PREX/CREX Design Document
Version 3.0

Abstract

This document describes the principles and critical parameters of the PREX-II and CREX experimental design. Experimental requirements throughout the hall are described. Most of the components specific to these experiments are in the pivot area, with a new scattering chamber, vacuum assembly, collimators, and radiation shielding. The intent of this document is to provide a list of the critical parameters as well as present the design concept in its current state of detail. Although some descriptions of the concept are detailed, most details do not represent requirements and could be changed as needed throughout the design process. An attempt is made to clearly label parameters that are critical requirements.

The standard Hall A equipment as well as interface to the standard Hall A configuration (*e.g.* mechanical supports) are not specified here. Tolerances described in this document refer only to experimental concerns. Mechanical tolerances to assure the fit of each assembly must still be specified as the design is completed.

This design document is supported by a SolidWorks CAD model which can be used as a reference for additional details. This document will be updated, with each update tagged with a version number and date. These updates will be refinements of the basic design presented here, and will not include significant new elements.

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Contents

1. Overview of Experimental Requirements

The PREX-II and CREX experiments are very forward-angle measurements made at relatively low energies, which will determine the helicity-correlated asymmetry of electrons from unpolarized, neutron-rich nuclei. The experiments require high luminosity, achieved with both thick targets and high beam current. They will radiologically activate components near the target region and potentially produce high levels of radiation in the hall during running.

This experimental design has been developed using detailed simulations of accepted particles (measurement simulation) and of the radiation in the hall (radiation simulation). These tools should be used to evaluate the effect of any changes to the experimental design detailed in this document.

There are important considerations for achieving the required statistical precision and systematic accuracy. Both the high-field Moller and the Compton beam polarimeters will be required. The collaboration will build and install integrating detectors for the asymmetry measurement and additional tracking detectors in the spectrometer focal plane.

The most restrictive design constraints for this experiment lie near the spectrometer pivot. An initial design for a new scattering chamber, beam collimator, optics sieve slits, vacuum connection, acceptance-defining collimators, and shielding is presented here which will achieve the experimental figure of merit while controlling radiation levels in the hall and at the site boundary.

For both experiments, the measurement of the Q^2 distribution, and therefore the spectrometer calibration, is a critical source of systematic uncertainty. The spectrometer pointing must be measured to high precision using the recoil difference for elastic scattering from hydrogen compared to that of a heavy nucleus. The current plan for this is to use a water cell target, where elastic peaks for hydrogen, oxygen and iron (from the steel windows) are visible, all from the same target with the same value for energy loss.

Several commissioning steps will be required for each of the PREX and CREX experiments. These include standard detector alignment, optics calibration, and measurement of the accepted distribution from the thick production target. It is desirable to make a pointing calibration at the start of each measurement, in part because there will be slightly different systematics for this calibration at different beam energies.

1.1. PREX-II

The production target will be 0.5mm thick isotopically enriched ^{208}Pb. This is 10% of a radiation length. The experiment is being designed for a beam energy of 1.068 GeV. The asymmetry is expected to be about 600 parts per billion, with a relative statistical error of about 3%. The leading systematic errors will be polarimetry, detector linearity, and kinematics normalization, each of which may count as about 1% relative to the measured asymmetry.

An original run of PREX demonstrated suitable control of these leading systematic errors. Three problems limited the effectiveness of this earlier run: a) Excessive radiation damage to electronics in the hall limited up-time; b) Radiation damage to elastomer seals on the beamline and on the septum vacuum vessels just downstream of the target led to leaks and ultimately left the experiment unable to run; c) two of the three lead production targets eventually failed in the beam due to melting.

The target issue will be solved by employing the same target design, but with a larger ladder with more targets available. (See Section 2.1.1.)

The design of the pivot region will use only metal seals in the high-radiation area. A combination of better collimation and shielding around the collimator region will reduce the total radiation load on control electronics. All these aspects are discussed in further detail in the following sections.

1.2. CREX

CREX will use the JLab ^{48}Ca target. This target is about 0.78 g/cm^2 thick. The target will be mounted with a net rotation about the vertical axis of about 45°, so that a density of about 1.1 g/cm^2 is presented to the beam. This experiment is designed for a beam energy of E=1.8 GeV-2.2 GeV for the calcium measurement, with a central scattering angle of about 5°. At these kinematics, the asymmetry is expected to be 2.3 ppm, with a planned statistical precision of measurement of about 65 ppb. The leading systematic uncertainties are again expected to be the kinematic normalization and polarimetry. The total systematic uncertainty should approach 1%.

CREX is expected to face radiation issues similar to PREX, and will benefit from the same design improvements as PREX. The isotopically enriched ^{48}Ca target owned by JLab is damaged by oxidation. As described in Sec. 2.1.2, the effect of this contamination is suppressed, and a rough cleaning of the existing target should suitably control this contribution to the systematic error.

1.3. General Design Considerations

These experiments will produce high electromagnetic and neutron radiation in the hall compared to typical running conditions of previous experiments in Hall A. Especially components near to the target or downstream of the target may receive high radiation dose levels. The current design has eliminated the use of elastomer seals around the target region and the radiation dose to most sensitive electronics has been evaluated to be comparable to previous successful experiments. Introduction of elastomer seals and final positions of electronics (if different from current locations) will need to be evaluated with the full simulation.

There are two important general considerations which help to reduce the radiation levels in the hall. The first is the attempt to transport as much beam power as possible into to the beam dump, but to control radiation production by stopping as much as the un-transportable power as possible into a single, well defined collimator location. Radiation shielding around this beam collimator is then used to mitigate the radiation production from that region.

1.4. Requirements

The requirements for the experimental hardware are reviewed below.

- **Vacuum System:** Near the target region there will be significant radiation damage during running and significant radiological activation. At small angles downstream of the target, all vacuum seals must be metal. Elastomer seals at other locations in the pivot region should be avoided if possible, and should be evaluated for damage by simulation. Possible radiation damage of all control or monitoring hardware (motors, pumps, sensors, etc.) on the target chamber or collimator box should also be considered.

- **Beamline collimator:** To prevent excess electromagnetic radiation to be distributed around the experimental hall, a beamline collimator is used in front of the septum to catch scattering larger than $\sim 0.78°$. This collimator absorbs about 2 kW of beam power during the PREX production running. An initial design of this collimator, with tolerances on construction and alignment, is presented in Sec. 2.4.

- **Q1 collimators:** The acceptance-defining collimators are placed after the septum and before the Q1 magnets. The construction and alignment tolerances of these collimators is described in Section 2.7.

- **Alignment:** the critical apertures are the beam aperture in the beamline collimator, the inner edge of the septum vacuum vessels, and the collimators in the entrance to the Q1s. The vacuum system may be hard coupled with flanges, or connected with bellows to facilitate alignment as needed. The septum vacuum vessels have a horizontal alignment tolerance of ±2 mm.

- **Neutron shielding:** Shielding is required to degrade the high rate of moderate energy neutrons emitted from the beam collimator. This shielding uses high-density polyethylene, described in Section 2.8. As described in that section, the tolerances on the construction and alignment of these shielding elements are quite loose.

- **Skyshine shielding:** Heavy nuclear shielding is required over the collimator and over the target to reduce the site boundary dose caused by skyshine neutrons. These components also have very loose tolerances. These are described in Section 2.8.1.

