Summary of beam parameter requirements for MOLLER

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November 15, 2022

MOLLER docdb:403
This note provides a listing and summary of requirements for the beam performance for the MOLLER experiment. In some cases, the these exceed the nominal 12 GeV performance parameters.

1. **Run averaged helicity-correlated beam asymmetries.** The goals for run-averaged helicity-correlated beam asymmetries are listed in Table 1. As discussed in the MOLLER 2022 TDR, it is expected that these are achievable given the plans for the new Pockels cell, expected improved matching optics, and slow-reversals.

2. **Random Beam Position and Intensity Noise at Target** The goal for the accuracy of beam corrections imposes requirements on the "jitter" (random noise) in the beam properties. These goals are shown in the Table 1. These jitter requirements will be achieved assuming that the beam jitter properties are similar for the 12 GeV upgraded machine as for 6 GeV operations. Some recent initial experience with 11 GeV beam in Hall A suggests that the beam jitter properties for 15 Hz window pairs are similar to the 6 GeV machine.

3. **Match to Design Beam Optics** It will be necessary with have the accelerator optics "well matched" during the PREX experiment. In particular, the helicity-correlated

Beam Property	Required 1 kHz random fluctuations	Required cumulative helicity-correlation
Intensity	< 1000 ppm	< 10 ppb
Energy	< 110 ppm	< 1.4 ppb
Position	< 50 μm	< 0.6 nm
Angle	< 10 μrad	< 0.12 nrad

Table 1: *Goals for run-averaged values and 1 kHz differential noise in helicity-correlated beam asymmetries.*

beam asymmetries are exacerbated if beam optics do not match design throughout the injector and linacs. If the beam is not matched through the BSY and into the hall, then beam spot sizes and beta-function phases are not well described by the optics model, and the various constraints on the beam line optics are more difficult to meet. It is therefore expected that matching must be done from the injector through delivery into Hall A early in the PREX commissioning period. A factor of 100 in suppression of transverse orbit amplitude is desired, a factor of 10 is suppression is required.

4. **Fast Feedback:** The fast feedback system for position and energy lock will be needed. The ability to pause the data collection and feedback on both the position and energy will be required for correction sensitivity monitoring (beam modulation).

5. **Beam Modulation:** Air core steering coils in the Hall A beamline and the energy vernier (presumably in SL20) will be used to modulate beam position, angle, and energy in order to measure sensitivity to those parameters. It will be necessary to "pause" position lock and energy lock during these modulation periods. This calibration cycles will be run every few minutes during data taking, with a total duty cycle between 5-15%.

6. **Phase Advance:** The successful use of the beam modulation system requires a significant phase advance between the modulation magnets and between the monitors used to characterize the beam motion, so that independent motions spanning the beam phase space can be observed. The MOLLER collaboration will work with accelerator to design optics with sufficient phase advance between modulation magnets.

7. **Beam Energy** The MOLLER figure-of-merit is proportional to the beam power, and the experiment is designed for 11 GeV beam energy at 65 μA beam current. If beam energy is less than design, this will correspond to a loss of figure of merit corresponding to $\sqrt{(\Delta E/E)}$.

8. **RF trip rate and recovery time** MOLLER run planning is assuming a beam uptime of 90% during steady production running. The expected ramp time on the production target will be about 25 seconds. It is assumed that the average recovery time before beam can return is 40 secconds, implying that < 6 beam trips per hour is required to achieve the goal of 90% efficiency.

9. **Helicity Reversal Frequency** MOLLER will require the helicity reversal frequency to be selectable to be 1920 Hz or 960 Hz. A multiplet of 64 windows (for 1920Hz) or 32 windows (for 960Hz) will need to be used to cancel 60 Hz line noise. This will require new firmware and control software for the JLab helicity board, but it is not expected that this will require new hardware. The helicity flip rate will need the option or either locking to the 60Hz line phase (with any variation in timing occuring during the settle period) or running from an internal clock, asynchronous with the line phase. The settle time between integration windows should be variable between 10 μs and 30 μs.

10. **Polarization Orientation** MOLLER is highly sensitive to components of transverse polarization. The experiment will require regular correction for both vertical and horizontal transverse polarization. These polarization components will be measured continually in the experimental hall, with corrections for drifts envisioned to occur daily during regular running, or in a shorter time scale after any significant linac energy rebalancing.

11. **Priority in source configuration:** MOLLER will require priority in the source configuration (centering on the Pockels cell, etc.). In order to tune the source to minimize HC beam asymmetries, it will also be necessary to control setpoints for common devices such as the Insertable Halfwave Plate, Rotating Waveplate, and Pockel cell voltages.

12. **Time for source configuration:** Dedicated time for configuration of the laser optics of the source will be required. This includes time to configure and characterize laser optics on the laser table, and then several shifts to characterize and calibrate the source configuration using the electron beam. It is assumed that 3 dedicated shifts may be required in the injector for any significant change in the source configuration.

