PREX/CREX Design Document
Version 0.1 beta

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 would be allowed to be changed as needed by the design process. An attempt is made to clearly label parameters that are critical requirements at the top of each section.

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 the 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.

The collaboration is committed to preparing this apparatus for running in early 2018. The collaboration will prepare an application for scheduling in 2018, which is due on August 1, 2016.

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, will use thick targets and high beam current, which 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 proposed here.

There are important considerations for achieving the required statistical precision and systematic accuracy. Both the high-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. Design concepts for a new scattering chamber, beam collimator, optics sieve slits, vacuum connection, acceptance-defining collimators, and shielding have been developed to achieve the experimental figure of merit while controlling radiation levels in the hall and at the site boundary.

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) Finally, 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. The design of the pivot region will use only metal seals in the high-radiation area, and 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 ^{48}Ca target. This target is about 0.78 g/cm^2 thick. The target will be mounted with a net rotation 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=2.2 GeV for the calcium measurement, with a central scattering angle of about 4°. At these kinematics, the asymmetry is expected to be 2.2 ppm, with a planned statistical precision of measurement of about 100 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.

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.

Two important general considerations 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. Changing configurations between PREX/CREX

A limited number of steps are required to change between the PREX and CREX configurations. One goal of the design is to minimize personnel exposure in the pivot region during this changeover.

- Switch cooling between Calcium and Lead production target ladders.
- lock out motion of unused production and ancillary ladders, enable motion of the new target ladders.
- remove previous integrating detectors, install new integrating detectors, and align ancillary tracking detectors. Survey will be required for the new installed detectors.

Several commissioning steps will be required for each of the PREX and CREX experiments. These include standard detector alignment, optics calibration, pointing calibration, and measurement of the accepted distribution from the thick production target.

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 is Figures 1-3.

2.1. Targets

Table 1 contains a full list of targets for the CREX and PREX configurations. In addition to the production targets, there are non-isotopically enriched backup targets on each cryogenically cooled latter for commissioning and test studies. A thick carbon 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.

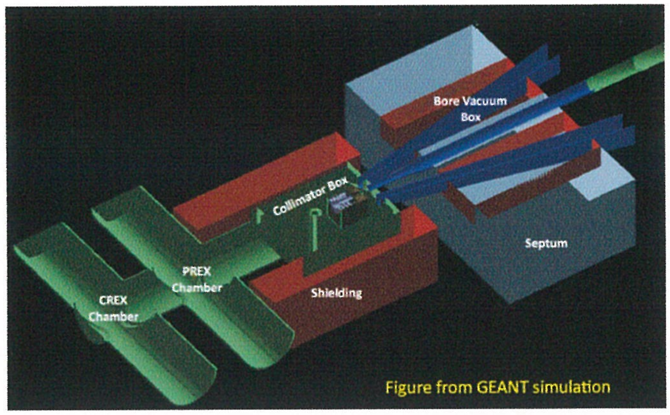

Figure 1: Perspective view of the pivot region with midplane cut, from simulation visualization.

