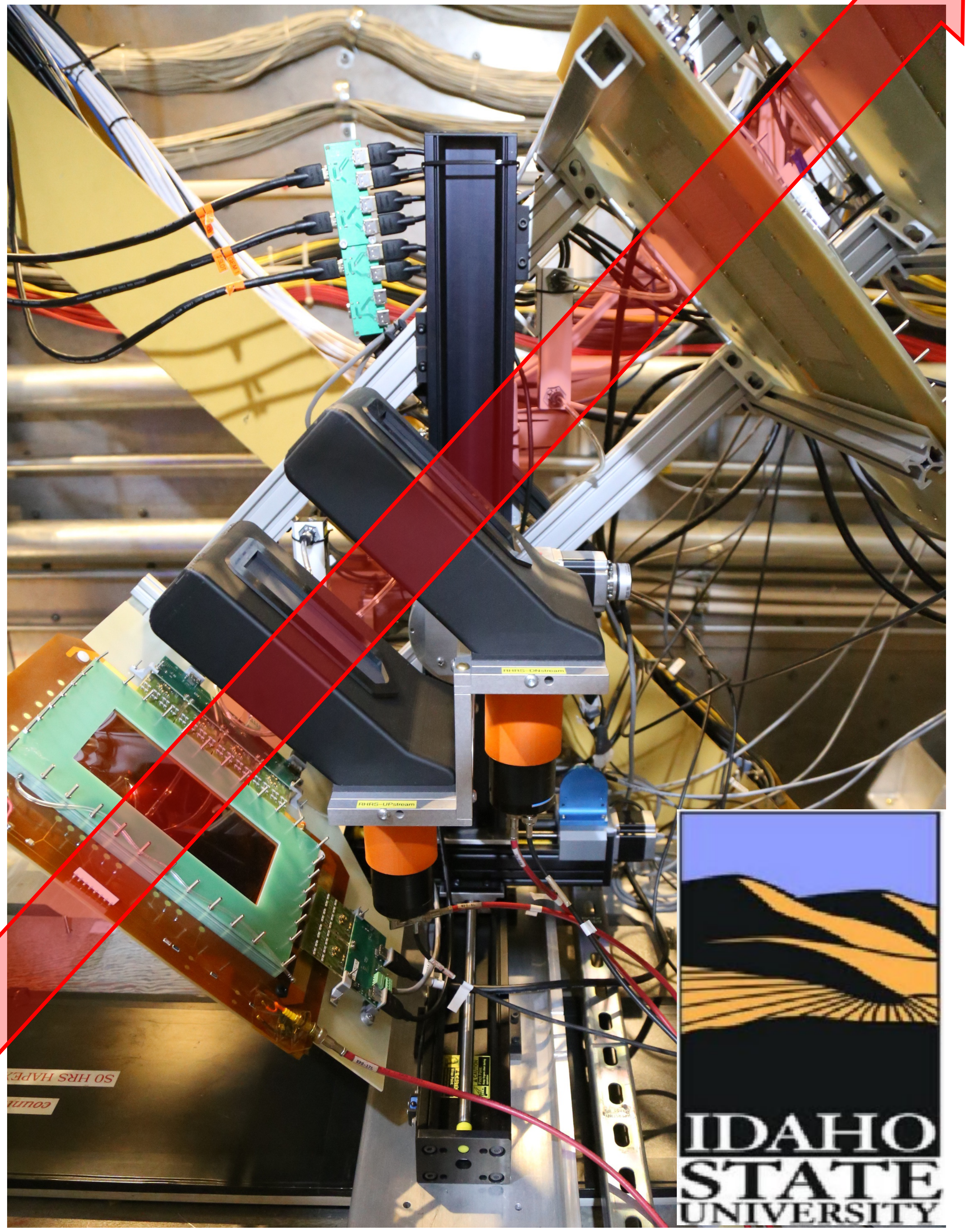
Beam Asymmetry	MOLLER Run-I (Required for UPP)	PREX-II (achieved)
Intensity	<40 ppb	25 ppb
Energy	<6 ppb	1 ± 0.6 ppb
Position	<4 nm	2 ± 2 nm
Angle	< 0.5 nrad	0.2 ± 0.4 nrad

- PREX Performance:
  - During last year's PREX-II run, we have achieved the full table of requirements for MOLLER Run-I (necessary for the UPP's)
  - This was achieved using the new Pockels cell that is critical for MOLLER (**risk retired, due to the required reduction in dead time at the higher rep. rate**)

PREX Detectors



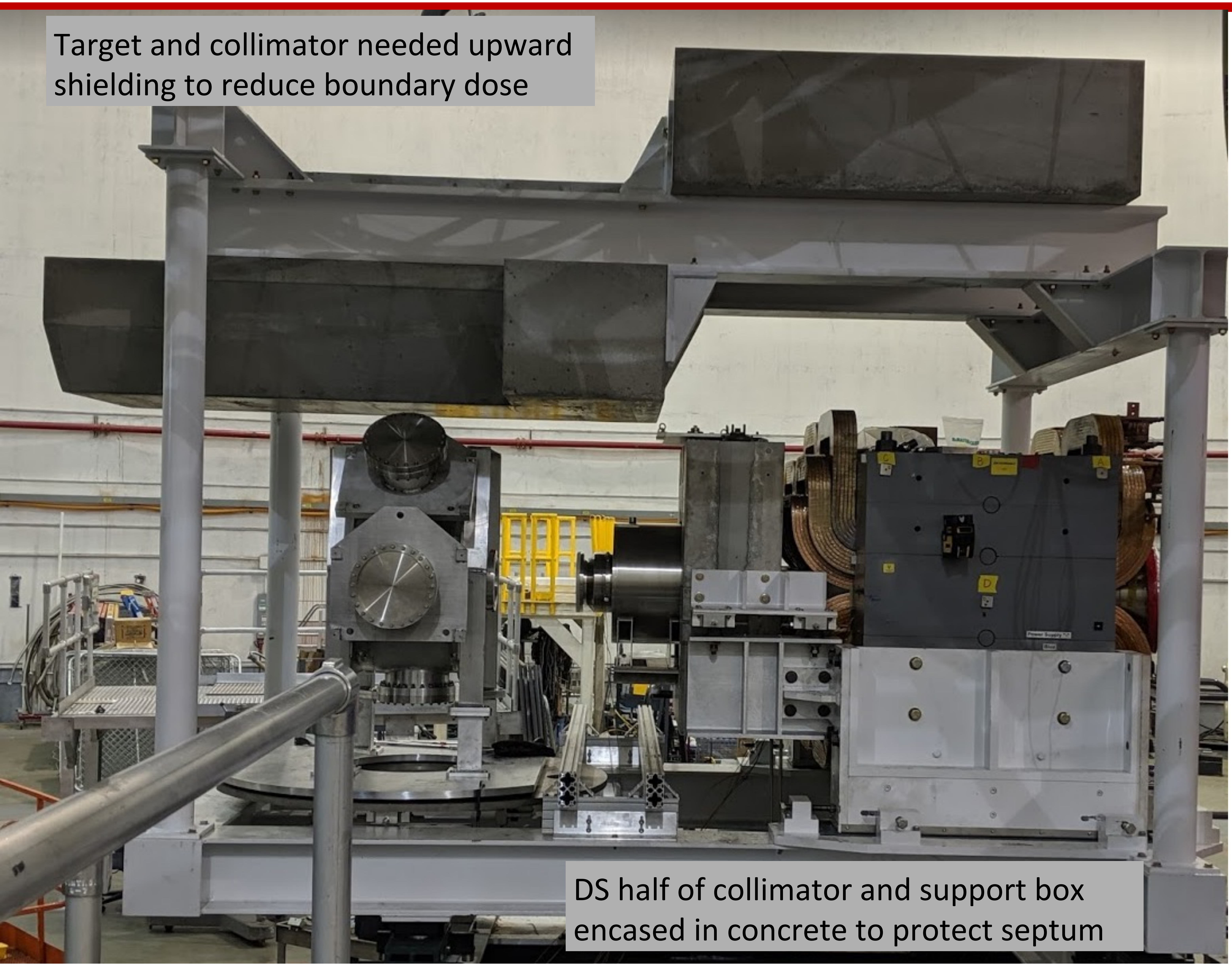
New thin quartz detectors



<u>Experiment Status</u>:

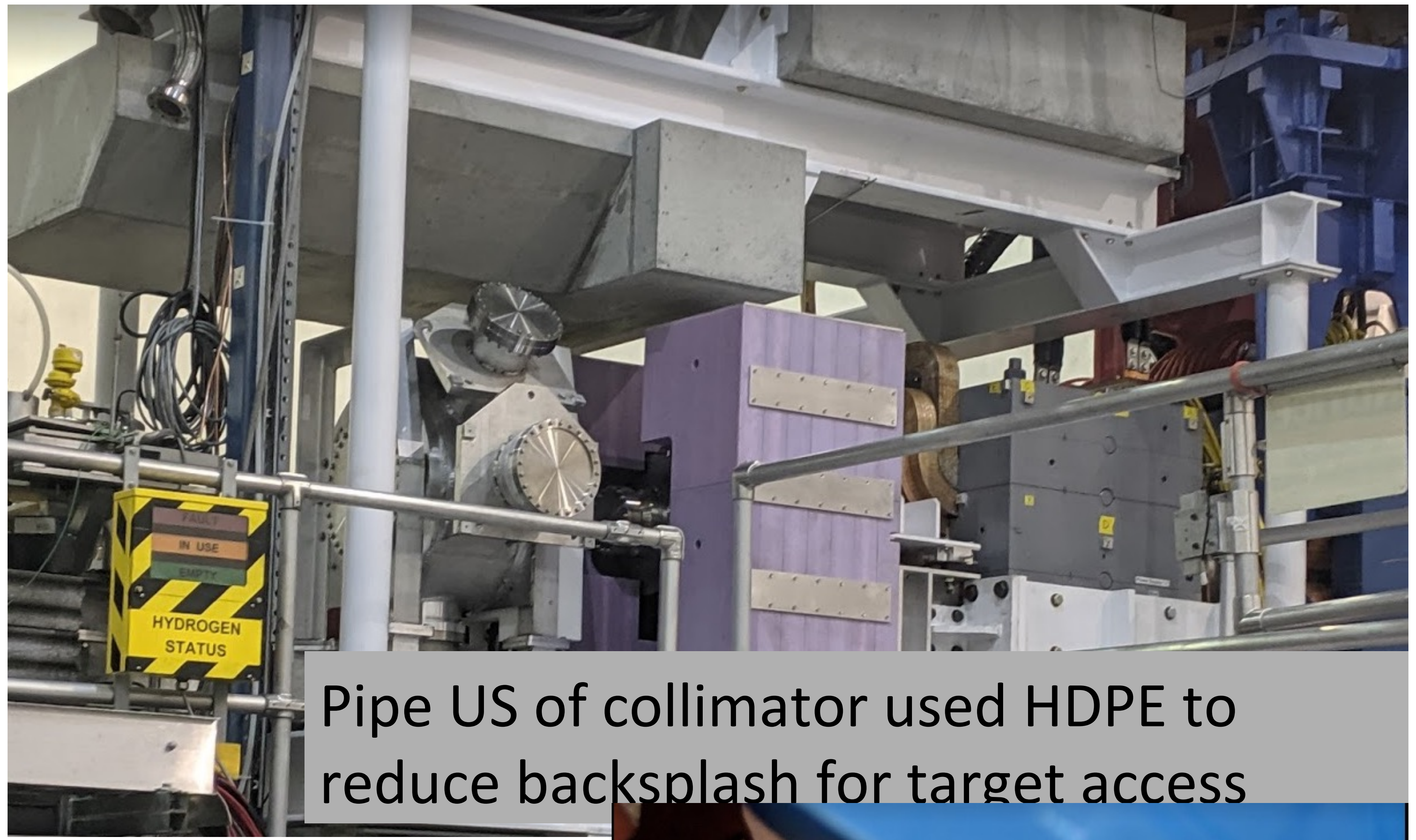
- PREX-II took place over summer 2019 and completed successfully in early September 2019
  - ➢ Integrated flux rates were >2 GHz per arm (Left and Right HRS); 26% detector resolution
- CREX (Calcium Radius Experiment) ran from Dec 2019 to March 2020 using same apparatus as PREX-II; ran 6 more weeks in Aug – Sep 2020

PREX shielding strategy: localize power deposition and requisite shielding



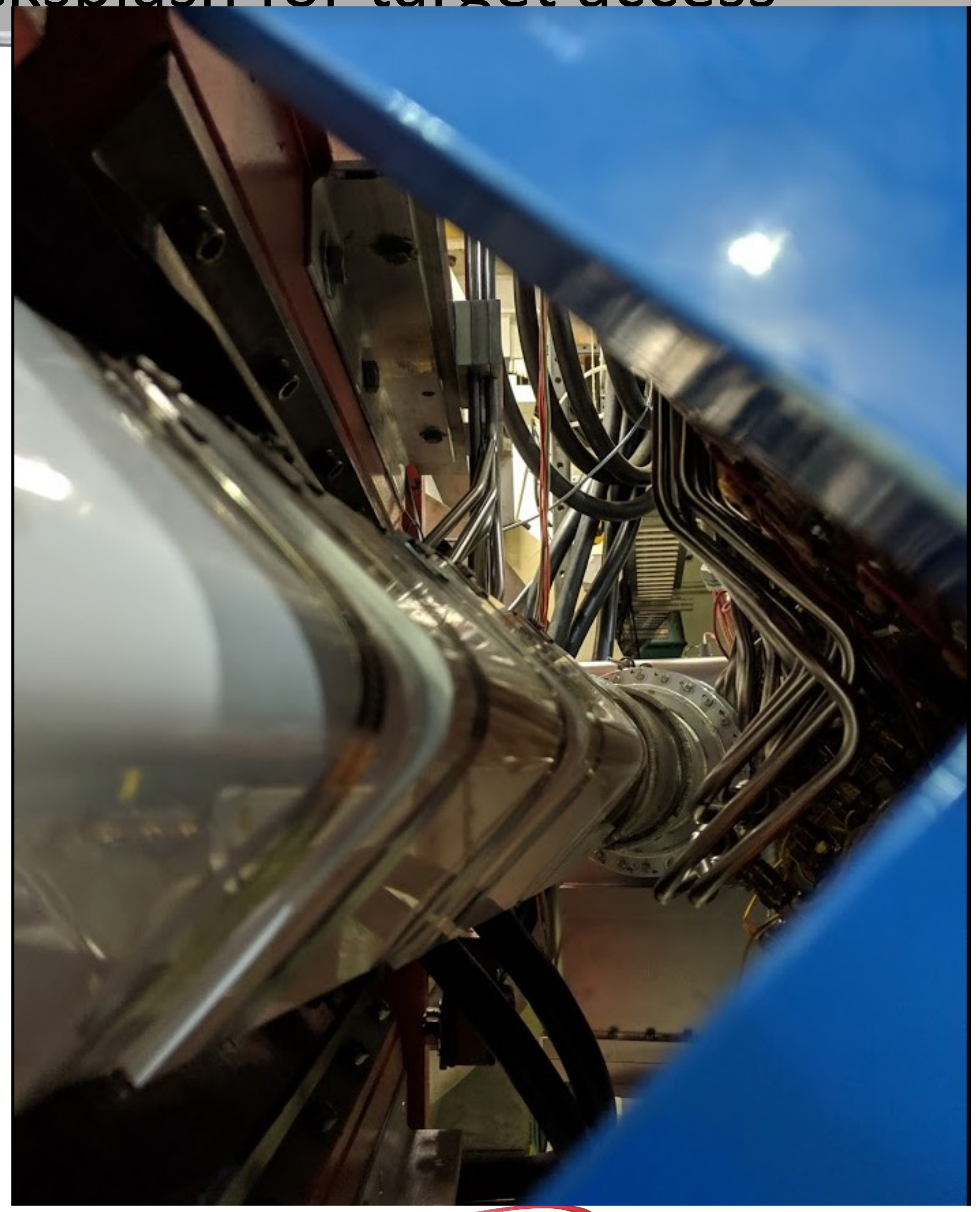
Target and collimator needed upward shielding to reduce boundary dose

