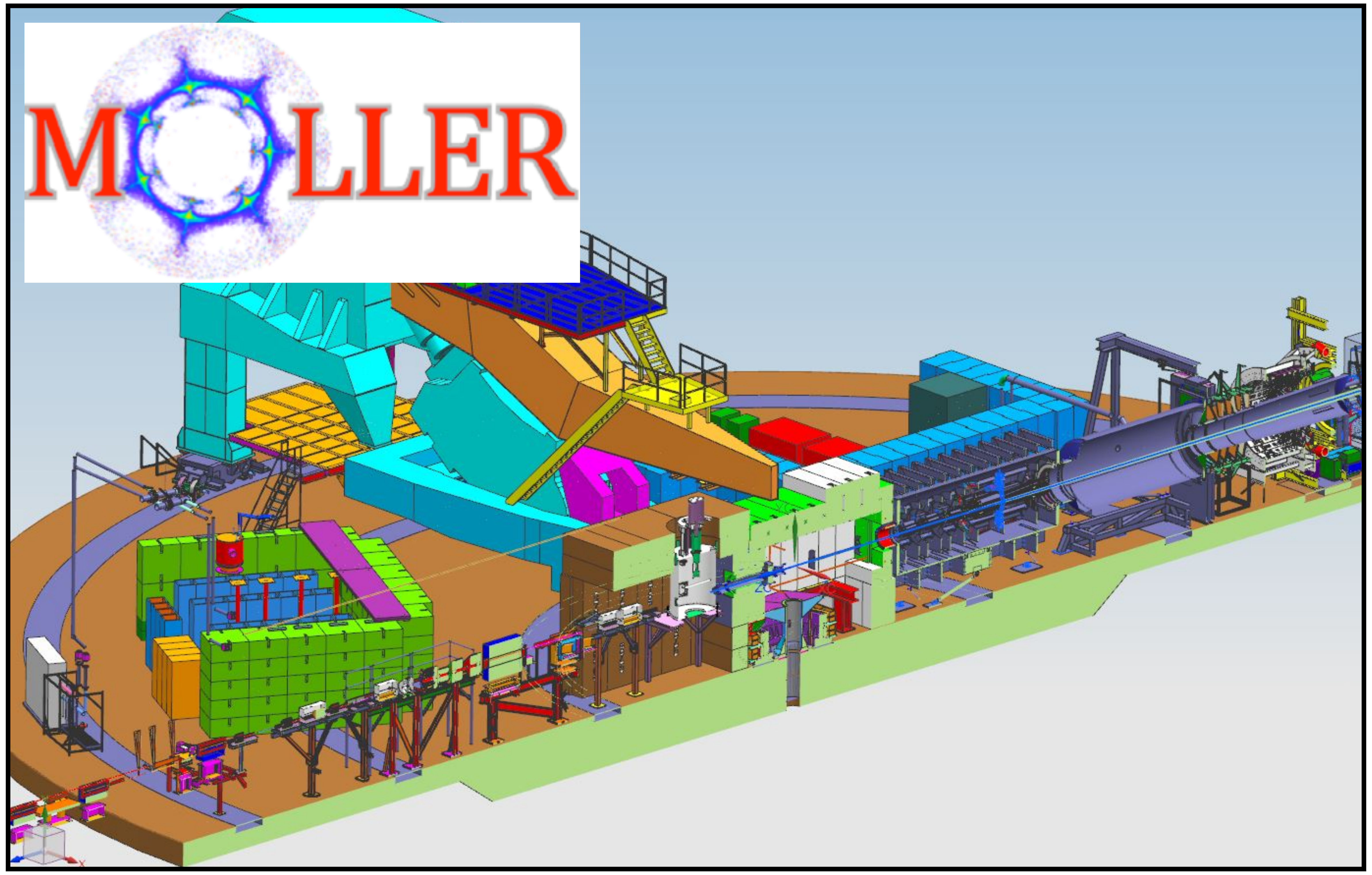
Commissioning The MOLLER Assembly



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Outline

- Completing the MOLLER project
- Beam trajectory alignment requirements
- Details on Initial low current commissioning
- Transition to high current
- Production running
- Spectrometer optics commissioning
- Run Phases

Completing the MOLLER project: KPPs and TOP

KPPs: Each system also requires assembly in Hall A, and….

System	Data sufficient for satisfying Threshold and Objective KPPs
Target Assembly	Operation with heater load
Spectrometer magnets	Operation and current variability for 24 hours
Thin-quartz main detector system	Response for $\beta \sim 1$ particles, can be satisfied from cosmic ray plus beam test data
Shower-Max detectors	Response for $\beta \sim 1$ particles, can be satisfied from cosmic ray plus beam test data
GEM detectors	Operation and efficiency from cosmic-ray test data
DAQ - Integrating and Counting	Stress-test with pulsar trigger, data transfer to Mass Storage System
Spectrometer, detectors, shielding, collimation	Alignment tolerances (survey) as specified, and pre-assembly magnetic axis measurements

Transition to Operation: Successful transition to operations will be achieved when Hall A management and staff and the MOLLER collaboration are able to operate the equipment safely and successfully with minimal guidance from the MOLLER project team.

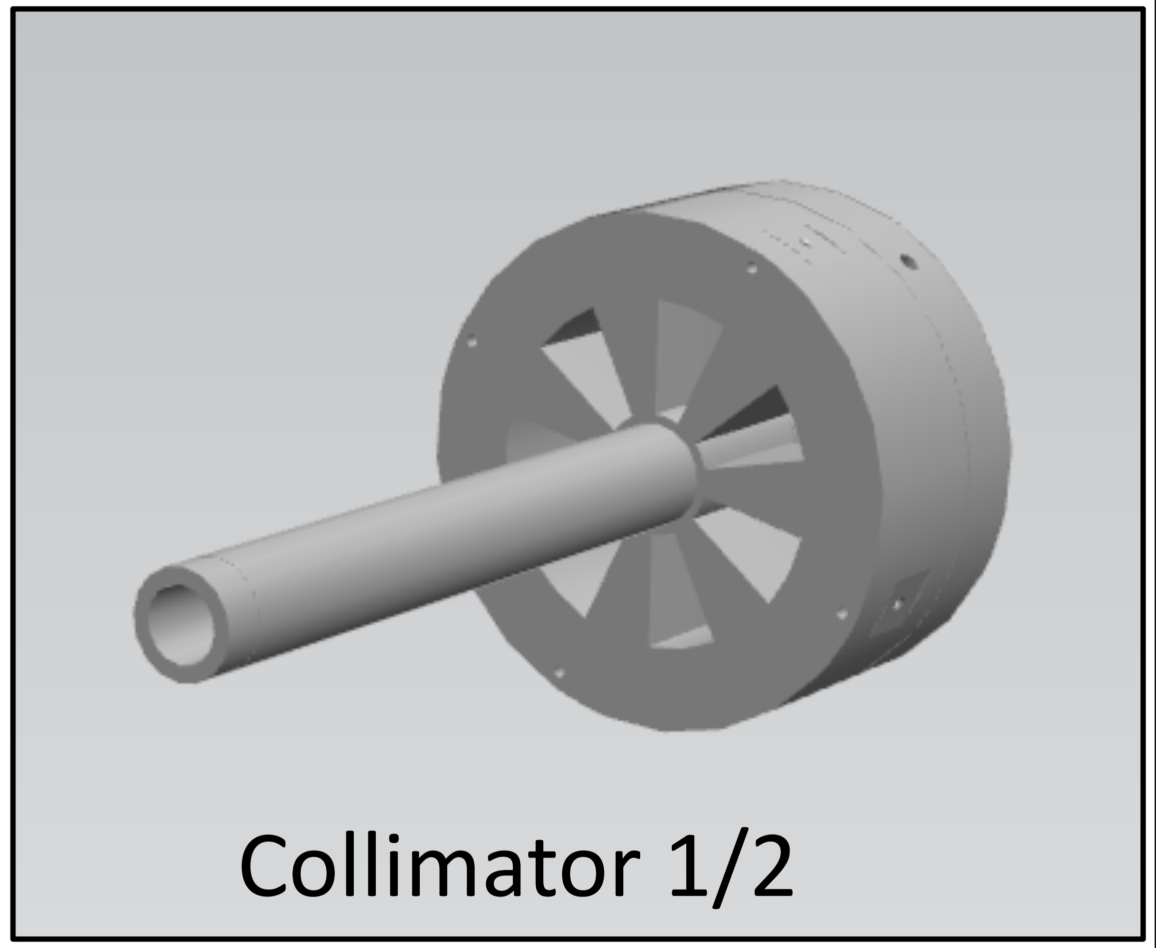
Beam Trajectory and Apparatus Alignment Plan

