Design and Simulation of a Spin Rotator for Longitudinal Field Measurements in the Low Energy Muons Spectrometer

Z. Salman\textsuperscript{a,}\textsuperscript{*}, T. Proksch\textsuperscript{a}, P. Keller\textsuperscript{b}, E. Morenzoni\textsuperscript{b}, H. Saadaoui\textsuperscript{a}, K. Sedlak\textsuperscript{a}, T. Shiroka\textsuperscript{a}, S. Sidorov\textsuperscript{c}, A. Suter\textsuperscript{a}, V. Vrankovic\textsuperscript{c}, H.-P. Weber\textsuperscript{a}

\textsuperscript{a}Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
\textsuperscript{b}Laboratory for Developments and Methods, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
\textsuperscript{c}Large Research Facilities, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

Abstract

We used \textsc{Geant4} to accurately model the low energy muons (LEM) beam line, including scattering due to the 10-nm thin carbon foil in the trigger detector. Simulations of the beam line transmission give excellent agreement with experimental results for beam energies higher than \(\sim 12\) keV. We use these simulations to design and model the operation of a spin rotator for the LEM spectrometer, which will enable longitudinal field measurements in the near future.

Keywords: Low energy muons, \textsc{Geant4} simulations, Spin rotator

1. Introduction

The low energy muons (LEM) spectrometer\cite{1, 2} is a unique instrument that enables muon spin precession measurements in thin films and multilayers. This is possible due to the tunable implantation energy (1-30 keV) of the muons, allowing depth resolved \(\mu\)SR measurements between 1-300 nm. The geometry of the LEM beam line results in a muon spin polarization that is parallel to the surface of the studied samples. Together with the available magnets in the spectrometer, \(\mu\)SR measurements on LEM are restricted to either zero field (ZF) or transverse field (TF) applied either in or out of the sample plane. However, for many systems, in particular magnetic ones, the availability of longitudinal field (LF) capability is of great importance, e.g. to distinguish between static or dynamic internal fields, or to decouple them.

Currently, a project is underway at PSI to develop a spin rotator (SR) for the LEM spectrometer to enable LF measurements. An ideal spin rotator is formed by a combination of static magnetic \((B)\) and a perpendicular electric \((E)\) fields which satisfy \(v = E/B\), where \(v\) is the velocity of the muons. This ensures that the beam is not deflected when passing through the SR. When passing through the SR, the spin of the muon is rotated by an angle \(\theta = \gamma B t_0\), where \(\gamma\) is the muon’s gyromagnetic ratio and \(t_0\) is the time it spends in the SR. Typically, for a surface muon beam line \((\sim 28\) MeV/c), a rotation of 90\(^\circ\) for TF measurements requires magnetic fields of \(\sim 0.1\) T and electric fields of \(\sim 7.5\) kV/mm over a length of \(\sim 1.5\) meters. Such requirements make the design and construction of these SRs a technically challenging task, and usually only a rotation of 40\(^\circ\) – 50\(^\circ\) is achieved with a single spin rotator. Fortunately, the low

\textsuperscript{*}Tel. +41-56-310-5457

Email address: zaher.salman@psi.ch (Z. Salman)
energy of the muons after the moderator on the LEM beam line simplifies the SR requirements considerably. In this paper we accurately model the current LEM beam line using Geant4[3, 4]. We then use these simulations to design and model the operation of a SR for LEM and optimize the transmission of the beam line. Using these simulation we expect to eventually achieve a spin rotation in the range –90° to +90°. Moreover, we make small modifications to the trigger detector that will increase the number of muons on the sample, e.g. by 15 – 30% at 15 keV beam energy.

2. Simulations

Geant4 simulations were used to implement the beam line starting from the moderator and ending at the sample chamber. The purpose of these simulations is to test the reliability of a more recent version of Geant4 (4.9.3p2) in mimicking the transport of low energy muons in the beam line, and in particular predicting the scattering of keV muons from the 10-nm thin carbon foil in the trigger detector. Previous versions of Geant4 have been poor in reproducing the transmission measured experimentally, mainly due to underestimated scattering from the carbon foil. For example, Paraïso et. al. [5] had to implement the Meyer scattering [6, 7] in order to estimate the transmission and reproduce experimental results. However, such implementation was not forward compatible and required heavy programing to introduce it into Geant4. Meanwhile, Geant4 scattering processes implementation have evolved dramatically in the last few years, which enables reproducing the expected scattering from the basic (and computationally light) “Multiple Scattering” physics process.

