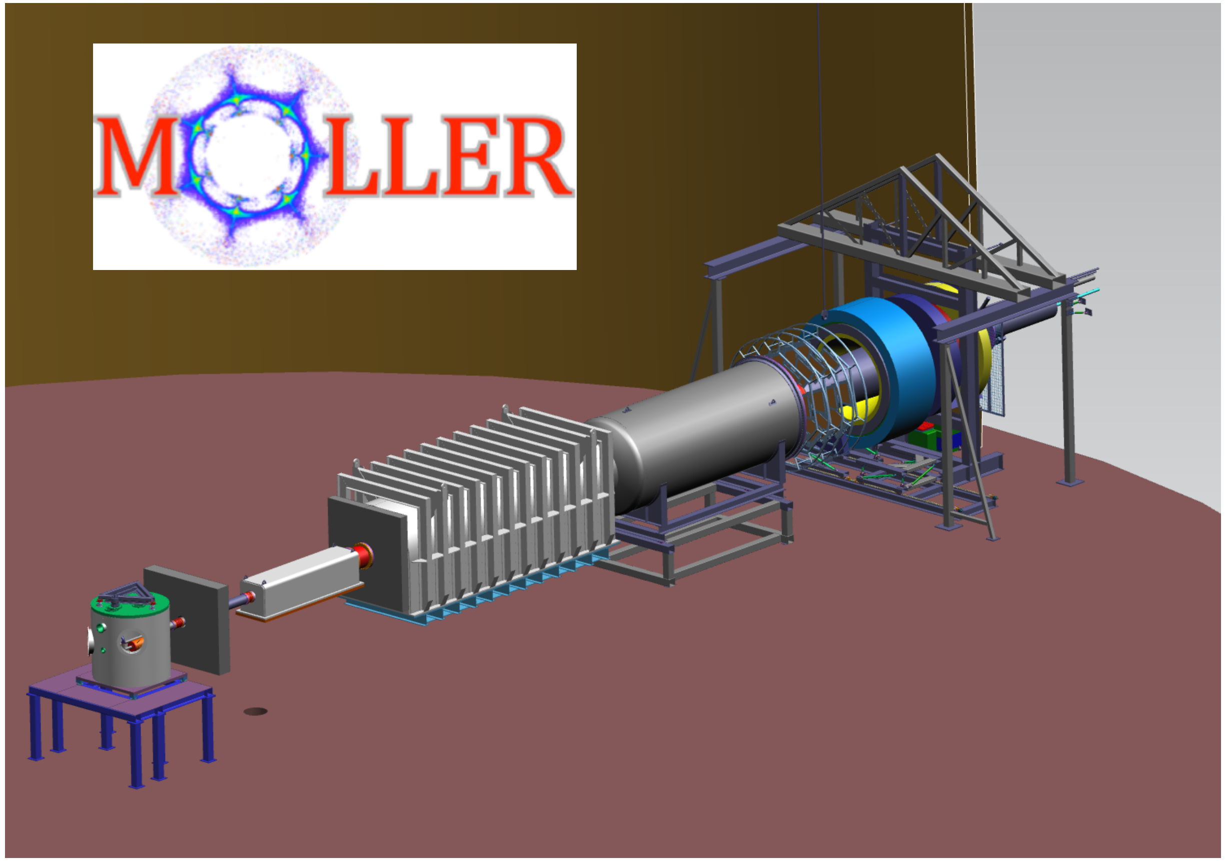
MOLLER Science

Impacts on Design and Engineering



Kent Paschke - Scientific Coordinator – U. Virginia

High Precision Measurement

$$A_{PV} = \frac{\frac{A_{expt}}{P_b} - f_b A_b}{1 - f_b}$$

$A_{expt} \sim 26$ ppb

$\sigma_{expt} = 0.54$ ppb

$\frac{\sigma_{expt}}{A_{expt}} = 2.1\,\%$

- Support high luminosity
- Maintain acceptance and normalizability
- Control noise
- Avoid potential “false” asymmetries

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

$$\sigma_{A_{expt}} = \frac{\sigma_{\mathtt{pair}}}{\sqrt{N}}$$

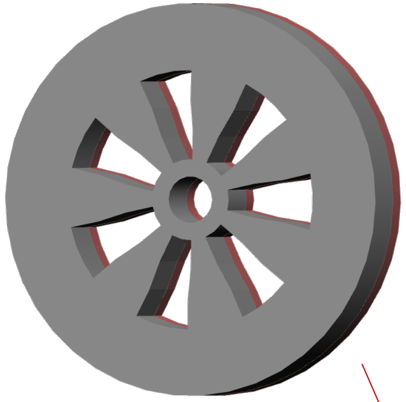
$N_{pair} = (8.3x10^7)\, N_{days}$

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**

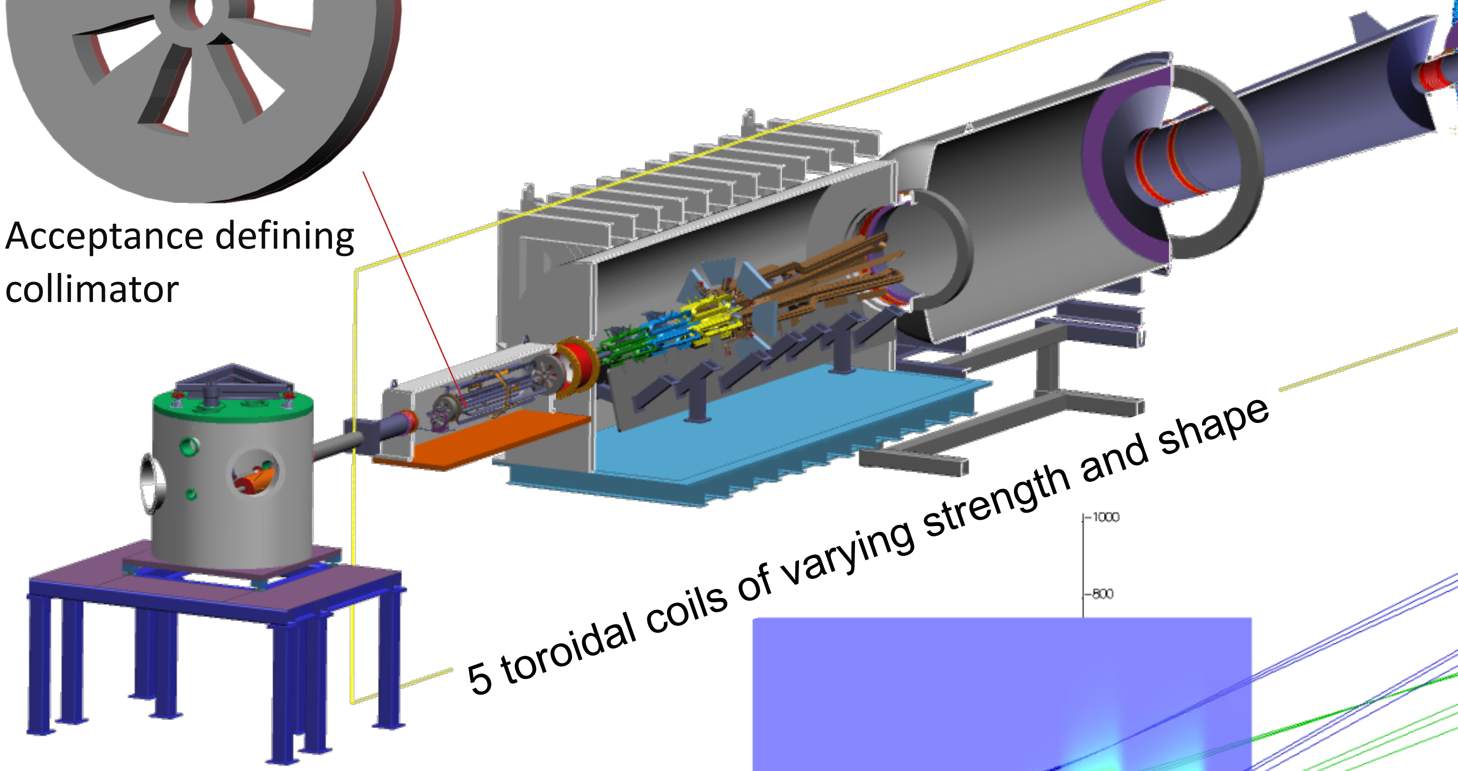
Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Norm. of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \to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

MOLLER Spectrometer

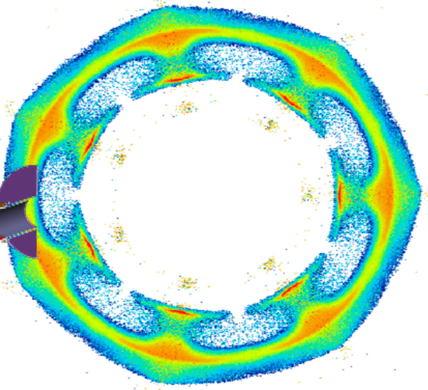
Full azimuthal acceptance for Møller scatters from 6 < θ_{lab} < 20 mrad

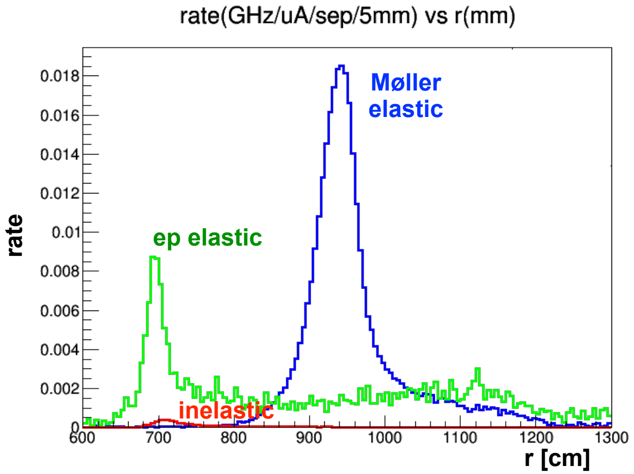


Acceptance defining collimator

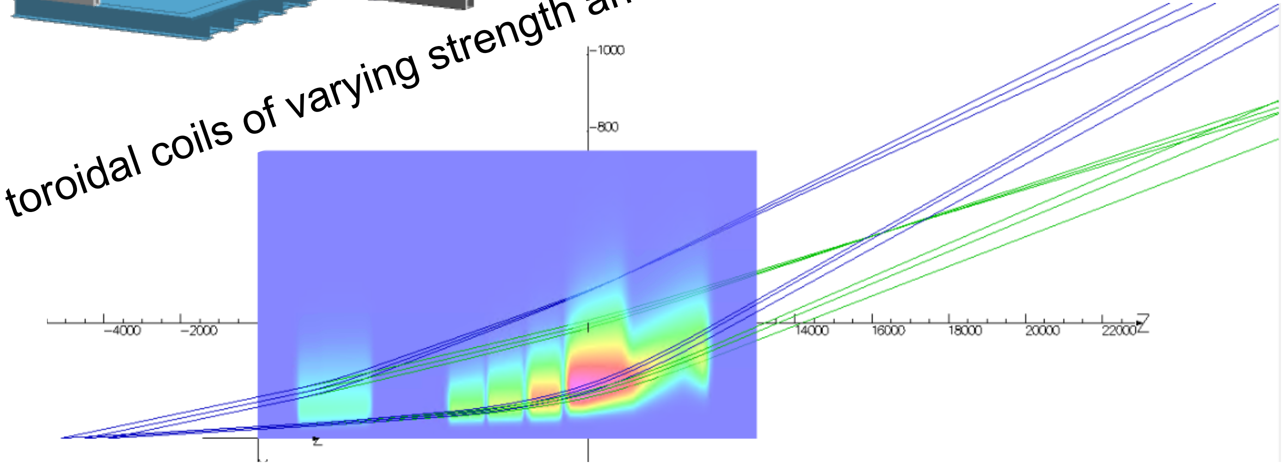


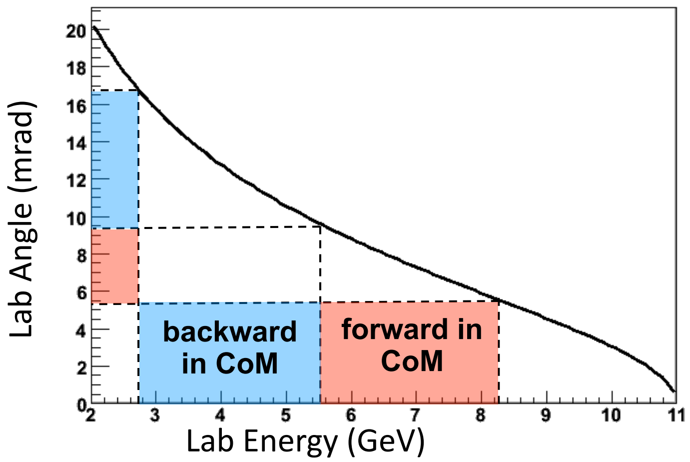
5 toroidal coils of varying strength and shape





radial field component focuses the smaller angles and stretches the larger angles over the azimuth

