Commissioning the MOLLER apparatus

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Scope:

Here we aim to describe what we need to do when beam is available, to verify that the apparatus is installed and aligned correctly.

MOLLER ERR process

ERR 1 (Design Phase) Patrizia organized probable ERR reviewers to observe in August Director's Review and fall IPR. These reviews and their participation served to statisfy this ERR. *DONE*

ERR 2 (Construction Phase) will occur before assembly in hall (*ie. before summer 2025*)
To assess if the apparatus can meet the physics goals and includes assessment of the maturity of analysis software. At this review the team needs to present an experiment installation plan, timeline, resource requirements and copies of safety documentation and operations manuals, preliminary OSPs, preliminary commissioning and run plans.

ERR 3 Safety and readiness for operation. Near conclusion of assembly period. Will be necessary for operation of experimental equipment, for example, energizing the magnets.

- All Final documentation - (*from my notes: documentation review seems to be the most emphasized piece of the review*)
- Safety Check lists
- Experimental procedures both for shift leaders and shift takers and for experts
- Proof of readiness for expedient data analysis towards publication.

Next year, we will need to present commissioning and run plans

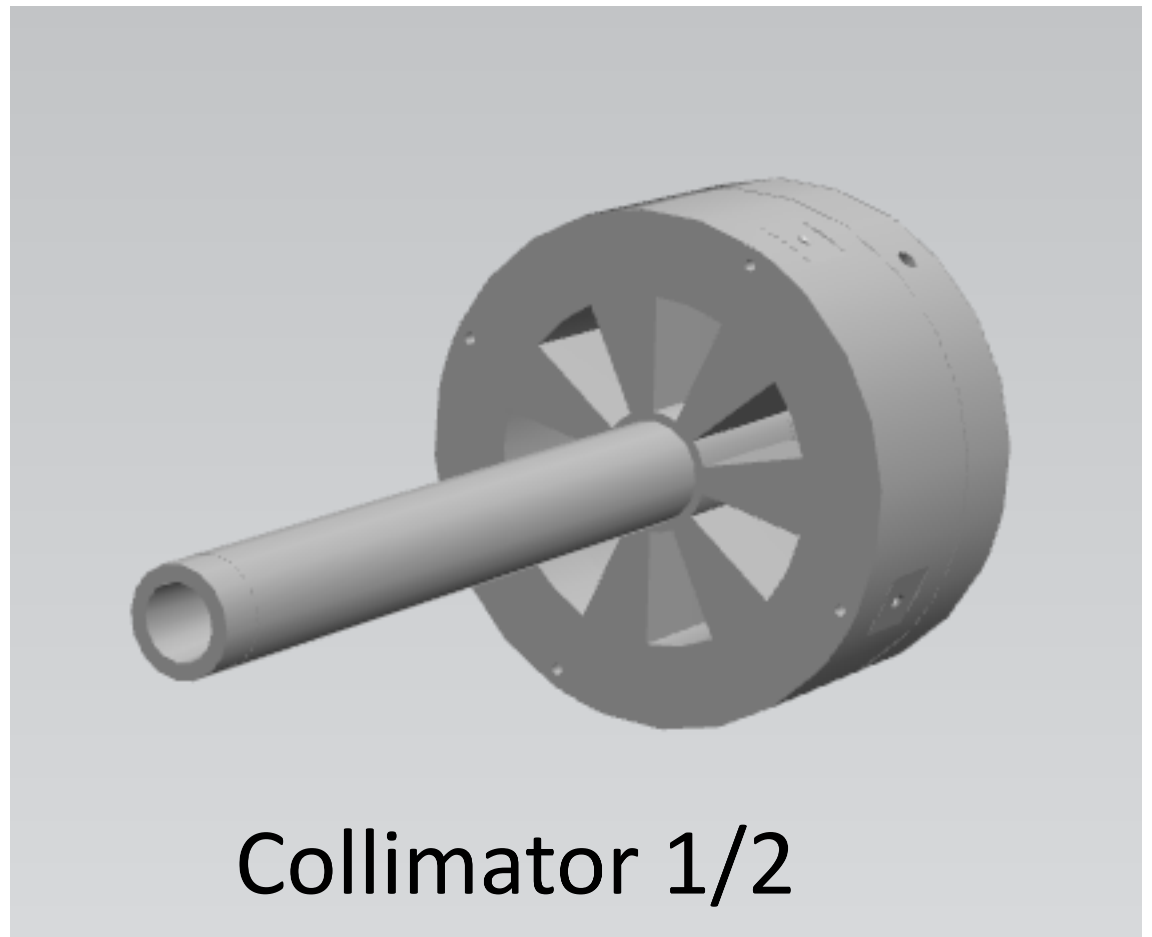
Beam Trajectory and Apparatus Alignment Plan