3. Results and Discussion

3.1. Transmission of the current LEM beam line

The beam average position, transmission and root mean square (RMS) envelope as a function of z along the beam line are shown in Fig. 1 for different energies. We use shaded areas in the top panel of Fig. 1 to visualize the positions of the electrostatic lenses L1, L2 and L3, the trigger detector chamber, TD, the last electrostatic focusing element, RA, and S the sample position. The settings of the electrostatic fields in the different beam line elements were fixed to their experimental values for the corresponding beam energy. Note that, as expected, the largest transmission loss occurs after TD, due to multiple scattering and muonium formation in the carbon foil. A deflection in the horizontal x direction in the beam position after TD is due to the electric fields in the trigger detector which are not aligned with the beam axis [5]. In order to compare with Meyer scattering and experimental results, we extract the transmission

![Figure 1: The average position of the muon beam (top), its transmission (middle) and RMS (bottom) as a function of z. The different colors indicate different transport settings at the moderator (beam energy). The solid and dashed lines in the top and bottom panels indicate values in the horizontal x and vertical y directions, respectively. The various beam line elements are highlighted in the top panel.](image)
from the TD to the sample. These values are plotted in Fig. 2 as a function of energy, and compared to old simulation [5] (based on Meyer scattering in the carbon foil) and experimental results. As can be clearly seen here, the results of the current simulation are in excellent agreement with the experimental values for energies $\geq 12$ keV, showing that the current $\mu$SR simulation code can reproduce a realistic transmission through the LEM beam line. This code is used in what follows as the basis for designing and implementing a spin rotator in the LEM beam line for LF measurements.

3.2. The LEM Spin Rotator

Currently, the initial spin of the beam is perpendicular to its momentum due to a 90° bend in the beam line between the moderator and the sample position. For LF $\mu$SR measurements using the available magnets and spectrometer, one needs a spin rotator (SR) after the moderator. However, space limitations impose a small footprint of $\sim 40 \times 40 \times 40$ cm$^3$ on the SR. Taking these limitations into consideration we designed a SR which is composed of a dipole magnet, producing a vertical magnetic field, and a set of conducting plates to produce a corresponding transverse horizontal electric field (see Fig. 3).

The main considerations in the magnet design were its physical length, uniformity/homogeneity and sufficient magnetic field amplitude (using a reasonable current) to achieve a full 90° spin rotation at typical muon energies ($< 20$ keV). For the electrostatic plates, we aimed at providing an electric field that compensates the deflection of the beam due to the magnetic field while maximizing beam transmission through the SR. The field maps used in the simulations were calculated using commercial software for finite element calculations [8].

3.3. Transmission of the beam line with the spin rotator

We distinguish between two SR operation modes: (I) SR off, i.e. TF mode and (II) SR on (90°), i.e. LF mode. In these simulations we follow a 3 step tuning procedure for the beam line for various initial beam energies. In the first step, working with SR off, we tune the settings of L1 and L3 with a realistic beam to obtain maximum transmission through the beam line up to the carbon foil in the TD. In the second step we use the optimal settings of L1 and L3 to tune the electric and magnetic fields of the SR. The aim here is to obtain a 90° spin rotation with no deflection of the beam off axis (before and after the SR). For this step we use a point like parallel muon beam. Finally, in the third step, using the tuned SR we optimize the settings of L1 and L3 again with a realistic beam to obtain maximum transmission through the beam line until the carbon foil. The result of the first step is a beam line tune for TF mode, while the results of step three is a beam line tune for LF mode.

![Figure 2](image1.png)

**Figure 2:** The transmission from the trigger detector until the sample as a function of beam energy. The circles are values estimated from the current simulations with Geant4 (4.9.3p2), the squares are estimates using Geant4 with Meyer scattering [5], and the triangles are experimental values. All values were normalized to those at 20 keV beam energy.

![Figure 3](image2.png)

**Figure 3:** A schematic of the SR showing the magnet and electrostatic plates and rods. $\pm V$ is the potential applied on the plates.

In Fig. 3 we show a schematic of the final SR design, where the magnet poles width and length are 260 mm (along x and z, respectively) with a gap of 152 mm between them (along y). The cross section of the poles was also shaped to achieve high uniformity. The shape and size of the electrostatic plates were adjusted to match the magnetic field properties and optimize beam transmission though to the spectrometer. The final dimensions of the plates are 370 mm length (along z), 110 mm height (along y) and a gap of 100 mm (along x) between them. Six additional rods running along the top and bottom edges of the plates were added to improve the uniformity of the electric field.
The electrostatic potential of the rods (equal for top and bottom) is set relative to the plates as shown in Fig. 3. The resulting effective lengths of the magnetic and electric fields on the axis of the SR are 29.5 and 40.4 cm, respectively. This mismatch was found to maximize transmission and optimize the properties of the beam profile.