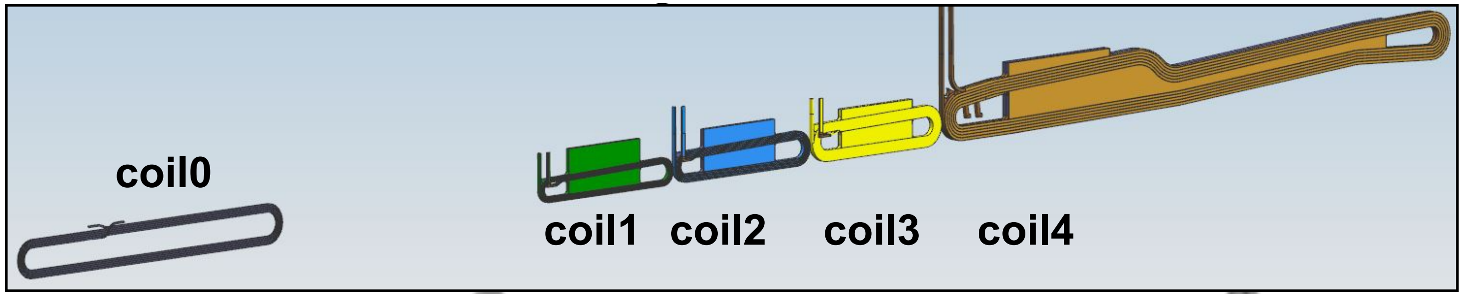


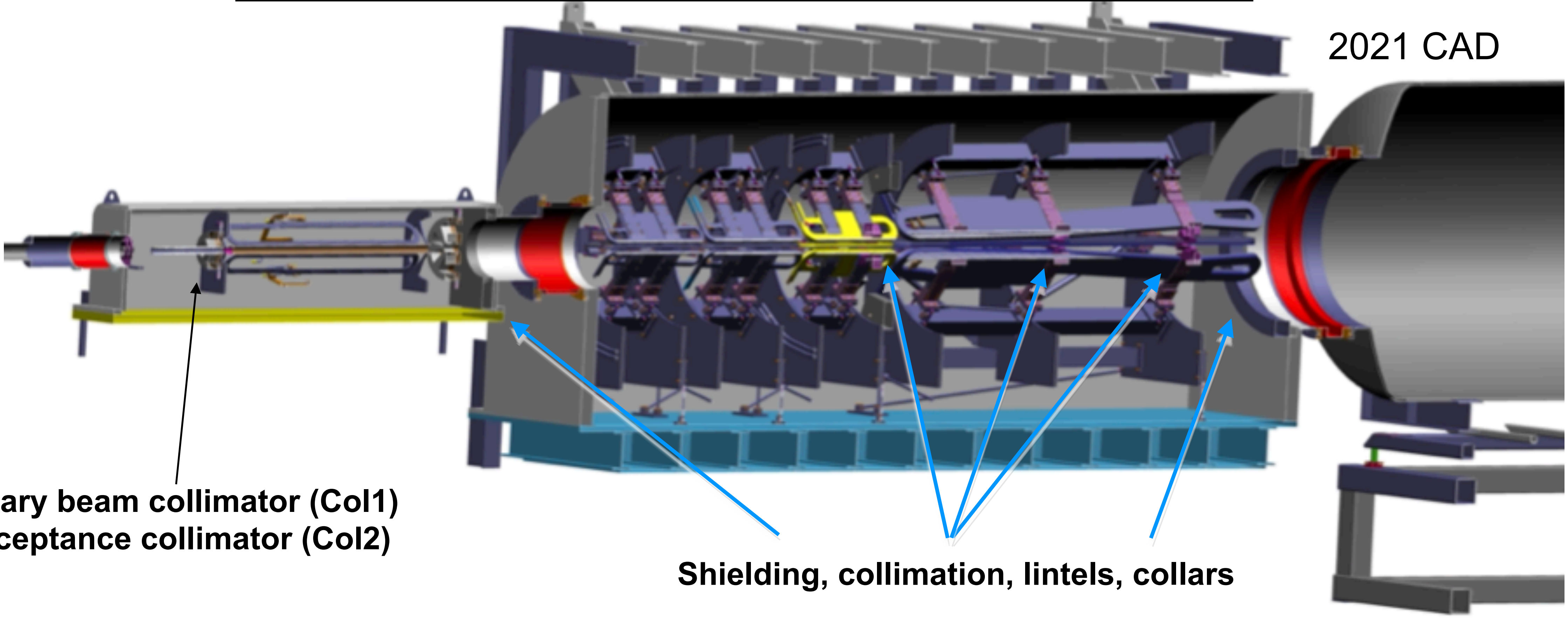


map E-θ correlation for ee scattering to detector

Spectrometer Outline

This will be detailed in the Spectrometer presentation




2021 CAD

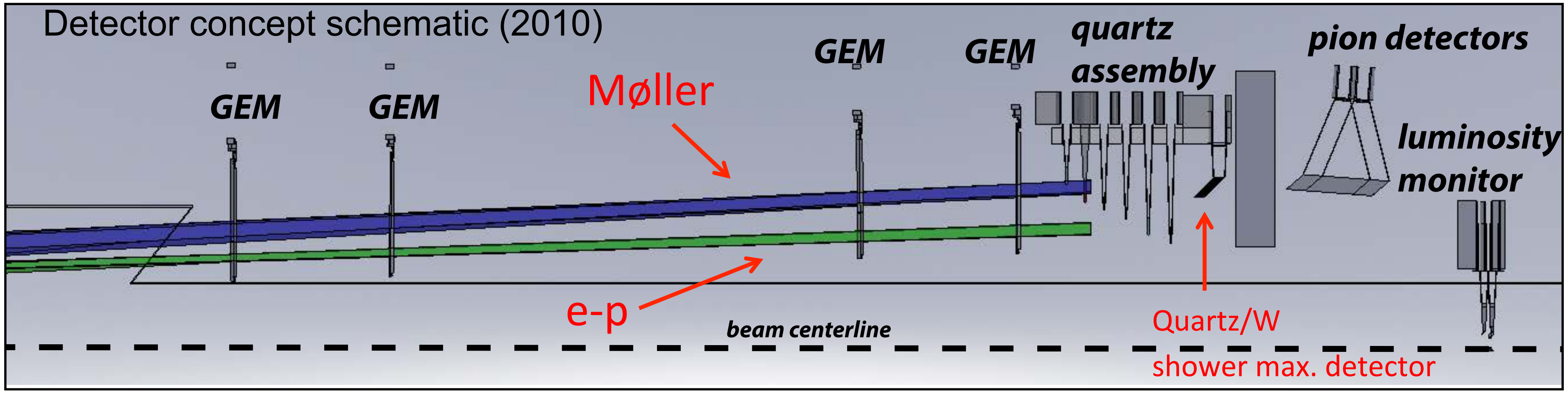
primary beam collimator (Col1)
+ acceptance collimator (Col2)

Shielding, collimation, lintels, collars

Detectors

Integrating mode: asymmetry measurement

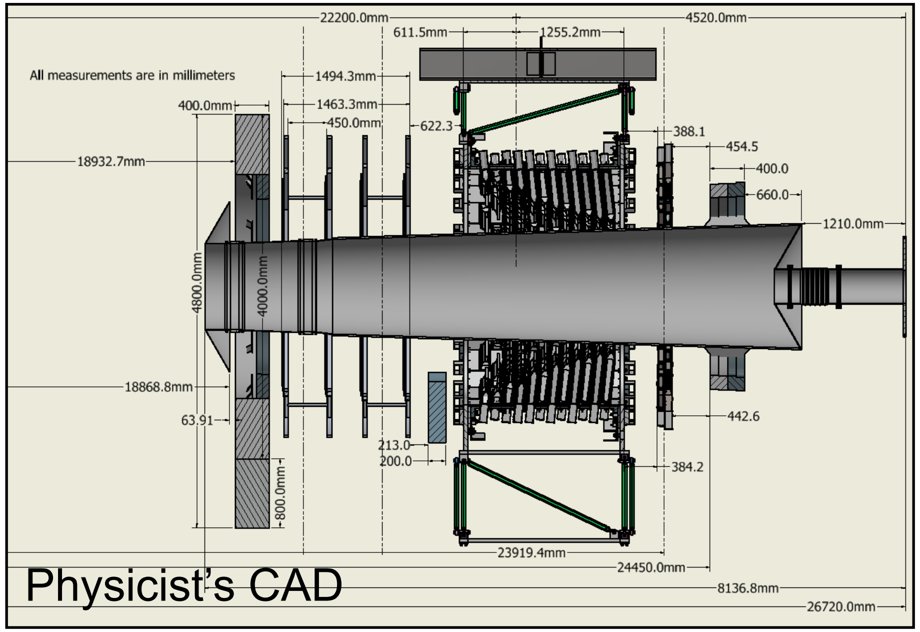
Counting mode: counting/tracking for calibration


Detector concept schematic (2010)

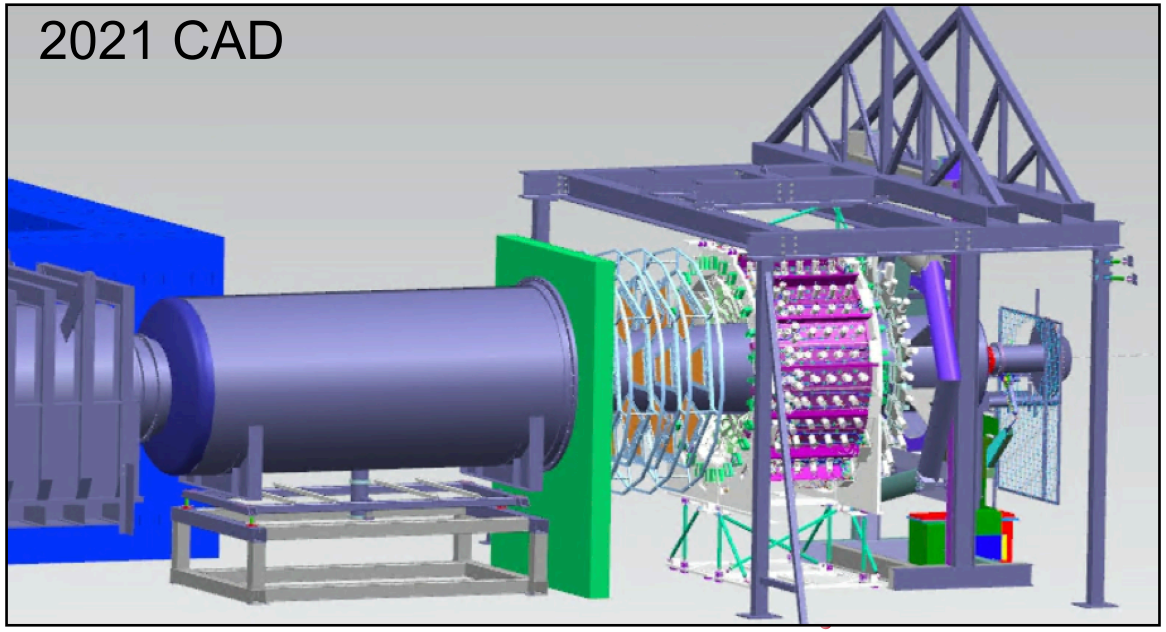
Dedicated weekly meetings alternate between detector and mechanics

