DRAFT: Meeting the MOLLER Beam Requirements

January 2019

1 Introduction

This document reviews the outlook for meeting the beam requirements for the MOLLER experiment. The first section discusses the “standard” helicity-correlated beam asymmetries (HCBA), including differences in the intensity, position, angle, energy, and RMS spot size between the beam helicity states. As summarized in this section, requirements for MOLLER are close to what has been achieved in previous experiments, and it is expected that these requirements can be met without significant new investment.

The second section deals with the ”asymmetric halo” issue that is primarily related to the Qweak experience. The nature or source of this halog during Qweak is not precisely defined. At this time, there is no specific hardware changes that are proposed to fix this asymmetry halo. This section describes the effects seen in Qweak, and presents tools and techniqus that can be used to study this during PREX/CREX in 2019.

2 Helicity-Correlated Beam Asymmetries

The so-called "standard" HCBA have traditionally been quoted as the zeroth and first moment of the asymmetry in the beam intensity profile in the experimental hall. These are measured by RF monitors, typically using cavity monitors for intensity and strip-line monitors for position. There is no monitor that isolates the second moment of asymmetry in the intensity profile, but a bound on the RMS spot size asymmetry is typically quoted using observations of the laser in the polarized source.

The most demanding requirements concern the run-averaged values for the beam asymmetry. Noise (or "jitter") in the intensity or trajectory of the beam obscures the true systematic asymmetry generated at the polarized source, with precision on small beam asymmetries achieved by integrating over periods of time. It is expected that MOLLER will use feedback techniques for both intensity and position differences that will promote faster convergence of statistical noise in the HCBA, as well as greatly reducing any systematic asymmetry.

In addition, there will be several "slow reversals" for the asymmetry measurement. These change the polarization state in the hall relative to the recorded helicity and relative to the voltage applied to the Pockels cell. Three methods will be using: an insertable half-wave plate in the laser optics of the polarized source, spin manipulation with the Wien filter and solenoids in the electron beamline in the low-energy region of the injector, and a small change in the beam energy which changes the $g-2$ spin precession between in the injector and the experimental hall by a half-integer rotation. The quoted goals for the run-averaged HCBA are assumed to be averaged over data sets using the slow-reversals, which will further suppress any systematic asymmetries generated in the polarized source. This suppression is most critical for the spot-size asymmetry, which cannot be directly measured and must be bounded to provide a large margin of safety.

The requirements for these HCBA are summarized in Table 1, along with the beam parameters previously achieved in the HAPPEX-II (3 GeV in 2005) and Qweak (1 GeV in 2010-2012) experiments. The anticipated improvements that will lead to success for the MOLLER experiment are described in more detail below.

	HAPPEX-II (achieved)	Qweak (achieved)	MOLLER (required)
Intensity asymmetry	400 ppb	30 ppb	10 ppb
Energy asymmetry	0.2 ppb	0.4 ppb	< 0.7 ppb
position differences	2 nm	2.5 nm	1.2 nm
angle differences	0.25 nrad	0.1 nrad	0.12 nrad
size asymmetry (quoted)	–	$< 10^{-4}$	$< 10^{-5}$

Table 1: MOLLER beam asymmetry requirements compared to the approximate magnitude of run-averaged asymmetries achieved in previous experiments.

Intensity Asymmetry For previous measurements, the intensity asymmetry was controlled well within required limits. Intensity jitter has not been found to be a limiting factor. The limits for control of the intensity asymmetry will be determined by feedback efficiency and data set selection. With a greater focus on this parameter, it is expected that current technology will be able to meet the MOLLER intensity asymmetry requirement.

Position and Angle Differences In previous experiments, position and angle differences in averaged to small values that approach the design values quoted for the MOLLER experiment. It is worth noting that these run-averaged values required significant cancellation over the full data set, and might be considered fortuitous. For this reason, additional efforts to suppress position differences are planned beyond the work that was so successful in past experiments.

The MOLLER collaboration has set an ambitious goal to achieve position differences of 20 nm or less in the early injector. In addition, it is expected that cancellations via slow reversals will further suppress position differences by a factor of 10 (this is consistent with past experience). The collaboration also aims for a factor of 100 suppression of position differences from adiabatic damping. Finally, it expects to use feedback to drive faster convergence of the position noise, and this should reduce position difference an order of magnitude or more.

Taken together, these goals would imply that position/angle differences at the level of 0.002 nm (and approximately 0.0002 nrad) would be achieved. This would be a full factor of 500 better than the MOLLER goal.