DS half of collimator and support box encased in concrete to protect septum

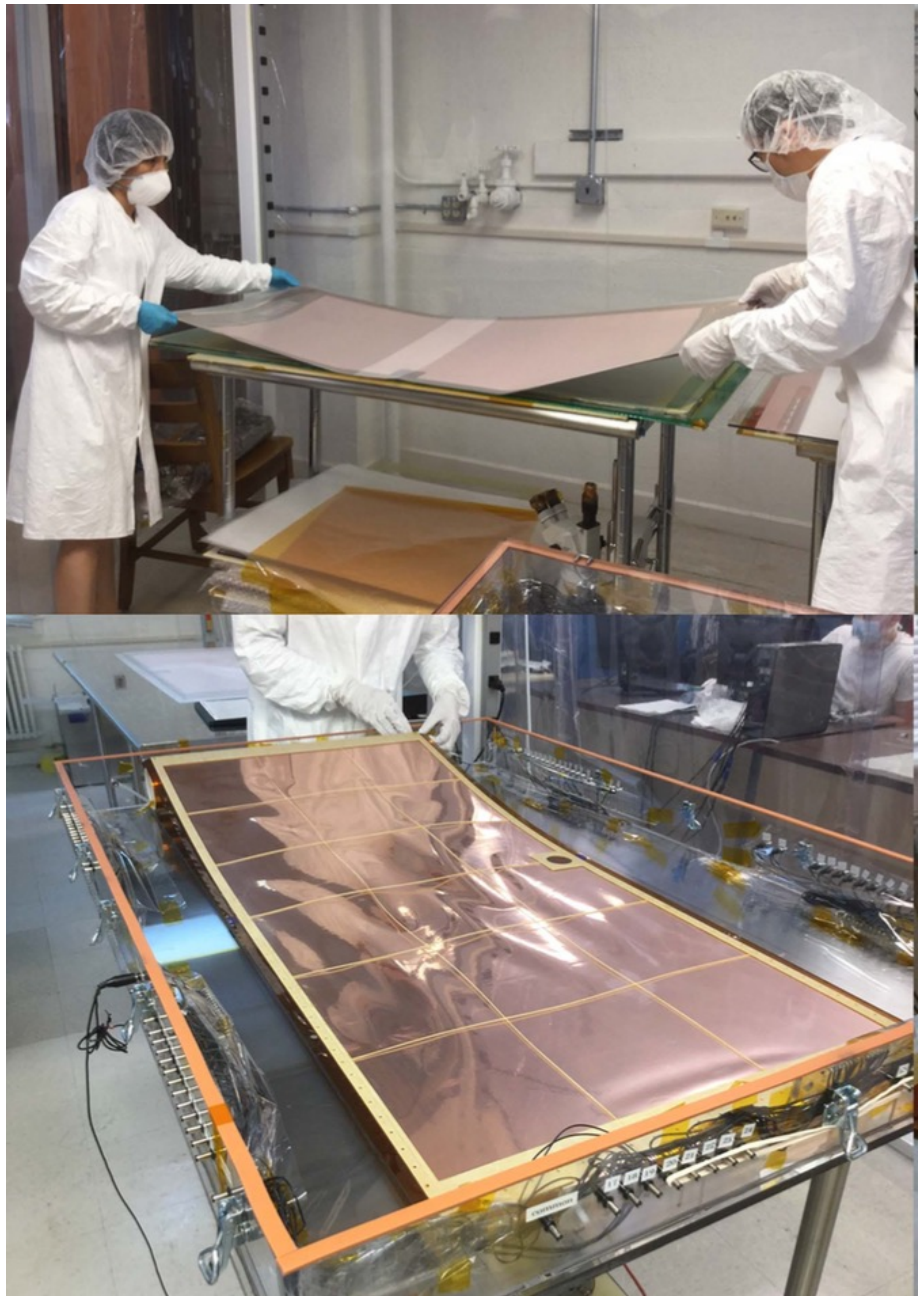


Pipe US of collimator used HDPE to reduce backsplash for target access

Beam pipe DS of Septum shielded to protect