MOLLER Beamline (and beam)

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MOLLER

Outline

- Beam asymmetry requirements
- Injector upgrade
- Beamline upgrade
- Beam monitors
- Other beamline issues
- Control of transverse polarization P_T
- Polarimetry

Some Documentation:

- Upcoming Technical Design Report (nearly final!)
- Hall A Beamline optics design *J. Benesch and Y. Roblin JINST 16 T12007 (2021)*
- Beam Requirement document https://moller.jlab.org/cgi-bin/DocDB/public/ShowDocument?docid=403

Beam Corrections

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

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

Creates noise and also a systematic false asymmetry from average difference

Monitor resolution
Calibration imprecision

Parameter	Noise (65 μA)
Statistical Width	**~82 ppm**
Beam Intensity Resolution	10 ppm
Beam Position Noise	7 ppm

Systematic uncertainty budget

Error Source	Fractional Error (%)
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3

Beam Property	Assumed Sensitivity	Accuracy of Correction	Required 1 kHz random fluctuations	Required cumulative helicity-correlation	Systematic contribution
Intensity	1 ppb / ppb	$\sim$1%	$<$ 1000 ppm	$<$ 10 ppb	$\sim$ 0.1 ppb
Energy	-0.7 ppb / ppb	$\sim$5%	$<$ 108 ppm	$<$ 1.4 ppb	$\sim$ 0.05 ppb
Position	1.7 ppb / nm	$\sim$5%	$<$ 47 μm	$<$ 0.6 nm	$\sim$ 0.05 ppb
Angle	8.5 ppb / nrad	$\sim$5%	$<$ 4.7 μrad	$<$ 0.12 nrad	$\sim$ 0.05 ppb
Spot Size	0.012 ppb / ppm	-	-	$<$ 10 ppm	$\sim$ 0.1 ppb

Keep beam asymmetries small

- Special techniques with the polarized source laser optics
- Beam transport configuration to avoid exacerbating differences
- “slow reversals” that flip the sign of beam asymmetries
- feedback

Beam correction analysis

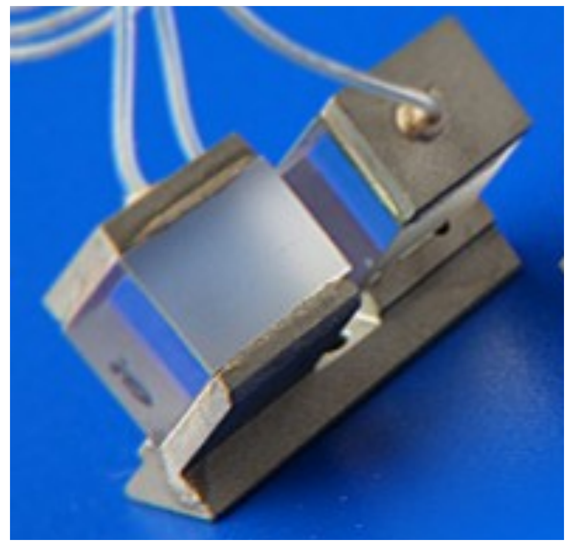
Two calibration techniques

- beam modulation for calibration
- linear regression

Combined, for precision and accuracy in the PREX-2 analysis

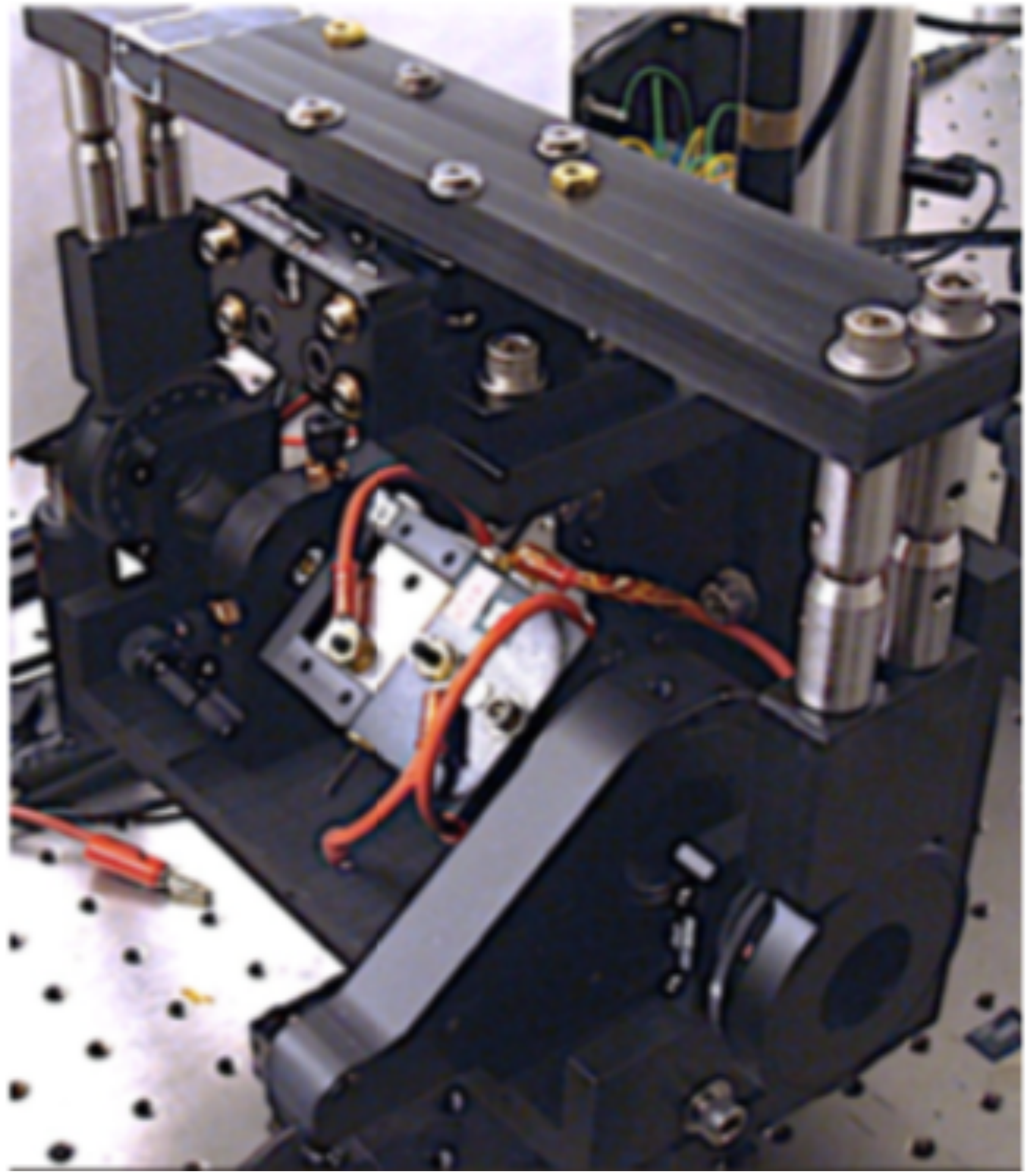
- Removed >90% noise
- 4% precision on total correction