- Compact region
- Clear signal path before detectors limits support points

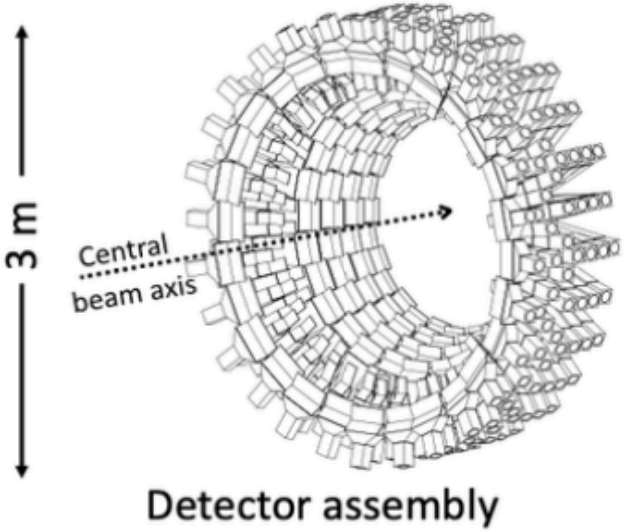
Details are in the Detector presentation

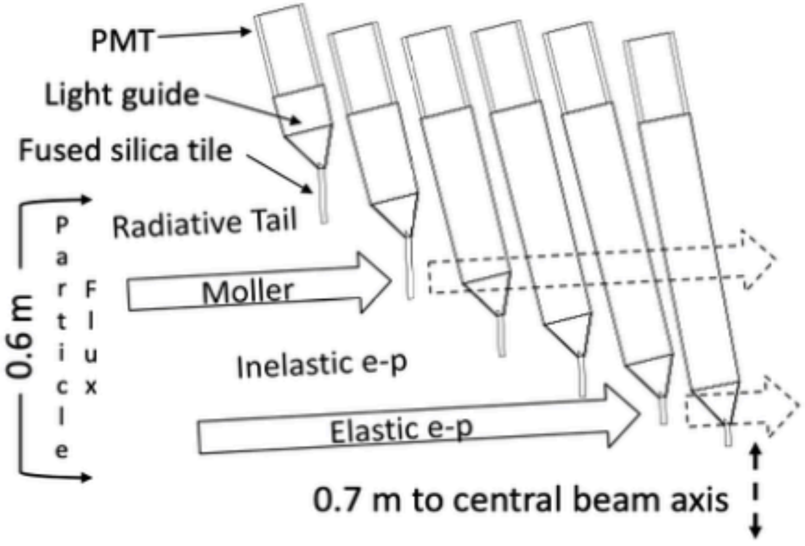


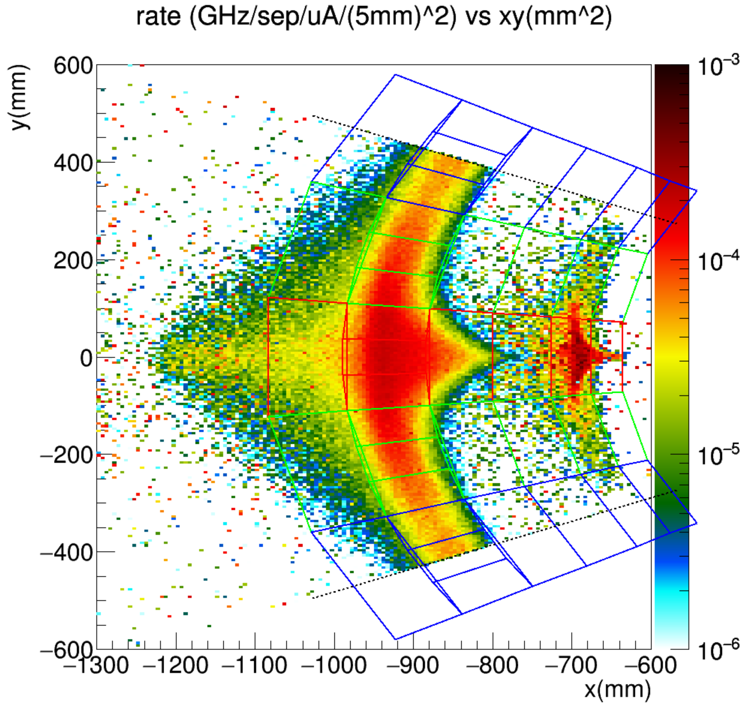
Physicist's CAD

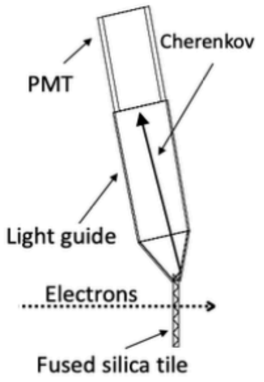

2021 CAD

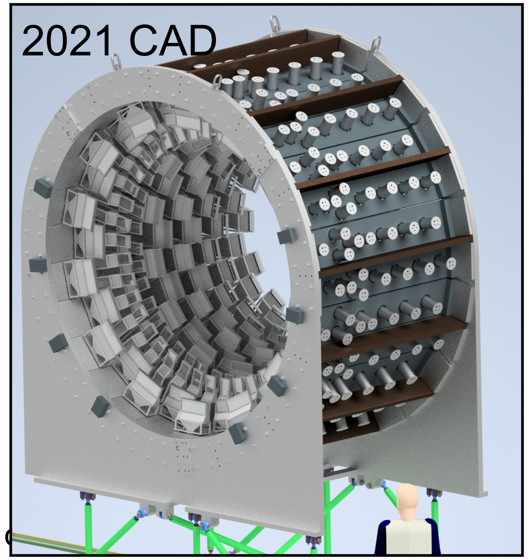
Primary detectors











- Primary A_{PV} measurement uses an array of thin quartz detectors
- High level of segmentation separates irreducible backgrounds from Møller signal
- Preliminary engineering design of main detector assembly satisfies physics requirements

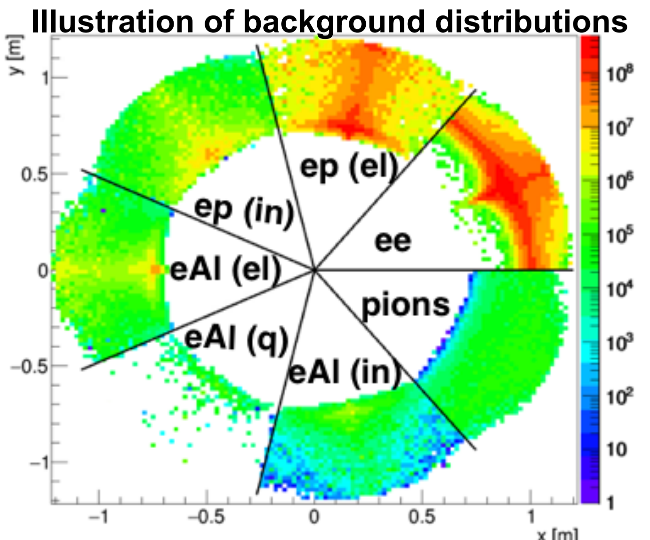
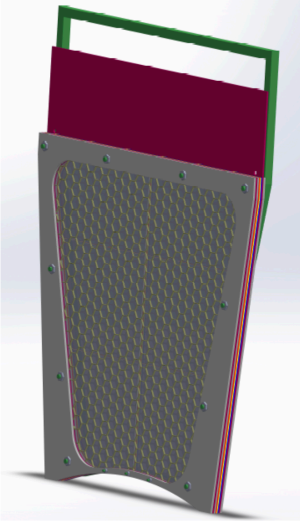
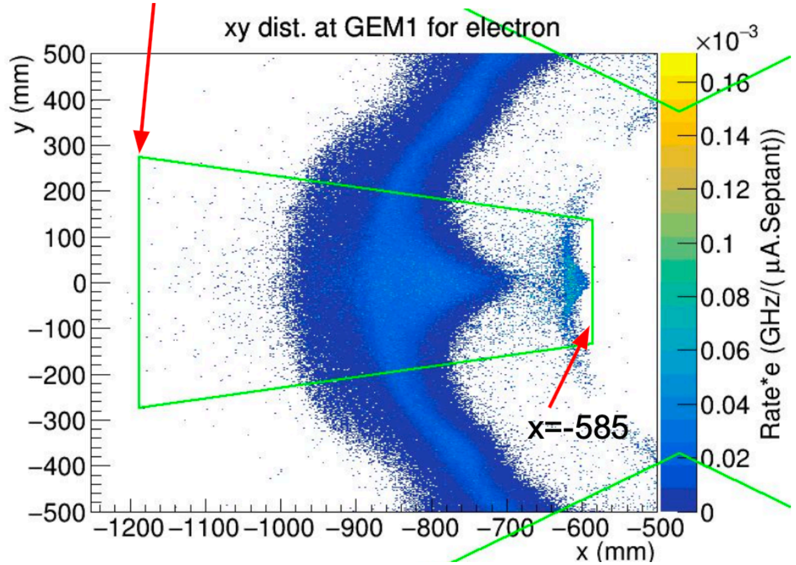


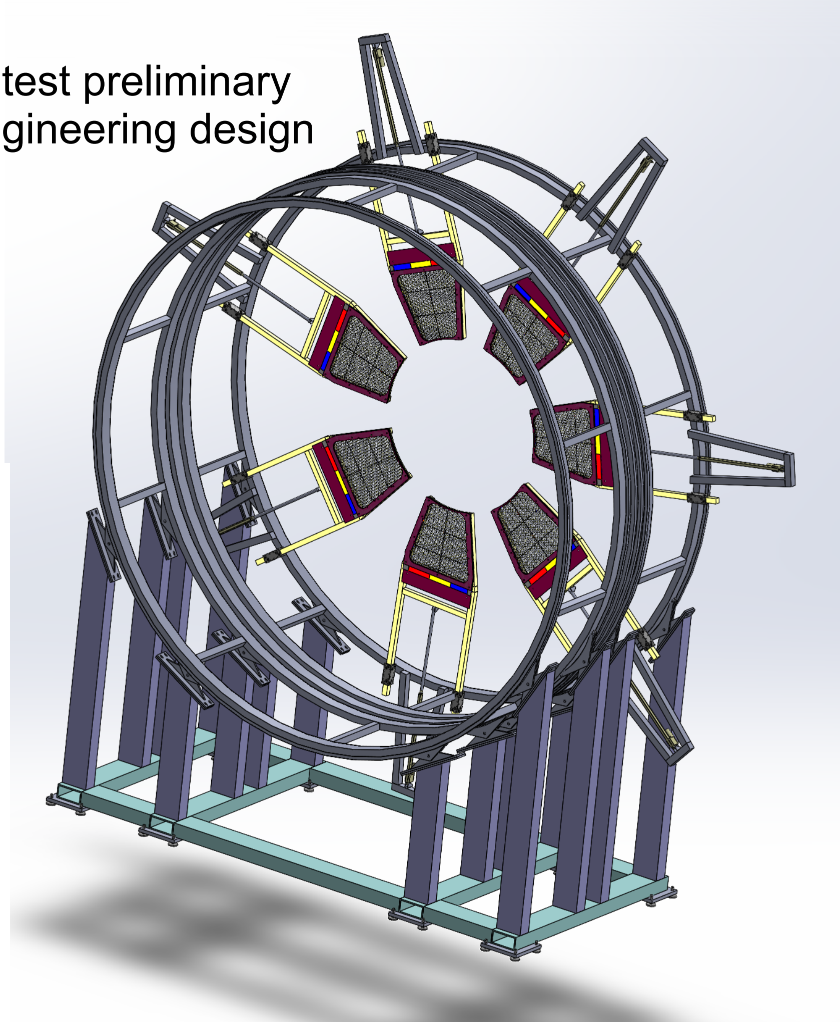
Illustration of background distributions

