Test of LGAD as Potential Next-Generation SR Spectrometer Detectors

Authors: Guo, Dr. Yuhang, Li, Dr. Qiang, bao, Dr. yu, Ziwen Pan, Lv, Dr. You, Stewart, Dr. Rhea, Hillier, Prof. Adrian, Cottrell, Prof. Stephen, Baker, Prof. Peter, Lord, Prof. James, Mr. Lei Liu, Liang, Prof. Zhijun, Fan, Prof. Yunyun, Li, Dr. Mengzhao, Zhao, Prof. Mei, Gaobo, Dr. Xu, Feng, Dr. Meichan, Dr. Yuhang Guo

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Abstract

Muon Spin Rotation/Relaxation/Resonance (SR) is a versatile and powerful non-destructive technology for investigating the magnetic properties of materials at the microscopic level. The SR technique typically utilizes fully spin polarized beams of positive muons generated at particle accelerator facilities and measures the evolution of the muon spin polarization inside a sample to extract information about the local magnetic environment in materials. With the development of accelerator technologies, intensities of muon beams are being continuously improved, which will cause a pile-up problem to the SR spectrometer. This problem is becoming especially challenging at intense pulsed muon sources since the instantaneous data rates are expected to be much higher. The first muon source in China, named MELODY, is currently under construction and will be a pulsed source of muons operated at a repetition frequency of only 1 Hz due to limitations of the accelerator system at CSNS. Consequently, there is a strong motivation to operate MELODY at significantly higher muon intensities. This necessitates an upgrade of the detector system inside the spectrometer, which should be smaller and faster to accommodate the increased intensity per pulse of muons. The Low Gain Avalanche Diode (LGAD), characterized by a typical pulse width of 2 ns and a segmentation size in the centimeters range, has the potential to significantly improve the counting rates of SR spectrometers that utilize a high intensity pulsed muon source. Thus, it is expected that the LGAD detector is a promising candidate to enhance the performance of SR spectrometers at the new MELODY muon source. To validate this, tests on the LGAD were conducted at the ISIS pulsed muon source at the Rutherford Appleton Laboratory, UK. This paper will describe the setup of the candidate LGAD devices and the subsequent analysis of the experiment data.

Full Text

Preamble

Test of LGAD as Potential Next-Generation µSR Spectrometer Detectors

Yu-Hang Guo,[1],[2] Qiang Li,[1],[2],† Yu Bao,[1],[2],‡ Zi-Wen Pan,[3] You Lv,[1],[2] Rhea Stewart,[4] Adrian D. Hillier,[4] Stephen P. Cottrell,[4] Peter J. Baker,[4] James S. Lord,[4] Lei Liu,[1],[2] Zhi-Jun Liang,[2] Yun-Yun Fan,[2] Meng-Zhao Li,[1],[2] Mei Zhao,[2] Gao-Bo Xu,[5] and Mei-Chan Feng[1],[2]

[1]Spallation Neutron Source Sciences Center, Dongguan 523803, China
[2]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[3]State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026, China
[4]ISIS Pulsed Neutron and Muon Source, STFC Rutherford Appleton Laboratory, Didcot OX11 0QX, UK
[5]Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China

Muon Spin Rotation/Relaxation/Resonance (µSR) is a versatile and powerful non-destructive technology for investigating the magnetic properties of materials at the microscopic level. The µSR technique typically utilizes fully spin-polarized beams of positive muons generated at particle accelerator facilities and measures the evolution of muon spin polarization inside a sample to extract information about the local magnetic environment. With the development of accelerator technologies, muon beam intensities are being continuously improved, which will cause a pile-up problem for µSR spectrometers. This problem is becoming especially challenging at intense pulsed muon sources since the instantaneous data rates are expected to be much higher. The first muon source in China, named MELODY, is currently under construction and will be a pulsed source operated at a repetition frequency of only 1 Hz due to limitations of the accelerator system at CSNS. Consequently, there is strong motivation to operate MELODY at significantly higher muon intensities. This necessitates an upgrade of the detector system inside the spectrometer, which should be smaller and faster to accommodate the increased intensity per pulse. The Low Gain Avalanche Diode (LGAD), characterized by a typical pulse width of 2 ns and segmentation size in the centimeter range, has the potential to significantly improve the counting rates of µSR spectrometers that utilize a high-intensity pulsed muon source.