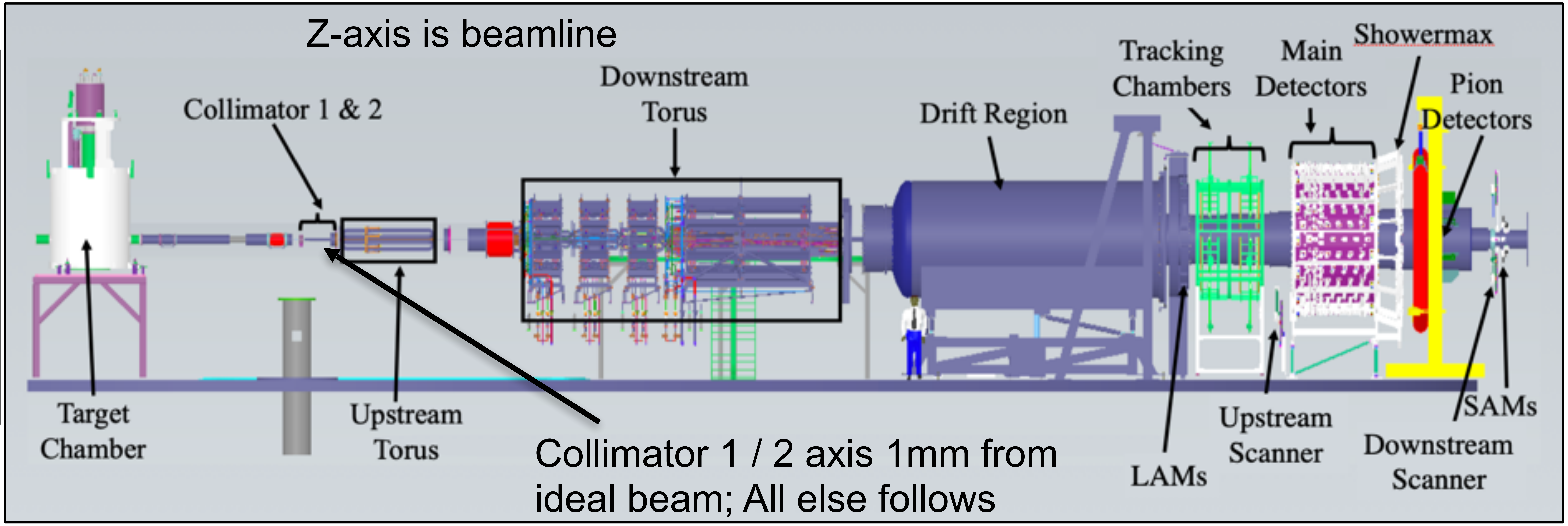
Early commissioning at low current must establish the correct installation and alignment of the MOLLER apparatus

- Essential to be on target nipples due to Al background. Goal: ±1mm from target center
- ±1mm on the collimator 1 & 2 assembly. Variation in acceptance drives this requirement. Very little effect on power deposited or background inside that range.
- Beam must center on dump (few mm tolerence)
- Magnetic axis (and fringe field) is important for controlling beamline backgrounds, driving requirements on magnet alignment. This will be studied/checked during commissioning.

- Center of detector array has reasonably loose tolerance. Ultimately this will be calibrated out using tracking data. Goal ±1 mm, but much greater tolerance than collimator alignment.
- *Constraint: it may be that about ±3mm beam position ("zero angle") beam shift will be available from field strength on beamline*

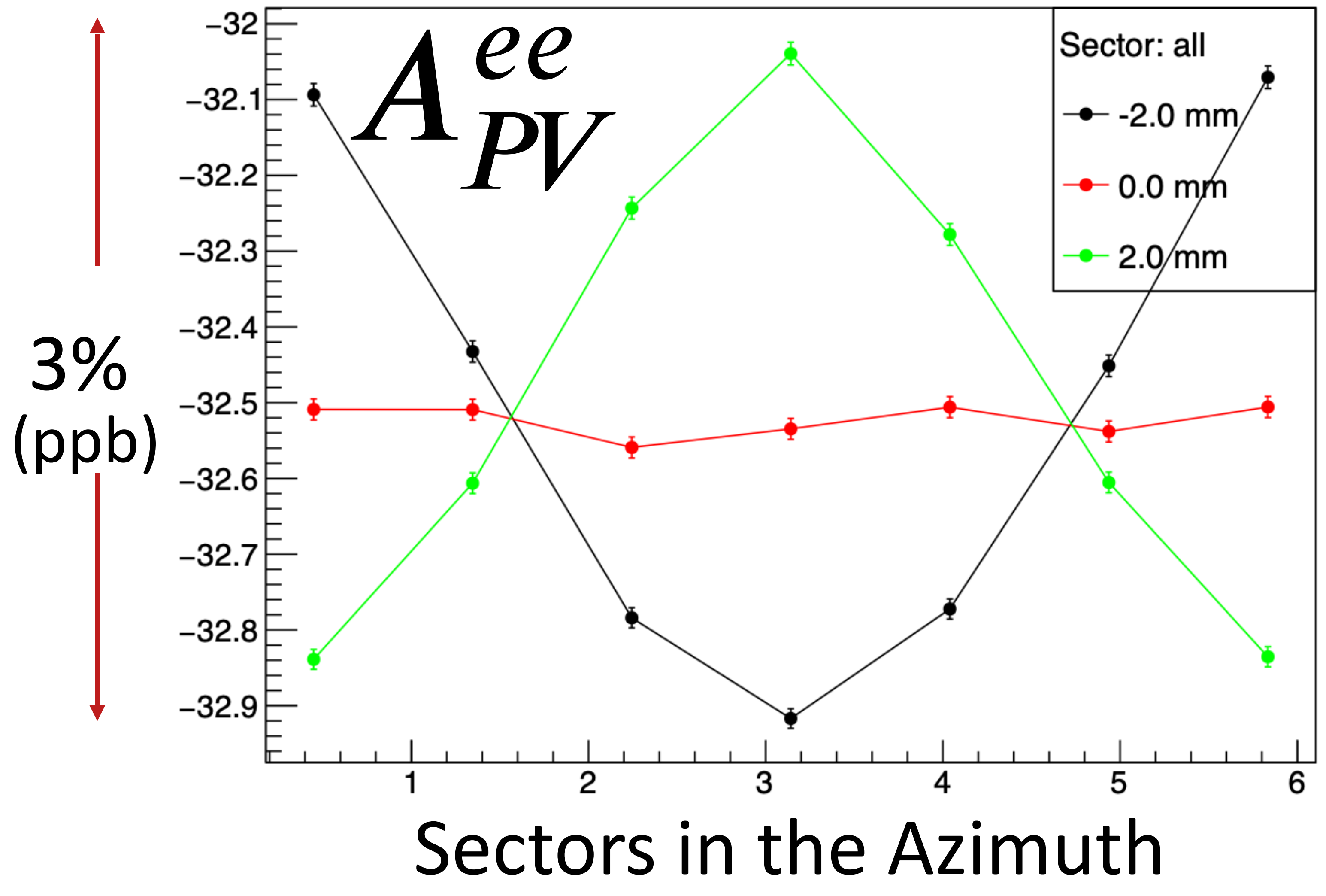
Key to Beam Trajectory is Transverse Position at Collimator 2

