Muon beams in applied magnetic fields: comparison of simulation and experiment

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December 5, 2005

Abstract

We report the results of experiments designed to test simulations of the μ^+SR experiment. A beam-profile monitor was used with a 5 T superconducting solenoid to study effects related to the motion of incoming muons in applied magnetic fields. These were compared with results generated from GEANT4 simulations. Good agreement is found between the two approaches in simple cases, but more accurate beam and field parameterisation is required to make further progress.

1 Introduction

The full instrument simulations of a muon-spin relaxation (μ^+SR) spectrometer involves modelling three distinct processes: the motion of muons into the spectrometer where they are stopped by the sample, the paths of decay positrons and the detection of these positrons in the instrument's detector arrays. The first of these steps has now been completed, with a working simulation of the incoming muon beam realised using GEANT4 [1], after testing against other numerical simulations. In this report we discuss experimental tests of this program for the case of applied magnetic fields with the principal field direction oriented along initial muon momentum direction. The application of a large magnetic field to a sample in a μ^+SR experiment has a significant effect on the incoming muon beam, which must be known, in detail, if a spectrometer is to function successfully at high fields.

The experiments were carried out in the period 05/09/05 - 08/09/05 in the πE3 area at the Swiss Muon Source, Paul Scherrer Institute, Villigen, CH. The

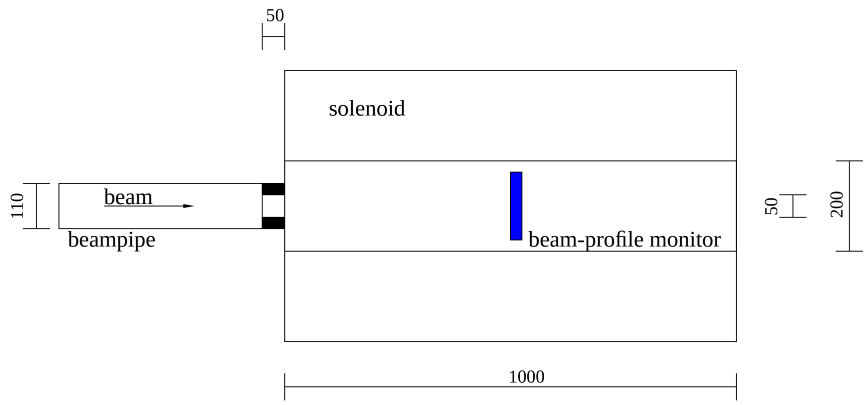

Figure 1: Apparatus used in the experiments. The muon beam travels up the evacuated beampipe, through a 50 mm diameter collimator (shown in black) and into the air filled magnet bore. The muons are detected by the beam-profile monitor (shown in blue). All measurements are given in millimetres.

magnetic field was applied using the Avoided Level Crossing (ALC) solenoid, measuring approximately 1 m in length with its bore (radius 0.1 m) directed along the z-direction. Muons are directed with their principal momentum direction parallel to z. A muon beam profile monitor (BPM) [2], equipped with scintillating fibre readout by avalanche micro-channel photodiodes, was used to detect the muon positions at the centre of the solenoid. The configuration used for the experiments is shown schematically in figure 1.

For the simulations, muons are injected at $z = -1$ m, with kinetic energy 4.12 MeV. The momentum is directed principally along the z-axis, with a divergence of 1.7 degrees (this value was previously determined experimentally). The beam is modelled with a Gaussian intensity profile with a full width at half maximum intensity FWHM=7 cm. The surface of the BPM is the plane $z = 0$. At this point, the muon position is recorded. The magnetic field profile $\mathbf{B}(\mathbf{x})$ was calculated for the ALC solenoid geometry using the Biot-Savart Law. For the results discussed here, the field was calculated at 5 cm intervals, and a tri-linear interpolation employed to approximate the field at any point in space. The geometry for the simulations was that shown in figure 1, where the beampipe is assumed to be evacuated, while the magnet bore is air filled.