The goal of < 20 nm in the injector would about a factor of 10 better than what has been previous achieved for Qweak and for PREX (before cancellation with slow reversals). The introduction of transverse Pockels cells, and in particular the incorporation of control of the steering effects caused by electric field gradients, provide sufficient degrees of freedom to suggest that 20 nm is achievable. In addition, the new Pockels cell incorporates a precise mechanism for position control which will be suitable for feedback. Recent beam tests have shown that position differences of about 5 nm can be achieved in 30 minutes.

Qweak used helicity-correlated correction magnets to reduce position differences. The system was stable, so that it was only necessary to adjust the corrector set points daily. The use of the transverse Pockels cell with dynamic feedback will be a significant improvement.

HAPPEX-II saw a reduction of position differences from the injector to the hall of a factor between 10 and 30. This is compared to a theoretical maximum reduction (in the 3 GeV hall, compared to the 100 keV injector) of about 95, so HAPPEX-II realized 10-30% of the benefit from adiabatic damping[1]. For MOLLER at 11 GeV,

---

[1] QWeak did not run with optimized design matching, at the choice of the collaboration who did not invest the time for a systematic match through beam delivery. The position differences in the injector were as small as had yet been achieved during JLab operations, but in the experimental

it is expected that the injector will be higher energy (up to 200 keV in the injector), suggesting that the emittance should be reduced by a factor of $p/p_0 \sim 22,000$, and the position differences by about a factor of 150. Simply scaling this maximum compared to the HAPPEX-II experience suggests a factor of 15-50 improvement in position differences[2].

For MOLLER, it is reasonable to expect that the match to design optics will be much better than in the 6 GeV era. One significant factor is improvements in beam diagnostic procedures, such as the Raytrace utility for measuring beam emittance throughout the accelerator. In addition, plans for an increased injector energy (from 100 keV to 200 keV) and reduced phase-space coupling in the injector (from reorganization of injector optics and new 1/4-cryo cavity) will reduce the single largest source of phase space correlations. These improvements will be combined with recently developed analysis techniques that make matching more deterministic and routine, such as is used in the Optics Restoration and Finalization Procedure (ORFP) matching. It is reasonable to expect that the optics should more closely match design and the adiabatic damping should be improved relative to previous attempts. The benefits of such techniques will be tested in the PREX/CREX experiments in 2019.

While it has not been proven that the nominal goal of a factor of 100 can be achieved, it is a reasonable target. The technical risk in not achieving it is covered by the improved source laser control, feedback and slow reversals.

Size Asymmetry There has not been a method for measuring, or adjusting, the spot size asymmetry for any previous experiments. Bounds have been placed on the possible helicity correlated spot-size asymmetry through measurements of the spot-size asymmetry on the laser beam (including both the intensity and "Δ-phase" polarization profiles), with a safety margin to account for reasonable models of photocathode non-uniformity. This approach will be used again to achieve the required spot-size asymmetries for the MOLLER experiment.

Beyond the bound that will be achieved on the laser spot size asymmetry, there is an additional suppression of this effect for the MOLLER experiment due to the injection of stochastic noise through synchrotron radiation. This noise increases the emittance of the beam, but does so in a manner which is independent of the helicity-correlated asymmetries from the polarized source. The emittance at the high energy hall is seen to be a factor of 10 times larger than the minimum emittance observed, before significant synchrotron emission noise is added. This can be modeled as an

---

hall there was no evidence of adiabatic damping, if fact, the position differences were measured to be larger than in the injector.

[2] In this discussion, the increase in emittance due to synchrotron radiation at high energy has been neglected. The helicity-correlated position differences are not affected by the addition of this stochastic noise - it is not truly the emittance of the beam that determines the reduction of the HCBA, but rather the compression of the transverse dimension of motion due to the relativistic boost. The addition of non-helicity-correlated noise (through synchrotron radiation) is not relevant in this case.

addition of noise σ_S to the original beam size in the injector σ_I:

$$\sigma = \sqrt{\sigma_I^2 + \sigma_s^2} \tag{1}$$

Because a helicity-correlated change in the spot-size has an effect that scales with the beam size, it is the spot-size asymmetry that matters. The spot size asymmetry in the hall comes from a difference in spot size:

$$\delta\sigma = \sqrt{(\sigma_I + \delta\sigma_I)^2 + \sigma_s^2} - \sqrt{(\sigma_I - \delta\sigma_I)^2 + \sigma_s^2} \tag{2}$$

leading to a spot size asymmetry in the hall that compares to that in the injector as

$$\frac{\delta\sigma}{\sigma} = \left(\frac{\sigma_i}{\sigma_s}\right)^2 \frac{\delta\sigma_i}{\sigma_i} \tag{3}$$

This leads to a factor of ~ 10 suppression in the spot size asymmetry at high energy, relative to the bounds achieved at lower energy.