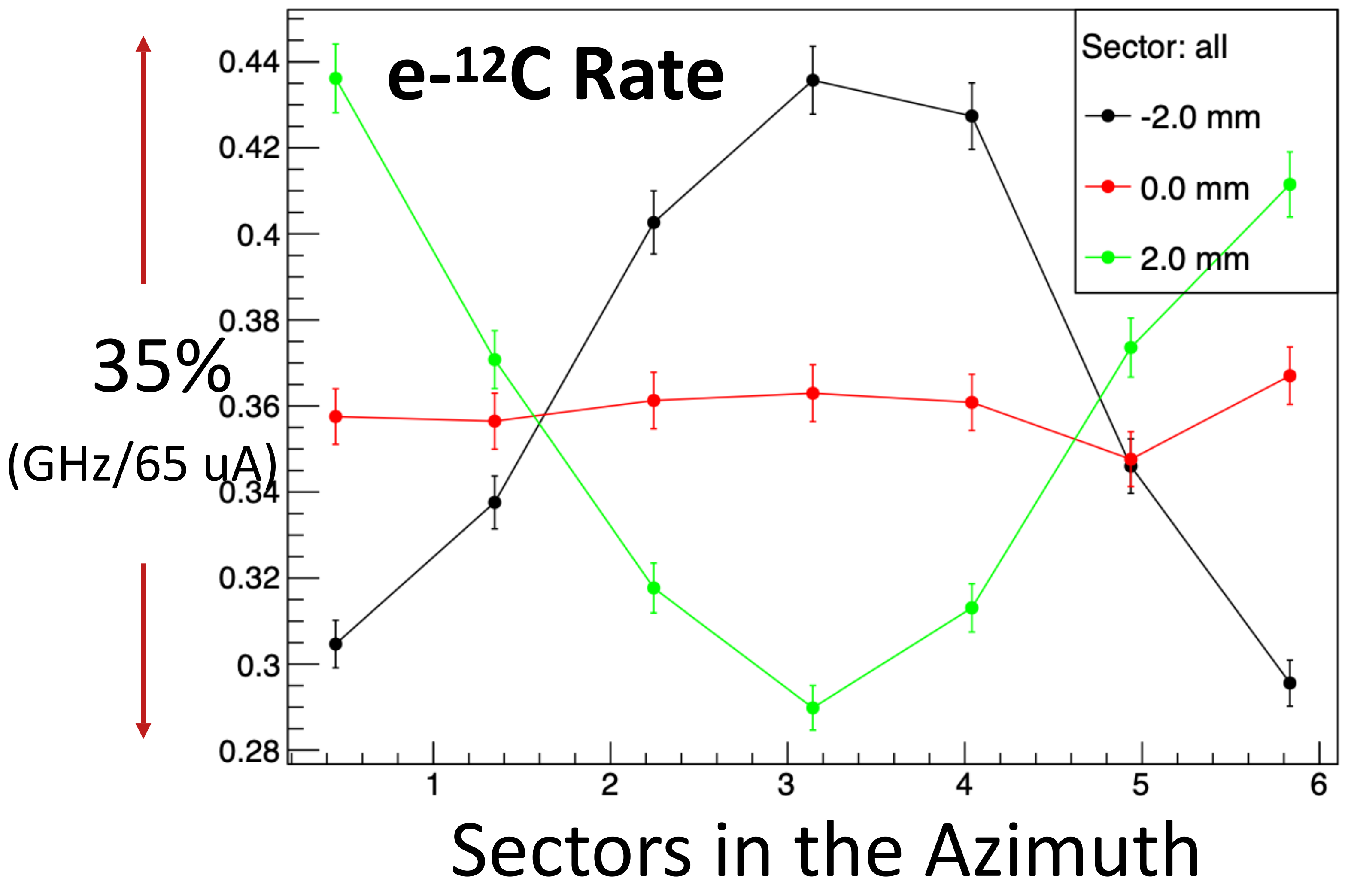




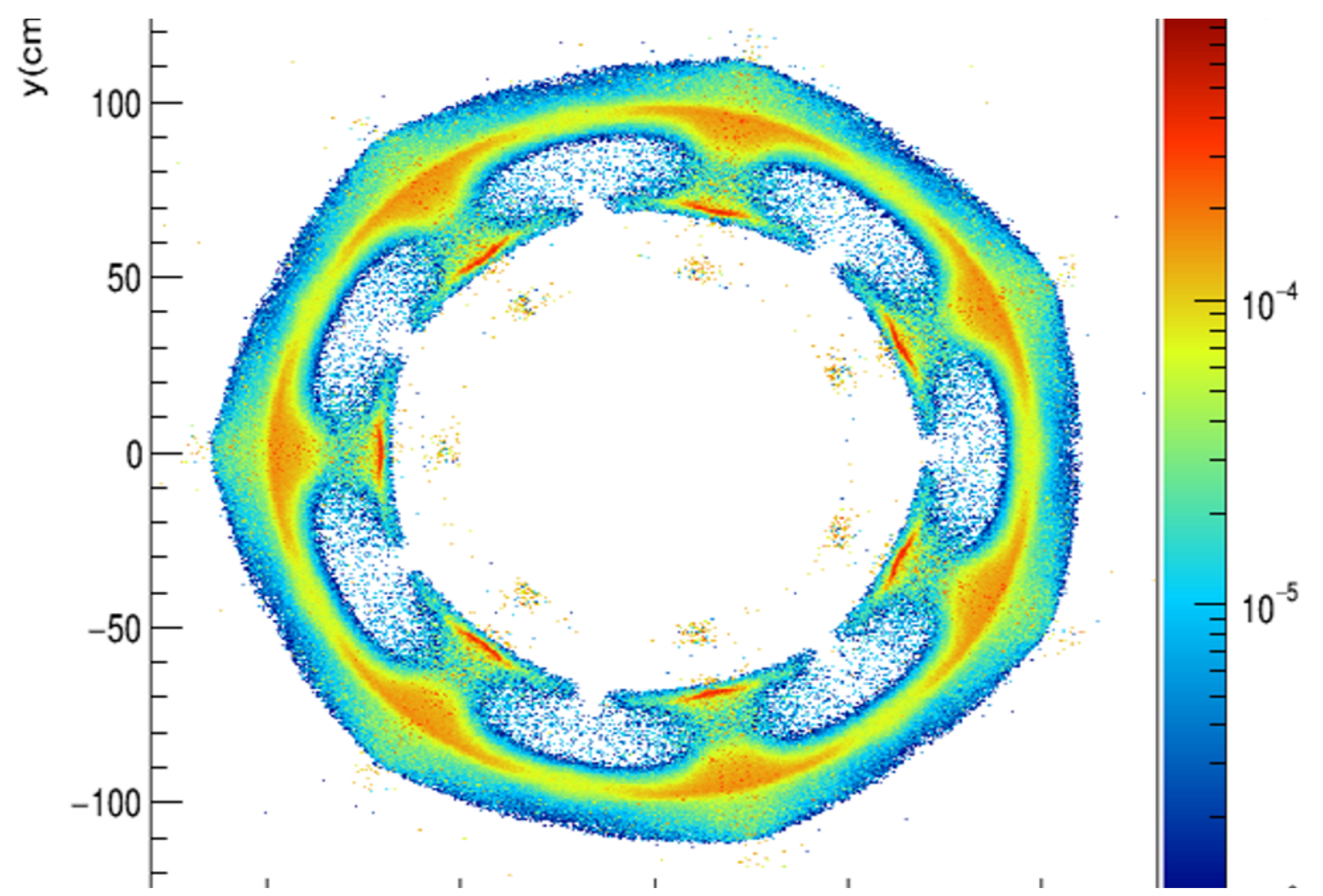
- The main physics measurement is $A_{PV} = K \times F_{kine} \times Q_W^e$; $A_{meas} = K \times \langle F_{kine} \rangle \times Q_W^e \times P_L$
- The factor $\langle F_{kine} \rangle$ is evaluated via tracking measurements in-situ
- Main discovery in simulations: the systematics of $\langle F_{kine} \rangle$ are acceptably minimized if the beam trajectory is directed such that it traverses collimator 2 within 1 mm of its geometric center
- Our tracking diagnostics can determine when this condition is achieved during commissioning
- It then suffices to ensure that the angle of approach is such that the beam goes through target nipples and arrives at the beam dump without generating beamline backgrounds