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

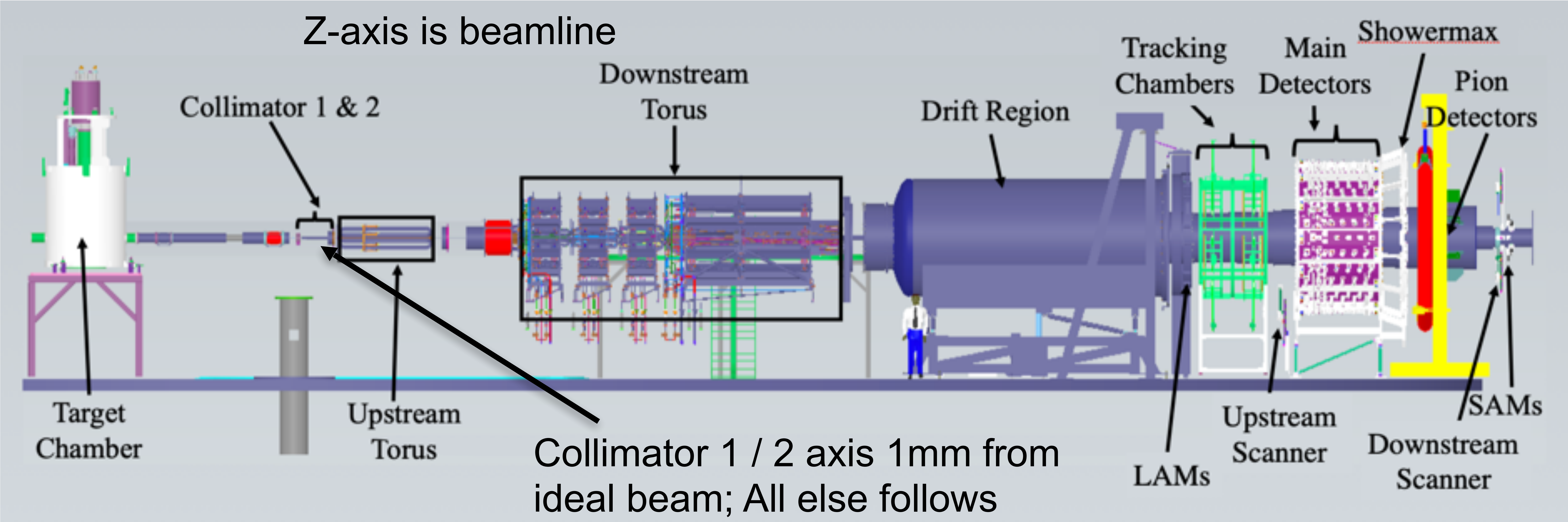
Summary Considerations

- ±1mm on collimator 1 / 2 is fine. Very little effect on power deposited or background inside that range. Variation in acceptance is the strongest requirement.
- Essential to be on target nipples, but this has reasonable tolerance (aim for ±1mm from target center)
- Magnetic axis (and fringe field) is critical for controlling beamline backgrounds - the optimum will be found empirically during commissioning
  - This requirement factors into magnet alignment tolerances, ~1mm alignment of each coil set
- Center of detector array also reasonably loose tolerance (aim for ±1 mm). Ultimately this will be calibrated out using tracking data
- *Only about ±2mm beam position ("zero angle") beam shift is available from field strength on beamline*

