TITLE: **MOLLER Experiment Scattering Medium Considerations**

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Contents

Executive Summary 3

1. Introduction 4

2. Physics Criteria 4

  2.1 Description of the relevant geometry 6

  2.2 Comparison of the helium and vacuum configurations 7

  2.3 Source of backgrounds in helium configuration 9

3. Engineering Criteria 11

  3.1 Design and Assembly Criteria 11

  3.2 Operation and Safety Criteria 13

4. Summary and Conclusion 15

Appendix 16

Executive Summary

The April 2019 MOLLER Director's Review committee recommended assessing the impact of the additional material of the beam pipe in the central region in the helium configuration. There was a specific recommendation to complete and document the engineering analysis and cost estimates of the vacuum vs. helium gas choice, weighing the risks to other parts of the apparatus, and to commit to one design. The Spectrometer Group and He/vacuum "Task Force" have worked diligently since the April 2019 Director's Review to explore the possibility of using helium as a scattering medium in the MOLLER experiment. The engineers have worked on the pre-conceptual designs of the downstream magnet enclosure for both the vacuum and helium configuration, as well as more costing estimates. This information was entered into a Pugh matrix to aid in the decision-making process – refer to the appendix for an explanation of how the Pugh matrix works.

The physicists have performed extensive simulations of the backgrounds in the two cases, including air in the hall outside of the enclosures, beam pipes appropriate for the scattering medium in each configuration, as well as entrance and exit windows separating the magnet enclosures from the target scattering chamber and the hall. The conclusion is that the engineering benefits (including cost) of the helium option are far outweighed by the ability to achieve the necessary statistical and systematic uncertainty on the Physics measurement when operating in vacuum.

Therefore it is our recommendation to use vacuum as the scattering medium in both the upstream and the downstream magnet regions.

1. Introduction

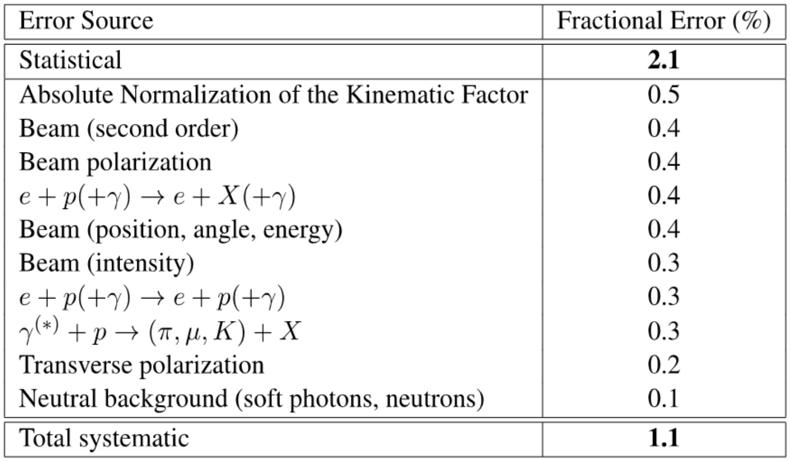
This document summarizes the relevant physics and engineering considerations for the choice of scattering medium, which were entered into a Pugh matrix.

This document is written to accompany version 14 of the Pugh matrix, which is organized into three main sections related primarily to Physics (Table 1), Design and Assembly (Table 4), and Operation and Safety (Table 5). Below we present information used to choose the weights and scoring in this Pugh matrix for each of these sections. The full Pugh matrix excel spreadsheet can be found in the MOLLER document database DocDB 514 .

2. Physics Criteria

The statistical and specific systematic uncertainties in the MOLLER experiment are listed in Table 1. Most of the systematic uncertainties related to the choice of scattering medium are due to the unacceptable increase of backgrounds in the helium configuration due to the need for a central beam pipe (explained in more detail below).

Table 1 – *Summary of the uncertainties in the MOLLER asymmetry measurement.*



Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization 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
Total systematic	**1.1**

From the parameters listed in Table 1, Physics criteria can be extracted for use within the Pugh matrix as shown in Table 2.

