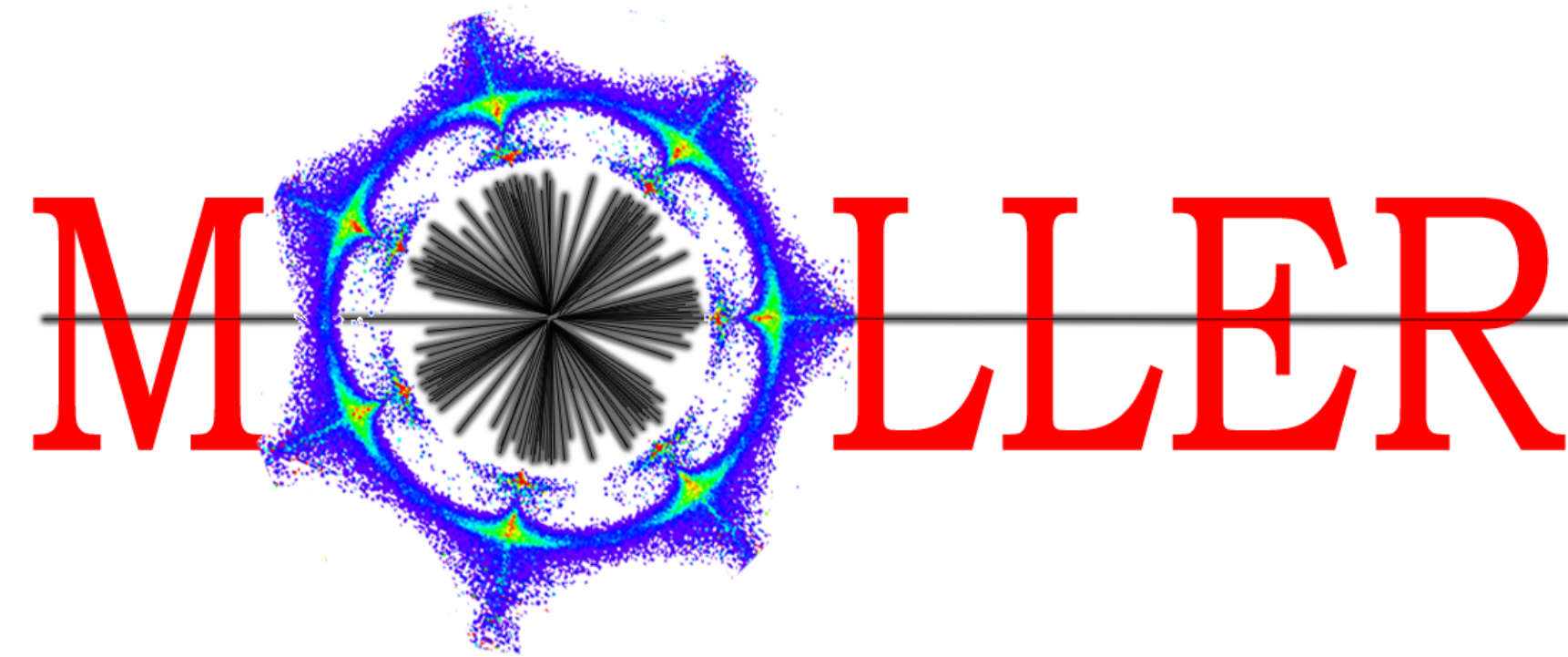


Measuring the Weak Charge of the Electron: The MOLLER Experiment

November 12, 2025

Kent Paschke



A Search for New Physics using Precision at Low Energies

*Low energy measurements offer complementary probes of **new physics at multi-TeV scales***

EDM, $g_\mu-2$, weak decays, β decay, $0\nu\beta\beta$ decay, DM, CLFV...

Parity-Violating Electron Scattering: Low energy weak neutral current couplings
(SLAC, Jefferson Lab, Mainz)

$$A_{PV} \sim 32 \text{ ppb} \quad \delta(A_{PV}) \sim 0.8 \text{ ppb}$$

$$\delta(Q^e_W) = \pm 2.1 \% \text{ (stat.)} \pm 1.1 \% \text{ (syst.)}$$

Search for new flavor diagonal neutral currents

Unique (purely leptonic) new physics reach

Best Collider $\delta(\sin^2\theta_W)$:

$A_I(\text{SLD}): 0.00026$

$A_{fb}(\text{LEP}): 0.00029$

CMS(prelim): 0.00031

MOLLER projected:

$$\delta(\sin^2\theta_W) = \pm 0.00024 \text{ (stat.)} \pm 0.00013 \text{ (syst.)}$$

→ $\sim 0.1\%$ Matches best collider (Z-pole) measurement

Best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require the
Giga-Z factory, linear collider, neutrino factory or muon collider

MOLLER Reach

$$\Lambda_{RR-LL}^{ee} \sim 38 \text{ TeV}$$

Erler et al., Ann.Rev.Nucl.Part.Sci. (2014)

MOLLER

$A_{PV} \sim 32$ ppb with goal of 2% statistical, 1% systematic uncertainty

High luminosity and optimized acceptance

Møller Rate ~ 130 GHz

- signal = 1/3000 of beam electrons

Control Noise 91 ppm at 960 Hz

Integrate time

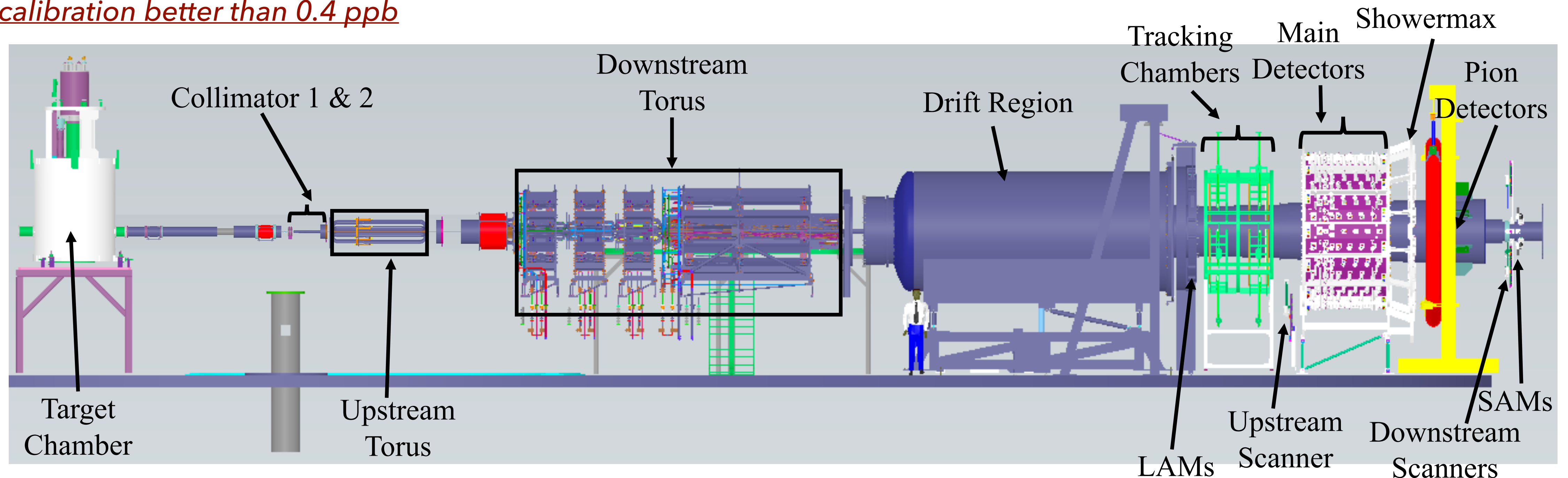
- 344 beam days (~ 3 -4 calendar years)

Controlling Systematic Uncertainty

- calibration better than 0.4 ppb

JLab: precision instrument with 25 years of high precision PVES experiments

MOLLER collaboration: 40+ years of experience including E158, Qweak, PREX/CREX



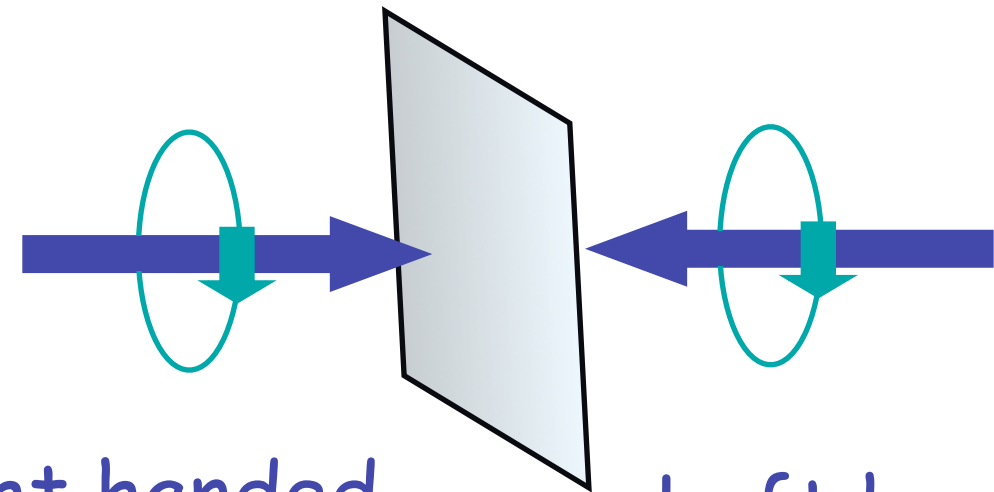
*Parity Violating Electron Scattering:
Probe of Weak Interaction*

Parity Transformation

Parity transformation

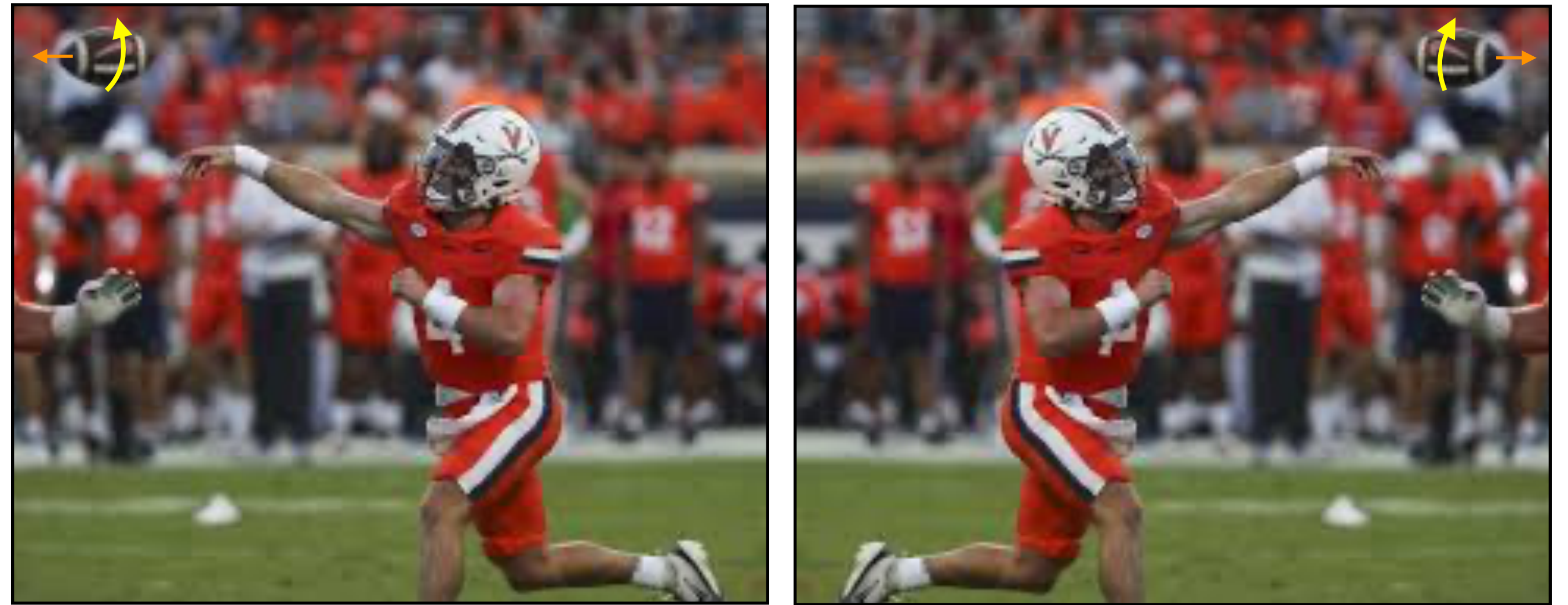
$$x, y, z \rightarrow -x, -y, -z$$

$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{S} \rightarrow \vec{S}$$



Right handed

Left handed



Cavalier QB Chandler Morris

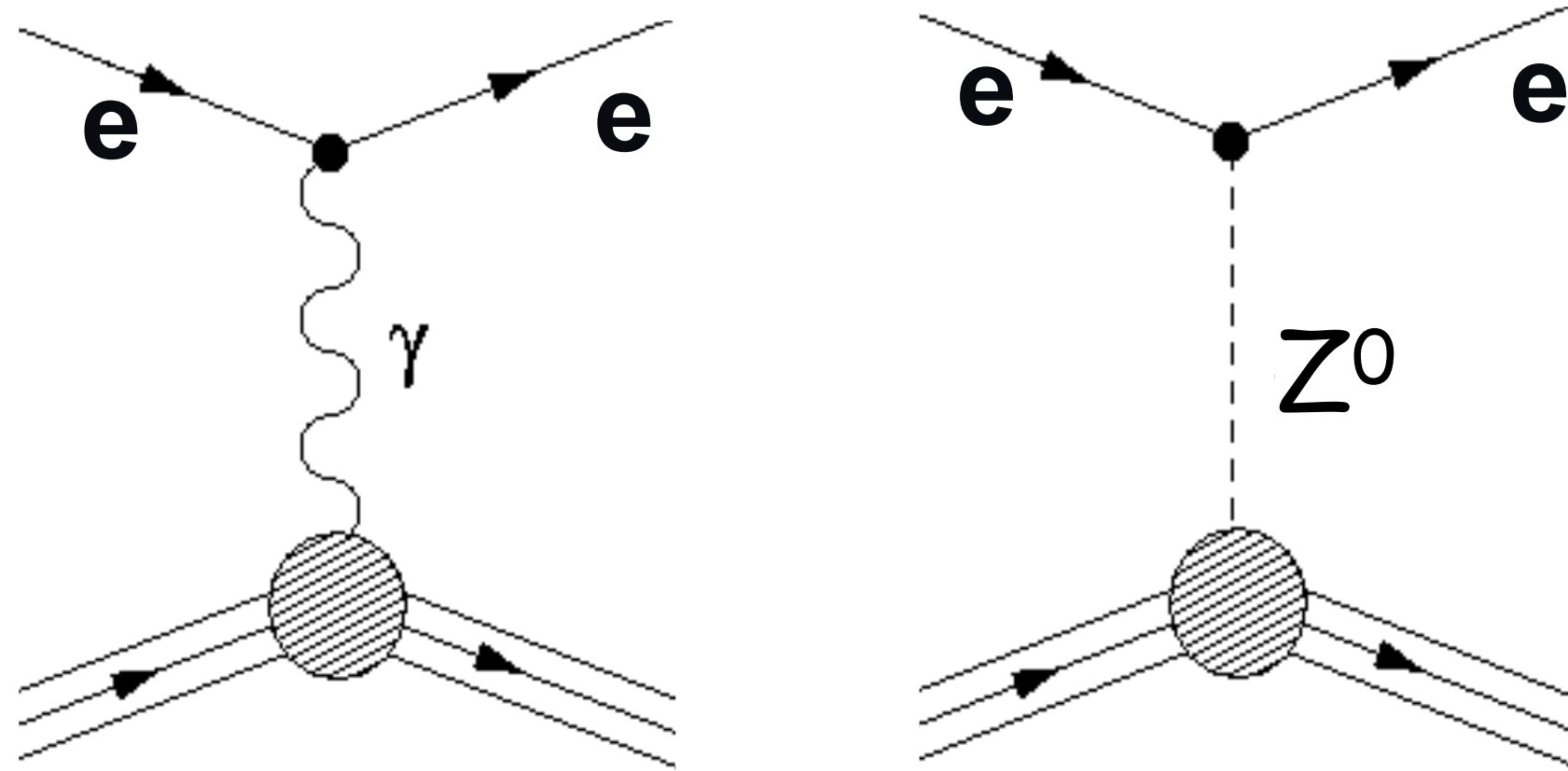
Parity transformation is analogous to reflection in a **mirror**:

... reverses momentum but preserves angular momentum

... takes right-handed (helicity = +1) to left-handed (helicity = -1).



