Functional Requirements for the MOLLER Polarization Orientation Feedback Control

Executive Summary

MOLLER requires that the beam polarization orientation, averaged over data collection, is within ±0.03° of longitudinal such that the total transverse polarization fraction $P_T/P_L < 0.05\%$. This bound exceeds the precision of the techniques used to configure the spin launch angle to the halls, and the expected long-term stability of the beam launch angle and precession during transport. For this reason, MOLLER will require periodic feedback to control the spin orientation suitably close to pure longitudinal over the course of data collection.

The frequency of feedback on the spin orientation will need to be responsive to observed running conditions. The transverse polarization will be monitored by the MOLLER apparatus, with a precision on each component of transverse polarization of 1–2% corresponding to 0.5°–1° in spin orientation in 4 hours of continuous data taking. This diagnostic measurement which will enable the prescription of small ($\sim 1^\circ$) corrections to the spin orientation at a suitable time scale to achieve the ultimate requirement on the average transverse polarization.

The correction mechanism should be capable of approximately 1° changes with a precision of 0.25° performed as often as once per shift which, assuming steady running at moderate (80%) efficiency, would be the highest frequency that the MOLLER apparatus could support at 1° precision. The more likely scenario is that the spin orientation will stable within about 1° over the course of about a day, and so the best frequency for feedback would be once per day. Greater stability in the spin orientation would allow for longer timescales, but only with a higher precision in the correction mechanism to take advantage of smaller correction prescriptions.

The subsequent sections of this document provide background information to further explain this functional requirement.

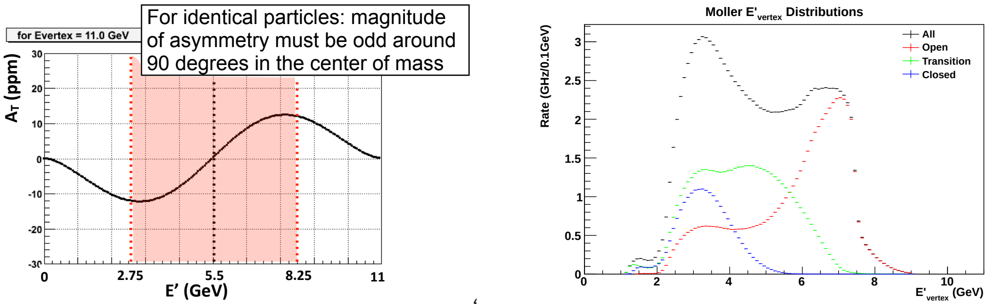
1 Transverse polarization asymmetry in the MOLLER apparatus

The acceptance for the MOLLER measurement includes electrons that are elastically scattered around 90° ± 30° in the center of mass (COM). For identical particles, the transverse analyzing power A_T must be zero at 90° in the COM, and must be opposite sign between the forward and backward angles. The maximum A_T of around 12 parts per million (ppm) occurs at the very edges of the scattered electron momentum acceptance. A_T is of opposite sign at these two extremes. This is illustrated in Fig. 1a, which shows A_T as a function of E' for a beam energy of 11 GeV, with the acceptance of the MOLLER apparatus approximated in the shaded region. Because MOLLER accepts both COM forward and backward angle scatters, A_T averaged over the polar angle acceptance is suppressed by about an order of magnitude from the peaks of 12 ppm.

The MOLLER spectrometer measures a differing mix of forward- and backward-scattered electrons in the "closed", "transition", and "open" segments, as illustrated in Fig. 1b. For this reason, the expected analyzing power in these segments will be dramatically different. Figure 2 shows the simulated average A_T around the azimuth for the open, transition and closed tiles as a function of their position in the azimuth. The error bars on each point corresponds to the statistical precision of an asymmetry measurement that can be achieved in about 1 hour of continuous data collection.

Averaging over the 7 azimuthal septants also cancels the A_T asymmetry. In practice, this cancellation should be expected to be about an order of magnitude, due to imperfections in the azimuthal symmetry of the apparatus. For this reason, it is important to limit the contribution of the transverse analyzing power A_T by suppressing the transverse polarization.