Key to Beam Trajectory is Transverse Position at Collimator 2



Collimator 1/2

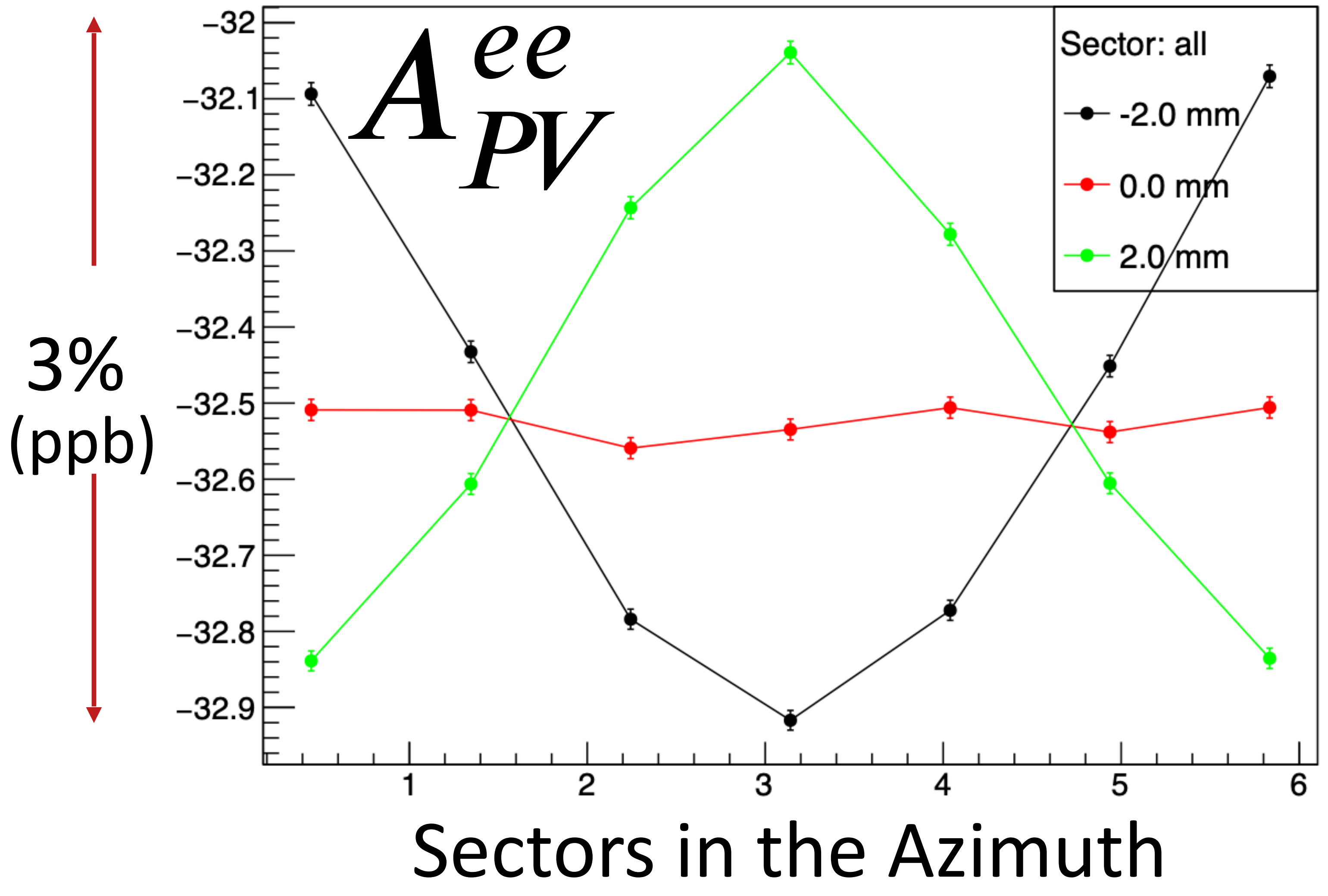


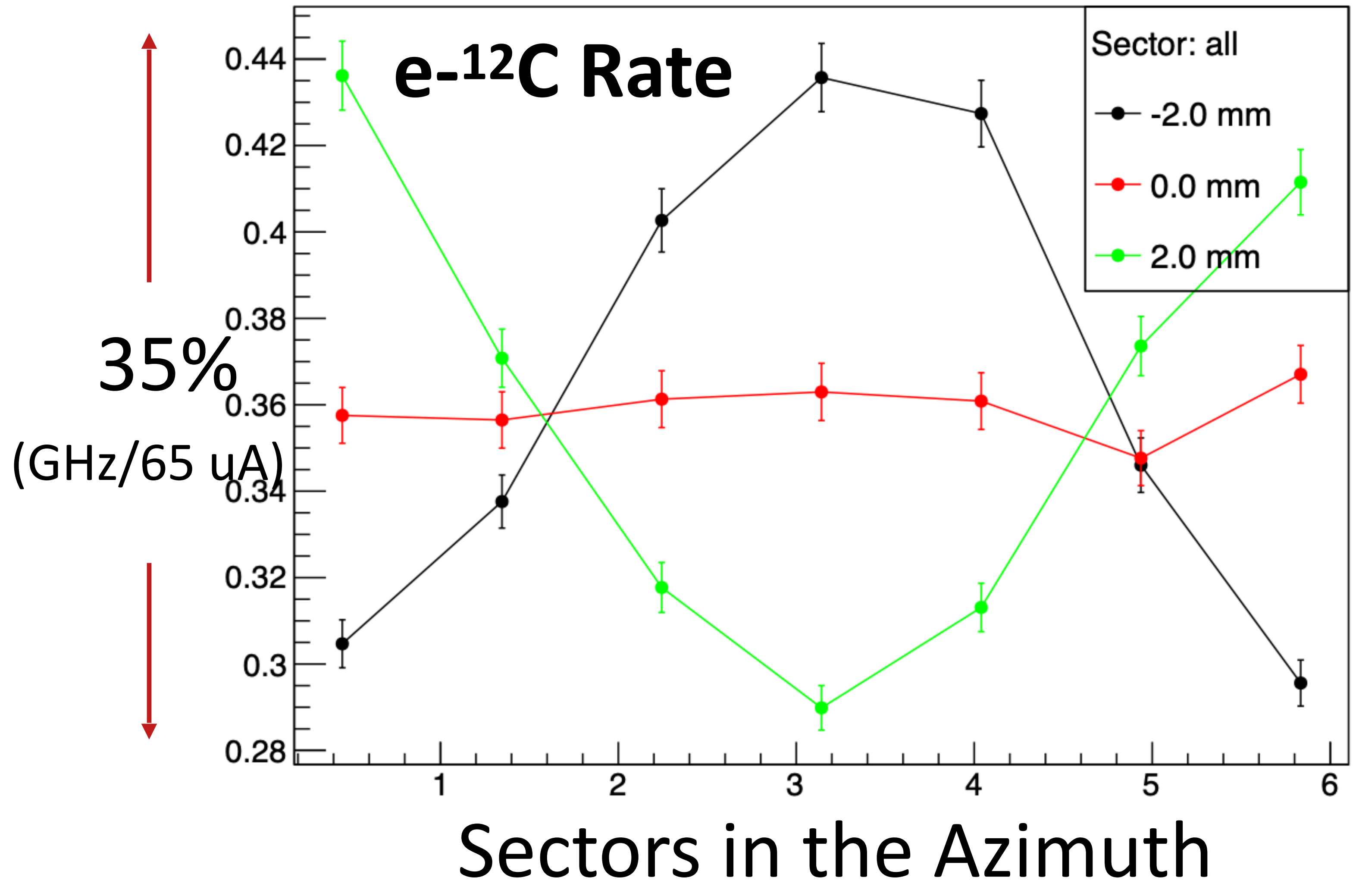
Z-axis is beamline

Collimator 1 / 2 axis 1mm from ideal beam; All else follows

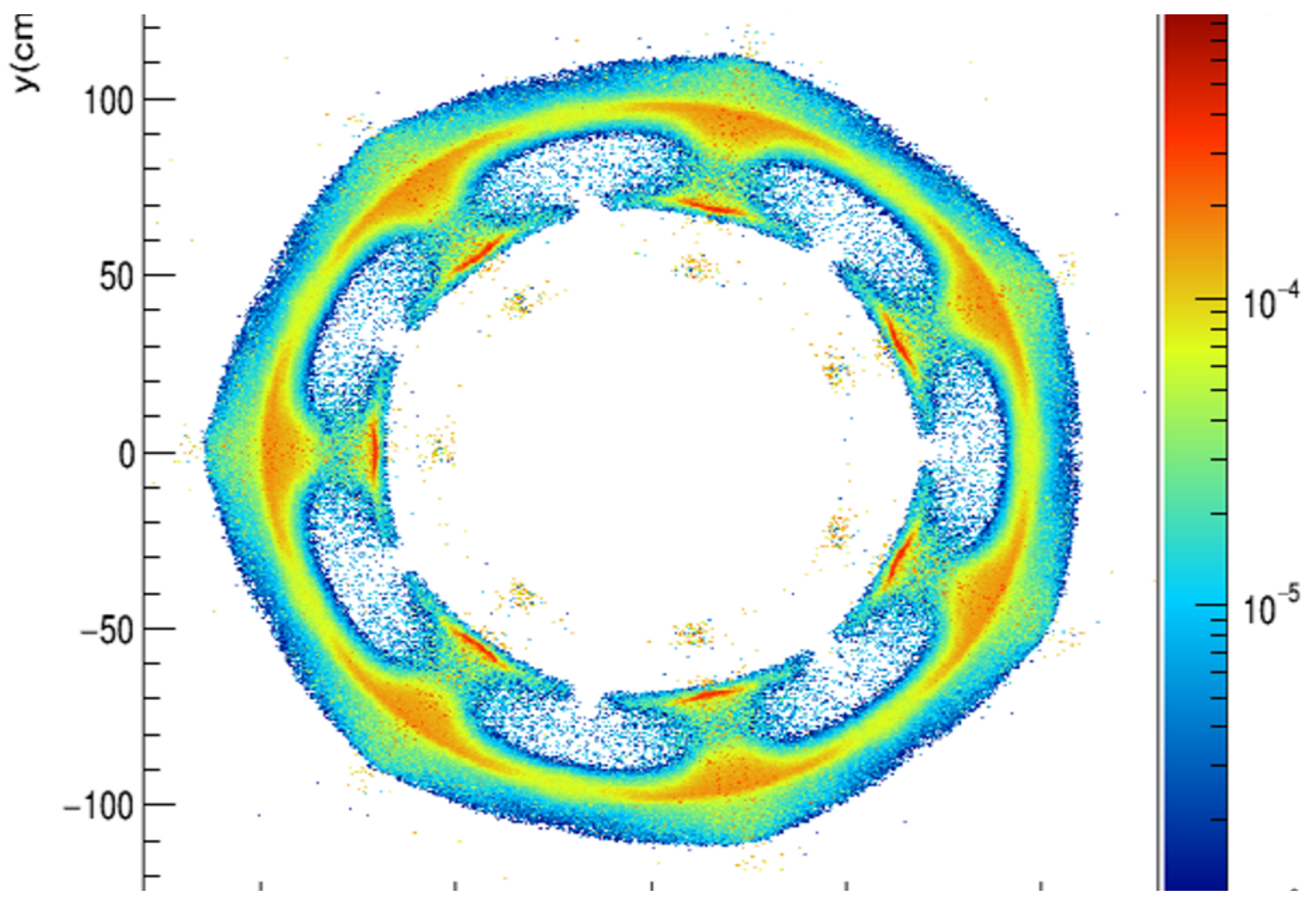
- The main physics measurement is $A_{PV} = K \times F_{kine} \times Q_W^e$; $A_{meas} = K \times \langle F_{kine} \rangle \times Q_W^e \times P_L$
- The factor $\langle F_{kine} \rangle$ is evaluated via tracking measurements in-situ
- Main discovery in simulations: the systematics of $\langle F_{kine} \rangle$ 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