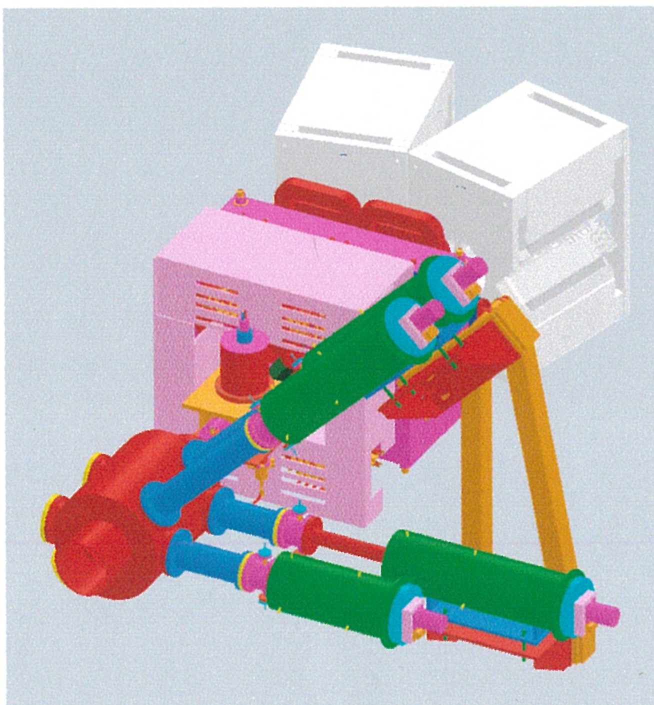

Figure 2: Perspective view of the pivot region in default design model. Here the radiation shielding has been removed for visualization

2.1.1. Lead Production Targets

The 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. The design is the same as for PREX-I, but there will be twelve targets instead of three to account for any possible failure/melting of the targets during production running. Ten of the targets will contain isotopically-pure ^{208}Pb and two others will be chemically pure lead.

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

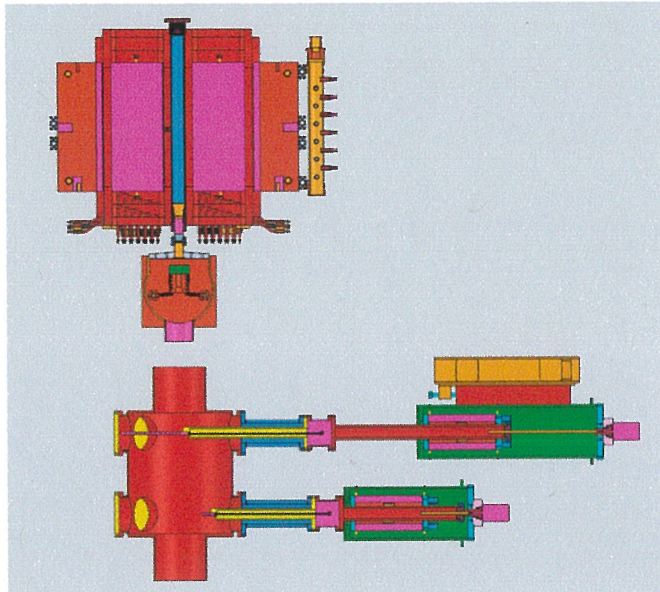

Figure 3: Top View of horizontal midplane cut through the pivot region. The radiation shielding has been removed. The gaps in the vacuum systems are just minor incompletions of default CAD model.

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.

2.1.2. Calcium Target

The calcium production target will use the existing 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 02 g/cm^2 ^{40}Ca target will be used to investigate HRS resolution relative to inelastic states.

2.1.3. Water Cell

The watercell target will be similar to what was used for PREX-1, and 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.

2.2. Scattering Chamber

Requirements: *The scattering chamber must be made of aluminum, use metal seals for all beam-line connections, and provide two separate cryogenically cooled target positions at* $z = -105 \pm 5$ *mm for the lead targets and* $z = -152 \pm 5$ *mm for the calcium targets. (*$z = 0$ *is the hall pivot.) Each location must have a separate optics ladder, with a watercell target that can be operated remotely during the run. The relative positions of the optics and production targets must be within 1 mm at each location. Targets in each ladder must positioned relative to the center of the beam with a tolerance of 2 mm.*

A preliminary design for the scattering chamber is shown in Figures 4 and 5. Furthermore, a preliminary design of this assembly exists in an I-deas CAD model by Wayne Sachleben and Silviu Covrig.