The most important criteria (indicated by weights of 10 in the Pugh matrix), are the acceptance of the experiment, (which is directly related to the statistical precision), and minimization of the charged particle background. Of equal importance is our ability to determine the sensitivity to beam position differences at the target, which will be compromised by backgrounds which vary in time. We will also be more sensitive to beam halo and spot size variations in the case of helium, because of the central pipe and the required shielding. The minimization of rate from neutral backgrounds as well as the ability to deconvolute the elastic and inelastic electron-proton scattering asymmetries are nearly as important as the aforementioned criteria, all of which are compromised in the helium case. The remaining criteria address the remaining (non-beam related) systematics uncertainties listed in Table 1.

Table 2 – *Physics section of the Pugh matrix comparing vacuum and helium scattering media. (Vacuum is the baseline or reference and helium is being compared to it).*

#	**Criteria (Critical to Quality)**	**Weight (1 - 10)**	**VACUUM (BASELINE)**	**HELIUM @ 1 atm**
	PHYSICS			
1	Charged particles in the background should be minimized	10	0	-1
2	Largest Physics acceptance (Statistical error)	10	0	-1
3	Sensitivity to beam halo	10	0	-1
4	Position sensitivity of background source	10	0	-1
5	Minimal sources of neutral background (soft photons, neutrons)	8	0	-1
6	Ability to determine the inelastic and elastic contributions in Moller ring	8	0	-1
7	Ability to measure the backgrounds from photo-production with auxiliary detectors	5	0	-1
8	Minimal material in the path of the secondary scattered particles (Moeller envelope)	2	0	-1
9	Normalization of kinematic factor	2	0	0

2.1 Description of the relevant geometry

The geometry of the magnet enclosures and related beampipes is shown in Figure 1, which shows a cartoon, roughly to scale but with an exaggerated aspect ratio, of the side view of an open sector. There is a detailed description of the figure in the caption. Indicated in the figure are the approximate locations (from beam center outward in radius) of the inner and outer photon envelopes, and the tracks generated in TOSCA for the elastic and moller electrons (colored by increasing θ_{lab}) in the center of the open sector. The magnet enclosures and beam pipes are designed to stay out of the path of scattered particles. The toroidal magnets would be located within their respective enclosures but are not shown here. The location of the downstream toroid is indicated by the contour plot of the magnetic field. The beam collimator (not shown) is located upstream of the upstream torus, immediately followed by the acceptance defining, or primary" collimator.