Summary of "standard" beam asymmetry challenges for MOLLER As has been described above, the beam asymmetry requirements for MOLLER all appear to be well within existing technology. The most significant technical advance that will enable these goals are the new Pockels cell technology in the source. The anticipated improvements in the polarized source (such as the higher photogun voltage and upgraded 1/4 cryounit) are expected to help achieve a match to the optimized beam optics design. In addition, new diagnostic and analysis tools will improve the matching procedure throughout the accelerator. These accelerator improvements will provide a significant margin of safety.

3 Beyond the usual PQB

The Qweak experiment saw a significant false asymmetry that was ascribed to a helicity-correlated change in the beam distribution on target. This is often referred to as a “halo” effect. It should be noted that there is not clear evidence to tie this effect to a specific technical definition of “halo”.

Three separate detector systems observed this false asymmetry. The main detectors for the experiment were one of these. Another was the “lumi” monitors, which measured slightly lower angle scattered particles than the main detector but in line-of-sight of the target and with no magnetic field to sweep away low energy Møller scatters. The so-called “auxiliary” detectors, composed of portions of a detector (such as a bare PMT, or a PMT with just the light guide) which were placed out of the elastic stripe near the main detectors, also saw the asymmetry. The ratio between the false asymmetry observed in each detector system was fairly constant throughout the run.

While the consistency between the detector systems allowed for sufficient correction for the Qweak result, the characteristics of the beam that led to this effect were never precisely determined. Measurements taken while blocking the spectrometer aperture for some octants were able to demonstrate an asymmetry background signal that corresponded to the observed background asymmetries during production running. This asymmetry of this component could be changed with quad settings in the beam line (presumably changing the beta function at the target to enhance or suppress the effect of an asymmetric halo), or by changing the laser phase relative to the master phase. These observations are consistent with some beam halo interacting with the beamline or collimation, but not definitive about the shape, extent, or source of the halo.

There is more than one candidate for the fundamental cause of such an asymmetric beam halo. Injector studies showed asymmetries in the longitudinal RF beam bunch profile, but it is not yet clear how to connect this to the observed asymmetric halo effects. Other models under consideration are bleed through from other halls, or fringes in the laser beam spot on the source photocathode producing asymmetric halo distributions well off of the central electron trajectory.

Studies using the Hall A SAMs One intriguing aspect was that each of the Qweak detector systems that observed these “halo” asymmetries was seen to be significantly non-linear with the measured beam current. This non-linearity was not constant in time, with large variations in magnitude and even at some some points changing sign. The effect was different in magnitude for each detector system, but these varied together, so a larger-than-average non-linearity observed in the lumi monitors would predict a larger-than-average non-linearity in the main detectors.

To explain these observations, a model was proposed in which the beam was asymmetric in some halo region, which was less likely to produce signal in the detectors (presumably due to geometric acceptance effects). The beam current monitor is not very position sensitive, so it would accurately measure the average current fluctuation even while a spatial distribution to the intensity asymmetry would change the average asymmetry in any given detector. The largest false asymmetries are seen at times when the non-linearity over the charge noise is seen to be greatest.

This provides some hope for a convenient diagnostic tool. In Hall A, Small Angle Monitors (SAMS, formerly known as "LUMI" monitors) in the beamline between the target and the dump provide high-rate monitoring of small-angle scatters from production targets. They have extremely well-understood linearity and noise characteristics. When used at high beam currents with a moderately thick target they can provide a high precision test of the non-linearity of detector relative to the intensity jitter of the beam. In addition, at these small scattering angles the parity-violating asymmetry is expected to be very small. These detectors will be installed during the PREX-2 and CREX experiments, and will be used in investigations of both non-linearity of their response to beam intensity noise, and in the measurement of systematic "false" asymmetries that could be caused by halo. In addition, the "halo" monitor which can be used to investigate the intensity of a position halo or tail will be available for beam studies in Hall A.

Summary of plans for MOLLER As described above, during the PREX/CREX run period we will attempt to use the non-linearity of small-angle monitors over the measured beam intensity noise as a tool for studying this asymmetry halo. It is hoped that this can establish a diagnostic technique, which can correlate an observed effect with other diagnostics in the injector or accelerator. The results of those studies will also help inform planning for continuing these studies opportunistically during subsequent 11 GeV running.

The design of the MOLLER spectrometer will attempt to remove any "single bounce" path from the target or primary beam collimator to the Moller detectors. Simulations will estimate how backgrounds in the signal region vary with position on the collimator and target, allowing estimates of the possible effect of a range of halo distributions.

Clearly more information is needed to demonstrate that this possible effect is fully controlled for MOLLER, but existing hardware and technology appear to provide the necessary tools for testing the effect in advance of the MOLLER production runs.