13. **Control of helicity-asymmetries on other source lasers** MOLLER will require feedback mechanisms to control the helicity-correlated charge asymmetry of the Hall B and Hall D lasers (measured before the slit) and the Hall C laser. This has typically been accomplished with IA cells on each laser beamline.

14. **Helicity-Correlated Beam Spot Size:** No direct method exists to measure helicity-correlated differences in the beam spot size. The possible helicity-correlated spot-size asymmetry will be bounded on the laser beam, with a safety margin to account for reasonable models of photo-cathode non-uniformity, to be $< 10^{-4}$, with an expected order-of-magnitude suppression through injector spin reversal for a final expected value of $< 10^{-5}$. It is also expected that the helciity-correlated spot size asymmetry at the experimental target will be further suppressed by adiabatic damping from the injector combined with the addition of stochastic noise from synchrotron radiation.

15. **Injector Spin Reversal** Spin rotation in the injector provides a method for a convincing "helicity flip" which does not interfere with the beam profile or mechanisms which might lead to a spot size asymmetry or other helicity-correlated beam asymmetries. MOLLER will use a spin rotation with a period of about 5-7 days. The new double-Wien system planned for installation in the injector will be used to provide this helicity flip, as well as make the regular small corrections to the spin launch angle to preserve a minimized transverse polarization for the MOLLER measurement.

16. **Halo** 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". Studies will continue

during the upcoming PREX and CREX runs to attempt to characterize halo. There is not currently a halo requirement specified for MOLLER.

17. **Beamtune and halo acceptable for Compton polarimeter:** In order to meet the precision goals of the experiment, it will be necessary to have reliable data from the Compton polarimeter continuously during production. It is therefore necessary that the beam be suitable for the use of the Compton polarimeter.

    A commonly-used criteria for operation of the Compton is a counting rate of 100 Hz/μA in the Compton photon and electron detector, with the Compton laser off. The halo restriction is such that the Compton detector is the only instrument available at CEBAF which is suitable for monitoring this parameter at this level. This specification matches the requirement for use of the Compton system for most of the operational lifetime of the system. It is expected that PREX experimenters will be closely collaborating with accelerator personnel to optimize the Compton photon background counting rates.

18. **Laser optics slow reversal:** A waveplate in the injector is used to change the helicity of the beam relative to the voltage on the Pockels cell and the helicity reporting signal. This is an important slow reversal, and must be done frequently. MOLLER aims at changing at performing this reversal every 2-4 hours. This change would take less than 1 minute if performed using an automated script, however, it must be coordinated with other experimental halls who must correct their record of the beam helicity. A process should be designed to make this process efficient, with a goal of a 2 minute change to occur approximately every 2-4 hours.

19. **Beam Energy Slow Reversal:** At 11 GeV, the total number of g2 spin rotations will be large, on the order of 120π. It will be possible to flip the spin orientation, while maintaining very similar beam optics properties, by changing the energy of the accelerator by about 100 MeV. (For a symmetric linac configuration change, the beam energy change needed is $\sim$93 MeV.) This interval is small enough to not require invasive reconfiguration of the experiment: backgrounds, spectrometer optics, etc. will remain very similar. This type of reversal is expected to be very effective in that all sources of HCBAs will be reversed under this operation. However, since this method is disruptive to other halls, MOLLER expects to only employ a g-2 reversal a few times over the duration of the entire run. Over the duration of all the production running, a total of 10 energy flips are planned, with at least one such flip during run I, 3 flips in run II and 6 flips in run III, or effectively a configuration change every 10 weeks during production running. The exact frequency and the nature of the configuration change would be chosen after detailed consultation with the Accelerator and Physics Divisions.

20. **Full transverse polarization calibration:** MOLLER is planning to calibrate the detector using several periods, each lasting 2 to 3 shifts, of 100% transverse polarization in Hall A. This will provide a sensitive test of systematics. These measurements would be best performed at the time of each beam energy change for g 2 slow reversal.

21. **Duty factor during steady running :**During steady running periods when all hardware is working, there are expected interruptions in beam delivery from periodic RF trips and planned configuration changes. The experiment assumes that the total duty factor is ¿ 88% when accounting for RF trips and recovery time, laser optics slow reversals, and injector spin manipulation slow reversals

22. **Efficiency on configuration change** There are many configuration changes that will be required during the course of running. These include beam line optics changes for measurements with the Møller polarimeter (weekly), injector spin manipulation slow reversal (weekly), energy-change slow reversal (every 10 weeks), transverse polarization studies (every 10 weeks), and low current calibration studies (every 10 weeks). An efficient transition between these configurations is anticipated.

23. **Low Current (tracking mode) beamline operation** While MOLLER takes most data at high currents, low currents (about 100 nA) will be required during calibration runs for tracking detectors to measure the spectrometer properties. The beam will need to be steady, with trajectory controlled at the 100 μm level, during these tracking calibration periods.