Thus, the LGAD detector is expected to be a promising candidate to enhance the performance of µSR spectrometers at the new MELODY muon source. To validate this, tests on the LGAD were conducted at the ISIS pulsed muon source at the Rutherford Appleton Laboratory, UK. This paper describes the setup of the candidate LGAD devices and the subsequent analysis of the experimental data.

Keywords: µSR Technology, µSR Spectrometer, Low Gain Avalanche Diode, Application of Ultra-fast Detector

Introduction

Non-Destructive Technologies (NDT) are a class of powerful experimental techniques used to investigate material properties. Nuclear Magnetic Resonance (NMR) and Electron Spin Resonance (ESR) techniques, which are representative NDTs, usually require both high magnetic fields and low temperatures to produce a thermal equilibrium spin polarization environment. NMR also requires specific target nuclei, thus restricting their application. By contrast, Muon Spin Rotation/Relaxation/Resonance (µSR) is relatively versatile [**?**].

The muon is an excellent and complementary probe of magnetism local to where it stops in materials [**?**]. In µSR applications, fully spin-polarized positively charged muons (μ^+) produced by an accelerator muon source are implanted into a sample [**?**]. Upon implantation, the muons rapidly thermalize before their spins begin to precess about the local magnetic field at the muon stopping site, which is characteristic of the magnetic properties of the material being studied [**?**]. The muon is an unstable particle with a lifetime of approximately 2.2 µs. The μ^+ decays into a positron and two neutrinos. Since decay positrons are preferentially emitted along the momentary muon spin direction at the point of decay, the precession of muon spin polarization can be deduced by comparing the number of emitted positrons detected at different angles around the sample. From this signal, it is possible to characterize in detail the local magnetic fields that the muon spins experienced, revealing information about magnetic, superconducting, and dynamic properties of materials at the microscopic level. Based on observation of the time evolution of implanted muon spin polarization, the µSR technique provides a versatile method to perform measurements without applying an external magnetic field, making it an essential tool in many frontier fields including materials science, condensed matter physics, and chemistry [**?**, **?**].

µSR experiments are strongly dependent on the muon source used, which can be classified into two types: continuous wave (CW) muon sources and pulsed muon sources, each offering complementary strengths. On a CW muon source, such as the CMMS facility at TRIUMF [**?**], the SµS facility at PSI [**?**], and the MuSIC facility at RCNP [**?**], µSR experiments usually have good time resolution to the level of nanoseconds or less, but statistics are count-rate limited because there is only a single muon in the sample at a time [**?**]. On a pulsed muon source such as the ISIS facility at RAL [**?**] and the MUSE facility at J-PARC [**?**], µSR instrument count rates are much higher and measurement backgrounds are lower, enabling good statistics even at longer times. However, the time resolution, and therefore the maximum strength of magnetic field the muons can measure, is set by the width of the muon pulse, which is typically on the order of 100 ns. This means it can often be useful to measure using both continuous and pulsed muon beams for a given experiment.

The first surface muon source in China (called MELODY, short for the Muon Station for Science Technology and Industry) [?] is currently under construction at the China Spallation Neutron Source (CSNS) campus [?, ?]. MELODY is designed to provide a pulsed muon beam with intensity in the range of 10^5 muons per pulse, retaining the ability to increase intensity to the level of 10^6 muons per pulse or more with future upgrades. However, limited by the operation plan of the CSNS accelerator, the frequency of MELODY is only 1 Hz. This will greatly limit the statistics of µSR experiments [?] and provides strong motivation to run MELODY at higher intensity. But higher muon intensity per pulse will also cause a pile-up problem in the detectors. Decay positrons will be incident on detector channels closely spaced in time, resulting in challenges in accurately measuring the time of individual positron events.

