Intensity measurement of the surface muon beam of MELODY

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Abstract. A Muon station for science, technology and industry project will be constructed at China Spallation Neutron Source. The Phase I project will provide a surface muon beam with a pulse width of 130 ns at a rate over 10^5 $\mu+$/pulse. Beam intensity is the key design parameter of this project. Accurate measurement of the intensity is also essential for the calibration of the µSR spectrometer. The key to the surface muon intensity measurement is to distinguish background positrons from muons. A double-stacked scintillator detector based on PMT readout scheme has been proposed, which can determine the intensity of muons and background positrons by using pulse shape discrimination method. Detailed description of the detector principle and simulated results will be presented.

1. Introduction

The Muon station for sciEnce, technoLOgy and inDustrY (MELODY) at China Spallation Neutron Source (CSNS) will be the first muon source in China [1, 2]. MELODY will focus on multidisciplinary research based on µSR technique as well as particle physics, and nuclear physics [3, 4]. A pulsed surface muon beam and a µSR spectrometer will be built in the phase I project. Table 1 lists the key parameters of the pulsed surface muon beam. The CSNS accelerator facility provides a 1.6 GeV proton beam that drives the muon production target at a repetition rate of 1 Hz to produce surface muons. These muons are collected by solenoidal magnets and transmitted to the experimental area. The majority of the contamination of the muon source is the positrons, which have the same momentum as surface muons. Most of the positrons are filtered by the Wien Filter during the delivery, while a fraction of positrons can be transported with muons to the experimental area [5].

Beam intensity is the key parameter for the muon beam. Accurate measurement of the beam intensity is also essential for the µSR spectrometer design. The beam intensity measurement detector (BIMD) is proposed to measure the beam intensity and estimate the ratio of background positrons. It is located at the outlet of the beam tube after the last quadrupole magnet, as shown in figure 1.

Table 1: Key parameters of the pulsed surface muon beam.

Parameters	Value
Muon Momentum (MeV/c)	29.8
Pulse Repetition (Hz)	1
Pulse Width (ns)	130
Intensity (μ^+/s)	10^5
Beam Spot (mm^2)	30×30
Background	e^+(∼29 MeV/c)

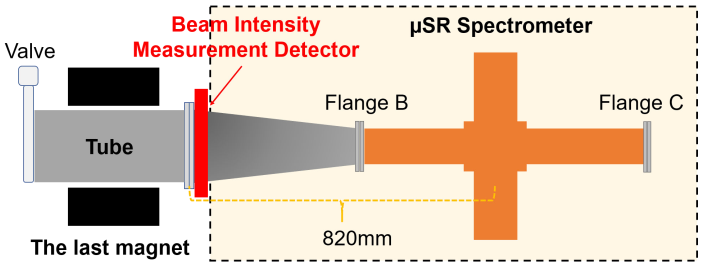


Figure 1: Layout of the BIMD at MELODY.

2. Solution of BIMD

It is unrealistic to measure the intensity of pulsed muon beam with counting method due to a large number of particles hitting the detector nearly simultaneously [6]. We adopt the destructive technique based on energy deposition measurement in scintillator detector [7]. In order to distinguish background positrons from muons, a double-stacked scintillator detector scheme with PMT and waveform-sampling readout electronics is proposed. As shown in figure 2, the surface muons deposit all the kinetic energy and stop in the Scint1 while the background positrons pass through Scint1 and Scint2. The stopped muons in Scint1 then decay into positrons with a time constant of 2.2 μs. These decay positrons also deposit energy in Scint1 and Scint2. Therefore, the energy deposition in Scint2 contains two different components, the one deposited by the background positrons and the other deposited by the decay positrons. The latter decreases exponentially with time and it can be reconstructed by fitting method. In Scint1, it contains one more component than Scint2, the energy deposited by surface muons. By using pulse shape discrimination method, the energy deposited by different particles can be reconstructed. According to the energy deposition, the intensity of surface muons and background positrons can be obtained respectively.