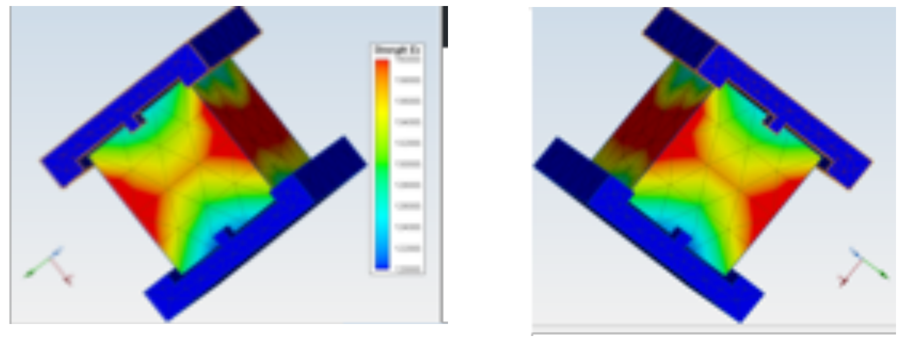
Polarized Source Laser Components

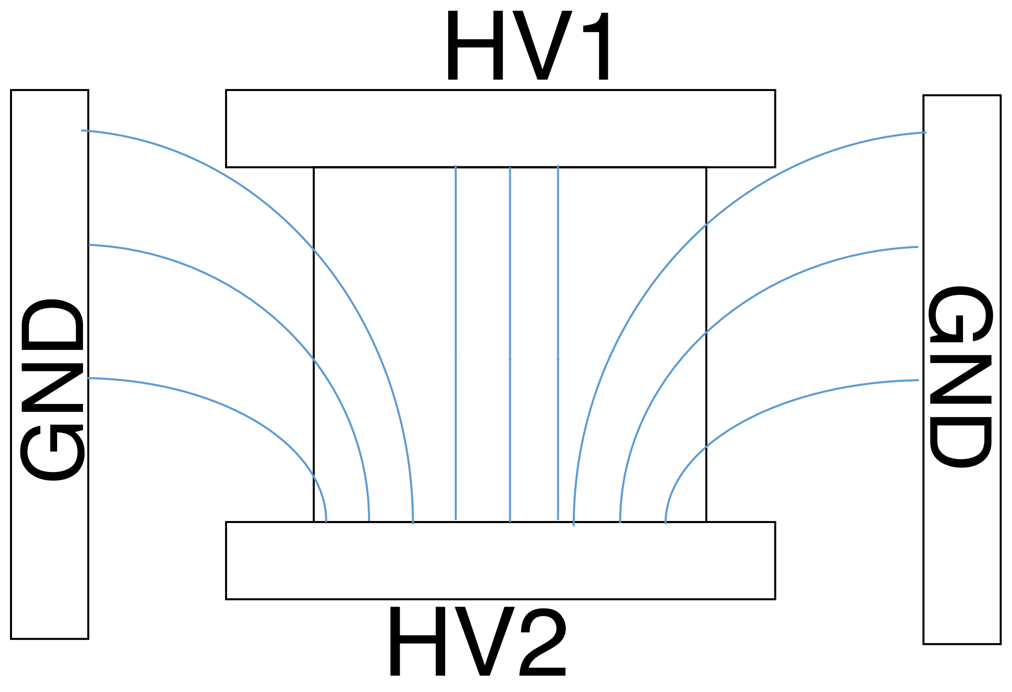


Goal: 2kHz flipping, ~10 μs transition

RTP cell developed for this purpose, in use since 2019

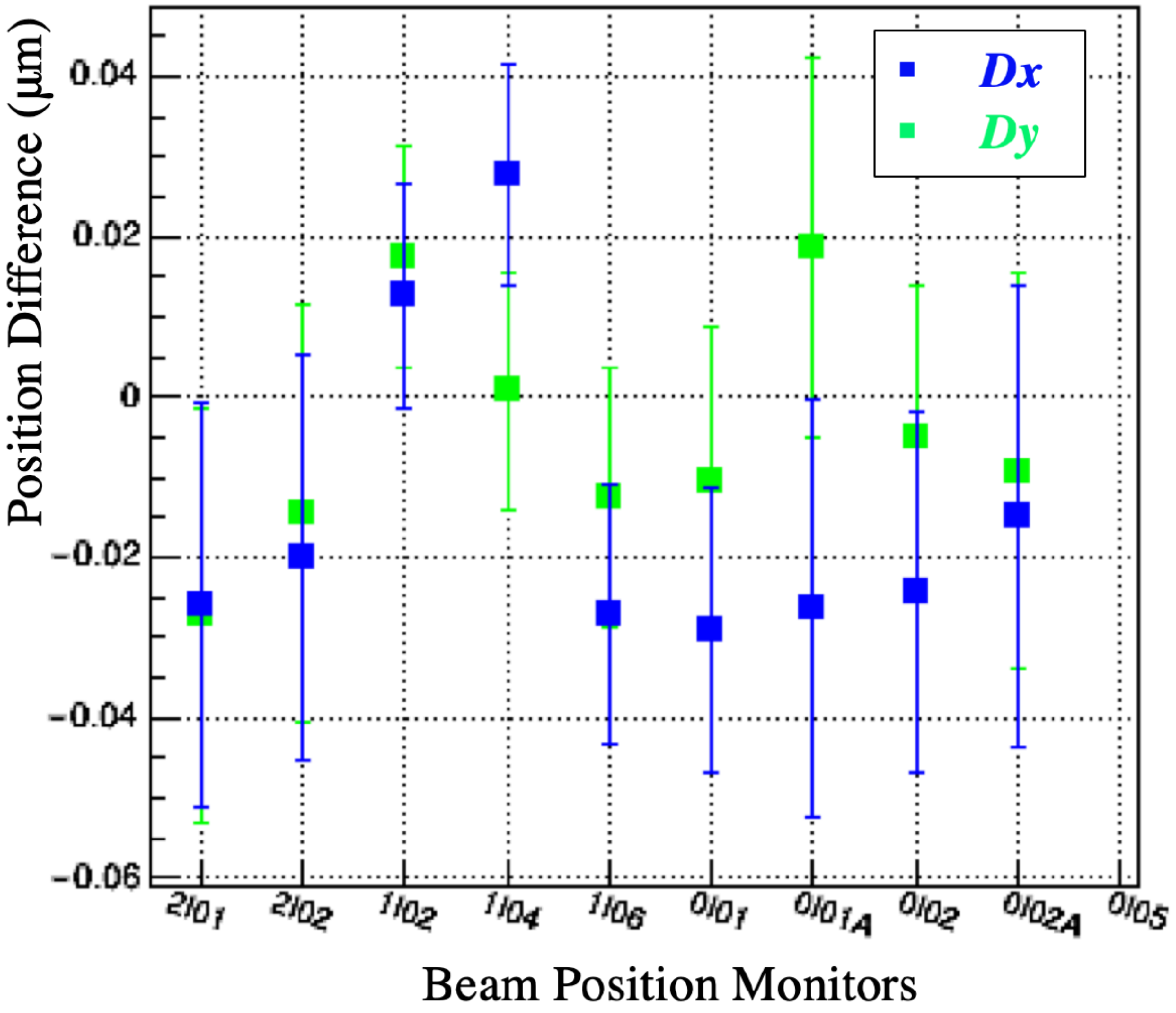






E-field non-uniformity drives steering - a new degree of freedom now utilized for control

Electron beam in injector: Δx, Δy <30nm



Configuration study for PREX-2 summer 2019

Slow Flips

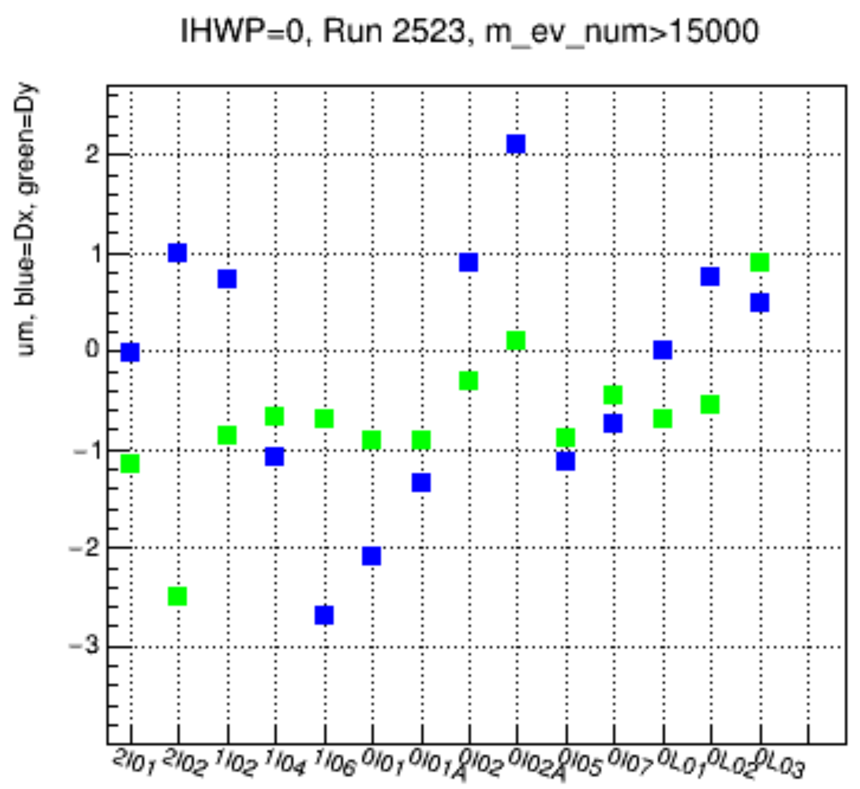
Injector Halfwave Plate

- Reverses circular polarization relative to PC voltage
- frequent changes (few hours)

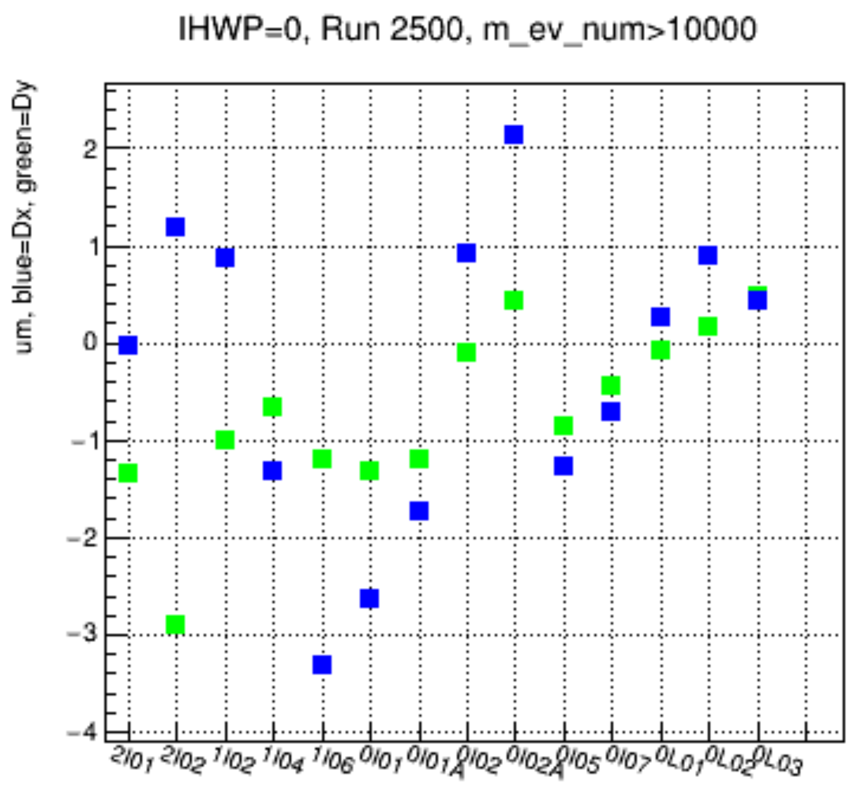
Injector Spin Manipulation

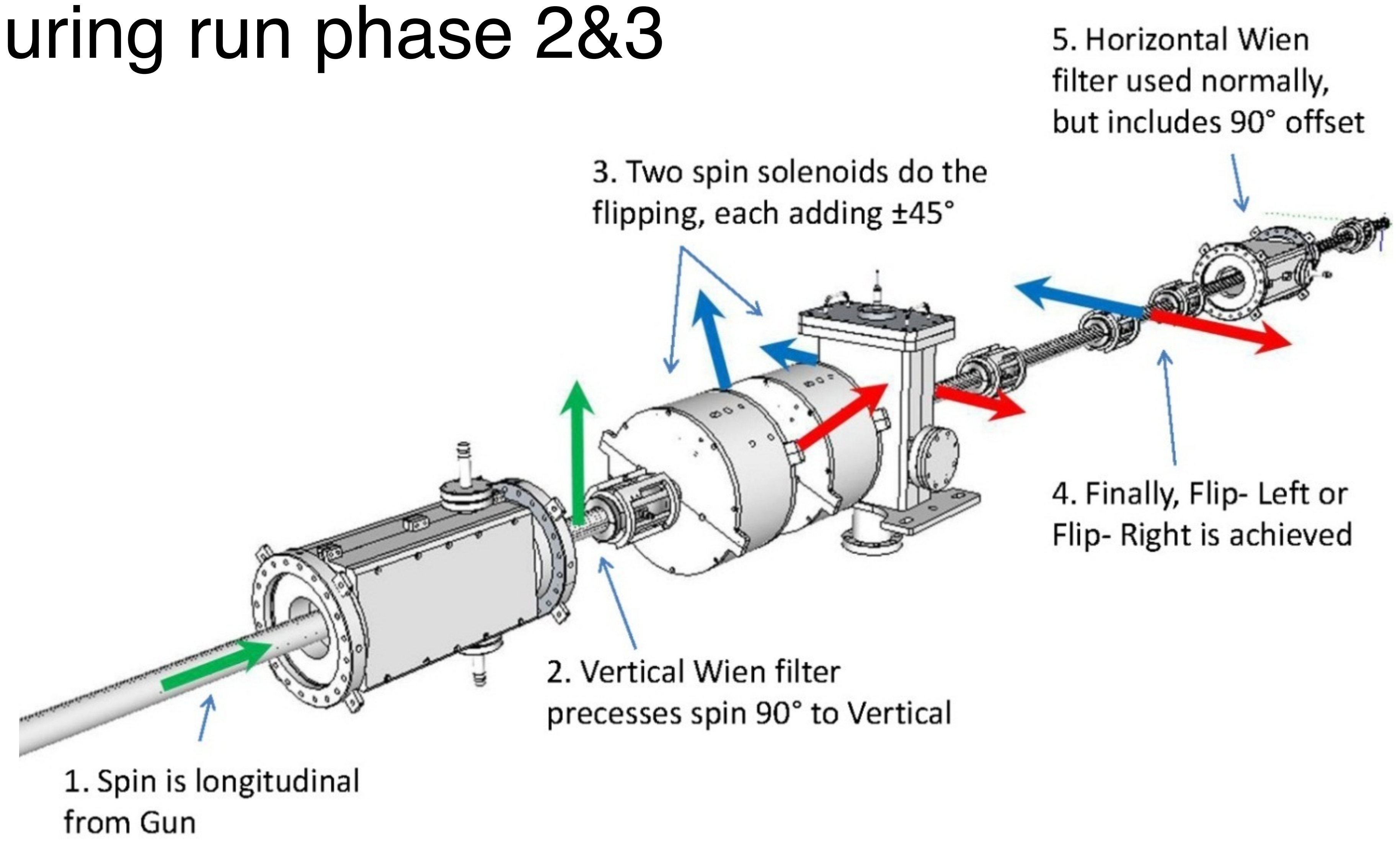
- Solenoids + 2 Wien rotations in low-E injector
- ~ weekly reversals during run phase 2&3

- Flip Left



- Flip Right





Energy spin flip (g-2)

- precession in accelerator arcs
- Modest shift in beam energy (ΔE~100 MeV)
- intend a few reversals per annual run period

$\Delta E \sim 10^{-4}$ is $\Delta\phi \sim 2°$, so this must be tuned to very high precision. The experiment itself will provide the required read back of ϕ!