The basic principle of this systematic control is as follows. First, it is expected to be possible, by passive setup procedures, to limit the transverse component of the beam polarization at the target to be approximately within 1° of longitudinal at the start of physics running. The ϕ modulation associated with A_T will be measured by the MOLLER apparatus to a very high precision during production data collection within a few hours. A small transverse polarization component of only 1% or so can be reliably extracted, distinguishing potential modulation from other systematic effects such as helicity-correlated beam position fluctuations.



(a) Beam-normal single-spin asymmetry A_T vs. scattered electron energy

(b) Scattered electron energy distributions in ring-5 tile categories: red (open), green (transition) and blue (closed)

Figure 1: *The characteristic behaviour of the beam-normal single-spin analyzing power A_T in Møller scattering as a function of E' at 11 GeV beam energy (left figure with the shaded region showing the approximate acceptance) coupled with the different acceptances of the 3 different tile categories (right figure) leads so very different expectations of the beam normal-single spin asymmetry, as shown in Fig. 2*

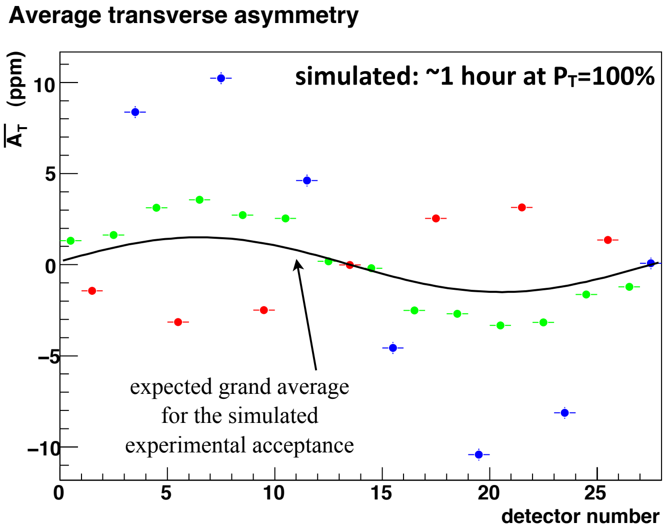


Figure 2: *Simulated values of the transverse asymmetries for* 100% *transverse polarization for the three different types of azimuthal detectors in the Møller ring - open (red), transition (green), and closed (blue). The expected transverse modulation is large enough to reliably determine the beam polarization transverse component to within about 1% within a few hours of production running. This will allow for a "manual" feedback technique to minimize the transverse beam polarization.*

2 Requirements on systematic control of transverse polarization

MOLLER will measure a parity-violating longitudinal-beam-polarization asymmetry A_{PV} in elastic electron-electron scattering. The asymmetry, averaged over the detector, will be about 32 parts per billion (ppb). MOLLER aims for a statistical precision of 2.1%, corresponding to an absolute uncertainty on the asymmetry of 0.7 ppb. To avoid competition with this statistical uncertainty, MOLLER aims to keep the sum of all estimated systematic uncertainties to be around 1%. The goal for the uncertainty associated with the transverse polarization is 0.2%.

As described above, the transverse analyzing power A_T reaches a maximum of about 300x the average A_{PV} in the MOLLER apparatus. Averaging over the polar angle acceptance of the MOLLER spectrometer will reduce this by a factor of about 10, so $\langle A_T \rangle \sim 1$ ppm. Due the imperfect azimuthal symmetry that should be expected for the realistic apparatus, the asymmetry will cancel over the azimuth by only about another order of magnitude. Thus, the average accepted analyzing power will be about 120 ppb, compared to A_{PV} of 32 ppb. To keep the total contribution below 0.2% of A_{PV}, it will be necessary to keep the transverse polarization below

$$P_T < A_{PV} * 0.2\%/120 \text{ ppb} = 0.055\% P_L \tag{1}$$

This corresponds to forcing the average spin orientation at the production target to be $\pm 0.03^\circ$ of pure longitudinal polarization.

This level of control is far beyond the expected precision for configuration of the spin launch angle, and even beyond the expected stability of spin precession during operation. For this reason, feedback will be required to force the spin alignment to converge to a value within this limit.