We use fast plastic scintillator as the sensor of BIMD. It has a peak emission of ∼391 nm, a light yield of ∼10000 photos/MeV, and a light attenuation length of 120 cm. The light pulses produced in the scintillator are collected and further processed to electric pulses by the PMT. A readout system based on wave-sampling technique have been developed [8]. It can operate with 12 bit ADC and 1 GHz sampling rate. The signal pulses exported from PMT1 and PMT2 are finally sampled by the readout electronics.

3. Simulation setup

Energy response of BIMD was simulated with Geant4. As shown in figure 3, the geometry model includes beam tube, window, and two layers of plastic scintillator. The inner diameter of the beam tube is 300 mm and the outer diameter is 304 mm. A beryllium window with a thickness

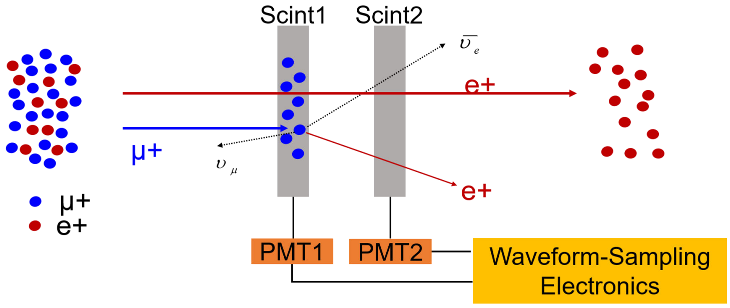


Figure 2: Schematic diagram of BIMD based on double-stacked scintillator detector.

of 100 μm is used in the simulation. Both the scintillators are set as a block with a side length of 150 mm and a thickness of 5 mm. The distance between the window and Scint1 is 100 mm, and it is 20 mm between the scintillators.

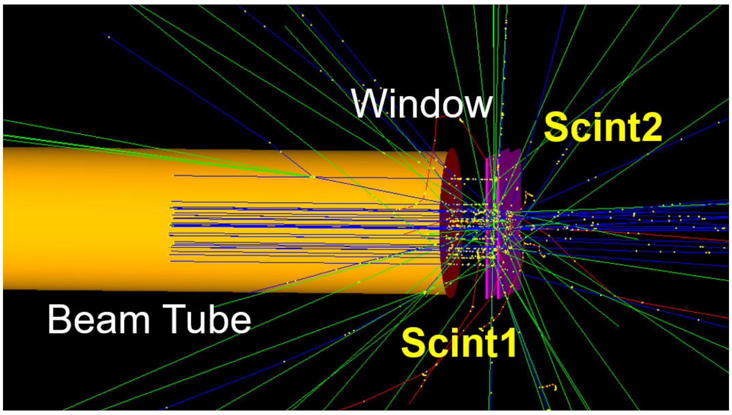
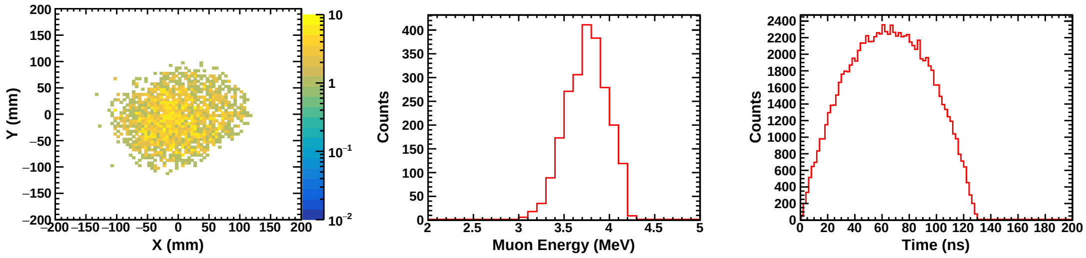


Figure 3: Geometry setup of the simulation.