Tracking detectors

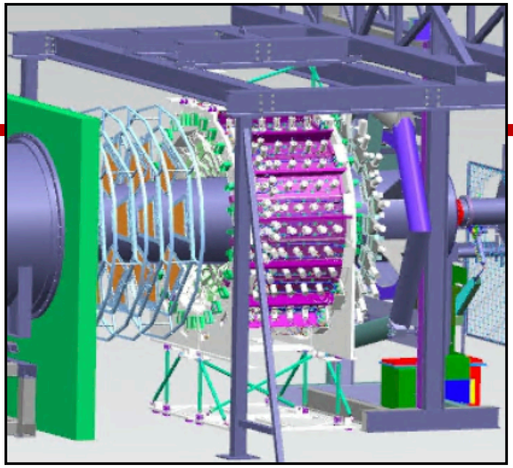
Narrow gap between conical vacuum pipe and signal inner edge
Curved inner edge of GEM chamber



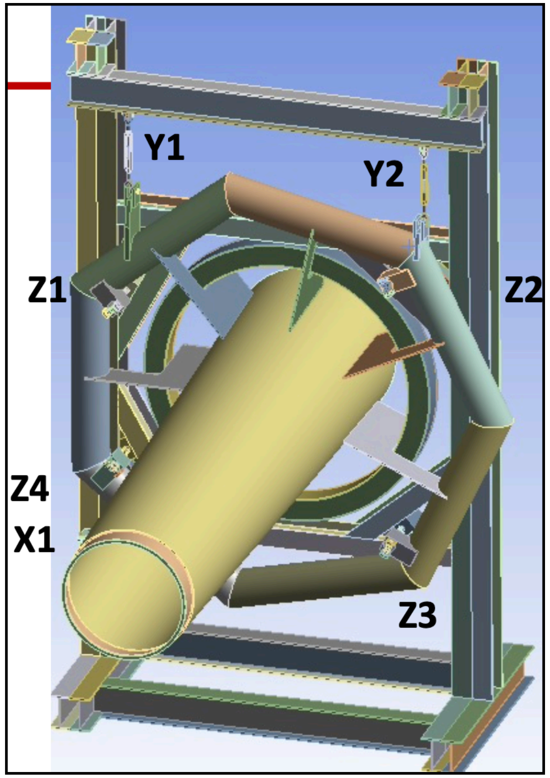




Latest preliminary
engineering design

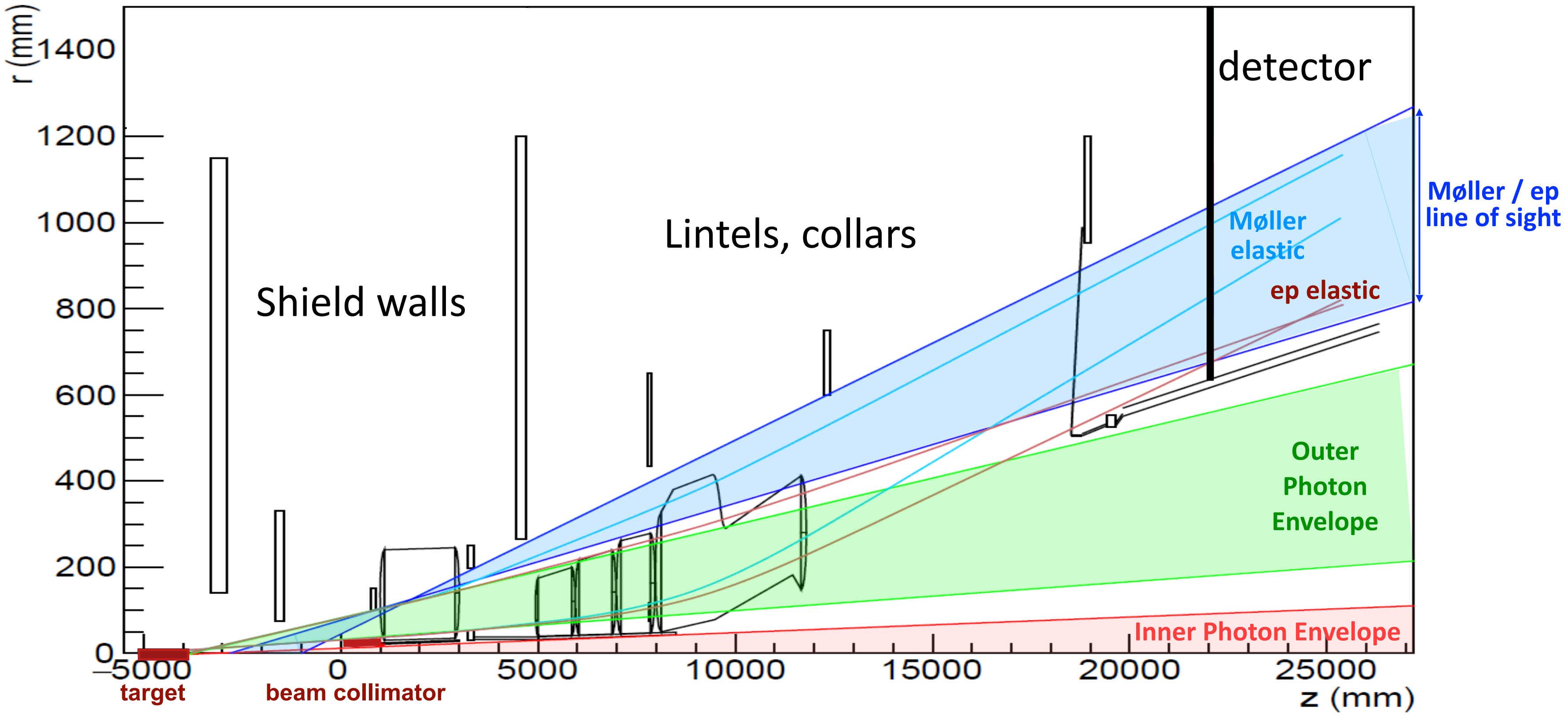


Detector region beampipe
- support at one end



see: Detector and
Infrastructure presentations

Shielding and Collimation



Irreducible background: radiated and/or inelastic ep or aluminum scattering, pions

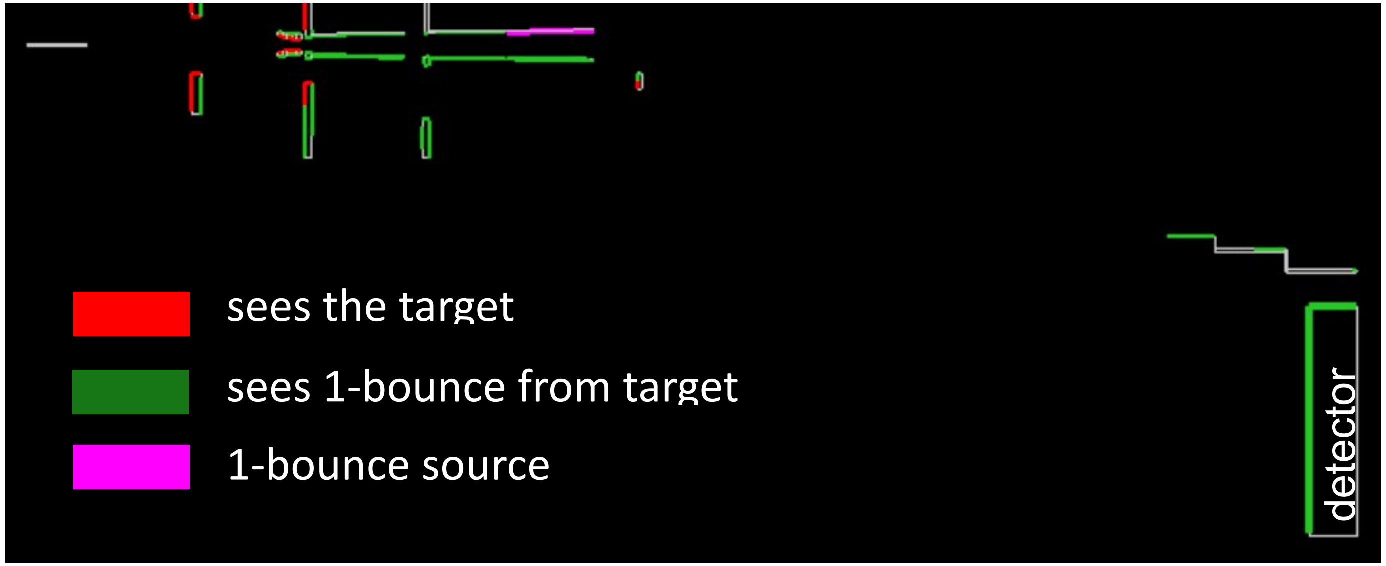
Reducible background: rescattering from photons or radiative tail *e*± from target

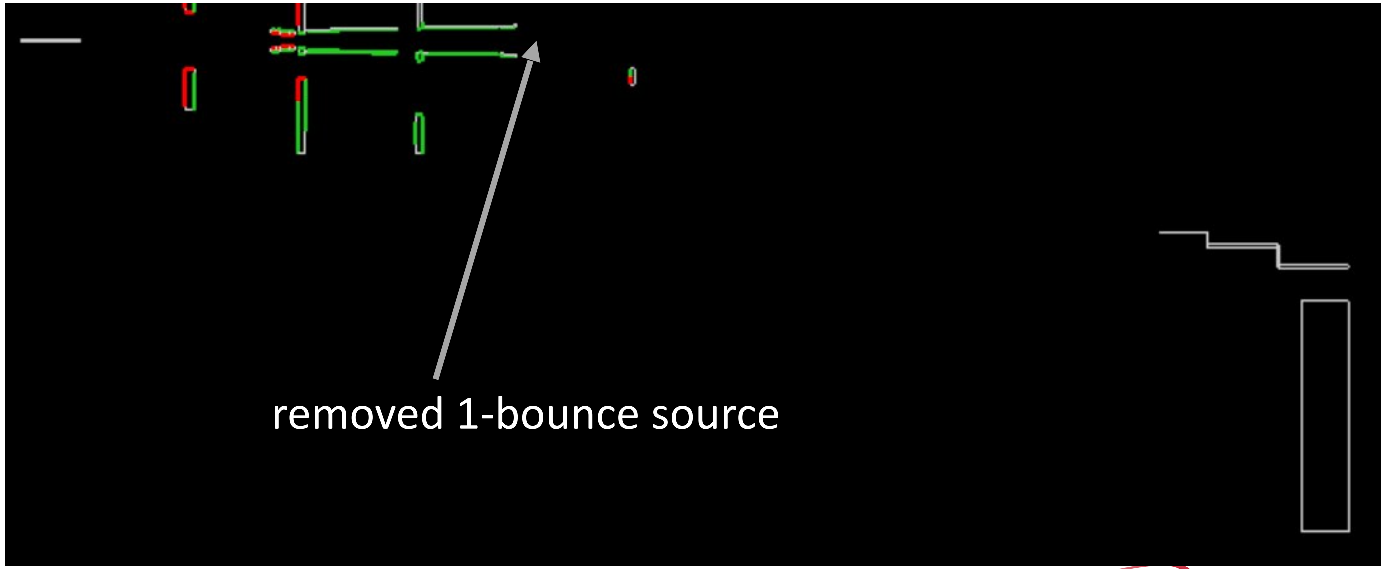
Hygiene on reducible background sources is a major focus