cooling lines for Q1 collimators



GEM Technology



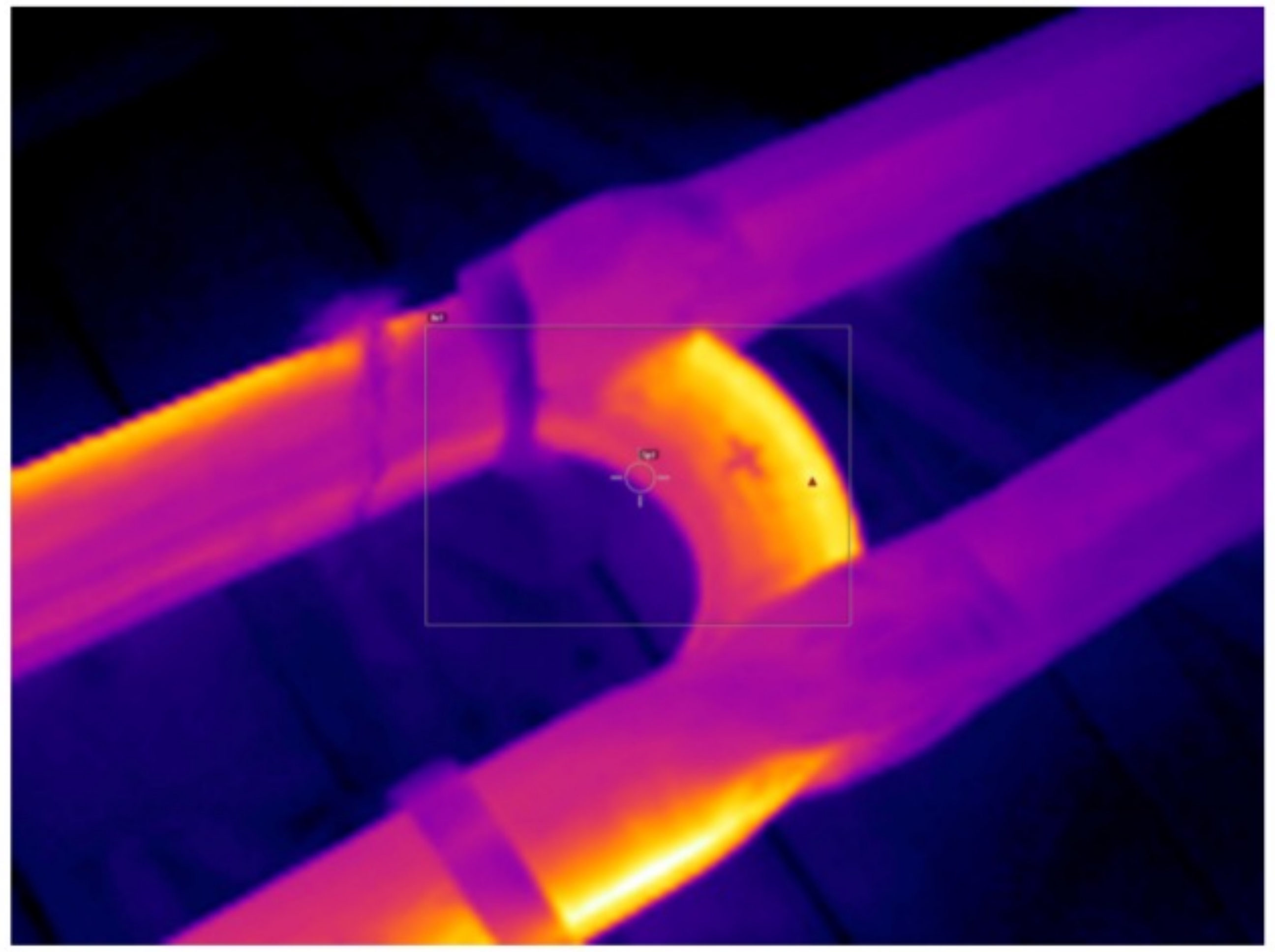
PRad GEMs assembly

SBS GEMs cosmic test stand

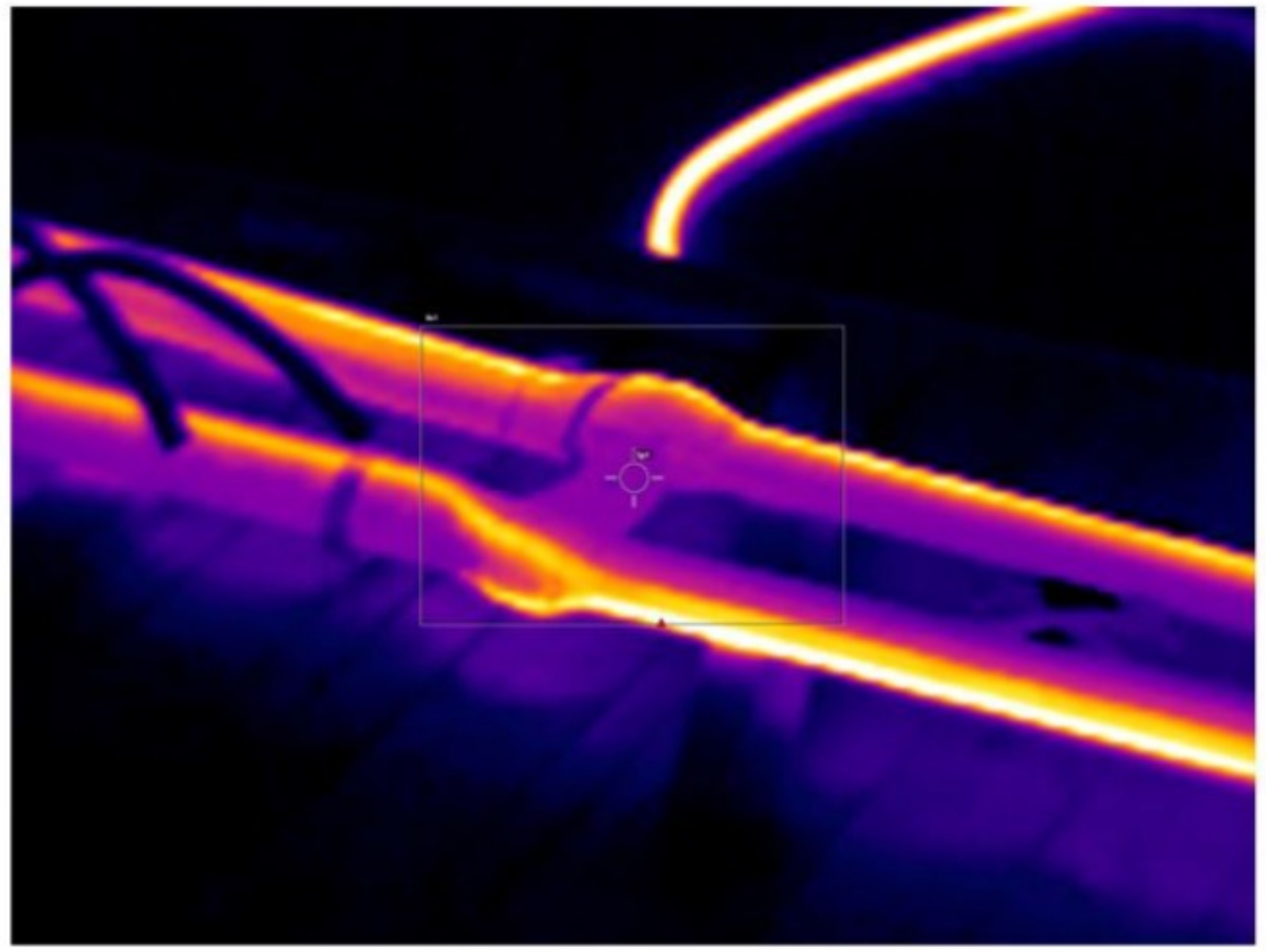
Prototype Coil (SBU, MIT-Bates and Everson Tesla