Weak interaction violates mirror symmetry



Scattering cross-section

$$\sigma = |\mathcal{M}_\gamma + \mathcal{M}_Z|^2$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{\frac{\text{diagram with } \gamma \text{ and } Z^0}{|\text{diagram with } \gamma|^2}}{\frac{|\text{diagram with } \gamma|^2}{|\mathcal{M}_\gamma|^2}} \propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$

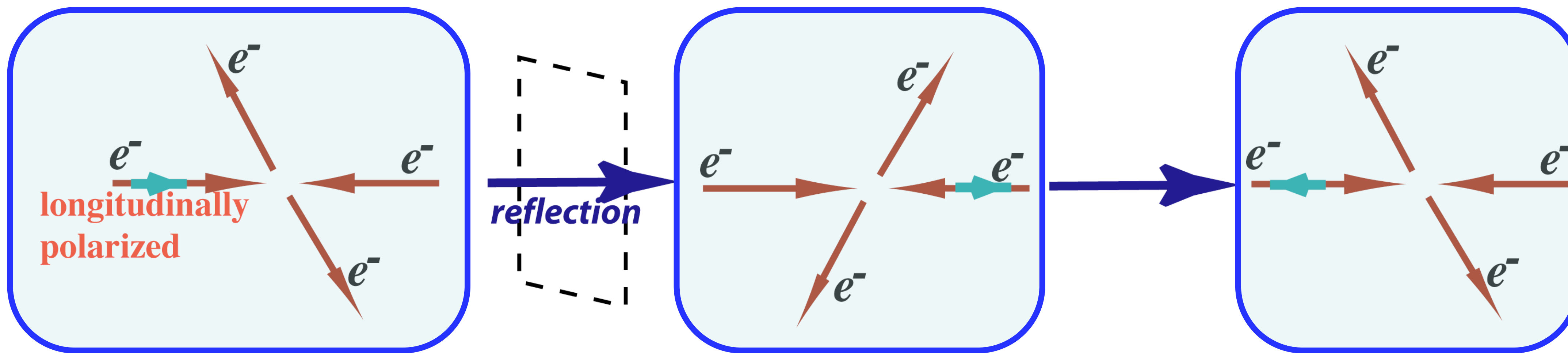
Well understood within the Electroweak Standard Model

- interference of electromagnetic and weak amplitudes
- known values for electron & quark weak neutral current coupling

But new physics could *also* appear here - too ephemeral to be seen directly, but contributing in a similar way here, slightly modifying this asymmetry from the Standard Model expectation

Electron Scattering and Parity-violation

Center of mass frame



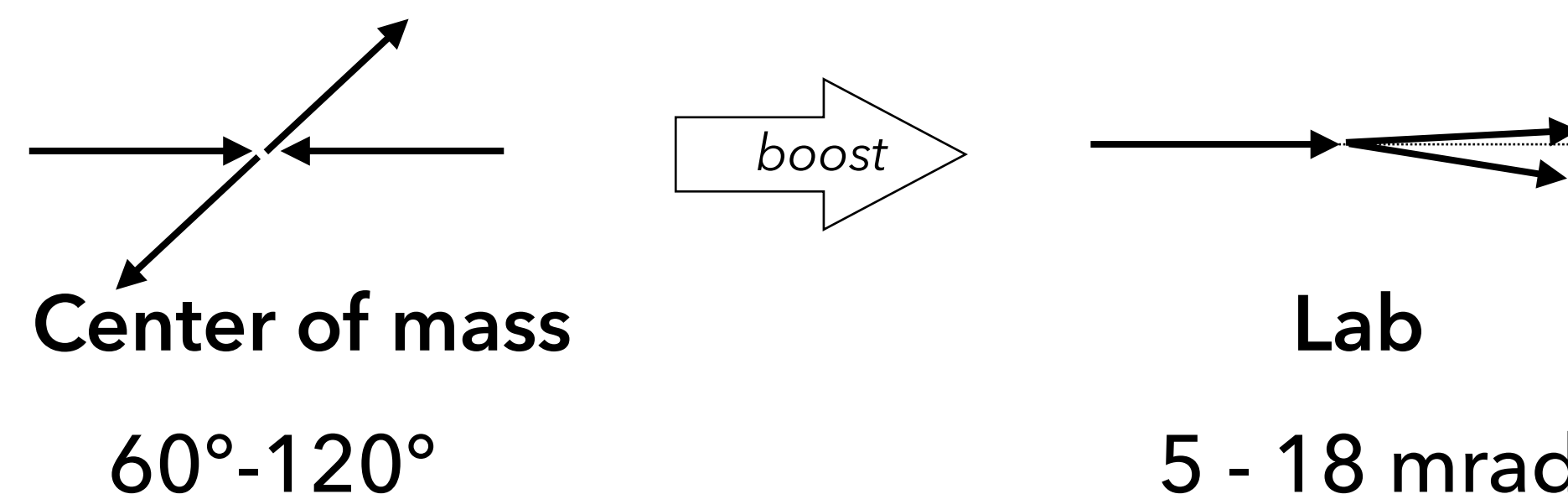
right-handed incident electron

left-handed incident electron

- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference

Identical particles ($e^-e^- \rightarrow e^-e^-$)

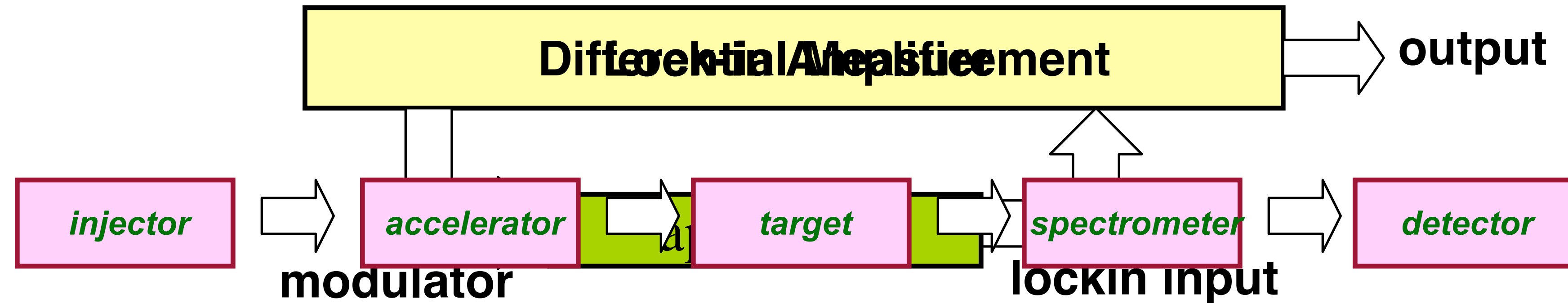
Boosted to Lab Frame



Measuring A_{PV}

Goal: 10^{-8} asymmetry measurement at the few percent level

How do you pick a tiny signal out of a noisy environment?



Measure fractional rate difference
between opposing helicity states

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

$A_{\text{measured}} \sim -35$ ppb with 2% precision
 $N \sim 2.5 \times 10^{18}$ electrons!

High rates to get statistical precision, but also:

Control Noise - quiet electronics, stability

Low backgrounds

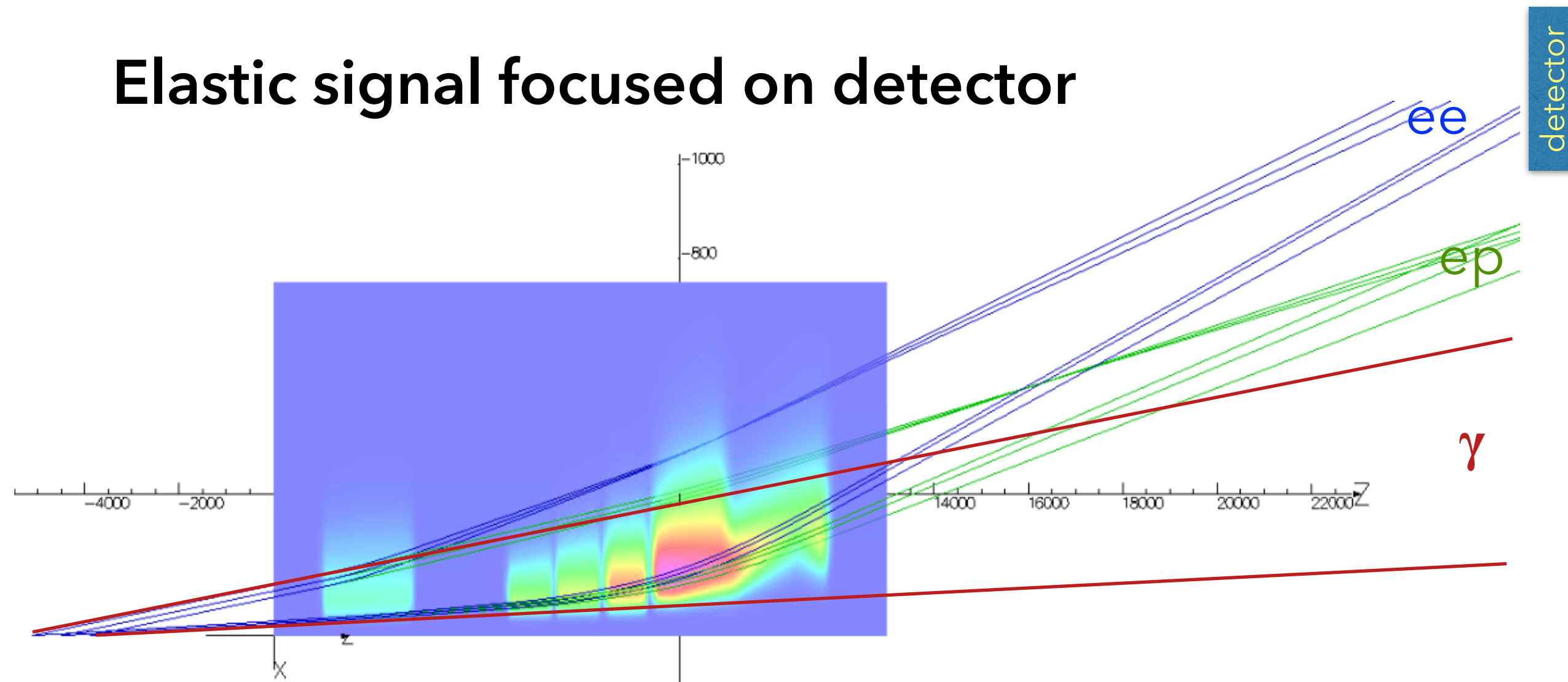
Polarimetry

Kinematics

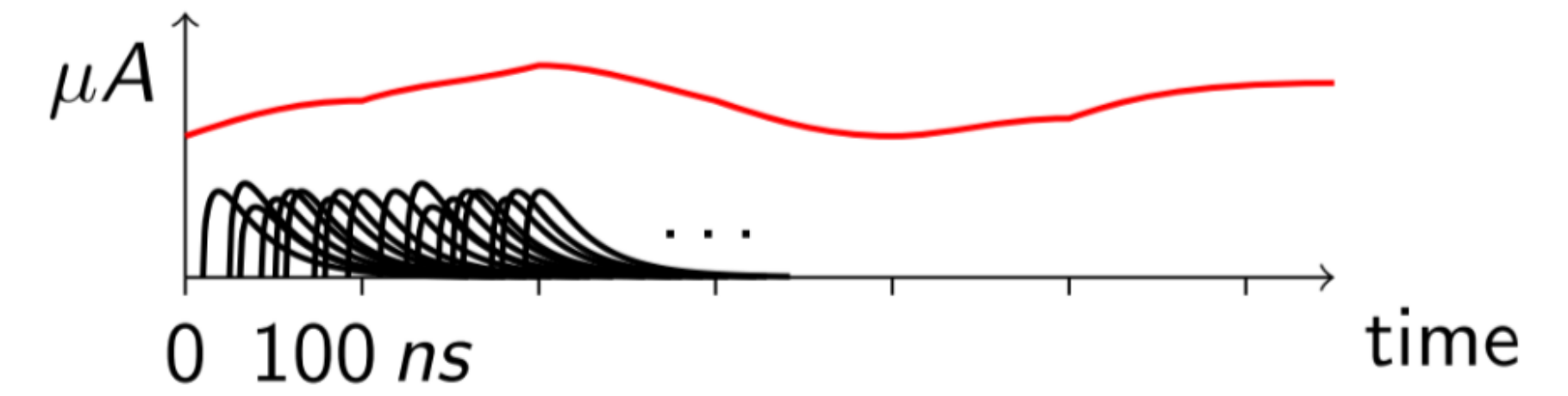
False Asymmetries - electronics, beam motion