Therefore, to utilize a higher-intensity muon source, detectors used in µSR spectrometers need to be faster and more highly segmented. A smaller detector pixel size decreases the possibility of multiple decay positrons reaching a single detector at overlapping times, while a faster detector with narrower signal width increases the likelihood of accurately distinguishing signal arrival times. The dominant detector technology applied in recently developed µSR spectrometers is the "scintillator with SiPM" system, which usually has a signal pulse width on the order of 100 ns and a detector pixel size of several square centimeters. The research group at MELODY is designing a µSR spectrometer following the "scintillator with SiPM" method [?]. Many efforts have been contributed to study the performance of this spectrometer running on MELODY. Results show that a µSR spectrometer based on a scintillator with SiPM detector system cannot utilize the full muon flux per pulse available at MELODY and would waste muon beam resources.

A novel detector type, the Low Gain Avalanche Diode (LGAD) [?], is a promising candidate to solve this problem. LGAD is an advanced detector technology developed in recent years to measure particle arrival time at the end cap of ATLAS and CMS under heavy irradiation at LHCb. During development, the research group from China has achieved many accomplishments: The group from IHEP has presented the design of LGAD with shallow carbon and deep N++ layer [?, ?], which has greatly improved radiation hardness to 2.5×10^{15} n_{eq}/cm^2. They have also contributed many efforts to improve LGAD performance [?]. Meanwhile, the group from USTC of China has conducted studies on the dynamic properties of LGAD [?].

The notable features of LGAD are listed in Table 1. Given the small signal pulse width without detector dead time, the response of LGAD to charged particles is very fast. This fast response, along with small segmentation size, benefits improving the counting rates of µSR spectrometers and addresses some limitations of scintillator-SiPM based technologies. In addition, LGAD' s thin active volume reduces multi-counting effects among neighboring channels in a detector matrix, and its good irradiation hardness enables stable operation, especially under the high-radiation environment at a high-intensity muon source.

One possible shortcoming is the dead area of ordinary LGAD, which occupies 50 µm on the edge of each segmentation channel. This leads to a slight decrease in detection efficiency to about 85%, which could be optimized in future LGAD designs.

Besides LGAD, some types of fast timing resolution detectors have also been developed. However, their performance is not as perfect as LGAD and not very suitable for µSR experiments. The microchannel plate (MCP) is fast and has good spatial resolution, but its dead area occupancy is large. Only positrons entering the microchannels can produce significant signals. Since the channels are usually several µm in diameter with pitch distances of several µm, the detection efficiency of MCP is much lower than LGAD, limiting its applications in µSR experiments. The SiC detector and diamond detector have advantages of short pulse width and good irradiation performance. However, SiC is limited by its sensitive depth, which is usually in the range of 20 to 30 µm. It is typically applied in detecting alpha particles and is not suitable for detecting muon decay positrons. Diamond detector performance is unstable due to its polarization phenomenon. It is not a good option for µSR experiments based on cost considerations, as a large detector matrix would need to be established if applied. Based on these detection characteristics, LGAD is expected to be a good candidate to replace the scintillator technology widely applied in existing µSR spectrometers and will improve count rate capability by utilizing increased muon source flux.

Table 1 . Selected performance parameters of LGAD detector [**?**].

Performance	Parameters
segmentation size	1.3×1.3 mm^2
active area	1.2×1.2 mm^2
active thickness	50 µm
timing resolution	10 30 ps
full pulse width	2-3 ns
irradiation hardness	$> 10^{15}$ n_{eq}/cm^2

To demonstrate this, a test experiment has been conducted at the ISIS pulsed muon source at RAL, which will be discussed in this paper. The instrumentation used for this test experiment is described in Chapter II, including the characteristics of the muon source, the CHRONUS muon instrument, and the detector setup. In Chapter III, a summary of the data, the progress of data analysis, and a discussion of results is presented. Finally, in the last chapter, the experiment and its conclusions will be summarized and the application of LGAD in µSR technology will be prospected.