Relatively small “source” terms for re-scattering could create difficult-to-model backgrounds

see: Spectrometer presentation

Background Hygiene: design for “2-bounce” shielding





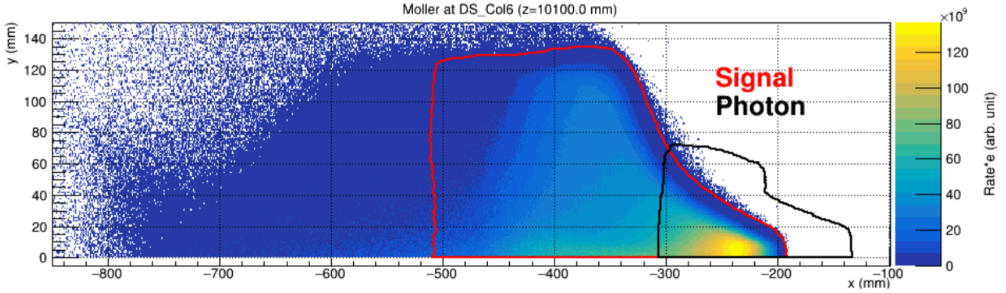
Avoid “1-bounce” line-of-sight to target

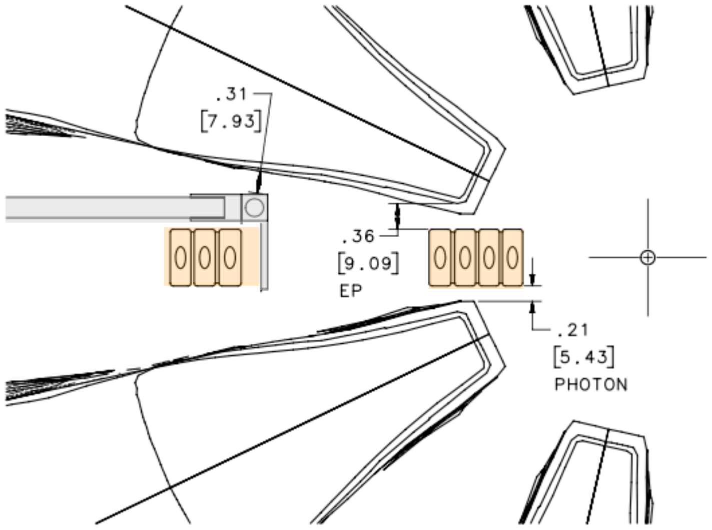
- Python code
  - Target, collar, collimators, beam shields, detector (600, 690-1300 mm)
  - Uses straight lines to simulate an isotropic source (with random position, angle)
  - Surfaces that “see” the target (red) become new sources
- Tolerance study
  - move the collimators and/or coils by +/-1 mm w/o seeing green on the detectors

Envelopes

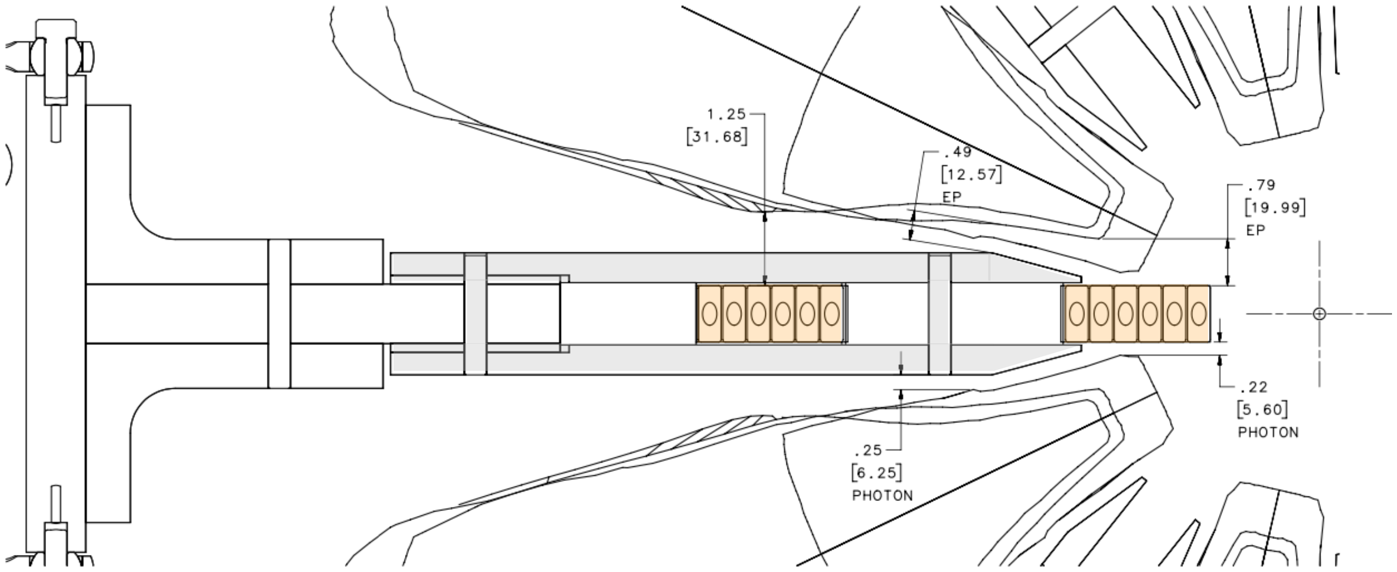
Engineering is guided by "envelopes" of *ee*, *ep*, and photon distributions as they traverse the spectrometer (demarcated at 0.1% of maximum flux).

This defines open regions for support structures, defines for tolerance for acceptance path and identifies regions of close approach for further study.





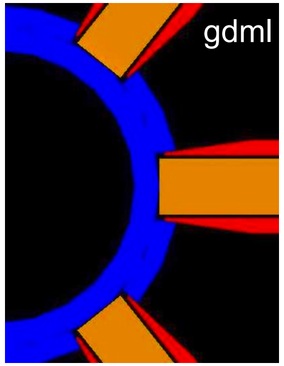
SECTION W-W
DOWNSTREAM TORUS SUB-COIL 1
APPROX. Z=4980mm



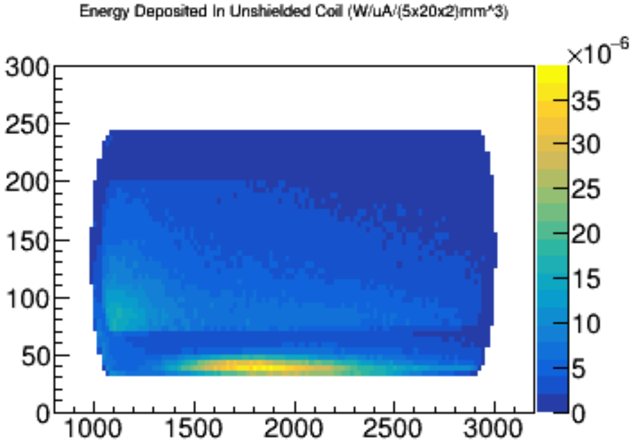
SECTION AD-AD
DOWNSTREAM TORUS SUB-COIL 3
APPROX. Z=7300mm

Shielding and Collimation Various wedges or collimation with high-Z material

see: Spectrometer presentation

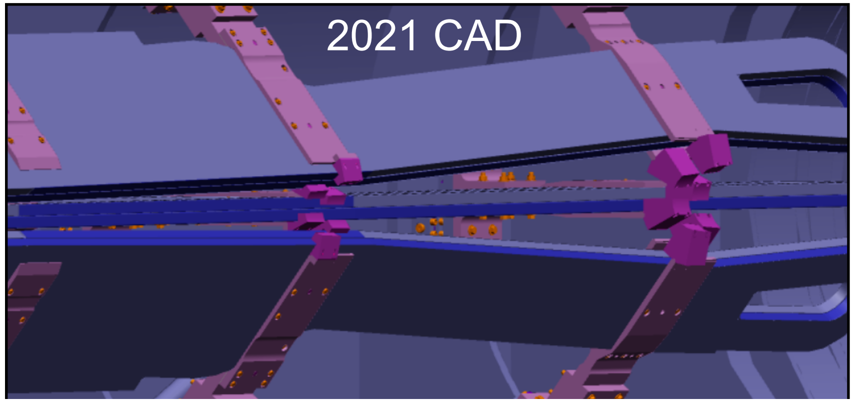


Coil 0 shield

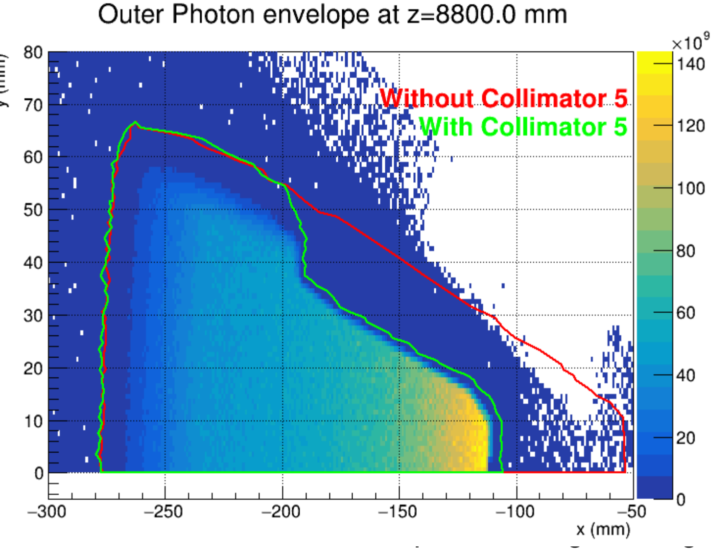


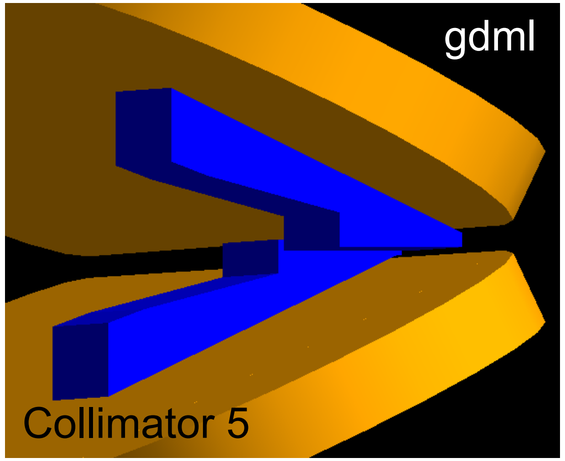
Wedges protect US Torus coils (“coil0”) from radiation dose, as low-energy e^+ from target are swept into coil through acceptance, or low energy e- swept out of beamline into coil

Collimator 6 (coil 4): Intercept off-axis scatters in beampipe that are swept out between coils by magnet fringe fields

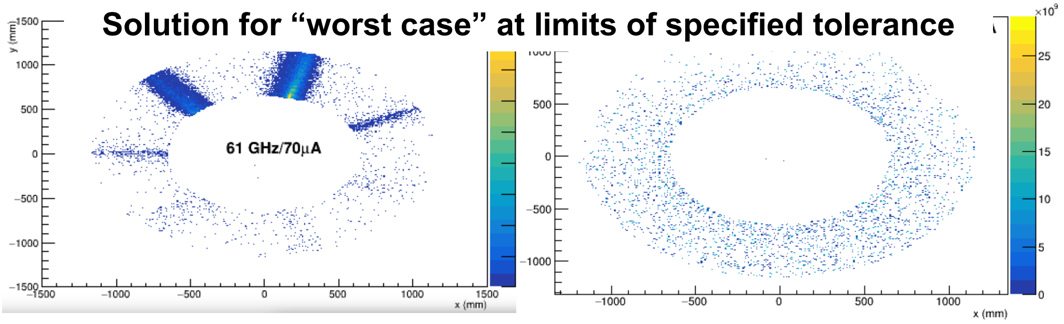


Collimator 5 (coil 3): Protect support structure from edges of photon distribution, which are not focused like the charged envelopes