Measuring A_{PV}

Elastic signal focused on detector

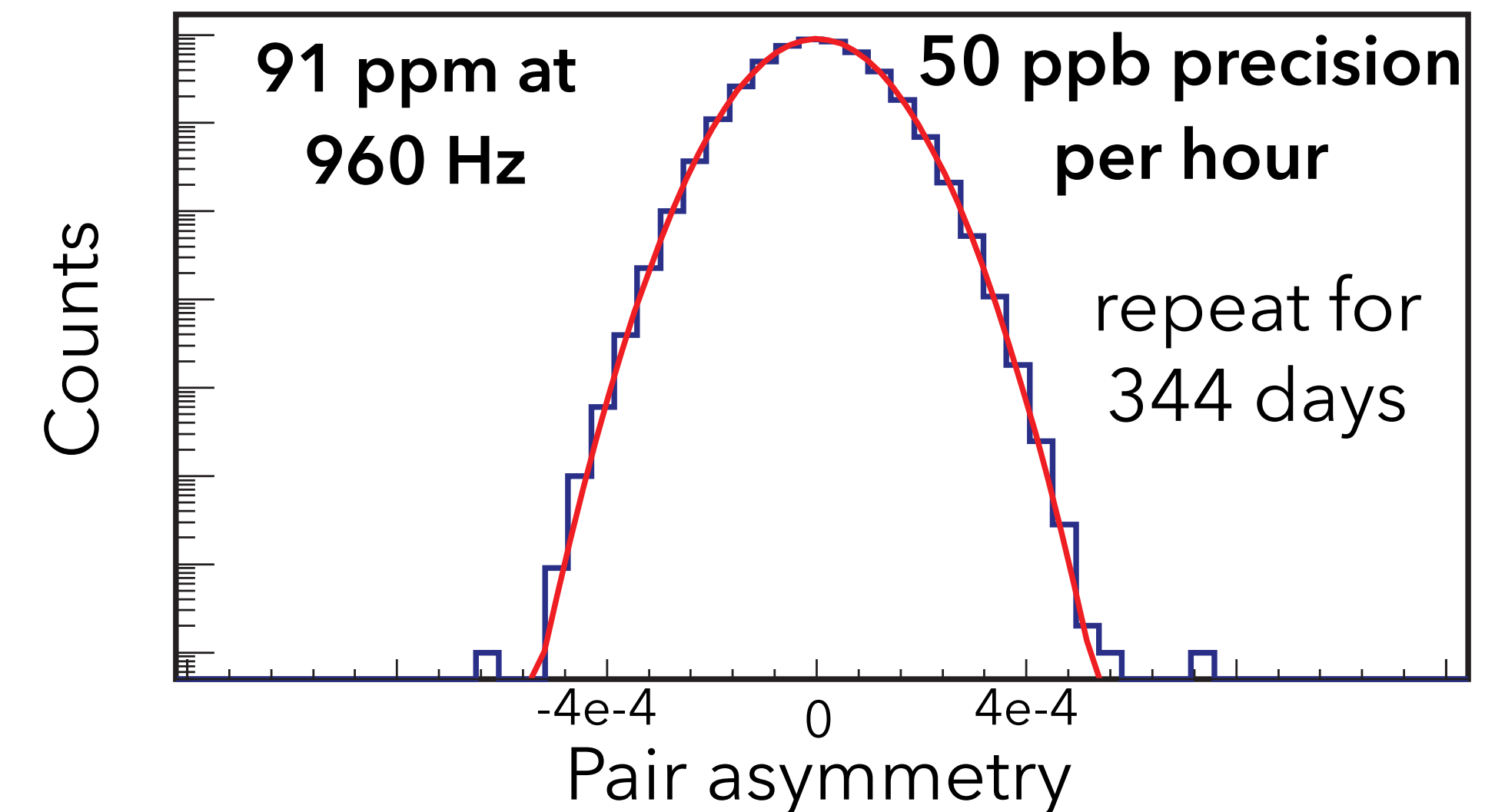
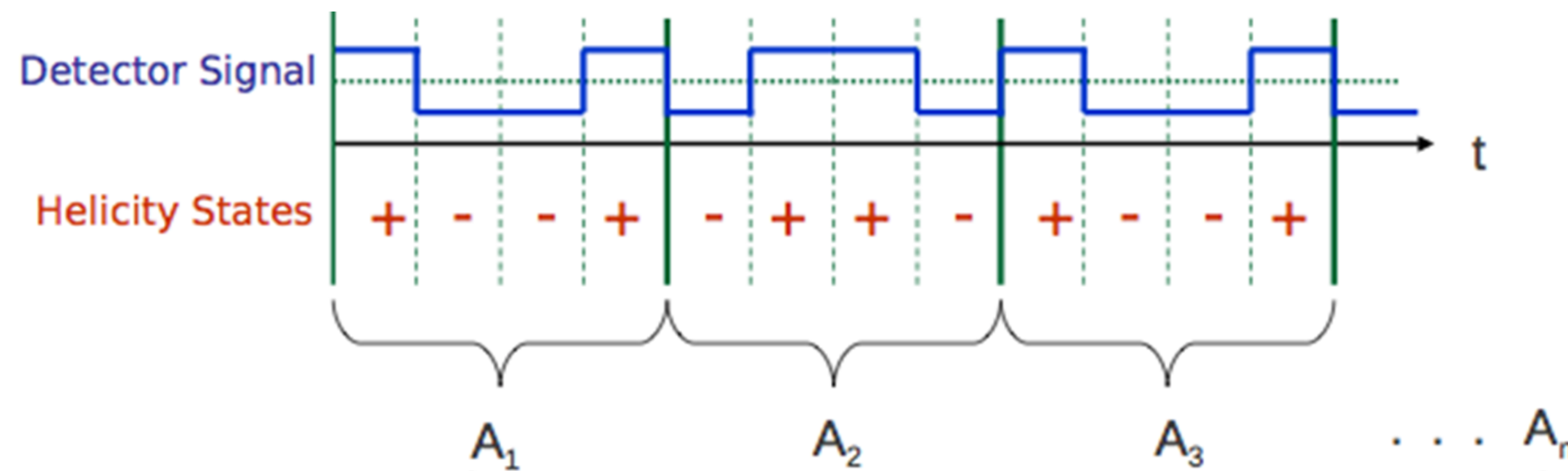


Integration of detector current

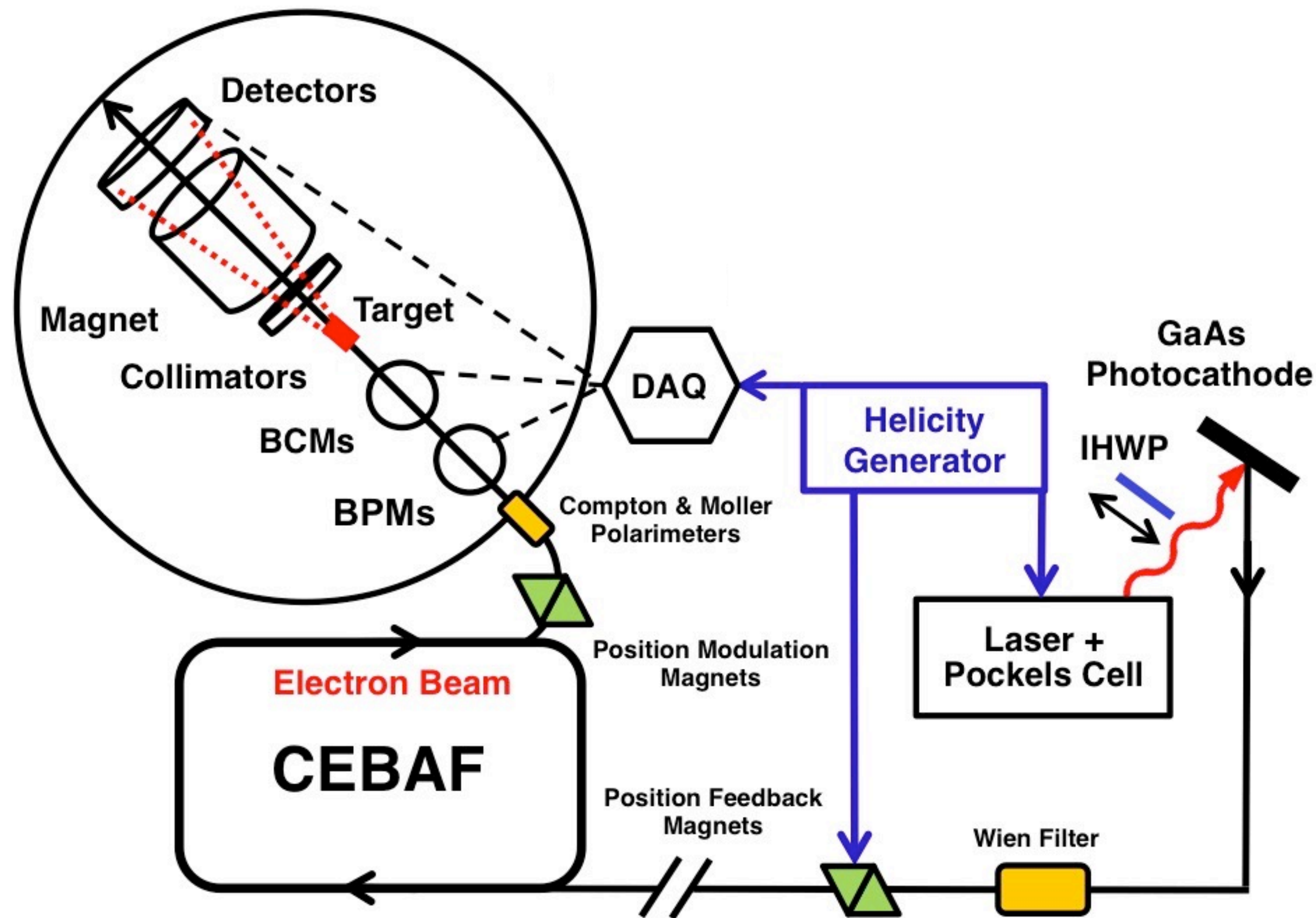


~ 130 GHz signal rate

Rapid (1kHz) measurement over helicity reversals

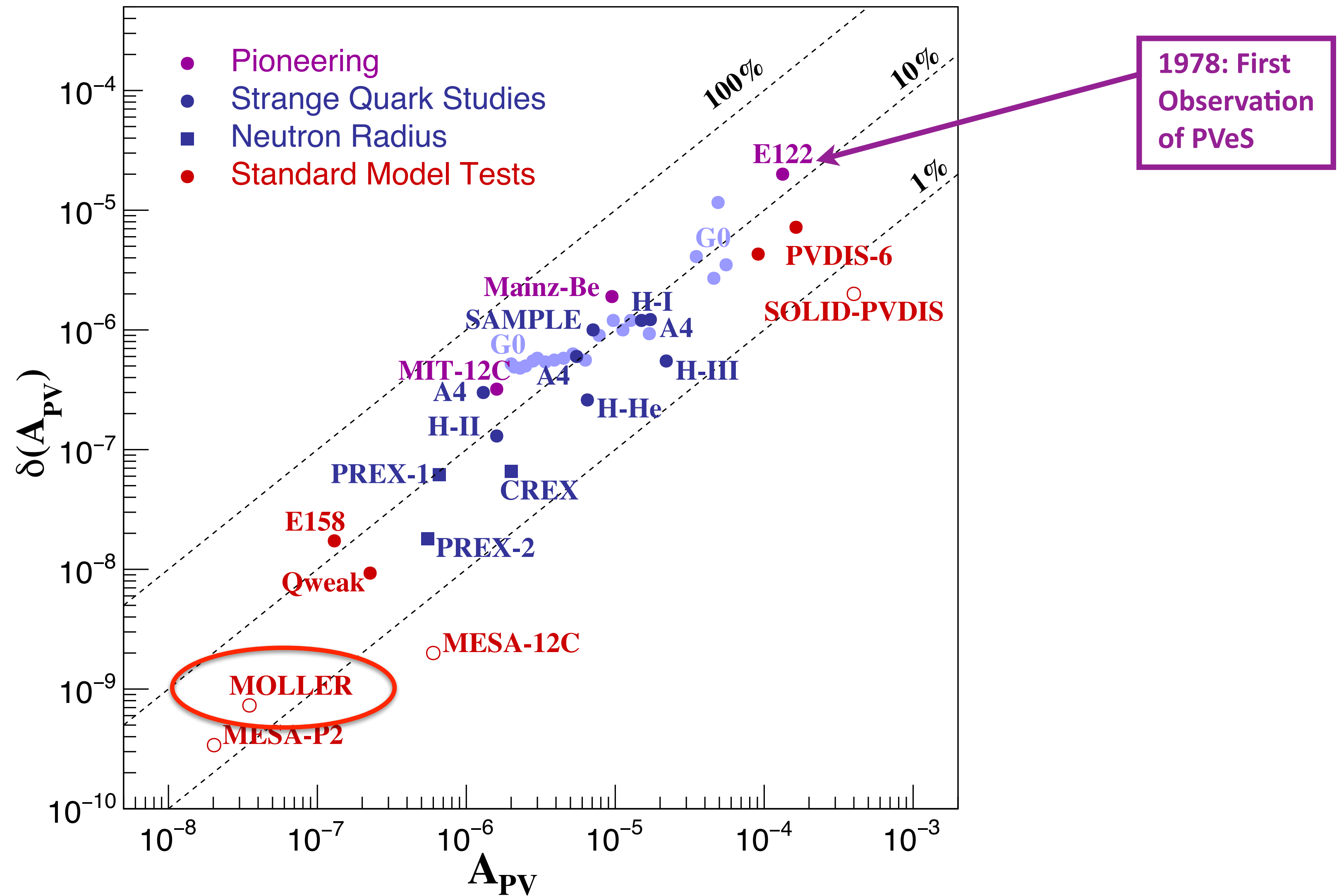


The Entire Accelerator Complex is our Apparatus



- **Polarized Source Laser** - rapid reversal, keep spin states the same intensity, position, shape...
- **Spin Manipulation** - crossed E and B fields, to rotate spin in low energy injector
- **Position/Energy Modulation** - for calibrating detector sensitivity
- **Polarimeters**
- **Precise monitors** for beam current and position
- **High luminosity Targets**
- **Spectrometers** for isolating signal from background
- **Detectors and data acquisition** for low noise measurement
- **RF accelerator** for precise, low noise, stable, well-understood accelerated beam