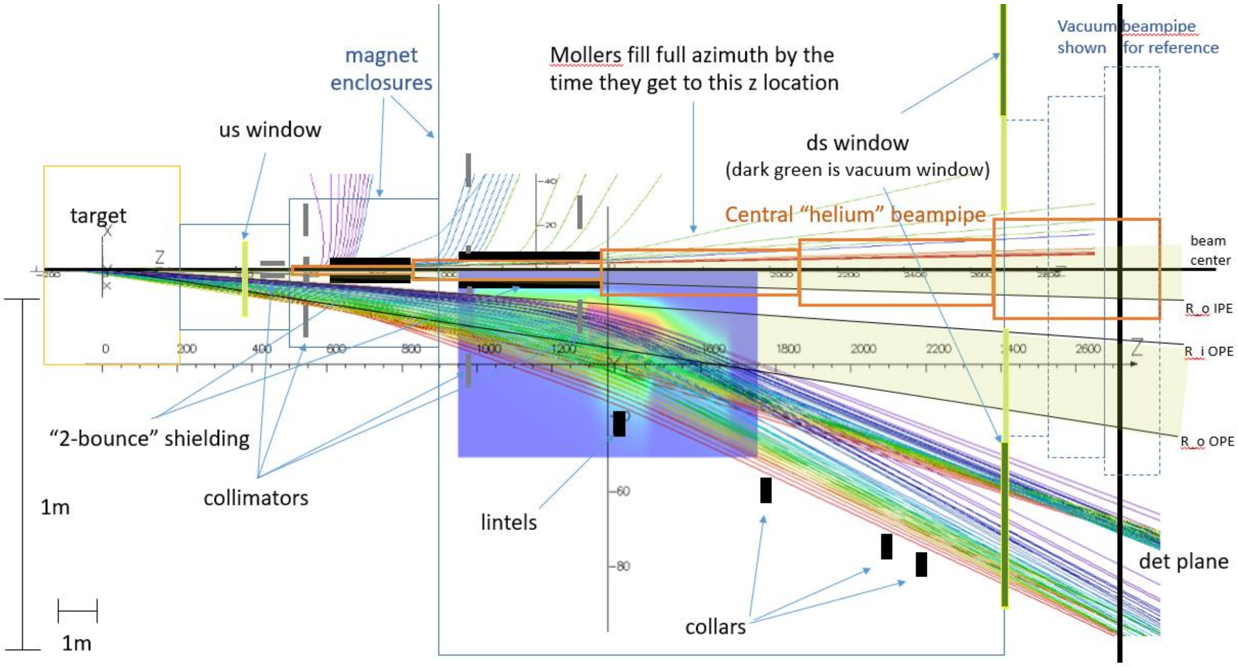


Figure 1 – *Cartoon of the MOLLER apparatus, highlighting the relevant geometry and the differences between the helium and vacuum configurations. The colored tracks, superimposed on a contour plot of the field in the center of an open segment, were produced in a TOSCA simulation. The beam is incident on the target from the left. Moller and elastic electron tracks are shown in bright colors extending to the detector plane. Approximate locations of the inner and outer photon envelopes (IPE and OPE, respectively) are indicated by yellow regions. Some of the shielding ("2-bounce", lintels, and collars) are indicated by black shapes. The locations of the upstream and downstream magnet enclosures are indicated by a blue line. The downstream beampipe for the vacuum case is indicated by a dashed blue line. The central helium pipe is shown in orange (number of telescopes actually much higher than indicated). The positions of the upstream entrance and downstream exit window for the magnet enclosures is indicated by green lines. The darker green lines for the exit window emphasize that the windows have a smaller radial extent in the vacuum configuration.*

The purpose of the first, or beam, collimator is to stop the primary beam particles that would not be transported cleanly to the dump entrance. The beam collimator itself becomes a source of background, however, it is localized and can be shielded. The shielding consists of the "2-bounce" shields, the primary collimator and the cleanup collimator (collimators 2 and 4 respectively). Stray fields in the center of the magnets will deflect charged particles in the central beam that have lost energy by radiating significantly in the target and make it through the beam collimator (shown as washed-out tracks in Figure 1). The low angle tracks shown correspond to a scattering angle of 2.4 mrad and were generated in four different energy ranges (1-10 MeV, 10-100 MeV, 100-1000MeV and 1000-11000 MeV), with ten equal steps in each range. Note that there are no collimators or shielding in the TOSCA simulation. The 2-bounce shielding will stop the lowest energy particles. The highest energy particles continue on to the dump. A relatively small range of medium-high energy charged particles are deflected onto the detector plane. The 2-bounce shielding, lintels and collars will be optimized to minimize the effect of this source of background.

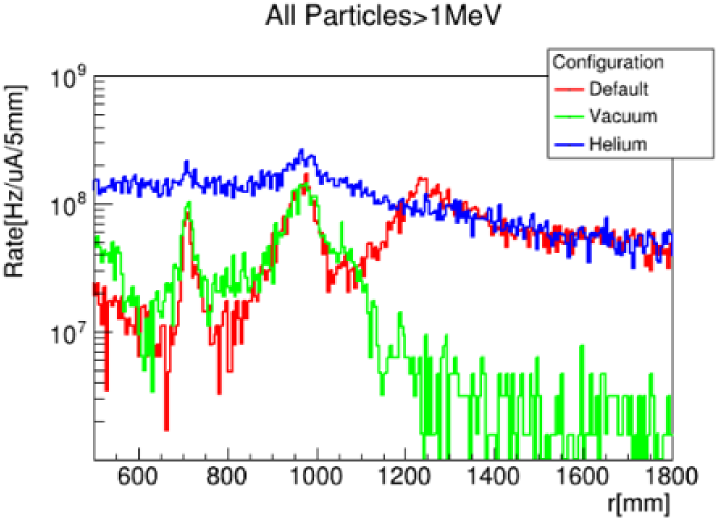


Figure 2 – *Plot of the rate-weighted radial distribution of all particles at the detector plane (z location of ring 5, the moller ring. The green (blue) lines are for a realistic vacuum (helium) configuration. The red line is for the default (historical) configuration. Note that the vertical scale is a log plot, and that a detector response factor of 1/300 has been applied for photons.*