Optics Ladder	
Carbon Hole	~ 0.1 g/cm^2
Watercell	
Tantalum foil	0.1 ± 0.05 g/cm^2
thick C	0.5 ± 0.1 g/cm^2
thin C	0.01 ± 0.005 g/cm^2
thin ^{208}Pb (PREX only)	0.05 ± 0.01 g/cm^2

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

CREX Physics	
Carbon Hole	~ 0.1 g/cm^2
^{48}Ca (tilted)	1 ± 0.1 g/cm^2
^{40}Ca	1 ± 0.1 g/cm^2
^{40}Ca	1 ± 0.1 g/cm^2
thin ^{40}Ca	0.2 ± 0.05 g/cm^2
thick C	0.5 ± 0.1 g/cm^2

Table 1: Targets required for PREX and CREX physics and optics calibrations.

The calcium production ladder should be able to be pulled back from the scattering chamber, behind a gate valve. Gas inlets should be used to provide the option of retracting the target, and purging the chamber with argon to product the target from oxidation in the event of vacuum failure in the scattering chamber.

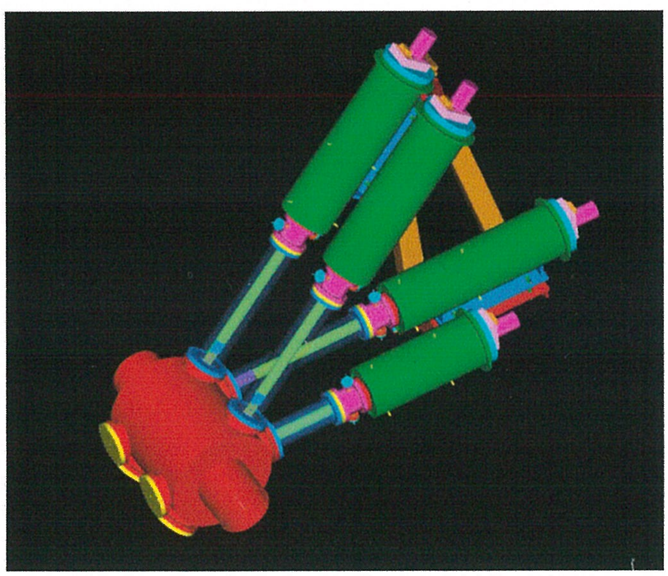

Figure 4: Perspective view of proposed scattering chamber.

Any use of elastomer seals in this region 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 2. These estimates were made using 1 cm thick HDPE cylinders, coaxial with the beam with length 10 cm, 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 many polymers.

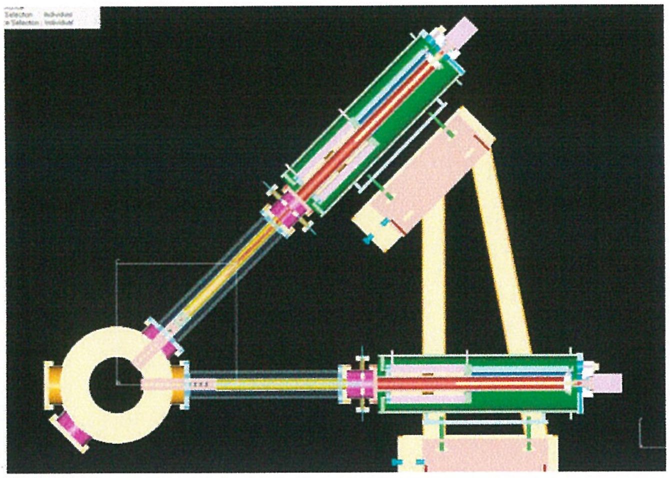

Figure 5: End view of proposed scattering chamber.

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

2.3. Collimator Box

Requirements: *The beamline aperture must be open with a radius of* 1.6 ± 0.1 *cm. The box must be aligned with the beam aperature centered on the ideal beamline to with 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 septum-bore vacuum vessels that transport the accepted scattered particles to the HRS. The box houses the beam collimator, and includes a housing for this collimator for easy removal. Sieve slits for optics calibration are also in this box. A tungsten shield is used to attenuate upgoing high-energy neutron flux, and the box is surrounded by high density polyethylene (HDPE) shielding to attenuate moderate energy neutrons.