Figure4 shows the beam profile and energy distribution of muons at the outlet of beam tube. The initial position of beam particles and energy of muons are randomly sampled from these distributions, while the energy of positrons is set to a constant value of 29 MeV. The time structure of the beam pulse is shown in figure 4c, it is set as a parabolic distribution with a baseline time width of 130 ns. The number of particles in a beam pulse is set to 100000, and the ratio of muons can be adjusted in the range of 0 to 1.



(a) (b) (c)

Figure 4: (a) Beam profile, (b) Energy distribution of muons, (c) Time structure of beam pulse.

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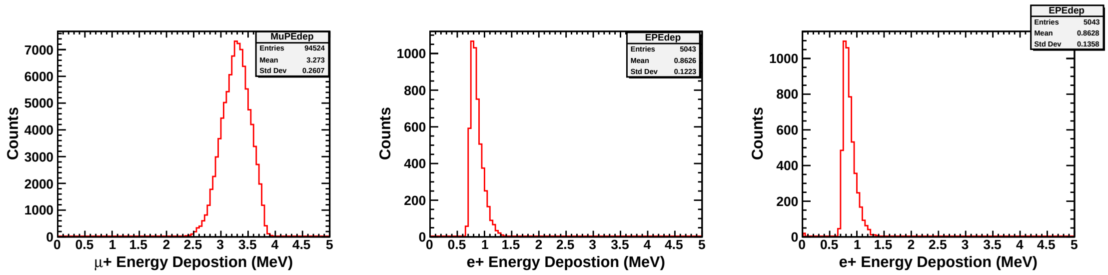
4. Simulation results

4.1. Energy deposition

The surface muons deposit energy and stop in the Scint1. Figure 5a shows the energy deposition in the Scint1 by the surface muons, which shifts left compared to the initial energy spectrum shown in figure 4b due to the window. An average energy deposition per muon in Scint1 of 3.27 MeV ($I_{\mu+}$) is obtained. The background positrons can pass through Scint1 and Scint2, and its energy deposition in two scintillators are shown in figure 5b, figure 5c respectively. It deposits almost the same energy in Scint1 and Scint2 with an average energy deposition per positron in each scintillator of 0.86 MeV (I_{e+}). The decay positrons from the stopped muons in Scint1 also deposit energy in the two scintillators, and it decreases exponentially with time. The key to the beam intensity measurement is to distinguish and reconstruct the energy deposited by different particles.



(a) (b) (c)

Figure 5: Energy deposition of muons in Scint1 (a), energy deposition of background positrons in Scint1 (b) and Scint2 (c).

Figure 6 shows the energy deposition dependent on time in Scint1 and Scint2, which have a very sharp peak followed by a long exponentially decaying tail. The peak structure is similar to the time structure of beam pulse, which is mainly caused by the surface muons and background positrons. The long tails are caused by the decay positrons.

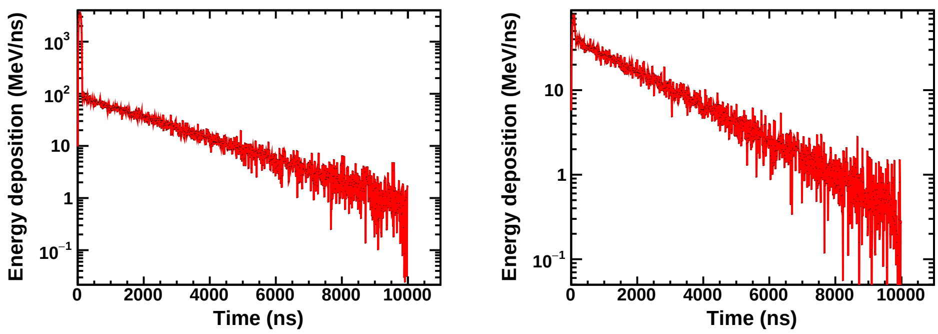


Figure 6: Energy deposition dependent on time in Scint1 (left) and Sint2 (right).