- **PREX targets:** The PREX production targets must be helium cooled. Performance during PREX-I suggests that 6 targets are likely to be needed to complete the run. The collaboration intends to use 10 targets, which is nearly a factor of two margin of safety.

- **CREX target:** It is desirable to also cryo-cool the ^{48}Ca target, but thermal calculations suggest that water cooling would likely be sufficient if cryo-cooling is not feasible. It is intended that the calcium target will be isolated from the beam line, in a vessel that can either be maintained at vacuum or purged by a dry, non-oxidizing gas, in the case of a vacuum failure on the beam line or scattering chamber.

- **Optics and Pointing Calibration:** One of the leading systematic errors lies in determining the Q^2 distribution of the accepted particles. The sieve slits will need to be remotely insertable so that optics calibration data can be taken throughout the run as needed without needing to enter the radiologically activated region near the pivot. The angle of the spectrometer will be calibrated using the difference in recoil momentum from hydrogen vs a heavy nucleus. To do this precisely, it is necessary that a target is available with hydrogen plus a heavy nucleus. A watercell with iron windows will be sufficient and has been successfully used in the first run of PREX. It is desirable to be able to repeat this measurement during the course of the run.

1.5. Figure of Merit

A recent change in the experimental design has been the decision to run CREX at the same scattering angle as PREX (5 degrees). The achievable precision is close to that of the original proposal for the optimized beam energy of 1.9 GeV. The loss of precision is acceptable even for beam energies up to 2.2 GeV. The advantages of the single target location include a simpler design, the septum will be safely inside its proven operation range, and reduced production of radiation during the CREX run.

The CREX FOM is ultimately the error bar on the radius of the neutron distribution for the proposed run time of the experiment. In general a smaller scattering angle will optimize at a higher beam energy, but would be less efficient due primarily to loss of geometric acceptance. The FOM depends on cross-section, acceptance, and asymmetry, but also on the sensitivity of the asymmetry to the neutron radius. In addition, the FOM should be optimized using an estimate for systematic uncertainties, which can be added in quadrature with statistical error bars to produce the total uncertainty on the neutron point radius. As a result, the FOM is not simply a function of Q^2, but depends also on the scattering angle (or, equivalently, the beam energy) even at a fixed Q^2.

Figure 1 shows the achievable precision for the original 4° and 5° configurations of CREX. These are calculated using the simulated experimental acceptance and weighted by rate. The acceptance functions for each configuration are calculated using a GEANT4 simulation of the HRS (G4MC), which has been benchmarked against the original HAMC simulation tool (which used optics transfer matrices from SNAKE) and also against the acceptance function measured during the original PREX. The sensitivity of A_{PV} to the neutron radius, which varies with the accepted kinematics, is included in this calculation. The proposed current, polarization, and run time (150 μA, 85%, 25 days) is assumed. An additional 3% increase of the statistical error is included to account for detector resolution. The statistical uncertainty on the neutron radius is shown in red. The total uncertainty, shown in black, also includes a systematic uncertainty on the measured asymmetry of 1.2%, consistent with the proposal. The original proposal optimized the precision at 4 degrees given the constraints of compatibility with 2.2 GeV beam energy and keeping the central scattering angle $\geq 4°$. A similar precision can be achieved with a scattering angle at 5° and beam energy of 1.9 GeV.

Table 1 lists the approximate fractional error in the neutron radius for different beam energies for the 5° configuration. The precision of the CREX measurement is acceptable for any beam energy between 1.8 GeV and 2.2 GeV.

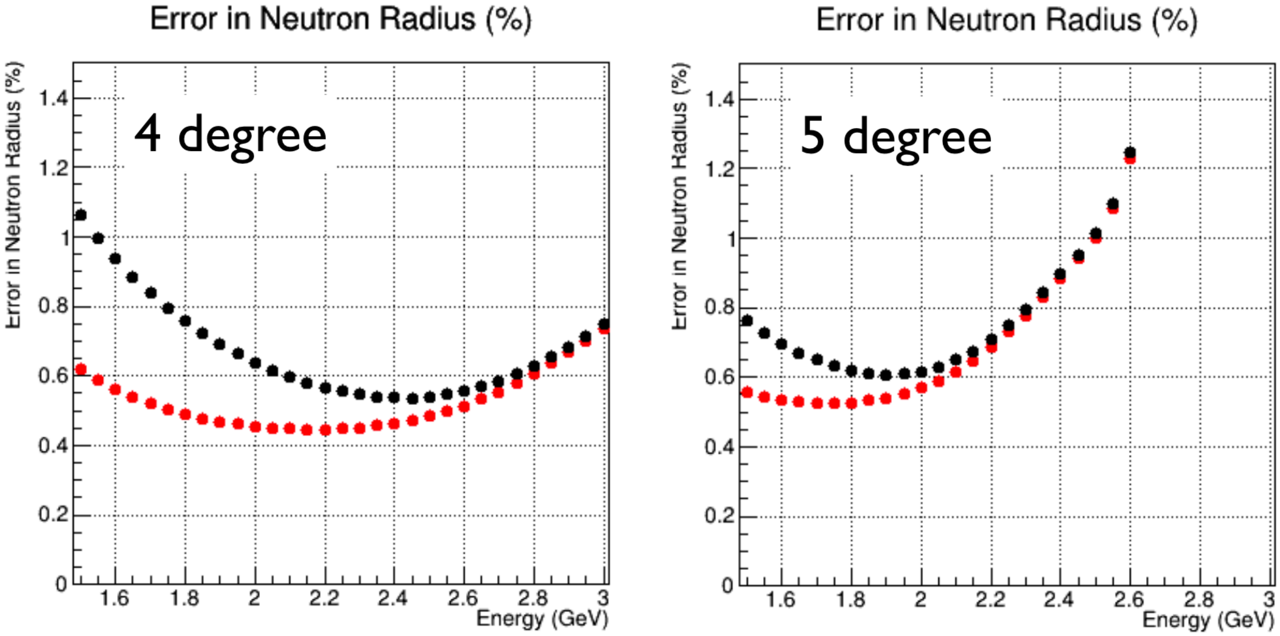


Figure 1: The CREX Figure of Merit as a function of beam energy, averaged over the acceptance. Left is for the 4° configuration, right is for 5°. The black points include the effect of an assumed 1.2% systematic uncertainty.

2. Pivot Region

The pivot region consists of the scattering chamber, collimator assembly, and septum. There is a continuous vacuum connection, without windows, through the scattering chamber, the septum and HRS magnets. The vacuum should be $< 10^{-5}$ Torr for good momentum resolution, to prevent oxidation of the calcium target, and to avoid convective heating of the cryogenically cool target ladder. Elements of the pivot region can be seen in Figures 2-4.

The experimental acceptance should be defined by a collimator in the entrance the first quadrupole of the HRS. Plots of the intercept of accepted scattered electrons with planes at various

angle	energy	rate [MHz]	A_{PV} [ppm]	$\delta A/A$ (stat) [%]	$\delta R/R$ (total) [%]
5°	1.8 GeV	130	2.16	2.0	0.62
5°	**1.9 GeV**	**79**	**2.28**	**2.4**	**0.61**
5°	2.0 GeV	48	2.37	3.0	0.62
5°	2.1 GeV	28	2.44	3.8	0.65
5°	2.2 GeV	16	2.49	4.9	0.71

Table 1: Summary of the achievable CREX precision for selected beam energies. The optimized kinematics are listed in bold face. The statistical error on the asymmetry measurement is listed, assuming 85% polarization. A 1.2% systematic uncertainty is assumed when calculating the total uncertainty as a percent of the neutron radius. The original proposal aimed to achieve a 0.6% uncertainty.

z positions are shown in Fig. 5. Each plot is only above beam height ($y = 0$), and symmetry for the distribution below the beam height should be assumed.