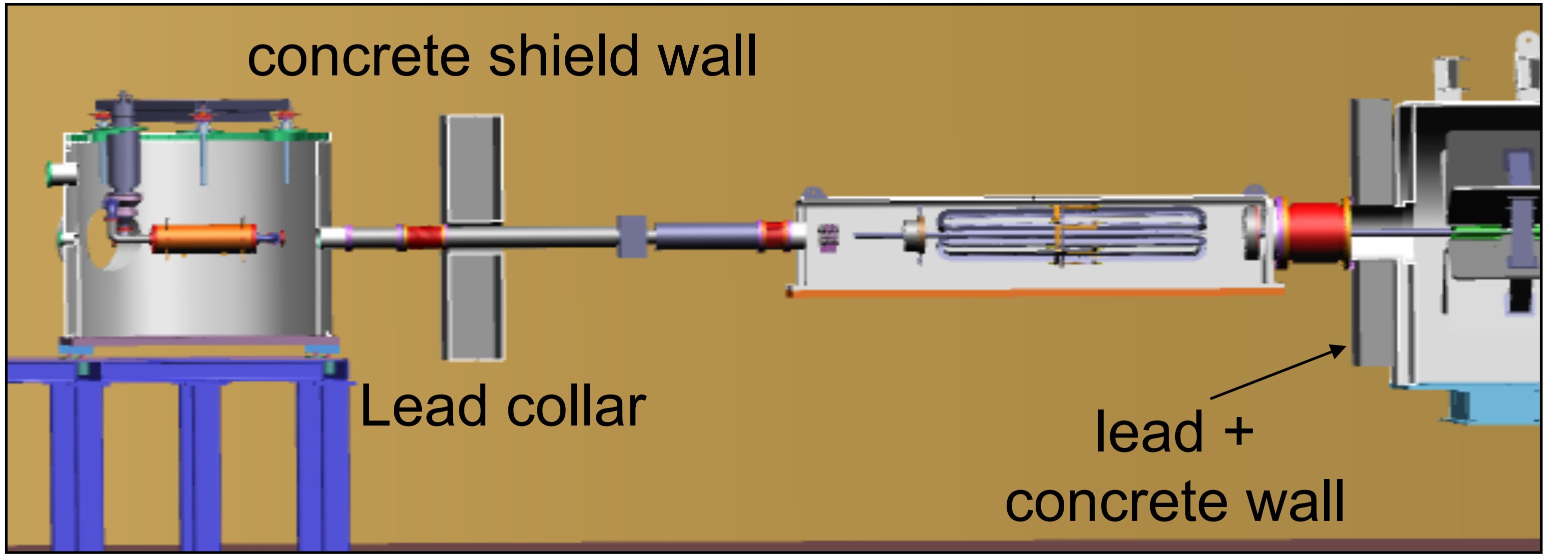


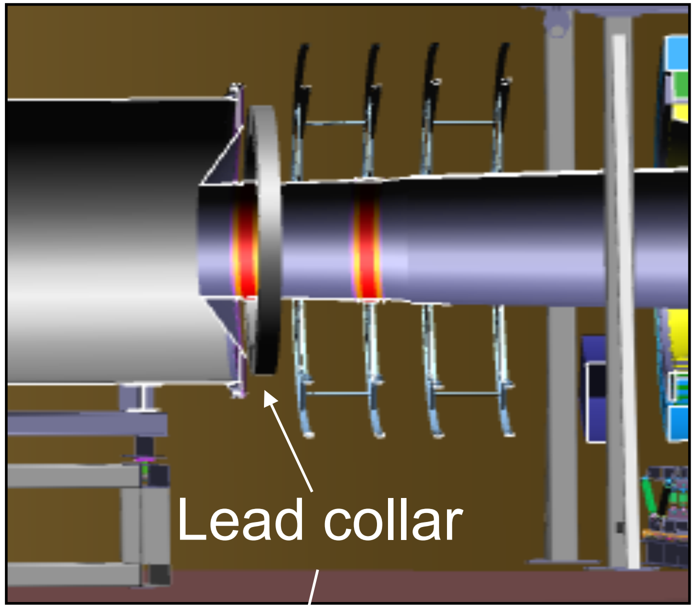


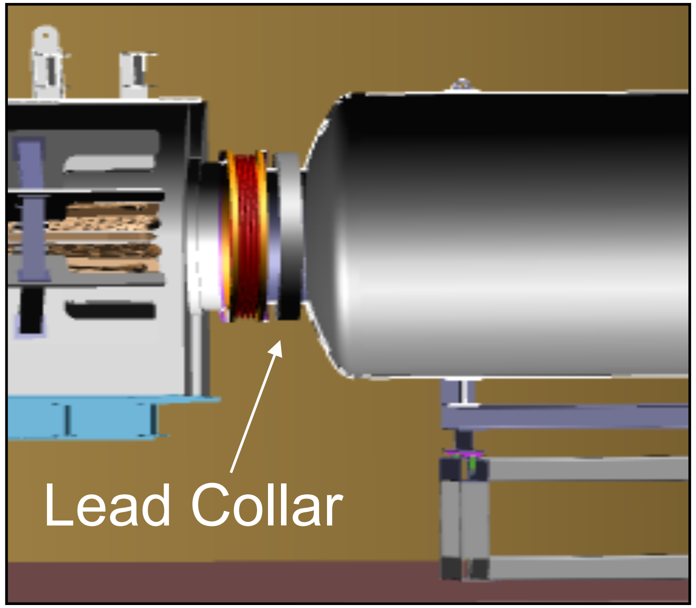
Solution for “worst case” at limits of specified tolerance



Collars and Shielding



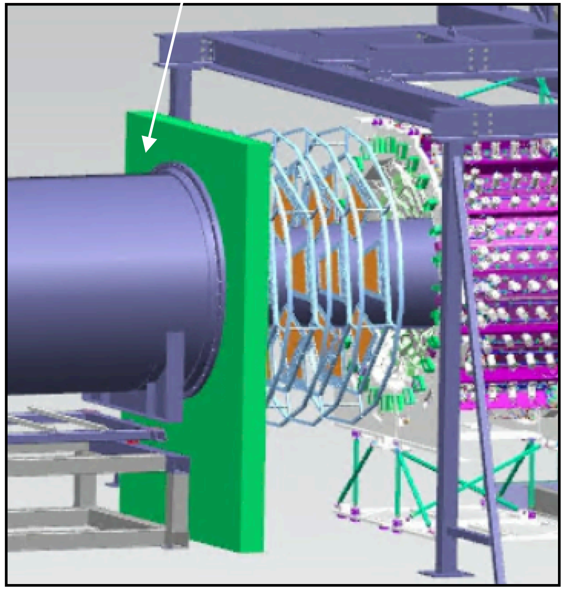




Radiated flux swept out by spectrometer, re-scatters in vacuum enclosures, support structures, etc.

Eliminated using lead collars and barite + concrete shield walls

see: Spectrometer and Infrastructure presentations



Ferrous Materials

Double-spin *ee* or *γe* scattering from ferrous material can have large asymmetry.

Estimate false asymmetry A_f as

$$A_f = f_r P_e P_s A_n$$

f_r rate fraction of process

P_e incident electron polarization

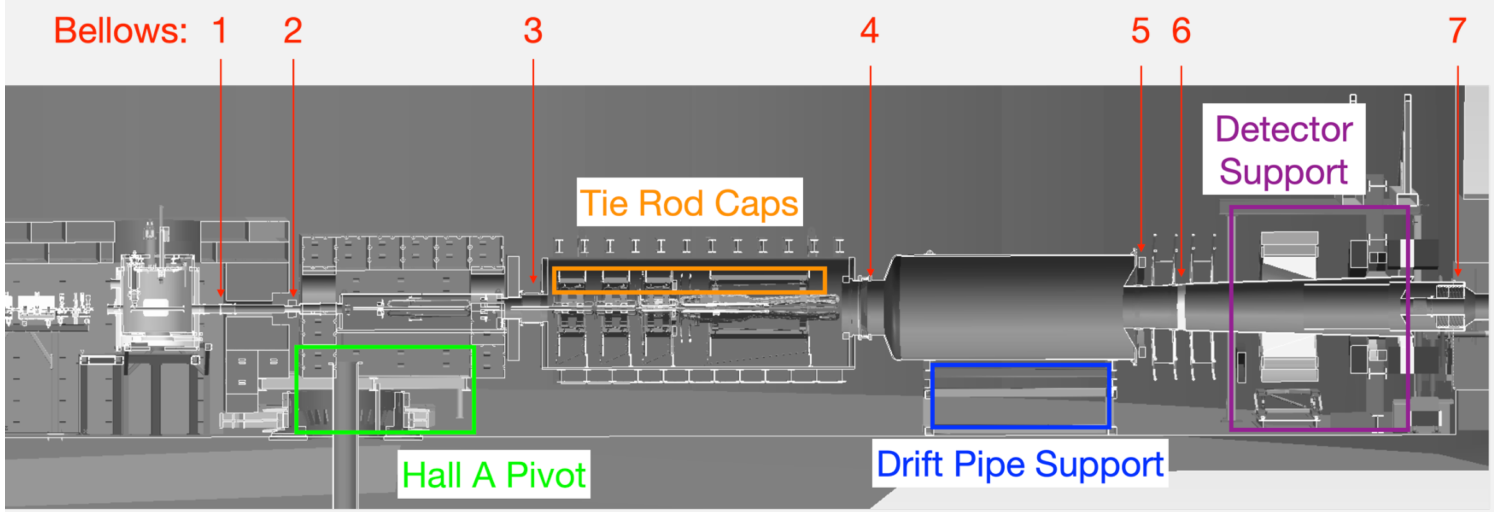
P_s material electron polarization

A_n analyzing power

Goal: $A_f < 10^{-11}$

In ~1G ambient field:

- mild steel: $P_s \sim 10^{-2}$
- Stainless steel: $P_s \sim 10^{-5} \sim 10^{-7}$
- Inconel 625: $P_s \sim 10^{-8}$
- Aluminum (paramagnetic): $P_s < 10^{-9}$