Segment Type	Rate [10^{10} Hz]	δ_A	$A_{T,\mathtt{max}}$	$2\delta_A/A_{T,\mathtt{max}}$	δ (direction)
Open	5.1	37 ppb	3.5 ppm	2.1%	1.2°
Transition	4.6	39 ppb	3.5 ppm	2.2%	1.3°
Closed	2.2	56 ppb	10 ppm	1.1%	0.66°

Table 1: *Precision on measurement of spin orientation in the MOLLER apparatus. Statistical uncertainty* $\delta_A = 1/\sqrt{RT}$*, assuming 4 hours of continuous measurement.*

3 Feedback operational requirements

The usual feedback technique employed for the parity-violation experiment focuses on reducing average values of noisy parameters, rather than on reducing the noise itself. The feedback acts only on long-term integration, optimally with a correction gain of 1, while setting any fast proportional or derivative response to zero. In such a system, if there is no systematic offset, the feedback injects any statistical shift in a measurement period, into the next measurement period but with an opposite sign. In a linear system, this serves to cancel the statistical offset, period by period. With the assumption that the noise in each integration period is canceled in the subsequent period, then the deviation from zero of the average falls as 1/N, as there is only the noise from the final measurement period remaining in the accumulation of N periods of data. Any systematic offset is also removed by the first correction, and similarly averages away. The tradeoff for the improvement of the long-term average is an increase in the observed variation, as the system injects noise from each period into the subsequent period, increasing the RMS of these measurements by $\sqrt{2}$. Performance is limited by realistic imperfections, but the result of "faster than statistical" cancellation of noise is frequently achieved. This is a standard technique for the control of beam noise in a parity-violation measurement.

It is assumed to be desirable to keep the magnitude of spin orientation correction small, at the level of 1° or so. These corrections will be most effective if the precision of the correction mechanism is small relative to the statistical uncertainty of the applied correction, so $\sim 0.25^\circ$ or better. Table 1 shows the precision of the measurement of the transverse polarization asymmetry for a measurement of 4 hours of continuous beam time. The correlation between the asymmetry and sign in the open, transition, and closed sectors will be an important tool for demonstrating that the observed azimuthal asymmetry stems from transverse polarization rather than from helicity-correlated differences in the beam trajectory. From this, it appears that the required polarization orientation corrections will be measured in a period of 4-8 hours of continuous beam, to the precision of 0.5°–1°. This would be an appropriate frequency and precision for feedback. To illustrate, assuming this averaged to 1° precision with a 6 hour correction cycle, this should achieve an average of about $1^\circ/28 = 0.04^\circ$ in a PAC week of data production.

If the polarization orientation is observed to be very stable, it may also be possible to reduce the frequency of this feedback, for example, to once per PAC day. This frequency will need to be responsive to conditions observed during running. The feedback should be capable of approximately 1° shifts with a precision of 0.25° as often as once per shift. A more optimistic scenario of greater stability in the spin orientation would suggest daily feedback corrections.

4 Possible sources of spin orientation instability

If the beam polarization orientation is very unstable, this will affect the required frequency of correction in the feedback system, with more frequent and larger corrections needed to control drifts of the orientation. The horizontal transverse component will be subject to variation with changes in $g-2$ precession during acceleration, while both the vertical and horizontal components might vary with drifts in the spin manipulation solenoids and Wien rotators in the injector.

The sensitivity to spin precession is rather high. As a rough calculation[1], an electron will precess a total of more than 138 times on its way to Hall A. A change in total energy created by a uniform shift in linac gradient of 0.004% would change the precession by 1°. Similarly, a shift in the acceleration between the linacs, raising the energy of one while lowering the energy of the other, by 0.045% (moving about 0.5 MeV from one linac to the other) would also change the precession by 1°. This relatively high sensitivity to spin precession due to energy stability suggests that it might be necessary to place additional focus on monitoring and controlling energy shifts to improve stability and avoid increasing the frequency of polarization feedback. It might also be the case the we will need to feed back on the measured horizontal polarization component more often than the vertical component, if in fact the horizontal component is less stable than the vertical.

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[1] For a simple approximation, I used an injector energy of 150 MeV and a linac energy of 1080 MeV to achieve 10950 MeV in Hall A. I ignored the bend in the BSY into Hall A, and did not consider any radiative energy loss.