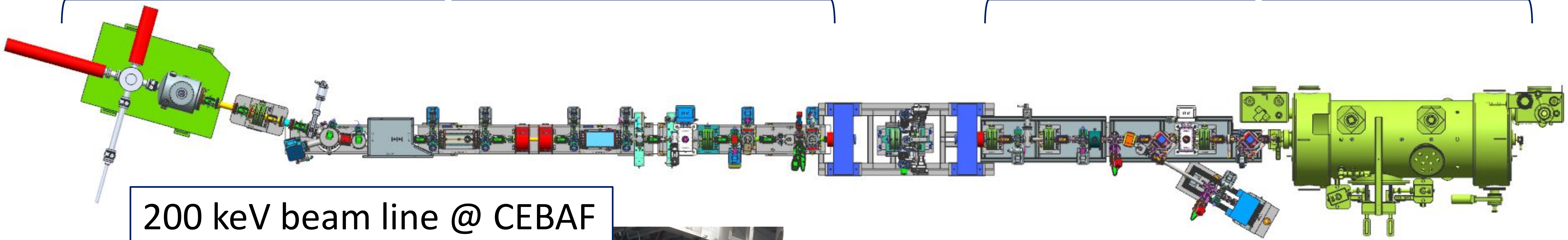
Injector Upgrade

Phase 1 (Installed Sep 2020 – May 2021)

- 200 keV Gun and Wien Filter Upgrade
- Improves Parity Quality Beam **Transmission**
- Commissioning May-Jul 2021

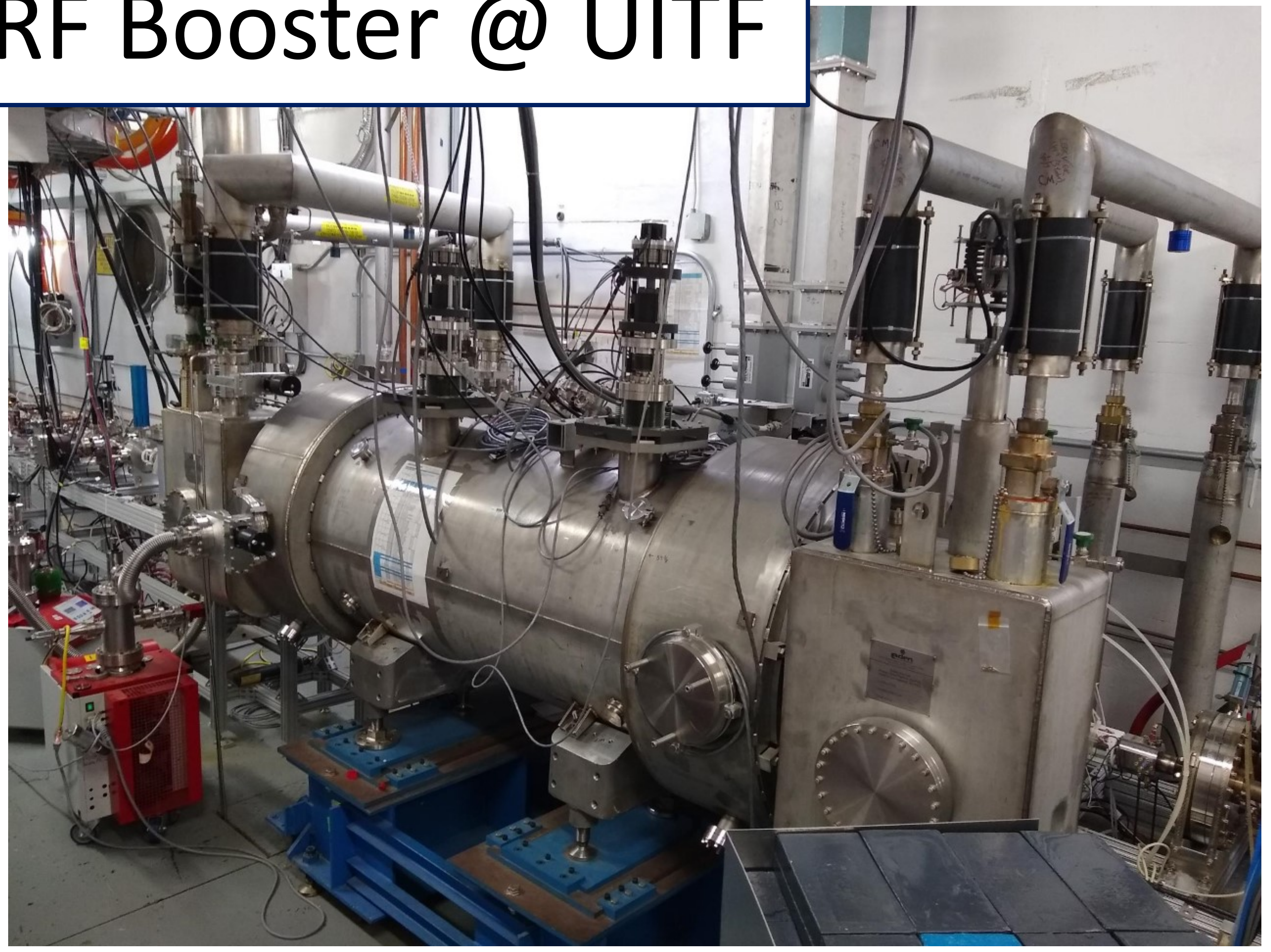
Phase 2 (Planned 2023 SAD)

- SRF Booster (2 & 7 cell booster to 10 MeV)
- Improves Parity Quality Beam **Optics**
- SRF Booster commissioned at UITF 2020-2021
- + new 200 keV gun



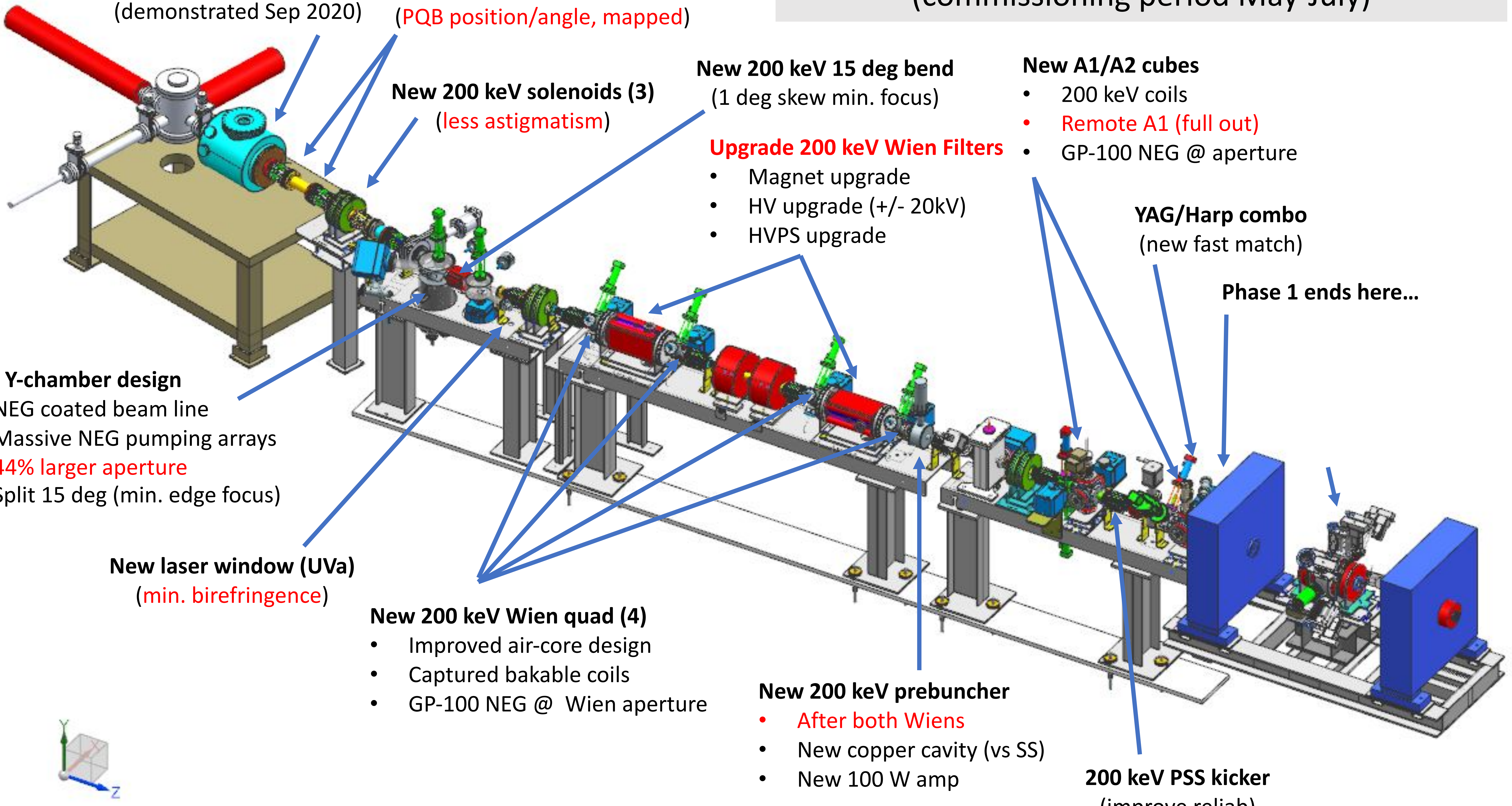
200 keV beam line @ CEBAF

SRF Booster @ UITF



Injector Upgrade

AIPINJ – Phase 1 Installation Completed May 2021
(commissioning period May-July)



200 kV w/o field emission
(demonstrated Sep 2020)

Additional NEG coated BPM
(PQB position/angle, mapped)

New 200 keV solenoids (3)
(less astigmatism)

New 200 keV 15 deg bend
(1 deg skew min. focus)

Upgrade 200 keV Wien Filters
- Magnet upgrade
- HV upgrade (+/- 20kV)
- HVPS upgrade

New A1/A2 cubes
- 200 keV coils
- Remote A1 (full out)
- GP-100 NEG @ aperture

YAG/Harp combo
(new fast match)

Phase 1 ends here…

New Y-chamber design
- NEG coated beam line
- Massive NEG pumping arrays
- 44% larger aperture
- Split 15 deg (min. edge focus)

New laser window (UVa)
(min. birefringence)

New 200 keV Wien quad (4)
- Improved air-core design
- Captured bakable coils
- GP-100 NEG @ Wien aperture

New 200 keV prebuncher
- After both Wiens
- New copper cavity (vs SS)
- New 100 W amp

200 keV PSS kicker
(improve reliab)