Takeaways from Beam Trajectory Simulations





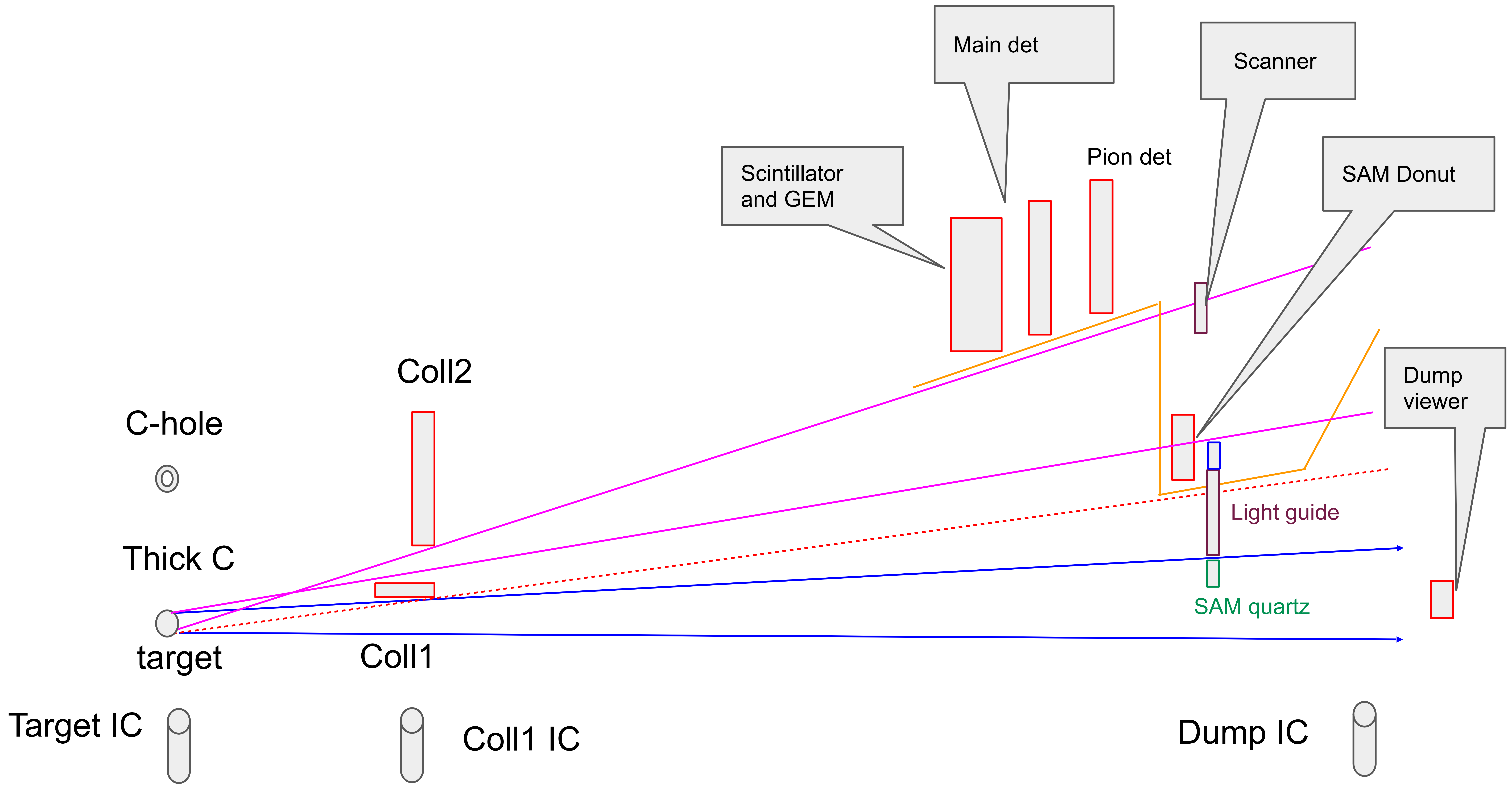
Heatmap of Scattered Flux



Transverse Plane 26 m from target

- Top left: effectively F_{kine}, with < 3% peak to peak modulation for 2mm offset. At 1 mm, the modulation averages to a systematic correction < 0.5%
- Middle: rate modulation for elastic scattering off a thin ^{12}C target. If the modulation is controlled to be less than 10%, the 1 mm requirement is met.
- These modulations are relatively insensitive to the angle of approach
- Thin quartz tracking (ring 2) counting and (independently) GEM tracking at low current and thin target can measure this. Plan for systematic control of relative rate over the azimuth at the 2% level.

Spectrometer Beamline Schematic



Outline of Beam Trajectory Alignment: Field Off

1. **Establish beam** in hall (tune mode with harps, beam dump viewer, etc., then CW. Spectrometer fields off).

2. **Target alignment check (fields off)**

   Use US and DS hole targets, with SAM trigger, to set vertical target position and establish the horizontal taget center. Should be within 1mm of ideal.

3. **Align Collimator2 acceptance channels and Collimator1 center, with fields off**

   Use scanner to observe Col 2 aperture profile edge, plus SAM balance and Col 1 power

   i) Use thick C target to measure radial profile with downstream scanner (Col 2 acceptance centering). Check beam bore with spatial variation with SAMs, and radiation or power monitors, and dump viewer to maintain reasonably centered beam.

   ii) Adjust beam position to center collimator 2 acceptance with downstream scanner (should be within 1mm of ideal beamline).

   iii) Use beam angle to restore SAM balance and position on dump viewer, while adjusting beam position to keep scanner edges uniform.

   iv) Ideally, bore power minimum (collimator 1) agrees with acceptance channel center, and target window center.

Outline of Beam Trajectory Alignment: Field On

4. Turn on Spectrometer fields, establish tune beam on established axis to beam dump

5. Acceptance Tuning (Spectrometer fields on)

- Use rate distribution response to beam position to more carefully align Collimator 2 acceptance
- Counting in Ring 2. Verify with GEM rate maps.
- Beam line response measured at same time (SAMs): can be used to tune position vs angle, if needed
- Should match zero-field trajectory

6. Verify beam on magnetic axis with low energy

- Establish 1-pass beam with spectrometer magnets off.
- Turn on magnets individually, observing changes on dump viewer

7. Complete low current commissioning using the established trajectory

Initial low-current commissioning

At 5 pass / 11 GeV

Magnet Fields off:

- Commission hole target and solid target
- Raster commissioning
- Collimator 1 “hole finding”
- Locating collimator 2 (scanner with field off)

Get magnets on:

- Watch for deflections when energizing magnets
- commission quartz and scint counting, GEM heatmaps
- count Ring 2 with quartz
- beam movement, count Ring 2 variations
- complete “neutral axis” studies
- initial GEM parameter commissioning data
- all detectors: LAM, SAM, pion det, Shower max
- LH2 target commissioning with low current
- Rate measurements with LH2
- Exercise moving collimators
- Blocker collimator background rates
- Sieve data with GEMS
- Initial Møller polarimeter commissioning

Go to 1pass / 2.2 GeV

Final magnet alignment study

- Fields off, energize individually, test deflections

Primary goals:

- *Define optimum trajectory through collimators and spectrometer*
- *Verify alignment of apparatus*
- *Detector checkout*

Once complete, ready for high current!