This box will be made of aluminum. Only metals seals should be used on this vacuum enclosure. The septum bore vessels will attach directly to the downstream face of the vacuum box, while it will be necessary for the beampipe to attach to a flange on a extension pipe, welded into the scattering chamber box.

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 de-position.*

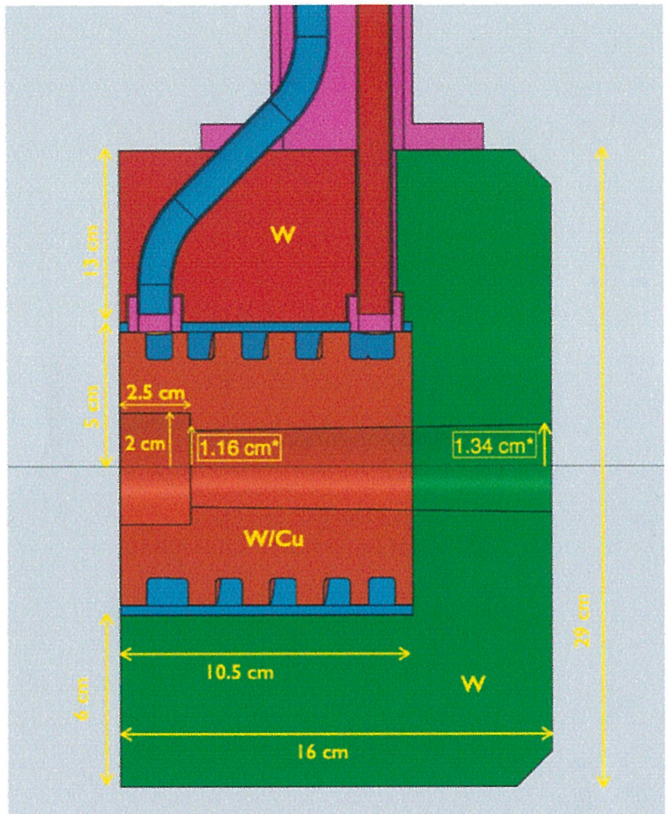

Figure 6: Side view of the beam collimator.

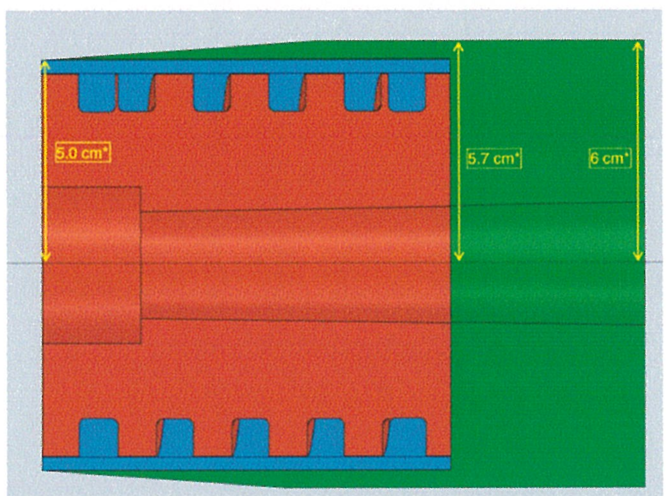

Figure 7: Top view of the beam collimator.

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 scintered 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 to water lines on the top of the collimator at each end. Dimensions are labeled in the illustrations in Fig. 6 and 7.

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 total power for production running expected to be about 2.1 kW. The water lines will run upward through the collimator jacket.

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. At least 2.5 cm of tungsten shielding on the upstream and downstream faces of the collimator is required.

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 feedthroughs 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 face of the collimator should be angled at 5° to align the sieve channels to the central angle of the PREX collimator. When used for CREX, the aperture through each sieve hole will be limited but acceptable.