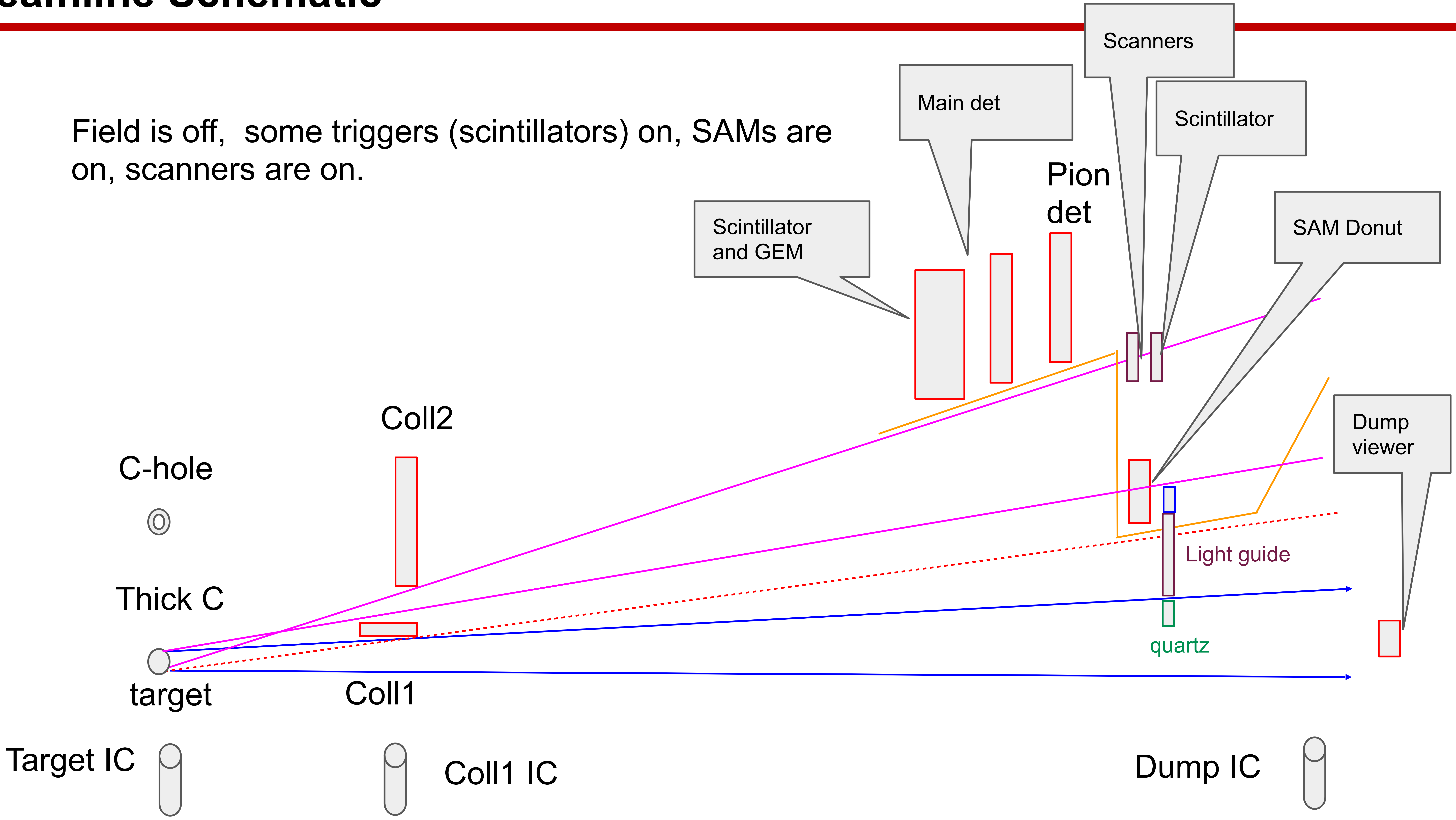


Transverse Plane 26 m from target

- The top left plot is effectively F_{kine} ; one can see the modulation for 2 mm is < 3% peak to peak. A 1 mm modulation gets averaged out such that the systematic error is < 0.5%
- The middle plot shows the 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
- The tracking system is capable of counting at low current and a thin target; systematic control of relative rate over the azimuth is required at the 2% level. This could also be measured by counting in the ring 2 main detectors.

Beamline Schematic

Field is off, some triggers (scintillators) on, SAMs are on, scanners are on.



Outline of Beam Trajectory Alignment

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 target, with SAM trigger, to establish target position. Should be within 1mm of ideal.
3. **Align Collimator2 acceptance channels and Collimator1 center, with fields off**
   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.
4. **Acceptance Tuning (Spectrometer fields on)**
   - Use rate distribution response to beam position to more carefully align Collimator 2 acceptance
   - Beam line response measured at same time (SAMs): can be used to tune position vs angle, if needed
5. **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

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
- initial GEM parameter commissioning data
- count Ring 2 with quartz
- beam movement, count Ring 2 variations
- complete “neutral axis” studies
- all detectors: LAM, SAM, pion det, Shower max
- LH2 target commissioning with low current
- Rate measurements with LH2
- Exercise moving collimators
- 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.

We must assume there is no going back.