2.2 Comparison of the helium and vacuum configurations

There are three configurations referenced in this document. The default, VVA and HHA configurations. The realistic vacuum and helium configurations are the VVA and HHA (vacuum, or helium, in both magnet enclosures, air between the end of the downstream enclosure and the detectors). The "default" configuration noted in Figure 2 and Table 3 is the one we have been using in simulation historically. It has real materials for collimators and coils, but no windows, lintels or collars,and vacuum everywhere. The rates for this default configuration are shown for comparison to the realistic vacuum and helium configurations, and because the charged particle rate is the primary electron rate from moller, radiated elastic and inelastic scattering (~170 GHz). The percentage of elastic and inelastic electrons need to be less than 15%.

Table 3 – *Summary of the charged and neutral rates for the default, vacuum, and helium configurations. Includes primary electron rates as well as charged backgrounds. Uncertainties are less than 10% (around 2% for the high energy range). Default case here is real collimators (includes slit scattering) but has no air or windows. The rates are also broken down by energy range (low – 1 < E < 10 MeV, mid – 10 < E < 100 MeV, high – E > 100 MeV. Note that the detector response factor of 1/300 has been applied for photons.*

Part	Conf\KE	All	Low	Mid	High
e±	Default	170	0	1	169
	VVA	205	33	12	159
	HHA	402	80	147	175
γ	Default	0.40	0.27	0.12	0.01
	VVA	1.07	0.72	0.28	0.07
	HHA	2.92	2.03	0.81	0.08

The beam and primary collimator, 2-bounce shielding, lintels and collars as well as the magnet enclosures and even the length of air are essentially the same in both the vacuum and helium configurations. There are significant differences between the exit window and beam pipe downstream of the downstream magnet enclosure in the two configurations. The downstream beampipe in the vacuum configuration can have a much larger radius. It fits between the outer radius of the outer photon envelop and the inner radius of the elastic electron envelop. As seen in Figure 1, there also needs to be a “central” beampipe in the helium case, and this pipe must fit between the outer radius of the inner photon envelop and the inner radius of the outer photon envelop, including in the downstream section.

The radial distributions at the detector plane for the different configurations are shown in Figure 2 with totals for the moller ring provided in Table 3. The helium configuration (blue) shows a significantly higher background rate over the whole radius than the vacuum case (green). Our uncertainty estimates and pre-conceptual shielding designs have assumed a small charged particle background (mostly from the elastic radiative tail and the inelastic electrons), and a “raw” photon rate approximately equal to that of the primary electrons.

As can be seen in the table, the VVA option has higher contributions from both charged and neutral backgrounds than the default simulation. This is not unexpected; the shielding was optimized without taking into account slit scattering, and with optimization these background levels can be minimized. In the helium configuration, the charged background rate is equal to the primary rate, and the neutral (photon) backgrounds are nearly three times as big as in the vacuum case (with a detector response factor of 1/300). The background charged particle rate in particular must be mitigated in order to achieve the statistical and systematic goals, since charged particles of any energy above a few MeV produce the same number of photoelectrons in the quartz tiles. Even more concerning is the source of those backgrounds.