Bellows: inconel 625

Hall A Pivot, Tie Rod ends, Detector support: mild steel

Drift pipe and downstream torus support: possibly mild steel

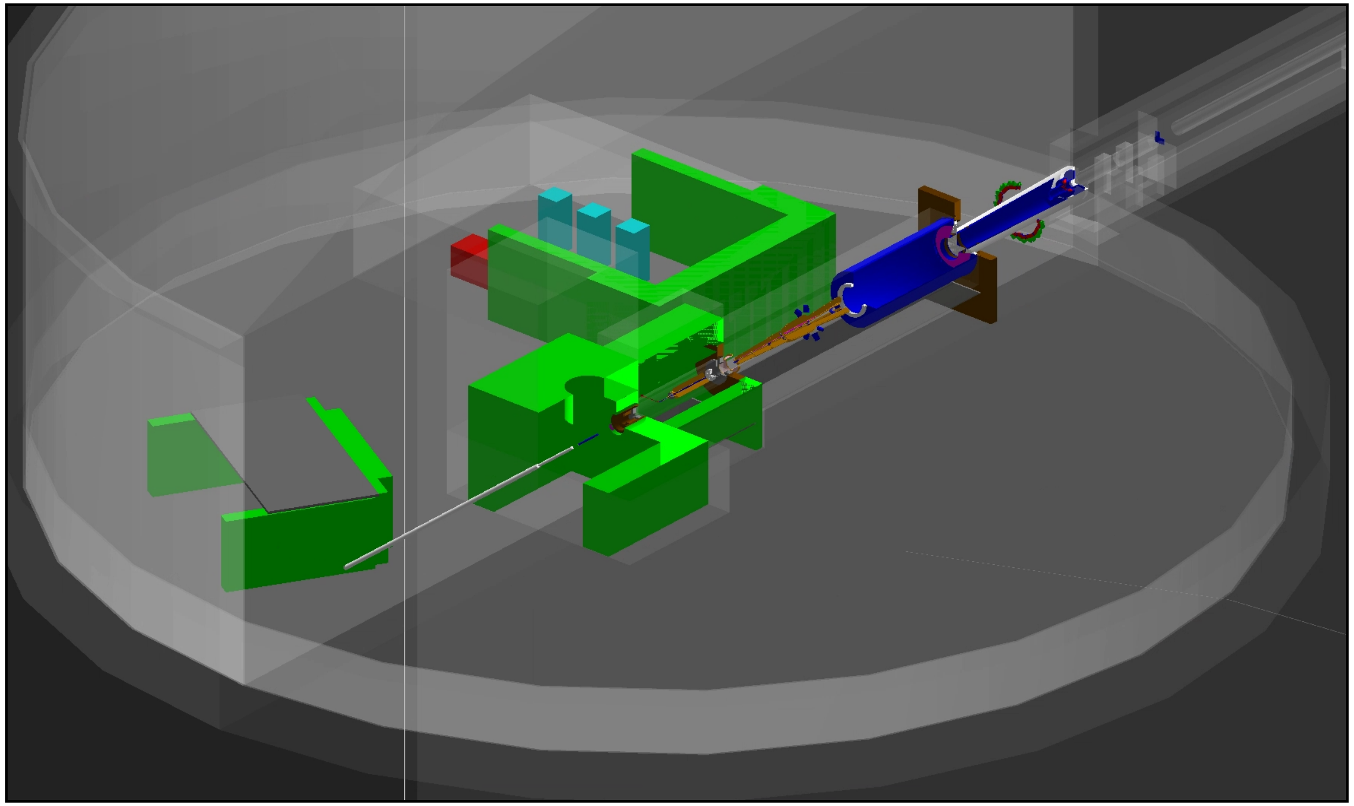
f_r bound of 10^{-2}-10^{-9} corresponds to 10^{-6}-10^{-13} absolute rate

Simulations in G4, using *ad hoc* "biasing" for rare event estimation

Guidance for engineering, using conservative estimates of $P_e A_n \sim 1\text{-}10^{-3}$

- ruled out stainless bellows downstream of torus coils
- required concrete wall downstream of US Torus and Drift Pipe

Radiation Shielding needed for High Luminosity



Dominant source is target, primary collimation, and US torus sweeping radiated flux.

Contained by shielding huts over these components

Weekly meeting on shielding

Realistic designs have been achieved incorporating with physical constraints in hall

Hall Electronics

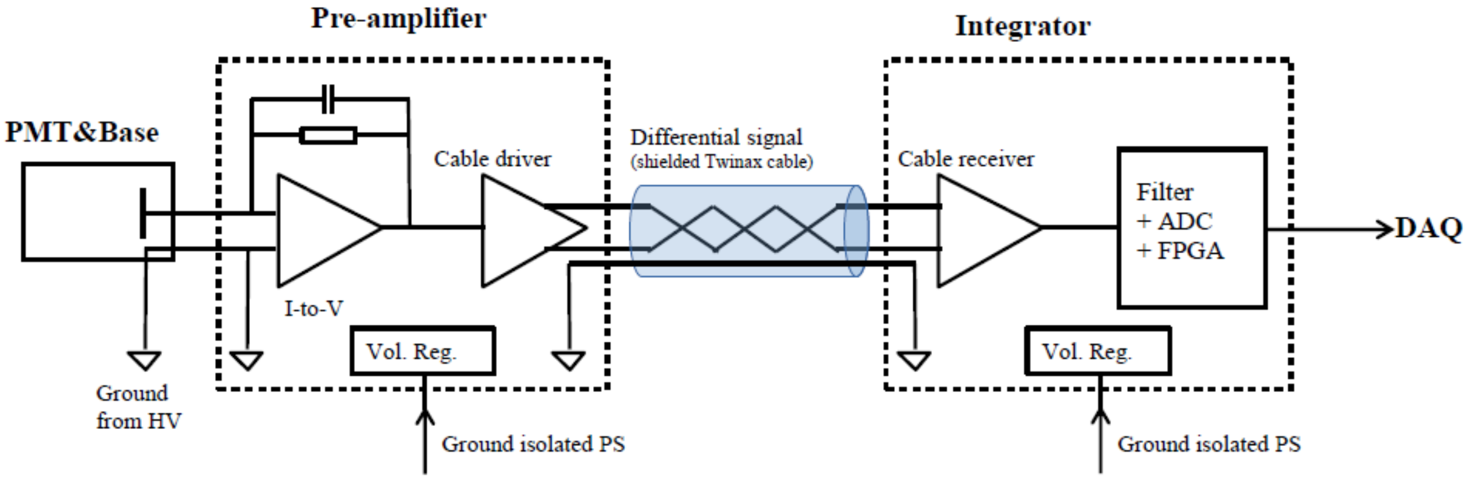
- Additional shielded enclosures for power supplies, slow controls, data acquisition, etc.
- Designed using GEANT4 simulation

Boundary dose

- High energy neutrons penetrate the hall roof overburden, rescatter in atmosphere to create dose at lab site boundary. Stringent annual limits for this dose.
- Estimates from GEANT4 and FLUKA, benchmarked to past operational experience
- Roof, downstream walls of shielding huts control this neutron flux

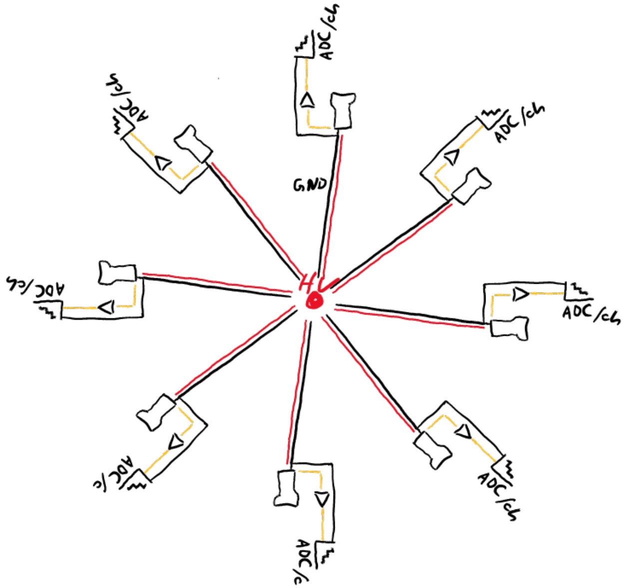
see: Infrastructure presentation

Detector Readout Electronics



Fully differential signal between preamp and integrators

hub-spoke for robust, single point grounding



Designed so that integrated pedestal and electronics non-linearity contribute negligibly over counting statistics

Low Noise Integrating ADCs: next generation of Qweak ADCs built by TRIUMF

- Key improvements
  - Input bandwidth: 50 kHz → ~1 MHz
  - ADC sampling rate: 500 ksps → 15 Msps

Development by U. Manitoba and TRIUMF (NSERC & CFI funding), with support from JLab for interfacing with CODA

Prototype ADC boards already in production

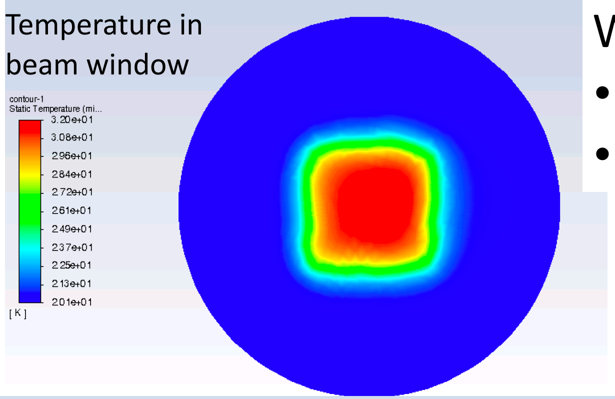
see: Detector and DAQ presentation

Target

There is a lot of progress toward operational engineering.

The critical science parameter is noise from target boiling

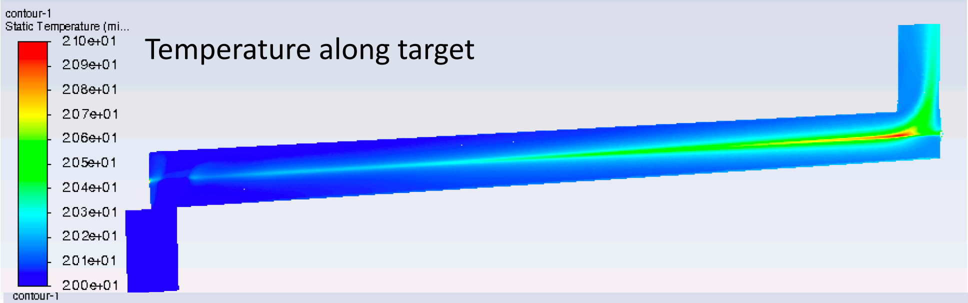
CFD simulations verify expected performance



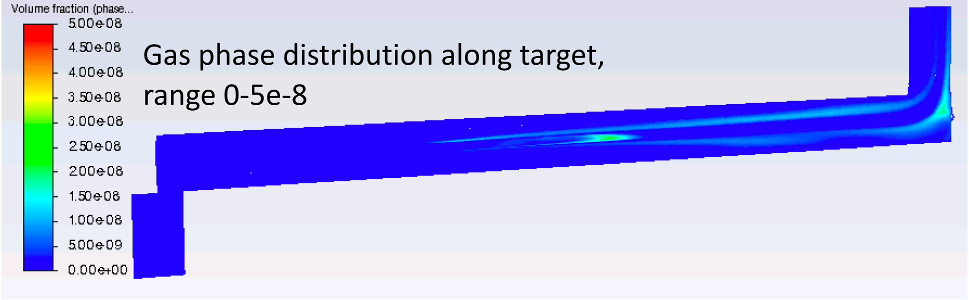
Temperature in beam window

With 5x5 raster, 70 μA beam current

- Average density loss 0.7%
- Gas phase fraction 0-5e-8



Temperature along target



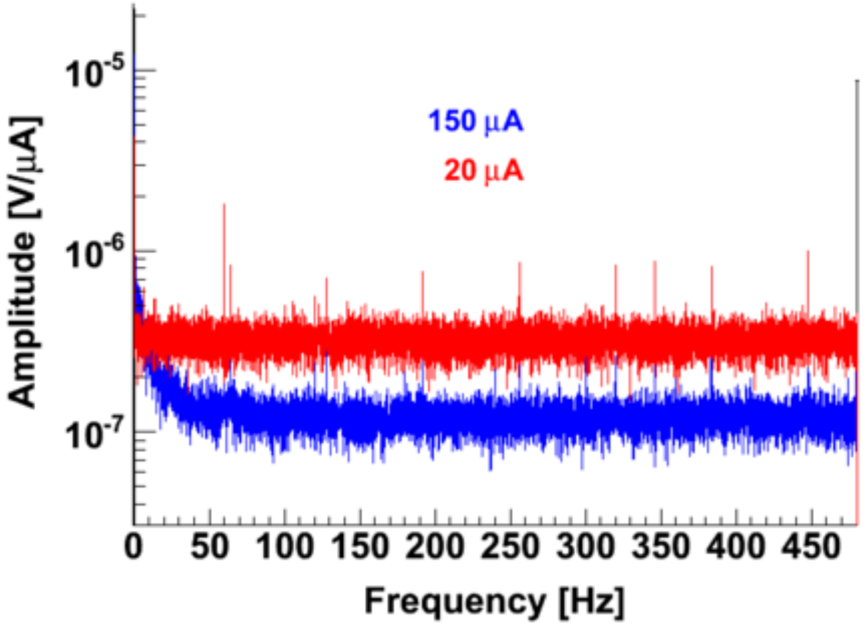
Gas phase distribution along target, range 0-5e-8

Parameter	Value
Nominal Luminosity @65 μA	$2.2{\cdot}10^{39}$ cm^{-2} sec^{-1}
Relative density reduction @ 70 μA	$< 1\%$
Density fluctuations @1920 Hz	< 30 ppm
Aluminum end window thickness	≤ 0.127 mm

The key to controlling this source of noise is rapid measurement.