- 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

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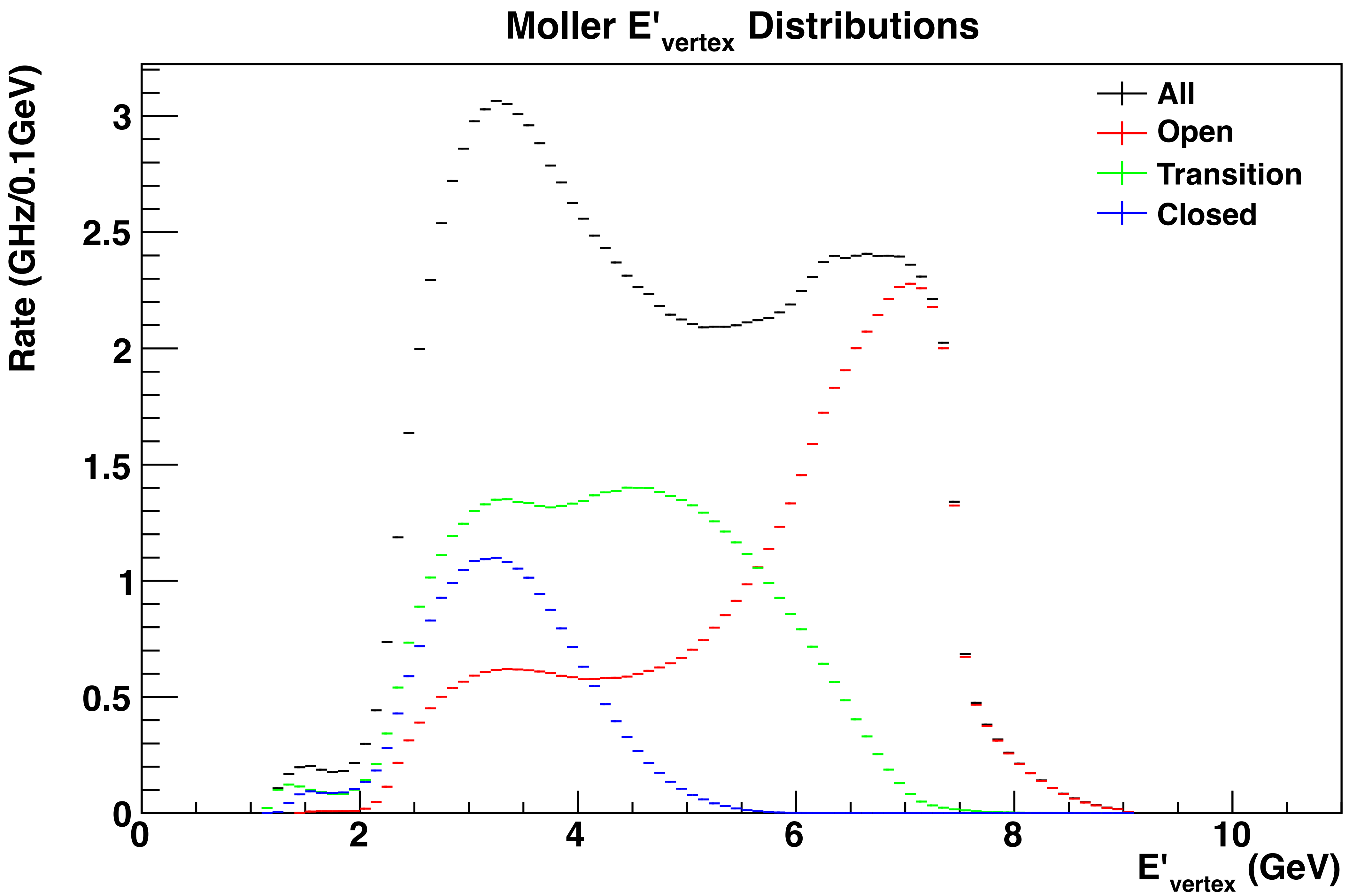
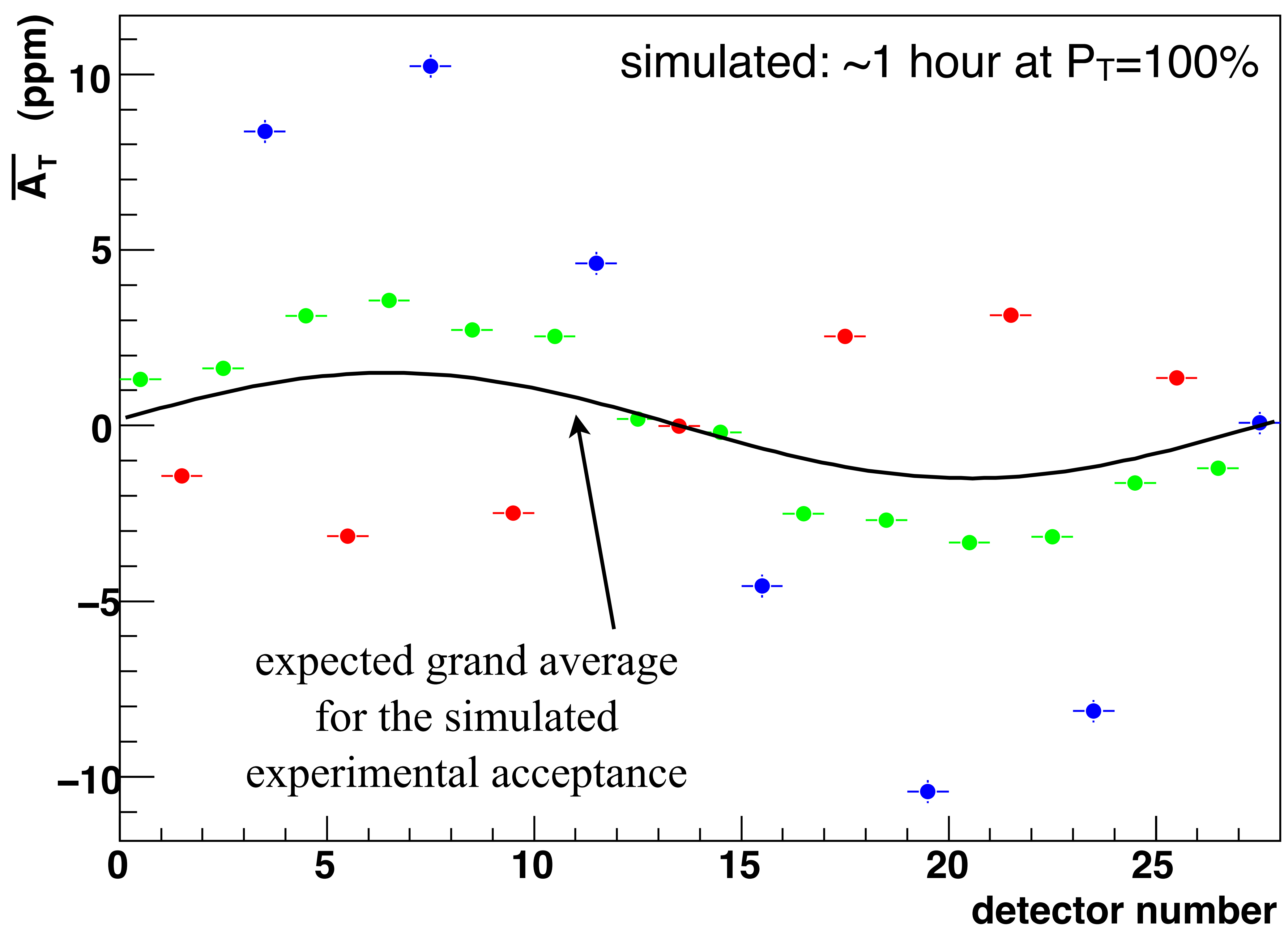
Ideally, in “early” to “not-so early” production running we would test our ability to measure asymmetries and expected correlations between elements of our detector