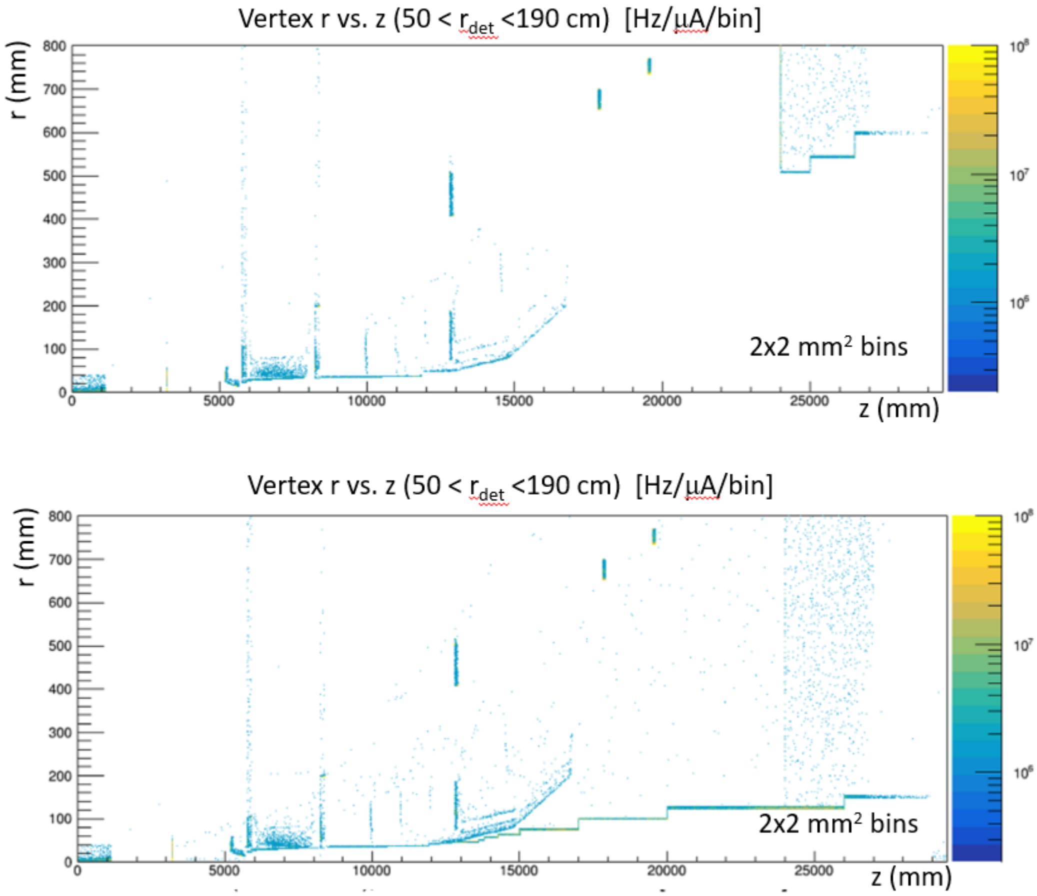


Figure 3 – *Rate weighted 2D plots of the origin of all particles in the vacuum case (top) and the helium case (bottom) in square bins (summed over the whole azimuth – all 7 coils). Shows the source of background particles that hit the detector plane in a radial range that includes the entire detector array (vertical and horizontal scales are not the same). Note that the rates per bin are higher (more light green/yellow) in the helium configuration. Note that you also need to integrate over the whole picture – not only is rate density higher but there is more material acting as a source.*

2.3 Source of backgrounds in helium configuration

The increase in backgrounds in the helium configuration is not primarily due to the presence of the helium itself, but rather due to the need for a central beampipe. In the vacuum configuration, the charged particles which are deflected through large angles (and are not shielding by the "2-bounce" shielding) interact with the vacuum vessel at a radius which causes the resulting background to miss the detector region (including the light guides and PMTs). Those that are only slightly deflected can still make it cleanly to the dump. In the helium configuration, however, all of those deflected charged particles interact with the central beampipe. The pipe subsequently becomes a significant, extended source of both charged and neutral backgrounds (see Figure 3).

At this point in time we do not have a viable solution for mitigating this new source of background (z-range from 15000 to 24000 mm and r-range from 50 to 120 mm in the bottom panel of Fig. 3) in the helium configuration to an acceptable level. The extent of the beamline is simply too large, and would require significant shielding. Consider cylindrical shells of high z material encasing the central pipe. They would need to be quite thick, and it is likely there is not sufficient room between the inner and outer photon envelopes. This would require a redesign of the beam collimator and/or the inner radius of the acceptance defining collimator (affecting the statistical precision).