- **Fabrication at vendor**

- **Thermal imaging during full current testing**

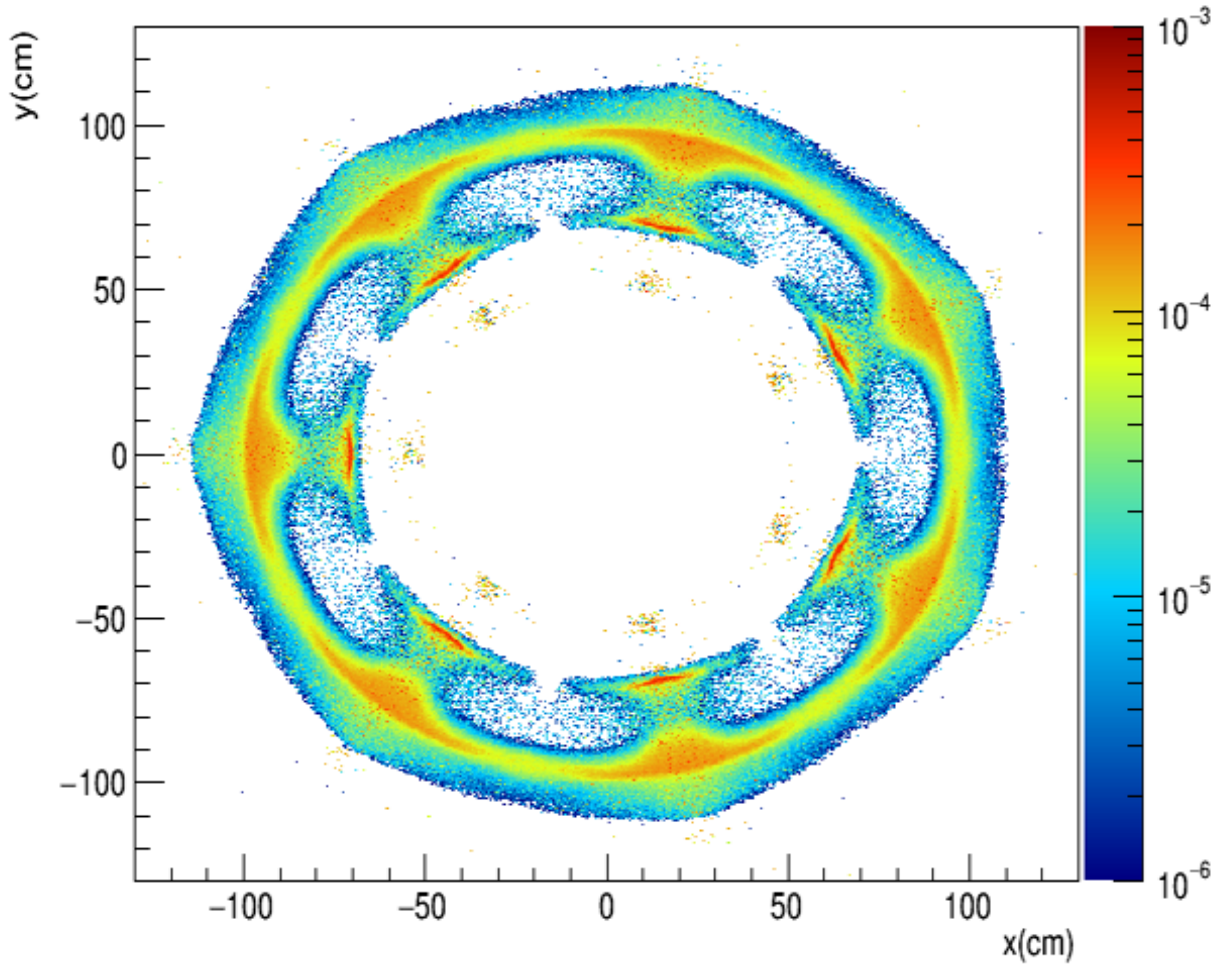


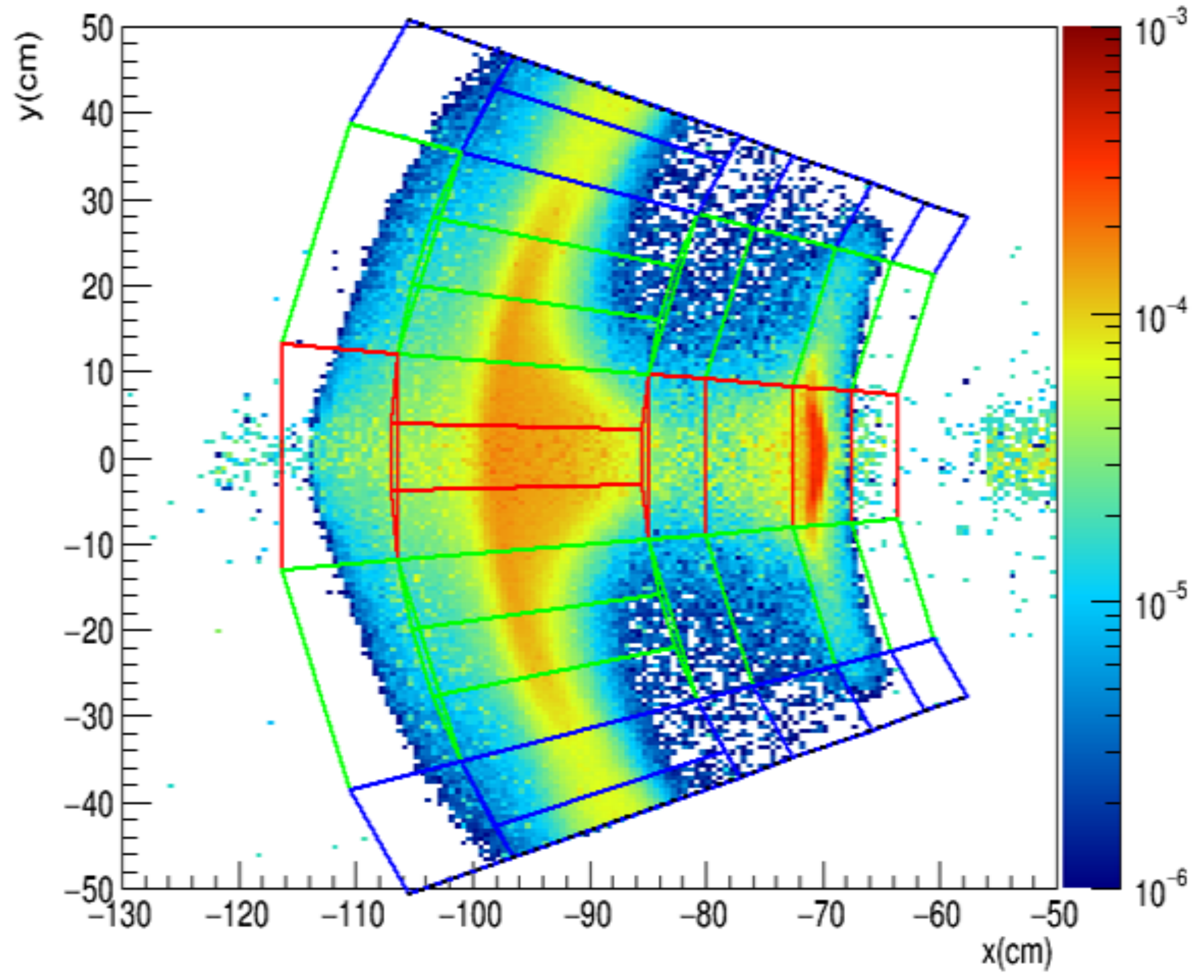
Temp gradient on nose. Hotspot delta = 23.3 C