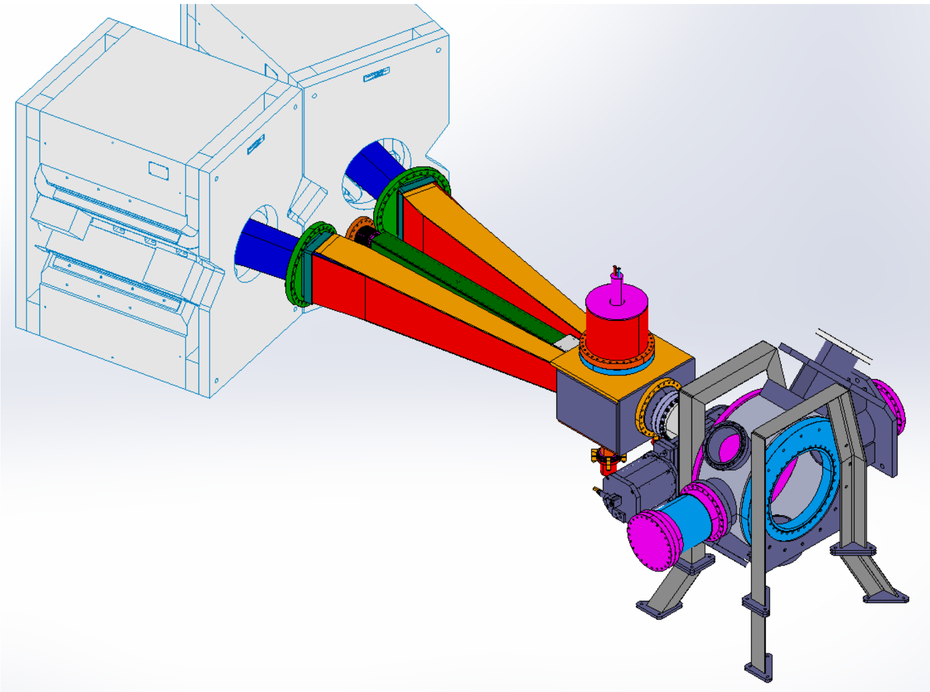


Figure 2: Perspective view of the pivot region. The target chamber is the final design, other components are the reference design. All shielding has been left off to expose the vacuum system.

2.1. Targets

Table 2 contains a full list of targets for the PREX/CREX combined configuration. In addition to the production targets, there are non-isotopically enriched backup targets on the cryogenically cooled ladder for commissioning and test studies. A thick carbon target on the cooled ladders will also be used for systematics studies. The warm target ladder will be used for calibration targets that will be run exclusively at low currents. There are a total of 16 targets on the production ladder, and 5 targets on the optics ladder.

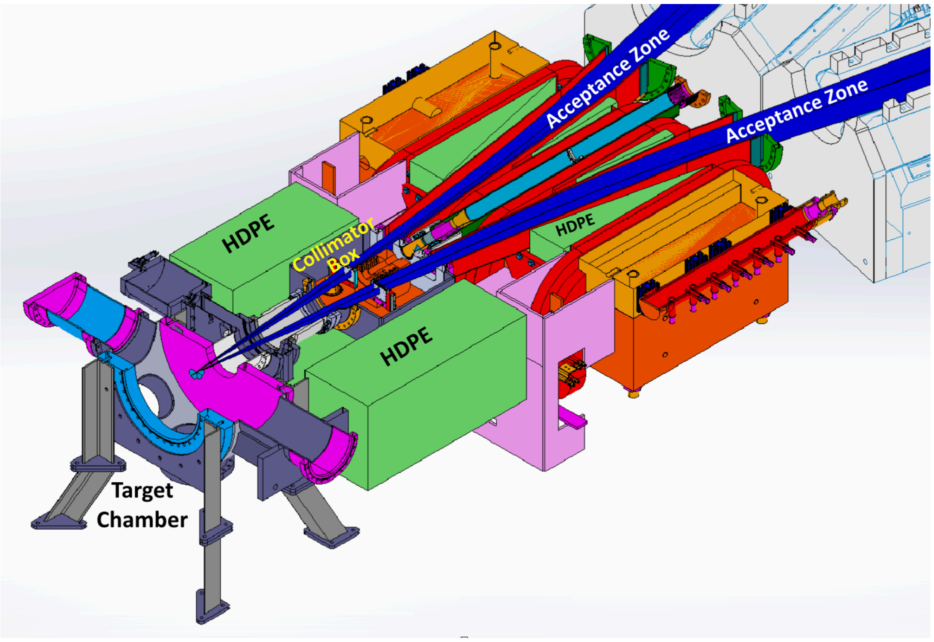


Figure 3: Perspective view of the pivot region with midplane cut, with HDPE shielding. The target chamber is the final design, other components are the reference design.

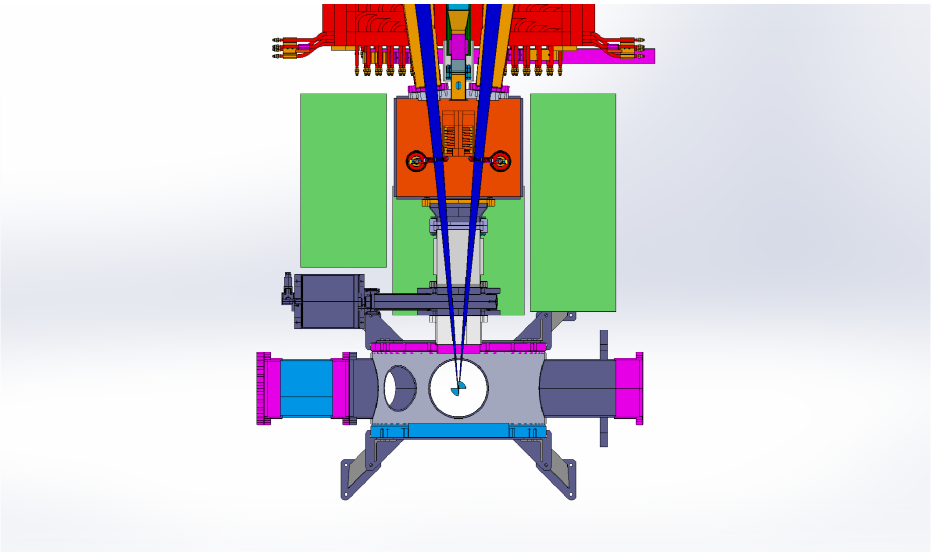
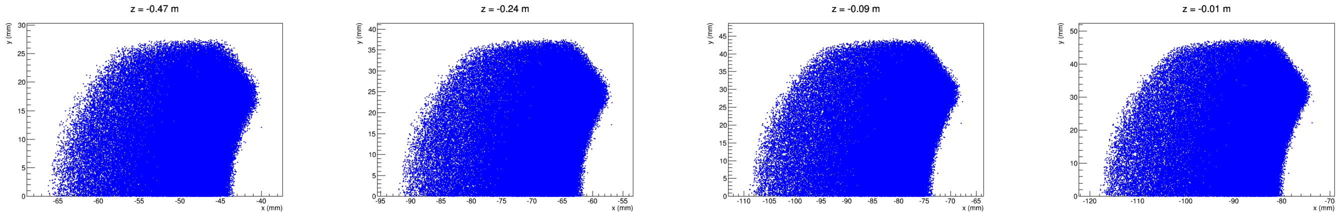


Figure 4: Top View of horizontal midplane cut through the pivot region.