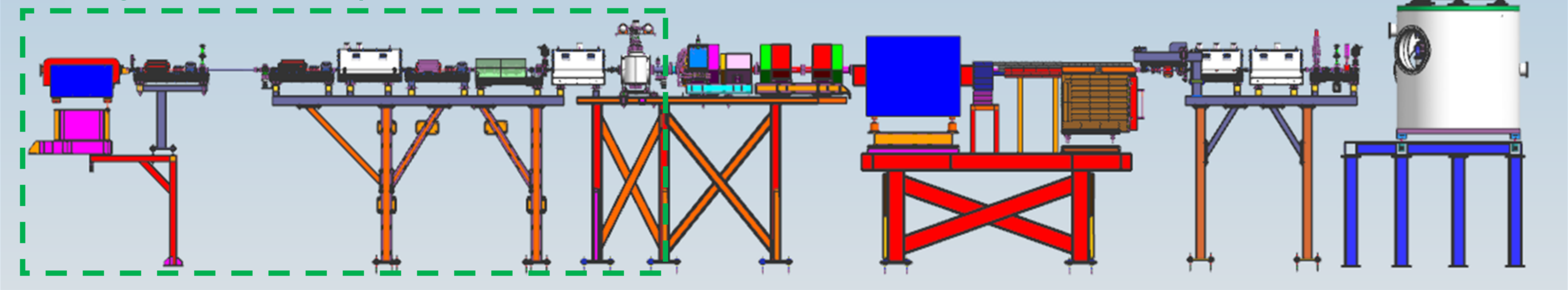
Hall A Beamline Upgrade

- Reduce beam line length to fit MOLLER target location 4.5 m upstream of the usual target location.
- Improve **raster** operation, no longer requiring beamline optics

- Introduce additional quads & correctors to improve beam line optics (profile, correction range)
- Relocate cavity Beam Position Monitors (BPMs) for improved resolution
- Improve ground isolation of Beam Current Monitors (BCMs) and add BCM redundancy

- Move Moller polarimeter target magnet upstream by 30 cm for 11 GeV operation

Stage 1 installation (planned for '23-'24 Hall down):

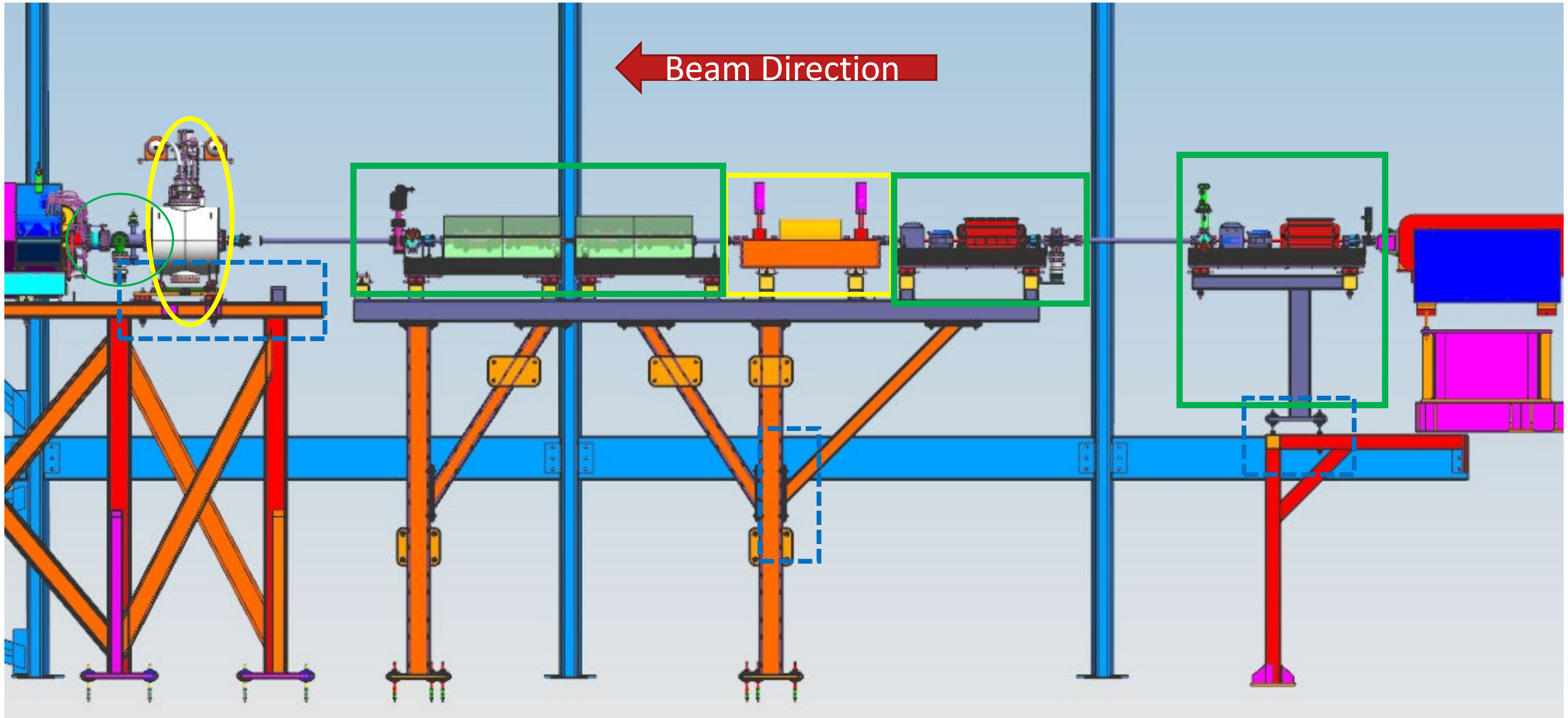


- Relocate raster girder, add new stronger MCG dipole correctors and quadrupoles. Møller polarimeter target moved.
- BCM box not changed, raster hardware not changed.

Begin studying Moller polarimeter optics with new configuration, plus opportunities to take advantage of new beamline optics

Prototype Installation Scope: Stage 1

from the Installation Preliminary Design Review, June 2022



New Installation
- Girders
  - Raster Mag: 2
  - Quad Girders: 2
- Supports
  - Pedestal: 1
  - Top Frame Weldment
  - Support Brackets for Moller Shift
- Vacuum
  - Drift Spools
  - Vacuum Diag. Cross

Relocate Existing Items
- Moller Target – Shift 30cm Upstream, onto New Support Features
- UNSER Girder – Remove Existing UNSER and Re-Install on New Platform

Other Mods
- New Support Features Welded to Moller Stand
- Holes in Support Structure for Pedestal
- Will have to Weld new Pads in Place for Stand

BCM resolution

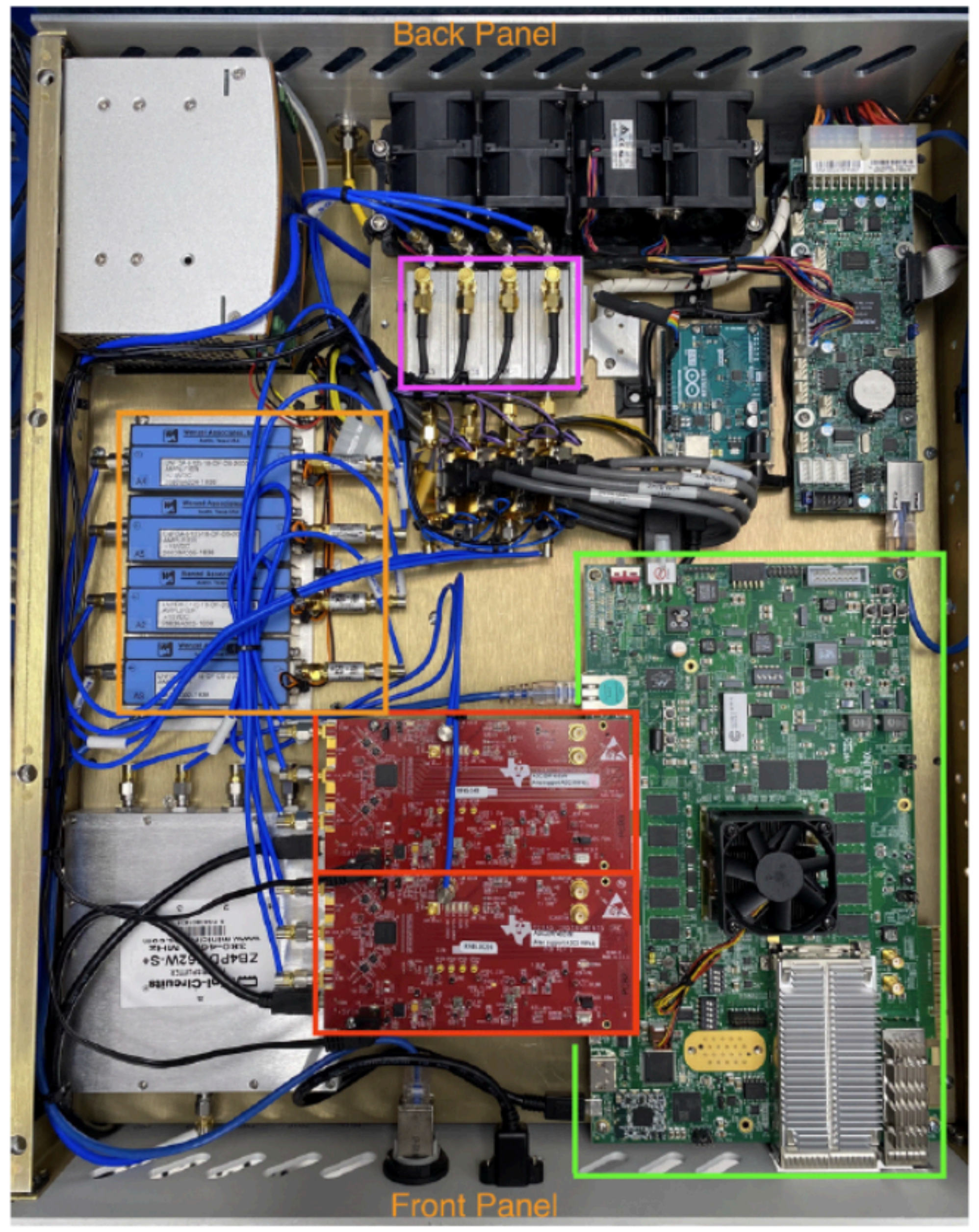
Existing BCM receivers

- Bench tests suggest 22 ppm resolution is expected for each monitor with the newest installed receivers
- Previous (well-known) electronics: ~42ppm
- Seven BCMs on MOLLER beamline: so assuming sqrt(7), existing precision about 8.5 ppm, previous about 16ppm
- Multiple high precision BCMs are a powerful cross-check, allowing tests for expected or unexpected discrepancy

Goal is 10 ppm per monitor, to enable systematic studies with better resolution

Two strategies for improvement

- JLab electronics to be qualified, and further improvements possible
  - Beam tests to qualify fielded electronics
  - Bench tests suggest further improvements by improving local oscillator
  - Eliminating digital—analog—digital readout chain
- LBNL digital processor prototype (Kolomensky and group)
  - Uses fast sampling ADC's capable of direct RF sampling
  - Eliminates need for local oscillator
  - Initial bench studies give ~ 10 ppm resolution for 960 Hz window pairs
  - Further beam tests required



LBNL prototype receiver

Readout

- Existing receivers use Digital-to-Analog Convertor → Integrators, matching detector readout chain
- Option to use digital readout favored, still being explored. Requires a match to electron detector readout

Additional Topics

BPM receivers - Stripline SEE receivers are no longer maintainable. Need benchmarking for in-beam performance of new digital receivers.