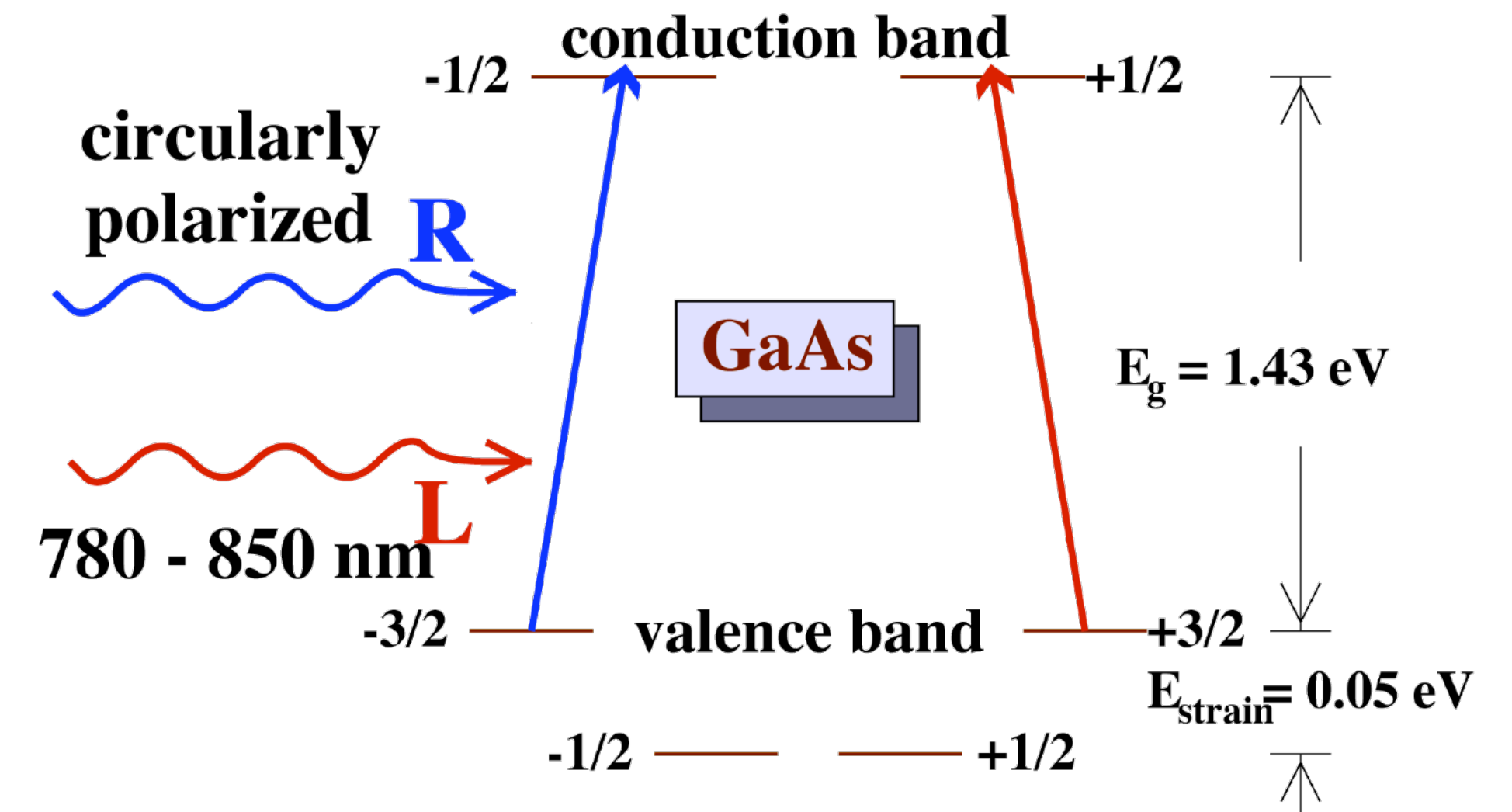
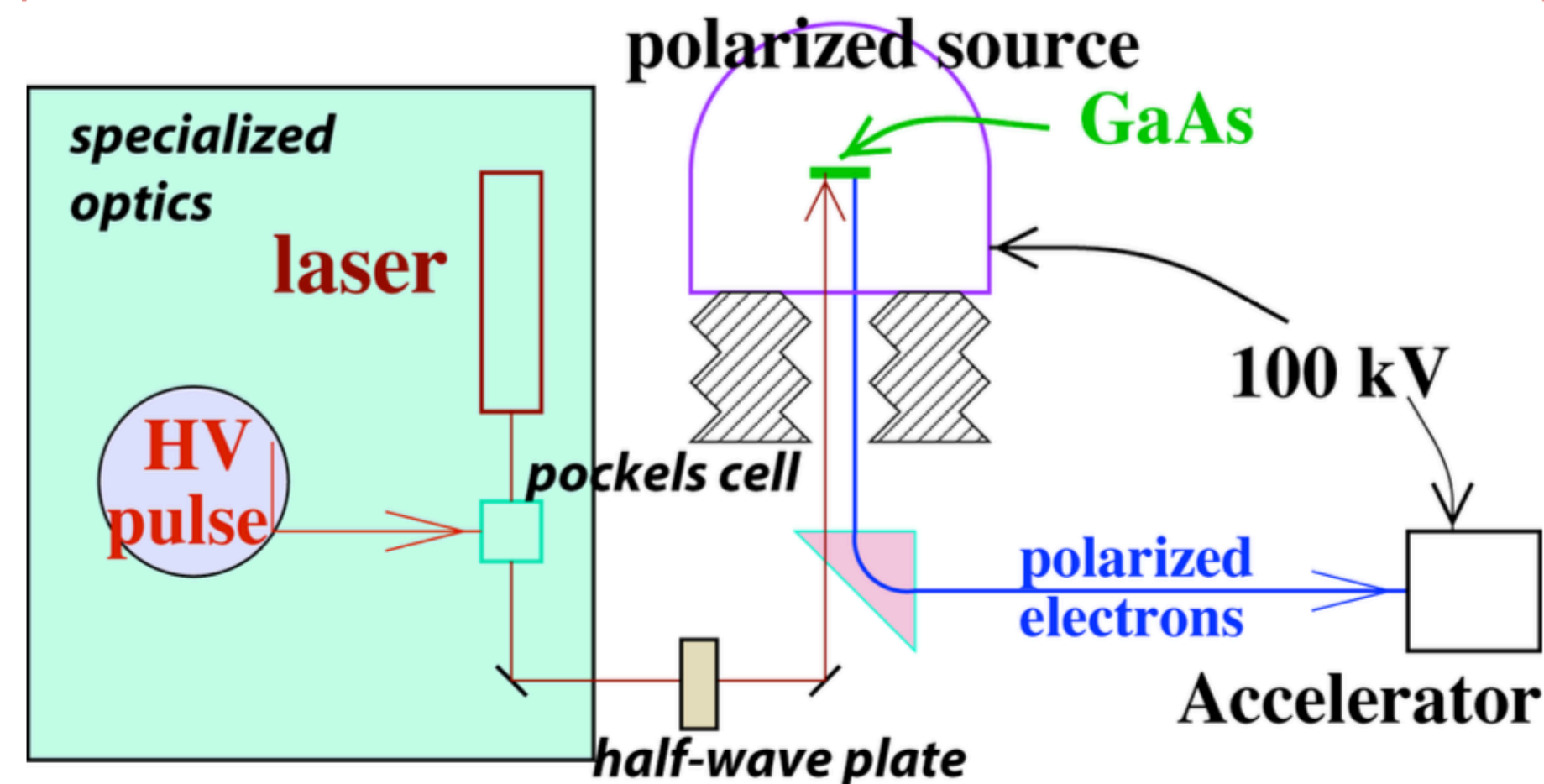
Progress in PVeS studies



Broad program studying the structure of protons and nuclei, and searching for new physics

MOLLER apparatus

Polarized Electrons for MOLLER



Average beam asymmetry between polarization states must be small
Goals: < 10 parts per billion intensity, < 6 Angstroms position difference

Beam generation and delivery must be low noise and no asymmetry between polarization states

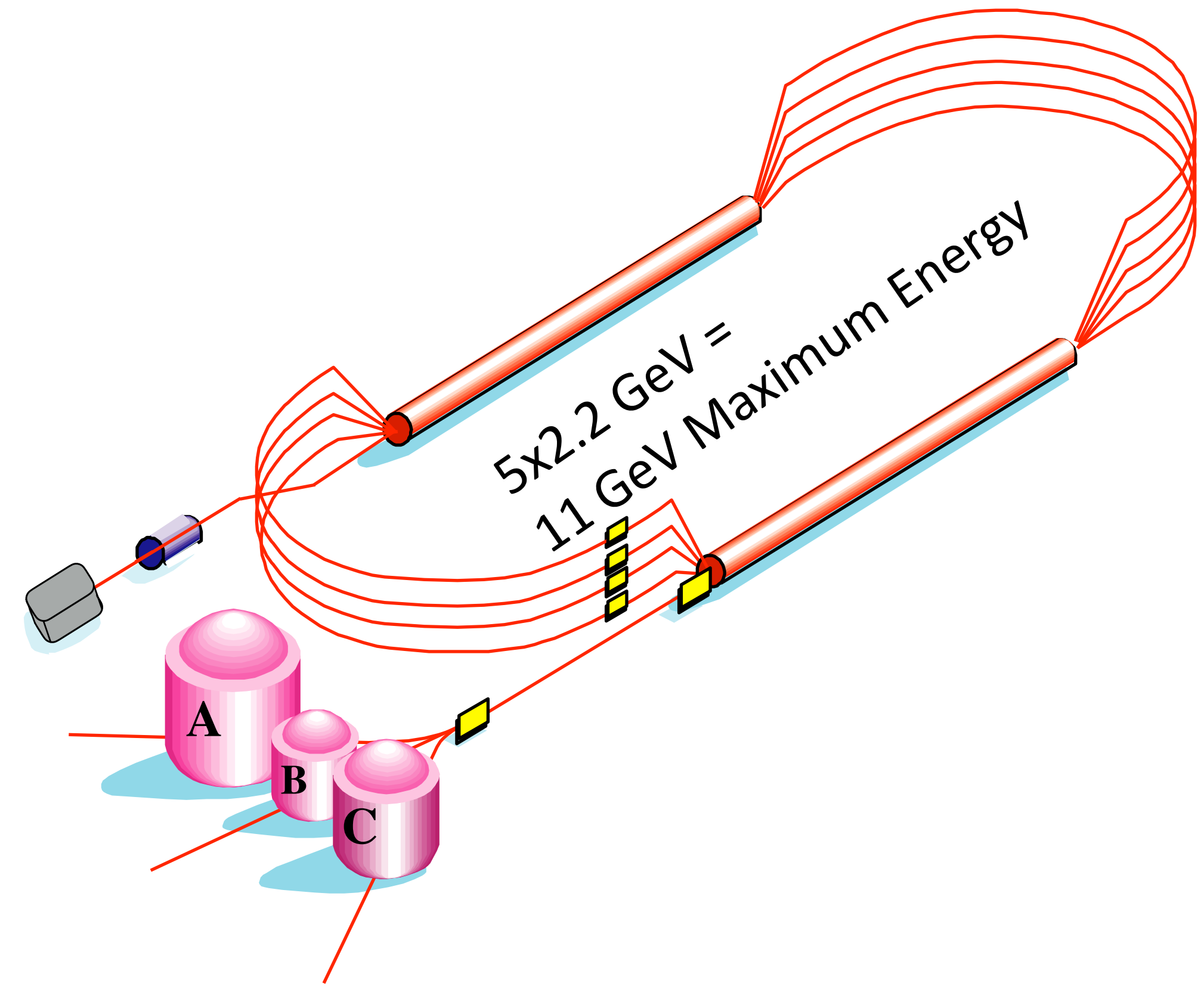
- High intensity, high polarization through photoemission from GaAs photocathode
- Rapid-flip of beam helicity by reversing laser polarization with Pockels cell
- Beam must look the same for the two polarization states
- Photocathode has preferred axis: analyzing power for linear light - source of asymmetry!
- In addition to avoiding asymmetry, noise is crucial to keep low in order to average down to 6 Angstroms!

CEBAF at JLab

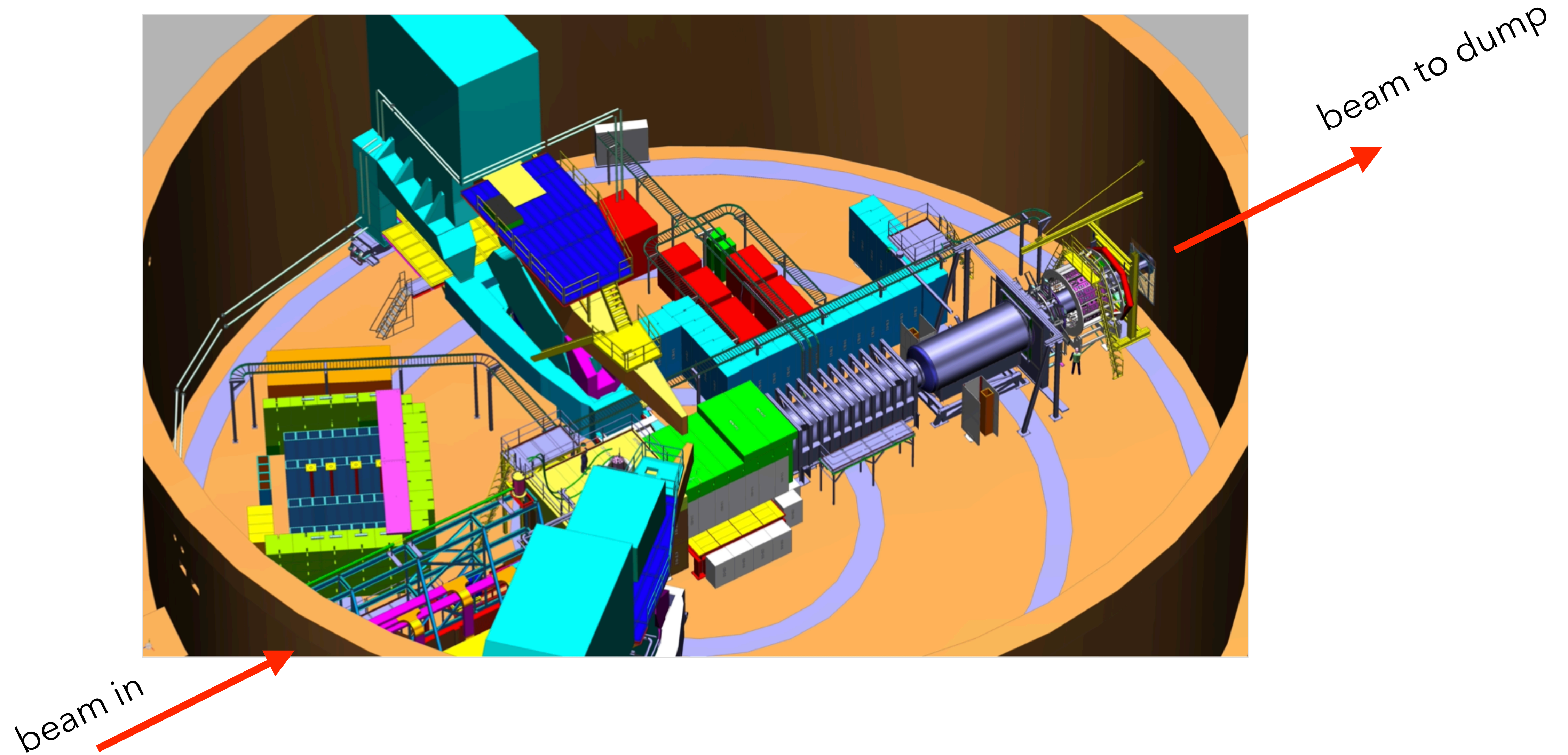
Superconducting, continuous wave, recirculating linac

1500 MHz RF, with 3 interleaved 500 MHz beams

Superconducting RF is makes a clean, quiet beam... perfect for precision experiments