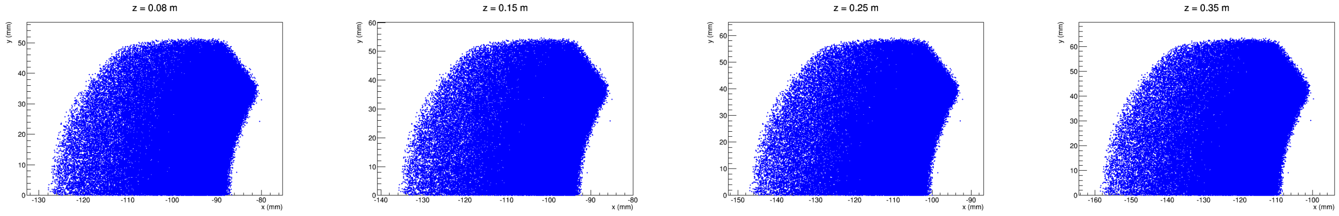
2.1.1. Lead Production Targets

The design of the lead targets will be the same as for PREX-I. In that run, about 82 Coulombs of beam was collected on a total of three lead targets. Two of the targets eventually were damaged, with the last target not showing degradation after running for a week at 70 μA. Simply taking 82 C over three targets, one might assume the lifetime of each target is, on average, 27 C. (This ignores the fact that one target wasn't degraded, and also ignores that the length of survival of each target appeared to increase with increasing thickness of diamond layer, so we might plausibly expect better performance from our PREX-2 targets.)

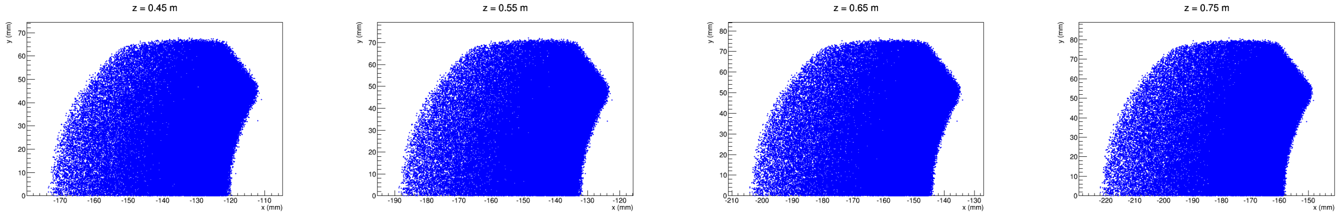
PREX-2 is expecting to collect about 150 C total charge, suggesting that 5–6 targets may be required. PREX-2 intends to use a ladder with 10 isotopically-enriched targets. The safety margin, with 10 targets, is about 66%. In addition, it is desirable to add two additional targets



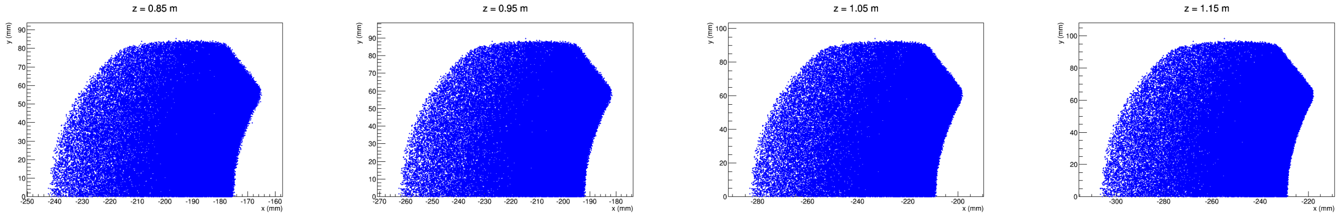
(1) z= −470 mm (2) z= −240 mm (3) z= −90 mm (4) z= −10 mm



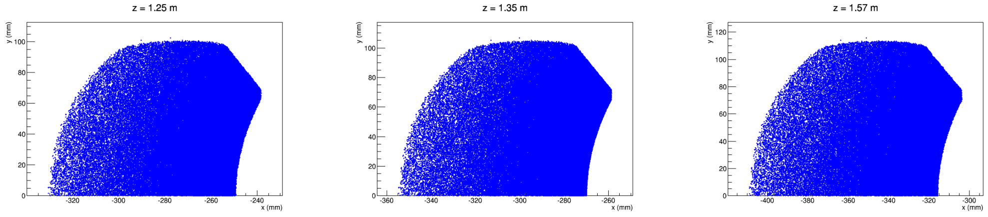
(5) z= 80 mm (6) z= 150 mm (7) z= 250 mm (8) z= 350 mm



(9) z= 450 mm (10) z= 550 mm (11) z= 650 mm (12) z= 750 mm



(13) z= 850 mm (14) z= 950 mm (15) z= 1050 mm (16) z= 1150 mm



(17) z= 1250 mm (18) z= 1350 mm (19) z= 1570 mm

Figure 5: *These figures are not final, and will be updated soon.* Plots of transverse positions, x vs y, at various z locations, for accepted tracks. The design should allow passage of these tracks through the pivot region.

Optics Ladder	
Carbon Hole	~ 0.1 g/cm^2
Watercell	
Tantalum foil or thin C foil	0.1 ± 0.05 g/cm^2
thin natural Pb	0.05 ± 0.01 g/cm^2
thin ^{40}Ca	0.05 ± 0.01 g/cm^2

Production Ladder	
Carbon Hole	~ 0.1 g/cm^2
(9X) ^{208}Pb/Diamond	0.5 mm
^{208}Pb/Graphite	0.5 mm
^{48}Ca (tilted)	1 ± 0.1 g/cm^2
^{40}Ca	1 ± 0.1 g/cm^2
thick C	0.5 ± 0.1 g/cm^2
Pb/Diamond	0.5 mm
Pb/Graphite	0.5 mm

Table 2: Targets required for PREX and CREX physics and optics calibrations.

with un-enriched lead, in order to facilitate studies of the target damage.

Each lead target consists of a 0.5 mm thick lead square sandwiched between two foils of diamond which are each 0.25 mm thick. The foils are 1 inch square. A thin layer of Apiezon L vacuum grease (a pure hydrocarbon with high thermal conductivity) is applied to the lead/diamond interface to improved the contact. Belleville ("spring-like") washers are used in the clamping assembly to maintain a force that squeezes the lead and diamond together and ensure contact at all times as it changes temperature in the beam. A silver-based paste compound that is used for heat-sinking in the semi-conductor industry is applied between the diamond and the copper, but is kept out of the central area where the beam intercepts the target. Thermal calculations show that if the thermal contact is good the targets will function with rastered beam (4 x 4 mm) at $\geq 100\mu$A. The main uncertainties are the quality of the thermal contact and the integrity of the diamond as it degrades in radiation.