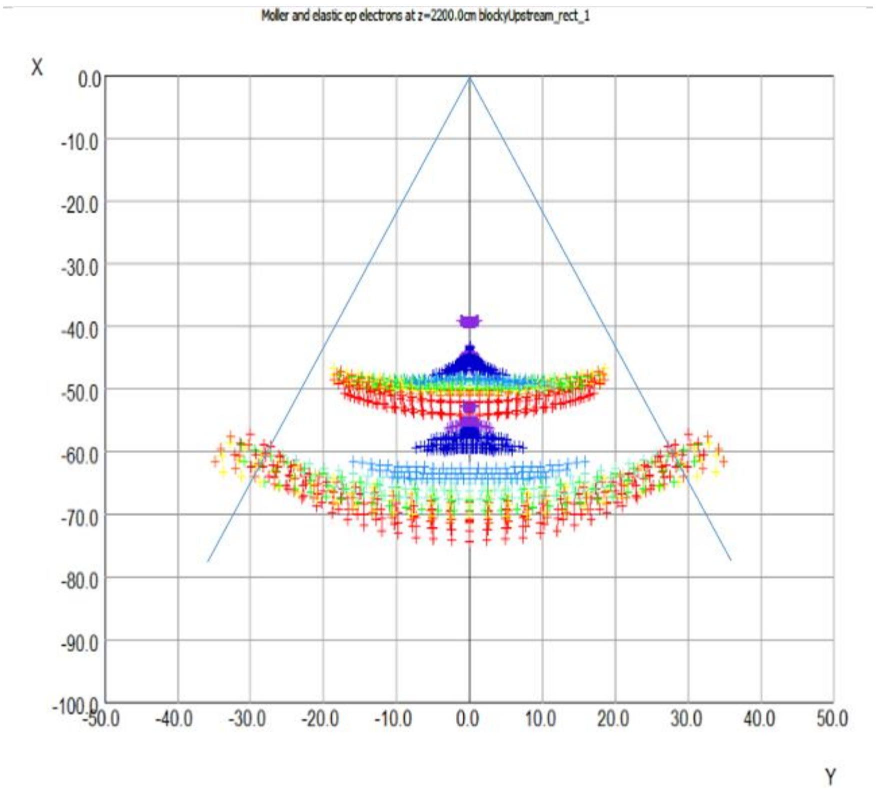


Figure 4 – *TOSCA plot of the hit ('+' symbols) distribution of unradiated primary moller and elastic electrons at the midpoint between the detector plane (z location of ring 5, the moller ring) and the z location where the mollers fill the full azimuth. This is a possible location for supports which would go into the beam center in order to support the helium pipe and its required shielding. The colors correspond to scattering angle (blue is approximately 5 mrad, red is 21 mrad). The beam center is at (0,0). The elastic envelop is at lower radius (X~ -50 cm). The and the moller envelop is at larger radius (X~70 cm). The blue lines extending from the beam centerline indicate the edges of the septant. Note that the moller envelop from this septant would overlap the envelop from the adjacent septant.*

Assuming a shielding solution were found, it would be impossible to support it without reducing the acceptance of the experiment. The moller envelop fills the full azimuth beginning near the end of the downstream torus (see Figure 1). No supports can reach into the inside radius of the moller envelop between this point and downstream of the detectors, or the acceptance of the experiment will be reduced. This means that it would be difficult, if not be impossible, to support the central beampipe in the helium configuration without reducing the acceptance. With shielding designed to shield the entire length of the pipe, supports from the floor to the beampipe in this long stretch will certainly be required.

A significant reduction in acceptance (corresponding to a decreased statistical precision in the absence of increased running time) would result if such supports were needed. Figure 4 shows the moller envelop in a single septant extending beyond the edge of the septant; if the envelop for the adjacent septant were plotted, they would overlap and the center of the overlapping portion would be the blue line. Without actually designing supports, but with modest assumptions for their thickness and factoring in the need for clearances, we estimate a reduction in the statistical precision by at least 30%. This does not take into account the effect on the systematic uncertainties or the risk in adding material that will become a source just before the detectors.

3. Engineering Criteria

3.1 Design and Assembly Criteria

The Pugh matrix for the criteria that fall under design and assembly is shown in Table 4. Even without factoring in the additional shielding and engineering needed to design the supports for the central beampipe and the shielding, the cost differential between the helium and vacuum configurations is not as large as originally thought. This eliminates one of the drivers for considering this option initially.