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 septum will be used in 3-coil configuration, similar to the g2p configuration. Table 3 lists the expected parameters for operating the septum for each measurement. Shims will be use to reduce the vertical bore dimension, and so reduce the coil current and thermal power relative to

	PREX	CREX
$\int B \cdot dl$ (T·m)	0.49 (0.03)	1.21 (0.06)
Current (A)	430	1020
power (kW)	75	430
Water flow rate (gpm)	15	80
water temperature (°C)	20	20
differential pressure (psi)	100	100

Table 3: Expected parameters for maximum septum operation. The uncertainty is given in paraenthesis. At the moment, there are significant uncertainties in all parameters except the integrated field.

the required field integral. The shims are expected to reduce the vertical dimension by 1". The septum alignment is allowed a vertical tolerance of 1/4". The horizontal alignment tolerance of 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. Septum Vacuum Vessels

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. The cross-sectional vertical and horizontal dimensions of this box will be specified, and a keep out zone defined in CAD will be provided by the experiment. This vessel will be made of 1/4" aluminum, with aluminum flanges for each connection.

2.6.2. Septum Beam Pipe

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

The septum beampipe will be made with magnetic steel. It will be integrated with a rectangular, soft-iron box surrounding it to assist with magnetic shielding.

Additional magnetic shielding will be designed to cover beyond the flanges at the end of the vacuum beampipe. Each shield will be made of soft iron, and have 1/2" thick vertical walls. They will extend from over the rectangular beam shield to the collimator box on the upstream side, and from the rectangular beam shield to the vacuum vessel flanges connecting to the Q1 beam pipe.

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. 8. 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.

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.

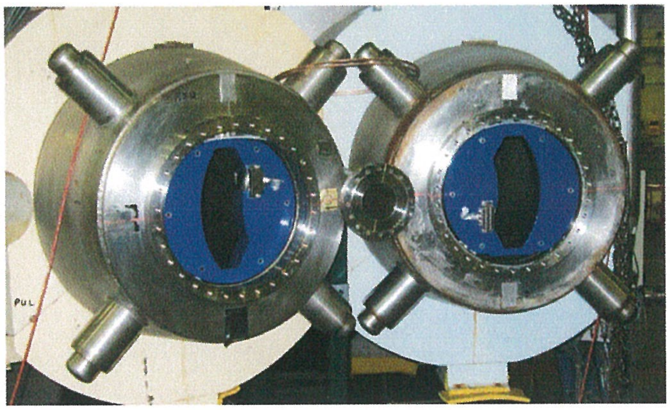

Figure 8: Q1 acceptance collimators installed for PREX-I.

2.8. Radiation Shielding

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

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. 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.

No dimensions for this shielding are critical, so tolerances on dimensions of the assemblies and positioning are more than 1 cm.

2.8.1. Calcium Target Skyshine Shield

A platform holding a 16 cm layer of lead above the lead target will attenuate high-energy, upgoing neutrons. Space available for shielding above the calcium target is restricted by the angled ancillary target mover assembly, so about half of the solid angle is covered. The mass of this assembly will be about 500 kg.

2.8.2. Collimator Skyshine Shield

A 6 cm thick tungsten block is positioned over the front of the collimator box, to attenuate upgoing neutrons from the collimator. The position of this block is restricted by the collimator housing. The block is 45 cm wide and 30 cm long (along the beamline). The downstream face of the block is about 10 cm upstream of the collimator. The mass of this shield is about 160 kg. An illustration of this shield is visible if Figure 9.

2.8.3. HDPE Neutron Shield

The proposed HDPE shielding around the collimator region is shown in Figure 9. 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.)