A graphite backing will be used for one isotopic and one natural lead target. The trade-off for graphite is that it has a lower thermal conductivity and is only expected to support 60μA beam operation, but the graphite structure is thought to be much more robust against radiation damage.

The spacing of one of these 1" targets to the next is expected to be about 1/4". Figure 6 is a photograph of the PREX-I target ladder.

2.1.2. Calcium Target

The calcium production target will use the existing JLab 0.78 g/cm^2 ^{48}Ca foil. This will be mounted at 45° in order to increase the effective target thickness to 1.1 g/cm^2. A 1.1 g/cm^2 ^{40}Ca target will also be used for commissioning and systematics studies, and a thinner 0.2 g/cm^2 ^{40}Ca target will be used to investigate HRS resolution relative to inelastic states.

The existing JLab ^{48}Ca target has been damaged by an uncertain amount of oxidation. This layer is expected to be rather thin, and can be scraped off with a blade. Studies are underway

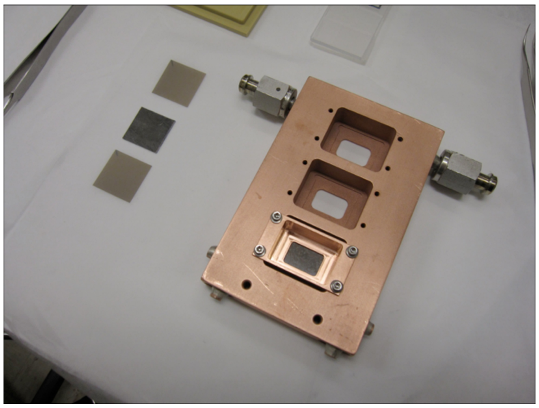


Figure 6: Photograph of the PREX-I target ladder.

to estimate how much contaminate might be expected to remain after the scraping. The likely contaminants (nitrogen, oxygen, carbon) all have asymmetries that are within about 10% of the expected ^{48}Ca asymmetry. Assuming Z^2 scaling for cross-sections, a total of 10% oxygen (by number) would correspond to a background fraction of about 1.6%, and so a false asymmetry of 0.16%. Knowing those contaminant levels to 10% or better will sufficiently bound the systematic uncertainty.

2.1.3. Water Cell

The watercell target will be similar to what was used for PREX-I. It will be used for the same purpose of measuring the difference in central momentum between scattering from a free proton and a heavy ($A > 2$) nucleus for a precision spectrometer calibration. It is expected that this target will be about 5 mm of water, between 0.05 mm stainless steel windows.

It is essential that a tool such as the watercell is available to facilitate a pointing calibration. The fraction of hydrogen to heavier nuclei is a critical parameter - the hydrogen peak is difficult to precisely measure on top of the radiative tail of the lead elastic scattering at 1 GeV beam energies.

It is desirable to perform several pointing measurements during the run, including between the PREX and CREX production runs. For this reason, we intend to mount the watercell on the optics ladder, independent of the cryo-cooled production ladder. Along with remote control to enable the water flow through the target, this will allow its use multiple times during the running period.

2.2. Scattering Chamber

Requirements: *The scattering chamber will be made of aluminum, use metal seals for all beam-line connections, and provide two target movers both with* $z = -105 \pm 1$ *cm. One ladder will be cryogenically cooled, with 18 target locations. The other will support a watercell target that can be operated remotely during the run, and 5 other optics or auxiliary targets which will be used only at low currents. Targets in each ladder must be positioned relative to the center of the beam with a tolerance of 2 mm.*

The scattering chamber is under fabrication, and design is near completion on all remaining components of the target system. The scattering chamber design is shown in Fig. 2. The target movers are not included in this figure.

A cap on the beam left side of the scattering chamber can be removed to expose the end of the production target ladder for installation of the calcium target. In this way, the calcium targets can be installed after the vacuum system is prepared, to protect against oxidation.

radial distance from target	Integrated dose (Gy)
25 cm	4.8×10^4
50 cm	2.5×10^4
100 cm	1.0×10^4

Table 3: Estimates of integrated dose during the CREX experiment, for plastic cylinders at fixed radius from the beam.

A vacuum pump will be used on the scattering chamber. Metal seal gate valves upstream and downstream of this chamber are included, to isolate the chamber from the beamline in the case of a lose of beamline vacuum. An inert gas purge system will be used to protect the calcium target in the event of vacuum failure on the scattering chamber.

This chamber will be made of aluminum. All beamline seals will be metal seals. The downstream gate valve and exit beampipe will be stainless steel. Any use of elastomer seals in this region (for example: on the target movers) will need to be carefully vetted. An estimate of the integrated radiation dose during CREX for seals that are near the target is shown in Table 3. These estimates were made using 1 cm thick HDPE cylinders, coaxial with the beam with length 10 cm along z, at radii of 25 cm, 50 cm, and 1 m. This calculation suggests that the integrated dose may be over the nominal damage threshold for most polymers.

2.3. Collimator Box

Requirements: *The box must be aligned with the beam aperture centered on the ideal beamline within a tolerance of 1 mm. All other tolerances are mechanical.*

The collimator box connects the scattering chamber to three separate vacuum volumes on the downstream side: the beam pipe running through the septum magnet and the left and right spectrometer vacuum boxes that penetrate the septum bore. The box houses the beam collimator, and includes a housing above for this collimator to assist in de-installation. Sieve slits for optics calibration are also in this box.

This box will be made of aluminum. Only metals seals should be used on this vacuum enclosure. The spectrometer vacuum boxes will attach directly to the downstream face of the collimator box, while it will be necessary for the beampipe to attach to a flange on a extension pipe.

2.4. Beam Collimator

Requirements: *The inner bore of the beam collimator has a radius tolerance of 0.2 mm. The width of the collimator is designed to subtend an angle of* $3.45° \pm 0.1°$ *to each side of the beam. It is specified with a tolerance of 0.5 mm on construction and 1 mm on alignment, so that it does not interfere with acceptance. The 1 mm alignment tolerance is also sufficient to not significantly increase the deposited beam power. The collimator is anticipated to operate at 2.1 kW power deposition.*

The beam collimator assembly consists of two pieces: a 70% W / 30% Cu alloy collimator, cut to allow cooling water flow and brazed inside a copper jacket. (This component is based on the design of the Qweak tungsten collimator.) This inner collimator is housed in a larger jacket made of sintered tungsten. The inner collimator has a total radius of 5 cm, and length of 10.5 cm. The water channel is about 5 mm in the radial dimension, spiraling around the collimator and attached