The presence of the central beampipe in the helium configuration will necessitate ~10-100x more precise positioning (not yet studied) in order to keep helicity-correlated beam properties associated with backgrounds under control. Irrespective of whether the internal environment is helium or vacuum, the ability to see, access and service the magnets will be difficult in either case once the magnet is enclosed within its enclosure. Hence, the additional assembly time, alignment time and alignment-related hardware included in the costs. We have a conceptual design for Collimators 1 and 2, where they have been integrated to form one component, which can then be aligned more easily and assembled with the upstream torus before installation in the hall. The downstream torus coils will also be aligned during assembly (outside the hall) on its strongback/frame structure - using adjustable bolts and shims - we aim to be able to align the coils with respect to each other and the geometrical (mechanical) center of the entire magnet assembly within the required tolerances provided by the collaboration.

It is likely that the mechanical (geometric) center of the magnet coil/strongback/frame assembly may not coincide with the magnetic optic center (i.e. the null point). Our current plan and costs therefore also allow for low current energization of the magnet, (with the vacuum chamber ends still open), and field measurement to determine where the magnetic axis is with respect to the geometrical axis.

We have a simplified cylindrical vacuum chamber (to keep design and fabrication costs low) with removeable end flanges which will allow us to 'shoot' our alignment lasers along the Z-direction during installation in the hall - the individual coils should not need any further adjustment at this stage. The entire vacuum chamber has been designed with adjustable supports, which will allow us to move the entire chamber (with the magnet inside) to ensure that the geometrical center, the beam line center and the collimator centers are aligned within the required 1 mm. Admittedly this will be a challenge, so we have allowed for additional time and multiple surveys during the installation phase.

Coil movement when pulling vacuum is a concern - we have some ideas to ensure that the magnet weight is transferred to its support legs and frame, which are much more massive structures, and should therefore experience less movement. The adjustable chamber supports can also be used to allow for this movement. The chamber will also have optical ports with graticules marked on the magnet structure so that any movement can be visually observed during pump down and coil energization - in case we have to adjust the whole vacuum chamber position slightly.

Installation will actually be more difficult in the helium configuration because of the presence of the central beam pipe.

Penetrations for a one atm helium enclosure or for a vacuum enclosure would be about the same. For both cases, all penetrations will have to be leak tight. The upstream window will be in place in either configuration to separate the target scattering chamber and the magnet enclosures. This window should be easier to design in the vacuum case because the pressure difference is less. In either case this window may need to be cooled.

With regards to the pumping system, the set up is likely to be less complicated and therefore less expensive for the helium case as fewer pumps will be required to pump down the enclosure and then let it up to a helium atmosphere. For the vacuum case, depending on what level of vacuum is required, outgassing from non-vacuum-friendly components (e.g. epoxy in the coils and trapped volumes) might necessitate the use of a cryogenic panel to assist with the removal of these contaminants. If we require a vacuum level of about 1E-4, it appears that two large turbo pumps could handle the load, but it obviously depends on actual out-gassing rates. The large turbo pumps are included in the costs. We have also included for a LN2 cryogenic panel and a transfer line in the costs, in case the pumps cannot handle the outgassing or micro-water leaks. In order to minimize or even eliminate water leaks within the chamber, we could redesign so that only brazed and welded connections reside within the chamber - unfortunately this means more penetrations through the vacuum wall.

The vacuum chamber will be non-magnetic – primarily aluminum with non-magnetic bolts – this has all been included in the estimated costs.

Table 4 – *Design and Assembly section of the Pugh matrix comparing vacuum and helium scattering media.*

#	**Criteria (Critical to Quality)**	**Weight (1 - 10)**	**VACUUM (BASELINE)**	**HELIUM @ 1 atm**
	DESIGN AND ASSEMBLY			
1	Alignment tolerances	10	0	-1
2	Ability to align individual coils relative to one another outside of the enclosure	5	0	0
3	Ability to align complete magnet assembly + enclosure after installation wrt to the beam line.	5	0	0
4	Ease of installation of the magnet and enclosure	4	0	-1
5	Ability to validate alignment of coils within the closed enclosure at the level of specified tolerances	10	0	0
6	Ease of penetrating environmental enclosure - for services (water, power, instrumentation, mechanical linkages)	4	0	0
7	Upstream window	6	0	0
8	Smaller (less complicated?) pumping system	3	0	1
9	Reduced use of less strain-tolerant components (e.g. ceramic breaks for electrical isolation)	4	0	1
10	Lowest cost	3	0	1
11	Significant additional shielding for the He case	6	0	-1

3.2 Operation and Safety Criteria

The Pugh matrix for the operation and safety criteria is shown in Table 5. As with the design and assembly criteria, we considered most of these to be a wash between the helium and vacuum configurations (resulting in a score of 0). Getting access into a one atmosphere helium enclosure should generally be more straightforward, but not significantly so as the enclosure would still need to be let up to air and seals would still have to be broken.