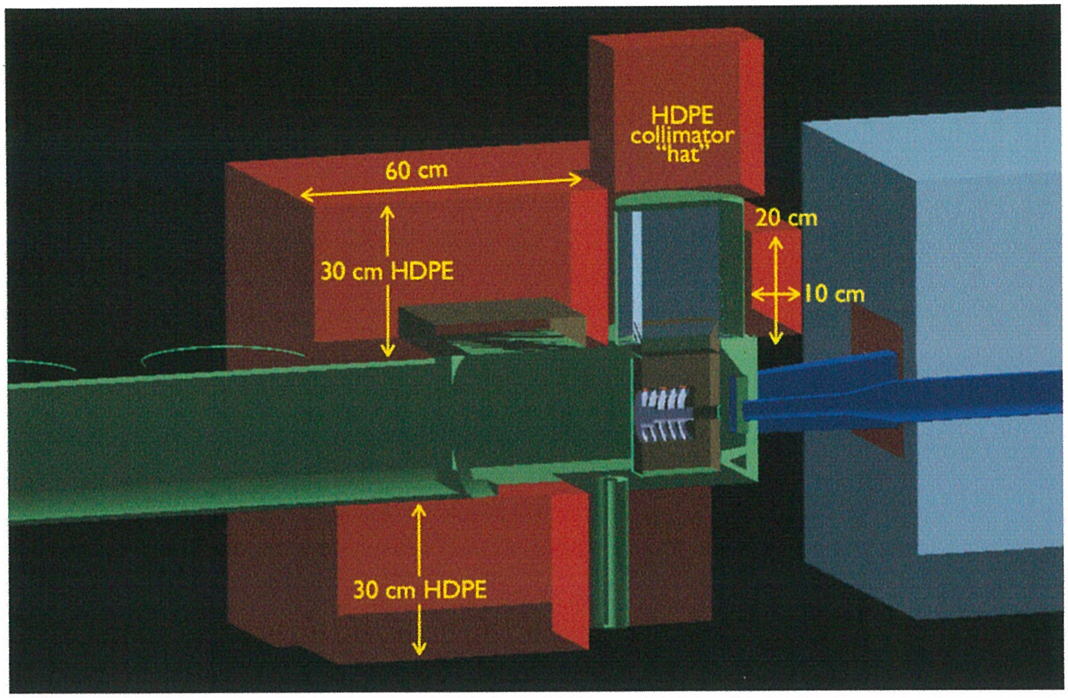

Figure 9: Perspective view (with vertical midplane section) of the pivot region with HDPE shielding.

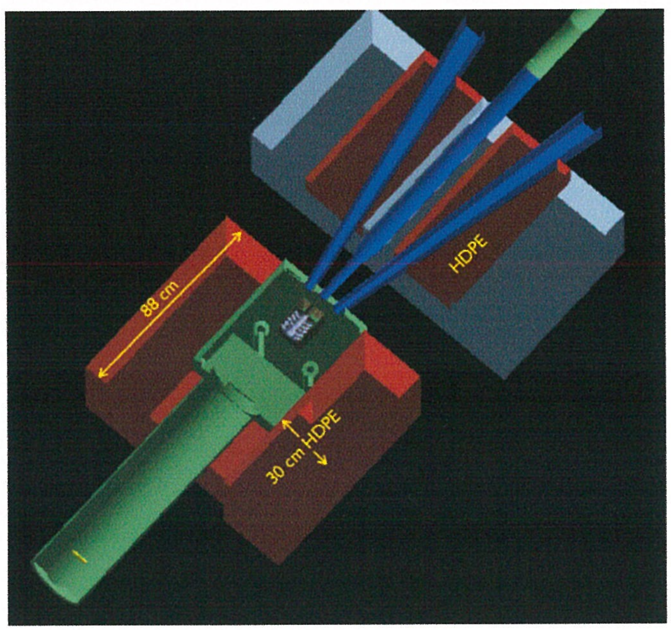

Figure 10: Perspective view (with horizontal midplane section) of the pivot region with HDPE shielding.

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 88 cm long, 70 cm high, and 30 cm thick.
- a layer on top between these shields, 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.

- a block between the 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.

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

Each 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 version of design document.