Transition to high current

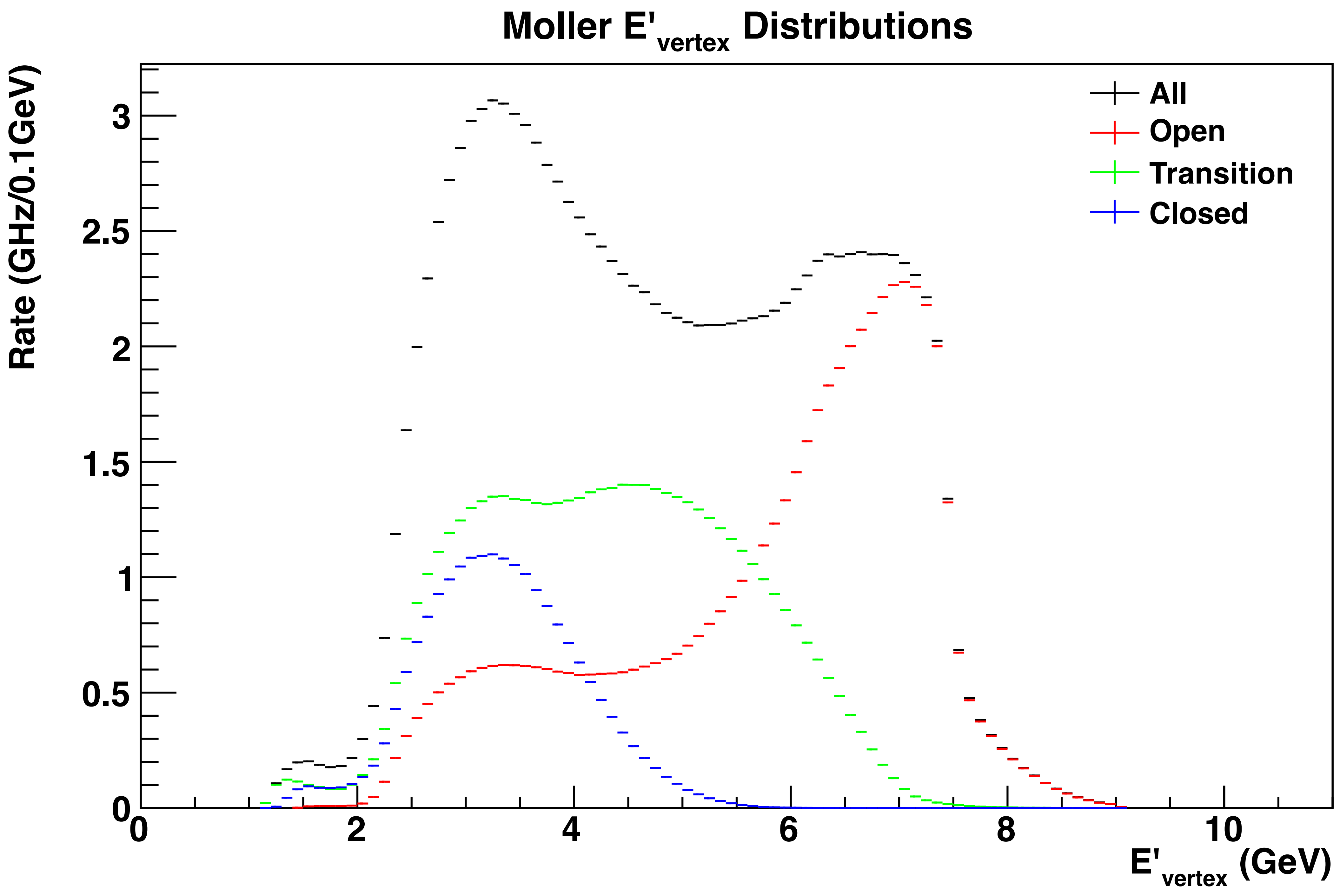
We must be convinced the apparatus is correctly assembled and aligned before transitioning to high current.

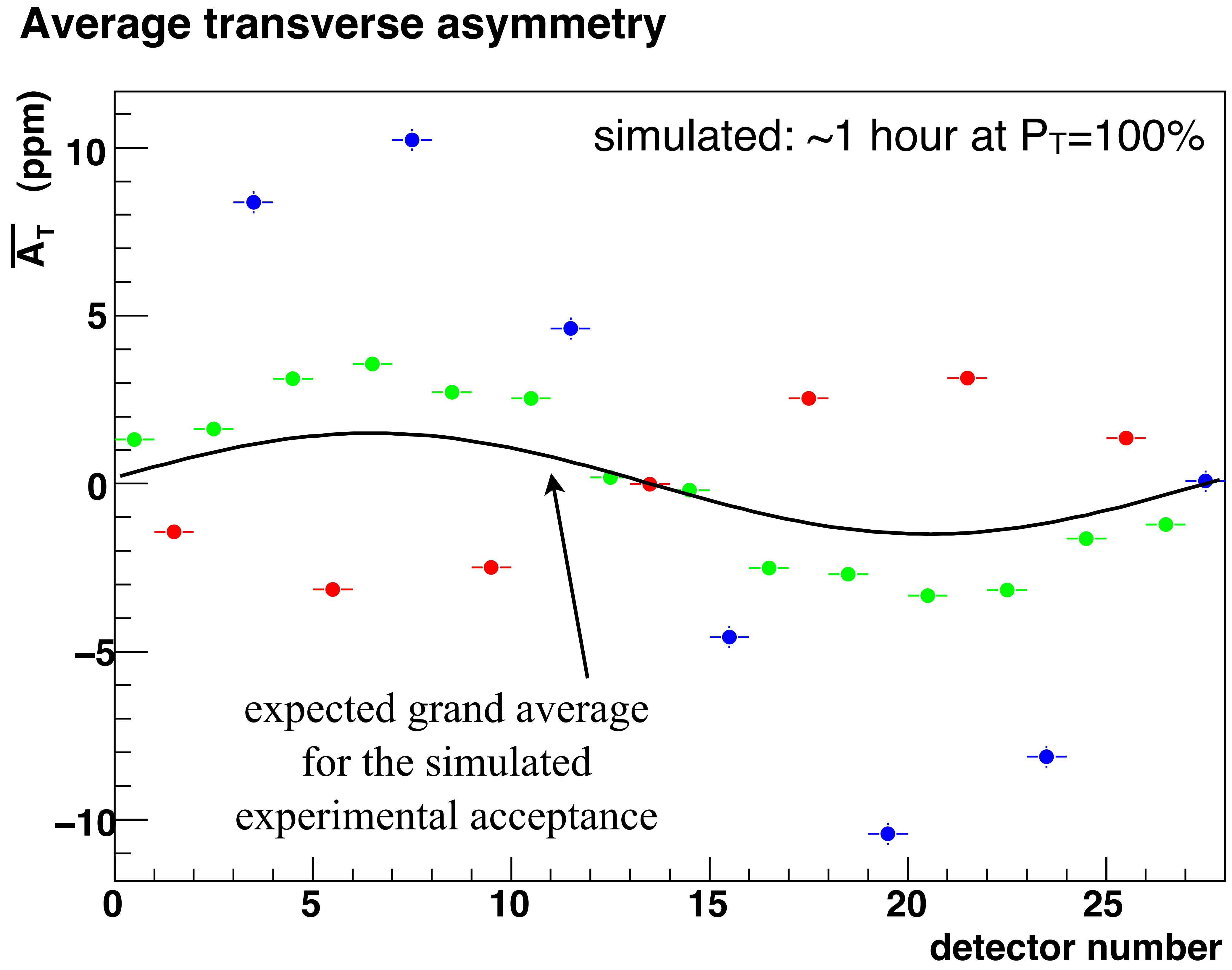
– Establish high current operations (beam, spectrometer, ion chambers, etc)
– Commission target at high current
– Calibrate beam monitors
– Commission detector systems at high current - most of this “looks like” production
    – widths, beam modulation and corrections, correlations, Compton polarimeter
– Early production running
– not so early production running
– … more production running

Ideally, in “early” to “not-so early” production running we would test our ability to measure asymmetries and expected correlations between elements of our detector

Transverse polarization provides this opportunity

Measured and calculated for *ee* scattering





- Mini spin dance with Moller polarimeter can verify null longitudinal polarization
- Unique signature of transverse beam polarization provides test of apparatus and calibration of acceptance
- 50 ppb error on A_T*P_b in 4 hours: 1 degree precision on transverse polarization during longitudinal running
- 50 ppb error on A_T is goal for early high-current running

High current commissioning

~1 week at 5 pass / 11 GeV, up to 65 uA

Commission:

- Ion chamber, beamline, target
- Detectors in integrating mode
- Beam, beam monitors, beam modulation

~3-4 days, 100% transverse polarization

- need a total of 1 good shift + commissioning time
- need either vertical or horizontal polarization
- Need 99.5% P_T (<10% P_L) setup possible with Moller polarimeter
- Could create P_H with energy offset (~40 MeV) or P_H or P_V in injector

Continue with “long term integration” commissioning (aka “production”)

- will need P_T minimization
- Compton commissioning

Spectrometer optics commissioning

- This studies are not necessary before transition to high luminosity
- These studies would be less efficient without allowing for time to analyze commissioning data (align GEMs, test tracking analysis, evaluate rotator reproducibility, etc.)
- We need to be ready to be efficient with the low pass data, which will be a significant undertaking. We should expect to run those configurations only once.