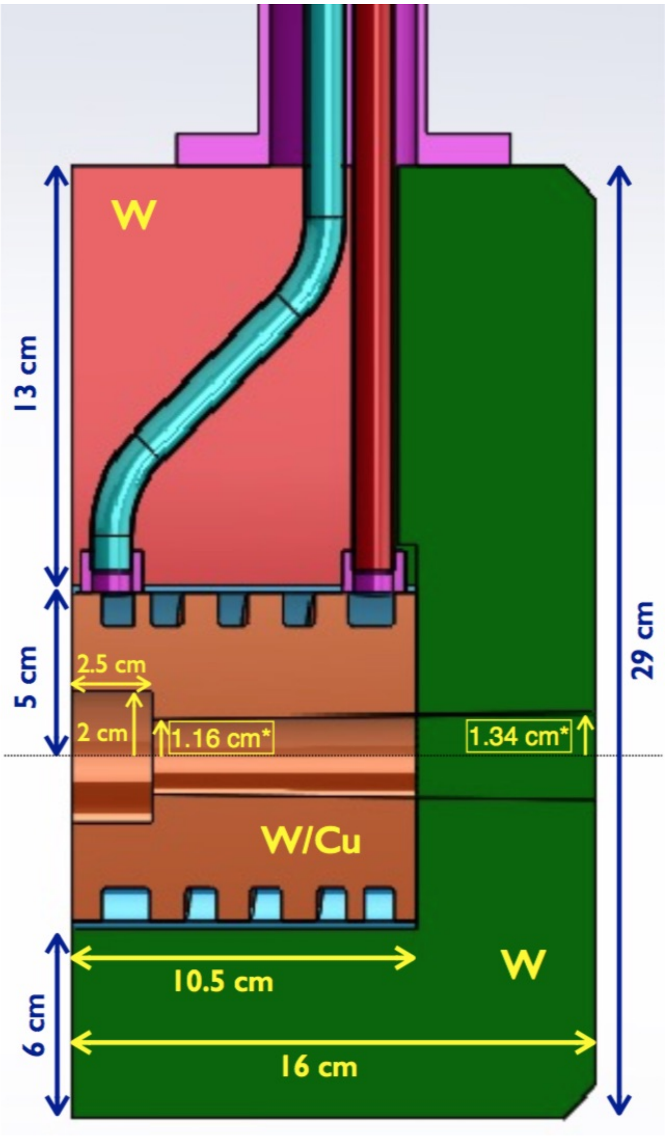


Figure 7: Side view of the beam collimator.

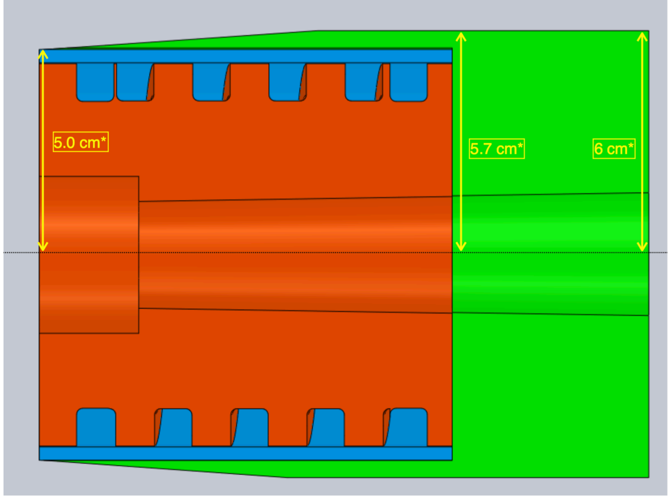


Figure 8: Top view of the beam collimator.

	PREX	CREX
Current	70 μA	150 μA
Power/μA	28.8 W/μA	6.8 W/μA
Total power	2020 W	1020 W

Table 4: Power deposited in beamline collimator, for PREX and CREX at 5° scattering angle, 1.05 GeV and 2.0 GeV beam energies, respectively.

to water lines on the top of the collimator at each end. Dimensions are labeled in the illustrations in Fig. 7 and 8.

The tungsten jacket is 12 cm wide at the downstream side. It does not extend all the way to the front of the inner collimator on the sides. It extends 13 cm above and 6 cm below the inner collimator for a total height of 29 cm. It is about 16 cm in length. The front face of the jacket is flush with the front of the inner collimator.

There is a 2 cm radius, 2.5 cm long cylinder removed from the front of the inner collimator. This puts the peak beam power deposition inside the tungsten collimator, rather than close to the front face.

The beam bore through this collimator matches a conical opening angle of 0.78° from the PREX production target. On the back end of the tungsten jacket, this corresponds to a radius of 1.34 cm. At the narrowest point, 2.5 cm downstream of the collimator front face, the beam bore has a radius of 1.16 cm.

The collimator is positioned with the front face 22 cm upstream of the pivot, or 83 cm downstream of the PREX production target.

The beam bore radius tolerance is 200 microns. The location of the beam bore and of the vertical (left- and right-hand side) edges of the collimator should be positioned with a tolerance of 1 mm. The tolerance on the position of the collimator along the beamline is 3 mm.

The collimator will be water cooled, with a maximum total power for production running expected to be about 2.1 kW (Table 4). The water lines will run upward through the collimator jacket. It is assumed that this will need a closed cooling circuit due to tritium production in the cooling water.

The collimator will be held by a vertical support, and rest on floor of the collimator box. It should have some alignment pinning, to support the 1 mm alignment tolerance.

After operation, this collimator will be lifted up into the collimator housing, which contains shielding that will limit the radiation dose from the activated collimator materials.

2.4.1. Collimator Housing

A housing will be attached to the top of the collimator box. This is intended to simplify the dis-assembly of the system after beam operations.

In the conceptual design, at least 2.5 cm of tungsten shielding on the upstream and downstream faces of the collimator is required. This shielding should be installed at the start of de-installation, to avoid activating the shielding during beam delivery. This housing must include a motion feedthrough that allows the collimator to be lifted into the housing. This operation does not need to be performed under vacuum.

2.5. Sieve Slit Collimators

The sieve slits are the same dimensions as those used during PREX-I. Motion feed-through that can be remotely actuated should position the sieve optics collimator between a "beam out" position, in which they swing free of the spectrometer acceptance, and a precisely determined

”beam in” position, in which they do not interfere with the inner bore of the beamline collimator, but they do entirely cover the spectrometer acceptance.

The remote actuation will be necessary so that these can be used even after significant activation has started at the pivot. These can be either manual actuators connected to long handles, or some motorized system.

2.6. Septum

Requirements: *The septum will be used in the three-coil configuration as used during the g2p measurement. The alignment tolerance is* ±*2 mm in the horizontal, and* ±*1/4” in the vertical. The required excitation will be well less than the maximum that was used during the g2p experiment, so the configuration parameters for this magnet are well known.*

The septum will be used in 3-coil configuration, similar to the g2p configuration. Also as for g2p, shims will be used to reduce the vertical bore dimension by 2”, and so reduce the coil current and thermal power relative to the required field integral. The available acceptance with these shims has been considered in calculating the experimental figure of merit.

The septum alignment is allowed a vertical tolerance of 1/4”. A horizontal alignment tolerance of 2mm is required, to avoid interfering with acceptance on the front end and to align the beam pipe with the primary beam on the back end.

2.6.1. Spectrometer Vacuum Boxes

Requirements: *A keep out zone for this box will be provided by the experiment. The vertical dimension will be constrained to be small enough to fit the necessary shims in the septum. No additional tolerance will be needed for the specified keep out zone.*

A vacuum box in the acceptance bore of each side of the septum will connect from the collimator box to the HRS vacuum pipe. This vessel will be made of 1/4” non-magnetic stainless steel. The cross-sectional vertical and horizontal dimensions of this box will allow acceptance of the tracks as show in in Fig. 5. A keep-out zone is defined in CAD to help guide design and visualization.