Modulation system - Driven modulation to calibration detector sensitivity to beam parameters. Unclear whether existing function generators remain viable.

Fast Feedback / Feed Forward - In PREX-2/CREX the system was problematic - not stable, producing large noise expansion at the 240 Hz flip frequency. Must interface with modulation system (pause/resume). A functioning system can be useful for controlling random jitter to reach systematic goals. Stable lock for average energy also required at ~10^{-4}.

Beam excursion protection - The CREX and recent GEN incidents are concerning. MOLLER should be pretty robust, but the USTorus / collimator region is just not serviceable. Improved engineered controls and a careful fault analysis are required.

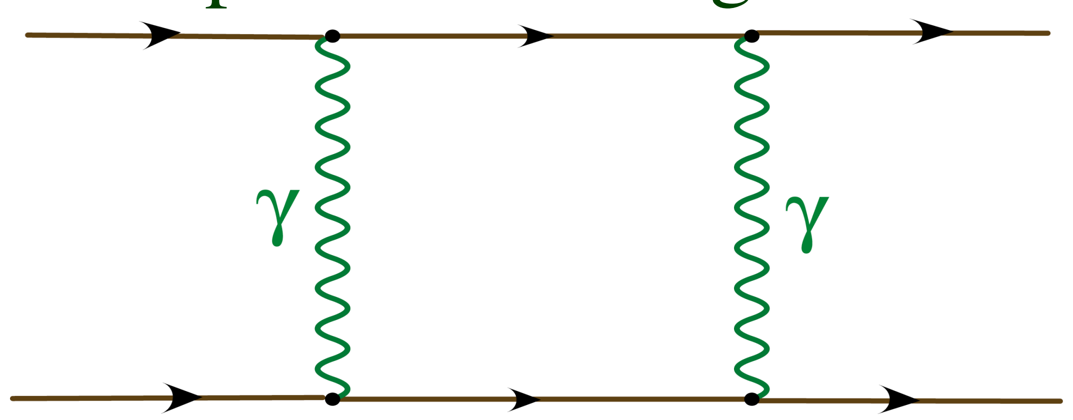
Transverse Analyzing Power

electron beam polarized transverse to beam direction

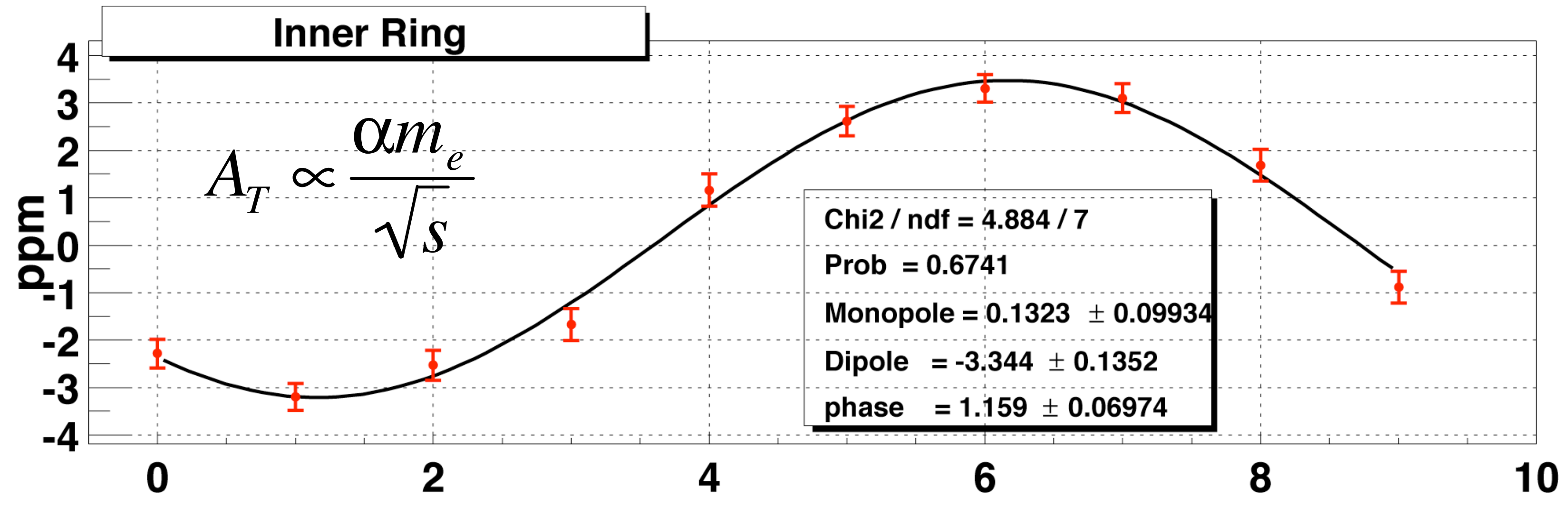
$$A_T \propto \vec{S}_e \cdot \left(\vec{k}_e \times \vec{k}'_e\right)$$

(a left-right analyzing power)

Interference between one- and two-photon exchange

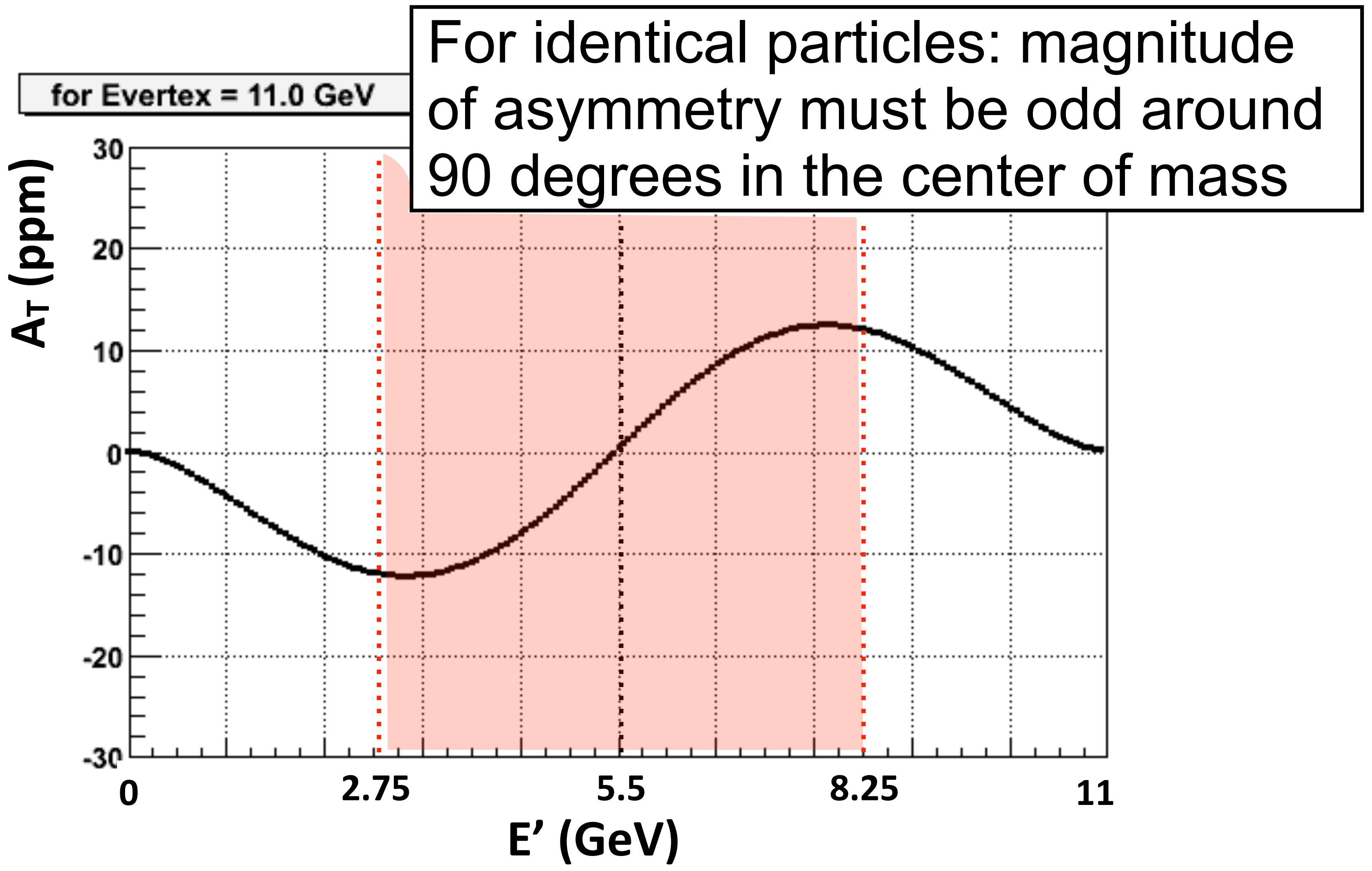


Measured at E158



Theory References:

1. **A. O. Barut and C. Fronsdal, (1960)**
2. **L. L. DeRaad, Jr. and Y. J. Ng (1975)**
3. **Lance Dixon and Marc Schreiber:hep/ph-0402221**