~1 week data total, low current 1 nA - 1 μA

Full optics commissioning
- GEM performance, optics study, ~1 day with 5-pass
- ~ 1 day each with 3-pass, 2-pass, 1-pass for optics calibration

Acceptance, detector response study (5 pass, ~1 day)
- LH2 target, no sieve

Background study (5 pass, ~ 1day)
- LH2 target, blocker

Run Phases

Run Period	1 kHz Width	PAC Days (prod)	Stat Error $\sigma(A_{meas})$	Stat Error $\sigma(A_{PV})$	Efficiency	Calendar Weeks (prod)	Calendar Weeks (calib)
I	101	14	2.96 ppm	11.4%	40%	5	6
II	96	95	1.08 ppm	4.2%	50%	27	3
III	91	235	0.65 ppm	2.5%	60%	56	4
Total		344	0.55	2.1		88	13

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	–

Run Phase 1

- Spectrometer optics, acceptance, alignment
- First look at backgrounds
- Beam monitor resolution
- Beam correction tools
- Beam quality (asymmetry and halo)
- Polarimetry precision

Result: precision of SLAC-E158

and systematic control

Error Source	Fractional Error (%) Run 1	Fractional Error (%) 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**

Ultimate performance not required on day 1, but commissioning and Run Phase 1 are the foundation for ultimate MOLLER success

Summary

- The collaboration has outlined a workable plan for commissioning the MOLLER apparatus and confirming the alignment can meet physics goals
- The plan is based on realistic G4 simulations of the apparatus, which demonstrate that the commissioning studies will have sufficient precision to qualify the MOLLER assembly
- This plan provides for an efficient transition to high-current operation and data production, while testing the apparatus and confirming performancence expectations.
- A phase approach of improving precision accounts for the required calibrations and studies associated with production data collection, to achieve the ultimate proposed performance

Appendix

Outline of commissioning plan

Low current commissioning (<1uA beam current, often 1-5 nA, arbitrary polarization)

- ~ 2 weeks 5 pass (~11 GeV) (alignment, detector, target, spectrometer commissioning)
- ~ 1 day at 1 pass (final magnet alignment check, should not be in first days of commissioning)

High current commissioning (up to 65 uA beam current)

- ~1 week, ~11 GeV, any polarization (beamline, target and detector commissioning)
- ~ 4 days transverse polarization (beamline, detector, spectrometer commissioning)
- Continue with longitudinal running ("long-term integration" aka "production")

Low current optics calibration (sometime later in the run period, includes lower passes)

- few nA, arbitrary polarization
- ~4 days at 5 pass
- ~1 day each runs with 1-, 2-, and 3-pass running

Time estimates in calendar days

MOLLER project KPPs

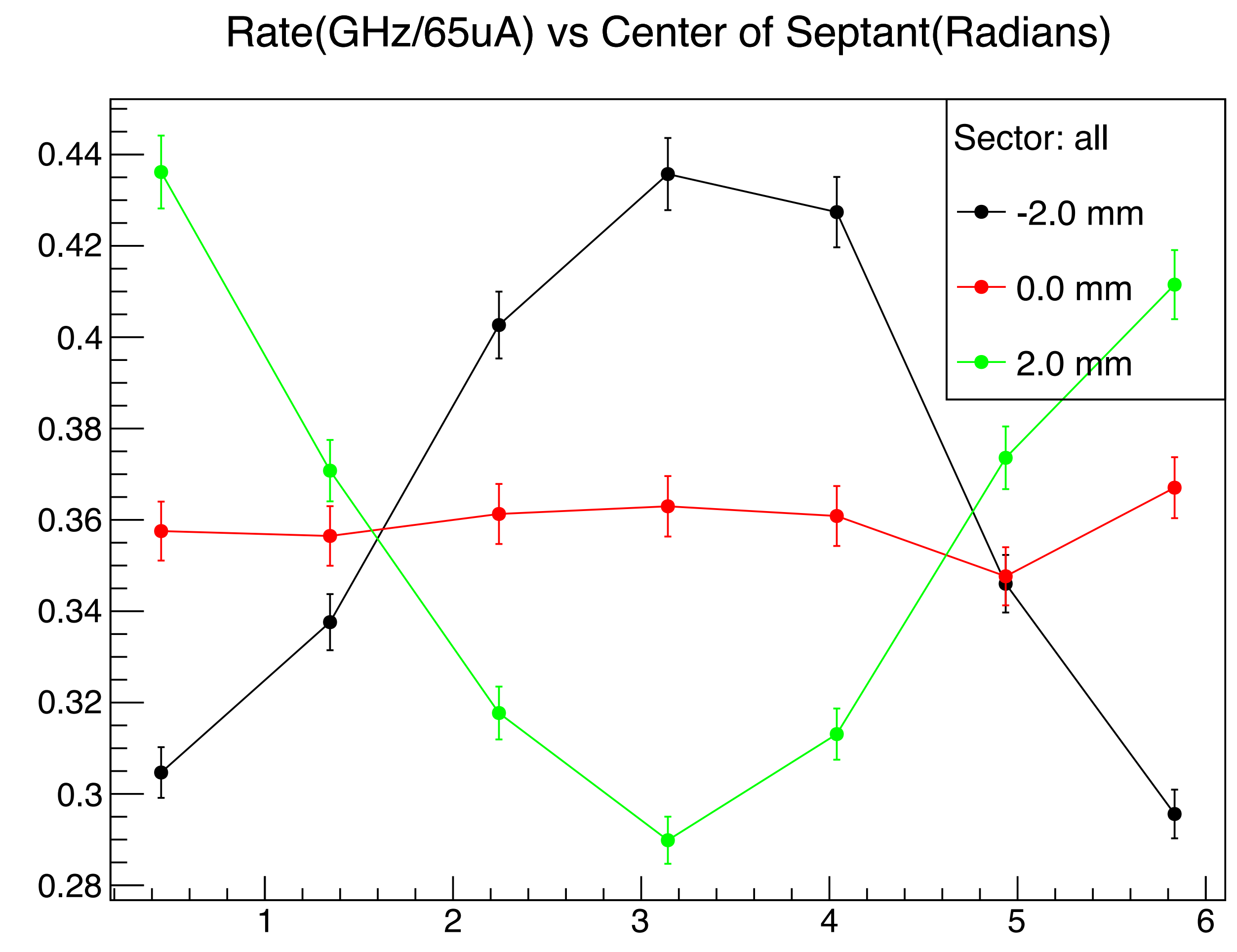
Key Performance Parameters	Threshold KPPs	Objective KPPs
Cryogenic liquid hydrogen and solid target systems assembled in Hall A and tested.	Demonstrate liquid hydrogen target operation with ≥1.4[1] kW load from heater at nominal operating density.	Demonstrate liquid hydrogen target operation with ≥3.1 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 s <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 Alignment Specification document.	Same but to objective tolerances in documentation.