The downstream window must be vacuum safe and therefore thick enough to support the vacuum load. This is not a concern with the helium, however in this configuration the window has 2x the radial extent of window in the vacuum configuration, and the support load has to be considered.

An upstream window in the vacuum case will mitigate the risk of a water leak spoiling the beam line vacuum or cryopumping on the target. An US window has been included in the physics simulations for both the helium and vacuum configurations with appropriate thicknesses.

A one atm Helium atmosphere removes the risk of any coil movement due to pump down - as there is no pump down necessary. There are ways to control this even in the vacuum case.

If beam tube is present AND we use it to locate coils, damage to the windows due to coil motion on pump down could occur, but there is not much risk here if we put appropriate bellows in line.

Field will be "mapped" during tracking measurements; field mapping outside of the enclosure is more for quality control.

There is no additional ODH risk in Hall A from a helium environment. If one were to go into a shielding bunker or into the enclosure while filled with Helium that would be a risk but this is so easily handled.

Sensitive pressure and flow instrumentation will be needed. Leak rate should be very small so risk is low. Vacuum does not need to be very "good" for the optics, however it needs to be low enough so as not to promote voltage breakdown.

Within a vacuum environment, depending on the required vacuum level, outgassing may be an issue.

Table 5 – *Operation and Safety section of the Pugh matrix comparing vacuum and helium scattering media.*

#	**Criteria (Critical to Quality)**	**Weight (1 - 10)**	**VACUUM (BASELINE)**	**HELIUM @ 1 atm**
	OPERATION AND SAFETY			
1	Ease of maintenance - e.g. how easy would it be to get into the enclosure to make repairs	6	0	0
2	Downstream window must be vacuum safe and therefore thick enough	5	0	1
3	Minimal corrosion issues from air leakage into environment	1	0	1
4	Minimal movement due to thermal expansion/contraction of coils	8	0	0
5	Water leak spoils beam line vacuum, cryopumps on target	5	0	0
6	Chance of arcing due to gas/vacuum around coils	5	0	0
7	Chance of coils moving after alignment due to pump down	8	0	1
8	Risk in damaging window due to magnet motion	5	0	0
9	Ability to map magnet outside the enclosure	6	0	0
10	Ease of replacing a bad coil pack and realignment	4	0	0
11	Low Oxygen Deficiency Hazard conditions	5	0	0
12	Damage to PMTs due to Helium contamination	5	0	-1
13	Minimum outgassing of materials within magnet enclosures	3	0	1

4. Summary and Conclusion

The result of the Pugh matrix analysis is -61 for the helium option. Given that the weights can be somewhat subjective, the result was checked with equally weighted criteria, the result for the helium alternative is still negative. The impact on the ability to achieve the required statistical and systematic uncertainties is extremely detrimental in the helium case. In fact, at this time we do not have a viable helium configuration. It would take considerable effort (both physics simulation and engineering design) to come up with a possible helium configuration. Even were we to achieve one, that the engineering challenges and cost would be such that the benefit would no longer exist. Therefore it is the recommendation of the Spectrometer Group and Helium/Vacuum task force that the MOLLER experiment move forward with a vacuum configuration for the magnet enclosures.

Appendix

A Pugh matrix is a simple tool for methodically making a choice from several alternatives. “Pugh” comes from its originator, Stuart Pugh. It is most useful when there are two viable choices and there is poor buy-in from different members of a team, or if there is a design decision or policy that keeps being attacked or reconsidered. A set of criteria relevant to the choice of alternatives are listed. Each criterion receives a weight factor (1-10) denoting its relative importance compared to the other criteria, and then the alternatives are scored (-1, worse or +1 better) relative to the baseline (scored as 0). The team members then attempt to agree on the relative weights and the scores. Although the weighting may still be somewhat subjective, the scoring is less so. If the total for an alternative is negative, that means it is worse than the baseline.