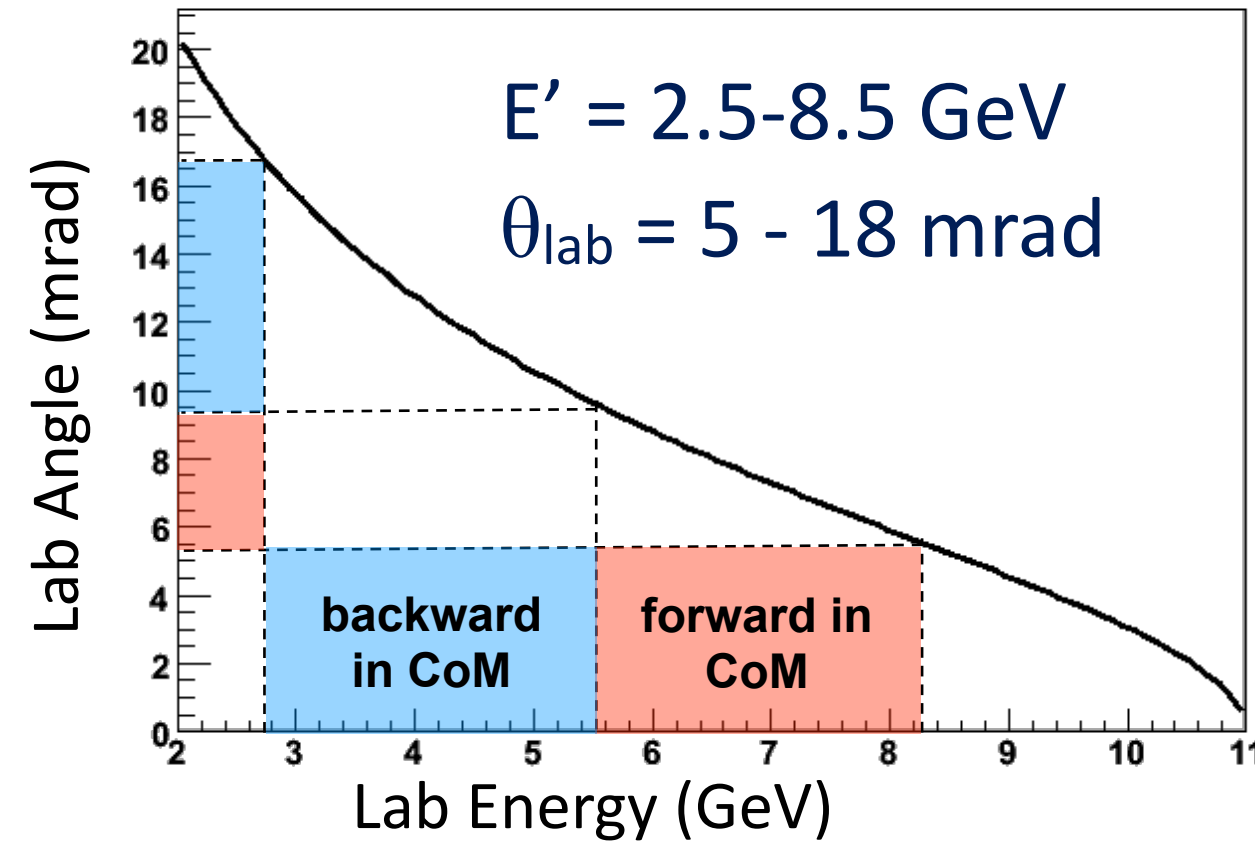


MOLLER in Hall A

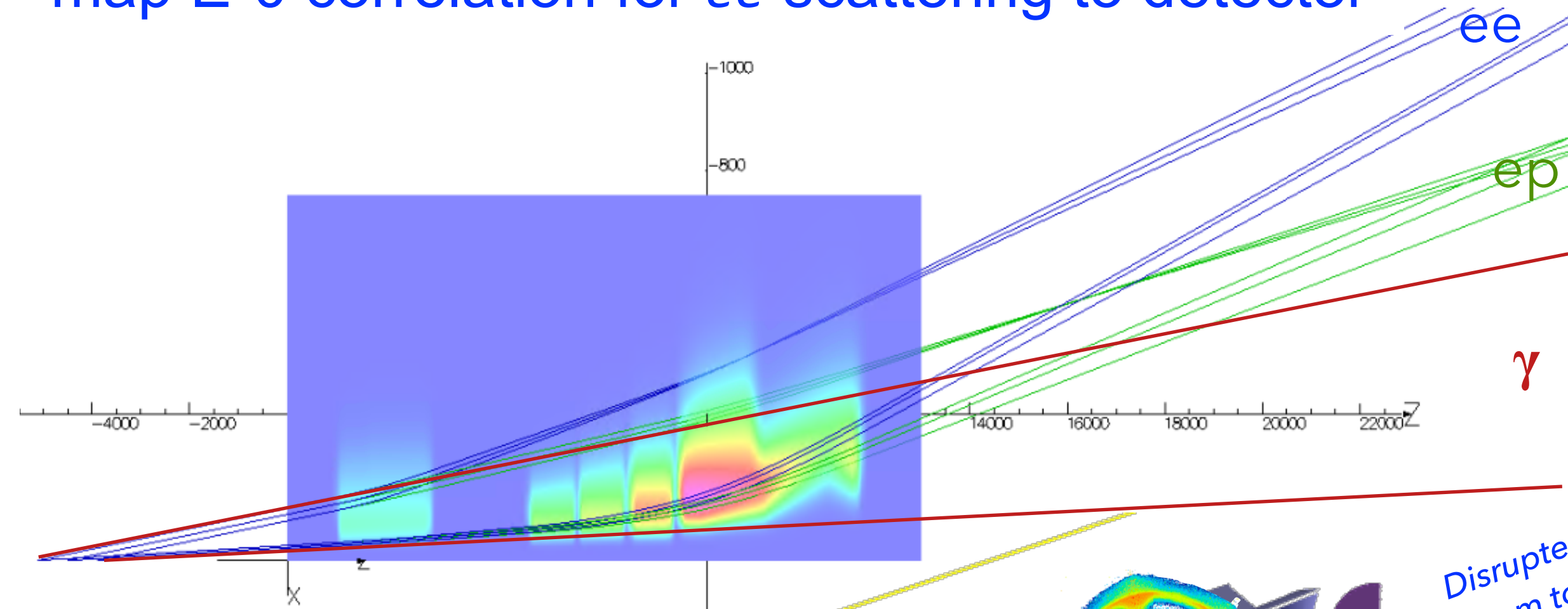


MOLLER Spectrometer

Optimized with COM $90^\circ \pm 30^\circ$

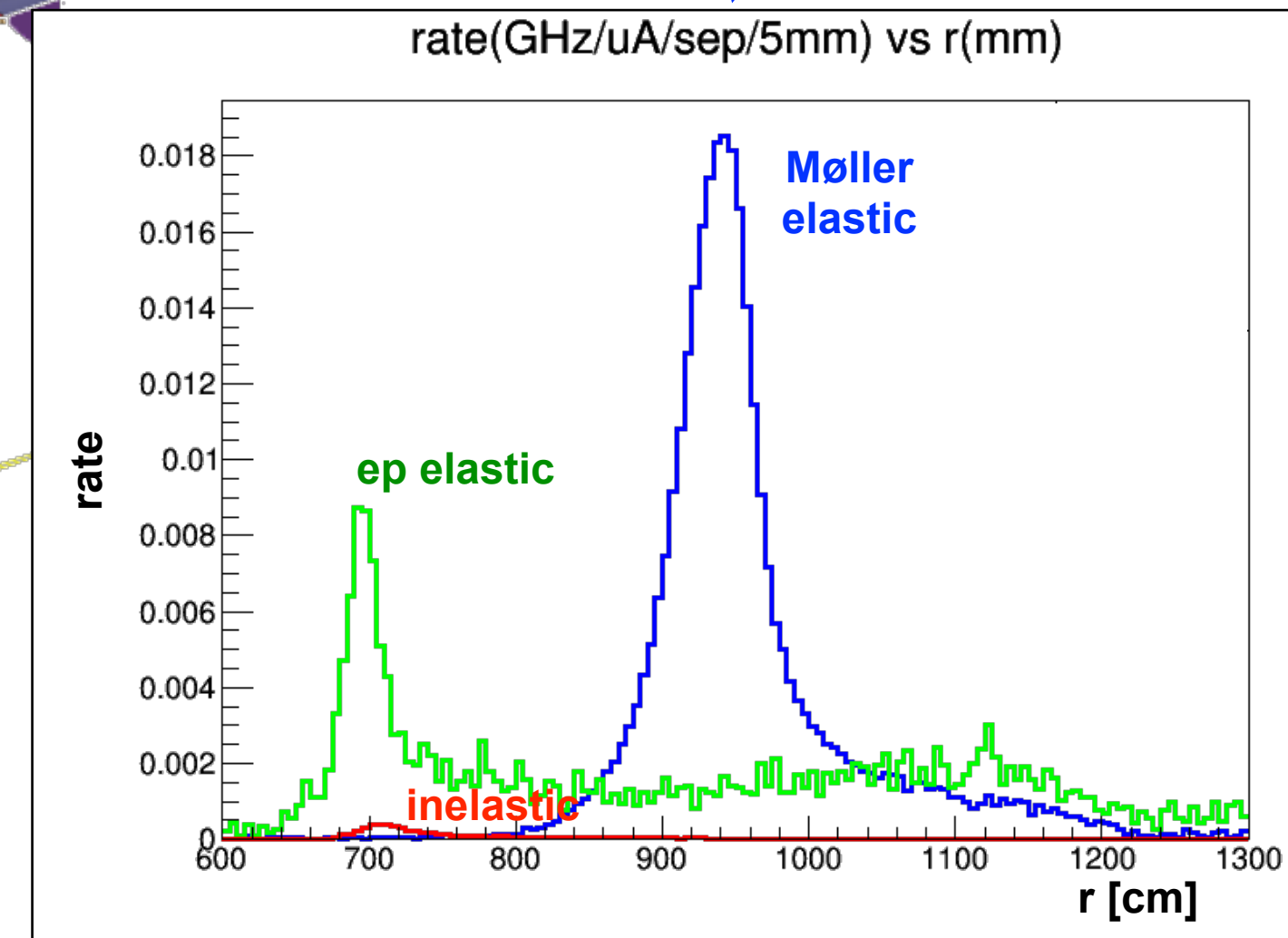
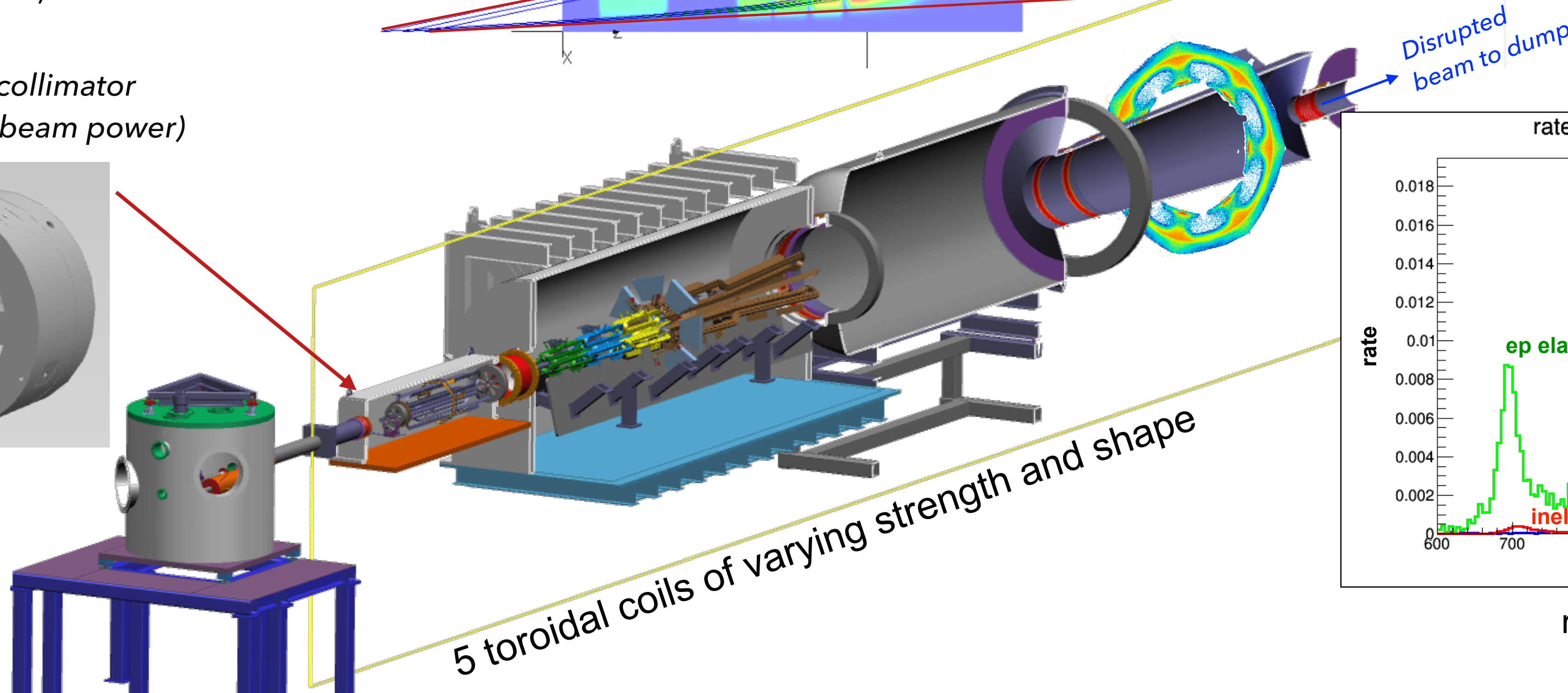
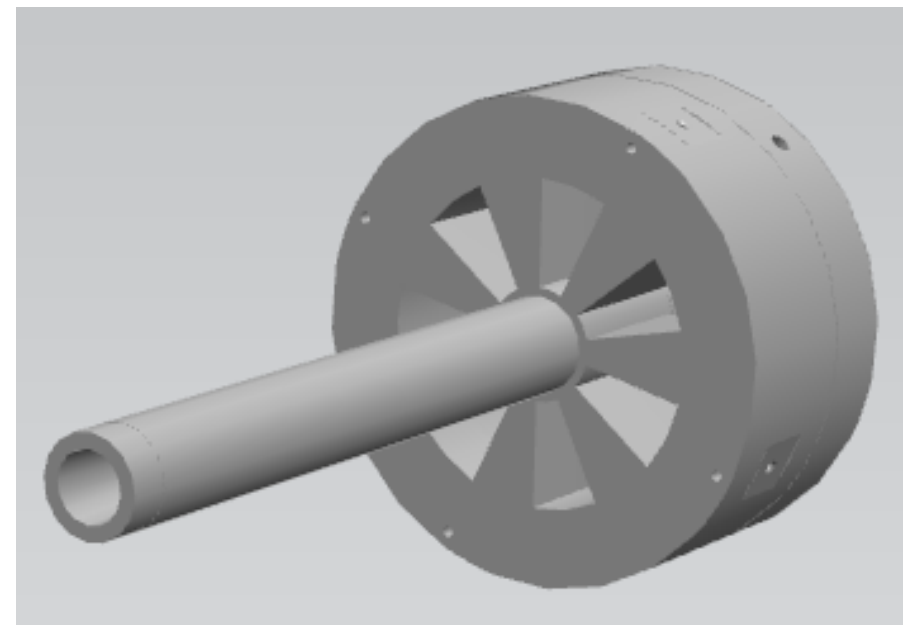


map E- θ correlation for ee scattering to detector



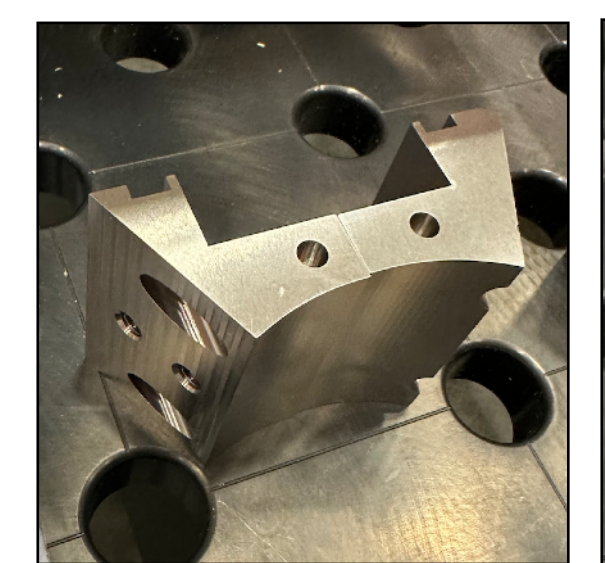
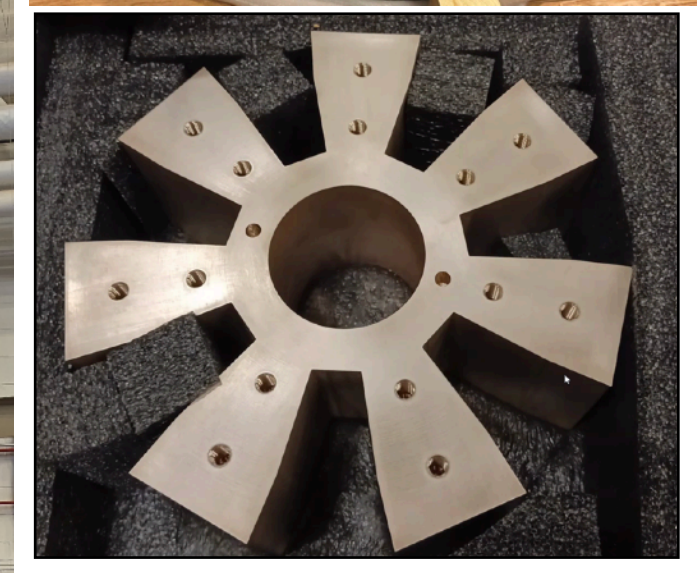
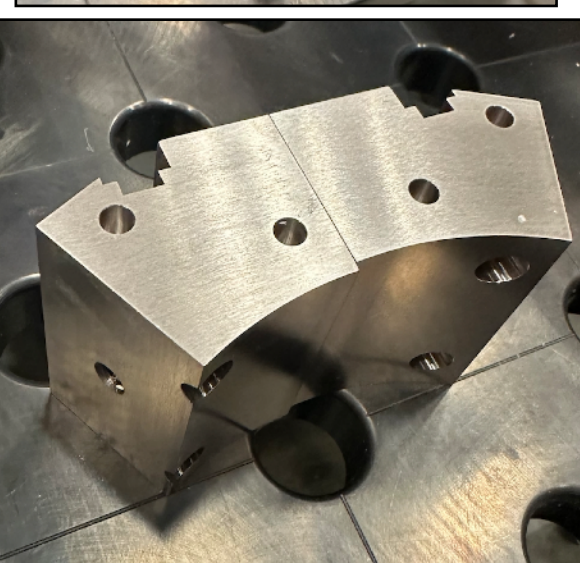
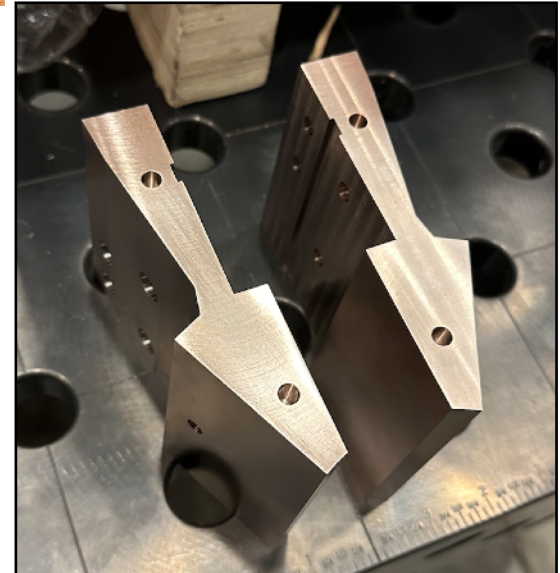
Azimuthal field separates ee , ep , and line of sight (γ) at detector plane