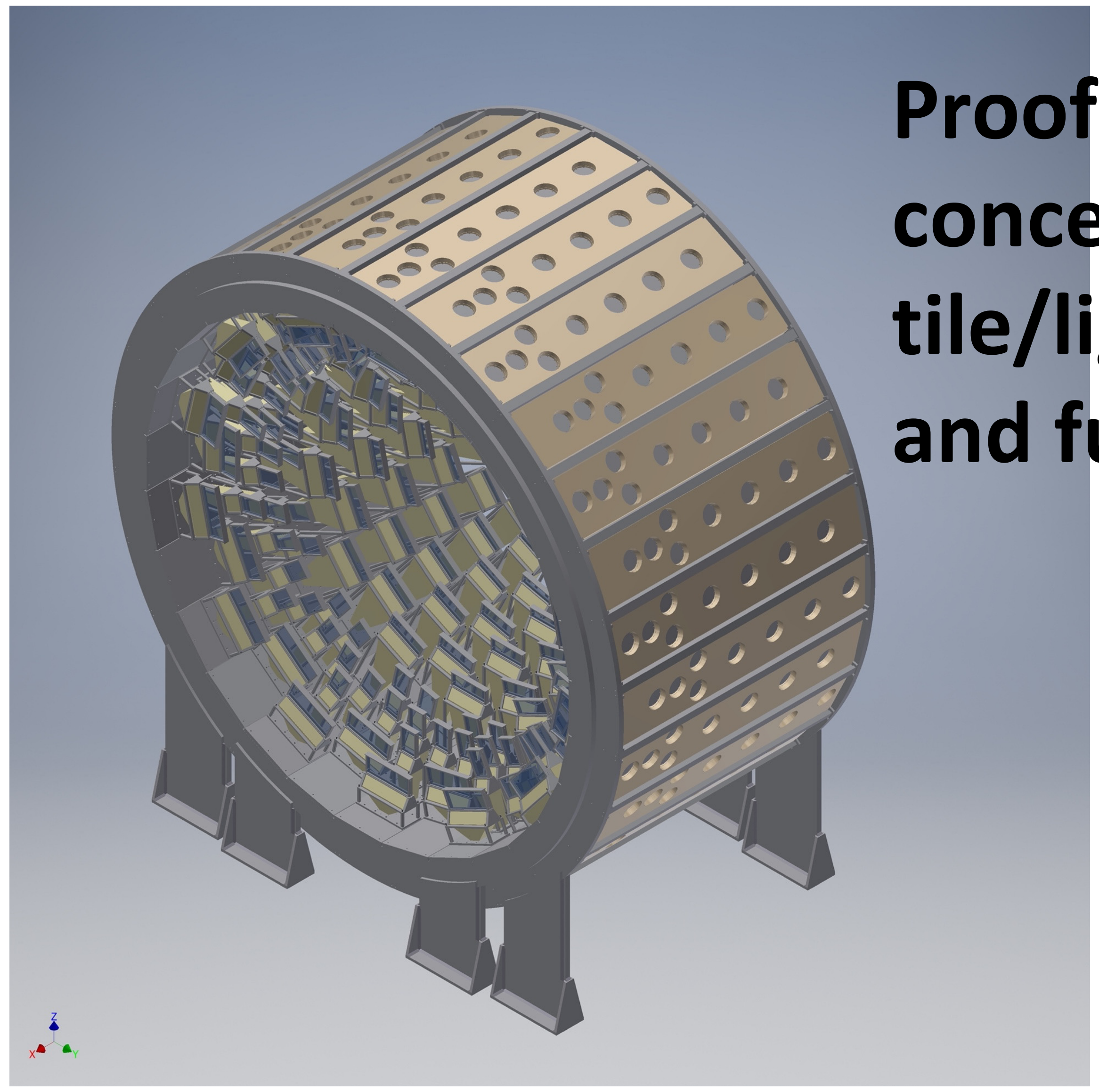
Out-of-plane bend. Hotspot delta = 29.7 C