Transverse polarization provides this opportunity

Measured and calculated for *ee* scattering



Average transverse asymmetry



- •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

High current commissioning

Commission: ~1 week At 5 pass / 11 GeV, up to 65 uA

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

A_T calibration: ~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 strictly necessary before transition to high energy
- 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

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

Backup

MOLLER Run Phase

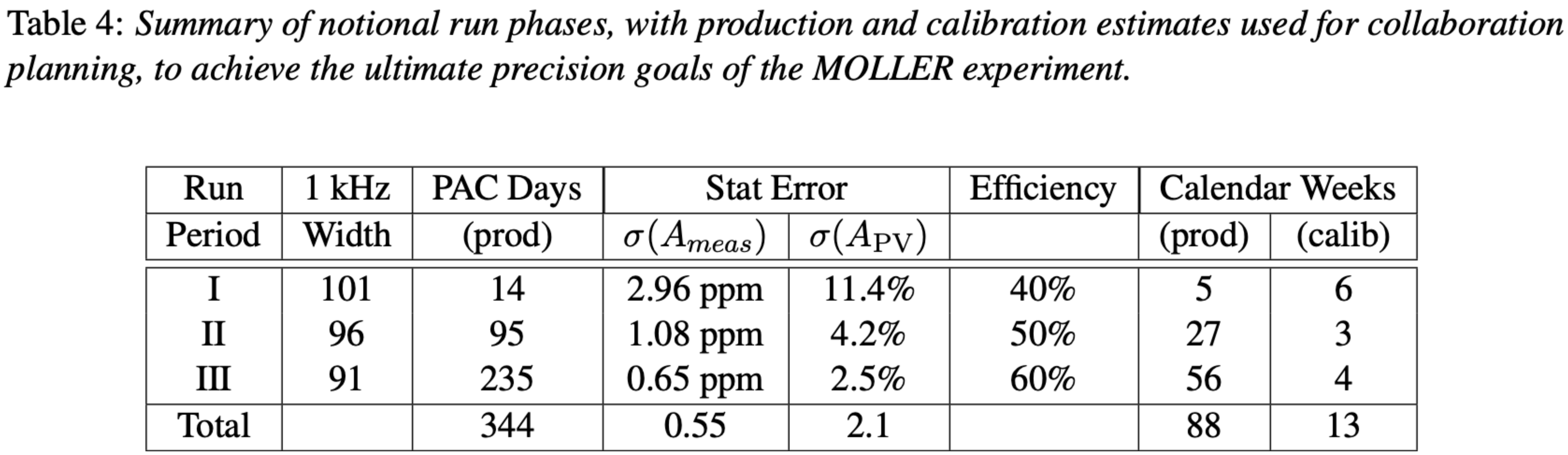


Table 4: *Summary of notional run phases, with production and calibration estimates used for collaboration planning, to achieve the ultimate precision goals of the MOLLER experiment.*

Run	1 kHz	PAC Days	Stat Error		Efficiency	Calendar Weeks	
Period	Width	(prod)	$\sigma(A_{meas})$	$\sigma(A_{\text{PV}})$		(prod)	(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

JLab Experimental Readiness Review process

1) Design Phase:
   - Before construction phase starts
2) Construction Phase: Before a scheduling request
   - Design of the equipment is finalized and manpower and resource requirements for equipment fabrication and installation are identified.
   - After this review, the experiment layout and components are considered frozen, and any design modifications will require approval by the Division Management.
3. Equipment Installation: Before running the experiment
   - The experiment is ready to be safely and effectively executed.

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