Acceptance defining collimator
5 kW power (0.7% of beam power)



radial flux distribution

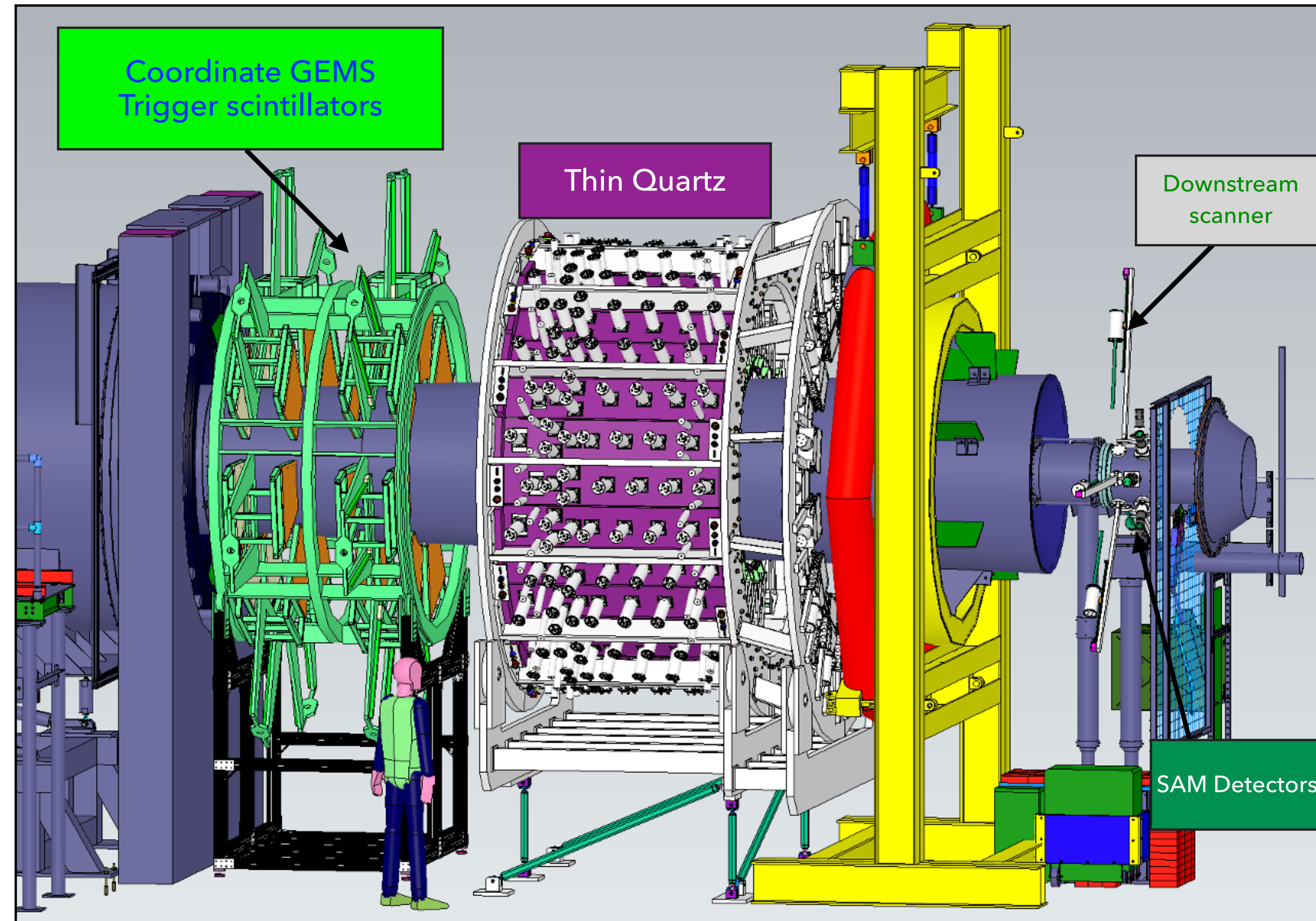
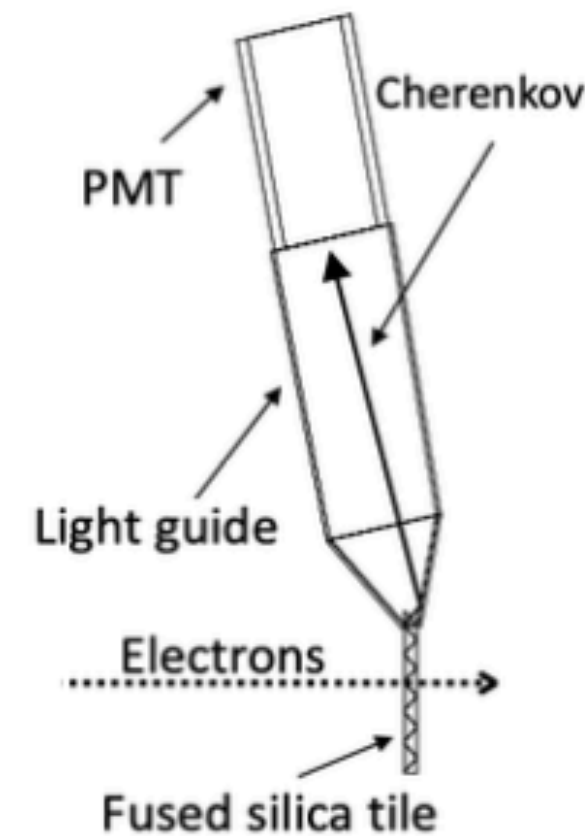
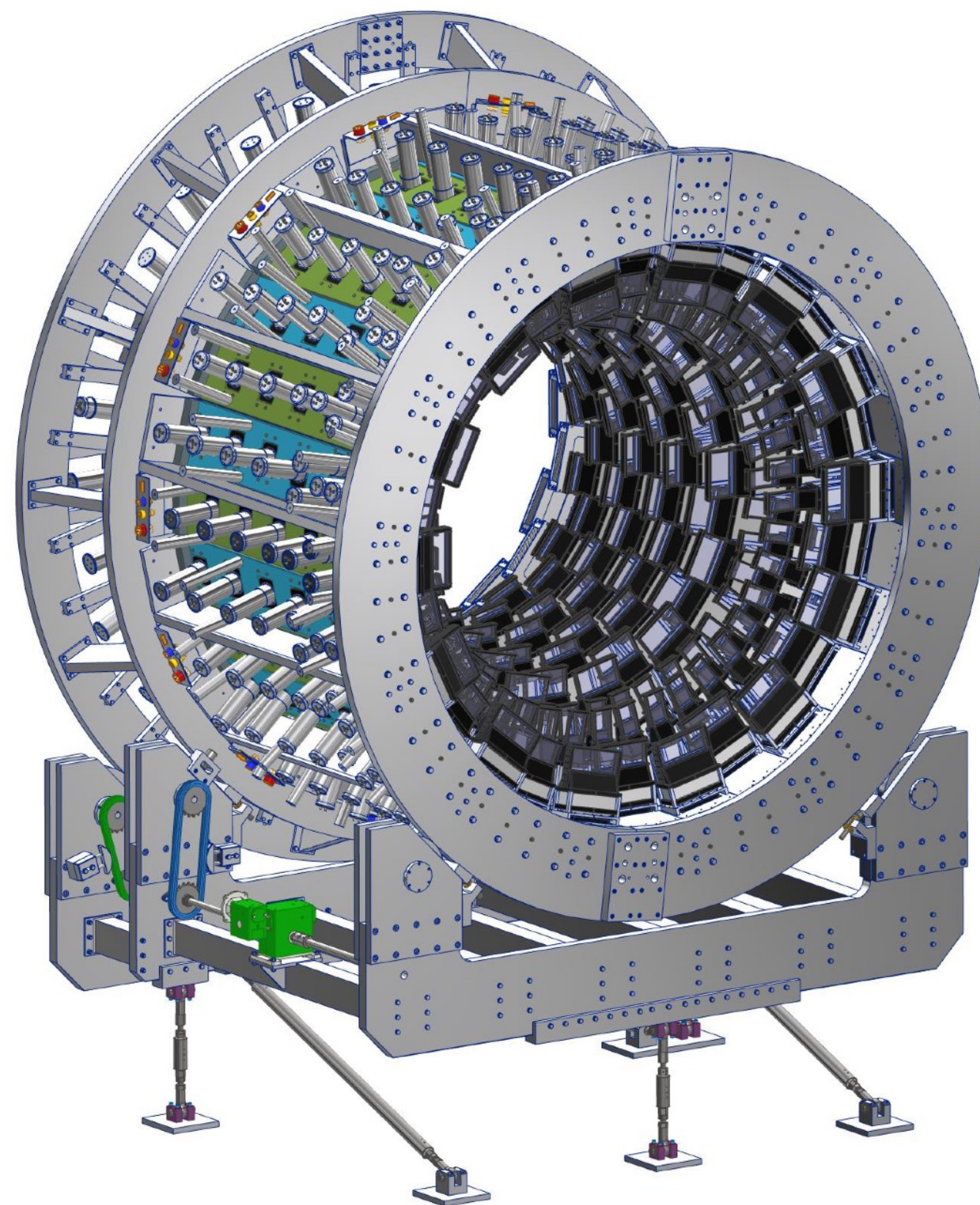
Spectrometer Components



Detector package

Primary A_{pV} measurement uses an array of thin quartz detectors

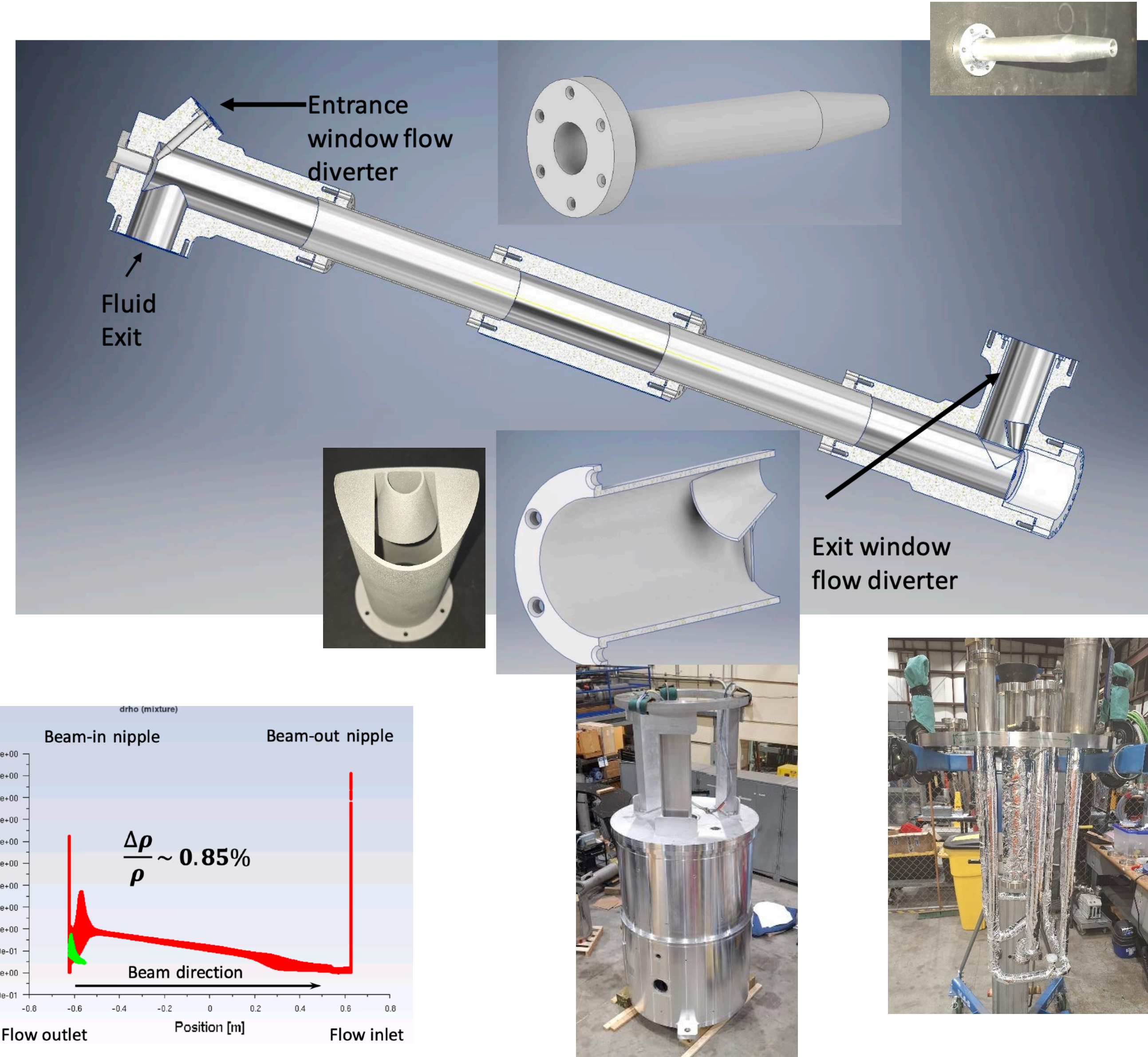
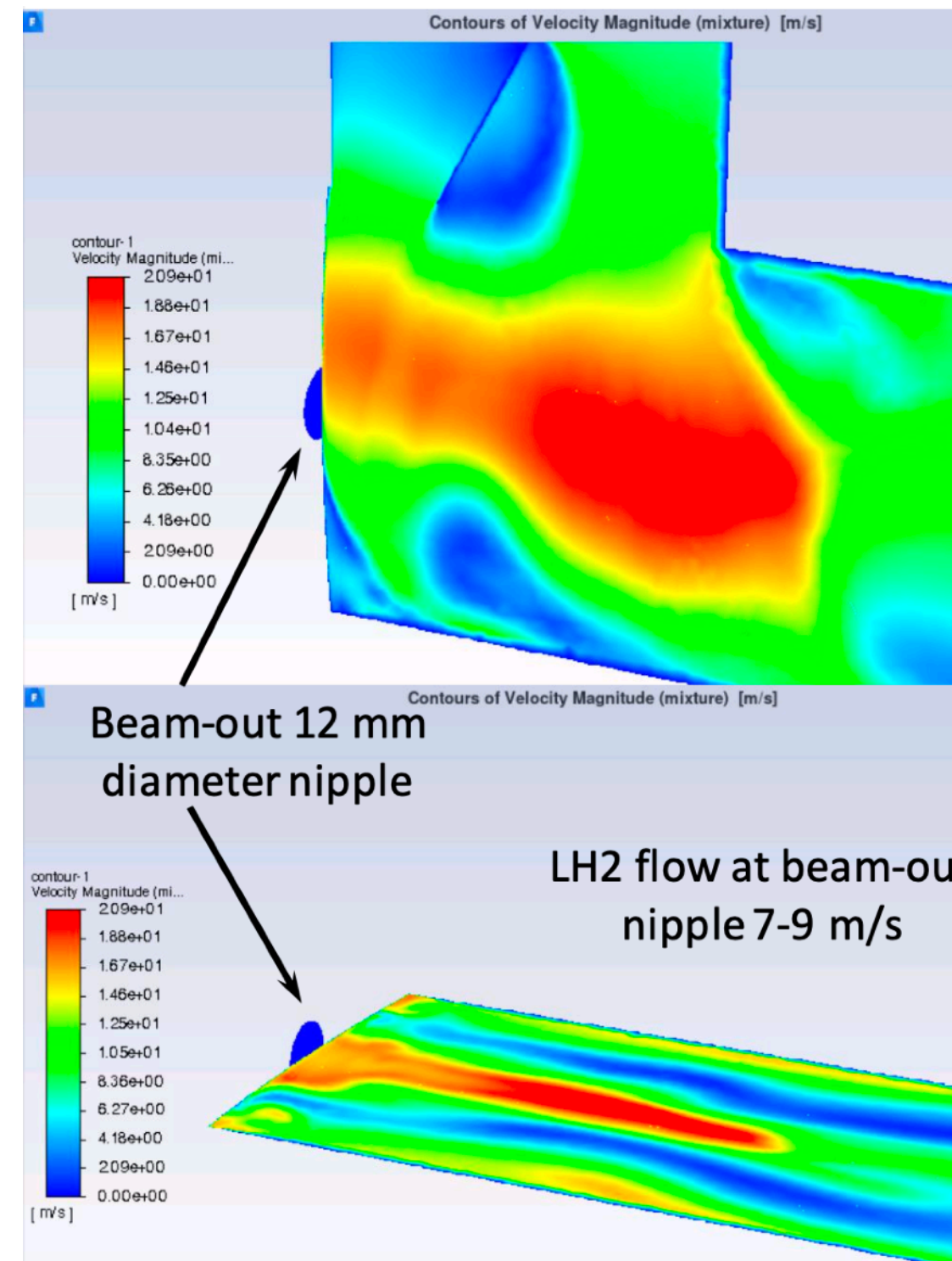
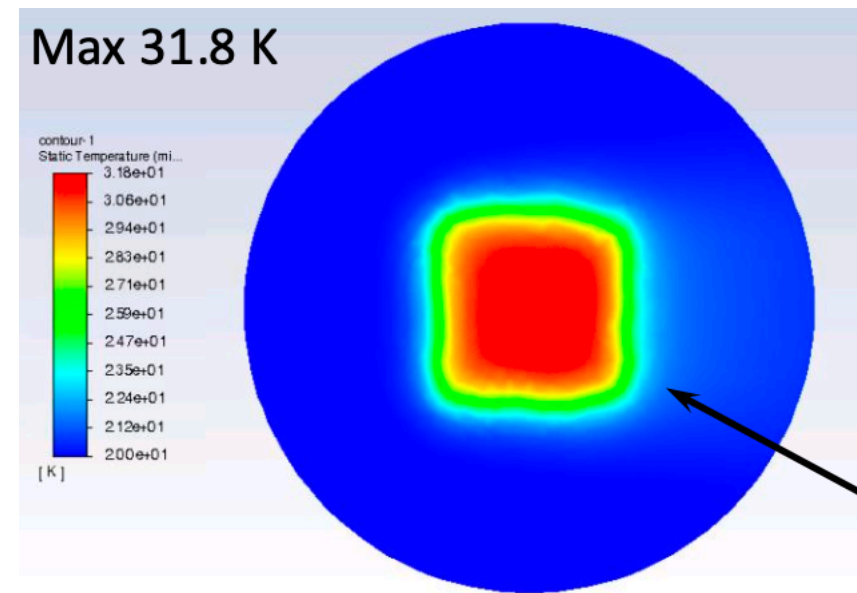
- 224 tiles total, over in 6 rings