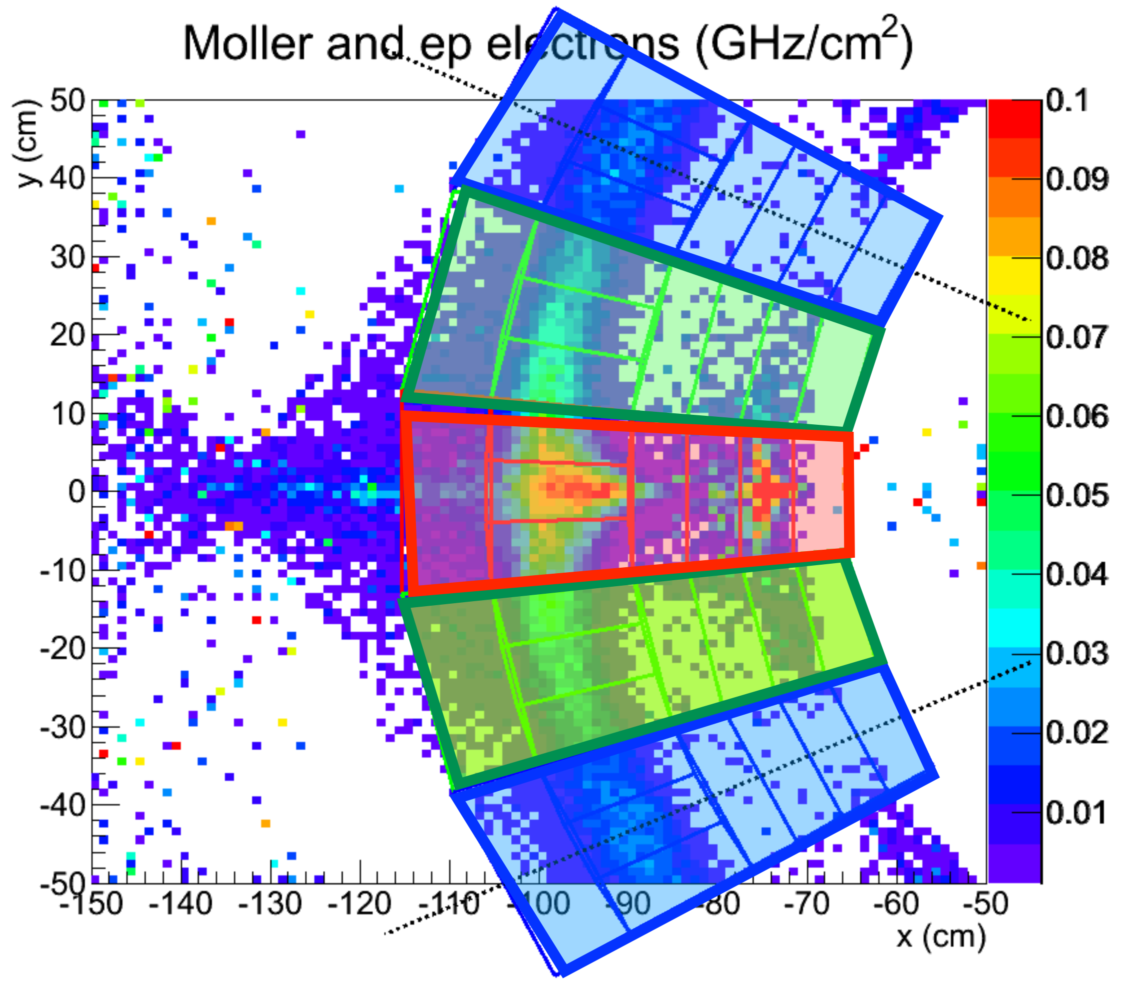


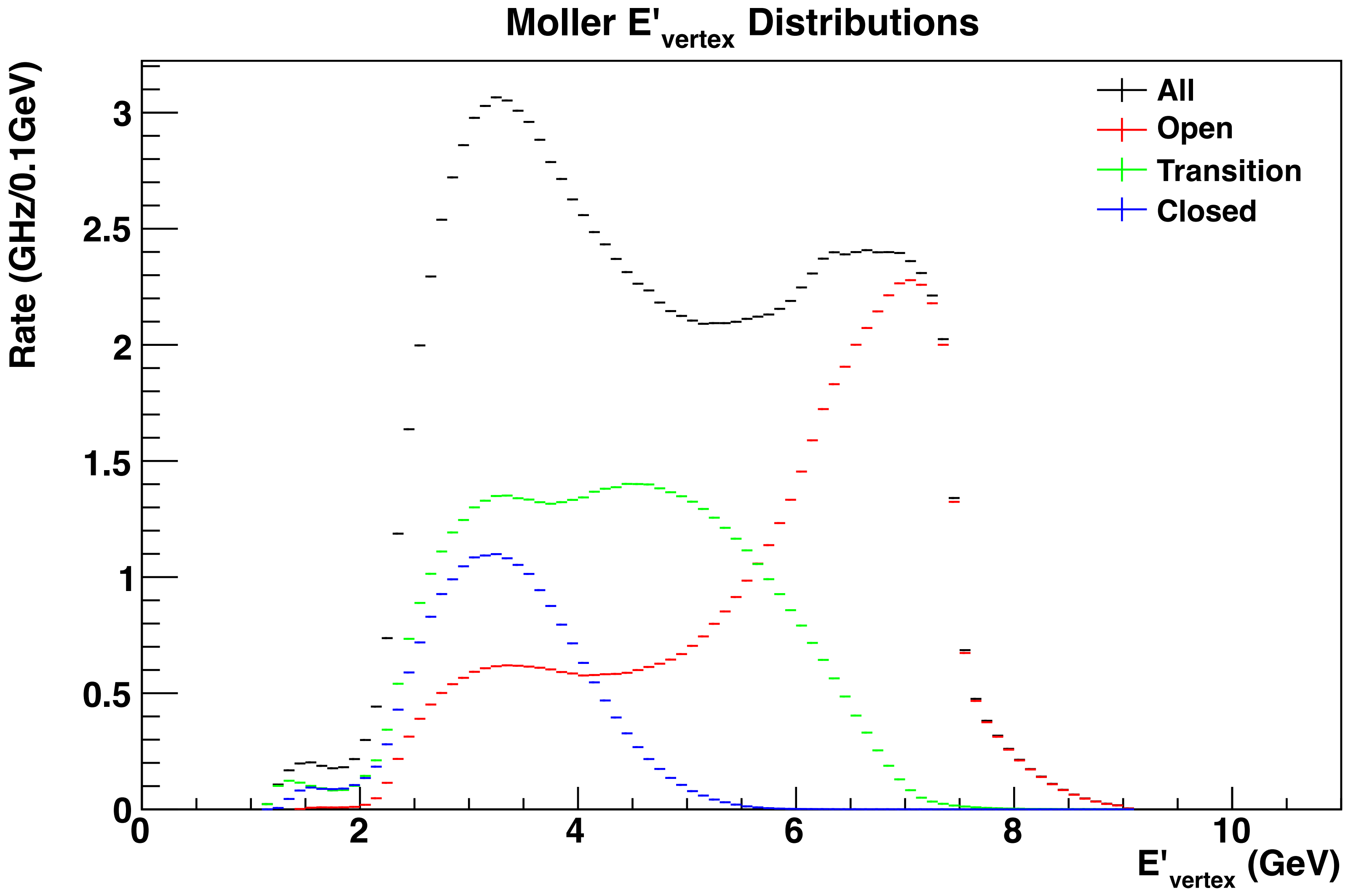
Potential systematic error in A_{PV}.
Suppressed by
- small transverse polarization
- azimuthal acceptance symmetry
- acceptance symmetry in c.m.s. polar angle

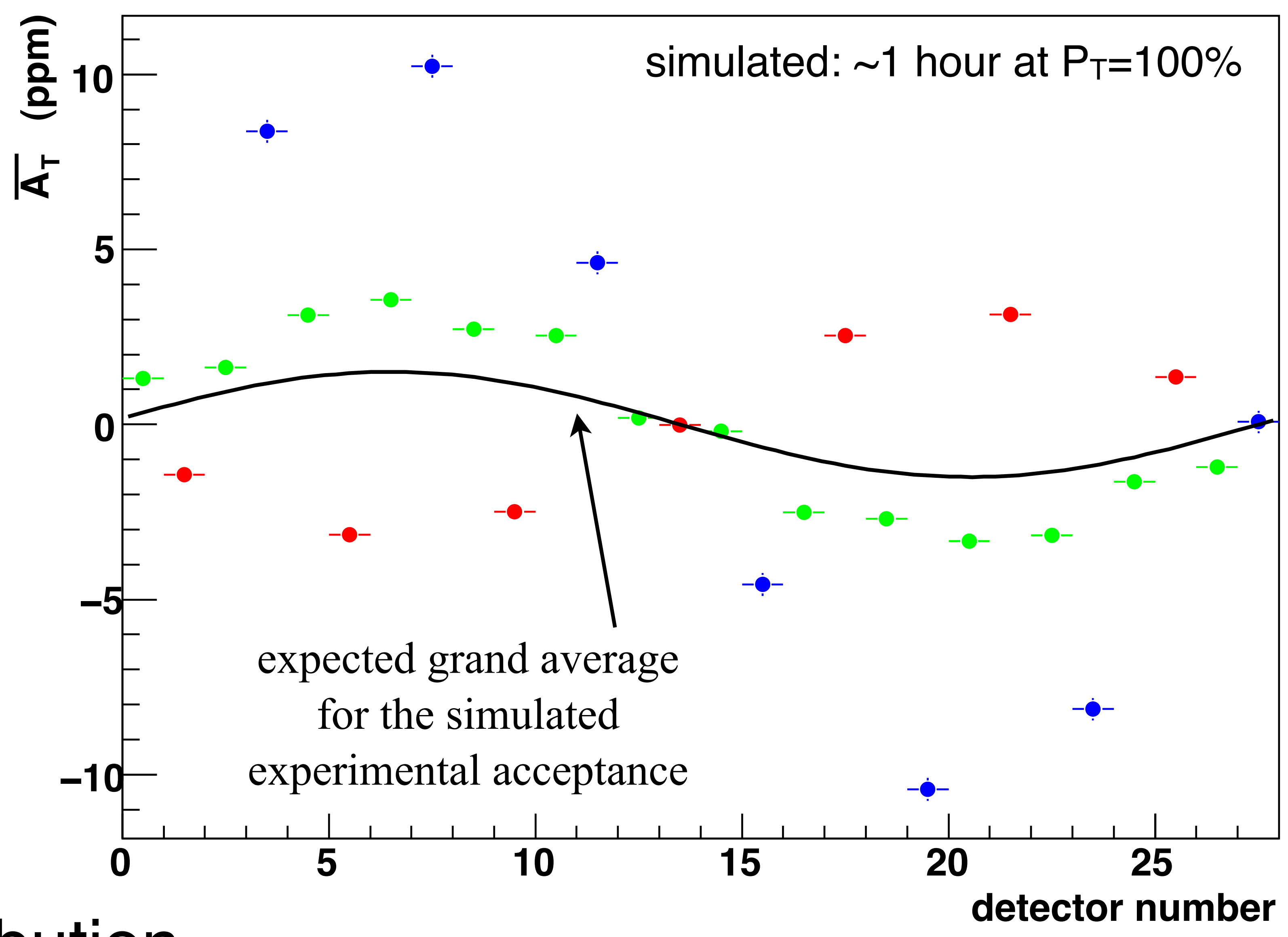
Parity experiments have always fretted about this, but the polarimeters optimized for longitudinal polarization were really bad at precisely measuring it

Transverse Polarization

Transverse polarization analyzing power has been measured and calculated for *ee* scattering
It is relatively quite large relative to A_{PV} but varies widely over the acceptance