2.6.2. Septum Beam Pipe

Requirements: *ID 3.25”, robust vacuum connections and magnetic shielding. Tolerances set by mechanical considerations, not physics.*

The existing septum beampipe will be used. It is made with magnetic steel, and integrated with a steel rectangular box surrounding it to assist with magnetic shielding.

Additional magnetic shielding will be used to cover between the collimator box and the septum beampipe, as shown in Fig. 9. The shield will be magnetic steel, and have 1/2” thick vertical walls. A similar shield will also be used for the downstream end of the septum beampipe.

2.7. Q1 Collimator

Requirements: *Specified acceptance shape. Alignment tolerance of 1 mm for vertical or horizontal displacement. Other tolerances set by mechanical considerations, not physics.*

A collimator will be needed in the aperture to each Q1. This collimator is designed to be the most strict cut on rays into the spectrometer, so it will define the spectrometer acceptance. This collimator will be similar to what was used in the first run, shown in blue in Fig. 10. The location of the collimator will define the scattering angle for the experiment. The collimators should be 8 cm thick tungsten. The shape of the acceptance will be provided by the experiment.

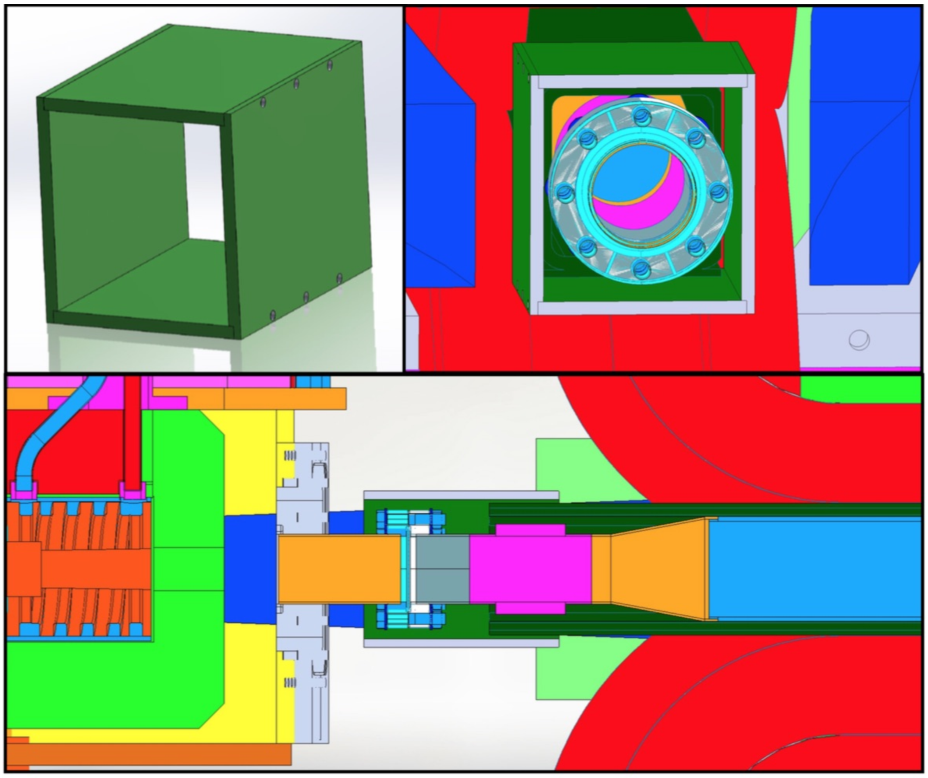


Figure 9: Magnetic shielding to reduce fringe field in beampipe between collimator and septum beampipe.

Symmetry between the two HRS is important; both left/right and up/down symmetry should be preserved. The collimators are to be surveyed and shimmed into position to an accuracy of 1 mm in the directions transverse to the beam. The tolerance on the location along the beam is less important, about 2 mm is fine. In PREX-I the surveying and shimming was done prior to building up the septum magnet, but how this is done for PREX-II depends on what is most practical.

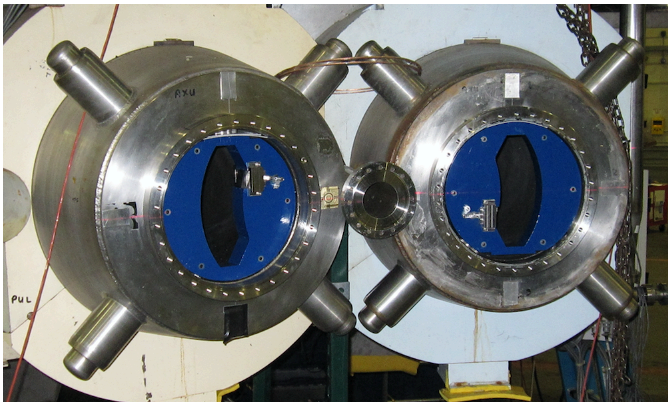


Figure 10: Q1 acceptance collimators installed for PREX-I.

2.8. Radiation Shielding

Requirements: *Approximation of specified shape and dimensions is ok. Deviations of* > 5 *cm in HDPE shielding thickness or* > 1 *cm in position will require re-evaluation with simulation, but are not obviously a problem. Tolerances set by mechanical considerations, not physics.*

High-density polyethylene (HDPE) is placed around the collimator in order to attenuate the moderate energy neutrons which drive much of the radiation damage to electronics in the experimental hall. Heavy material is placed above the collimator and above the calcium target location to attenuate upgoing, high-energy neutrons ($E_{neutron} > 30$ MeV) which drive the site-boundary dose rate. No dimensions for this shielding are critical, so tolerances on dimensions of the assemblies and positioning are more than 1 cm.

2.8.1. Skyshine Shield

A 6 cm thick tungsten block is positioned over the collimator box and extending upstream, to attenuate upgoing neutrons from the upstream face of the collimator. This block will be positioned as close as is feasible to the collimator upstream face, as allowed by the collimator housing. The block is 45 cm wide and 30 cm long (along the beamline). The downstream face of the block should be about 10 cm upstream of the collimator face. The mass of this shield is about 160 kg. This shield is visible in Figure 11. In this location, this shields high energy neutrons from the front of the beamline collimator, which is the largest contributor to the site boundary dose. This is supplemental to the self-shielding of the collimator for upgoing high energy neutrons (see the height of the tungsten jacket in Fig. 7).

Concrete blocks will be used over the collimator region (to further attenuate neutrons from the collimator region) and over the target region (to attenuate neutrons from the calcium target). In the reference design this is done with two blocks, each of which are 40 cm thick. The target block is positioned 50 cm above the beamline, ranges from 1.2 m upstream of the target to 70 cm downstream, and has a full width of 125 cm. To allow space for the optics target mover in the scattering chamber, a wedge is cut off of the beam right side of this block, starting at the upstream edge and continuing to about 20 cm downstream of the target. The mass of this concrete block is aobut 1,800 kg.

The collimator block in the reference design is positioned higher, about 1 meter above the beamline, in order to avoid possible mechanical interferences with the collimator housing or septum magnet. The upstream end of this block matches the downstream end of the target block. It is 140 cm long along the beamline, and 125 cm wide. The mass of this block is about 1,700 kg. Together, the two blocks attenuate about 55% of the power in high energy neutrons that would reach the hall roof in the CREX configuration, and about 40% of the power in high-energy neutrons in the PREX configuration.