Tracking chambers for calibration at 100,000x lower beam current (0.6 nA)

LH₂ Target

- 4.5 kW target power, 3.3 kW beam power
- 1.25m long LH₂ volume
- VERY stable!
 - density loss $\Delta\rho/\rho < 1\%$
 - density fluctuations $\delta\rho/\rho < 30$ ppm



How MOLLER Challenges SRF Performance

Robust, Stable Operation

The MOLLER apparatus requires time to stabilize after a beam interruption

- Accelerator recovery time: 0.5-few minutes
- Beam ramp time: ~ 0.5 minutes, part of target protection
- Target - thermal modulates with $\sim 2\text{K}$ amplitude, ~ 1 minute to stabilize
- Detectors - thermal changes in photocathode resistivity, ~ 1 minute at full signal to stabilize

High duty factor requires very few trips. Goal: < 6 trips per hour (20% loss of efficiency)

Beam trips related to SRF cavities

- Cavity trip
- Transient instabilities in cavities can deflect the beam (either transverse motion or in dispersive region due to energy change), triggering Beam Loss Monitor trips

Gradient Stability

MOLLER is *highly* sensitive to energy drifts due to g-2 spin precession of polarization

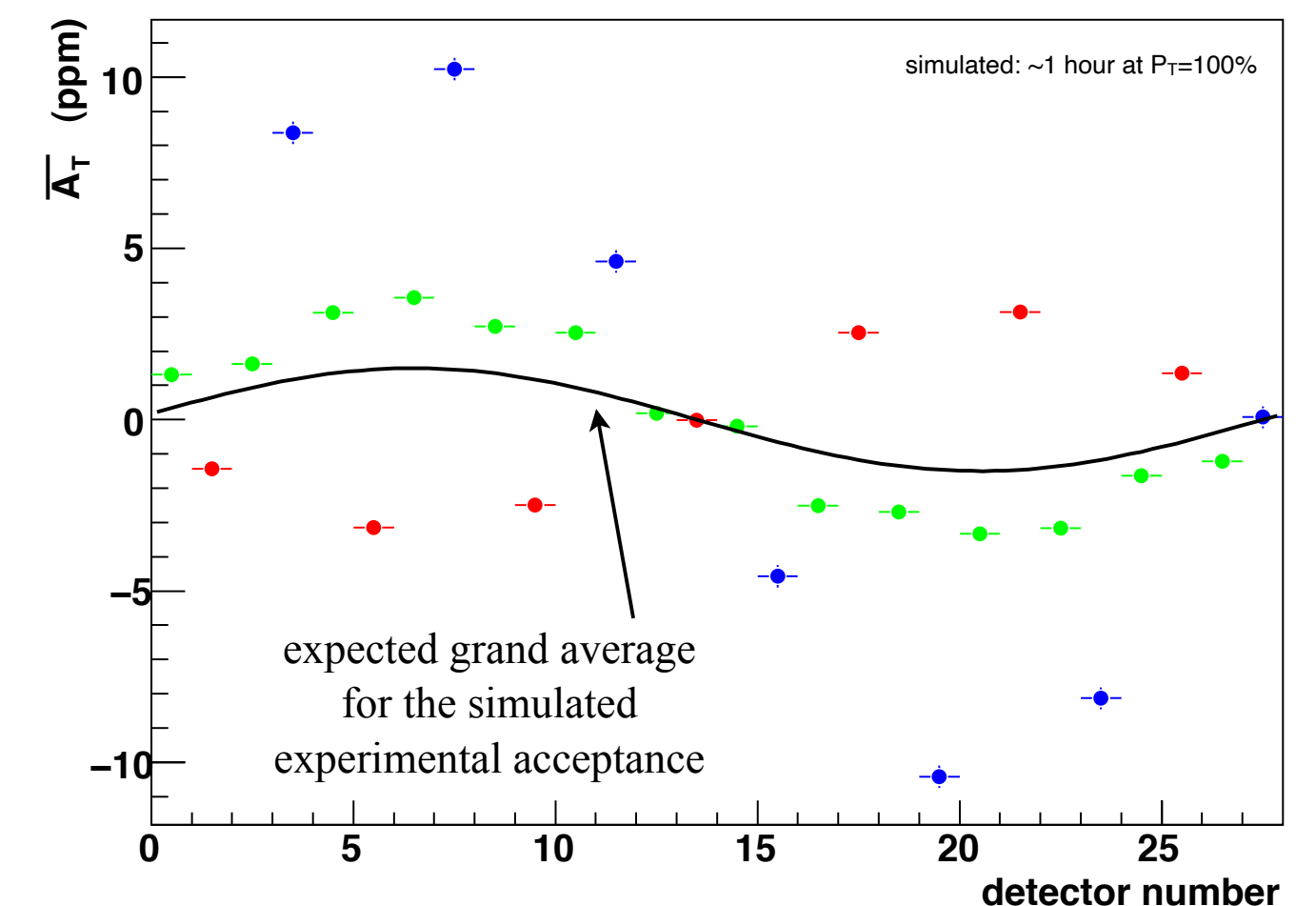
*A physics scattering asymmetry associated with transverse polarization creates a left-right asymmetry
~300 times larger than A_{PV}*

1 MeV (about 1 part in 10,000) would be 2° spin precession $\rightarrow$ false asymmetry $10\times A_{PV}$

This would require correction.

Goal: $<1^\circ$ average precession change per day, so $5e-5$ stability in beam energy. Energy locks will be used to control this, but stable operation makes this easier.

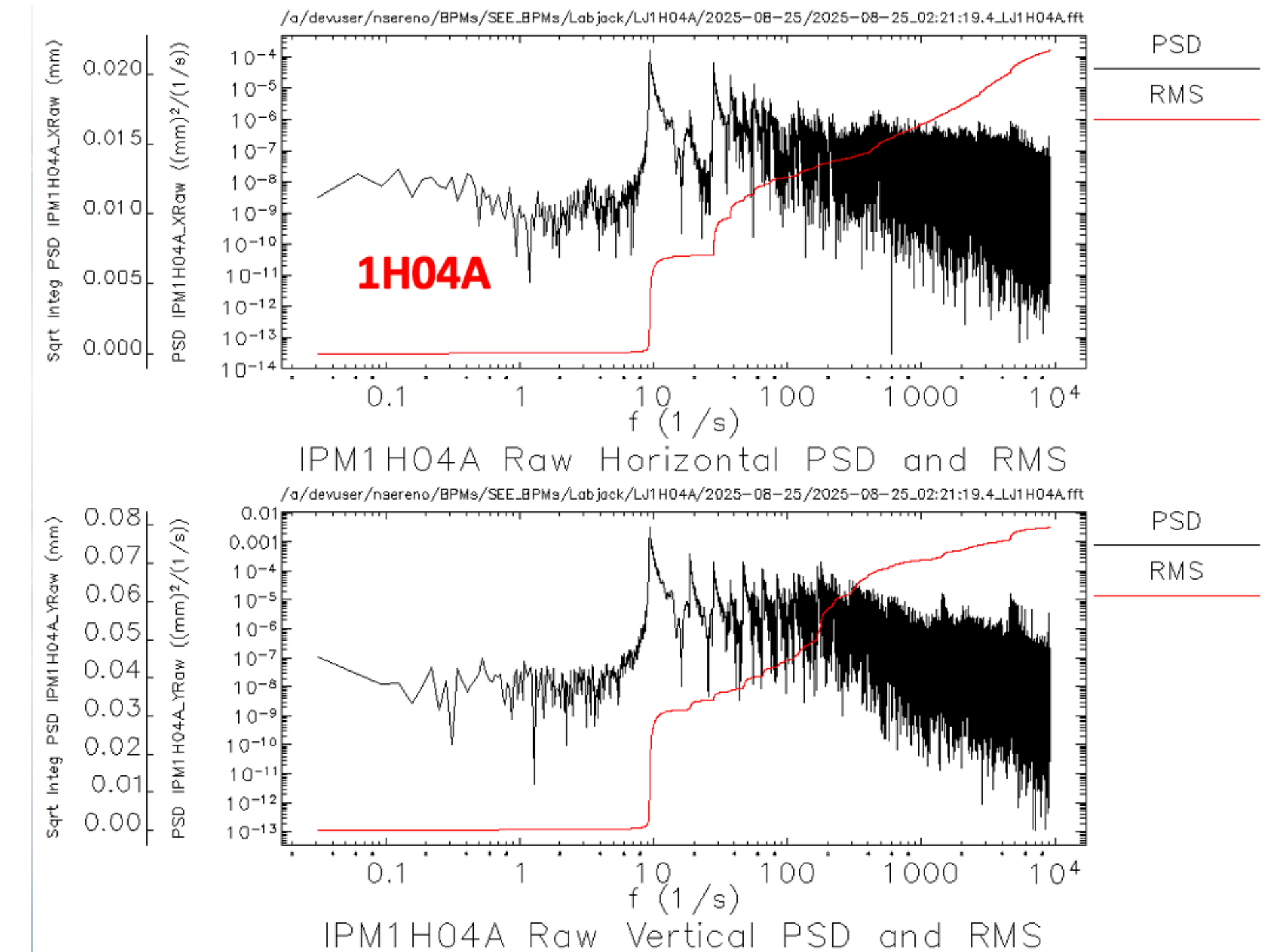
Average transverse asymmetry



Other (possible) SRF-related Challenges

Microphonics in RF cavity

- noise at 10Hz and harmonics, adding to random beam noise
- Appears to dominate noise frequency spectrum, but it isn't clear if this is critical after the MOLLER data collection "box-car" averaging