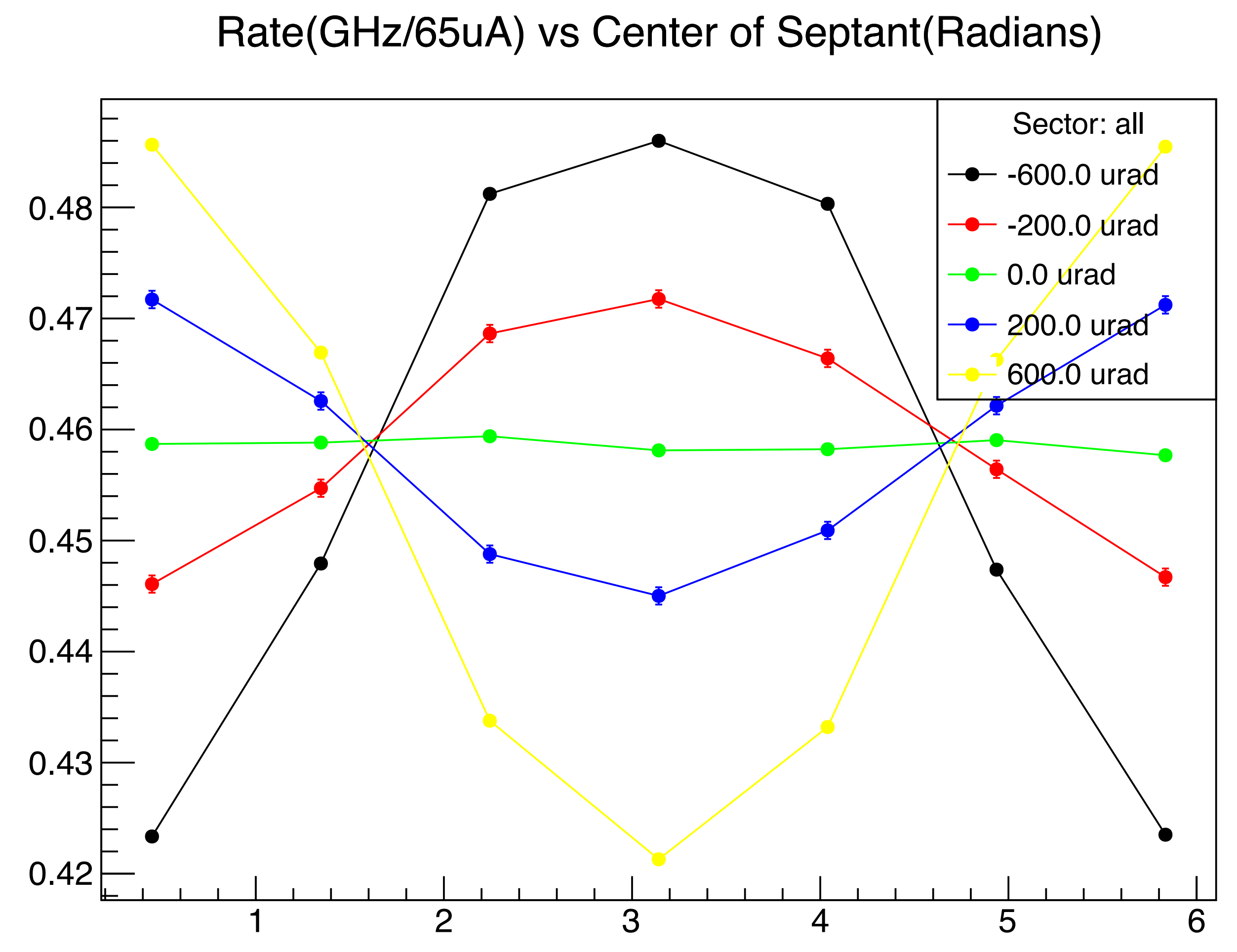
Simulation results

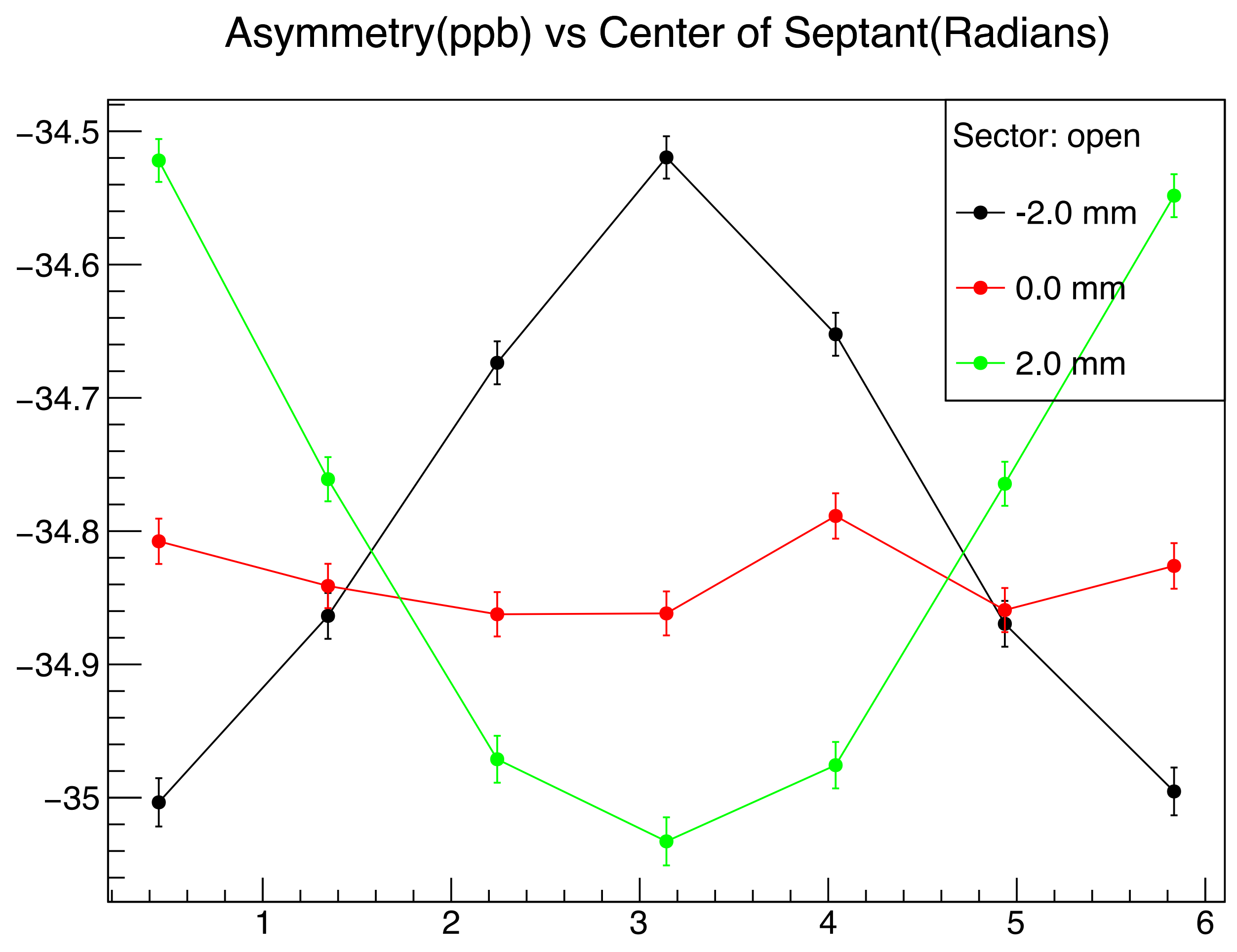
Rastered beam, thin C12 target, 11 GeV

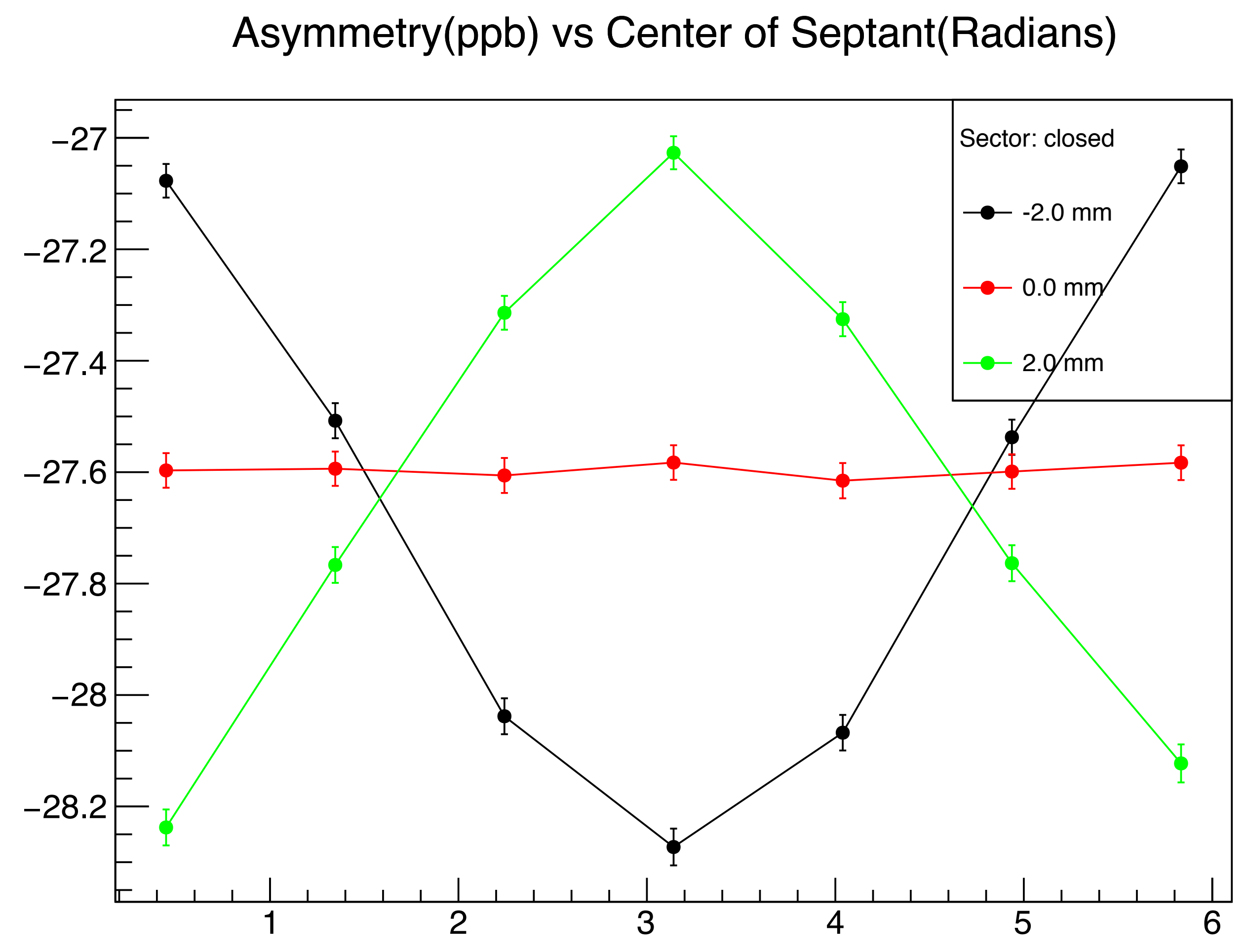
Carbon elastic modulation very sensitive!

Moller asymmetry much less sensitive









Overview of Positioning Requirements

Details in V. Berdnikov talk tomorrow

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Measurement of Lepton-Lepton Electroweak Reactions (MOLLER) Project

MOLLER

System Requirements Document for
MOLLER Assembly in Hall A (WBS 1.08) of the
MOLLER EXPERIMENT

U.S. DEPARTMENT OF ENERGY

Table 3: Alignment tolerance goals for the pion donut and detector beam pipe.

	dX (mm)	dY (mm)	dZ (mm)	Pitch (mm/m)	Yaw (mm/m)	Roll (mm/m)
Pion Donut	0.5	0.5	1.0	0.5/3.2	0.5/3.2	0.5/3.2
Detector Beampipe	0.5	0.5	1.0	0.5/7.0	0.5/7.0	0.3/1.2

Table 7: Alignment tolerance goals for detector systems to support structure fiducials and the support structure fiducials to the Hall CS.

	dX (mm)	dY (mm)	dZ (mm)	Pitch (mm/m)	Yaw (mm/m)	Roll (mm/m)
GEM structure	0.5	0.5	3.0	1.0/1.5	1.0/2.2	3.0/2.2
Main Det. structure	0.25	0.25	3.0	0.5/2.0	0.5/2.0	0.5/2.0

MOLLER-ASSEMBLY-SRD-REV-1.0_Jul26_2023.docx

Table 8: Alignment requirements to satisfy KPPs. All parameters represent alignment relative to the neutral beam axis (raster off) derived by survey of the incoming beamline elements. Unless otherwise specified, position (x,y,z) alignment tolerances are at the upstream end of the object. Pitch, yaw and roll represent rotations about the x, y, and z axes, respectively

	Threshold=Objective					
	dX (mm)	dY (mm)	dZ (mm)	Pitch (mm/m)	Yaw (mm/m)	Roll (mm/m)
LH Target	3.0	3.0	5.0	3.0/1.25	3.0/1.25	N/A
Vacuum window	1.0	1.0	5.0	N/A	N/A	N/A
Blockers A & B	3.0	3.0	3.0	N/A	N/A	3.0/0.2
Collimator 1&2	3.0	3.0	3.0	3.0/0.575	3.0/0.575	3.0/0.3
Collimator 4	3.0	3.0	3.0	3.0/0.15	3.0/0.15	3.0/0.5
TM0	3.0	3.0	3.0	3.0/1.8	3.0/1.8	3.0/1.0
TM1	3.0	3.0	3.0	3.0/0.8	3.0/0.8	3.0/2.0
TM2	3.0	3.0	3.0	3.0/0.8	3.0/0.8	3.0/2.0
TM3	3.0	3.0	3.0	3.0/0.8	3.0/0.8	3.0/2.0
TM4	3.0	3.0	3.0	3.0/3.5	3.0/3.5	3.0/2.0