Instrumentation Setup

The test experiment introduced above was conducted using the ISIS pulsed muon source at RAL in the UK. The LGAD detector was produced in China, and a test board carrying the LGAD detector and readout electronics was assembled in China and transported to the experiment at RAL. Details about the instrumentation used for this experiment will be discussed in this chapter.

A. The Muon Source

The experiment utilized the surface muon beam delivered to the CHRONUS instrument port, which is one of the suite of muon spectrometers at ISIS [**?**, **?**]. Fig. 1 shows a view of the CHRONUS instrument. It has 606 detectors and can be used for zero field (ZF), transverse field (TF), and longitudinal field (LF) µSR experiments. The magnetic fields are produced by red magnet coils fixed onto a Bosch framework. Fields of up to 3950 G can be applied. During our test, TFs of 0 Gauss, 50 Gauss, and 100 Gauss were applied during various tests conducted.

The beam snout through which muons are delivered to the experiment is obscured by the CHRONUS instrument in Fig. 1. The muon beam is produced upstream of the beam port, where 800 MeV protons are incident on a carbon target and the resultant muons are extracted and transported downstream to the experiment. Depending on the features of the proton beam, the extracted muon beam is provided at a repetition frequency of 40 pps, with the FWHM of each pulse around 55 ns [**?**]. Although muons are produced in double bunch mode, they can be delivered to CHRONUS as single or double pulses [**?**]. For this experiment, CHRONUS was configured for single bunch mode operation, which was most suitable for testing the LGAD system. This experiment was performed in parallel with a second set of experiments on a scintillator-based detector system being developed for the new µSR spectrometer on MELODY [**?**]. The intensity of the incident muon beam was in the range of 10^4 to 10^5 muons per second.

A T0 signal is available from the proton accelerator 4 µs in advance of the beam pulses arriving at the muon production target. This signal is used as a time reference to start monitoring the time evolution of muon spin polarization, which holds important information about the magnetic properties of the sample to be measured in µSR experiments.

Fig. 1 [Figure 1: see original paper]. Photo of CHRONUS. The coils are fixed by a Bosch framework and are able to provide uniform magnetic fields of up to 3950 G.

B. The Detector Setup and Devices

The layout of the detector setup can be found in the sketch shown in Fig. 2(a). The yellow ring indicates the magnet coils of the CHRONUS spectrometer, which generate a TF along the direction perpendicular to the plane of the paper. The sample is represented by the green block and placed in the path of the muon beam (as indicated by the red lines). The sample material is silver, which is paramagnetic and has a very weak nuclear moment. Therefore, the field inside the silver sample is approximately equal to the field generated by CHRONUS. The muon beam is incident from the left and implanted in the silver sample. Since the kinetic energy of surface muons is low, all muons will be stopped in the sample and then decay into positrons and neutrinos.

The muons provided by the source are to good approximation 100% spin-polarized, with the initial muon spin direction aligned opposite to the muon momentum. Because decay positrons are preferentially emitted along the direction of muon spin at the moment of decay, when muons stop in the material, the initial direction of emitted decay positrons will be distributed as shown by the black dashed line in Fig. 2(b). In the presence of a magnetic field in the sample, the spin of stopped muons will rotate under Larmor precession. After time t, the average direction of muon spins rotates to the right, and the direction of emitted decay positrons will be distributed as shown by the blue dashed line. When a detector is fixed beside the sample, the positron counts detected as a function of time will be influenced by muon spin rotation. Where muons precess in phase in a net magnetic field, an oscillation will be found coupled to an exponential signal that arises due to the muon lifetime, as shown in Fig. 2(c). The frequency of the oscillation depends on the magnetic field strength, whereas the amplitude depends on the magnetic volume fraction, detector location, and any degrader [**?**].