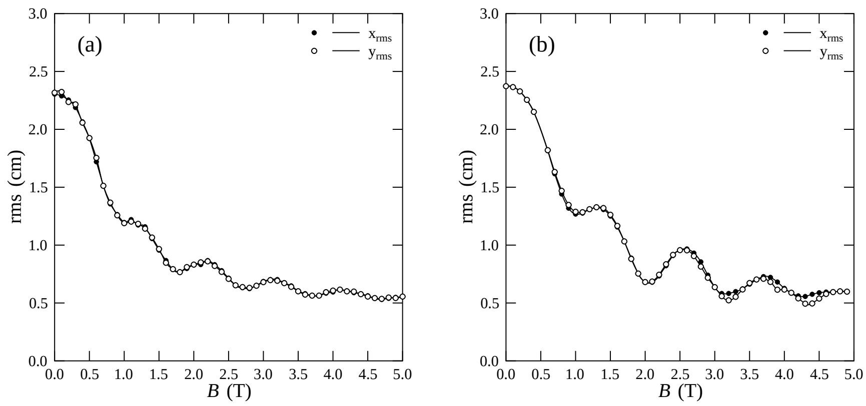

Figure 2: (a) Simulation results showing the rms beam-spot size oscillating with applied field for normal magnet operating conditions. (b) Measured results showing the rms beam-spot size oscillating with applied field for normal magnet operating conditions.

2 The beam profile as a function of applied field

2.1 Normal operating conditions

Comparisons were first made for normal operating conditions of the magnet. Figure 2 shows the simulated and measured values of the root mean square (rms) widths of the beam spot in the x- and y-directions as a function of applied field. We find a good level of agreement between the simulated results and the measurements. In both cases oscillations are found in the rms beamspot size as a function of applied field. This has been both measured [2] and simulated [3] previously. The inclusion of scattering due to the passage of the beam through approximately 0.5 m of air was found to be essential in achieving an acceptable level of agreement. The inclusion of a momentum bite acts to damp the oscillations. We found that a bite of 3 % led to the best agreement with the experimental data. The differences in the frequency of oscillation between the two approaches may be attributed to the approximate nature of the calculated field map.

Unexpectedly, small changes in the average position of the measured beam spot ($\langle x \rangle$ and $\langle y \rangle$) are found with changing field. This should not be observed if the field profile was static in space at all fields and suggests that the superconducting coils in the solenoid move slightly with varying field.

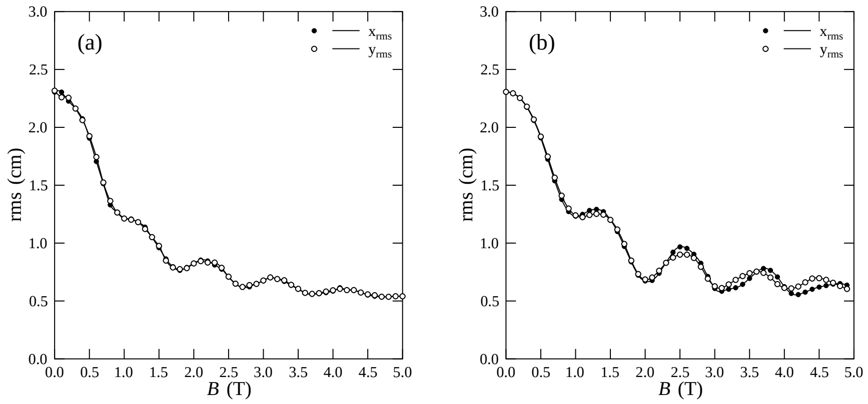

Figure 3: (a) Simulation of rms beam spot size in a field rotated by 1 degree. (b) Measurement of rms beam spot size in a field rotated by 1 degree

2.2 Tilted magnet

The solenoid was tilted in the x-z plane by 1 degree and the experiment repeated. Similarly, the calculated magnetic field profile was rotated by one degree and the simulations repeated. Figure 3 shows the simulated and measured widths of the beam spot size as a function of applied field. The tilting does not have a significant effect on the widths in either case.

Figures 4 and 5 show the evolution of the average beam positions ($\langle x \rangle$ and $\langle y \rangle$) with applied field. There is a significant discrepancy between simulated and measured results. The discrepancy is therefore not surprising given our measurement of a change in the average position in the untilted case suggestive of a moving magnetic field profile. Such an effect is not simulated in the calculations where it is assumed that the solenoid is stationary as the field is swept. The measured variation of the beam position in the tilted case is very similar to the unexpected behaviour measured under normal operating conditions. This also raises the question of whether the magnet coils were significantly tilted when the solenoid was rotated. We therefore cannot expect agreement with simulation for this case.