Main Integrating Detector Concept and Layout Challenges

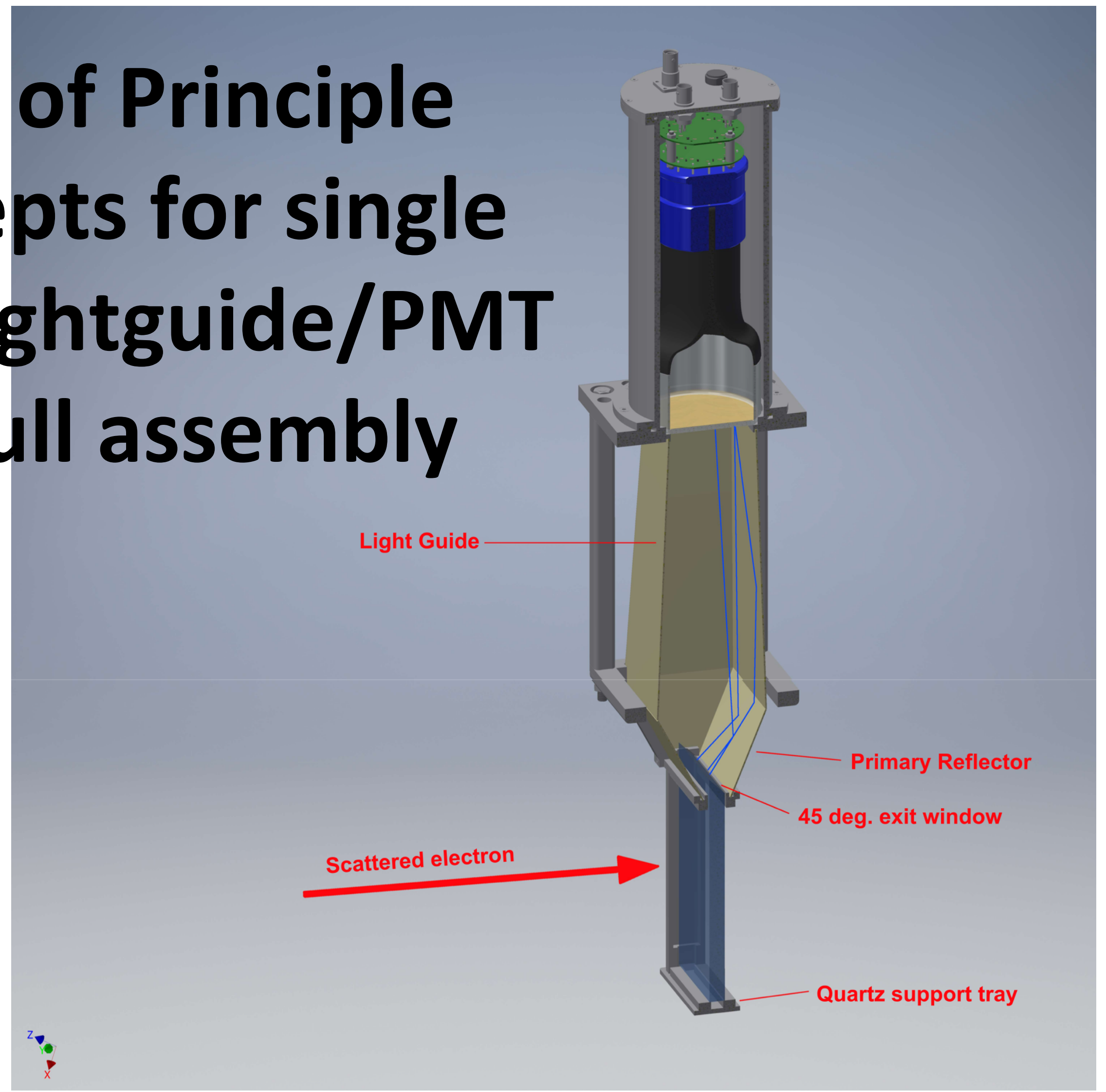


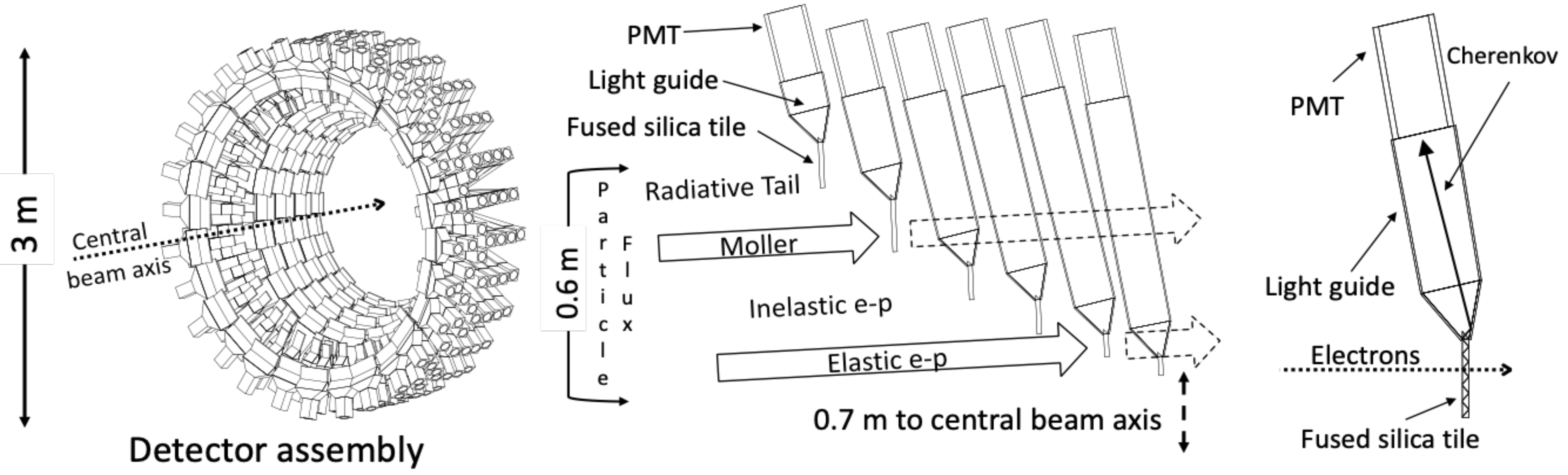


Wide variation in flux intensity and weights of different scattering processes: 1) e-e, 2) elastic e-p, 3) inelastic e-p



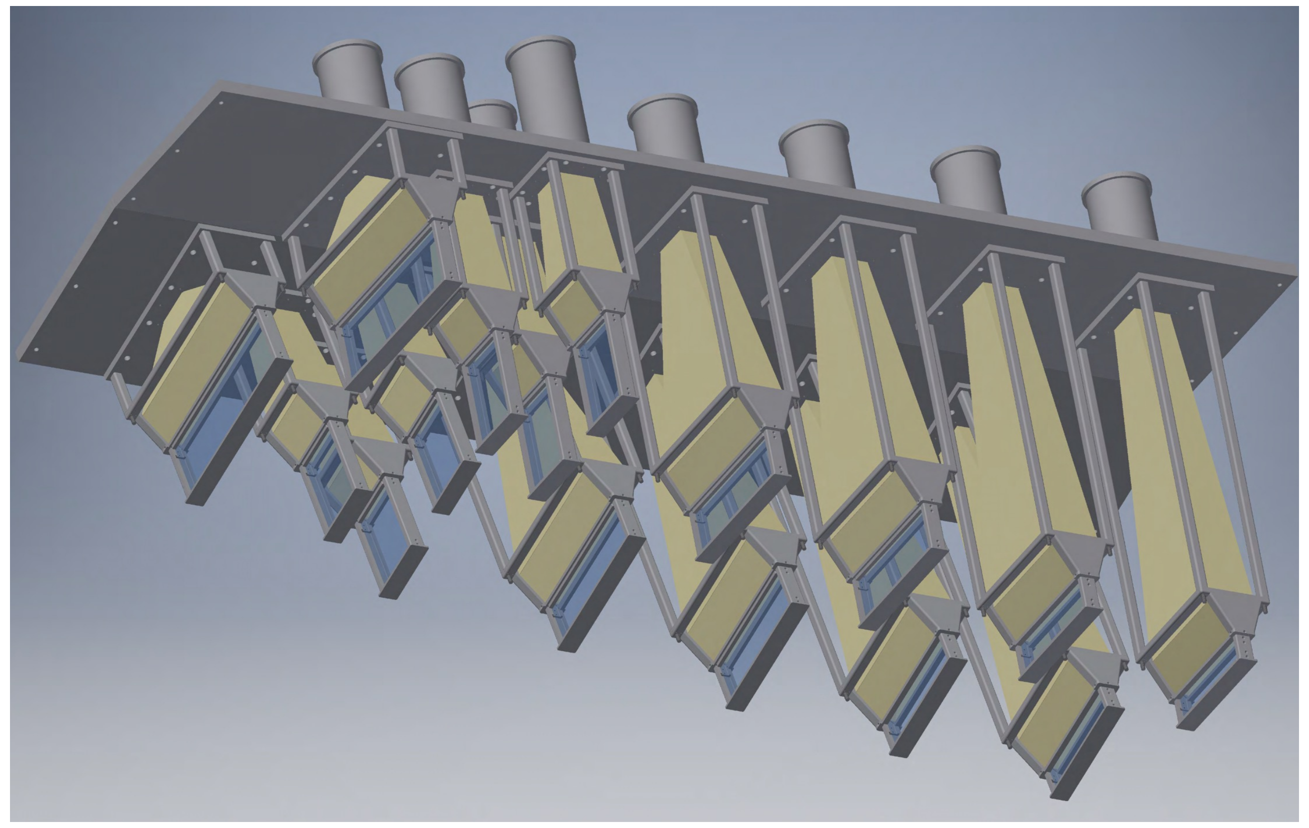
Proof of Principle concepts for single tile/lightguide/PMT and full assembly





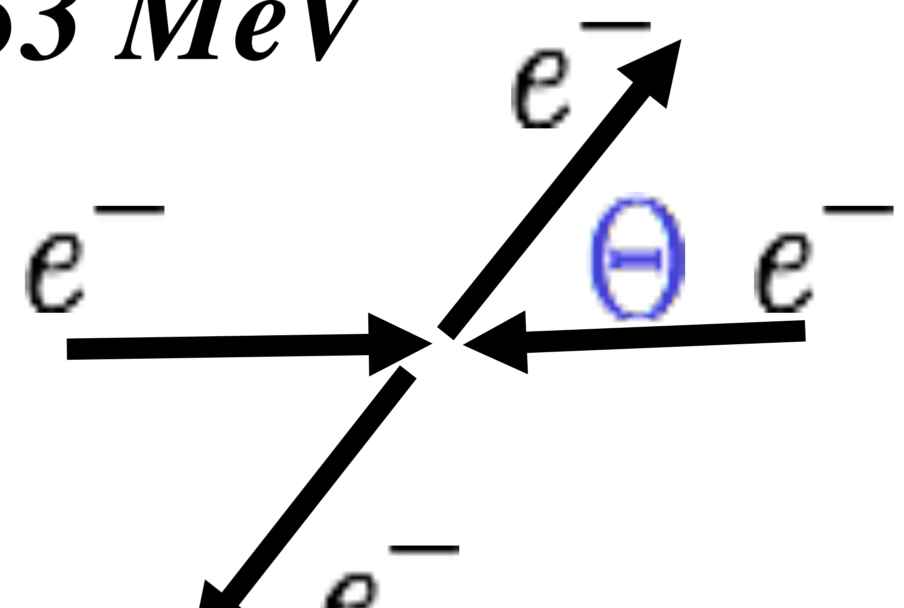
Physics constraints on the main detector assembly:

- **low mass except for quartz**
- **Design must allow ease of installation, de-installation and maintenance**



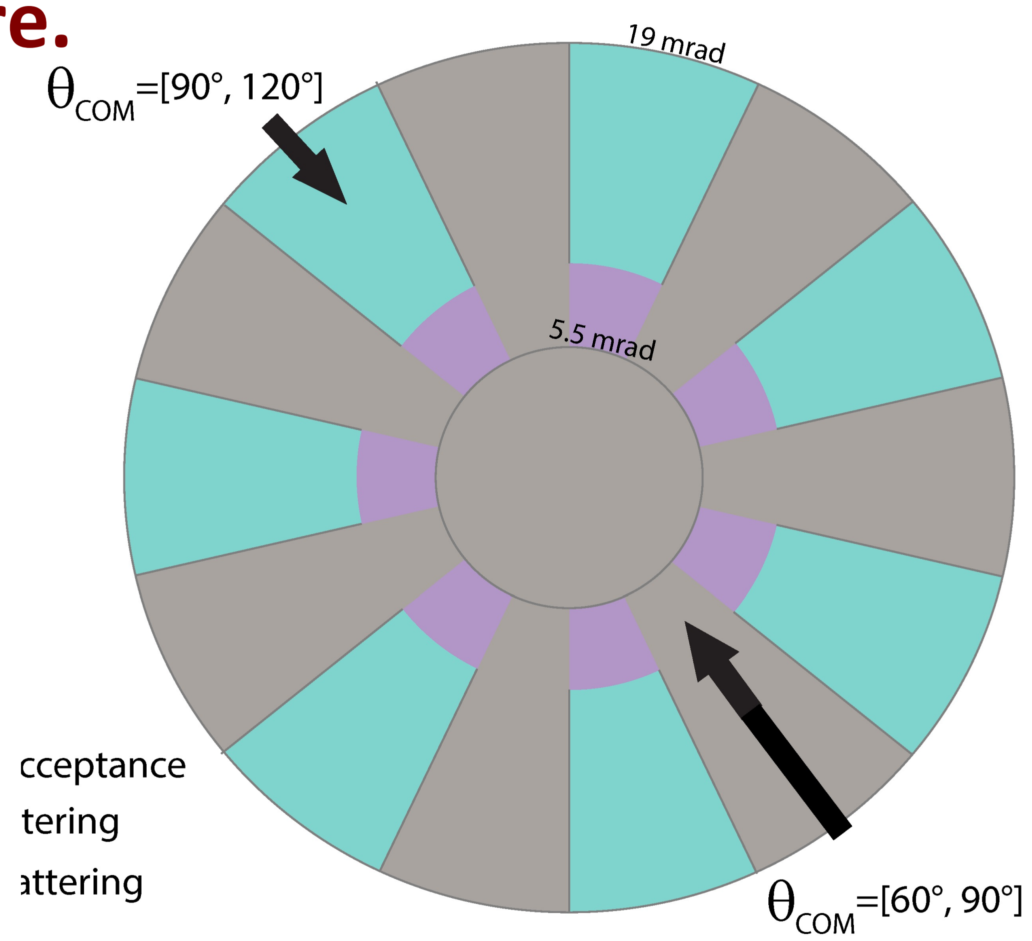
100% Azimuthal Acceptance for Møller Scattering

E_{COM} = 53 MeV

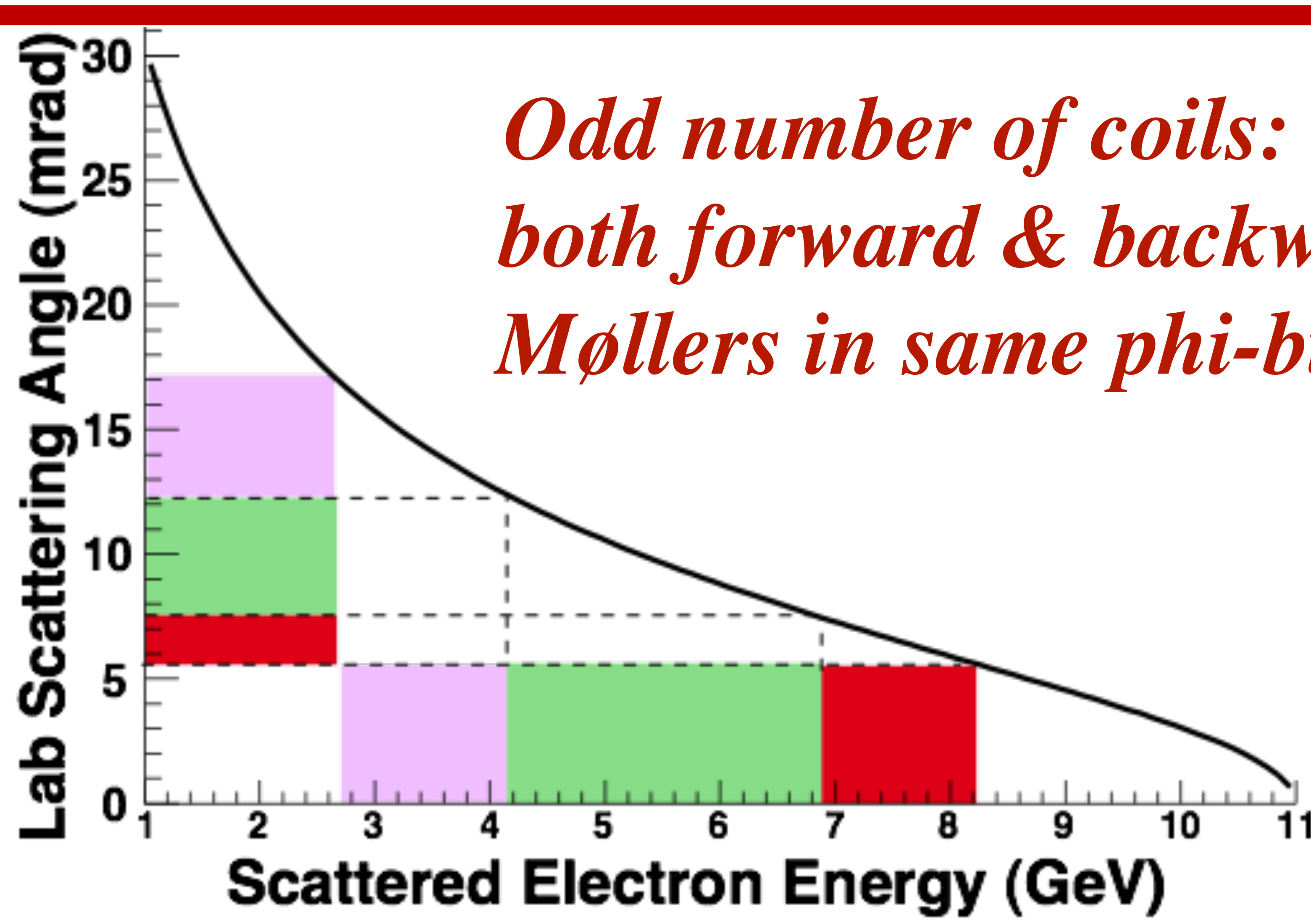


identical particles!

...are collected over here.



The rays that are blocked here...



Odd number of coils: both forward & backward Møllers in same phi-bite