GEM structure	3.0	3.0	5.0	5.0/1.5	5.0/2.2	5.0/2.2
Main Det. Structure	3.0	3.0	5.0	5.0/2.0	5.0/2.0	5.0/2.0
Drift beampipe	5.0	5.0	5.0	6.0/5.7	6.0/5.7	6.0/2.5
Detector beampipe	5.0	5.0	5.0	6.0/7.0	6.0/7.0	N/A
SAM beampipe	3.0	3.0	5.0	5.0/1.0	5.0/1.0	N/A

MOLLER Assembly in Hall A requirements are described in the SRD document including survey and alignment tolerances

The alignment goals are based on reasonably achievable values from survey instruments and techniques precision rather than accuracy required to achieve the physics goal

The threshold KPPs tolerances represent the minimum required to perform the MOLLER experiment

- **Beam Trajectory Requirements (Draft)**
    - *Rastered beam must be fully contained in the front and back target endcap nipples:* It is expected that the nipples are at least 15 mm in diameter, so there is freedom at the level of +/- 2 mm over and above a 1 mm transverse tolerance specification.
    - *Beam centered on collimator 2 within 1 mm:* This is the most important physics specification. Diagnostics are built in to be able to determine this without spectrometer fields being energized. The goal will be to get within the tolerance here while staying within the target nipples and cleanly transporting the exhaust beam to the beam dump.
    - *Beam power in collimator 1 relatively uniform*: Once the above is accomplished, this should be simply a verification step as a 1 mm tolerance entering the collimator (which is rigidly connected to collimator 2) should achieve the desired uniformity
    - *High power beam transported safely to beam dump:* the goal is to maintain all the criteria above as well as clean transport to the dump after the magnets are fully energized.
    - *Hybrid dipole field backgrounds in SAM region considered acceptable for physics:* Once the ideal trajectory has been defined above, diagnostics studies using the full blocker should be able to determine whether the backgrounds from fringe fields in the detector region are under control.

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