Field emission in cavities

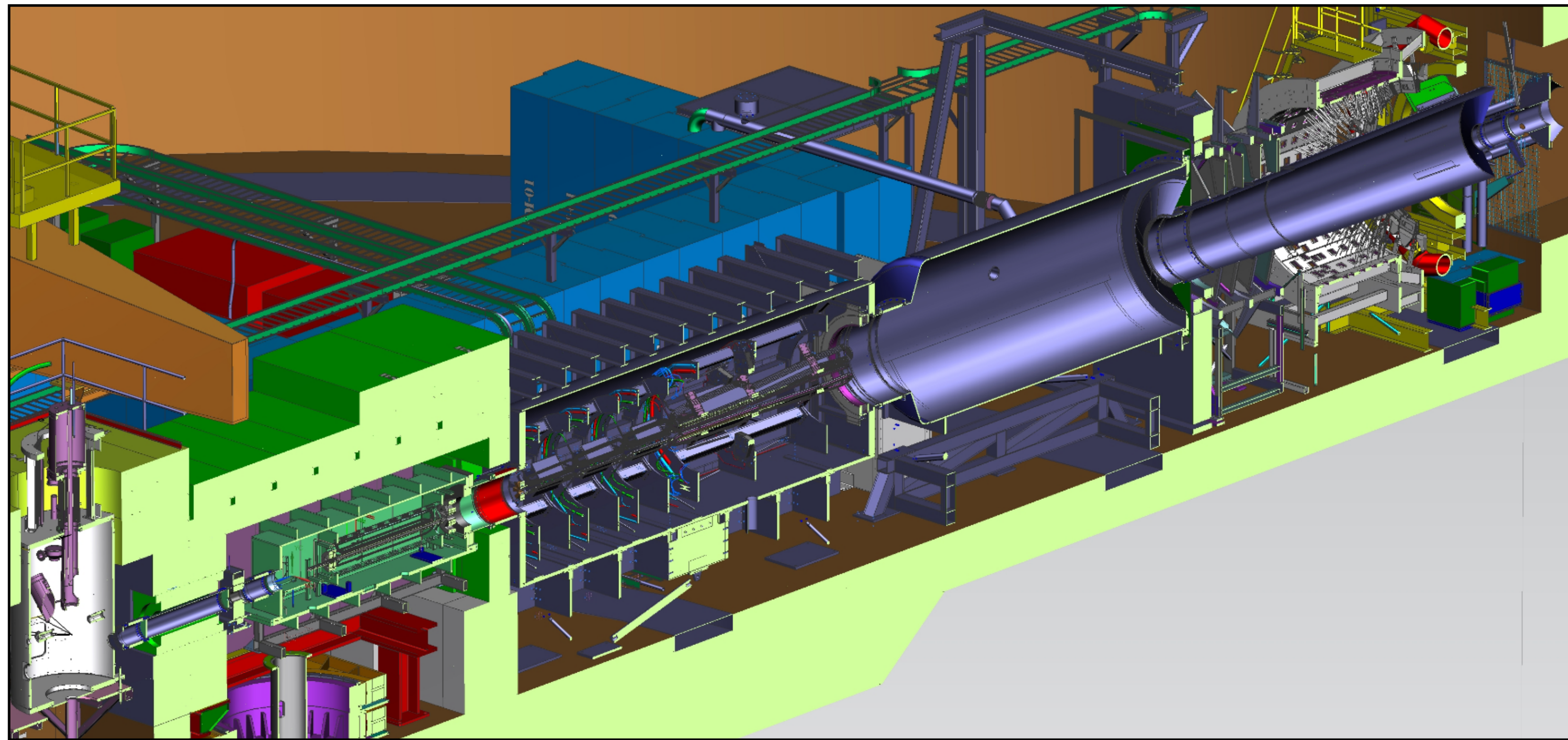
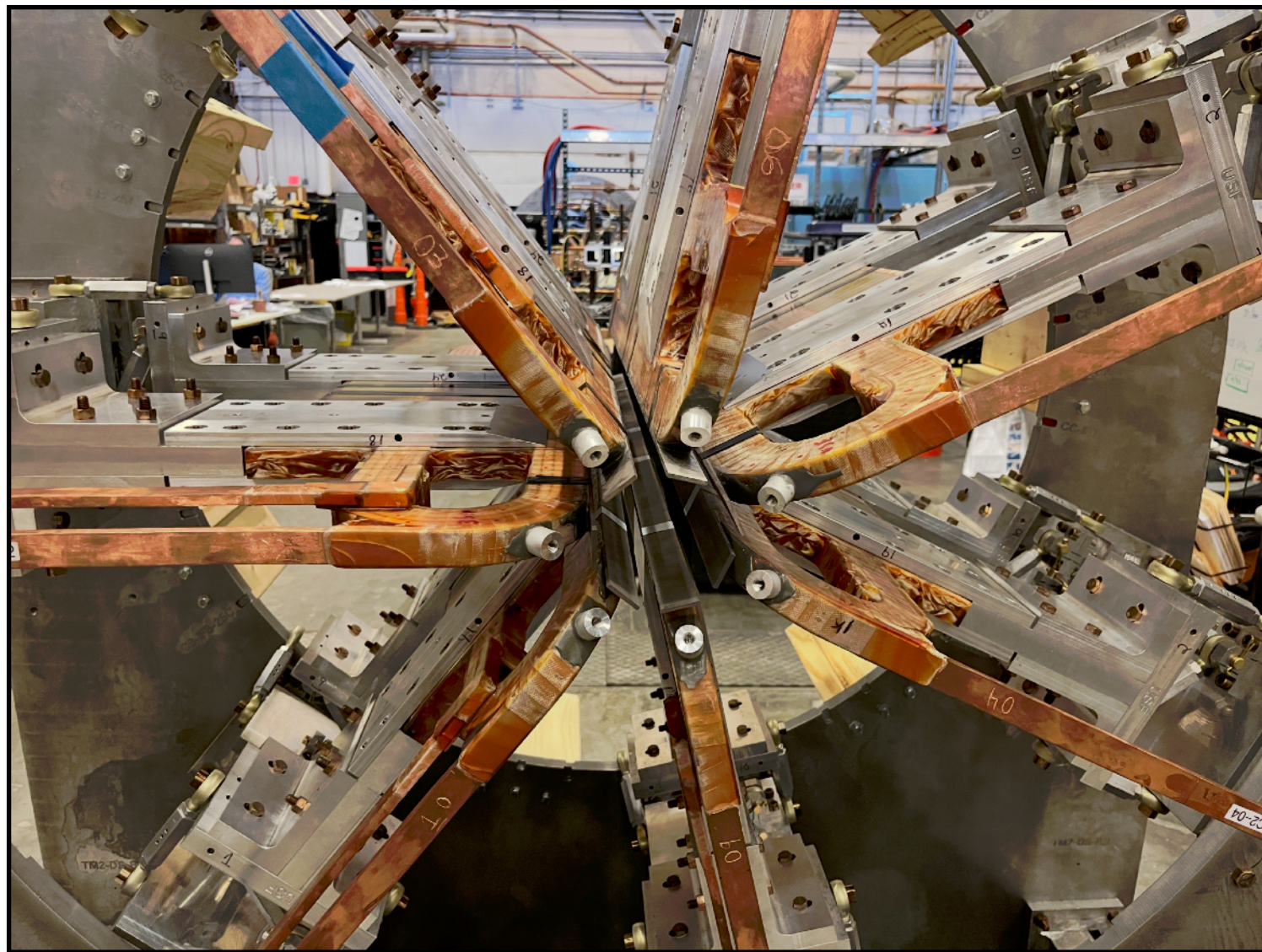
- Some indication that this can create "stray" current - electrons accelerated along with the bunches from the polarized source
- This would create poorly behaved halo even in high-current mode, produce excess beam in low beam current calibration mode

Summary

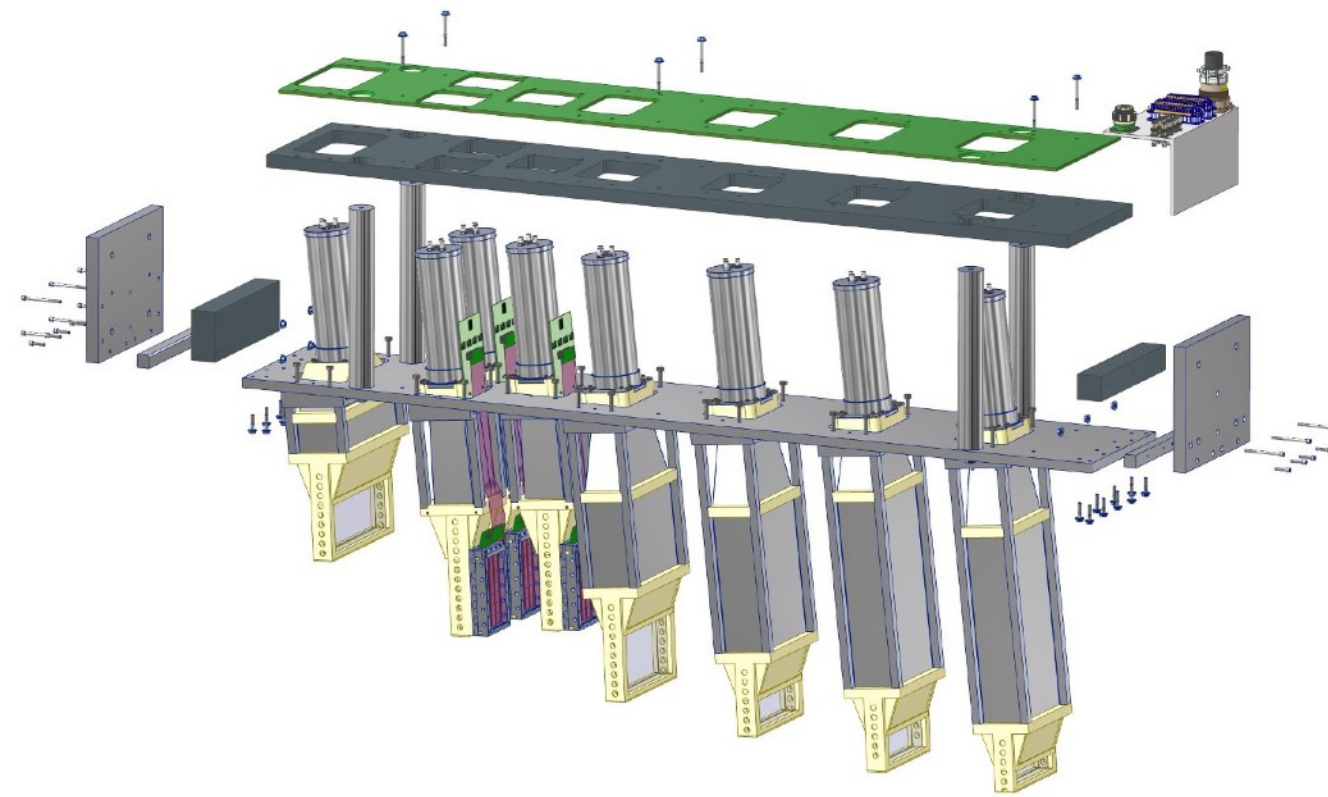
MOLLER, designed for ultra-high precision, will search for new interactions from 100 MeV to 10s of TeV, with reach into new physics phase space that cannot otherwise be accessed.

MOLLER is being assembled right now, and will begin running early 2027

Stable RF operation is critical for the efficient execution of experiment

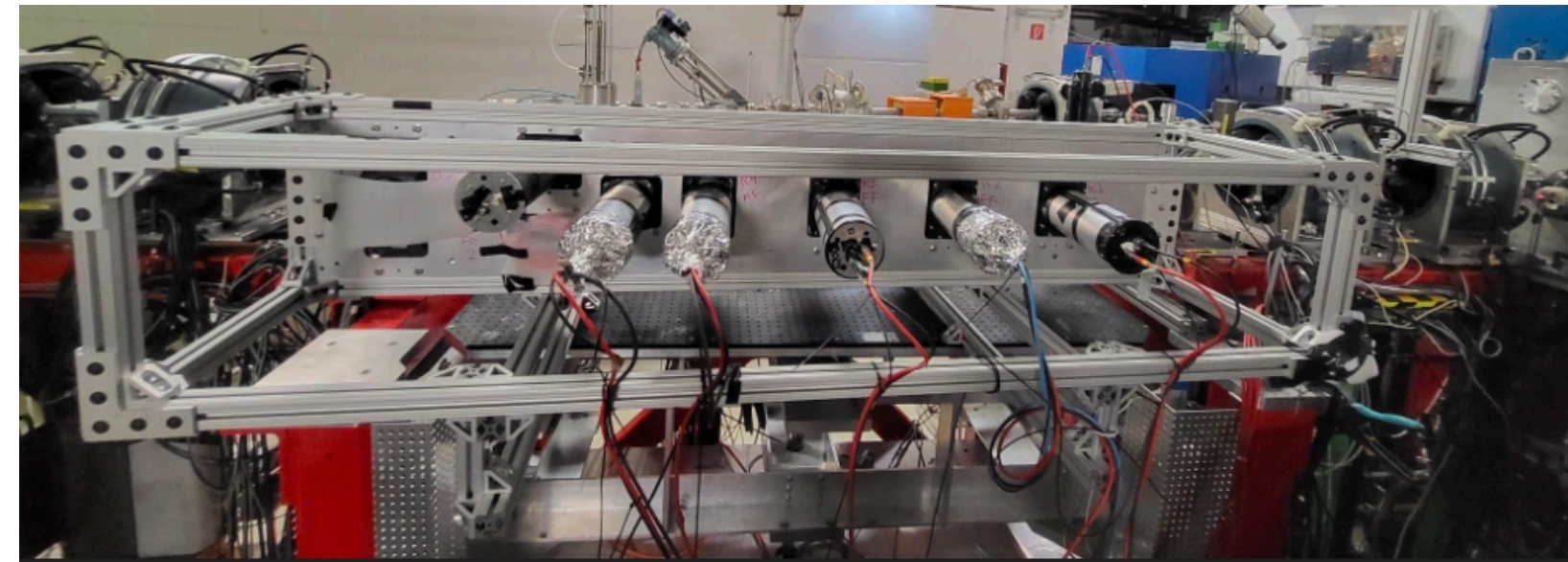


Detectors / electronics



thin quartz assembly modules
in cosmic test stand

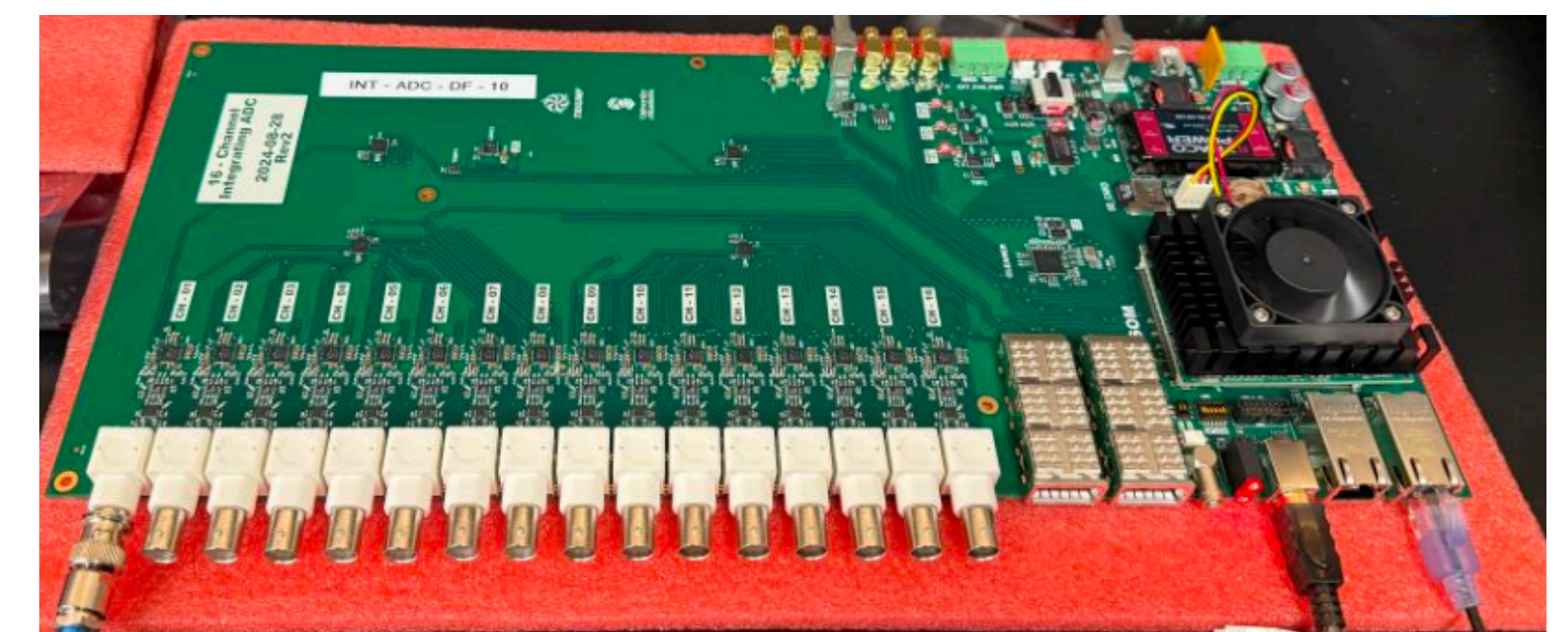
Main detector assembly
in Mainz test beam



low-noise electronics (Manitoba)



shower-max
detector



Beam pipe elements



Bellows 1 and 2



Bellows 3



Bellows 4



Bellows 5



Bellows 7



Detector Pipe with Neckdown window



Drift Pipe



SAM Pipe



Beam pipe