3 Masking experiment

An additional experiment involved inserting a 200 mm diameter cylindrical copper plate (of thickness 0.4 cm) at $z = -8.5$ cm (i.e. upstream of the BPM). The plate had a 0.5 cm hole positioned at $x = 1.0$ cm. The average position of the

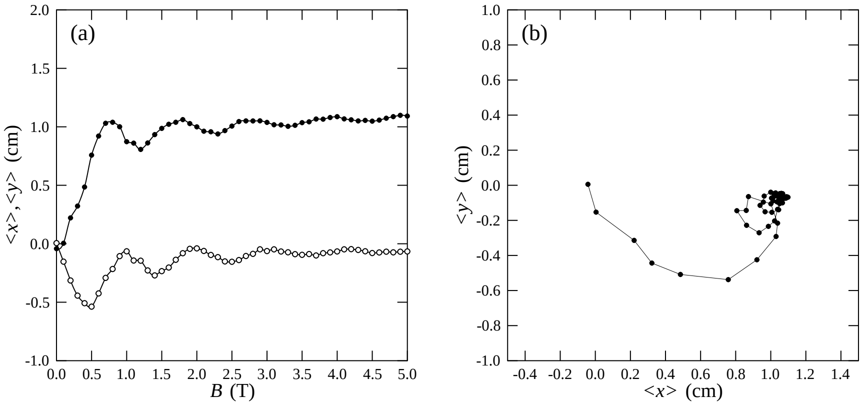

Figure 4: Simulation results for a tilting angle of 1 degree. (a) Average values $\langle x \rangle$ and $\langle y \rangle$ as a function of applied field. (b) Average values $\langle x \rangle$ and $\langle y \rangle$ plotted against each other showing the movement of the mean spot as the field is varied.

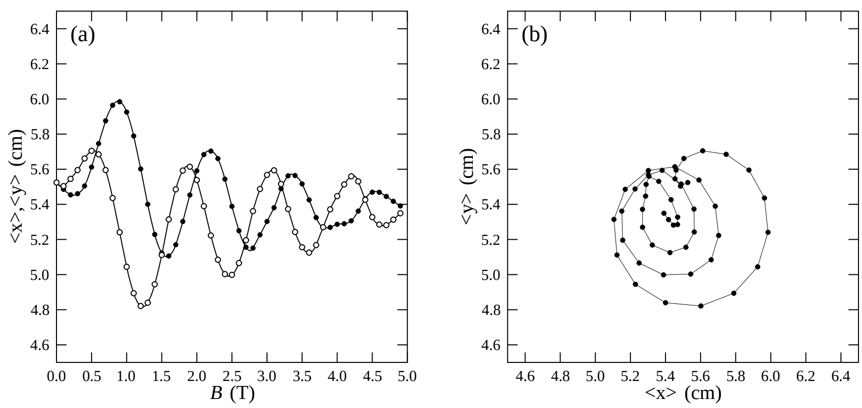

Figure 5: Measured results for a tilting angle of 1 degree. (a) Average values $\langle x \rangle$ and $\langle y \rangle$ as a function of applied field. (b) Average values $\langle x \rangle$ and $\langle y \rangle$ plotted against each other showing the movement of the mean spot as the field is varied.

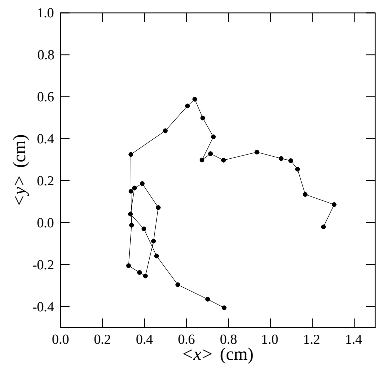

Figure 6: Simulation of the masking experiment Average values $\langle x \rangle$ and $\langle y \rangle$ plotted against each other showing the movement of the mean spot as the field is varied in increments of 0.1 T. Note that at B=0 T, $\langle x \rangle = 1.25$ cm and $\langle y \rangle = -0.02$ cm.

beam spot was recorded with varying field. The field was varied between 0 and 3 T in 0.1 T increments. In both the measured and simulated experiment erratic were observed in the evolution of the beam spot with increasing field. Figure 6 shows this behaviour for simulated results. Further simulations showed the irregularities in the motion to be due to air scattering and beam divergence, although the exact behaviour could not be completely reproduced. It is likely that more accurate beam and magnetic field parameterization would allow a better description of the experimental results through simulation.

4 Conclusions and future work

This work demonstrates the success of the muon simulations in modelling the incoming muon beam properties. It also emphasises that a detailed knowledge of beam and magnetic field properties are required to successfully implement a reliable simulation.

Future work will involve the design of experiments to test the modelling of the motion and detection of positrons in large applied magnetic fields. This may include a test of a detector array designed to function at high field.

References

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