Based on this principle, the LGAD is fixed in a plane to the side of the sample. Its zenith angle to the muon beam is deviated from 90 degrees to avoid the LGAD being hit by positrons present in the incident beam that miss the sample or are scattered by it. A signal will be generated and read by the readout system when a positron hits the sensitive detection area of LGAD.

The LGAD detector is bonded on a PCB, as shown in Fig. 3. The sensitive area is a 2.6 × 2.6 mm^2 square on the left part of the device as shown in Fig. 3(a). The remaining area on the PCB is occupied by amplifier circuits. Signals from the LGAD after amplification are read out from the SMA connector at the right edge of the PCB. The detector PCB is fixed by a clamp as shown in Fig. 3(b), with its sensitive area facing towards the sample in the beam. The distance from the sample to the detector is approximately 15 cm.

Fig. 2 [Figure 2: see original paper]. (a) Sketch of the horizontal profile of the device setup (not to scale). The green block indicates the sample in the muon beam. The yellow ring indicates the magnetic field coils of CHRONUS, which generate a magnetic field along the direction perpendicular to the plane of the paper. The LGAD is fixed to the side of the sample. Positrons are emitted when muons that stop in the sample decay, and the fraction that intersect the LGAD device will be detected. (b) Sketch of the field and expected evolution of muon spin polarization. The precession of the muon will influence the count of positrons detected by the LGAD. (c) Arbitrary illustration of the µSR signal influenced by muon precession. Units are arbitrary. Oscillations coupled to the exponential function are due to Larmor precession of muons about a net field. Details see text.

Fig. 3 [Figure 3: see original paper]. Photos of the LGAD detector under test. An LGAD of size 2.6 × 2.6 mm^2 is bonded on the detector PCB (a). The detector PCB is fixed by a clamp (b). The detectors used in this test are produced by the Institute of High Energy Physics, CAS. The yellow label in (b) does not represent any real information.

Table 2 . Summary of the statistics of the test.

TF (G)	DAQ time (h)	Count of events	Rate of events (per second)

C. The Readout System

The signal from LGAD is very fast. Typically, the width of the rising edge is around 700 ps and the full width of a signal is around 2 ns. Because of the very fast signal, a readout system with high sampling rate is needed. With this in mind, the Fast Read-Out System (FROS) [**?**] was taken to ISIS for the experiment to read and store signals generated by the LGAD detector. Photos of the FROS can be found in Fig. 4.

In total, two DAQ channels were loaded, making the system able to read signals from two detectors synchronously. (However, only one LGAD was used and connected to one of the DAQ channels in the FROS.) Besides the two DAQ channels, a controller in charge of DAQ control and data storage and a TCM board in charge of multi-channel clock alignment were loaded. The T0 signal introduced in Section II A was connected to the FROS. The timing clock on the DAQ channels was initiated as soon as the FROS received a T0 pulse. The voltage trigger threshold and the length of data acquisition were adjustable. The FROS records the waveform it receives immediately when the voltage threshold is triggered, as well as the time of the waveform data point (Ts0) since the most recent T0 pulse. In order to determine the time of signals produced by positrons (Ts), some signal processing was performed and will be introduced in Section III A. From Ts, the measured sample signal for a µSR experiment can be extracted after necessary analysis.

Fig. 4 [Figure 4: see original paper]. (a) Photo of the FROS. Two channels with 6.4 Gsps sampling rate are loaded. (b) Photo of FROS under test in lab. Thanks to the support of power supplies provided by ISIS muon group.

Analysis and Results

The progress of data analysis will be introduced in this chapter. In the first section, a summary of the data will be provided and the recorded waveforms will be displayed and discussed. In the second section, the analysis of µSR signals, which hold information about the evolution of muon spins, will be described. Lastly, the performance of LGAD in this test and future prospects for its application to µSR spectrometers will be discussed.

A. Waveform of Positron Signals

The statistics for the LGAD test are summarized in Table 2. The active time of data acquisition was around 31.4 hours in total. During the test, the event rate was kept at a stable and low level, approximately 2.3 events/s on average.