The placement of these skyshine shields are shown in Fig. 11 and Fig. 12.

2.8.2. HDPE Neutron Shield

The proposed HDPE shielding around the collimator region is shown in Figures 3, 4, and 11. The general rule is that 30 cm thick shielding (along the line-of-sight from the collimator) is desired, but down to 20 cm is still highly effective. (Beyond 30 cm thickness the shielding offers diminishing returns.) In space restricted regions, even 5 or 10 cm can be helpful, although the benefit is in general marginal so this should not be done if the additional small pieces create other problems.

The HDPE shield as shown consists of the following components:

- walls on either side of the collimator box which are about 70 cm high and 30 cm thick, and fill the available space between the scattering chamber assembly and the septum.
- A layer above the beamline and collimator box, below the concrete target skyshine shield, which stops short of the collimator housing on the downstream end. This layer covers the tungsten collimator skyshine shield. It has a uniform height of 30 cm.

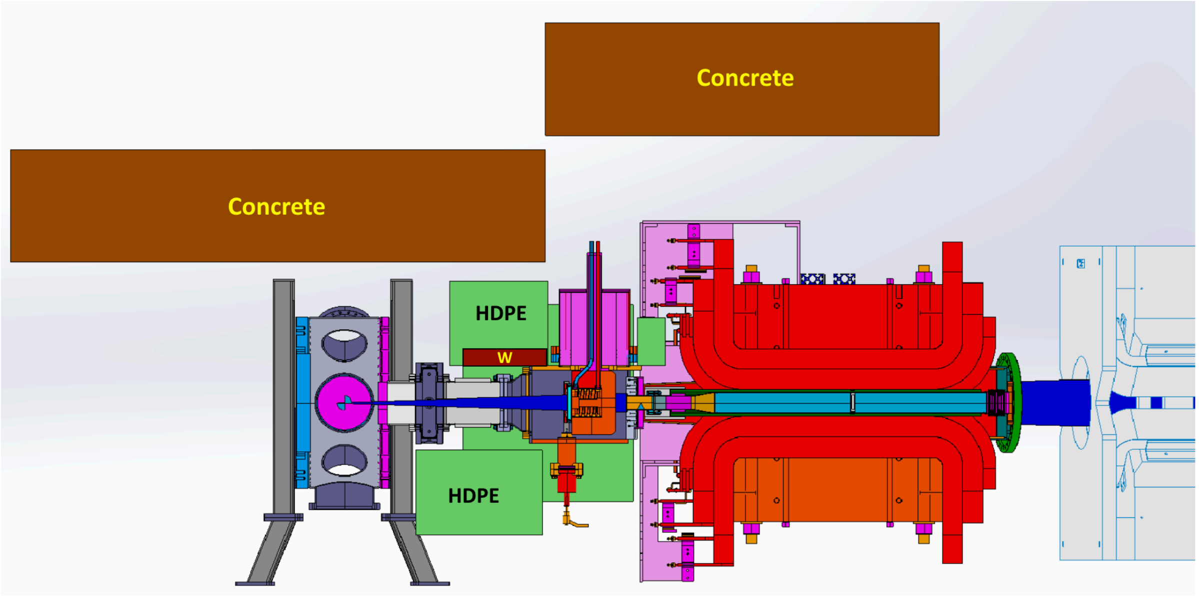


Figure 11: Side view of pivot region, with vertical midplane cut, showing location of the sky-shine shield relative to the scattering chamber and collimator.

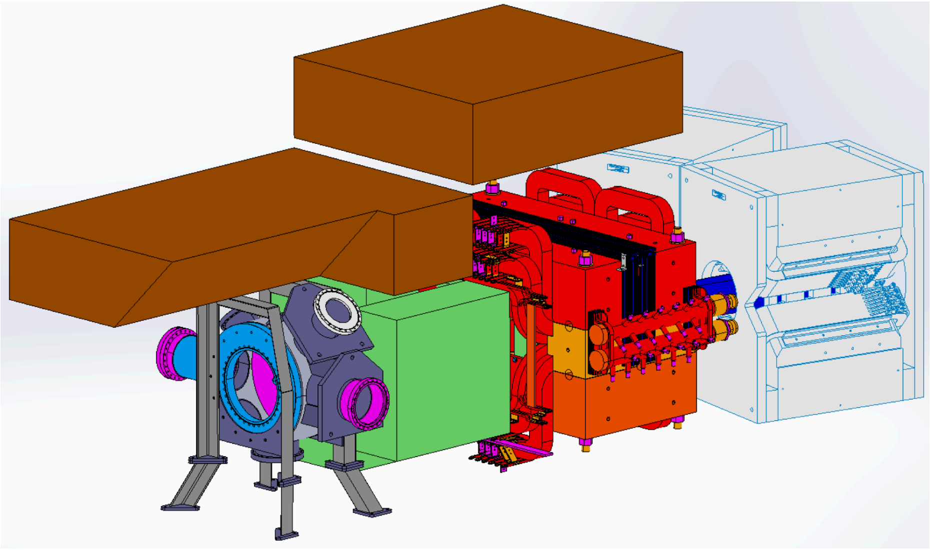


Figure 12: Perspective view of pivot region with sky-shine shielding blocks

- A block between the HDPE side walls, on the downstream side of the collimator housing. The block has a cross-section of 20 cm high by 10 cm thick.
- Additional plastic is added to the top of the collimator housing. This is of marginal benefit (the thick collimator jacket self-shields in this direction) and should be considered optional.
- A block between the scattering chamber assembly and the collimator box, below the beamline. This fills space between the HDPE side walls, and has a uniform thickness of about 30 cm.
- HDPE wedges are also inserted into the septum bore, to attenuate forward going neutrons.

There is a lot of flexibility in the design of this shielding, and changes to the geometry described here can be made without significantly degrading the benefit of the shielding.

3. HRS Installation

3.1. HRS Detector Configuration

Both experiment will use the VDC trackers, in addition to the experiment specific installation. All other HRS detectors in the standard package (*i.e.* the cerenkov detectors, calorimeters, and S2 scintillator plane) should be removed to avoid radiation damage .

3.2. Integrating Detector Installation

Each measurement uses thin quartz detectors, with phototubes to detect cerenkov radiation from particles traversing the quartz. These detectors will be designed, fabricated, installed and commissioned by the collaboration. Each will also include an LED system for studying system linearity.

The design and fabrication of the integrating electron detector and new GEM tracking chambers, along with the detector mounts, will be the responsibility of the collaboration.

4. Change Log

Version 0.1a Initial draft version of design document.

Version 1.0 Initial version of design document. Addition of acceptance plots in pivot region, a little more information about expected septum operation.

Version 2.0 Combined the two experiments to a single target location. Described CREX figure of merit vs beam energy. Described septum with shims. Added information on backgrounds in Calcium target. Updated and prioritized target list. Updated HDPE neutron shielding. Further detailed skyshine shielding. Updated drawing of beamline collimator. Update CAD illustrations of experimental apparatus.

Version 3.0 Incorporated final scattering chamber design (Silviu Covrig, Wayne Sachleben, Dave Meekins). Updated septum running parameters scaled from g2p conditions. Updated CAD figures to reflect additional design work on beamline (Ron Lassiter). Updated skyshine shielding to final reference design. Updated CAD illustrations.