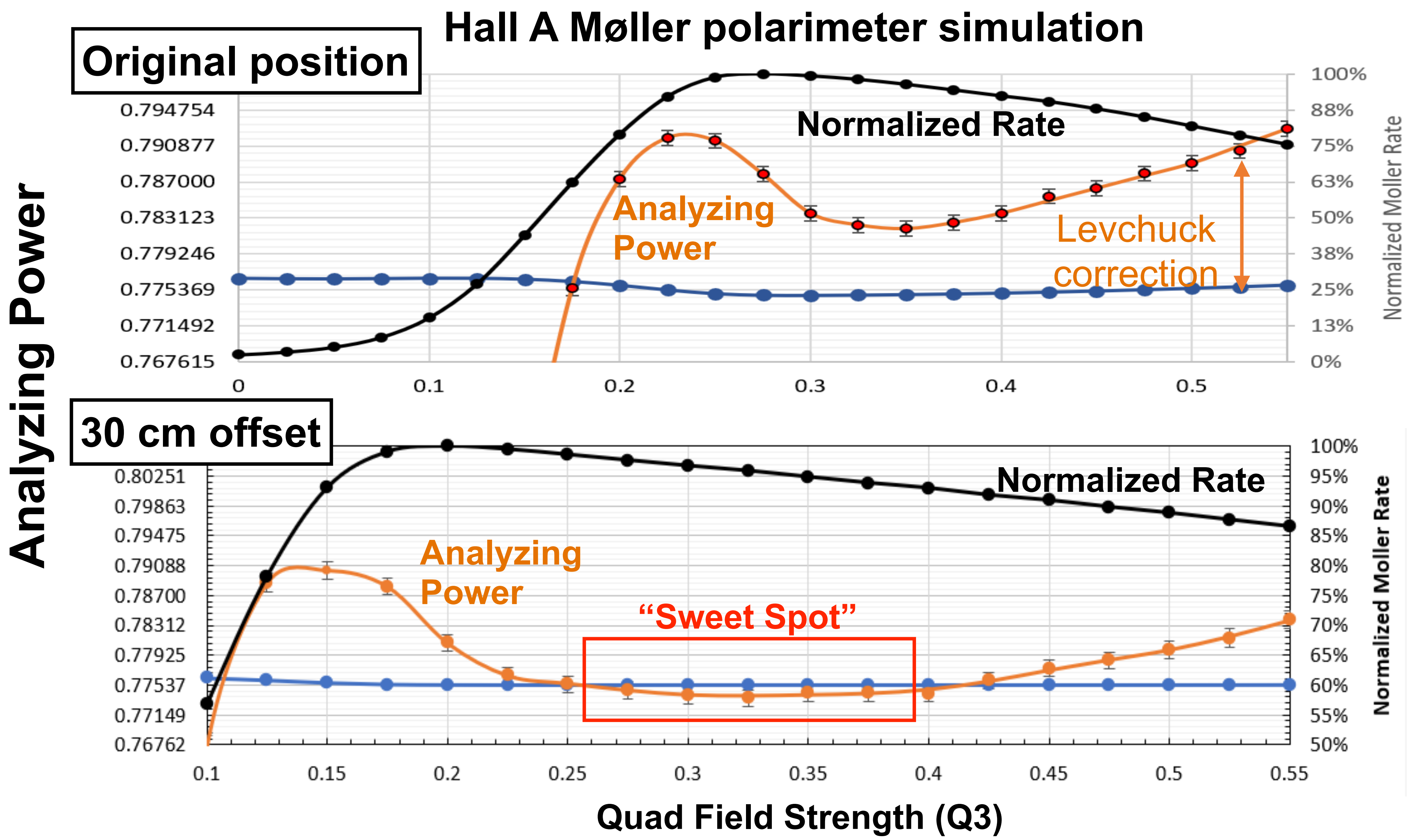
- Unique signature of transverse beam polarization over azimuthal detected distribution
- 50 ppb error on A_T*P_b in 4 hours: 1° precision
- Over entire run: feedback will hold transverse polarization small (<<1 degree)

  - Initial beam setup ~ 1-2 degrees vertical, similar in horizontal with spin dance?
  - 10^{-4} change in beam energy ~ 2° horizontal, so quality of beam energy lock will be important
  - 10^{-3} linac imbalance is also ~2° horizontal P_T
  - “Feedback” of integrated value of PT to correct offset. Expect to use Wien in injector, at 1° - 2° level
  - Over entire run, feedback will hold transverse polarization small (<<1 degree)
  - Note: this is also how the g-2 energy flip will be fine-tuned

Møller Polarimeter

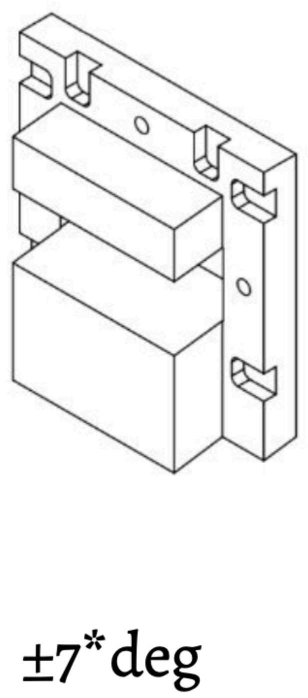
Møller spectrometer change (target move 30cm)

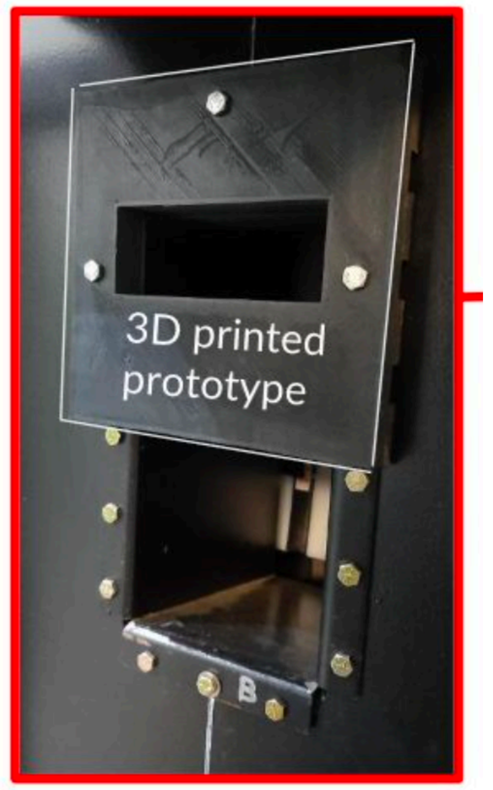
- Differential acceptance for tightly bound inner shell electrons will distort the theoretical analyzing power (Levchuk effect)
- 11 GeV optics requires a larger drift in Møller polarimeter spectrometer to minimize this distortion
- Large plateau in quad-scan with negligible correction represents tune is robust against small perturbations
- This is incorporated in the "Stage 1" beamline upgrade, to gain operational experience with new Møller polarimeter optics
- Polarimeter will be operable from 1.5-11 GeV.



Other upgrades described by Eric King yesterday:

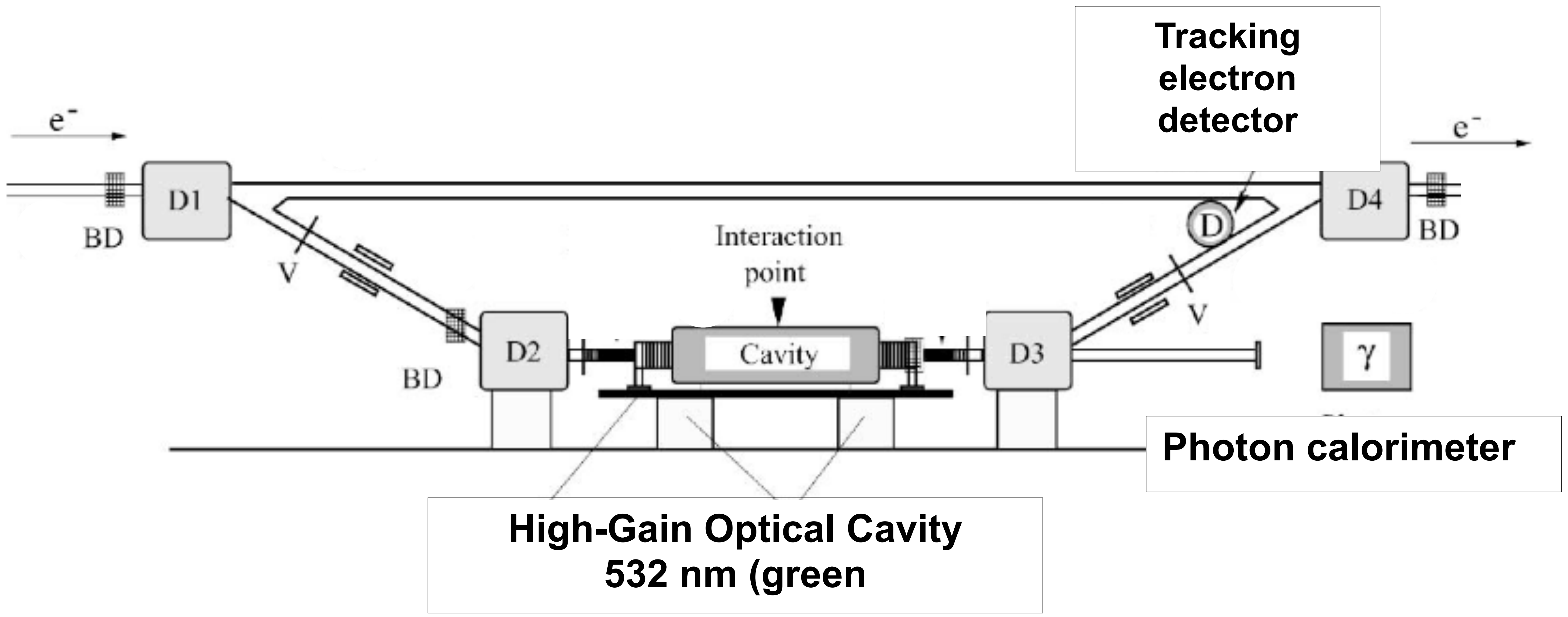
- Collimator to limit acceptance
- GEM trackers to verify acceptance model
- Upgrade dipole power supply for sufficient bend at 11 GeV





Compton Polarimeter

- New tracking electron detector
  - CFI supported HVMAPS planes
  - JLab diamond μstrip planes
- Upgraded laser
- Photon calorimeter optimized for 11 GeV
- DAQ requires preparation for 2kHz, incorporation of e- detector readout



Laser system work in JLab laser lab
(w/Cameron Cotton from UVa)