One concern in detecting muon decay positrons with LGAD is signal significance. The average energy of positrons is 29 MeV, which is very fast and in the state of a minimum ionization particle (MIP). Particles in the MIP state usually deposit low energy, making the signal insufficiently significant for detection. To investigate this concern, the waveforms of signals are summarized and demonstrated in Fig. 5. In Fig. 5(a), it can be seen that the full width of the waveform is around 2 ns, which is the reason for using FROS. The signals after amplification have an average amplitude of 101.2 mV, illustrated by the blue markers in Fig. 5(b). To evaluate oscillations of white noise in the waveform, the amplitudes of the baseline in every waveform are summarized and illustrated by the histogram with black open markers in Fig. 5(b). This can be fitted by a Gaussian function, from which the sigma of white noise amplitude is found to be around 2.8 mV, whereas the mean is approximately 0. Considering that the signal-to-background ratio is more than 30, this suggests that signals from muon decay positrons on LGAD are significant enough. Based on the fact that the signal is significant and that most muon decay positrons deposit a similar amount of energy in LGAD since they are in the MIP state, the detection efficiency of LGAD in µSR experiments would be around 85%, which is dominantly contributed by the dead area on the edge of each LGAD segmentation cell. Therefore, it is indicated that LGAD has the ability to detect muon decay positrons.

As introduced in Section II C, the time of the first waveform data point since the most recent T0 pulse (Ts0) was recorded along with the data package. However, the time of positron signals since the most recent T0 pulses (Ts) is more important in µSR experiments. Ts does not equal Ts0 since there is time walk during fast data acquisition, which causes variation in the length of waveform buffer before the positron signal. In other words, the positions of positron signals in the waveform are not constant. Thus, a correction to Ts0 should be applied utilizing the Constant Fraction Discrimination (CFD) method. As illustrated in Fig. 5(c), Ts1 represents the correction term from the first waveform data point to the time when the leading edge of the voltage waveform reaches the 50% CFD threshold. Then, Ts = Ts0 + Ts1 will be the corrected time of positron signals since the most recent T0 pulses.

Fig. 5 [Figure 5: see original paper]. (a) Demonstration of one of the waveforms recorded by the FROS. The full width of the waveform is around 2 ns. The white noise on the waveform baseline is relatively weak. (b) Comparison between the amplitude of positron signals (blue markers) and white noise (black open markers). A threshold of 50 mV was applied to FROS during the test. With Gaussian fitting, the sigma of the amplitude of white noise is around 2.8 mV, whereas the mean of the signal amplitude is more than 101 mV. The signal-to-background ratio is more than 30, which implies that signals from muon decay positrons on LGAD are significant enough. Details see text. (c) Illustration of waveform operations to get Ts. A 50% CFD is applied to get Ts1, which is the correction term of Ts0.

B. Result of the Analysis

The target of a µSR experiment is to acquire magnetic information about a sample from the evolution of muon polarization, which is characterized by the time of positrons detected by LGAD (f(t)). Thus, f(t) is measured most directly in a µSR experiment. The method to achieve this is illustrated in Fig. 6. Tp represents the time when the muon is produced. T1 represents the muon lifetime, including muon flight time and muon precession time in the sample. T2 represents the time when the decay positron is detected by LGAD. T0 represents the time when FROS receives the T0 pulse, which depends on the path length between the muon target and muon kicker, and the length of the T0 signal cable. During the test, T0 - Tp was always kept constant.

The most ideal situation would be to measure T1 - Tp. However, Tp cannot be measured exactly. Considering that T0 - Tp is fixed, that an absolute value of T1 - Tp is not necessary, and that T1 approximates T2 since positrons are very fast, T2 - T0 can be measured to obtain f(t) in the experiment.

Fig. 7(a), Fig. 7(b), and Fig. 7(c) show the measured f(t) under applied TFs of 0 G, 50 G, and 100 G, respectively. The open black dots with error bars are the data and the red lines are fits to the data, whereas the blue dashed lines are the exponential component acquired after fitting and deducting the oscillating component. The fitting results are listed in Table 3 .