Qweak used 1 kHz helicity flip

MOLLER will use 2 kHz flip



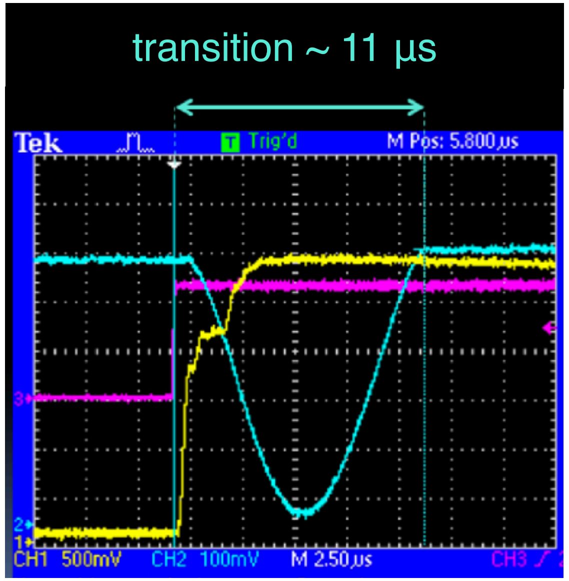
see: Target presentation

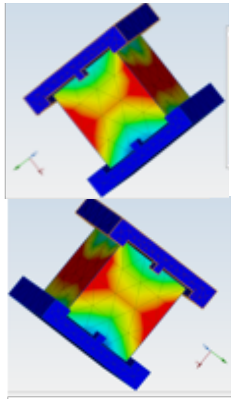
Polarized Source

Goal: 2kHz flipping, ~10 µs transition

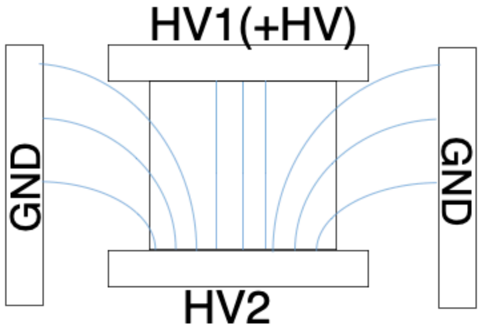
New technology needed: RTP cell

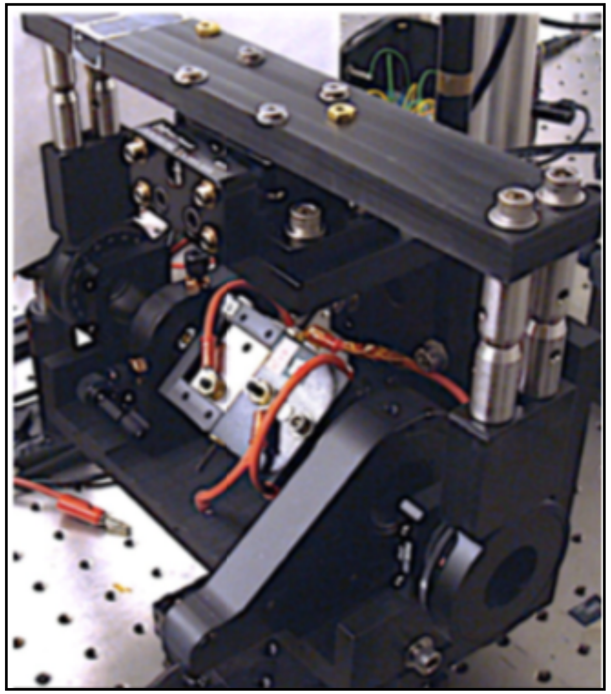
Two crystals, transverse field
No piezoelectric ringing
Much faster and more stable





E-field gradient steers beam use effect for position feedback





Installed 2019, used for PREX-2 and CREX

Next Steps: injector upgrades

Improves parity quality transmission + optics, source lifetime

Phase 1 (installed summer 2021)

- 200 keV Gun + Wien filter upgrade
- Collaborative beam studies have already started

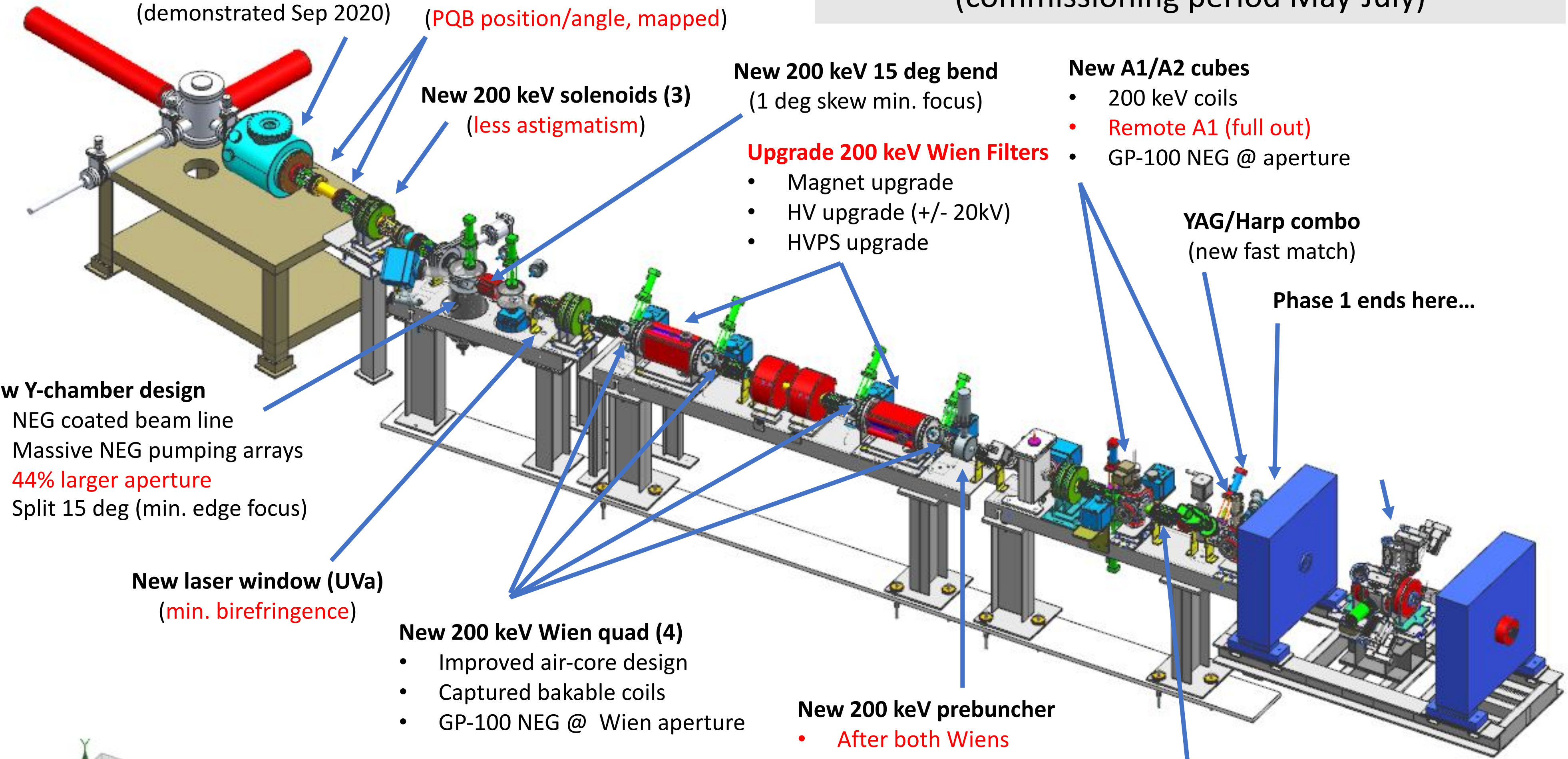
Phase 2 (future shutdown)

- SRF booster upgrade

	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 ppb
Position Difference	<0.6nm	<3nm	1 nm
Angle Difference	<0.13nrad	<0.6nrad	0.3nrad
Size Differences	<10ppb	<50ppb	5-30ppb

Phase 1 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

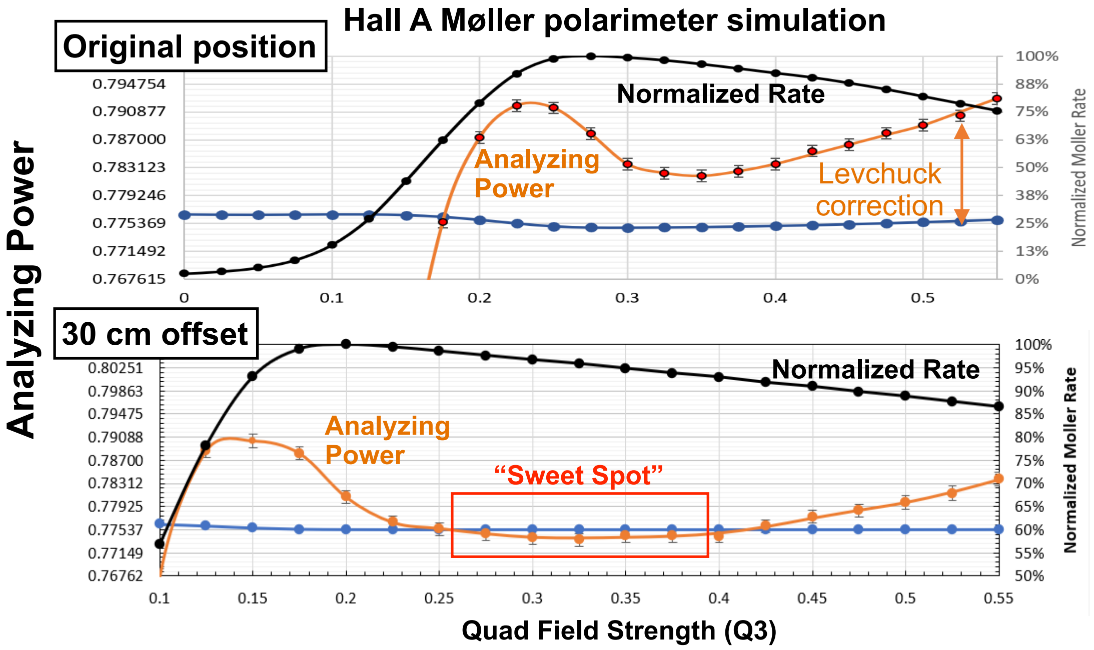
- Reduce beam line length to fit MOLLER target location 4.5 m upstream of the usual target location.
- Improve **raster** operation, no longer requiring beamline optics

- 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

Møller polarimeter

- 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 change is being planned early, to gain operational experience with new Møller polarimeter optics



also in: Infrastructure

Summary

Coherent, dedicated, collaborative effort to connect simulations with realizable engineering has resulted in continued progress after CD1

Weekly simulation meeting attended by physicists and engineers, with 25-30 attendees:
5-6 postdocs, 10 senior physicists, 5-6 engineers + students

Additional regular (weekly or bi-weekly) subgroup meetings (detectors, shielding, collimation, spectrometer, DAQ) between physicists and engineers

Task force subgroups on ferrous materials, alignment, grounding to refine specifications

Close coordination has led to effective use of design and engineering resources, advancing MOLLER engineering while maintaining the MOLLER figure of merit