![Figure 4](image-url)

Figure 4: The beam properties with the SR off (left) and on (right). The average position of the muon beam (top), its transmission (middle) and RMS (bottom) as a function of z. The different colors indicate different transport settings at the moderator (beam energy). The solid and dashed lines in the top and bottom panels indicate values in the x and y directions, respectively. The various beam line elements are highlighted in the top panel.

Typical settings for L1 and L3 tuned for maximum transmission with the SR off are shown in Table 1. Additionally,

Table 1: The optimal values of L1 and L3 settings with the SR off/on and the SR settings for 90° spin rotation for different beam energies.

| Beam Energy (keV) | L1 (off/on) (kV) | L3 (off/on) (kV) | E field (kV/100 mm) | B field (mT) |
|------------------|-----------------|-----------------|--------------------|-------------|
| 20               | 11/13           | 11/11           | 16.82              | -38.0       |
| 18               | 10/12           | 10/10           | 15.43              | -36.7       |
| 15               | 8/10            | 9/9             | 12.855             | -33.5       |
| 12               | 7/8             | 7/7             | 10.300             | -30.0       |
| 10               | 6/7             | 6/6             | 8.385              | -26.8       |
| 7.5              | 4/5             | 4/4             | 6.315              | -23.3       |

we provide optimized settings with the SR on as well as the electric and magnetic field magnitudes required for 90° rotation. Note that the settings of L1 are changed between SR on or off while L3 is not affected much. This is since the SR is not an “ideal” drift chamber, i.e. it also alters the properties of the beam as it passes through it. In Fig. 4 we can see that the x and y RMS with the SR off are identical as one expects in a drift chamber. However, they differ when the SR is on, since it acts as an effective lens in the x direction, which is the direction of forces in the SR. This is mainly due to the small mismatch between the electric and magnetic field amplitudes as well as the small inhomogeneity of the magnetic field within the SR (in particular off axis).

The corresponding time of flight (ToF) of muons from the moderator and TD to the sample are shown in Figs. 5(a) and (b), respectively. As expected, the ToF with the new arrangement of the TD closer to the sample is significantly smaller. We expect this will improve the timing resolution of LEM. For completeness, we also present the RMS of ToF for the current beamline compared to the beamline with SR in Fig. 5(c).
3.4. Transmission improvements of the beam line

In Fig. 5(d) we present the simulated transmission as a function of beam energy for different SR operation modes in comparison to the current beam line. We find that the transmission of the new beam line with SR is lower for high beam energies, but it exceeds the current situation at low energies. Note in Fig. 1 and 4 that most of the beam losses occur at the TD due to scattering in the carbon foil. Therefore it should be possible, in principle, to minimize losses by re-focusing the scattered muons, e.g., by means of an electrostatic lens located just downstream from the foil and as close as possible to it.

![Figure 5](image_url)

Figure 5: The energy dependence of the time of flight (ToF) from the moderator (a) and TD (b) to the sample, as well as the RMS (c) of the ToF at the sample position. (d) The transmission as a function of energy for the current beam line compared to the different spin rotator operation modes. The solid lines are a guide to the eye.

Due to space limitations, it is not possible to insert a full Einzel lens at this position. However, a simple cylinder aligned with the beam line and biased to a high positive electrostatic potential could act as an effective lens in this case. This was confirmed by inserting such a trigger lens (TL), 7 cm long and 13 cm diameter, ~12 cm downstream from the foil in the simulations. By scanning the voltage on the TL we find a dramatic change to the transmission of muons to the sample. The potential on the TL was optimized for different beam energies, and the resulting transmission at these optimal values are shown in Fig. 5(d). Comparing the transmission with the TL to the current beam line we obtain an impressive improvement, e.g., 15% and 30% at high energies and as high as 250% and 330% at low energies, with the SR off and on, respectively. Such a TL clearly offers an effective yet simple improvement in the counting rate, and is planned to be incorporated in the new beam line.

4. Conclusions

We have achieved a highly accurate simulation of the current beam line, based on recent versions of Geant4. These were used to test potential designs of a SR and optimize its properties to obtain maximum transmission of muons in the full energy range while maintaining adequate operation and a full ±90° rotation. Additional transmission enhancements were also obtained by adding an effective electrostatic lens downstream from the TD foil. The manufacture of the SR is underway and is expected to be installed in the LEM beam line at the beginning of 2012. This will significantly enhance the existing capabilities of the LEM spectrometer and provide the possibility of performing LFμSR measurements.

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