Table 3. Result of fitting the data measured at the three magnetic field conditions.

TF (G)	τµ (ns)	Bµ (G)	^{2}/NDF
0	2189 ± 15	-	-
50	1649 ± 12	52.2 ± 0.1	0.245 ± 0.004
100	2203 ± 7	104.0 ± 0.1	0.251 ± 0.004

Fig. 7(a) is fitted with an exponential function as expressed by (1):

$$f(t) = N_0 \cdot e^{-t/\tau_\mu} + C$$

where N_0 represents the starting intensity of muon decay, C represents a common background correction factor, and τµ represents the muon lifetime, fitted as 2.2 µs. This validates that LGAD performs well at detecting muon decay positrons, considering the coincidence with the expected theoretical value.

In Fig. 7(b) and Fig. 7(c), fitting is performed using asymmetry functions [**?**] as expressed by (2):

$$f(t) = N_0 \cdot e^{-t/\tau_\mu} \cdot (1 + A_0 \cdot P_i(t)) + C$$

where A_0 is the asymmetry factor depending on the covered solid angle of the detector and P_i(t) is the normalized projection of muon polarization along the detector direction. P_i(t) is calculated from the formula expressed by (3):

$$P_i(t) = \cos^2\theta + \sin^2\theta \cdot \cos(\gamma_\mu B_\mu t)$$

where γµ is the gyromagnetic ratio of the muon, with constant value of $2\pi \times$ 135.5 MHz/T, Bµ is the magnetic field seen by the muons, and represents the angle of the magnetic field with respect to the initial polarization. In this test, a TF was set in a perpendicular direction to the muon beam (as shown in Fig. 2(a)). Thus, (3) simplifies to (4):

$$P_i(t) = \cos(\gamma_\mu B_\mu t)$$

Considering a common background correction factor C and a timing bias correction factor b, the muon decay time detected by LGAD can be expressed by (5):

$$f(t) = N_0 \cdot e^{-t/\tau_\mu} \cdot (1 + A_0 \cdot \cos(\gamma_\mu B_\mu (t - b))) + C$$

With formula (5), the data in Fig. 7(b) and Fig. 7(c) are fitted. The µSR signals shown in Fig. 7 and expressed in (5) have two dominant components: the decay background and the asymmetry signal. The decaying background component is contributed by the nature of muon decays, which obey an exponential distribution with a mean lifetime of 2.2 µs. The asymmetry signal, which is a cosine function in time, corresponds to Larmor precession of the muon spin. This precessional component has been separated out and shown in Fig. 8 after fitting analysis. The amplitude A_0 (the asymmetry factor) is fitted to be around 0.25 under field configurations of 50 G and 100 G. This value is lower than that of scintillator with SiPM, which should be the portion contributed to improvement of muon source intensity since their distances to the target are approximately the same. Therefore, considering the narrower pulse width and smaller segmentation size, the µSR spectrometer utilizing LGAD could be capable of handling a muon source with greater intensity by two orders of magnitude.

In µSR applications, measuring magnetic field strength is important, which corresponds to the oscillation frequency of the µSR asymmetry signal. In general, the asymmetry oscillation weakens when timing resolution degrades. Therefore, measuring high-frequency asymmetry is not the advantage of pulsed muon source µSR experiments. However, this defect can be compensated by improving timing resolution. The dominant timing resolution in pulsed muon source µSR experiments is usually contributed by the beam pulse width, which is typically on the order of tens of nanoseconds. In comparison, timing resolution contributed by detectors is on the order of nanoseconds or better. Developing pulsed muon sources with lower pulse width is one trend for the future. By that time, fast timing resolution detectors like LGAD will surely play a much more important role in µSR experiments.