4.2. Beam intensity reconstruction

According to the energy deposition, the signal waveforms of scintillator detectors are obtained by using parametric modeling method. The average energy necessary to emit a photo of scintillator is set to 100 eV. The photo collection efficiency and quantum efficiency of PMT are set to 1%

and 10% respectively. Gain of the PMT is set to 10000. The number of photos and electrons processed in each step are randomly sampled from the Poisson distribution, including the photo emission and collection, electron emitting and amplification. Figure 7 shows the signal waveforms of Scint1 and Scint2 when the ratio of muons in a pulse is 95%. By fitting the signal tail with exponential function convoluted by parabolic function, the contribution of decay positrons can be obtained, as shown as the blue curve in figure 7 .

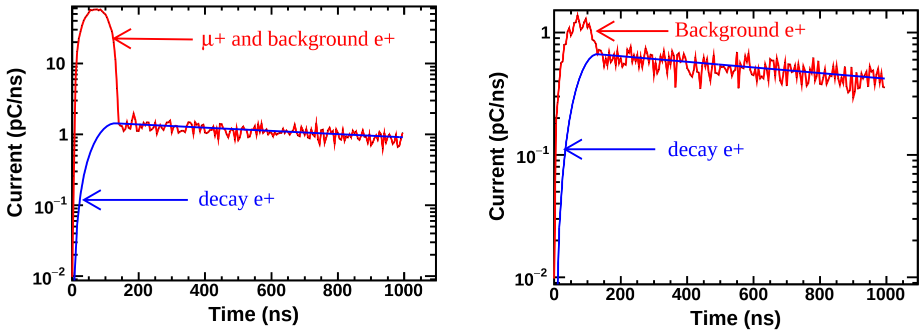


Figure 7: Signal waveforms of Scint1 (left) and Scint2 (right).

The intensity of background positrons and surface muons are calculated by the equation 1 and equation 2 respectively. Where $Q_{1\text{Total}}$ and $Q_{2\text{Total}}$ are the total induced charge of Scint1 and Scint2, which can be calculated by integrating the signal waveforms over time. $Q_{\mu+\text{Decay1}}$ and $Q_{\mu+\text{Decay2}}$ are the total charge induced by the decay positrons, and it is the area covered by the blue curve in figure 7. q_{e+} and $q_{\mu+}$ are the average charge induced by single background positron and single surface muon, which can be calculated from I_{e+} and $I_{\mu+}$. Table 2 shows the reconstructed results of the intensity with different muons ratio in a pulse. The reconstructed bias of muons intensity is less than 1% while it shows a lager value of background positron intensity. When the ratio of muons is 95%, the reconstructed bias is 0.7% and 2.3% respectively.

$$N_{e+} = \frac{Q_{2\text{ Total}} - Q_{\mu+\text{ Decay 2}}}{q_{e+}} \tag{1}$$

$$N_{\mu+} = \frac{Q_{1\text{ Total}} - Q_{\mu+\text{ Decay 1}} - (Q_{2\text{ Total}} - Q_{\mu+\text{ Decay2}})}{q_{\mu+}} \tag{2}$$

Table 2: Reconstructed intensity of muons and background positrons in a pulse.

μ+/e+ ratio	Simu μ+/e+ num	Reco μ+/e+ num	Reco μ+/e+ bias
50%/50%	49896/50104	49230/55990	1.3%/10.5%
90%/10%	89984/10016	89310/10880	0.8%/7.9%
95%/5%	94957/5043	94300/5160	0.7%/2.3%
99%/1%	98988/1012	98420/865	0.6%/17%

5. Summary

A beam intensity measurement detector based on double-stacked scintillator detector was proposed and simulated with Geant4. Simulated results show that BIMD can reconstruct the muon intensity accurately, and it can also discriminate positrons effectively. We have developed a readout system with Waveform-Sampling electronics, the BIMD prototype will be developed in the next step.

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