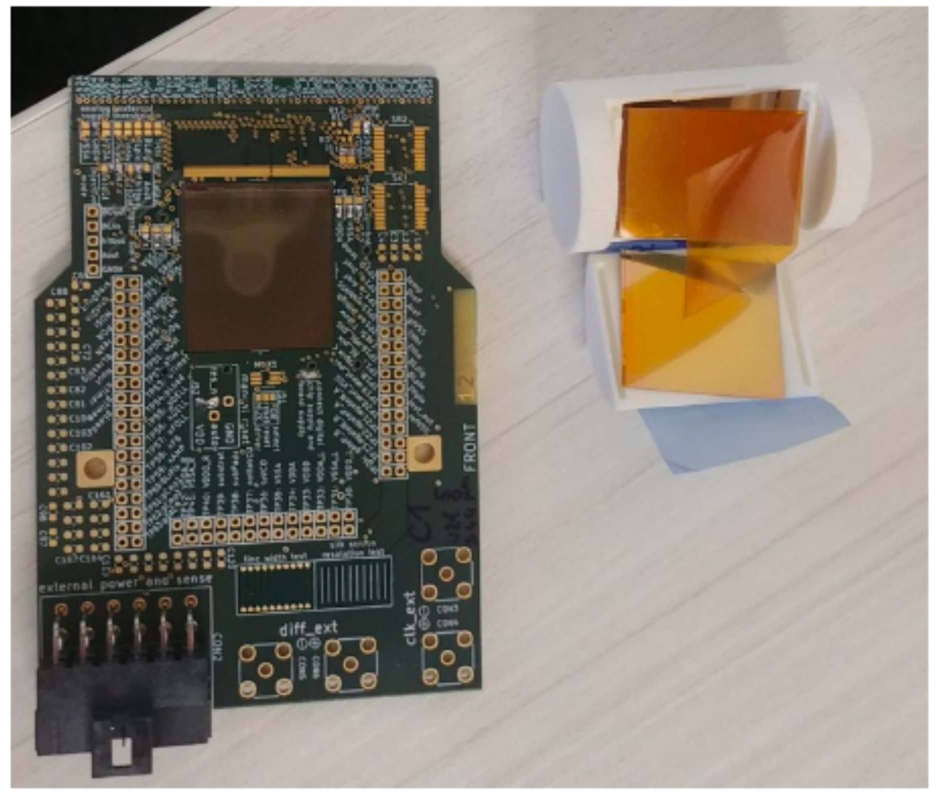
Goal: robust doubling and locking

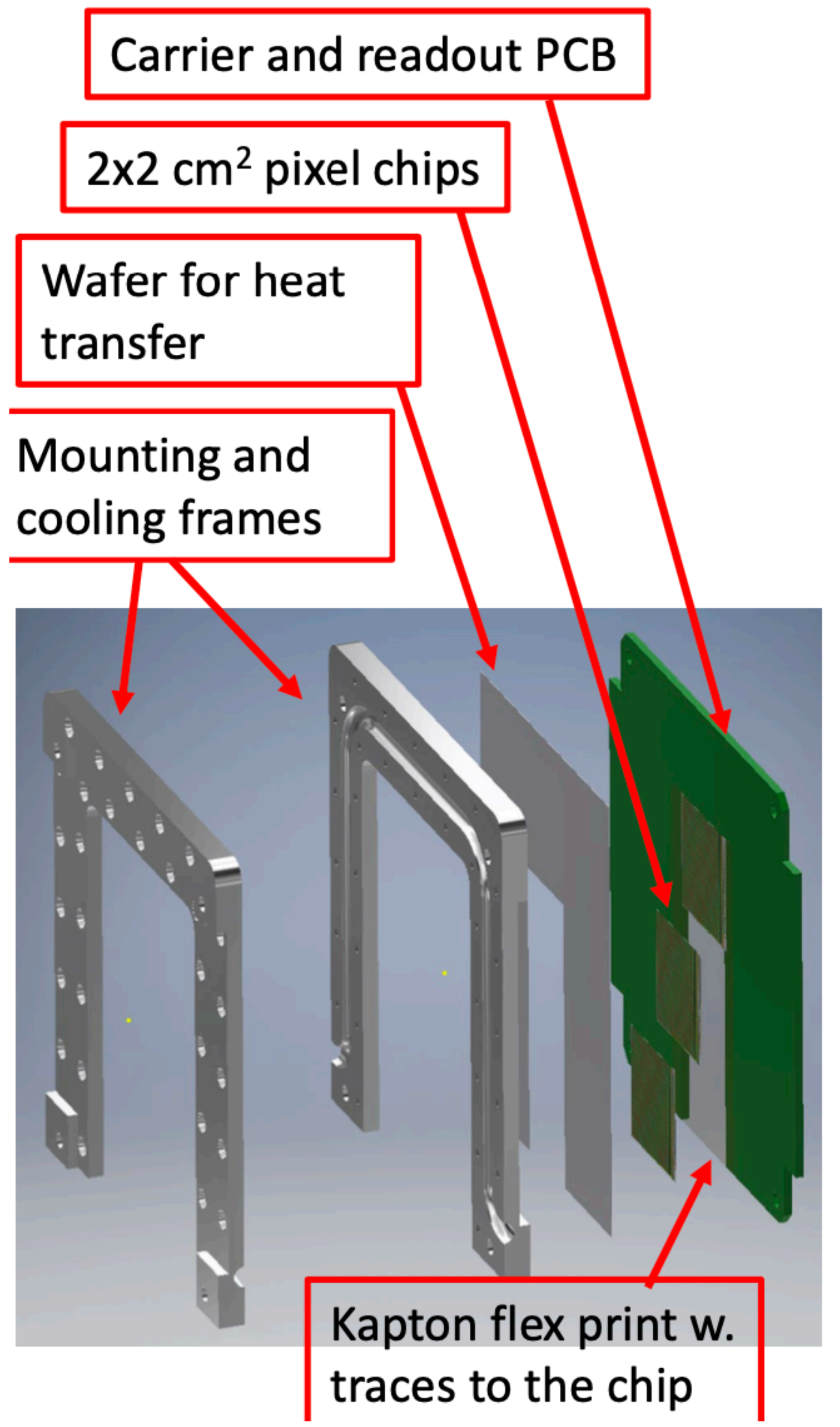
Trying for more robust and maintainable locking with commercial electronics
First success (low power lock)!

Compton Electron detector progress

Manitoba HVMAPS

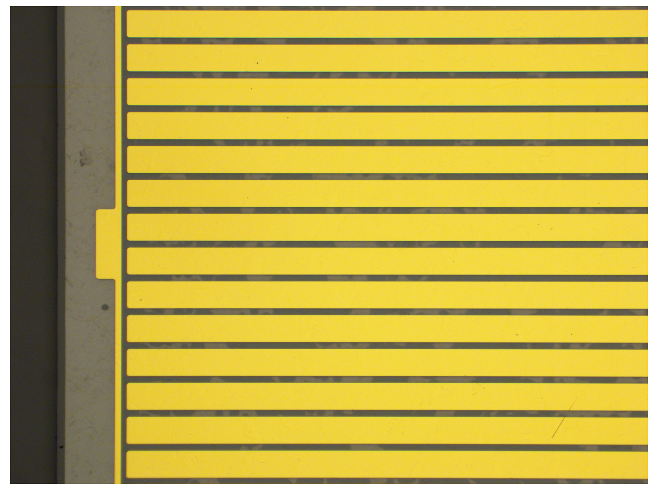
- HVMAPs will be also used in main MOLLER detector
- chips procured and detector configuration designed
- working on mounting, motion, and cooling in vacuum

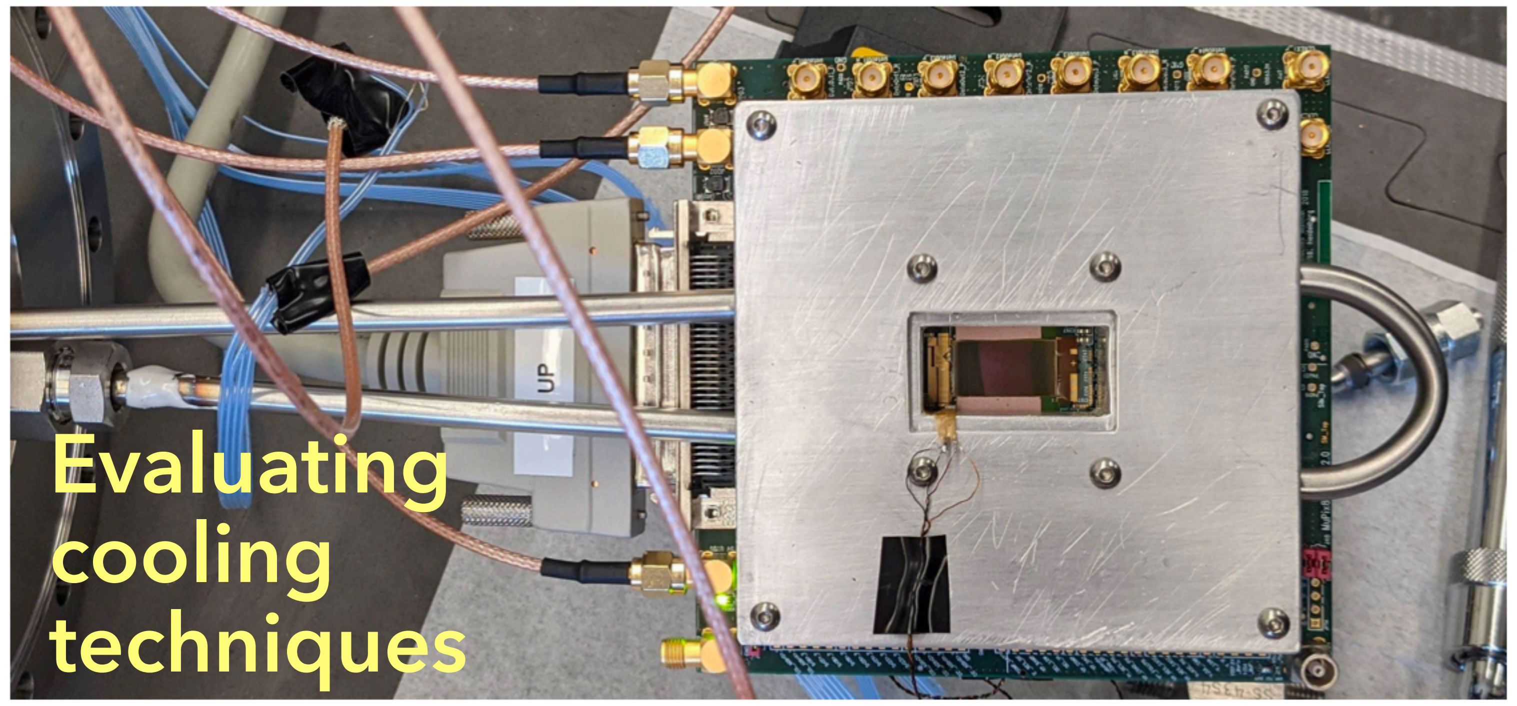




JLab HIPPOL diamond μstrip

- Trying to build off successful Qweak experience, but requires new diamond fabrication and significant upgrades
- Evaluating "FLAT-32" and "SAMPA" readout chips
- Diamond-strip test planes built and characterized (H.Kagan at OSU)





Work by Nafis Niloy

Run Phases

The experiment is designed for commissioning and calibrating beam delivery and monitoring

Run Phase 1

- Spectrometer optics, acceptance, alignment
- First look at backgrounds
- Test sufficiency of beam correction tools
- beam quality (asymmetry and halo)
- Tests of polarimetry precision

Result: near precision of SLAC-E158 with 14 days production

Run Phase 2

- statistical behavior of measured asymmetries
- quality of “slow” reversals (Wien, g-2)
- precision on background, normalization, beam corrections, polarization

Result: 2.5x beyond SLAC-E158, $\delta(\sin^2\theta_W)$=0.00044 (stat), 0.00047 (stat+syst)

Run Phase 3

- ultimate precision, ultimate systematic uncertainty

Result: $\delta(\sin^2\theta_W)$=0.00024 (stat), 0.00028 (stat+syst)

Progressively improve statistical power

Run Period	I	II	III
1 kHz Width Goal	101 ppm	96 ppm	91ppm
Width over counting statistics	23%	17%	11%
Excess noise over counting statistics	59 ppm	50 ppm	40 ppm
Allowance over ultimate goal	44 ppm	31 ppm	–

and systematic control

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
$e + p(+\gamma) \to e + X(+\gamma)$	2	0.4
Beam (position, angle, energy)	2	0.4
Beam (intensity)	1	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.6	0.3
$\gamma^{(*)} + p \to (\pi, \mu, K) + X$	1.5	0.3
$e + Al(+\gamma) \to e + Al(+\gamma)$	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**

Summary

MOLLER has been designed to run with high statistical power to achieve unprecedented precision with robust control of systematic uncertainties

- *The ultra-high precision MOLLER measurement will require careful attention to beam production, delivery, and monitoring*
- *Some MOLLER activities will require coordination with other operations*
- *The precision for determination of the beam transverse polarization with the MOLLER apparatus is a unique and powerful tool for testing absolute energy stability in CEBAF*
- *The improvements in the CEBAF and Hall A beamlines will be available for future Hall A measurements*
- *The goals of the experiment account for the ultimate performance of this apparatus to be achieved within a staged schedule*
- *There is still a lot of work to be done! (Collaborators welcome)*