In summary, compared to the "scintillator with SiPM" applied in conventional µSR spectrometers, the advantages of LGAD are as follows. Firstly, LGAD is much faster, which would break the dead time limitation of SiPM and improve the allowed counting rate of each single detector element. Secondly, LGAD is much smaller in size, making it possible to construct a detector matrix with high channel density and achieve a higher overall counting rate in the spectrometer. Thirdly, the active volume of LGAD is much thinner than scintillator, which naturally reduces multi-counting prevalence across neighboring detectors. Additionally, LGAD has a high signal-to-noise ratio since it is not sensitive to gammas compared to scintillator. Therefore, gamma annihilation background would be significantly decreased. Based on these advantages, LGAD is expected to be a good candidate for the next generation of detectors used in µSR spectrometers.

Fig. 6 [Figure 6: see original paper]. Demonstration of the method to achieve muon decay time. Details see text.

Fig. 7 [Figure 7: see original paper]. Result of the analysis. Distribution of muon decay time. Samples are placed under different magnetic fields of 0 G in plot (a), 50 G in plot (b), and 100 G in plot (c), respectively. Details see text.

Fig. 8 [Figure 8: see original paper]. Asymmetry signals in 50 G (left panel) and 100 G (right panel), after correction for the exponential decay.

C. Discussions

As introduced in Section I, the purpose of this test experiment is to demonstrate that LGAD is a promising detector technology to improve count rate capability when utilizing an intensive muon source. During the test, LGAD received a stable event rate of about 2.3 events per second (or around 0.06 events per muon pulse), while a parallel test on scintillator with SiPM for MELODY' s new µSR spectrometer received about 1 event per detector per pulse. Both event rates were limited by the intensity of the ISIS muon source, and neither detector reached their count rate capabilities. However, the relative count rate capability of both detection technologies can be roughly inferred based on pulse width and segmentation size. Since the pulse width of LGAD is around 2-3 ns, while the current pulse width of scintillator with SiPM is 15 ns, when both detectors reach the same pile-up rate, the muon source intensity utilizing LGAD would be 5-7 times greater than that utilizing scintillator with SiPM. From the perspective of segmentation size, since the area of LGAD is smaller, its counting rate should be lower than scintillator with SiPM, which will also benefit improvement of muon source intensity. Our test results show that the counting rate of LGAD is around 17 times lower than scintillator with SiPM, which should be the portion contributed to improvement of muon source intensity since their distances to the target are approximately the same. Therefore, considering the narrower pulse width and smaller segmentation size, the µSR spectrometer utilizing LGAD could be capable of handling a muon source with greater intensity by two orders of magnitude.

Conclusion and Prospects

A test of LGAD technology has been carried out using the CHRONUS instrument at the ISIS muon source, RAL, UK. The details of the experimental setup as well as subsequent data analysis have been discussed in this paper, from which several conclusions can be presented.

First, considering the coincidence between measured muon lifetime and expected theoretical value, LGAD is able to detect the very fast decay positrons from muon decays, which is vital for deducing the evolution of muon spin polarization in µSR experiments. Second, given that µSR signals are clearly observed for a test sample in different transverse magnetic fields, the LGAD data have provided explicit evidence of Larmor precession of muon spins. From this signal, magnetic fields in the sample have been extracted and found to correspond to expected applied magnetic fields. Third, based on fits to the asymmetry data, the asymmetry term as a function of time can be explicitly separated from the muon decay lifetime signal, which is essential for analyzing magnetic properties of materials in future µSR experiments. Finally, considering detector features of fast response and small pixel size, the speed of LGAD in detecting µSR signals is much faster than the scintillator system. This suggests that LGAD has the potential to enable full utilization of more intense pulsed muon sources and increase the efficiency of µSR experiments, which is especially relevant to a low repetition rate source such as MELODY.

Consequently, with the test of LGAD technology and subsequent analysis discussed in this paper, LGAD is proven to be a promising option for the design of next-generation µSR spectrometers. LGAD is especially expected to greatly improve the performance of future µSR spectrometers at the MELODY facility, allowing improved utilization of high-intensity muon beams.

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Note: Figure translations are in progress. See original paper for figures.